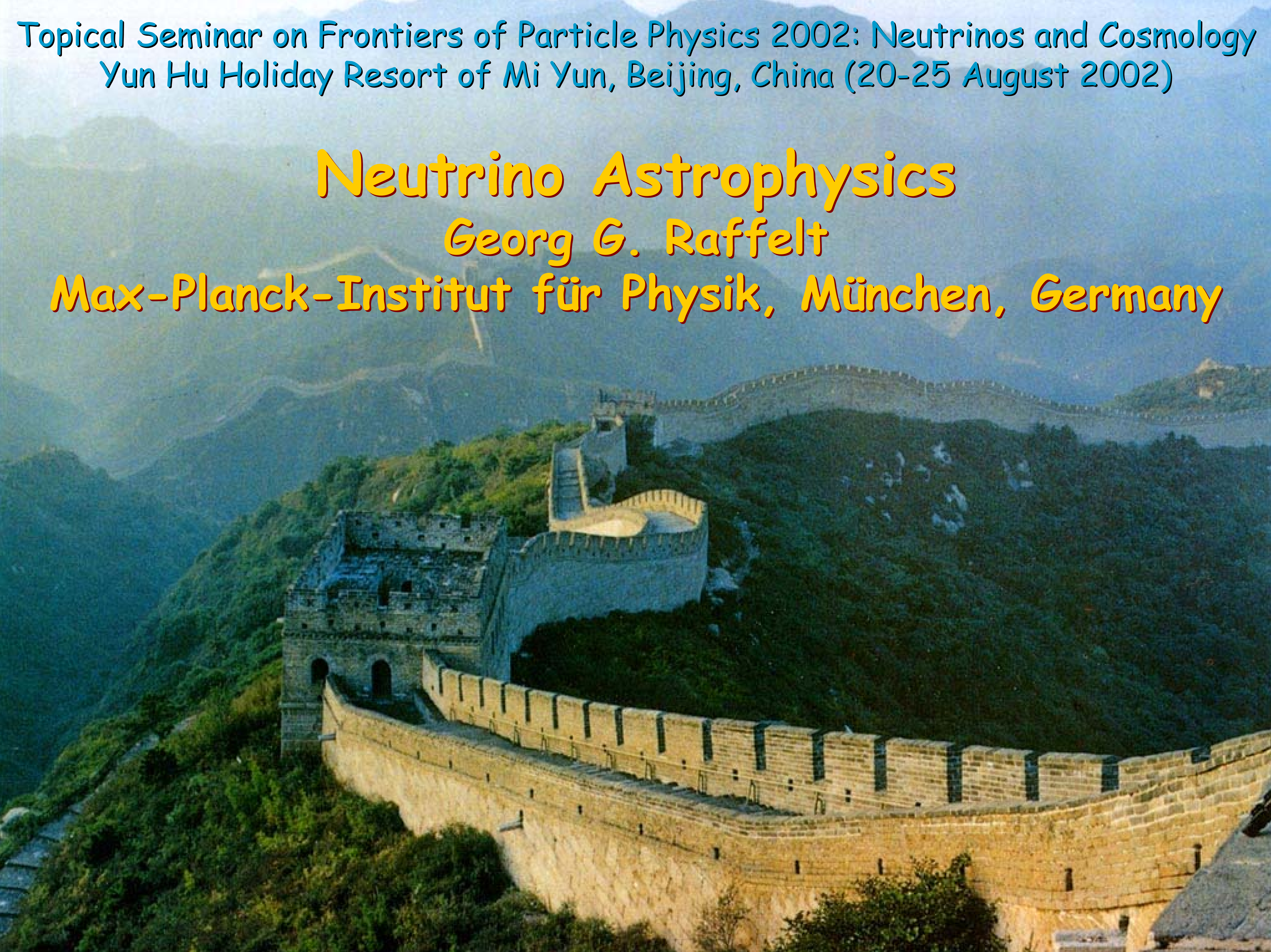
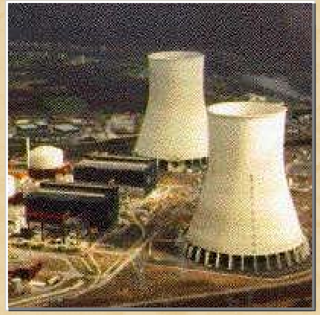

Topical Seminar on Frontiers of Particle Physics 2002: Neutrinos and Cosmology
Yun Hu Holiday Resort of Mi Yun, Beijing, China (20-25 August 2002)
Neutrino Astrophysics
Georg G. Raffelt
Max-Planck-Institut für Physik, München, Germany

Where do Neutrinos Appear in Nature?

✓ Nuclear Reactors

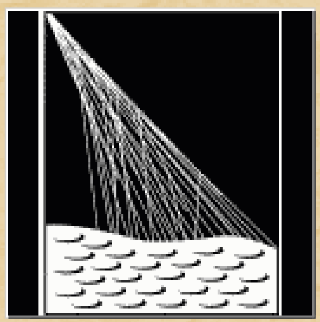


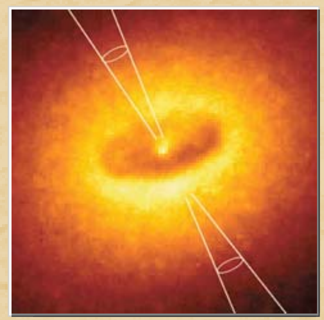
Sun ✓

✓ Particle-Accelerators

Supernovae
(Stellar Collapse)
SN 1987A ✓

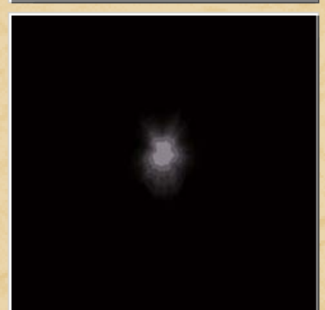
✓ Earth Atmosphere
(Cosmic Rays)





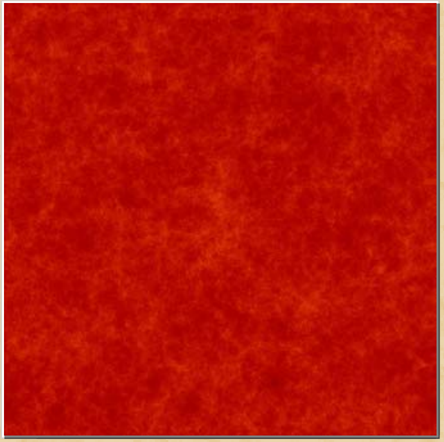
Astrophysical
Accelerators Soon ?

2002 ? Earth Crust
(Natural
Radioactivity



Cosmic Big Bang
(Today 330 ν/cm^3)
Indirect Evidence

Lecture I: Physics with Supernovae

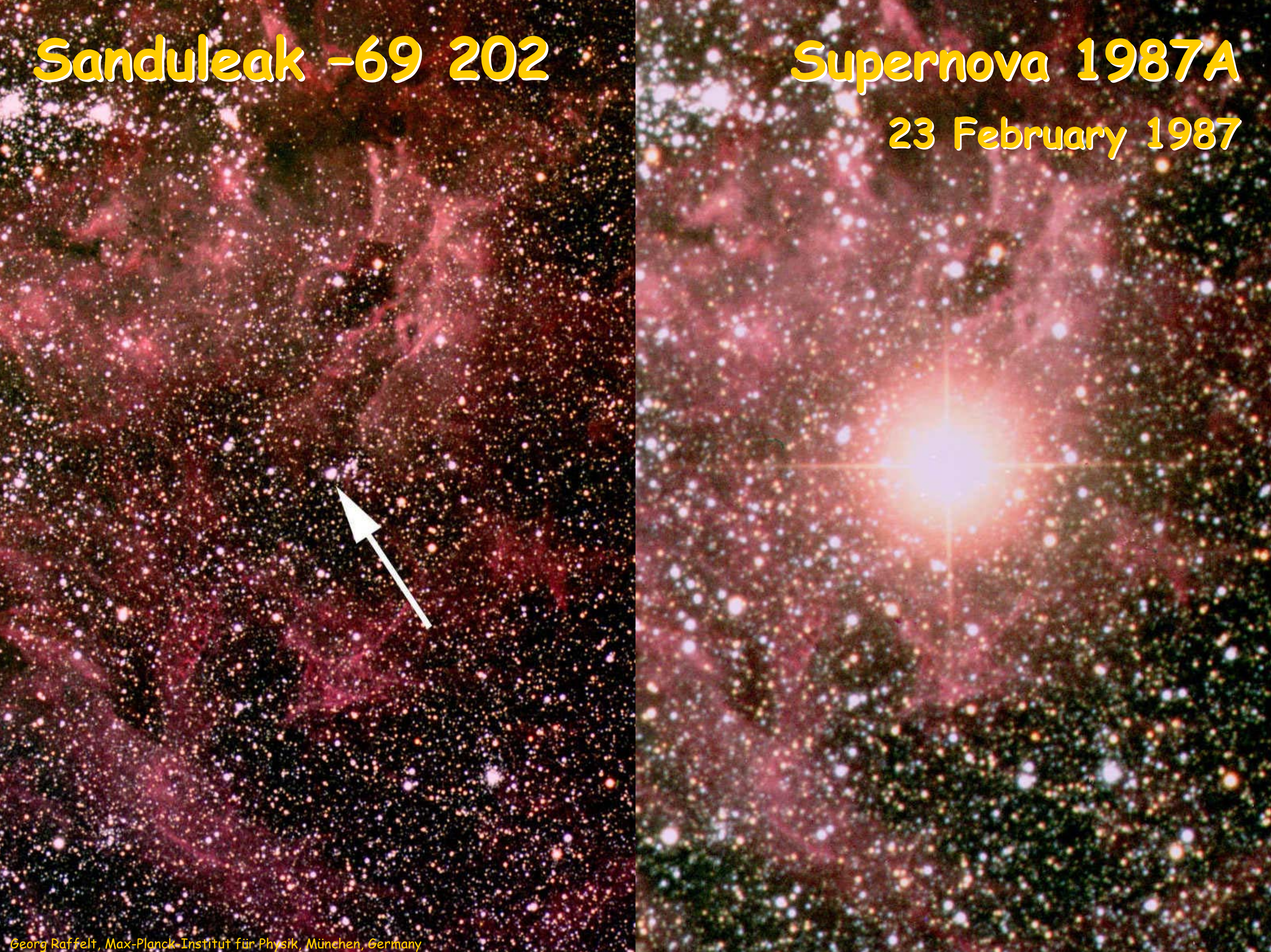


Lecture II: Cosmological Neutrinos

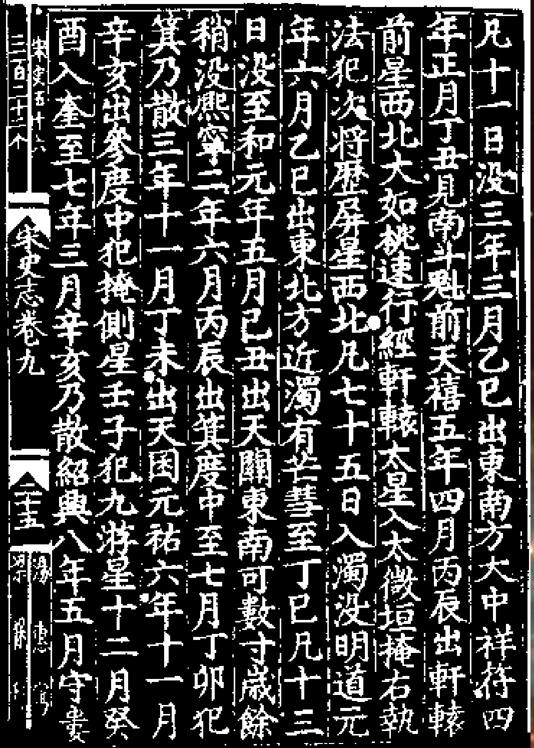

Sanduleak -69 202
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany


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

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

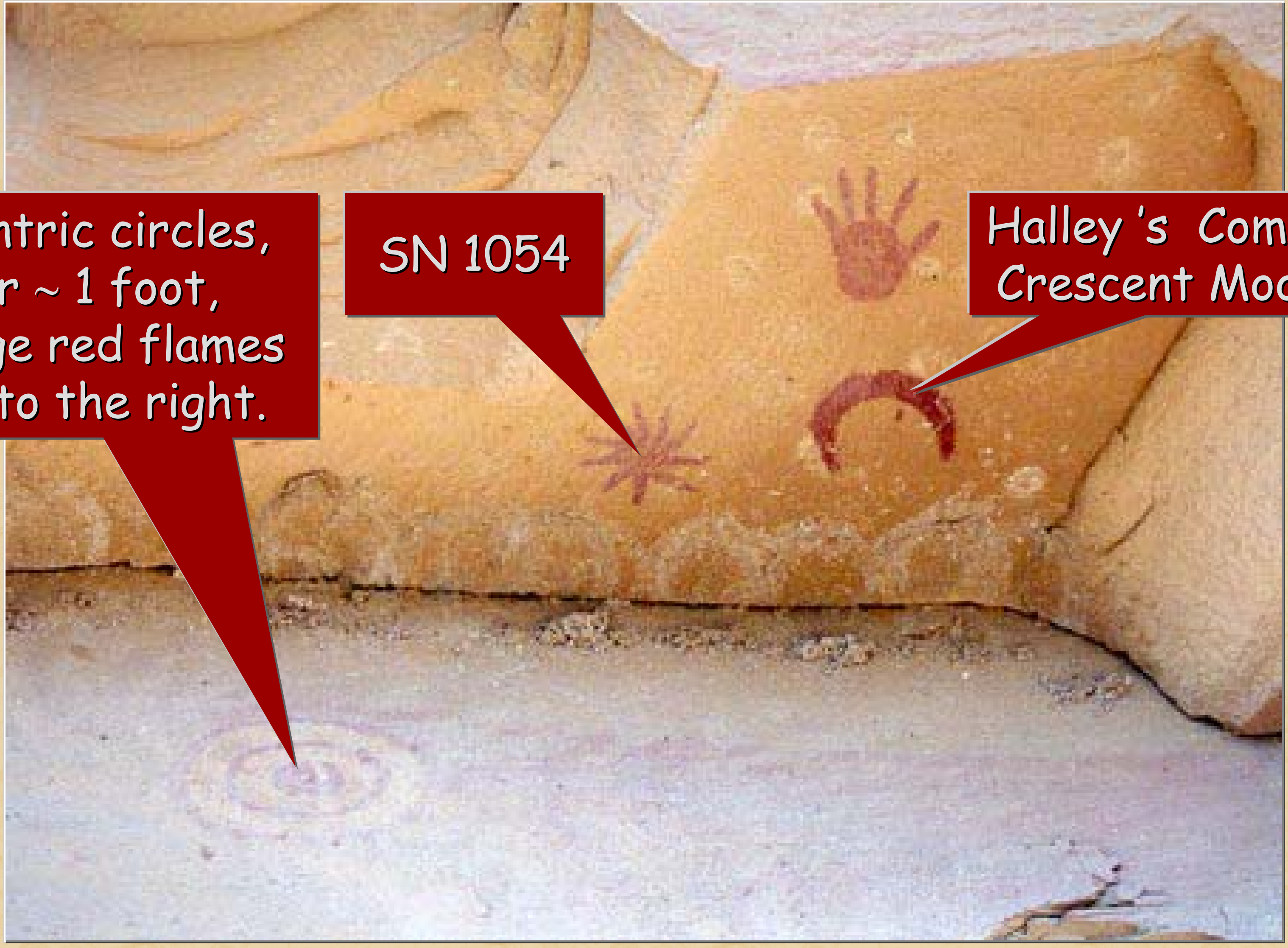


凡十一日没三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次将歷屏星西北凡七十五日入濁没明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日没至和元年五月己丑出天關東南可數寸歳餘
稍没熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

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

Supernova 1054 Petrograph

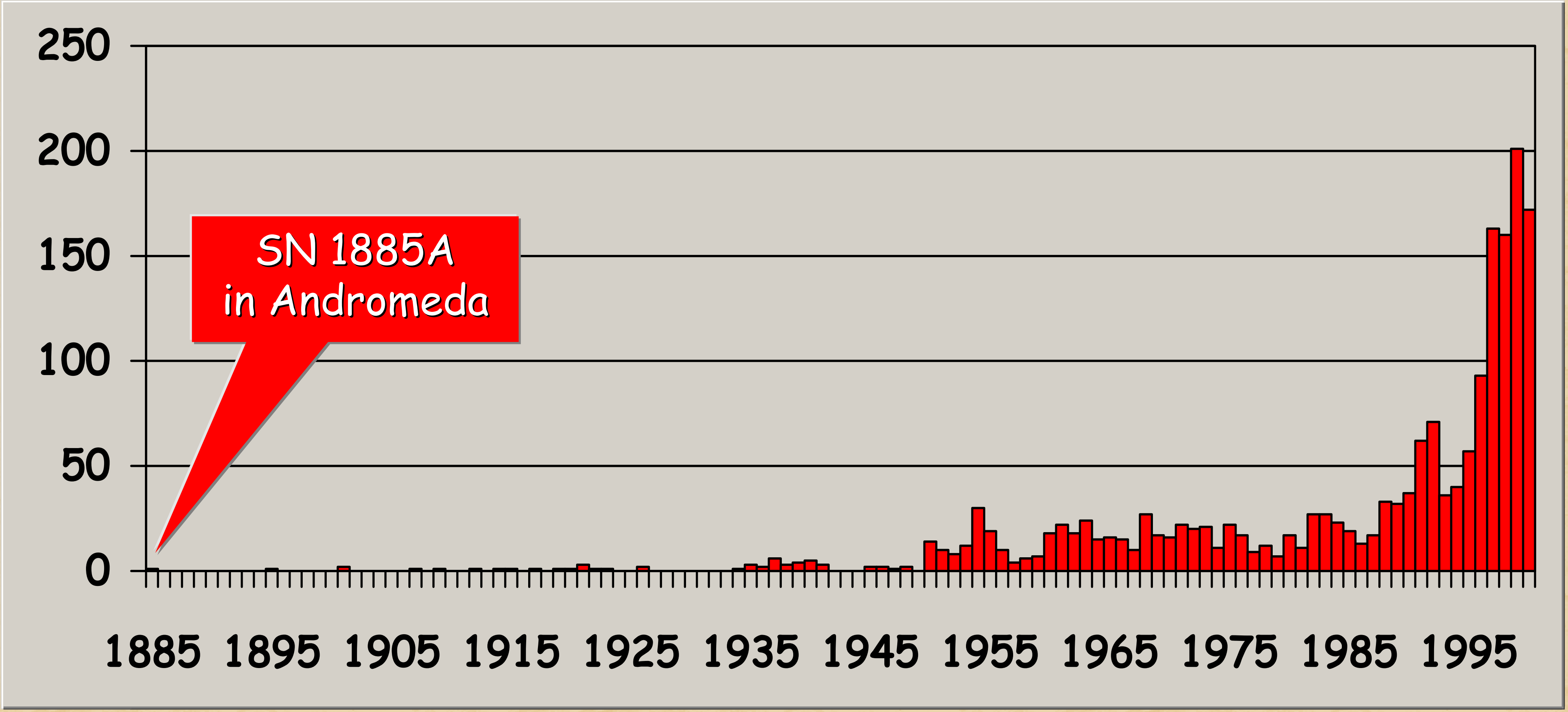


Possible SN 1054 Petrograph by the Anasazi people
(Chaco Canyon, South-Western U.S.)

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)			

Supernova Discoveries 1885-2000



Naming convention for supernovae:

SN 2000A, SN 2000B ... SN 2000Z,

SN 2000aa, SN 2000ab ... SN 2000az, SN 2000ba ... SN 2000fq

Lecture I: Physics with Supernovae

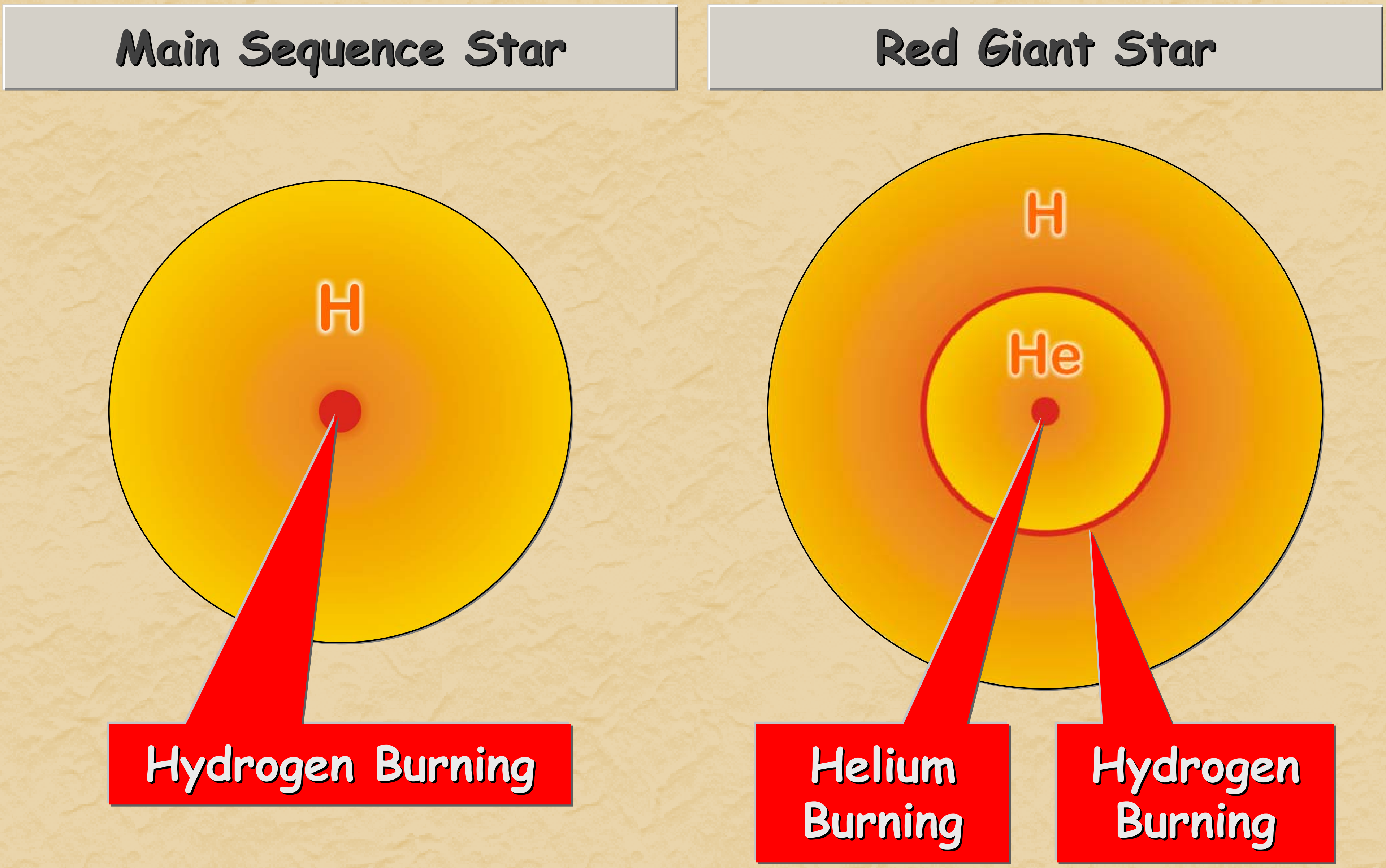
- Physical Mechanism of Core-Collapse Supernovae

- Supernova Neutrino Detection

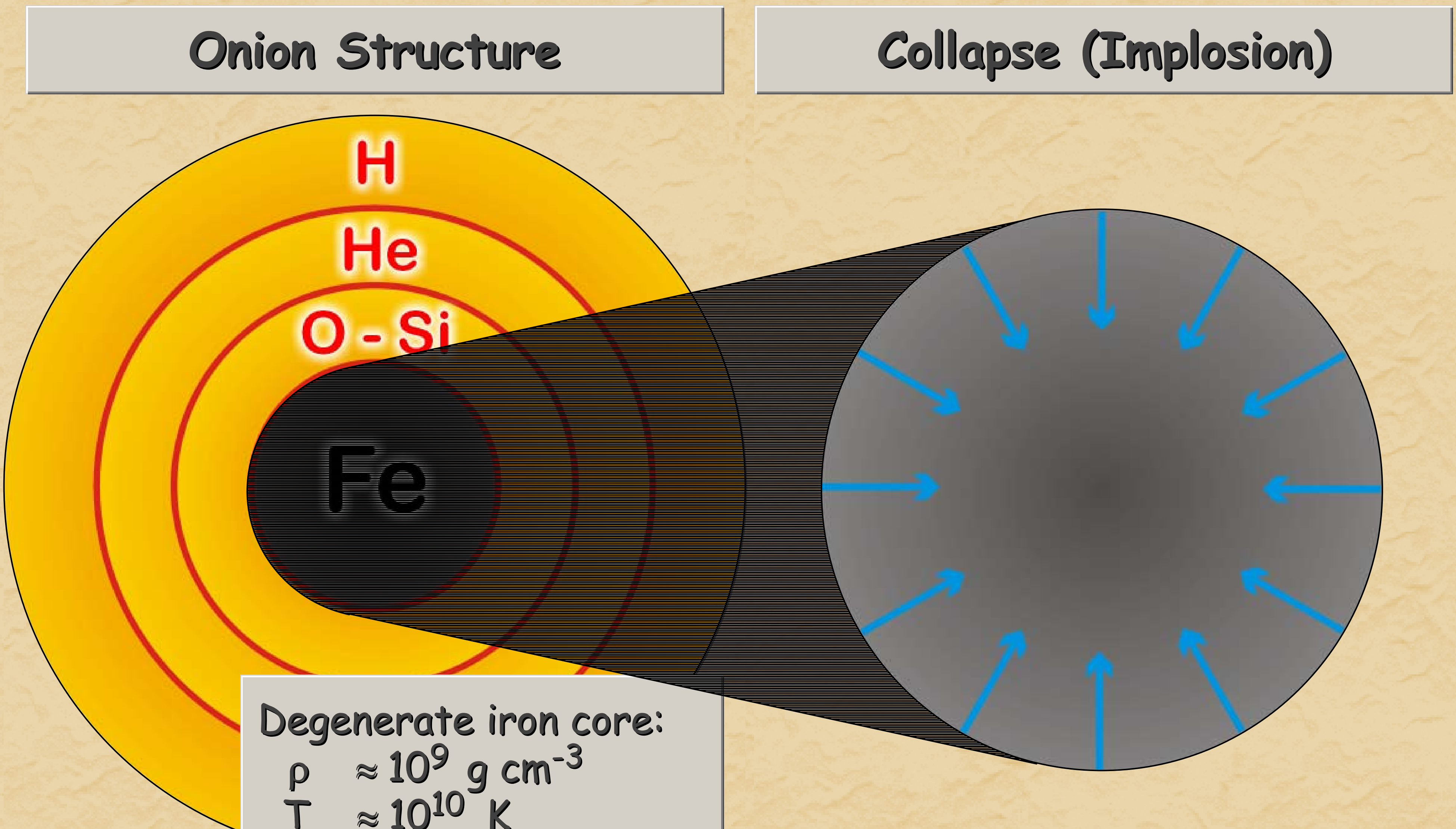
- Limits on Particle Properties

- Flavor Oscillations of Supernova Neutrinos

Stellar Collapse and Supernova Explosion



Stellar Collapse and Supernova Explosion



Degenerate iron core:

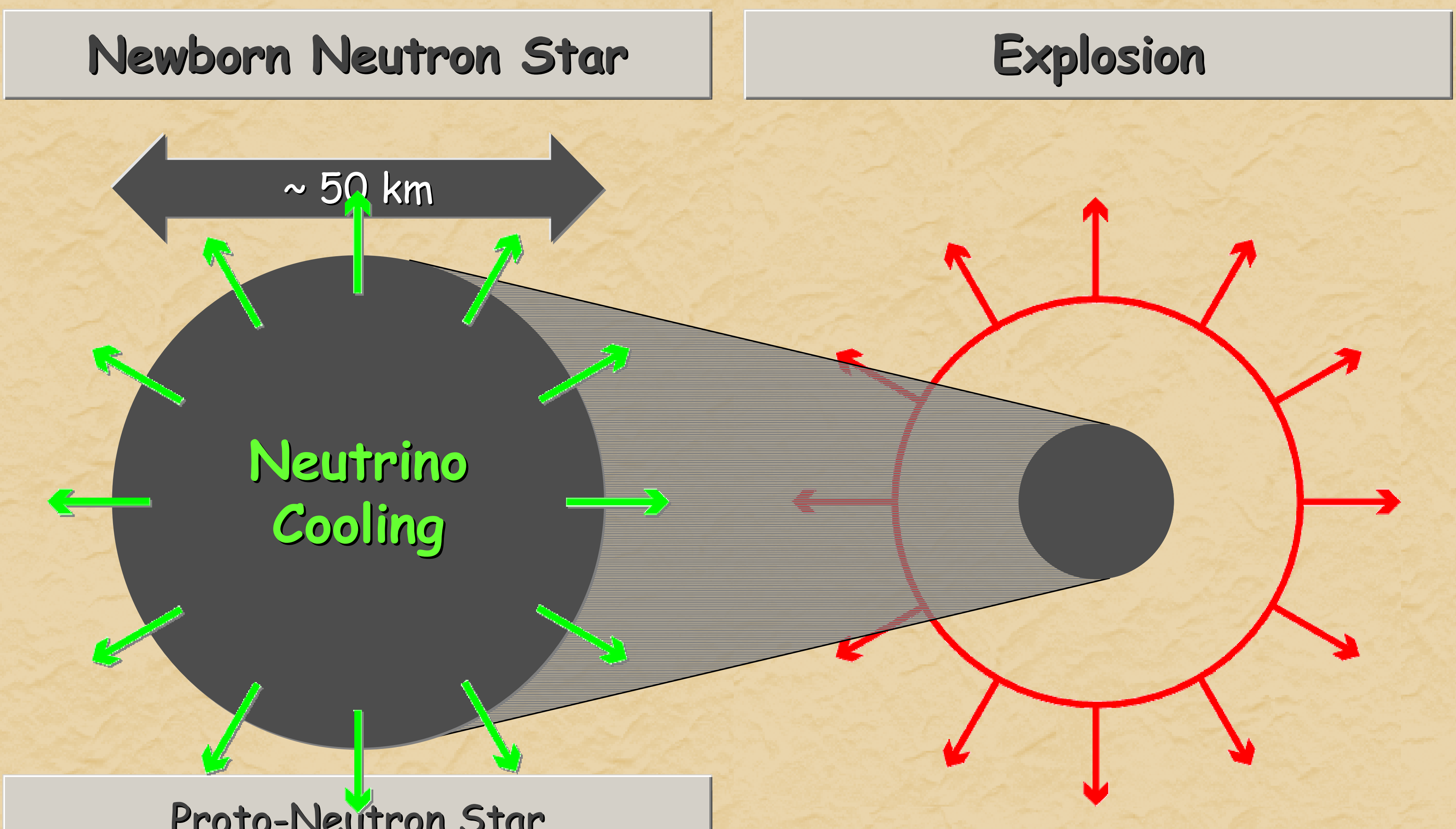
$\rho \approx 10^9\ \mathrm{g\ cm^{-3}}$

$T \approx 10^{10}\ \mathrm{K}$

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

$R_{Fe} \approx 8000\ \mathrm{km}$

Stellar Collapse and Supernova Explosion

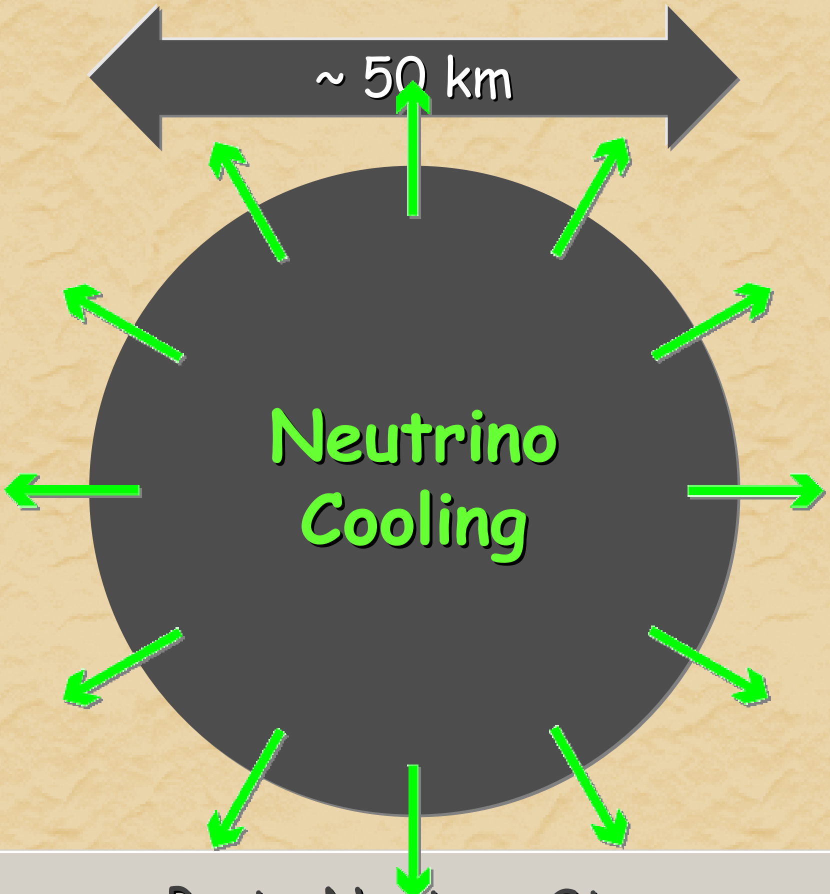


$\rho \approx \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \approx 30\ \mathrm{MeV}$

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

$T \approx 30\ \mathrm{MeV}$

Gravitational binding energy

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

This shows up as

99% Neutrinos

1% Kinetic energy of explosion (1% of this into cosmic rays)

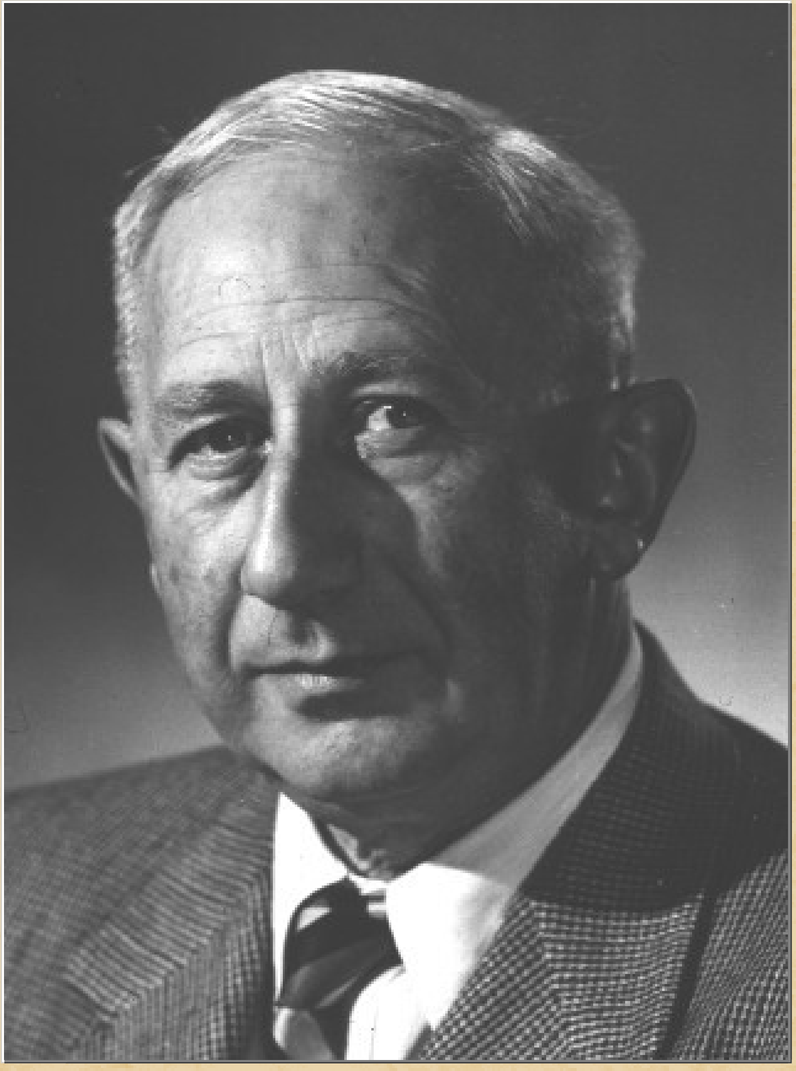
0.01% Photons, outshine host galaxy

Neutrino luminosity

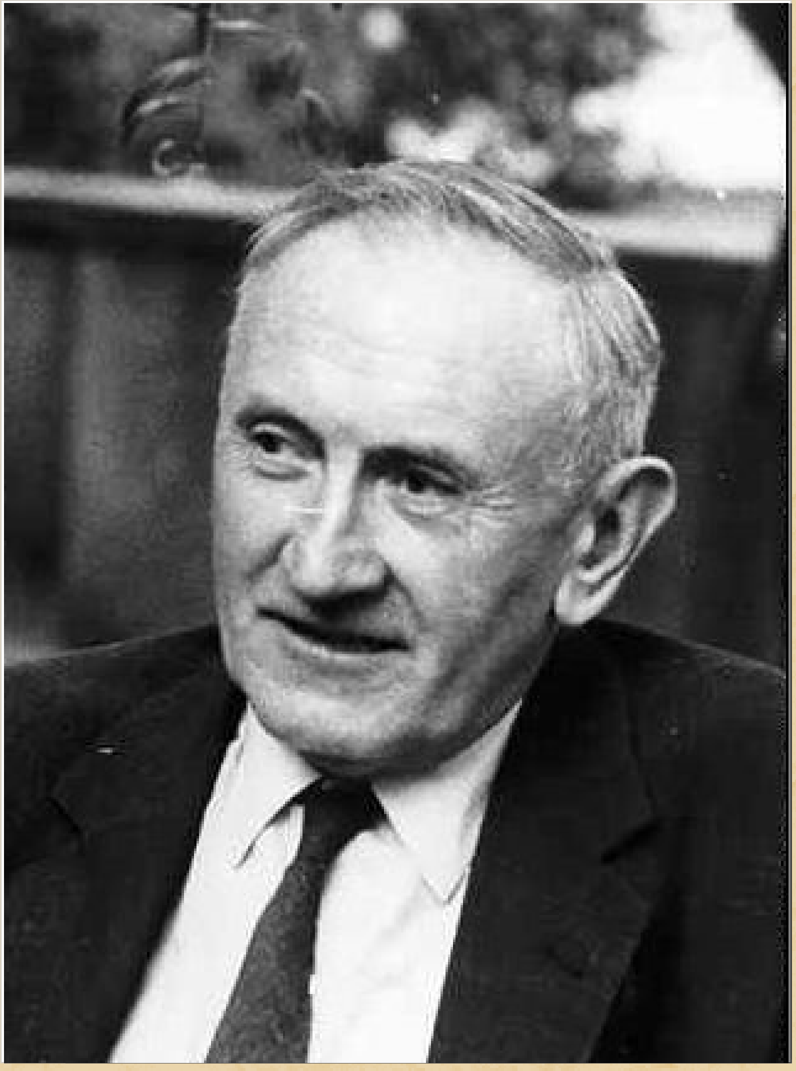
$L_\nu \approx 3 \times 10^{53}\ \mathrm{erg} / 3\ \mathrm{sec}$

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

While it lasts, outshines the entire visible universe



Walter Baade (1893-1960)

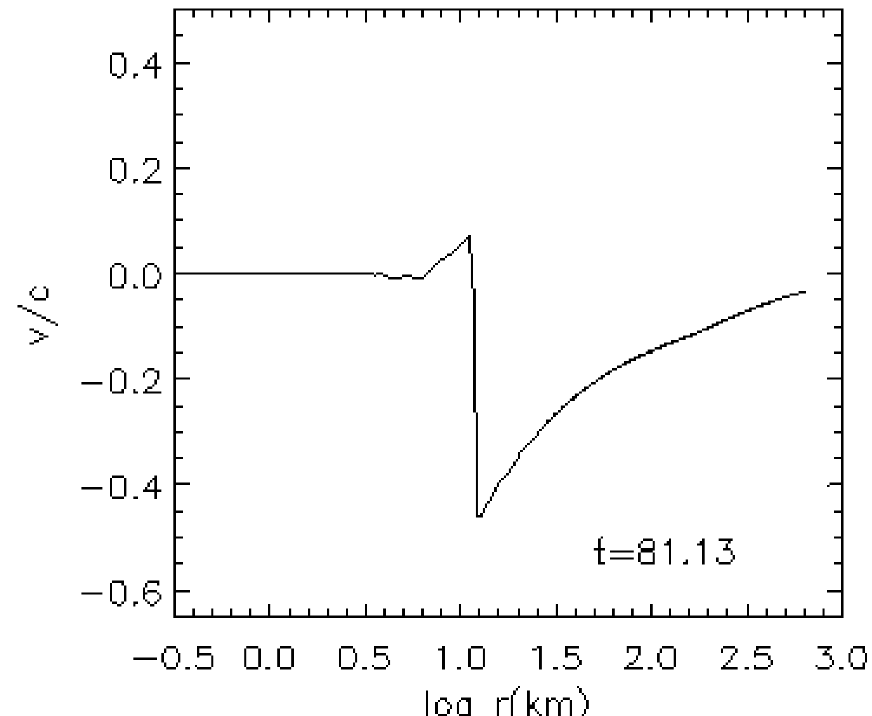


Fritz Zwicky (1898-1974)

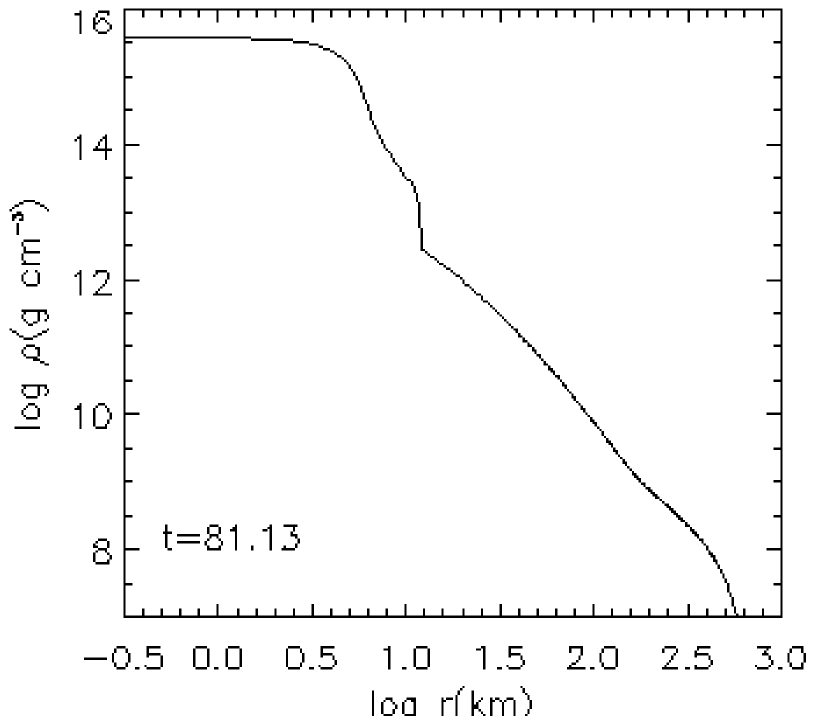
Baade and Zwicky were the first to speculate about a connection between supernova explosions and neutron-star formation [Phys. Rev. 45 (1934) 138]

Collapse and Prompt Explosion

Velocity



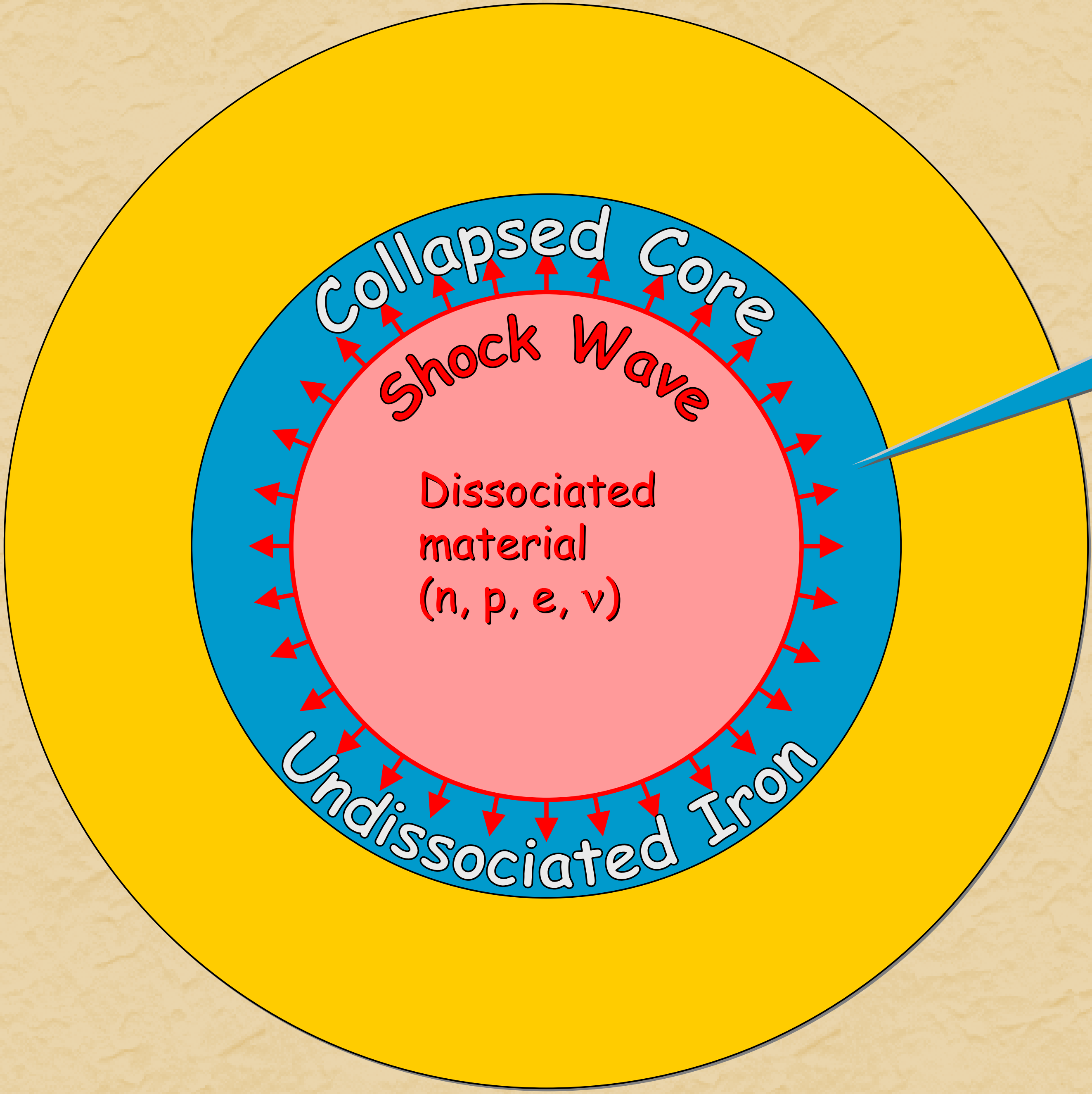
Density



Supernova explosion primarily a hydrodynamical phenomenon

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

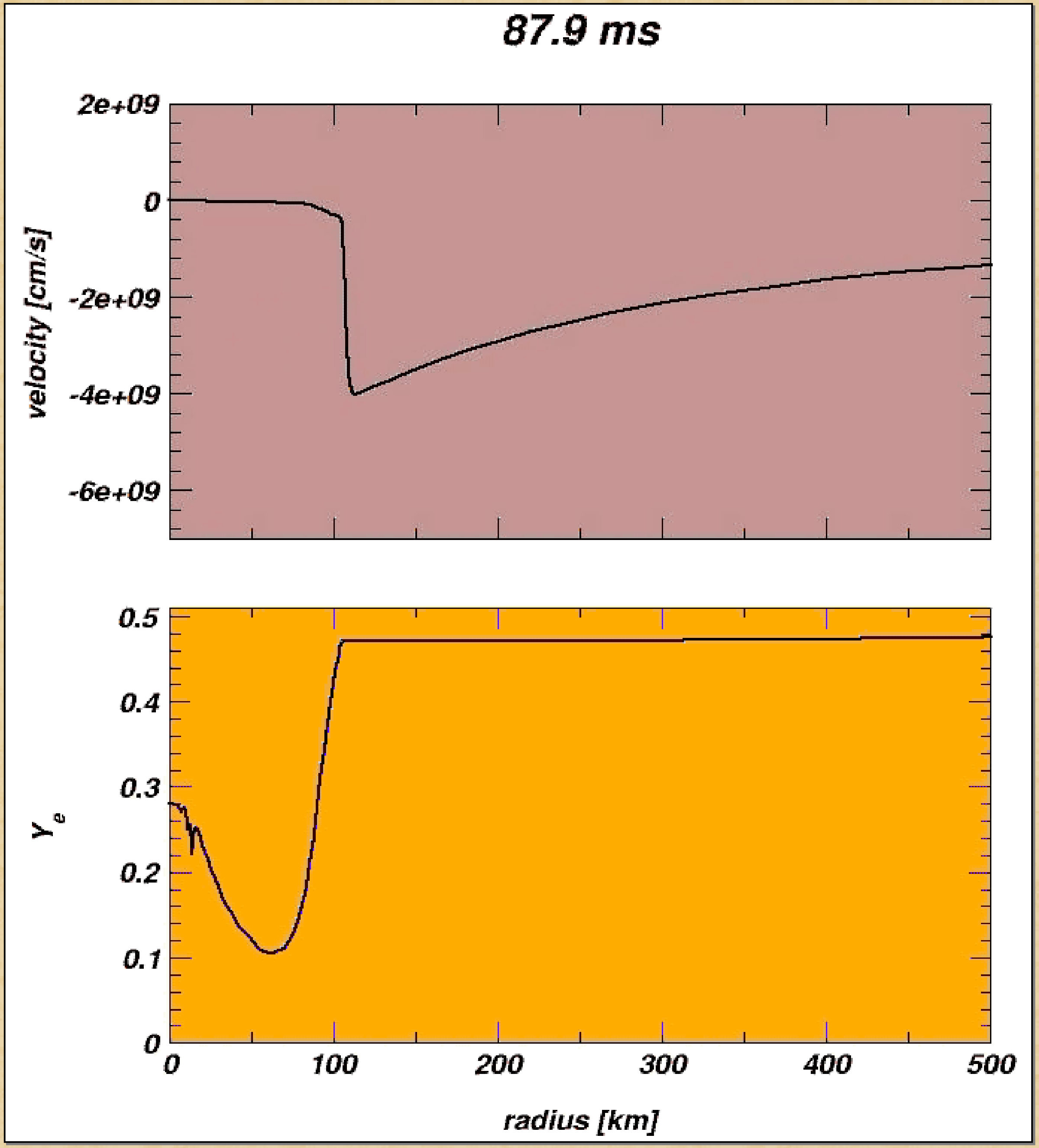
Why No Prompt Explosion?



- 0.1 M_{sun} Fe has 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

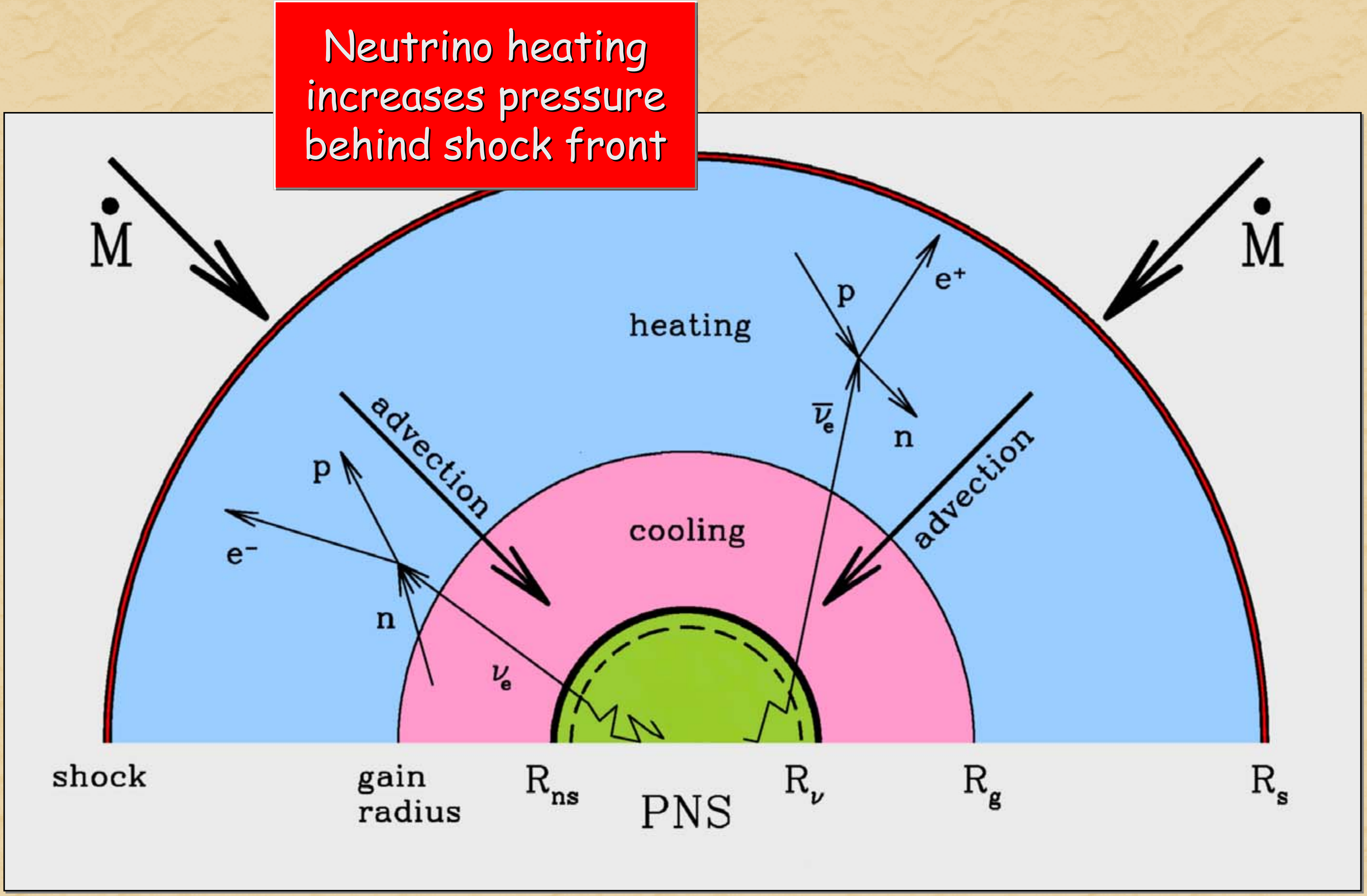
Failed Explosion



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

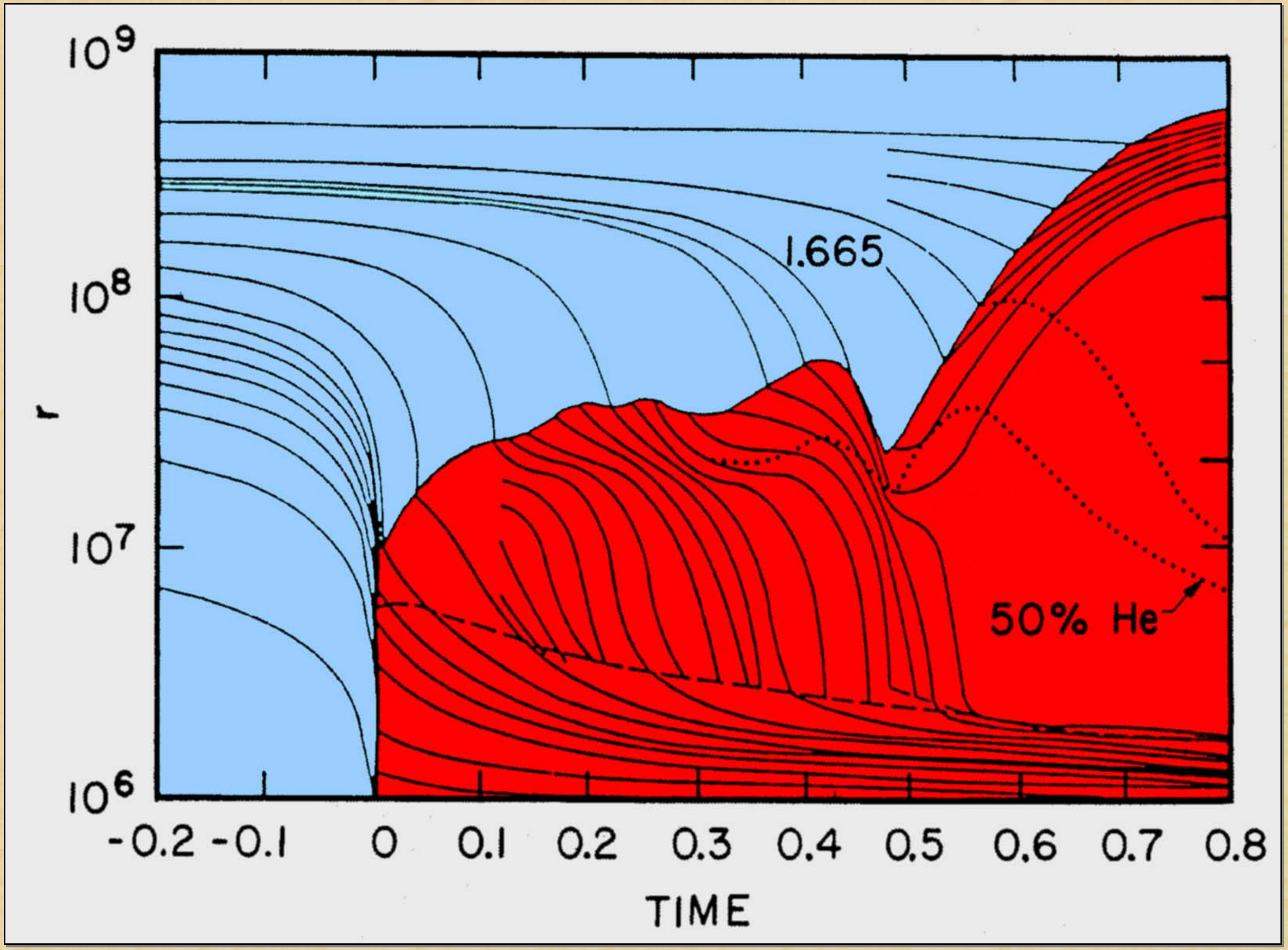
Movie courtesy of Bronson Messer, Oakridge group (2001)

Neutrinos to the Rescue



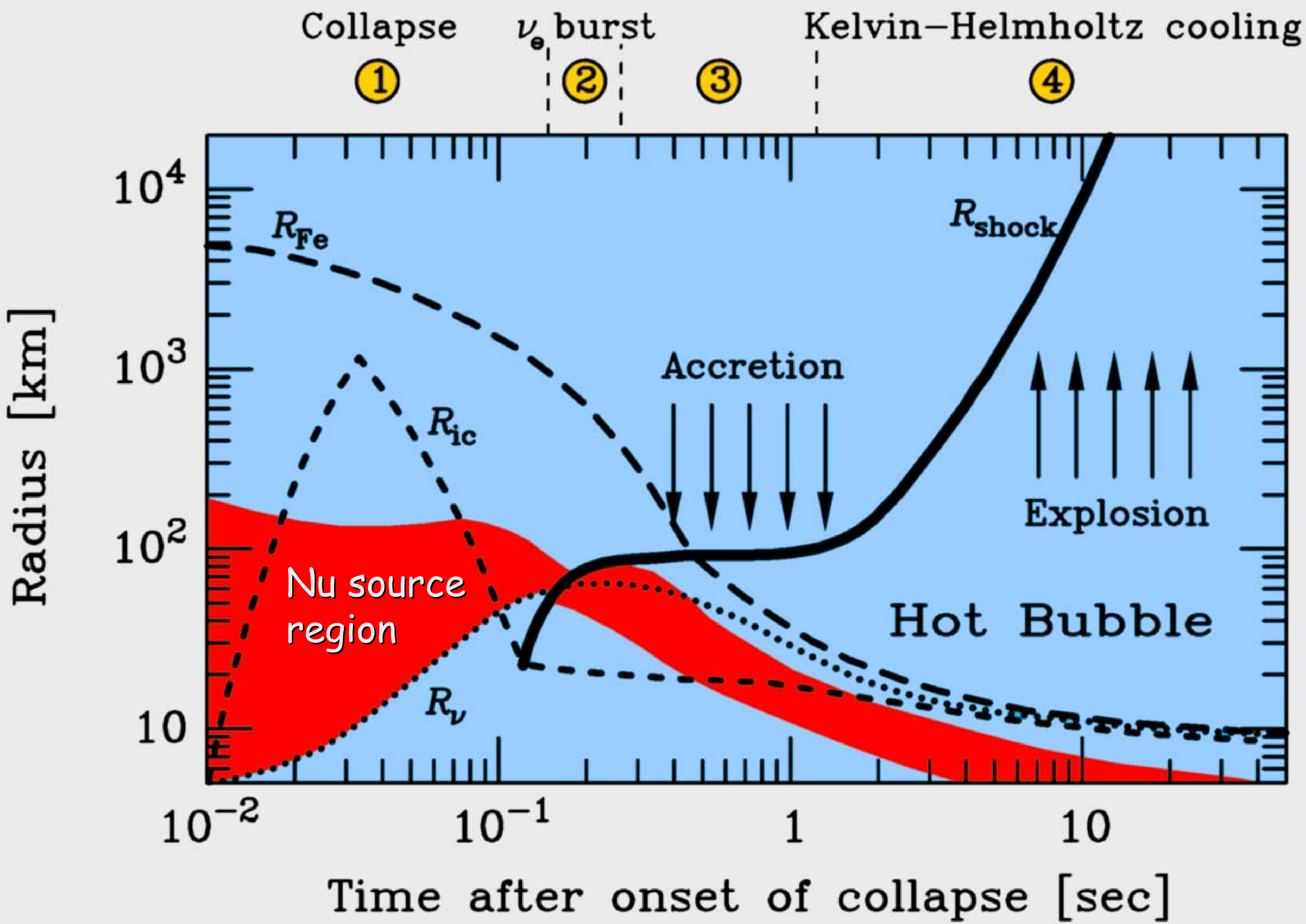
Picture adapted from Janka, astro-ph/0008432

Revival of a Stalled Supernova Shock by Neutrino Heating



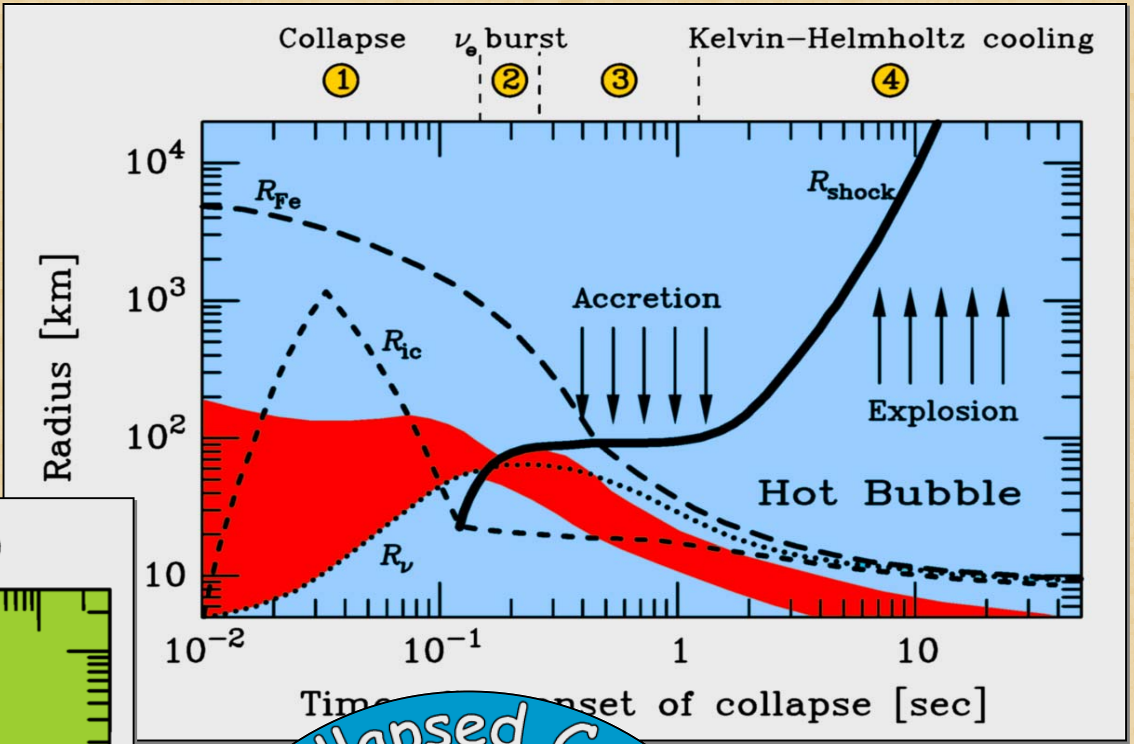
Wilson, Proc. Univ. Illinois Meeting on Numerical Astrophysics (1982)
Bethe & Wilson, ApJ 295 (1985) 14

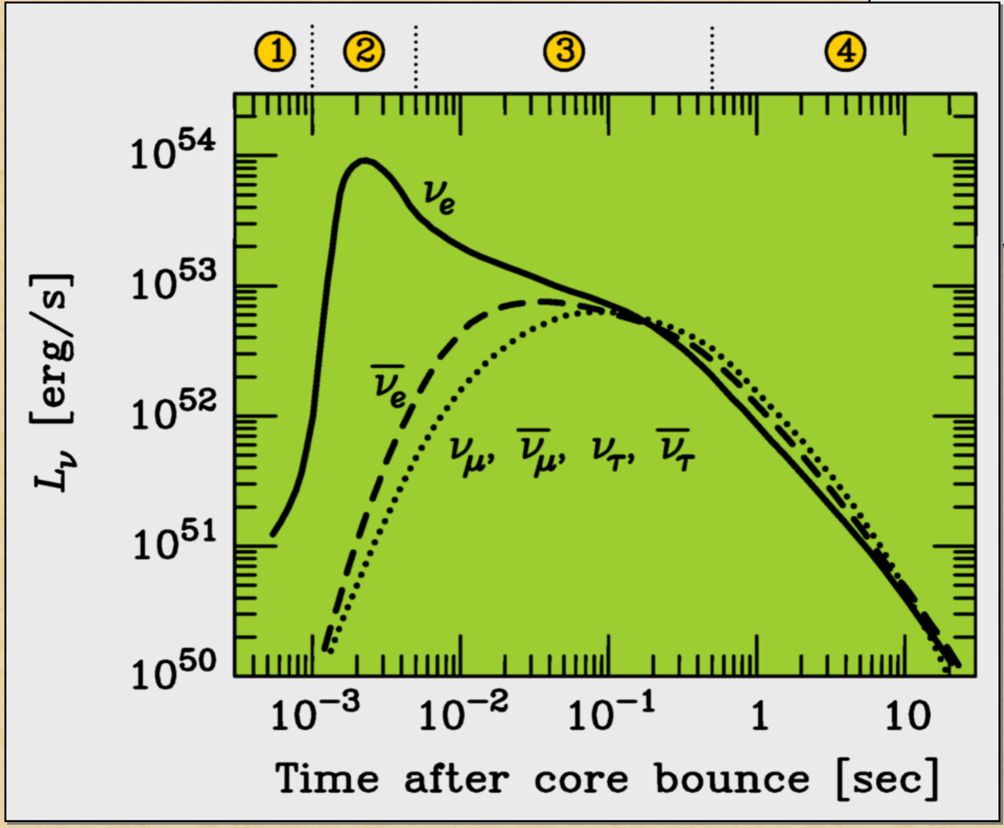
Supernova Collapse and Explosion

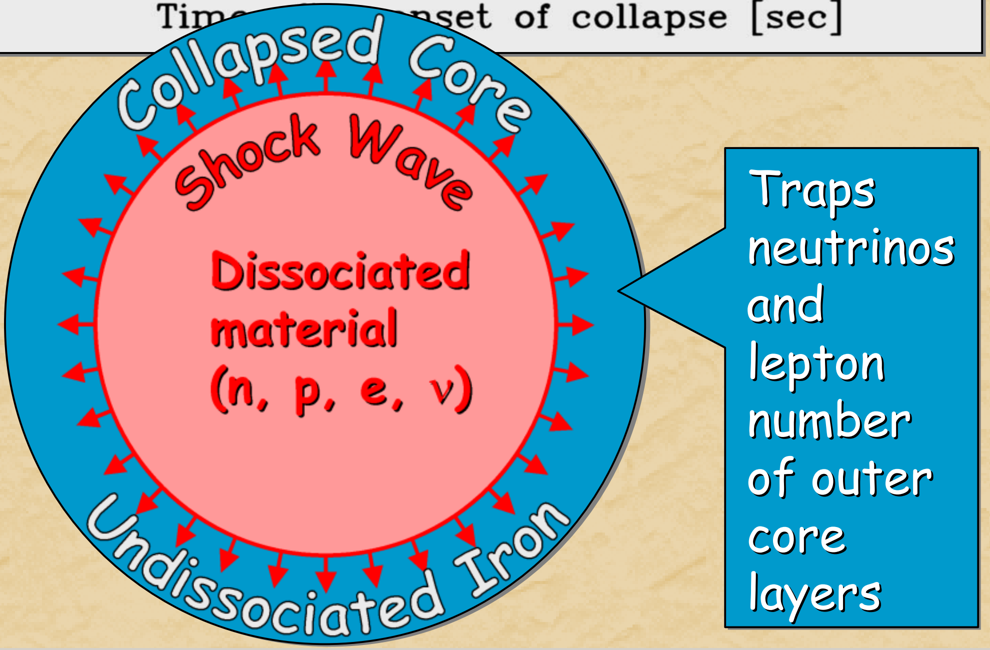


Structure of Supernova Neutrino Signal

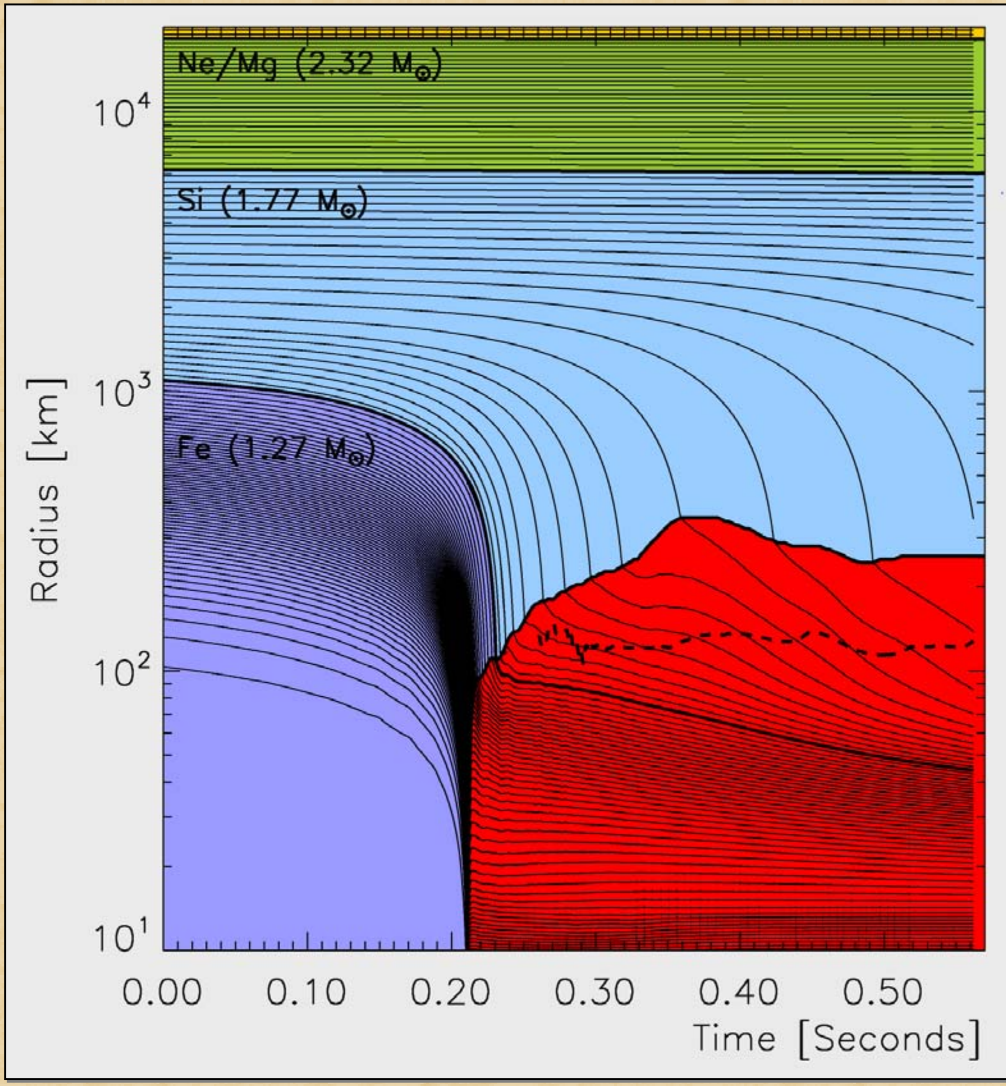
1. Collapse (infall phase)
2. Shock break out
3. Matter accretion
4. Kelvin-Helmholtz cooling

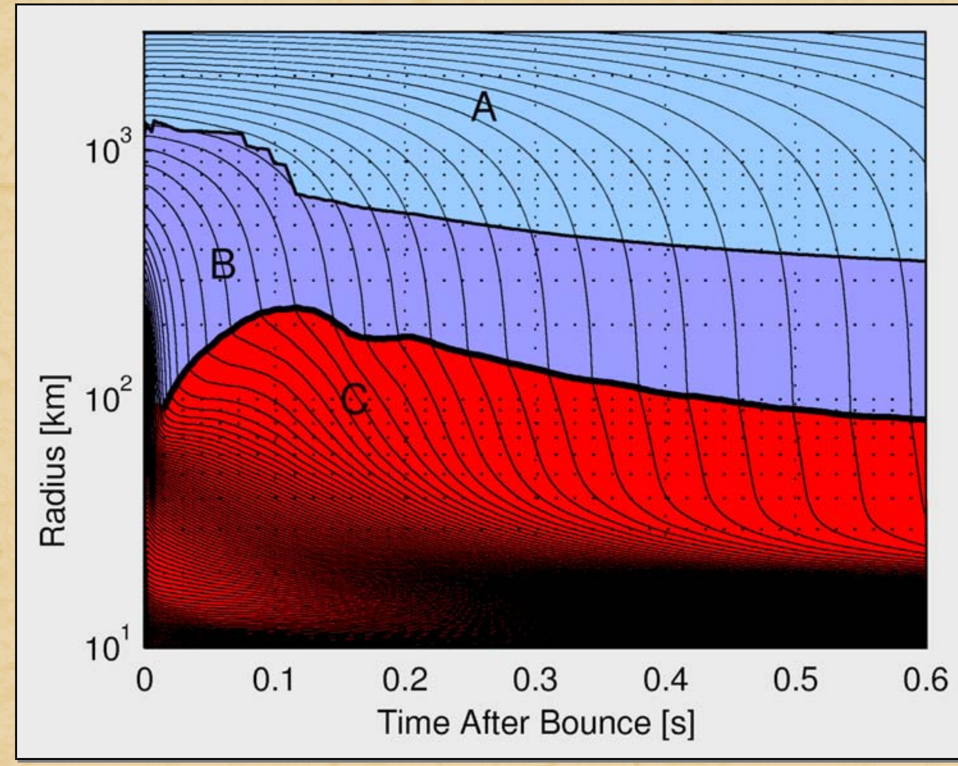






Failed Explosions in Spherical Symmetry



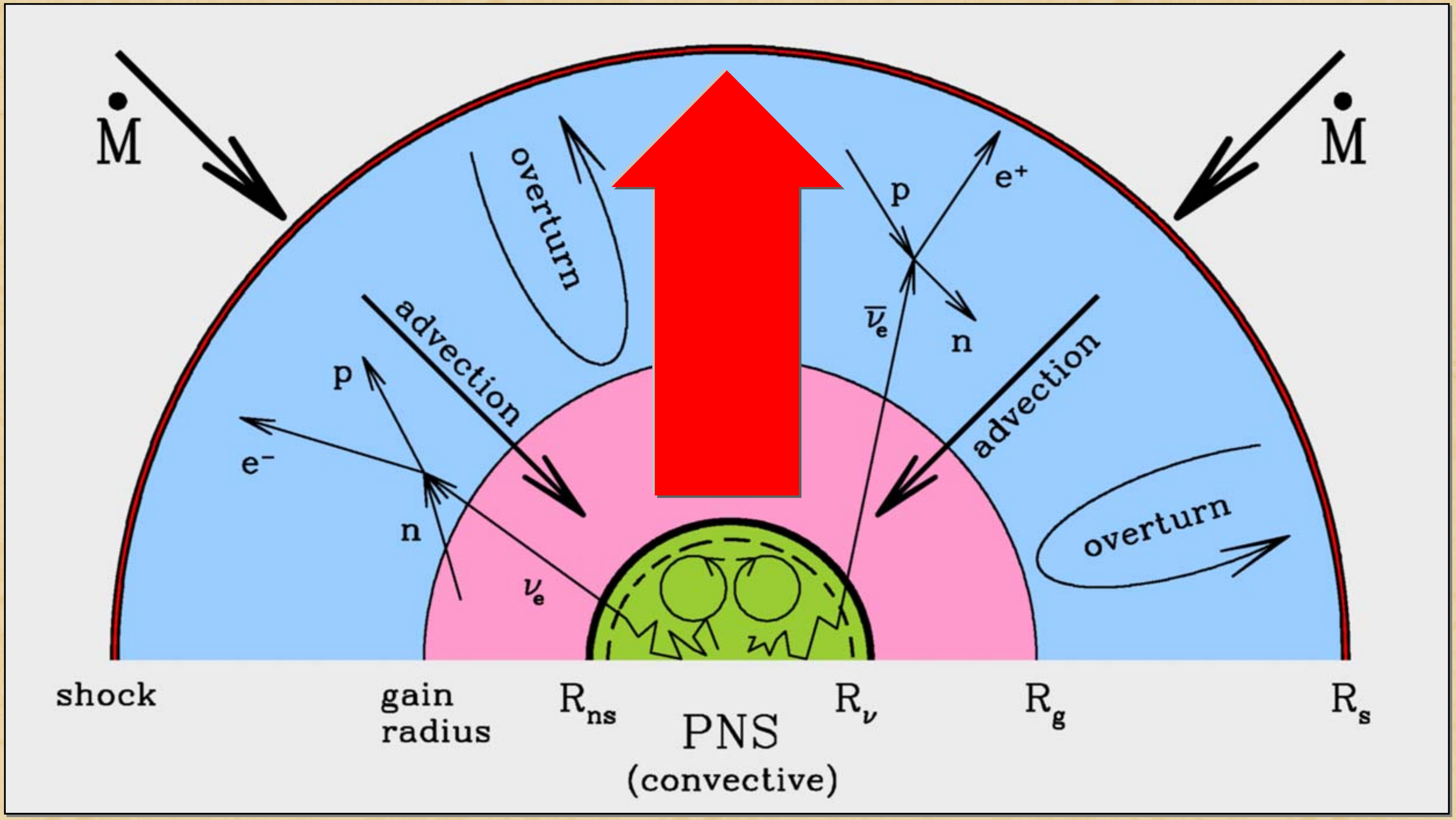


Mezzacappa et al., PRL 86 (2001) 1935

Rampp & Janka, ApJ 539 (2000) L33

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

Novel Forms of Energy Transfer?



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

Must not tranfer 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

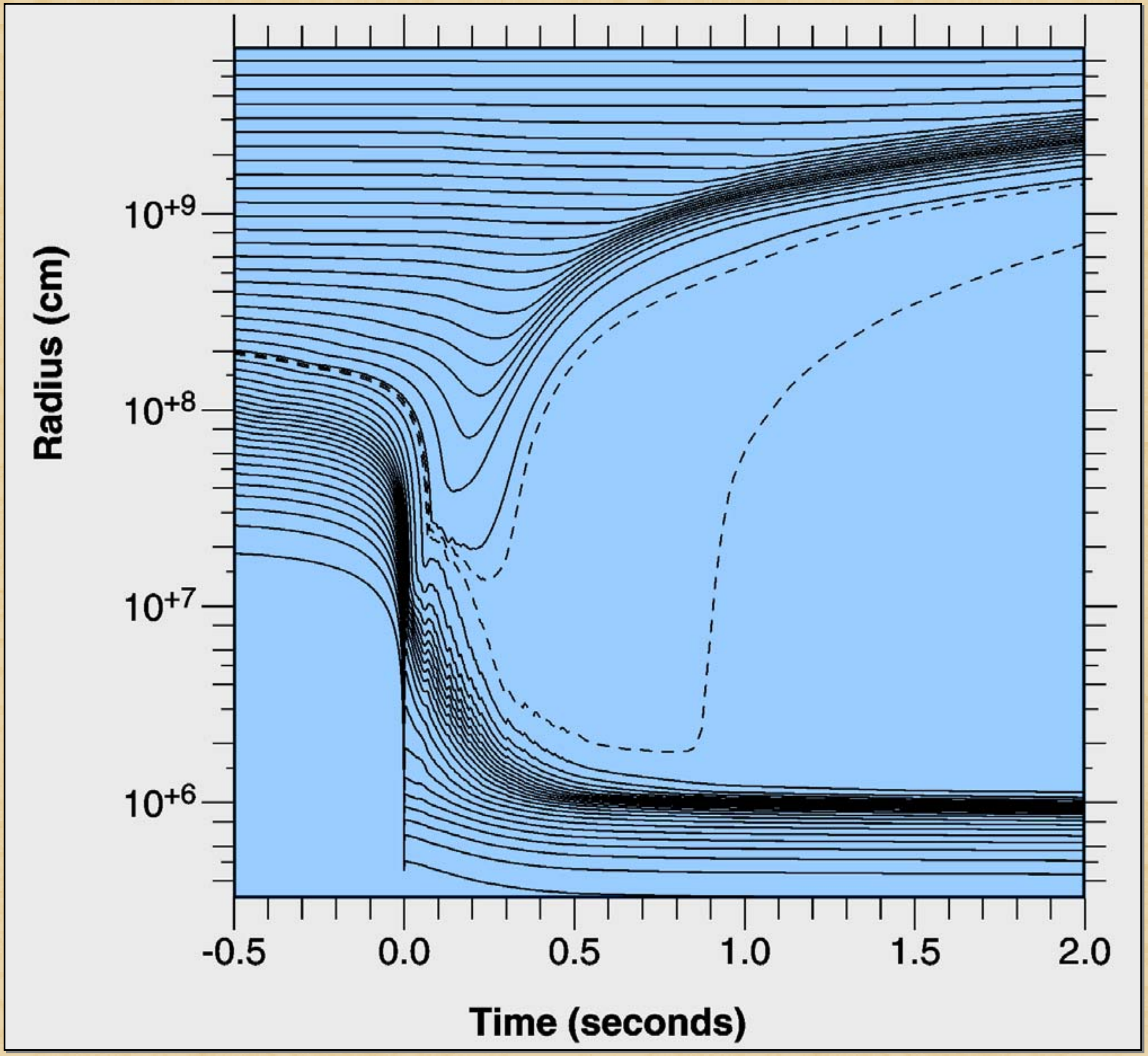
JAMES R. WILSON
Lawrence Livermore Laboratory
Received 1981 December 22; accepted 1982 April 1

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

Neutron-Finger Convection to the Rescue



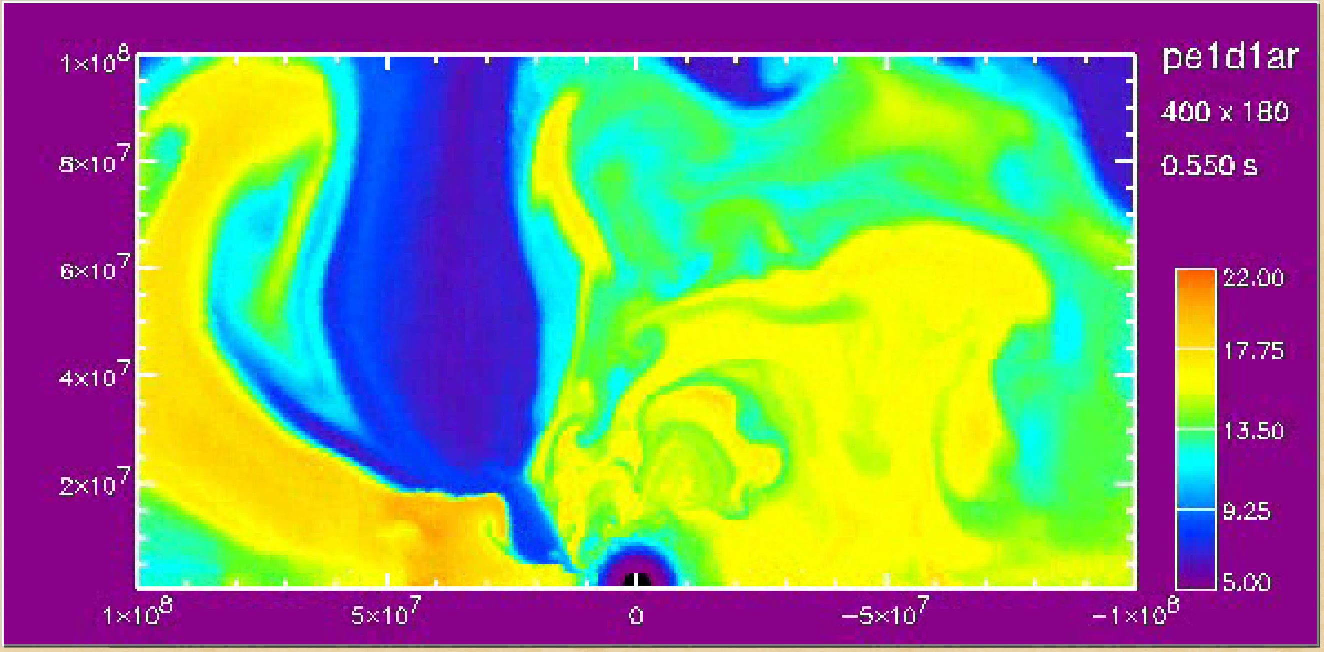
Livermore group obtains robust delayed explosions with 1-D code of Mayle & Wilson

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

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

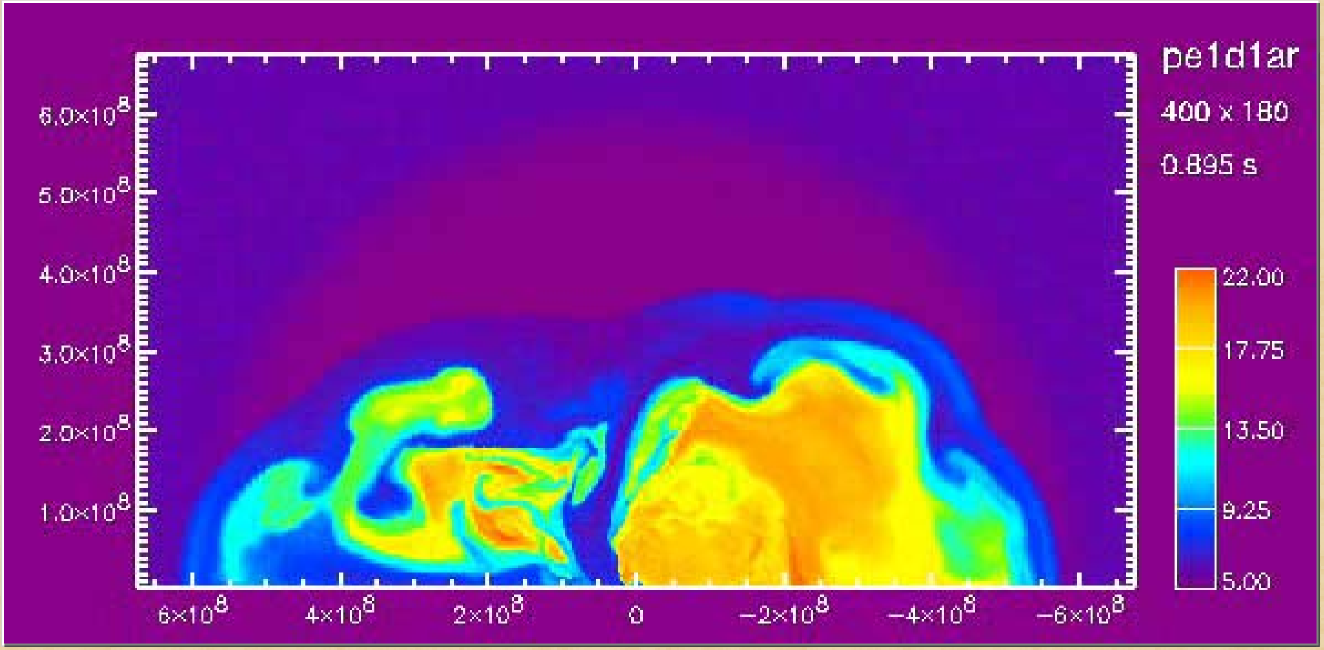
Convection in Supernovae (2-D Simulation)

1000 km



Entropy contours

Artificially triggered explosion

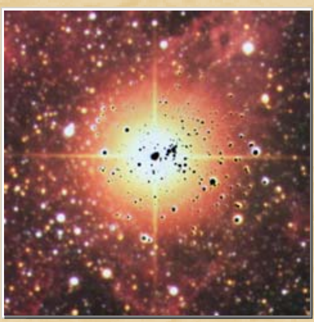


Movies courtesy H.-T. Janka

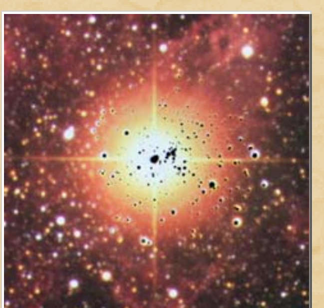
Theoretical Status of Supernova Explosions

- 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
- Next steps: 2-D and 3-D simulations self-consistently coupled with state-of-the-art neutrino transport



- Particle-physics models for new channel of energy transfer can be constructed
- Simplest neutrino flavor-oscillation scenario suppressed by large matter effects relative to small Δm



- New physical ingredients required?
- Explosion a magneto-hydrodynamical effect? (Strong B-fields and fast rotation possible)

Lecture I: Physics with Supernovae

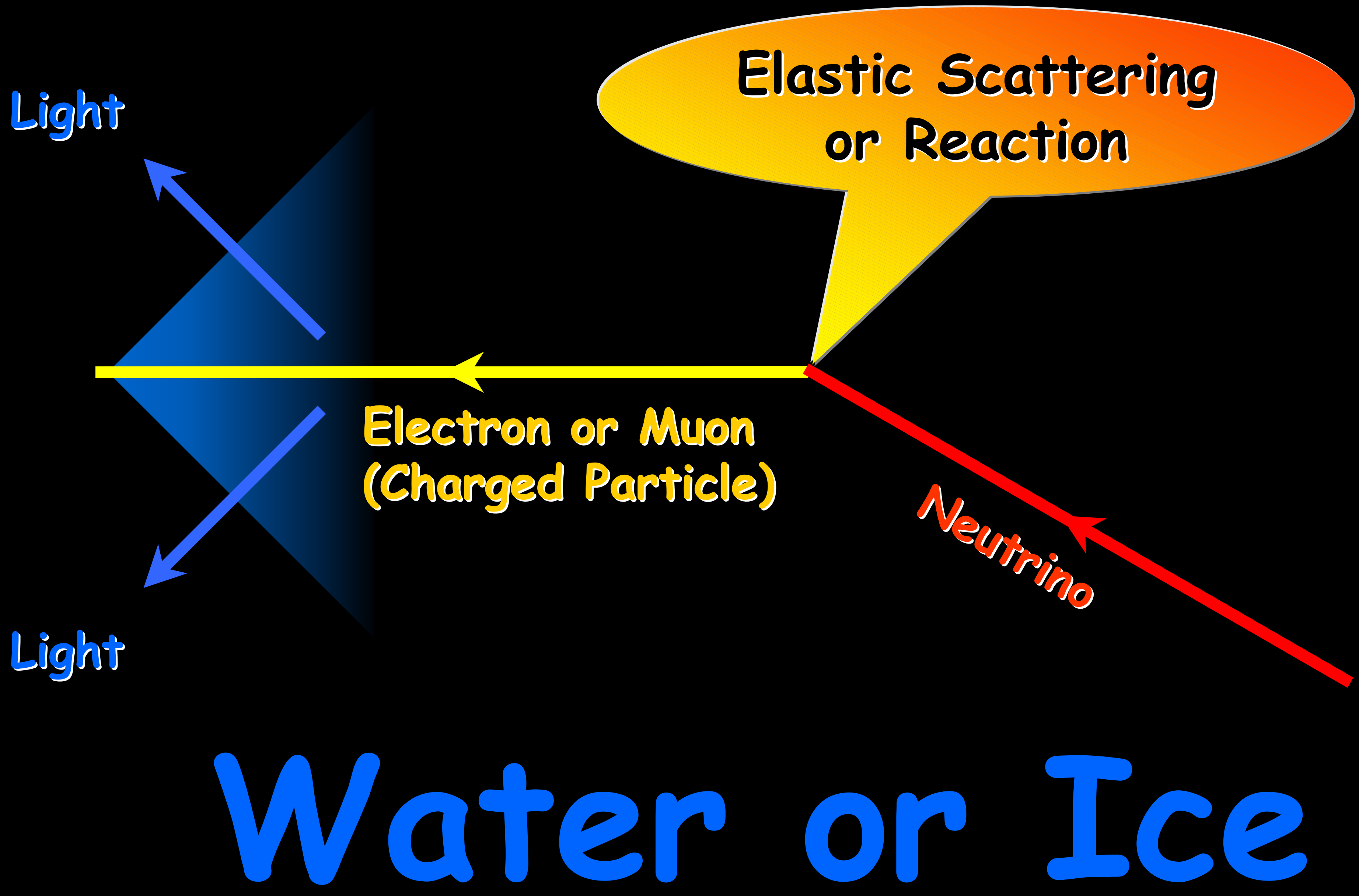
Physical Mechanism of Core-Collapse Supernovae

Supernova Neutrino Detection

Limits on Particle Properties

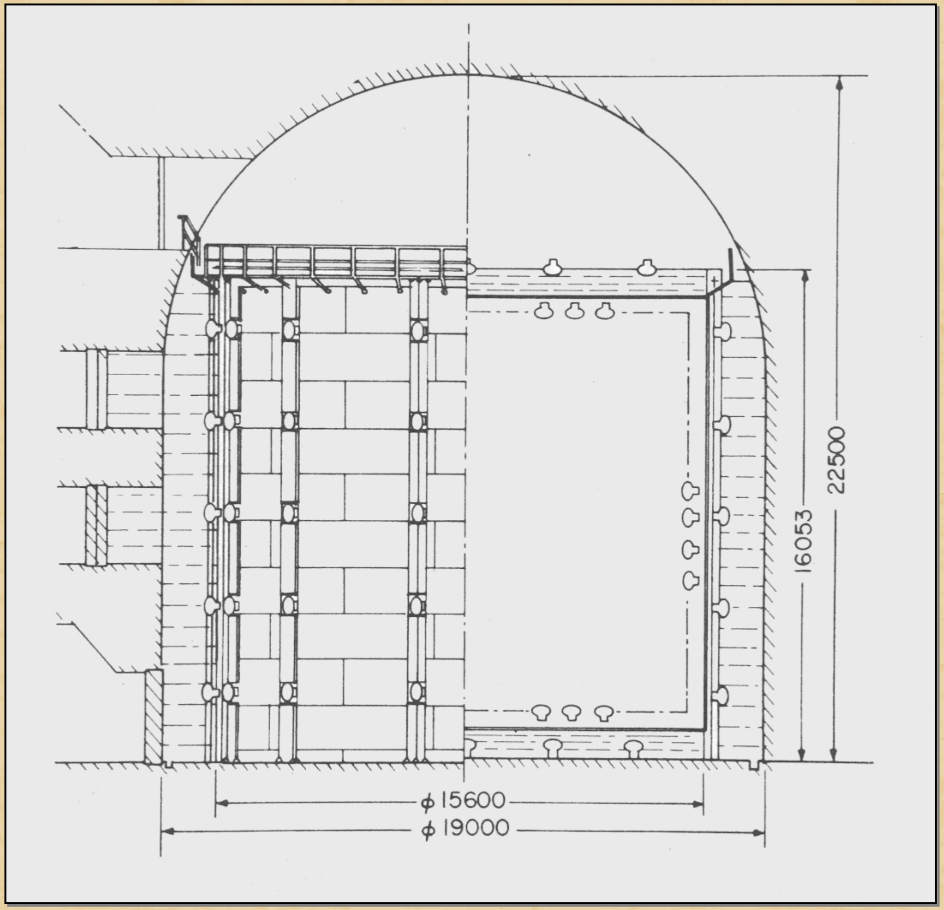
Flavor Oscillations of Supernova Neutrinos

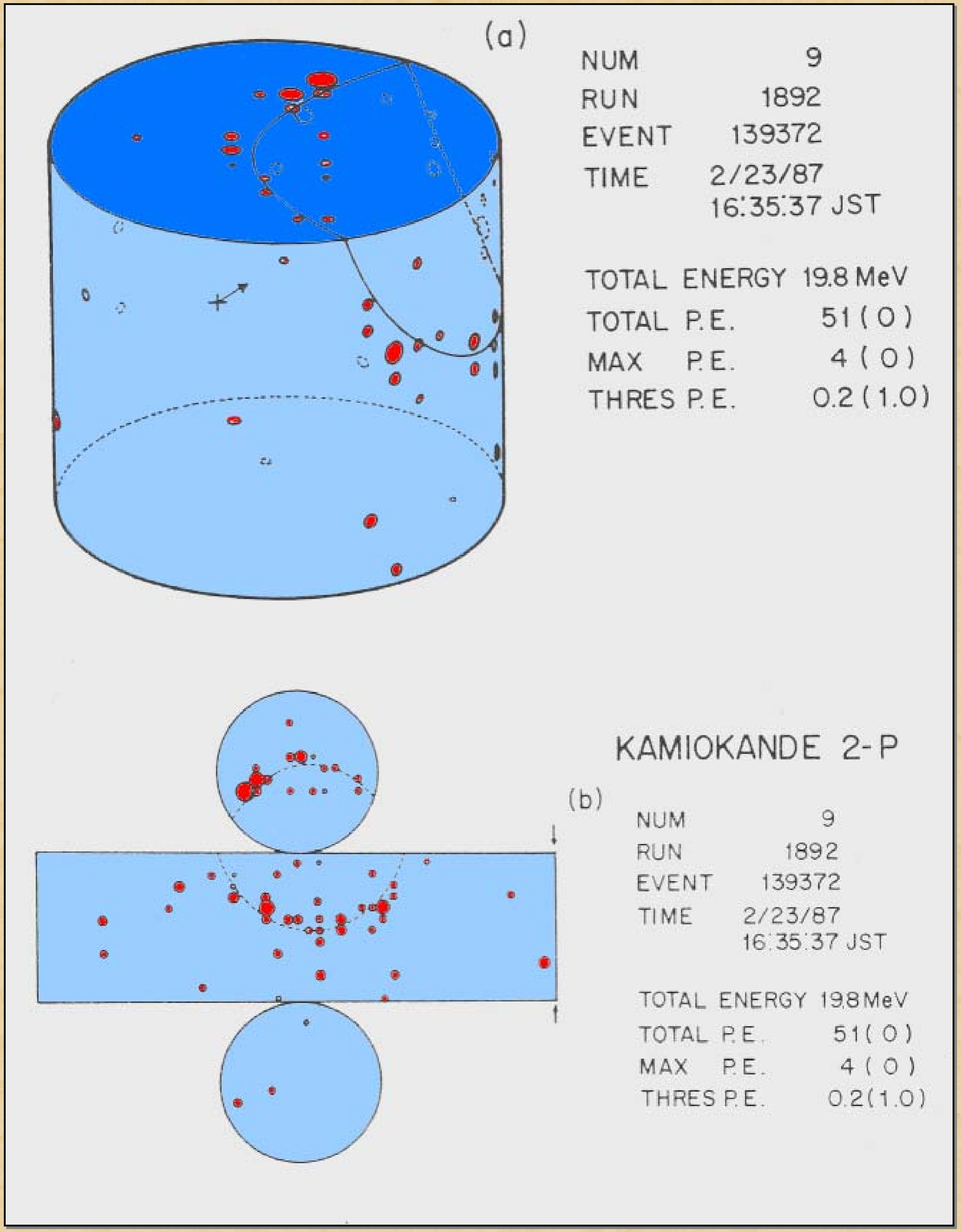
Cherenkov Effect



SN 1987A Event No.9 in Kamiokande

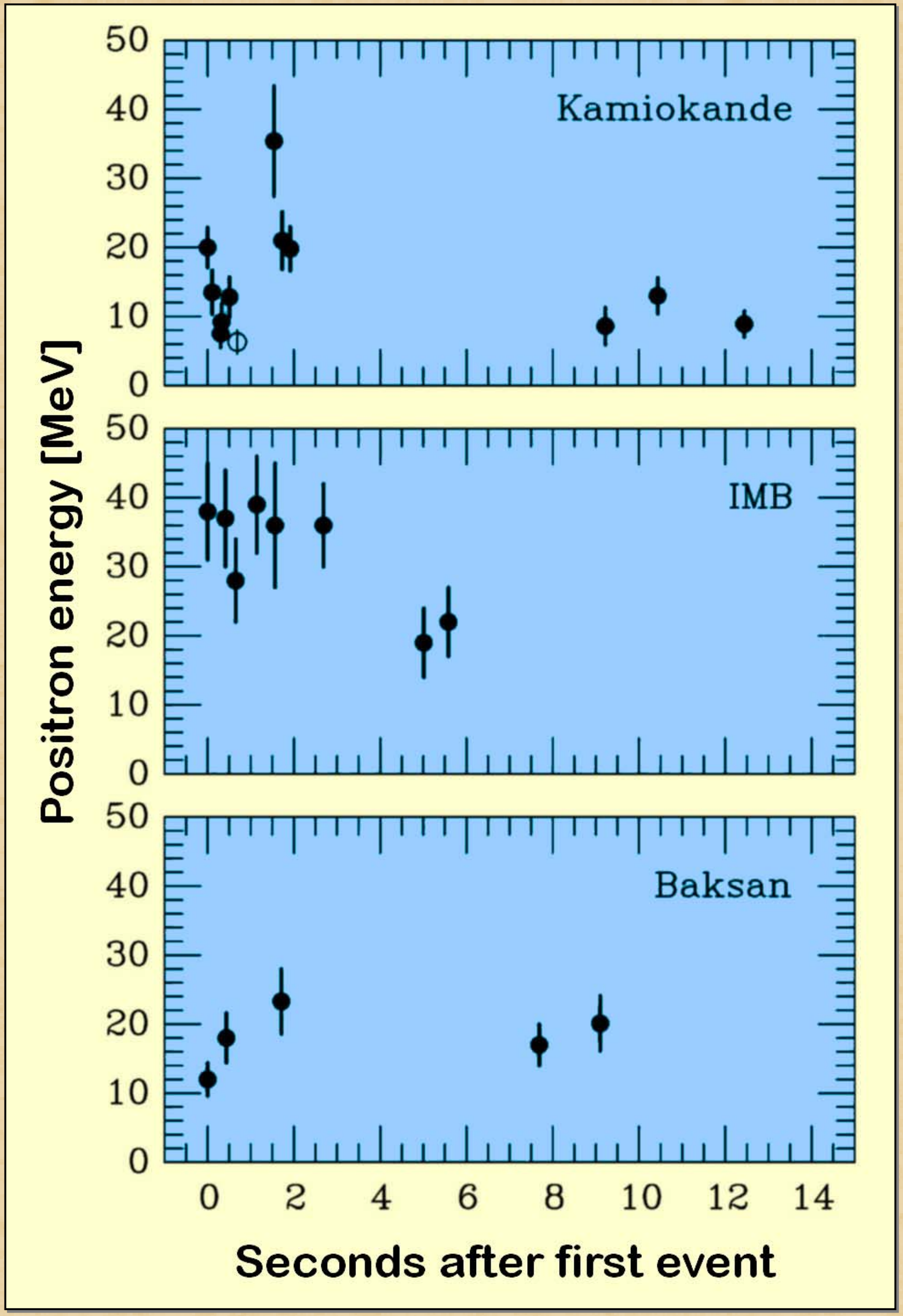
Kamiokande Detector





Hirata et al., PRD 38 (1988) 448

Neutrino Signal of Supernova 1987A



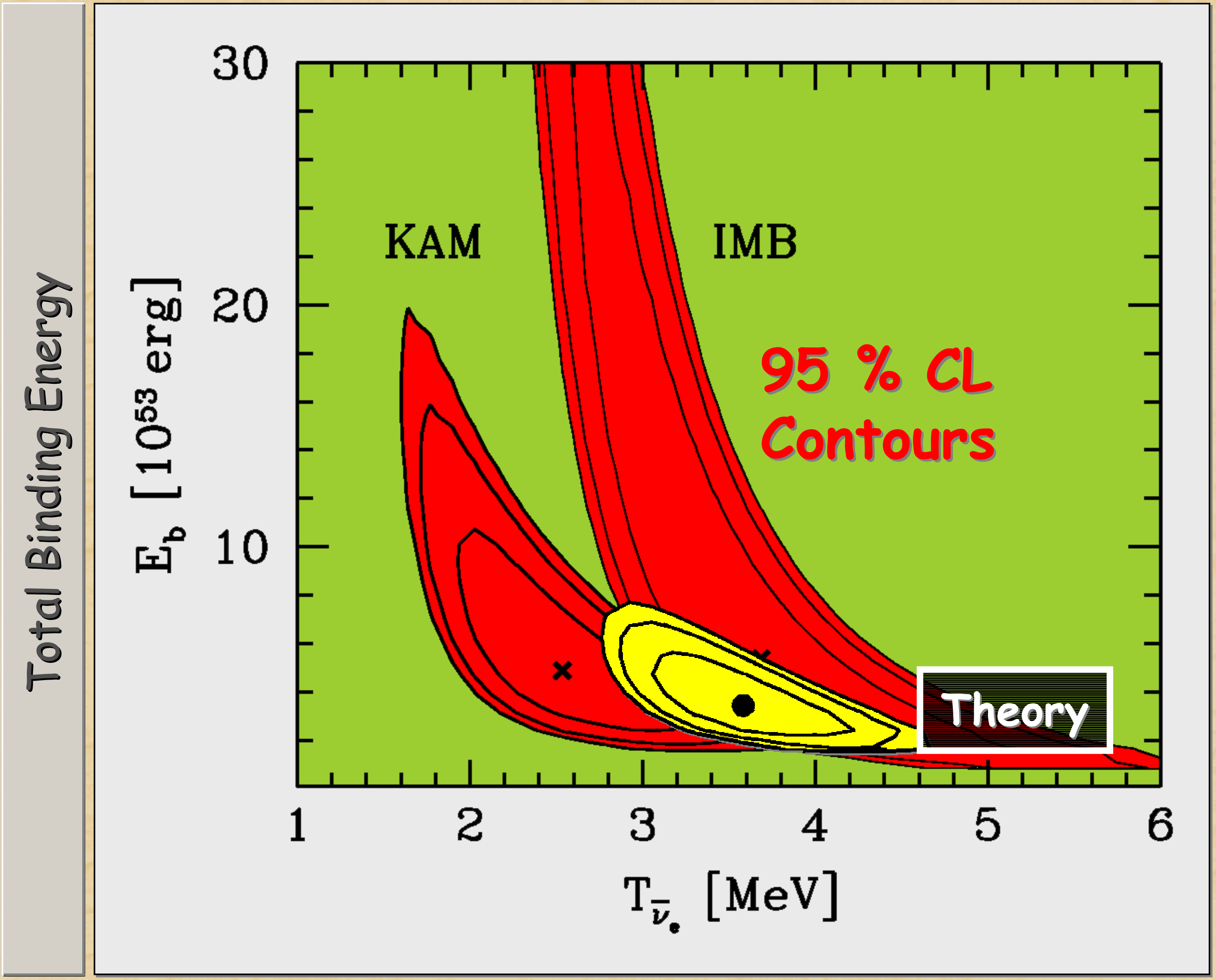
Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

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

Interpreting SN 1987A Neutrinos

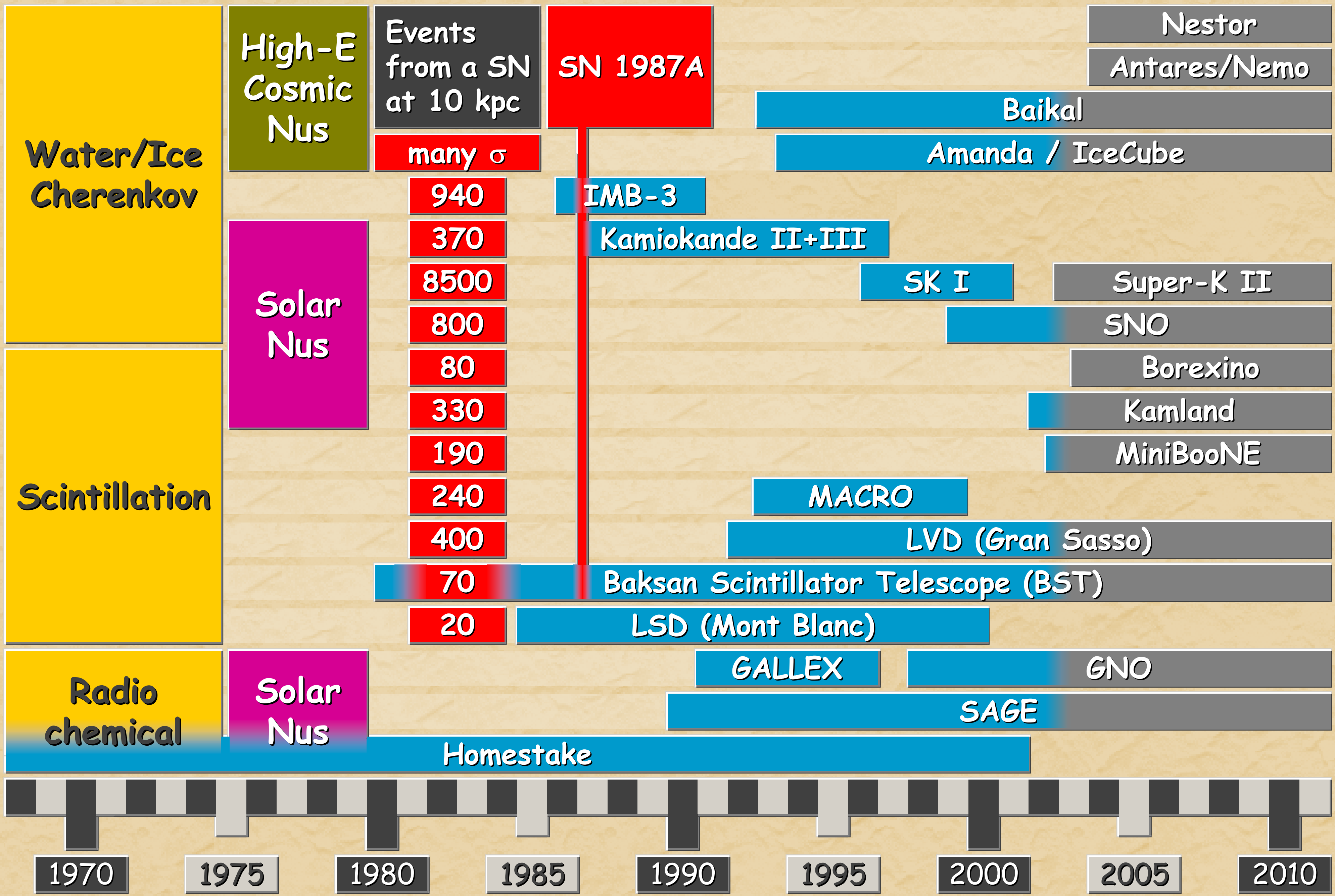


Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

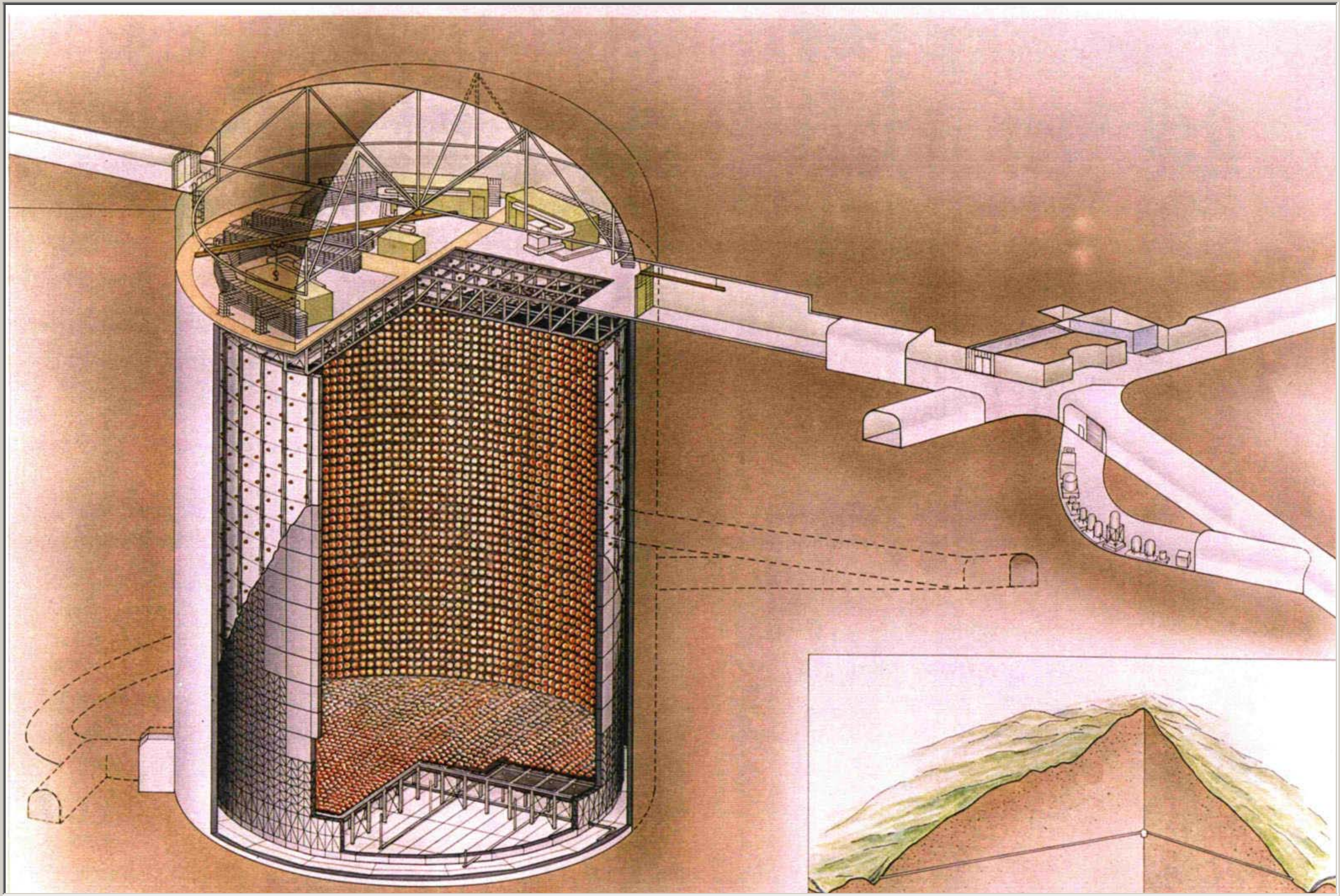
Assume thermal spectra and equipartition of energy between the six degrees of freedom ν_e, ν_μ, ν_τ and their antiparticles

e

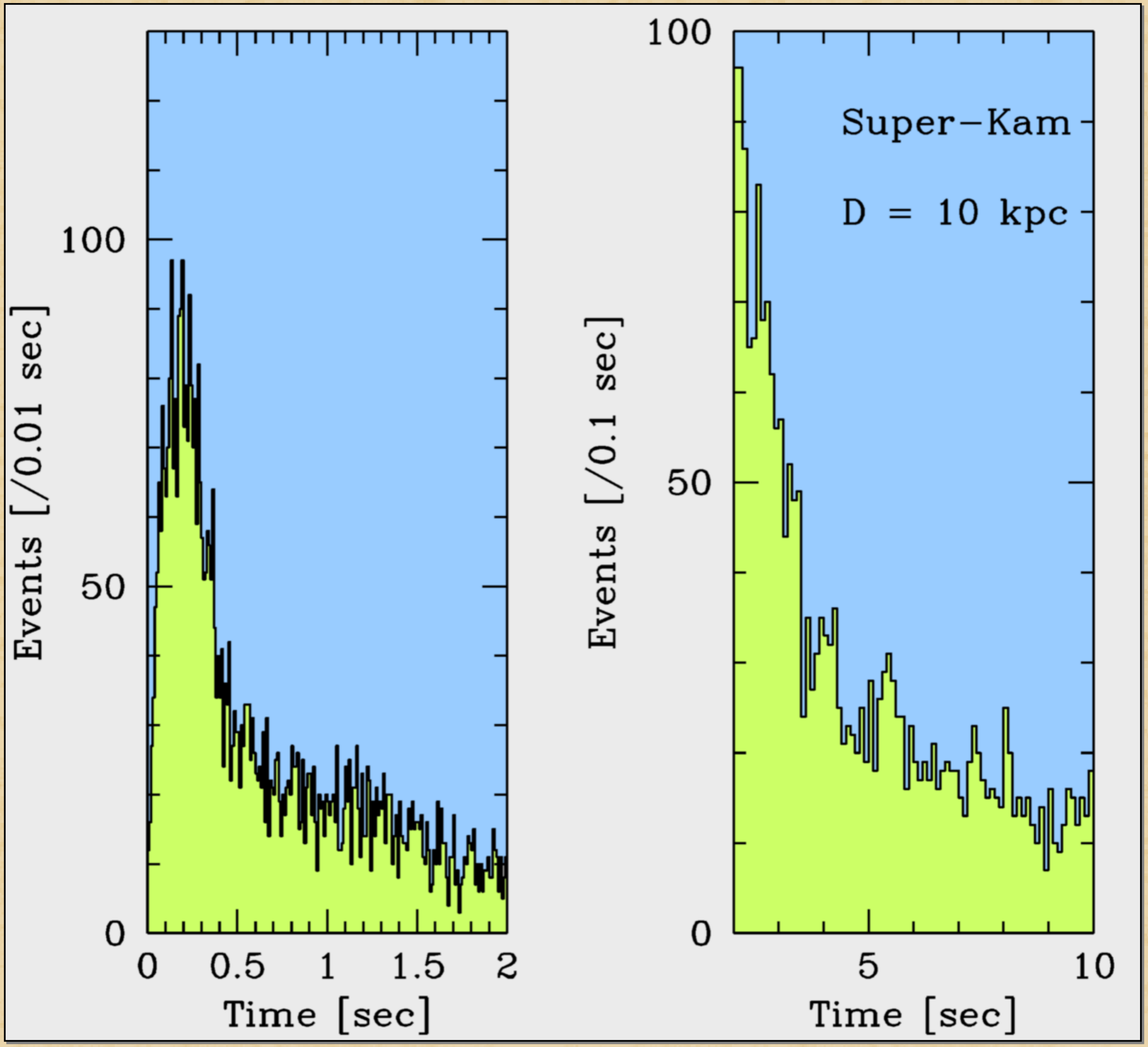
Short History of Neutrino Astronomy



Super-Kamiokande Neutrino Detector



Simulated Supernova Signal in Super-Kamiokande

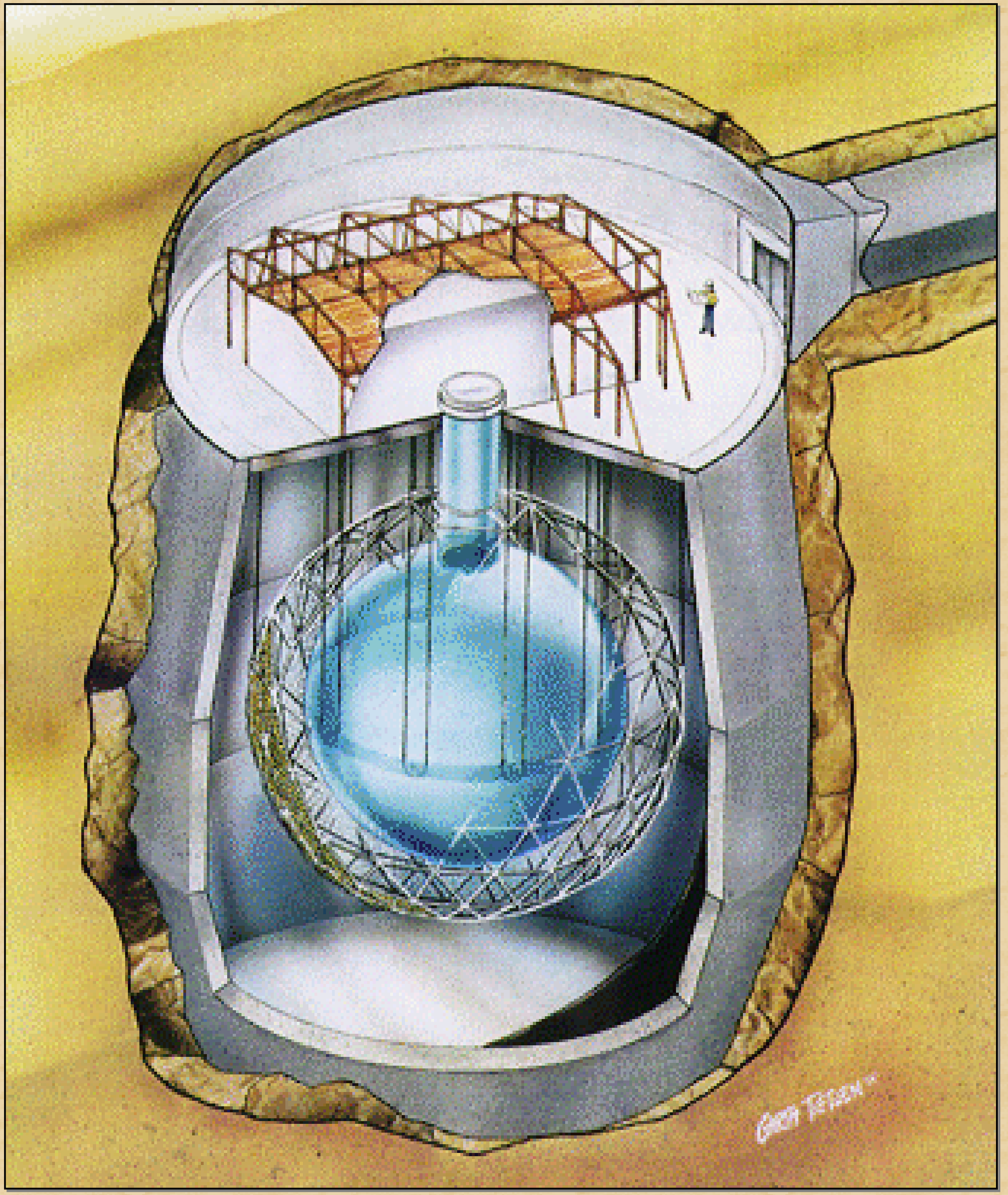


Total of about 8300 events for t < 18 s

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

Monte-Carlo simulation for Super-Kamiokande signal of SN at 10 kpc, based on a numerical Livermore model

Sudbury Neutrino Observatory (SNO)



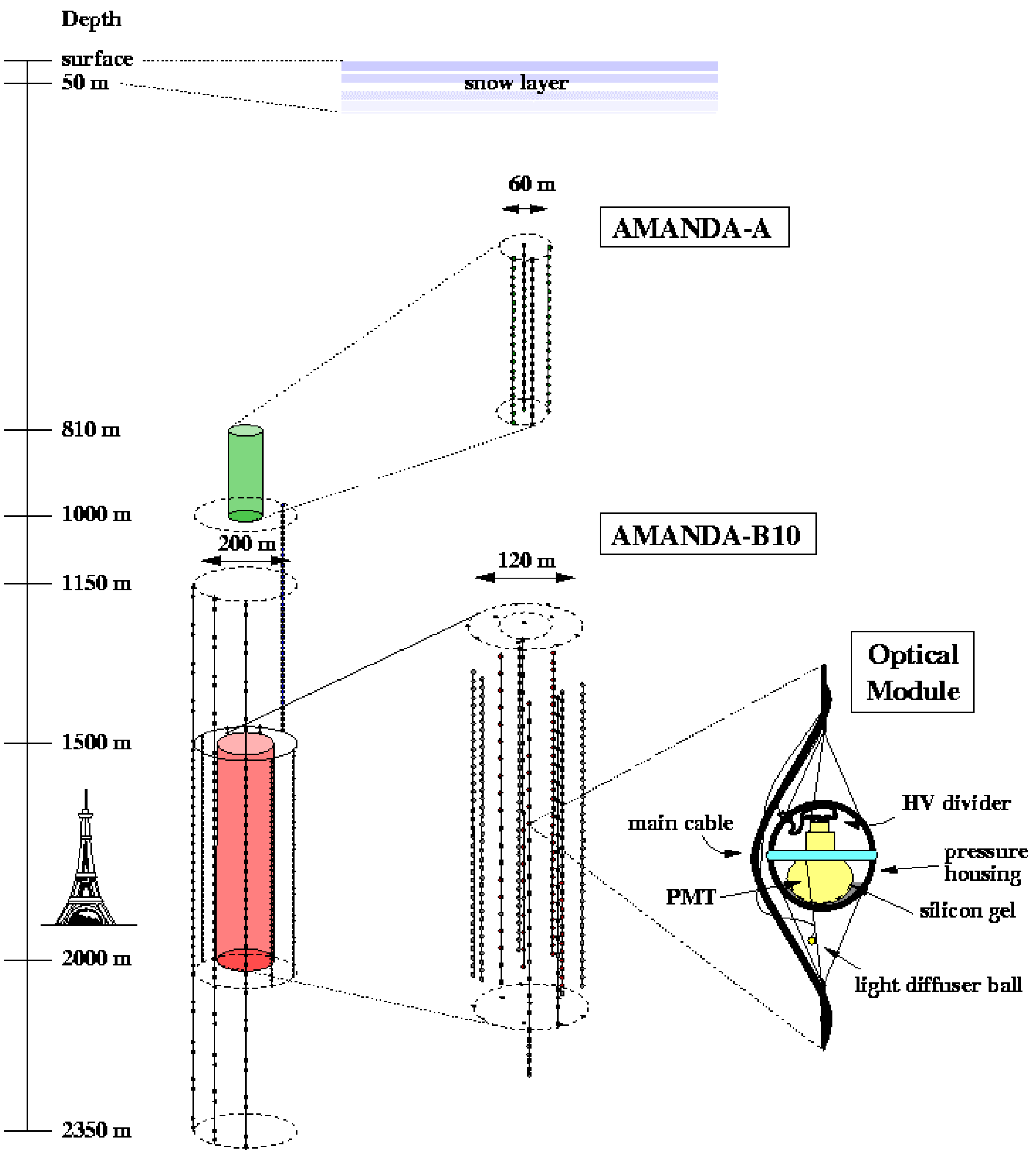
1000 tons of heavy water

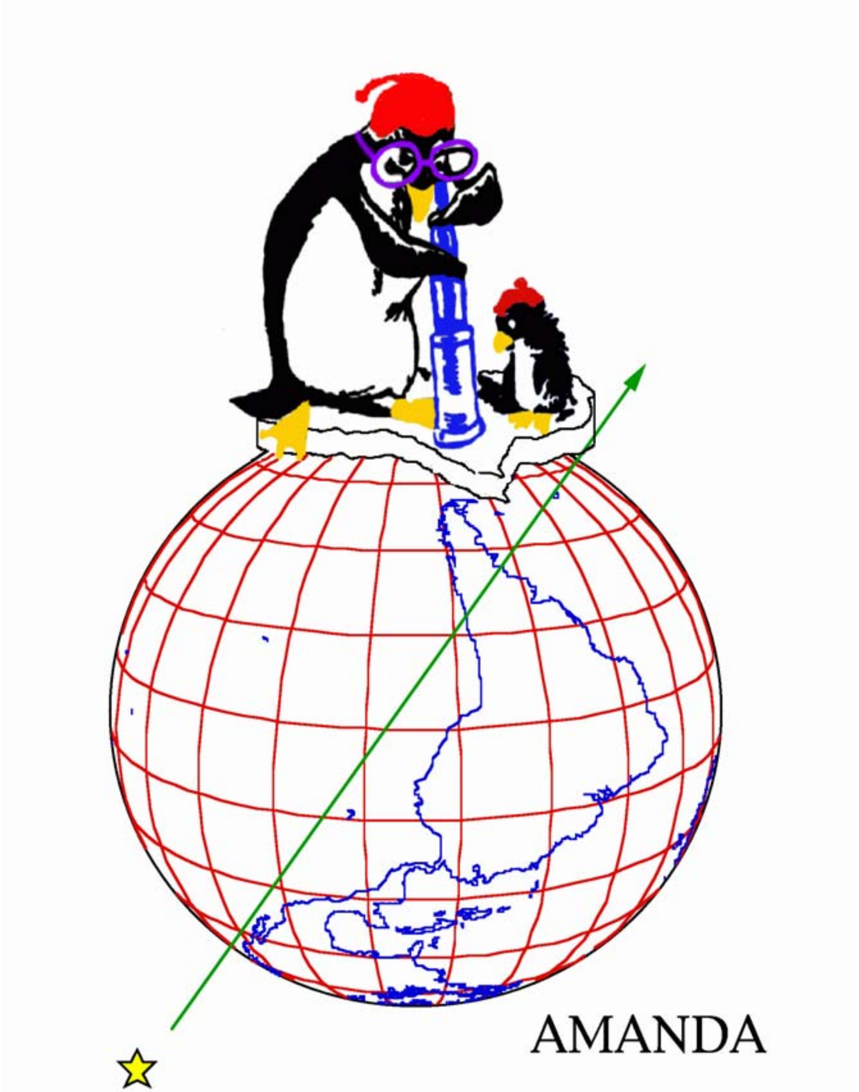
Events from a SN at 10 kpc
(no flavor oscillations)

Heavy water (1 kt)	Events:
CC: $\nu_e + d \to p + p + e^-$	72
CC: $\bar{\nu}_e + d \to n + n + e^+$	138
NC: $\nu_e + d \to \nu_e + p + n$	30
NC: $\bar{\nu}_e + d \to \bar{\nu}_e + p + n$	32
NC: $\nu_x + d \to \nu_x + p + n$	164

Light water (1.4 kt)	Events:
CC: $\bar{\nu}_e + p \to n + e^+$	331

AMANDA - Neutrino Telescope at the Southpole



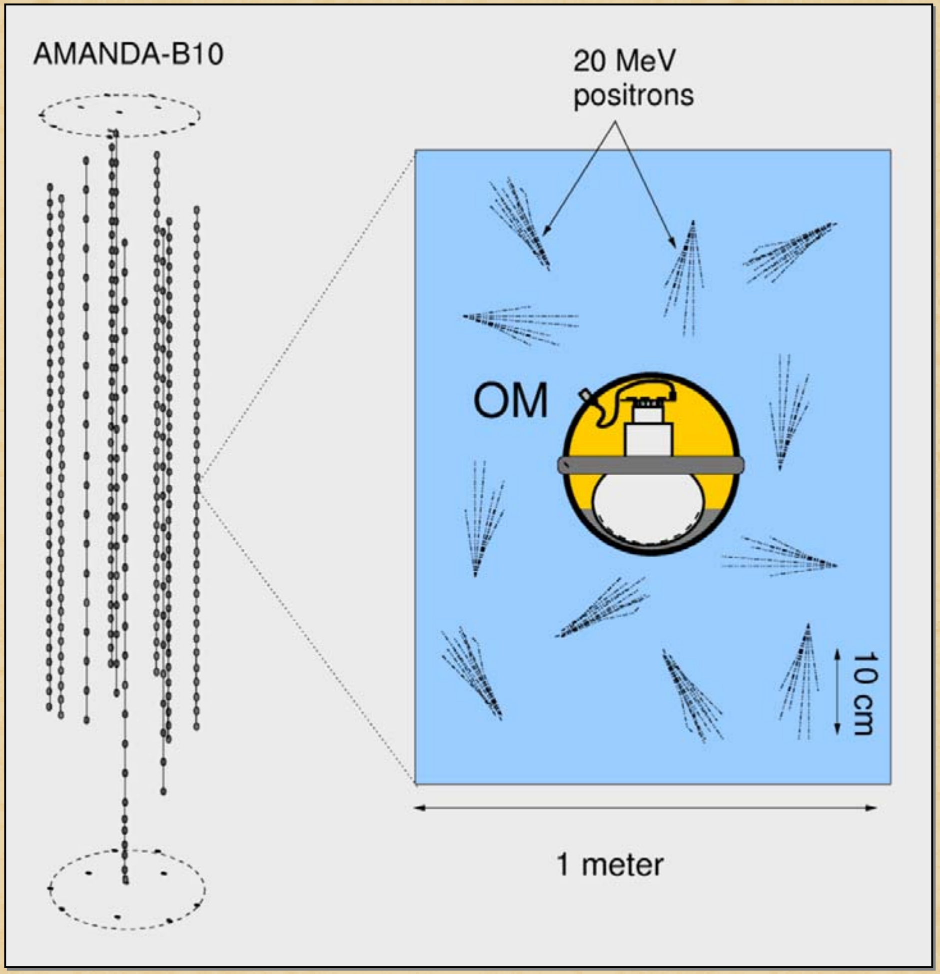


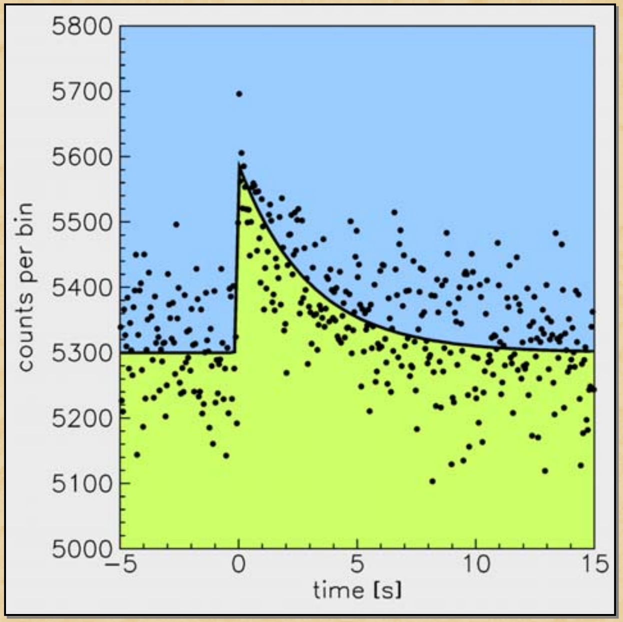
AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

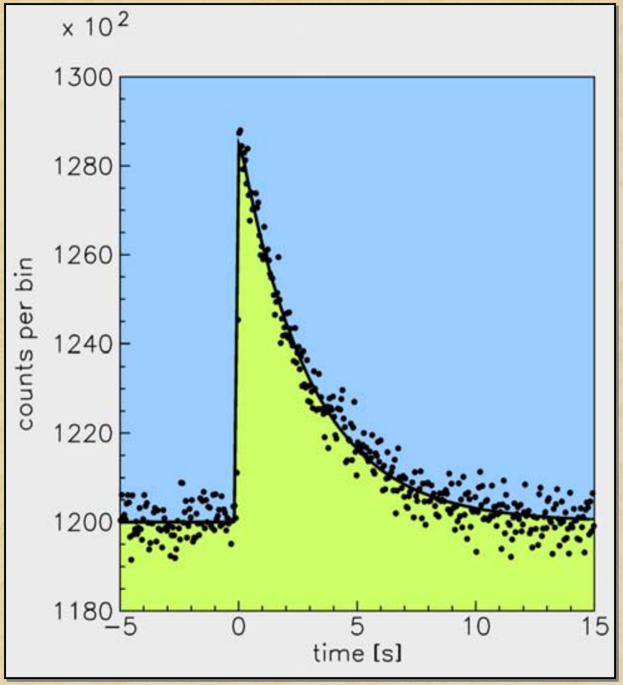
zoomed in on one
optical module (OM)

Amanda/IceCube as a Supernova Detector





SN @ 8.5 kpc
Signal in
Amanda

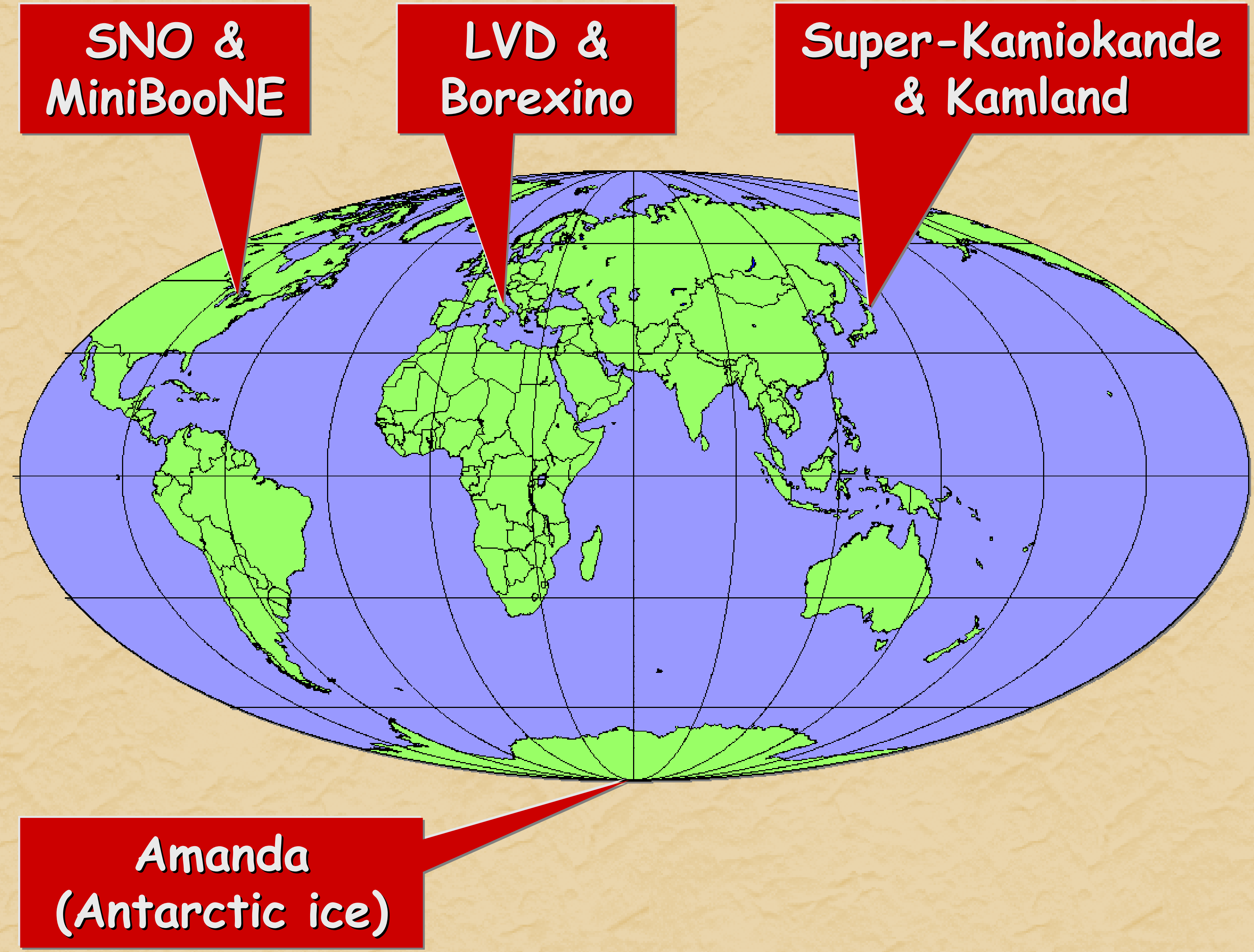


SN @ 8.5 kpc
Signal in
Ice Cube

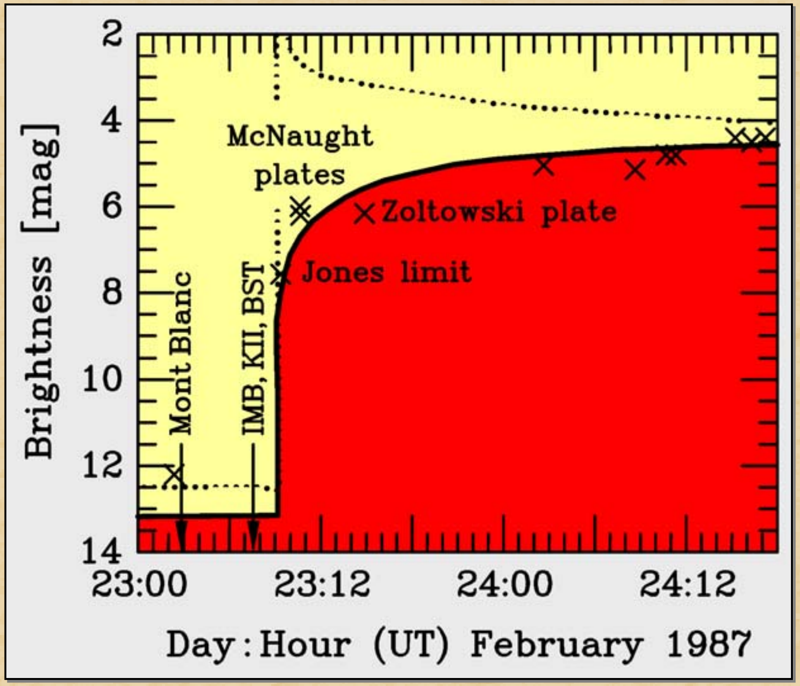
Amanda
Collaboration
(2001)

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

Large Detectors for SN Neutrinos

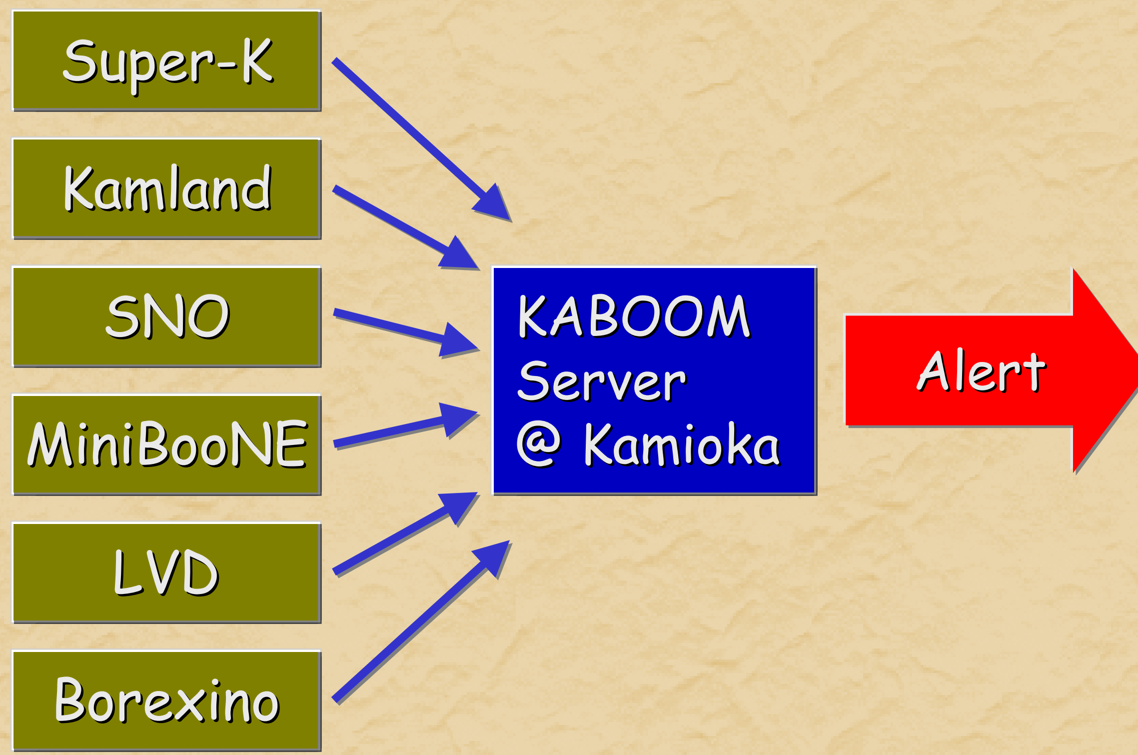


SuperNova Early Warning System (SNEWS)



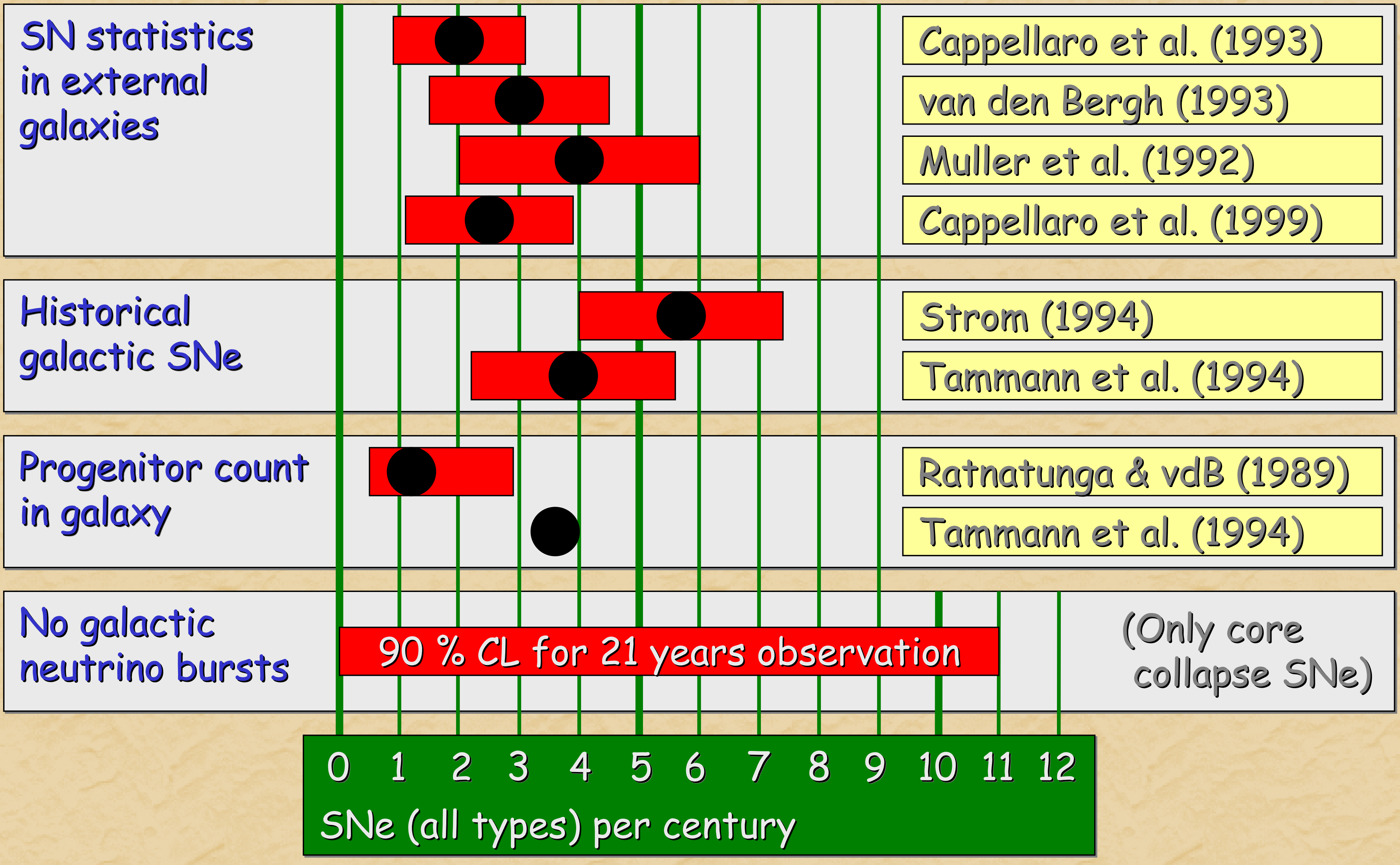
Supernova 1987A
Early Light Curve

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

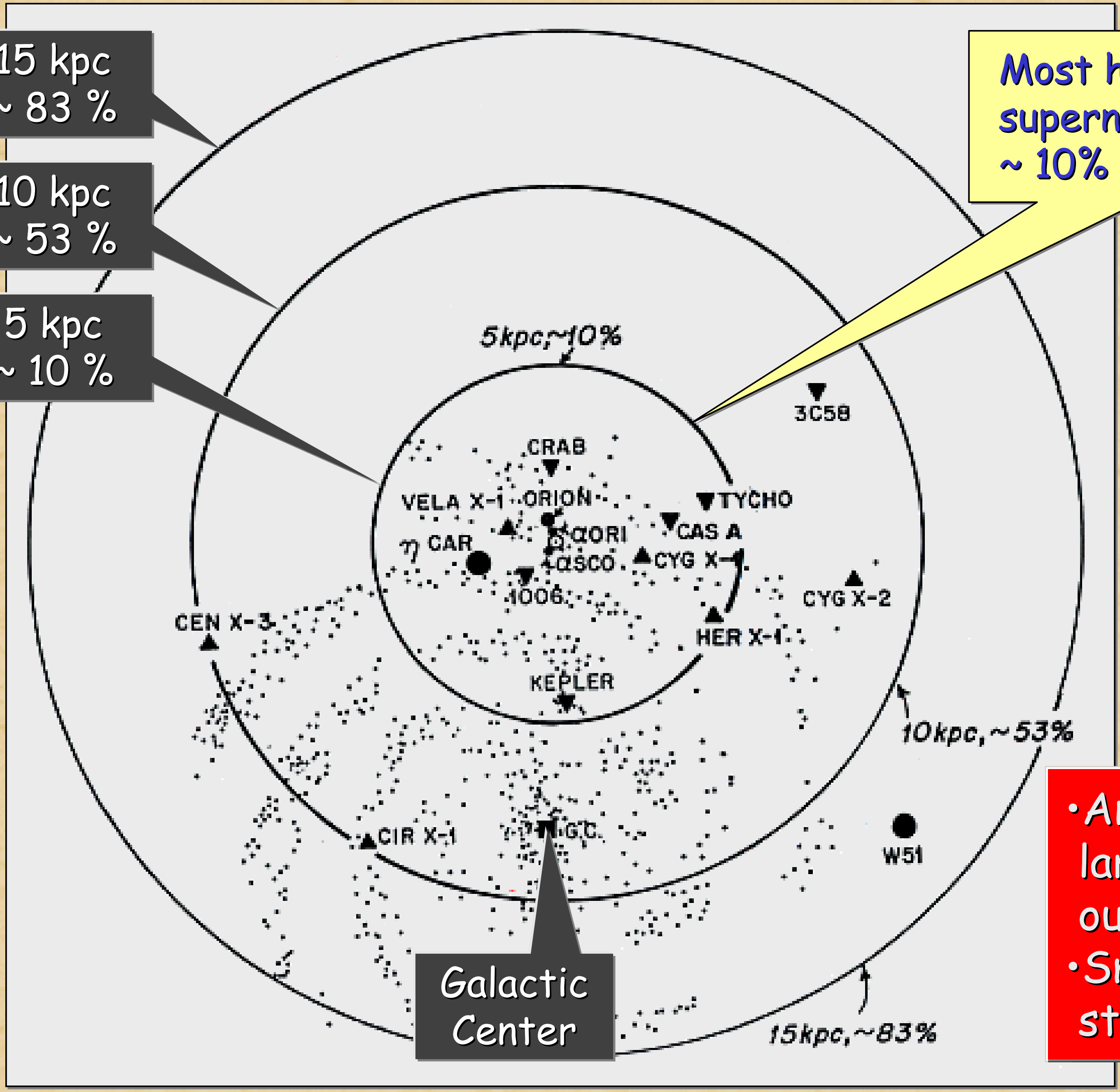


http://hep.bu.edu/~snnet

Estimates of the Galactic SN Rate



Galactic Supernova Events



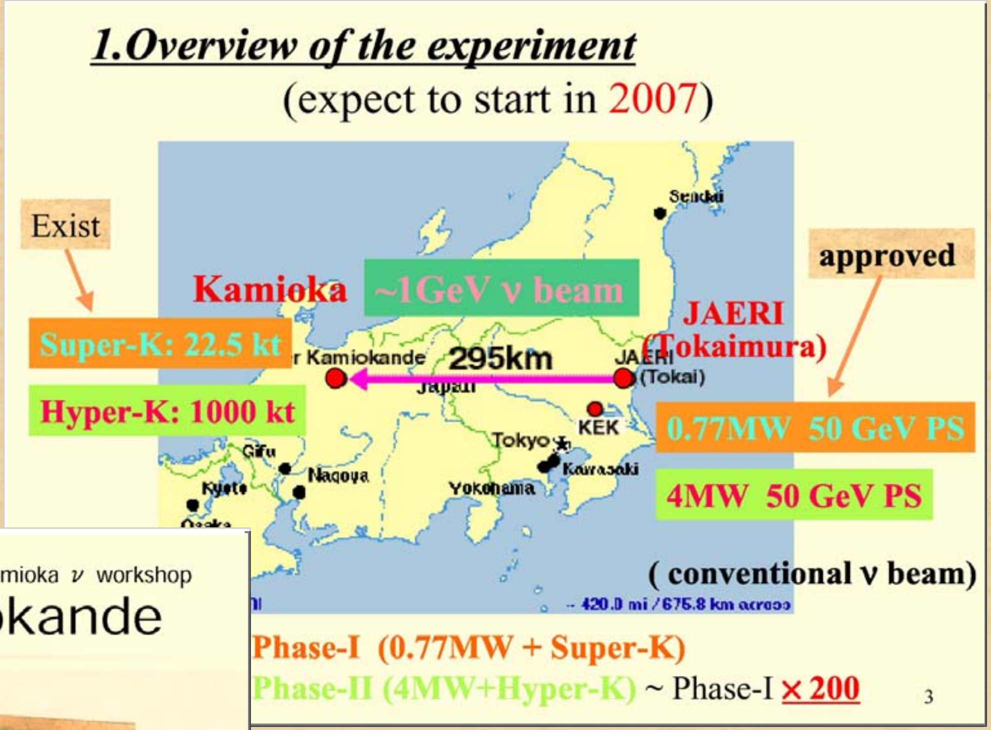
Most historical supernovae in ~ 10% of the galaxy

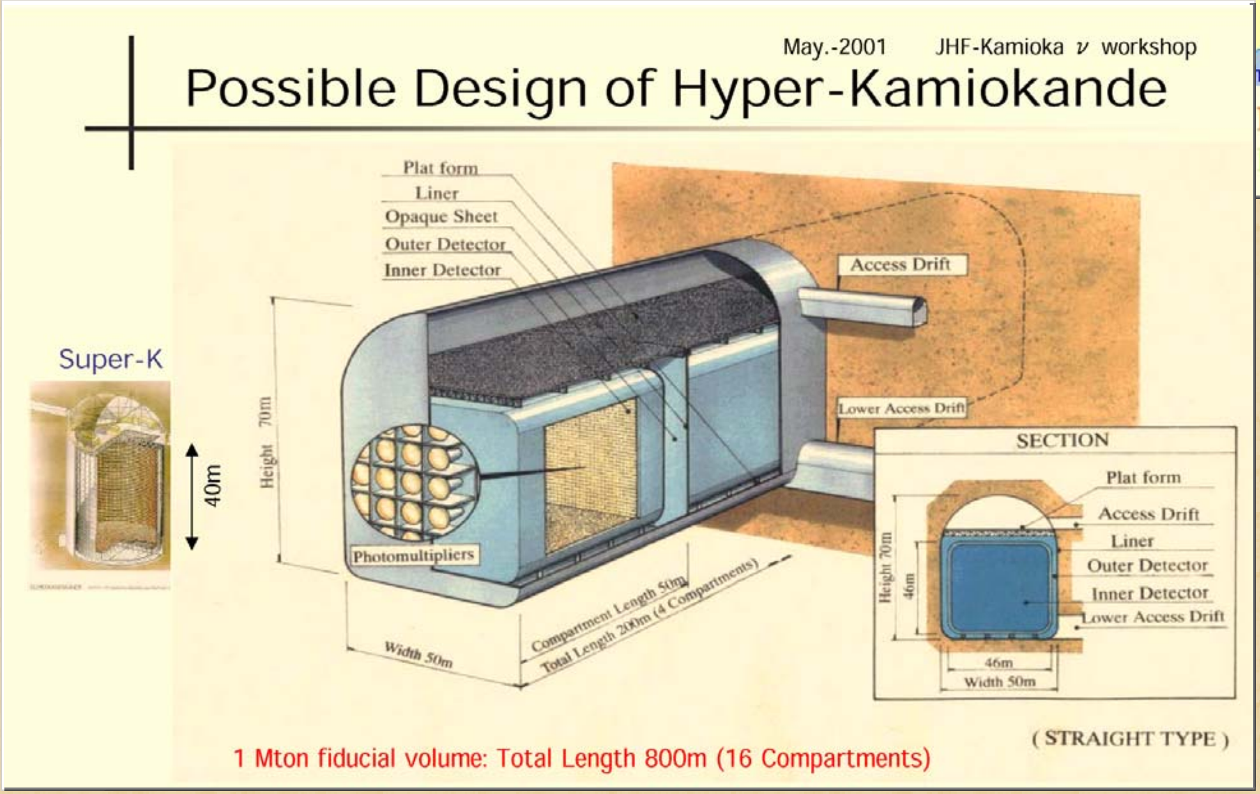
- Anomalously large rate in our galaxy?
- Small-number statistics?

Adam Burrows

The Future: A Megatonne Detector?

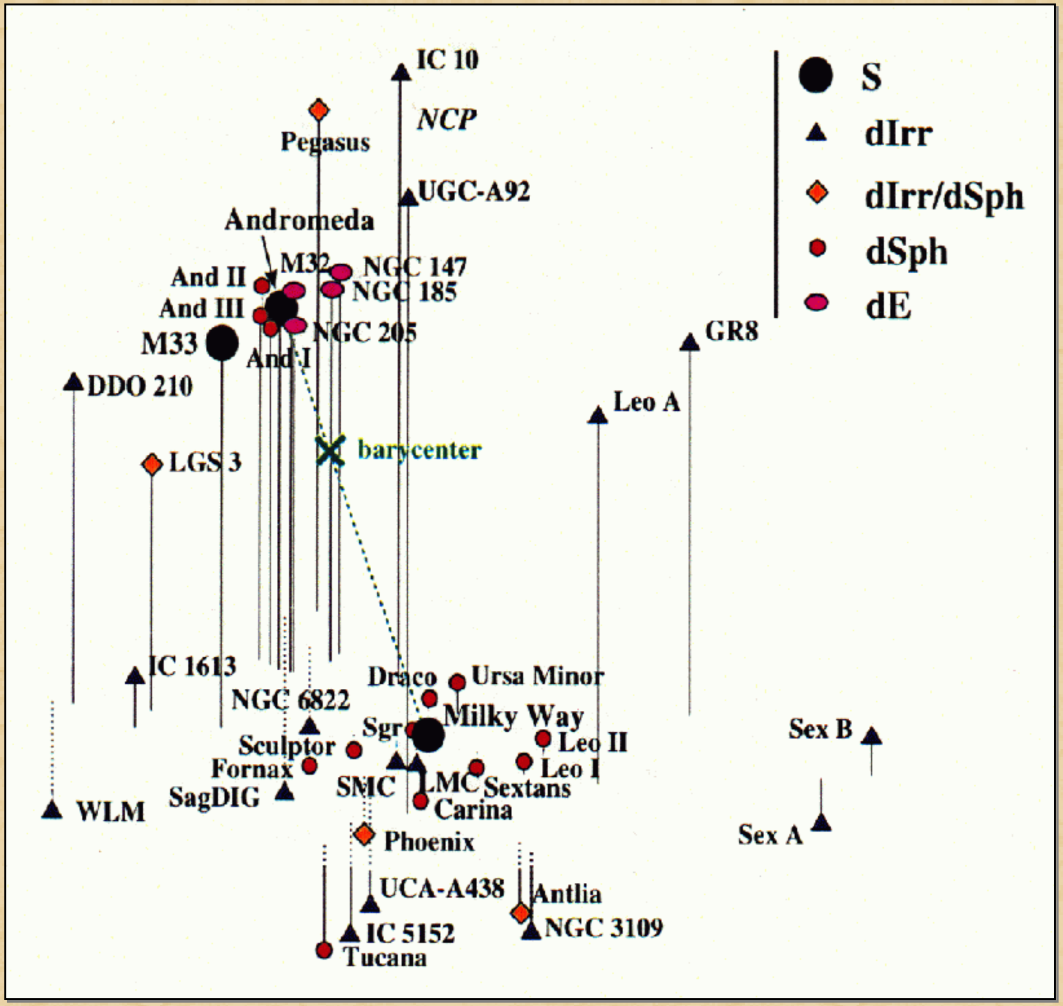
Megatonne detector motivated by
- Long baseline neutrino oscillations
- Proton decay
- Atmospheric neutrinos
- Solar neutrinos
- Supernova neutrinos
  (~10^5 events for SN at 10 kpc)



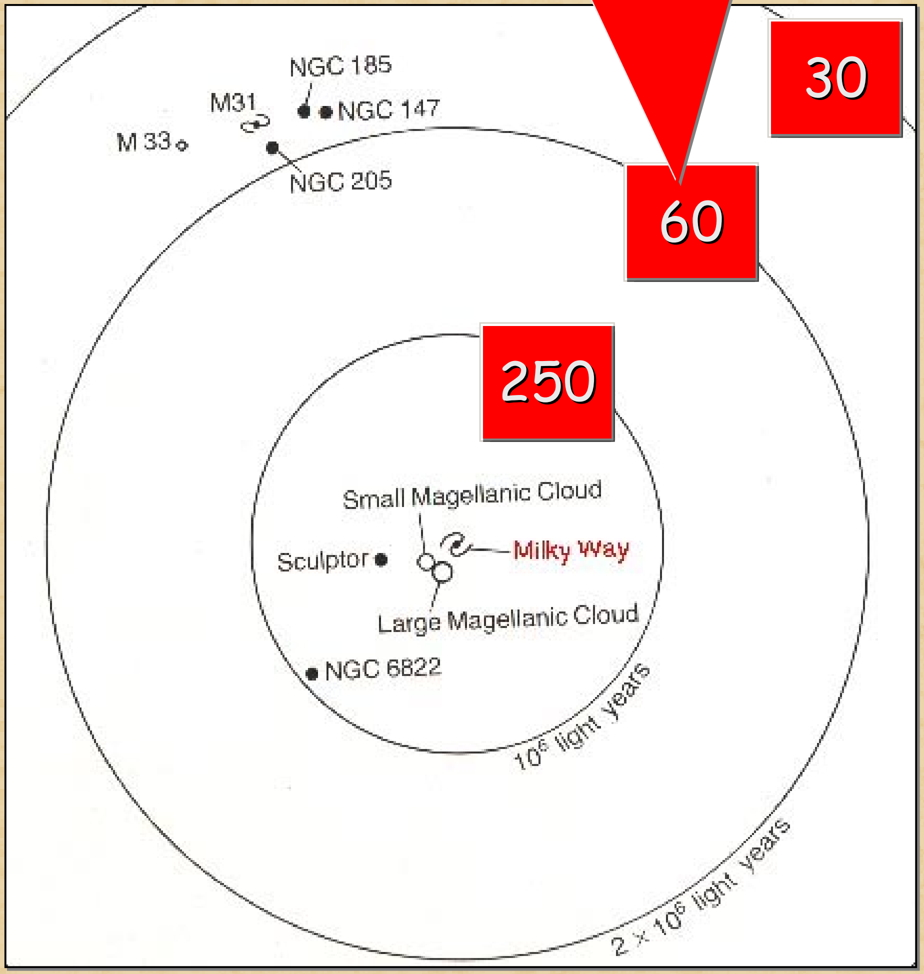


Similar discussions in
- USA (UNO project)
- Europe (Frejus Tunnel)

Local Group of Galaxies



Events in a detector with
30 x Super-K fiducial volume
(8000 events in SK at 10 kpc)



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 × 10^{33} erg/s
E_ν ~ 3 × 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

→

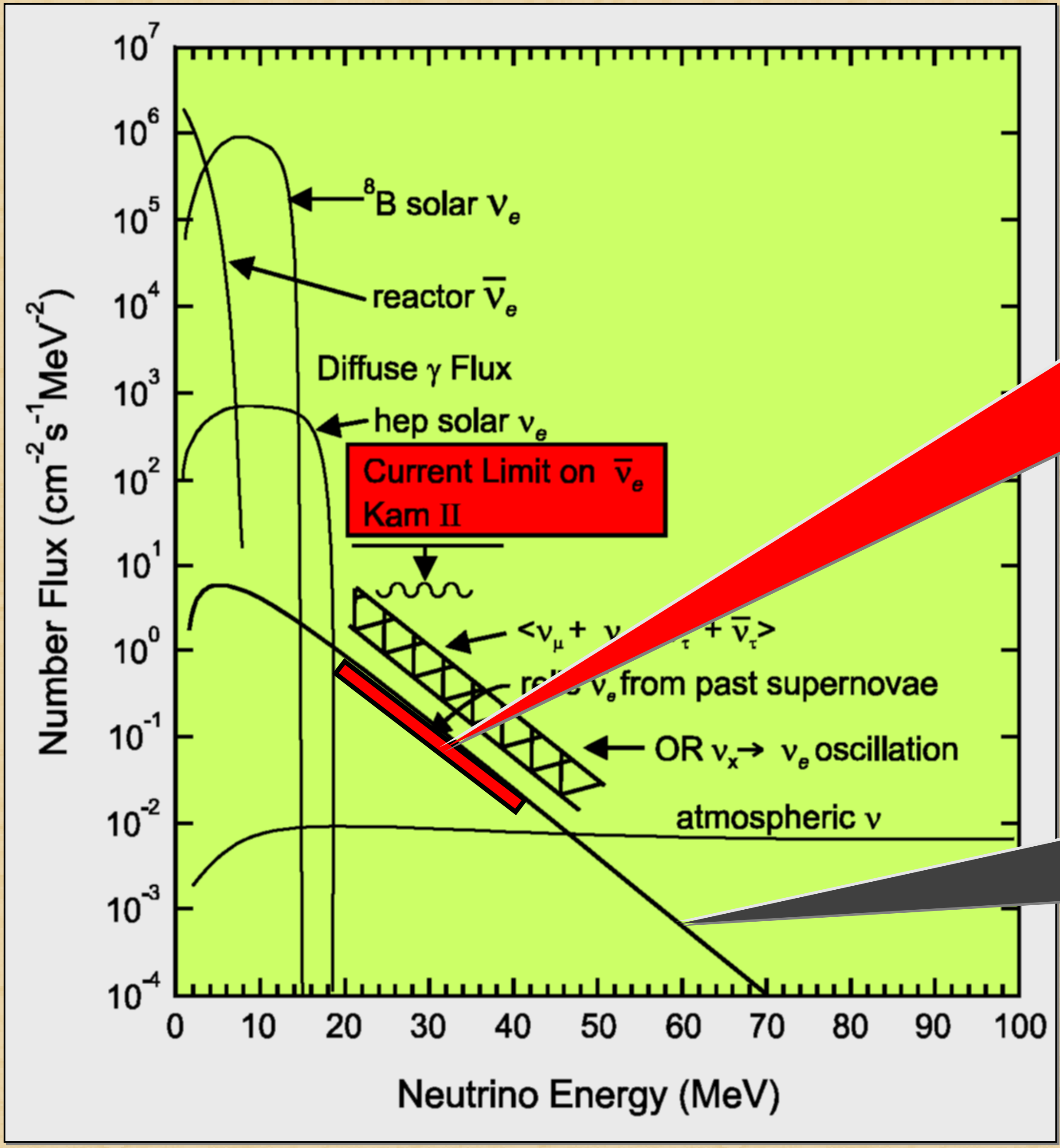
For galaxies, average nuclear & gravitational energy release similar

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 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 SN Neutrinos



Preliminary Super-K upper limit of 39 cm^{-2} s^{-1} for Kaplinghat et al. spectrum (Totsuka, private comm.) ~ factor 30 improvement

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

Cline, astro-ph/0103138

Lecture I: Physics with Supernovae

Physical Mechanism of
Core-Collapse Supernovae

Supernova Neutrino Detection

Limits on Particle Properties

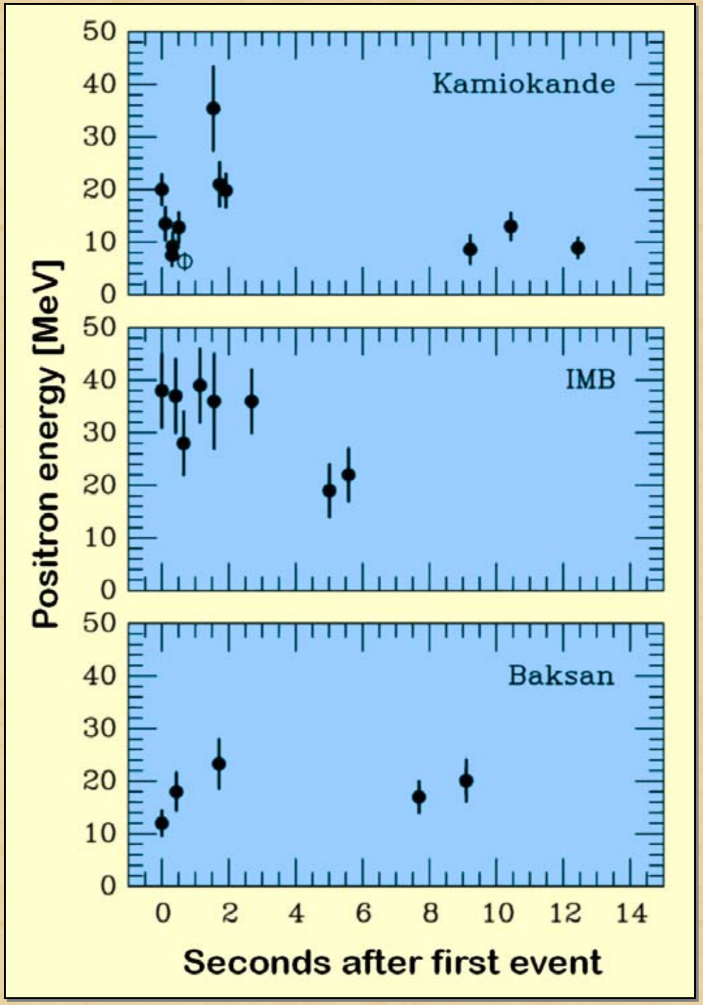
Flavor Oscillations
of Supernova Neutrinos

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



Neutrino Mass Limits by Signal Dispersion

Time-of-flight delay of massive neutrinos

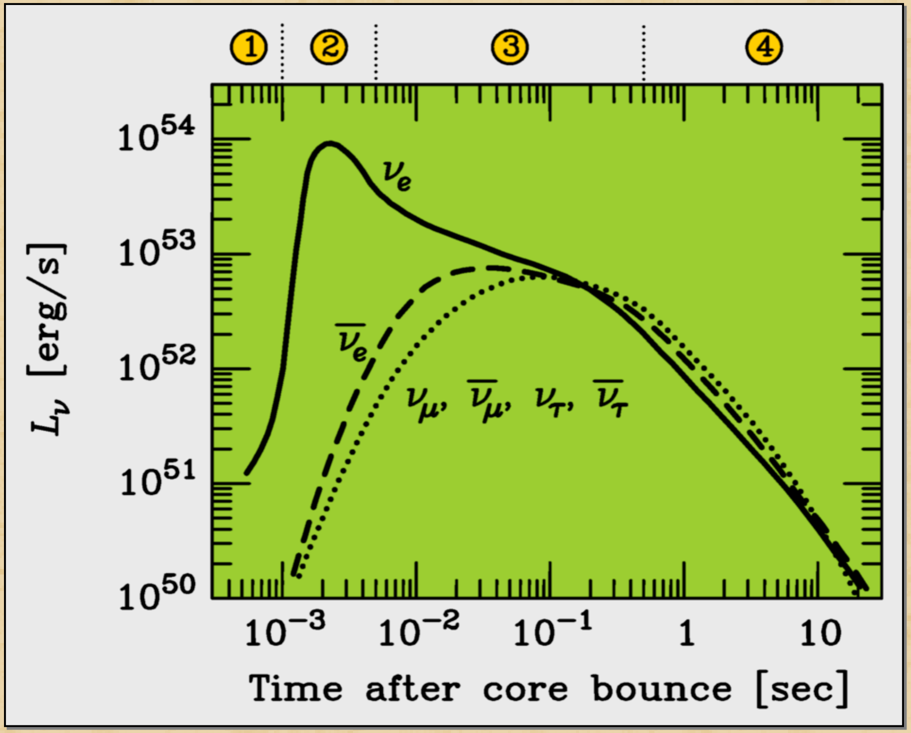
$$\Delta t = 2.57\,\mathrm{s}\left(\frac{D}{50\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{10\,\mathrm{eV}}\right)^2$$

SN 1987A

$E \approx 20$ MeV, $\Delta t \approx 10$ s, $D \approx 50$ kpc
Simple estimate or detailed maximum likelihood give similar results

$m_{\nu_e} < 20$ eV

Future Galactic SN (Super-K)



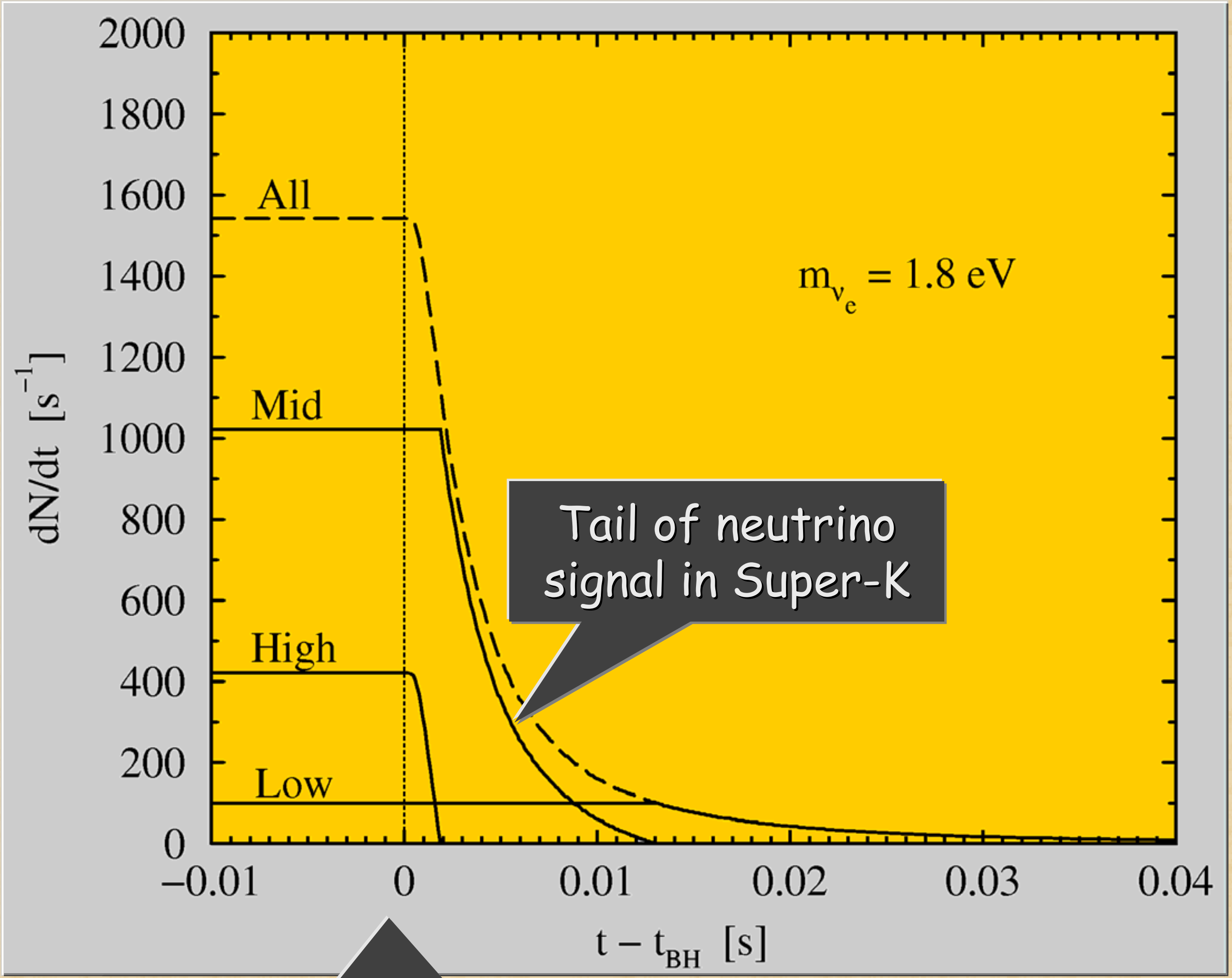
Neutrino Mass Limits by Signal Dispersion

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 give similar results	$m_{\nu_e} < 20$ eV
Future Galactic SN (Super-K)	$D \approx 10$ kpc, Rise-time 0.01 s Sensitivity approximately [T.Totani, PRL 80 (1998) 2040]	$m_{\nu_e} \sim 3$ eV
Future SN in Andromeda (Megatonne)	$D \approx 750$ kpc, $\Delta t \approx 10$ s Sensitivity approximately	$m_{\nu_e} \sim 1\text{-}2$ eV

Neutrino Mass from Early Black Hole Formation



Black hole formation

Beacom, Boyd & Mezzacappa, hep-ph/0006015

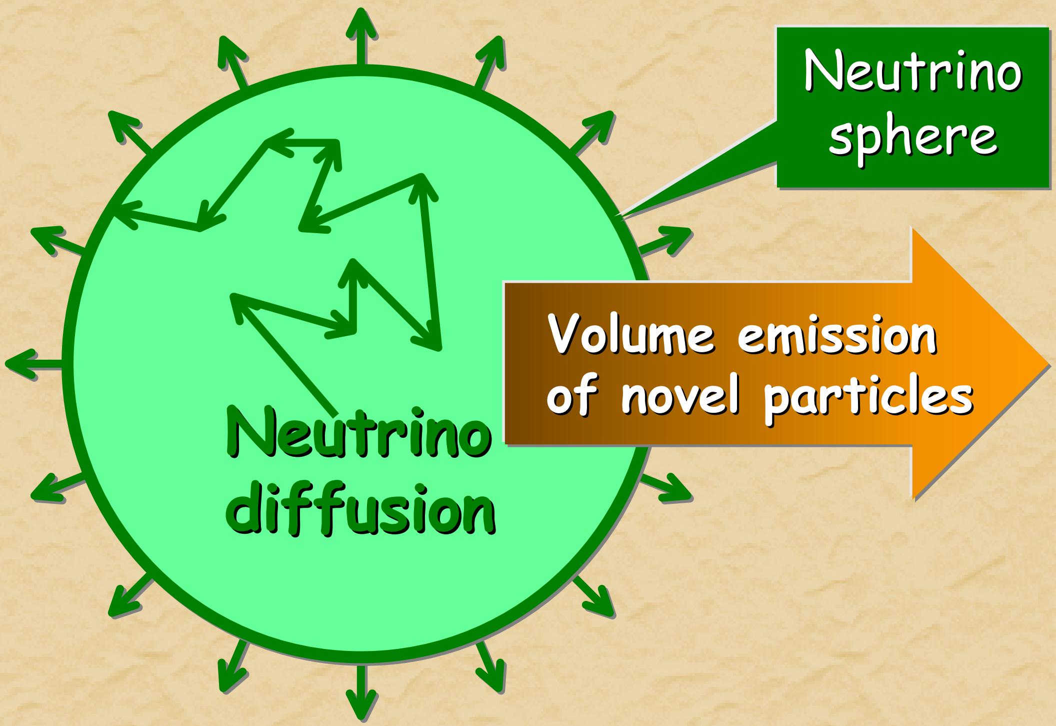
Super-Kamiokande sensitivity $m_\nu \sim 1.8$ eV

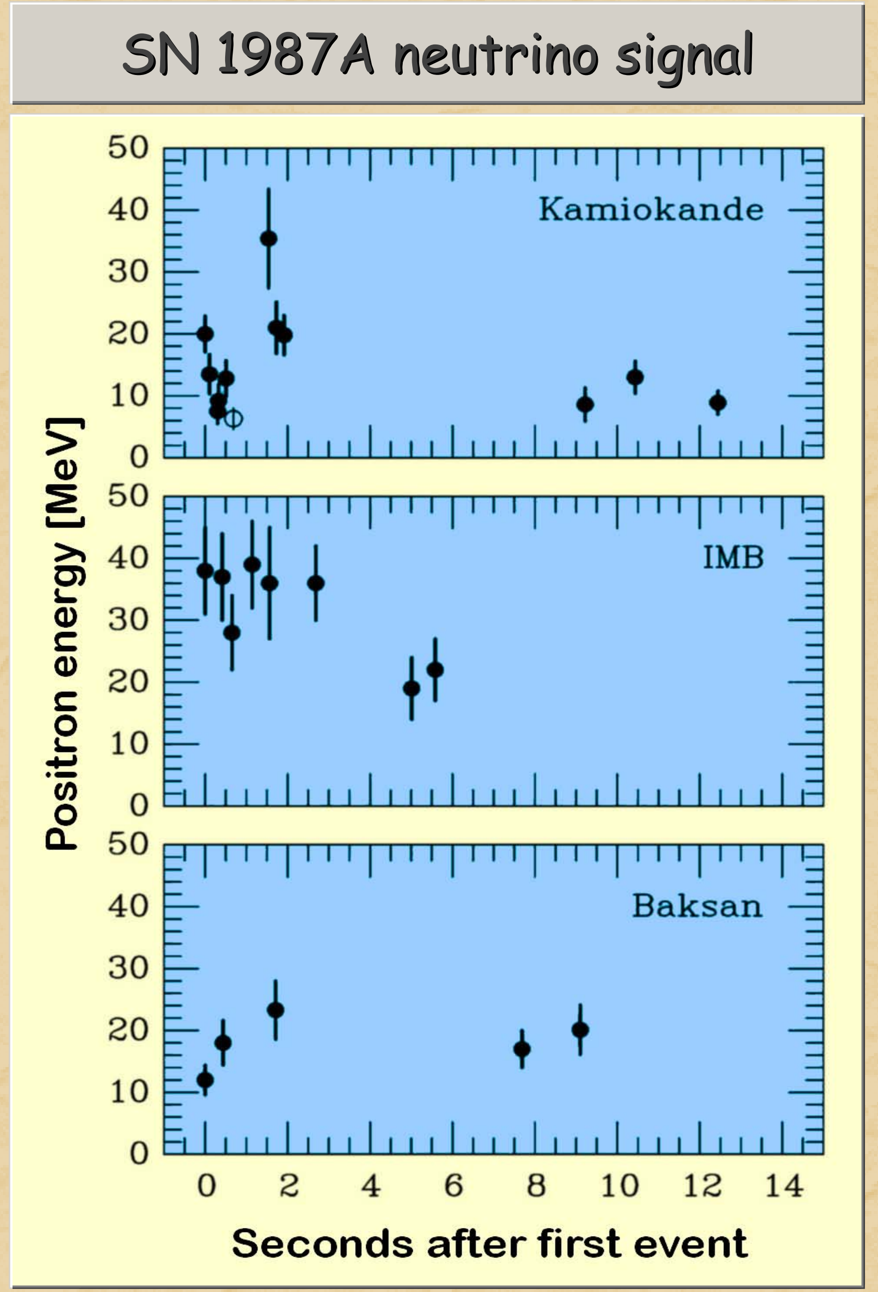
Neutrino Mass Limits and Future Sensitivity

Tritium endpoint	Mainz/Troitsk	2.5 eV
	KATRIN	0.3 eV
Supernova Nus Time-of-flight	SN 1987A	20 eV
	Super-Kamiokande	3 eV
	with black hole	2 eV
	with gravity waves	1 eV
Cosmic structure	2dF Redshift Survey	0.8 eV
	Sloan Digital Sky Survey	0.3 eV

- Assume 3 mass eigenstates with very small mass differences as indicated by atmospheric and solar neutrinos
- The cosmological limit refers to $m_\nu = \Sigma\, m_\nu/3$

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

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

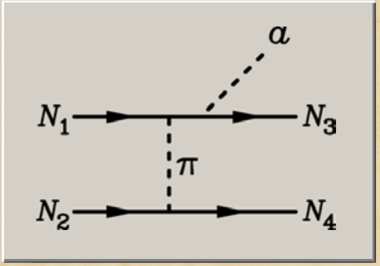
for $\rho \approx 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$ and $T \approx 30$ MeV

Axion Emission Processes in Stars

Nucleons

$$\frac{C_N}{2f_a}\overline{\Psi}_N\gamma_\mu\gamma_5\Psi_N\,\partial^\mu a$$

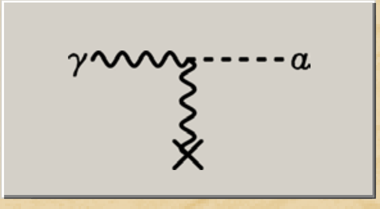
Nucleon Bremsstrahlung



Photons

$$\frac{C_e}{2f_a}\overline{\Psi}_e\gamma_\mu\gamma_5\Psi_e\,\partial^\mu a$$

Primakoff

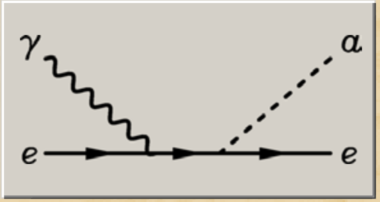


Electrons

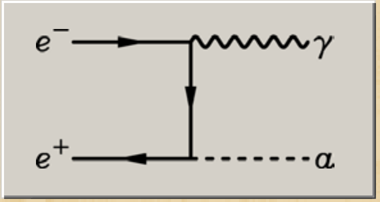
$$C_\gamma\,\frac{\alpha}{2\pi f_a}\,\frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}a$$

$$= -C_\gamma\,\frac{\alpha}{2\pi f_a}\,\vec{E}\cdot\vec{B}\,a$$

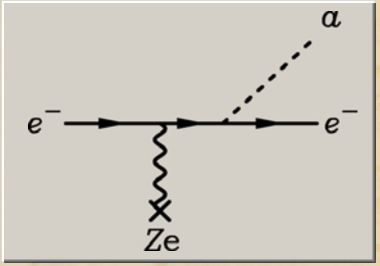
Compton



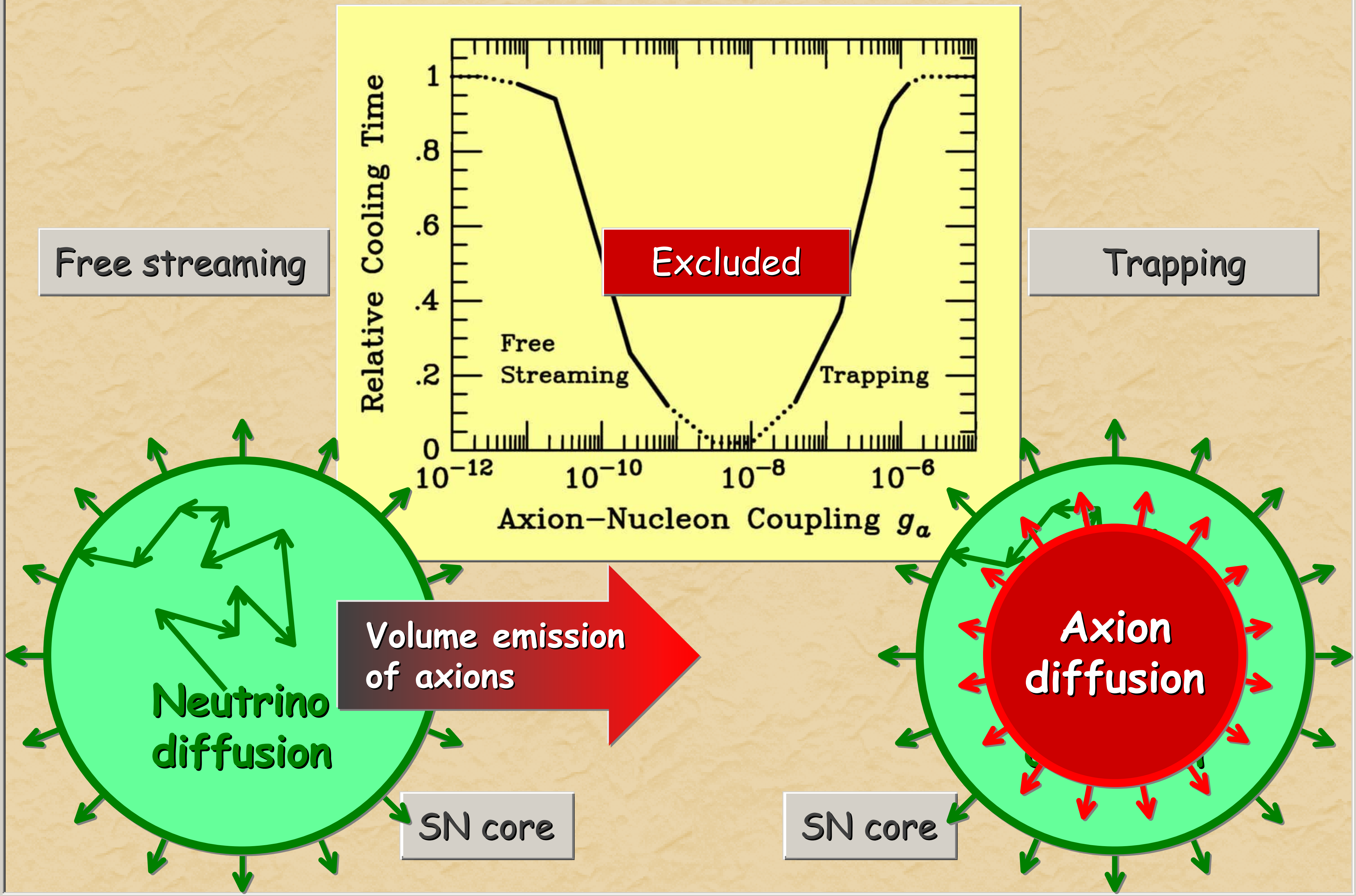
Pair Annihilation



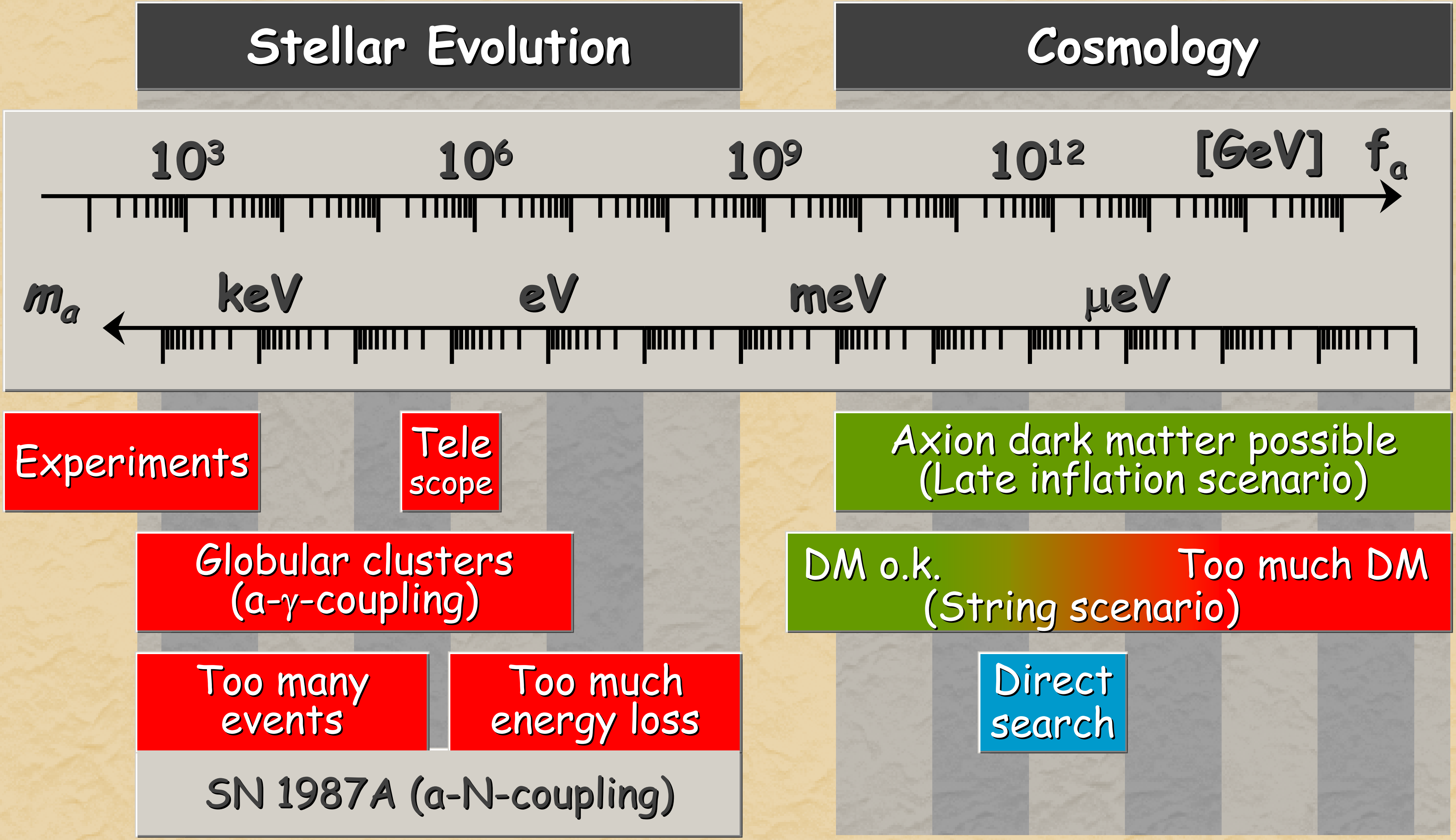
Electromagnetic Bremsstrahlung



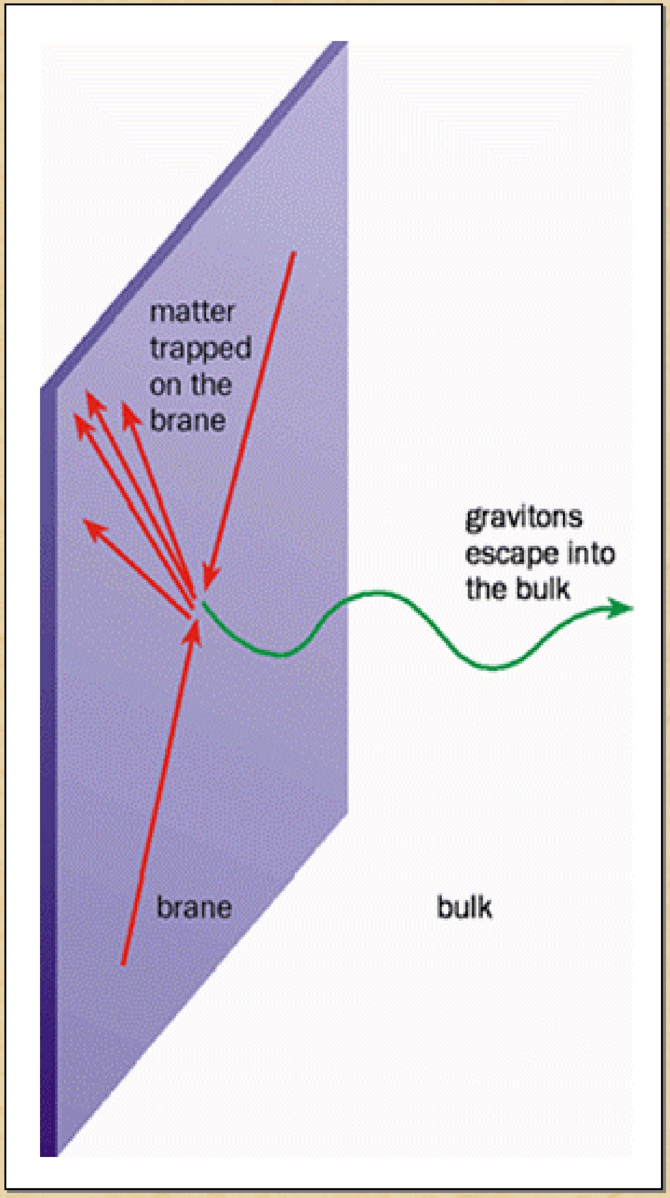
SN 1987A Axion Limits



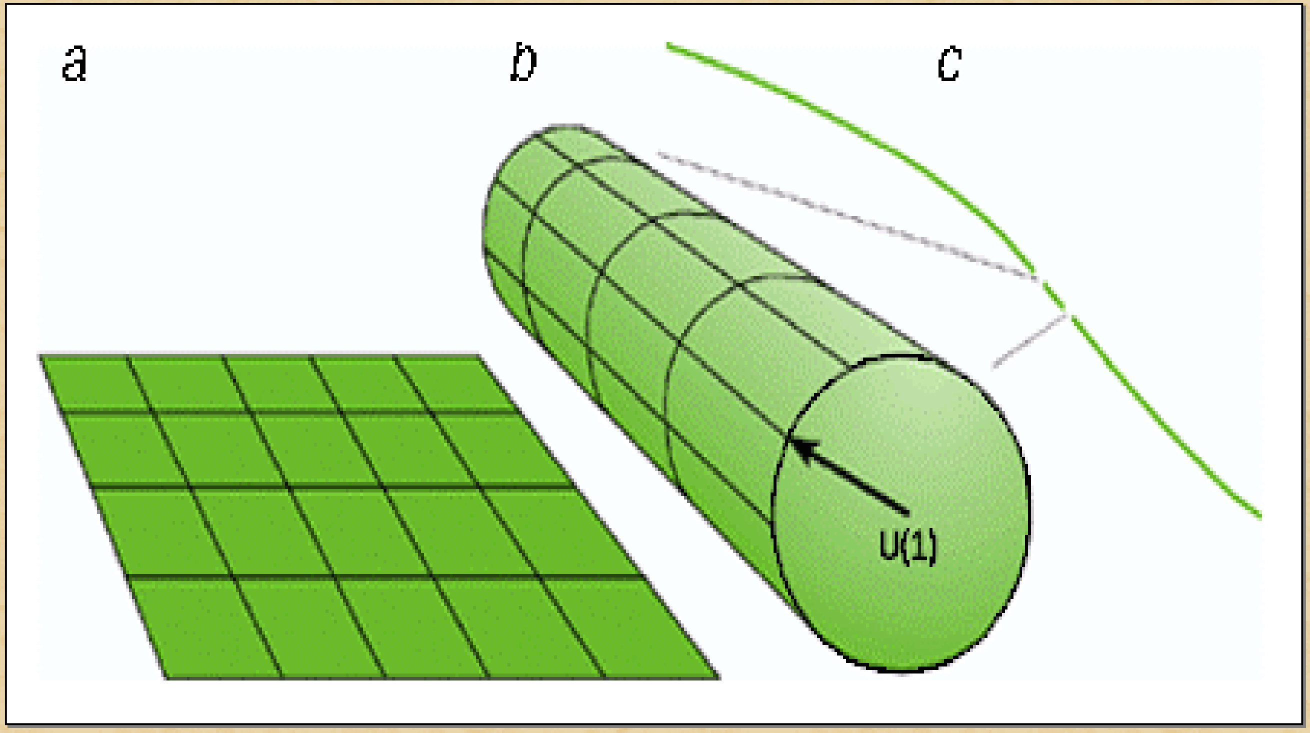
Astrophysical Axion Bounds



Large Extra Dimensions



- Fundamentally, space-time can have more than 4 dimensions (e.g. 10 or 11 in string theories)
- If standard model fields are confined to 4D brane in (4+n) D space-time, and only gravity propagates in the (4+n) D bulk, the compactification scale could be macroscopic



Supernova Limit on Large Extra Dimensions

Hierarchy problem solved by true Planck scale M being close to electro-weak scale in space with n extra dimensions, assumed to be compactified on n tori with periodicities 2πR.
Newton's law at large distances governed by $G_N^{-1} = M_{Pl}^2 \approx M^{n+2}R^n$

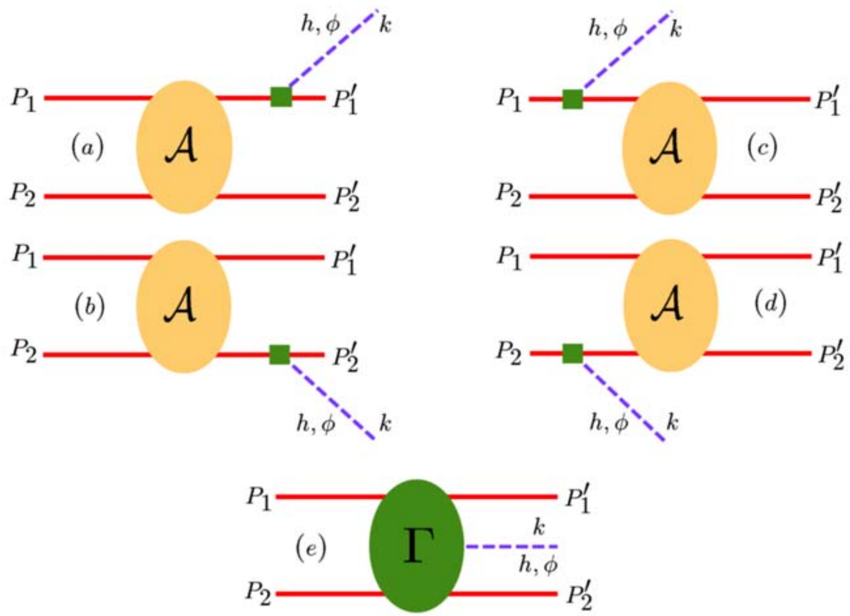


FIG. 1. *The leading diagrams contributing to processes $NN \to NNh$ and $NN \to NN\phi$. Nucleons are denoted by solid lines and the KK-modes h or ϕ are denoted by dashed lines. Solid squares denote an insertion of the single-nucleon energy-momentum tensor, while solid ovals containing $\mathcal{A}$ denote an insertion of the full NN scattering amplitude. The solid oval containing Γ denotes the non-pole vertex required for the sum of diagrams to satisfy $\partial_\mu M^{\mu\nu} = 0$.*

- SN core emits large flux of KK gravity modes by nucleon-nucleon bremsstrahlung
- Large multiplicity of modes

SN 1987A energy-loss argument:

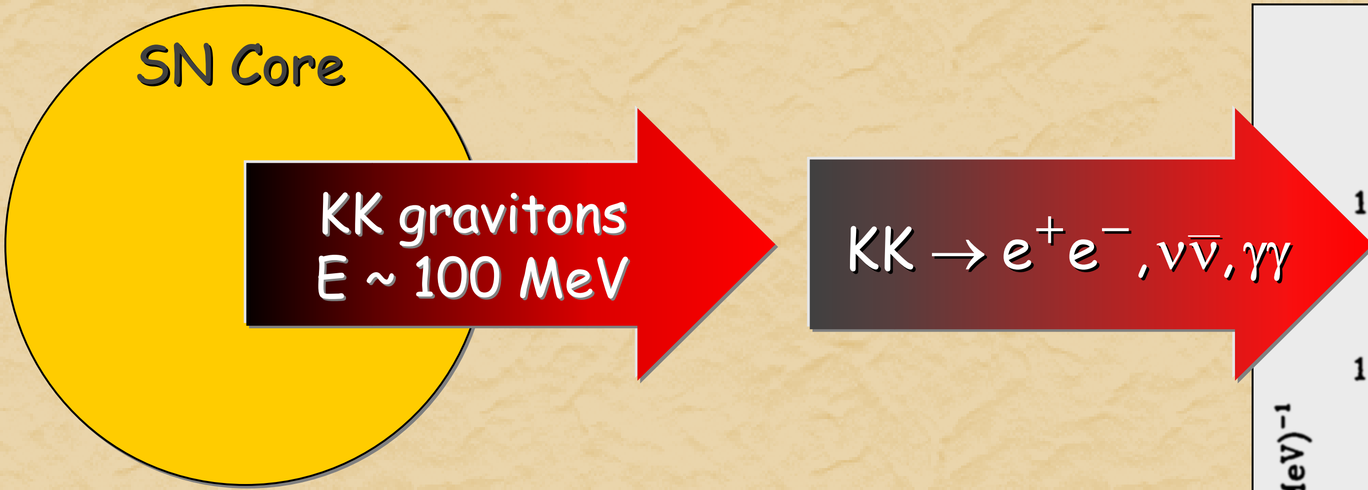
$R < 0.7 \times 10^{-3}$ mm (n = 2)

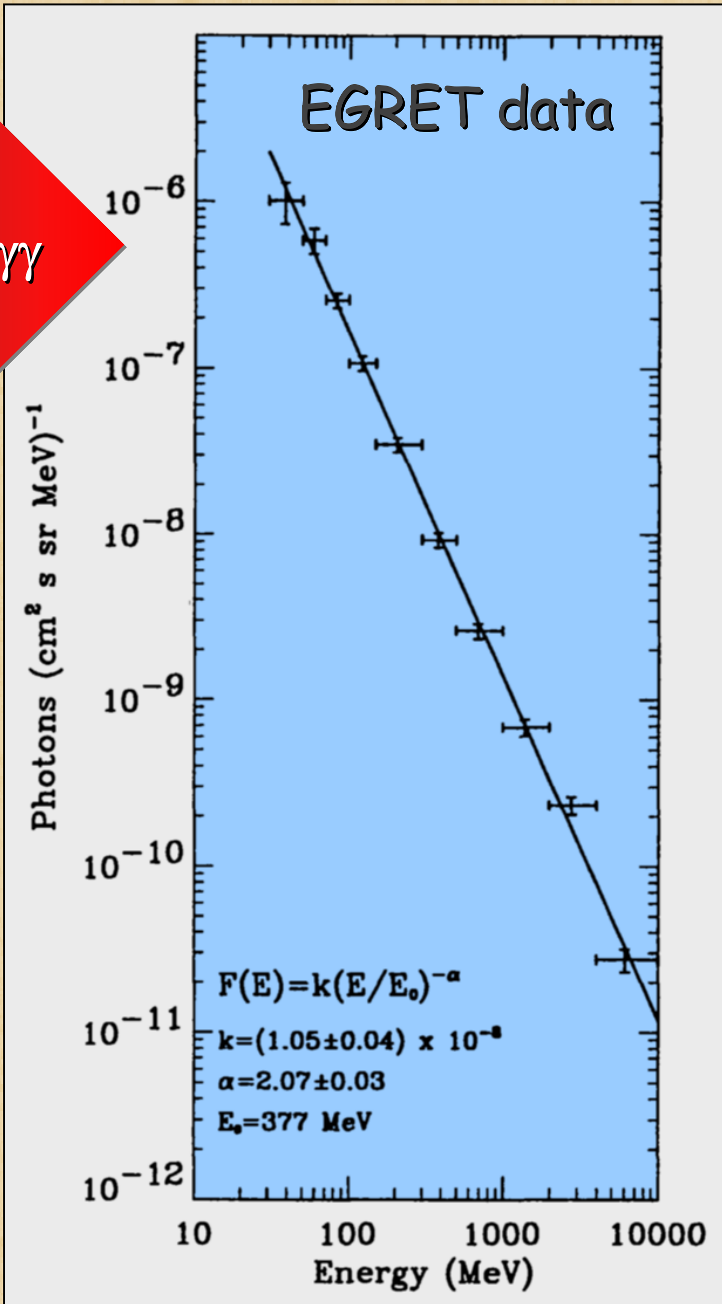
$R < 0.8 \times 10^{-6}$ mm (n = 3)

Is the most restrictive limit on such theories, except for cosmological arguments

Cullen & Perelstein, hep-ph/9904422
Hanhart et al., nucl-th/0007016

Improved Limits on Large Extra Dimensions





- From all SNe in the universe, KK decay contributes to diffuse cosmic γ-rays in 100 MeV range
- EGRET data & conservative estimate of SN rate:
  < 1 % of SN energy into KK gravitons
  i.e. 0.01 of SN 1987A cooling limit

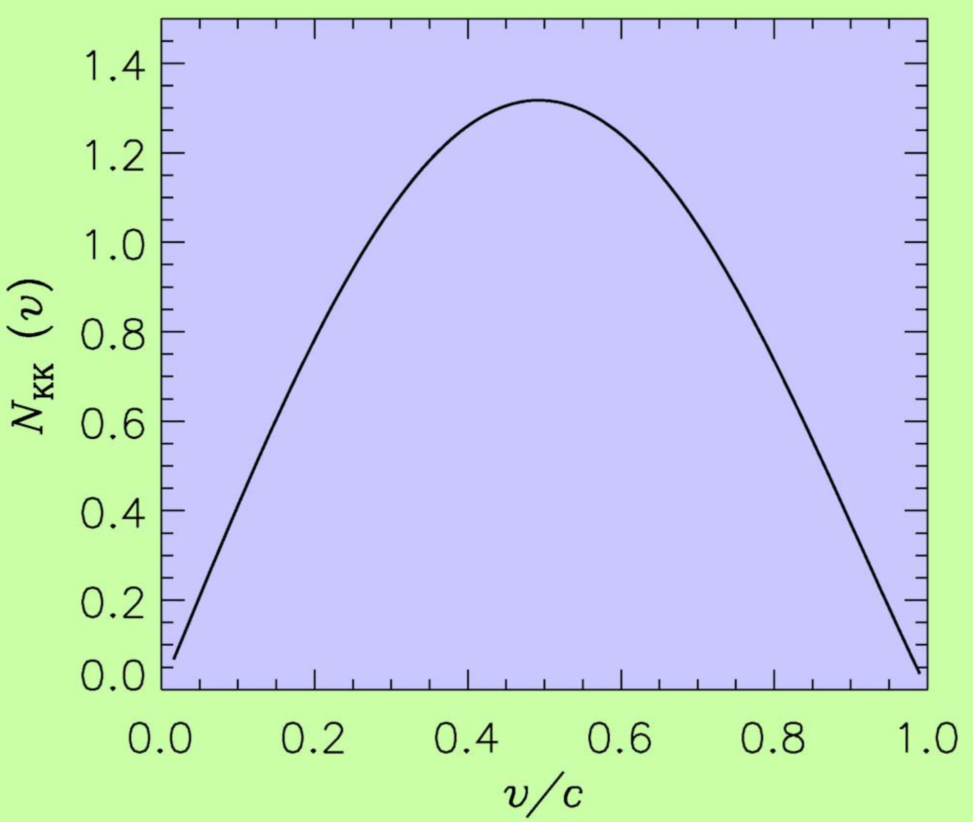
Our new limits $R < 0.1 \times 10^{-3}$ mm (n = 2)
$R < 0.2 \times 10^{-6}$ mm (n = 3)

Hannestad & Raffelt, hep-ph/0103201

KK Graviton Retention by Neutron Star

$$v_{escape} = \sqrt{\frac{2GM}{R}} \approx 0.6c$$

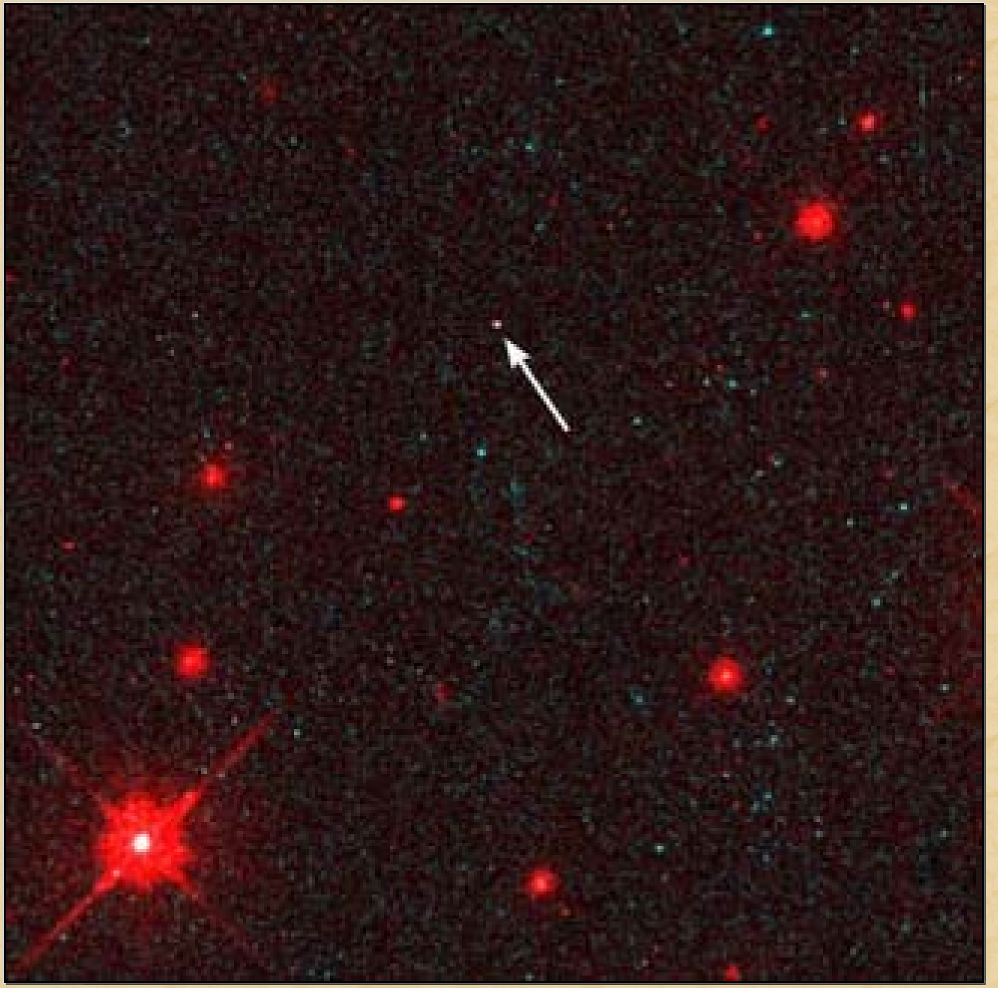
- Neutron stars retain 50-60% of KK gravitons in a halo
- Emits γ rays by KK decays



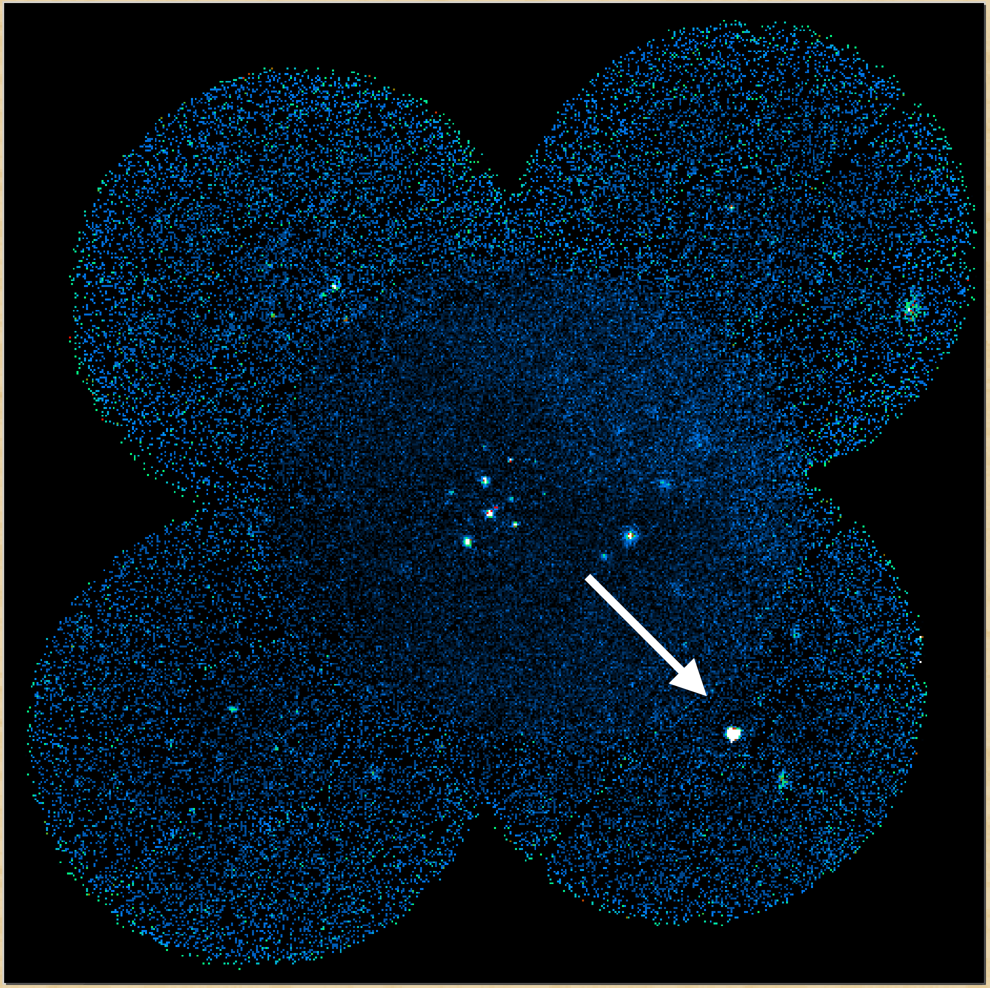
Velocity distribution of KK-gravitons emitted by supernova

Nearby Neutron Star RX J185635-3754

D = 61 pc (closest known neutron star), Age ~ 1.2×10^6 yr

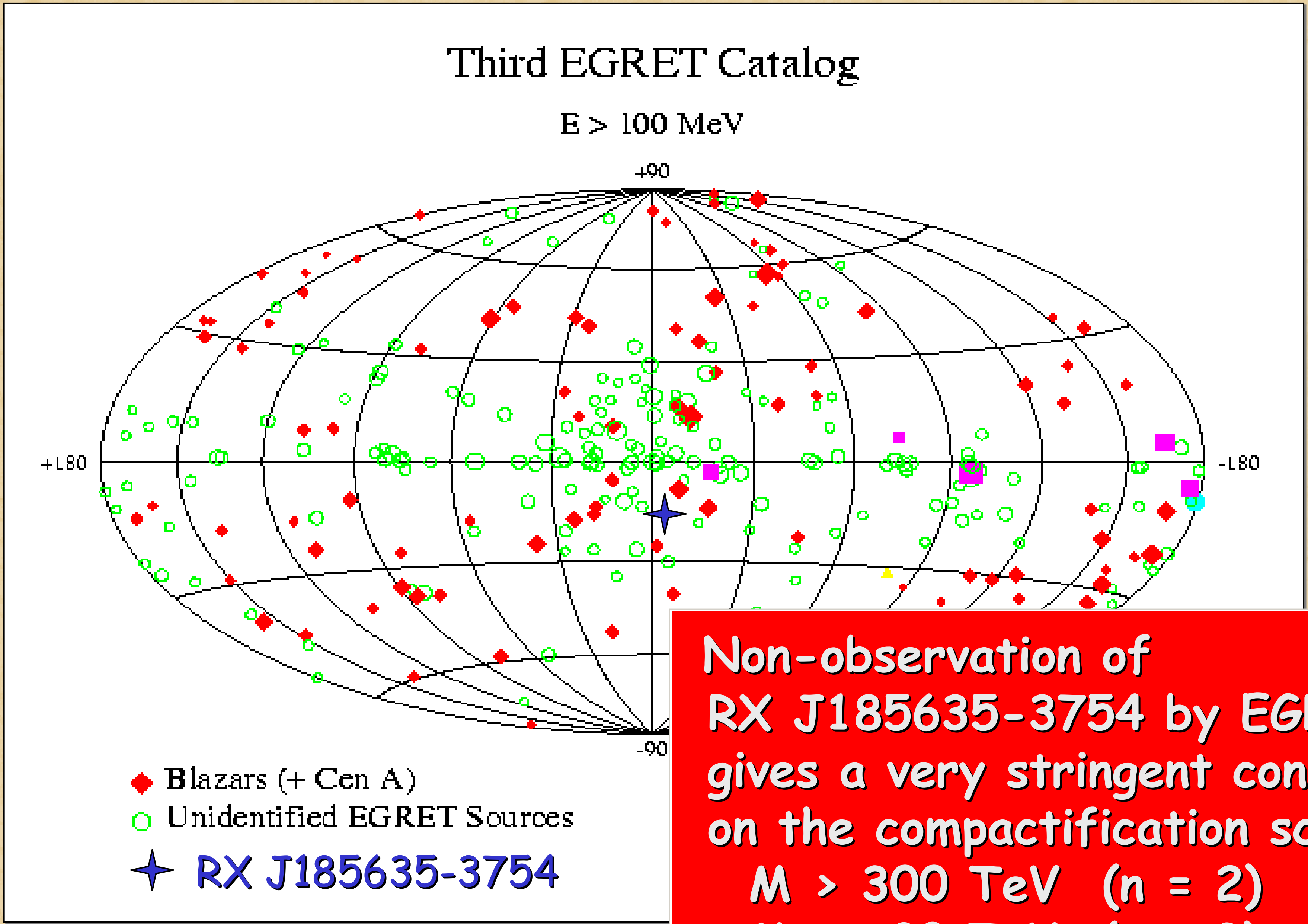


HST Image
(Walter & Matthews 1997)



ROSAT Image
(Walter, Wolk & Neuhauser 1996)

Third EGRET Catalog (Hartmann et al. 1999)



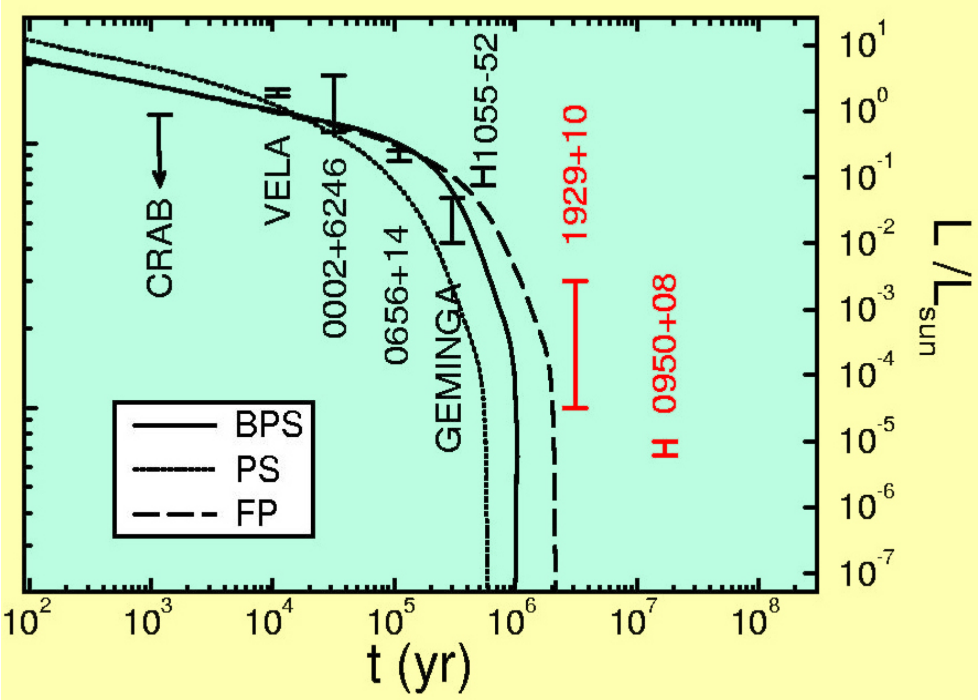
Non-observation of
RX J185635-3754 by EGRET
gives a very stringent constraint
on the compactification scale:

$M > 300$ TeV $(n = 2)$
$M > 20$ TeV $(n = 3)$

Neutron Star Excess Heat

- Neutron stars retain 50-60% of KK gravitons in a halo
- Emits γ rays by KK decays

Neutron star cooling calculations vs. observations (Pavlov, Stringfellow & Cordova 1996, Larson & Link 1999)



To avoid excess heating by KK decay

M > 1600 TeV (n = 2)

M > 60 TeV (n = 3)

Summary of Limits on Large Extra Dimensions

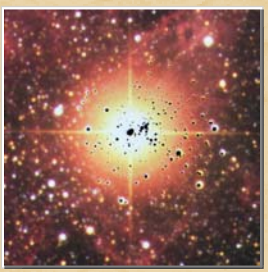
		M^{min} [TeV]		R^{max} [mm]	
		n = 2	n = 3	n = 2	n = 3
Laboratory experiments		0.6	-	0.2	-
SN 1987A neutrino signal		30	3	7×10^{-4}	8×10^{-7}
EGRET	Cosmic SNe	84	7	8×10^{-5}	2×10^{-7}
	Cas A	73	7	1×10^{-4}	2×10^{-7}
	PSR J0953+0755	300	19	8×10^{-6}	4×10^{-8}
	RX J185635-3754	454	27	3×10^{-6}	2×10^{-8}
Excess heat PSR J0953+0755		1680	60	2×10^{-7}	5×10^{-9}

Hannestad & Raffelt, PRL 88 (2002) 071301 [hep-ph/0103201]

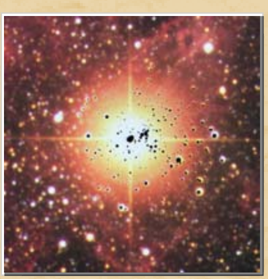
Lecture I: Physics with Supernovae

Physical Mechanism of
Core-Collapse Supernovae

Supernova Neutrino Detection



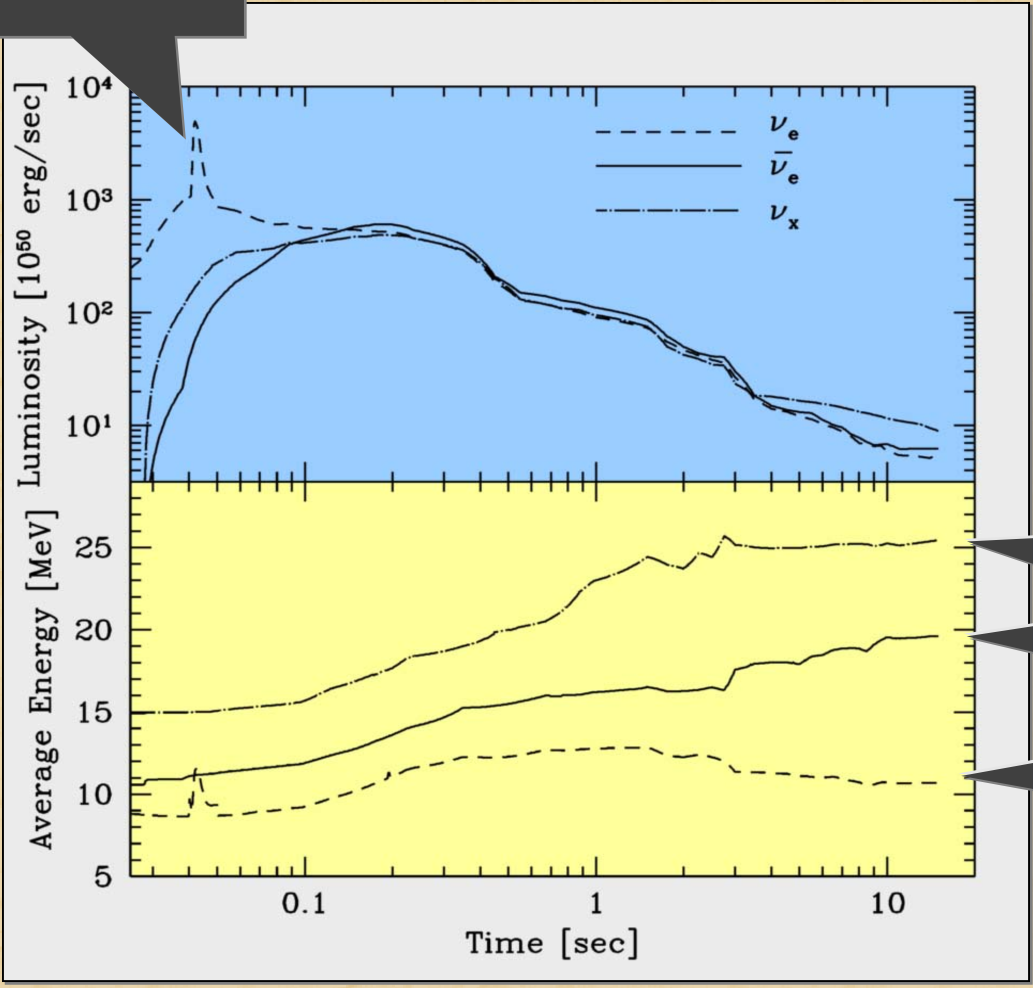
Limits on Particle Properties



Flavor Oscillations
of Supernova Neutrinos

Flavor-Dependent Fluxes and Spectra

Prompt ν_e deleptonization burst



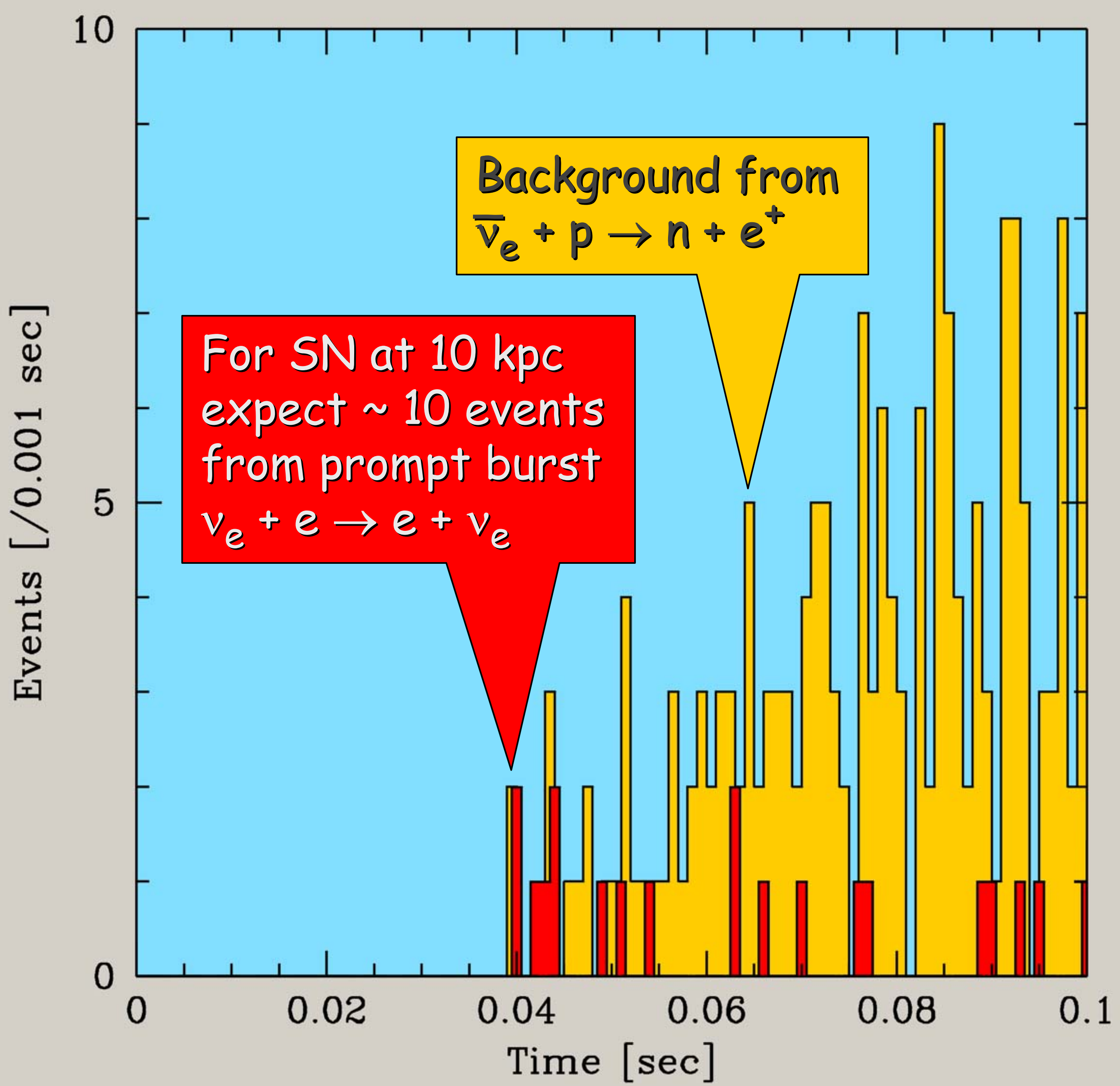
ν_x

$\bar{\nu}_e$

ν_e

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

Can we see the prompt neutrino burst?



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

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

Neutrino Spectra Formation

G.Raffelt
astro-ph/0105250

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 (NS)

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

$\nu N \leftrightarrow N \nu$

$\nu e \leftrightarrow \nu e$

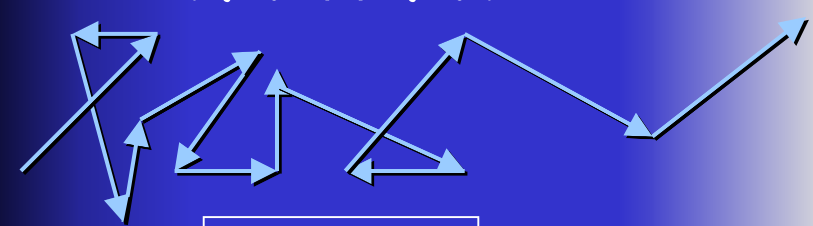
$NN \leftrightarrow NN\nu\bar{\nu}$

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

Thermal Equilibrium

Scattering Atmosphere

$\nu N \leftrightarrow N \nu$



Diffusion

Free streaming

Energy sphere (ES)

Transport sphere

Neutrino Spectra Formation

G.Raffelt
astro-ph/0105250

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

Thermal Equilibrium

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

$\nu_e\, n \leftrightarrow p\, e^-$

T_{NS}

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

Neutrino sphere (NS)

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

$\nu N \leftrightarrow N \nu$

$\nu e \leftrightarrow \nu e$

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

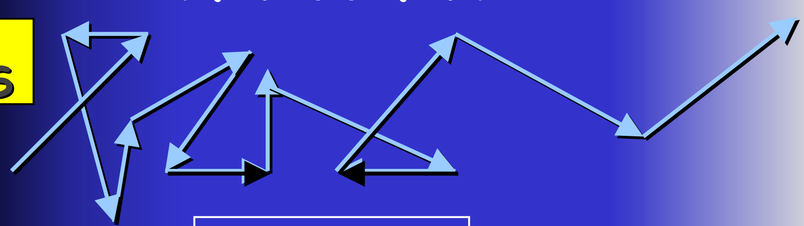
$e^+ e^- \leftrightarrow \nu \bar{\nu}$

Thermal Equilibrium

Scattering Atmosphere

$\nu N \leftrightarrow N \nu$

T_{ES}



Diffusion

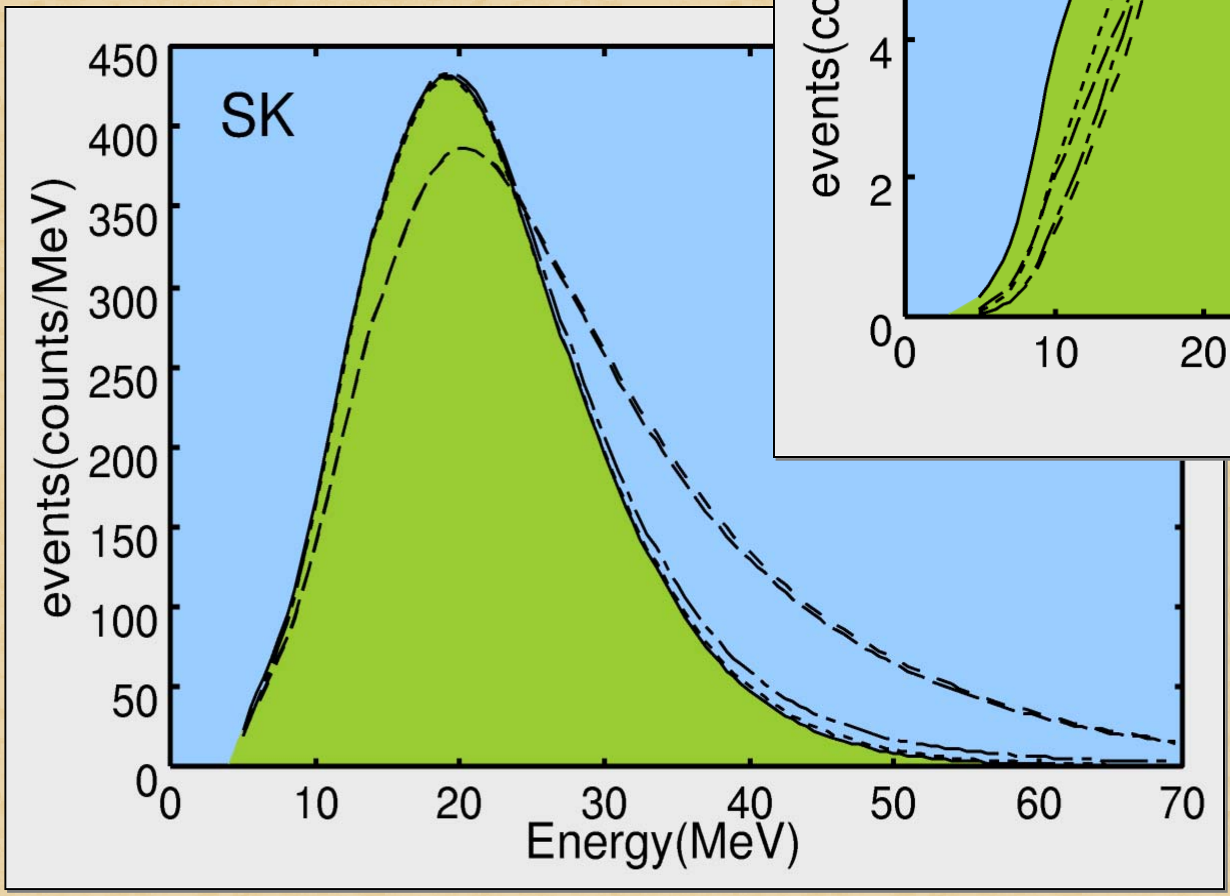
$T_{flux} \sim 0.6 T_{ES}$

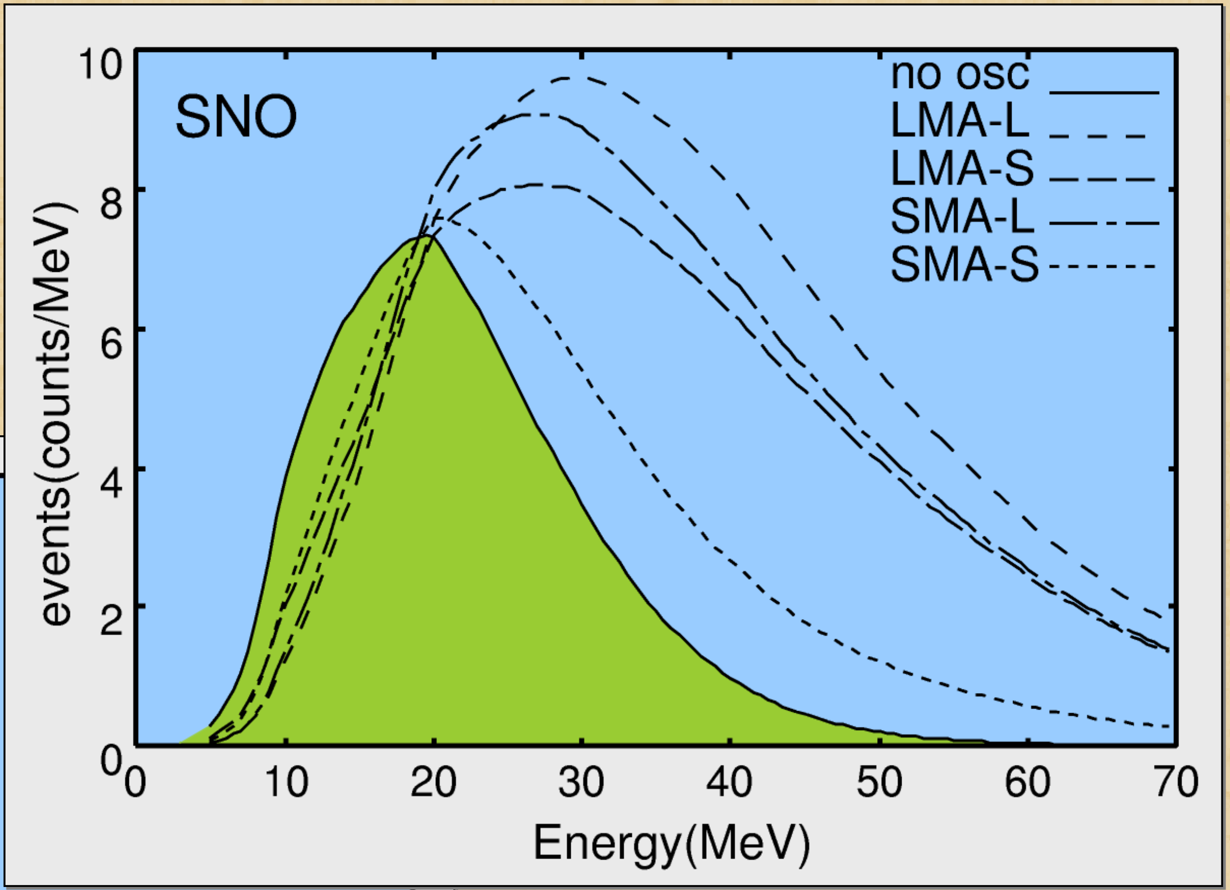
Energy sphere (ES)

Transport sphere

Three-Flavor Oscillation Scenario

Takahashi, Watanabe & Sato, hep-ph/0105204

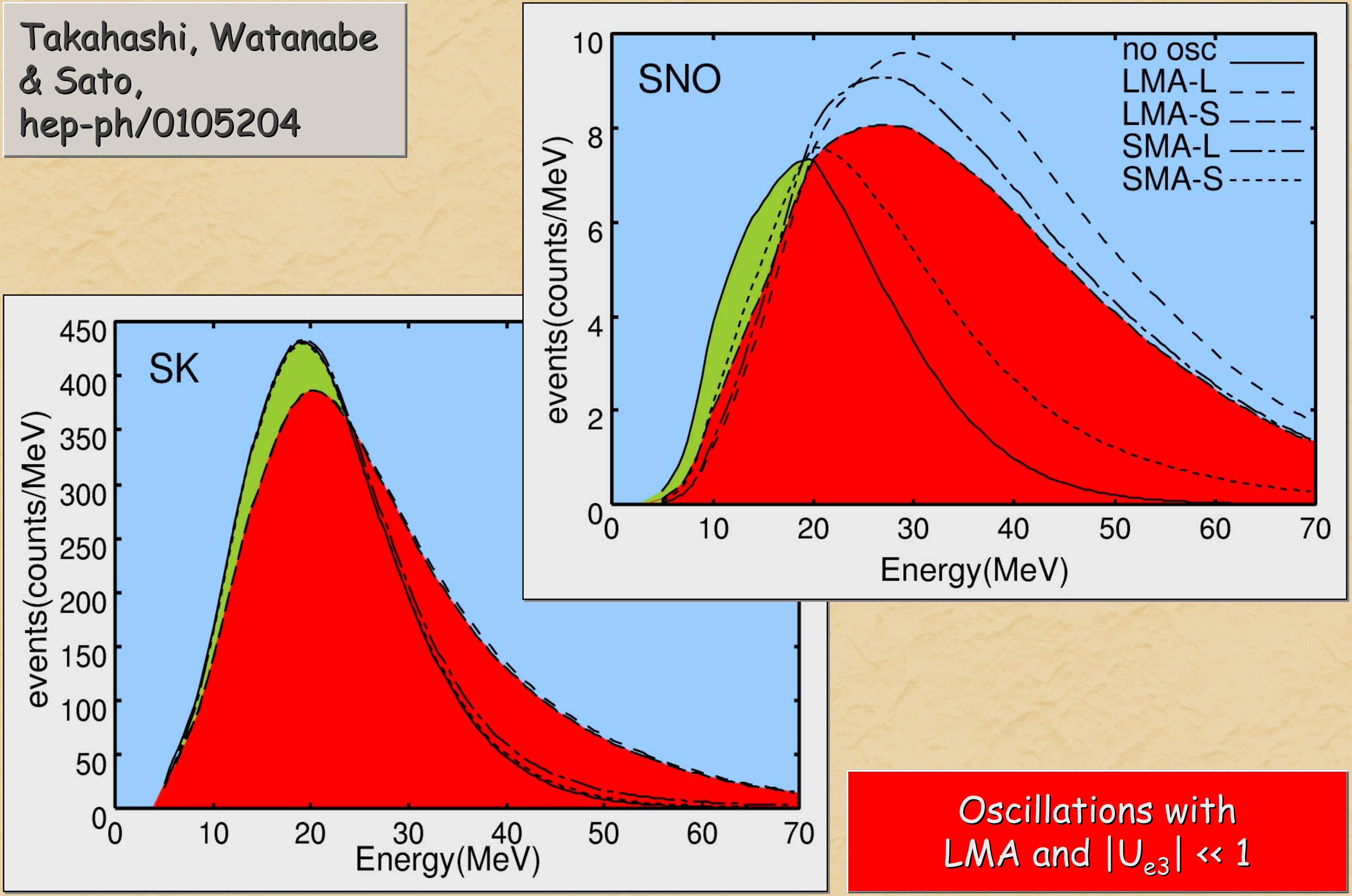




No Oscillations

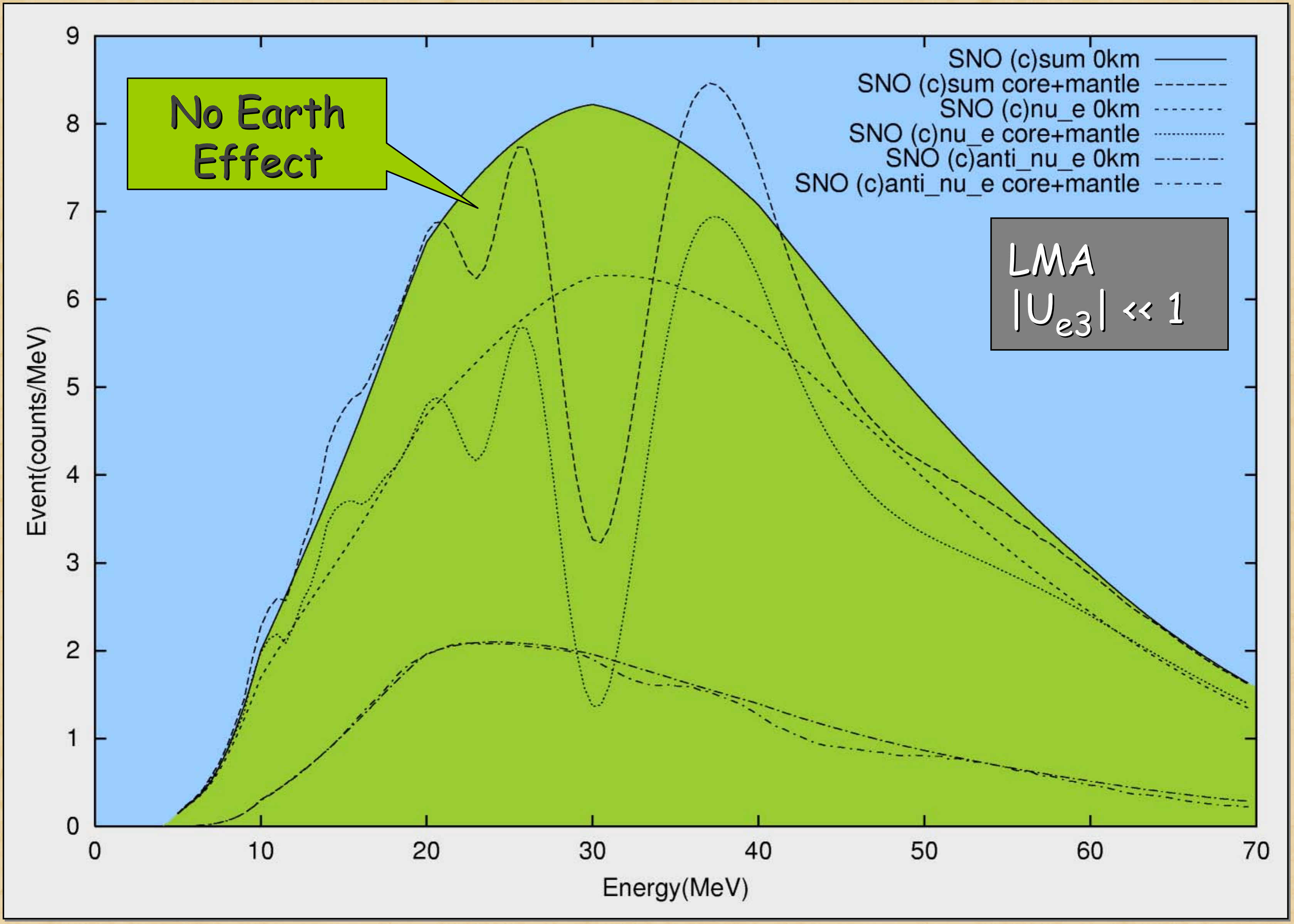
Three-Flavor Oscillation Scenario

Takahashi, Watanabe & Sato, hep-ph/0105204



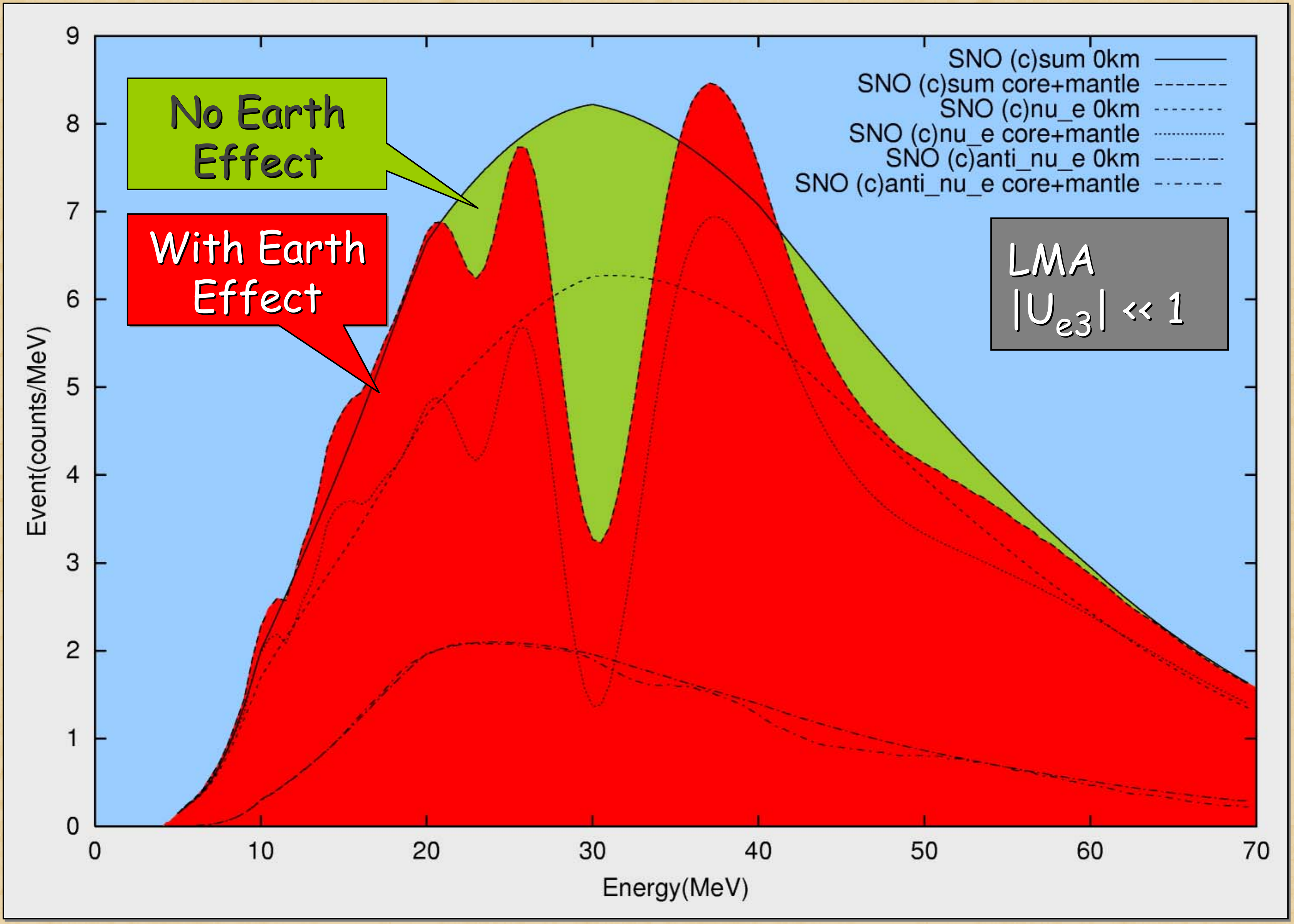
Oscillations with LMA and $|U_{e3}| \ll 1$

Earth Effect at SNO



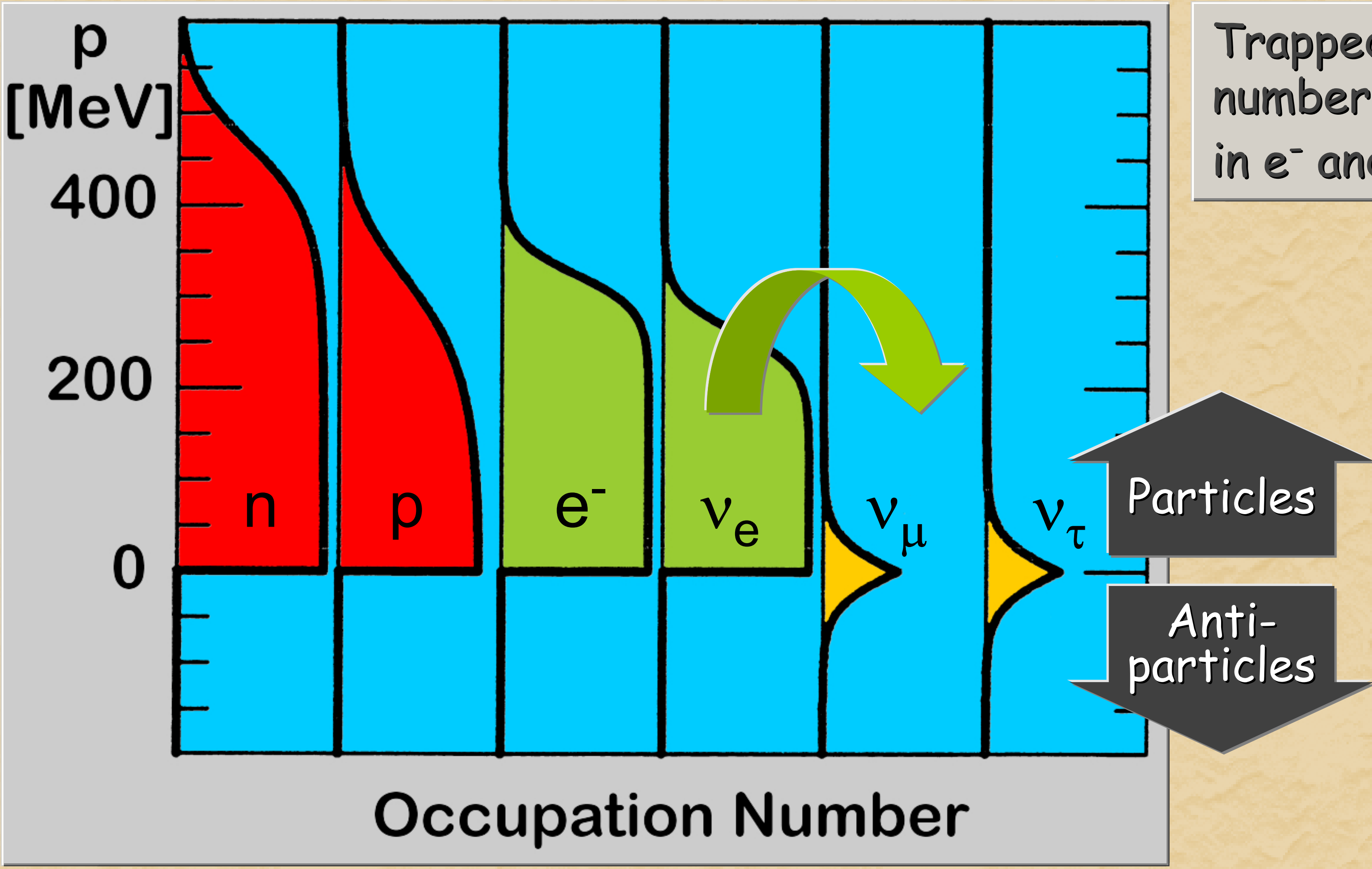
Takahashi, Watanabe & Sato, hep-ph/0012354

Earth Effect at SNO



Takahashi, Watanabe & Sato, hep-ph/0012354

Degenerate Fermi Seas in a Supernova Core



Trapped lepton number is stored in e^- and ν_e

In true thermal equilibrium with flavor mixing only one chemical potential for charged leptons and one for neutrinos

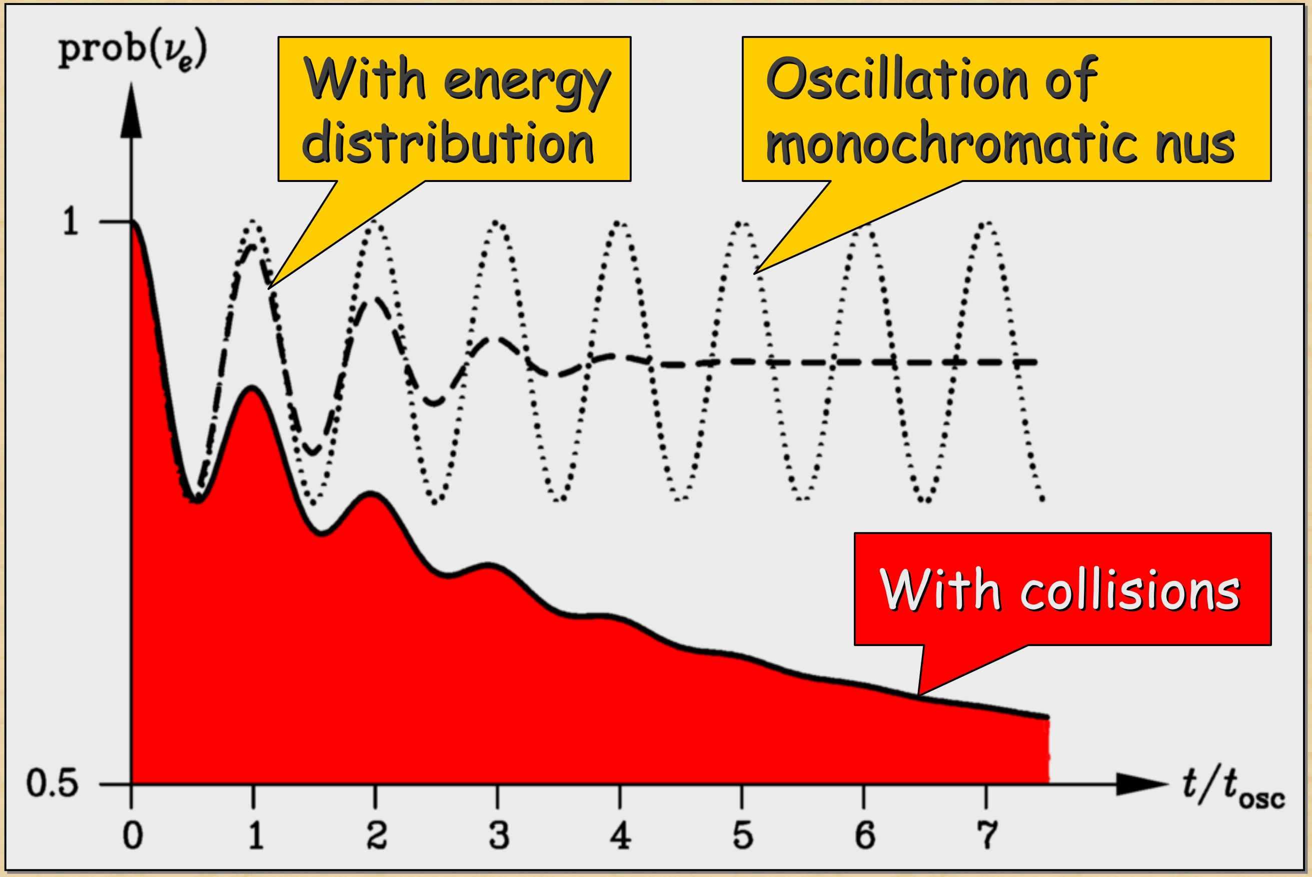
Time scale to achieve flavor equilibrium?

Flavor Relaxation in a Supernova Core

Neutrinos suffer collisions in a medium that can interrupt the coherence of flavor oscillations: The flavor content is "measured" and oscillations start from scratch from the "collapsed state".

Average oscillation probability $\frac{1}{2}\sin^2(2\Theta)$
Collision rate ~ damping rate Γ

→ Conversion rate $\frac{1}{2}\sin^2(2\Theta)\,\Gamma$

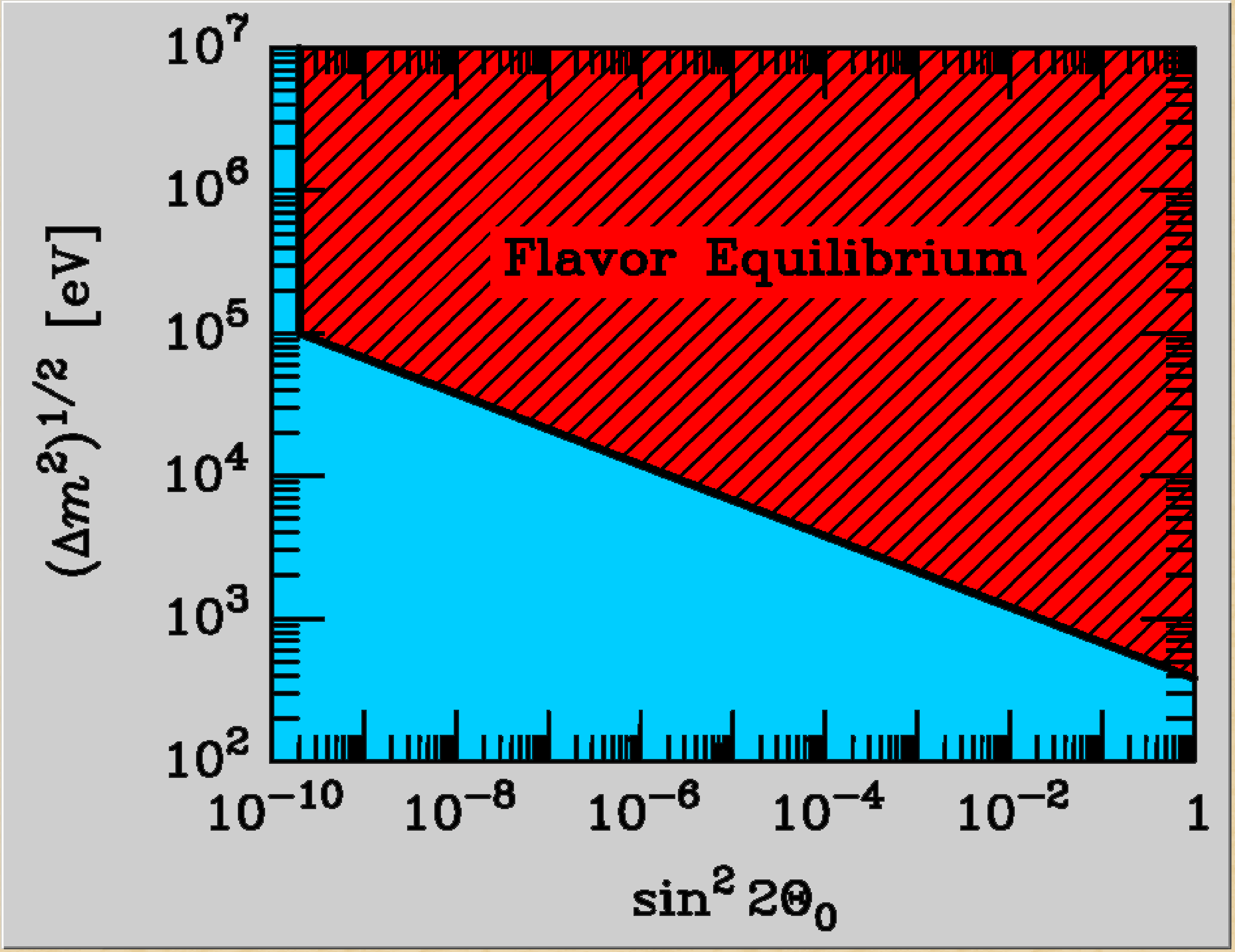


Θ is the mixing angle in the medium.
In a SN core, the weak potential corresponds to Δm ~ 10-100 keV

↓

Vast suppression of flavor conversion for sub-eV masses.

Flavor Conversion in a Supernova Core



Within ~ 1 sec flavor equilibrium is achieved between ν_e and ν_μ or ν_τ

Suppression of mixing angle by medium effects responsible for flavor-lepton number conservation in a supernova core

Conclusions of Lecture I

- Core-collapse supernova explosions probably explained by neutrino-driven delayed explosion mechanism
- But thus far no working numerical standard model
- Convection key to successful explosion?

High-statistics observation of a galactic SN is

- Crucial for empirical study of core-collapse event
- Not sensitive to sub-eV neutrino masses
- May differentiate between some mixing scenarios

If neutrino mixing parameters in currently favored regions

- Neutrino flavor oscillations not important for SN physics
- But crucial for detector signal interpretation
- Sterile nus and/or dipole moments can have strong effects

- Particle emission by supernova cores continues to provide most restrictive limits on various theories (axions, r.h. neutrinos, extra dimensions, ...)
- High-statistics observation would put these on firm grounds