Dark Matter and Neutrinos, IHP, Paris, 5–9 May 2025

Supernova Neutrinos

ORIGINS Excellence Cluster

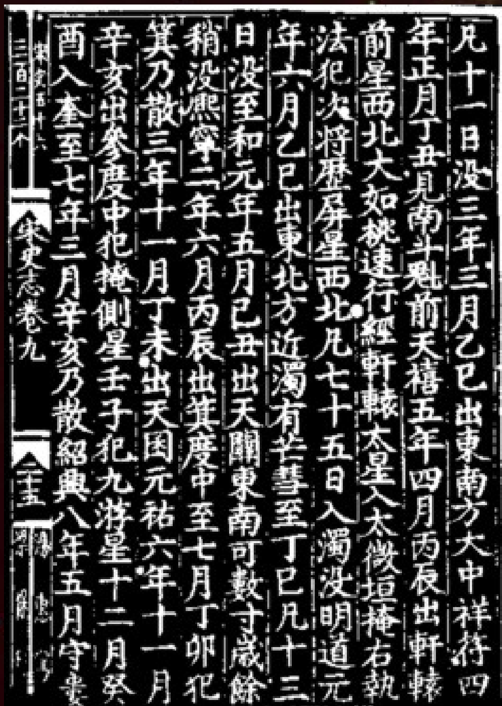
COSMIC WISPERS CA21106

MAX-PLANCK-INSTITUT FÜR PHYSIK

SFB 1258 Neutrinos Dark Matter Messengers

Georg G. Raffelt, Max-Planck-Institut für Physik, Garching

Crab Nebula – Remnant of SN 1054

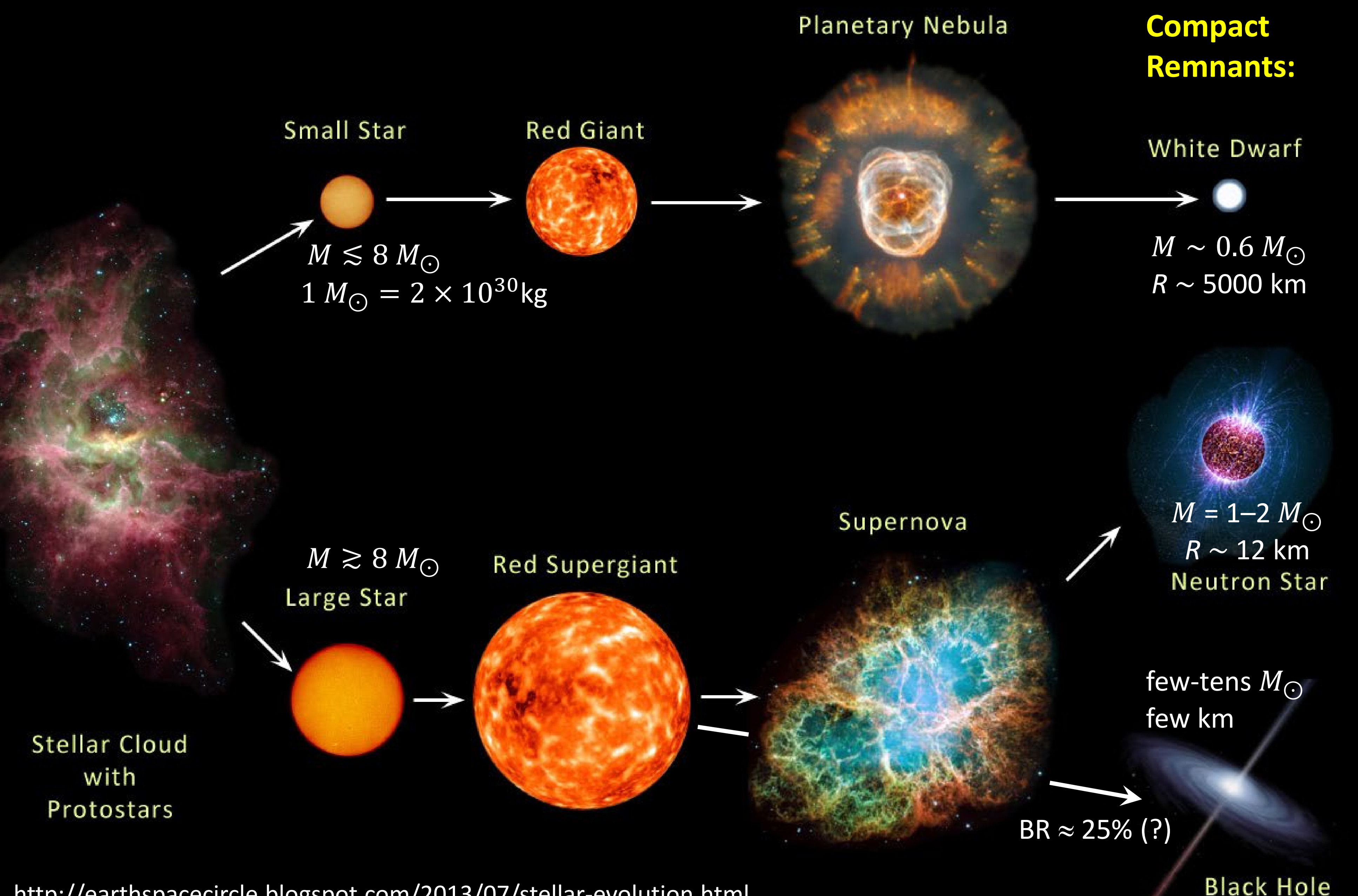


凡十一日没三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁没明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日没至和元年五月己丑出天關東南可數寸歲餘
稍没熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

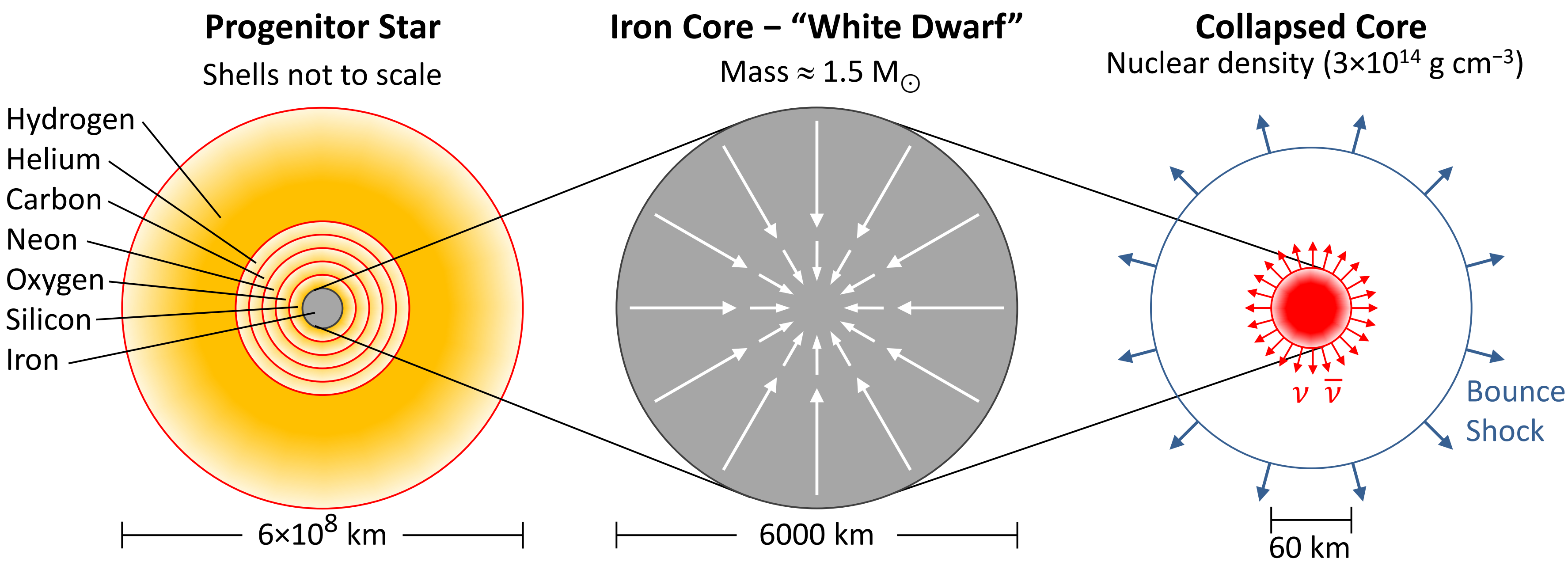
Crab Pulsar
Chandra X-ray composite image

EVOLUTION OF STARS



http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html

Stellar Collapse and Explosion



Gravitational binding energy

$$E_b \approx 3 \times 10^{53}\ \text{erg} \approx 15\%\ M_{SUN}\, c^2$$

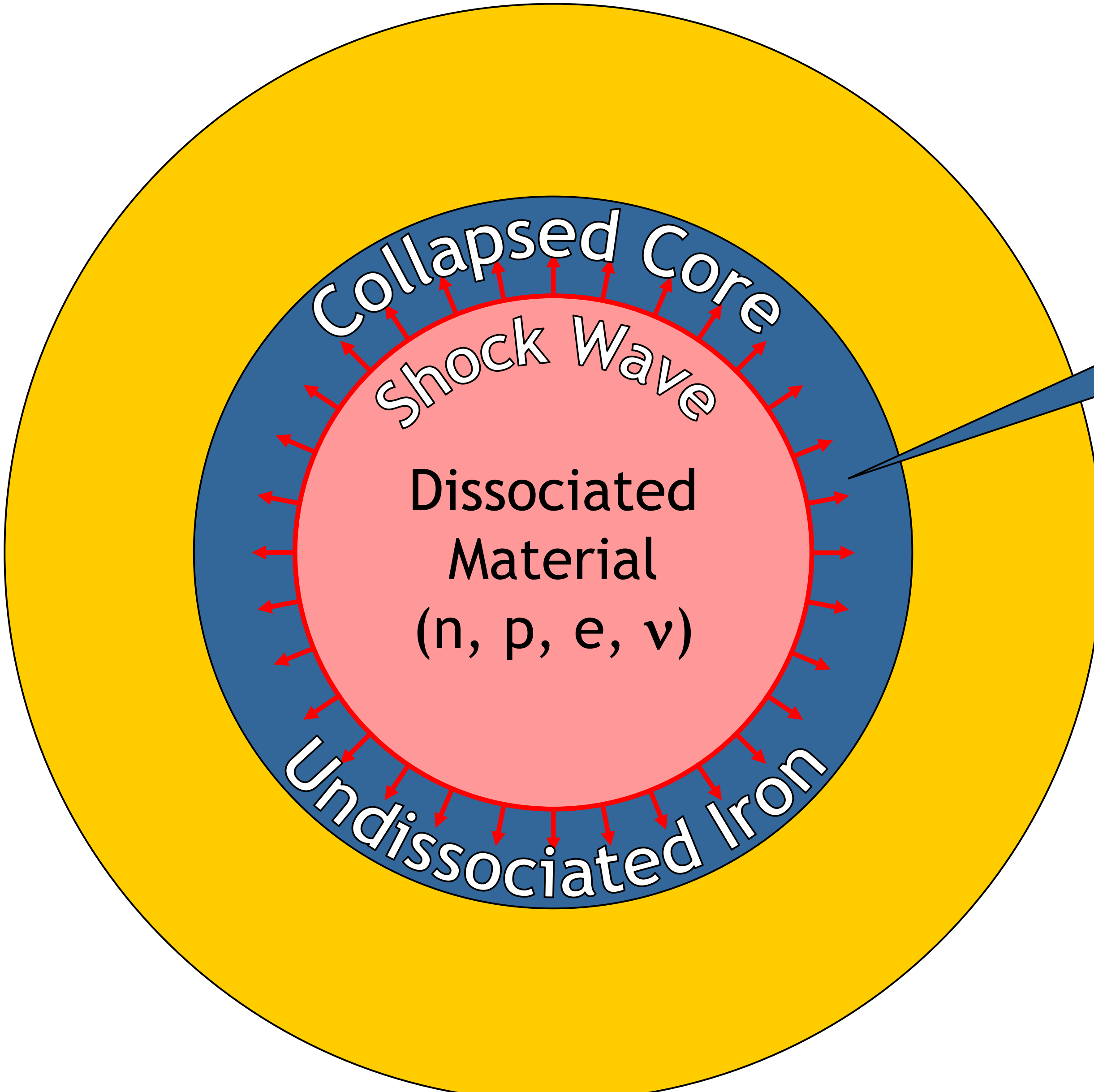
This shows up as

99% Neutrinos

1% Kinetic energy of explosion

0.01% Photons, outshine host galaxy

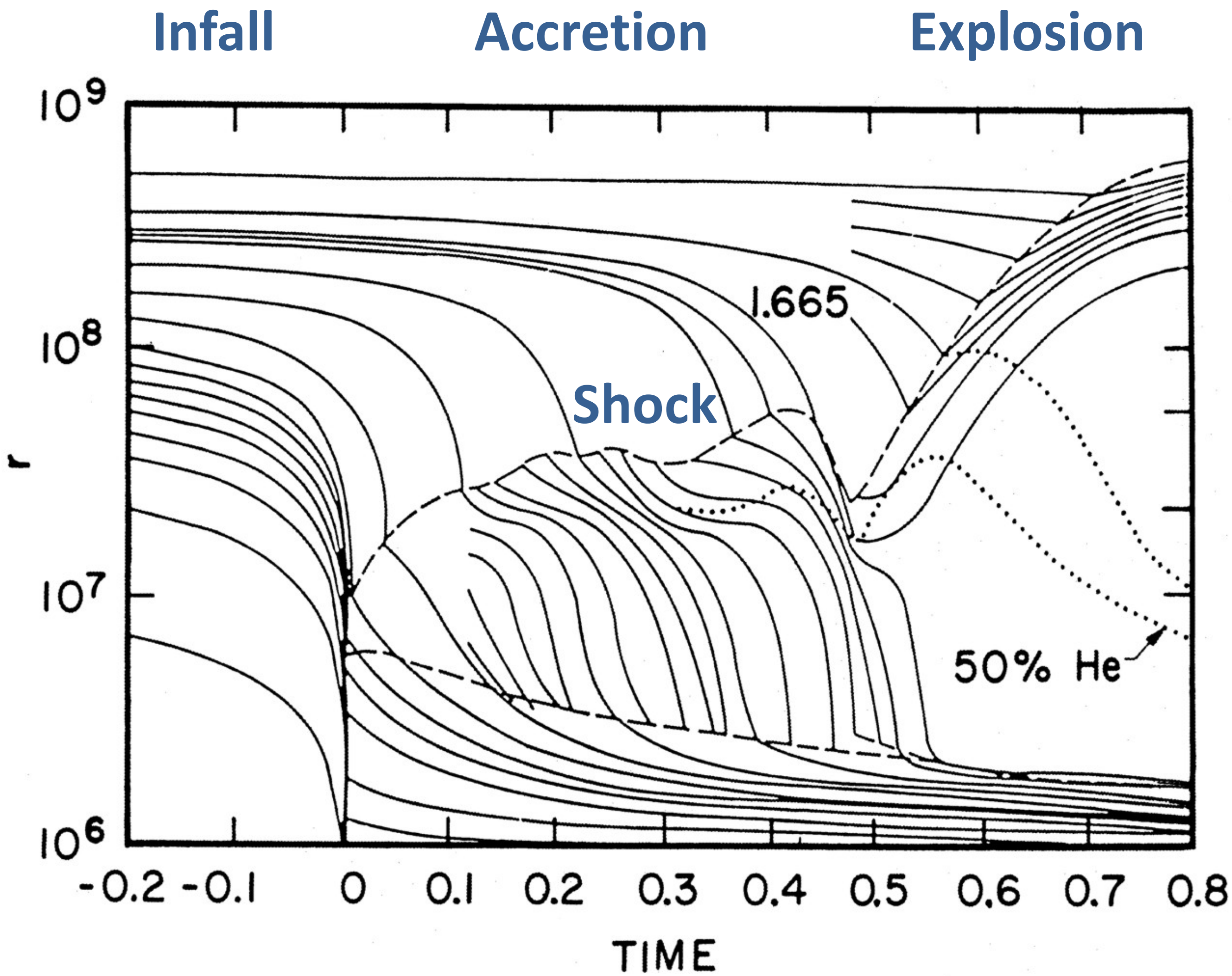
Why No Prompt Explosion?



- 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 (Neutrino-Driven) Explosion

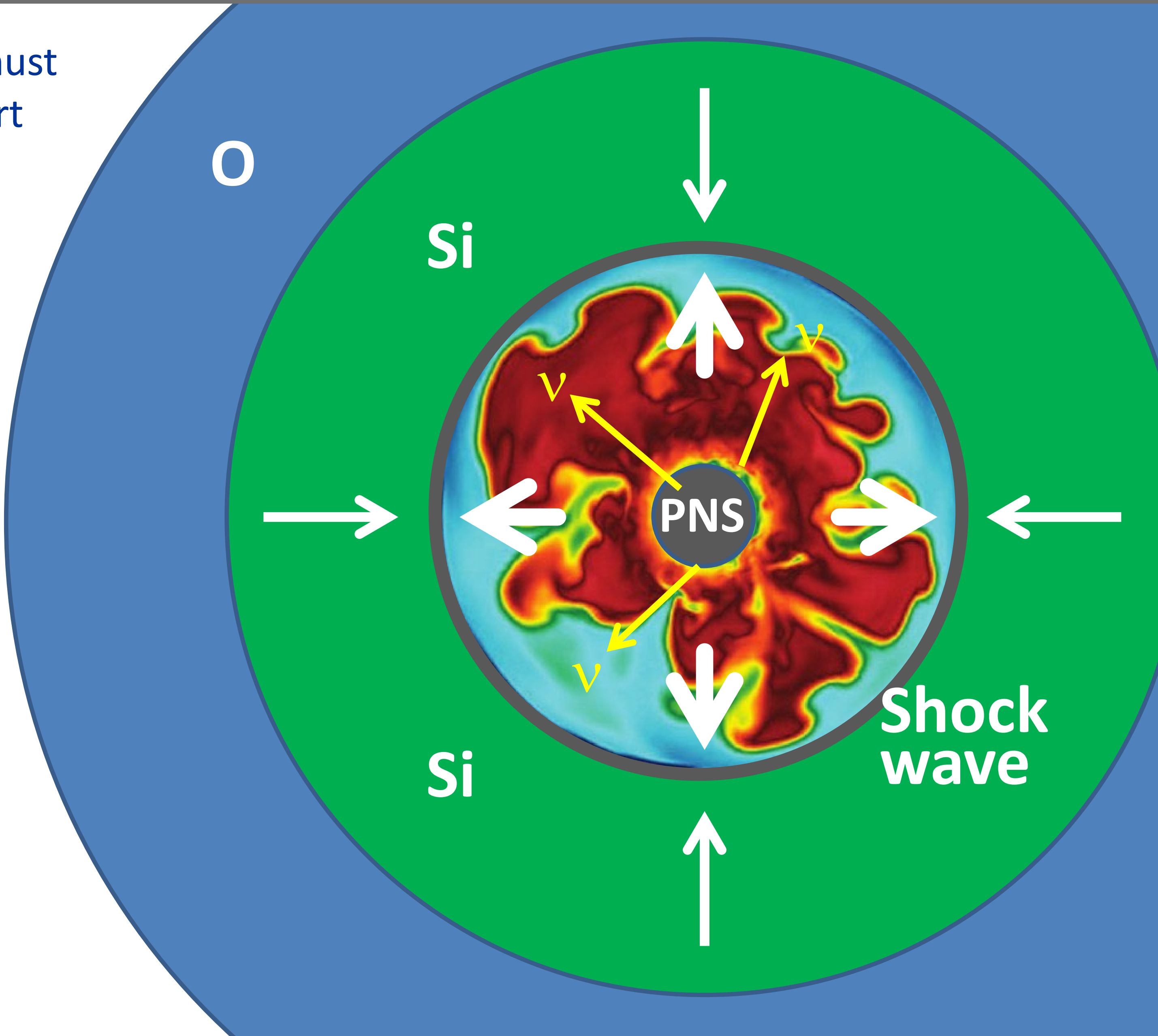


Wilson, Proc. Univ. Illinois Meeting on Num. Astrophys. (1982)
Bethe & Wilson, ApJ 295 (1985) 14

Shock Revival by Neutrinos

Stalled shock wave must receive energy to start re-expansion against ram pressure of infalling stellar core

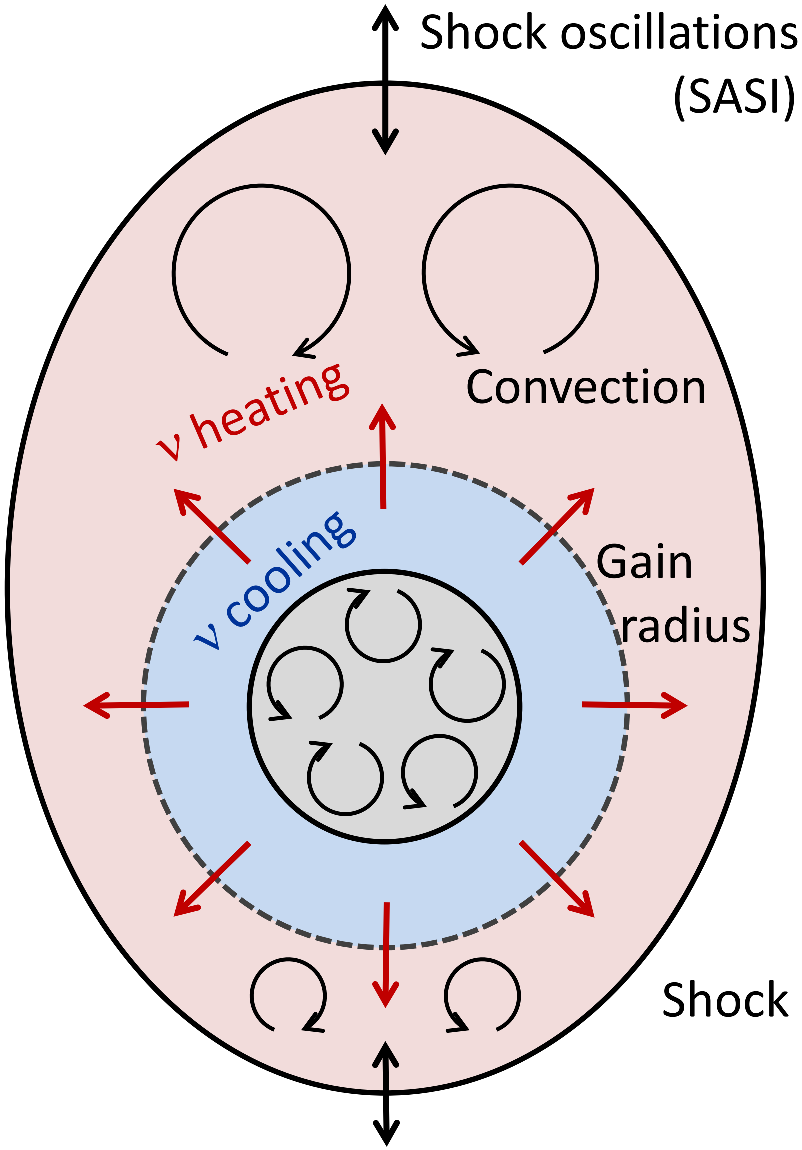
Shock can receive fresh energy from neutrinos!



Neutrino-Driven Mechanism – Modern Version

- Stalled accretion shock pushed out to ~150 km as matter piles up on the PNS
- Heating (gain) region develops within some tens of ms after bounce
- Convective overturn & shock oscillations (SASI) enhance efficiency of ν-heating, finally revives shock
- Successful explosions in 1D and 2D for different progenitor masses
- Details important (treatment of GR, ν interaction rates, etc.)
- Self-consistent 3D studies are performed, successful explosions

→ 3D Model of Princeton Group: https://youtu.be/i-Ly8aCoF7E



Adapted from B. Müller

Self-consistent 3D Supernova Models From −7 Minutes to +7 Seconds: A 1-bethe Explosion of a ~19 $M_\odot$ Progenitor

Robert Bollig,[1] Naveen Yadav,[1,2] Daniel Kresse,[1,3] Hans-Thomas Janka,[1] Bernhard Müller,[4,5,6] and Alexander Heger[4,5,7,8]

arXiv:2010.10506

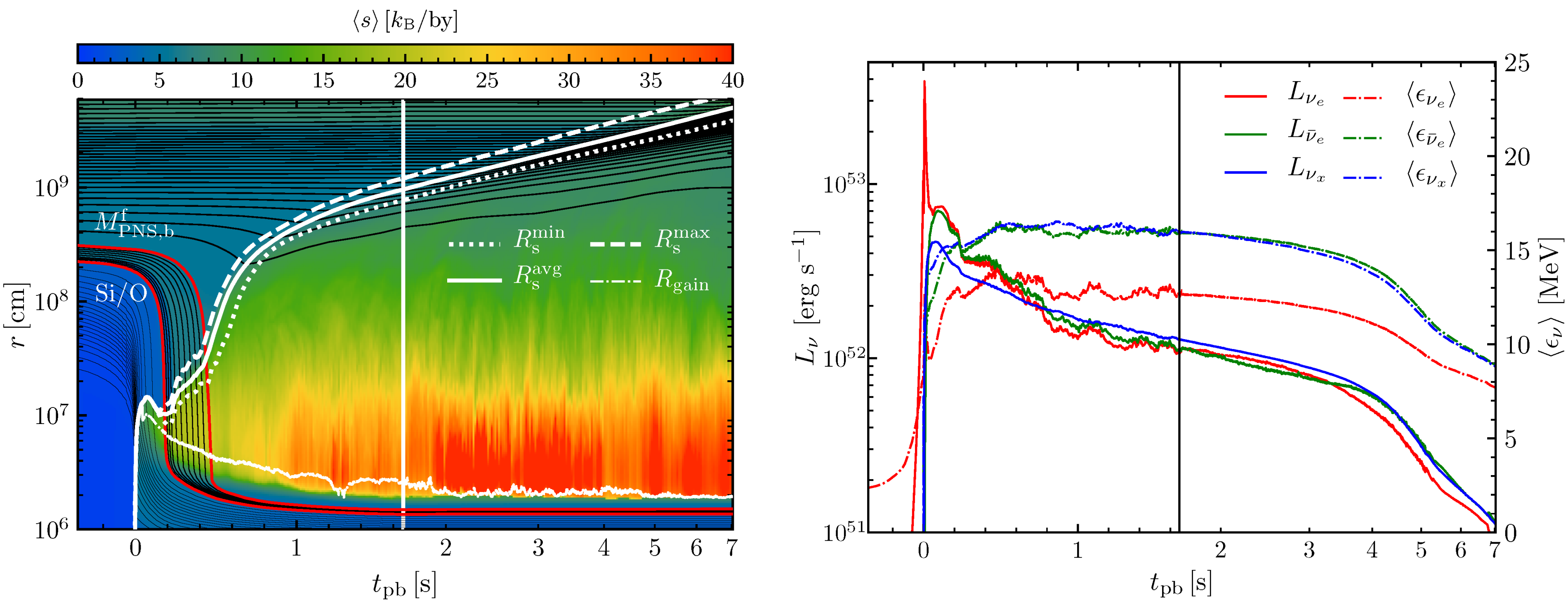


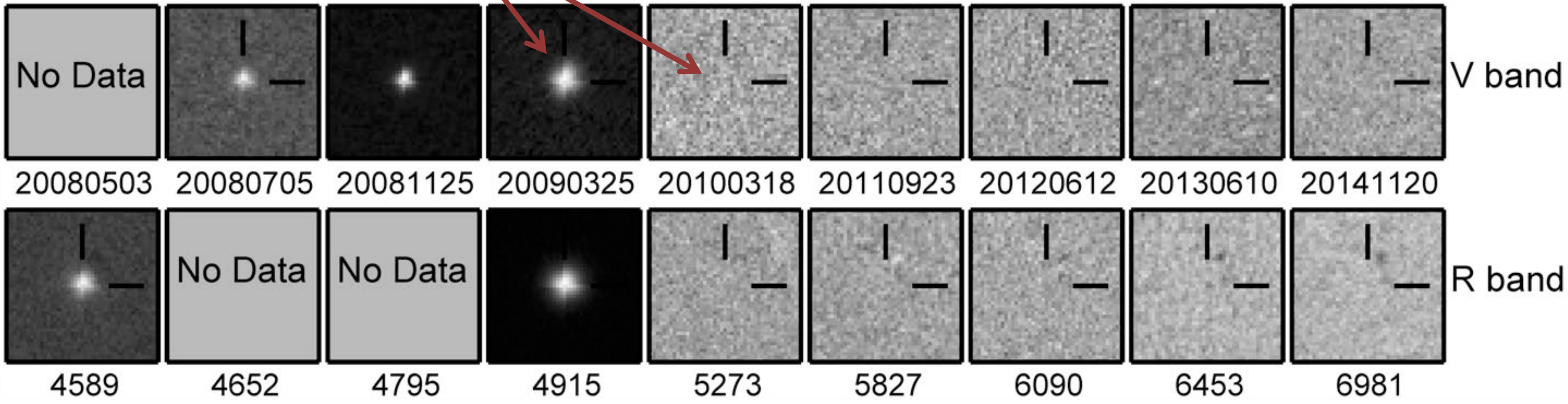
Figure 1. Explosion dynamics and neutrino emission of model `M_P3D_LS220_m−` and its extension `M_P3D_LS220_m−HC`. The time axes are chosen for optimal visibility. *Left:* Mass shells with entropy per nucleon color-coded. Maximum, minimum, and average shock radii, gain radius, and the mass shells of Si/O shell interface and final NS mass are marked. The vertical white line separates VERTEX transport (left, time linear) and HC neutrino approximation (right, time logarithmic). *Right:* Emitted luminosities and mean energies of ν_e, $\bar{\nu}_e$, and a single species of heavy-lepton neutrinos. The time axis is split as in the left panel. Right of the vertical solid line we show neutrino data from the artificially exploded 1D simulation.

Death Watch of a Million Supergiants

- Monitoring 27 galaxies within 10 Mpc for many years
- Visit typically twice per year
- 10^6 supergiants (lifetime 10^6 years)
- Combined SN rate: about 1 per year

First 7 years of survey:

- 6 successful core-collapse SNe
- 1 candidate failed SN



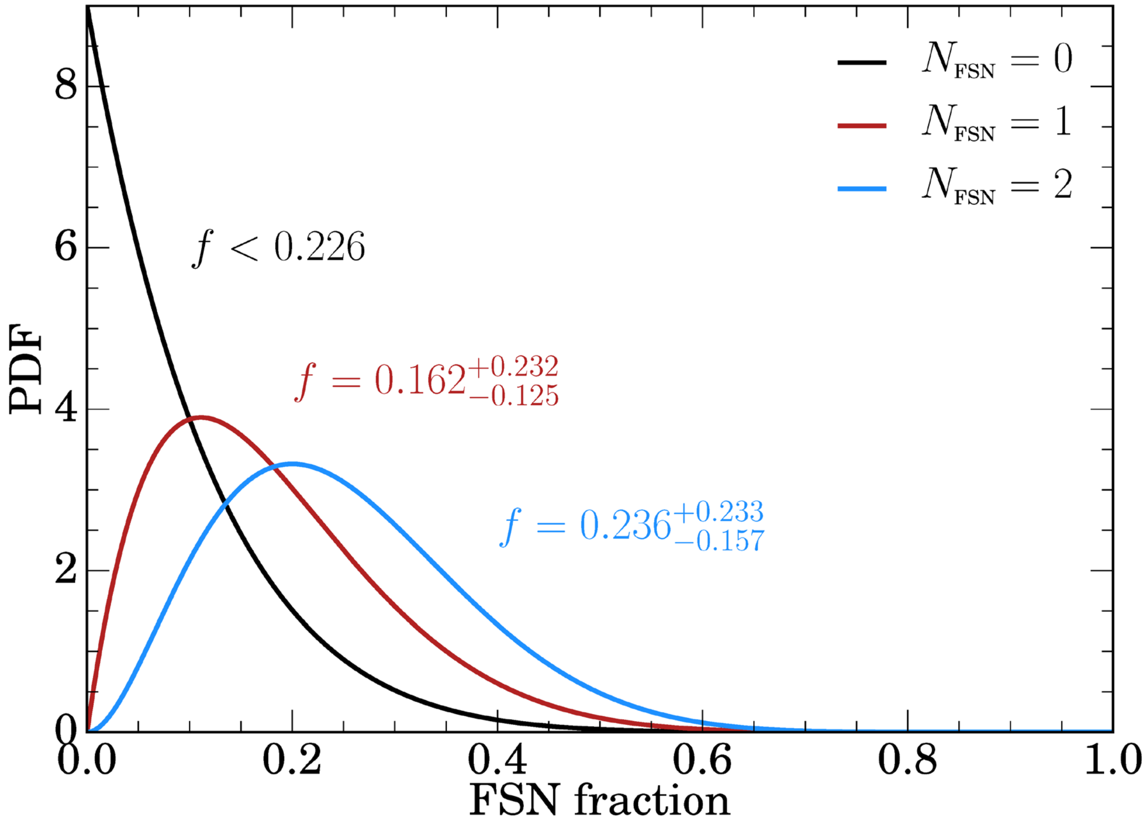
Gerke, Kochanek & Stanek, arXiv:1411.1761

Adams, Kochanek, Gerke, Stanek (& Dai), arXiv:1610.02402 (1609.01283)

Empirical Fraction of Black-Hole Formation

2020 update: 11 yr baseline, 8 SNe, 1 old & 1 new candidate for failed SN

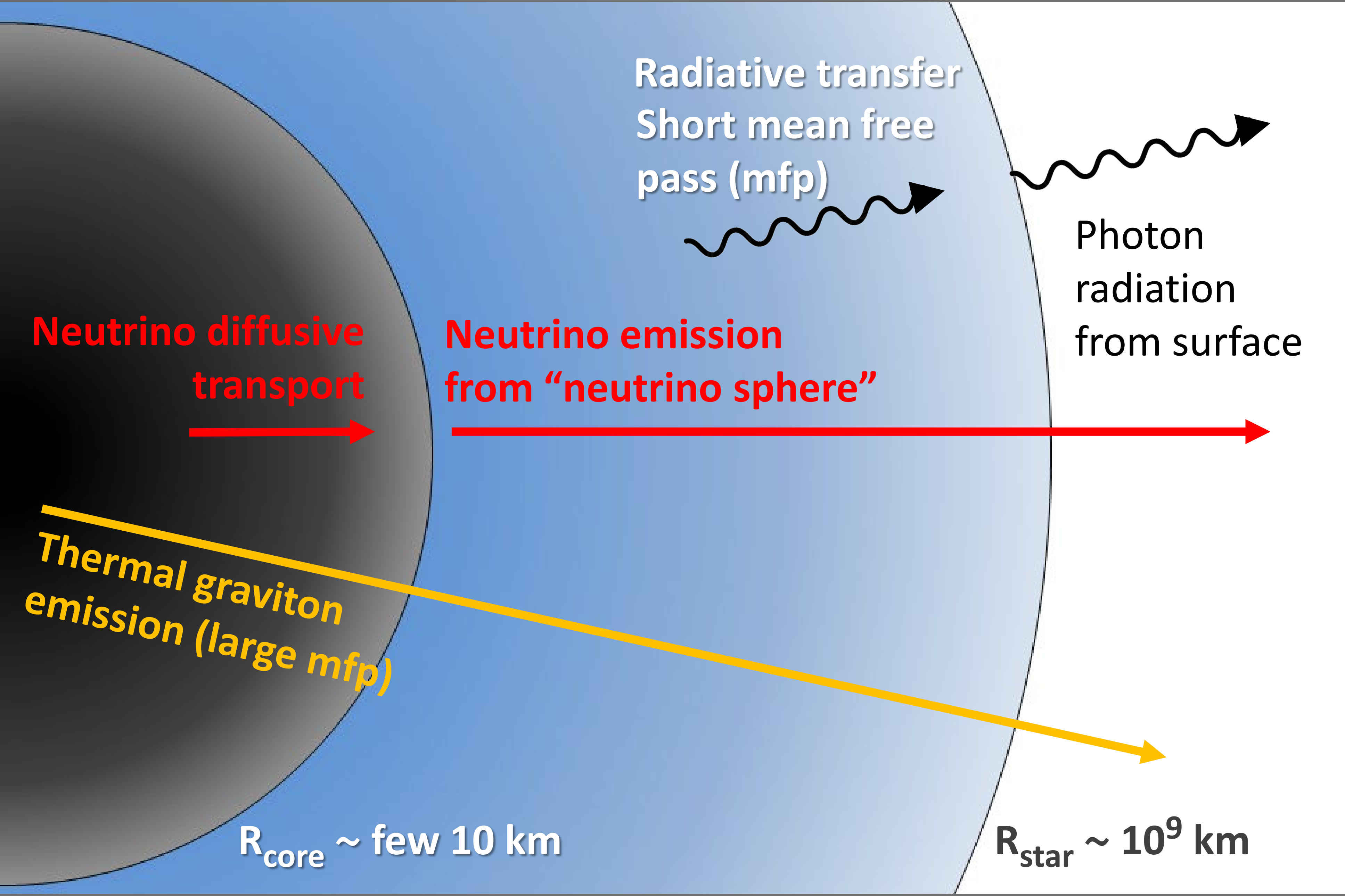
Neustadt, Kochanek, Stanek, et al., [arXiv:2104.03318]



Roughly a quarter of all core-collapses could lead to BH formation, in agreement with theory estimates!

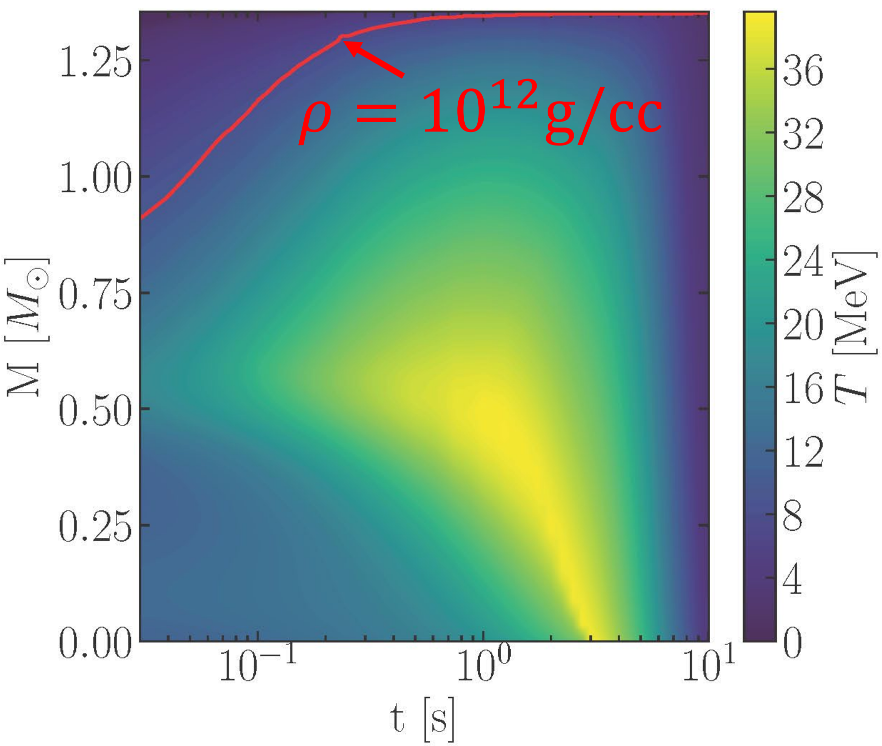
Neutrino Transport

Roles of Different Particles

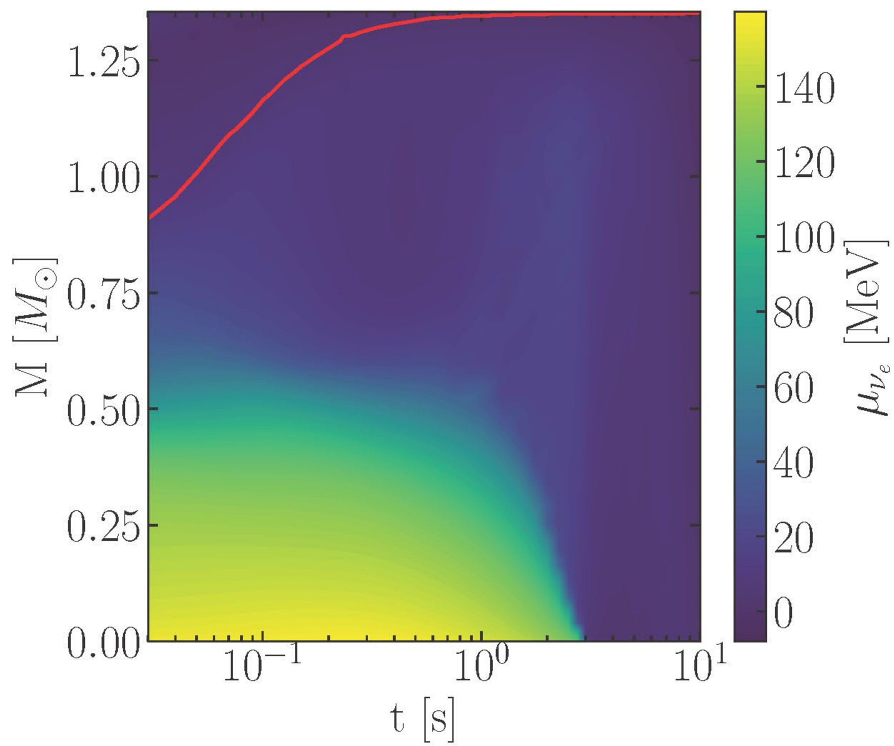


Inner Structure of a Typical Supernova Model

Temperature



ν_e Chemical Potential



SN core starts cold and heats up from outside in as in contracts and deleptonizes

Muonic SN model from Garching group, used in 2005.07141 and 2109.03244
Fiorillo, Raffelt & Vitagliano (arXiv:2209.11773)

Kinetic Equation for Neutrino Transport

Flavor-dependent phase-space densities (occupation number matrices)

$$\varrho = \begin{pmatrix} f_{\nu_e} & f_{\langle\nu_e|\nu_\mu\rangle} & f_{\langle\nu_e|\nu_\tau\rangle} \\ f_{\langle\nu_\mu|\nu_e\rangle} & f_{\nu_\mu} & f_{\langle\nu_\mu|\nu_\tau\rangle} \\ f_{\langle\nu_\tau|\nu_e\rangle} & f_{\langle\nu_\tau|\nu_\mu\rangle} & f_{\nu_\tau} \end{pmatrix}$$

Diagonal: Usual occupation numbers
Off-diag: Flavor coherence information

and similar for $\overline{\nu}$

Transport equation

$$\underbrace{\left(\partial_t + \vec{v}\cdot\vec{\nabla}_x\right.}_{\text{Streaming}} \underbrace{-\left.\vec{F}\cdot\vec{\nabla}_p\right)}_{\substack{\text{Gravitational forces} \\ \text{(redshift, deflection)}}} \varrho(t,\vec{x},\vec{p}) = \underbrace{-\mathrm{i}\,[\mathcal{H}(t,\vec{x},\vec{p}),\varrho(t,\vec{x},\vec{p})]}_{\substack{\text{Flavor oscillations} \\ (\text{vacuum, matter, } \nu\nu)}} + \underbrace{\mathcal{C}[\varrho(t,\vec{x},\vec{p})]}_{\text{Collisions}}$$

β

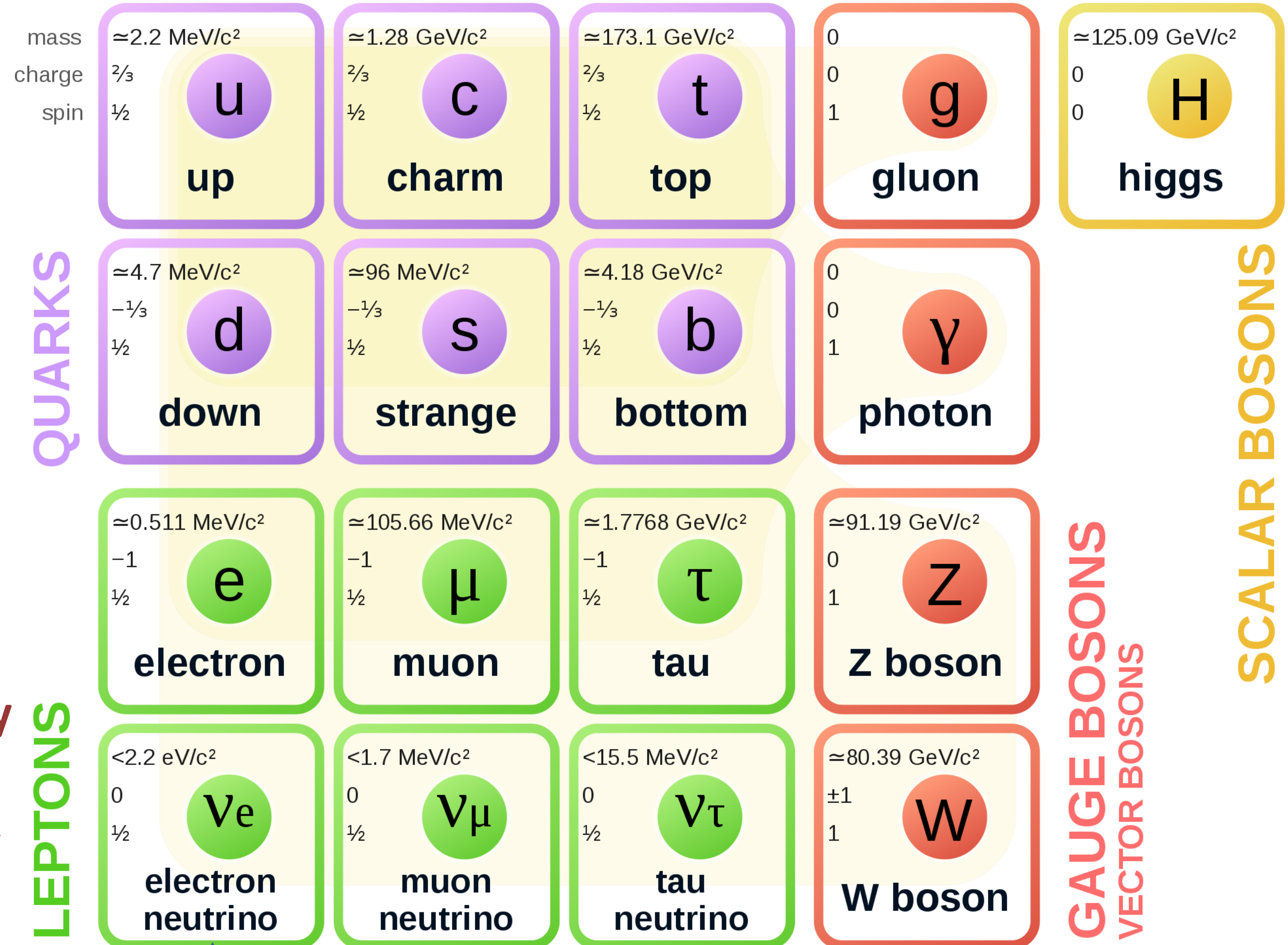
- $e^- + p \rightleftharpoons n + \nu_e$
- $e^+ + n \rightleftharpoons p + \bar{\nu}_e$
- $e^- + A \rightleftharpoons \nu_e + A^*$

- $\nu + n, p \rightleftharpoons \nu + n, p$
- $\nu + A \rightleftharpoons \nu + A$
- $\nu + e^\pm \rightleftharpoons \nu + e^\pm$
- $N + N \rightleftharpoons N + N + \nu + \bar{\nu}$
- $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$
- $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$
  ($\nu_x = \nu_\mu,\ \bar{\nu}_\mu, \nu_\tau$, or $\bar{\nu}_\tau$)
- $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Typical approximations in numerical simulations:

- **Reducing 6+1 dimensions**
  (Angular moments, ray-by-ray, …)
- **No gravitational deflection**
- **No flavor conversion (large matter effect!)**
- **No muons**
- **3-species transport: $\nu_e, \overline{\nu}_e, \nu_x$**

Second & Third Particle Generations in SN Physics



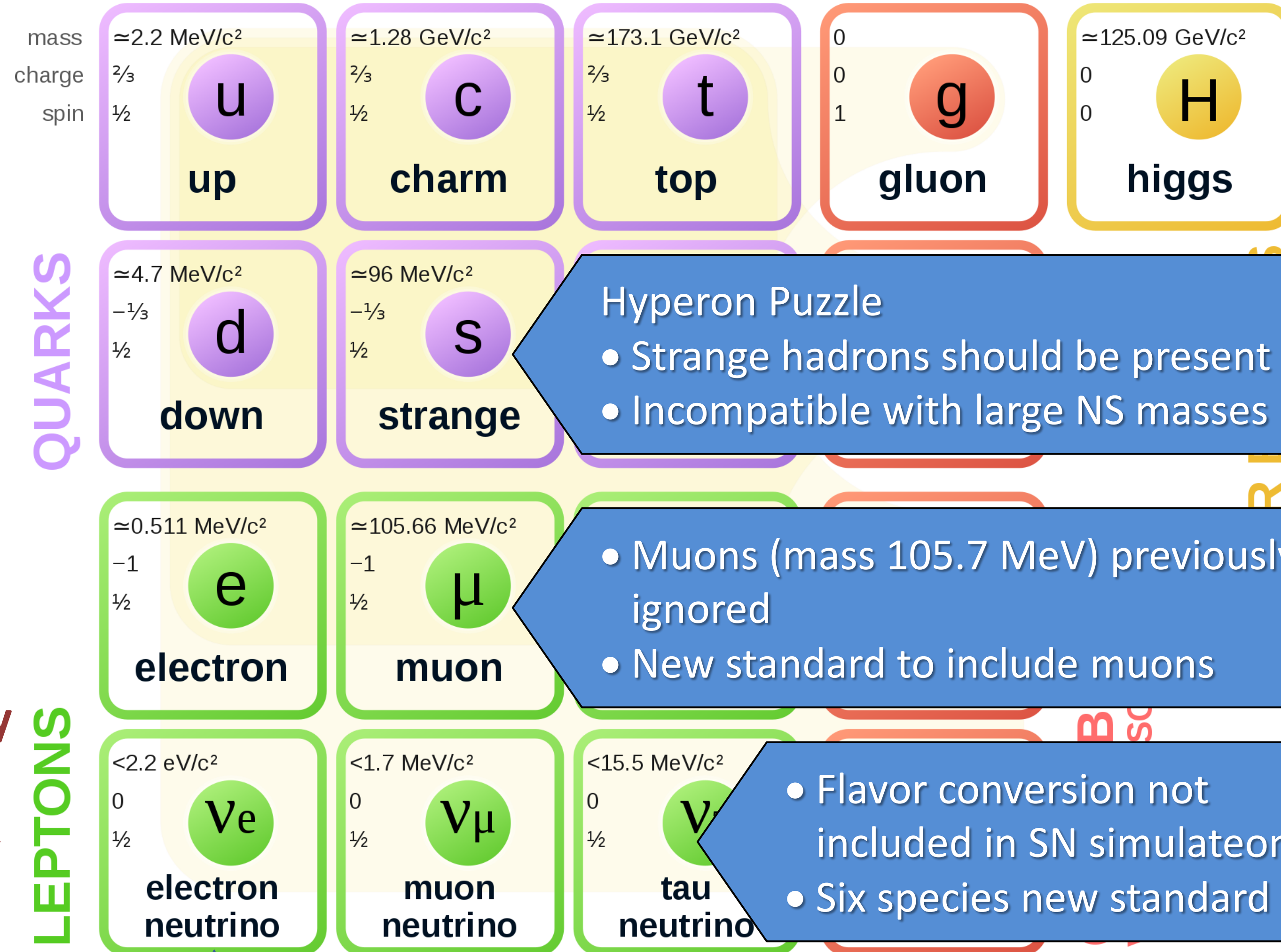
Early universe, stellar collapse & NS mergers naturally involve all flavor neutrinos →

Everyday physics and astrophysics only first family of fermions

$$\nu_x = \nu_\mu, \nu_\tau, \overline{\nu}_\mu, \overline{\nu}_\tau$$

in old SN simulations

Second & Third Particle Generations in SN Physics



Hyperon Puzzle
- Strange hadrons should be present
- Incompatible with large NS masses

- Muons (mass 105.7 MeV) previously ignored
- New standard to include muons

- Flavor conversion not included in SN simulateons
- Six species new standard

Early universe, stellar collapse & NS mergers naturally involve all flavor neutrinos →

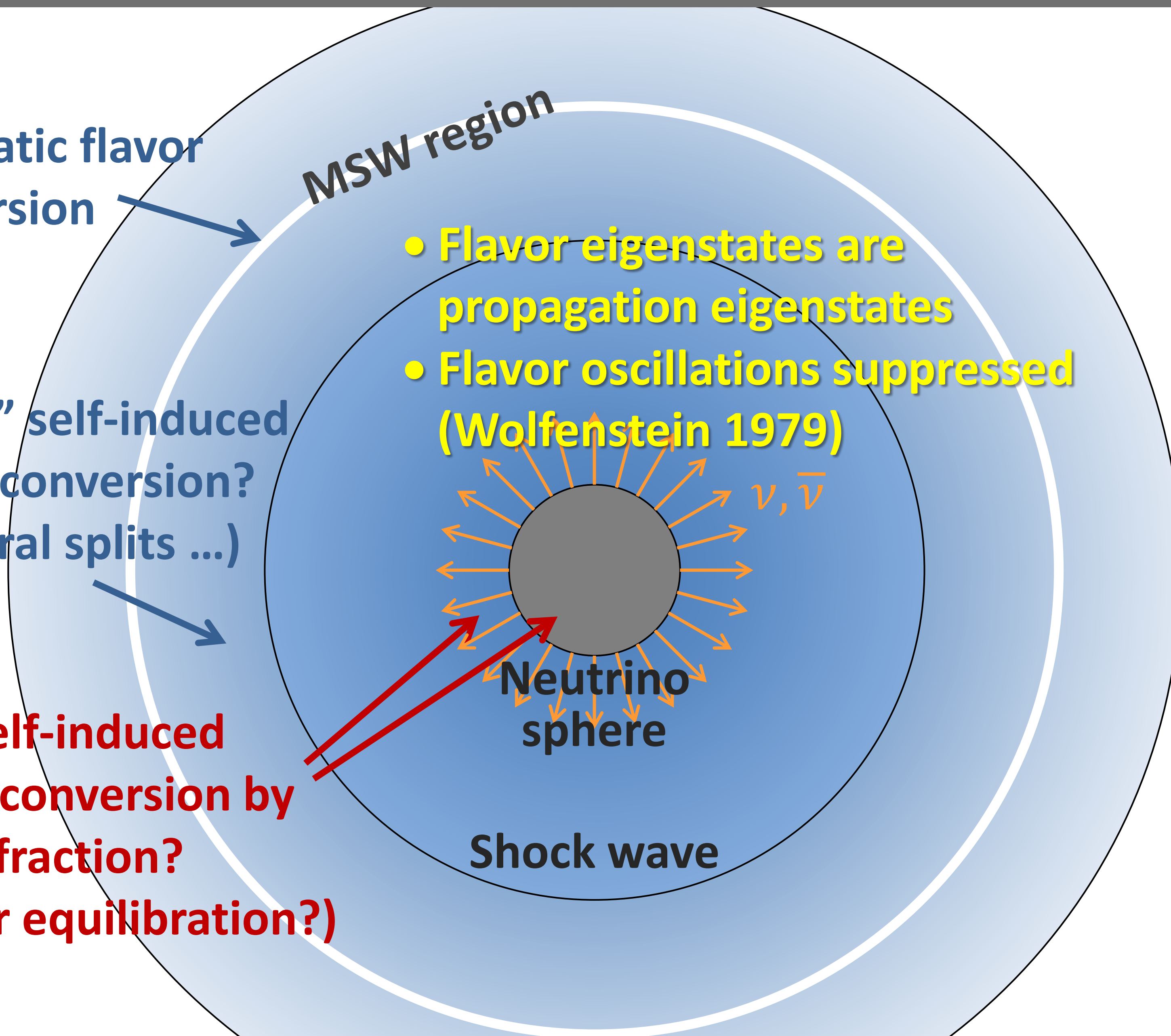
Everyday physics and astrophysics only first family of fermions

$$\nu_x = \nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$$

in old SN simulations

Flavor Conversion in Core-Collapse Supernovae

- Adiabatic flavor conversion
- "Slow" self-induced flavor conversion? (Spectral splits …)
- Fast self-induced flavor conversion by ν-ν refraction? (Flavor equilibration?)



Collective Neutrino Flavor Conversion

$$i\partial_t \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left(\underbrace{\frac{\mathbb{M}^2}{2E}}_{\text{Mass matrix}} + \underbrace{\sqrt{2}G_{\rm F}\mathbb{N}_\ell}_{\text{Charged lepton density}} + \underbrace{\sqrt{2}G_{\rm F}\mathbb{N}_\nu}_{\text{Neutrino neutrino refraction}}\right)\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$\mathbb{N}_\nu = \int \frac{d^3\vec{p}}{(2\pi)^3}\begin{pmatrix} f_{\nu_e} & \psi^*_{\nu_e\nu_\mu} & \psi^*_{\nu_e\nu_\tau} \\ \psi_{\nu_e\nu_\mu} & f_{\nu_\mu} & \psi^*_{\nu_\mu\nu_\tau} \\ \psi_{\nu_e\nu_\tau} & \psi_{\nu_\mu\nu_\tau} & f_{\nu_\tau}\end{pmatrix}$$

Occupation number

- Refractive back reaction of neutrinos on each other in neutrino-dense environments (Pantaleone 1992)

- **Active research field ca 40 papers/year recently**

- Field of flavor coherence
- Depends on $(\vec{p},\vec{r},t)$
- **Can develop unstable flavor waves in the presence of $\nu\nu$ refraction**
- **Similar to plasma instabilities**
- **Large flavor coherence despite matter**

Fast flavor waves in analogy to plasma waves

Damiano Fiorillo

Linear quantum kinetic equation for flavor coherence $\psi_{\vec{v}}(t,\vec{r})$

$$\left(\partial_t + \vec{v}\cdot\vec{\nabla}_{\vec{r}}\right)\psi_{\vec{v}} = -i\sqrt{2}G_{\rm F}\int d\vec{v}'(1-\vec{v}\cdot\vec{v}')\left(G_{\vec{v}}\psi_{\vec{v}'} - G_{\vec{v}'}\psi_{\vec{v}}\right)$$

Vlasov operator — Integral over velocity distribution

In Fourier space

$$\left(\omega - \vec{v}\cdot\vec{k}\right)\psi_{\vec{v}} = \cdots$$

Vanishes for Cherenkov condition:

Flavor wave $\left(\omega,\vec{k}\right)$ on resonance with some neutrinos: $\left(\omega - \vec{v}\cdot\vec{k}\right) = 0$

- Landau damping or **exponential growth**, depending on velocity distribution $G_{\vec{v}}$
- Interaction of collective waves with individual particles
- Interpret dispersion relation in terms of “flavor susceptibility” (system response to applied flavor field)
- Flavor waves like plasma waves, have quanta **flavomons**

Fiorillo & Raffelt (2023–2024), long list of papers, eg arXiv:2406.06708

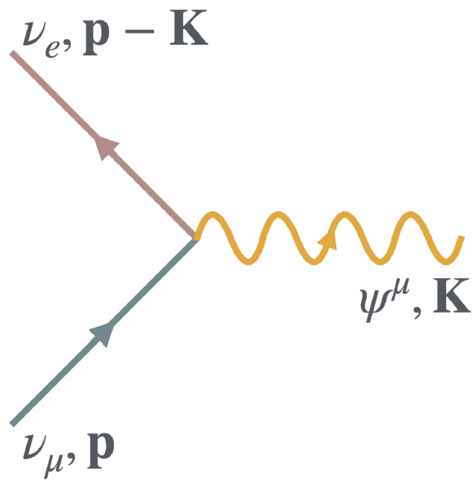
Collective flavor conversions are interactions of neutrinos with quantized flavor waves

Damiano F. G. Fiorillo [1] and Georg G. Raffelt [2]

[1] *Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany*
[2] *Max-Planck-Institut für Physik, Boltzmannstr. 8, 85748 Garching, Germany*

arXiv:2502.06935

Collective oscillations in dense neutrino gases (flavor waves) are notable for their instabilities that cause fast flavor conversion. We develop a quantum theory of interacting neutrinos and flavor wave quanta, which are analogous to plasmons, but also carry flavor. The emission or absorption of such flavor plasmons ψ, or *flavomons*, changes the neutrino flavor. When an angular crossing occurs, the process $\nu_\mu \to \nu_e + \psi$ is more rapid than its inverse along the direction of the crossing, triggering stimulated ψ emission and fast instability. Calculating the rate via Feynman diagrams matches the fast instability growth rate. Our novel ν and ψ kinetic equations, corresponding to quasi-linear theory, describe instability evolution without resolving the small scales of the flavomon wavelength, potentially overcoming the main challenge of fast flavor evolution.



- Quanta of flavor waves **(flavomons)** analogous to plasmons
- Collective flavor instability is
  $\nu_e \to \nu_\mu + \psi$ (stimulated)
  classically resonant Cherenkov emission

A new theoretical framework for collective flavor conversion. Will it be practically useful?

Pair-wise flavor conversion

- **True flavor conversion by neutrino masses**
  - Large mixing angle $\to$ large flavor conversion
  - Suppressed by matter refraction
  - Trapped electron lepton number remains conserved

- **Collective flavor conversion**
  - Redistributes flavor in neutrino phase space
  - Most importantly: $\boldsymbol{\nu_e\overline{\nu}_e \leftrightarrow \nu_x\overline{\nu}_x}$
  - Happens anyway by “hard” collisions (order $G_{\rm F}^2$)
  - **Speed up by refraction:**
    Much faster (order $G_{\rm F}$) by forward scattering

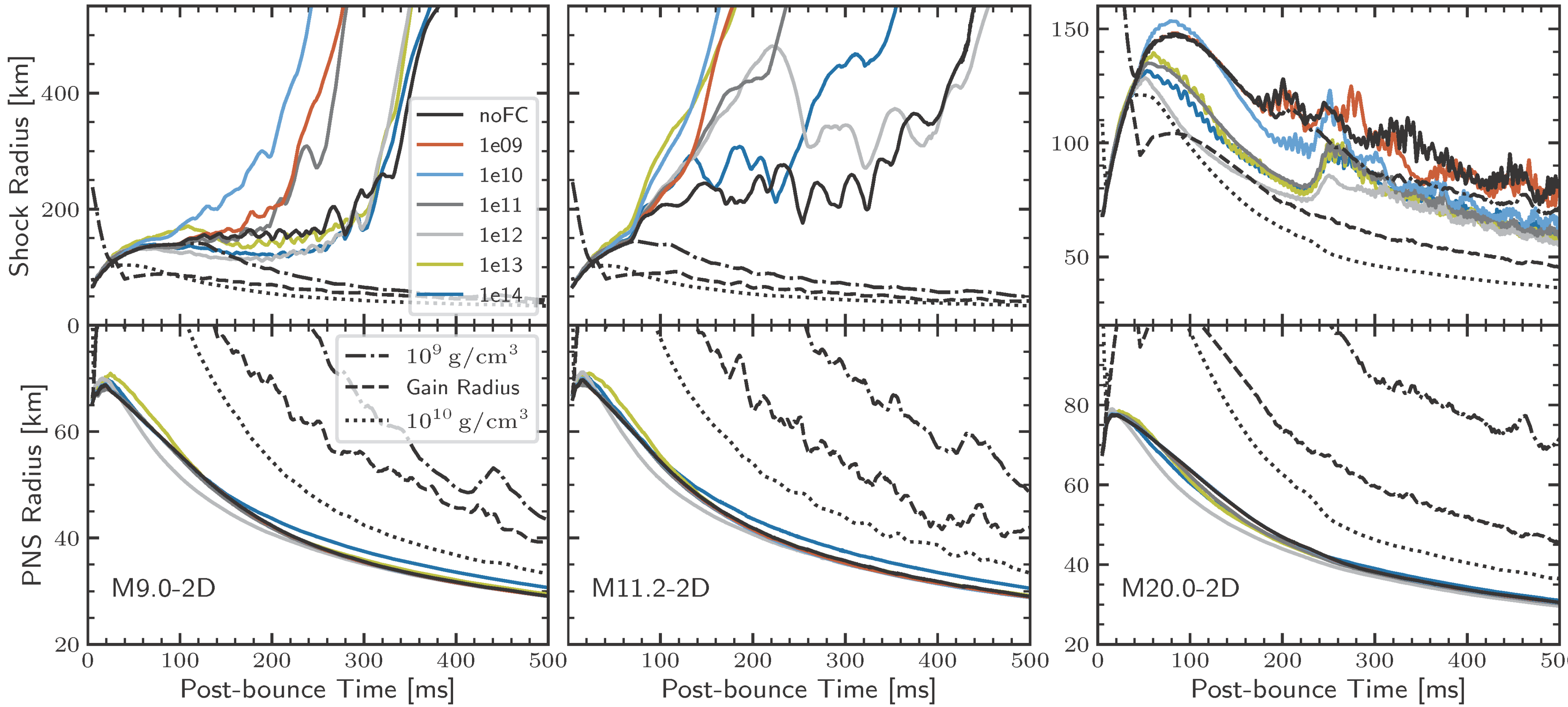
- **Local equilibrium on “fast” timescales?**

  - Many recent studies,
    fundamental, parametric or numerical

Fast Flavor Conversion – Help or Hinder Explosion

Explosion sets in earlier

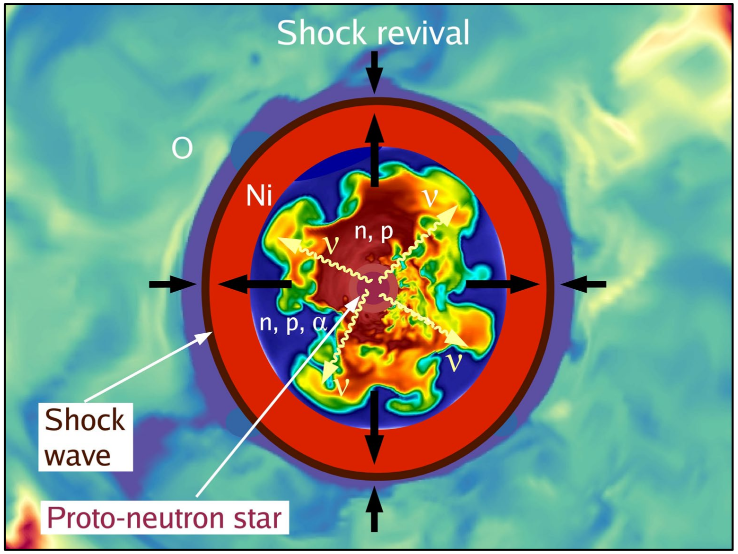
Contraction faster



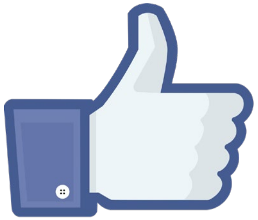
Ehring+, arXiv:2305.11207

See also Wang & Burrows, arXiv2503.04896

Why worry about detailed neutrino transport?



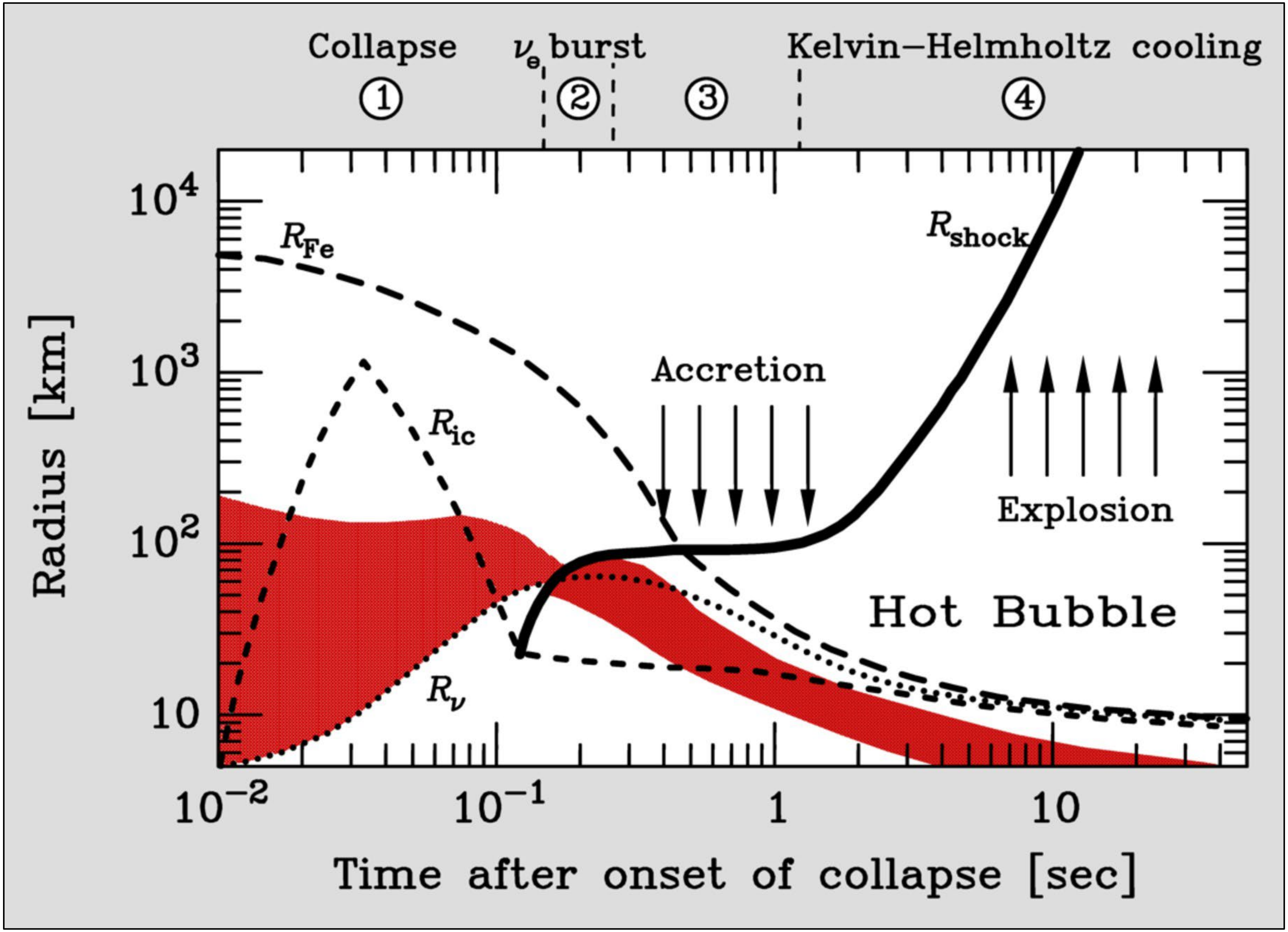
- Explosion mechanism:
  Shock-wave revival by nu energy deposition
- Nucleosynthesis in neutrino irradiated outflows in SNe and NS-mergers depends on flavor (beta reactions!)
- Signal interpretation of DSNB and next nearby SN
- **Collective flavor conversion: interesting theoretical problem in its own right**



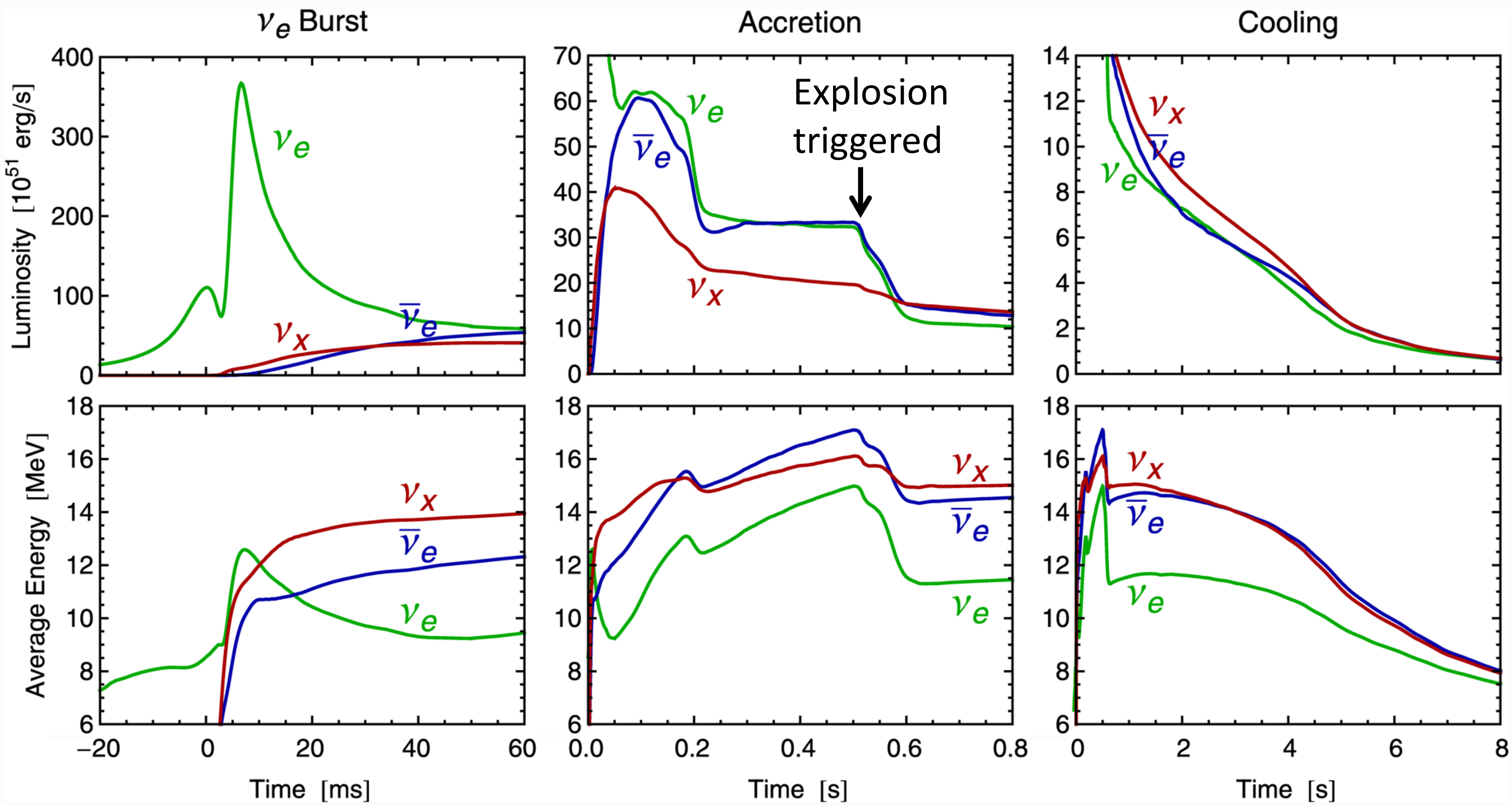
- **Theoretial frontier within standard physics**

Characteristics of Neutrino Signal

Supernova Delayed Explosion Scenario



Three Phases of Neutrino Emission



- Shock breakout
- De-leptonization of outer core layers

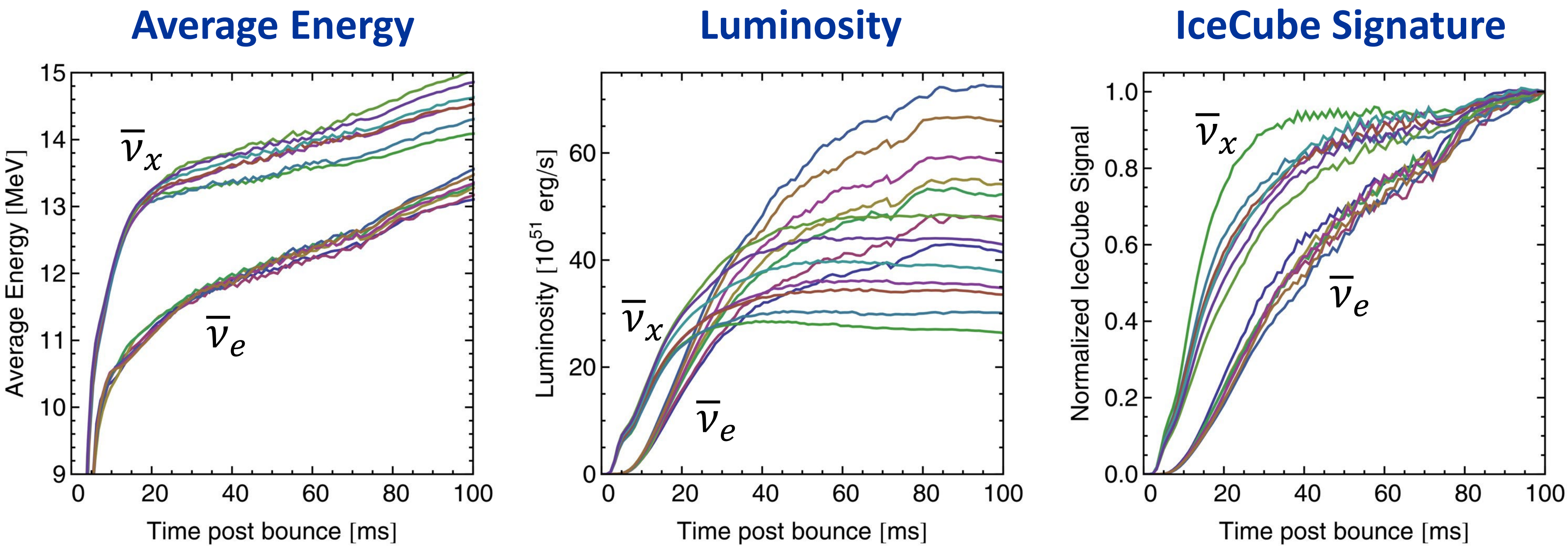
- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling on neutrino diffusion time scale

Spherically symmetric Garching model (25 $M_\odot$) with Boltzmann neutrino transport

Early-Phase Signal in Anti-Neutrino Sector

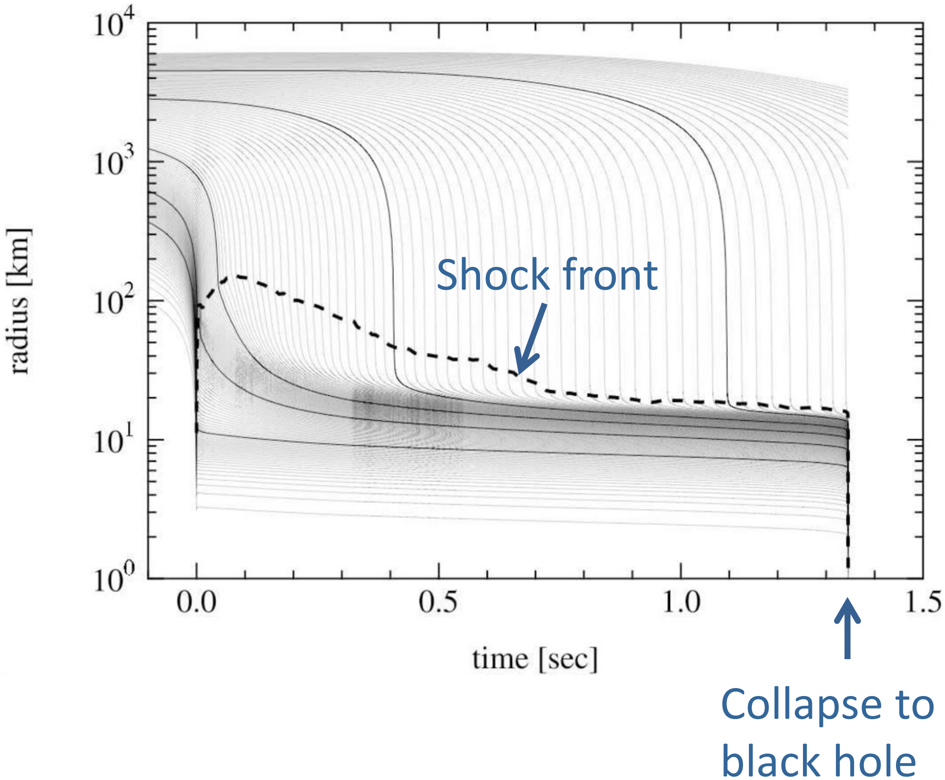
Garching Models with M = 12–40 $M_\odot$

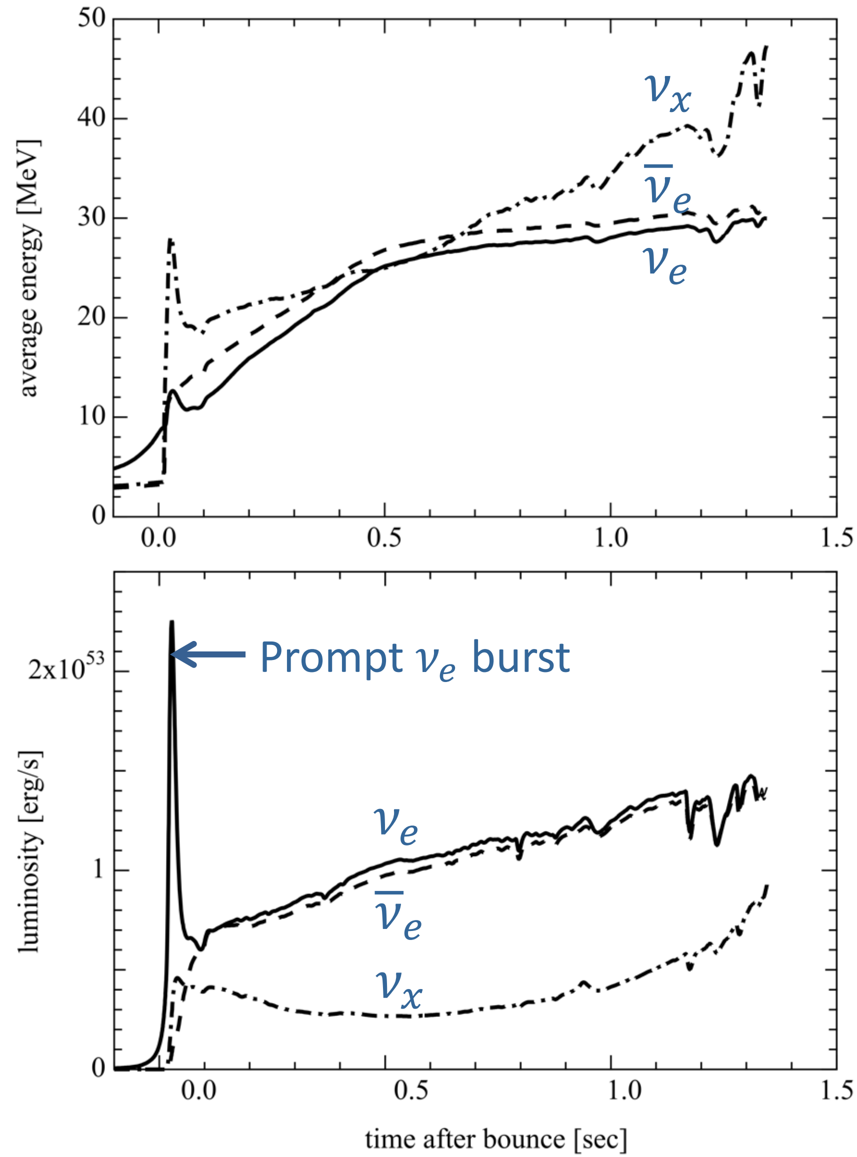


- In principle very sensitive to mass ordering, notably IceCube or HK
- "Standard candle" to be confirmed by other than Garching models

Abbasi et al. (IceCube Collaboration) A&A 535 (2011) A109
Serpico, Chakraborty, Fischer, Hüdepohl, Janka & Mirizzi, arXiv:1111.4483

Neutrino Signal of a Failed Supernova (40 M_{SUN})





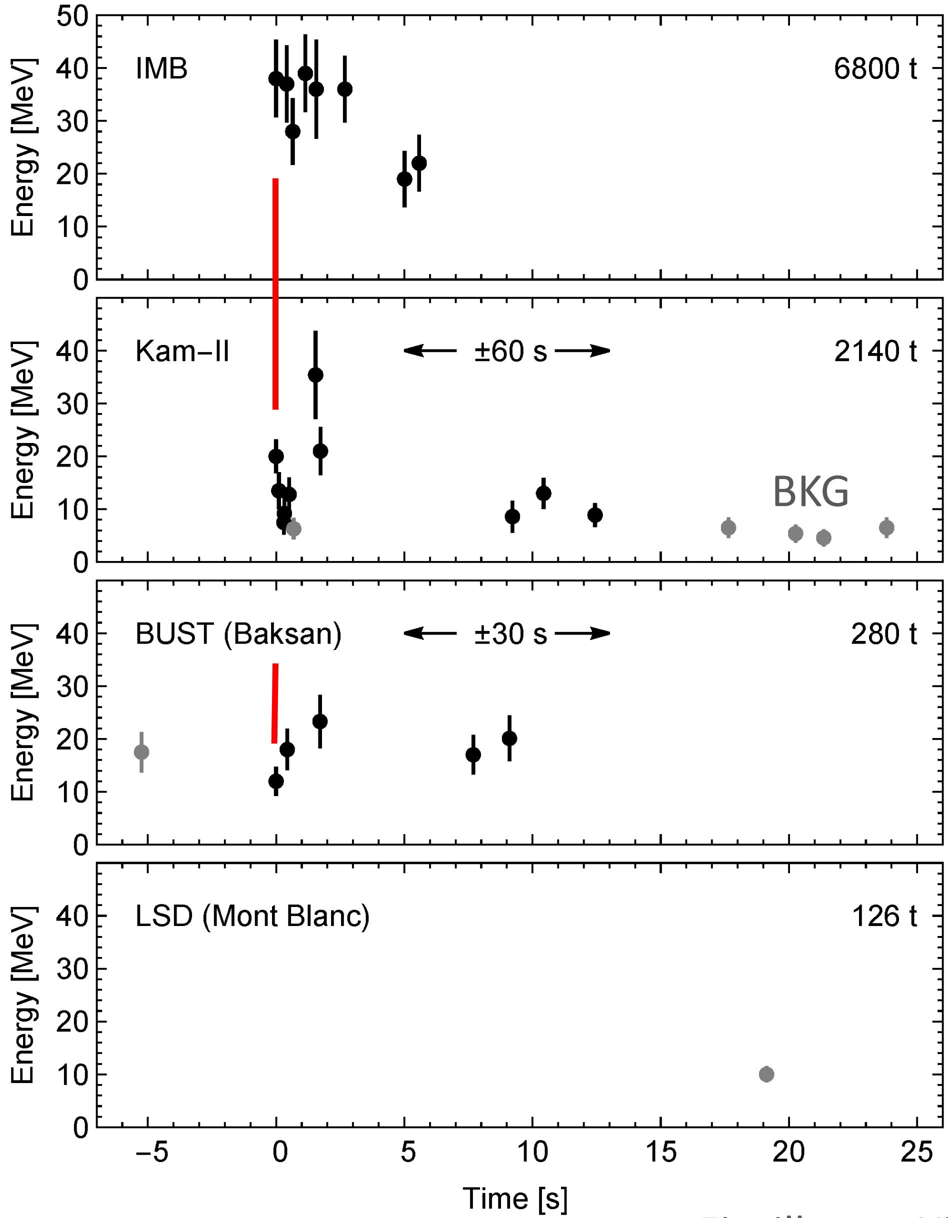
Sumiyoshi, Yamada & Suzuki, arXiv:0706.3762

Neutrinos from Supernova 1987A


Sanduleak –69 202


Supernova 1987A
23 February 1987

Neutrino Signal of Supernova 1987A



Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

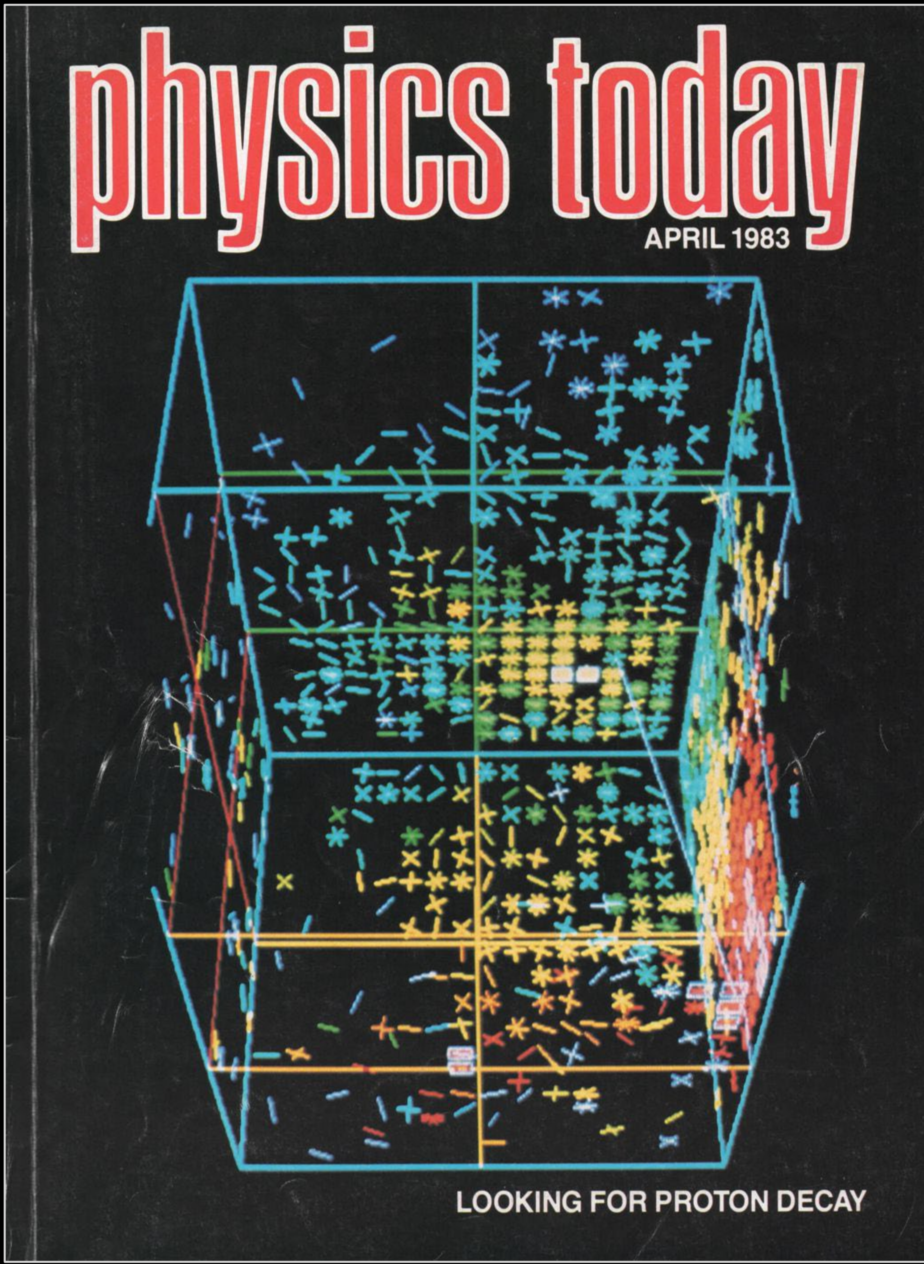
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

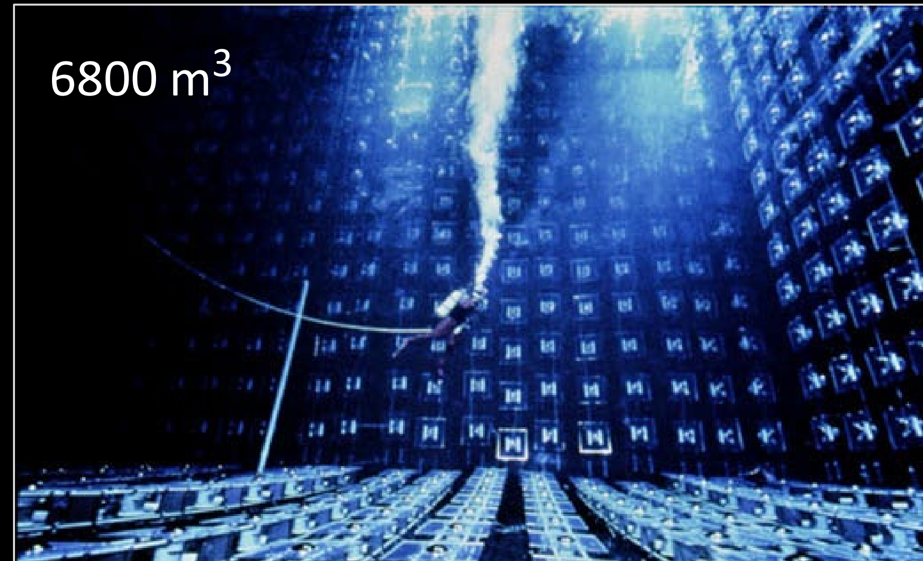
Baksan Scintillator Telescope
(Soviet Union), 200 tons (280 tons we)
Random event cluster ~ 0.7/day
Clock uncertainty +2/–54 s

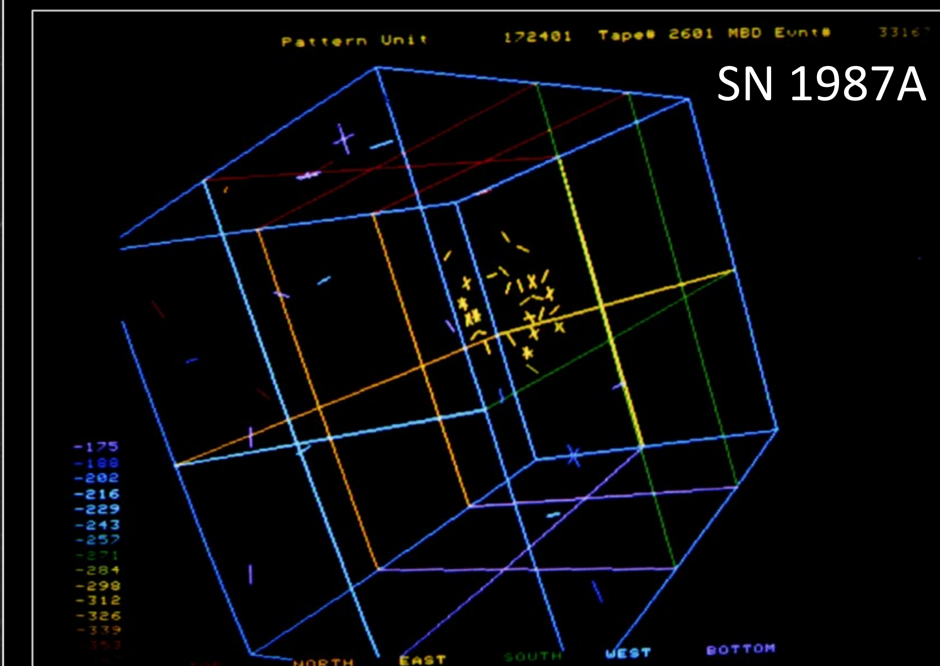
Liquid Scintillator Detector (Mont Blanc)
90 tons (126 tons we)
Minimal background
Clock uncertainty ±2 ms
Unexplaind burst few hours earlier

Fiorillo+, arXiv:2308.01403

Irvine-Michigan-Brookhaven (IMB) Detector

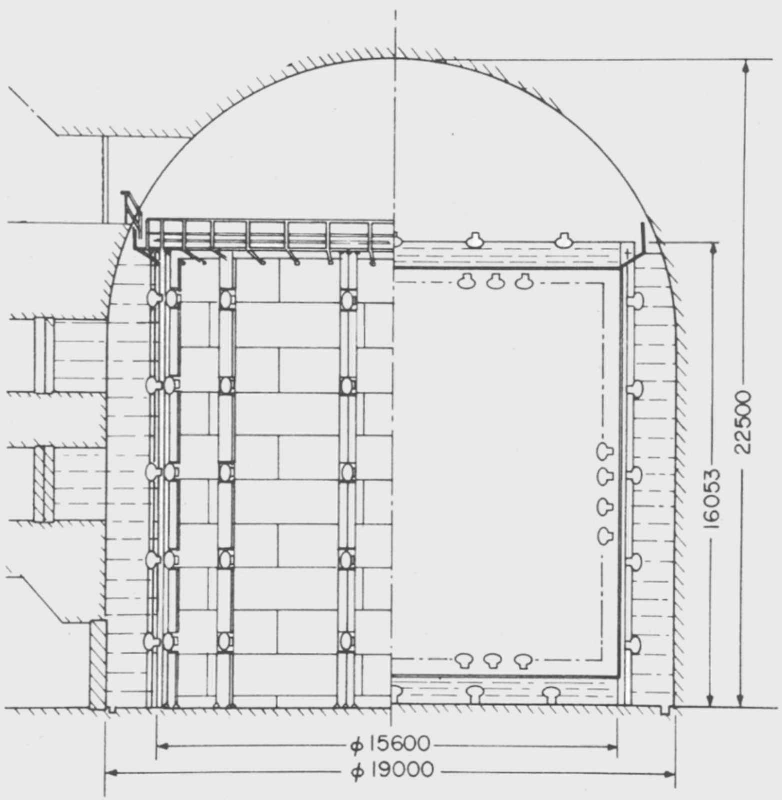




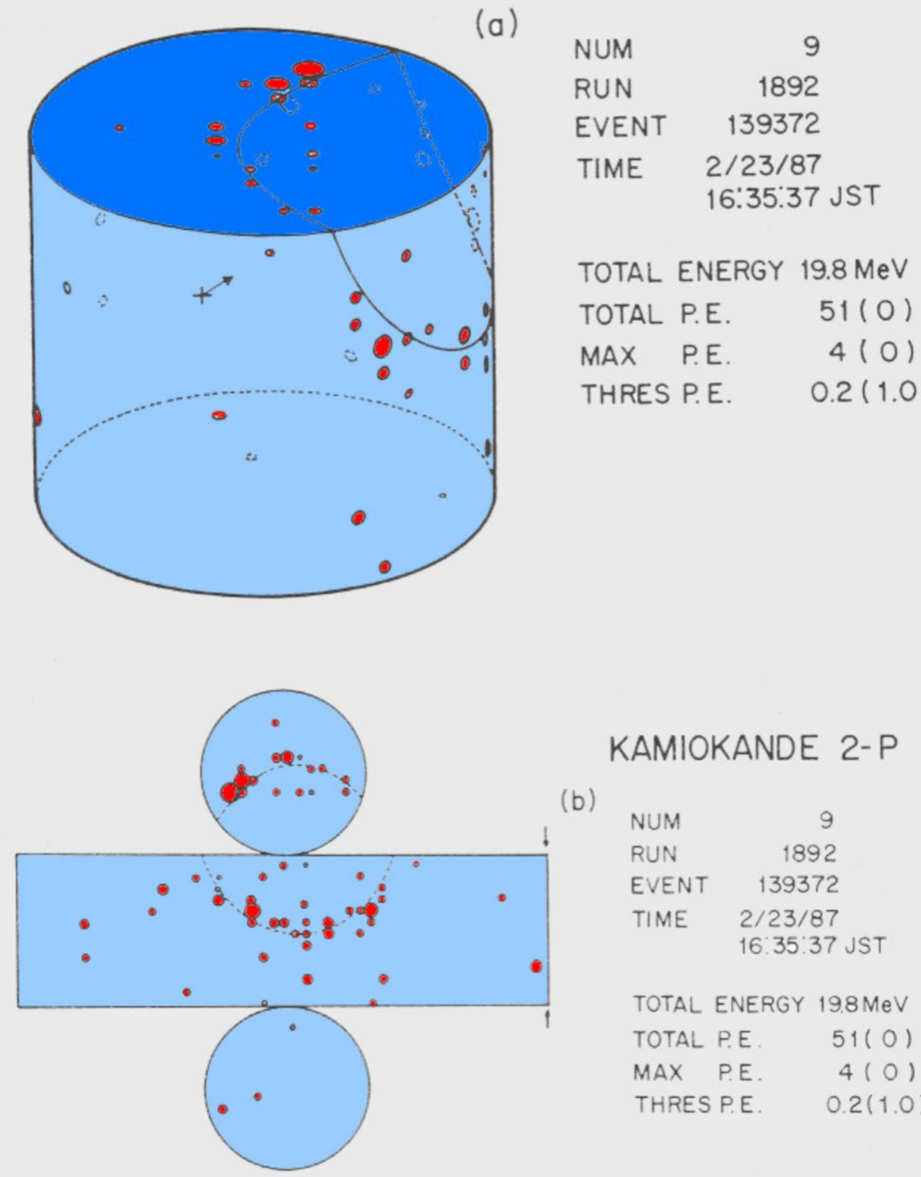


SN 1987A Event No.9 in Kamiokande

Kamiokande-II Detector
(2140 tons of water)

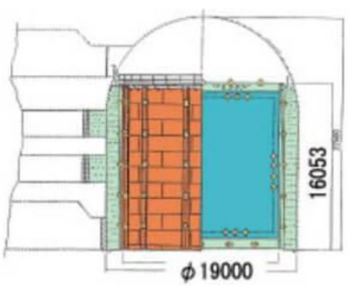


Hirata et al., PRD 38 (1988) 448

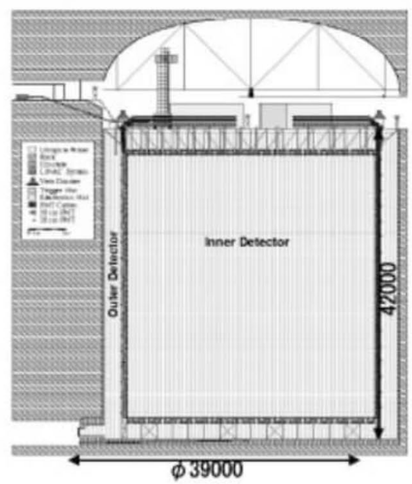


When collecting neutrinos, size definitely does matter!

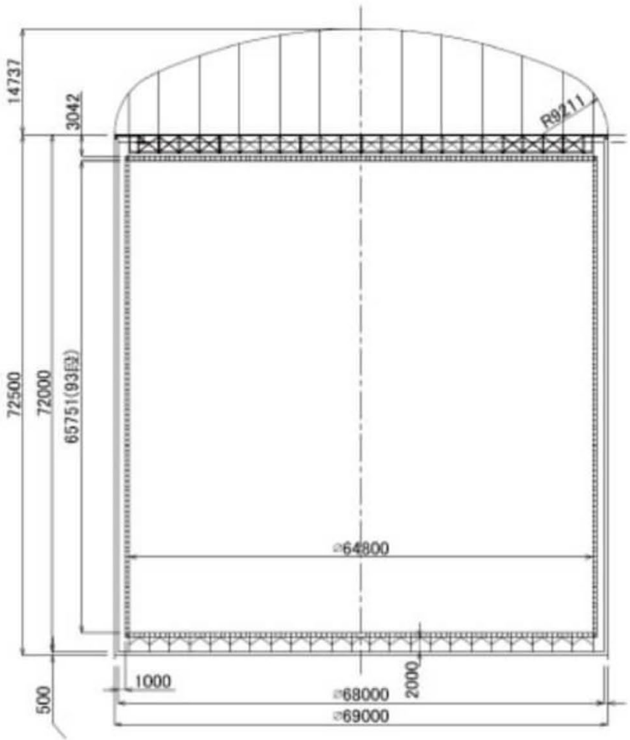
Credit
Mark Vagins



Kamiokande
(1983-1996)



Super-Kamiokande
(1996-present)



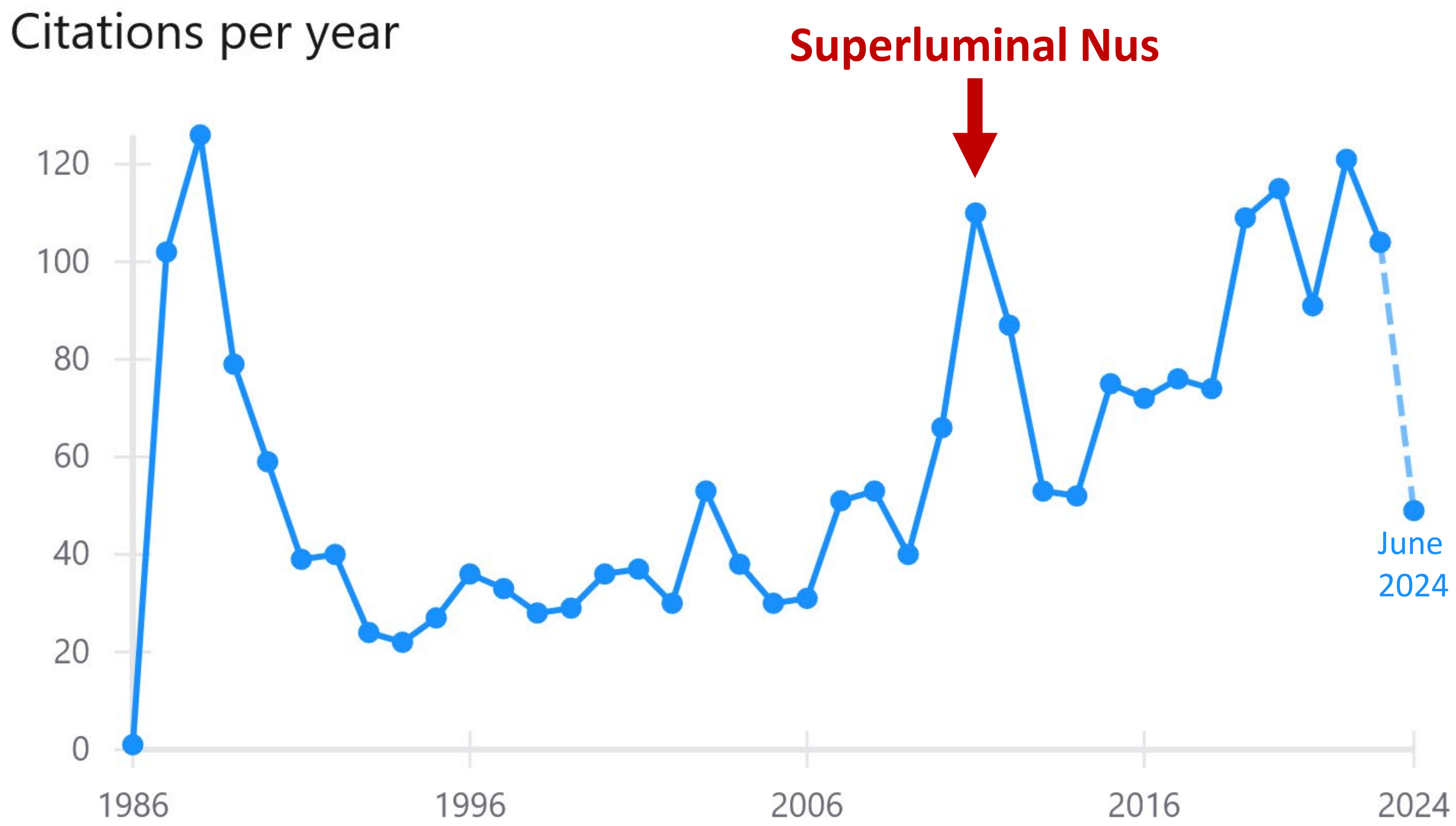
Hyper-Kamiokande
(to be started in 2027)

3 kilotons → 50 kilotons → 258 kilotons

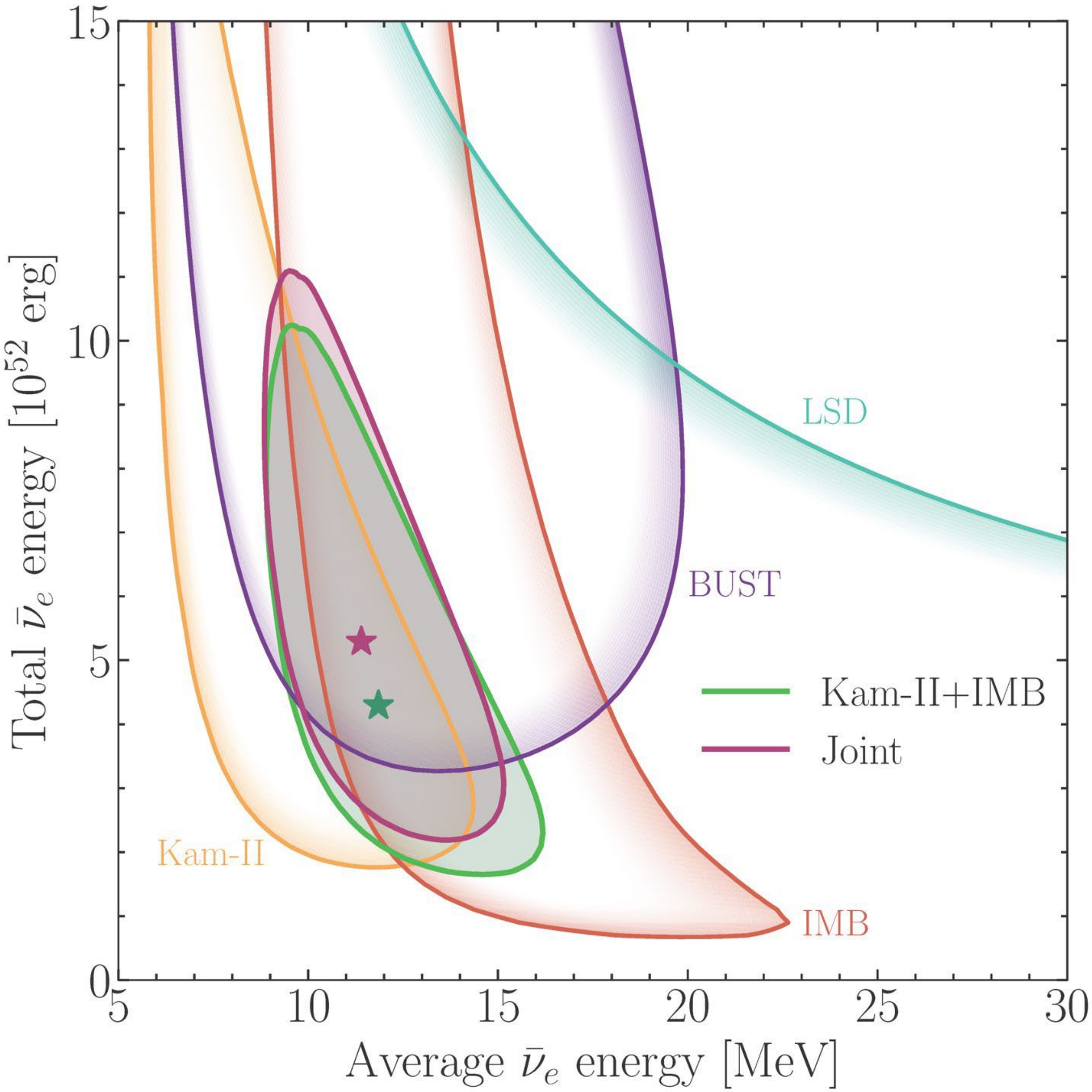
(1 kt fiducial) → (22.5 kt fiducial) → (178 kt fiducial)

Continuing Interest in SN 1987A Neutrinos

- Hirata et al (Kamiokande-II), PRL 58 (1987) 1490
  Observation of a neutrino burst from the supernova SN1987A
- Bionta et al (IMB), PRL 58 (1987) 1494, Observation of a Neutrino Burst in Coincidence with Supernova 1987A in the Large Magellanic Cloud



Generic Time-Integrated Analysis



Assume quasi-thermal $\overline{\nu}_e$ flux

(Maxwell-Boltzmann spectrum)

Distance 50 kpc

Likelihood fit with parameters

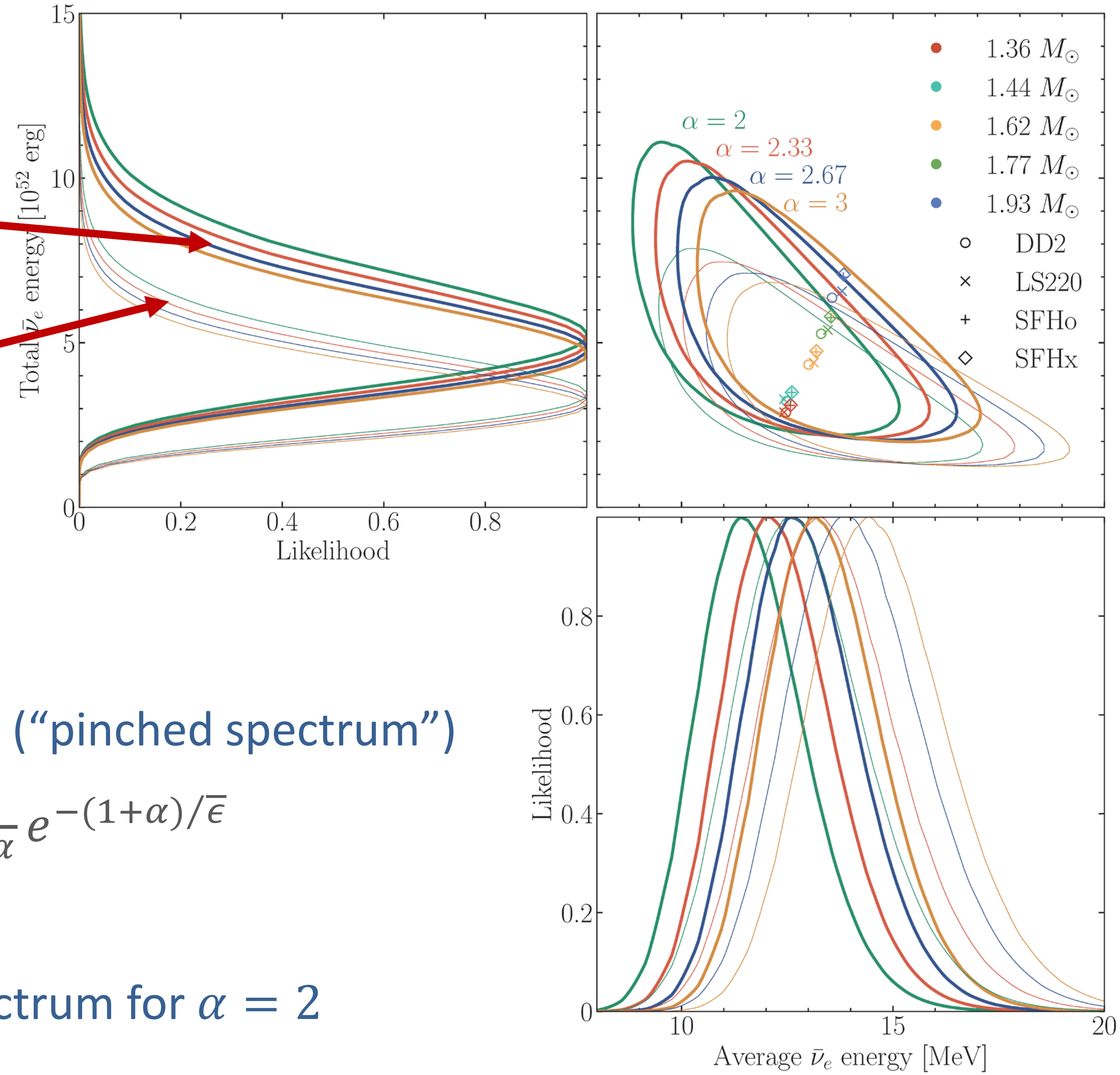
- Total emitted energy at source
- Average $\overline{\nu}_e$ energy

Fiorillo, Heinlein, Janka, Raffelt, Vitagliano & Bollig, arXiv:2308.01403

Time-Integrated Analysis with Pinched Spectra

With late events

Without late events



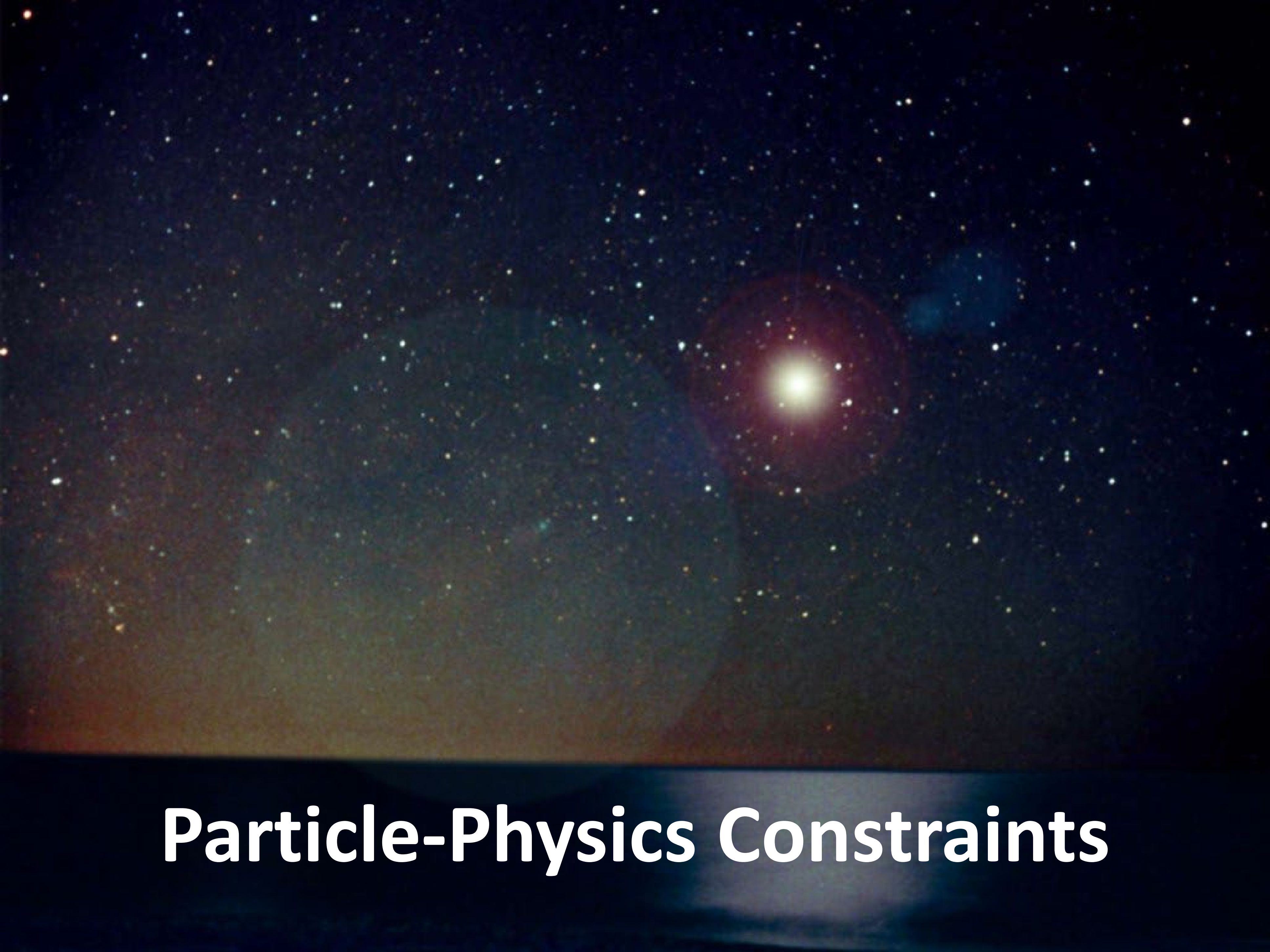
Quasi-thermal spectrum ("pinched spectrum")

$$f_\nu(\epsilon) \propto \frac{\epsilon^\alpha}{\bar{\epsilon}^{\,1+\alpha}} e^{-(1+\alpha)/\bar{\epsilon}}$$

Average energy $\langle\epsilon\rangle = \bar{\epsilon}$

Maxwell-Boltzmann spectrum for $\alpha = 2$

Fiorillo, Heinlein, Janka, Raffelt, Vitagliano & Bollig, arXiv:2308.01403



Particle-Physics Constraints

Neutrino Limits by Intrinsic Signal Dispersion

Time of flight delay by neutrino mass

G. Zatsepin, JETP Lett. 8:205, 1968

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

SN 1987A signal duration implies

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

Loredo & Lamb
Ann N.Y. Acad. Sci. 571 (1989) 601
find 23 eV (95% CL limit) from detailed maximum-likelihood analysis

- At the time of SN 1987A competitive with tritium end-point
- Today $\mathrm{m}_\nu < 0.45\ \mathrm{eV}$ from tritium
- Cosmological limit today $m_\nu \lesssim 0.1\ \mathrm{eV}$

"Milli charged" neutrinos

Path bent by galactic magnetic field, inducing a time delay

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

SN 1987A signal duration implies

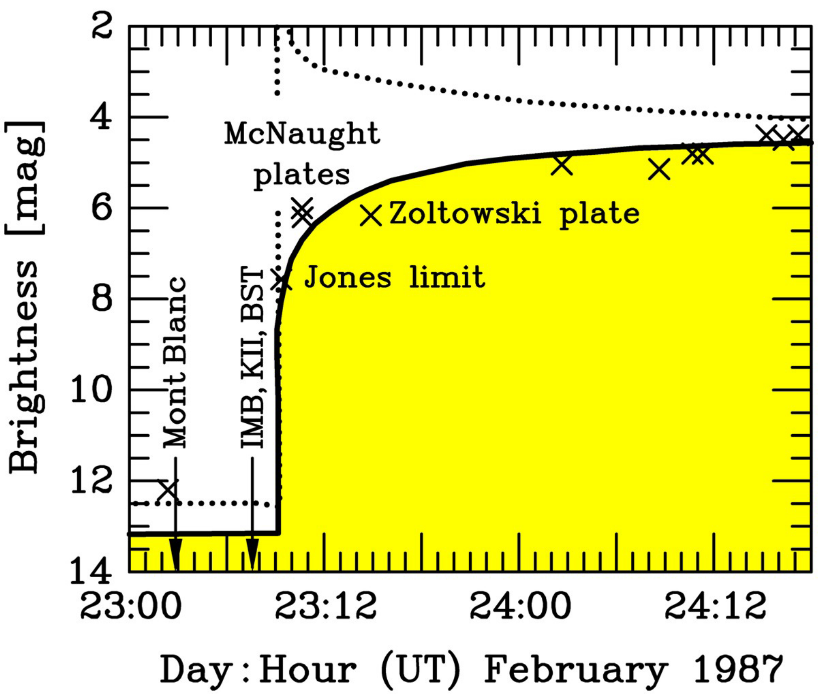
$$\frac{e_\nu}{e} < 3\times 10^{-17}\ \frac{1\mu G}{B_\perp}\ \frac{1\ \mathrm{kpc}}{d_B}$$

- Barbiellini & Cocconi, Nature 329 (1987) 21
- Bahcall, Neutrino Astrophysics (1989)

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

Do Neutrinos Gravitate?

Early light curve of SN 1987A



- Neutrinos arrived several hours before photons as expected
- Transit time for ν and γ same (160.000 yr) within a few hours

Shapiro time delay for particles moving in a gravitational potential

$$\Delta t = -2 \int_A^B dt\, \Phi[r(t)]$$

For trip from LMC to us, depending on galactic model,

$$\Delta t \approx 1\text{–}5 \text{ months}$$

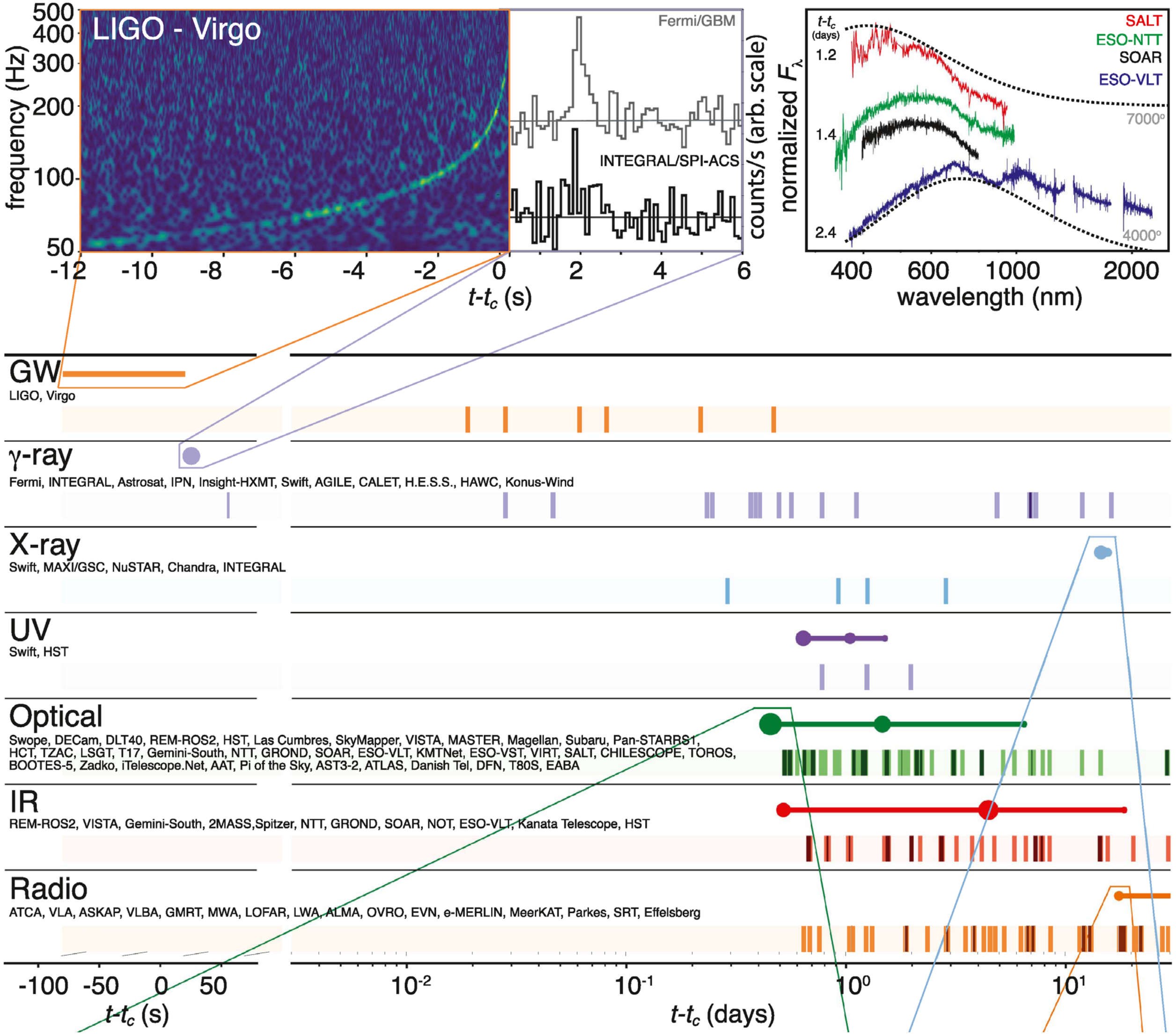
Neutrinos and photons respond to gravity the same to within

$$1\text{–}4 \times 10^{-3}$$

Longo, PRL 60:173, 1988
Krauss & Tremaine, PRL 60:176, 1988

GW vs Gamma-Ray Shapiro Time Delay

ApJ Lett. 848 (2017) L12

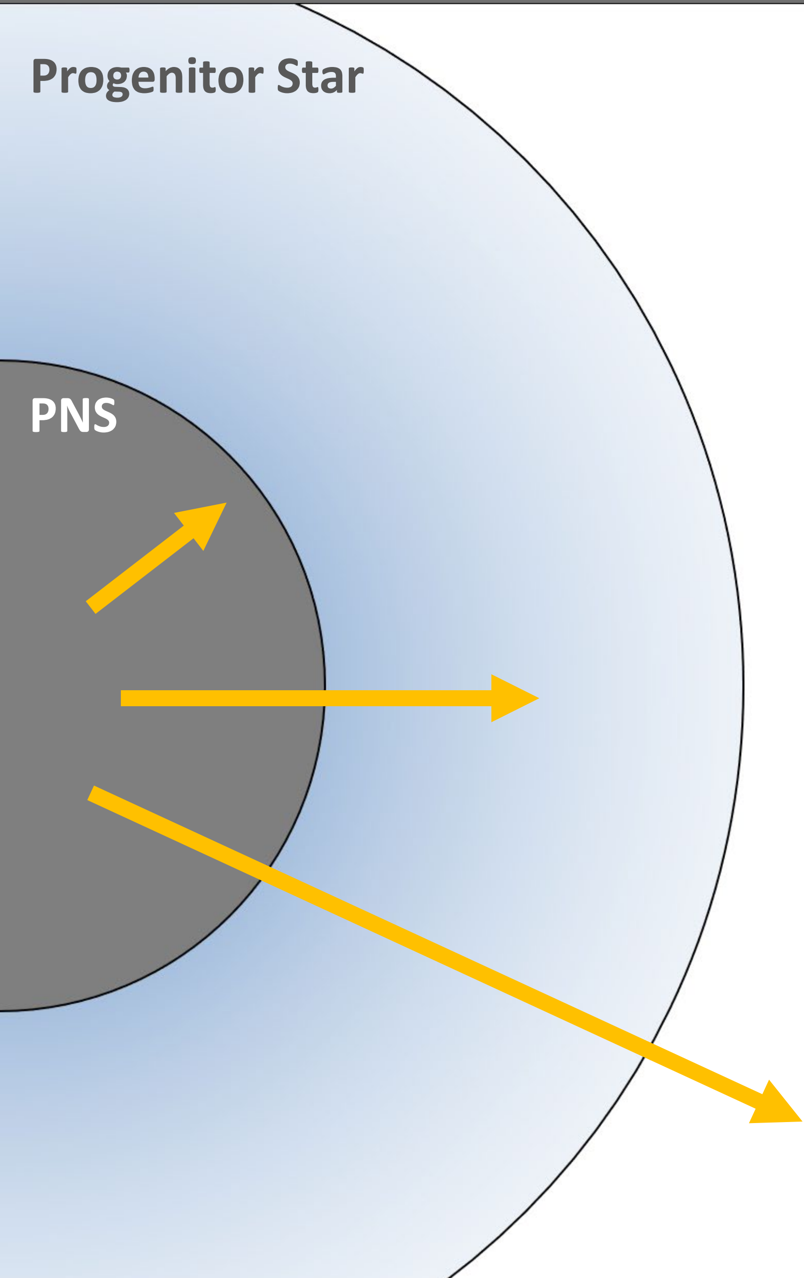


NS-NS Merger
- **GW170817**
- **GRB 170817A**

GWs & γ arrive within 2 s
Equal Shapiro time delay within $\sim 10^{-7}$

(Shoemaker & Murase arXiv:1710.06427)

Impact of New Particles



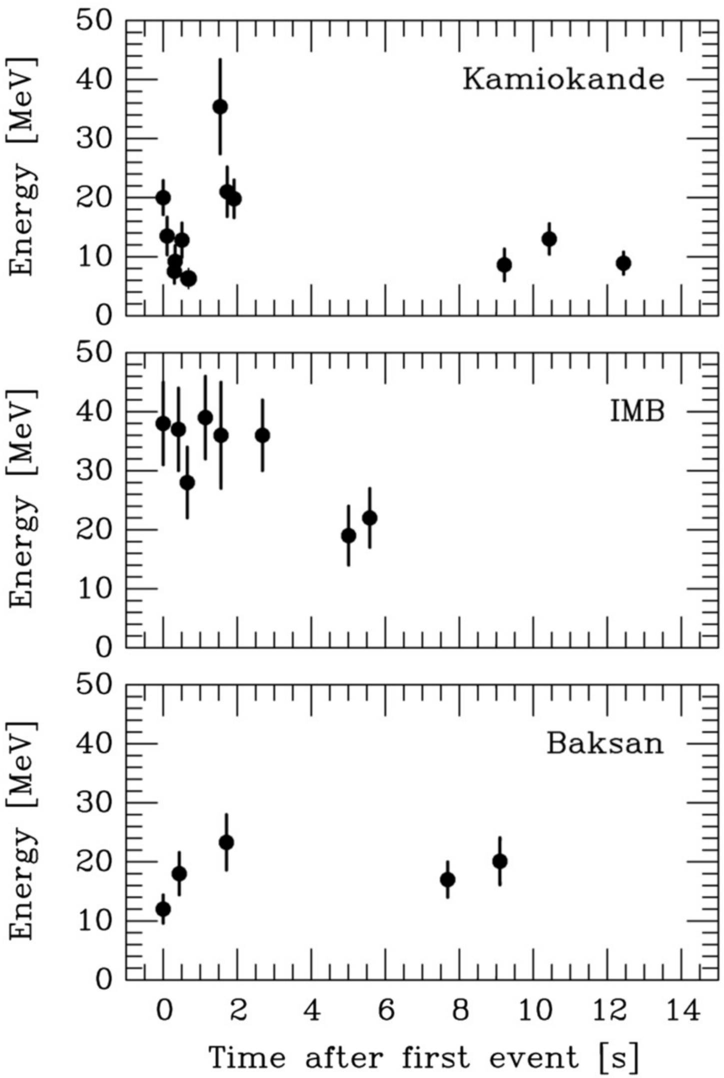
Energy and lepton transport
within PNS

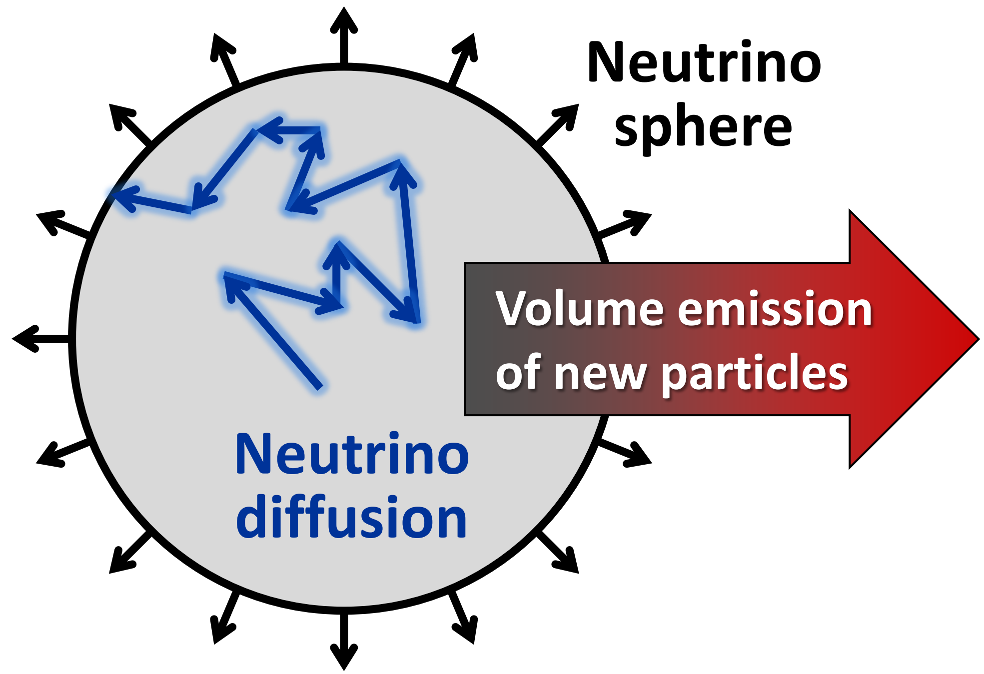
Energy transport beyond neutrino sphere
(directly or decay products)
- Explosion
- Nucleosynthesis

Detection (direct or decay products)
- SN 1987A, next nearby SN
- Diffuse background from all past SNe

Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal



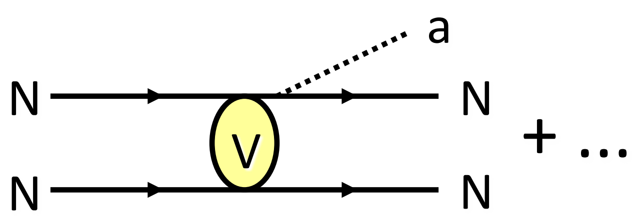


Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

Axion Emission from a Nuclear Medium

Axion-nucleon interaction: $\mathcal{L}_{\rm int} = \frac{C_N}{2f_a}\,\overline{\Psi}_N\gamma_\mu\gamma_5\Psi_N\partial^\mu a = \frac{C_N}{2f_a}J_\mu^A\partial_a^\mu$



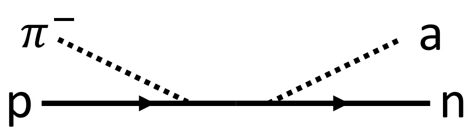
Nucleon-Nucleon
Bremsstrahlung

Axial-vector interaction implies dominance of spin-dependent process

- Interaction potential (one-pion exchange OPE often used, but too simplistic)
- In-medium coupling constants
- In-medium effective nucleon properties
- Correlation effects (static and dynamical spin-spin correlations)

→ For latest discussion see Carenza et al. arXiv:1906.11844

Thermal π^- contribute significant (dominant?)



→ For latest discussion see Carenza et al. arXiv:2010.02943

SN 1987A Axion Limits from Burst Duration

- Raffelt, Lect. Notes Phys. 741 (2008) 51 hep-ph/0611350
  Burst duration calibrated by early numerical studies
  "Generic" emission rates inspired by OPE rates
  $f_a \gtrsim 4 \times 10^8$ GeV and $m_a \lesssim 16$ meV (KSVZ, based on proton coupling)

- Chang, Essig & McDermott, JHEP 1809 (2018) 051 1803.00993
  Various correction factors to emission rates, specific SN core models
  $f_a \gtrsim 1 \times 10^8$ GeV and $m_a \lesssim 60$ meV (KSVZ, based on proton coupling)

- Carenza, Fischer, Giannotti, Guo, Martínez-Pinedo & Mirizzi, JCAP 10 (2019) 016 & Erratum 1906.11844
  Beyond OPE emission rates, specific SN core models: similar to Chang et al.
  $f_a \gtrsim 4 \times 10^8$ GeV and $m_a \lesssim 15$ meV (KSVZ, based on proton coupling)

- Carenza, Fore, Giannotti, Mirizzi & Reddy 2010.02943
  Including thermal pions $\pi^- + p \to n + a$ (factor 3 larger emission)
  $f_a \gtrsim 5 \times 10^8$ GeV and $m_a \lesssim 11$ meV (KSVZ, based on proton coupling)

- Bar, Blum & D'Amico, Is there a supernova bound on axions? 1907.05020
  Alternative picture of SN explosion (thermonuclear event)
  Observed signal not PNS cooling. SN1987A neutron star (or pulsar) not yet found.
  (but see "NS 1987A in SN 1987A", Page et al. arXiv:2004.06078)

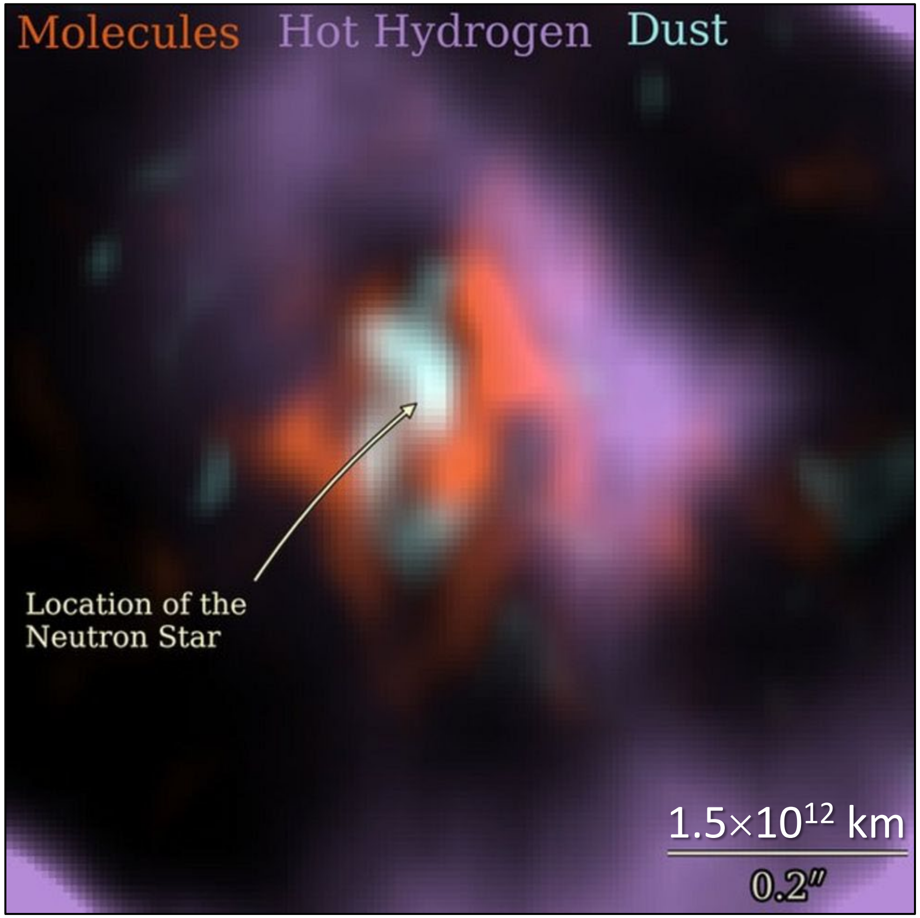
Where is the Neutron Star of SN 1987A?

No pulsar or neutron star has been seen until now (35 years later)

- Infra-red excess observed by ALMA: In "the blob" strong indication for NS Expected position, remnant hidden by dust [Cigan+ arXiv:1910.02960]
- Most plausible model: Thermally cooling non-pulsar NS [Page+ arXiv:2004.06078]

https://www.bbc.com/news/science-environment-50473482

Atacama Large Millimeter/Submillimeter Array (ALMA) at ESO in Chile



SN 1987A Signal Duration Too Long?

Fiorillo+ [arXiv:2308.01403](https://arxiv.org/abs/2308.01403)

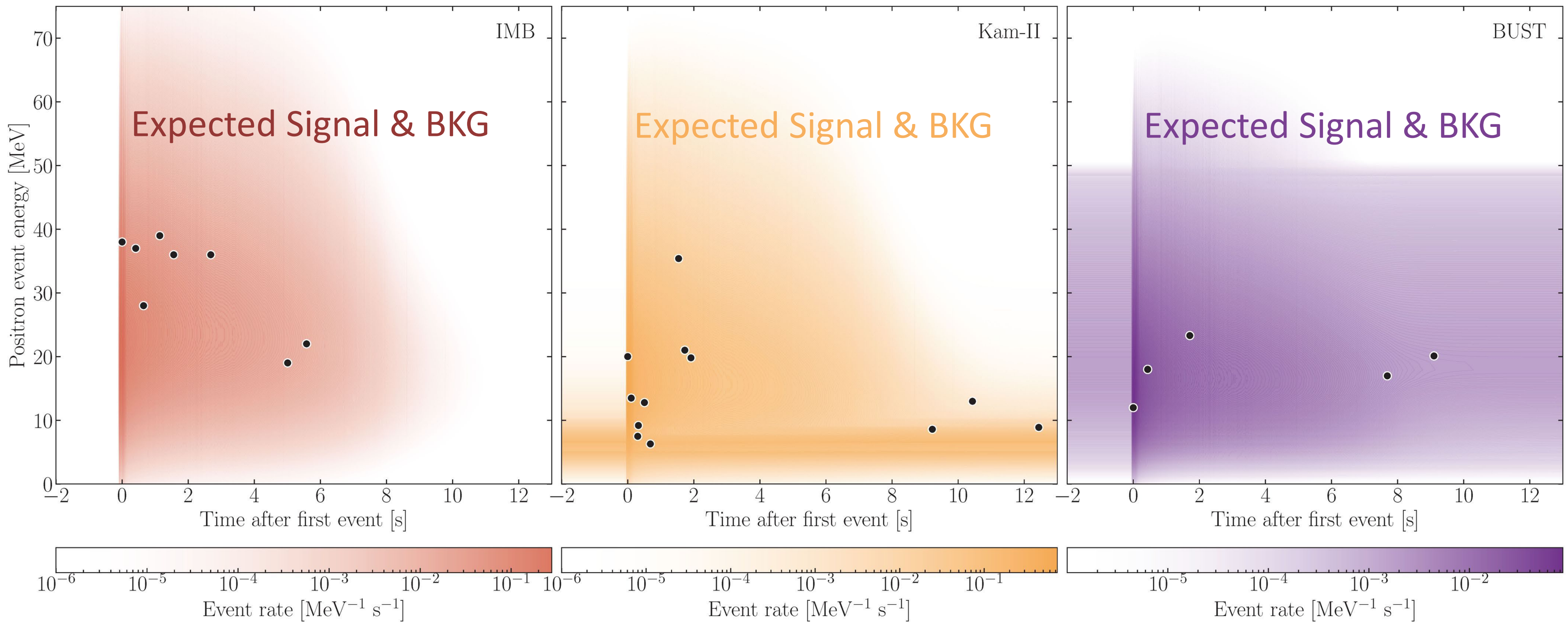


FIG. 17. Differential event distribution (signal and background) at each experiment, compared with the observations. Results are shown for model 1.44-SFHo without flavor swap; the offset time for each experiment is chosen as the best-fit value reported in Table VII.

- **In a suite of Garching models (no axions), expected signal always too short (PNS convection!)**
- **Deserves dedicated study**

Cooling Simulations of Five Neutron Stars

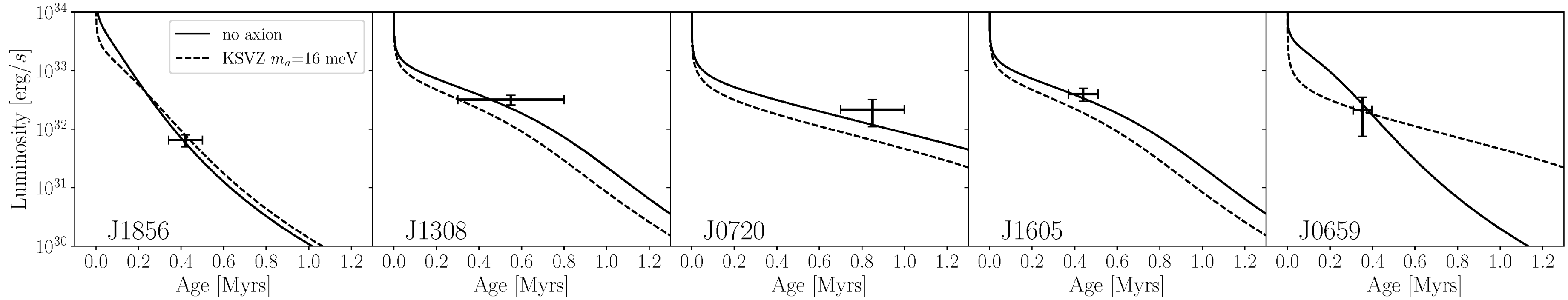
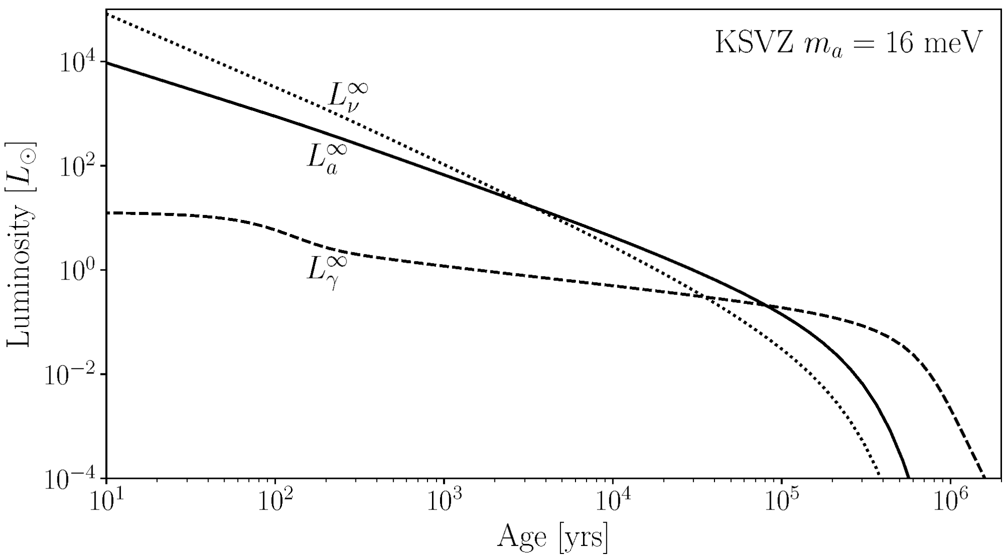


Figure 1. The luminosity and age data for each of the NSs considered in this work (see Tab. I). We show the best-fit cooling curves computed in this work for each of these NSs under the null hypothesis and with the axion mass fixed to $m_a = 16$ meV, which is our 95% upper limit on the QCD axion mass in the context of the KSVZ model.



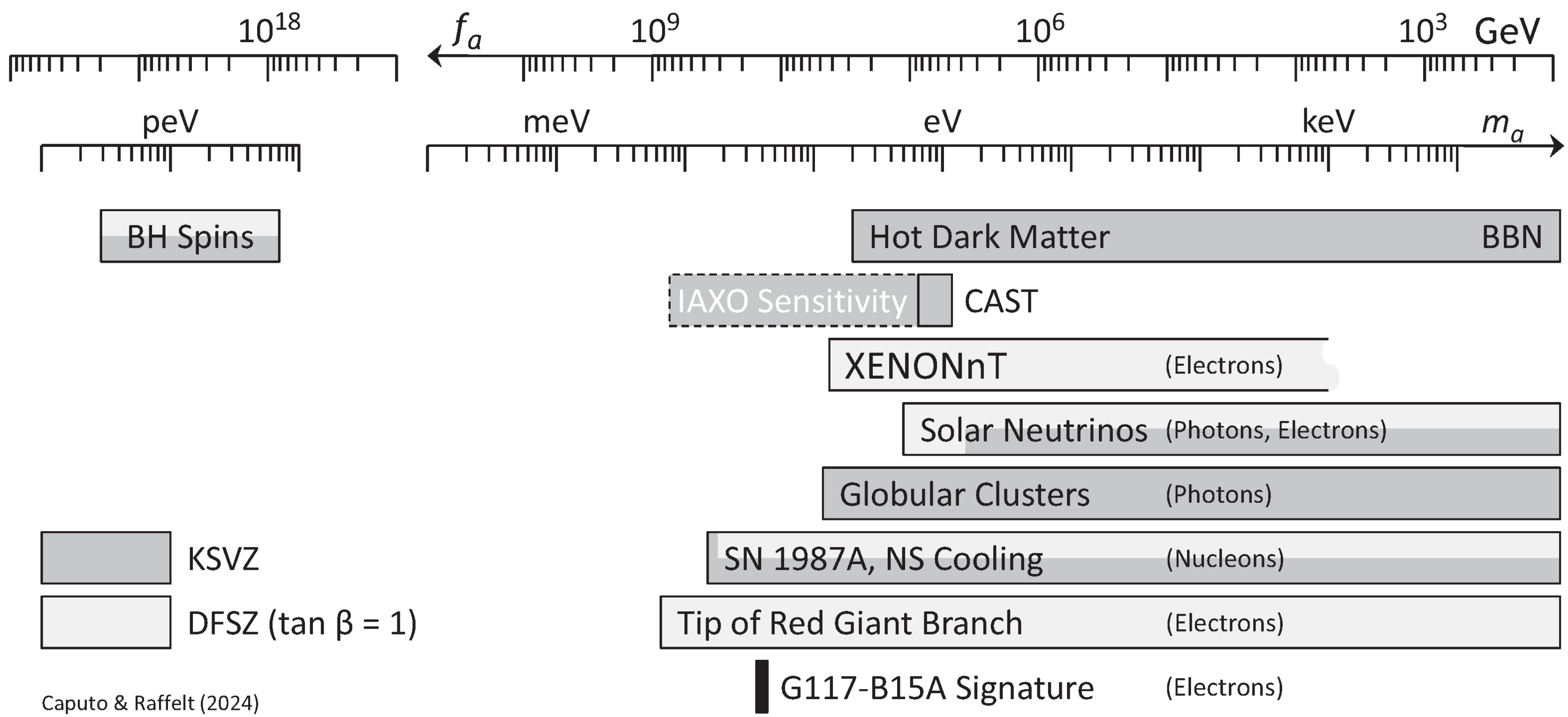
Cooling of J1605 with KSVZ axions, BSk22 EOS, SBF-0-0 superfluidity model, $M_{\rm NS} = 1.0\ M_\odot$

Upper Limit on the QCD Axion Mass from Isolated Neutron Star Cooling

Buschmann, Dessert, Foster, Long & Safdi, 2111.09892

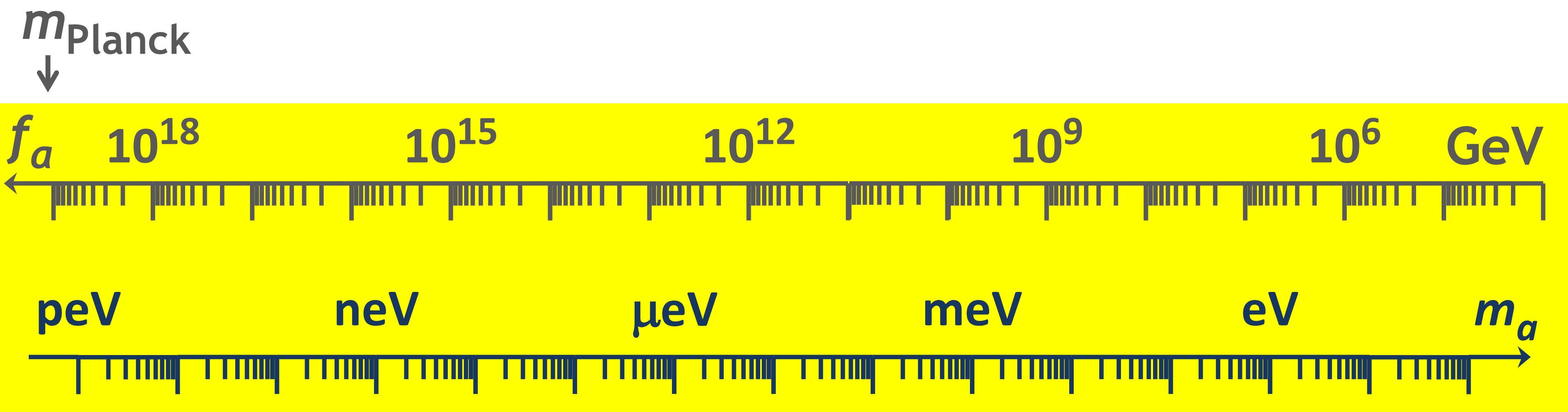
Astrophysical Axion Bounds

The 2024 Edition, Caputo & Raffelt, arXiv:2401.13728, 24 Jan 2024



- Many improvements over the years, but overall picture the same
- Specific QCD axion signatures hard to expect from cooling effects
- Best stellar detection opportunity probably (Baby)IAXO

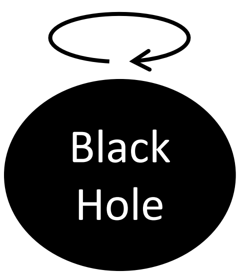
Astrophysical Axion Bounds and Opportunities

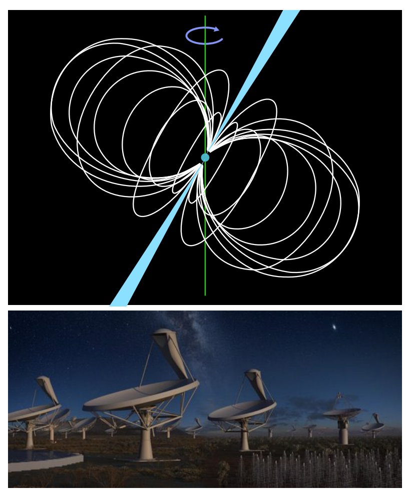


Super Radiance

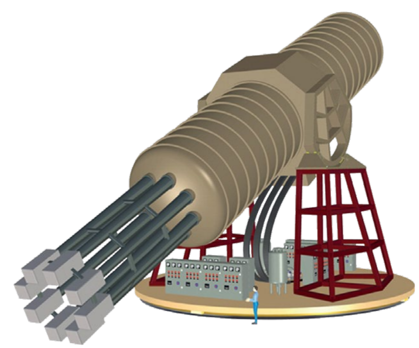
Opportunities for detection

Astrophysical Bounds (Energy loss of stars)



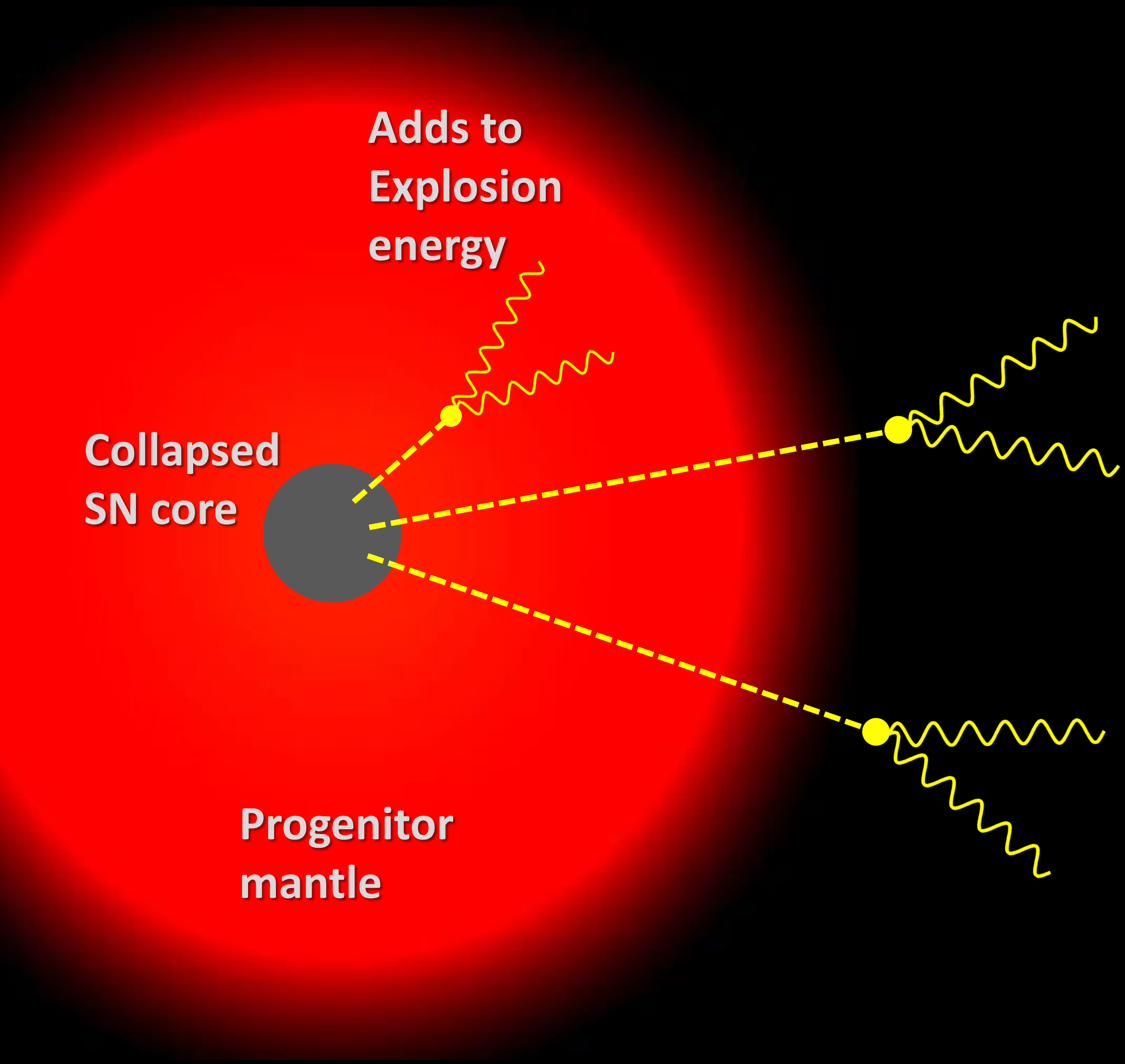


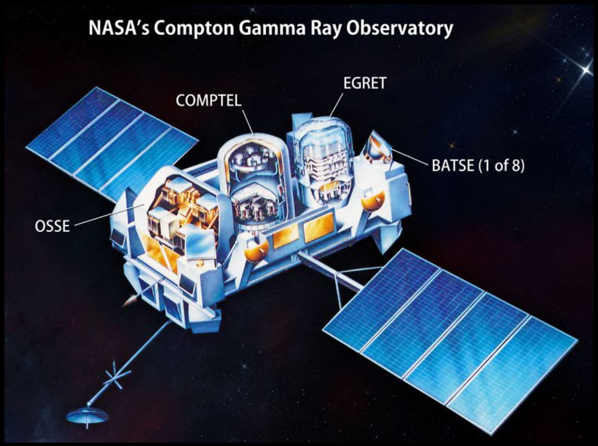
Axion conversion in neutron star magnetospheres



IAXO Solar Axion Telescope

Supernova Bounds on Radiative Particle Decays





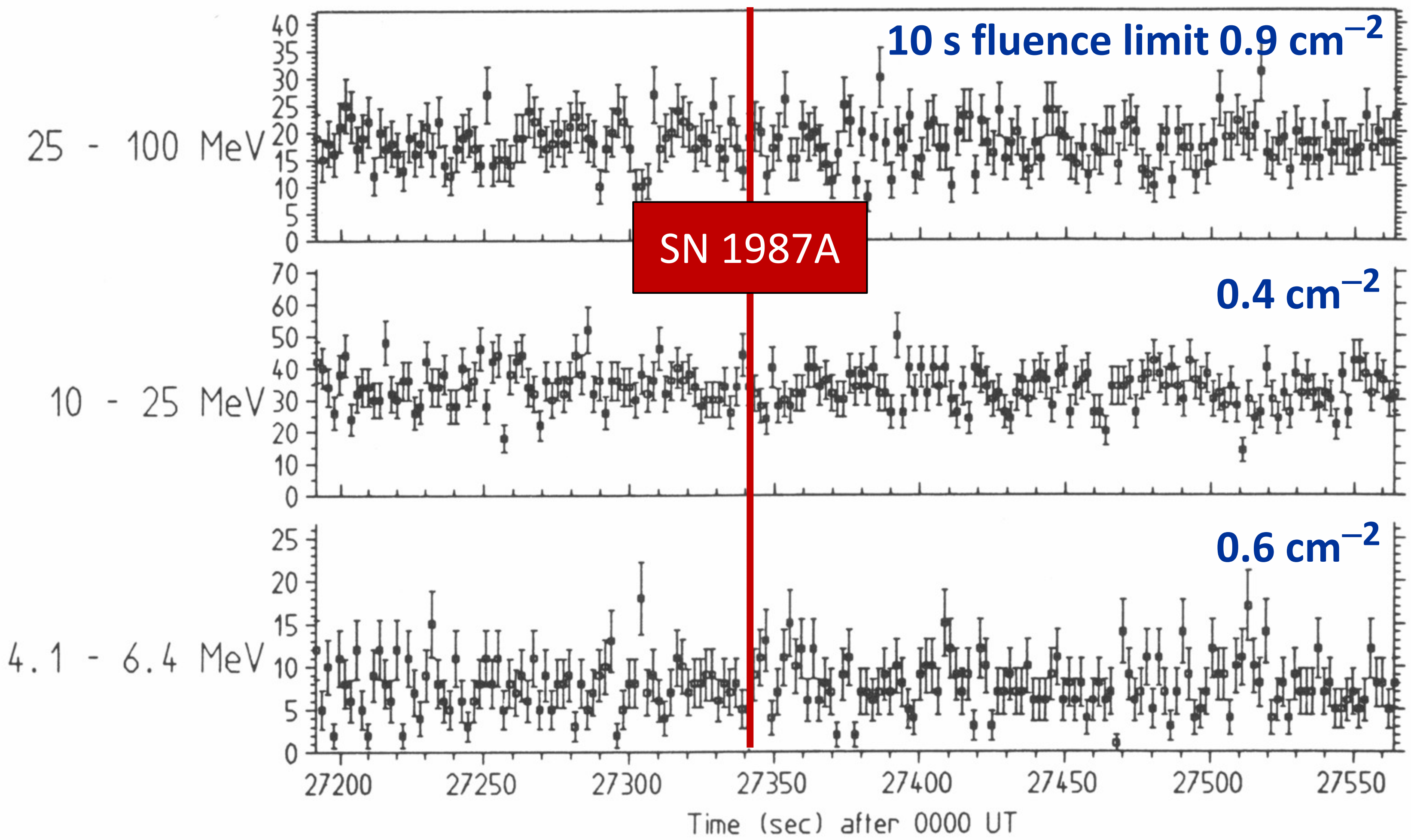
Cosmic gamma ray background
from all past supernovae

Solar Maximum Mission

No excess gamma rays
@ SN 1987A neutrino burst

Gamma-Ray Observations of SMM Satellite

Counts in the GRS instrument on the Solar Maximum Mission Satellite



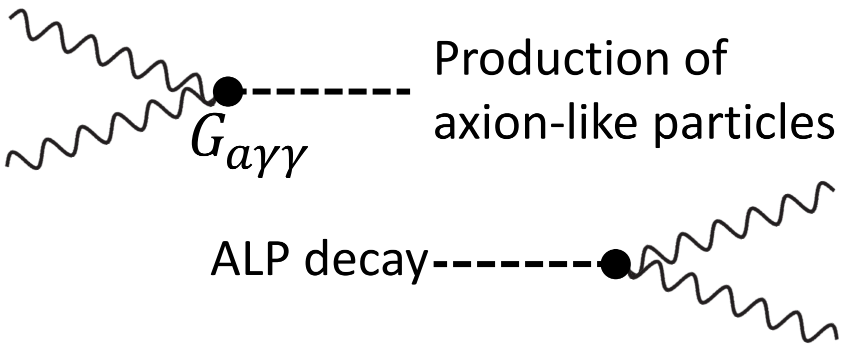
SN 1987A neutrino fluence $\sim 10^{10}\mathrm{cm}^{-2}$

$< 10^{-10}$ of neutrinos have decayed to photons on their way to Earth

Low-Energy Supernovae Severely Constrain Radiative Particle Decays

Andrea Caputo[1,2] Hans-Thomas Janka[3] Georg Raffelt[4] and Edoardo Vitagliano[5]

arXiv:2201.09890 (24 Jan 2022)

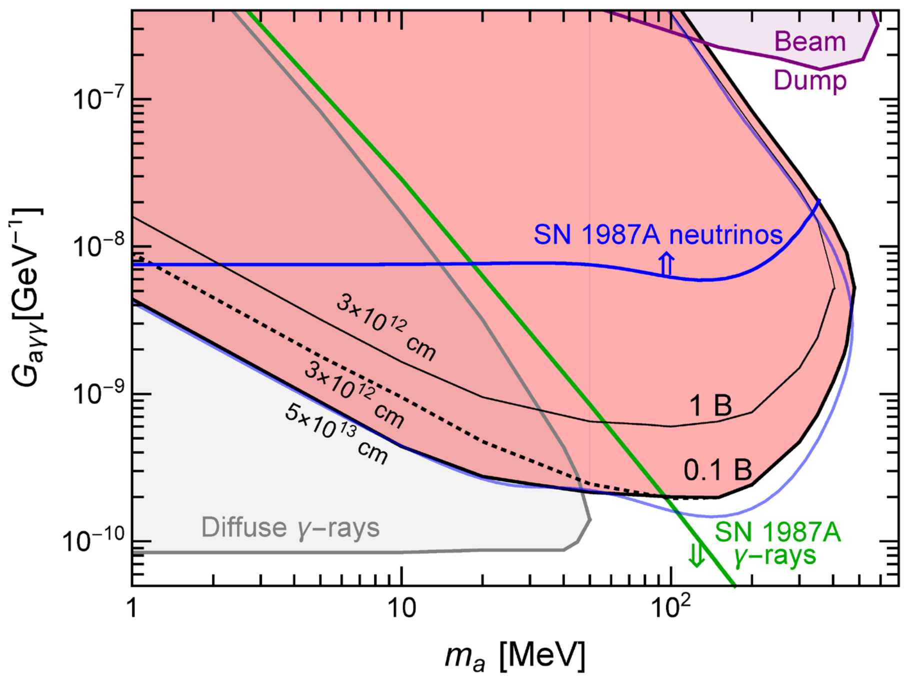


Typical SN explosion energy 1–2 B

Some SNe have very small observed explosion energies < 0.1 B
(e.g. subluminous type II-P SNe)

Restrictive limits on energy deposition in progenitor star by particle decays!

1 B (bethe) = 10^{51} erg
Neutron-star binding energy 200–400 B
($0.11–0.22\ M_{SUN}$)



Neutrinos from Next Nearby SN

Operational Detectors for Next Galactic SN Neutrinos

HALO (30)
SNO+ (300)

ORCA (100)

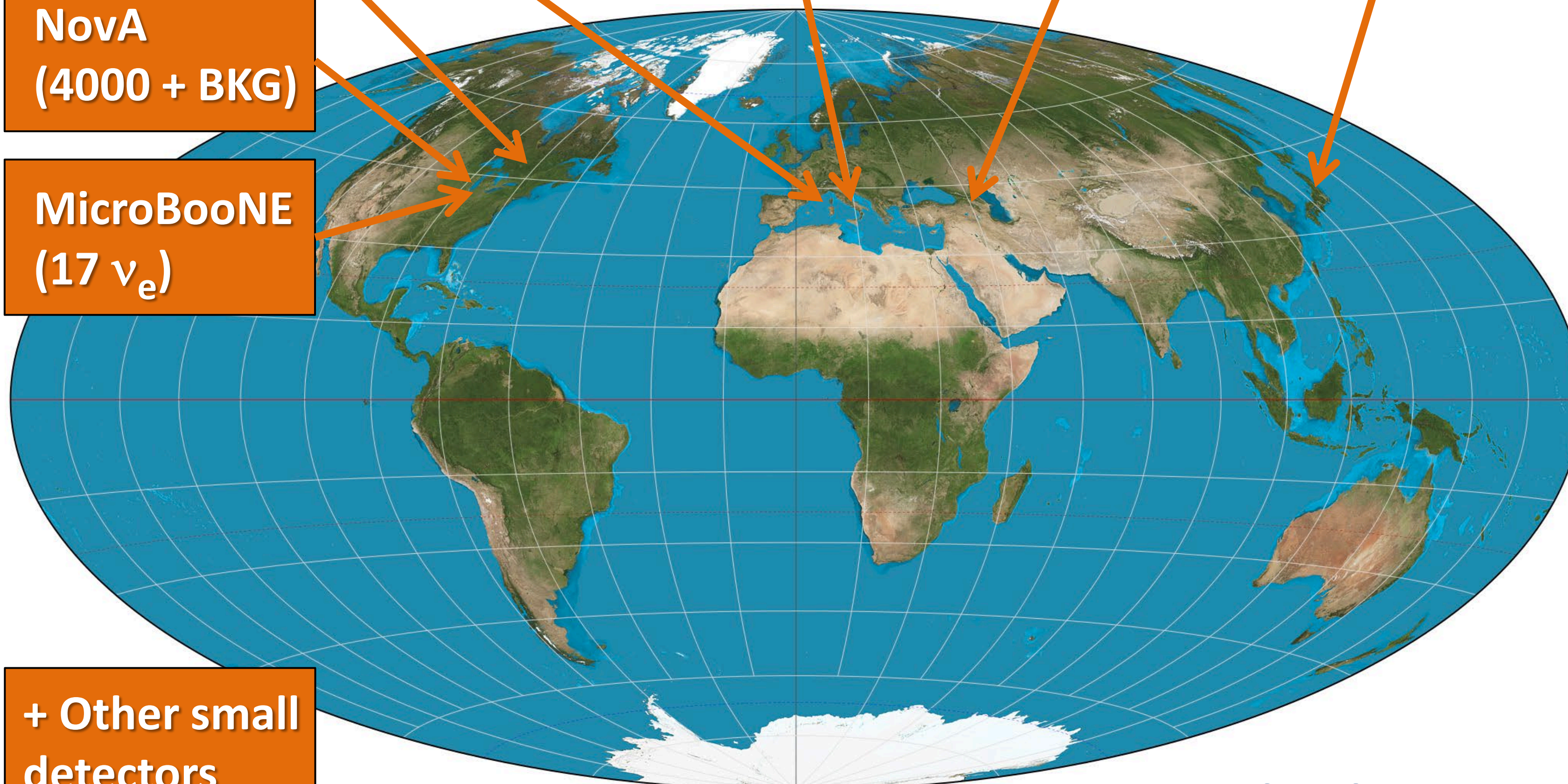
LVD (300)

Baksan (100)

Super-K (4000)
KamLAND (300)

NovA (4000 + BKG)

MicroBooNE ($17\ \nu_e$)

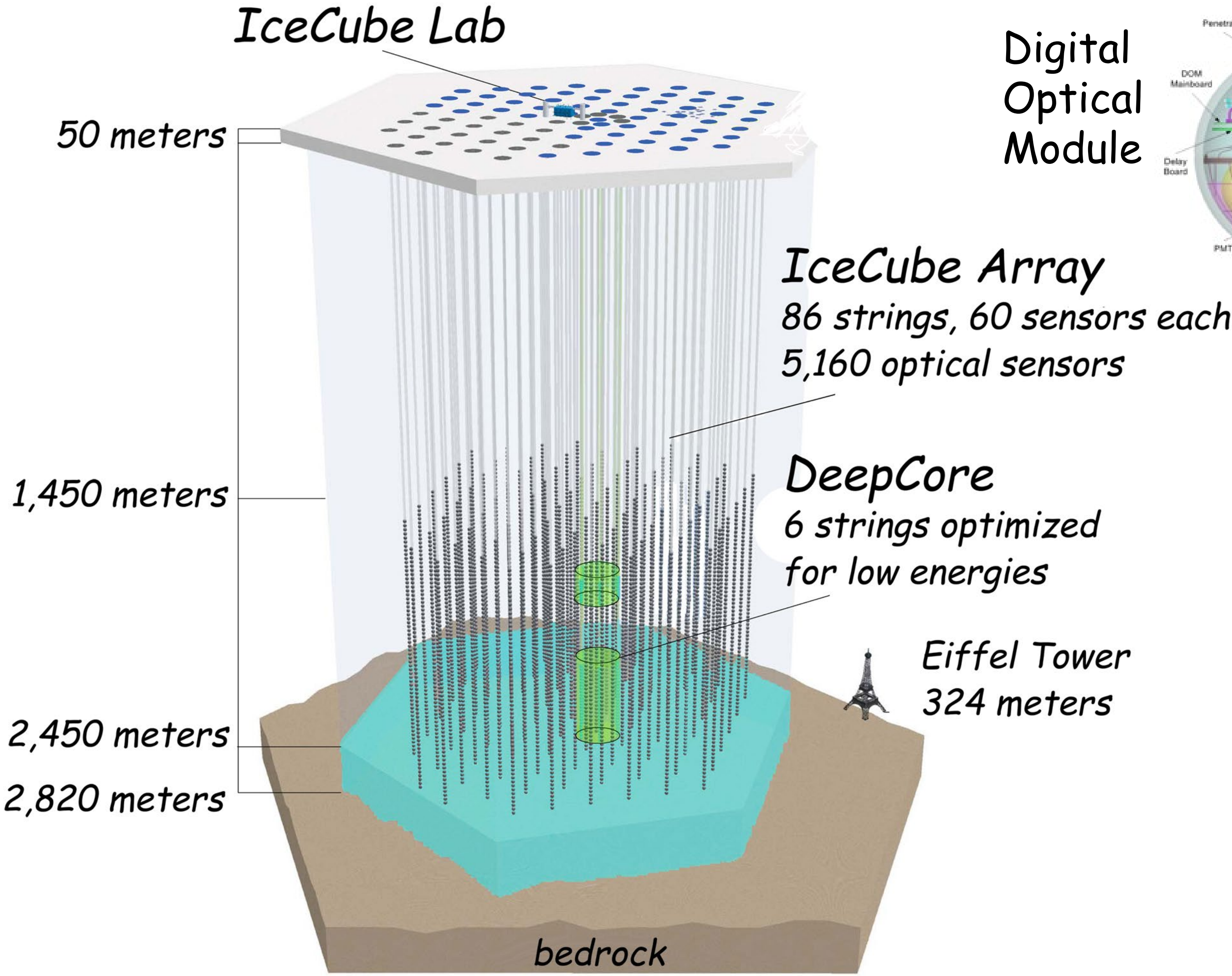


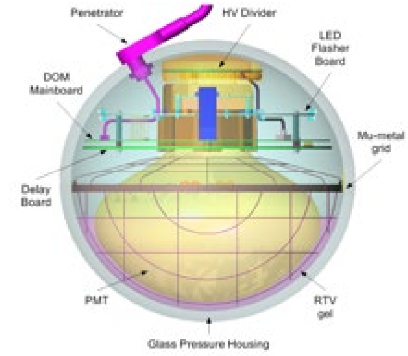
+ Other small detectors with some SN sensitivity

IceCube (10^6)

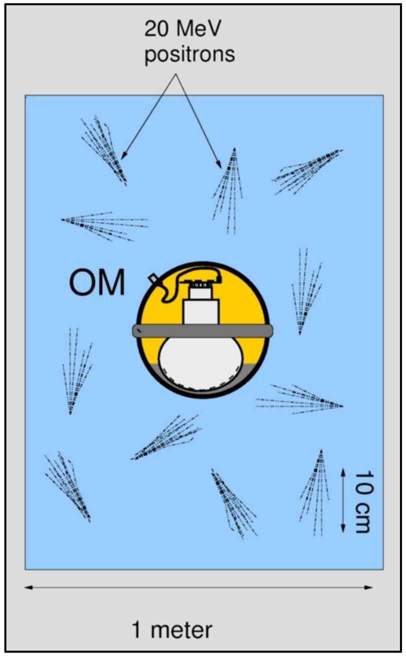
In brackets events for a “fiducial SN” at distance 10 kpc

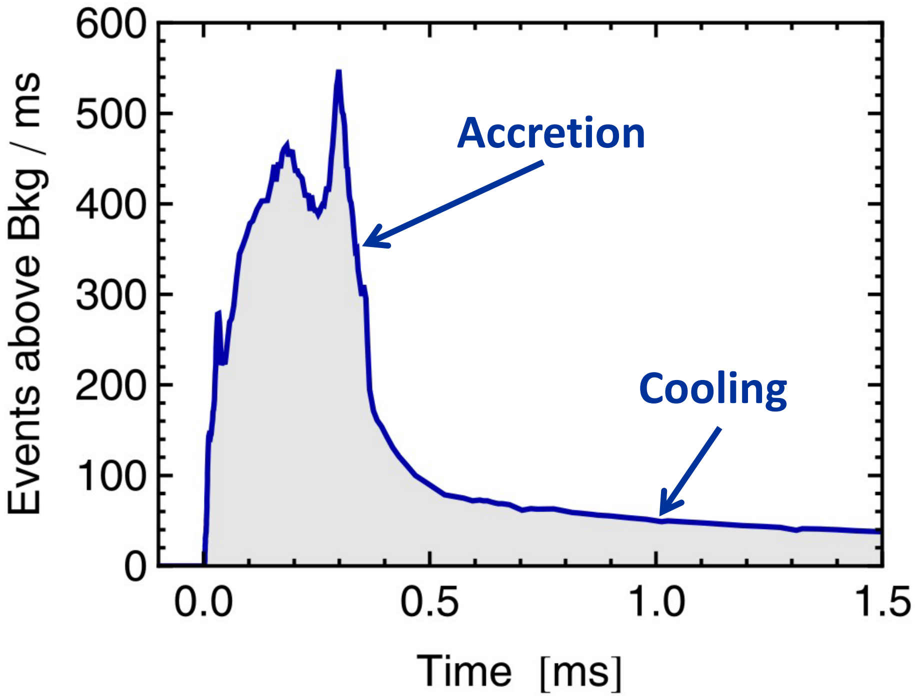
IceCube Neutrino Telescope at the South Pole





IceCube as a Supernova Neutrino Detector



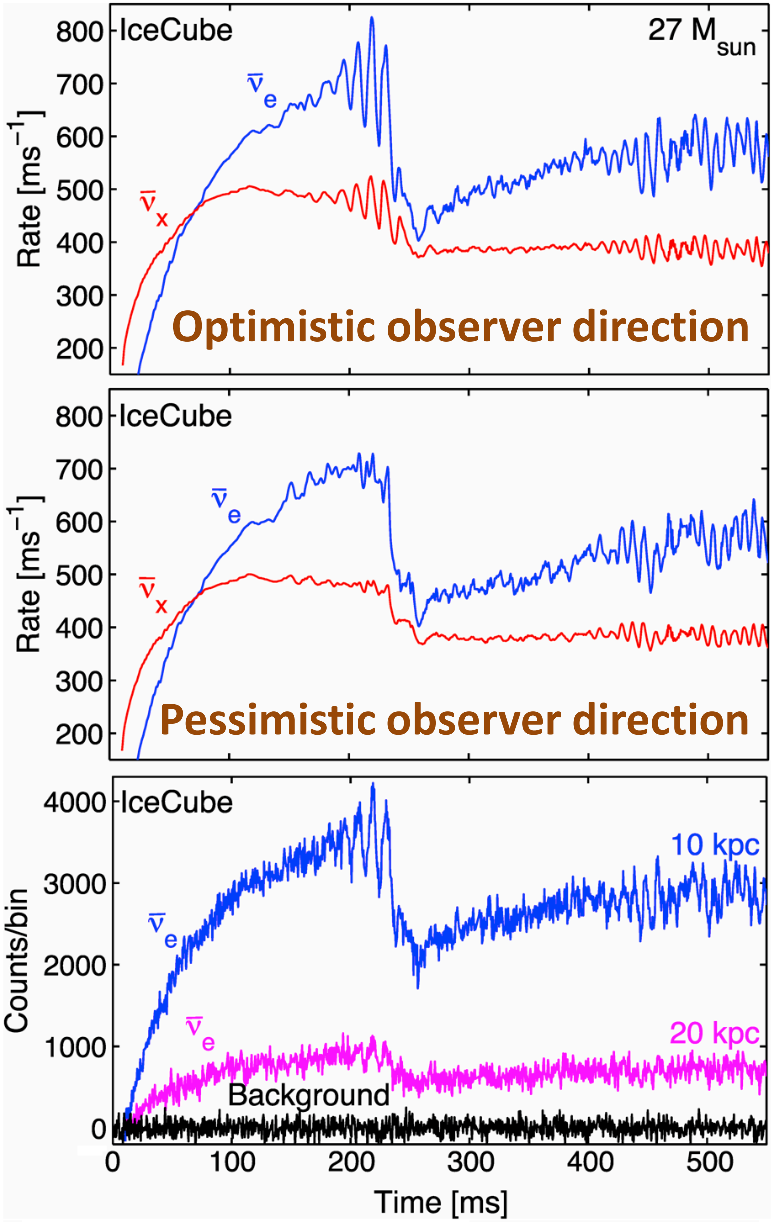


SN signal at 10 kpc
10.8 M_{sun} simulation of Basel group
[arXiv:0908.1871]

- Each optical module (OM) picks up Cherenkov light from its neighborhood
- ~ 300 Cherenkov photons per OM from SN at 10 kpc, bkgd rate in one OM < 300 Hz
- SN appears as "correlated noise" in ~ 5000 OMs
- Significant energy information from time-correlated hits

Pryor, Roos & Webster, ApJ 329:355, 1988. Halzen, Jacobsen & Zas, astro-ph/9512080. Demirörs, Ribordy & Salathe, arXiv:1106.1937.

SASI Detection Perspectives



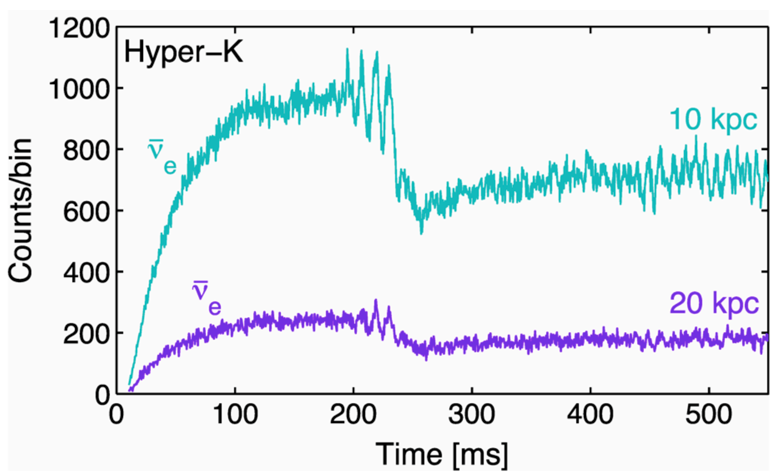
Neutrino signal variations from hydro instabilities detectable!

Neutrino mass time of flight sensitivity if observing these modulations

$m_\nu \lesssim 0.14\ \text{eV}$

arXiv:1202.0248

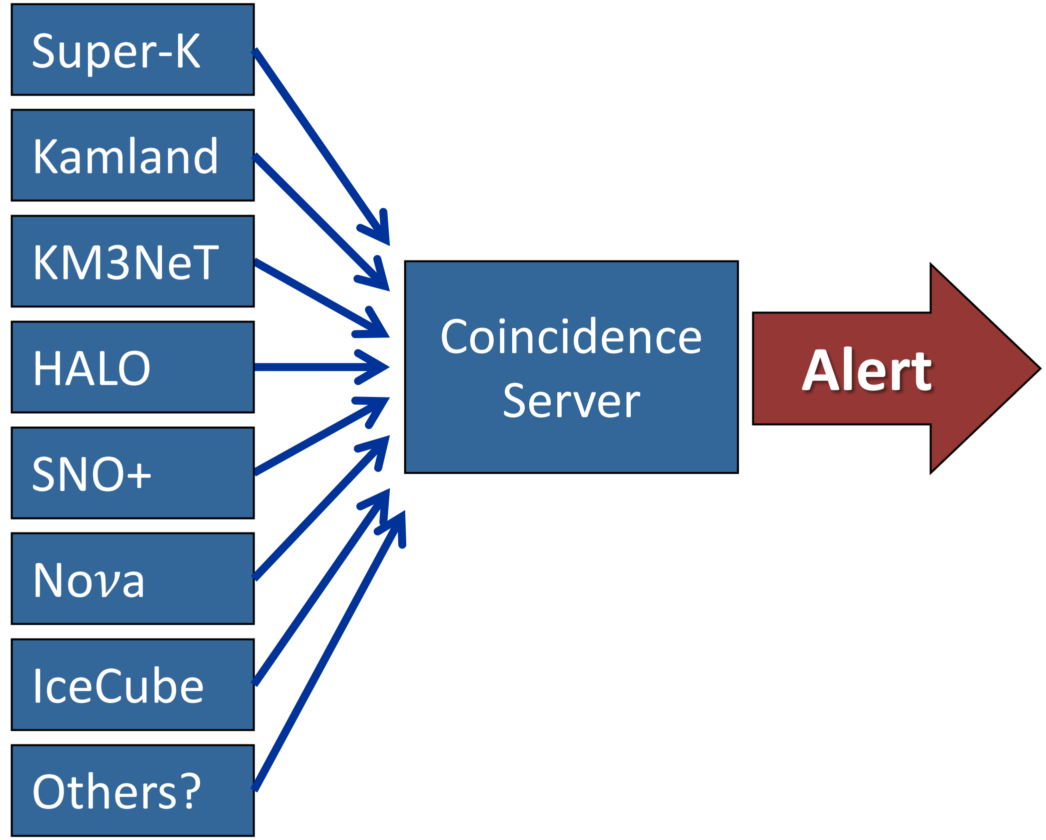
E.g. Lund+ arXiv:1006.1889
Tamborra+ arXiv:1307.7936
Walk+ arXiv:1807.02366



Includes shot noise

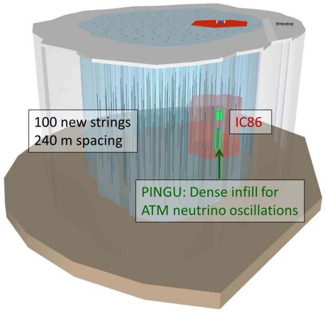
SuperNova Early Warning System (SNEWS)

https://snews2.org/



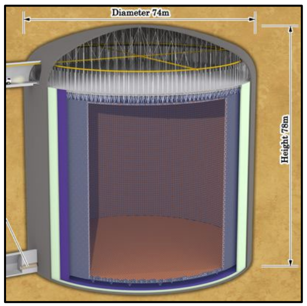
- Neutrinos arrive several hours before optical outburst
- Issue an alert to astronomical community
- Trigger to LIGO, NOvA, GCN

Next Generation Very-Large-Scale Detectors (2025+)



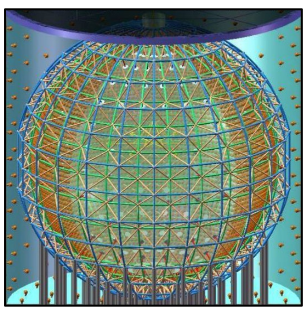
IceCube Gen-2
- Dense infill (PINGU)
- Larger volume (statistics for high-E events)

Doubling the number of optical modules

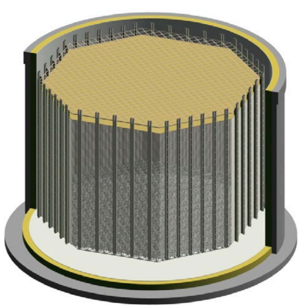


Megaton-class water Cherenkov detector

Hyper-Kamiokande (260 kt), under construction
SN nu statistics comparable to IceCube,
but with event-by-event energy information



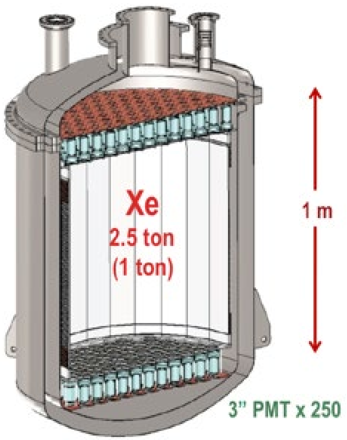
Scintillator detectors (20 kiloton scale)
- JUNO in China for reactor nus (commissioning 2025)
- Jinping Liquid Scintillator Detector (4 kt, early studies)
- Baksan Large Volume Scintillator Detector (10 kt) (Russia, early studies)

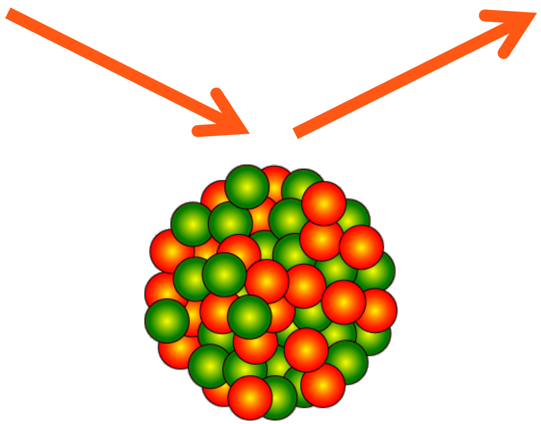


Liquid argon time projection chamber (>2028)

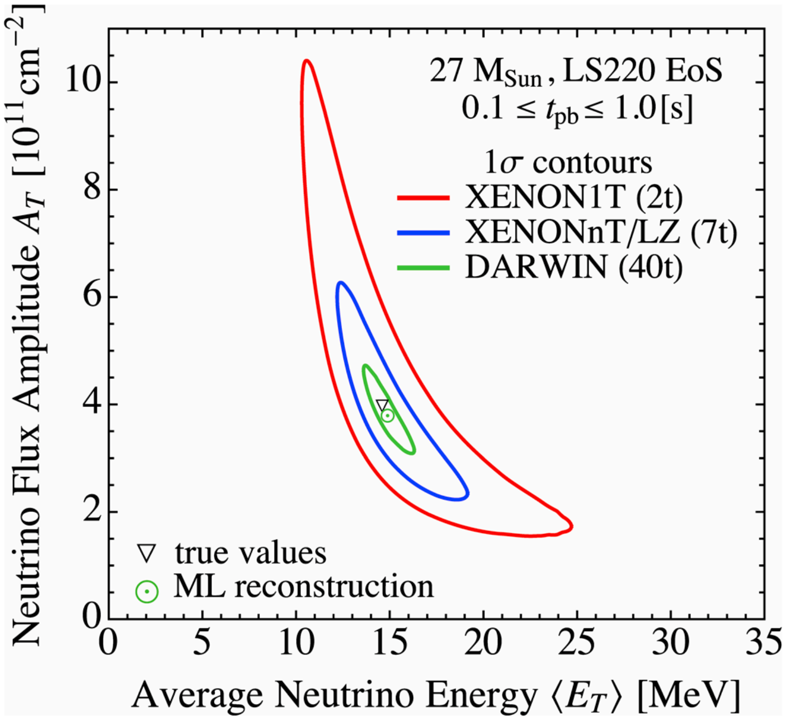
For long-baseline oscillation experiment DUNE
- Unique SN capabilities (CC ν_e signal)
- But cross sections poorly known

Xenon Dark Matter Detectors





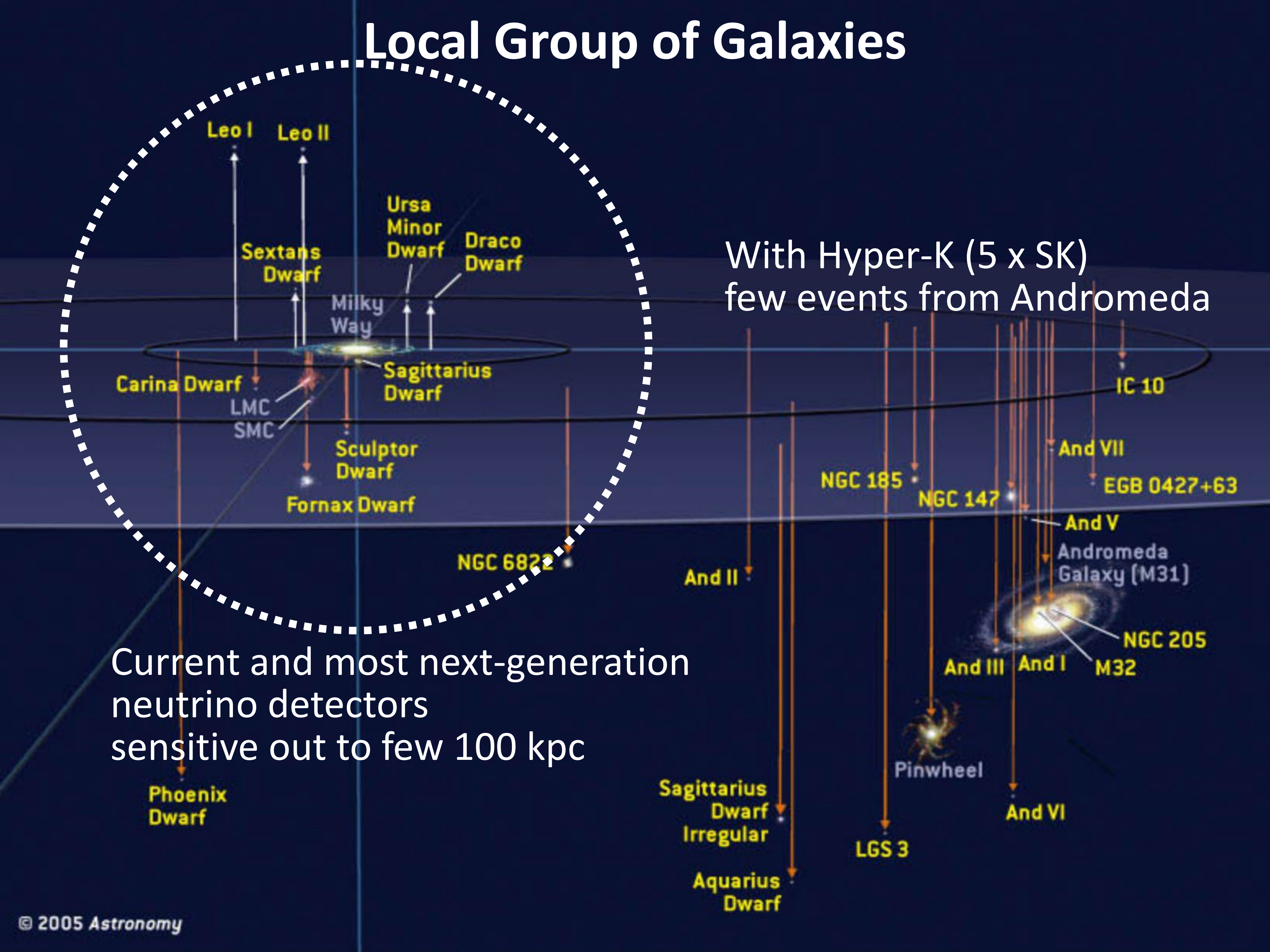
- Coherent scattering of low-E nus on Xe (77 neutrons)
- All 6 nu species contribute



Pinning down SN neutrino flux and average energy

See for example
Horowitz et al. (astro-ph/0302071)
Chakraborty et al. (arXiv:1309.4492)
XMASS Collaboration (arXiv:1604.01218)
Lang et al. (arXiv:1606.09243)

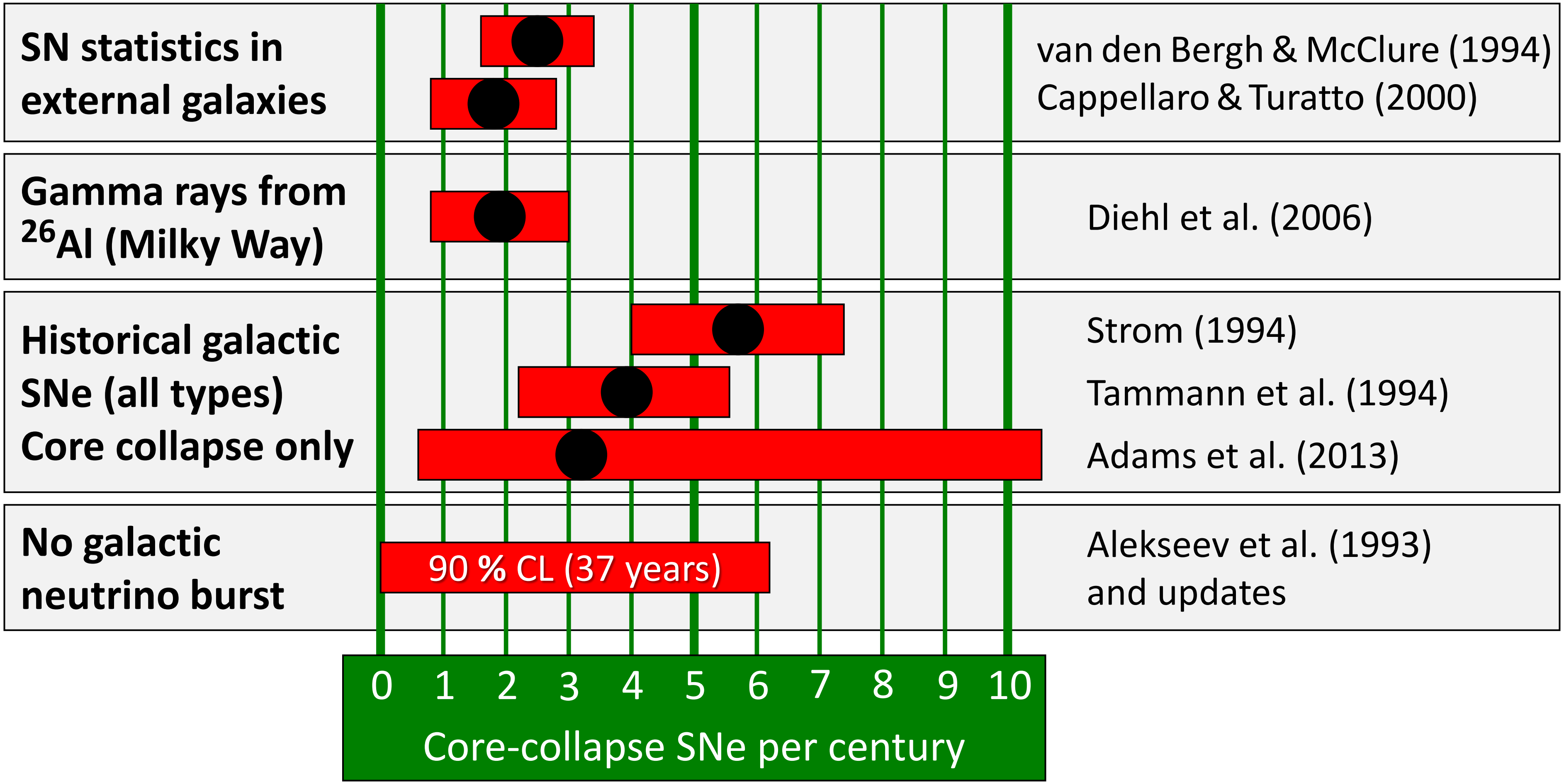
Local Group of Galaxies



With Hyper-K (5 x SK)
few events from Andromeda

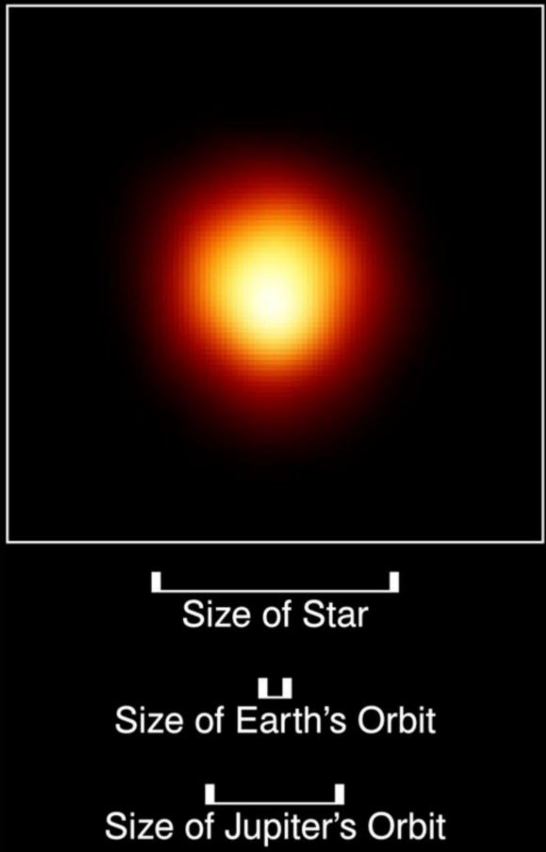
Current and most next-generation
neutrino detectors
sensitive out to few 100 kpc

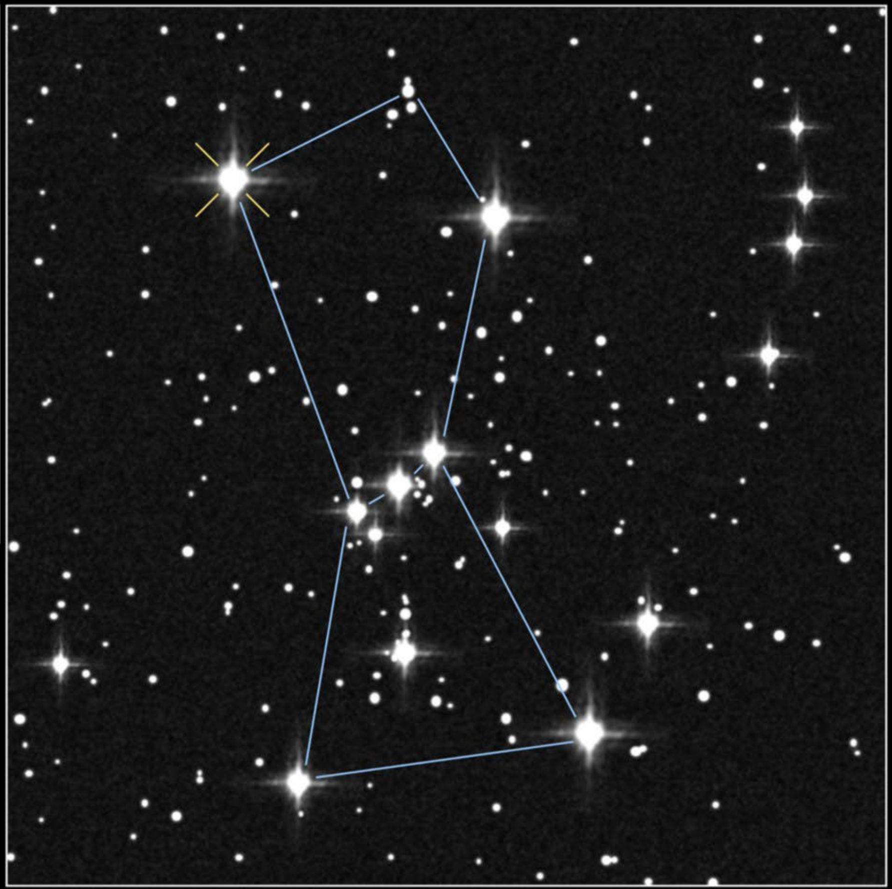
Core-Collapse SN Rate in the Milky Way



van den Bergh & McClure, ApJ 425 (1994) 205. Cappellaro & Turatto, astro-ph/0012455.
Diehl et al., Nature 439 (2006) 45. Strom, A&A 288 (1994) L1.
Tammann et al., ApJ 92 (1994) 487. Adams et al., ApJ 778 (2013) 164.
Alekseev et al., JETP 77 (1993) 339.

The Red Supergiant Betelgeuse (Alpha Orionis)





First resolved image of a star other than Sun

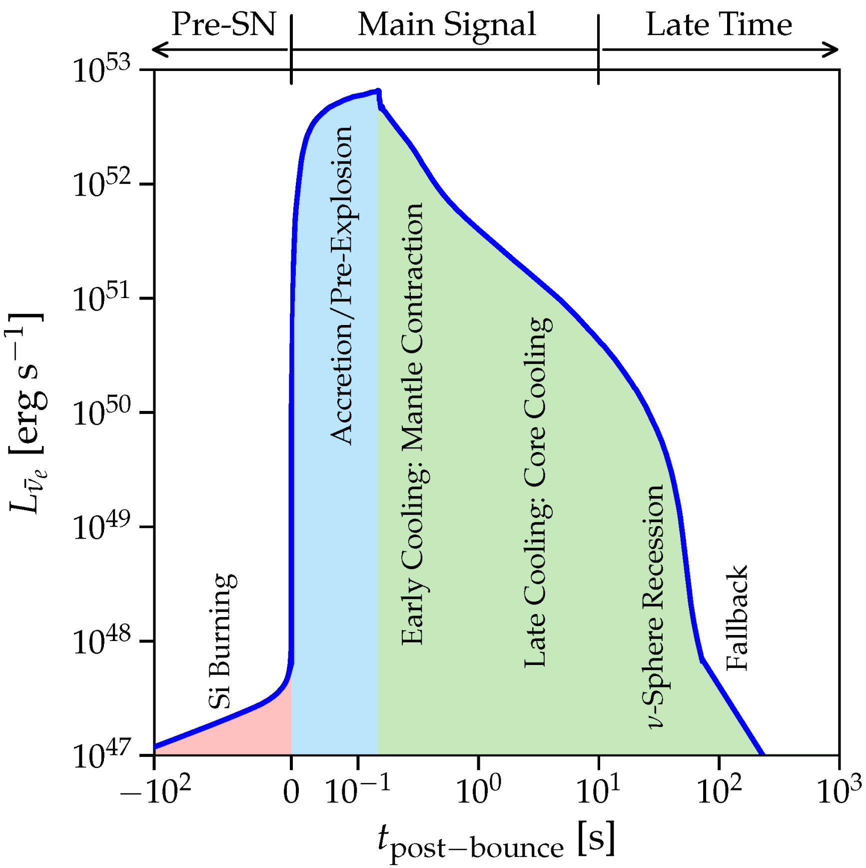
Distance (Hipparcos) 130 pc (425 lyr)

If Betelgeuse goes Supernova:

- 6×10^7 neutrino events in Super-Kamiokande
- 2.4×10^3 neutrons /day from Si burning phase (few days warning!), need neutron tagging [Odrzywolek, Misiaszek & Kutschera, astro-ph/0311012]

Five Phases – Many Physics Opportunities

Li, Roberts & Beacom [arXiv:2008.04340]



Phase	Physics Opportunities
Pre-SN	early warning, progenitor physics
Neutronization	flavor mixing, SN distance, new physics
Accretion	flavor mixing, SN direction, multi-D effects
Early cooling	equation of state, energy loss rates, PNS radius, diffusion time, new physics
Late cooling	NS vs. BH formation, transparency time, integrated losses, new physics

TABLE I. Key physics opportunities from detecting supernova neutrinos in different phases.

Many large detectors online for next decades

Every year a 3% chance

I am optimistic to see more supernova neutrinos!

Diffuse SN Neutrino Background

Distance Scales and Detection Strategies

N >> 1 : Burst

N ~ 1 : Mini-Burst

N << 1 : DSNB

Rate ~ 0.01/yr

Rate ~ 1/yr

Rate ~ 10^8/yr

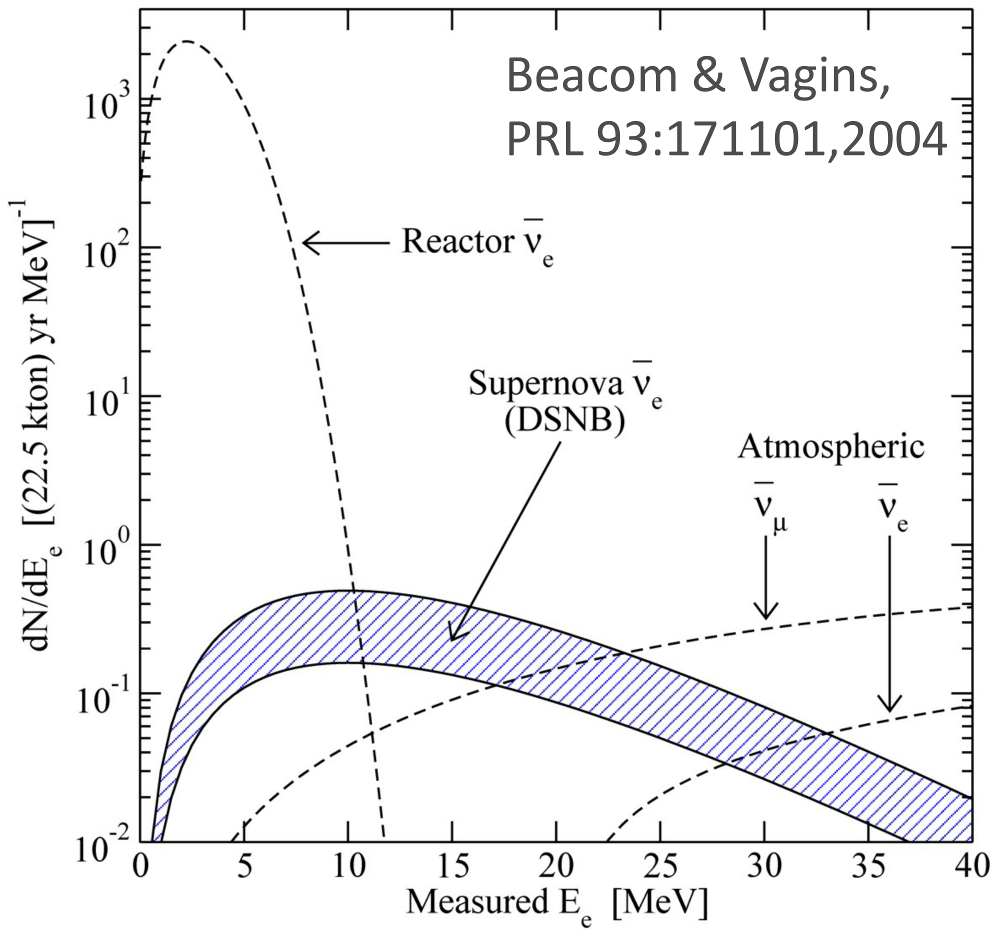
high statistics,
all flavors

object identity,
burst variety

cosmic rate,
average emission

Diffuse Supernova Neutrino Background (DSNB)

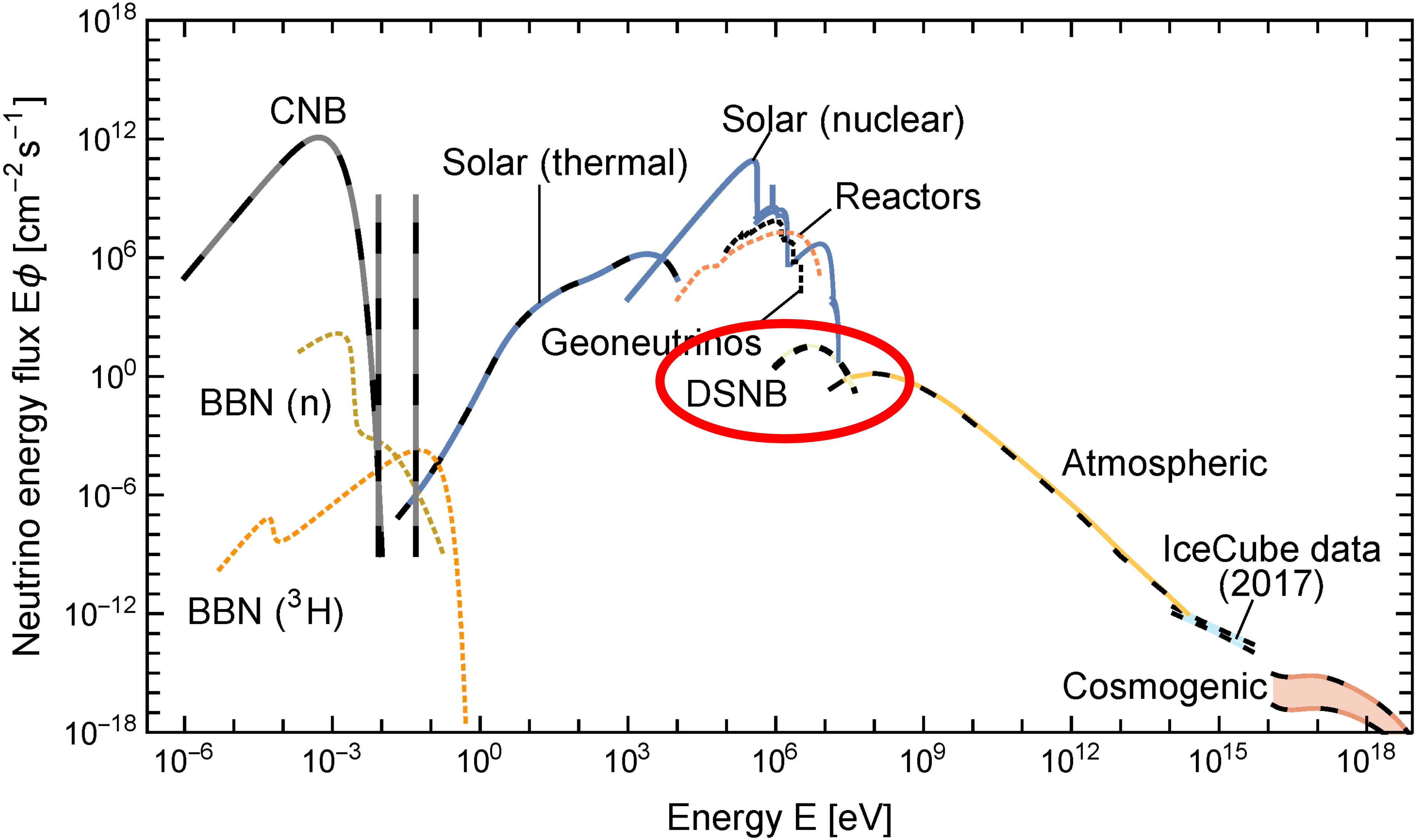
- A few core collapses/sec in the visible universe
- Emitted ν energy density
  $\sim$ extra galactic background light
  $\sim$ 10% of CMB density
- Detectable $\overline{\nu}_e$ flux at Earth
  $\sim 10\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
  mostly from redshift $z \sim 1$
- Confirm star-formation rate
- Nu emission from average core collapse & black-hole formation
- Pushing frontiers of neutrino astronomy to cosmic distances!



Window of opportunity between reactor $\overline{\nu}_e$ and atmospheric ν bkg

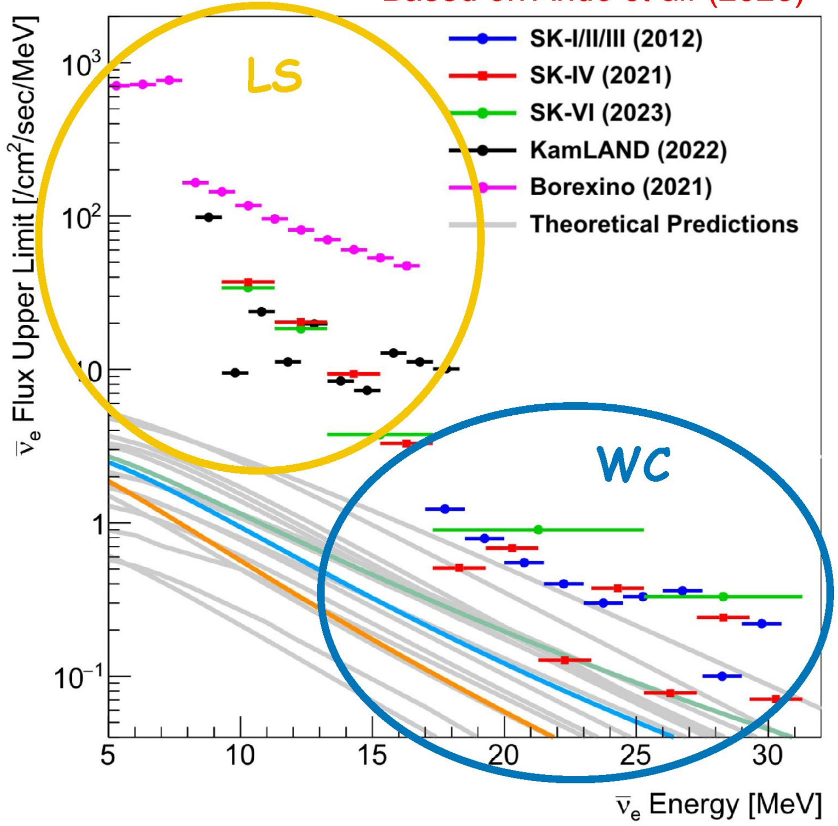
Grand Unified Neutrino Spectrum (GUNS) at Earth

Vitagliano, Tamborra & Raffelt, arXiv:1910.11878



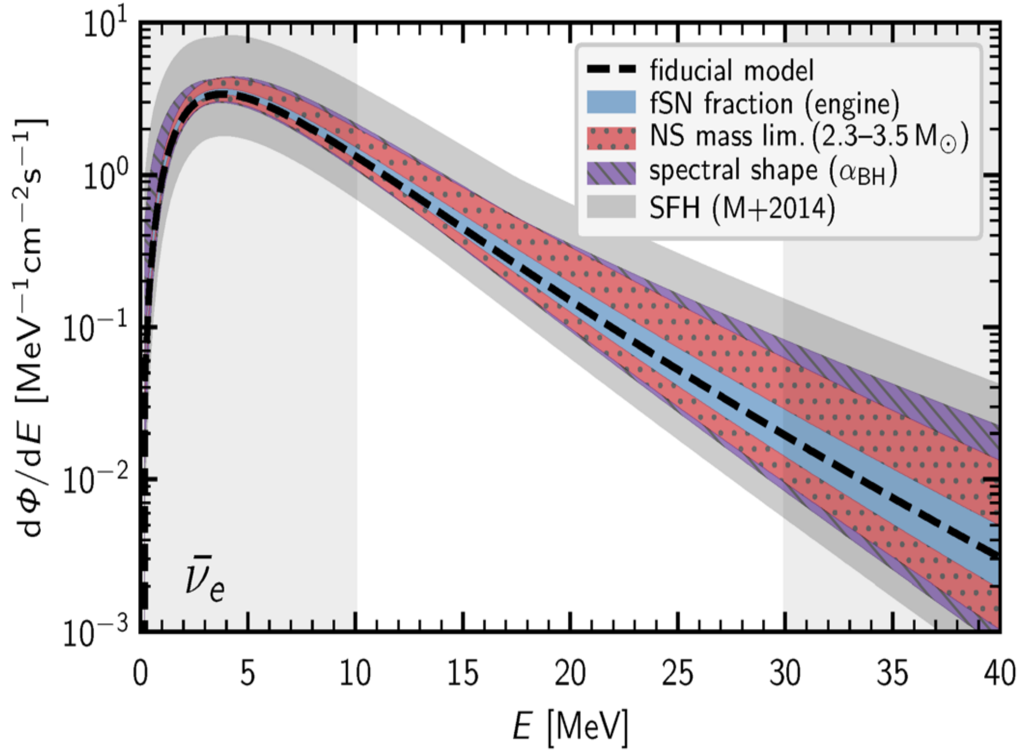
DSNB Predictions and Limits

Based on Ando *et al.* (2023)



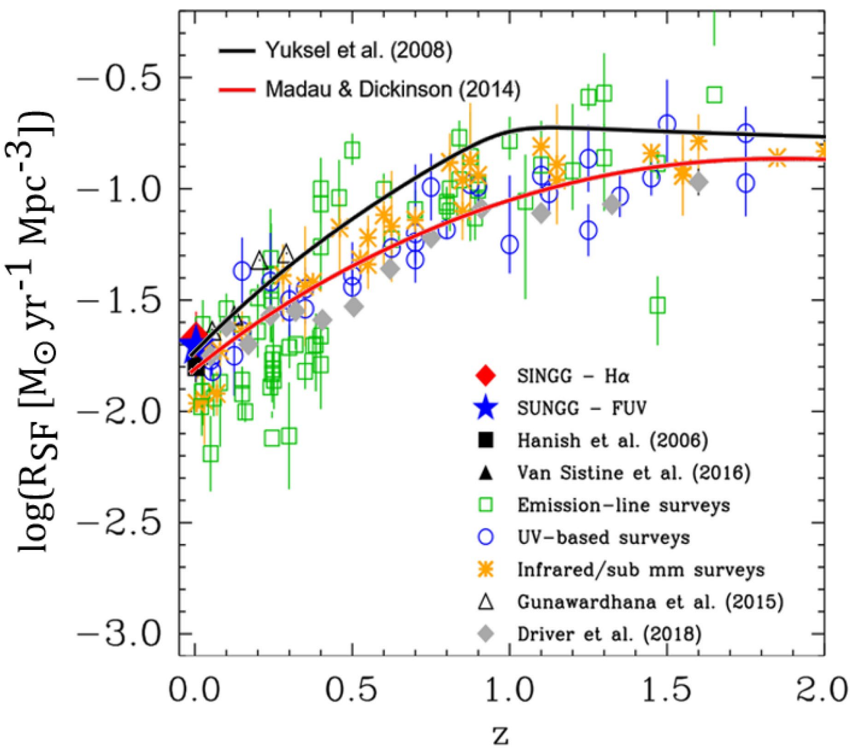
Current limits, in this form taken from Saki Fujita @ Mainz Workshop

Kresse+
Stellar Collapse Diversity and DSNB
arXiv:2010.04728



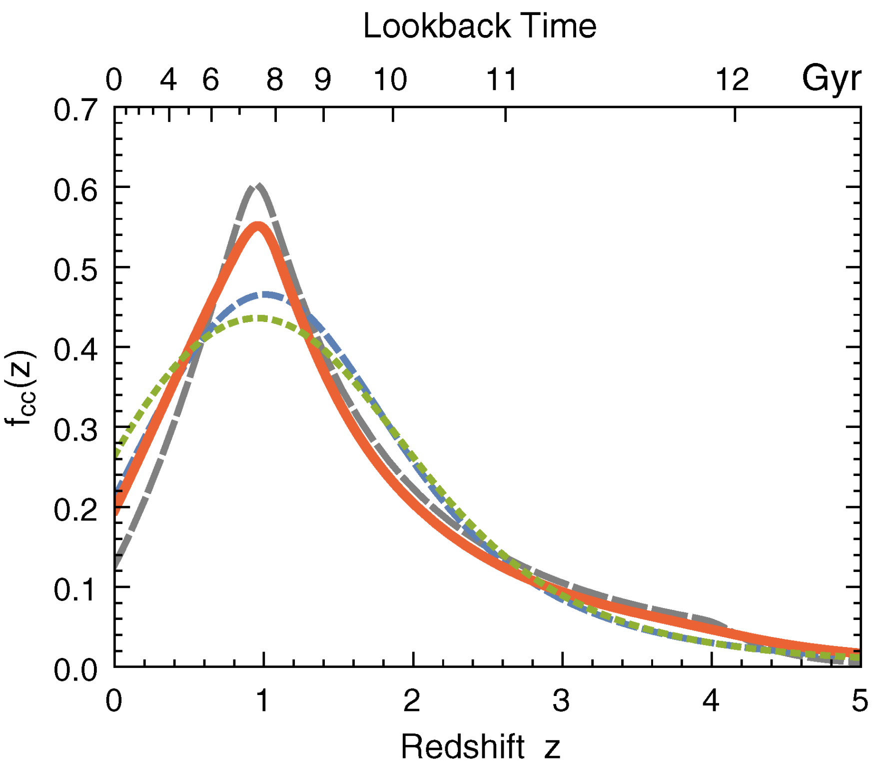
Cosmic Star Formation Rate

Cosmic star formation rate (per comoving volume)



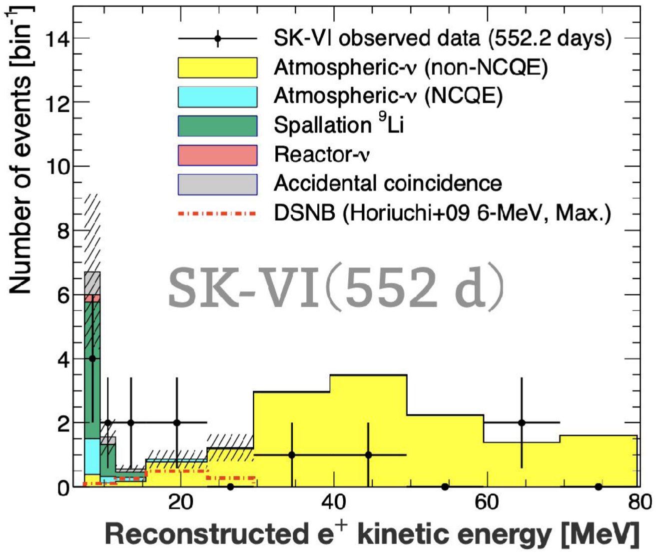
Ando+ arXiv:2306.16076

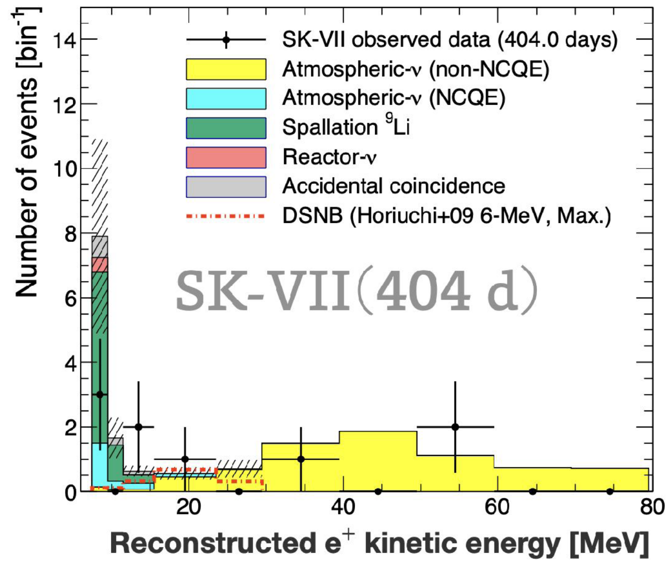
Redshift distribution after including cosmological model



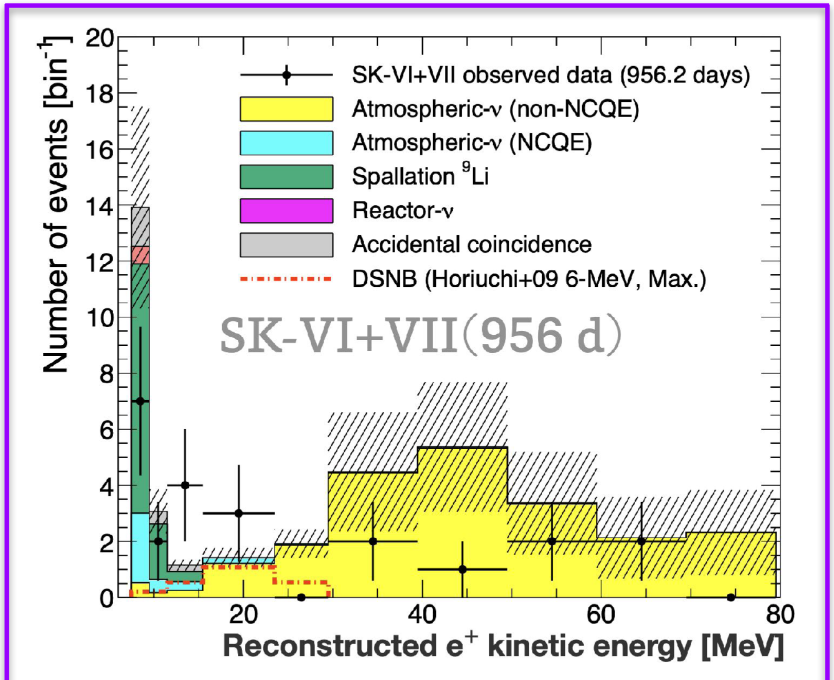
Vitagliano+ arXiv:1910.11878

Energy Spectrum in SK-Gd





Results shown at Neutrino 2024

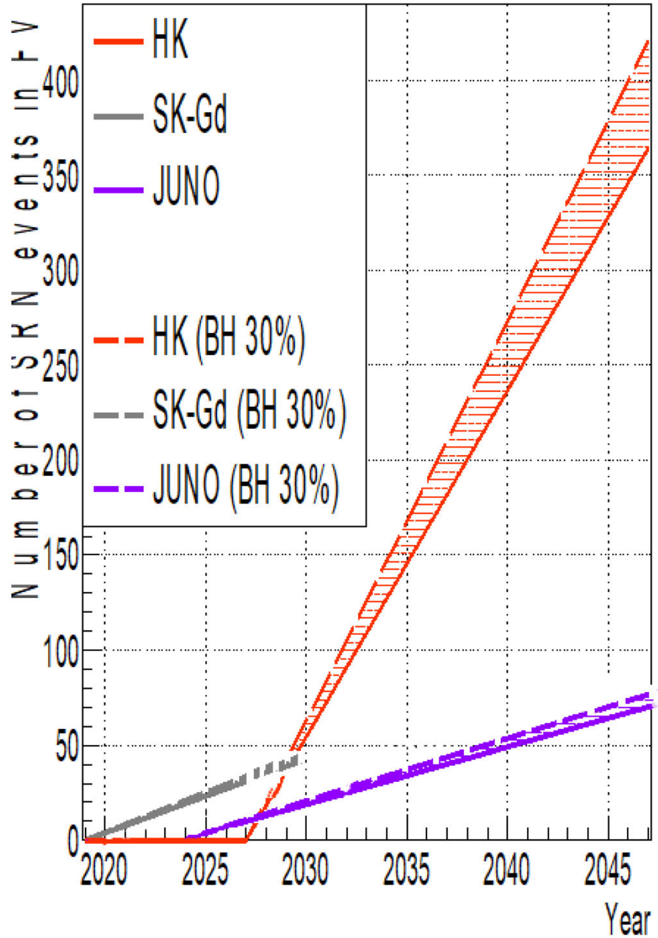


- ➔ Total of 956 days of SK-Gd data
- ➔ New ML-based neutron tagging and NCQE reduction
- ➔ No statistically significant excess but **minimum p-value of 0.04**

Slide from Saki Fujita

Expected number of DSNB events in HK

Credit
Mark Vagins



Conditions

SK-Gd (22.5 kton H_2O + Gd)

Low energy threshold : 10 MeV
neutron tagging by Gd-loading

Started data-taking in 2020

Aim for the first discovery

JUNO (20 kton LS)

Low energy threshold : 12 MeV

Start data-taking in 2025

Hyper-K (187 kton H_2O)

Energy threshold : 16 MeV?

Start data-taking in 2027

Aim for the precise flux and energy spectrum measurement

~4 events/yr in HK w/ H tag

- Stellar collapse
- Star formation rate
- Heavy element synthesis

Adding gadolinium to HK is being preserved as a future upgrade option → >10 DSNB events/yr