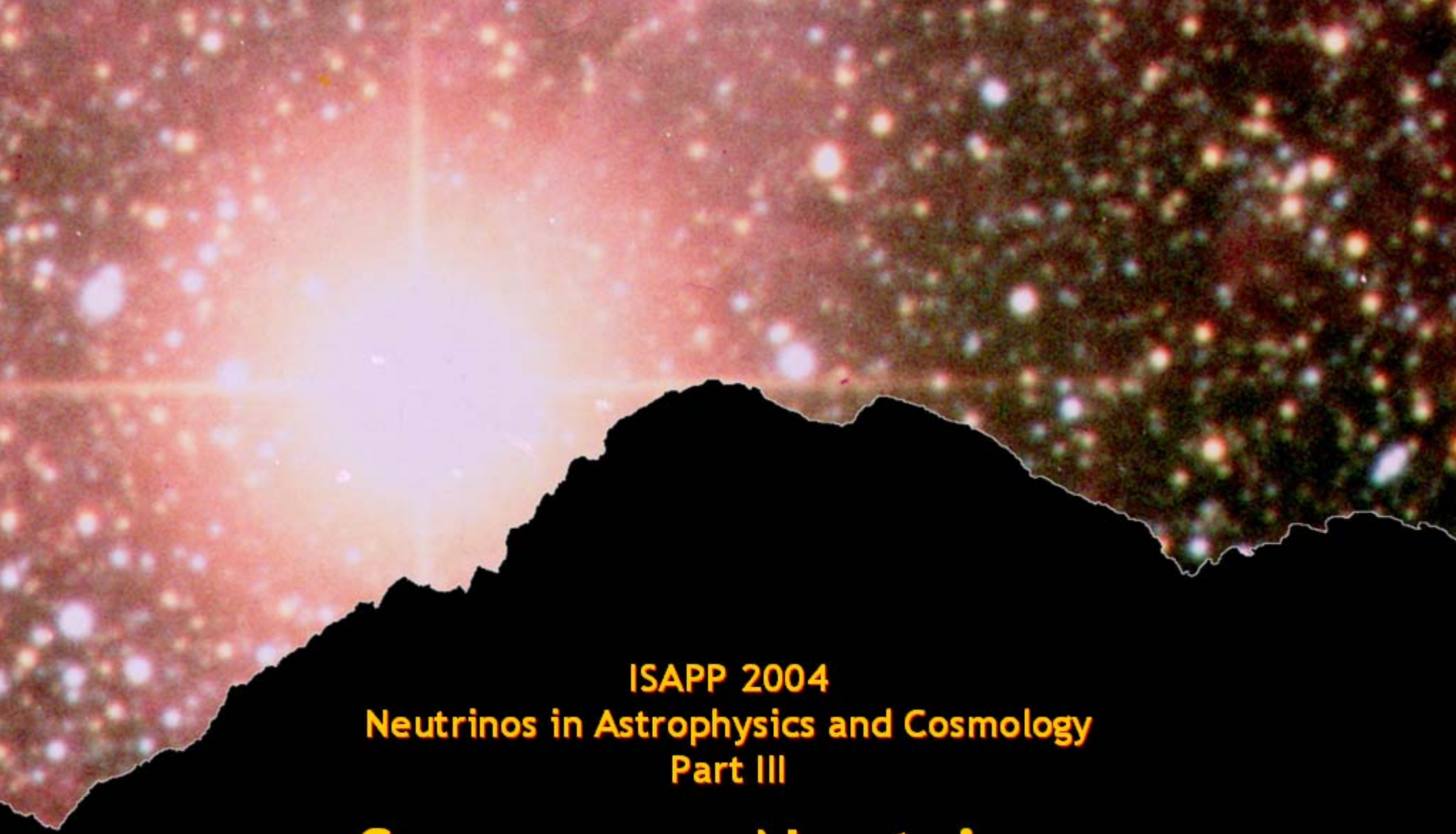


ISAPP 2004
Neutrinos in Astrophysics and Cosmology
Part III

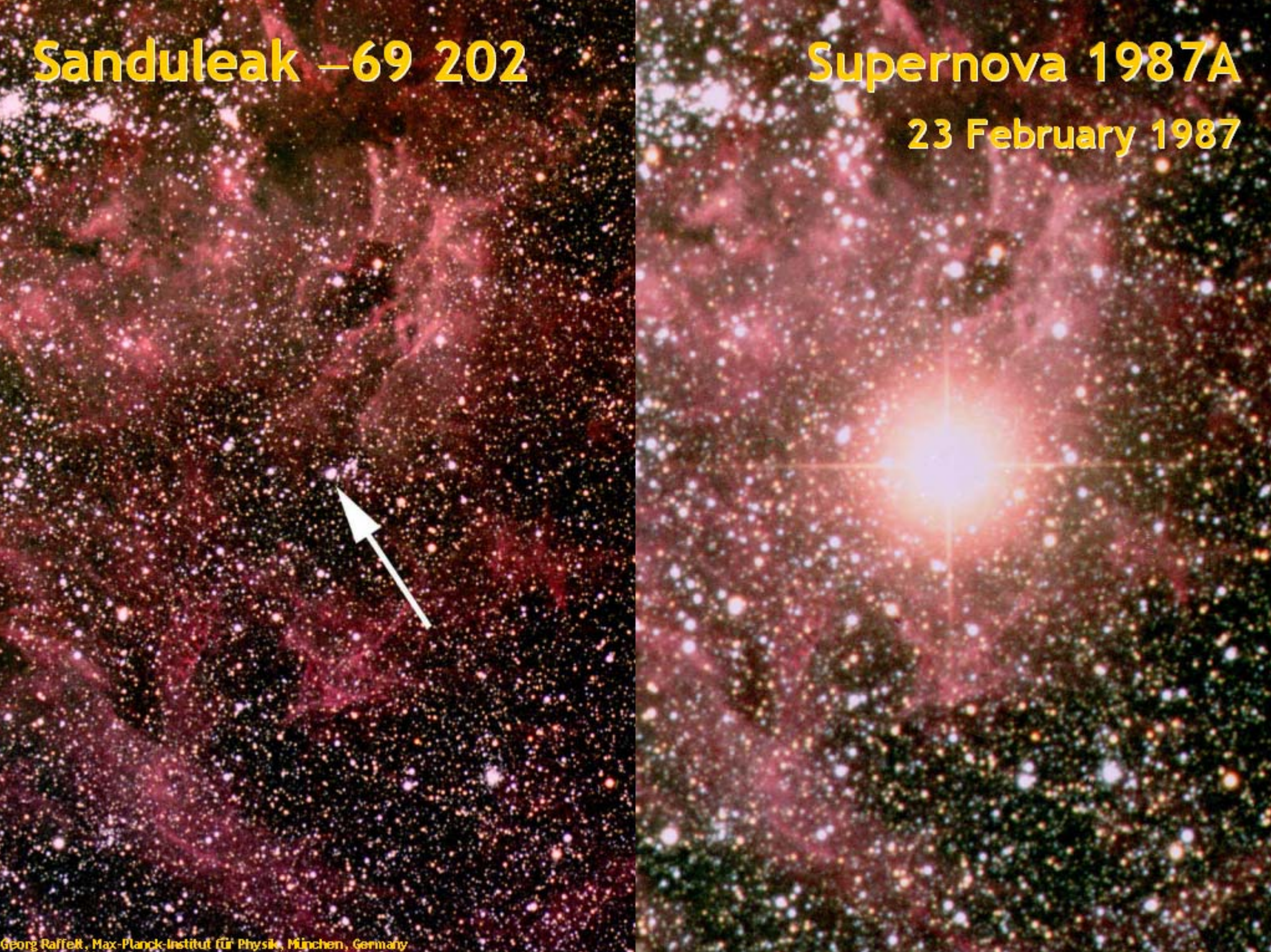
Supernova Neutrinos

Georg G. Raffelt
Max-Planck-Institut für Physik, München, Germany

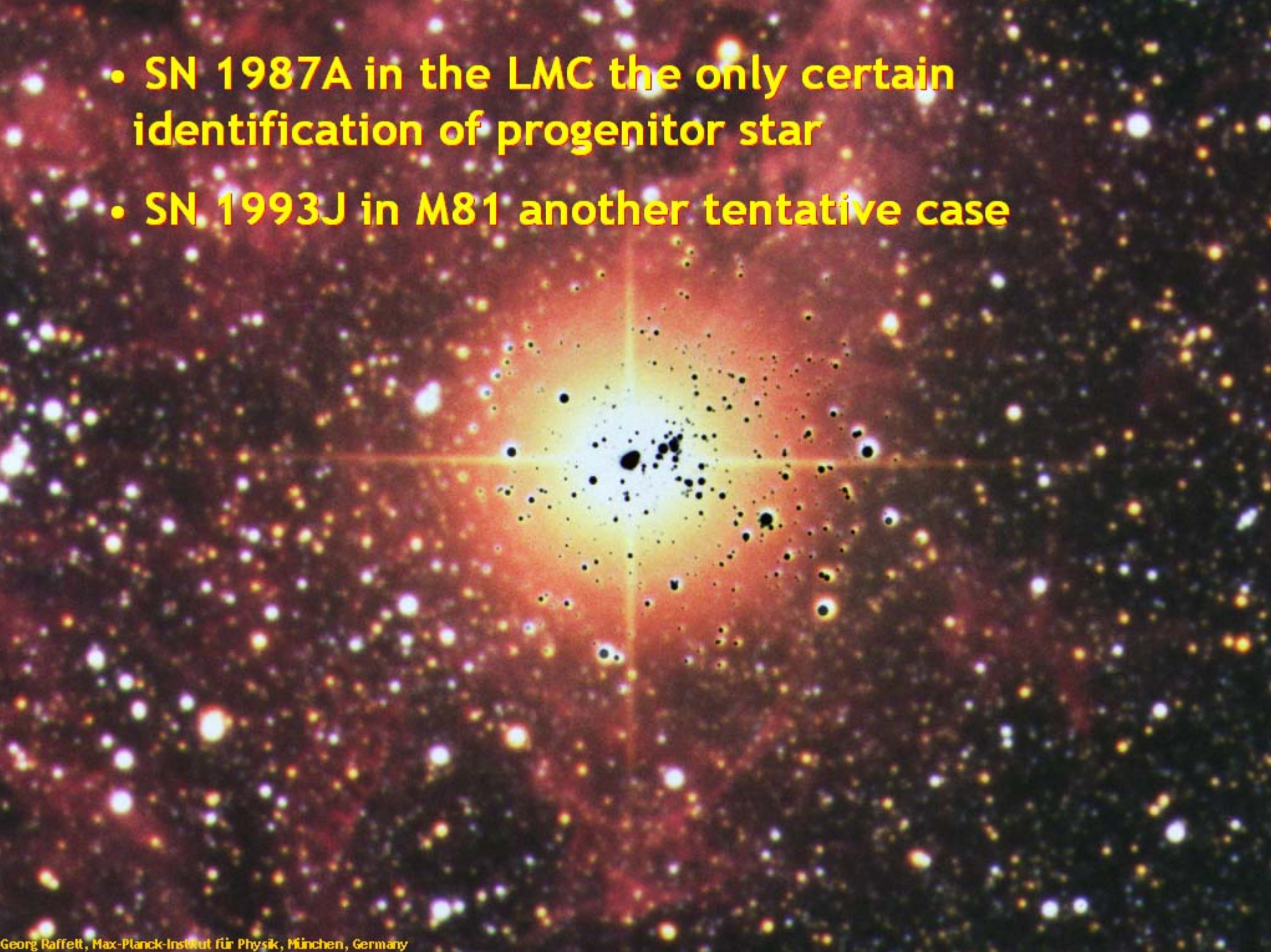

Sanduleak –69 202
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany


Tarantula Nebula

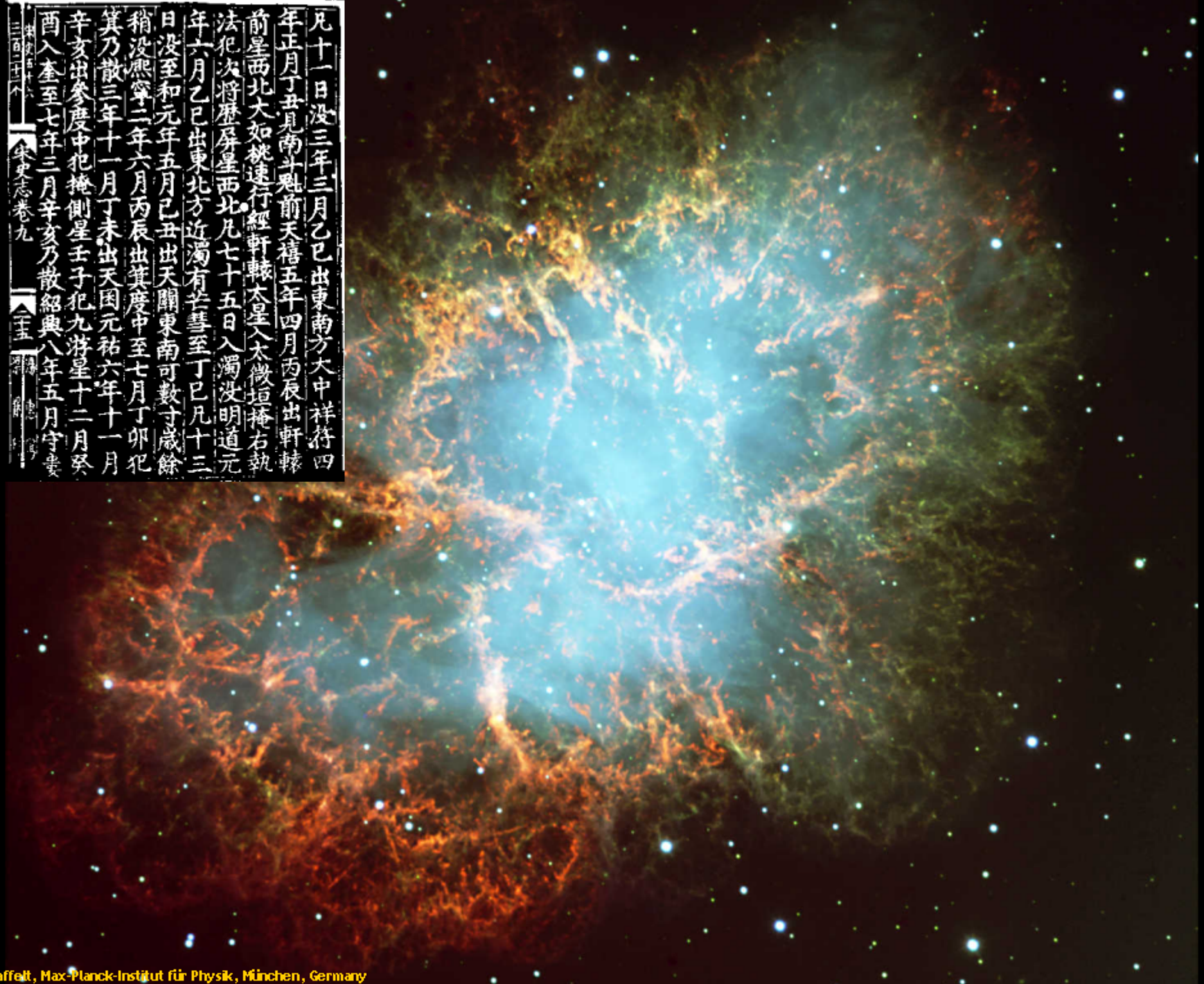

Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)


Sanduleak –69 202
Supernova 1987A
23 February 1987
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

- SN 1987A in the LMC the only certain identification of progenitor star
- SN 1993J in M81 another tentative case

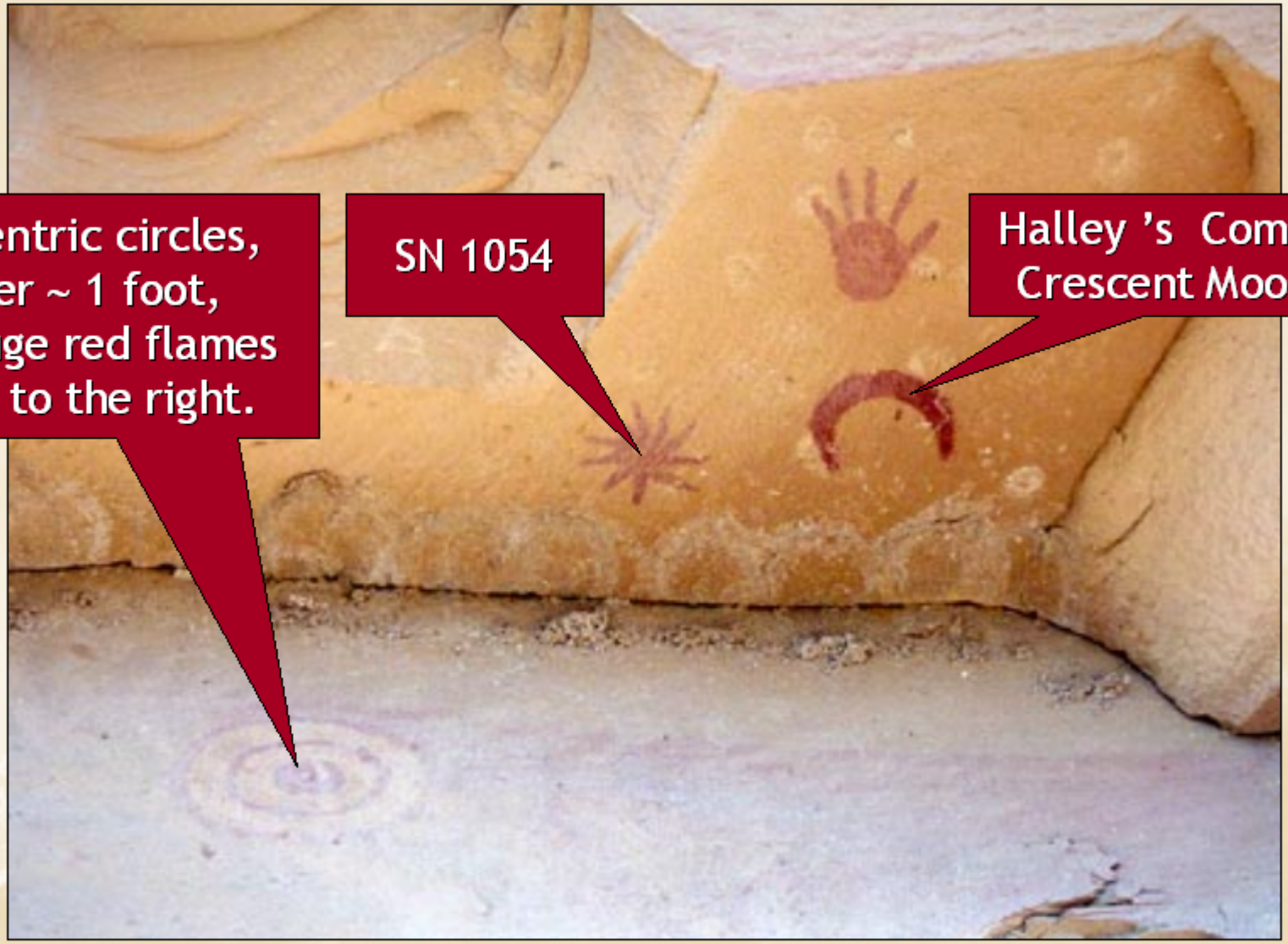


Georg Raffelt, Max-Planck-Institut für Physik, München, Germany



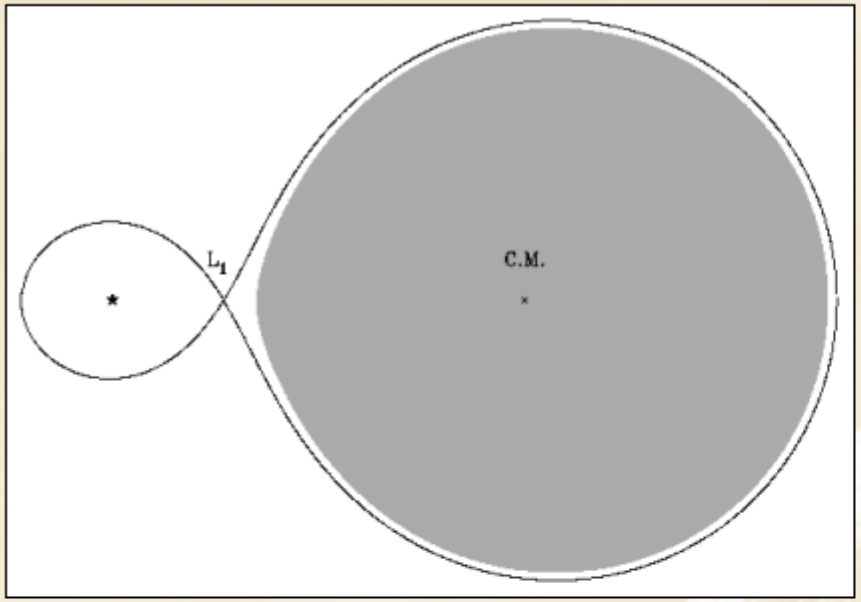
凡十一日沒三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅太星入太微垣掩右執法犯次將歷屏星西北凡七十五日入濁沒明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日沒至和元年五月己丑出天關東南可數寸歲餘稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

Supernova 1054 Petrograph

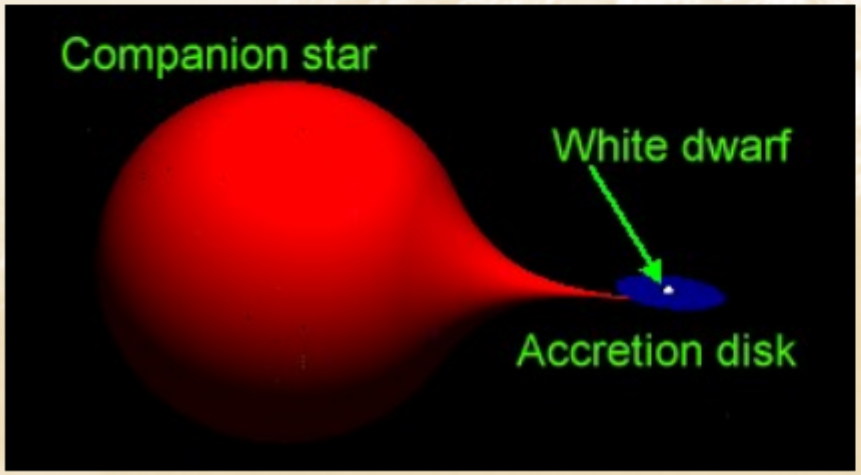


Possible SN 1054 Petrograph by the Anasazi people
(Chaco Canyon, South-Western U.S.)

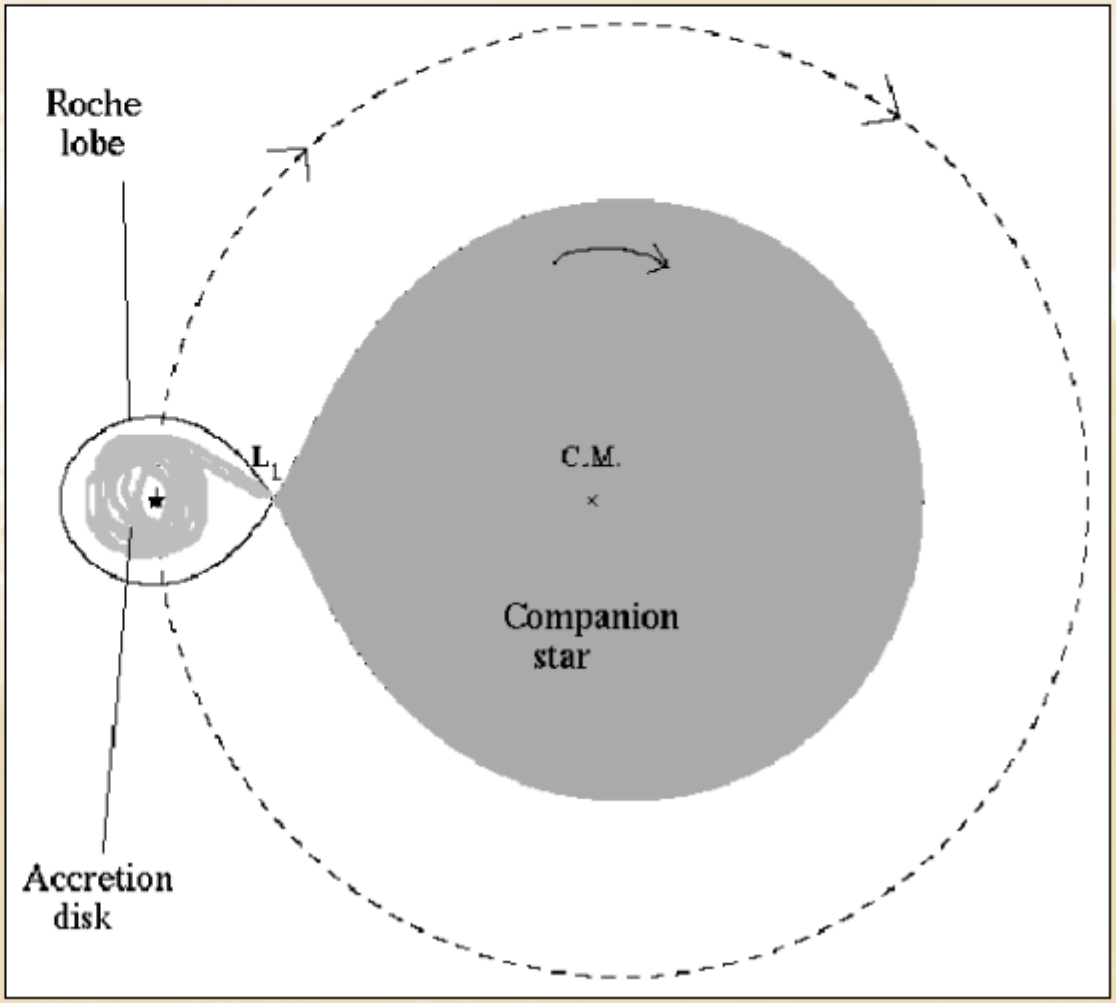
Mass Transfer in Binary Stars



Binary system of white dwarf and evolved companion star, beginning to fill the "Roche lobe"

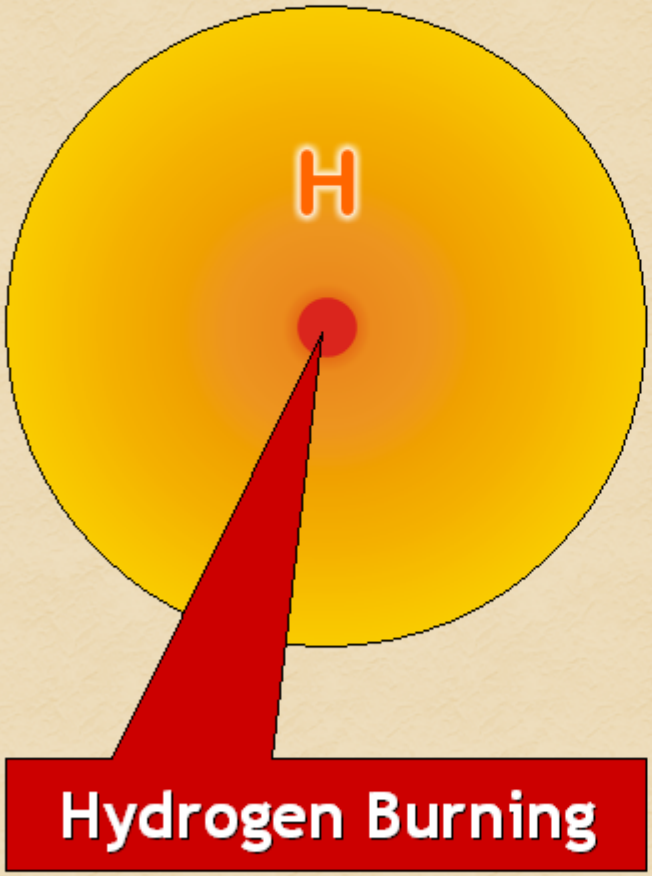


Roche-lobe overflow feeds mass to the compact star

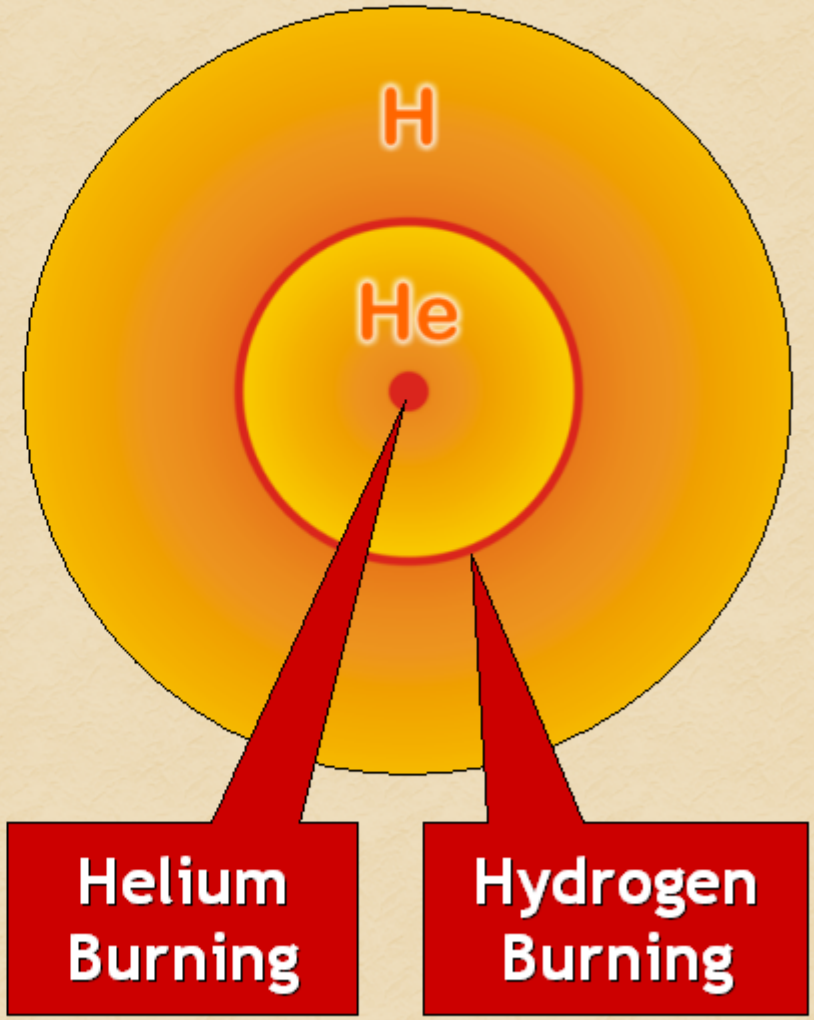


Stellar Collapse and Supernova Explosion

Main-sequence star



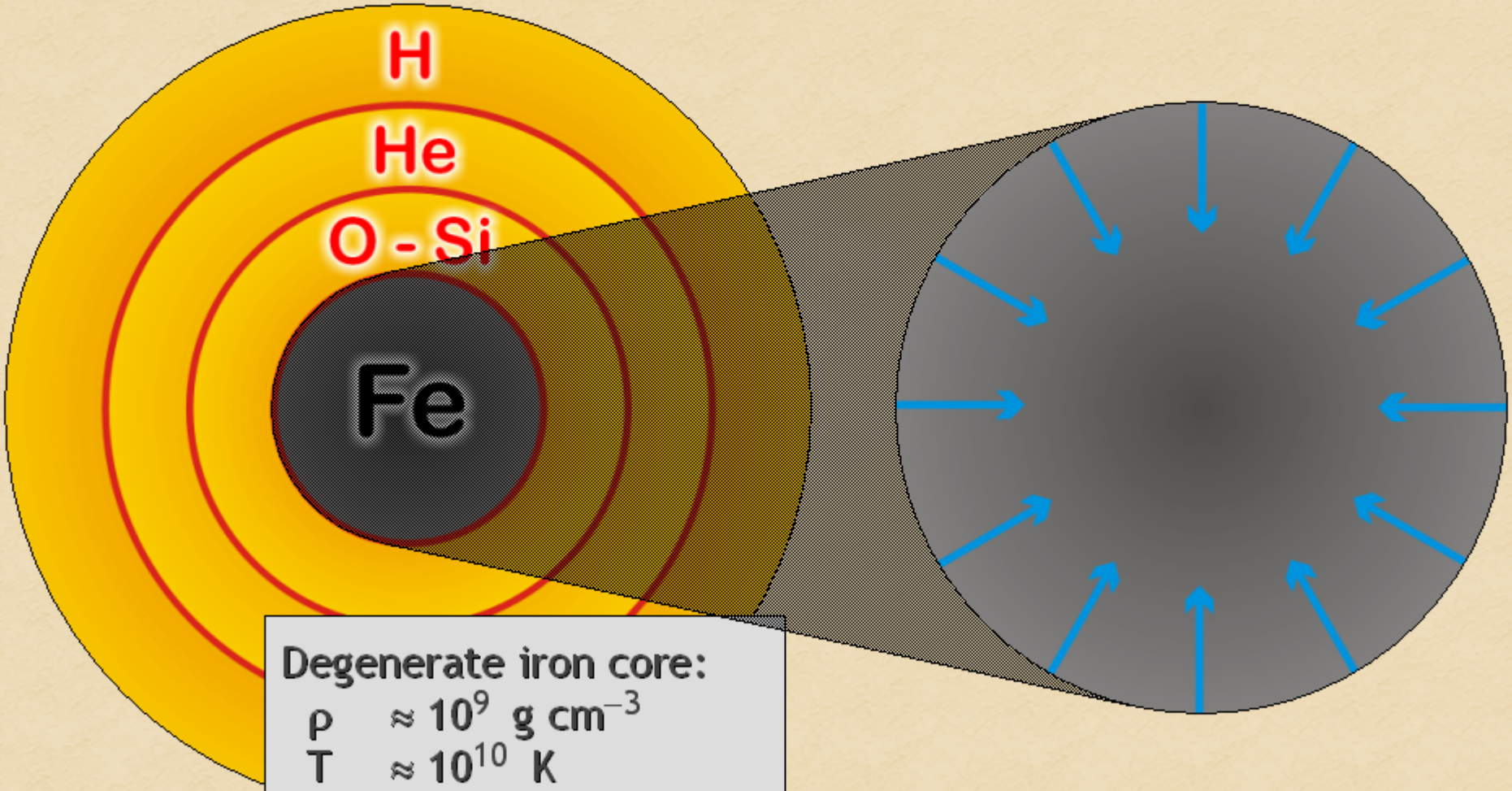
Helium-burning star



Stellar Collapse and Supernova Explosion

Onion structure

Collapse (implosion)



Degenerate iron core:

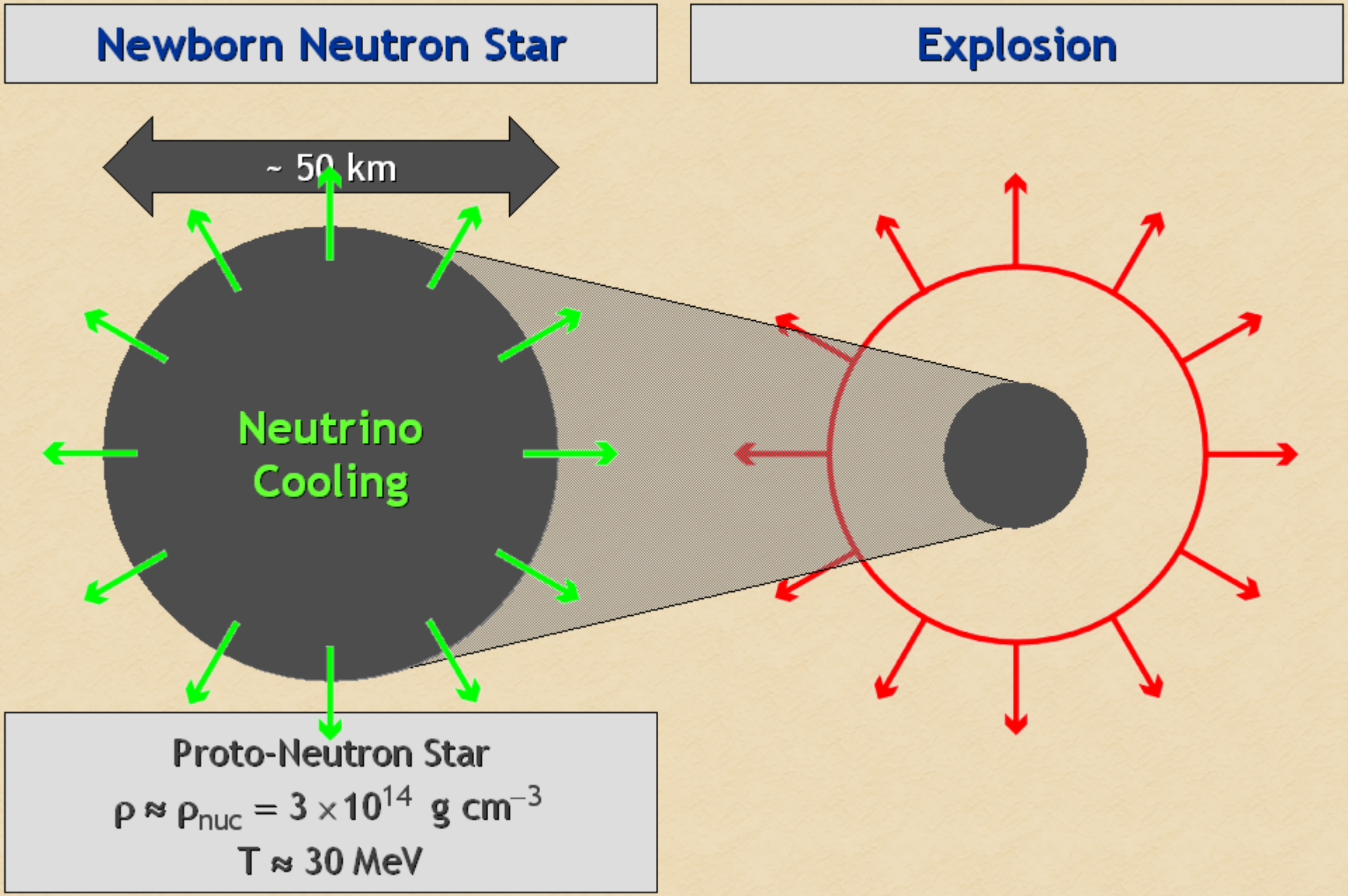
$\rho \approx 10^9$ g cm^{-3}

$T \approx 10^{10}$ K

$M_{Fe} \approx 1.5\ M_{sun}$

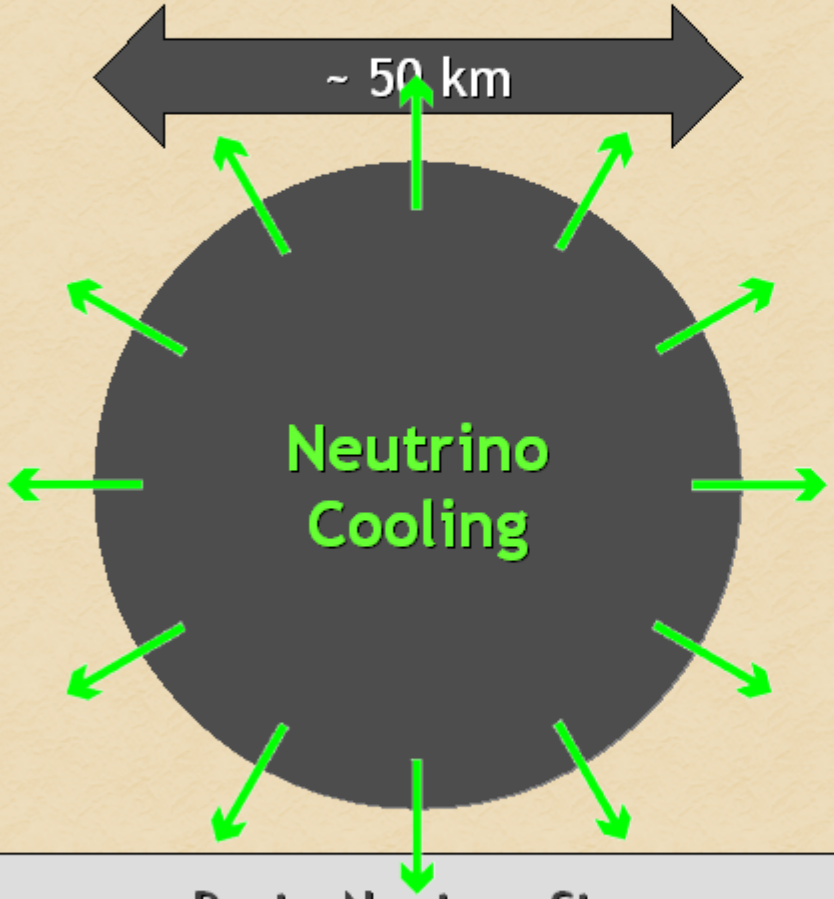
$R_{Fe} \approx 8000$ km

Stellar Collapse and Supernova Explosion



Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

$\rho \approx \rho_{nuc} = 3 \times 10^{14}$ g cm^{-3}

$T \approx 30$ MeV

Gravitational binding energy

$E_b \approx 3 \times 10^{53}$ erg $\approx 17\%\ M_{SUN}\, c^2$

This shows up as

99%	Neutrinos
1%	Kinetic energy of explosion (1% of this into cosmic rays)
0.01%	Photons, outshine host galaxy

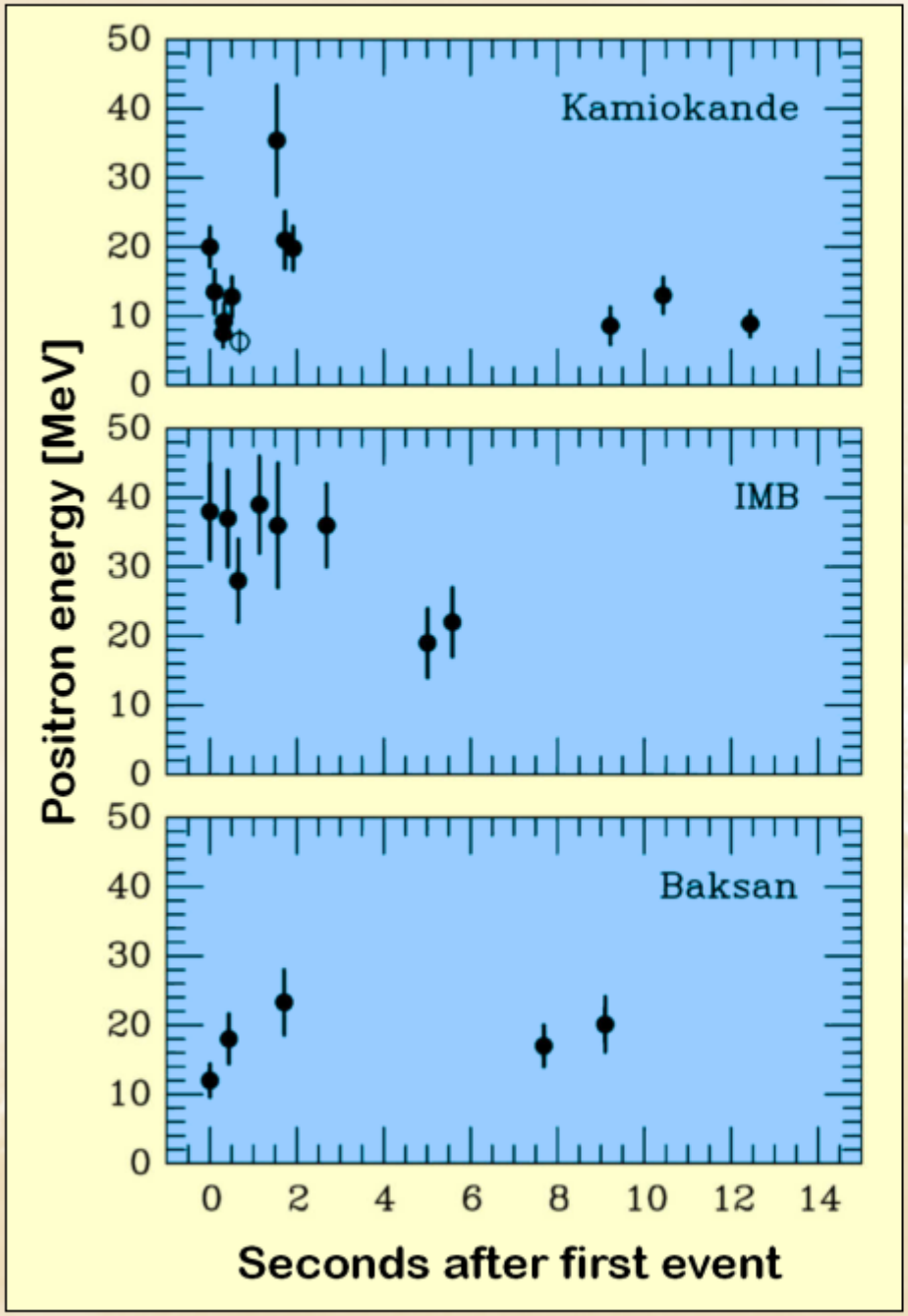
Neutrino luminosity

$L_\nu \approx 3 \times 10^{53}$ erg / 3 sec

$\approx 3 \times 10^{19}\ L_{SUN}$

While it lasts, outshines the entire visible universe

Neutrino Signal of Supernova 1987A



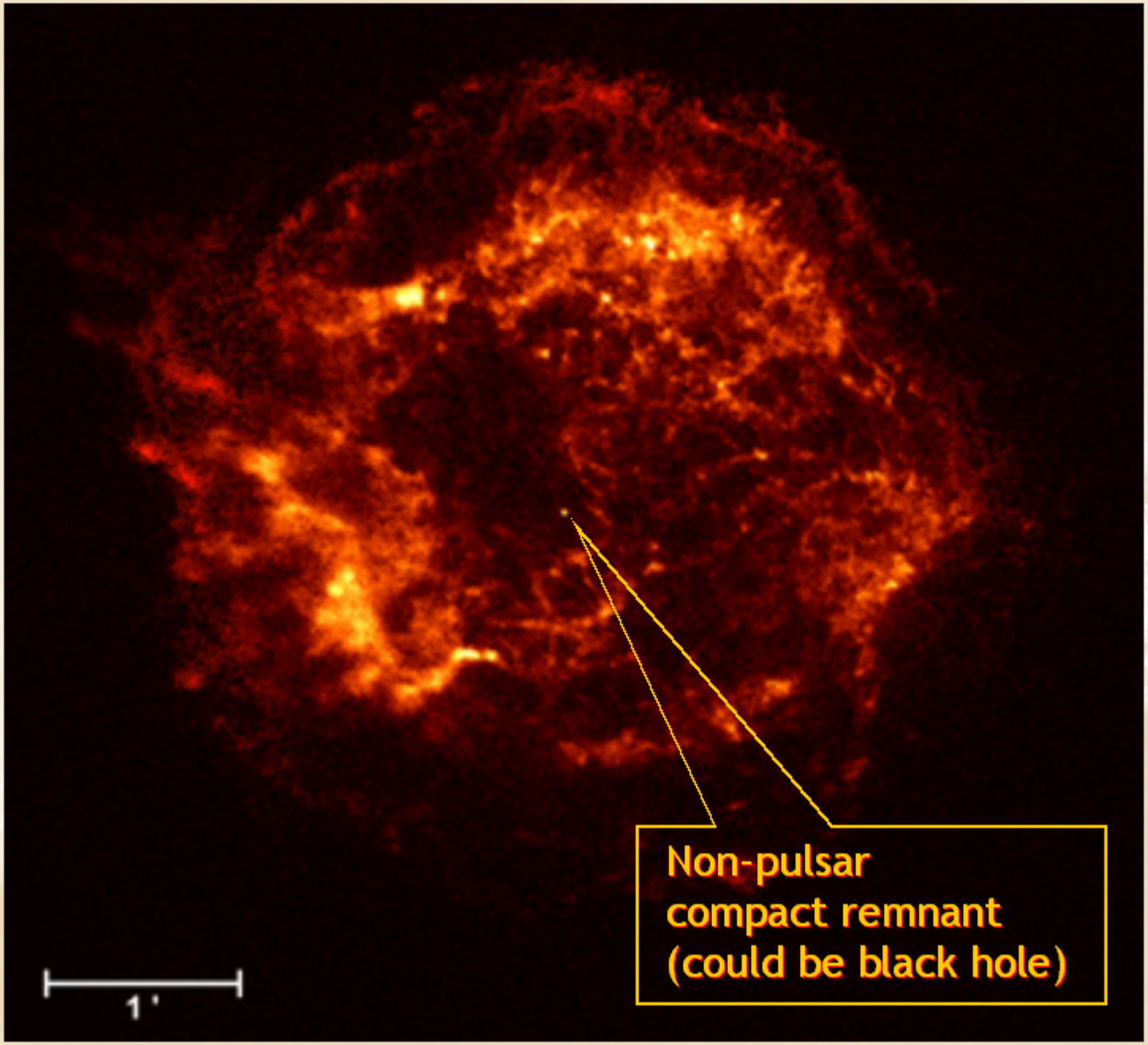
Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union)
Clock uncertainty +2/-54 s

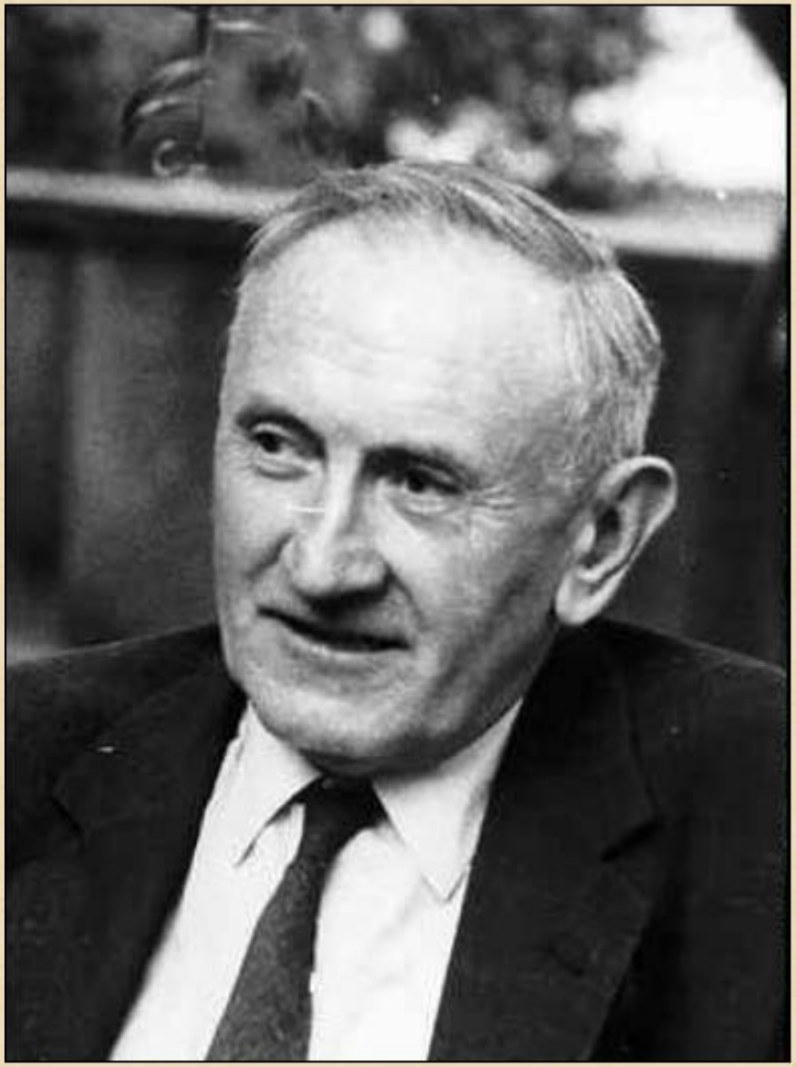
Within clock uncertainties,
signals are contemporaneous

Supernova Remnant in Cas A (SN 1667?)



Chandra
x-ray image

Walter Baade (1893–1960)

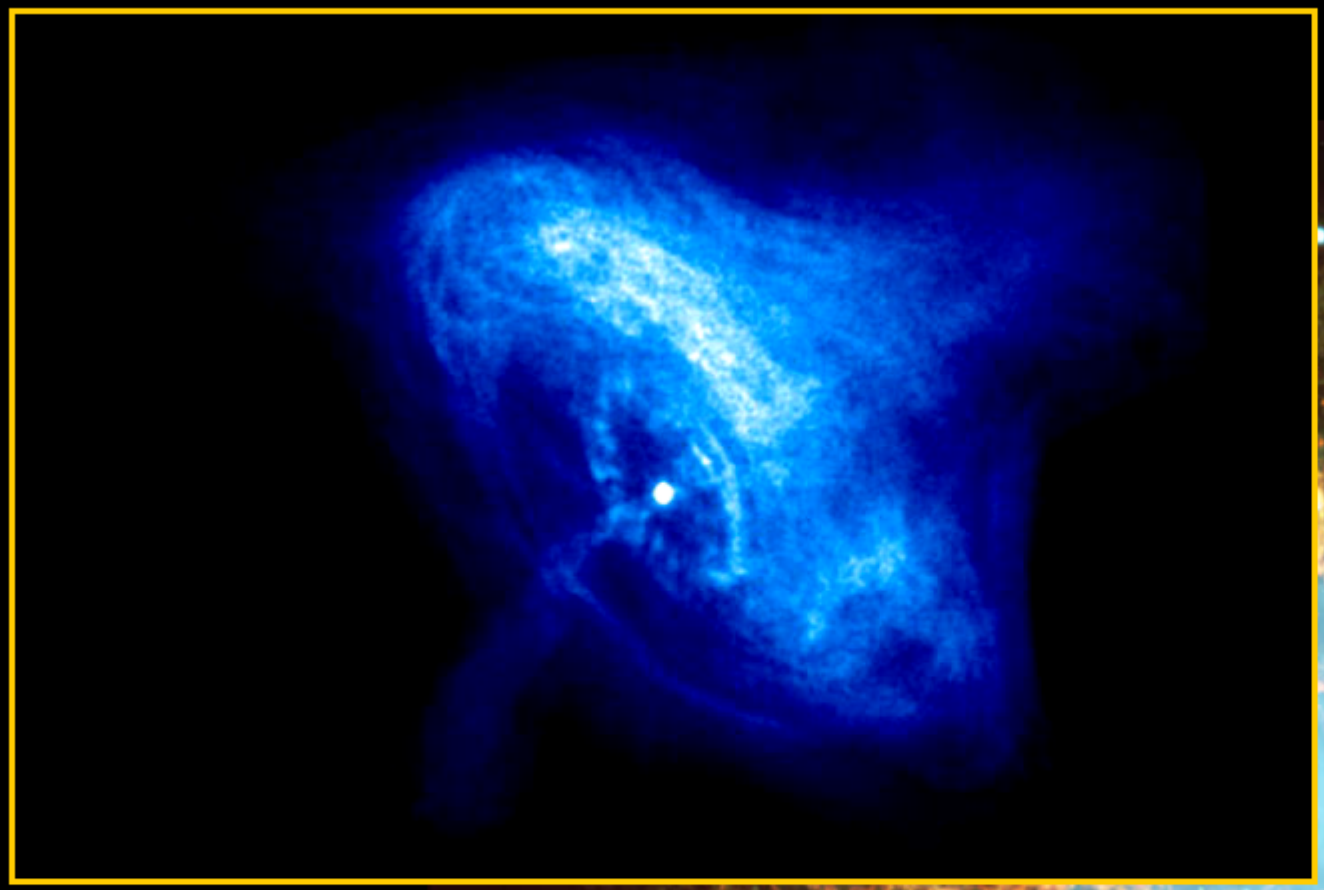


Fritz Zwicky (1898–1974)

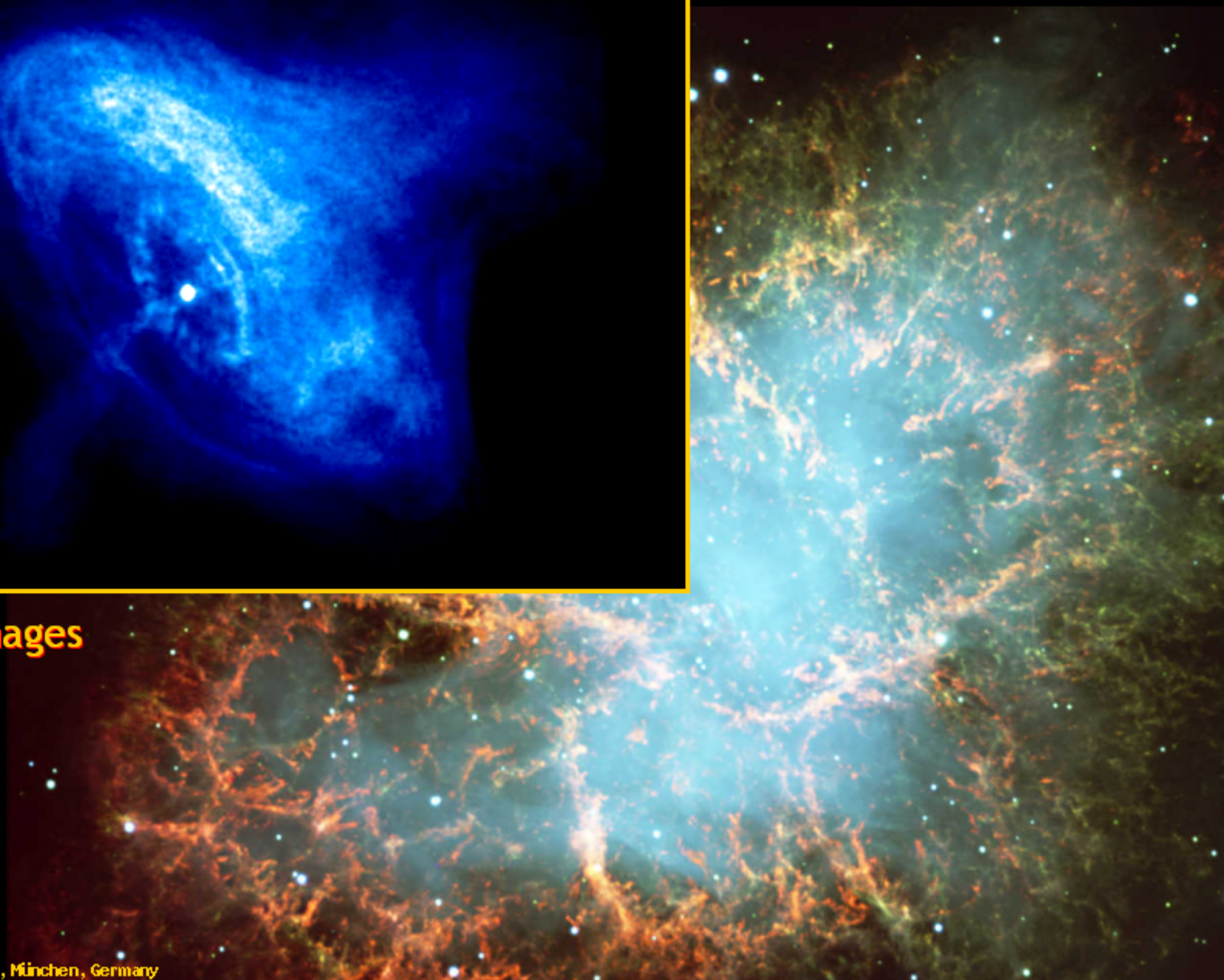
Baade and Zwicky were the first to speculate about a connection between supernova explosions and neutron-star formation

[Phys. Rev. 45 (1934) 138]

The Crab Pulsar



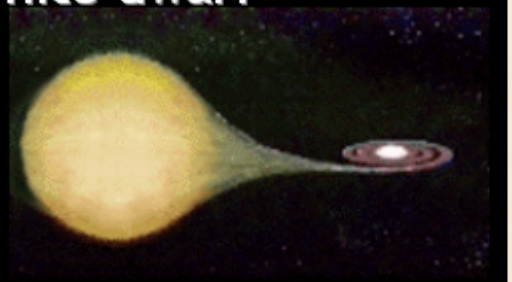
Chandra x-ray images

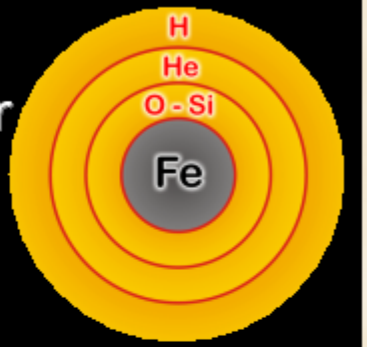


Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

Type Ia vs. Core-Collapse Supernovae

Type Ia	Core collapse (Type II, Ib/c)
• Carbon-oxygen white dwarf (remnant of low-mass star) • Accretes matter from companion	• Degenerate iron core of evolved massive star • Accretes matter by nuclear burning at its surface





Chandrasekhar limit is reached – $M_{Ch} \approx 1.5\, M_{sun}\, (2Y_e)^2$

C O L L A P S E S E T S I N

Nuclear burning of C and O ignites → Nuclear deflagration ("Fusion bomb" triggered by collapse)	Collapse to nuclear density Bounce & shock Implosion → Explosion
Powered by nuclear binding energy	Powered by gravity
Gain of nuclear binding energy ~ 1 MeV per nucleon	Gain of gravitational binding energy ~ 100 MeV per nucleon 99% into neutrinos

Comparable "visible" energy release of ~ 3×10^{51} erg

Supernovae the Power Supply for Cosmic Rays?

Required power supply	$L_{CR} = V_D \rho_{CR} / \tau_{res}$ $\approx 5 \times 10^{40}$ erg/s $\approx 10^7 L_{Sun}$
Disk volume	$V_D = \pi R^2 d \approx \pi (15 \text{ kpc})^2 200 \text{ pc}$ $\approx 4 \times 10^{66} \text{ cm}^3$
Energy density in CRs	$\rho_{CR} \approx 1 \text{ eV / cm}^3$
Residence time in galaxy	$\tau_{res} \approx 6 \times 10^6$ yrs

Suggestive of supernovae:

- One SN explosion deposits ~ 3×10^{51} erg in kinetic energy of ejecta into the interstellar medium (ISM)
- Rate approx. 1 SN / 30 years / galaxy

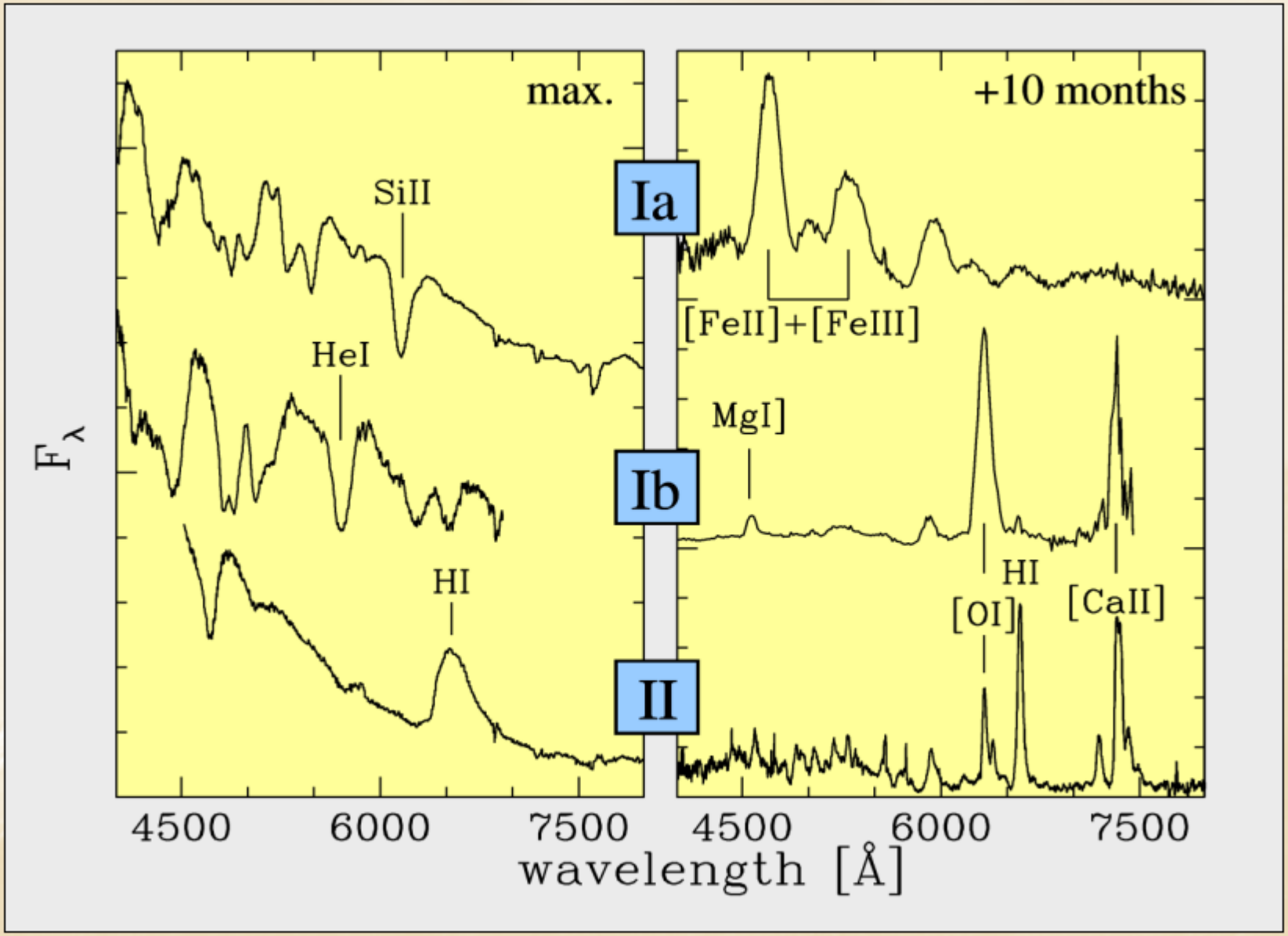
Total average energy deposition: $L_{SN} \approx 3 \times 10^{42}$ erg/s $\approx 50 L_{CR}$

Efficiency of a few percent required

Classification of Supernovae

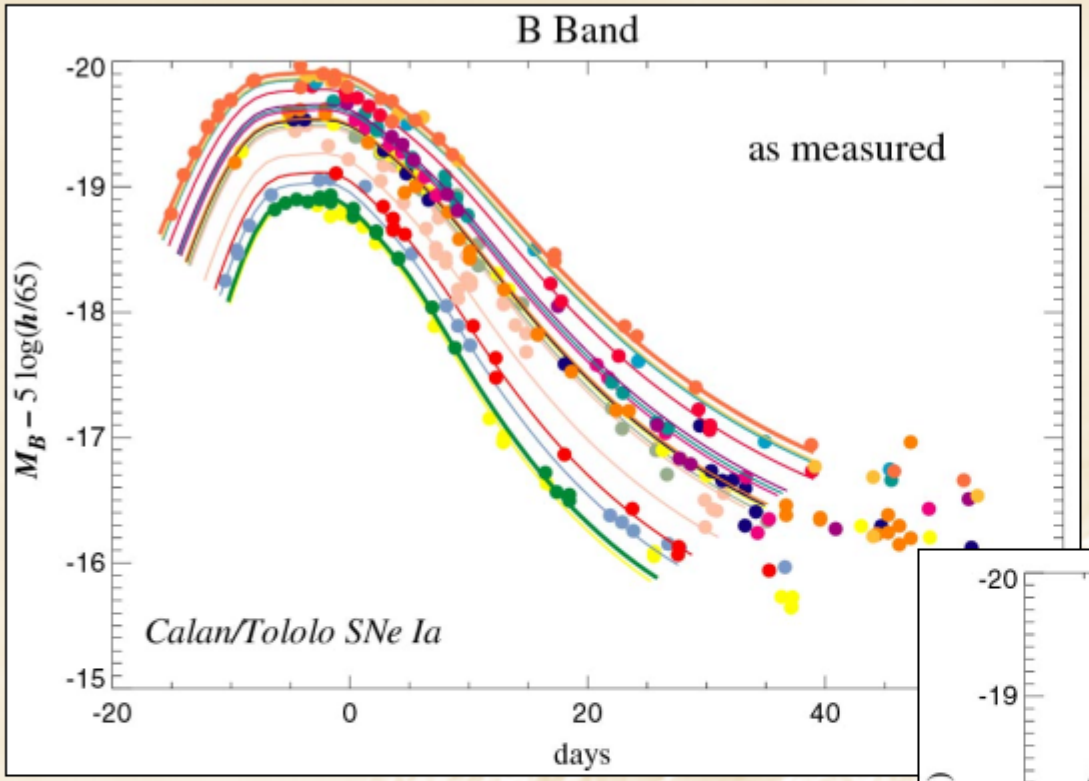
Spectral Type	Ia	Ib	Ic	II
Spectrum	No Hydrogen			Hydrogen
	Silicon	No Silicon		
		Helium	No Helium	
Physical Mechanism	Nuclear explosion of low-mass star	Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)		
Light Curve	Reproducible	Large variations		
Neutrinos	Insignificant	~ 100 × Visible energy		
Compact Remnant	None	Neutron star (typically appears as pulsar) Sometimes black hole ?		
Rate / h^2 SNu	0.36 ± 0.11	0.14 ± 0.07		0.71 ± 0.34
Observed	Total ~ 2000 as of today (nowadays ~200/year)			

Typical Spectra of Different Supernova Types



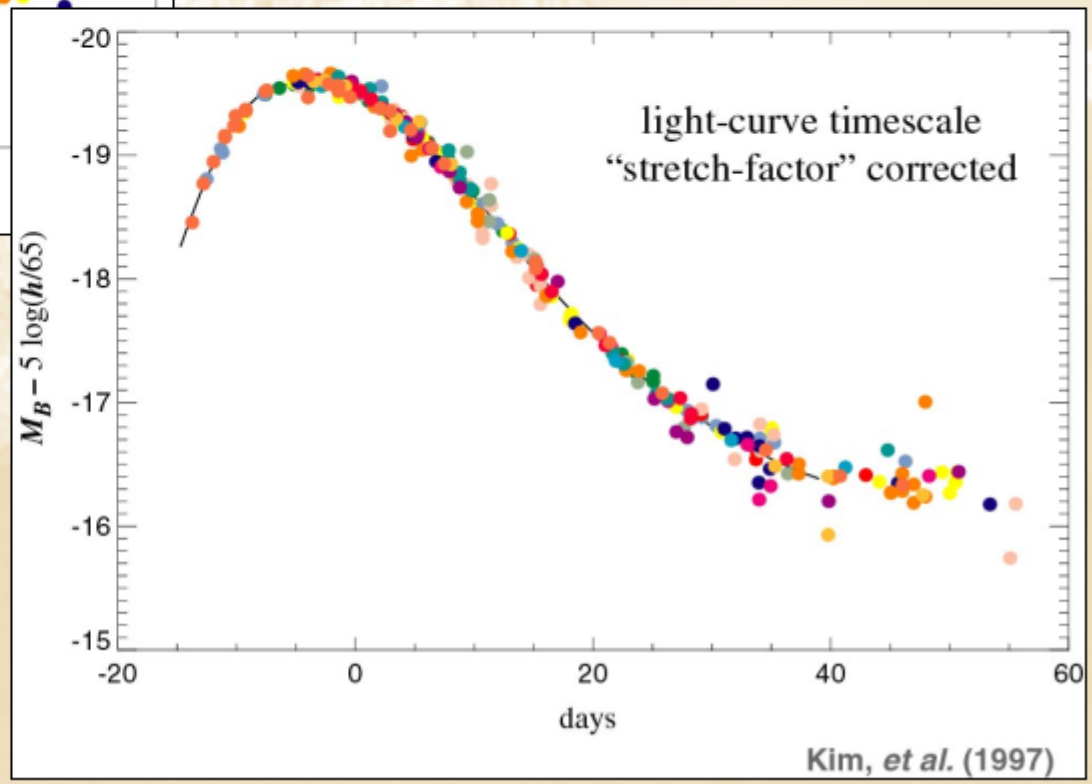
Cappellaro and Turatto, astro-ph/0012455

Universal Supernova Ia Light Curve

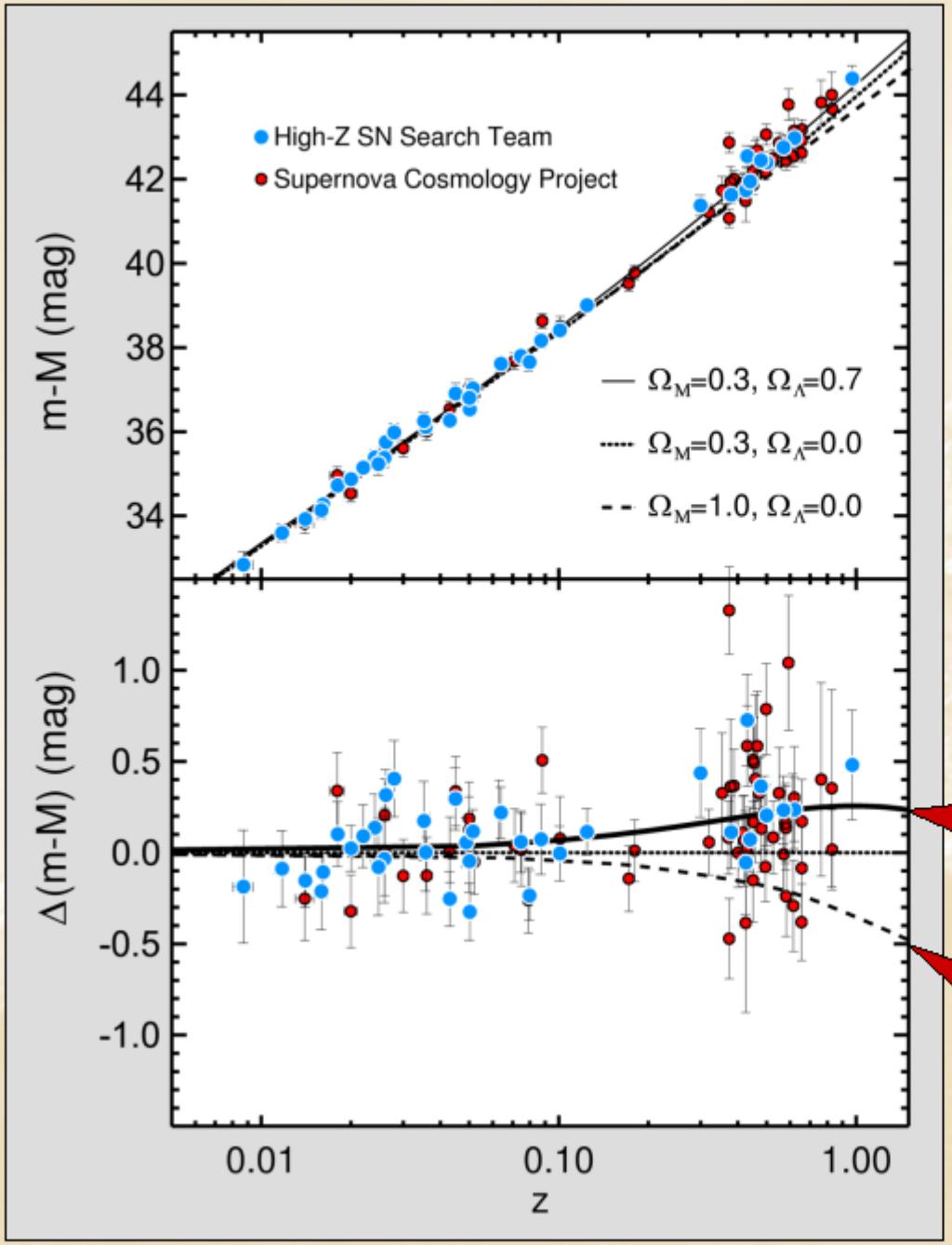


Supernova Ia lightcurves are empirically a 1-parameter family

After transformation
a universal light curve,
i.e. a de-facto standard candle



Hubble Diagram

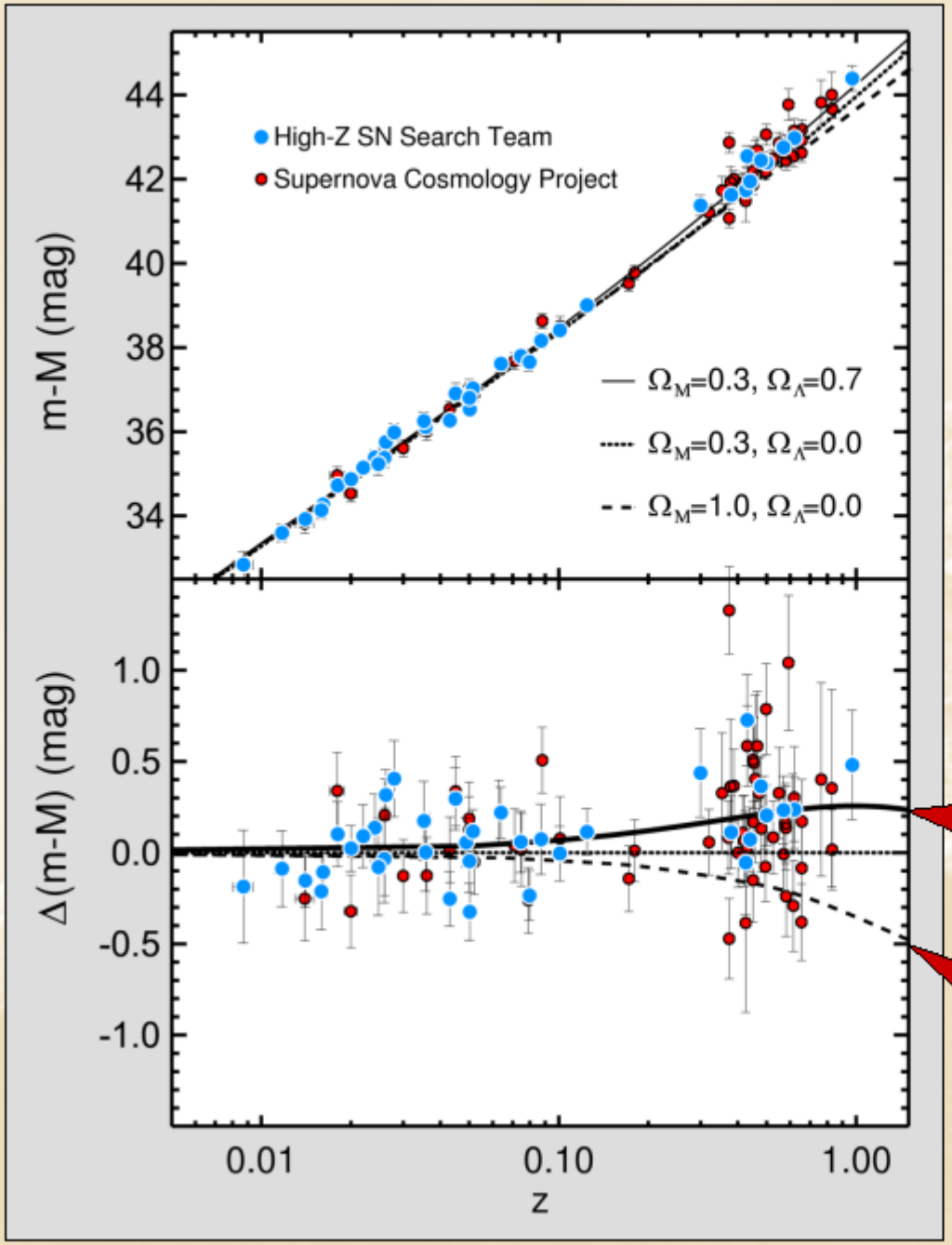


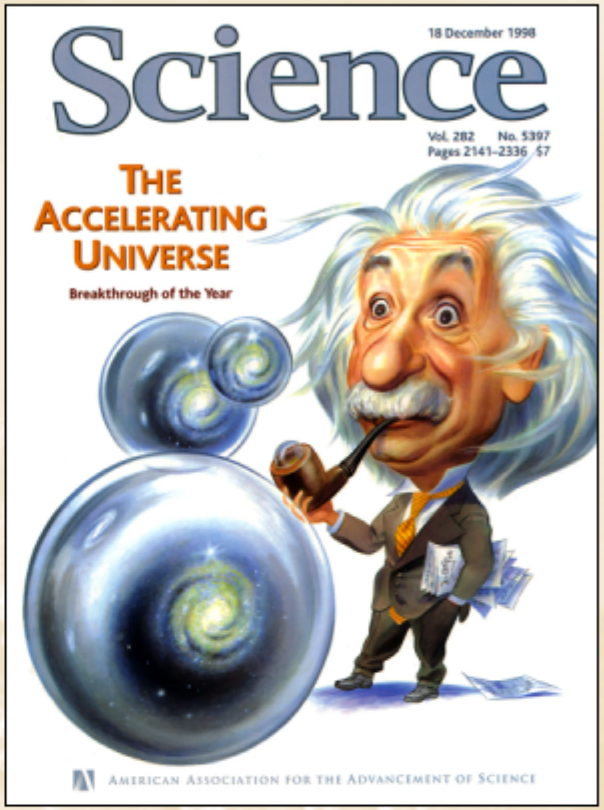
Supernova Ia as cosmological standard candles

Accelerated expansion ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$)

Decelerated expansion ($\Omega_M = 1$)

Hubble Diagram

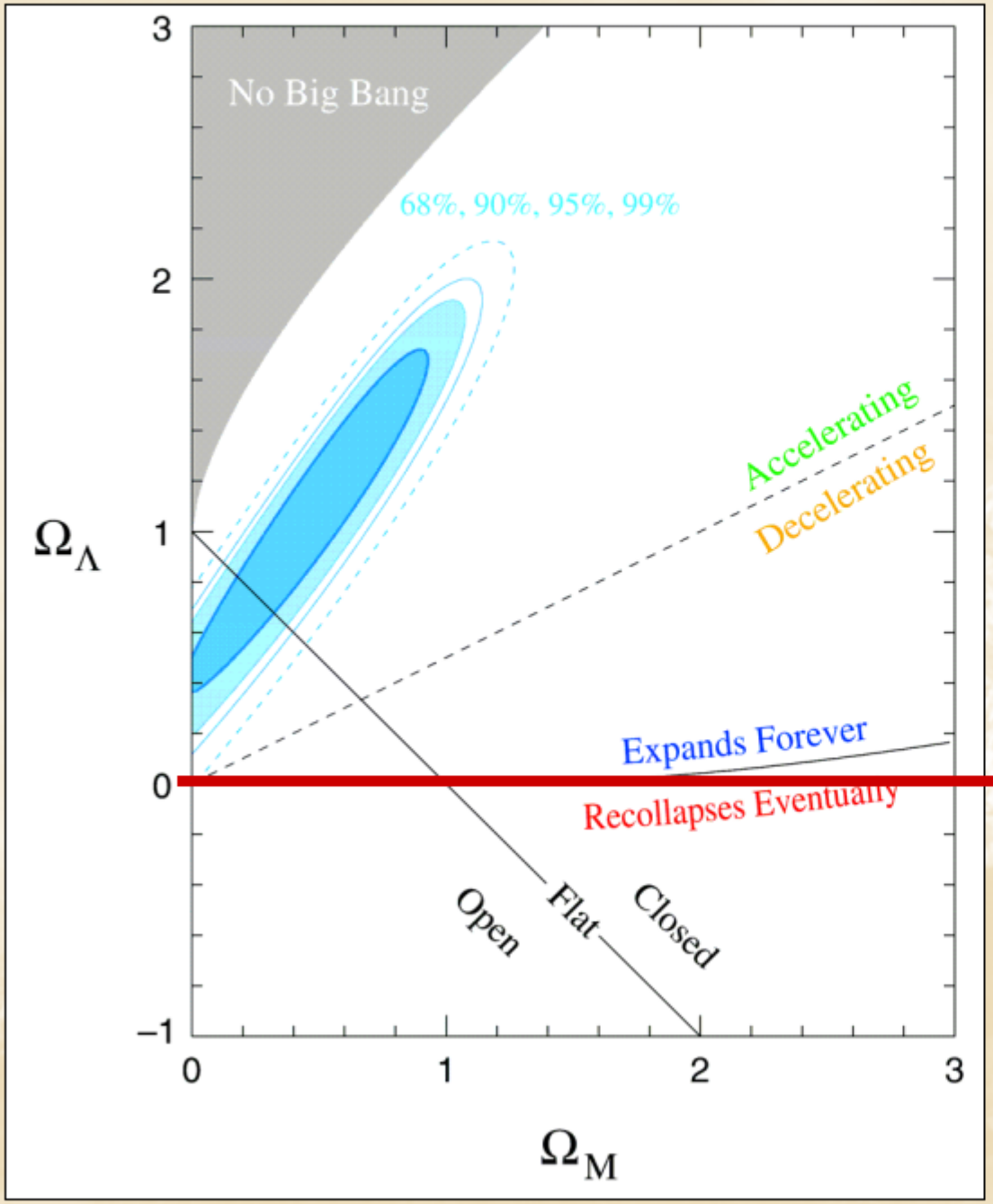




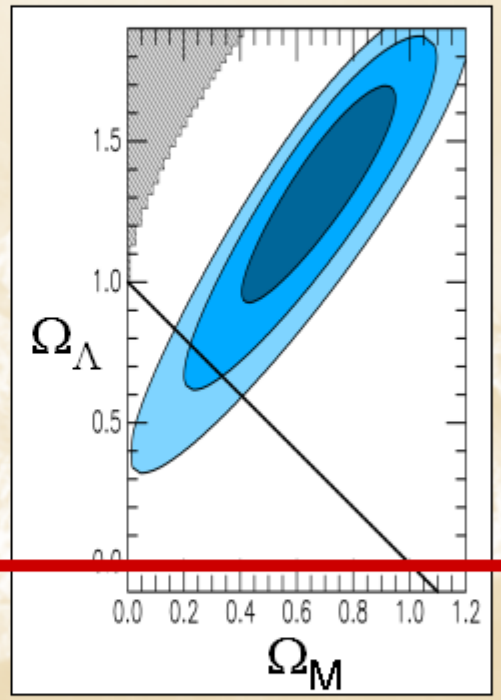
Accelerated expansion
($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$)

Decelerated expansion
($\Omega_M = 1$)

Fitting Cosmological Parameters



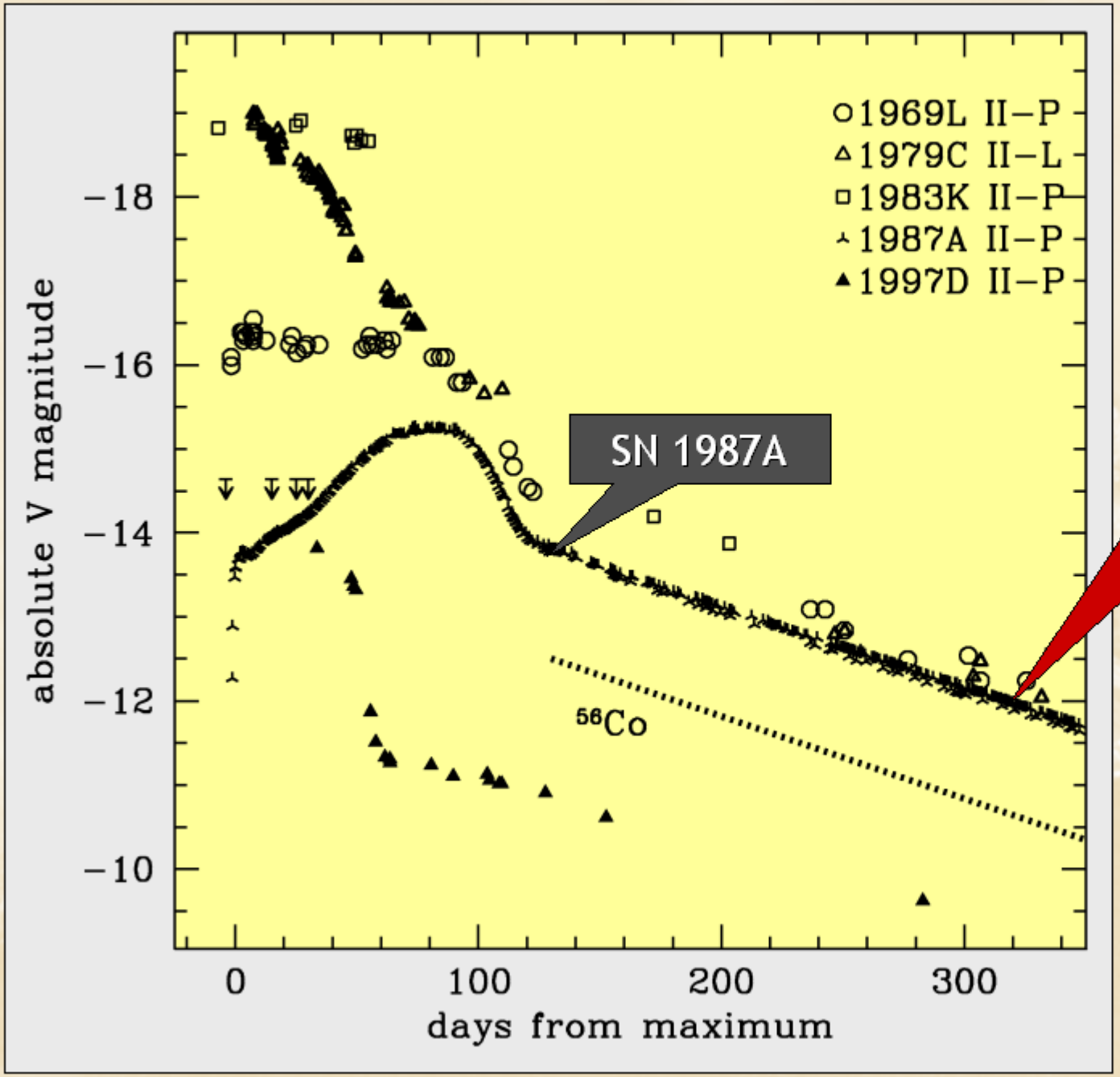
High-z supernova team (Tonry et al.) astro-ph/0305008



$\Lambda = 0$ excluded at many sigma

Cosmological Supernova Project (Knop et al.), astro-ph/0309368

Examples for SN II Light Curves



Powered by radioactive decay of ^{56}Co

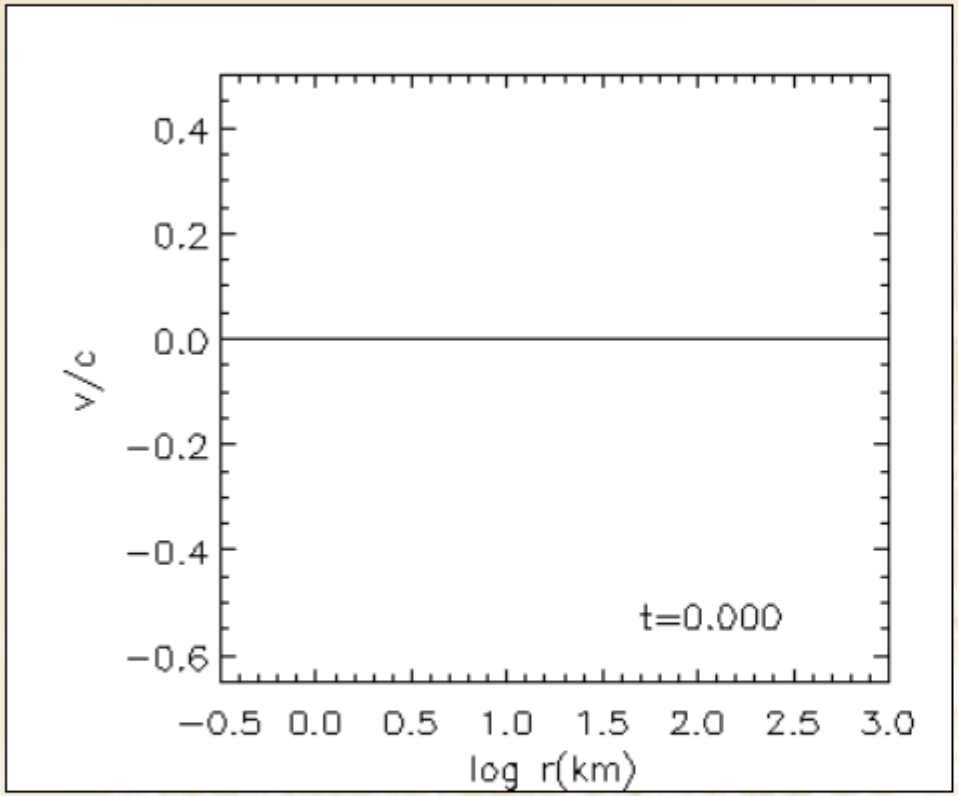
Cappellaro & Turatto, astro-ph/0012455

Explosion Mechanism for Core-Collapse SNe

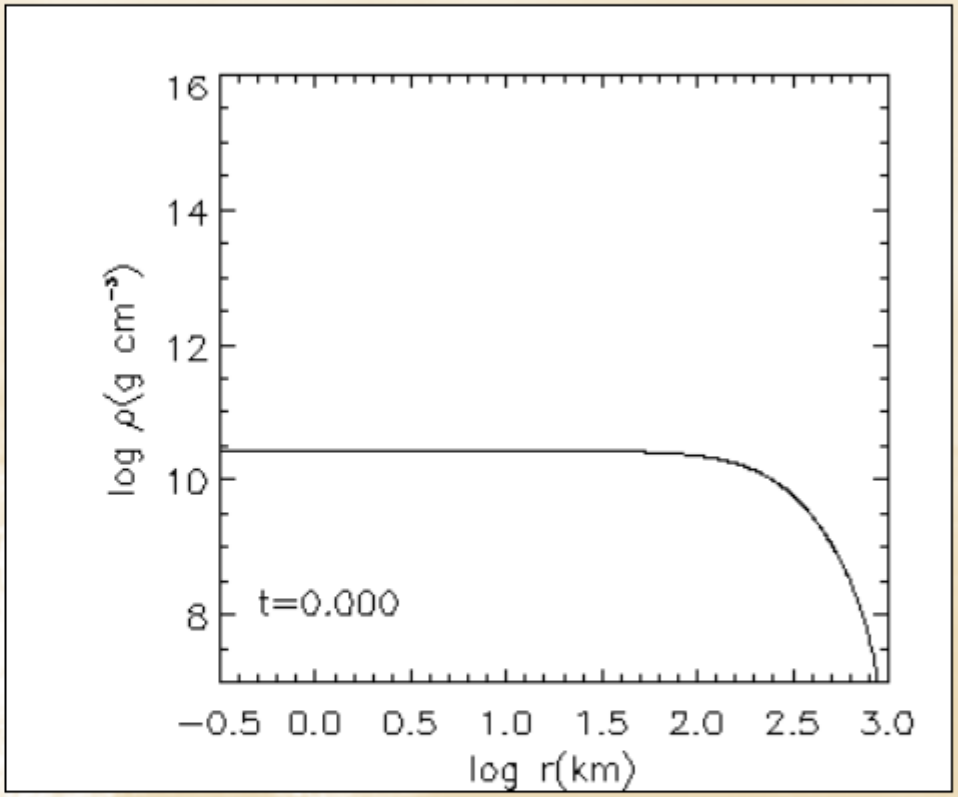
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

Collapse and Prompt Explosion

Velocity



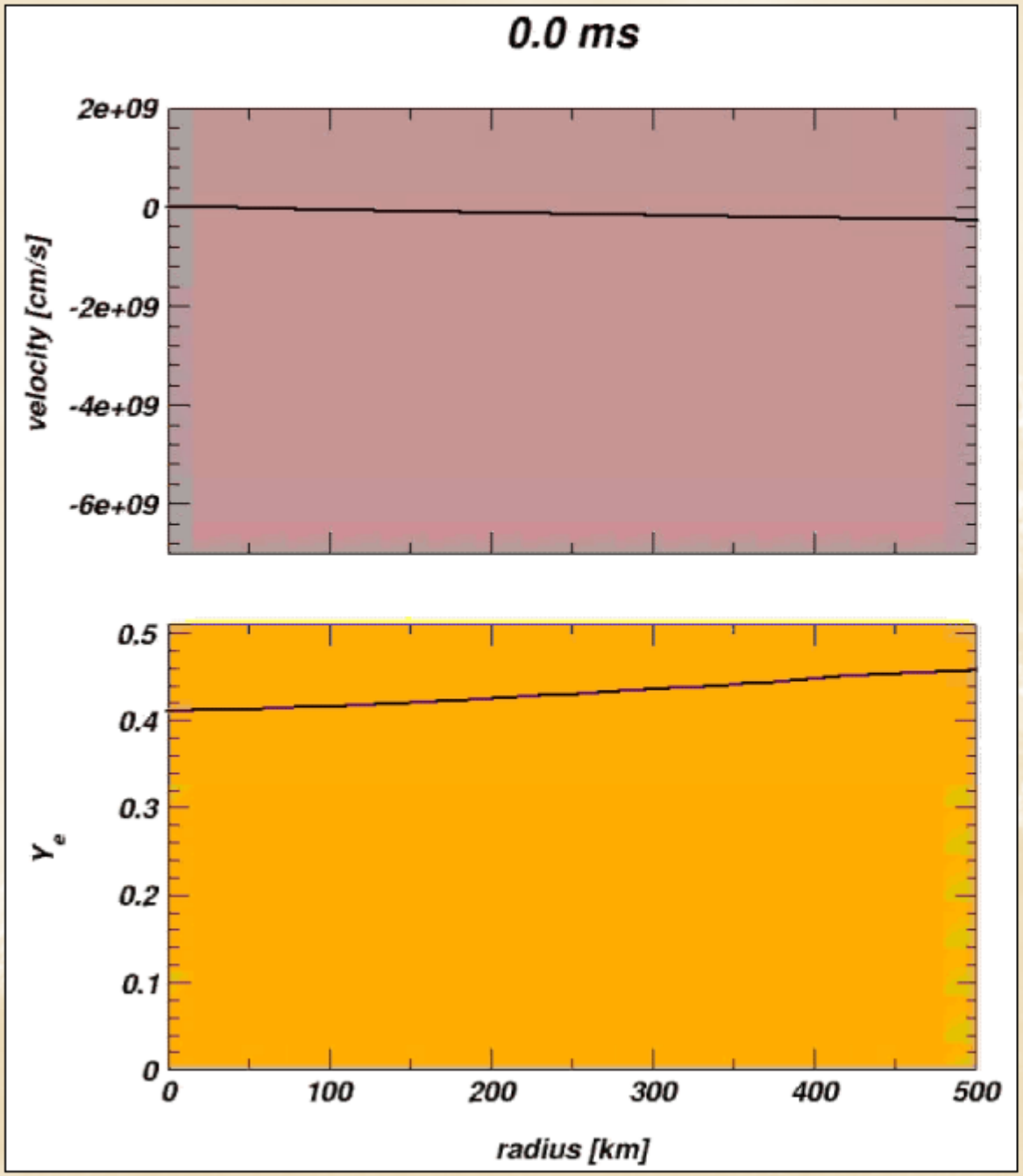
Density



Supernova explosion primarily a hydrodynamical phenomenon

Movies by J.A.Font, Numerical Hydrodynamics in General Relativity
http://www.livingreviews.org

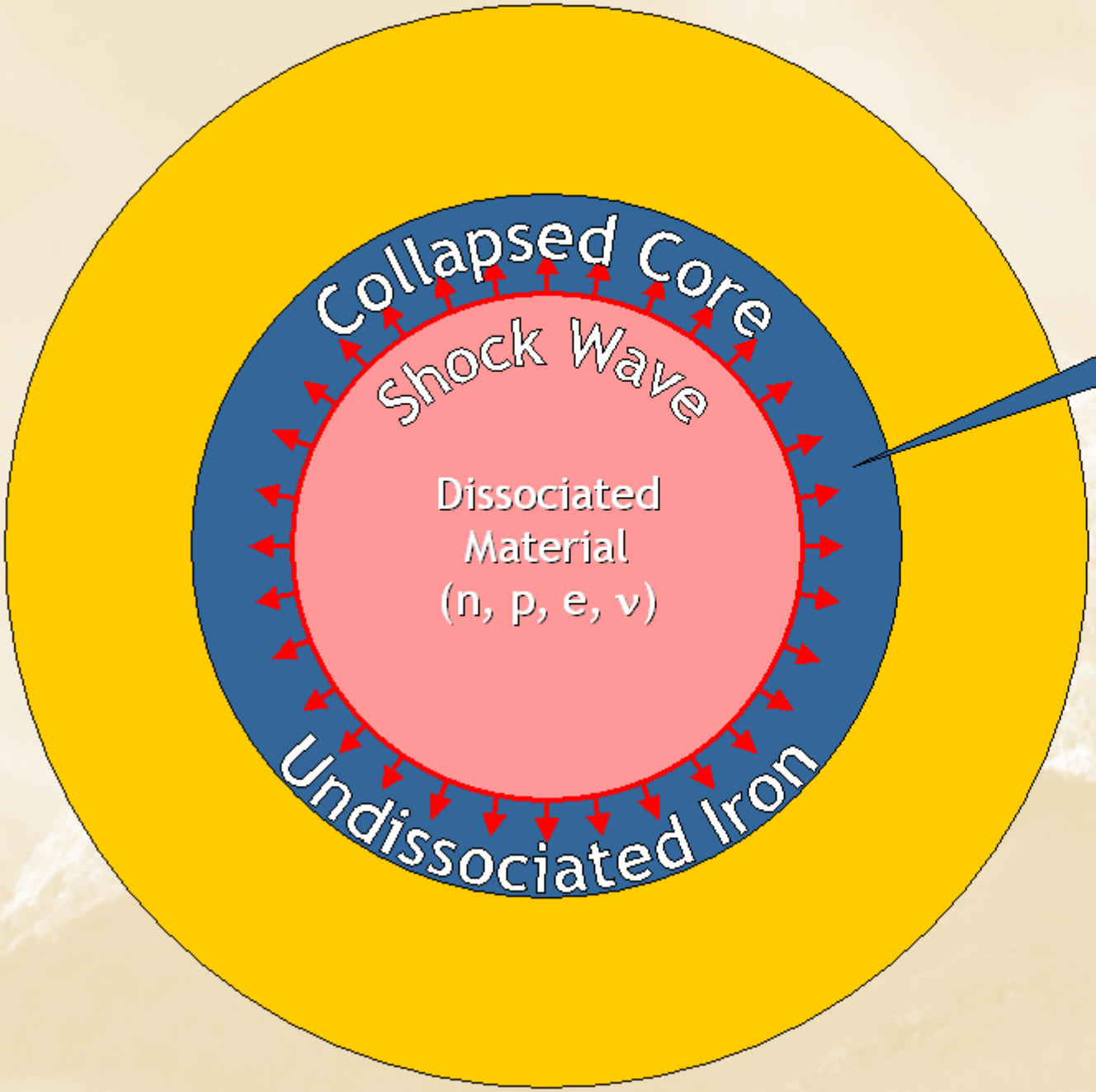
Failed Explosion



Spherically symmetric simulation of a 15 M_{sun} stellar model with state-of-the-art neutrino transport

Movie courtesy of Bronson Messer, Oakridge group (2001)

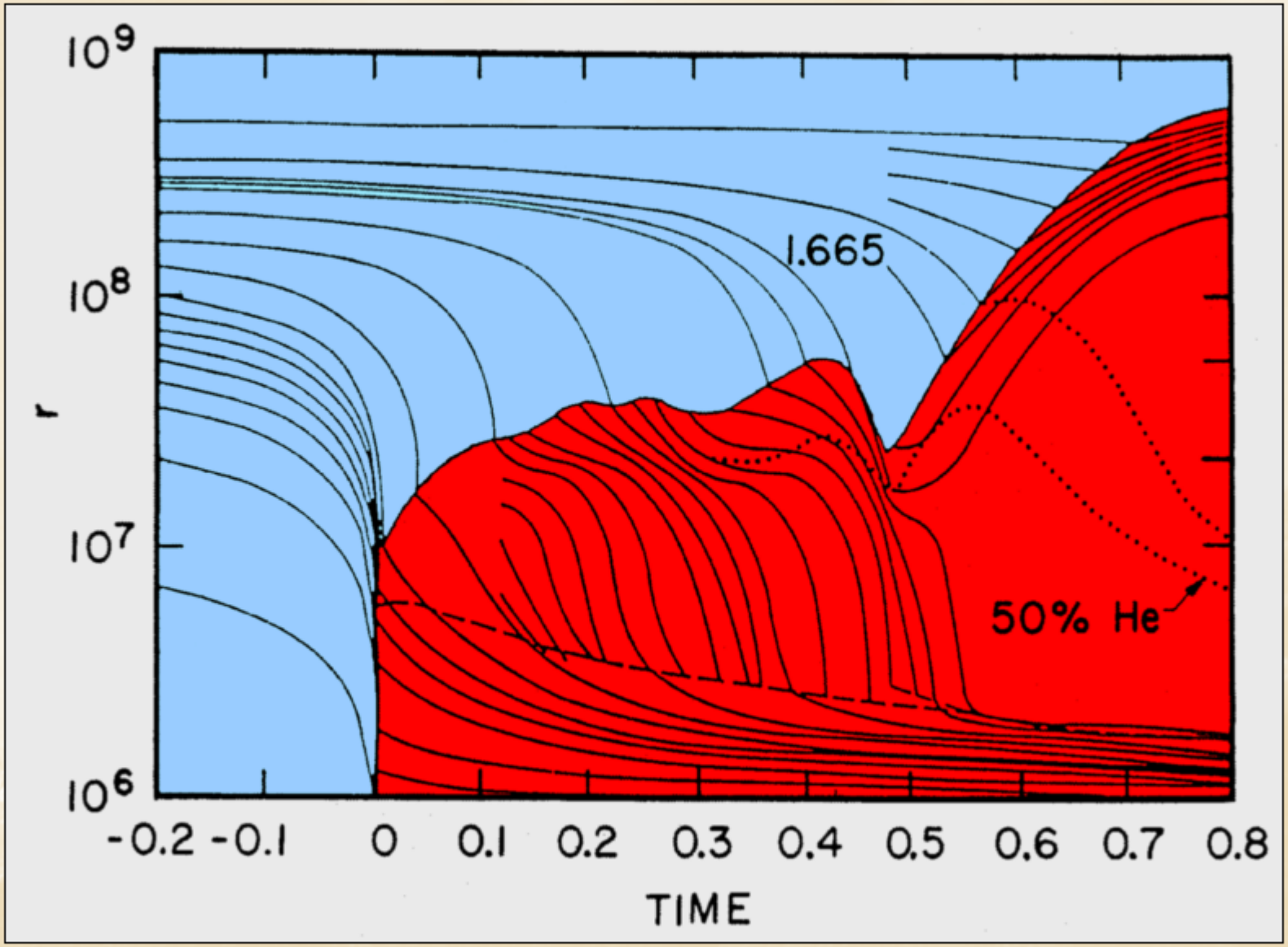
Why No Prompt Explosion?



- 0.1 M_{sun} of iron has a nuclear binding energy $\approx 1.7 \times 10^{51}$ erg
- Comparable to explosion energy

- Shock wave forms within the iron core
- Dissipates its energy by dissociating the remaining layer of iron

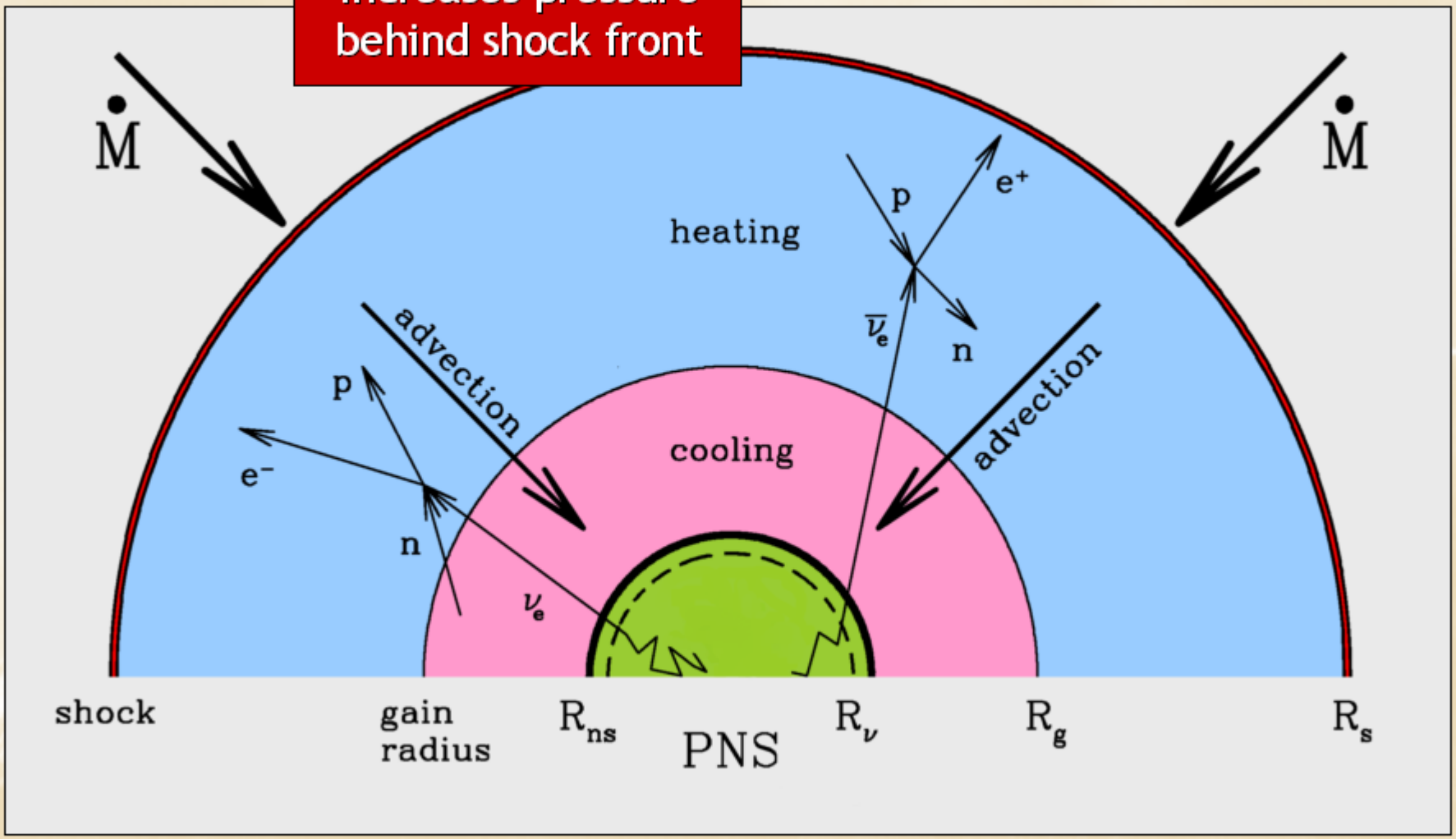
Delayed Explosion



Wilson, Proc. Univ. Illinois Meeting on Num. Astrophys.(1982)
Bethe & Wilson, ApJ 295 (1985) 14

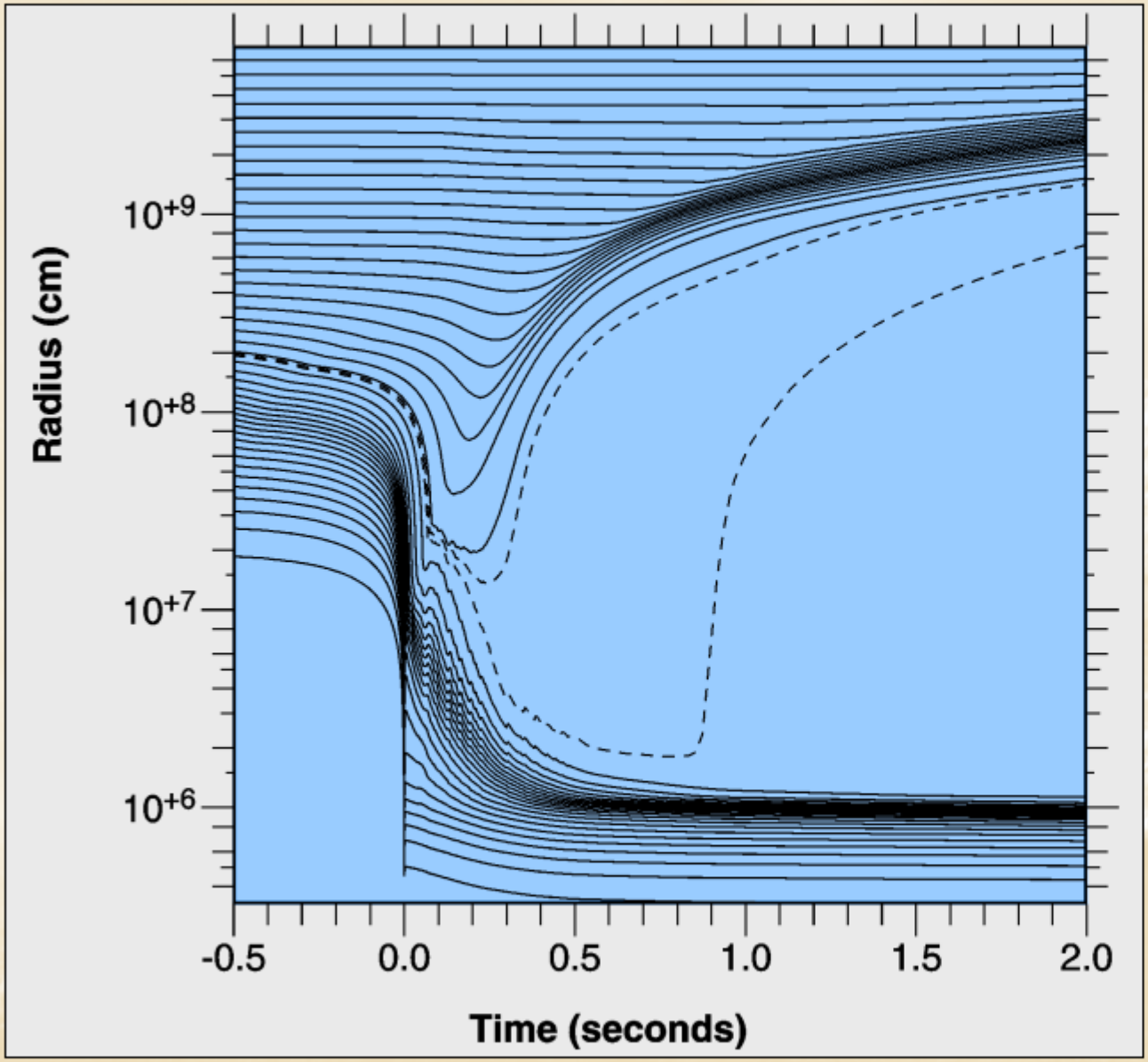
Neutrinos to the Rescue

Neutrino heating increases pressure behind shock front



Picture adapted from Janka, astro-ph/0008432

Explosions in Livermore Simulations

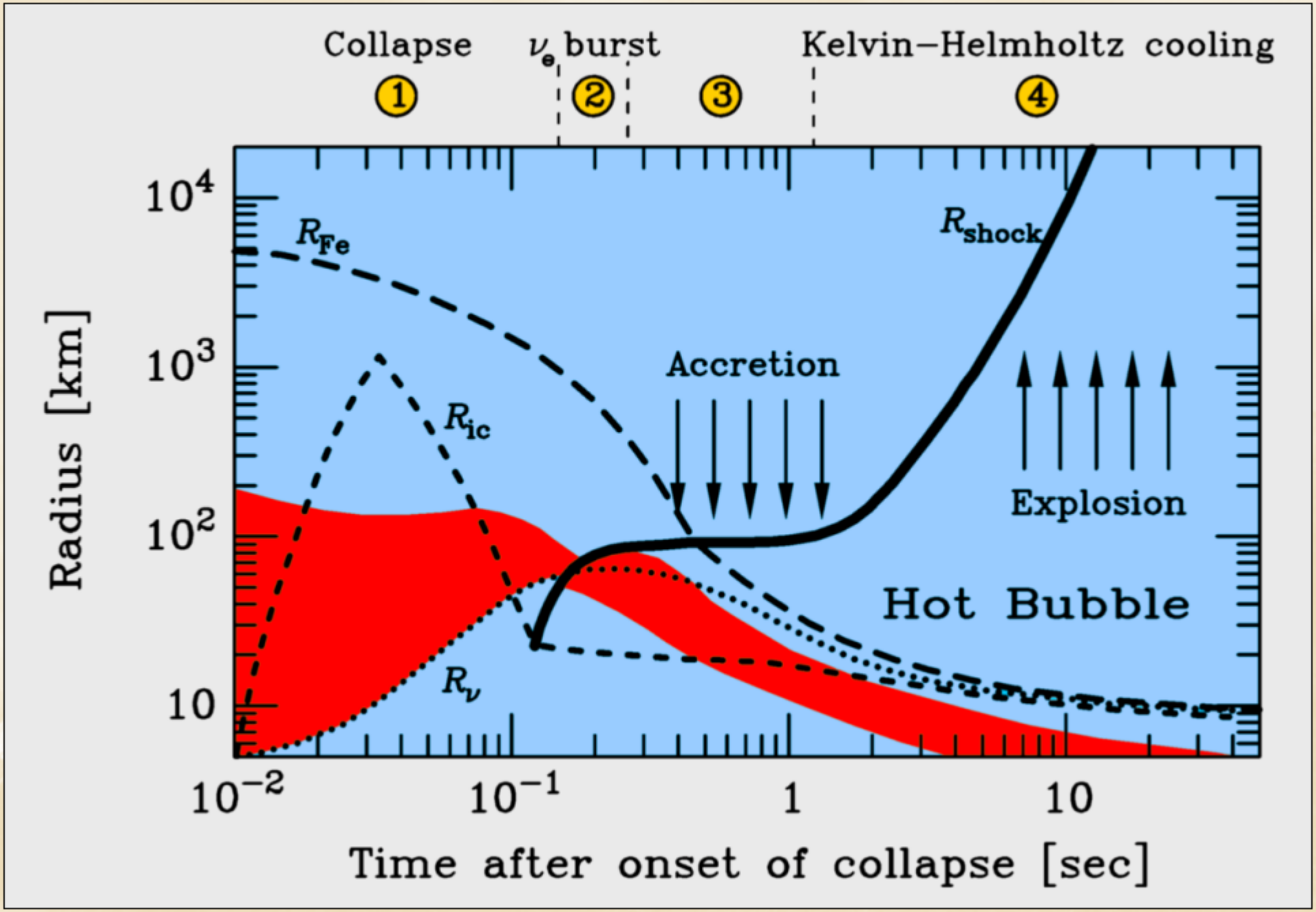


Livermore group obtains robust delayed explosions with 1-D code of Mayle & Wilson

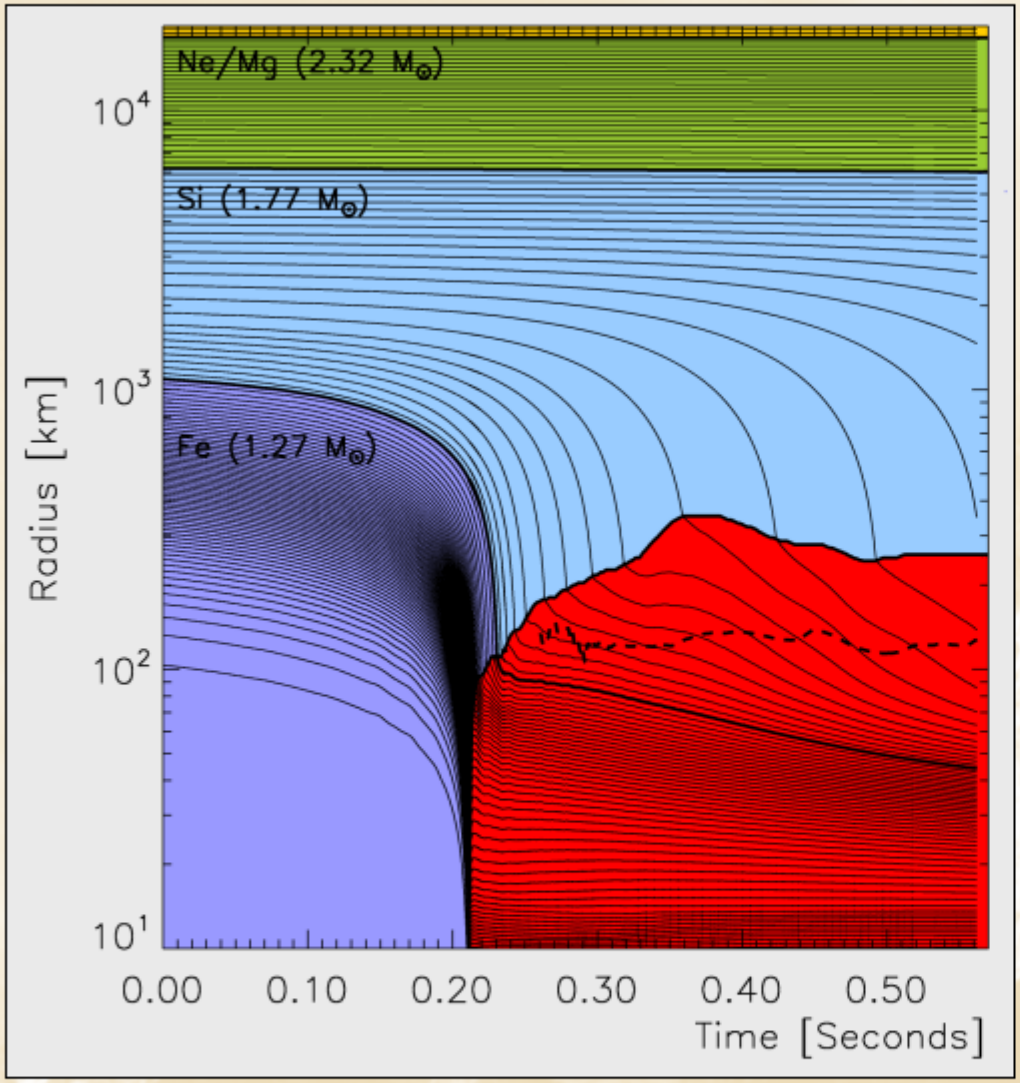
Neutrino luminosity is enhanced by neutron finger convection in proto neutron star

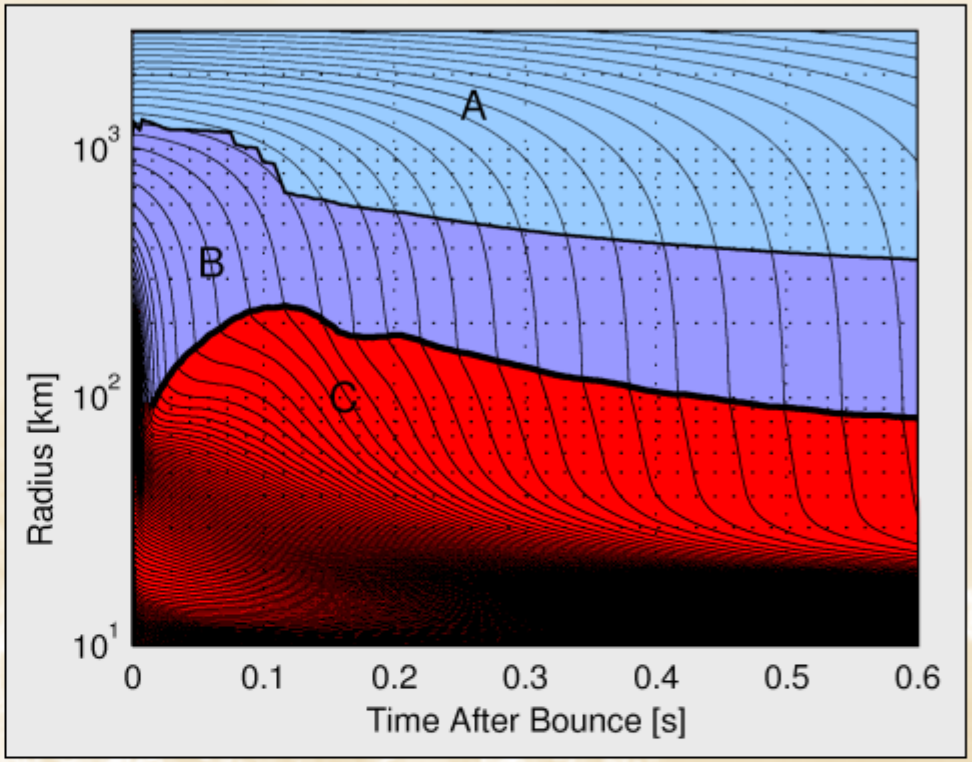
Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216

Supernova Delayed Explosion Scenario



Failed Explosions in Spherical Symmetry



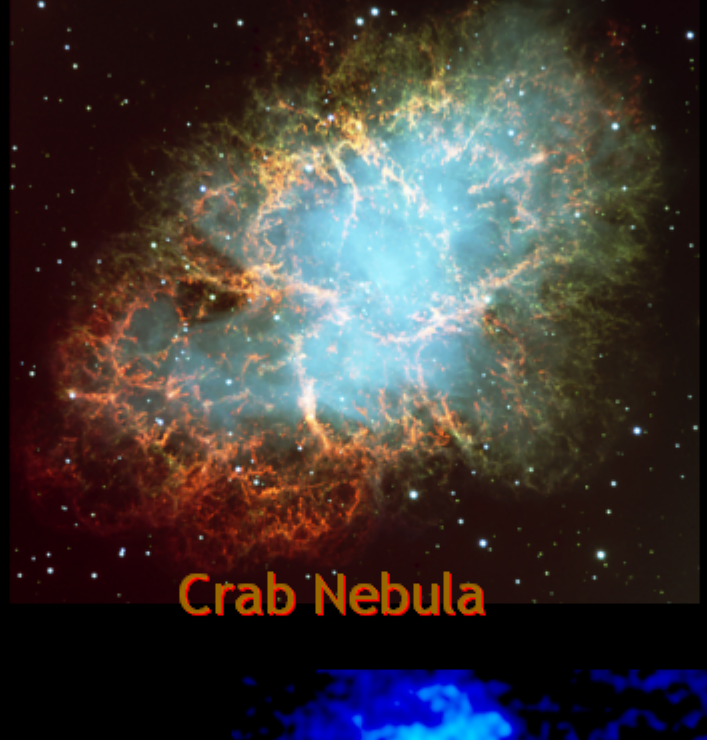


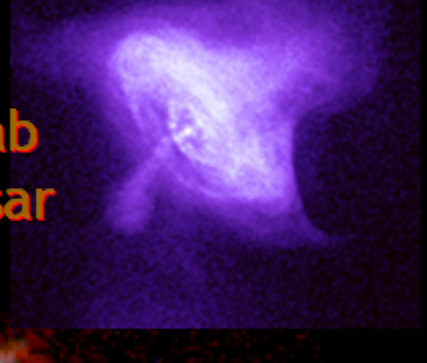
Mezzacappa et al., PRL 86 (2001) 1935

Rampp & Janka, ApJ 539 (2000) L33

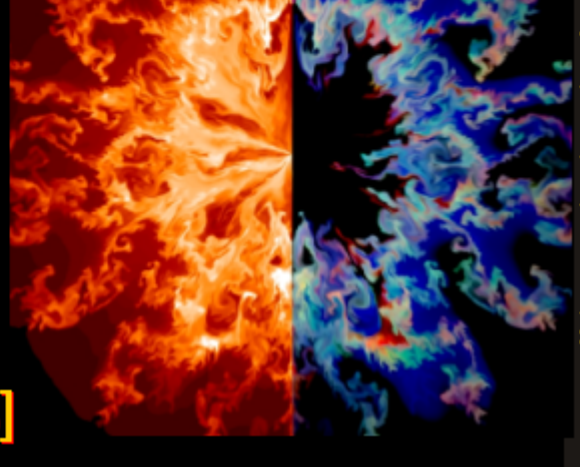
Spherically symmetric (1–D) simulations with state-of-the-art neutrino transport do not explode

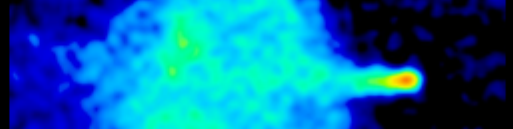
Spherical Symmetry in Astrophysics :-)





Convection in
SN simulations





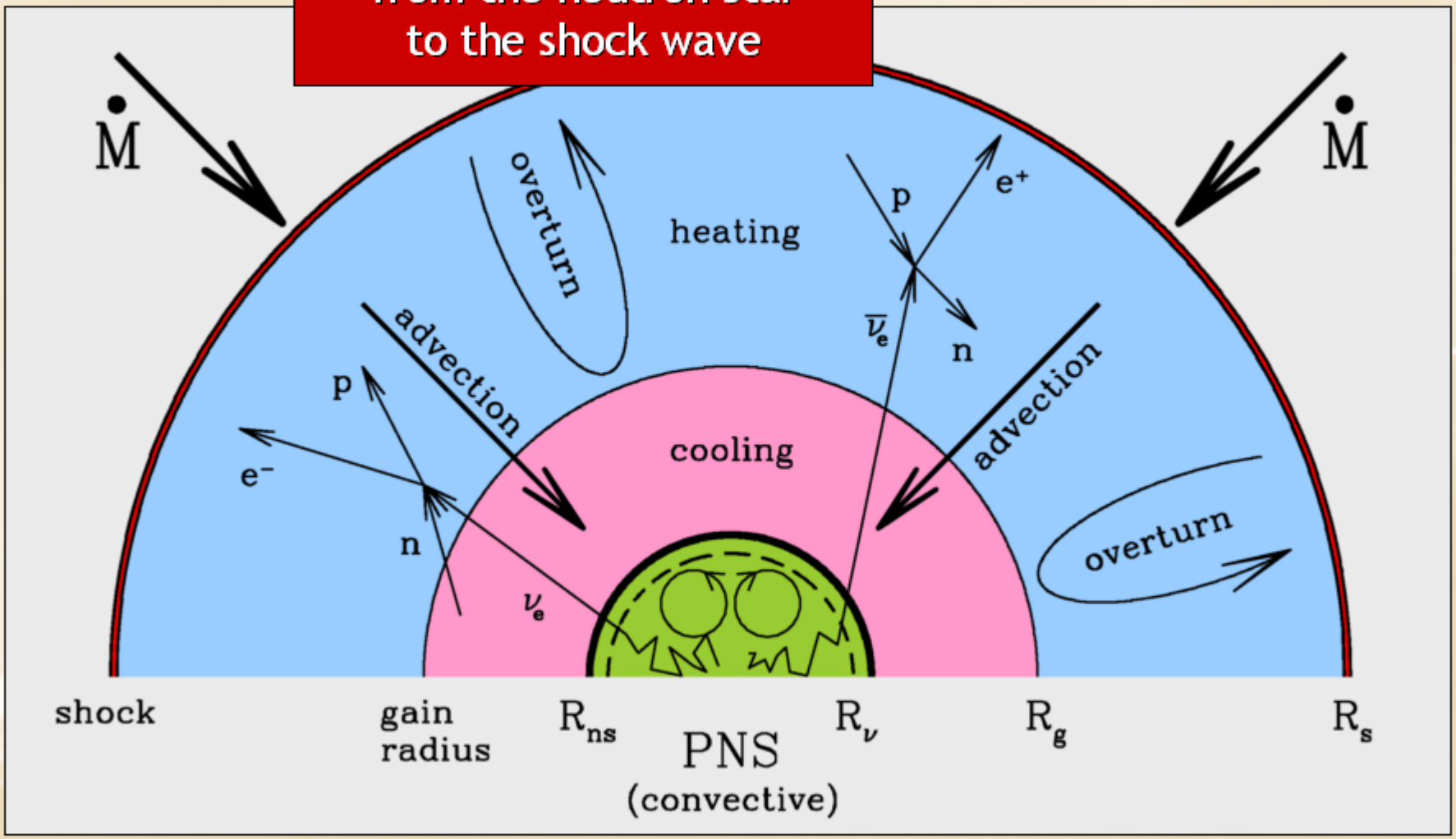
SNR G5.4-1.2
PSR 1757-24

SN 1987A

[Adapted after a slide by A.Burrows]

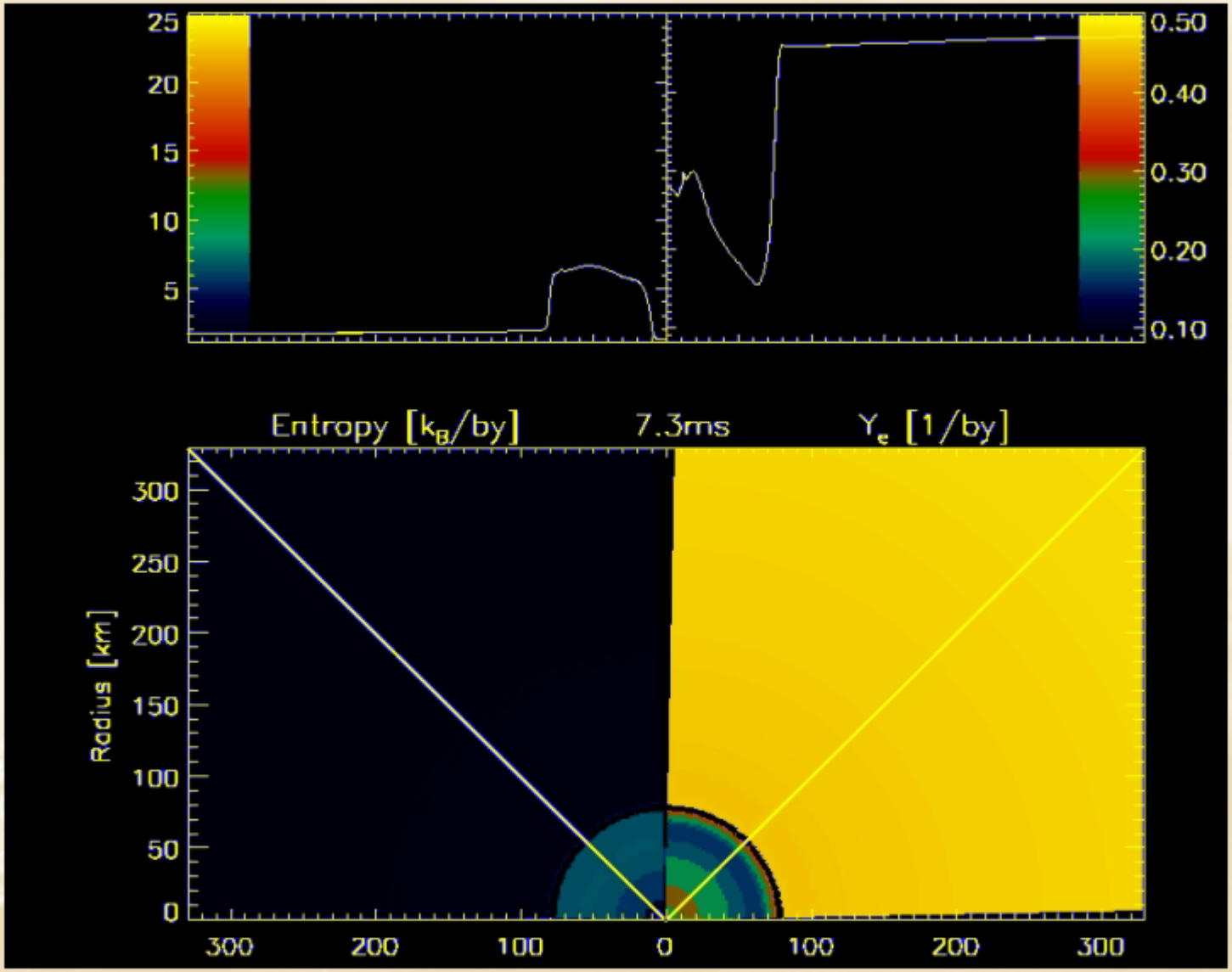
Convection to the Rescue

Convection dredges energy from the neutron star to the shock wave



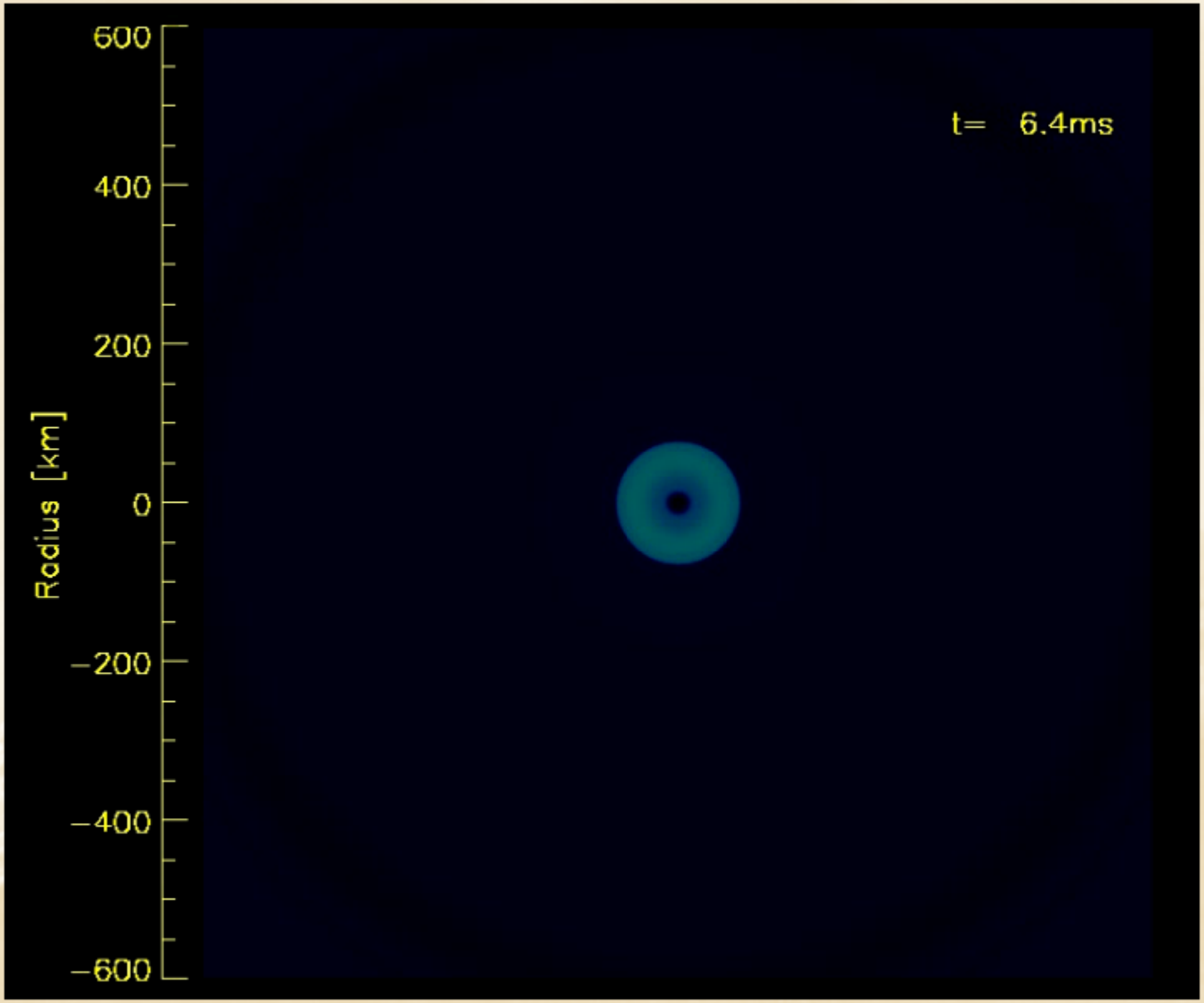
Picture adapted from Janka, astro-ph/0008432

Convection in Supernovae



2-D Simulation (90° wedge) by Garching Group
(H.-T. Janka et al.)

Convection in Supernovae

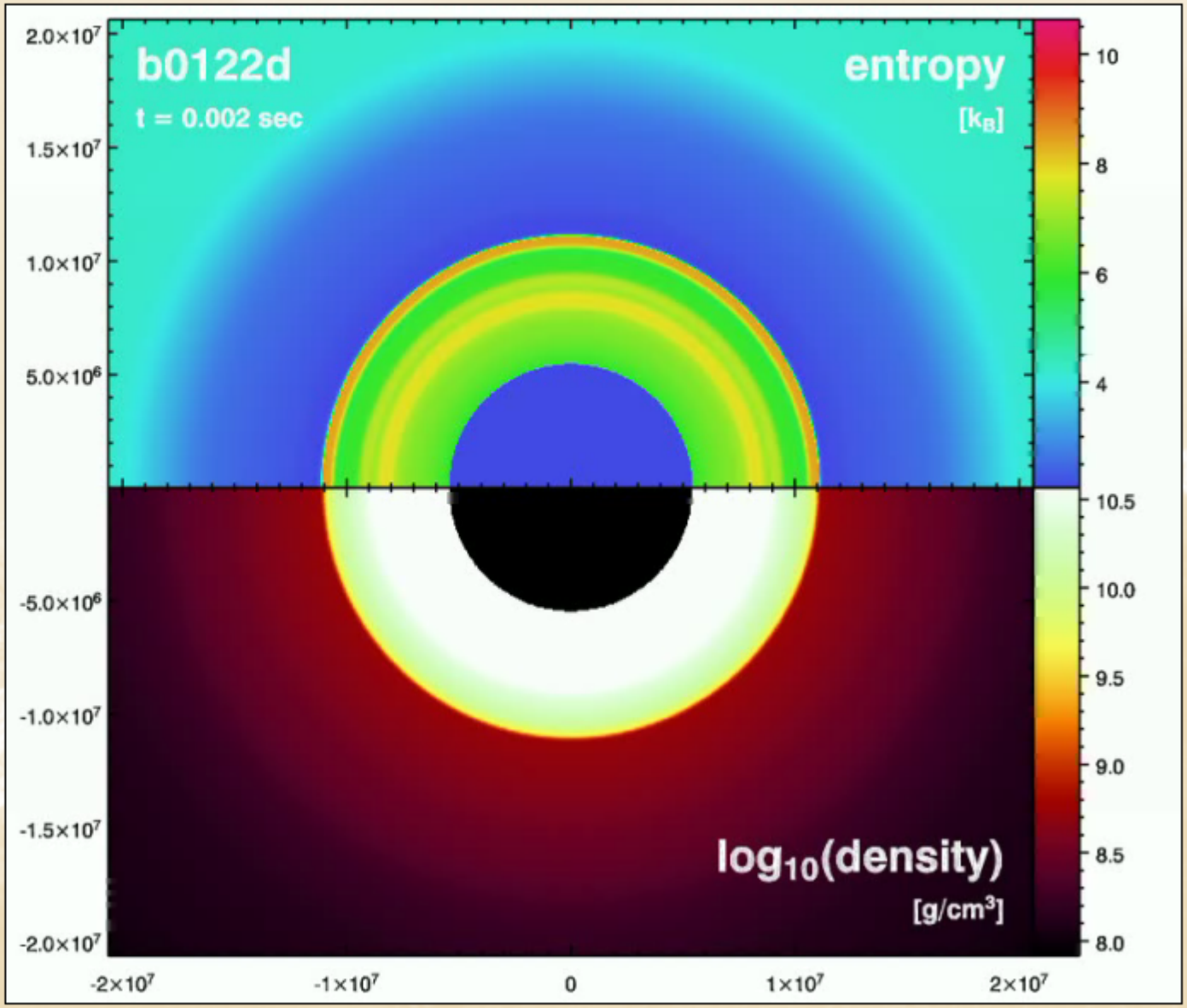


2-D Simulation (180° wedge) by Garching Group

Parametric 2D Studies (180°) by Garching Group

- If explosion develops slowly, convective structures have time to merge to low (l = 1 or 2) mode flow
- Very asymmetric shock expansion and mass ejection although boundary neutrino flux is isotropic

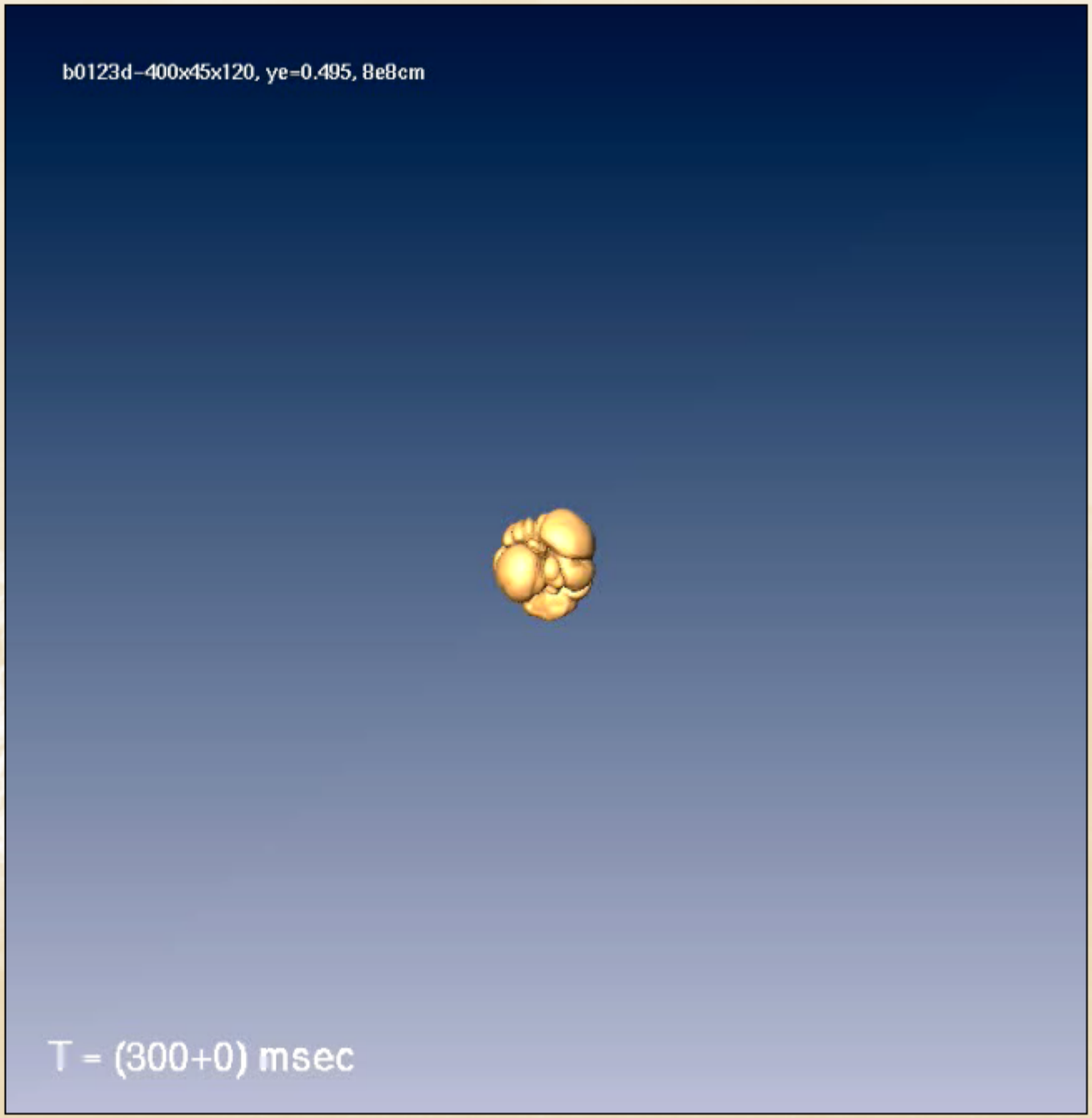
(Scheck et al., PRL 2004 and PhD Thesis)



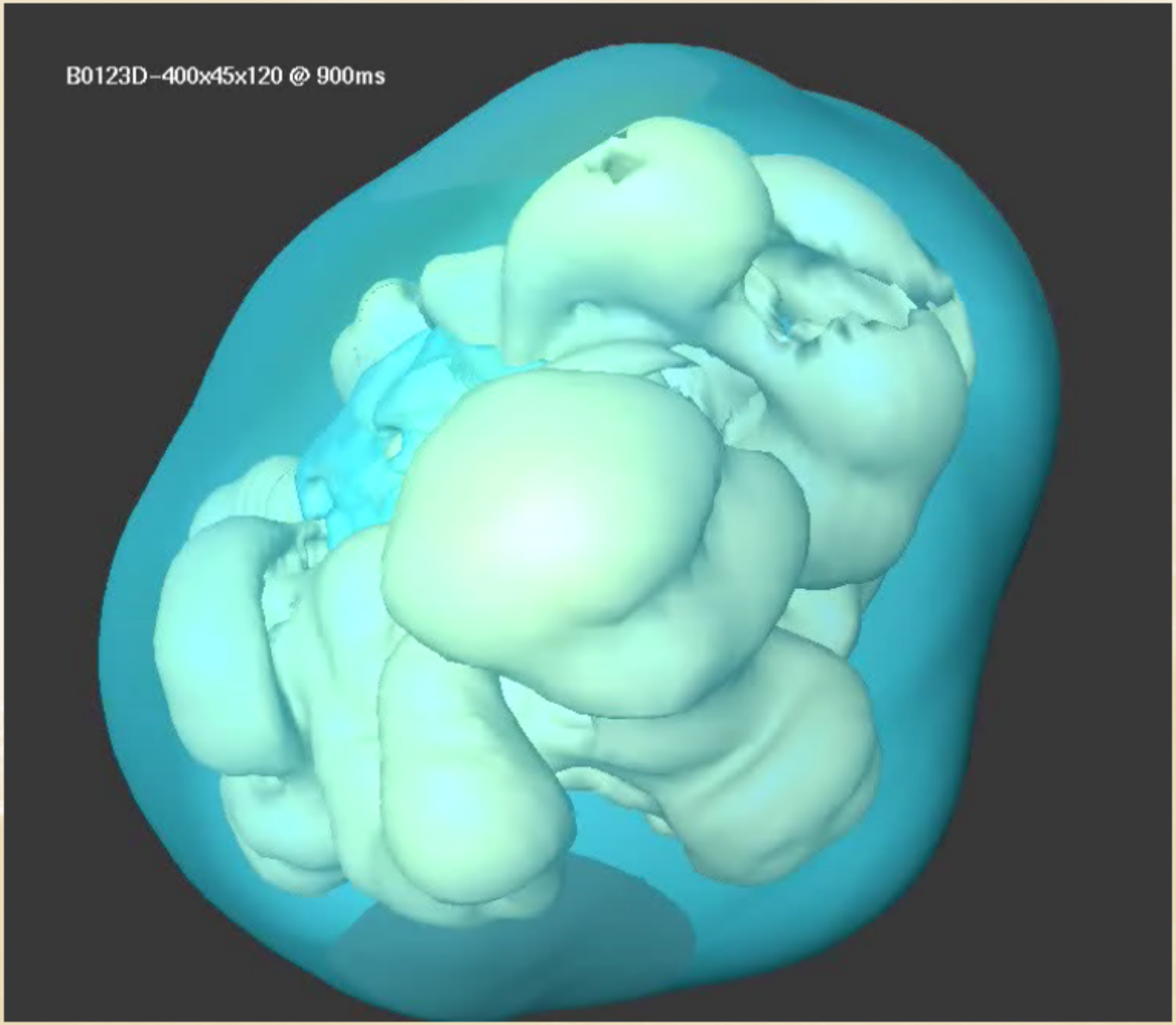
Parametric 3D Studies by Garching Group

- First explosions in 3D show also very large asymmetry
- Convection grows faster than in 2D
- Explosion energy somewhat higher

(L. Scheck PhD Thesis 2004)



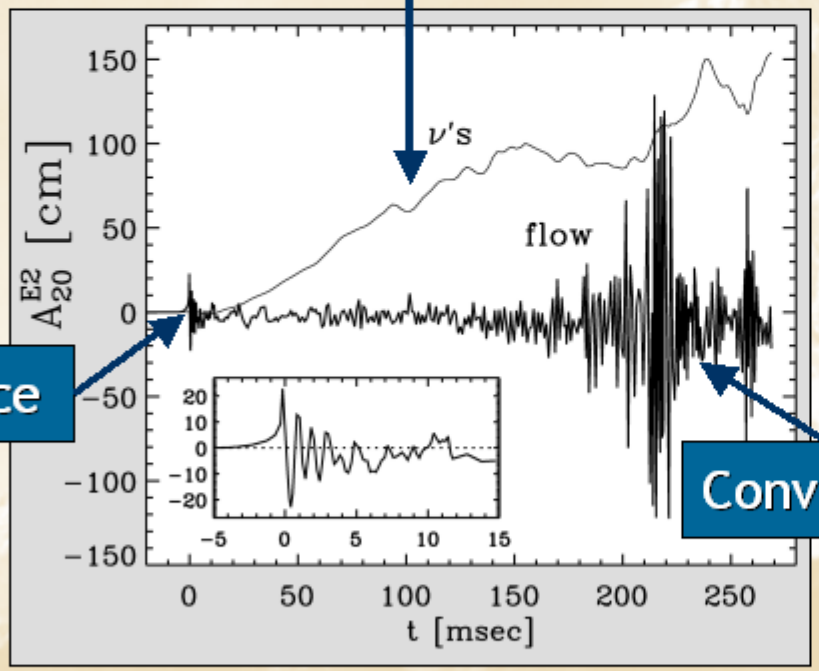
Parametric 3D Studies by Garching Group



Gravitational Waves from Core-Collapse Supernovae

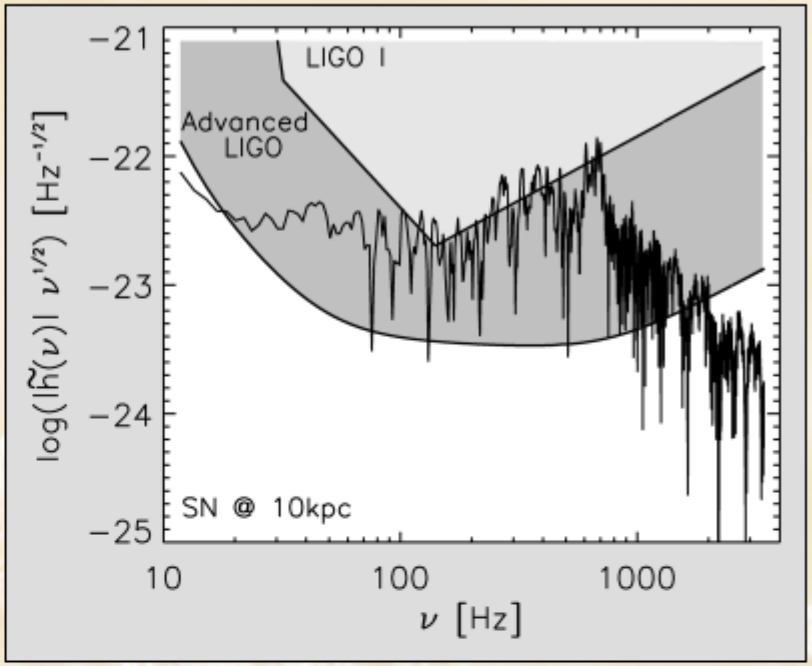
Müller, Rampp, Buras, Janka, & Shoemaker, "Towards gravitational wave signals from realistic core collapse supernova models," astro-ph/0309833

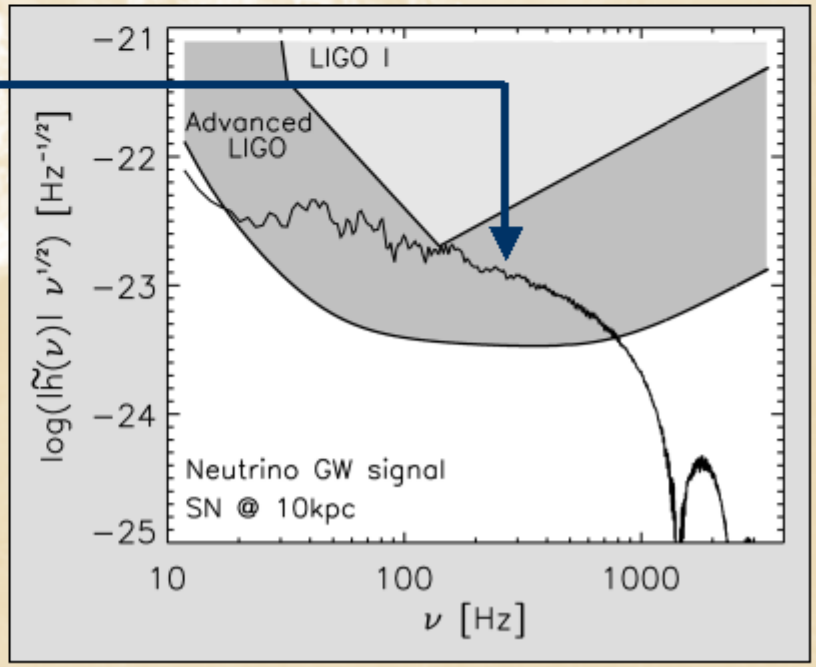
Asymmetric neutrino emission



Bounce

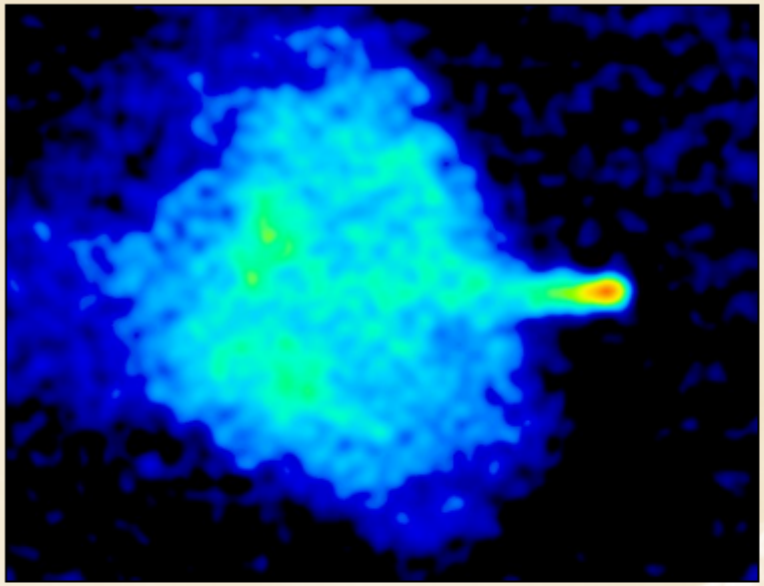
Convection



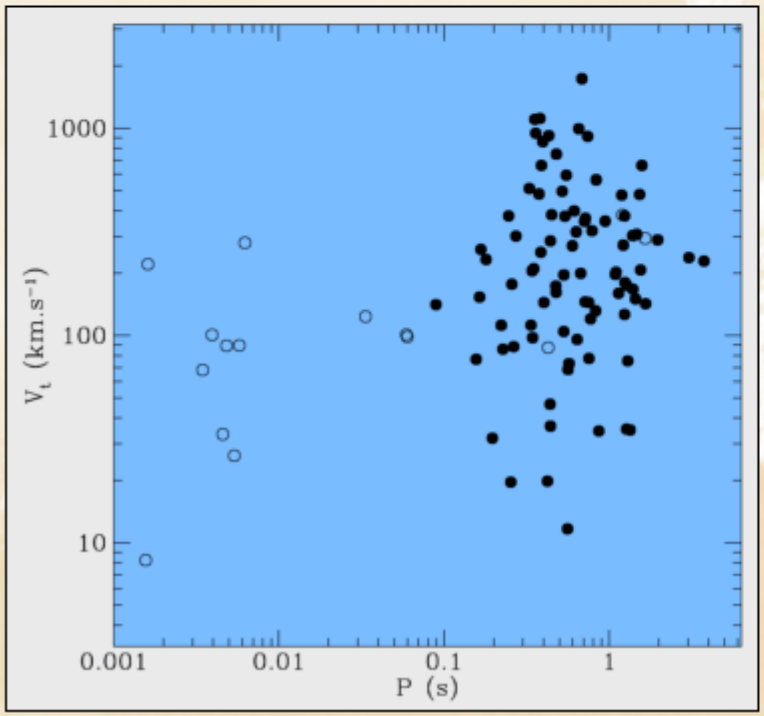


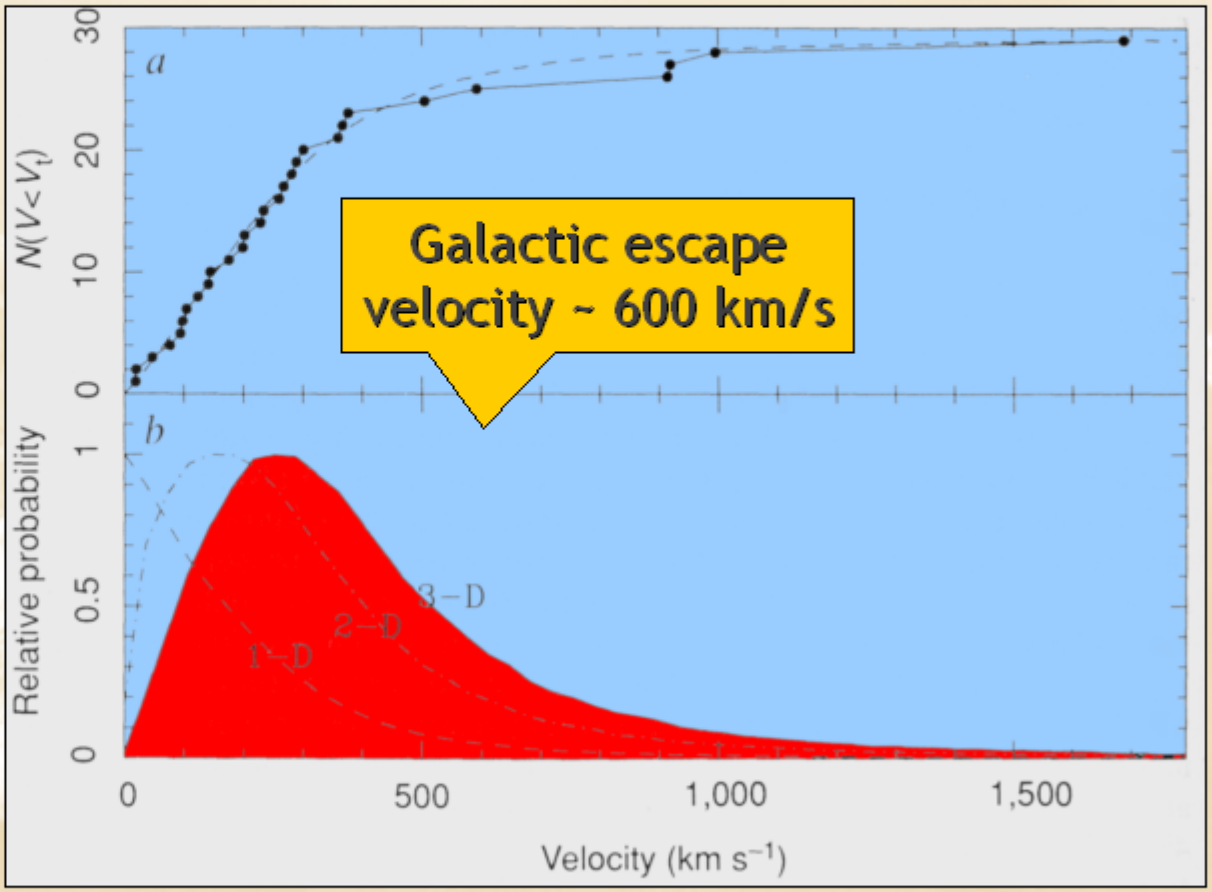
The gravitational-wave signal from convection is a generic and dominating feature

High-Velocity Pulsars



False-color radio image of the SNR G5.4-1.2 and the young radio pulsar PSR 1757-24 (v = 1300–1700 km/s away from the gal. plane)





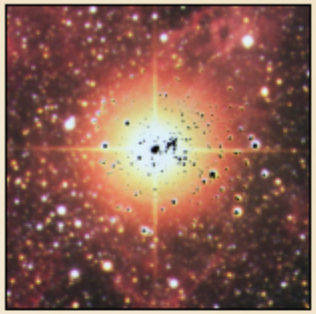
Pulsar velocity distribution
[Lyne & Lorimer, Nature 369 (1994) 127]

What Accelerates the Pulsars?

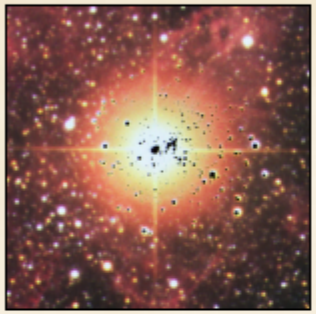
Neutrino Rocket	Required neutrino asymmetry $2.8\% \left(\frac{3\times10^{53}\,\mathrm{erg}}{E_{tot}}\right)\left(\frac{v_{kick}}{1000\,\mathrm{km/s}}\right)$ Caused by B-field induced asymmetry of neutrino transport coefficients (parity violation, dispersion effects & oscillations, asymmetric field distribution, ...)? Typically requires huge fields > 10^{15} Gauss
Matter Rocket	Hydrodynamically driven kicks • Asymmetric matter ejection, but convection not enough (?) • Pre-collapse asymmetry, perhaps caused by overstable oscillations of pre-supernova core?
Photon Rocket	Electromagnetically driven acceleration: Off-center global magnetic dipole moment & rotation accelerates star in one direction. (Slow process - not a "kick")

Dong Lai, Neutron Star Kicks and Asymmetric Supernovae, astro-ph/0012049

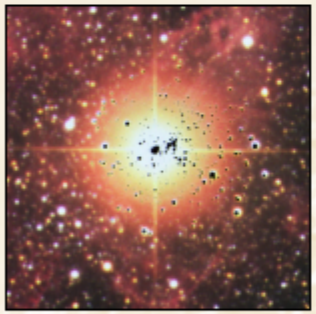
Theoretical Status of Supernova Explosions



- Spherically symmetric models do not explode, even with state-of-the-art Boltzmann solvers for neutrino transport
- Delayed explosion scenario requires enhanced neutrino luminosity at early times (~ factor 2)



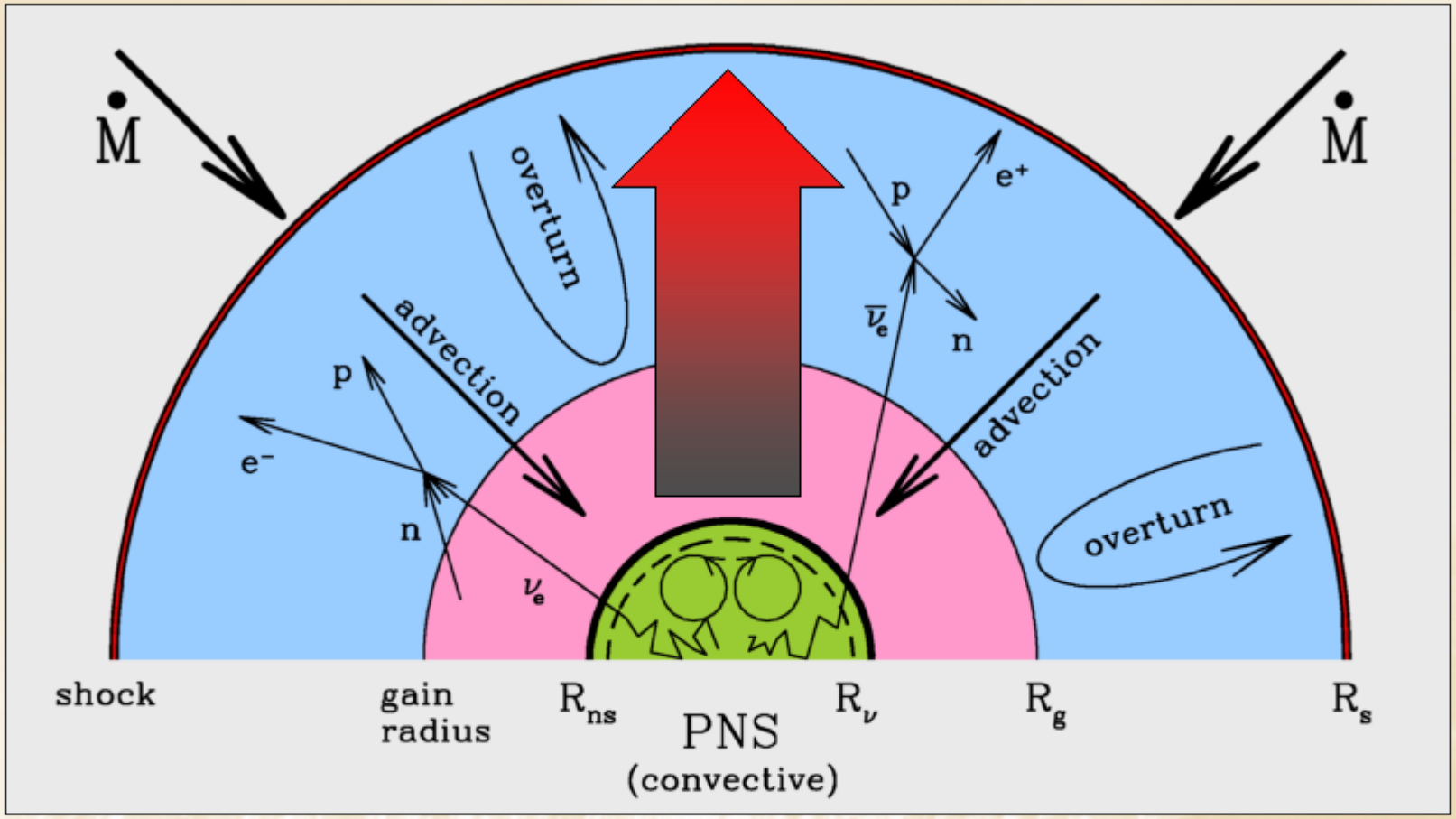
- Convection between proto neutron star (PNS) and shock wave and perhaps within PNS helps
- But 2-D simulations self-consistently coupled with state-of-the-art neutrino transport do not explode either



- New physical ingredients required?
- Explosion a magneto-hydrodynamical effect? (Strong B-fields and fast rotation possible)
- Nuclear equation of state very different?

Buras, Rampp, Janka & Kifonidis (MPA Garching),
Improved Models of Stellar Core Collapse and Still no Explosions: What is Missing?
[astro-ph/0303171, Phys. Rev. Lett. 90, 241101 (2003)]

Novel Forms of Energy Transfer?



New particles or neutrinos with novel properties could provide a channel of energy transfer from proto neutron star to shock wave

Must not transfer too much energy: Limits on decaying neutrinos [Falk & Schramm, PLB 79 (1978) 511]

Shock Revival by Novel Particles?

THE ASTROPHYSICAL JOURNAL, **260**:868–874, 1982 September 15

SUPERNOVAE INDUCED BY AXION-LIKE PARTICLES

DAVID N. SCHRAMM
The University of Chicago
AND
JAMES R. WILSON
Lawrence Livermore Laboratory
Received 1981 December 22; accepted 1982 April 1

ABSTRACT

It is shown that a new type of particle which may have been seen in a recent accelerator experiment may, if truly present, provide a mechanism whereby gravitationally collapsing massive stars may eject their outer mantles and envelopes in supernova explosions of $\sim 10^{51}$ ergs while leaving the cores to form neutron star remnants. These particles are "axion-like," which means they interact semiweakly, decay to two photons with lifetimes $\sim 10^{-3}$ s, and have masses $0.15 \leq M_a \lesssim 1$ MeV. It is hoped that future accelerator searches will be able to confirm or deny the existence of these particles, the presence of which would cause a dramatic solution to the long-standing gravitational-collapse supernova problem.

Subject headings: elementary particles — nuclear reactions — stars: collapsed — stars: supernovae

Viable Scenario with Axion-Like Particles

Coupled to nuclear medium
by bremsstrahlung

$N + N \rightarrow N + N + a$

PNS

Thermal flux of axion-like particles from "axion sphere"

Decay

$a \rightarrow e^+ + e^-$

Stalling shock wave

$$L = \frac{1}{f} \bar{\Psi}_N \gamma_5 \gamma^\mu \Psi_N \partial_\mu a$$

$$L = \frac{1}{f} \bar{\Psi}_e \gamma_5 \gamma^\mu \Psi_e \partial_\mu a$$

Apparently consistent with f = few 10^5 GeV and m = few MeV
Not excluded by other arguments, but also not independently motivated

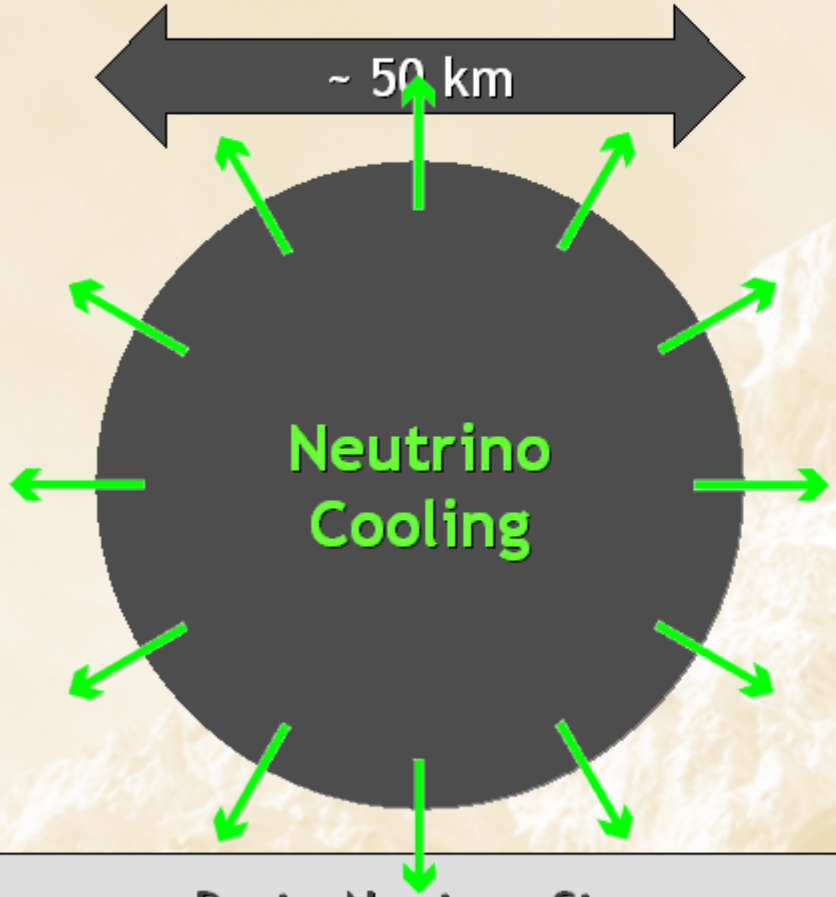
Berezhiani & Drago, PLB 473 (2000) 281

Neutrinos from Core-Collapse Supernovae

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

$\rho \approx \rho_{nuc} = 3 \times 10^{14}$ g cm^{-3}

T ≈ 30 MeV

Gravitational binding energy

$E_b \approx 3 \times 10^{53}$ erg $\approx$ 17% $M_{SUN}\, c^2$

This shows up as

99%	Neutrinos
1%	Kinetic energy of explosion (1% of this into cosmic rays)
0.01%	Photons, outshine host galaxy

Neutrino luminosity

$L_\nu \approx 3 \times 10^{53}$ erg / 3 sec

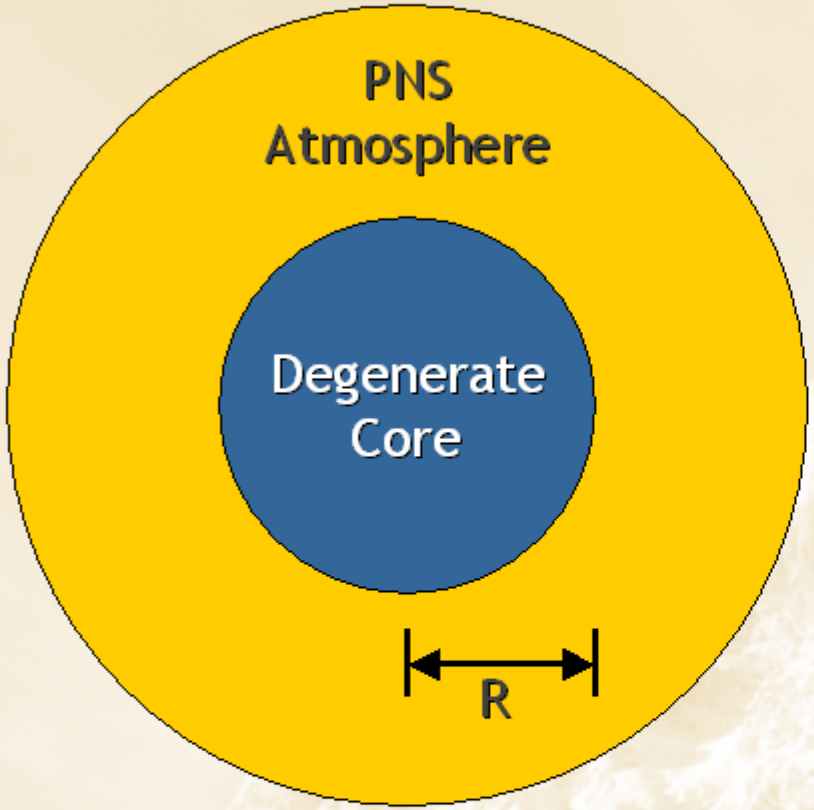
$\approx 3 \times 10^{19}\, L_{SUN}$

While it lasts, outshines the entire visible universe

What determines the size of the PNS?

Mass	Chandrasekhar mass of iron core of progenitor star Dimensional analysis: $M_{Ch} \approx G_N^{-3/2} m_N^{-2} = m_{Pl}^3 m_N^{-2} \approx 1.5 M_{sun}$ Same number from zero-T polytropic model
Density	Supported by nucleon degeneracy pressure Nuclear density $\rho \approx \rho_{nuc} = 3 \times 10^{14}\,\mathrm{g\,cm^{-3}}$
Radius	$\frac{4\pi}{3} \rho_{nuc} R^3 = M_{Ch}$ $R \approx 10.6$ km
Schwarzschild Radius	General $R_S = 2 G_N M$ Here $R_S = 2 G_N M_{Ch} = 2 m_{Pl} m_N^{-2} = 4.6$ km

What determines the neutrino energies?



Gravitational potential of a given nucleon

$$\Phi = -G_N M_{PNS} m_N R^{-1}$$

With $M_{PNS} \approx 1.5\ M_{sun}$ **and** $R \approx 30$ **km**

$$\Phi \approx -27 \text{ MeV}$$

Virial theorem (hydrostatic equilibrium)

assuming nondegenerate conditions,

$$\langle E_{kin} \rangle = -\tfrac{1}{2} \langle \Phi \rangle \approx 13 \text{ MeV}$$

Thermal equilibrium

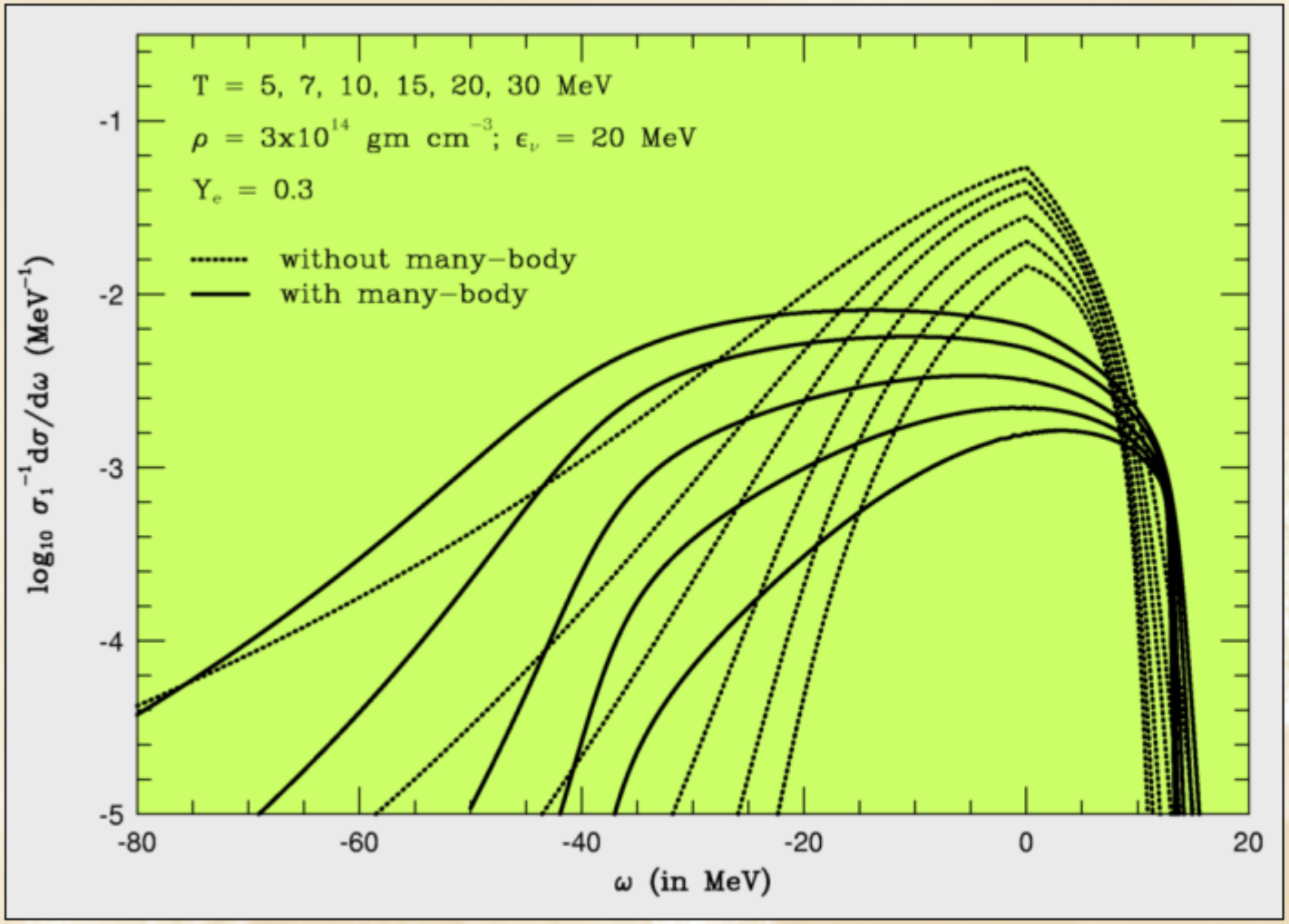
$$T = (2/3) \langle E_{kin} \rangle \approx 9 \text{ MeV}$$

- If the proto-neutron star (PNS) atmosphere is nondegenerate, its temperature is determined by the gravitational potential at the surface of the degenerate core and found in the ~ 10 MeV range
- Core contracts by accretion and/or cooling $\rightarrow$ T increases

What determines the time scale?

Main neutrino reactions	Electron flavor $\nu_e + n \rightarrow p + e^-$ $\bar{\nu}_e + p \rightarrow n + e^+$ Other flavors $\nu_e + N \rightarrow N + \nu$
Neutral-current scattering cross section	$\sigma(\nu N \rightarrow N\nu) = \frac{C_V^2 + 3C_A^2}{\pi} G_F^2 E_\nu^2 \approx 2 \times 10^{-40}\,\mathrm{cm}^2 \left(\frac{E_\nu}{100\,\mathrm{MeV}}\right)^2$
Nucleon density	$n_B = \frac{\rho_{nuc}}{m_N} \approx 1.8 \times 10^{38}\,\mathrm{cm}^{-3}$
Scattering rate	$\Gamma = \sigma n_B \approx 1.1 \times 10^9\,\mathrm{s}^{-1} \left(\frac{E_\nu}{100\,\mathrm{MeV}}\right)^2$
Mean free path	$\lambda = (\sigma n_B)^{-1} \approx 28\,\mathrm{cm} \left(\frac{100\,\mathrm{MeV}}{E_\nu}\right)^2$
Diffusion time	$t_{diff} \approx \frac{R^2}{\lambda} \approx 1.2\,\mathrm{sec} \left(\frac{R}{10\,\mathrm{km}}\right)^2 \left(\frac{E_\nu}{100\,\mathrm{MeV}}\right)^2$

Many-Body Effects on Neutrino Opacities

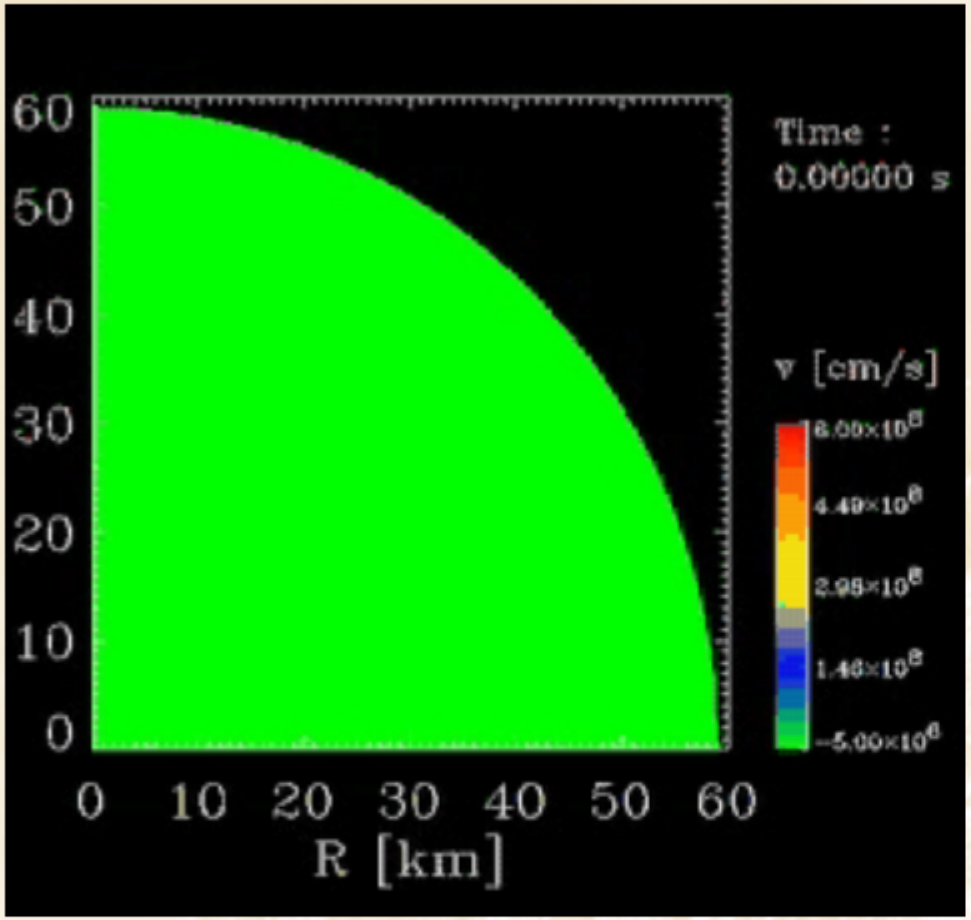


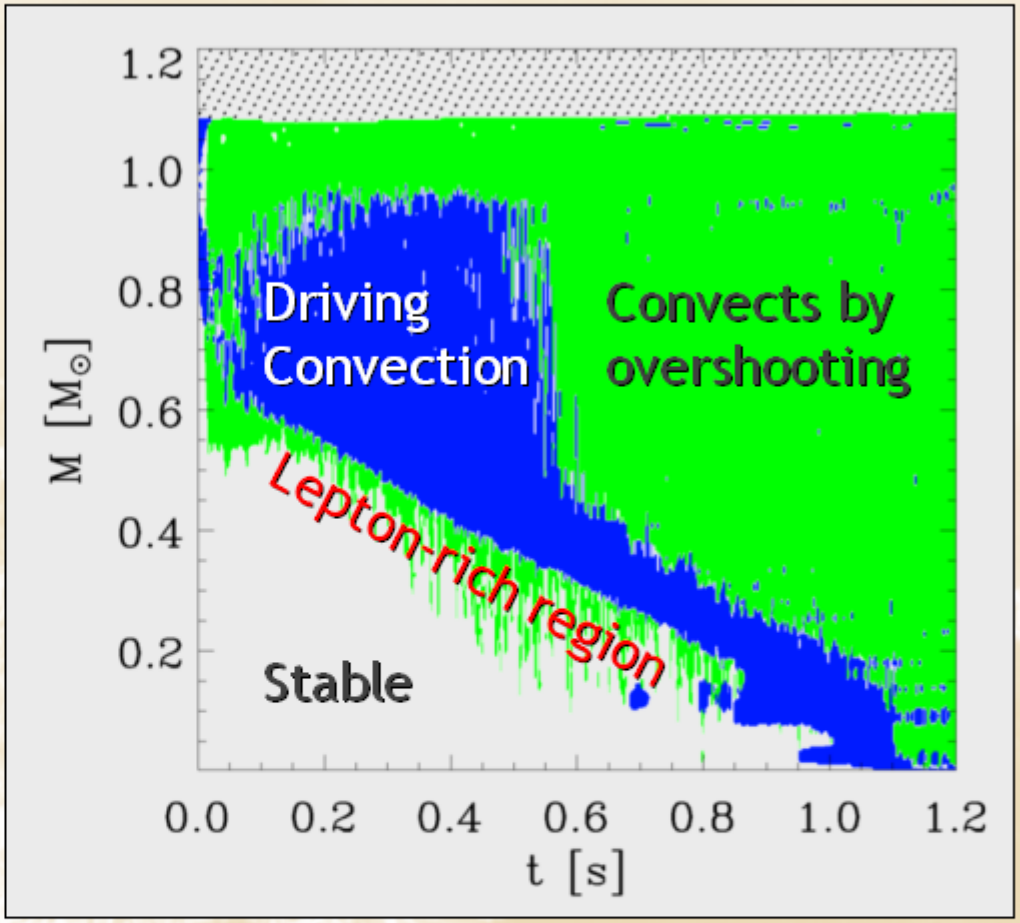
Burrows & Sawyer, astro-ph/9804264

See also Reddy, Prakash & Lattimer, PRD 58 (1998) 013009

Opacities with realistic many-body treatment not yet included in all numerical simulations

Convection in Proto Neutron Star

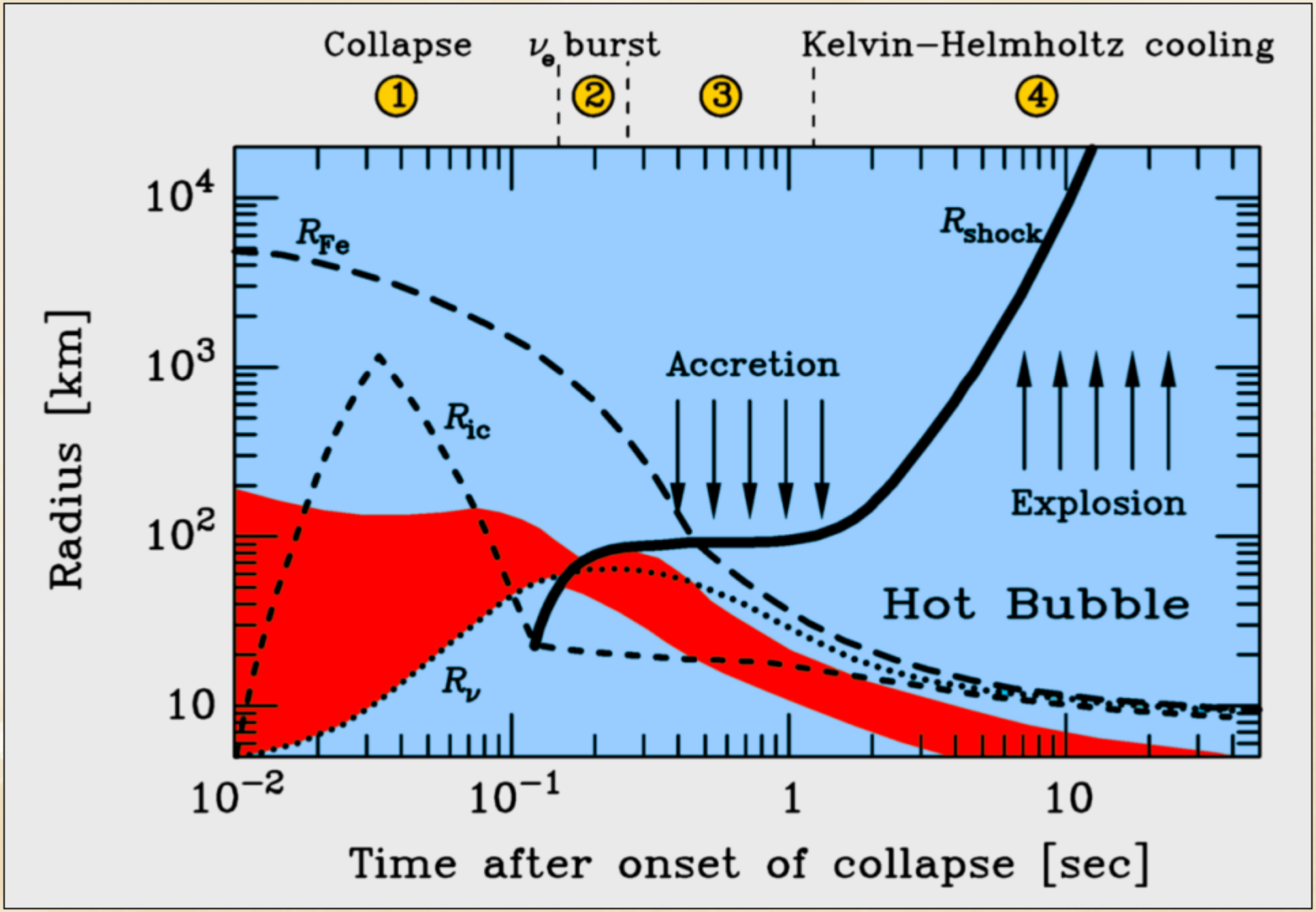




Time scale of deleptonization increased by ~ factor 2, i.e. same general magnitude as diffusive transport

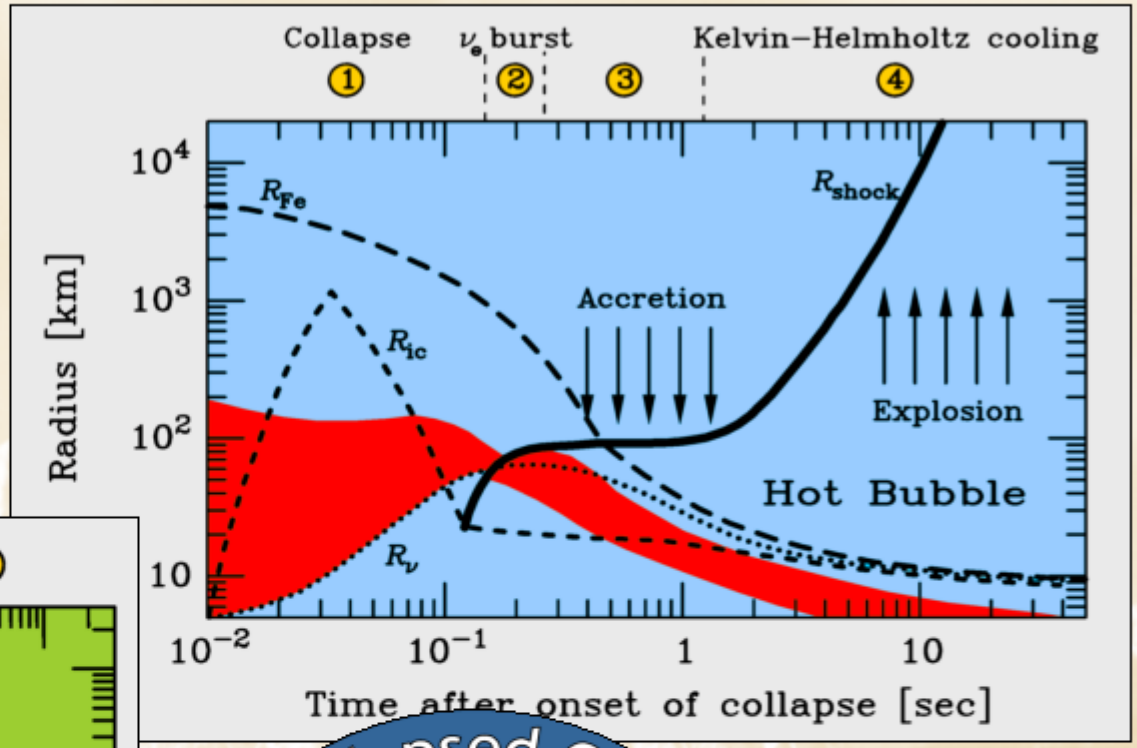
Keil, Janka & Müller, ApJ 473 (1996) L111

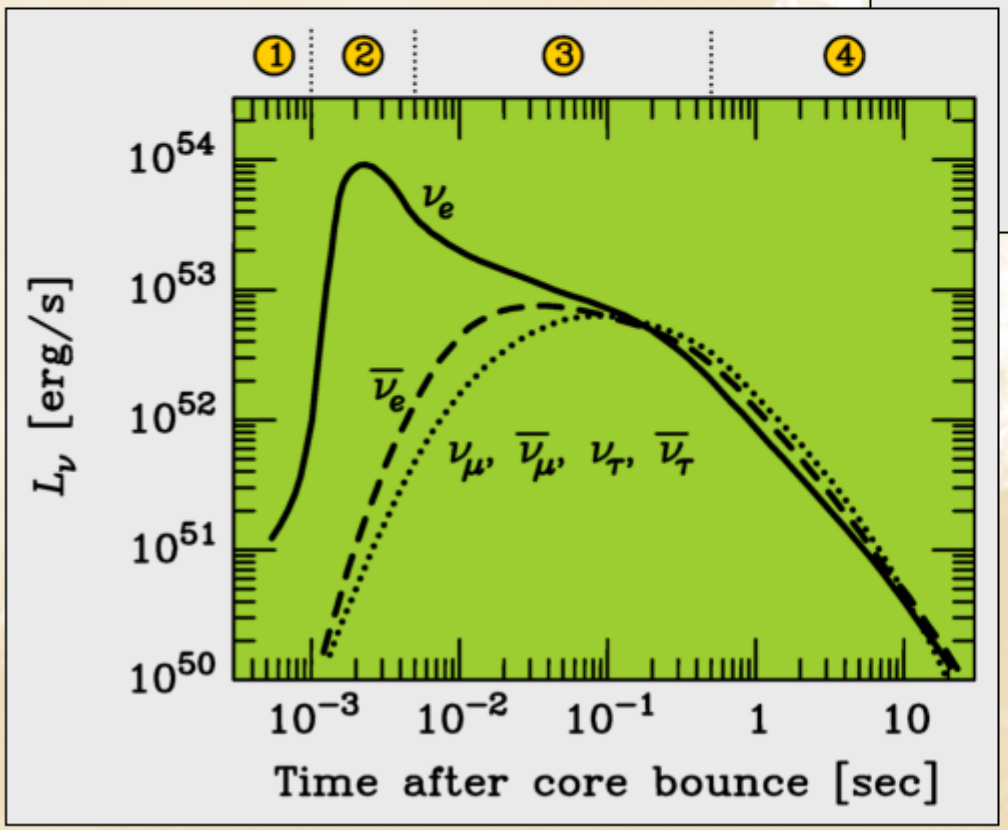
Supernova Delayed Explosion Scenario

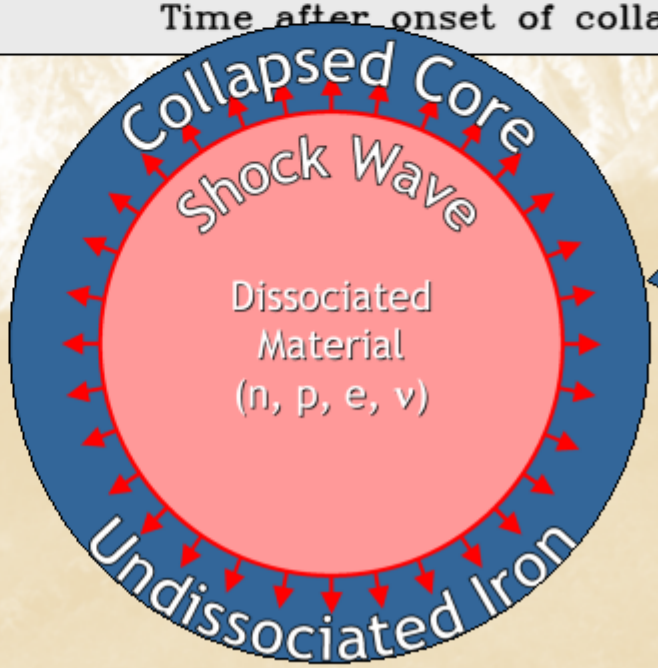


Structure of Supernova Neutrino Signal

1. Collapse (infall phase)
2. Shock break out
3. Matter accretion
4. Kelvin-Helmholtz cooling



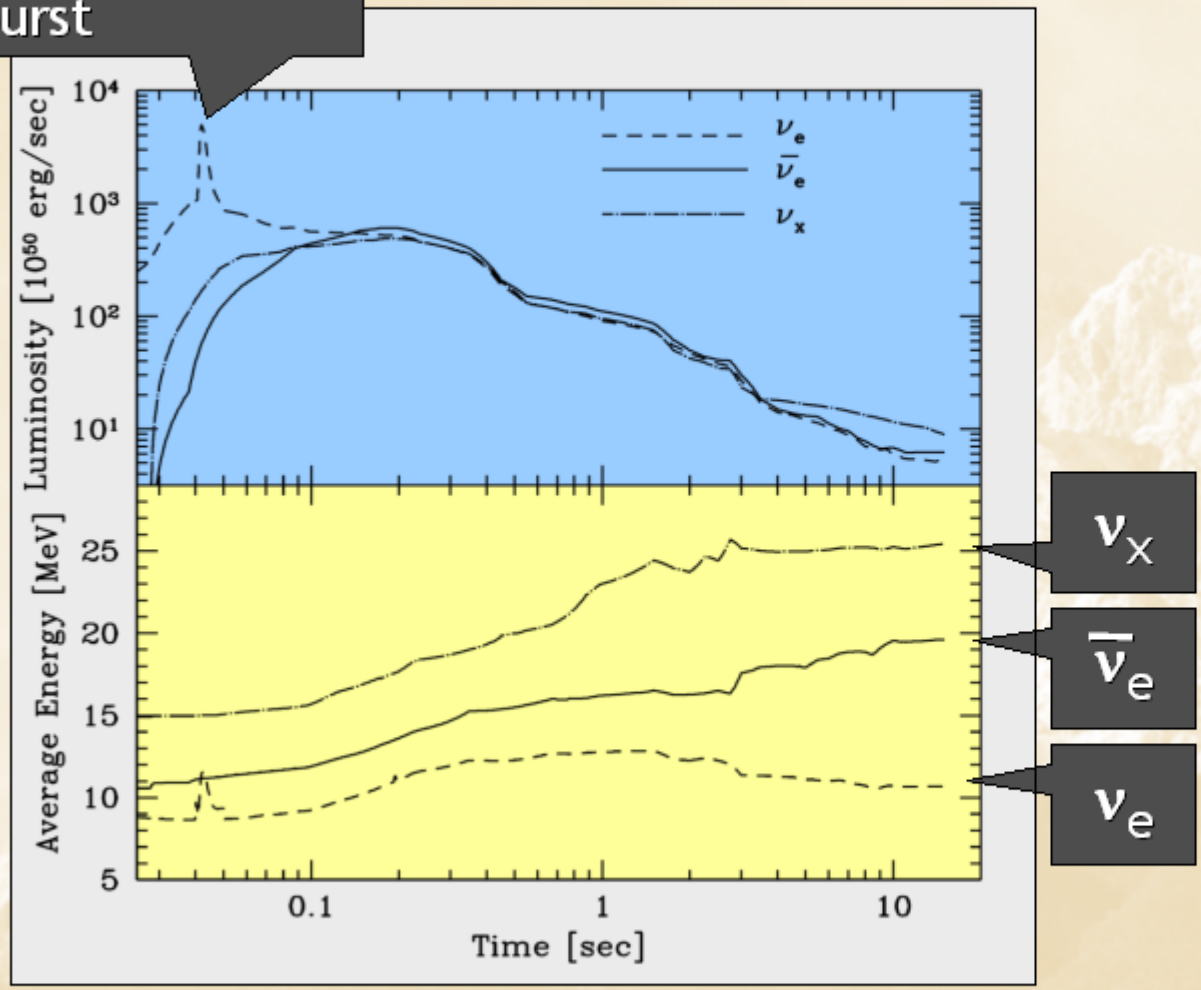




Traps neutrinos and lepton number of outer core layers

Flavor-Dependent Fluxes and Spectra

Prompt ν_e deleptonization burst



Livermore numerical model
ApJ 496 (1998) 216

Broad characteristics

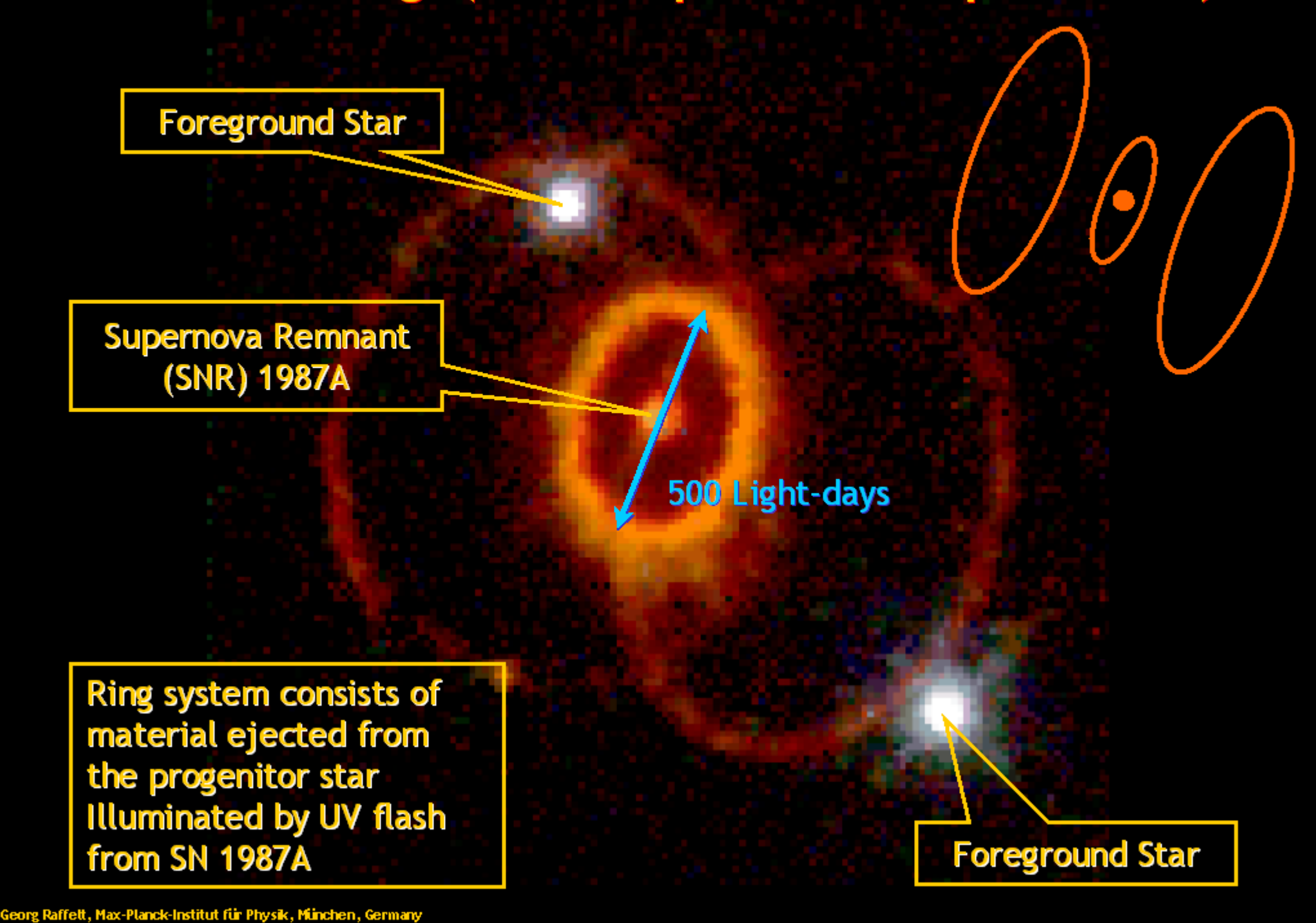
- Duration a few seconds
- $\langle E_\nu \rangle$ ~ 10–20 MeV
- $\langle E_\nu \rangle$ increases with time
- Hierarchy of energies
  $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$
- Approximate equipartition of energy between flavors


Supernova 1987A
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

SN 1987A Rings (Hubble Space Telescope Picture)

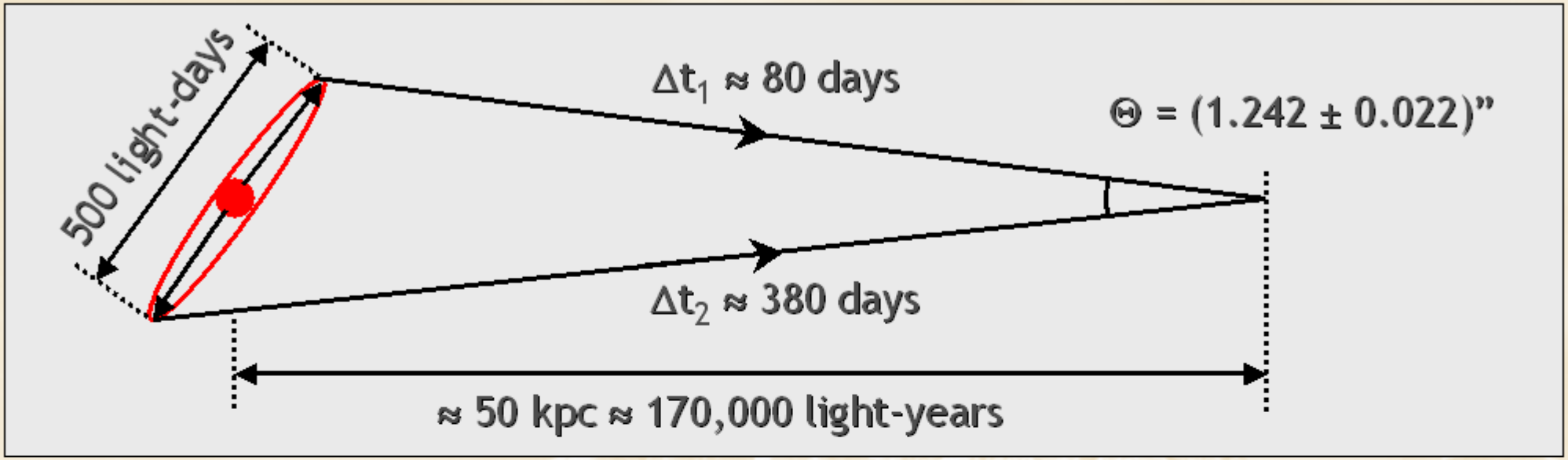
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

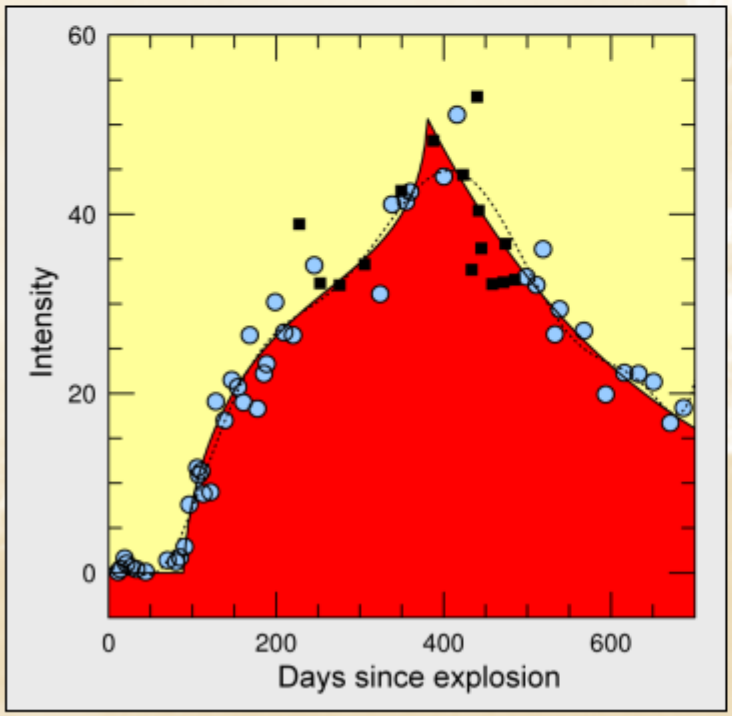
SN 1987A Rings (Hubble Space Telescope Picture)



Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

Distance Determination with Inner Ring



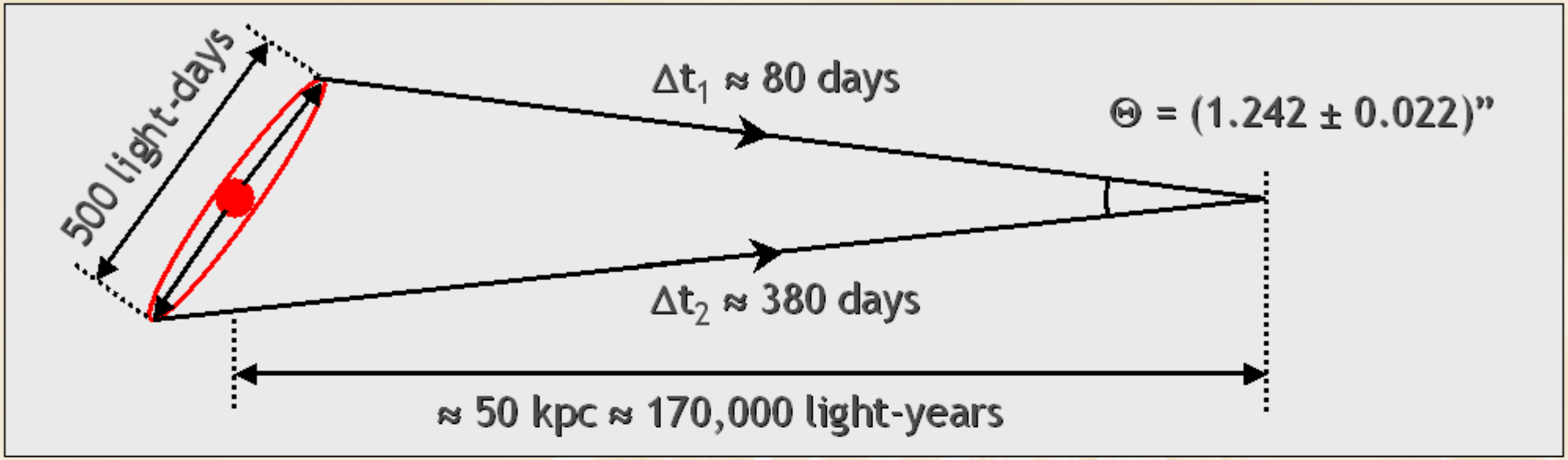


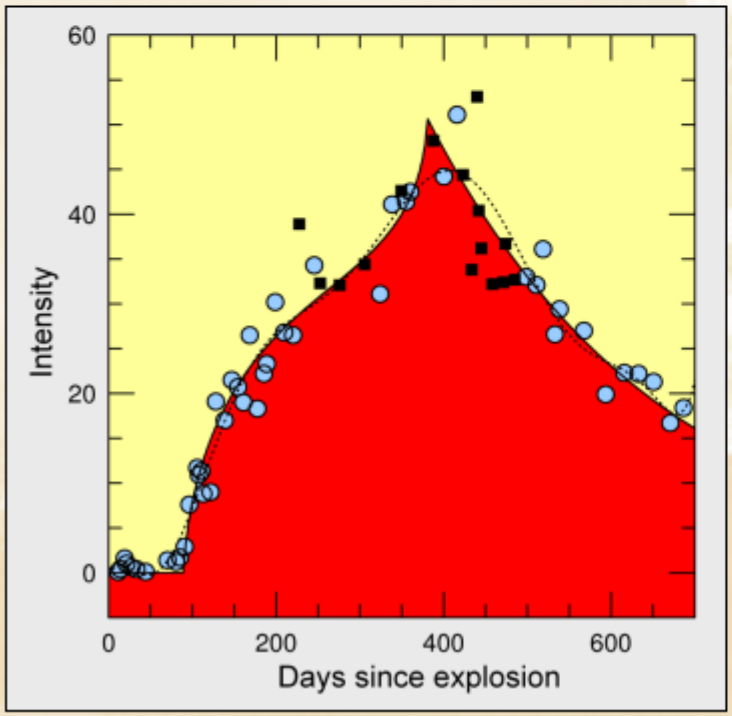
Angular diameter $\Theta_+ = (1.716 \pm 0.022)''$ measured by HST on 24-8-1990

Δt_1 and Δt_2 measured in UV by IUE satellite

Ni III] light curve SN 1987A ring, measured by IUE [Sonneborn et al. ApJ 477 (1997) 848, fit by Gould & Uza, ApJ 494 (1998) 118]

Distance Determination with Inner Ring





Distance to SN 1987A

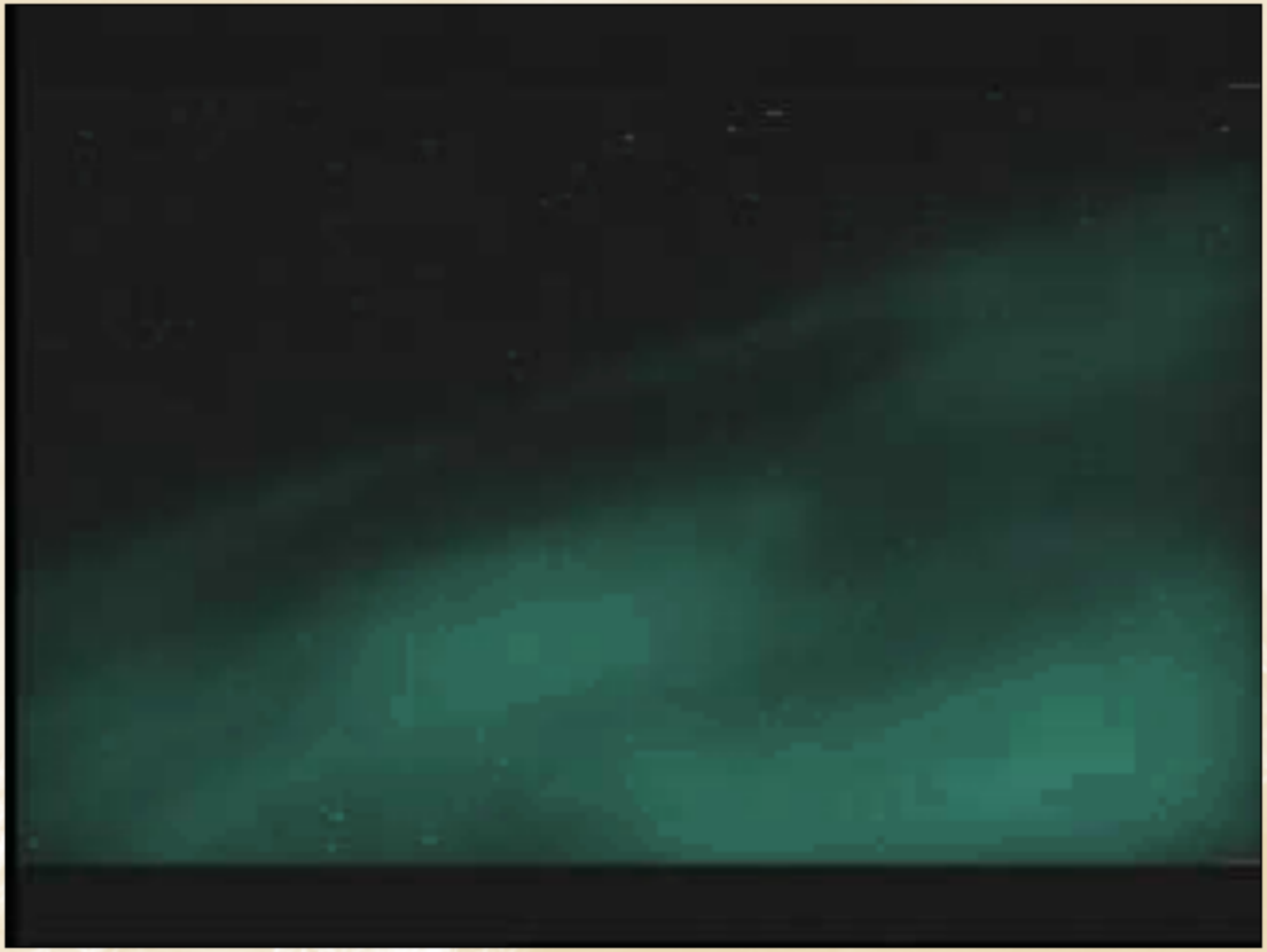
51.2 ± 3.1 kpc Panagia et al., ApJ 380 (1991) L23

51.4 ± 1.2 kpc Panagia, IAU Symposium 190 (1999)

47.2 ± 0.9 kpc Gould & Uza, ApJ 494 (1998) 118

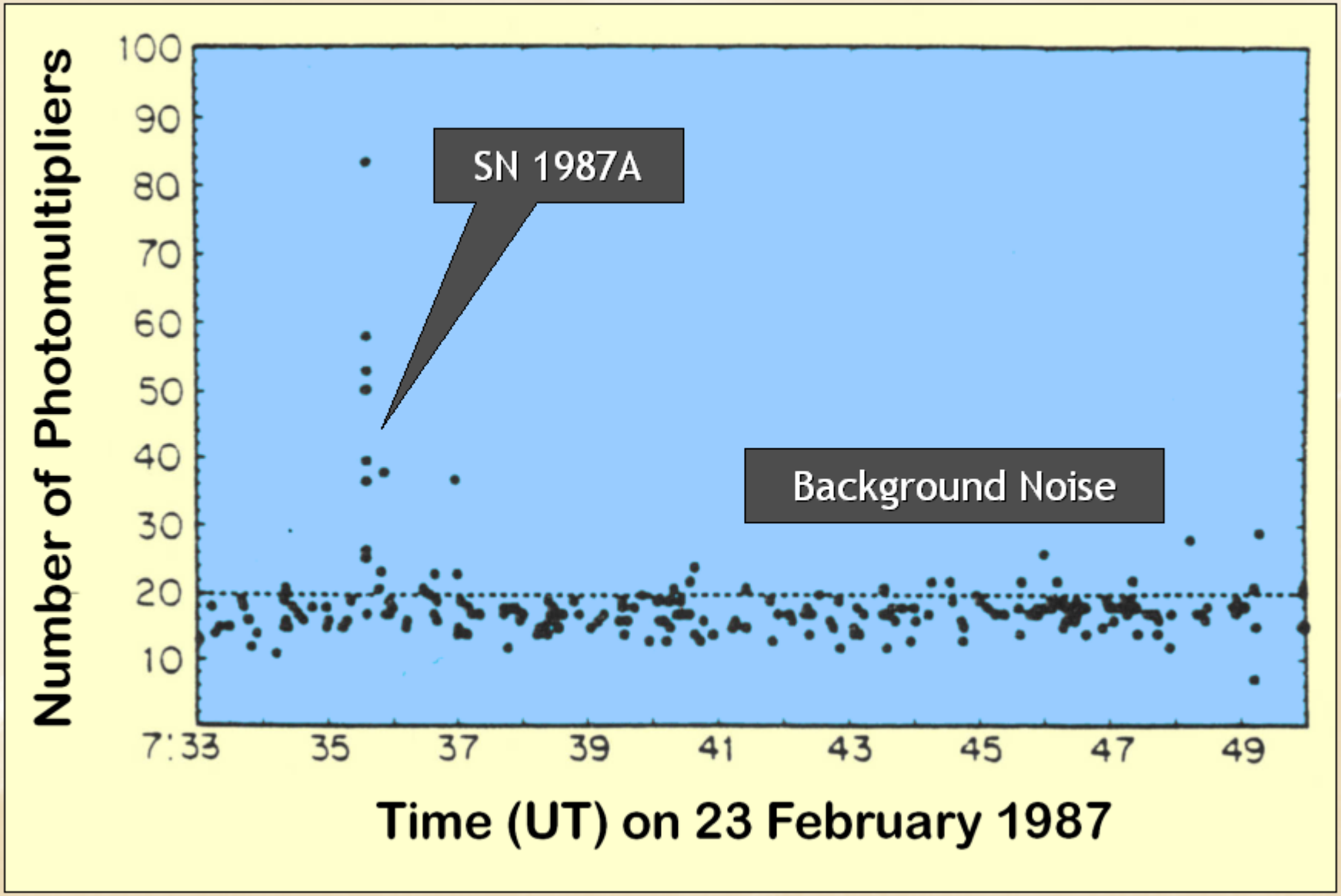
Ni III] light curve SN 1987A ring, measured by IUE [Sonneborn et al. ApJ 477 (1997) 848, fit by Gould & Uza, ApJ 494 (1998) 118]

Animation of SN 1987A Explosion

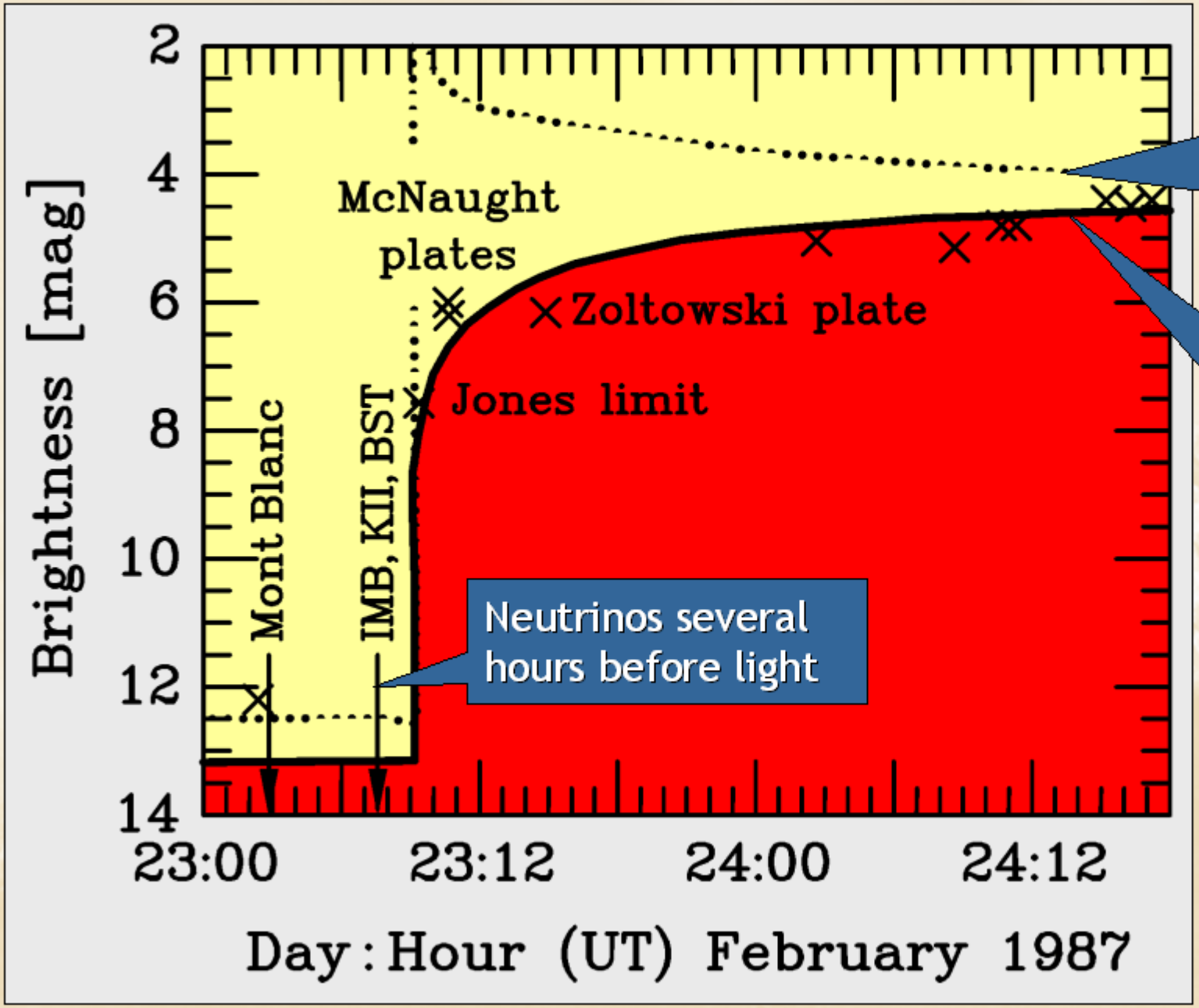


Animation by T. Goertel
Space Telescope Science Institute
http://www.stsci.edu

Neutrino Signal of SN 1987A in Kamiokande



Early Lightcurve of SN 1987A



Expected bolometric brightness evolution

Expected visual brightness evolution

Adapted from Arnett et al., ARAA 27 (1989)

Dispersion between Neutrinos and Photons

Transit time for photons and neutrinos are equal to within ~ 3h

Total transit time ~ 5×10^{12} sec
→ Equal for photons and neutrinos
within ~ 2×10^{-9}

(Longo 1987, Stodolsky 1988)

$$\left|\frac{c_\nu - c_\gamma}{c_\nu + c_\gamma}\right| < 10^{-9}$$

Shapiro time delay for particles moving through a gravitational potential

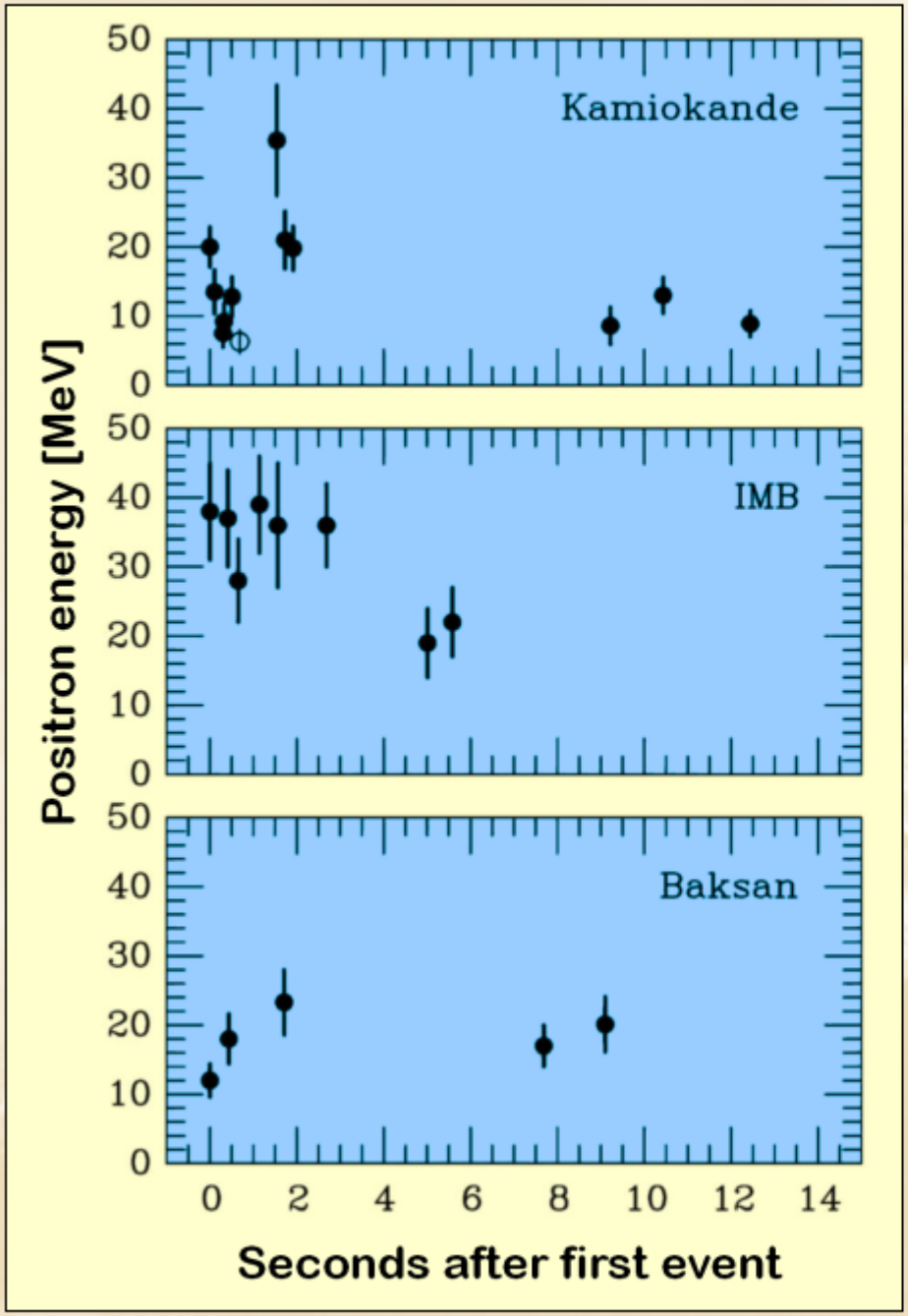
$$\Delta t_{Shapiro} = -2\int_A^B U[r(t)]\,dt \approx 2 - 6 \times 10^6 \text{ sec}$$

(Krauss & Tremaine 1988)

Equal within ~ $1 - 4 \times 10^{-3}$

- Provides limits on parameters of certain non-GR theories of gravitation
- Could be extended to neutrinos vs. anti-neutrinos or different flavors from signal of a future galactic SN

Neutrino Signal of Supernova 1987A



Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

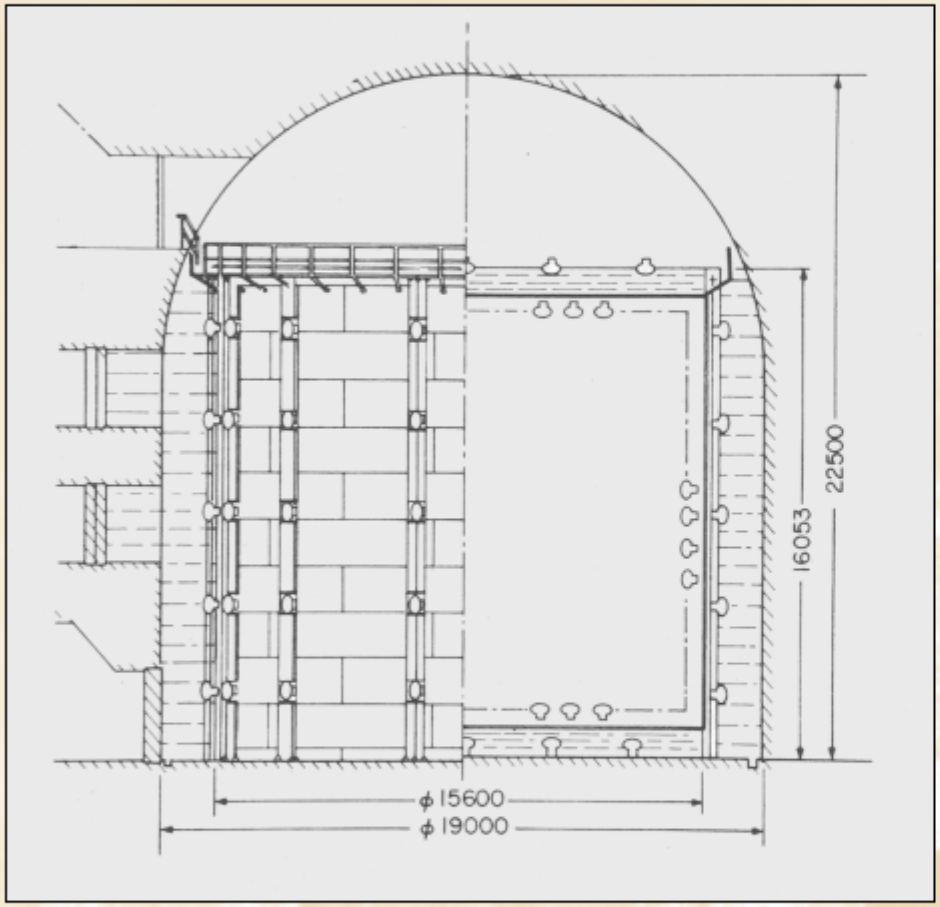
Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
Clock uncertainty ±50 ms

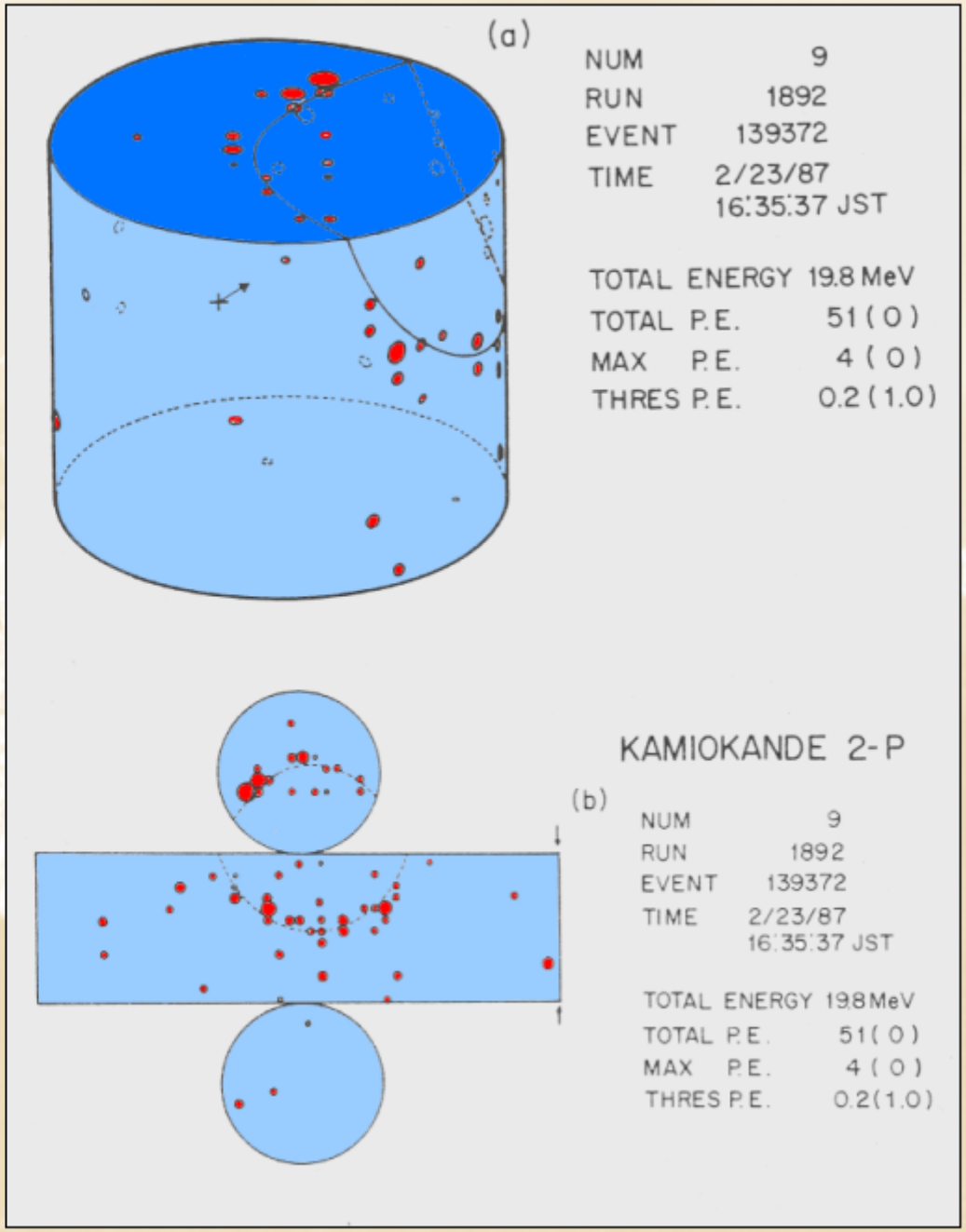
Baksan Scintillator Telescope
(Soviet Union)
Clock uncertainty +2/-54 s

Within clock uncertainties,
signals are contemporaneous

SN 1987A Event No. 9 in Kamiokande

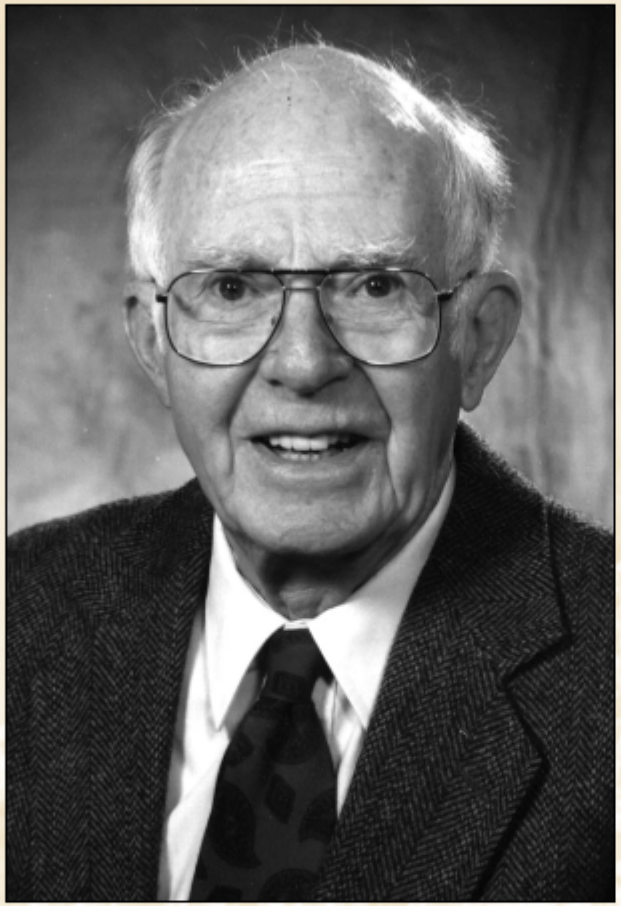
Kamiokande Detector





Hirata et al., PRD 38 (1988) 448

2002 Physics Nobel Prize for Neutrino Astronomy



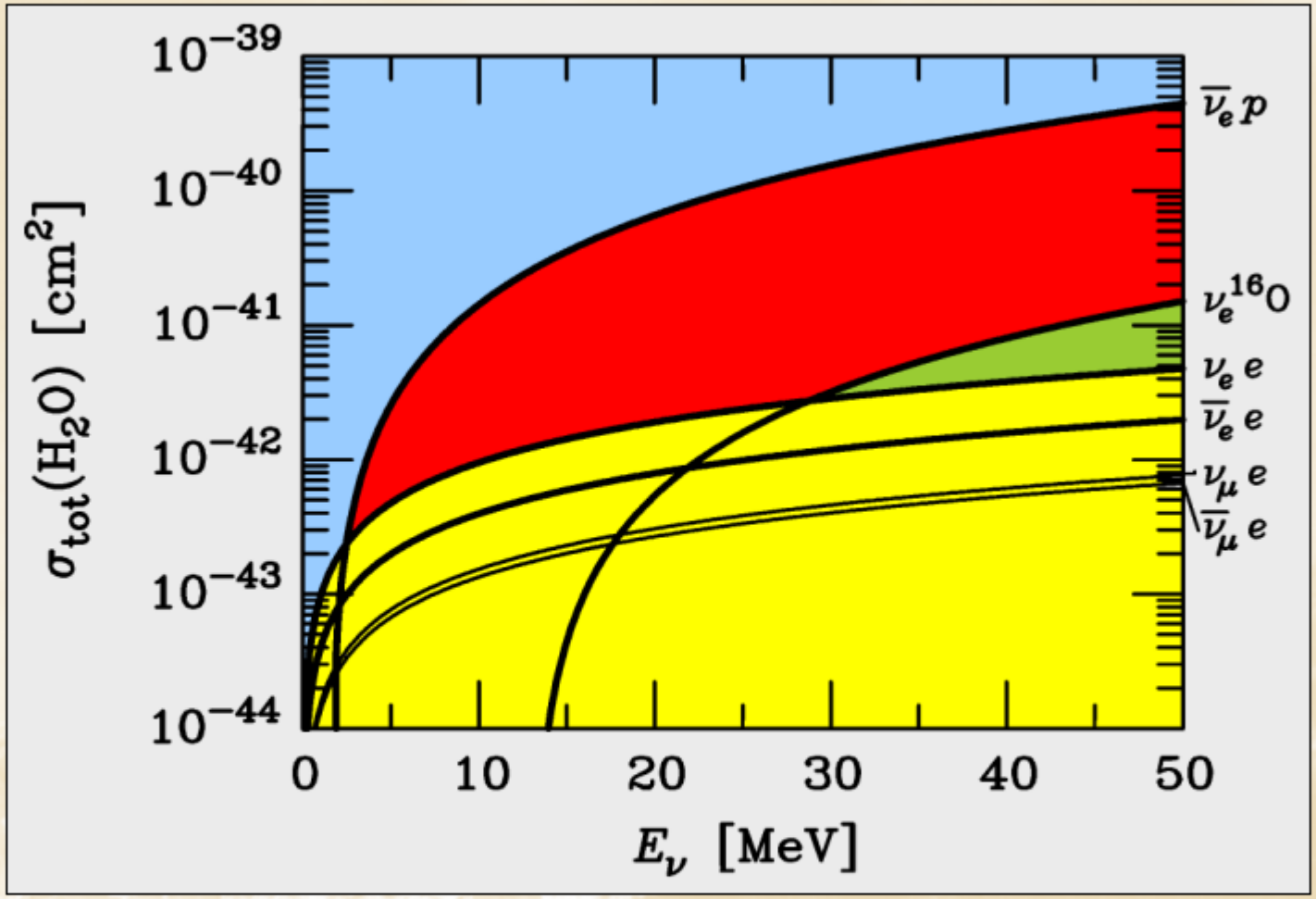
Ray Davis Jr.
(*1914)

Masatoshi Koshiba
(*1926)

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

Neutrino Cross Section in a Water Target

Cross section per water molecule

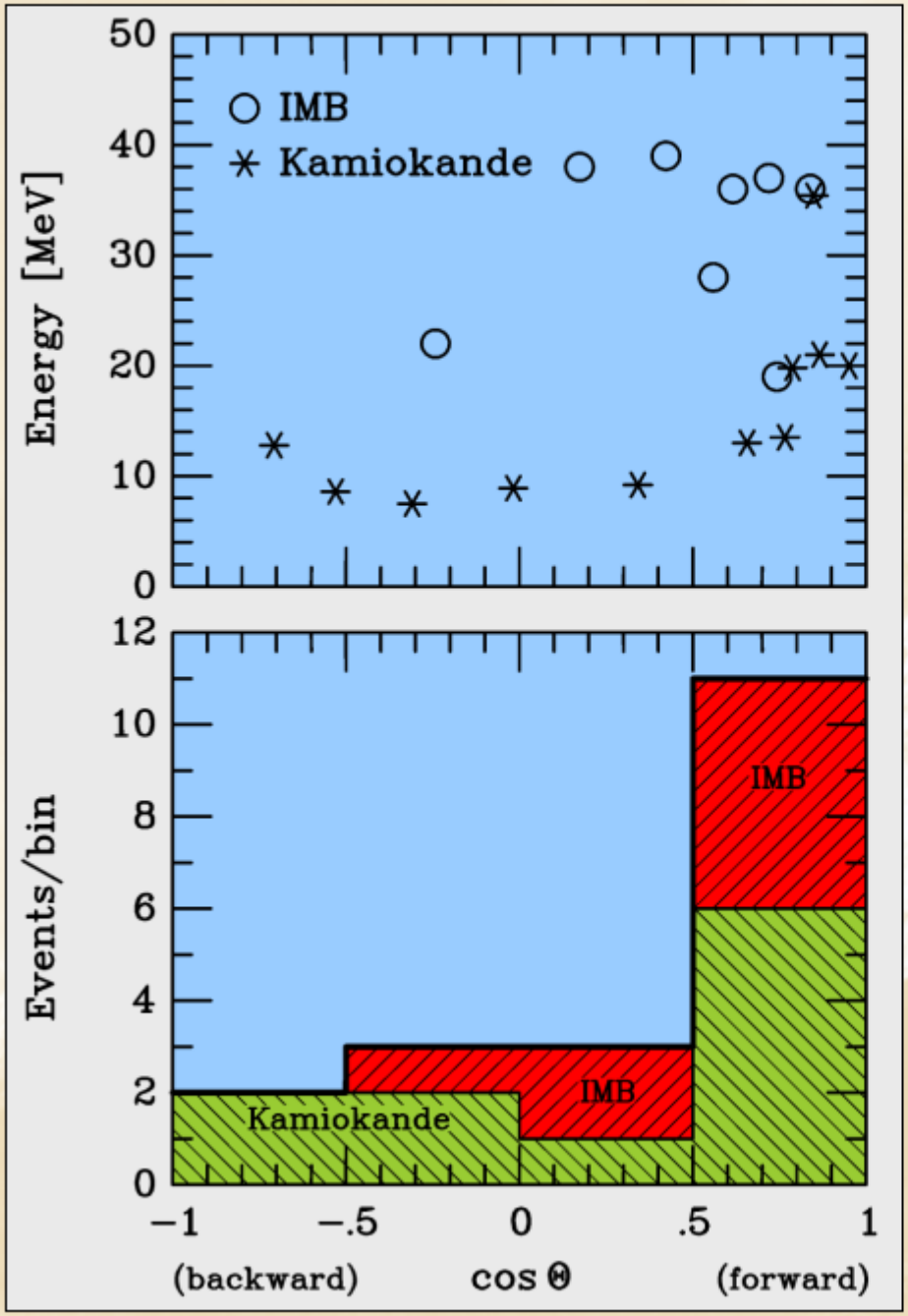


Main reactions: $\bar{\nu}_e + p \rightarrow n + e^+$ dominates for SN

$\nu_e + {}^{16}O \rightarrow {}^{16}F + e^-$

$\nu + e^- \rightarrow e^- + \nu$ dominates for Sun

Angular Distribution of SN 1987A Neutrinos



Main detection reaction

$$\bar{\nu}_e + p \rightarrow n + e^+$$

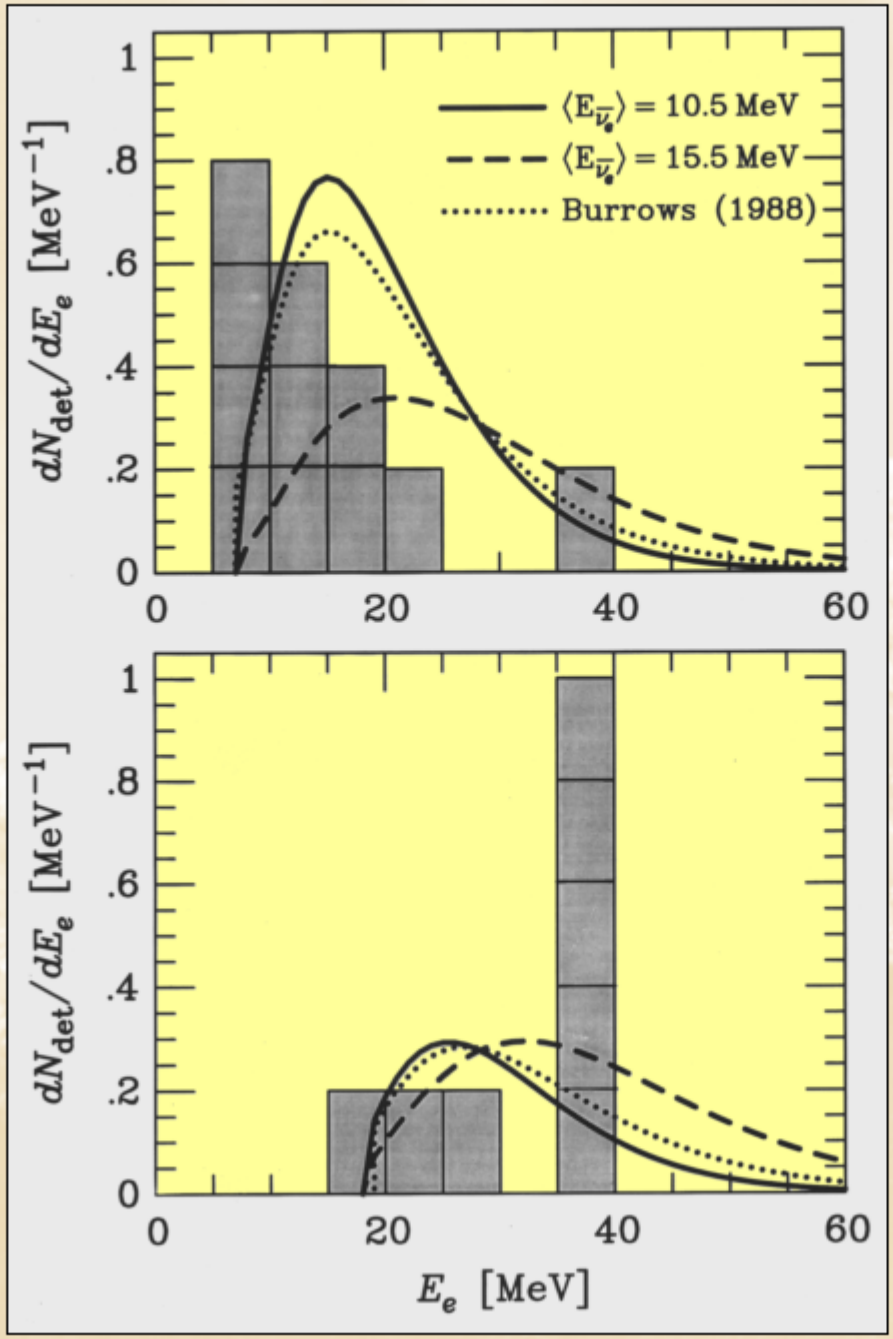
is essentially isotropic for the relevant energies.

Expect only a fraction of an event from forward-peaked reaction

$$\nu + e^- \rightarrow e^- + \nu$$

Observed signal compatible with isotropy only at approx. 0.1% CL, but no alternative known

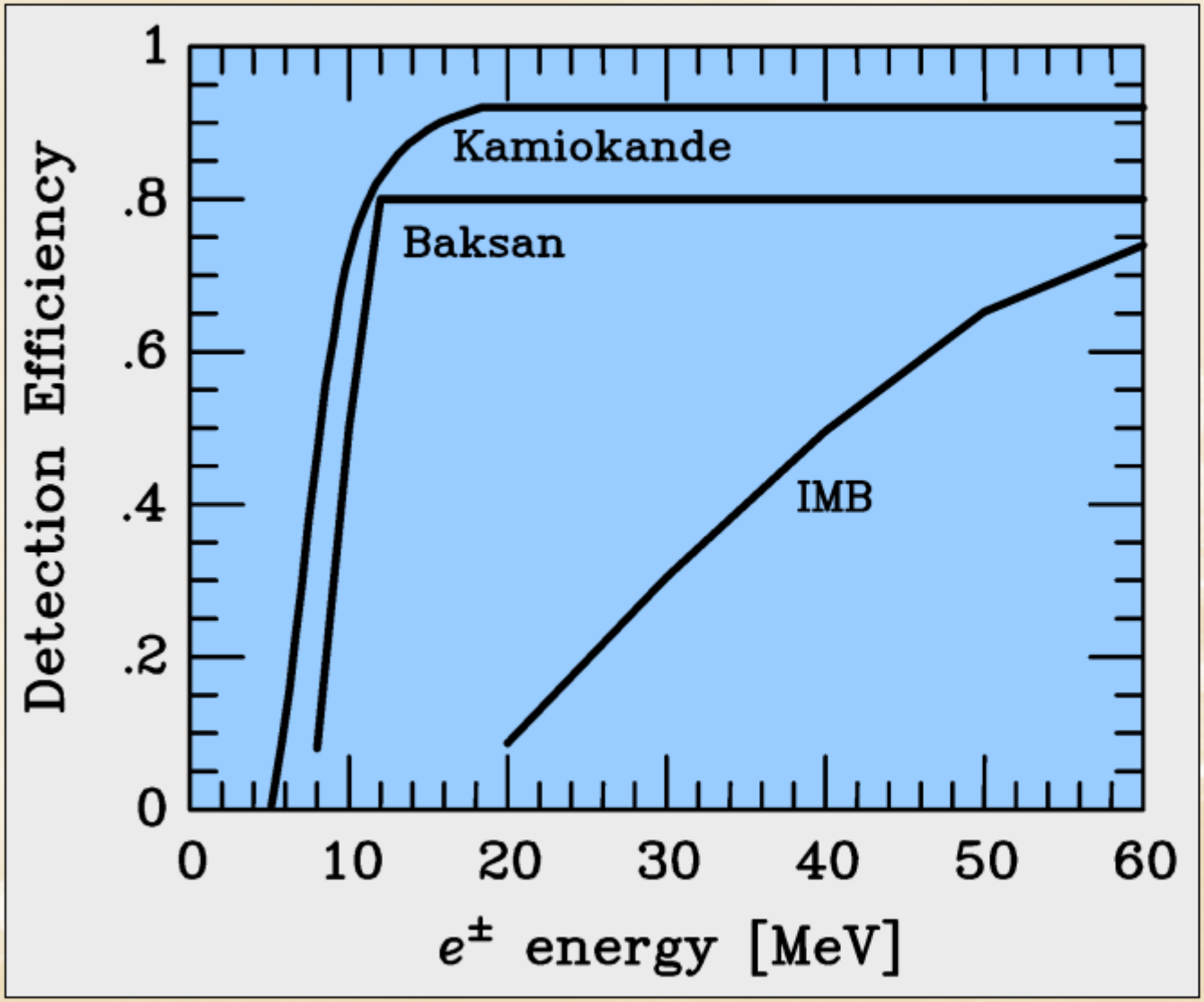
Energy Distribution of SN 1987A Neutrinos



Kamiokande II

IMB

Trigger Efficiencies at the Detectors



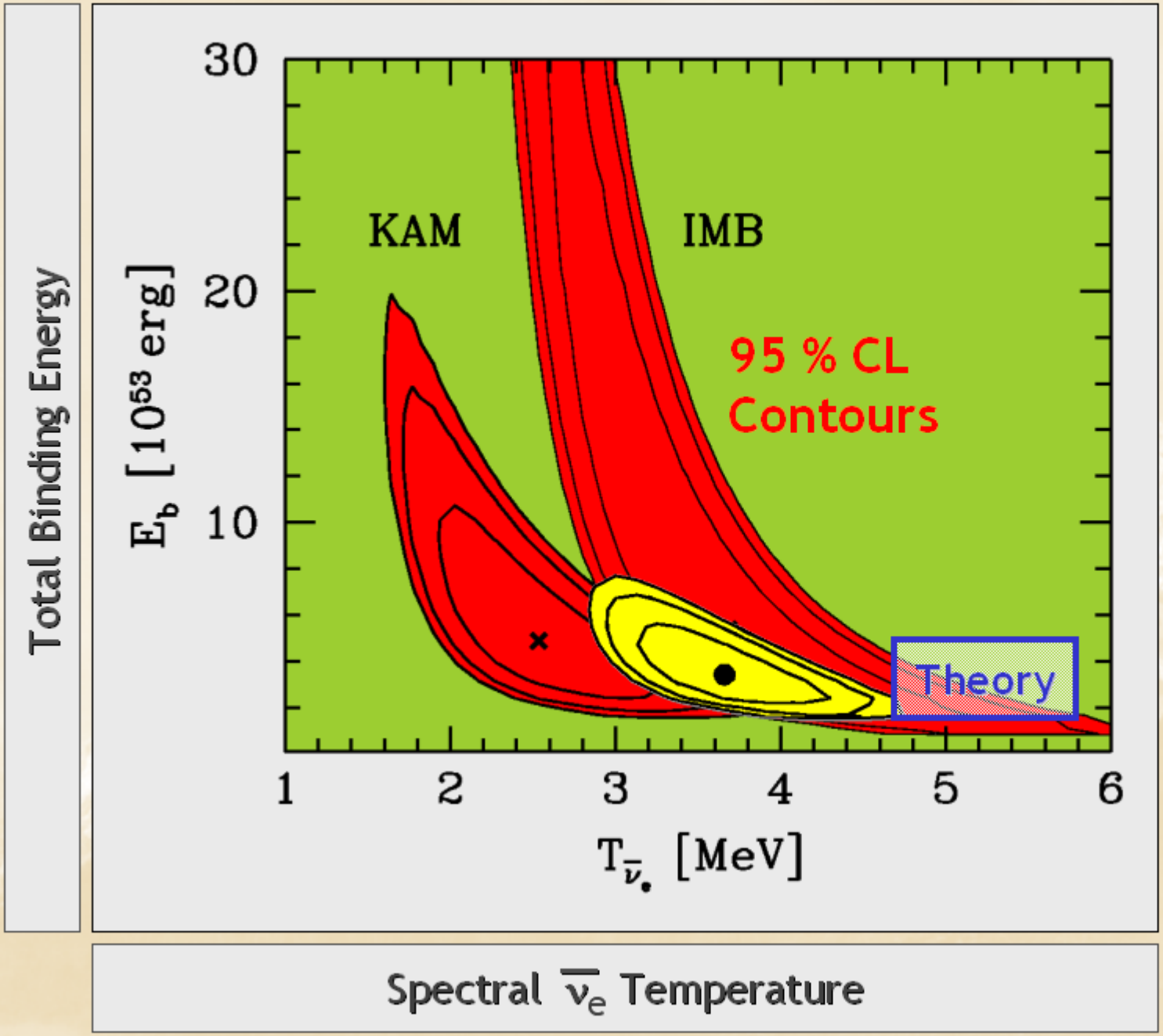
Fiducial volumes for SN 1987A detection

Kamiokande II
2140 tons water
(1.43×10^{32} protons)

IMB
6800 tons water
(4.6×10^{32} protons)

BST
200 tons scintillator
(1.88×10^{31} protons)

Interpreting SN 1987A Neutrinos



Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

Assume thermal spectra and equipartition of energy between the six degrees of freedom ν_e, ν_μ, ν_τ and their antiparticles

Particle Physics with SN 1987A

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

Neutrino Limits by Intrinsic Signal Dispersion

Time of flight delay by neutrino mass

$$\Delta t = 2.57\,\mathrm{s}\left(\frac{D}{50\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{10\,\mathrm{eV}}\right)^2$$

$$m_{\nu_e} \lesssim 20\ \mathrm{eV}$$

- Detailed maximum-likelihood analysis yields similar limit
- At the time of SN 1987A competitive with tritium end-point limits, today $m_{\nu_e} < 2.2$ eV
- Cosmological limit today $m_\nu \lesssim 0.4$ eV

For "milli charged" neutrinos, path bent by galactic magnetic field, inducing a time delay

$$\frac{\Delta t}{t} = \frac{e_\nu^2 (B_\perp d_B)^2}{6E_\nu^2} < 3\times 10^{-12}$$

$$\frac{e_\nu}{e} < 3\times 10^{-17}\left(\frac{1\,\mu\mathrm{G}}{B_\perp}\right)\left(\frac{1\ \mathrm{kpc}}{d_B}\right)$$

Assuming charge conservation in neutron decay yields a more restrictive limit of about 3×10^{-21} e

Neutrino Mass Limits by Signal Dispersion

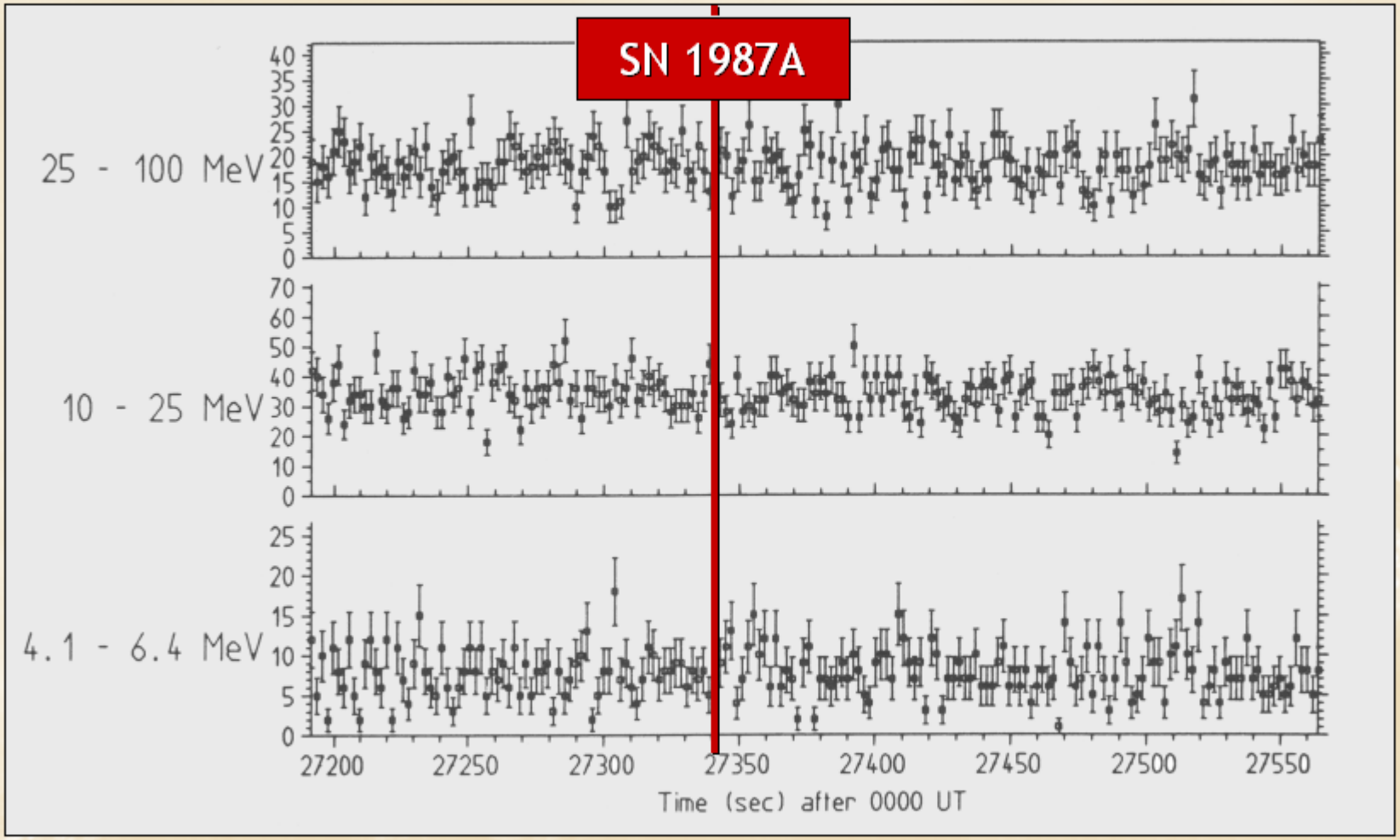
Time-of-flight delay of massive neutrinos

$$\Delta t = 2.57\,\mathrm{s}\left(\frac{D}{50\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{10\,\mathrm{eV}}\right)^2$$

SN 1987A	$E \approx 20$ MeV, $\Delta t \approx 10$ s, $D \approx 50$ kpc Simple estimate or detailed maximum likelihood analysis give similar results	$m_\nu \lesssim 20$ eV
Future Galactic SN (Super-K)	$D \approx 10$ kpc, Rise-time 0.01 s Sensitivity approximately [T.Totani, PRL 80 (1998) 2040]	$m_\nu \sim 3$ eV
With Black Hole Formation	$D \approx 10$ kpc, Cutoff "infinitely" fast Sensitivity approximately [Beacom et al., PRD 63 (2001) 073011]	$m_\nu \sim 2$ eV
Future SN in Andromeda (Megatonne)	$D \approx 750$ kpc, $\Delta t \approx 10$ s Sensitivity approximately	$m_\nu \sim 1$–2 eV

Gamma-Ray Observations of SMM Satellite

Counts in the GRS instrument on the Solar Maximum Mission Satellite



10s fluence limits

$0.9\ cm^{-2}$

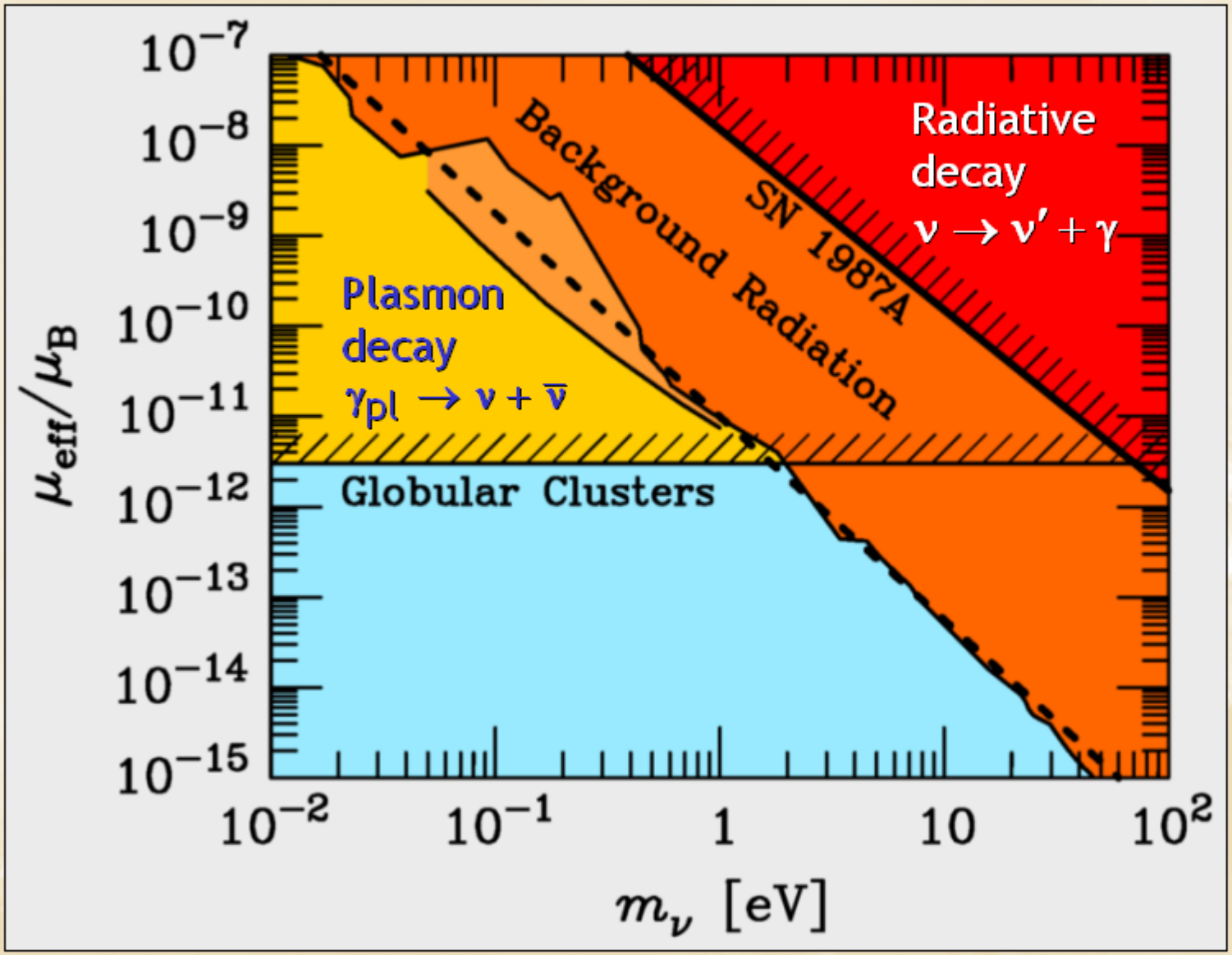
$0.4\ cm^{-2}$

$0.6\ cm^{-2}$

SN 1987A neutrino fluence ~ $10^{10}\ cm^{-2}$

$< 10^{-10}$ of neutrinos have decayed between SN and Earth

Neutrino Radiative Lifetime Limits

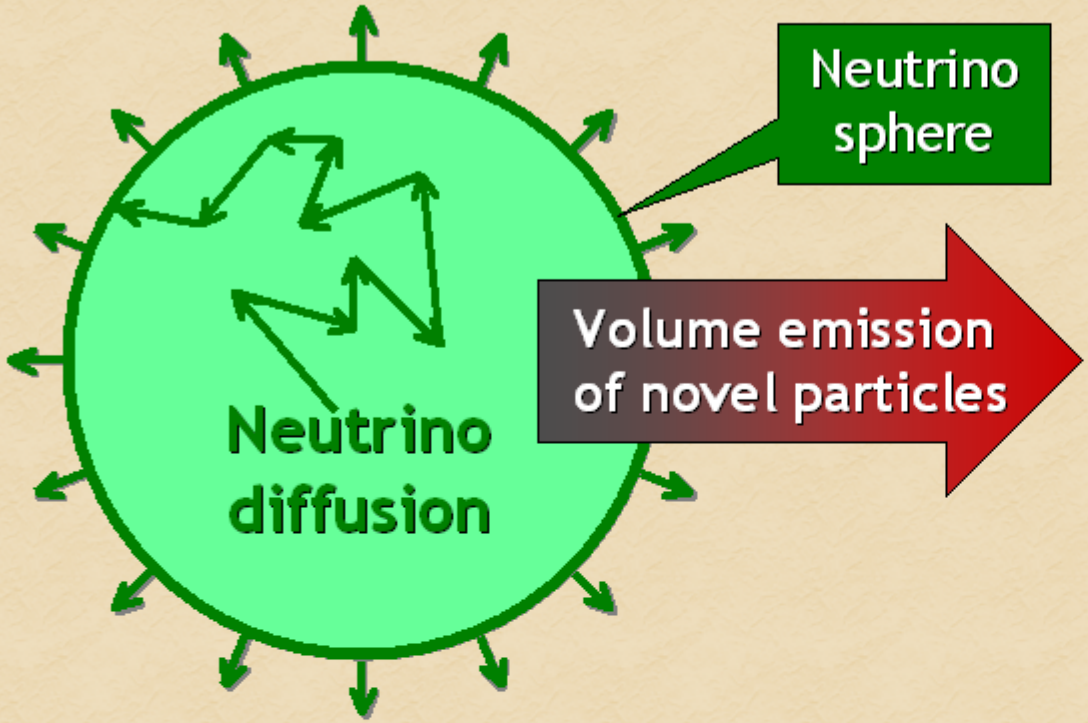


$$\Gamma_{\nu \to \nu' \gamma} = \frac{\mu_{eff}^2}{8\pi} m_\nu^3$$

$$\Gamma_{\gamma \to \nu \bar{\nu}} = \frac{\mu_{eff}^2}{24\pi} \omega_{pl}^3$$

For low-mass neutrinos, plasmon decay in globular cluster stars yields most restrictive limits

The Energy-Loss Argument

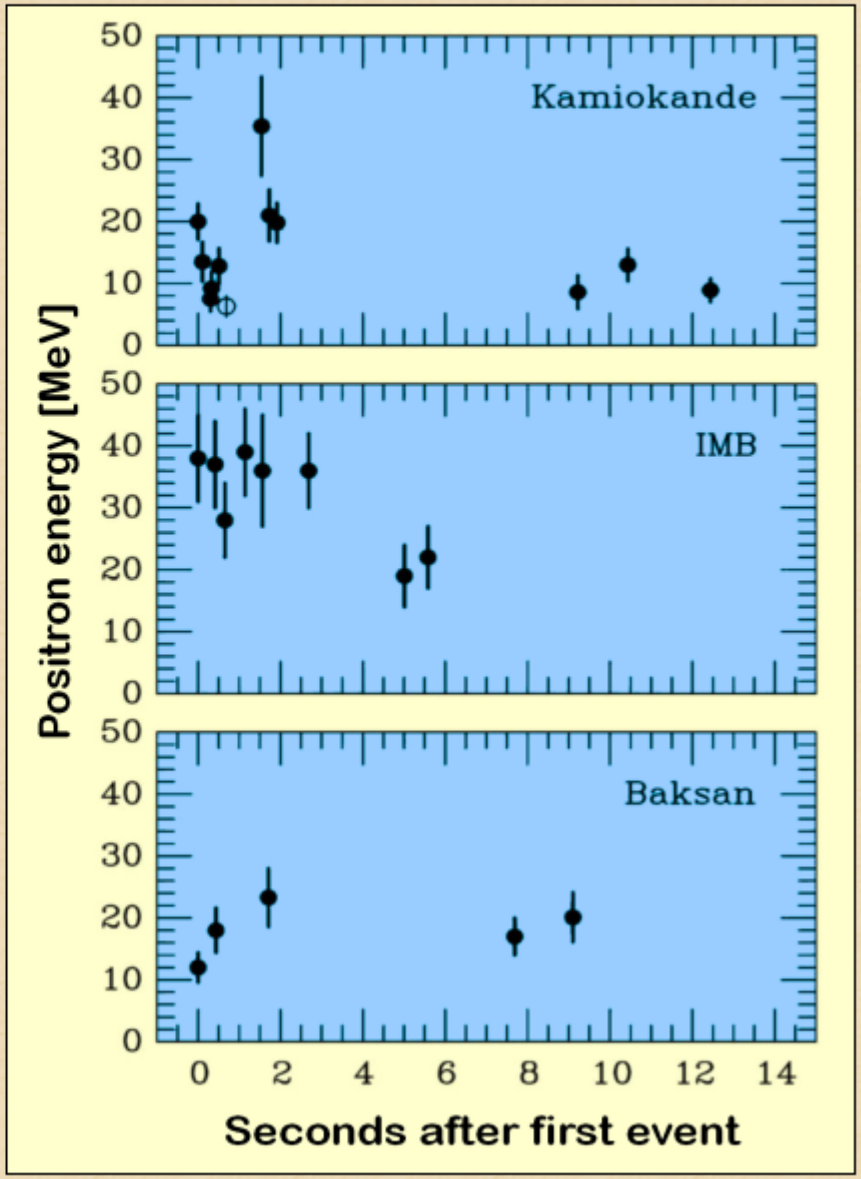


Assuming that the neutrino burst was not shortened by more than ~ ½ leads to an approximate requirement on a novel energy-loss rate of

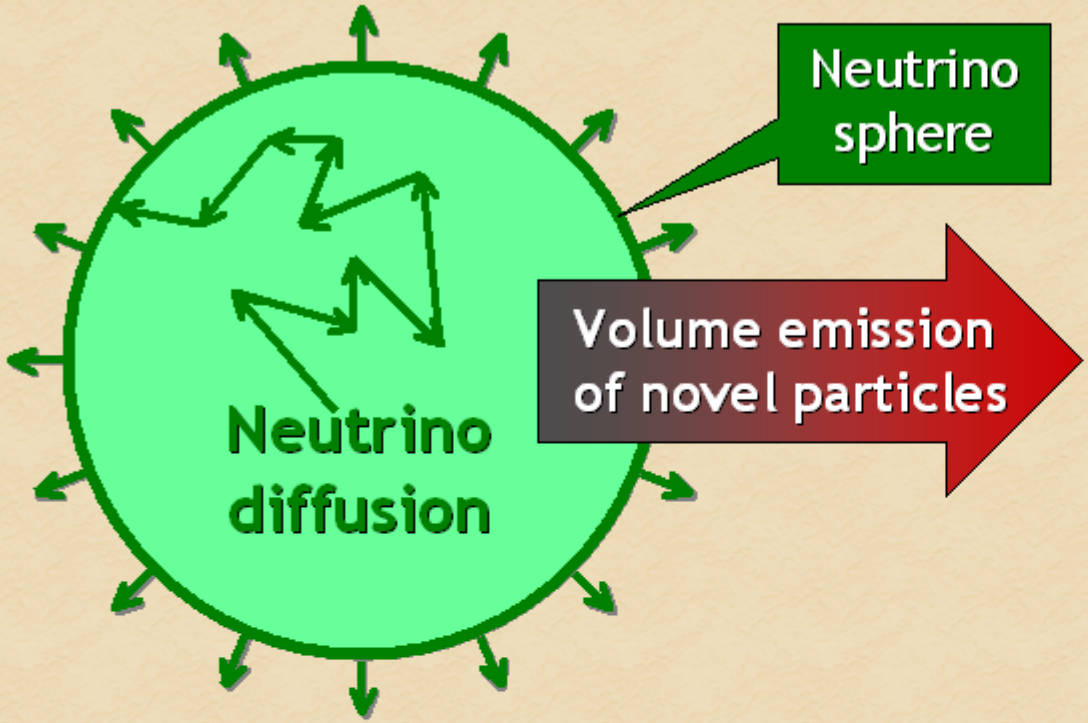
$$\varepsilon_X < 10^{19}\ \mathrm{erg\ g^{-1}\ s^{-1}}$$

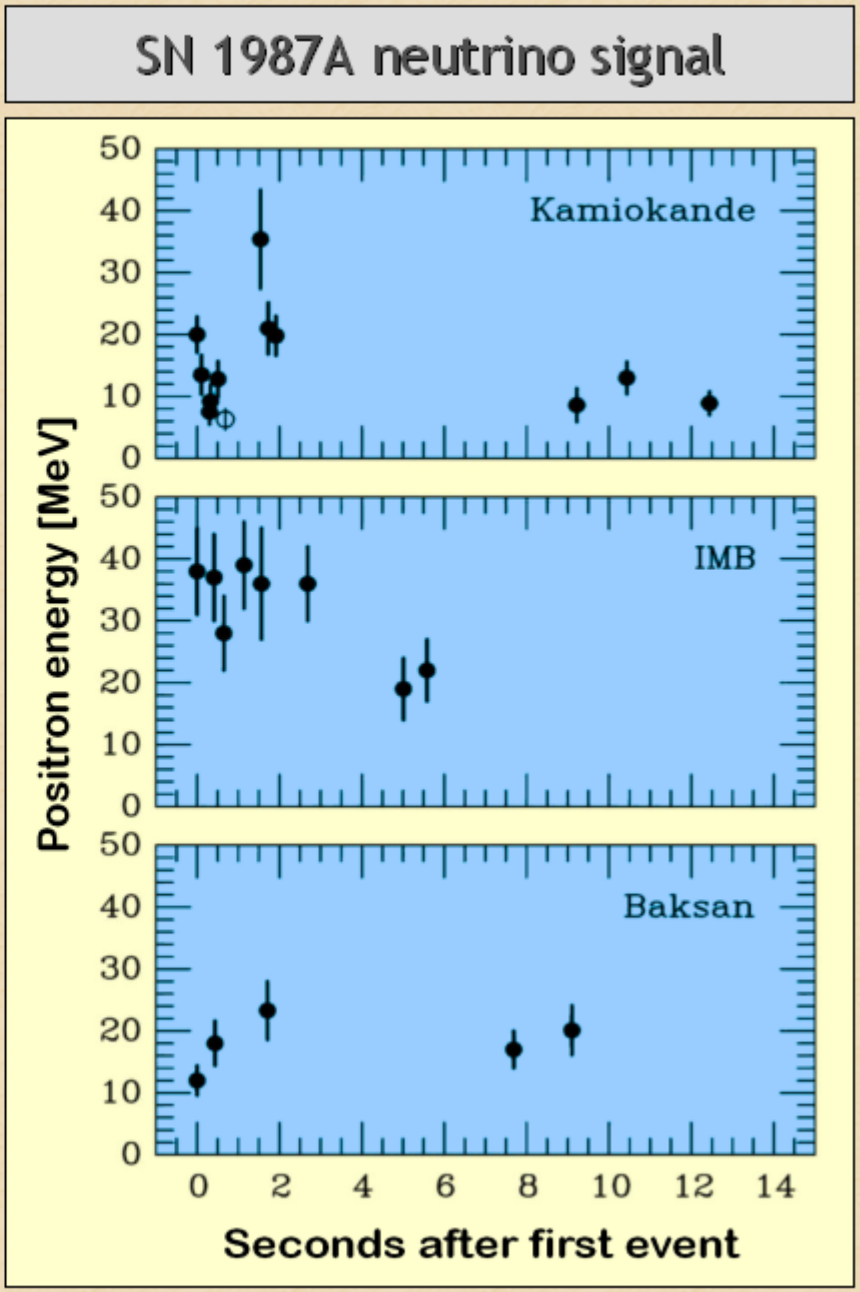
for $\rho \approx 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$ and $T \approx 30$ MeV

SN 1987A neutrino signal



The Energy-Loss Argument



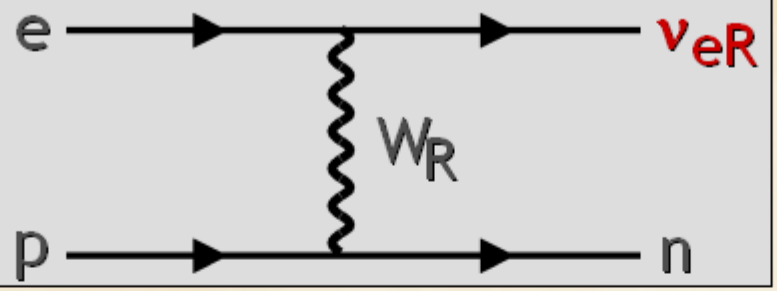


Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

Right-Handed Neutrinos (Dirac Neutrinos)

Right-handed currents



Average scattering rate in SN core involving ordinary left-handed neutrinos

$$\Gamma_L \approx 10^{10} s^{-1}$$

For right-handed neutrinos

$$\Gamma_R \approx \frac{G_R^2}{G_F^2} \Gamma_L$$

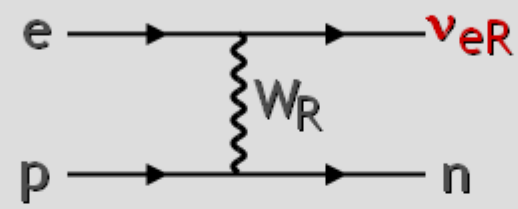
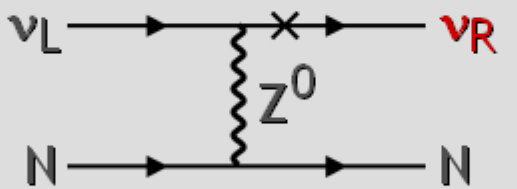
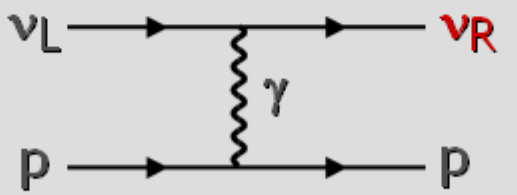
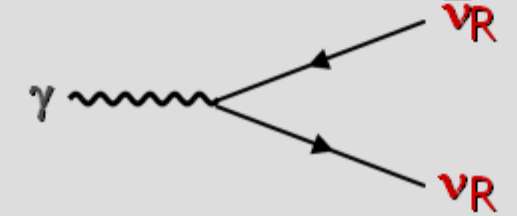
To avoid complete energy loss in ~ 1 s

$$\frac{G_R^2}{G_F^2} 10^{10} s^{-1} < 1 s^{-1}$$

$$G_R < 10^{-5} G_F$$

Dirac Neutrinos

- If neutrinos are Dirac particles, right-handed states exist that do not interact by ordinary weak interactions
- Couplings are constrained by SN 1987A energy-loss argument

Right-handed currents		$G_R \lesssim 10^{-5}\, G_F$
Dirac mass		$m_D \lesssim 30$ keV
Dipole moments		$\mu_\nu \lesssim 10^{-12}\, \mu_B$
Milli charge		$e_\nu \lesssim 10^{-9}\, e$

Right-Handed Neutrinos in the Early Universe

- If neutrinos are Dirac particles, will the right-handed components achieve thermal equilibrium in the early universe before big-bang nucleosythesis?
- This would modify the light-element abundances in significant ways, notably increase the helium abundance

	Required strength	SN 1987A limit
Right-handed charged current	$G_R \sim 10^{-3}\, G_F$	$G_R \lesssim 10^{-5}\, G_F$
Dirac mass	few 100 keV	30 keV
Dipole moment	$\sim 0.5 \times 10^{-10}\, \mu_B$	$10^{-12}\, \mu_B$

Sterile Neutrinos

Sterile (right-handed) neutrinos may exist that are not Dirac partners to ordinary neutrinos

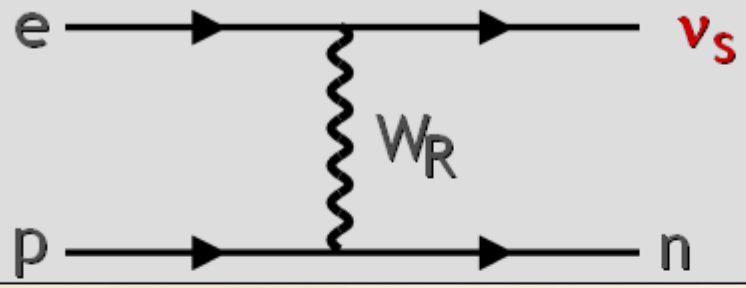
- Unknown mass m_s
- Unknown mixing angles with ordinary neutrinos Θ_{es}, $\Theta_{\mu s}$, $\Theta_{\tau s}$

Consequences and applications

- May (partially) account for some experimental oscillation results (LSND)
- Hot, warm, or cold dark matter contribution
- May affect big-bang nucleosynthesis
- Emission from supernova cores
- Affects r-process nucleosynthesis in the SN hot bubble
- Radiative decays → potentially detectable

Sterile Neutrinos

Active-sterile mixing



Electron neutrino appears as sterile neutrino in ½ $\sin^2(2\Theta_{es})$ of all cases

$$\Gamma_s \approx \frac{1}{2}\sin^2(2\Theta_{es})\,\Gamma_L$$

Average scattering rate in SN core involving ordinary left-handed neutrinos

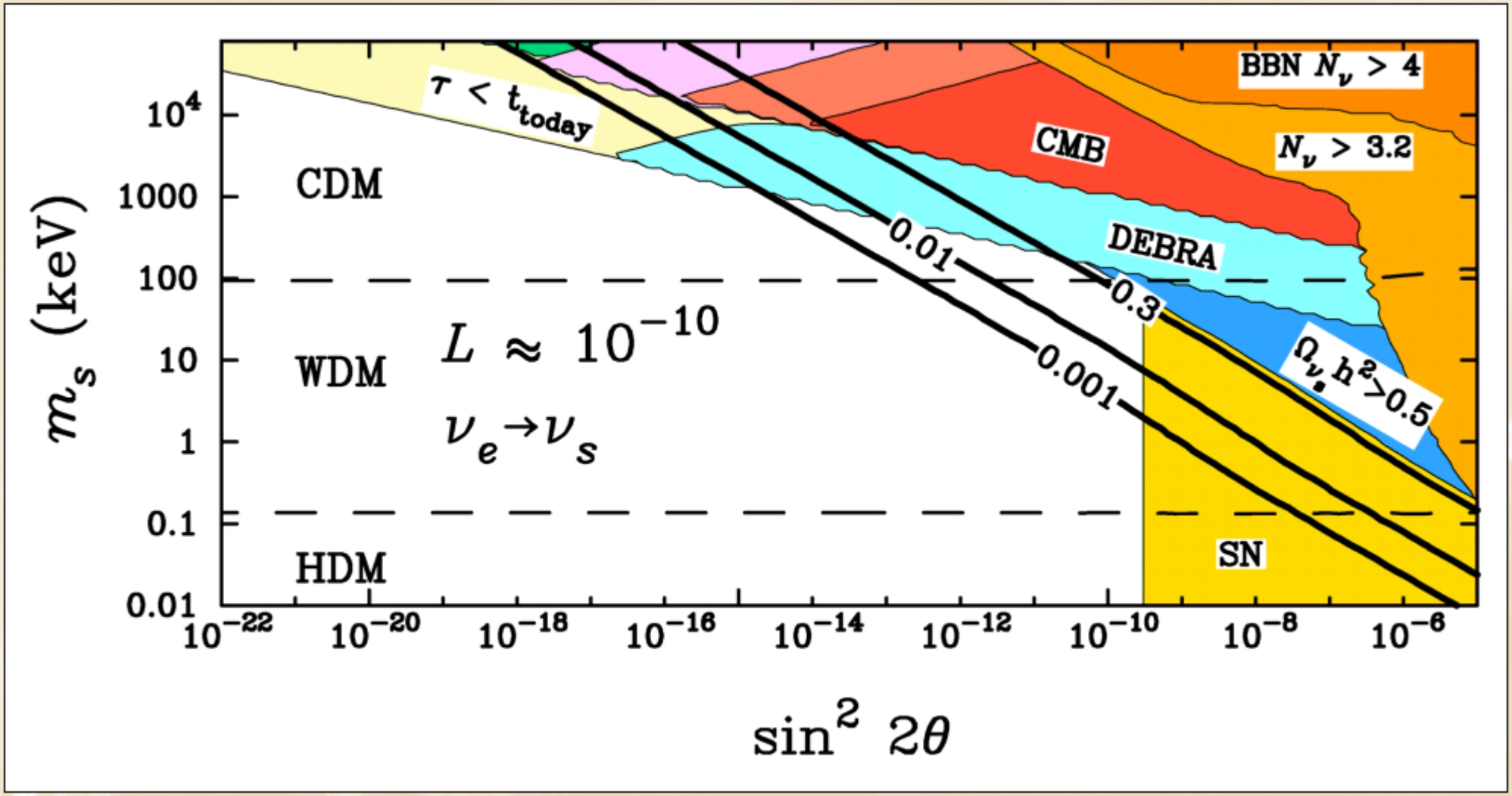
$$\Gamma_L \approx 10^{10}\,s^{-1}$$

To avoid complete energy loss in ~ 1 s

$$\frac{1}{2}\sin^2(2\Theta_{es})\,10^{10}\,s^{-1} < 1\,s^{-1}$$

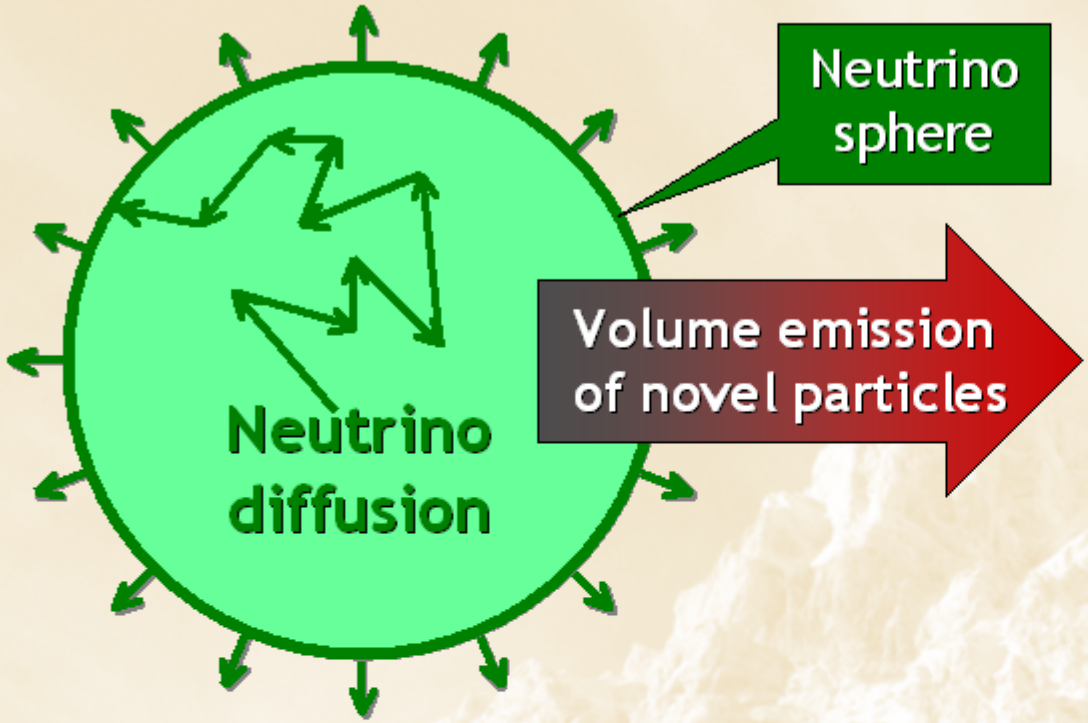
$$\sin^2(2\Theta_{es}) \lesssim 3 \times 10^{-10}$$

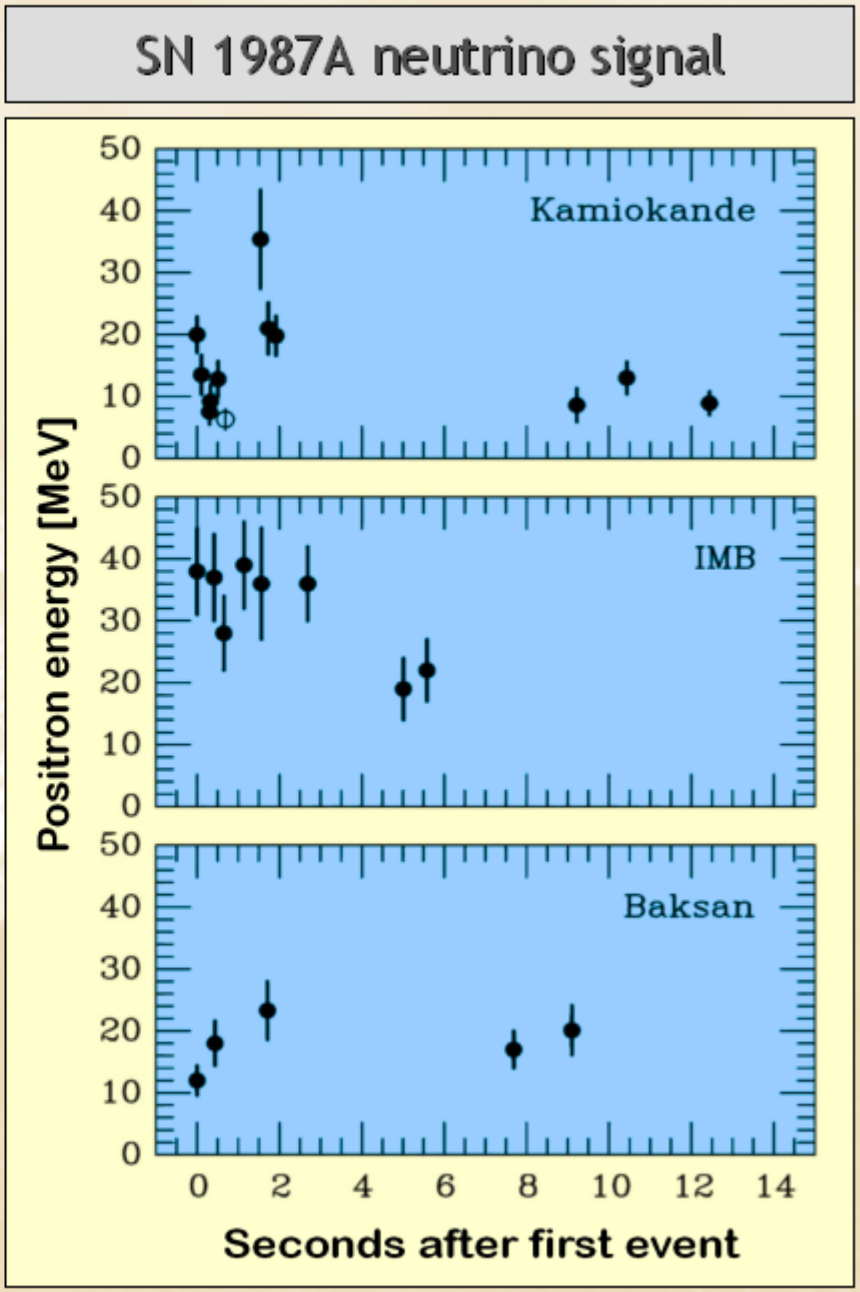
Sterile Neutrinos as Dark Matter



Abazajian, Fuller & Patel, Sterile neutrino hot, warm, and cold dark matter
astro-ph/0101524

The Energy-Loss Argument

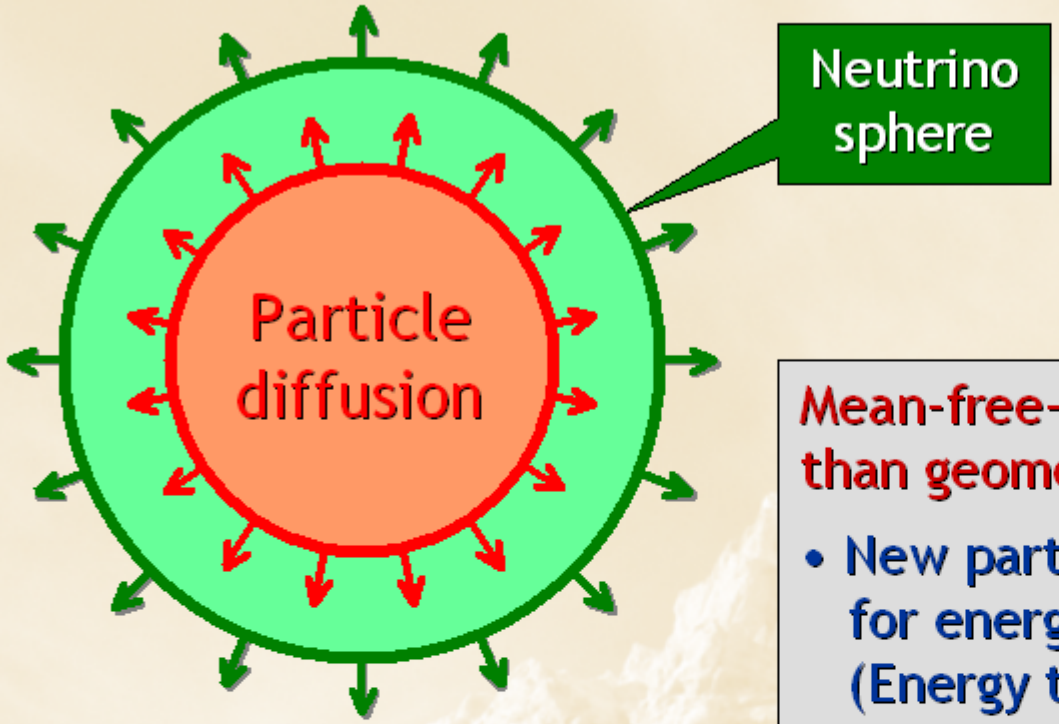




Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

The Energy-Loss Argument in the Trapping Limit



Mean-free-path of new particles less than geometric dimension of star

- New particles are more important for energy transfer than neutrinos (Energy transfer $\propto$ mfp)
- Efficiency of energy transfer must be less than that of neutrinos or else speed up cooling of PNS, again shortening the observed SN 1987A signal

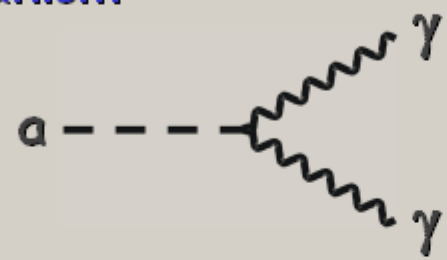
Axion Physics in a Nut Shell

Particle-Physics Motivation

CP conservation in QCD by Peccei-Quinn mechanism

→ Axions $a \sim \pi^0$

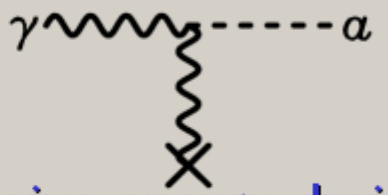
$m_\pi f_\pi \approx m_a f_a$



For $f_a \gg f_\pi$ axions are "invisible" and very light

Solar and Stellar Axions

Axions thermally produced in stars, e.g. by Primakoff production



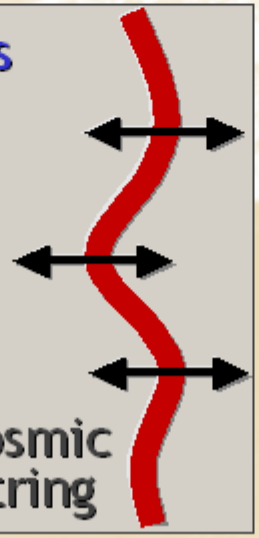
- No excessive energy drain: $m_a < 10$ meV
- Search for solar axions (CAST)

Cosmology

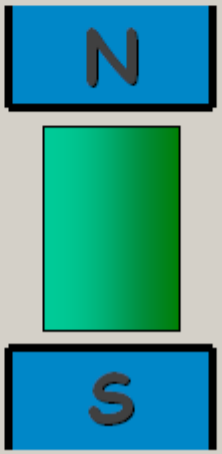
In spite of small mass, axions are born non-relativistically ("non-thermal relics")

→ "Cold dark matter" candidate

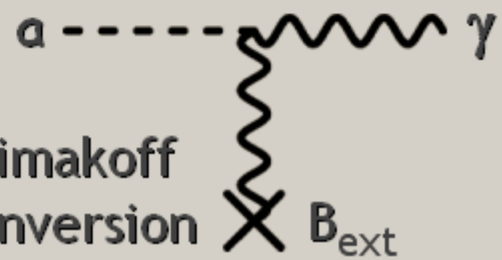
$m_a \sim 1\text{-}1000\ \mu\text{eV}$



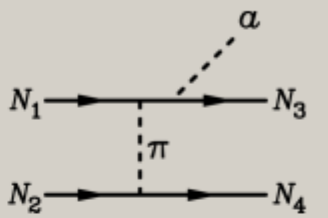
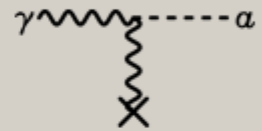
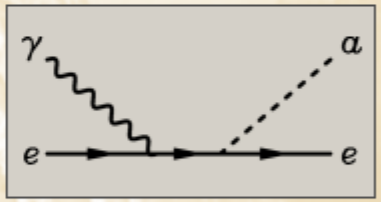
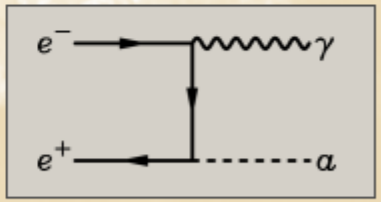
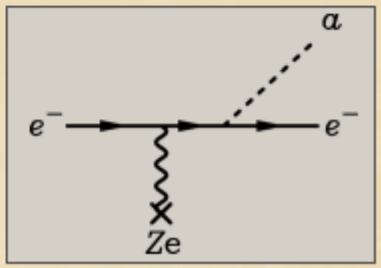
Search for Axion Dark Matter



Microwave resonator (1 GHz = 4 μeV)



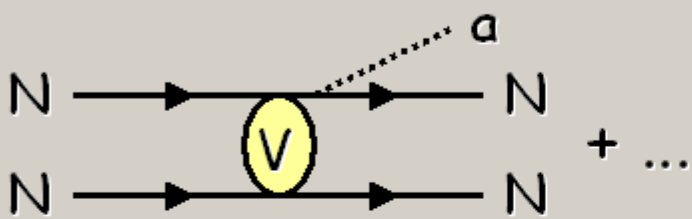
Axion or Graviton Emission Processes in Stars

Nucleons	$\frac{C_N}{2f_a}\bar{\Psi}_N\gamma_\mu\gamma_5\Psi_N\,\partial^\mu a$	Nucleon Bremsstrahlung	
Photons	$\frac{C_e}{2f_a}\bar{\Psi}_e\gamma_\mu\gamma_5\Psi_e\,\partial^\mu a$	Primakoff	
Electrons	$C_\gamma\frac{\alpha}{2\pi f_a}\frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}a$ $= -C_\gamma\frac{\alpha}{2\pi f_a}\vec{E}\cdot\vec{B}\,a$	Compton	
		Pair Annihilation	
		Electromagnetic Bremsstrahlung	

Axion Emission from Nuclear Medium

Axion-nucleon interaction of current-current form:

$$L_{int} = \frac{C_N}{2f_a}\Psi_N\gamma_\mu\gamma_5\Psi_N\partial^\mu a = \frac{C_N}{2f_a}J^A_\mu\partial^\mu a$$



Nucleon-Nucleon Bremsstrahlung

Energy loss rate (erg cm^{-3} s^{-1})

$$Q = \int d\Gamma_a \int d\Gamma_{Nucleons} |M|^2 \omega$$

axion energy

$$= \left(\frac{C_N}{2f_a}\right)^2 \frac{n_B}{4\pi^2}\int_0^\infty d\omega\,\omega^4 S(-\omega)$$

dynamical structure function

Difficulties include:

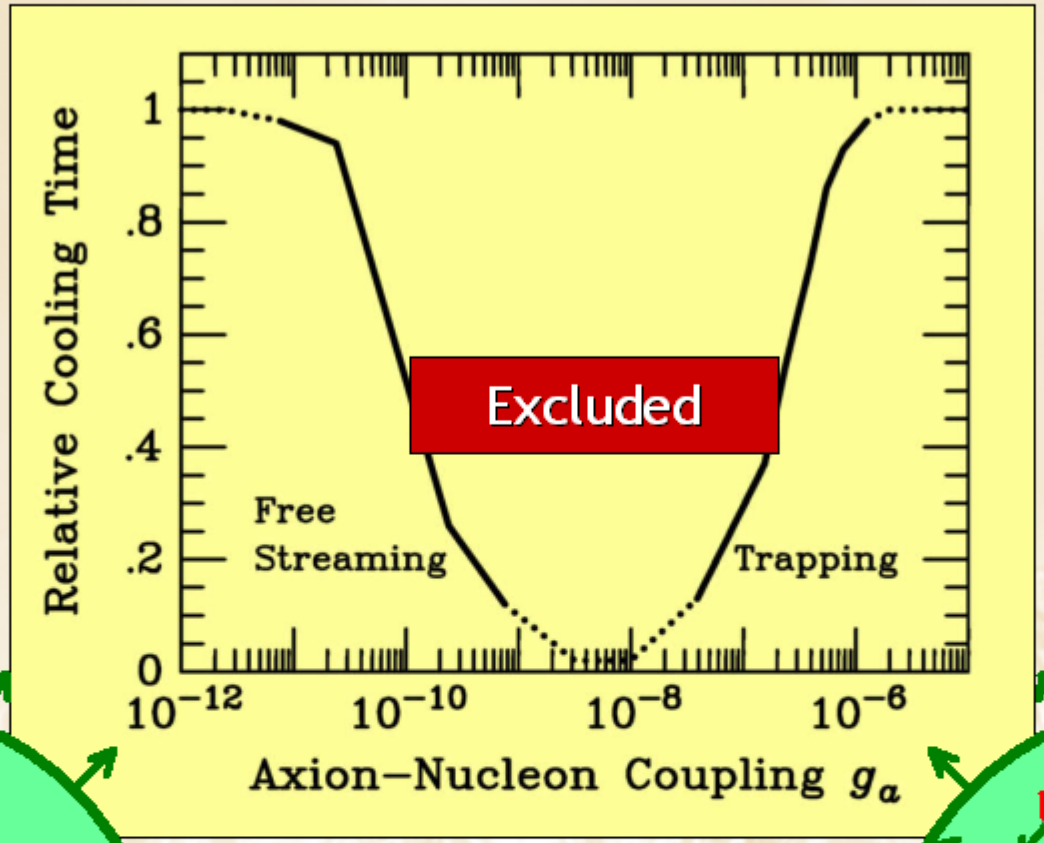
- Realistic nucleon-nucleon interaction potential (even in vacuum)
- Many-body effects (effective mass, spin-spin correlations ...)
- Axion couplings in the nuclear medium
- Multiple-scattering effects:

  Frequency of NN collisions exceeds typical axion energy

  $\tau_{coll} < \omega^{-1}$

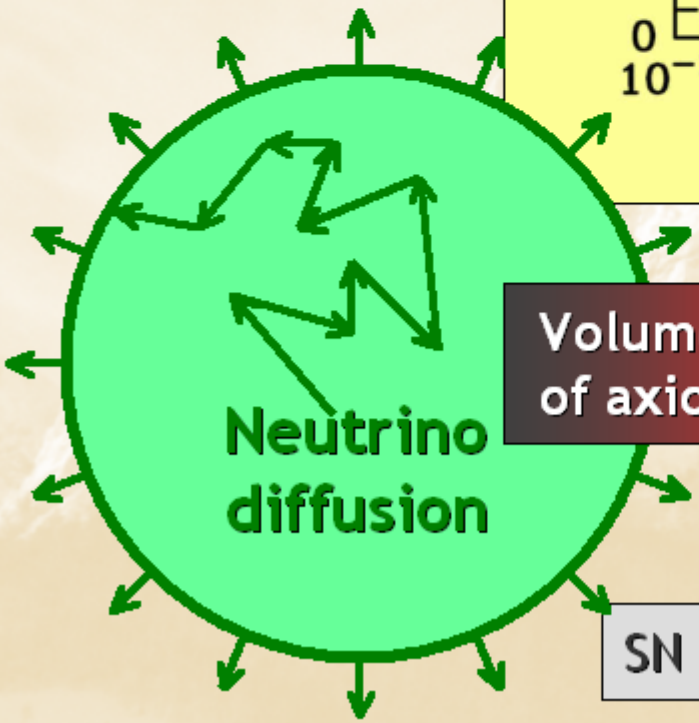
  Expect LPM-type destructive interference effects

SN 1987A Axion Limits

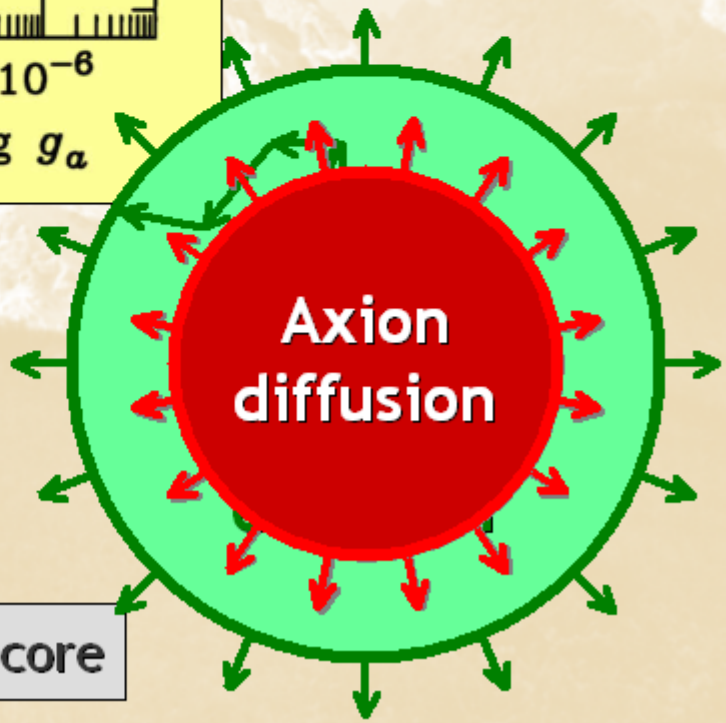


Free streaming

Trapping



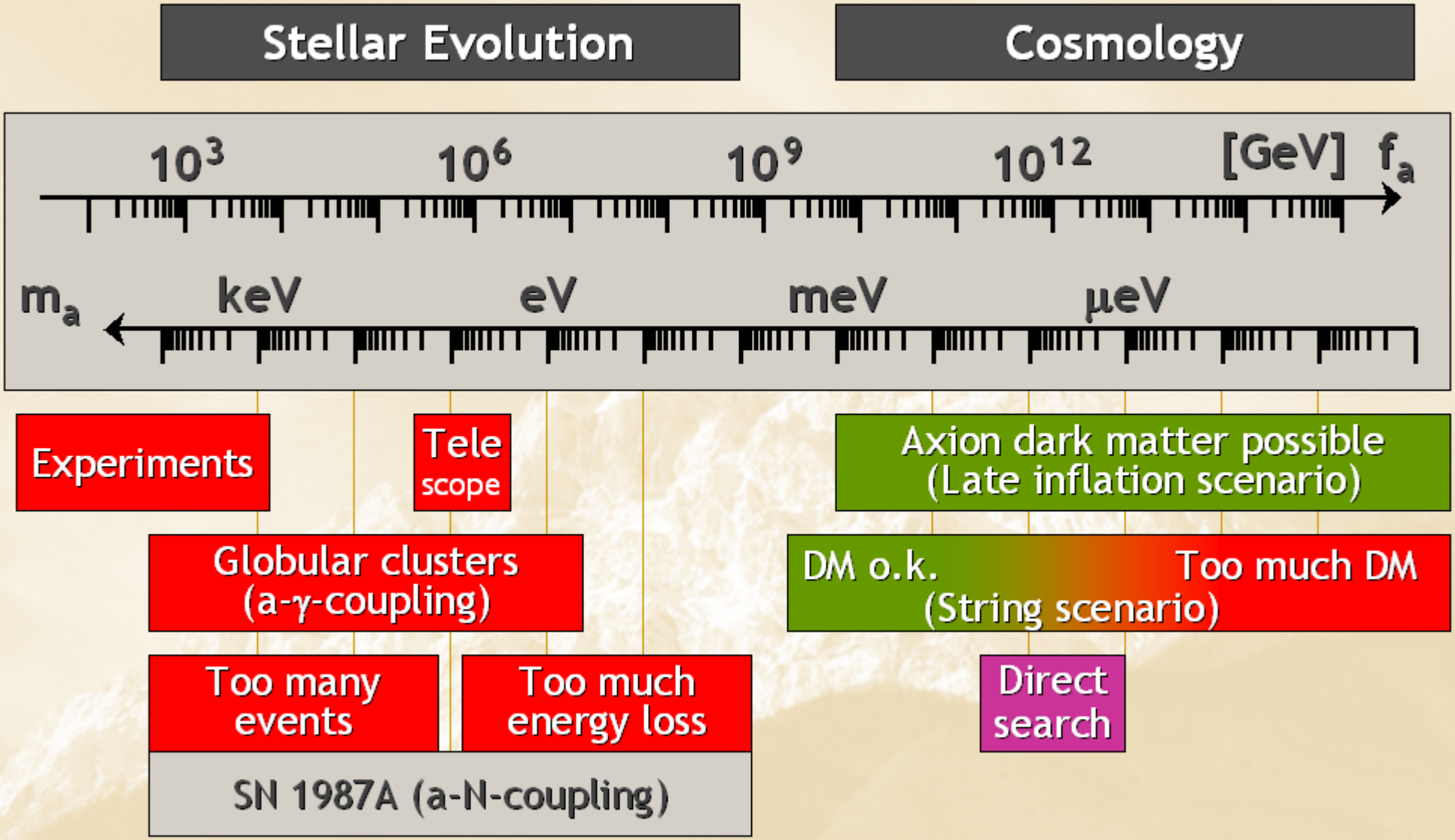
Volume emission of axions



SN core

SN core

Astrophysical Axion Bounds

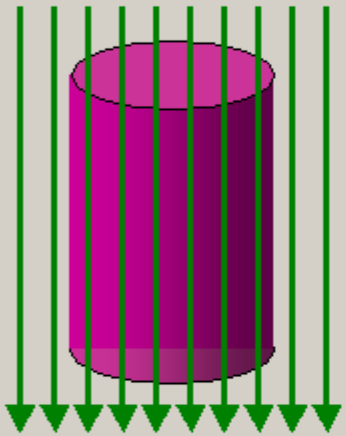


Experimental Search for Galactic Axions

DM axions m_a = 10-3000 μeV
Velocities in galaxy $v_a \approx 10^{-3}$ c
Energies therefore $E_a \approx (1 \pm 10^{-6})\, m_a$

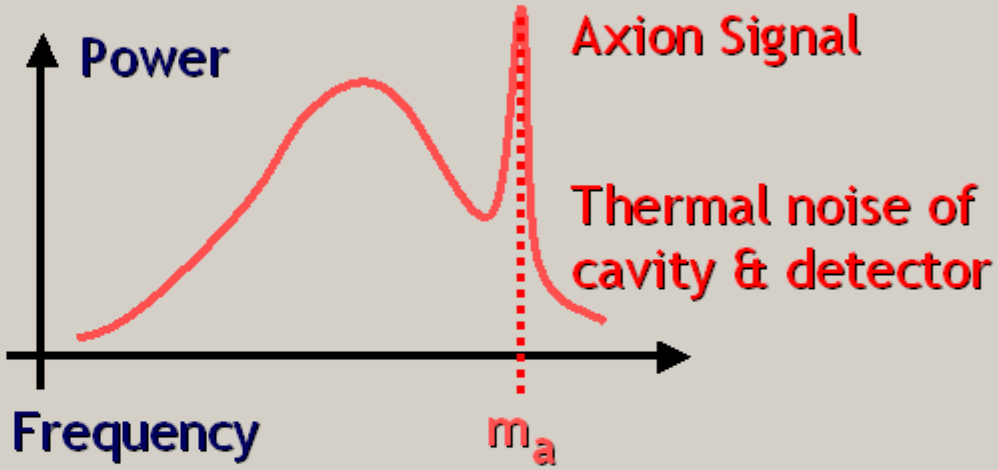
→ Microwave Energies (1 GHz ≈ 4 μeV)

Axion Haloscope (Sikivie 1983)

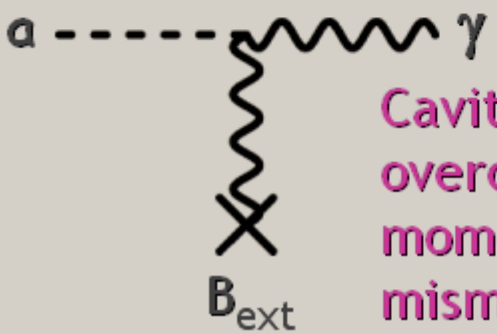


$B_{ext} \approx 8$ Tesla

Microwave Resonator
$Q \approx 10^5$



Primakoff Conversion



Cavity overcomes momentum mismatch

Power of galactic axion signal

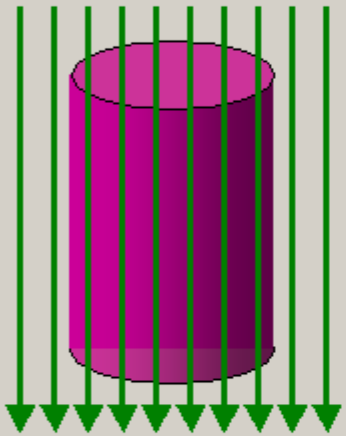
$$4\times10^{-21}\,\mathrm{W}\,\frac{V}{0.22\,\mathrm{m}^3}\left(\frac{B}{8.5\,\mathrm{T}}\right)^2\frac{Q}{10^5}\times\left(\frac{m_a}{2\pi\,\mathrm{GHz}}\right)\left(\frac{\rho_a}{5\times10^{-25}\,\mathrm{g/cm}^3}\right)$$

Experimental Search for Galactic Axions

DM axions m_a = 10-3000 μeV
Velocities in galaxy $v_a \approx 10^{-3}$ c
Energies therefore $E_a \approx (1 \pm 10^{-6})\, m_a$

→ Microwave Energies (1 GHz ≈ 4 μeV)

Axion Haloscope (Sikivie 1983)



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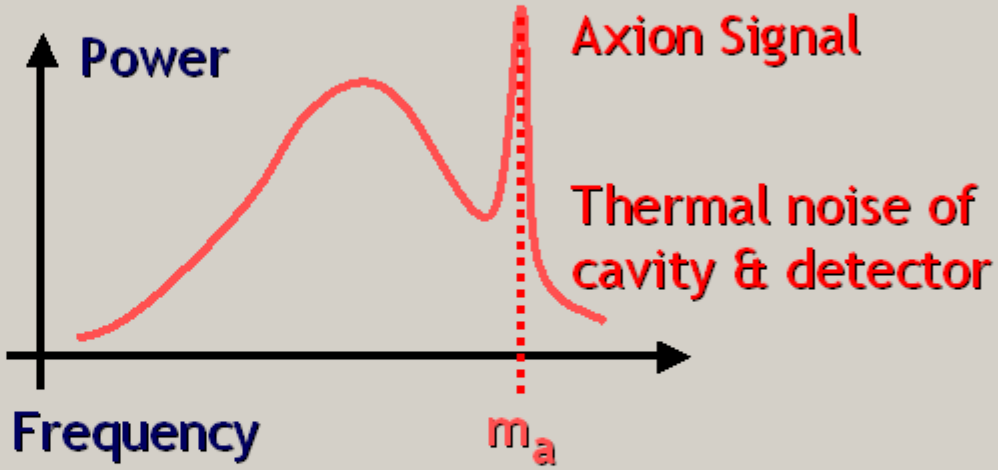
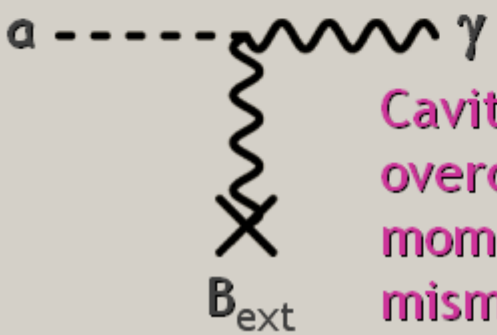


Primakoff Conversion



Cavity overcomes momentum mismatch

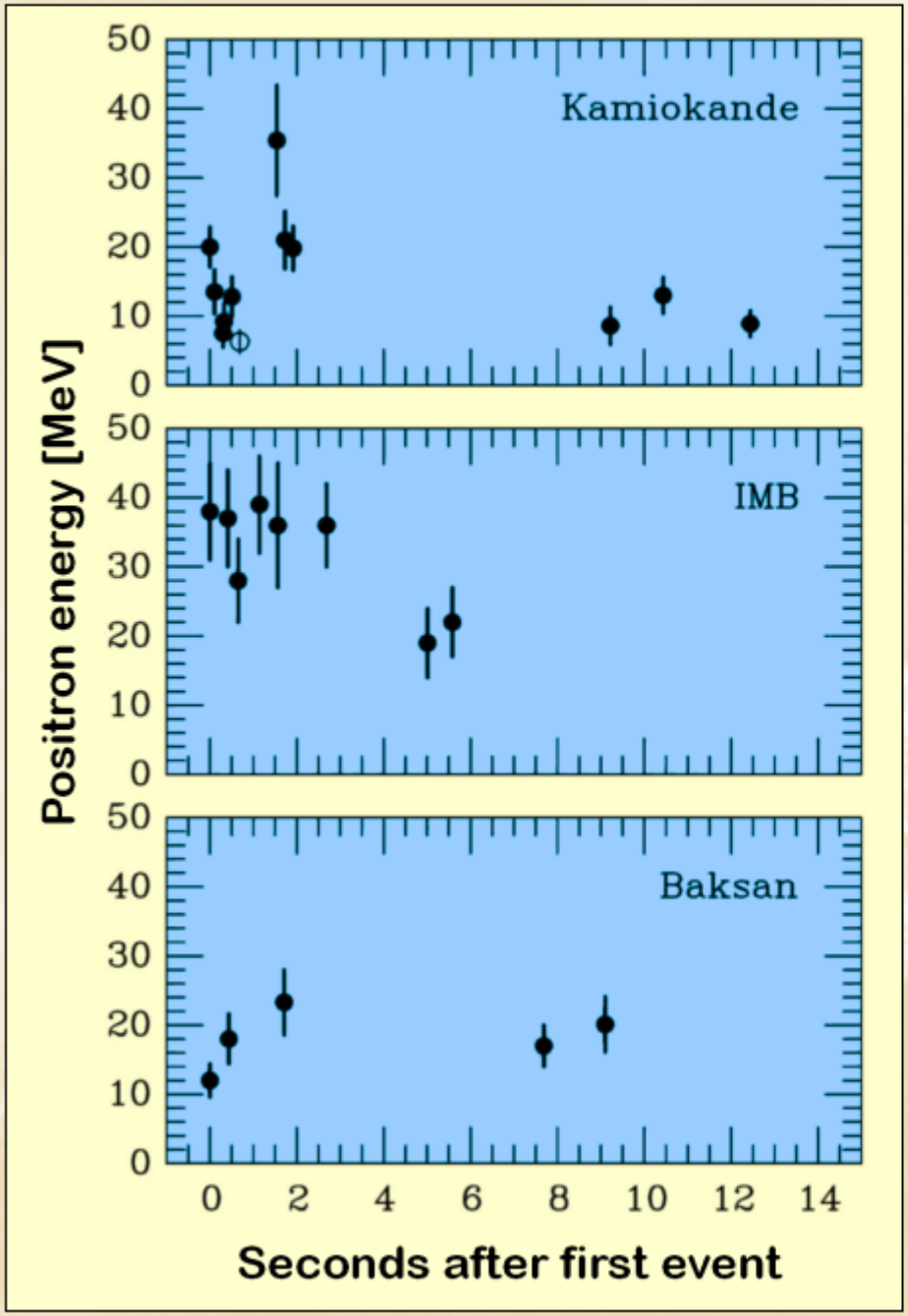
2 Experiments in Operation

- Axion Dark Matter Experiment (ADMX), Livermore, US
- CARRACK II, Kyoto, Japan

Neutrino Oscillations and a Future Galactic Supernova

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

Neutrino Signal of Supernova 1987A



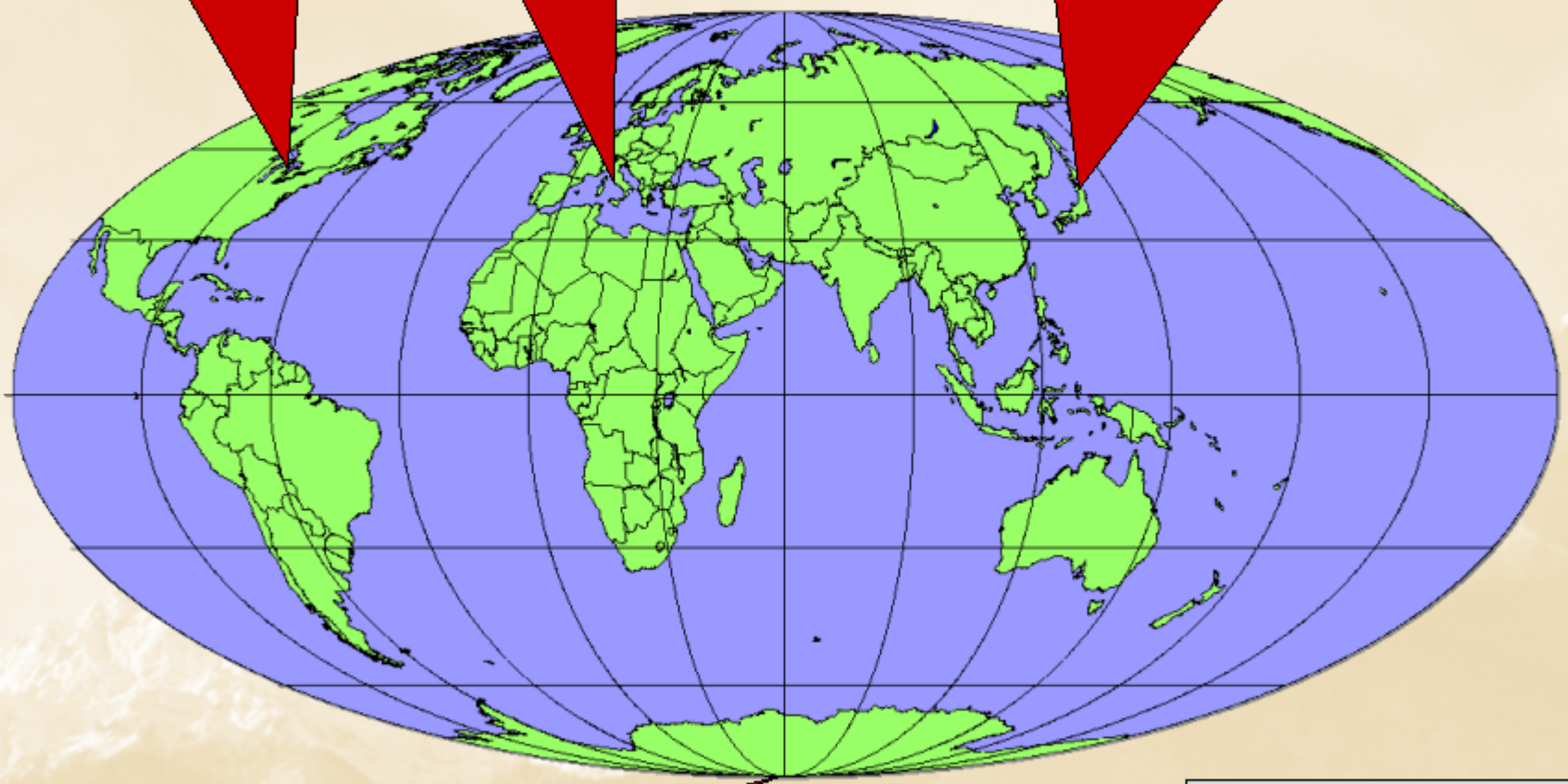
Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union)
Clock uncertainty +2/-54 s

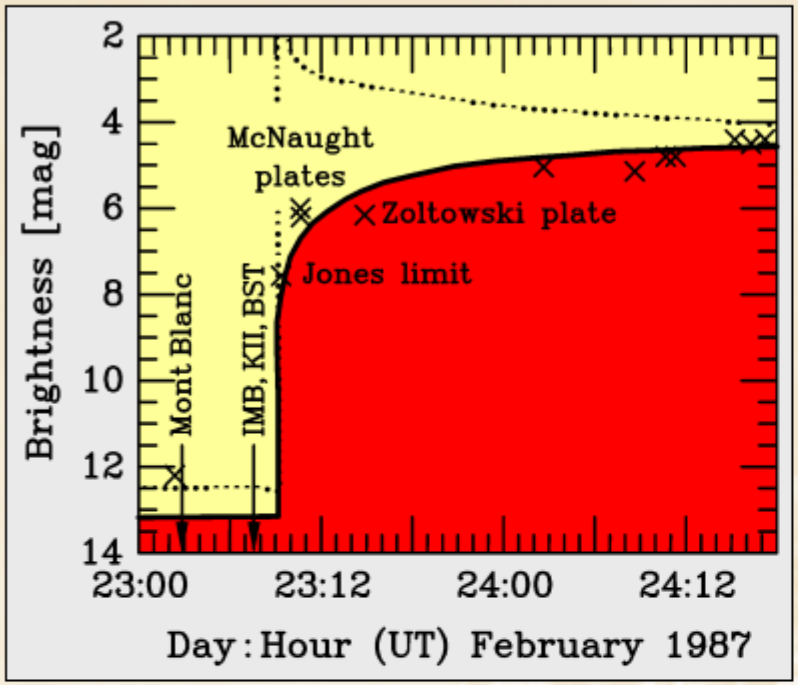
Within clock uncertainties,
signals are contemporaneous

Large Detectors for Supernova Neutrinos



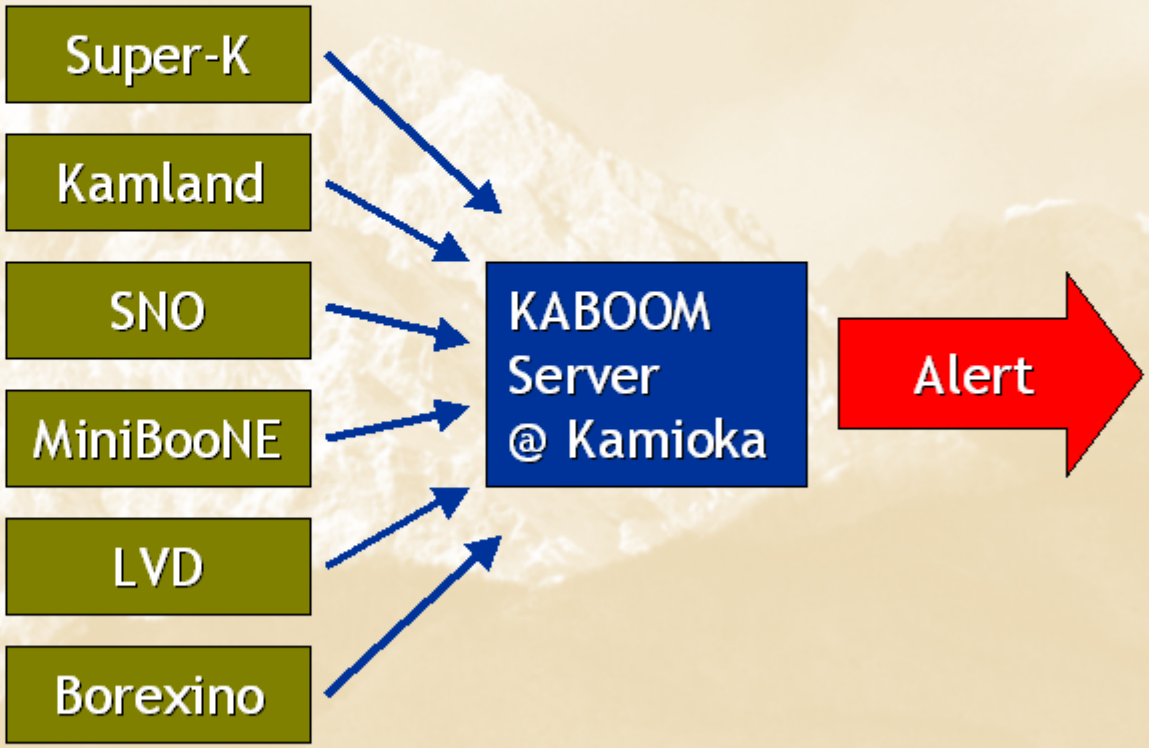
In brackets events for a "fiducial SN" at distance 10 kpc

SuperNova Early Warning System (SNEWS)



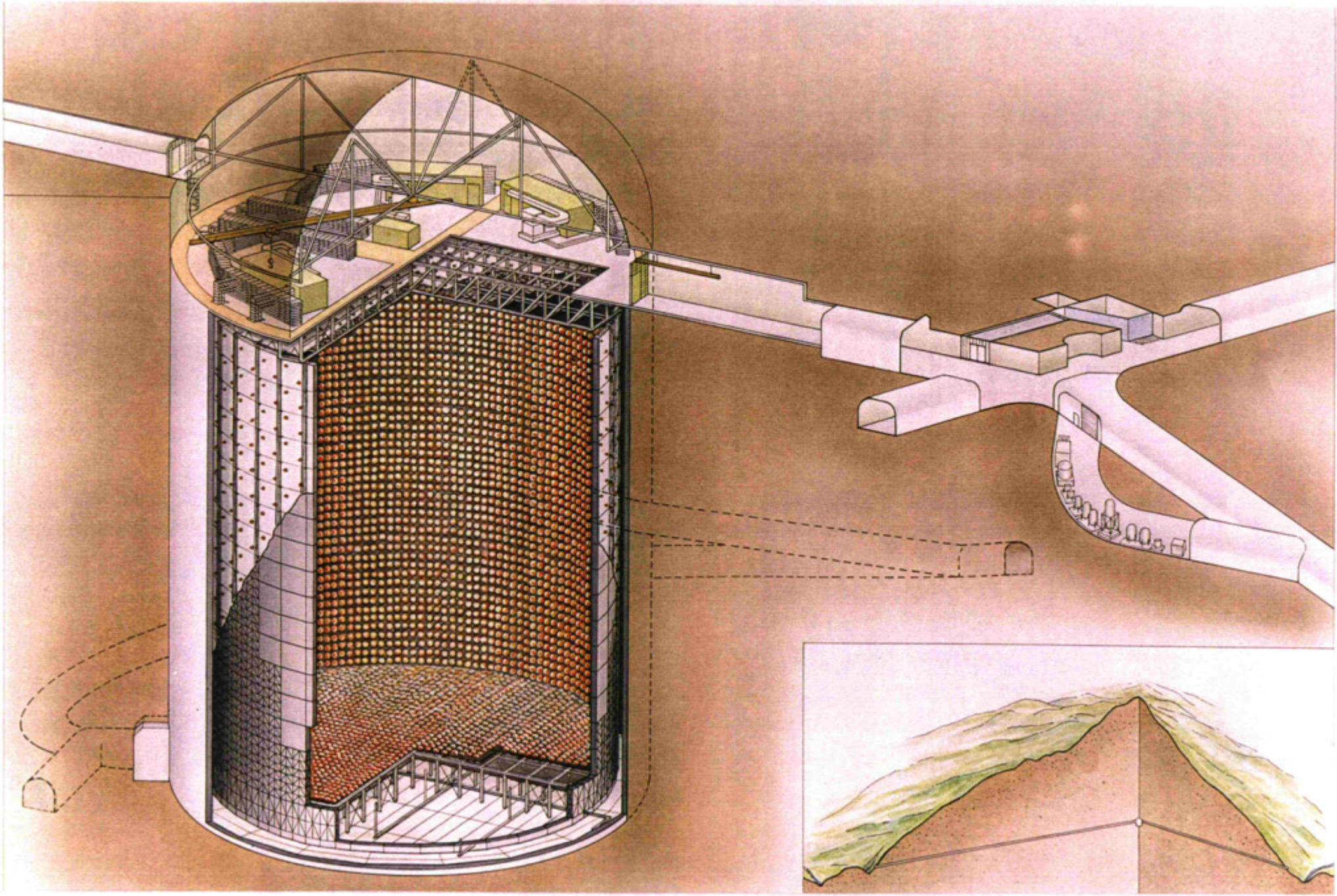
Supernova 1987A
Early Light Curve

Neutrino observation can alert astronomers several hours in advance to a supernova.
To avoid false alarms, require alarm from at least two experiments.

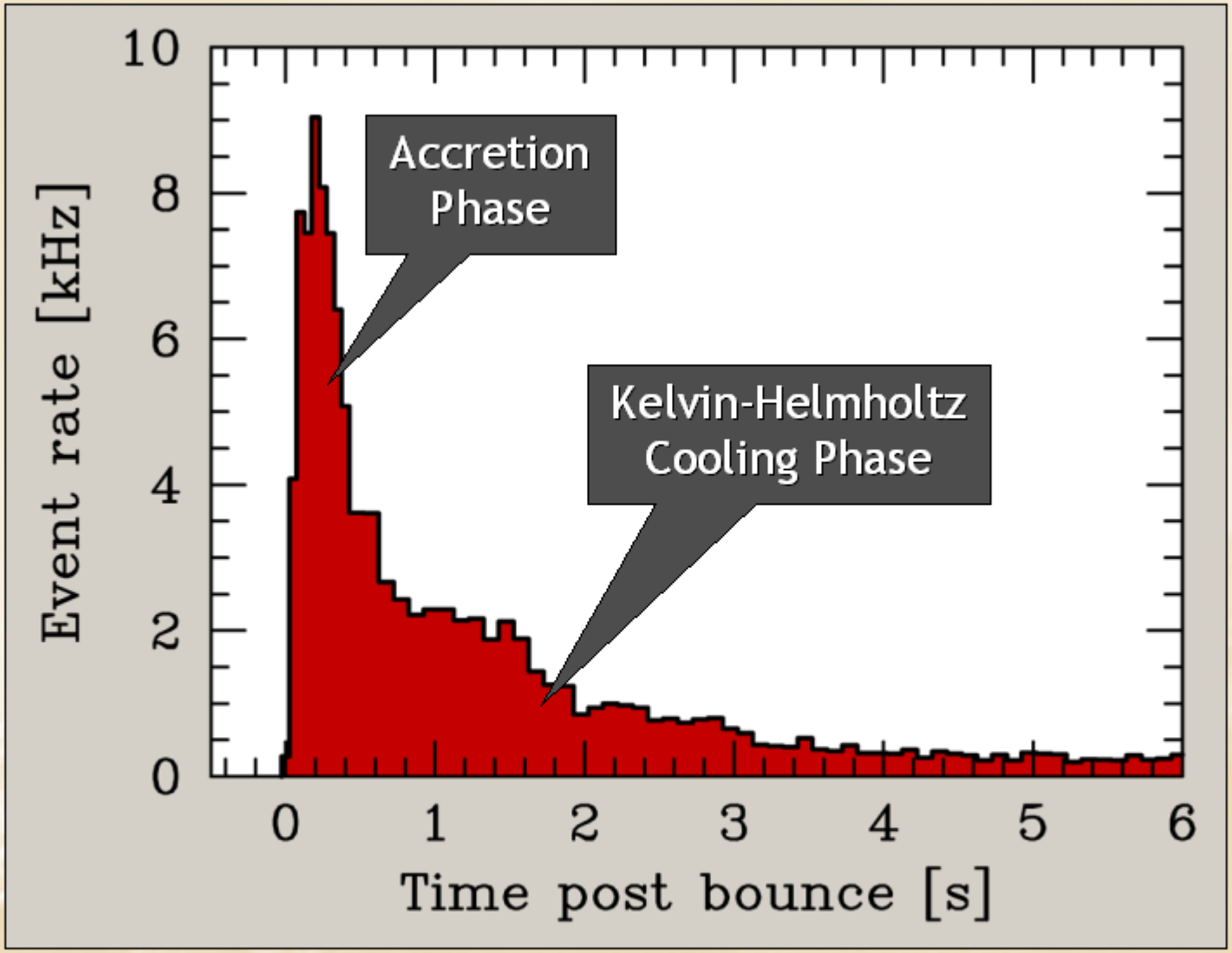


http://hep.bu.edu/~snnet
astro-ph/0406214

Super-Kamiokande Neutrino Detector



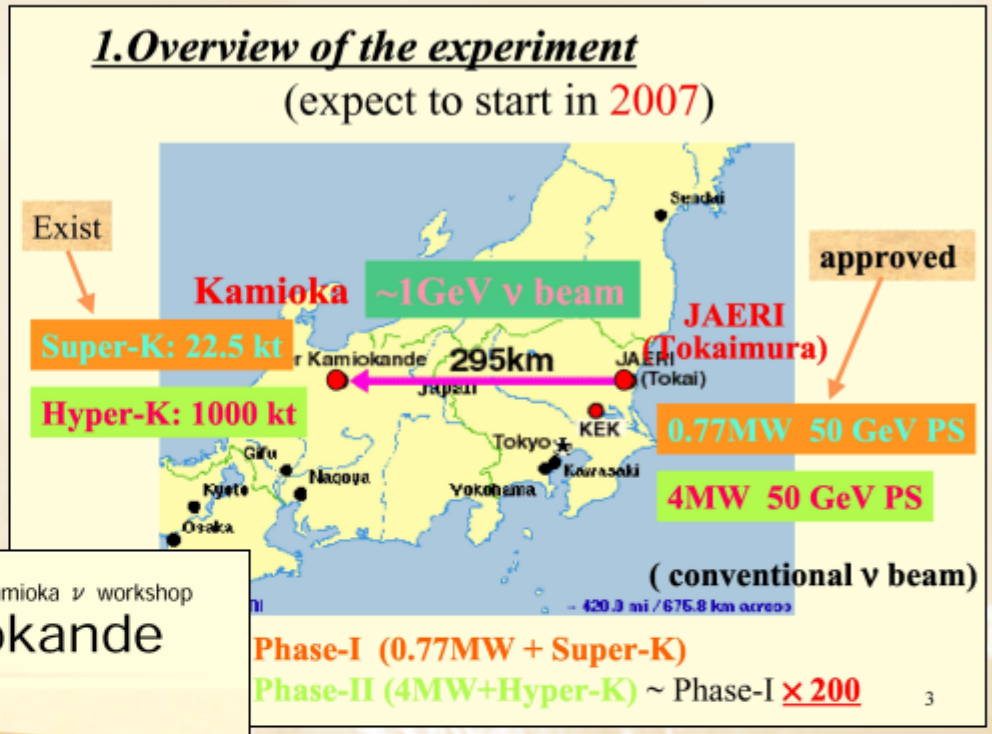
Simulated Supernova Signal at Super-Kamiokande

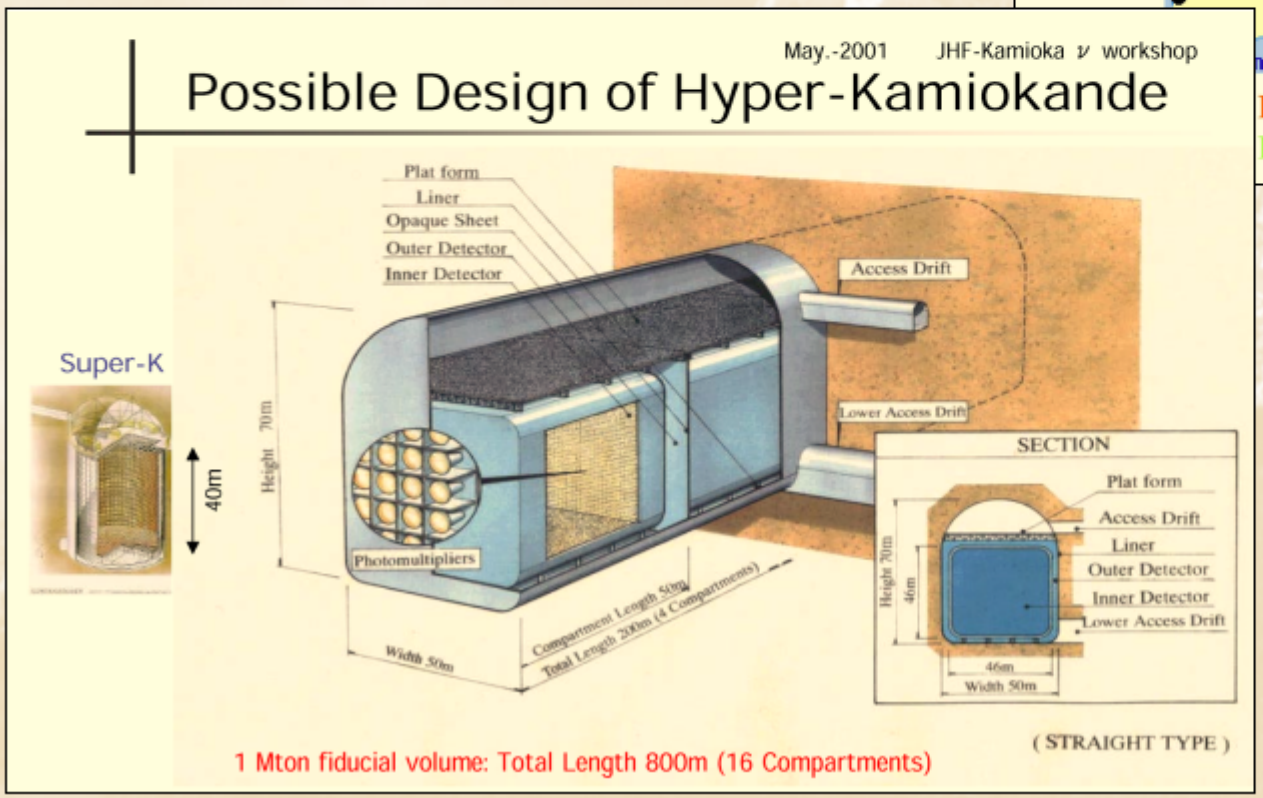


Simulation for Super-Kamiokande SN signal at 10 kpc, based on a numerical Livermore model
[Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216]

The Future: A Megatonne Detector?

Megatonne detector motivated by
- Long baseline neutrino oscillations
- Proton decay
- Atmospheric neutrinos
- Solar neutrinos
- Supernova neutrinos
  (~10^5 events for SN at 10 kpc)

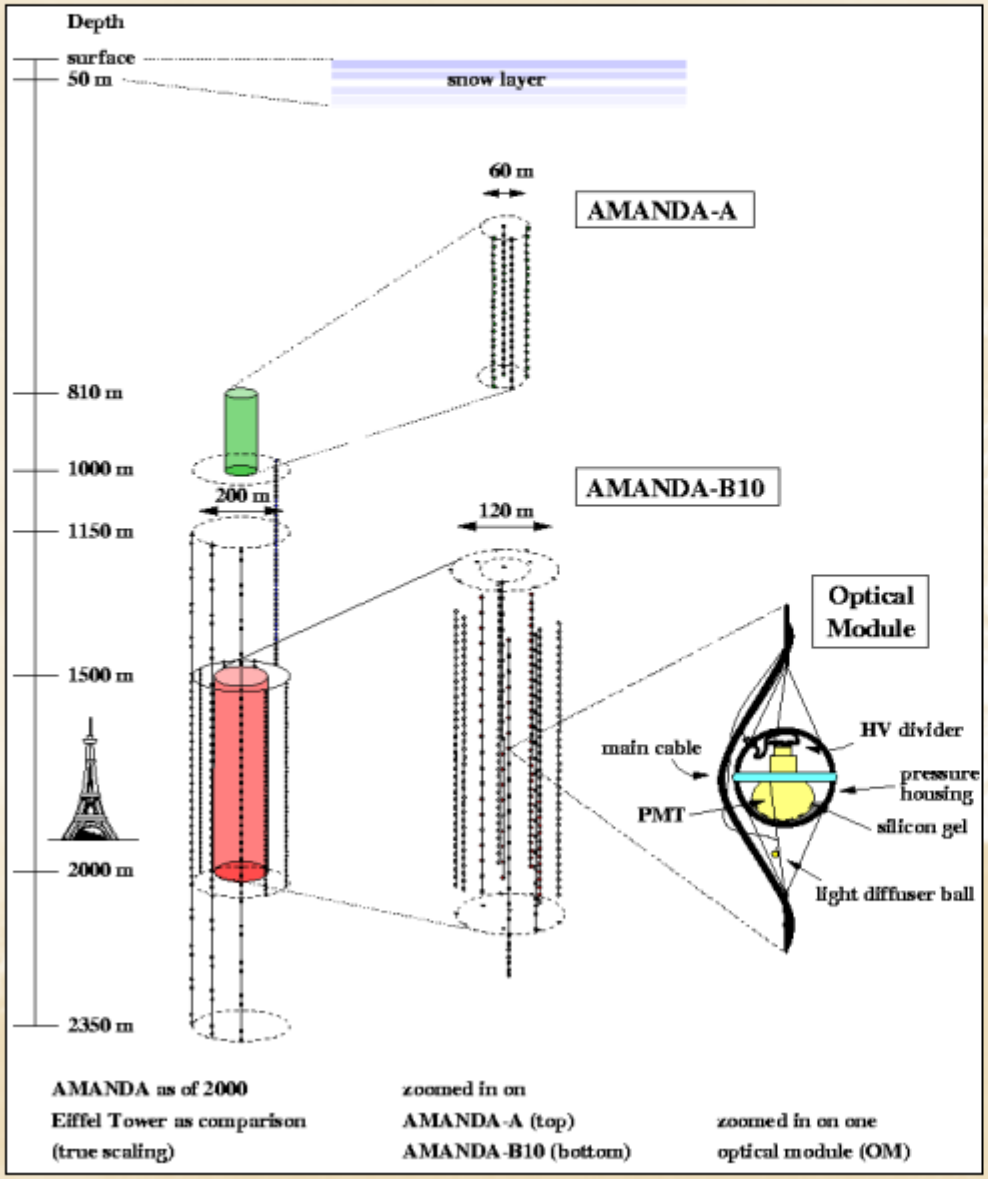




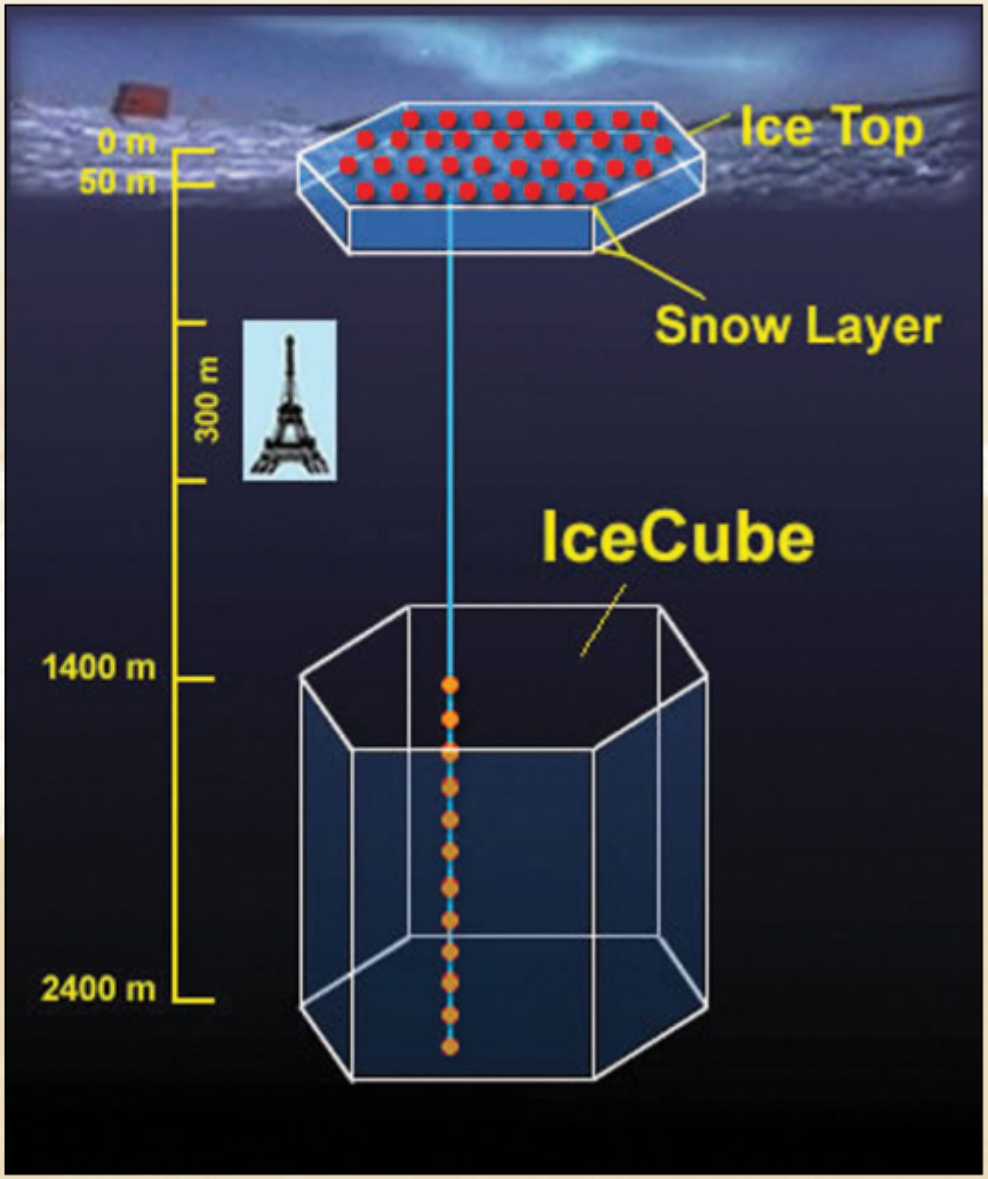
Similar discussions in
- USA (UNO project)
- Europe (Frejus Tunnel)

Southpole Ice-Cherenkov Neutrino Detectors

AMANDA II (0.1 km^3, 800 PMTs)



Future IceCube (1 km^3, 4800 PMTs)

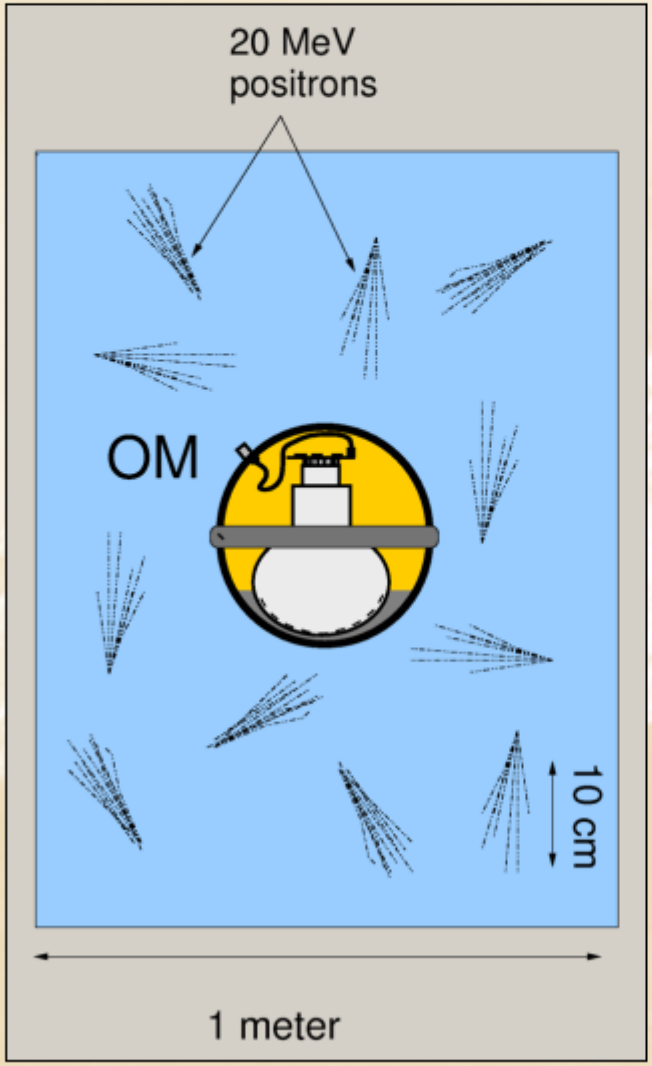


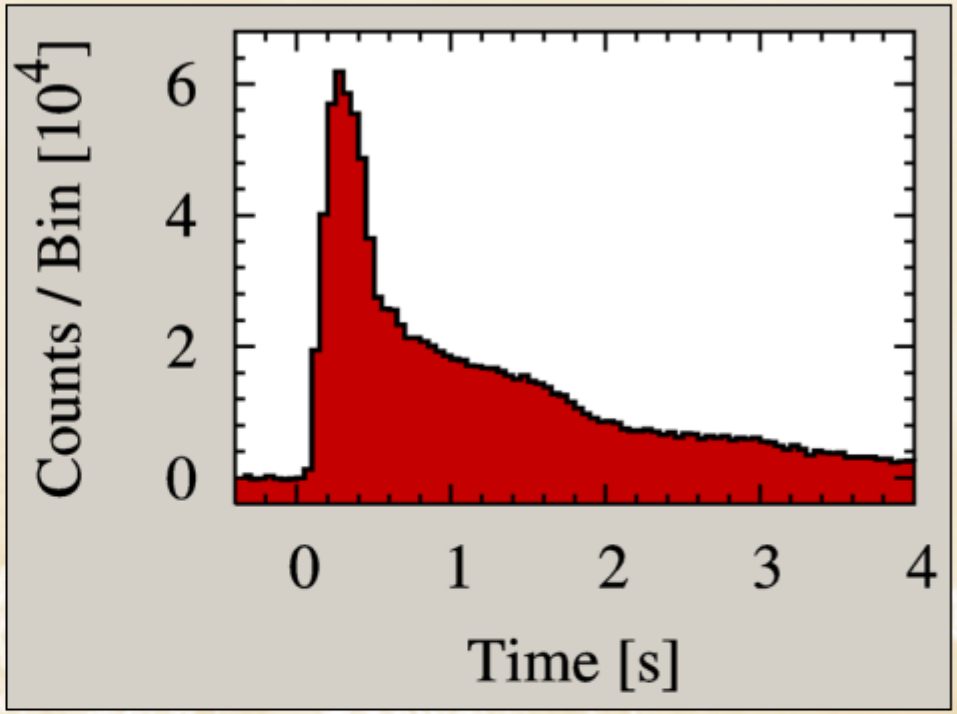
IceCube as a Supernova Neutrino Detector

Each optical module (OM) picks up Cherenkov light from its neighborhood. SN appears as "correlated noise".

~ 300 Cherenkov photons per OM from a SN at 10 kpc

Noise per OM < 500 Hz

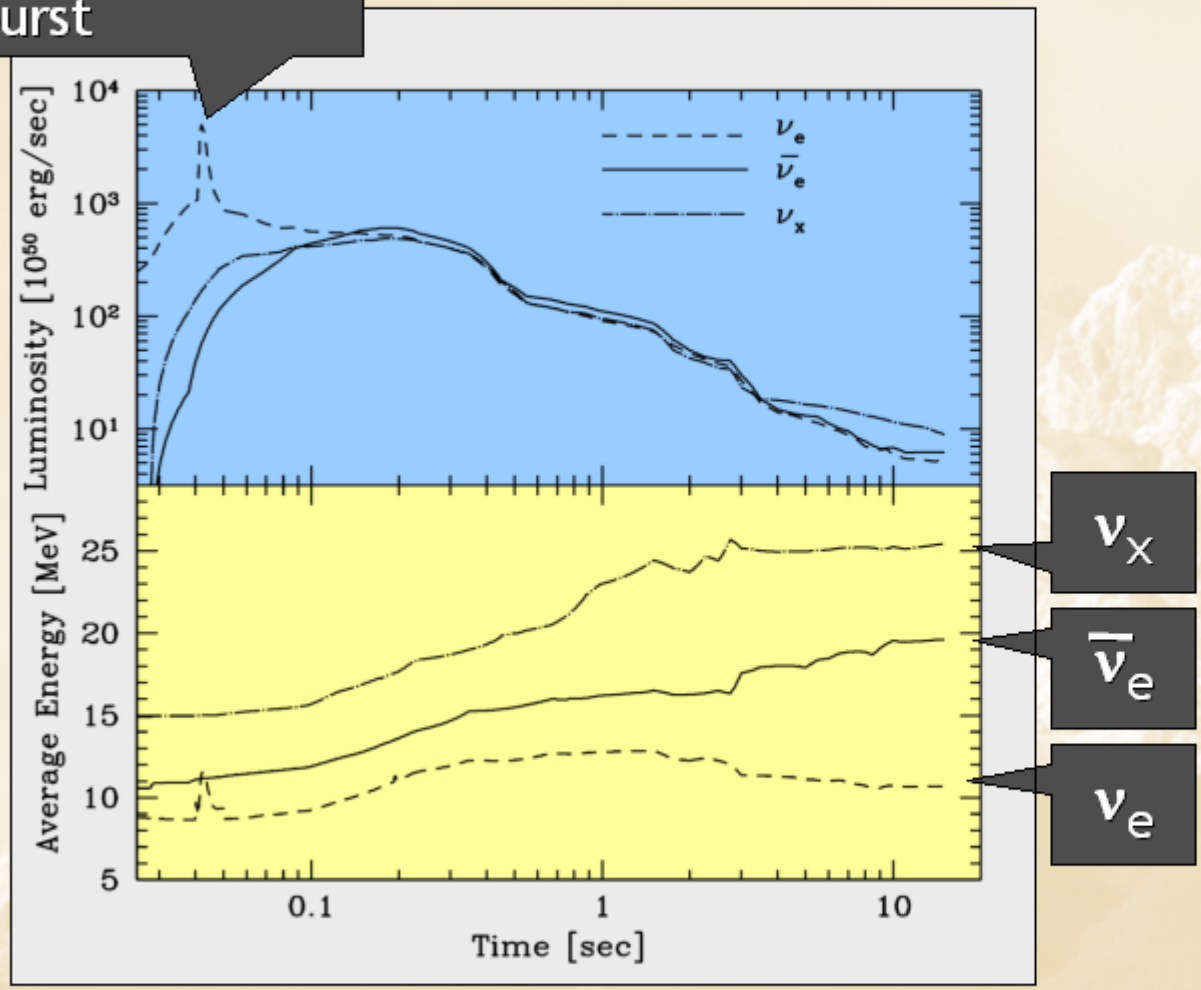




IceCube SN signal at 10 kpc, based on a numerical Livermore model
[Dighe, Keil & Raffelt, hep-ph/0303210]

Flavor-Dependent Fluxes and Spectra

Prompt ν_e deleptonization burst

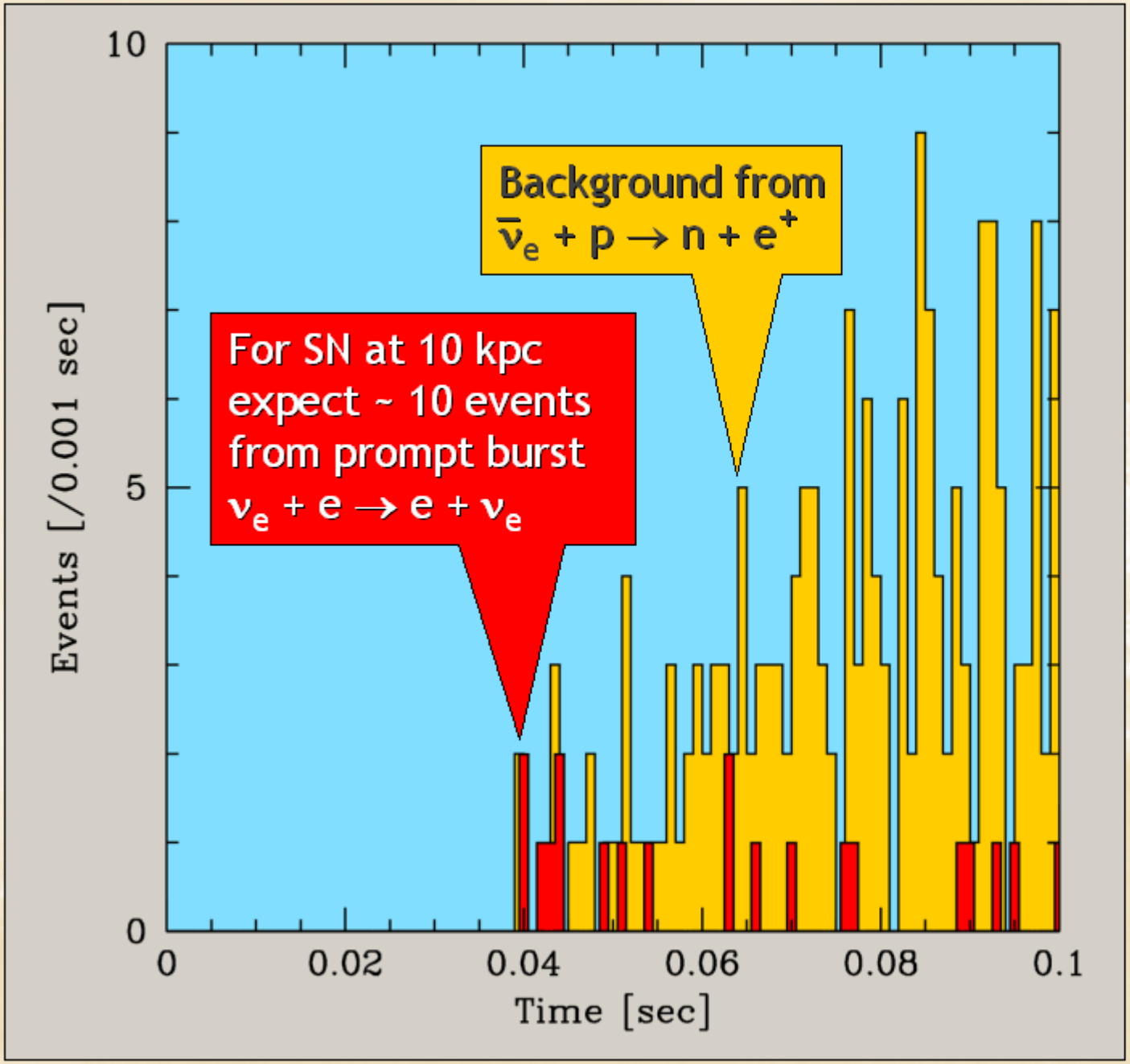


Livermore numerical model
ApJ 496 (1998) 216

Broad characteristics

- Duration a few seconds
- $\langle E_\nu \rangle$ ~ 10–20 MeV
- $\langle E_\nu \rangle$ increases with time
- Hierarchy of energies
  $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$
- Approximate equipartition of energy between flavors

Can we see the prompt neutrino burst in Super-K?

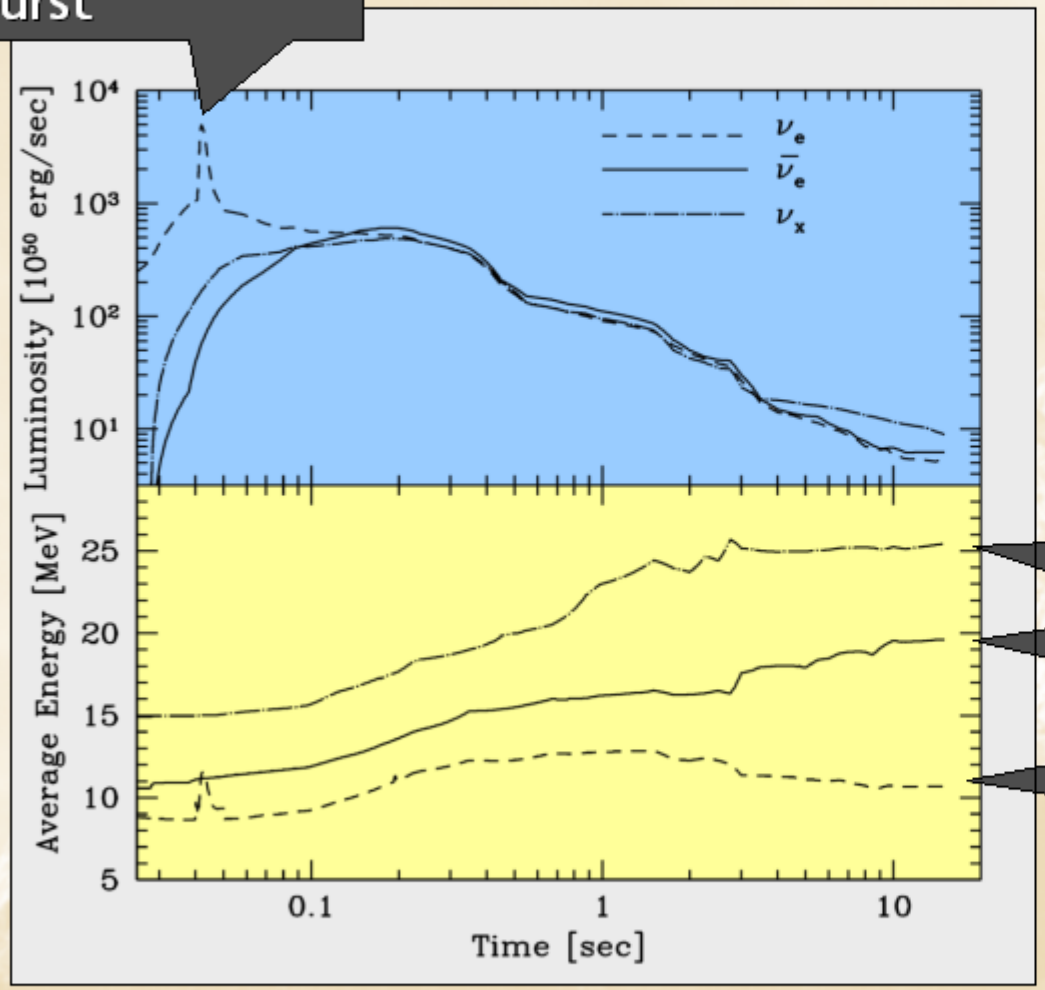


Monte-Carlo example for early SN signal in Super-Kamiokande

Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216

Flavor-Dependent Fluxes and Spectra

Prompt ν_e deleptonization burst



ν_x

$\bar{\nu}_e$

ν_e

Livermore numerical model
ApJ 496 (1998) 216

From these and similar studies the "standard" assumptions are

- Almost exact equipartition of energy among flavors
- Pronounced hierarchy of average energies

However, in traditional simulations transport of ν_μ and ν_τ schematic

- Incomplete microphysics
- Crude numerics to couple nu transport with hydro code

Supernova Neutrino Spectra Formation

Electron flavor $(\nu_e, \bar{\nu}_e)$

Thermal Equilibrium

$\bar{\nu}_e p \leftrightarrow n e^+$

$\nu_e n \leftrightarrow p e^-$

Free streaming

Neutrino sphere (T_{NS})

Other flavors $(\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau)$

$\nu N \leftrightarrow N \nu$

$\nu e \leftrightarrow \nu e$

$NN \leftrightarrow NN\nu\bar{\nu}$

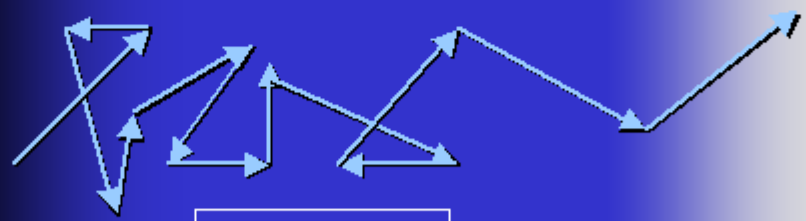
$e^+e^- \leftrightarrow \nu\bar{\nu}$

$\nu_e\bar{\nu}_e \leftrightarrow \nu_\mu\bar{\nu}_\mu$

Thermal Equilibrium

Scattering Atmosphere

$\nu N \leftrightarrow N \nu$



Diffusion

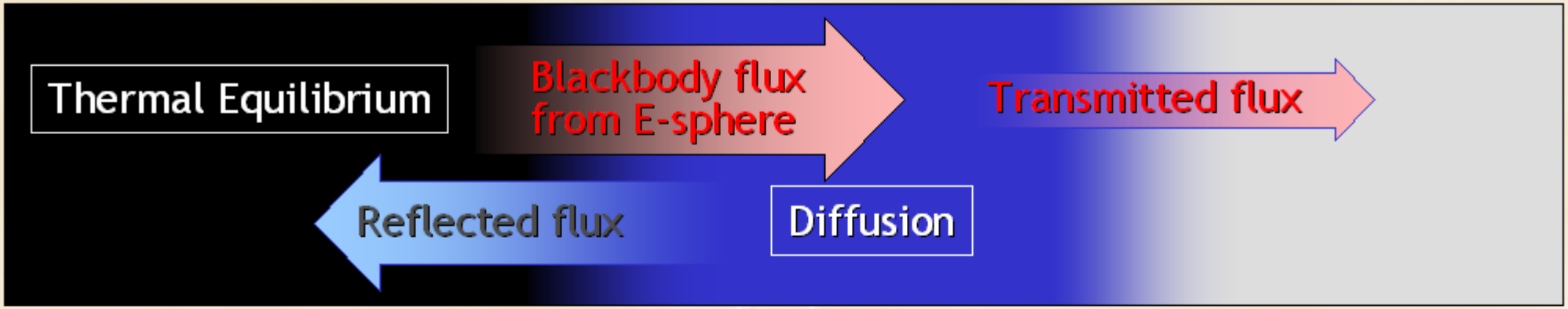
Free streaming

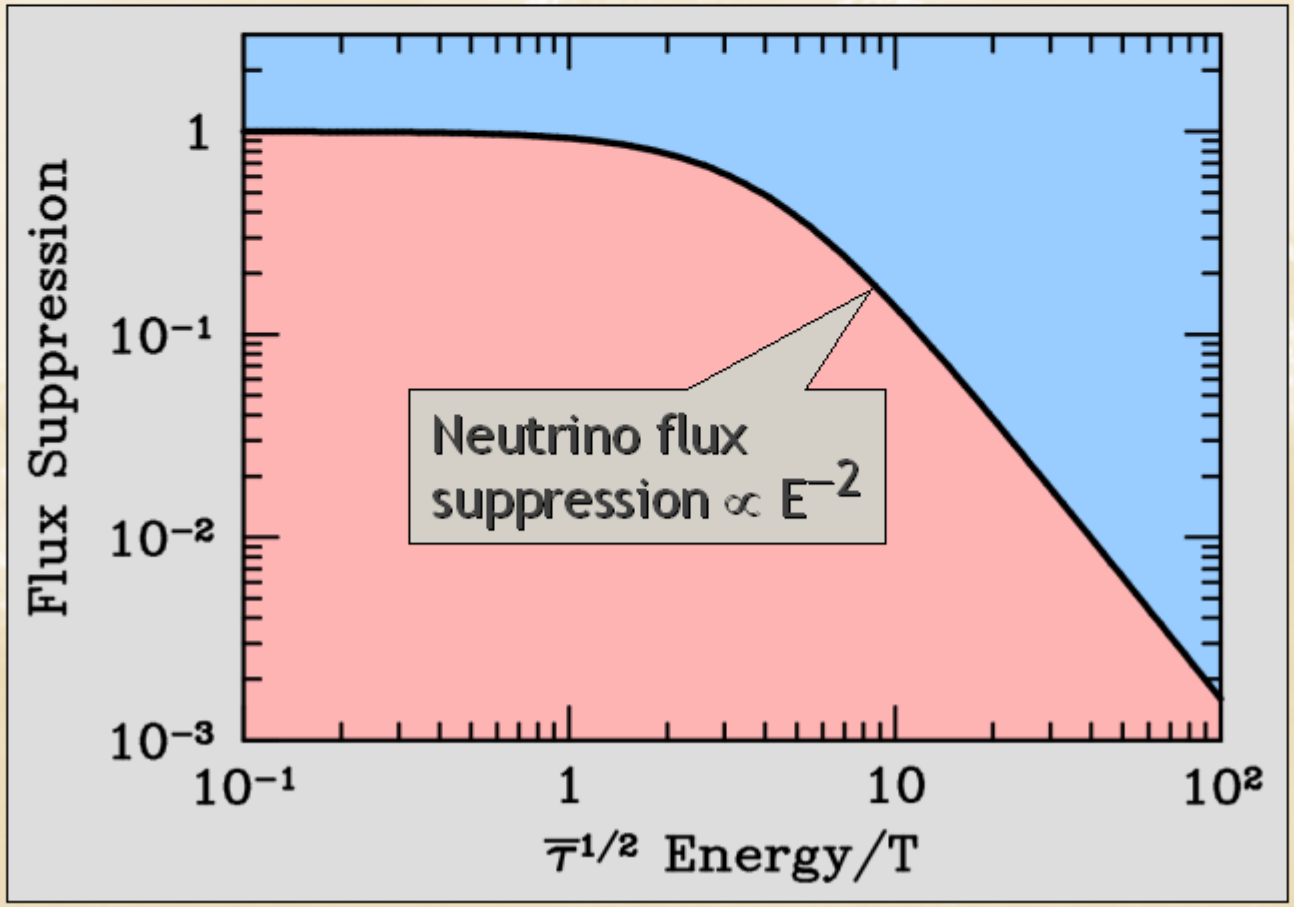
Energy sphere (T_{ES})

Transport sphere

Raffelt (astro-ph/0105250), Keil, Raffelt & Janka (astro-ph/0208035)

Scattering Atmosphere as a "Low-Pass Filter"





Supernova Neutrino Spectra Formation

Electron flavor $(\nu_e, \bar{\nu}_e)$

Thermal Equilibrium

$\bar{\nu}_e p \leftrightarrow n e^+$

$\nu_e n \leftrightarrow p e^-$

$T_{flux} \sim T_{NS}$

Neutrino sphere (T_{NS})

Other flavors $(\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau)$

$\nu N \leftrightarrow N \nu$

$\nu e \leftrightarrow \nu e$

$NN \leftrightarrow NN\nu\bar{\nu}$

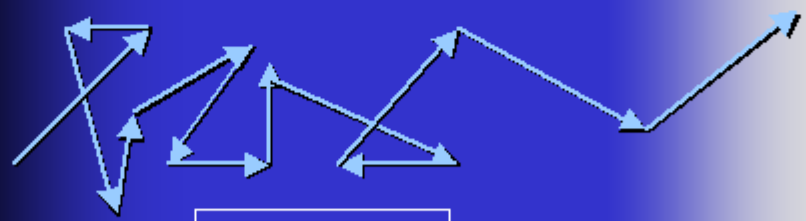
$e^+e^- \leftrightarrow \nu\bar{\nu}$

$\nu_e\bar{\nu}_e \leftrightarrow \nu_\mu\bar{\nu}_\mu$

Thermal Equilibrium

Scattering Atmosphere

$\nu N \leftrightarrow N \nu$



Diffusion

$T_{flux} \sim 0.6 T_{ES}$

Energy sphere (T_{ES})

Transport sphere

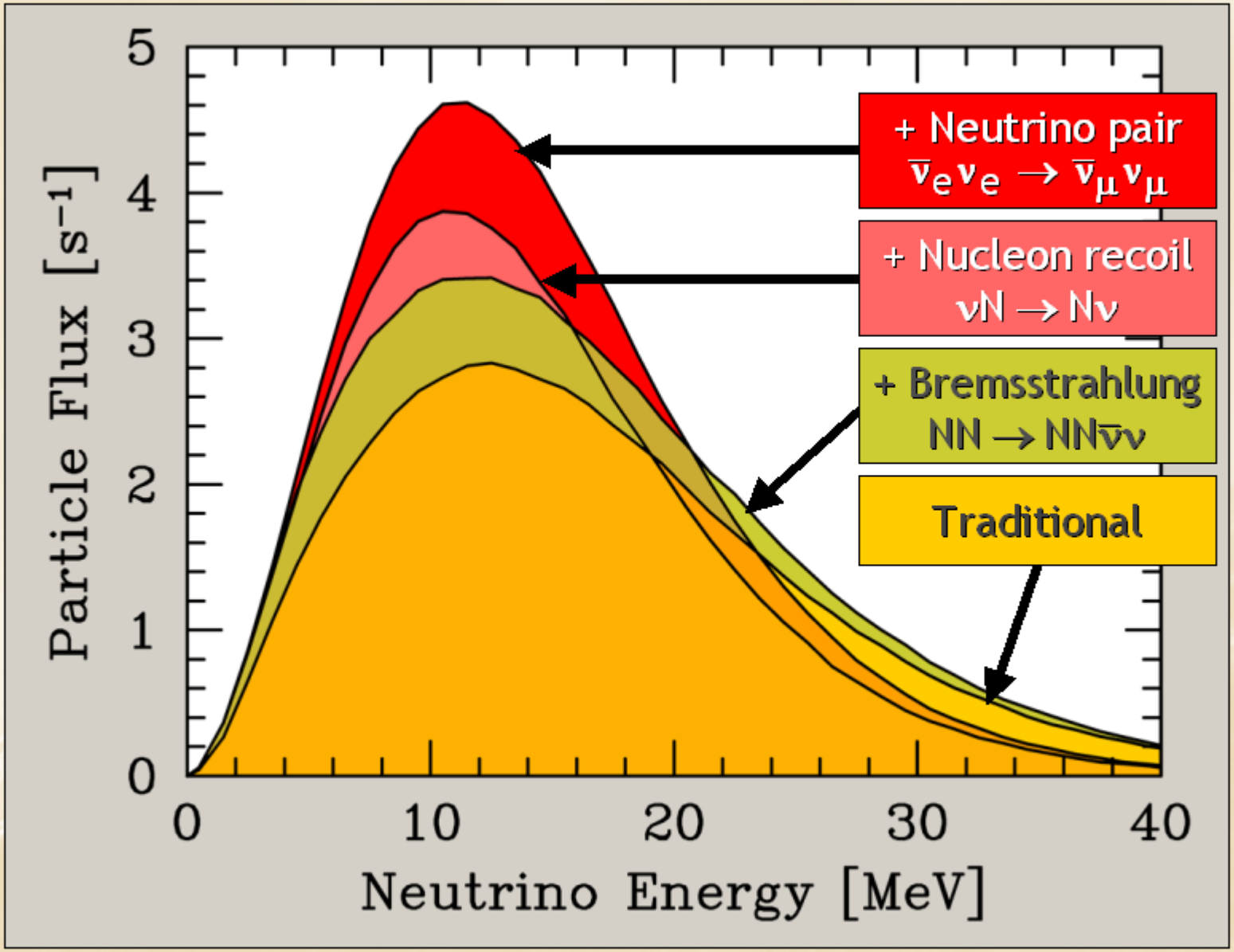
Raffelt (astro-ph/0105250), Keil, Raffelt & Janka (astro-ph/0208035)

Microphysics for Mu- and Tau-Neutrino Transport

	Traditional treatment	Dominant processes
Main opacity	$\nu + N \rightarrow N + \nu$	$\nu + N \rightarrow N + \nu$
Energy exchange	$\nu + e \rightarrow e + \nu$	$\nu + e \rightarrow e + \nu$ Recoil $\nu + N \rightarrow N + \nu$ [2,6,7]
Pair production	$e^+ + e^- \rightarrow \bar{\nu} + \nu$	$N + N \rightarrow N + N + \bar{\nu} + \nu$ [1-4] $\bar{\nu}_e + \nu_e \rightarrow \bar{\nu} + \nu$ [6,7]

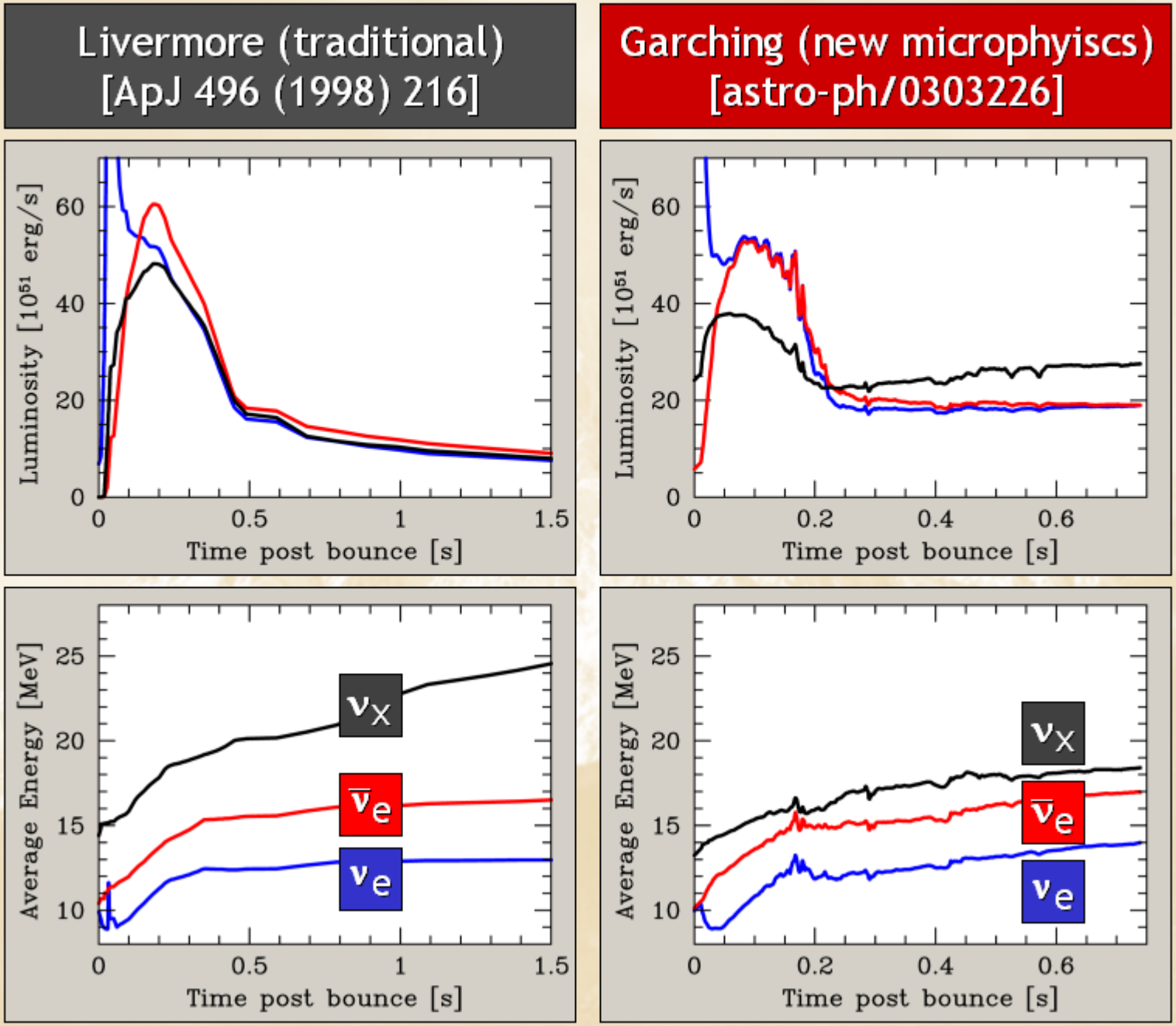
[1] Suzuki, Num. Astrophys. Japan 2 (1991) 267
[2] Janka, W.Keil, Raffelt & Seckel, PRL 76 (1996) 2621 [astro-ph/9507023]
[3] Hannestad & Raffelt, ApJ 507 (1998) 339 [astro-ph/9711132]
[4] Thompson, Burrows & Horvath, PRC 62 (2000) 035802 [astro-ph/0003054]
[6] Raffelt, ApJ 561 (2001) 890 [astro-ph/0105250]
[6] Buras, Janka, M.Keil, Raffelt & Rampp, ApJ (2003) [astro-ph/0205006]
[7] M.Keil, Raffelt & Janka, ApJ (2003) [astro-ph/0208035]

Flux and Spectra Modification by New Processes



Keil, Raffelt & Janka, ApJ (2003) [astro-ph/0208035]

Fluxes and Spectra from Numerical Simulations



Three-Flavor Neutrino Parameters

Atmospheric/K2K	CHOOZ	Solar/KamLAND	2σ ranges
$37^\circ < \theta_{23} < 54^\circ$	$\theta_{13} < 11^\circ$	$30^\circ < \theta_{12} < 36^\circ$	hep-ph/0405172

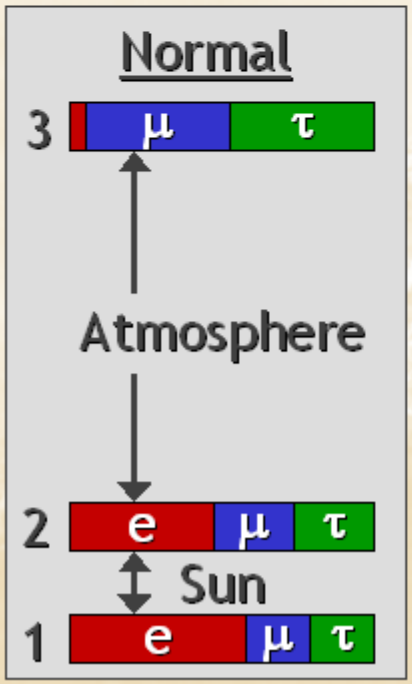
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta} s_{13} \\ & 1 & \\ -e^{i\delta} s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

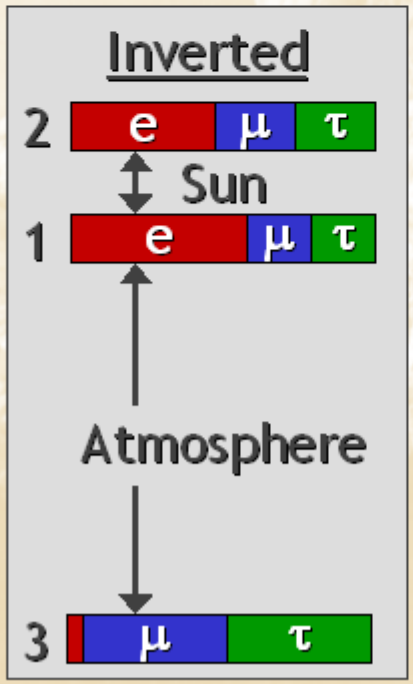
$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

Solar 75–92

Atmospheric 1400–3000

$\Delta m^2/\mathrm{meV}^2$



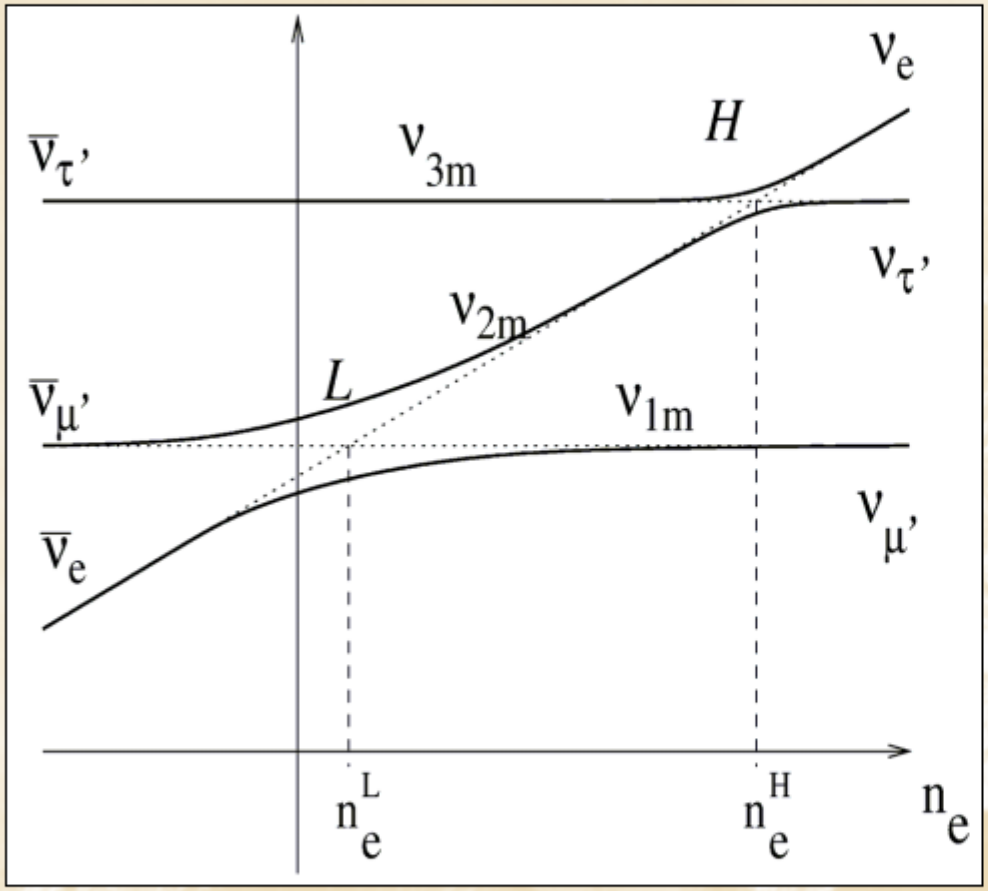


Tasks and Open Questions

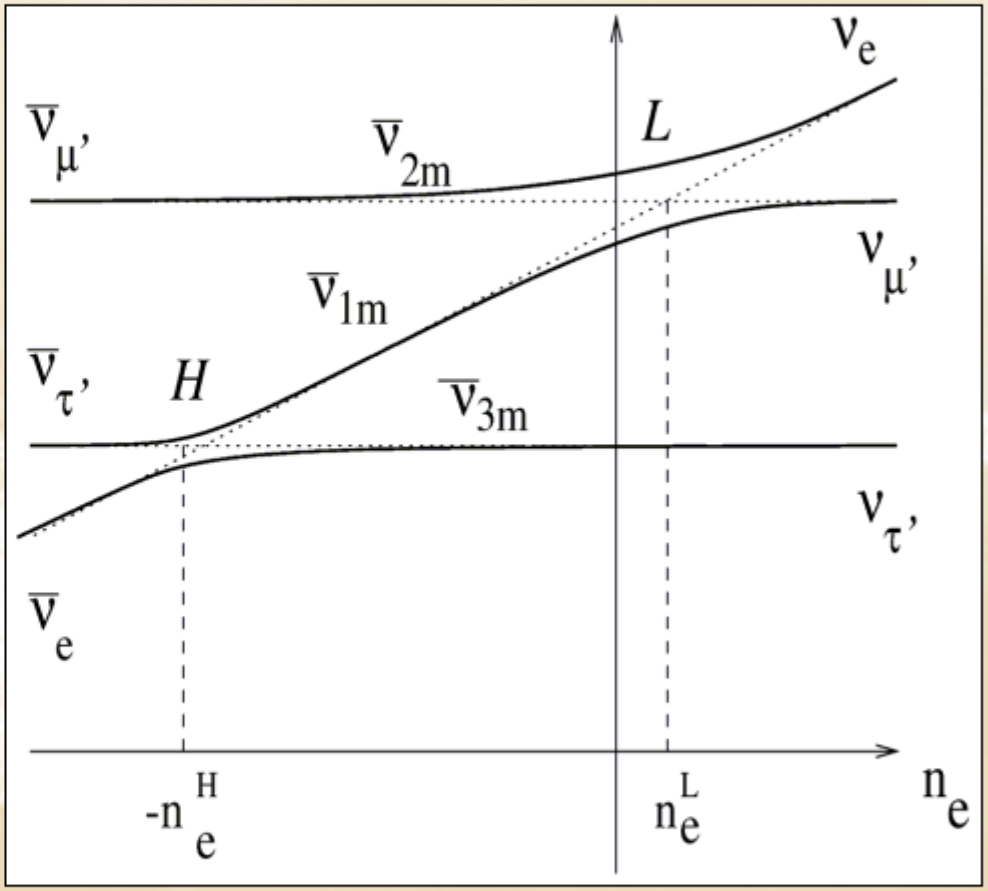
- Precision for θ_{12} and θ_{23}
- How large is θ_{13}?
- CP-violating phase δ?
- Mass ordering? (normal vs inverted)
- Absolute masses? (hierarchical vs degenerate)
- Dirac or Majorana?

Level-Crossing Diagram in a SN Envelope

Normal mass hierarchy

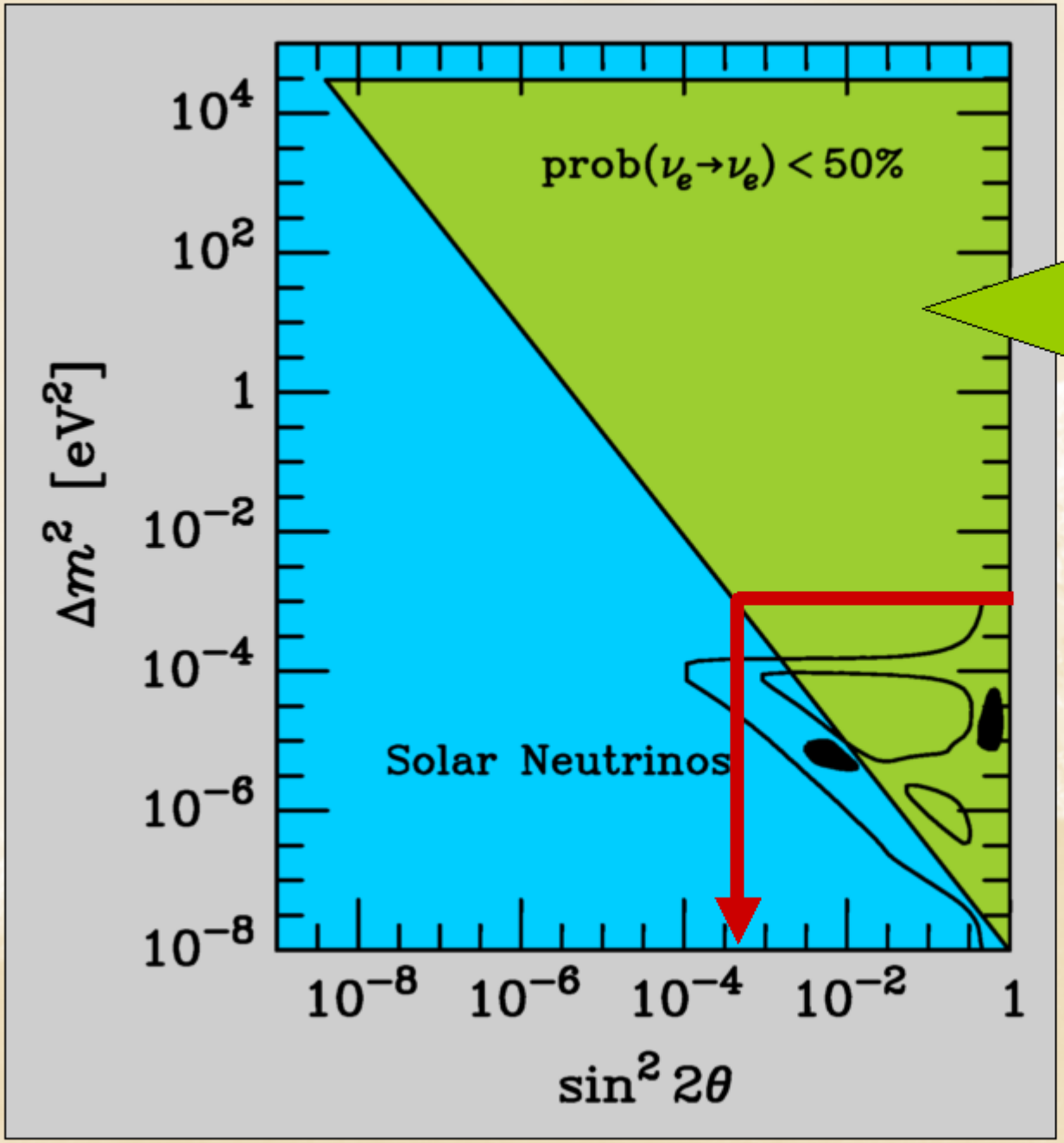


Inverted mass hierarchy



Dighe & Smirnov, Identifying the neutrino mass spectrum from a supernova neutrino burst, astro-ph/9907423

Resonant Oscillations in a Supernova Envelope



Adiabatic oscillations for a large range of mixing parameters

- 13-oscillations involve atmospheric mass difference
- Adiabatic for $\sin^2(2\Theta_{13}) > 10^{-3}$

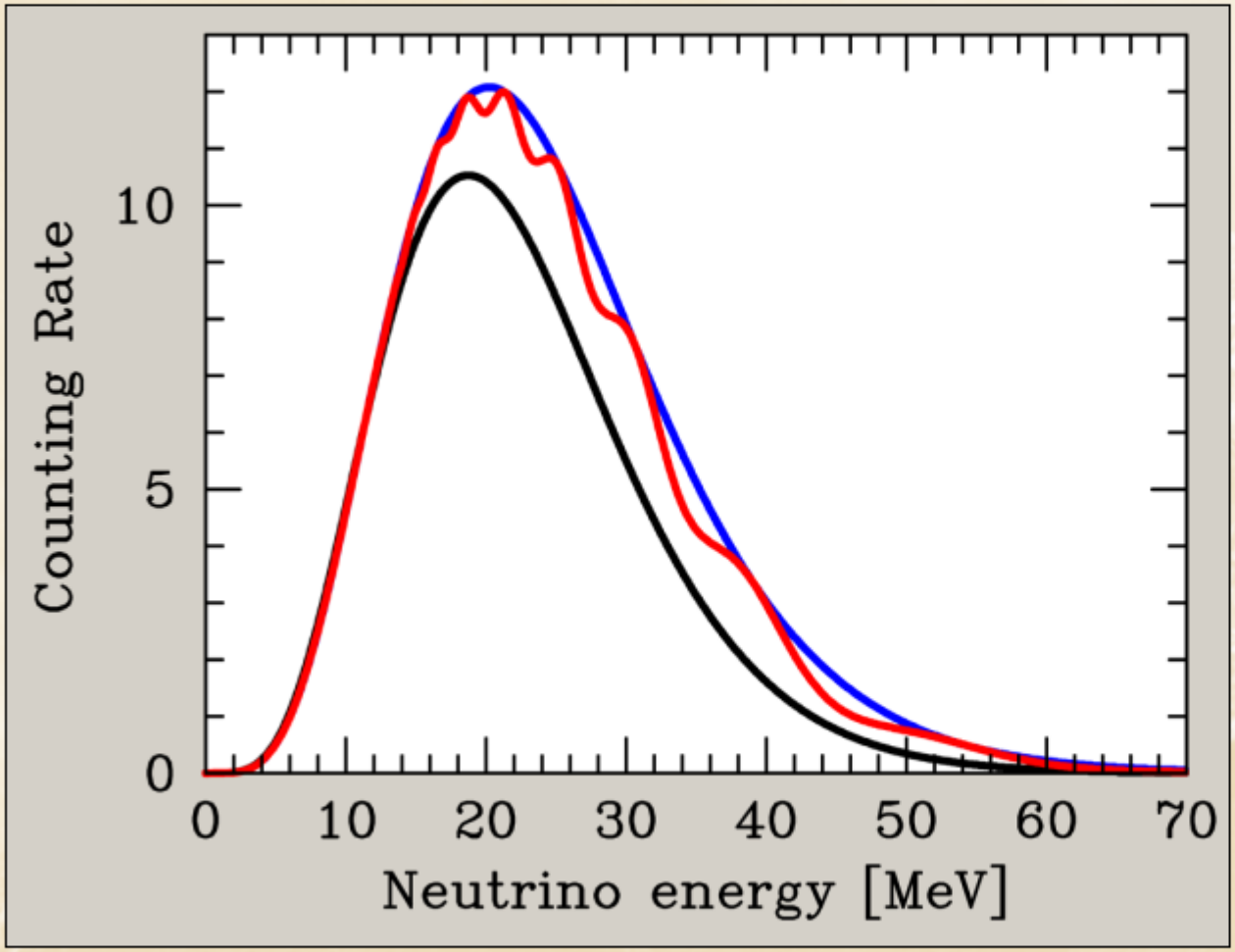
Spectra Emerging from Supernova

Assumed primary fluxes	F_e^0 for ν_e $F_{\bar{e}}^0$ for $\bar{\nu}_e$ F_x^0 for $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$
After leaving the supernova envelope, the fluxes are partially swapped	$F_e = p\,F_e^0 + (1-p)\,F_x^0$ $F_{\bar{e}} = \bar{p}\,F_{\bar{e}}^0 + (1-\bar{p})\,F_x^0$ $\frac{1}{4}\sum F_x = \frac{2+p+\bar{p}}{4}F_x^0 + \frac{1-p}{4}F_e^0 + \frac{1-\bar{p}}{4}F_{\bar{e}}^0$

$\sin^2(2\Theta_{13})$	Mass hierarchy	p	$\bar{p}$
$> 10^{-3}$	Normal	0	$\cos^2(\Theta_{12})$
	Inverted	$\sin^2(\Theta_{12})$	0
$< 10^{-3}$	Either	$\sin^2(\Theta_{12})$	$\cos^2(\Theta_{12})$

Oscillation of Supernova Anti-Neutrinos

Measured $\bar{\nu}_e$ spectrum at a detector like Super-Kamiokande



Assumed flux parameters

Flux ratio $\bar{\nu}_e : \bar{\nu}_\mu = 0.8 : 1$

$\langle E(\bar{\nu}_e) \rangle = 15\,\text{MeV}$

$\langle E(\bar{\nu}_x) \rangle = 18\,\text{MeV}$

Mixing parameters

$\Delta m^2_{sun} = 60\,\text{meV}^2$

$\sin^2(2\theta) = 0.9$

No oscillations

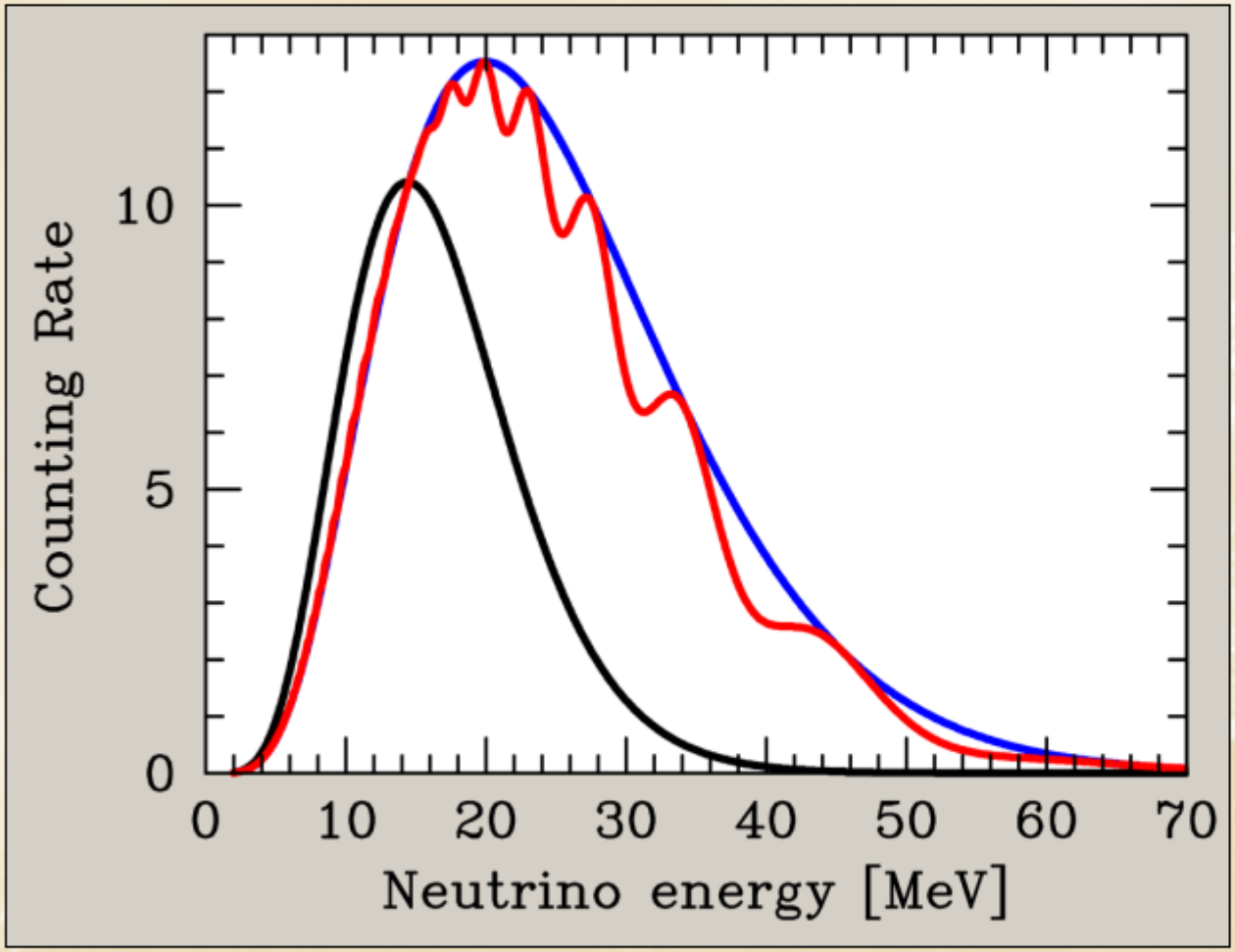
Oscillations in SN envelope

Earth effects included

Π(Dighe, Kachelriess, Keil, Raffelt, Semikoz, Tomàs), arXiv:hep-ph/0303210, hep-ph/0304150, hep-ph/0307050, hep-ph/0311172

Oscillation of Supernova Neutrinos

Measured ν_e spectrum at a detector like SNO, considering only CC reactions



Assumed flux parameters

Flux ratio $\nu_e : \nu_\mu = 0.9 : 1$

$\langle E(\nu_e) \rangle = 12\,\text{MeV}$

$\langle E(\nu_x) \rangle = 18\,\text{MeV}$

Mixing parameters

$\Delta m^2_{sun} = 60\,\text{meV}^2$

$\sin^2(2\theta) = 0.9$

No oscillations

Oscillations in SN envelope

Earth effects included

Π(Dighe, Kachelriess, Keil, Raffelt, Semikoz, Tomàs), arXiv:hep-ph/0303210, hep-ph/0304150, hep-ph/0307050, hep-ph/0311172

Implications of Observing Earth Effects

	normal hierarchy	inverted hierarchy	
Supernova nus: Earth effects appear in channels	$\bar{\nu}_e$	ν_e	$\sin^2(\theta_{13}) > 10^{-3}$
	ν_e and $\bar{\nu}_e$	ν_e and $\bar{\nu}_e$	$\sin^2(\theta_{13}) < 10^{-3}$

One plausible scenario

$\sin^2(\theta_{13}) > 10^{-3}$ established e.g. by long-baseline reactor expt.

Earth effects observed in $\bar{\nu}_e$ channel ?

Yes: Normal hierarchy

No: Inverted hierarchy or SN source spectra "anomalous"

Positively observing Earth effects in SN neutrinos gives us unique information about neutrino parameters

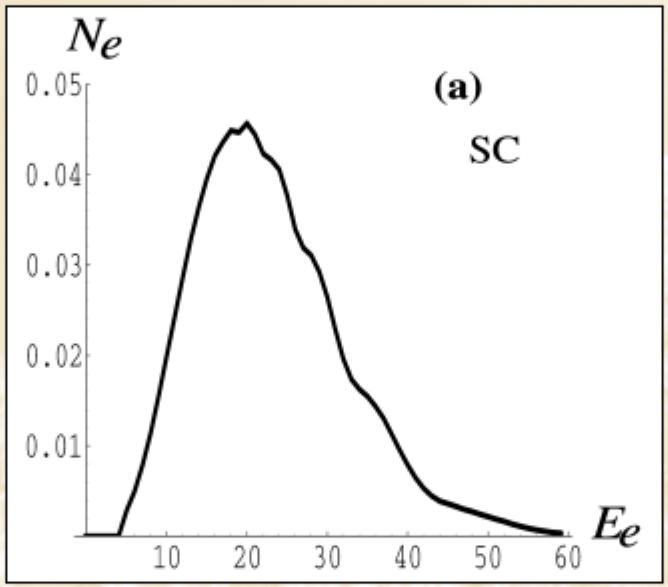
Not observing the effects in a SN signal is ambiguous: Can always be blamed on SN source spectra

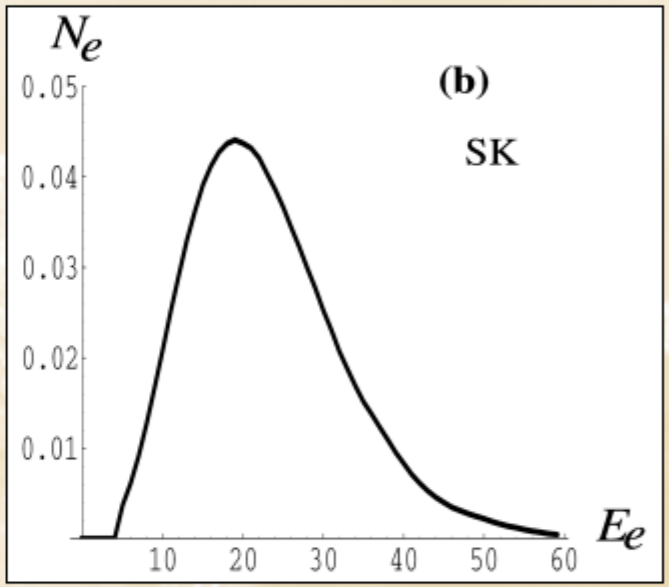
Robust Strategies for Observing Earth Effects

One detector observes SN shadowed by Earth

Case 1:
- Another detector observes SN directly
- Identify Earth effects by comparing signals

Case2: Identify "wiggles" in signal of single detector
Problem: Smearing by limited energy resolution



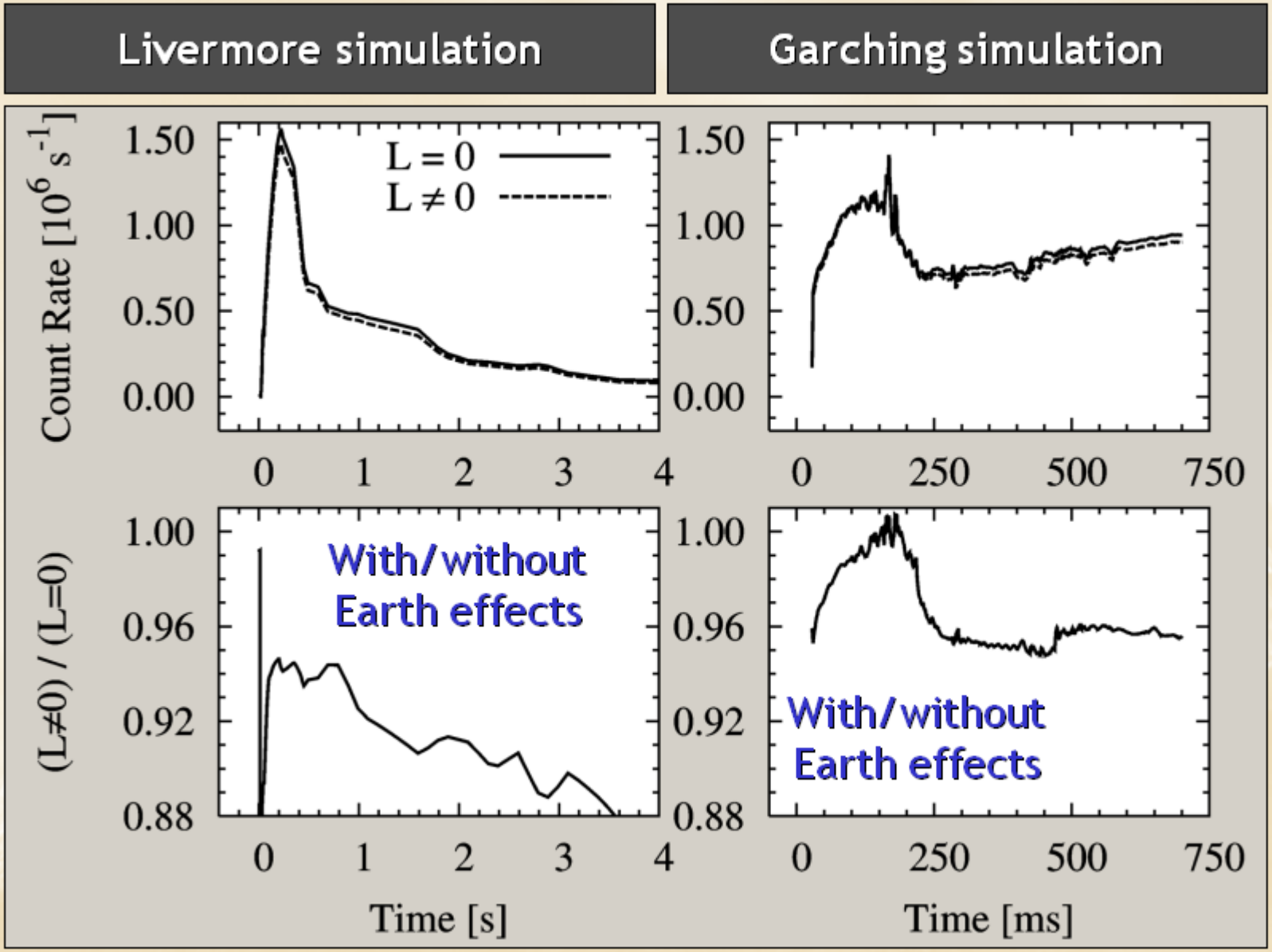


Scintillation detector
~ 2000 events
may be enough

Water Cherenkov
Need Hyper-Kamiokande
with ~ 10^5 events

Dighe, Keil & Raffelt, "Identifying Earth matter effects on supernova neutrinos at a single detector" [hep-ph/0304150]

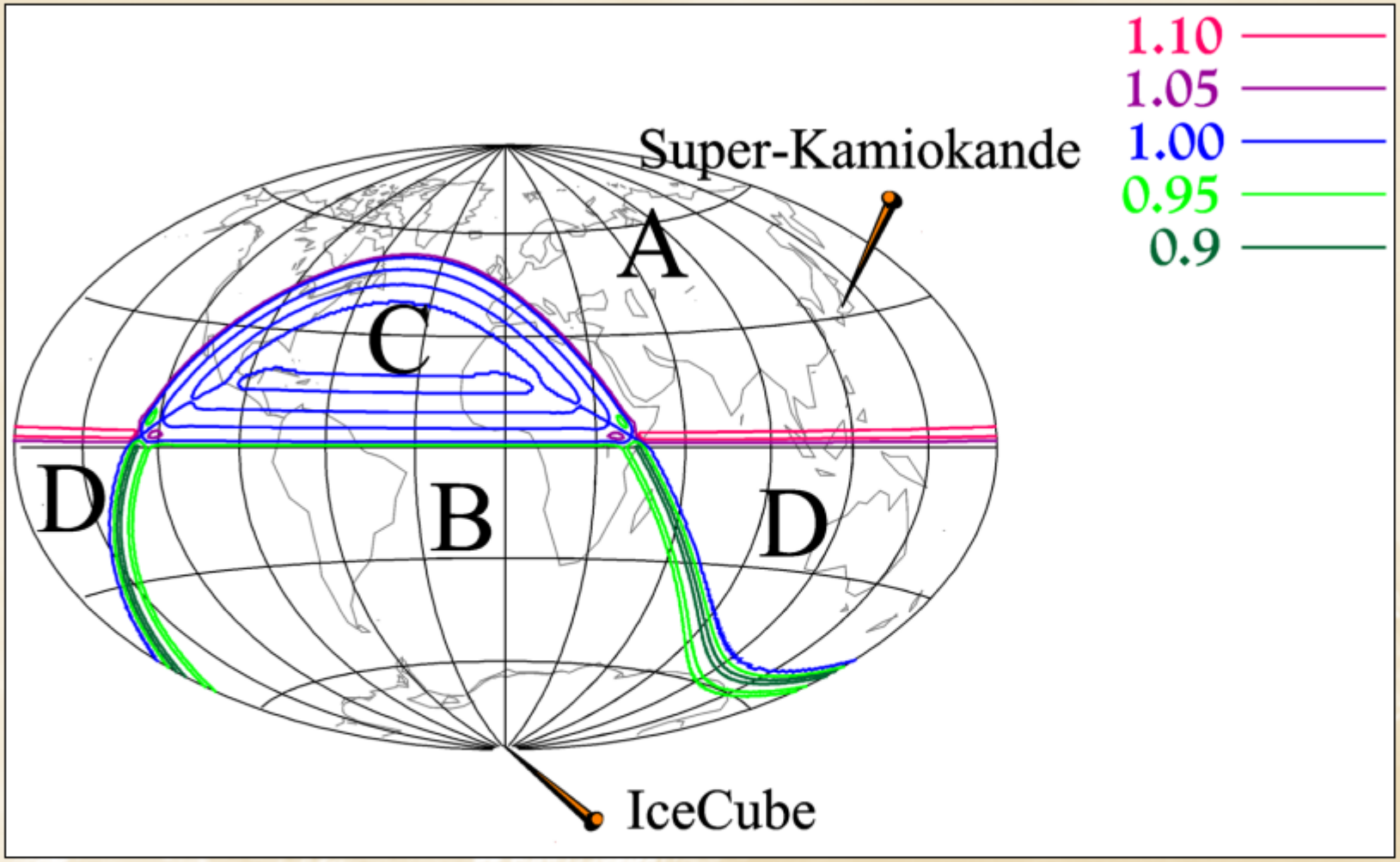
Observing the Earth Effects in IceCube



Dighe, Keil, Raffelt hep-ph/ 0303210

Statistical IceCube signal precision < 1%

Two-Detector Sky Coverage with Super-K & IceCube

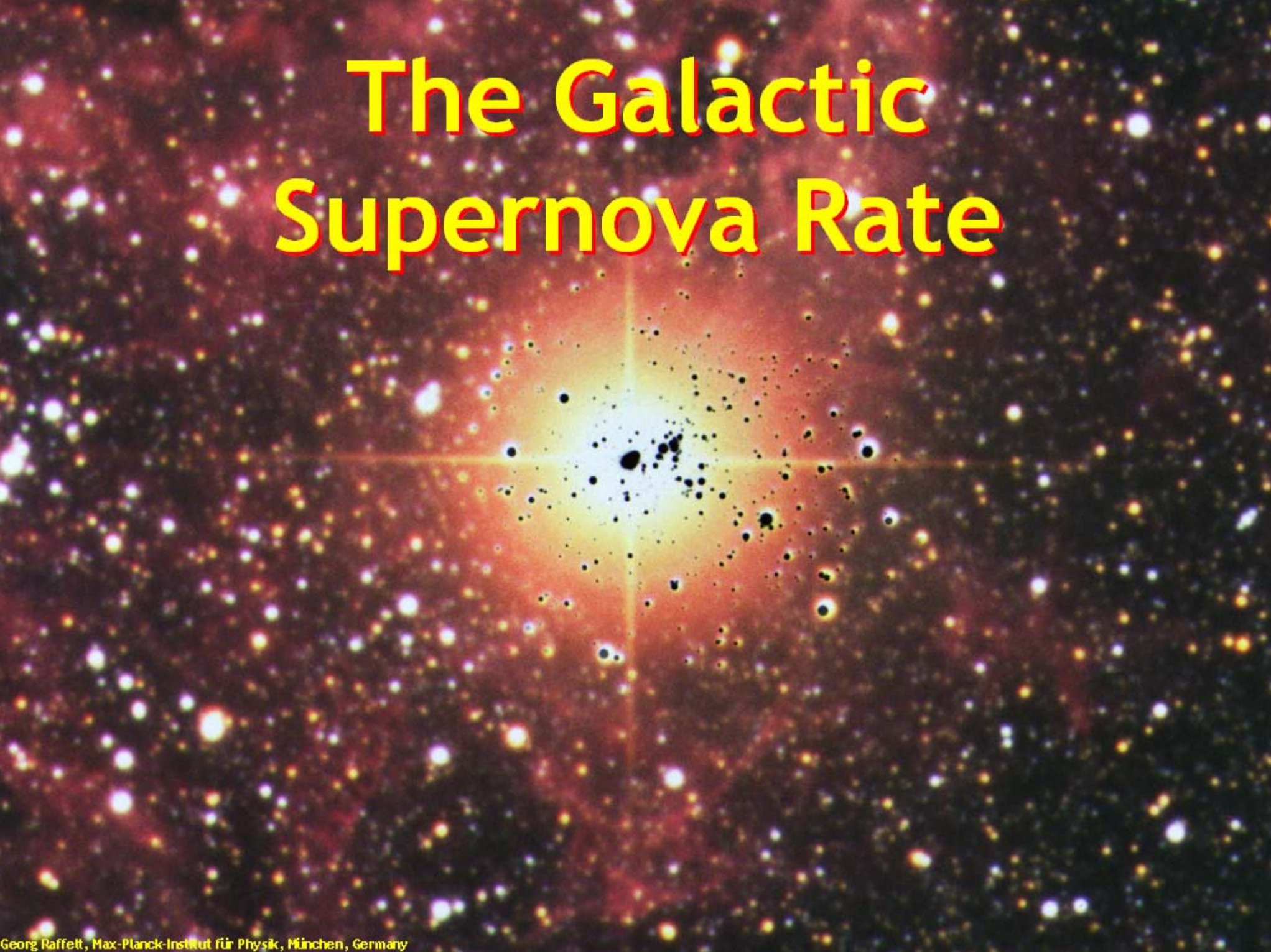


Dighe, Keil, Raffelt hep-ph/0303210

Earth effects appear in

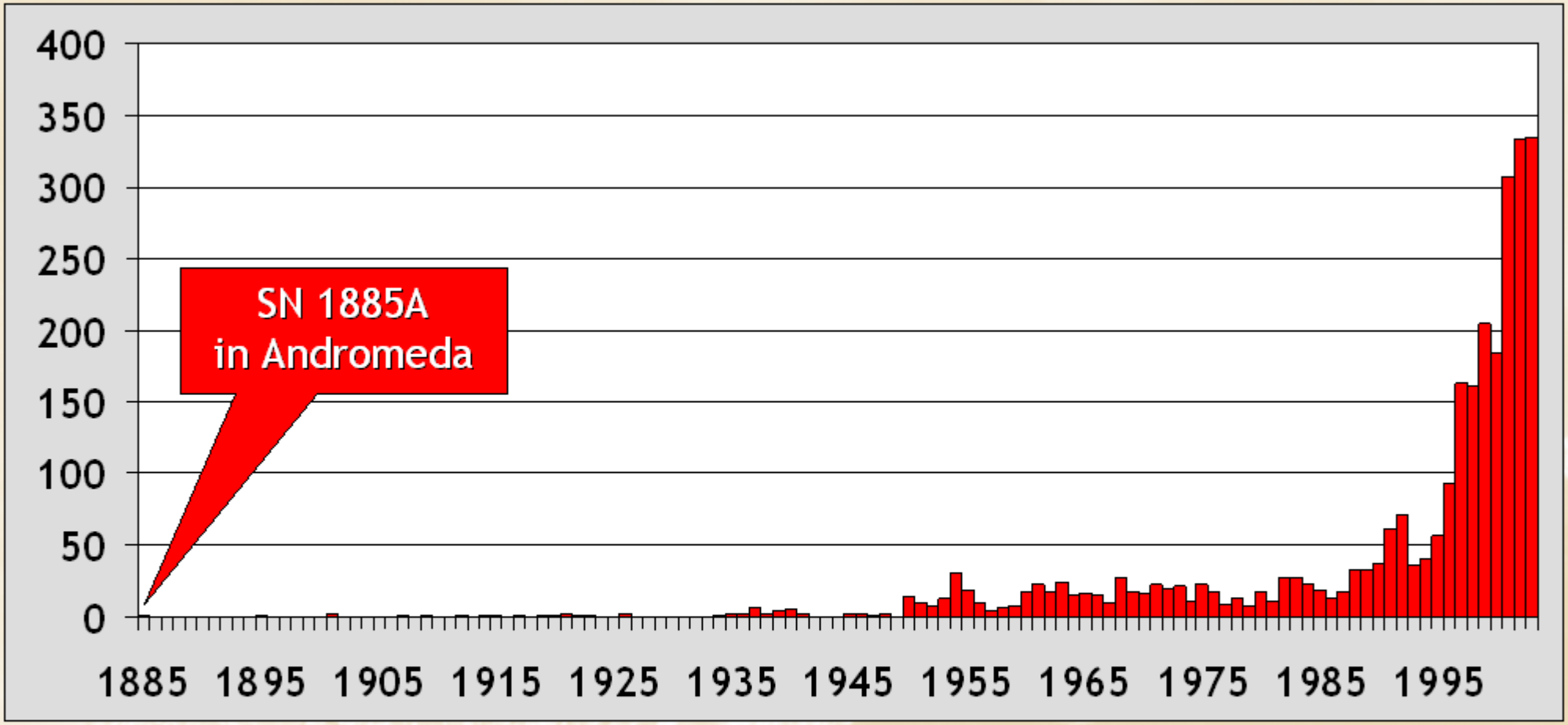
	IceCube	A	35%	Suitable for two-detector method
Super-K		B	35%	
Super-K	IceCube	C	15%	Approx. same signal in both detectors
		D	15%	

The Galactic Supernova Rate



Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

Supernova Discoveries 1885–2003



Naming convention for supernovae:

SN 2000A, SN 2000B … SN 2000Z,

SN 2000aa, SN 2000ab … SN 2000az, SN 2000ba … SN 2000gb, …

SN Statistics in External Galaxies

Cappellaro, Evans & Turatto, Astron. Astrophys. 351 (1999) 459
is latest study with largest sample

Limited controlled samples useful for this task:
- Photographic searches (7319 galaxies, 94 SNe)
- Evans' visual search 1980–1998 (3068 galaxies, 54 SNe)

Difficulties include:
- Galaxy blue luminosity (internal absorption)
- Distances (value of Hubble constant)
- Correction for inclination of galaxy (losing some SNe)
- Galaxy morphological classification
- Saturation in dense regions of photographic plates (galaxy cores)
- Limiting discovery brightness
- Intrinsic luminosity distribution of core-collapse SNe (many faint ones ?)
- Blue luminosity of Milky Way uncertain ($2.3 \pm 0.6 \times 10^{10}\ L_{sun}$)
- Morphological type of Milky Way

Supernova Rates

Multiply numbers with h^2		Supernova Type			
		Ia	Core Collapse		All
			Ib/c	II	
Galaxy Type	E-S0	0.32 ± .11	< 0.02	< 0.04	0.32 ± .11
	S0a-Sb	0.32 ± .12	0.20 ± .11	0.75 ± .34	1.28 ± .37
	SBc-Sd	0.37 ± .14	0.25 ± .12	1.53 ± .62	2.15 ± .66
	All	0.36 ± .11	0.14 ± .07	0.71 ± .34	1.21 ± .36

Measured in SuperNova unit: 1 SNu = 1 SN / 10^{10} $L_{sun,B}$ / 100 years

Milky Way Galaxy:
Type Sb–Sbc, $L_B = 2.3 \times 10^{10}$ $L_{sun,B}$, $h = 0.72$
About 2.0 ± 1.0 core-collapse SNe per century

Cappellaro & Turatto, Supernova Types and Rates, astro-ph/0012455

Some Galaxies with Many Observed Supernovae

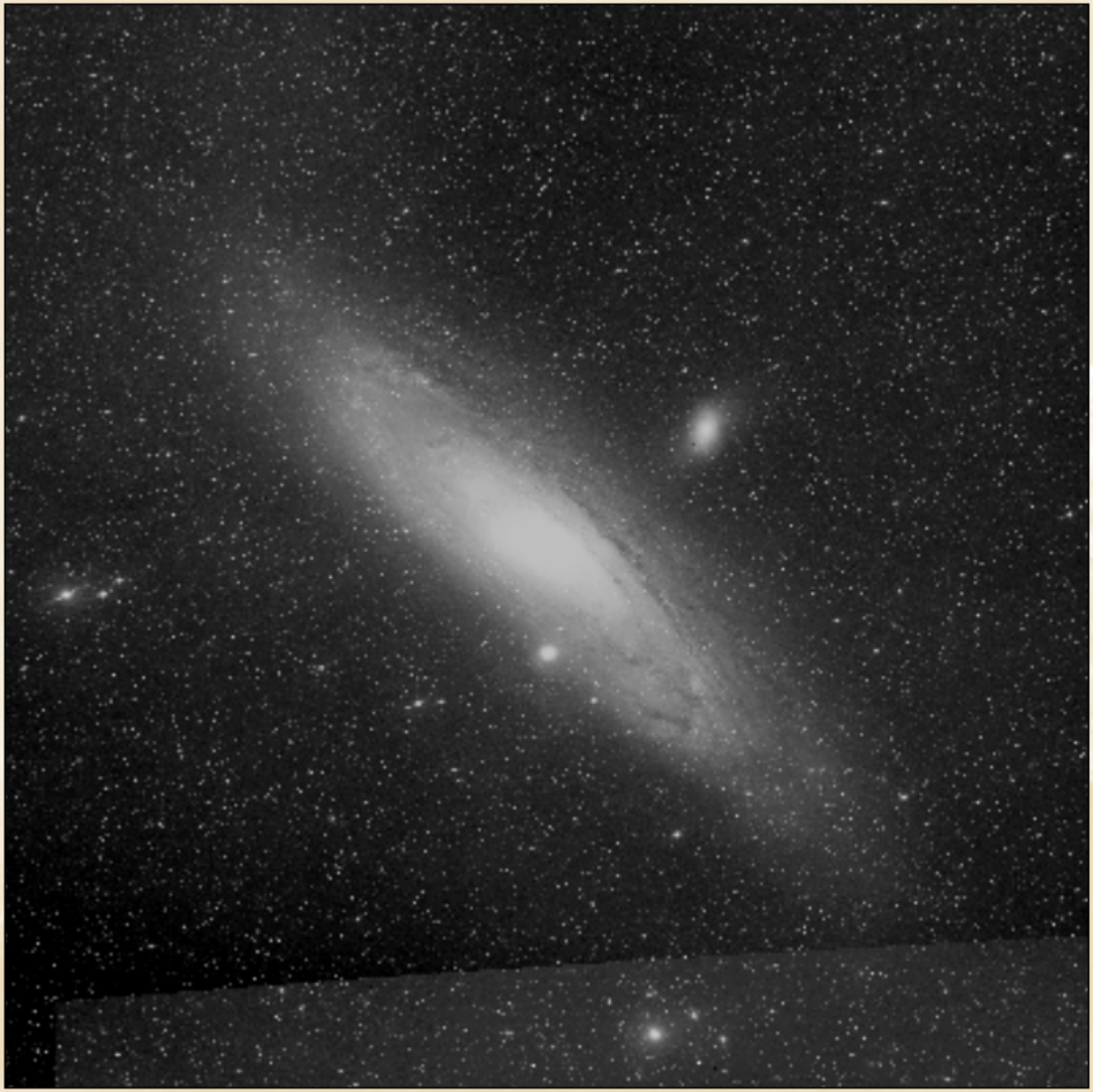
M83 (Southern Pinwheel)
D = 4.6 Mpc

Observed Supernovae:
1923A, 1945B, 1950B,
1957D, 1968L, 1983N

NGC 6946
D = 3.0 Mpc

Observed Supernovae:
1917A, 1939D, 1948B,
1968D, 1969P, 1980K

Andromeda Galaxy (M31)

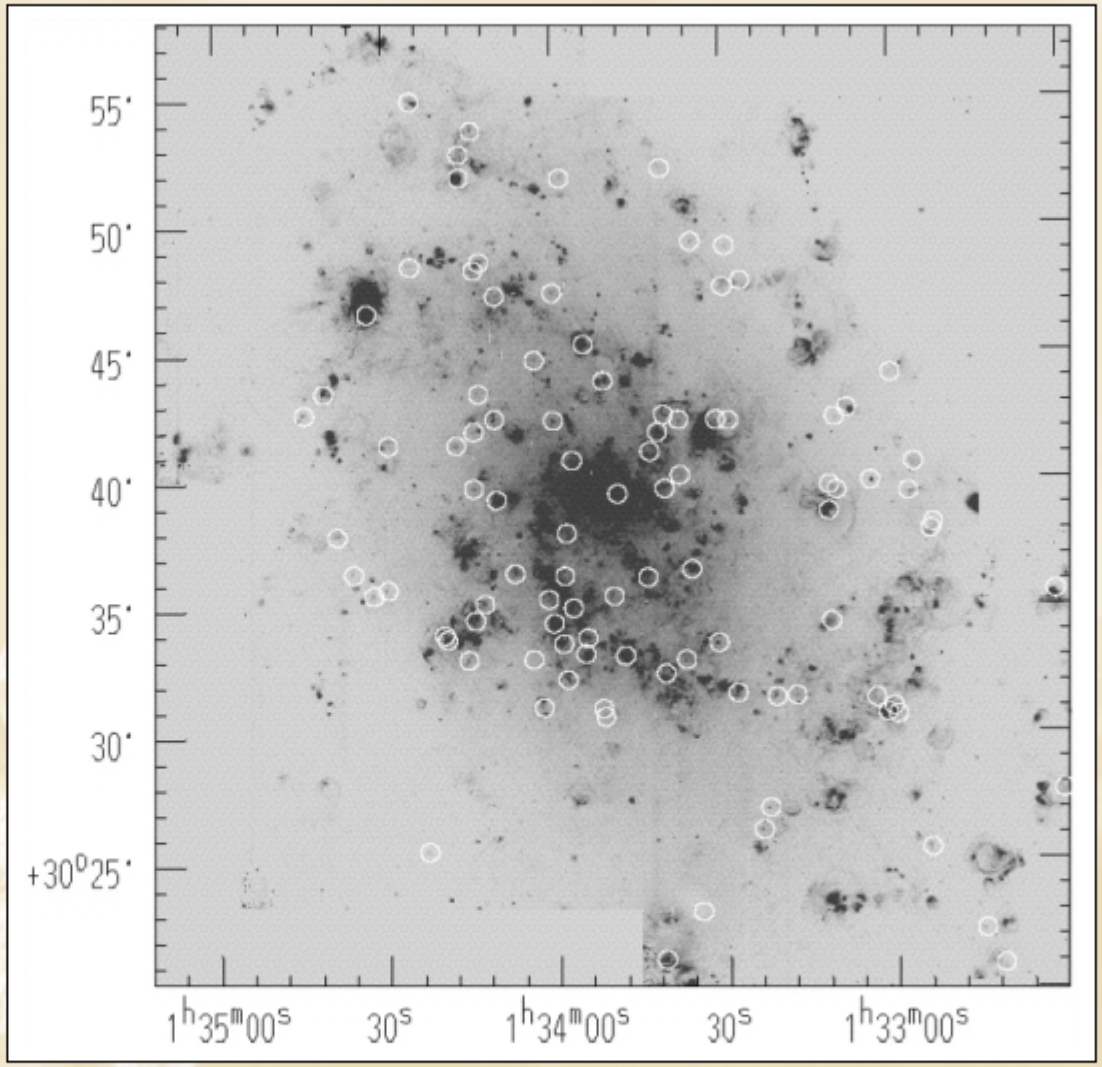


- SN 1885A is the only historical SN in Andromeda (M31) (distance 760 kpc)
- We see all of the galaxy - one probably would not have missed a SN by obscuration
- Probably low star formation rate (low FIR luminosity)

~ 1.2 SN/century
Tammann et al.
Ap. J. Suppl. Ser.
92 (1994) 487

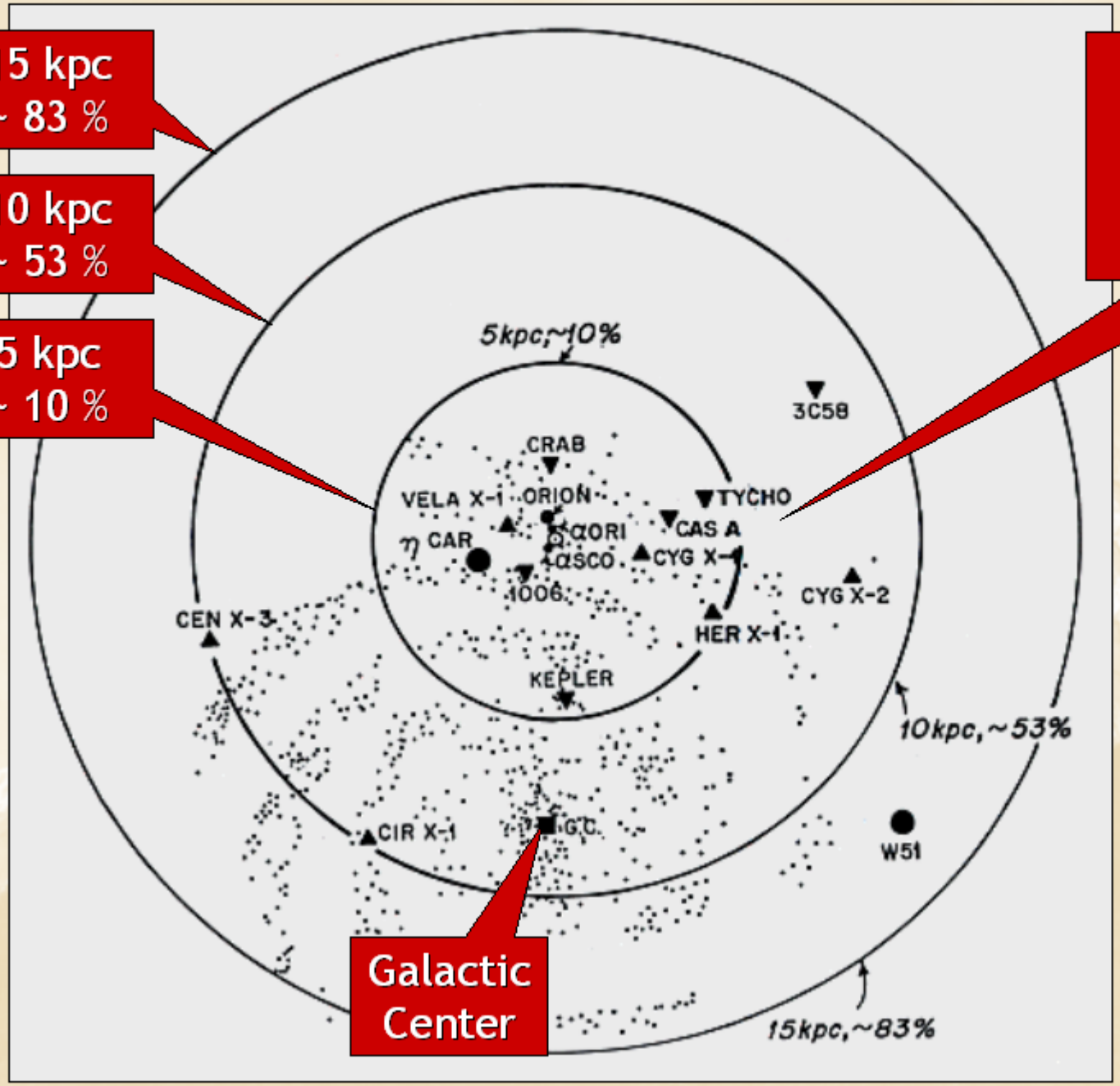
Supernova Remnants in M33 (Triangulum)

Hα image of M33 (Triangulum)



S.M. Gordon et al.,
A New Optical Sample of Supernova Remnants in M33
Astrophys. J. Suppl. 117 (1998) 89.

Galactic Supernova Events



15 kpc
~ 83 %

10 kpc
~ 53 %

5 kpc
~ 10 %

Most historical supernovae in ~ 10% of the galaxy

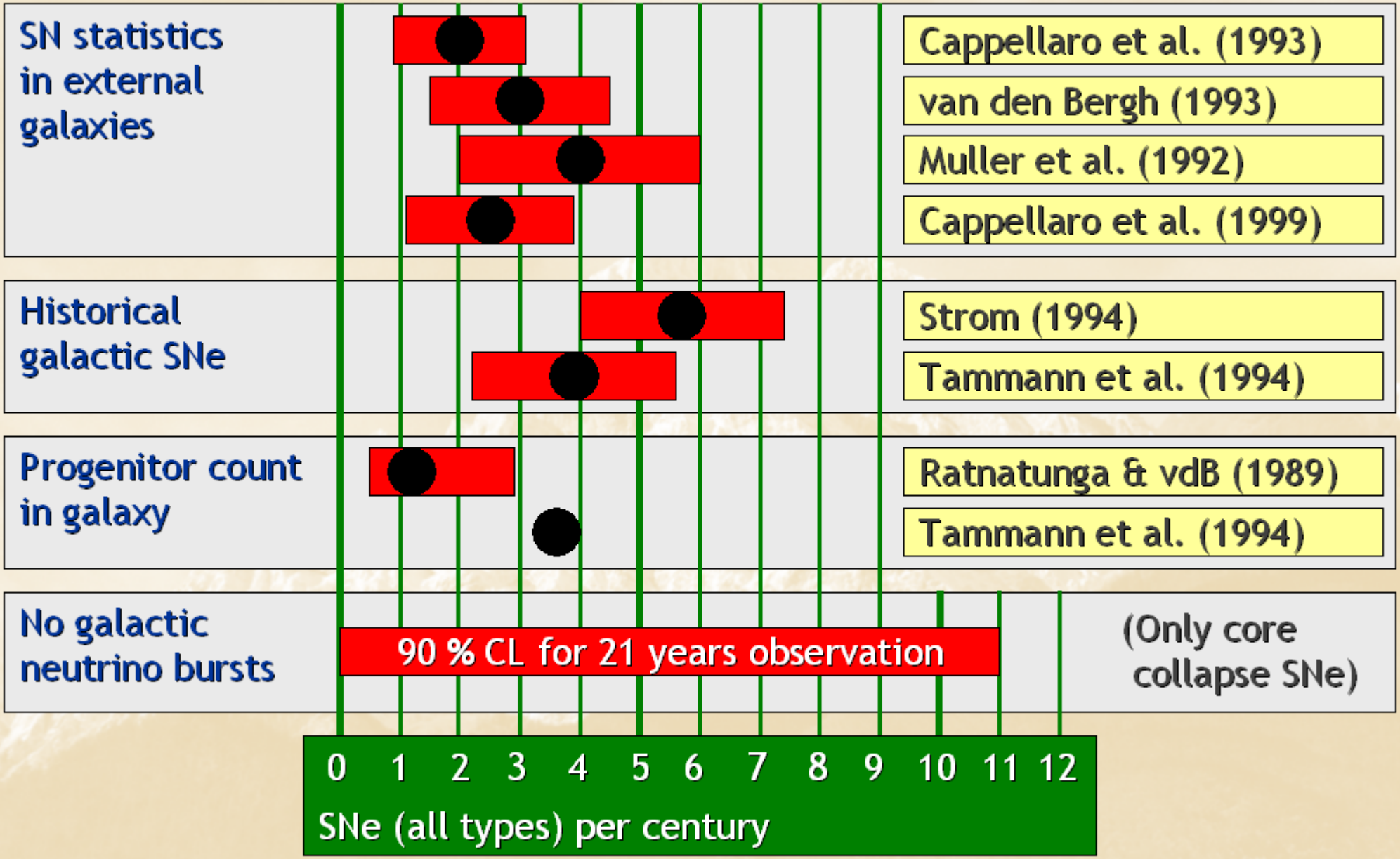
Galactic Center

Anomalously large rate in our galaxy?

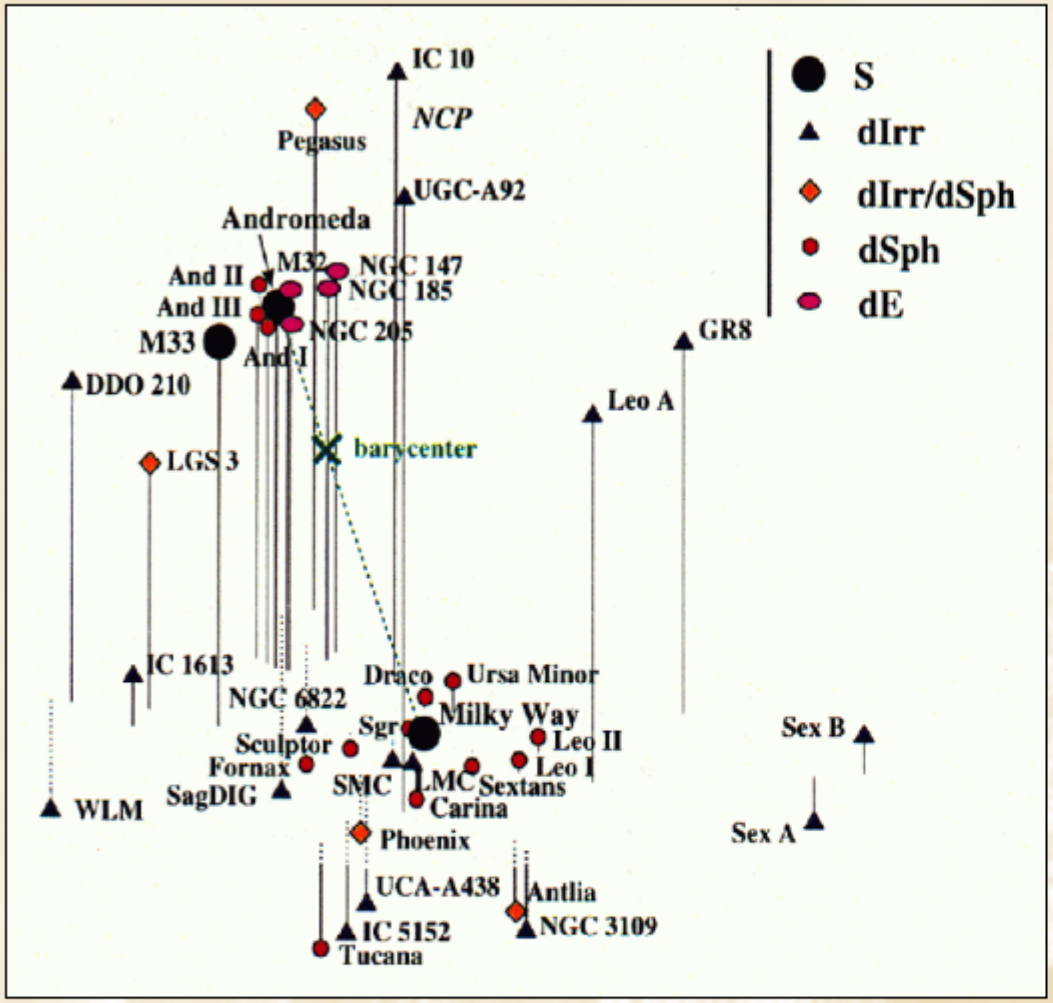
Small-number statistics?

Adam Burrows

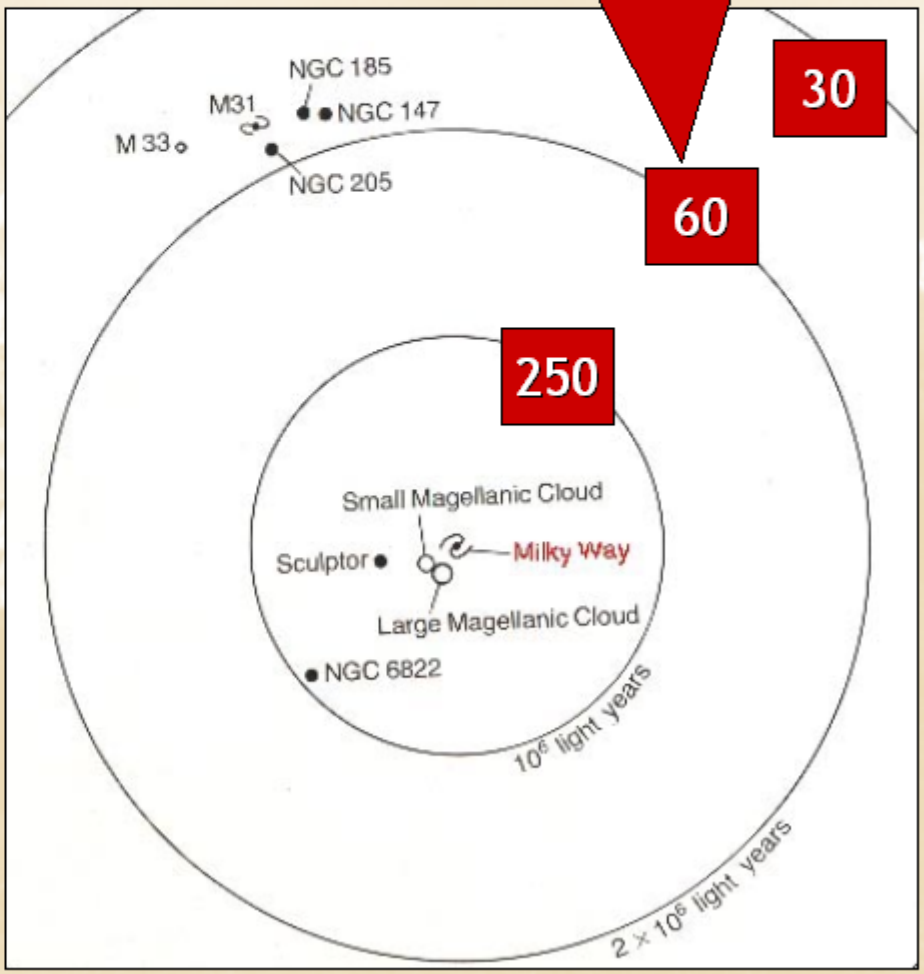
Estimates of the Galactic SN Rate



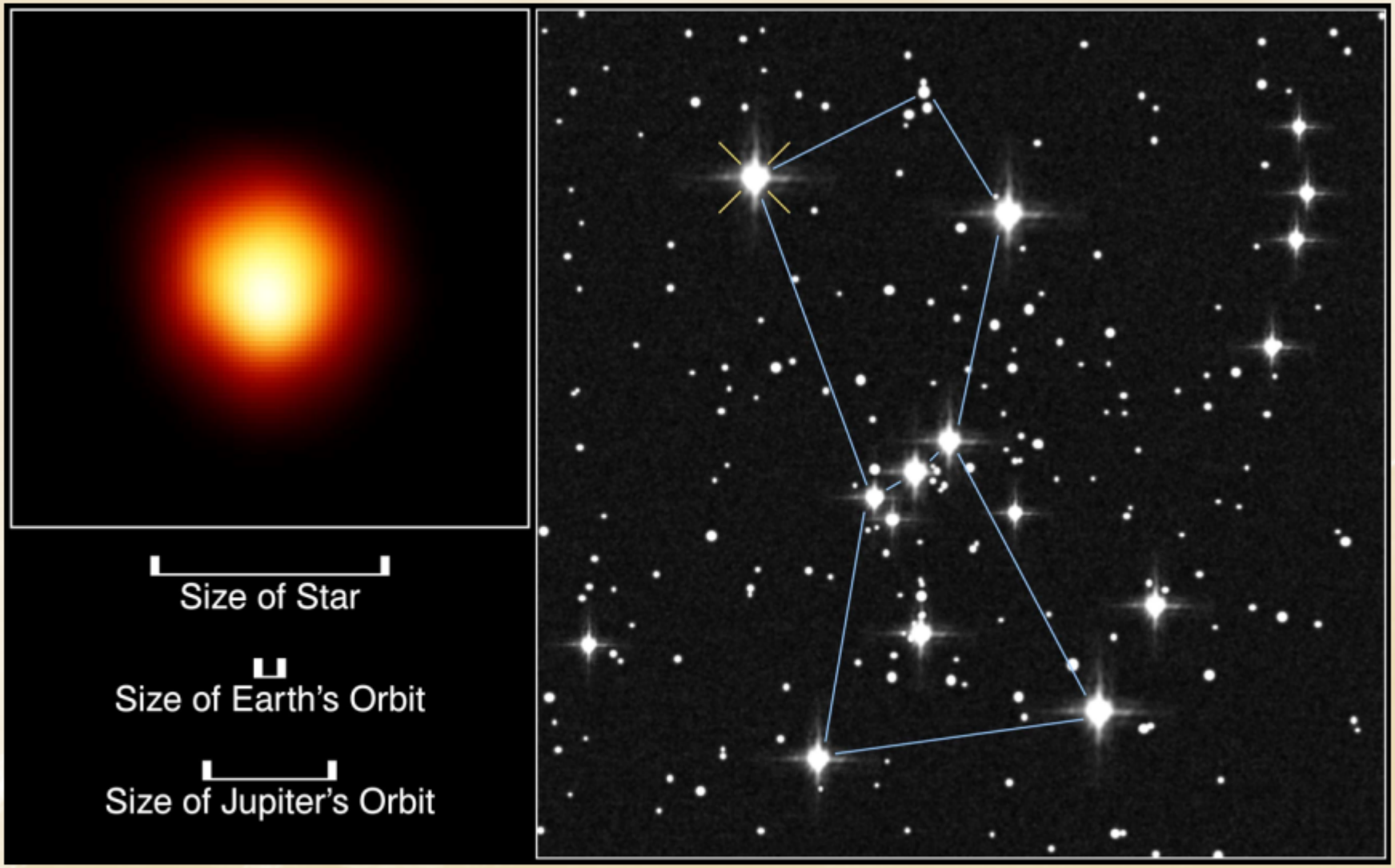
Local Group of Galaxies



Events in a detector with
30 x Super-K fiducial volume,
e.g. Hyper-Kamiokande



The Red Supergiant Betelgeuse (Alpha Orionis)



First resolved image of a star other than Sun

Distance (Hipparcos) 130 pc (425 lyr)

If Betelgeuse goes Supernova 6×10^7 neutrino events in Super-Kamiokande

Neutrinos From All Cosmic Supernovae

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

Diffuse Background Flux of SN Neutrinos

1 SNu = 1 SN / 10^{10} $L_{sun,B}$ / 100 years

$L_{sun,B} = 0.54\ L_{sun} = 2 \times 10^{33}$ erg/s

$E_\nu \sim 3 \times 10^{53}$ erg per core-collapse SN

→ 1 SNu ~ 4 L_ν / $L_{\gamma,B}$
Average neutrino luminosity of galaxies ~ photon luminosity

- Photons come from nuclear energy
- Neutrinos from gravitational energy

→ For galaxies, average nuclear & gravitational energy release comparable

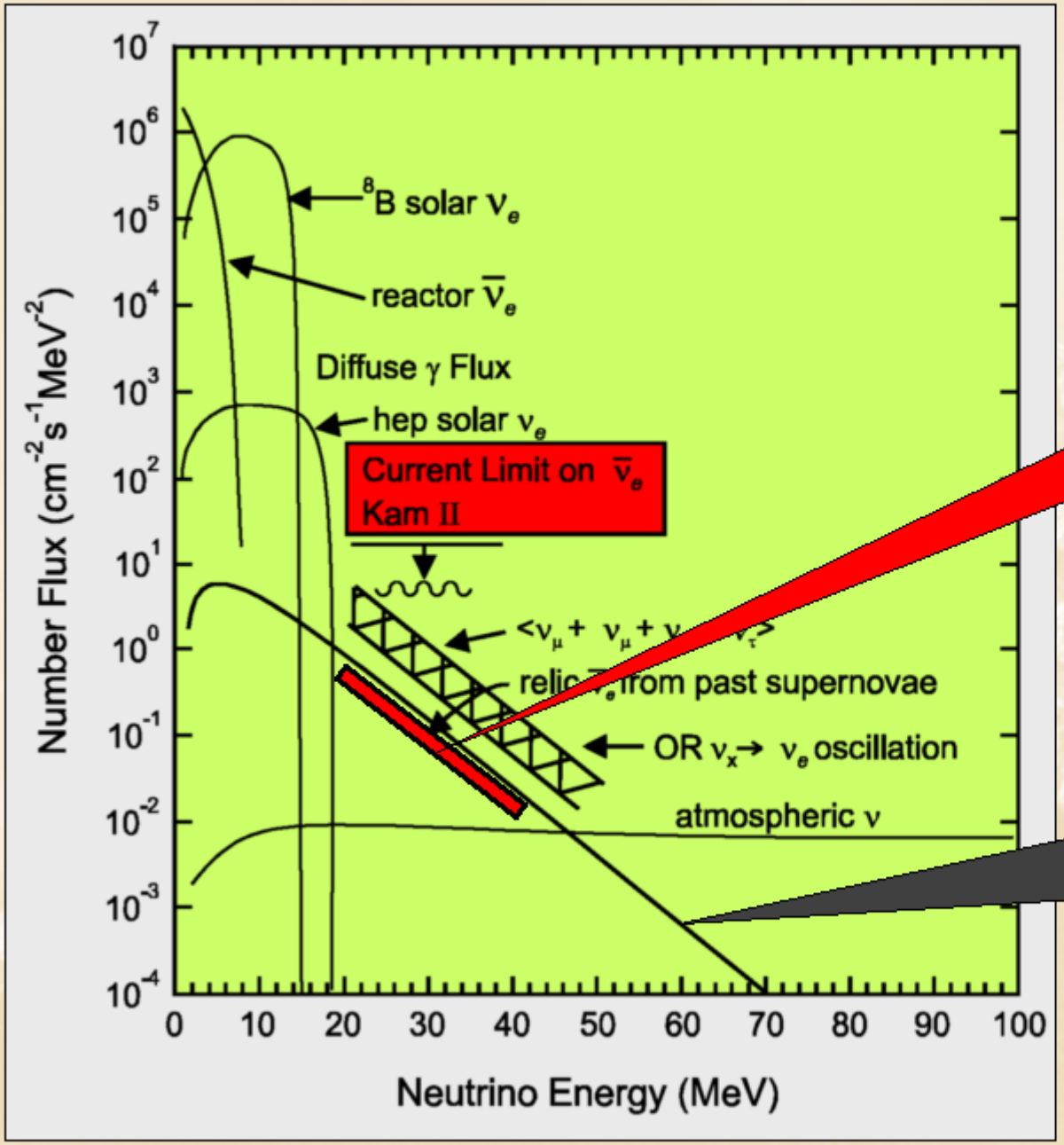
Present-day SN rate of ~ 1 SNu, extrapolated to the entire universe, corresponds to ν_e flux of ~ 1 $cm^{-2}\ s^{-1}$

Realistic flux is dominated by much larger early star-formation rate

- Upper limit ~ 54 $cm^{-2}\ s^{-1}$
  [Kaplinghat et al., astro-ph/9912391]
- "Realistic estimate" ~ 10 $cm^{-2}\ s^{-1}$
  [Hartmann & Woosley, Astropart. Phys. 7 (1997) 137]

Measurement would tell us about early history of star formation

Experimental Limits on Relic Supernova Neutrinos



Super-K upper limit
29 cm^{-2} s^{-1} for
Kaplinghat et al. spectrum
[hep-ex/0209028]

Upper-limit flux of
Kaplinghat et al.,
astro-ph/9912391
Integrated 54 cm^{-2} s^{-1}

Cline, astro-ph/0103138

Improved Sensitivity with Neutron Tagging

M.Vagins, Talk at NOON 2003, http://www-sk.icrr.u-tokyo.ac.jp/noon2003/

Super-Kamiokande limited by
- Solar neutrinos for $E_\nu < 18$–19 MeV
- Sub-Cherenkov muons from atm nus $\mu \rightarrow e + \nu_e + \bar{\nu}_\mu$

Solution:
Neutron tagging $\bar{\nu}_e + p \rightarrow e^+ + n$

Water: Neutron capture on protons
2.2 MeV gammas, invisible in SK

Add gadolinium to SK:
- Efficient neutron capture
- 8 MeV gamma cascade, easily visible
- 0.1% (100 tons of Gd Cl_3) achieves > 90% tagging efficiency

SN relic nus: A few events per year in SK with no background at all

A Modest Proposal

Pouring a bunch of stuff into Super–K is a big step, and not to be done lightly, no matter how promising things may look initially.

Here's what comes next:

1) Spend the next year or so exploring the chemistry, stability, and optical properties of $GdCl_3$ in detail.
2) Understand any changes needed in the SK water system and Monte Carlo the modified detector's response using what's learned above as input.
3) Build a small test tank (one supermodule) with exactly the same materials as in SK. Put in PMT's, cables, water, and $GdCl_3$ and let it sit for two years. Check for $GdCl_3$-induced damage.
4) If everything looks good, in the last month(s) of SK–II put in 9 tons of $GdCl_3$ to make sure we really understand our backgrounds. Look for reactor antineutrinos!