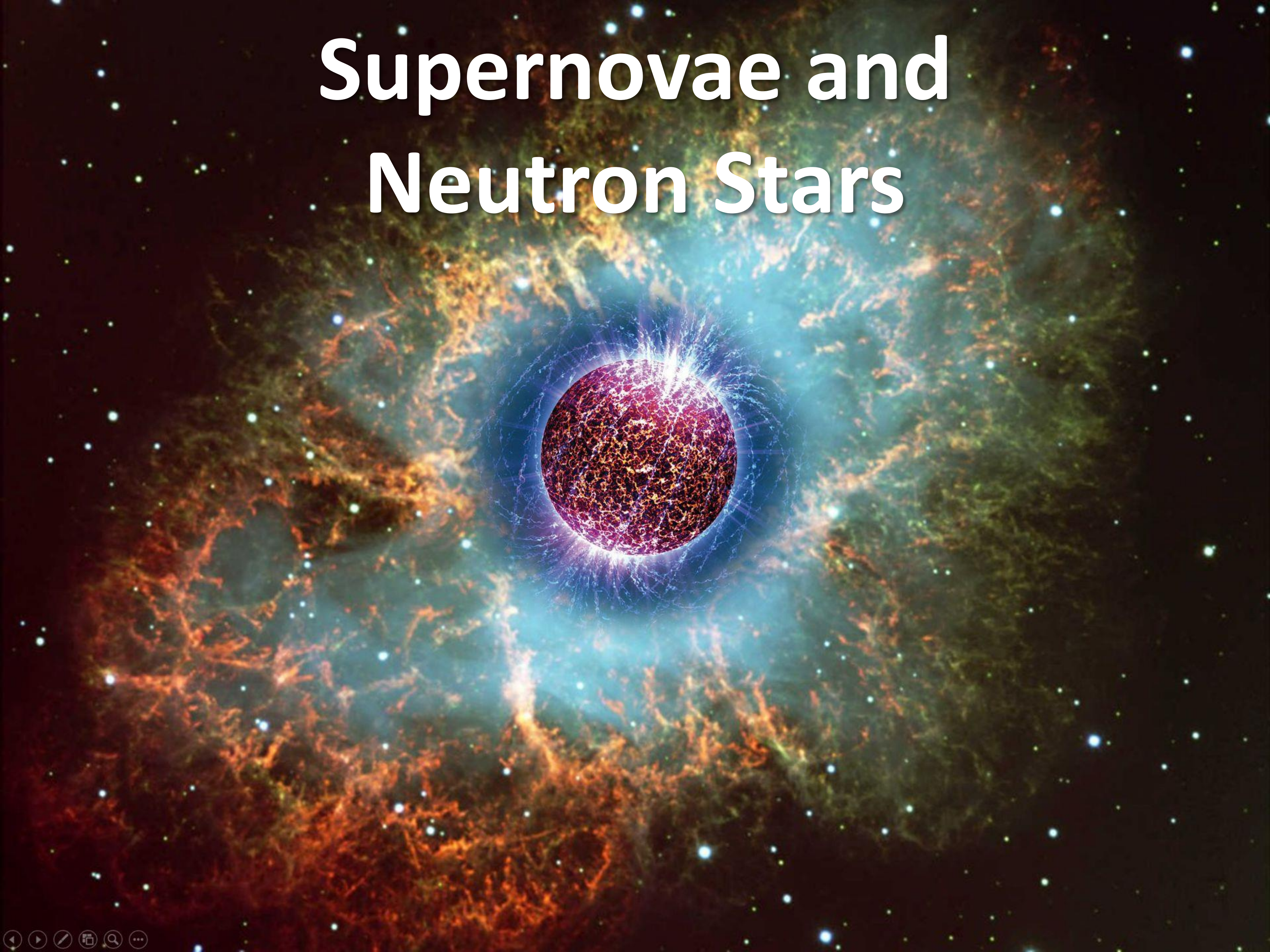
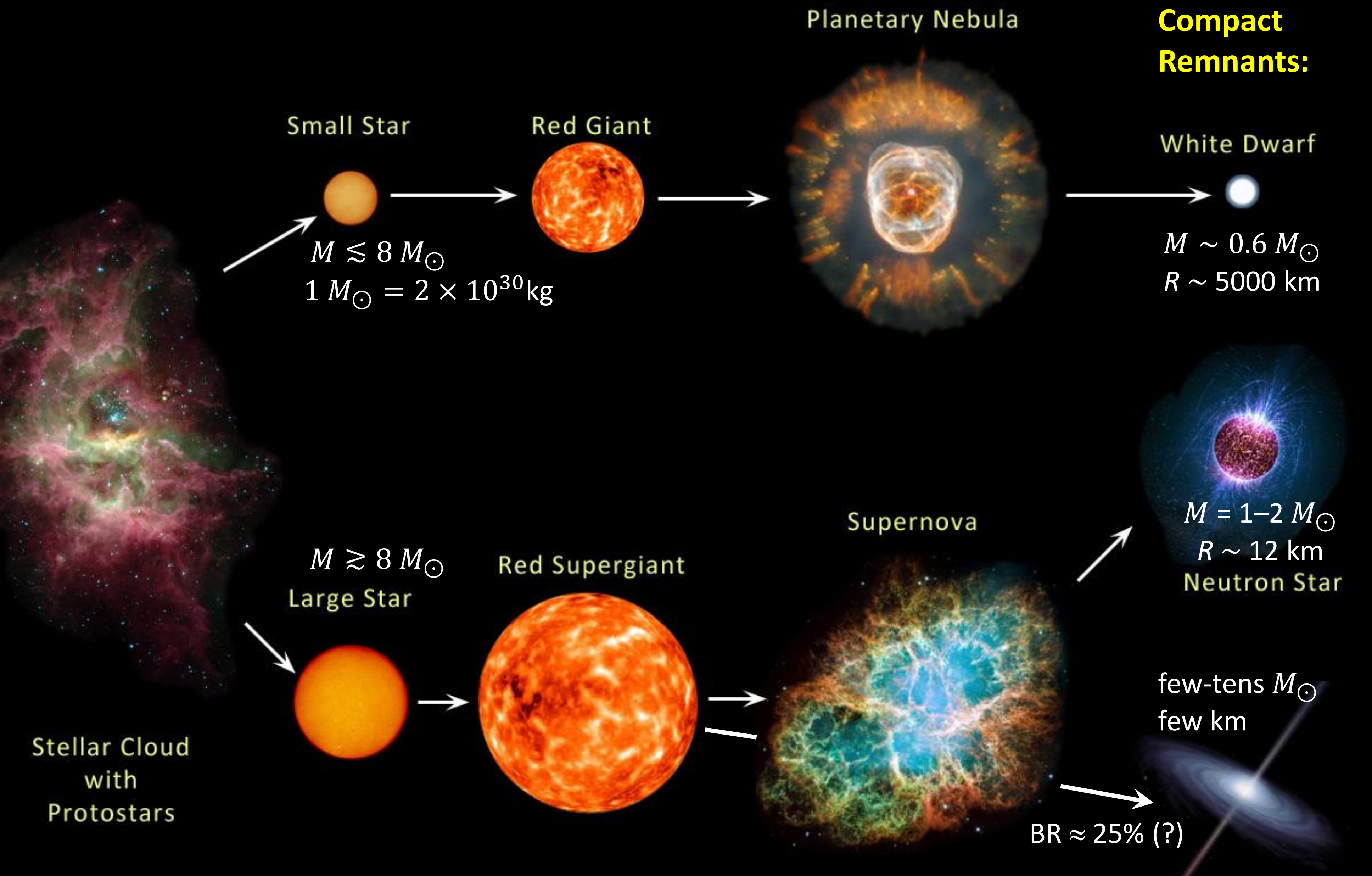
Supernovae and Neutron Stars



EVOLUTION OF STARS



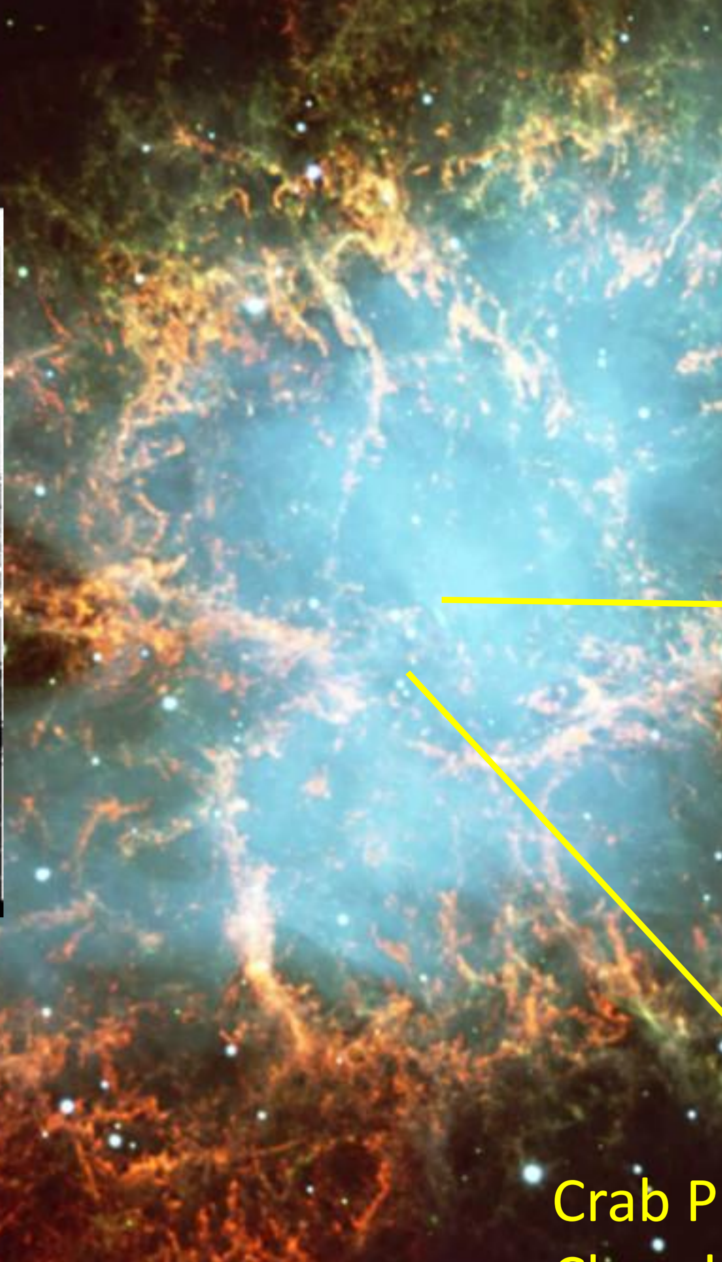
http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html

Crab Nebula – Remnant of SN 1054


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

宋史志卷九

Crab Nebula – Remnant of SN 1054

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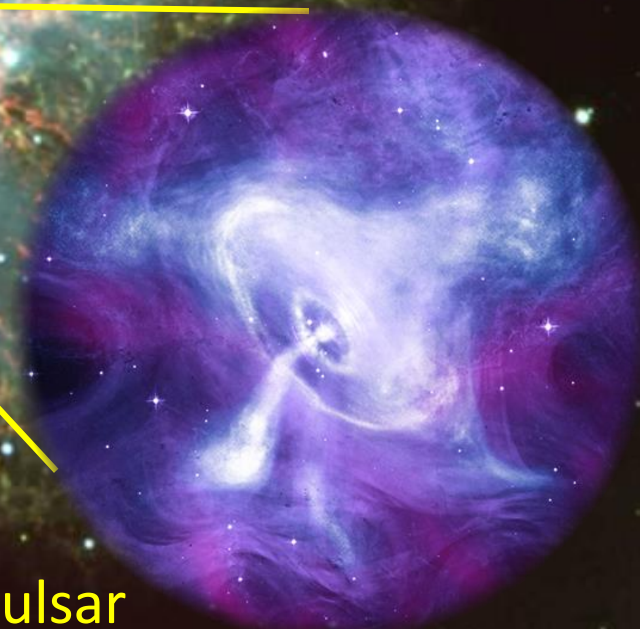


Crab Pulsar
Chandra X-ray composite image

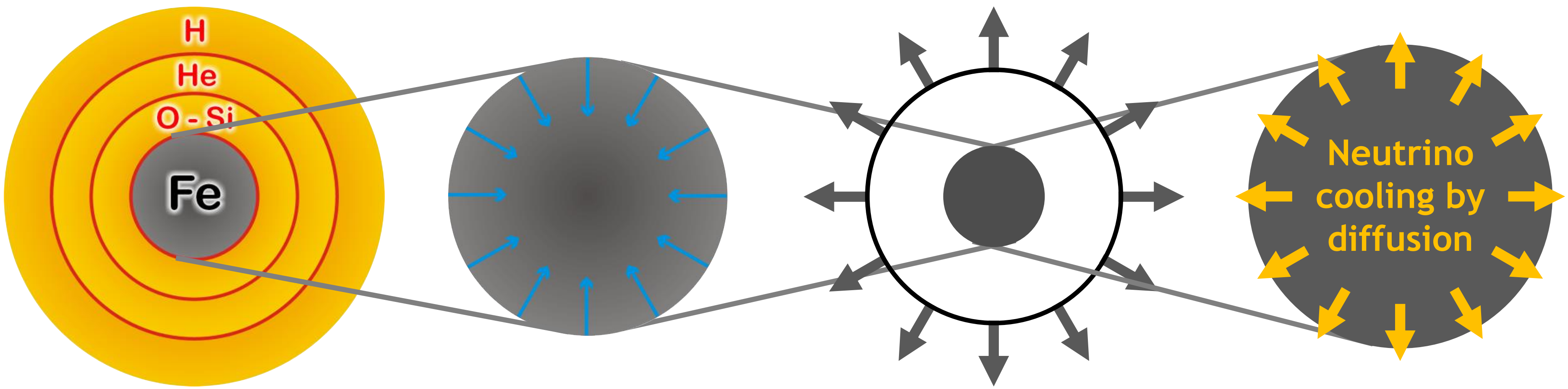
Core-Collapse Supernova Explosion

End state of a massive star $M \gtrsim 8\,M_\odot$

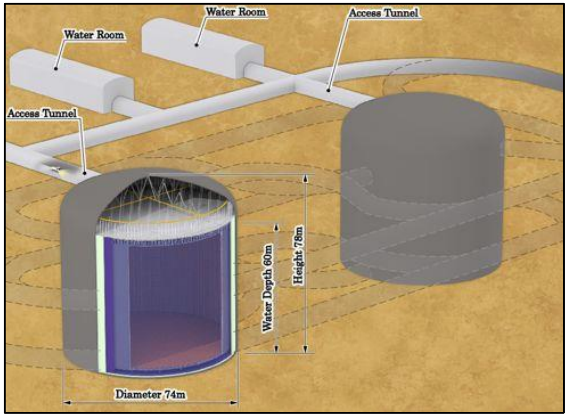
Collapse of degenerate core

Bounce at ρ_{nuc} Shock wave forms explodes the star

Grav. binding E $\sim 3 \times 10^{53}$ erg emitted as nus of all flavors

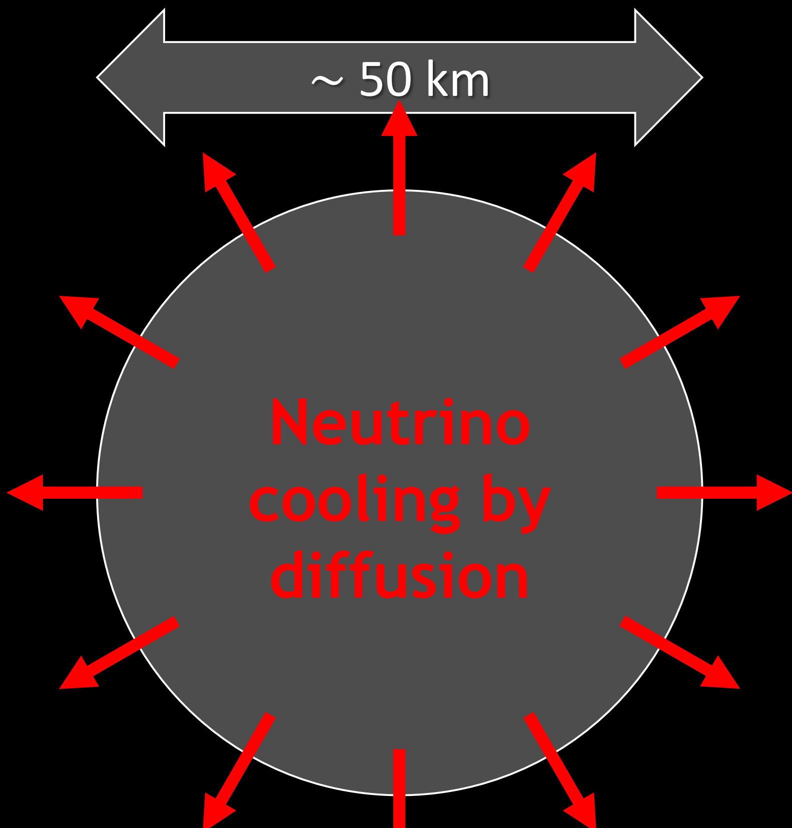


- **Huge rate of low-E neutrinos (tens of MeV) over few seconds in large-volume detectors**
- **A few core-collapse SNe in our galaxy per century**
- **Once-in-a-lifetime opportunity**



Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

$T \sim 10\ \mathrm{MeV}$

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
0.01%	Photons, outshine host galaxy

Neutrino luminosity

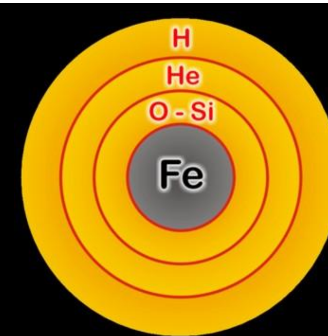
$L_\nu \sim 3 \times 10^{53}\ \mathrm{erg} / 3\ \mathrm{sec}$

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

While it lasts, outshines the entire visible universe

Thermonuclear vs. Core-Collapse Supernovae

Thermonuclear (Spectral type Ia)	Core collapse (Spectral 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



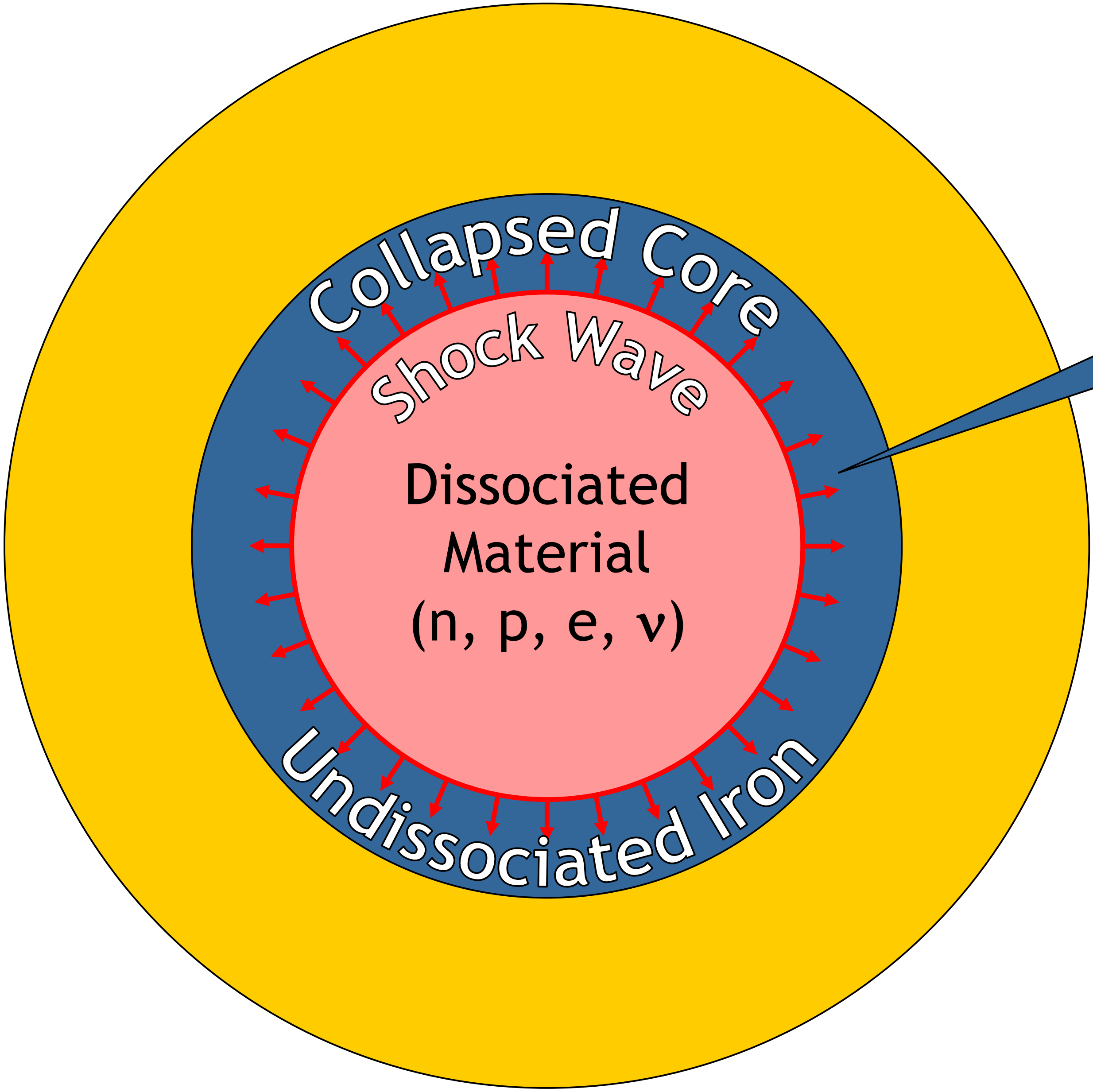
Chandrasekhar limit is reached — $M_{Ch} \approx 1.5\ M_{sun}\ (2Y_e)^2$

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

Thermonuclear	Core collapse
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 $\sim 3 \times 10^{51}$ erg

Why No Prompt Explosion?



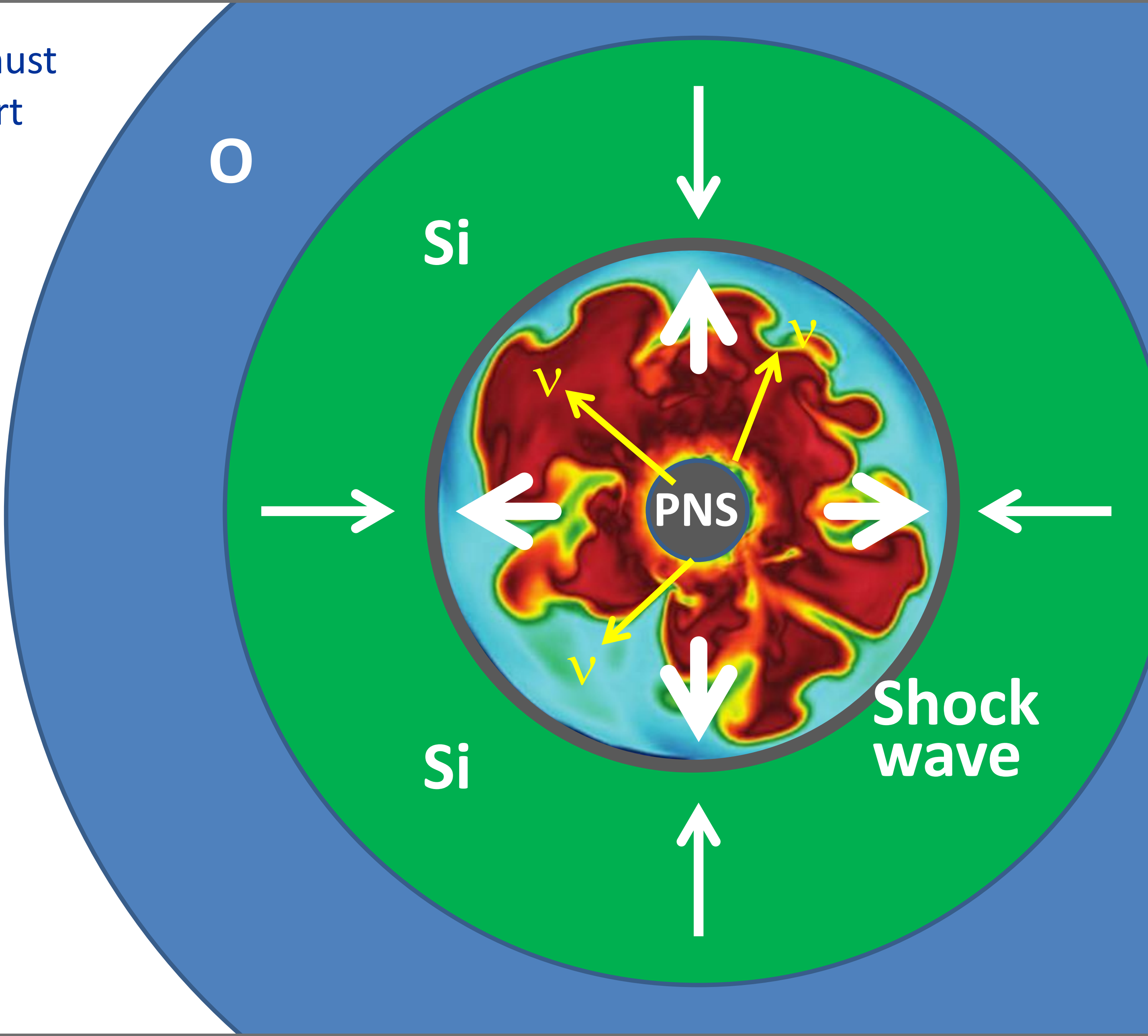
- 0.1 M_{sun} of iron has a nuclear binding energy ≈ 1.7 × 10^{51} erg
- Comparable to explosion energy

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

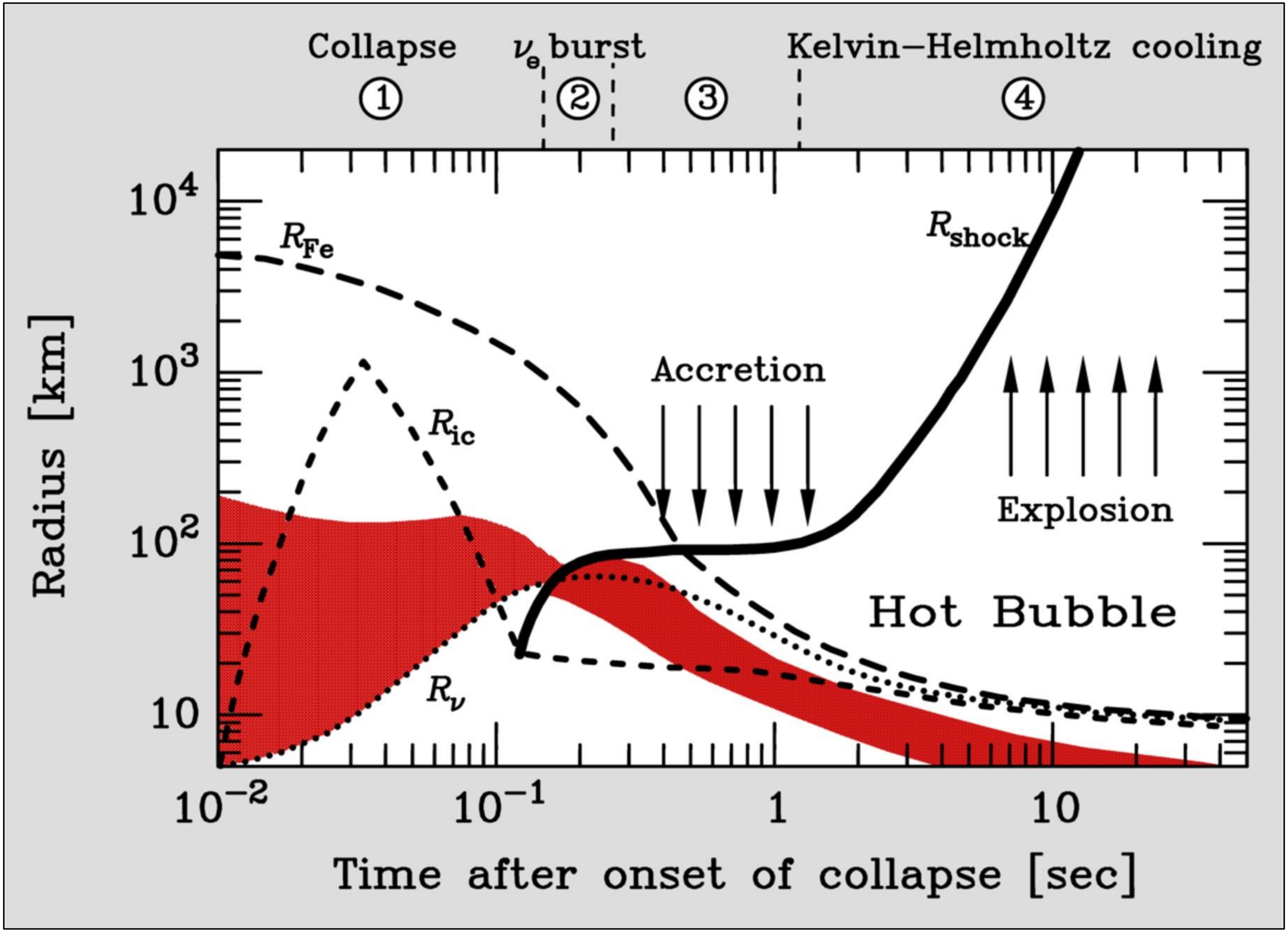
Shock Revival by Neutrinos

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

Shock can receive fresh energy from neutrinos!



Supernova Delayed Explosion Scenario



What determines the time scale?

Main neutrino reactions

$$\nu_e + n \to p + e^-, \;\; \bar{\nu}_e + p \to n + e^+, \;\; \nu + N \to N + \nu$$

Neutral-current scattering cross section

$$\sigma(\nu N \to N\nu) = \frac{C_\mathrm{V}^2 + 3C_\mathrm{A}^2}{\pi}\, G_\mathrm{F}^2 E_\nu^2 \approx 2 \times 10^{-40}\mathrm{cm}^2 \left(\frac{E_\nu}{100\ \mathrm{MeV}}\right)^2$$

Nucleon density

$$n_B = \frac{\rho_\mathrm{nuc}}{m_N} \approx 1.8 \times 10^{38}\ \mathrm{cm}^{-3}$$

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

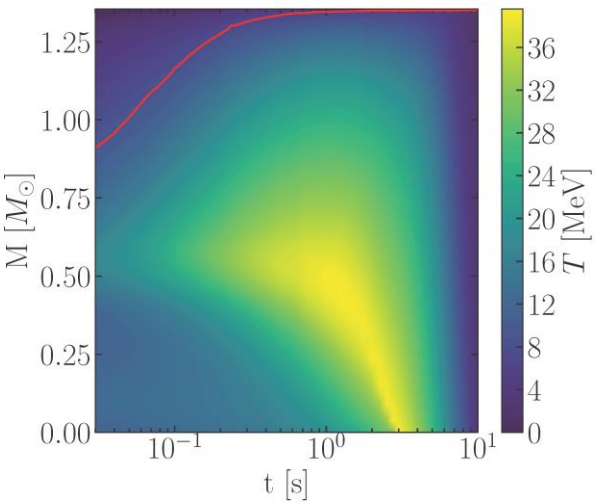
$$\lambda = (\sigma n_B)^{-1} \approx 28\ \mathrm{cm} \left(\frac{100\ \mathrm{MeV}}{E_\nu}\right)^2$$

Diffusion time

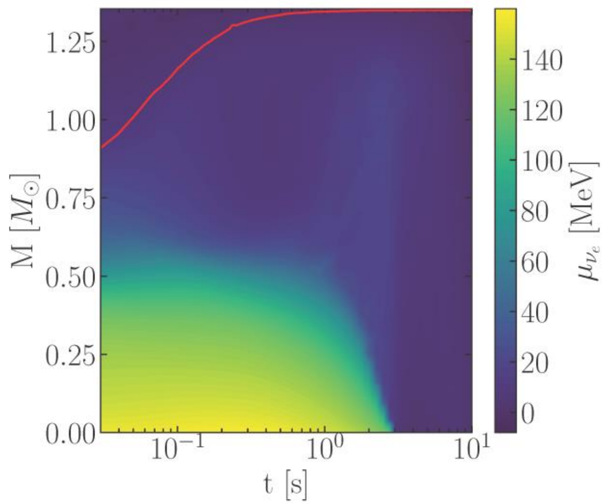
$$t_\mathrm{diff} \approx \frac{R^2}{\lambda} \approx 1.2\ \mathrm{s} \left(\frac{R}{10\ \mathrm{km}}\right)^2 \left(\frac{E_\nu}{100\ \mathrm{MeV}}\right)^2$$

Muonic SN model from Garching group, used in 2005.07141 and 2109.03244

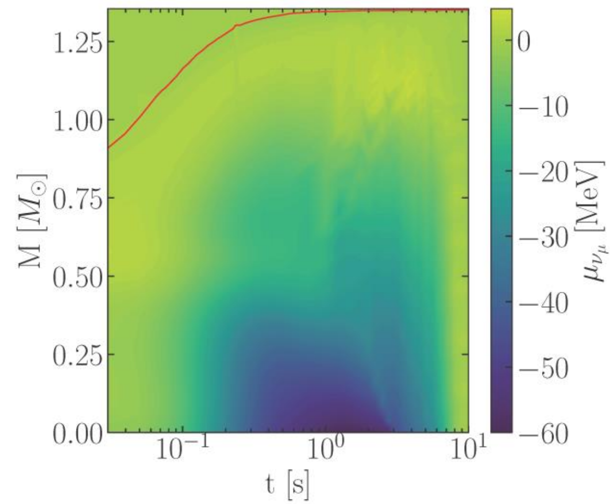
Temperature



ν_e Chem. Potential



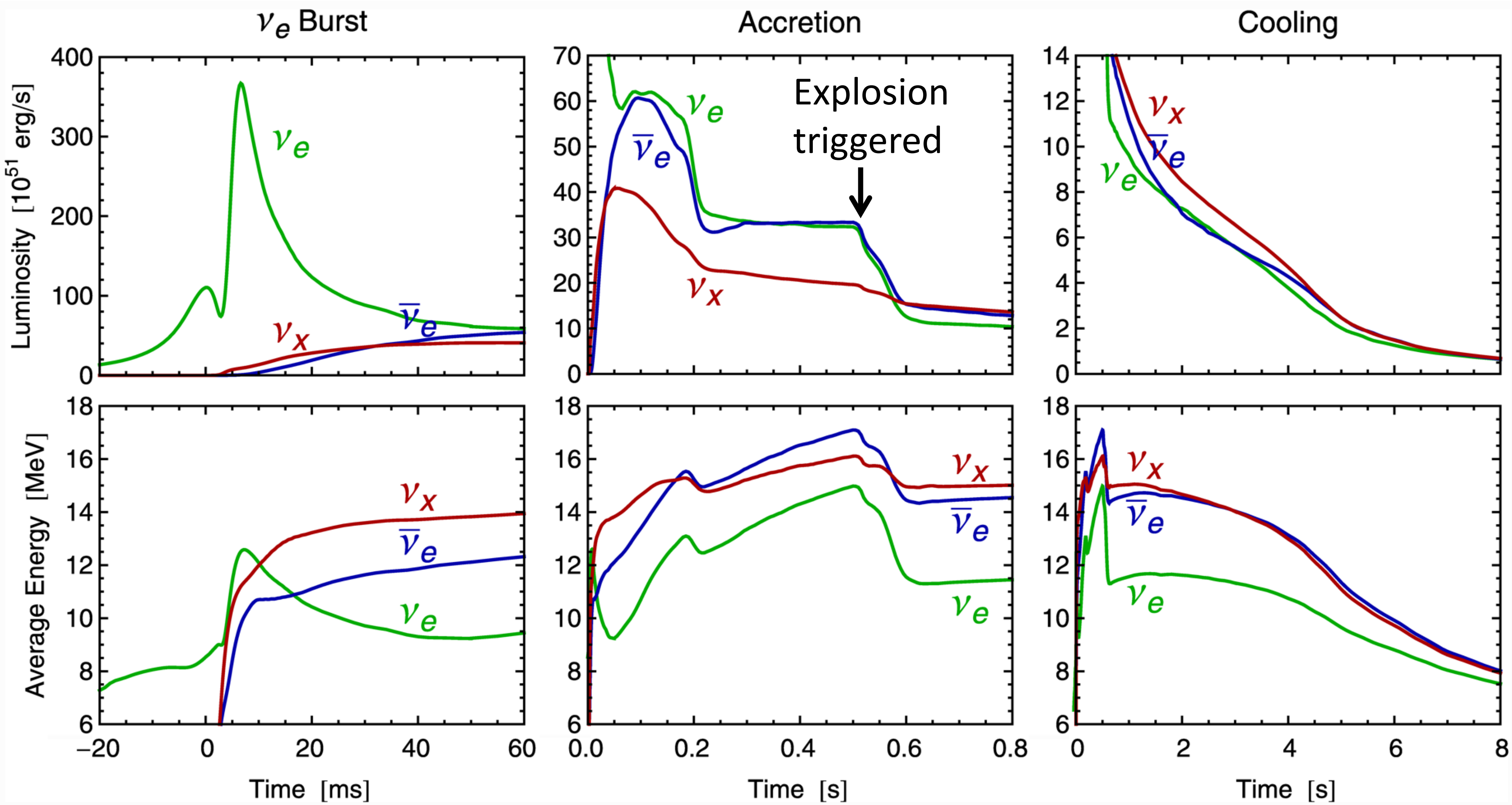
ν_μ Chem. Potential



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

Fiorillo, Raffelt & Vitagliano (arXiv:2209.11773)

Three Phases of Neutrino Emission



- Shock breakout
- De-leptonization of outer core layers

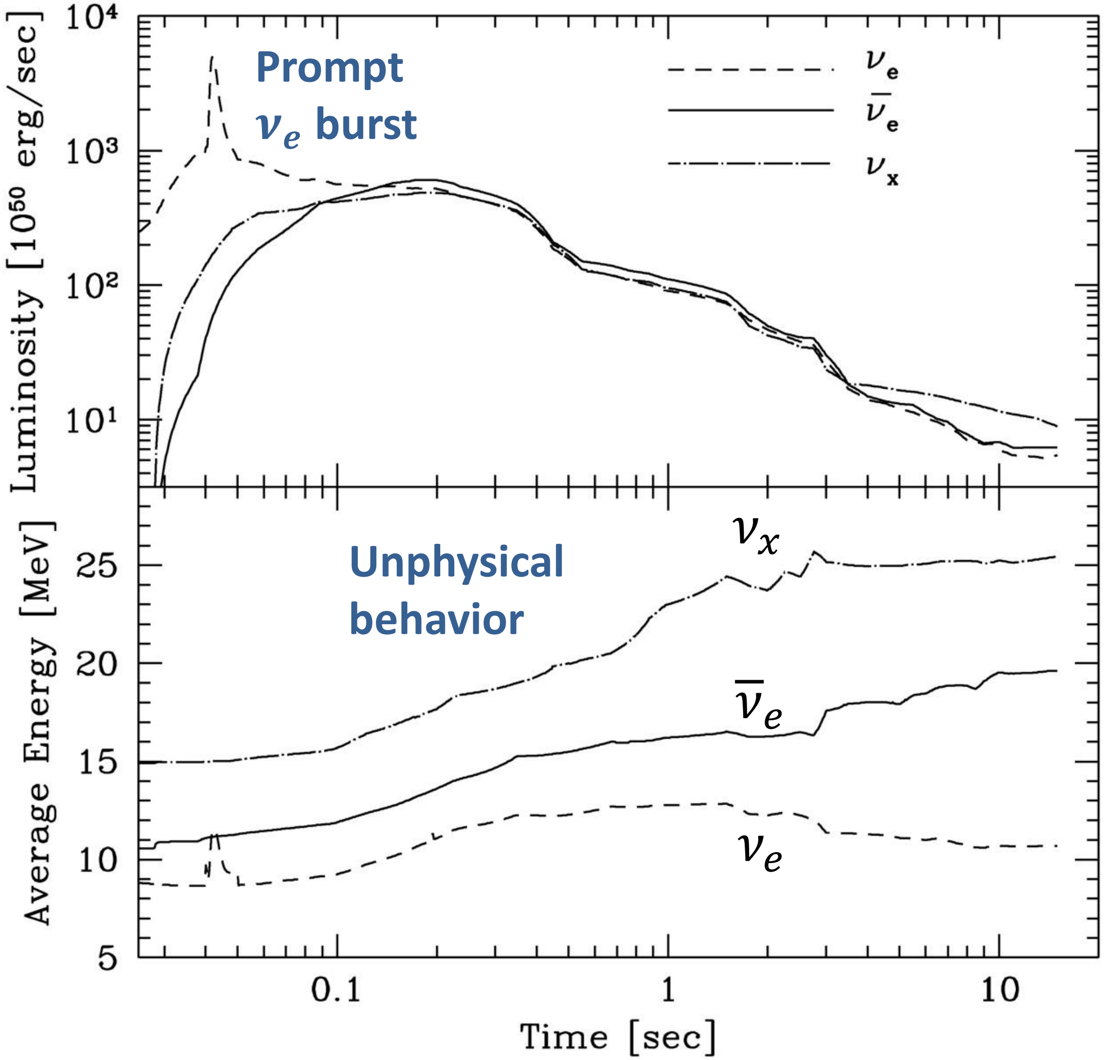
- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling on neutrino diffusion time scale

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

Livermore Fluxes and Spectra

Livermore numerical model, ApJ 496 (1998) 216



Pioneering work, but today only of historical interest

- Transport of ν_μ and ν_τ only schematic
- Incomplete microphysics
- Schematic numerics to couple nu transport with hydro code

What is an x-neutrino?

SN core: Large trapped e-lepton number (many electrons & electron neutrinos)
No trapped muon or tau lepton number

Typical interactions inside a SN core:

- Charged current $\nu_e + n \leftrightarrow p + e^-$ or $\overline{\nu}_e + p \leftrightarrow n + e^+$
- Neutral current $\nu_\tau + N \leftrightarrow N + \nu_\tau$ etc.,
  approx. same for $\nu_\mu, \overline{\nu}_\mu, \nu_\tau, \overline{\nu}_\tau = \nu_x$
  (but weak magnetism distinguishes
  eg $\nu_\tau + N \leftrightarrow N + \nu_\tau$ and $\overline{\nu}_\tau + N \leftrightarrow N + \overline{\nu}_\tau$)

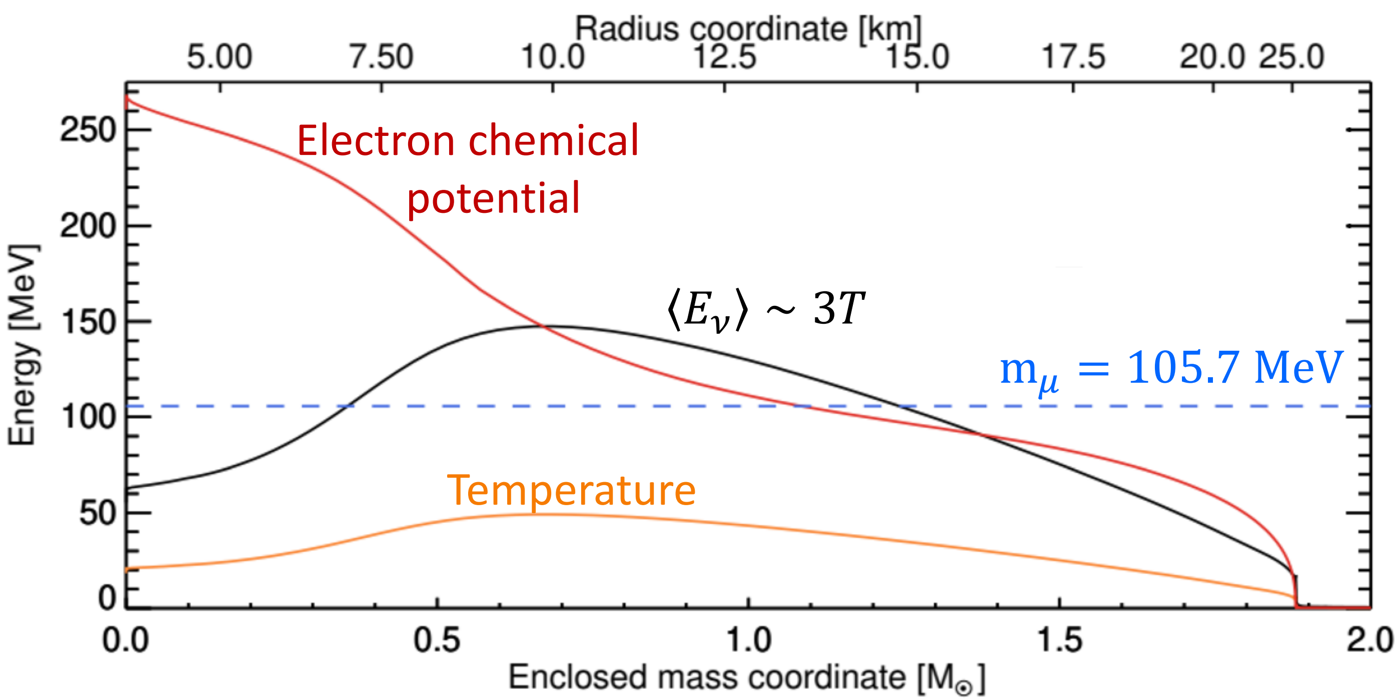
- $e^- + p \rightleftharpoons n + \nu_e$
- $e^+ + n \rightleftharpoons p + \bar{\nu}_e$
- $e^- + A \rightleftharpoons \nu_e + A^*$
- $\nu + n, p \rightleftharpoons \nu + n, p$
- $\nu + A \rightleftharpoons \nu + A$
- $\nu + e^\pm \rightleftharpoons \nu + e^\pm$
- $N + N \rightleftharpoons N + N + \nu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

Traditional SN simulations:
Three-species neutrino transport of $\nu_e, \overline{\nu}_e, \nu_x$ (representing any of $\nu_\mu, \overline{\nu}_\mu, \nu_\tau, \overline{\nu}_\tau$)
Neutrino transport is the numerically expensive part of SN simulations!

Flavor oscillations:
Typically studied in 2-flavor limit
(But anyway not included in numerical SN simulations)

Muonisation of a Supernova Core

- Muon production energetically favored $(m_\mu = 105.7\ \mathrm{MeV})$
- Local e-μ conversion prevented by large matter effect for ν oscillations (but BSM processes?)
- Emission of excess $\overline{\nu}_\mu$ flux builds up transient muon number density
- Emission of excess ν_e flux runs down electron lepton number (ELN)
- Requires six-species neutrino transport and muonic reactions (Robert Bollig's PhD)



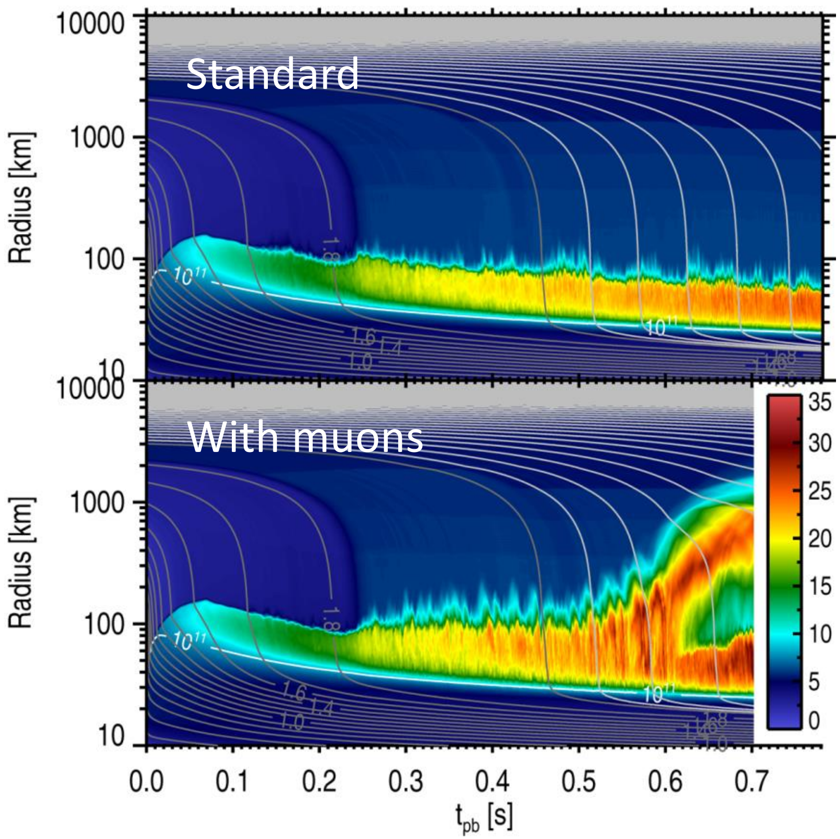
Proto neutron star (PNS) profile
350 ms postbounce

PRL 119, 242702 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2017

Muon Creation in Supernova Matter Facilitates Neutrino-Driven Explosions

R. Bollig,[1,2] H.-T. Janka,[1] A. Lohs,[3] G. Martínez-Pinedo,[3,4] C. J. Horowitz,[5] and T. Melson[1]

Average entropy/nucleon (2D model)

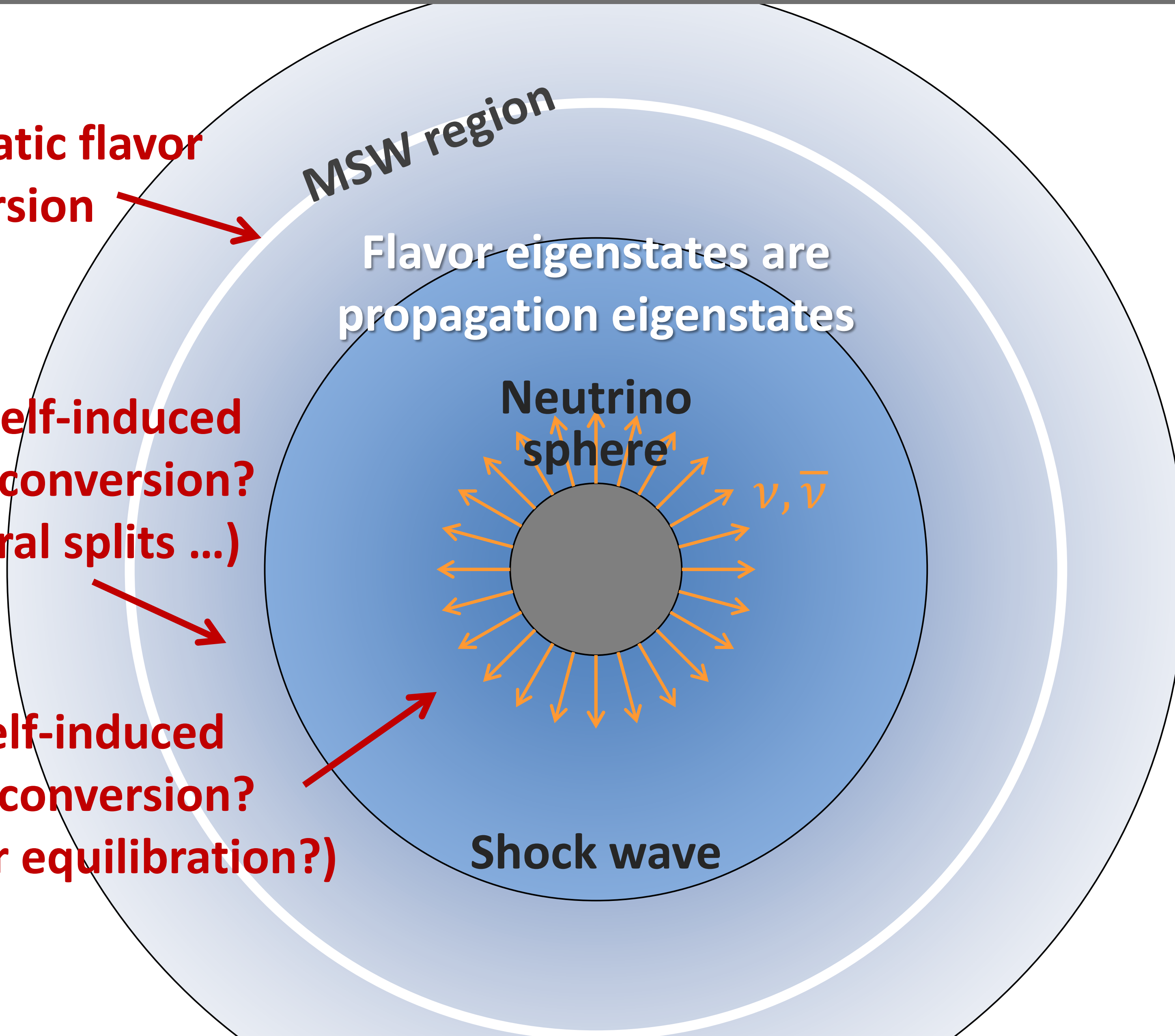


Muons

- Facilitate neutrino-driven explosion
- Affect compactness of hot NSs
- Change neutrino emission
- May affect ν oscillations / nucleosynthesis
- Affect grav. instability of hot NS → BH
- Should be included in SN and NS-NS/BH merger simulations
- Require six-species neutrino transport with coupling of different flavors

Flavor Conversion in Core-Collapse Supernovae

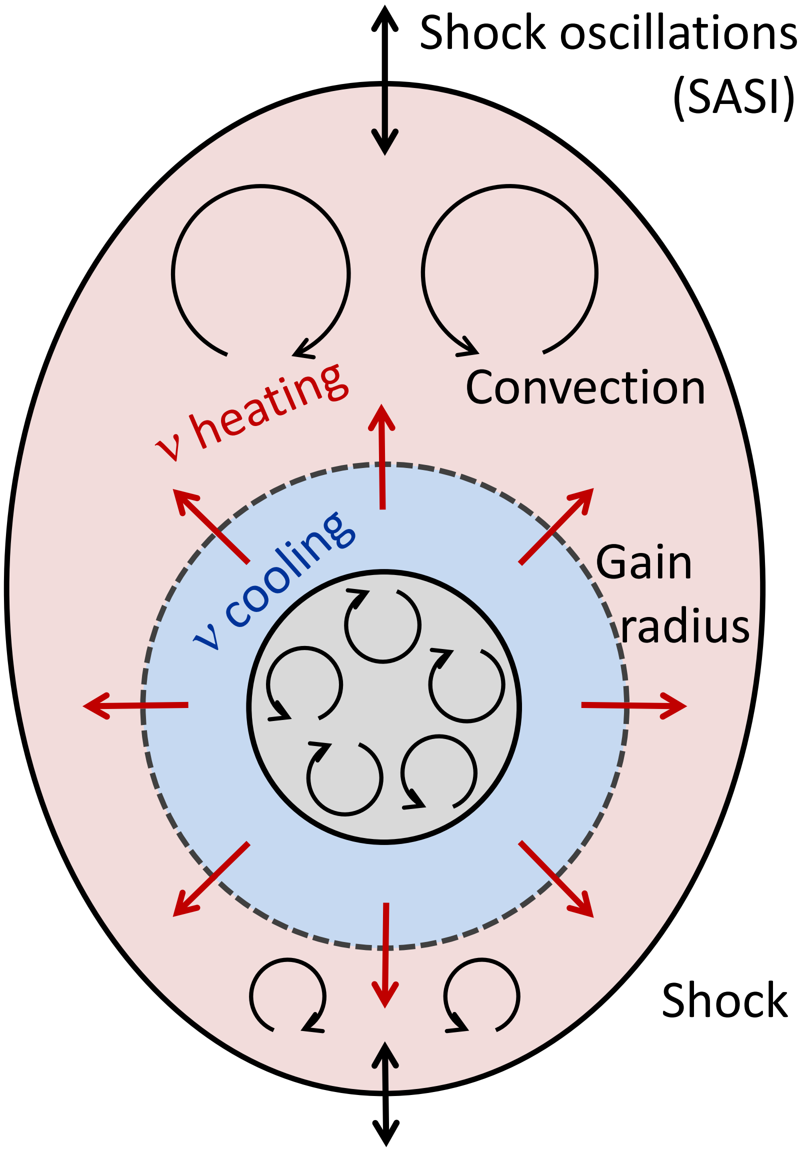
- **Adiabatic flavor conversion**
- **Slow self-induced flavor conversion? (Spectral splits …)**
- **Fast self-induced flavor conversion? (Flavor equilibration?)**



Neutrino-Driven Mechanism – Modern Version

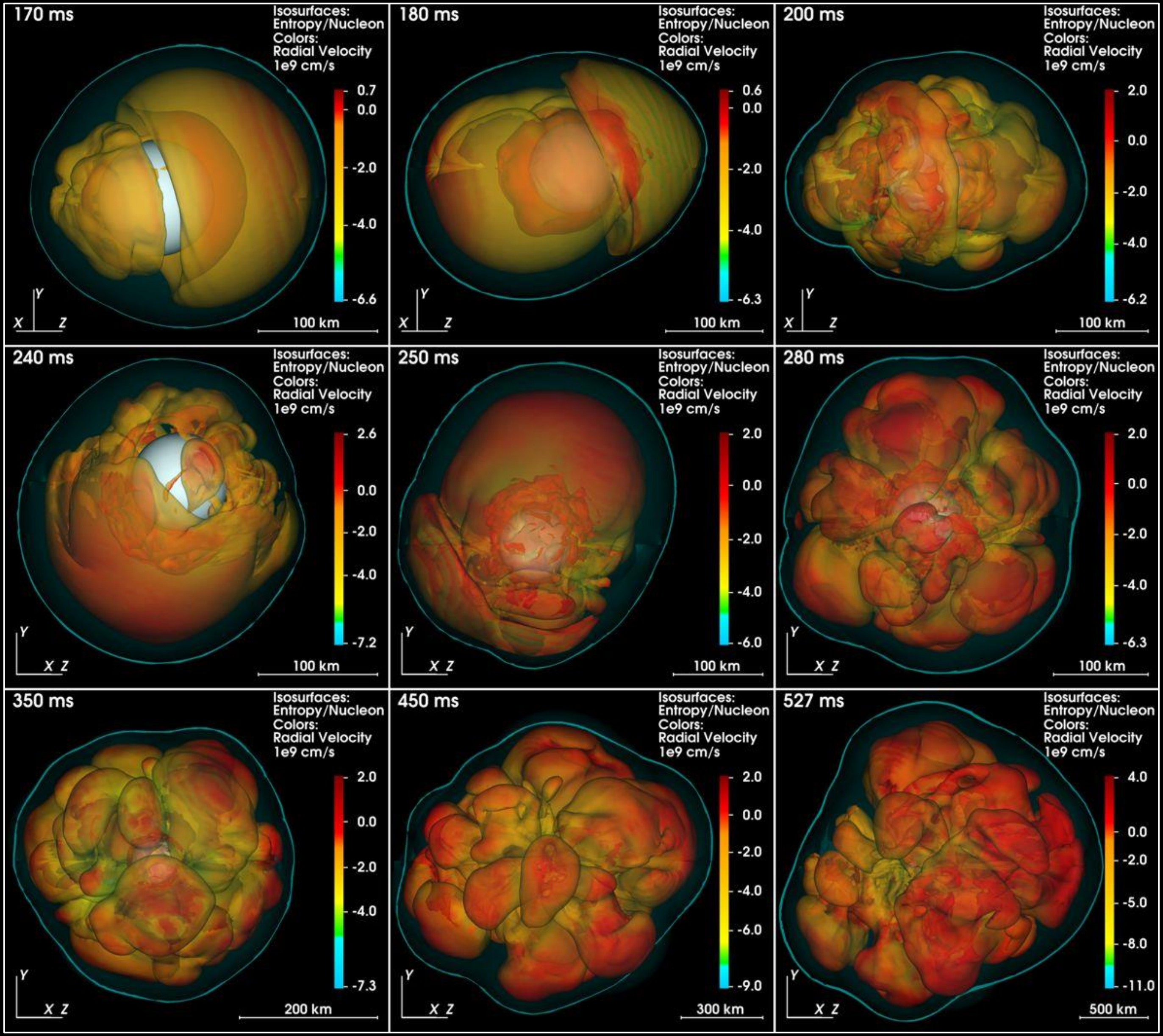
- Stalled accretion shock pushed out to ~150 km as matter piles up on the PNS
- Heating (gain) region develops within some tens of ms after bounce
- Convective overturn & shock oscillations (SASI) enhance efficiency of ν-heating, finally revives shock
- Successful explosions in 1D and 2D for different 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

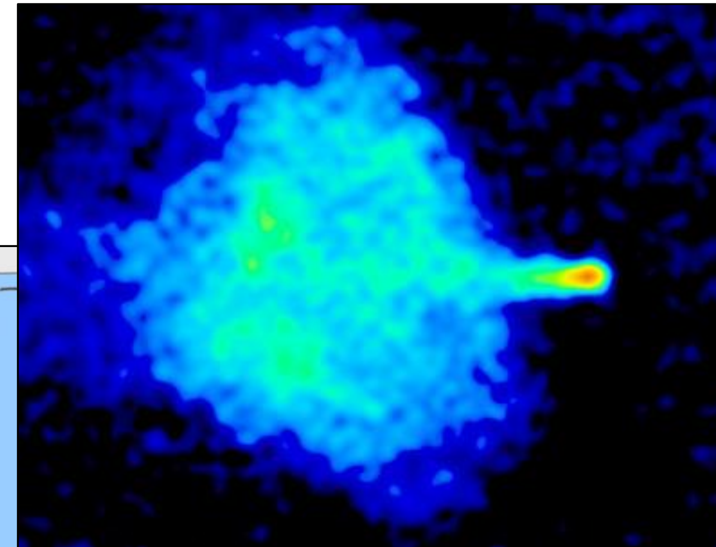
Breaking Spherical Symmetry (3D Effects)

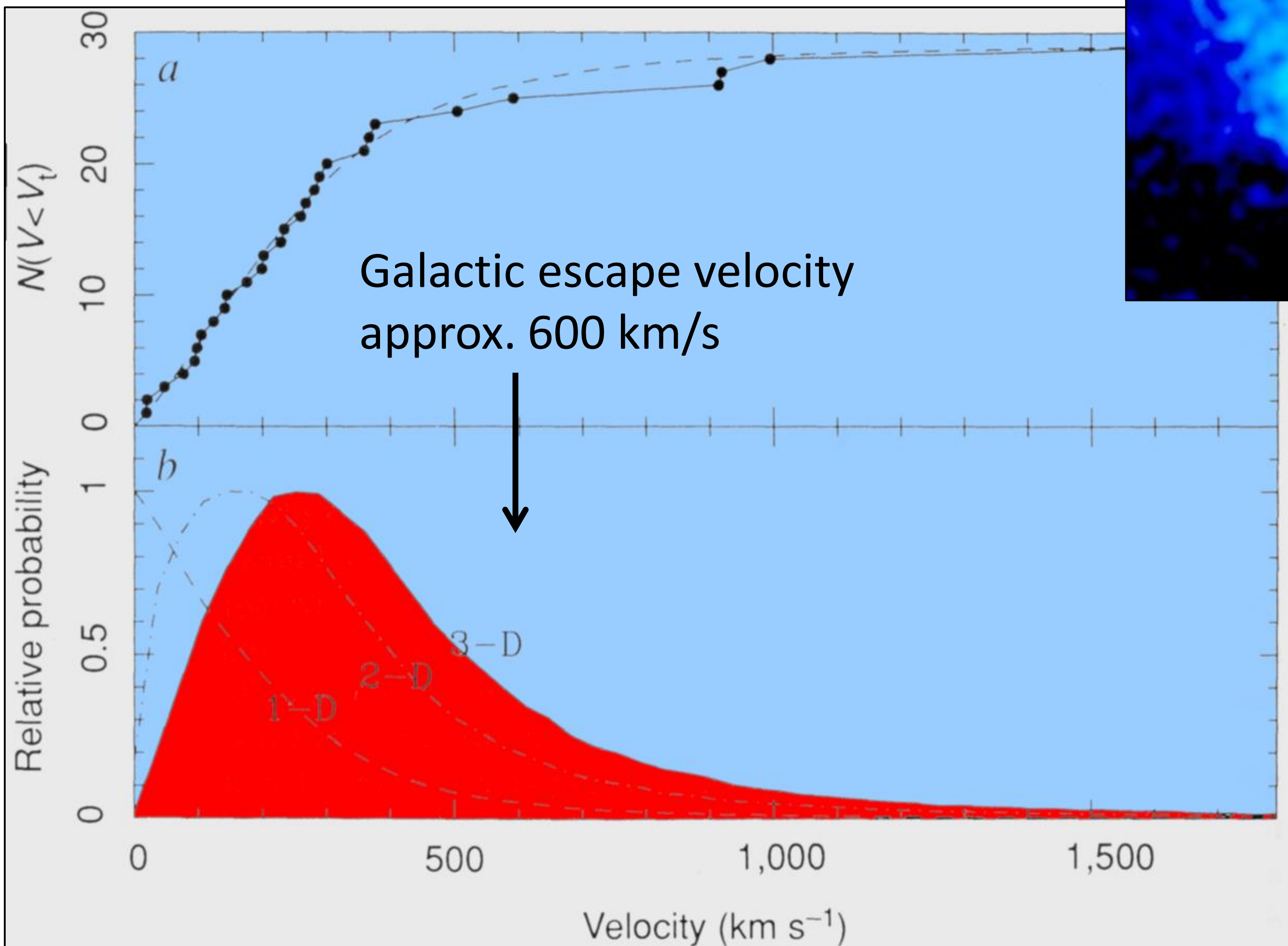


Melson, Janka, Bollig, Hanke, Marek & Müller, arXiv:1504.07631

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 galactic plane)

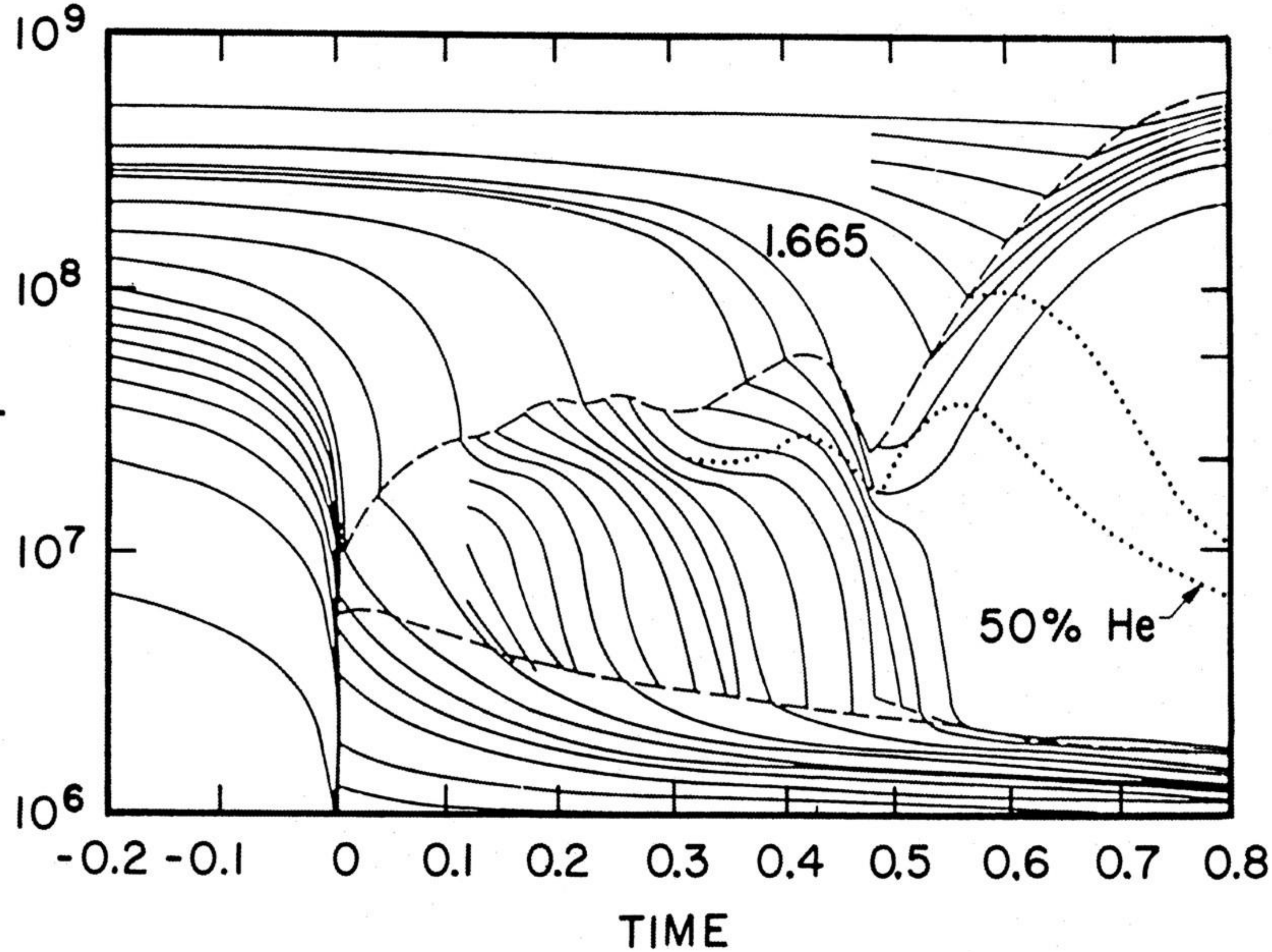




Pulsar velocity distribution

Lyne & Lorimer, Nature 369 (1994) 127

Delayed (Neutrino-Driven) Explosion



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

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

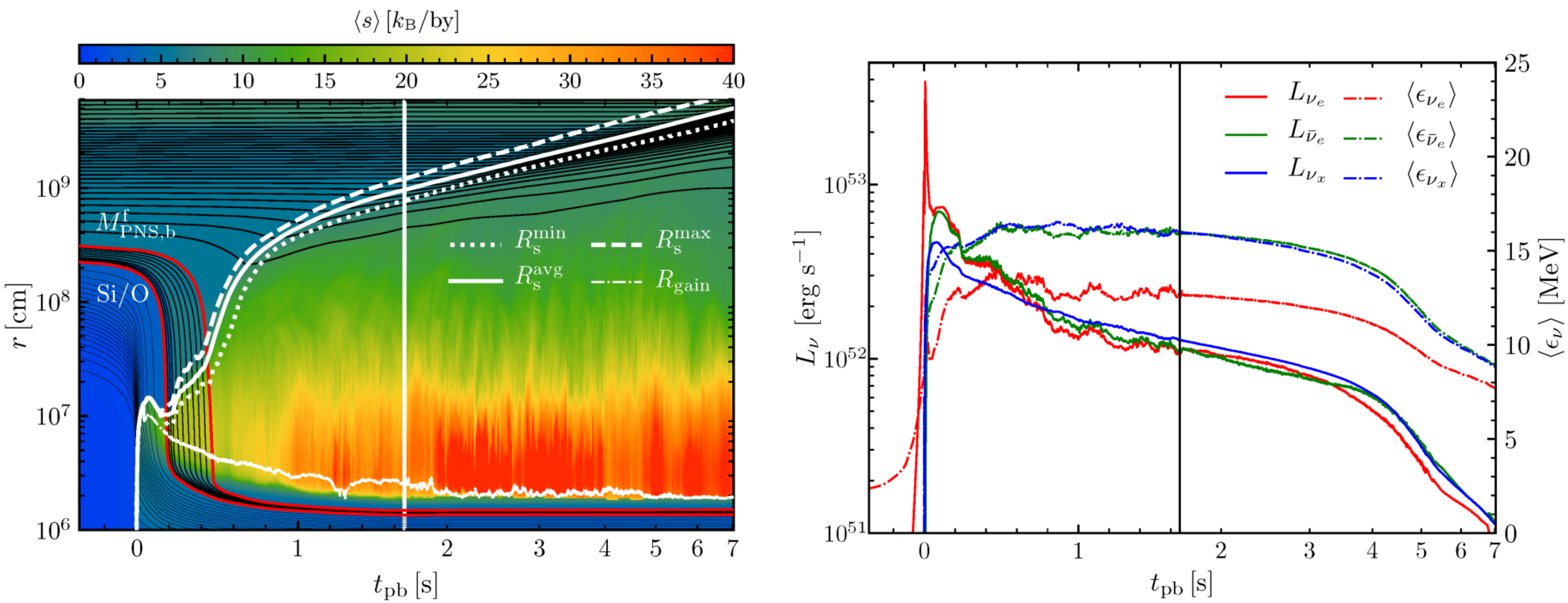
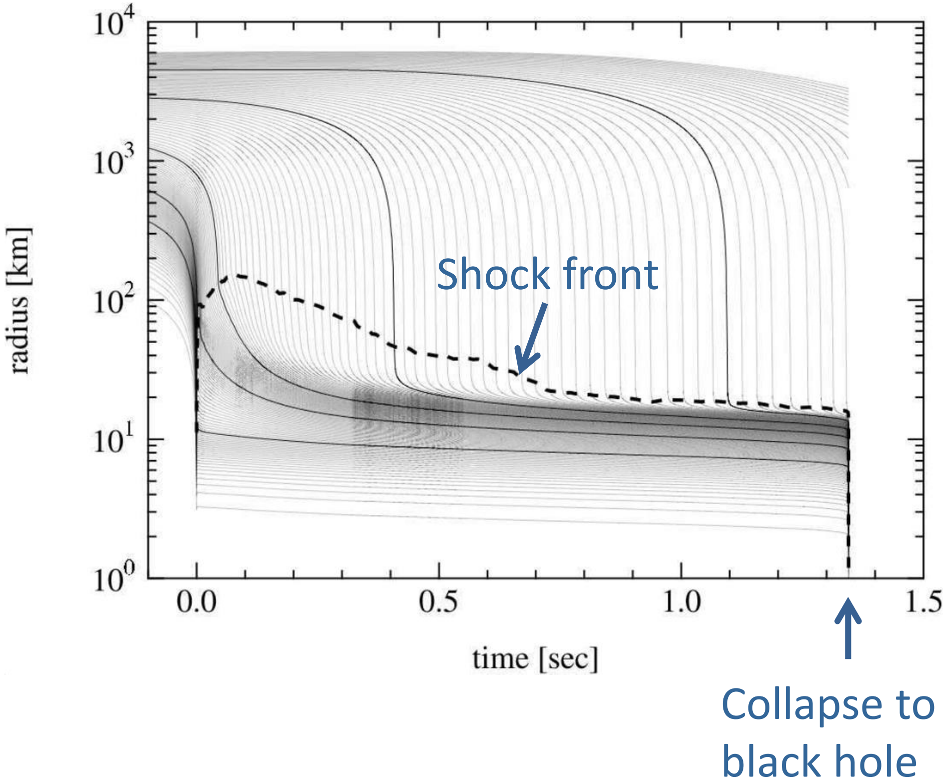
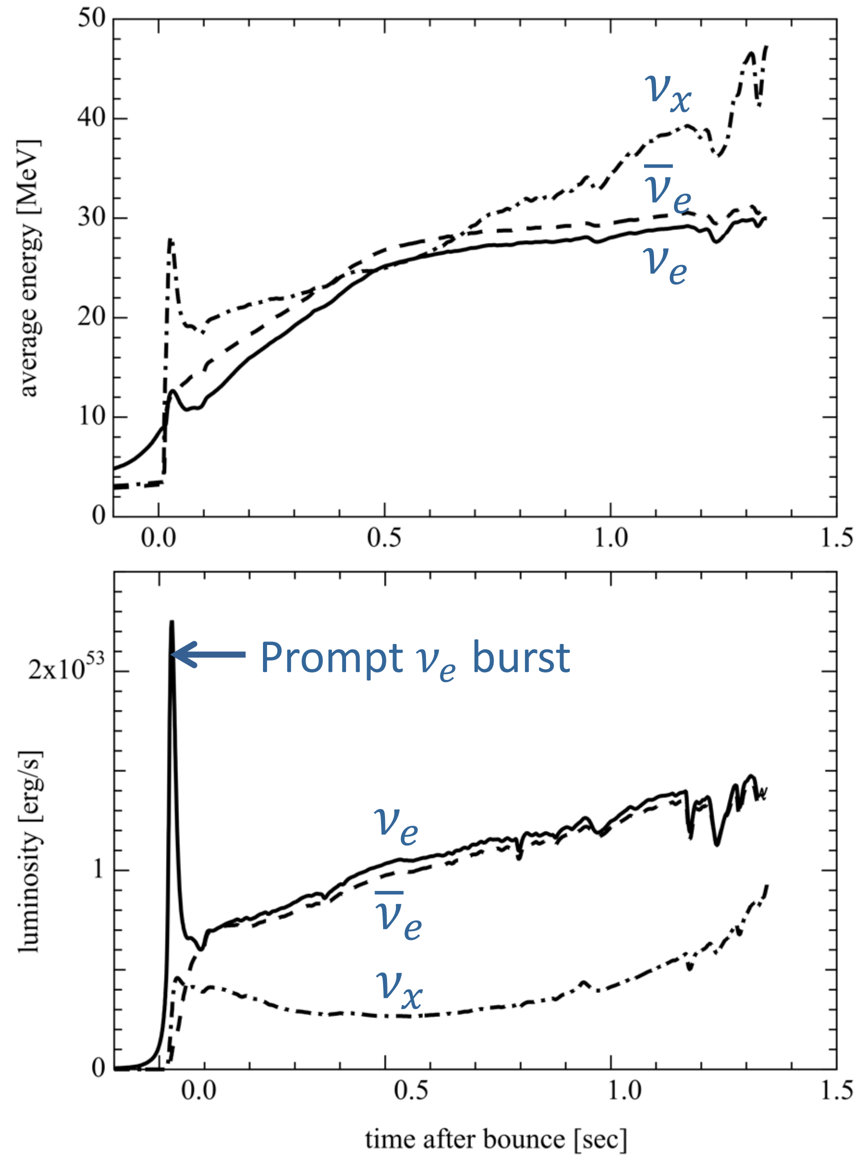


Figure 1. Explosion dynamics and neutrino emission of model `M_P3D_LS220_m−` and its extension `M_P3D_LS220_m−HC`. The time axes are chosen for optimal visibility. *Left:* Mass shells with entropy per nucleon color-coded. Maximum, minimum, and average shock radii, gain radius, and the mass shells of 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.





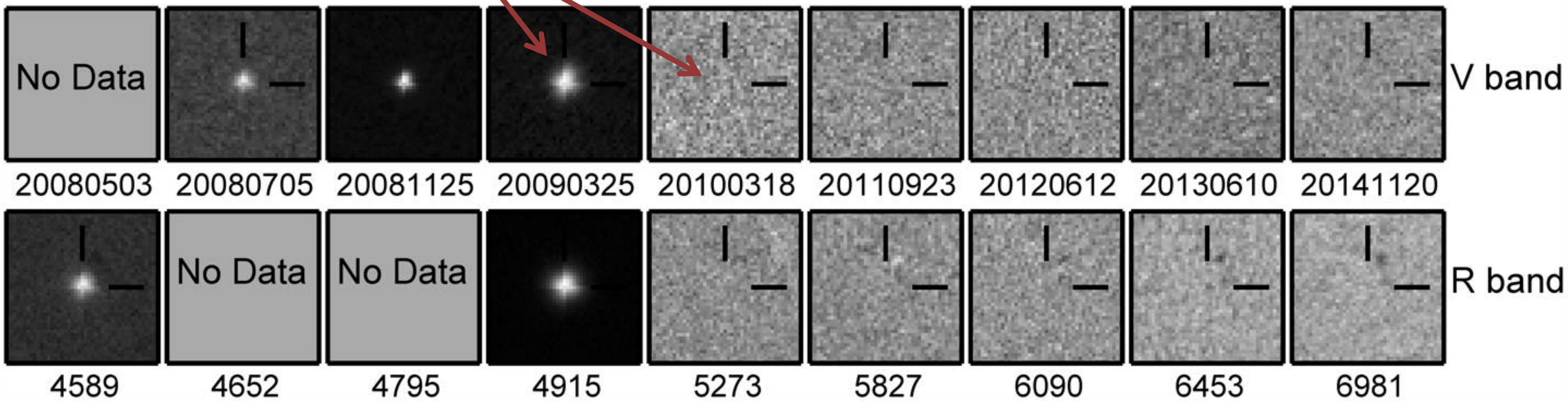
Sumiyoshi, Yamada & Suzuki, arXiv:0706.3762

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



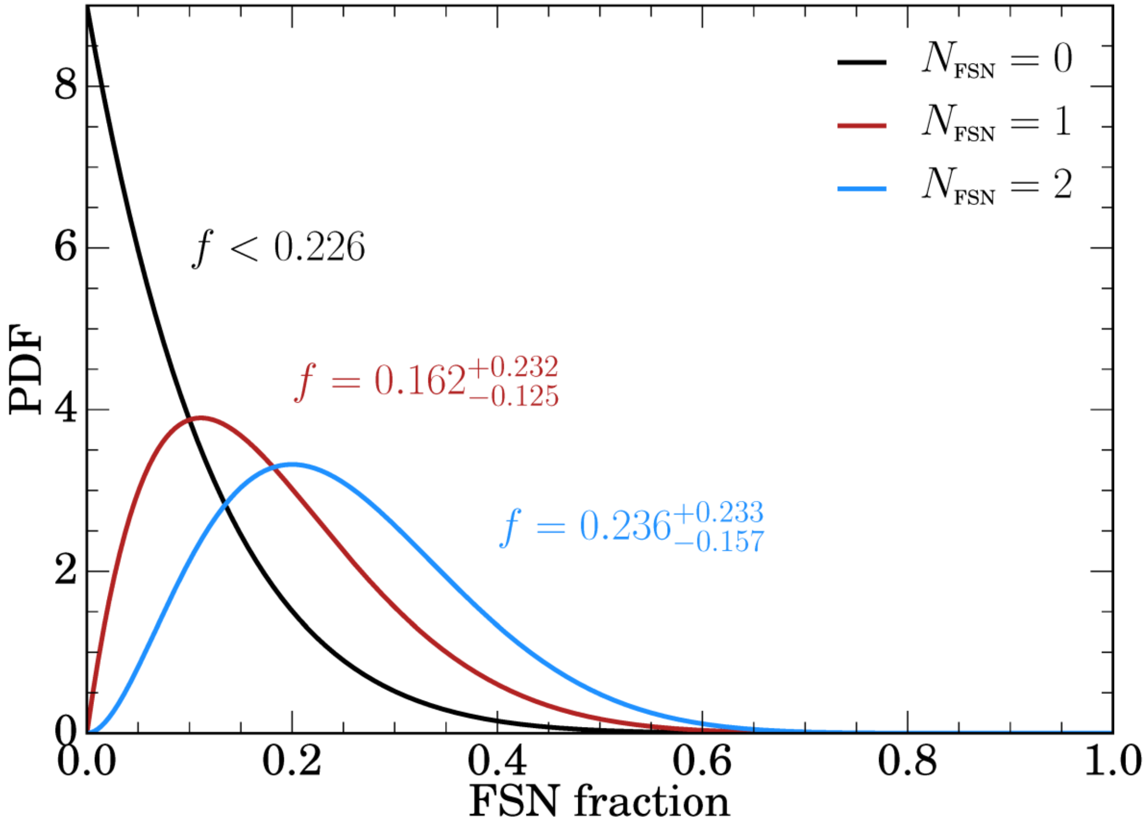
Gerke, Kochanek & Stanek, arXiv:1411.1761

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

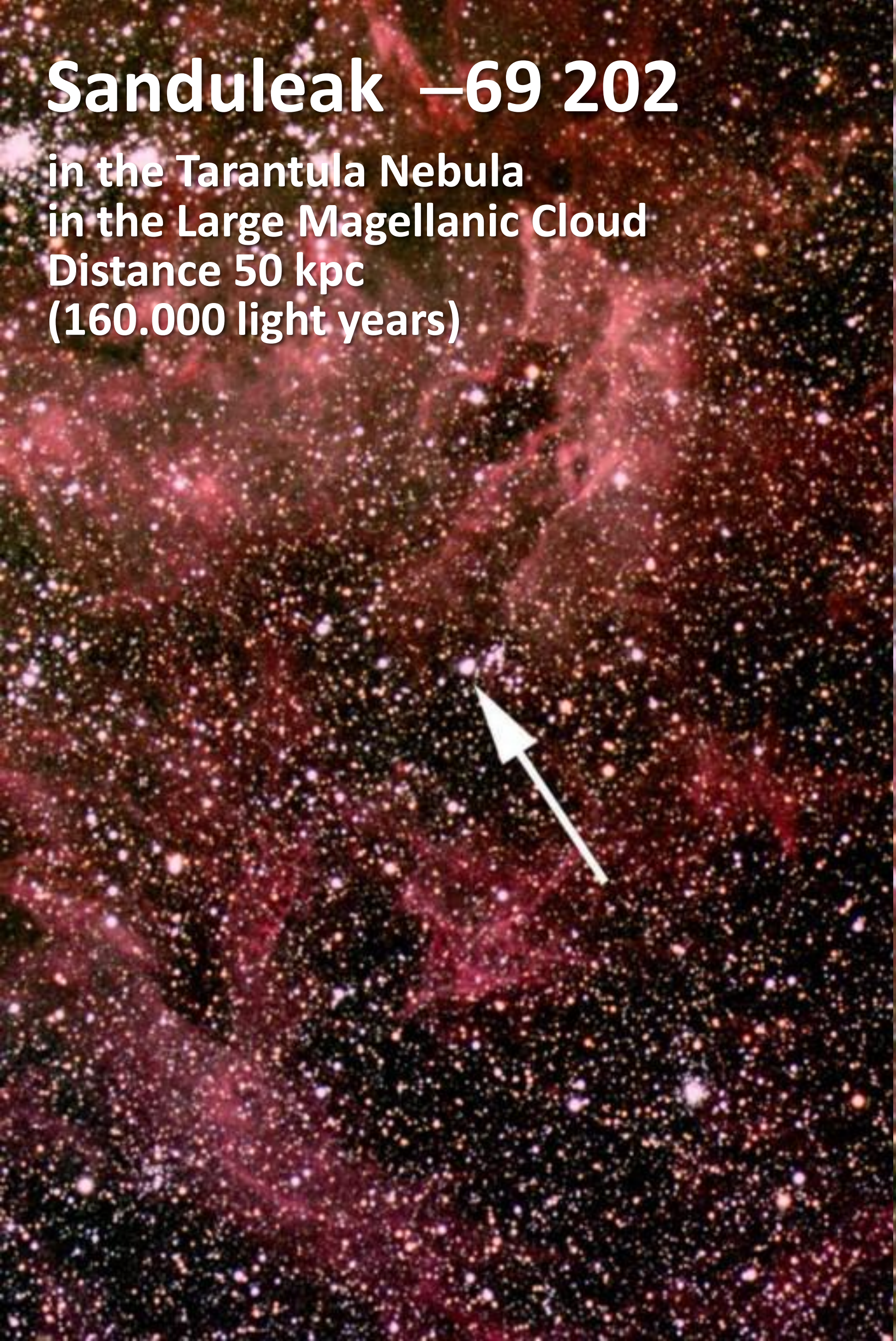
Empirical Fraction of Black-Hole Formation

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

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



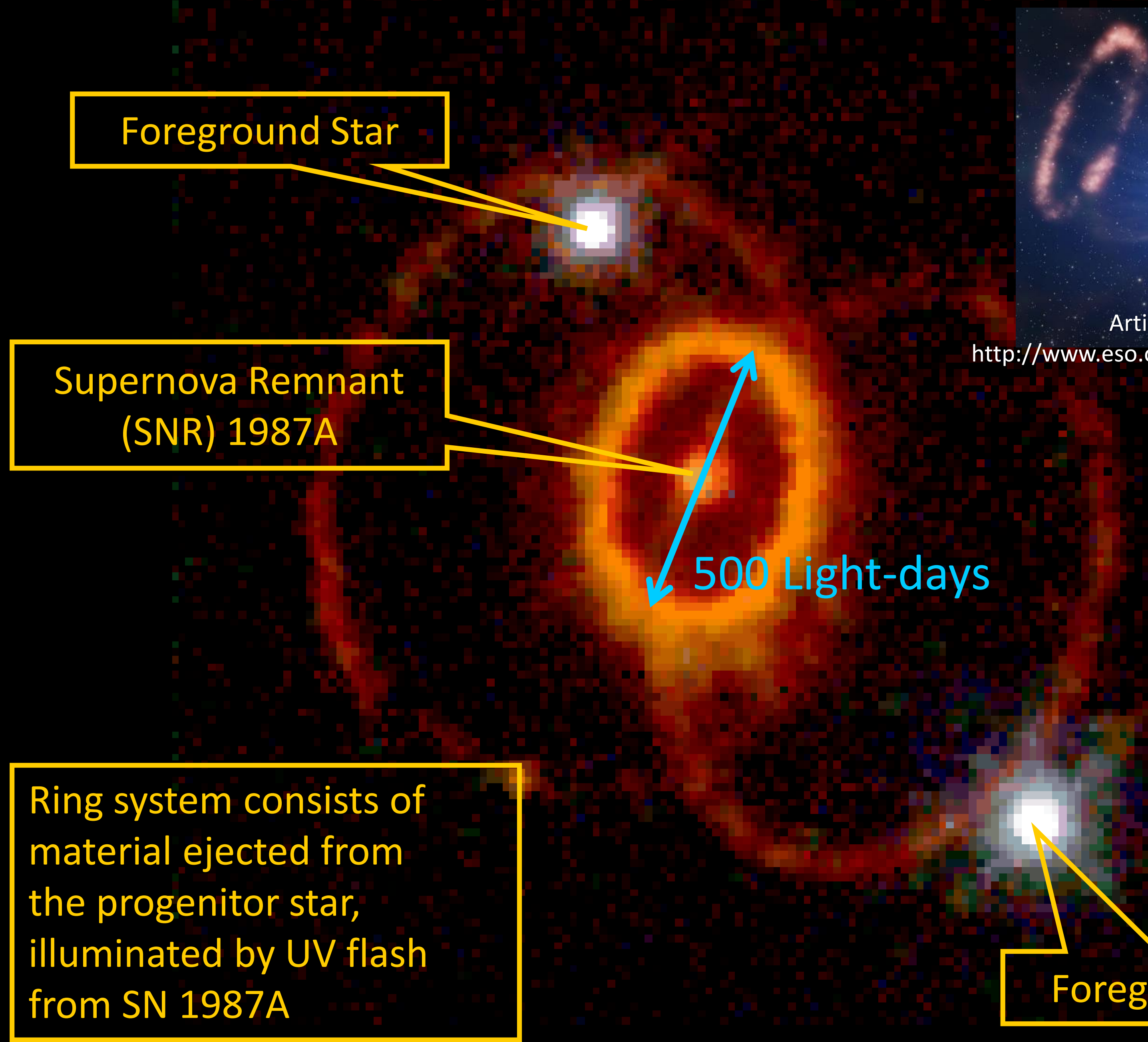
Roughly a quarter of all core-collapses could lead to BH formation, in agreement with theory estimates!


Sanduleak –69 202
in the Tarantula Nebula
in the Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)

Supernova 1987A
23 February 1987

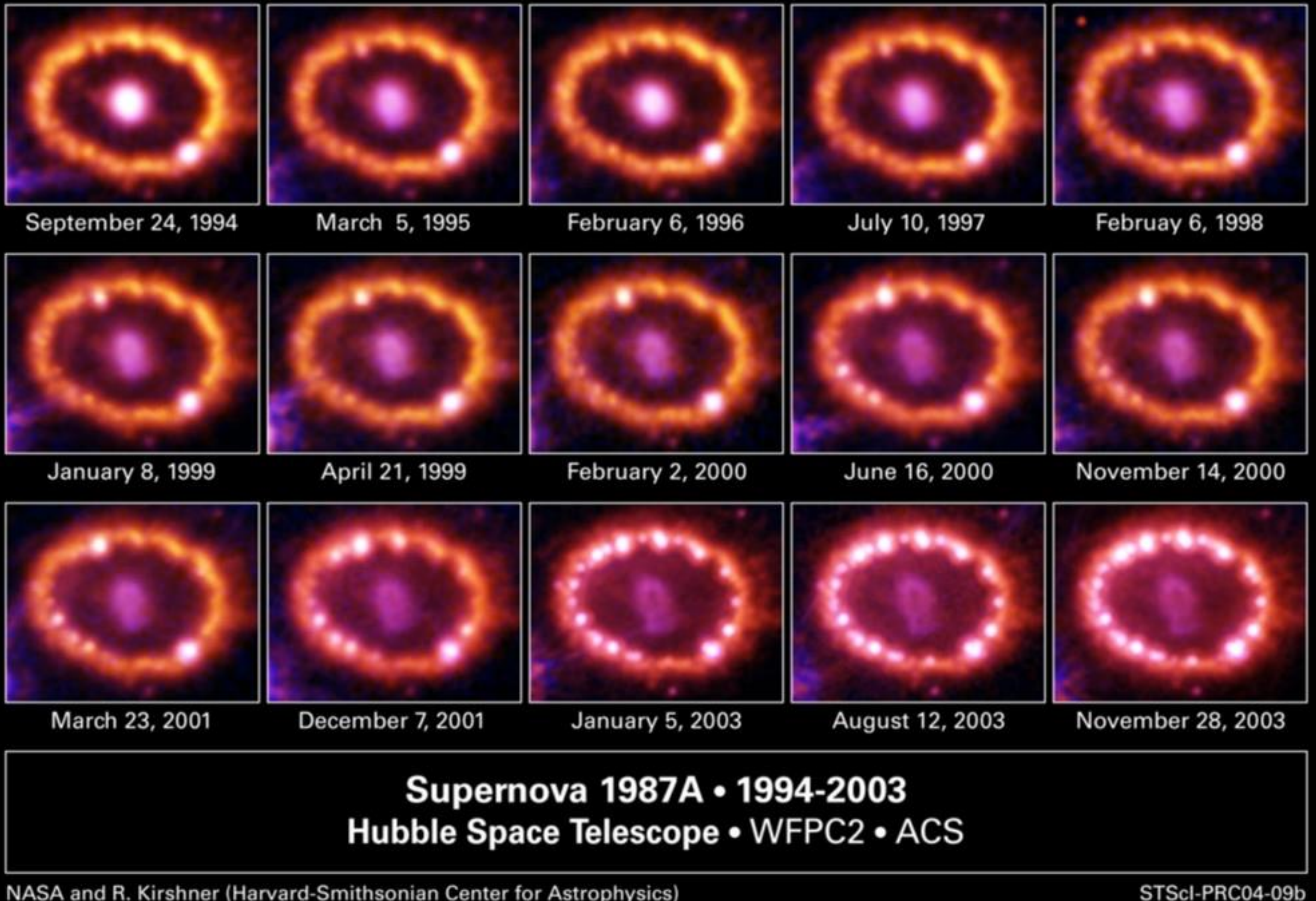
https://hubblesite.org/contents/media/images/2017/08/3987-Image.html?page=1&keyword=1987A

SN 1987A Rings (Hubble Space Telescope 4/1994)

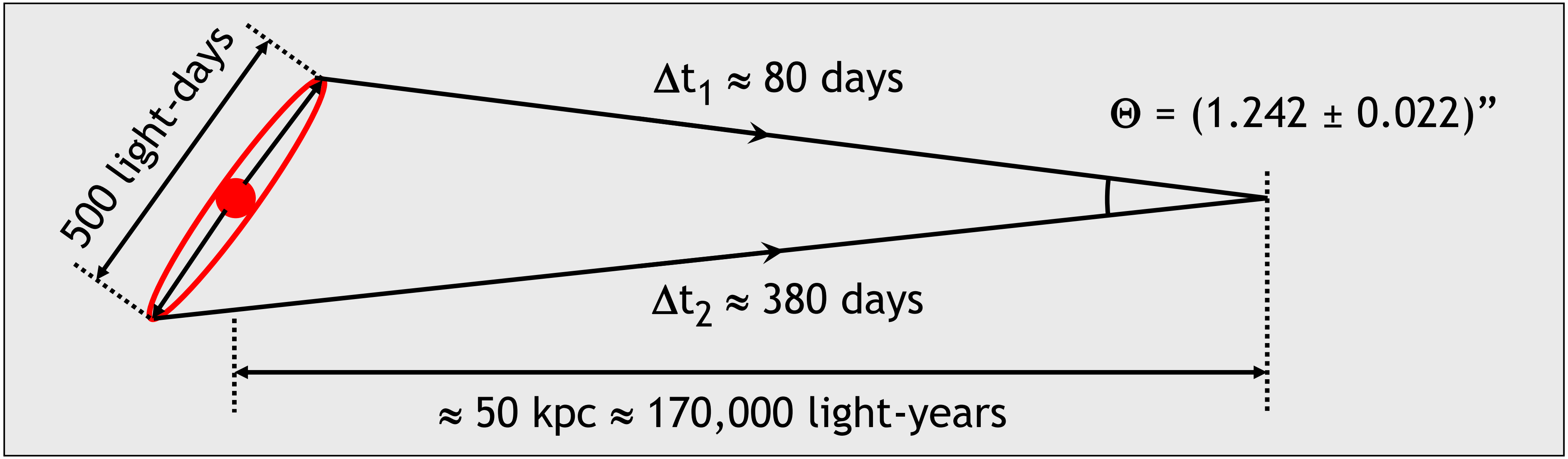


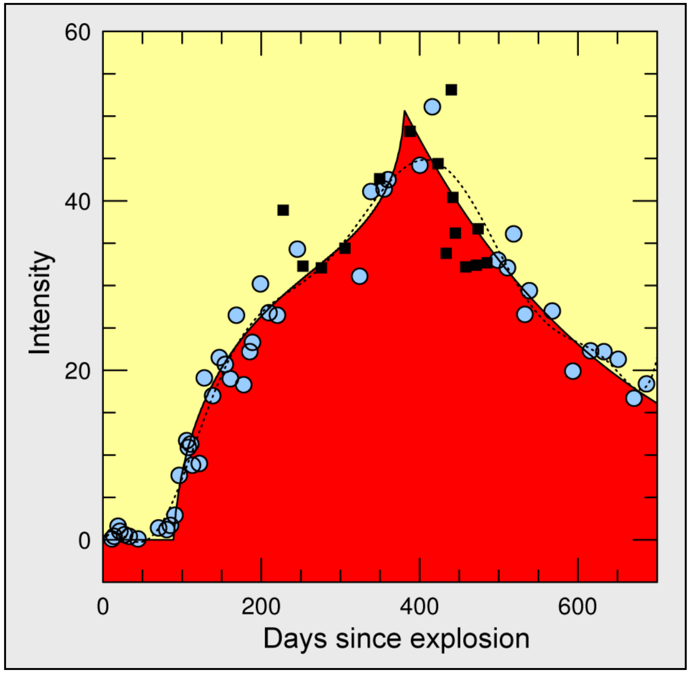
Artist's impression
http://www.eso.org/public/images/eso1032a

SN 1987A Explosion Hits Inner Ring



Distance Determination with Inner Ring

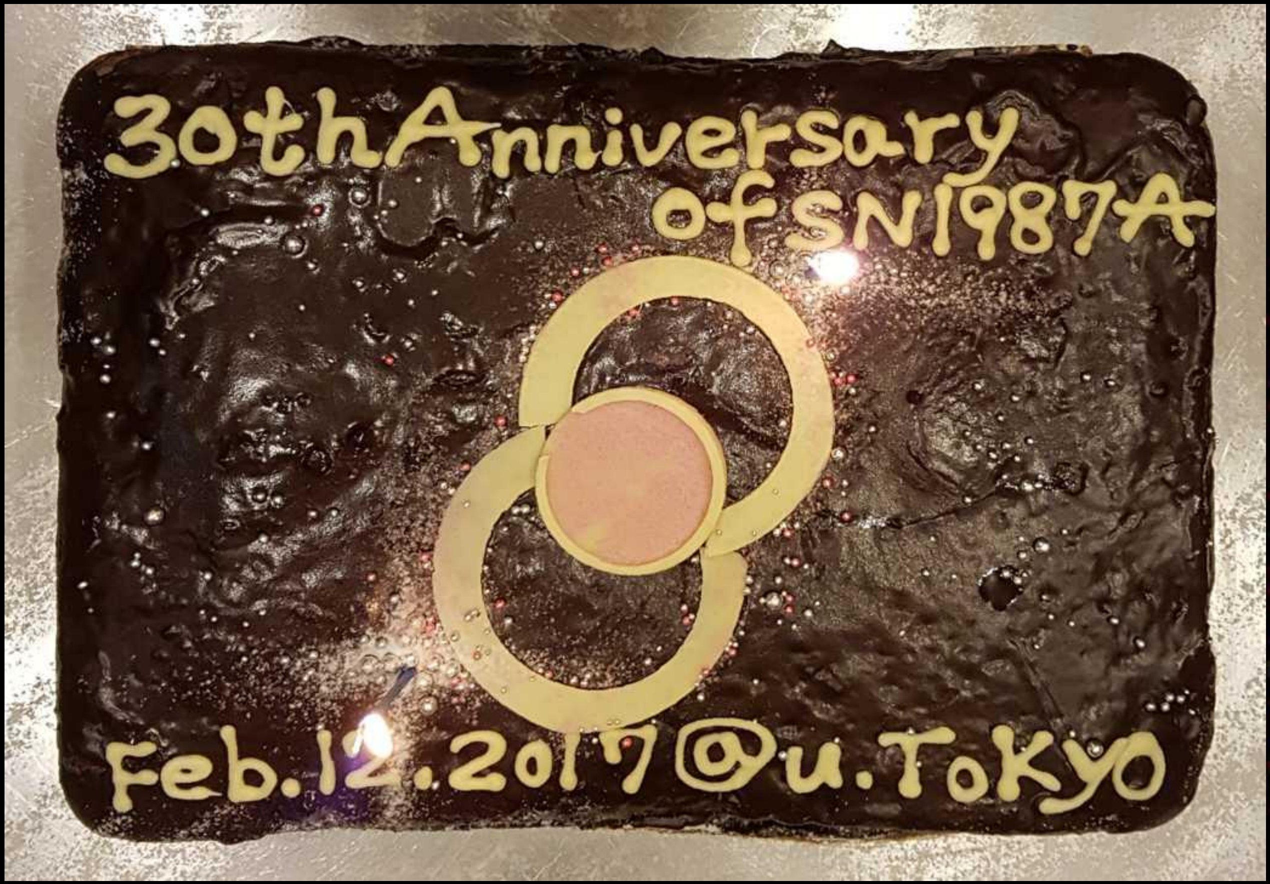
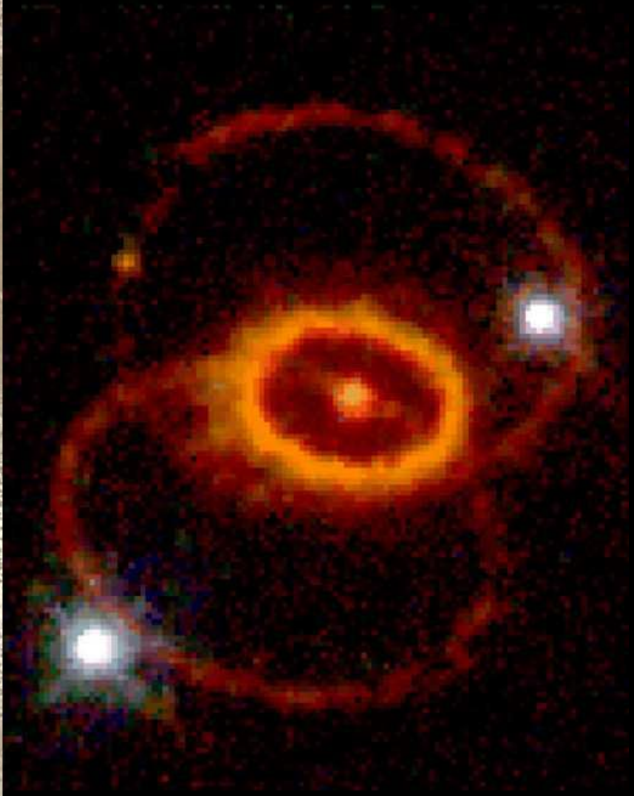




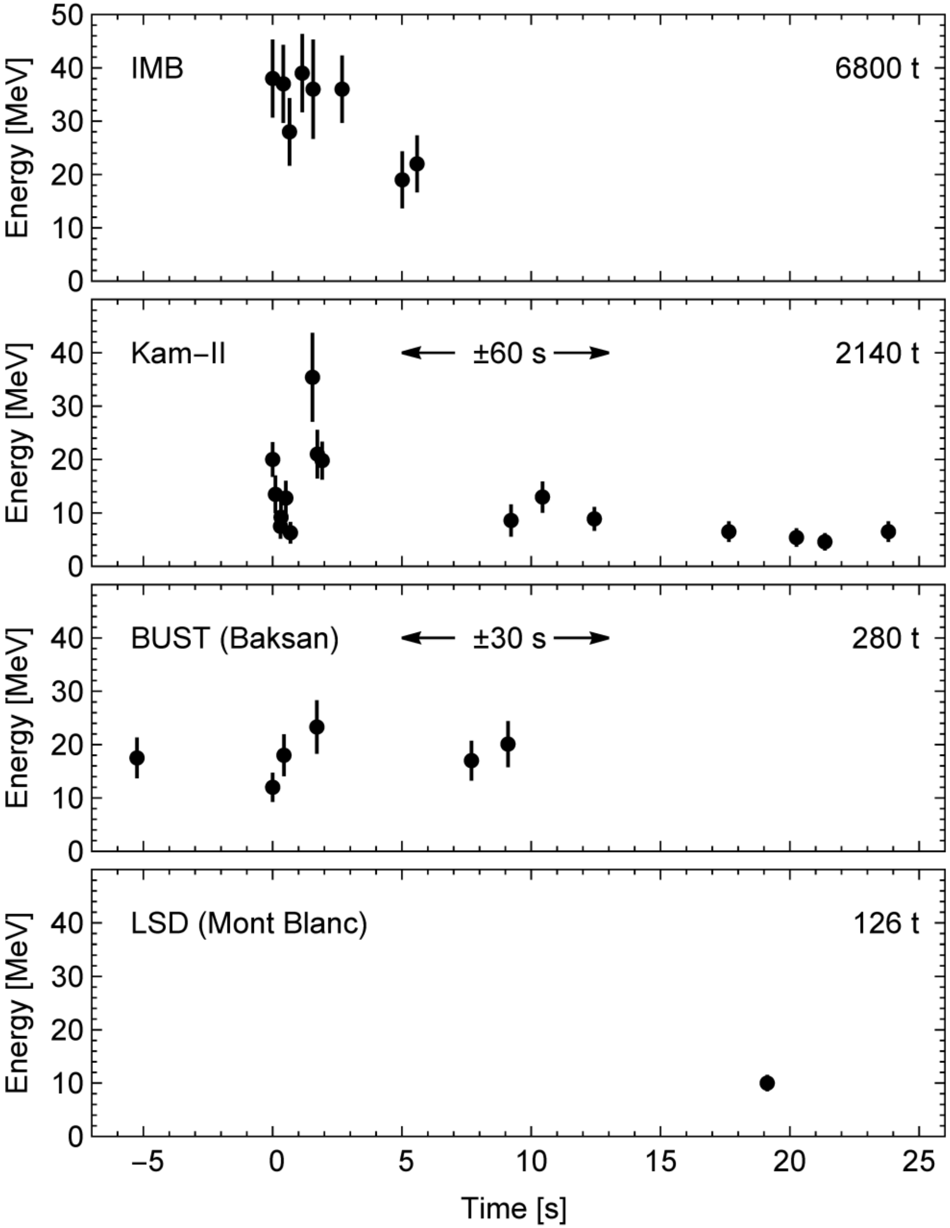
Distance to SN 1987A

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]


30th Anniversary
of SN1987A
Feb.12.2017 @u.Tokyo


Neutrino Signal of Supernova 1987A



Irvine-Michigan-Brookhaven (IMB), US

- Water Cherenkov
- High threshold
- Essentially no background

Kamiokande-II, Japan

- Water Cherenkov
- Bkg 0.187 Hz for $E \lesssim 7.5$ MeV

BUST (Baksan Underground Scintillator Telescope), Soviet Union

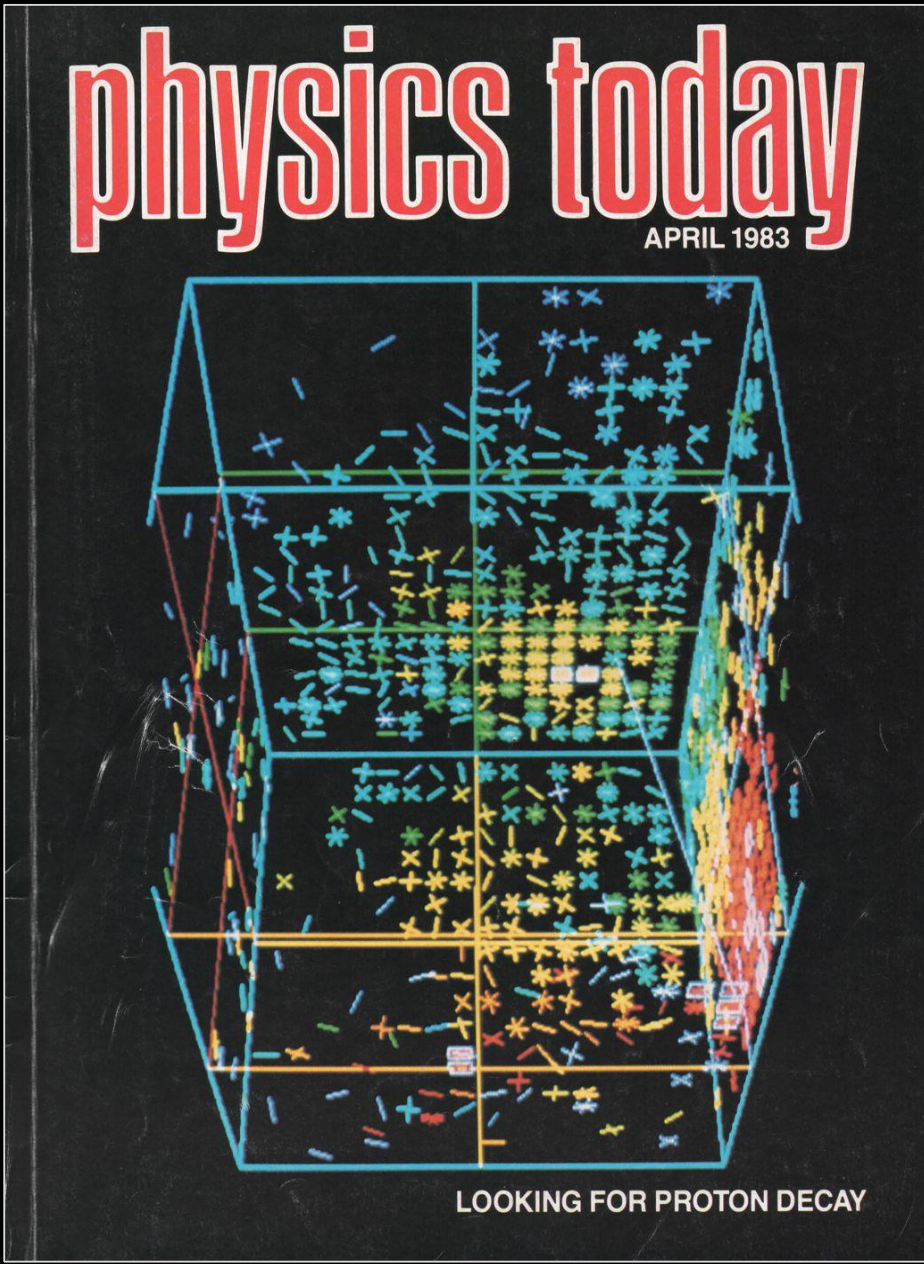
- 200 tons scintillator (280 tons w.e.)
- Bkg 0.034 Hz in signal region
- Upward signal/bkg fluctuation

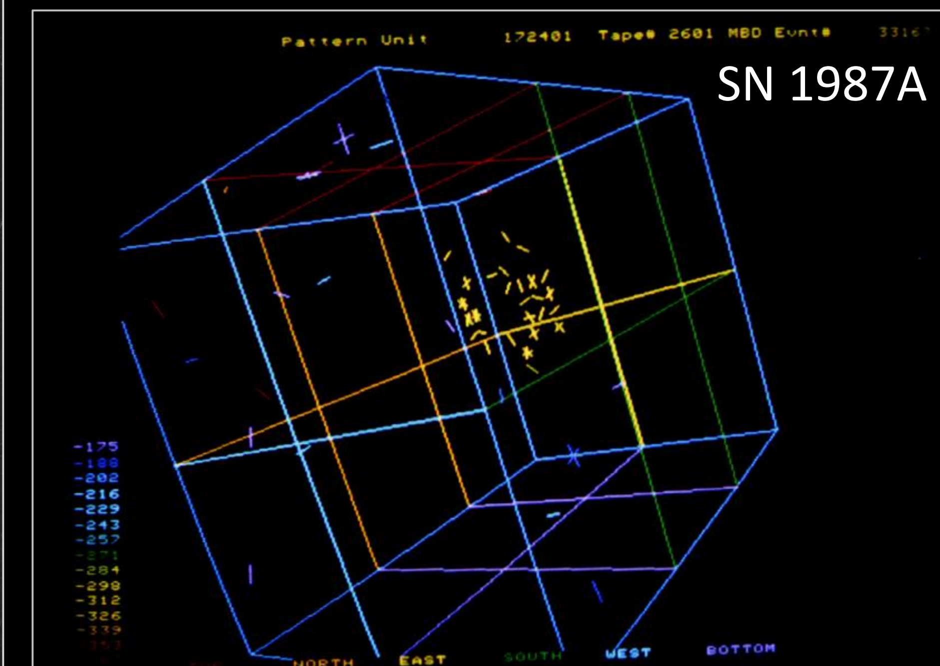
Liquid Scintillator Detector (LSD) Mont Blanc Tunnel (Italy/France)

- 90 tons scintillator (126 tons w.e.)
- Bkg 0.012 Hz in signal region
- Low threshold (expect 2/3 BUST events)

Fiorillo+, arXiv:2308.01403

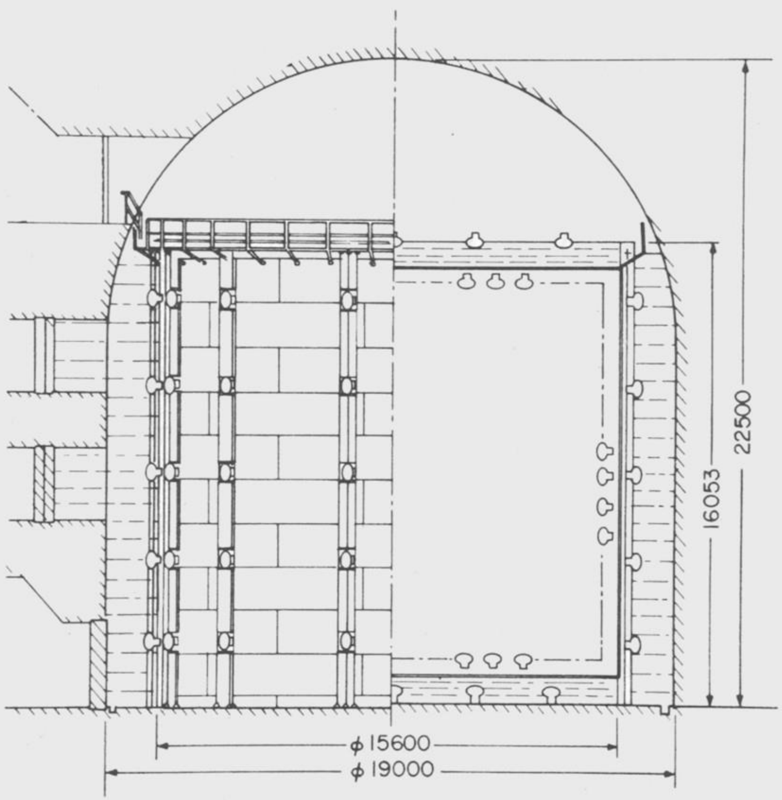
Irvine-Michigan-Brookhaven (IMB) Detector



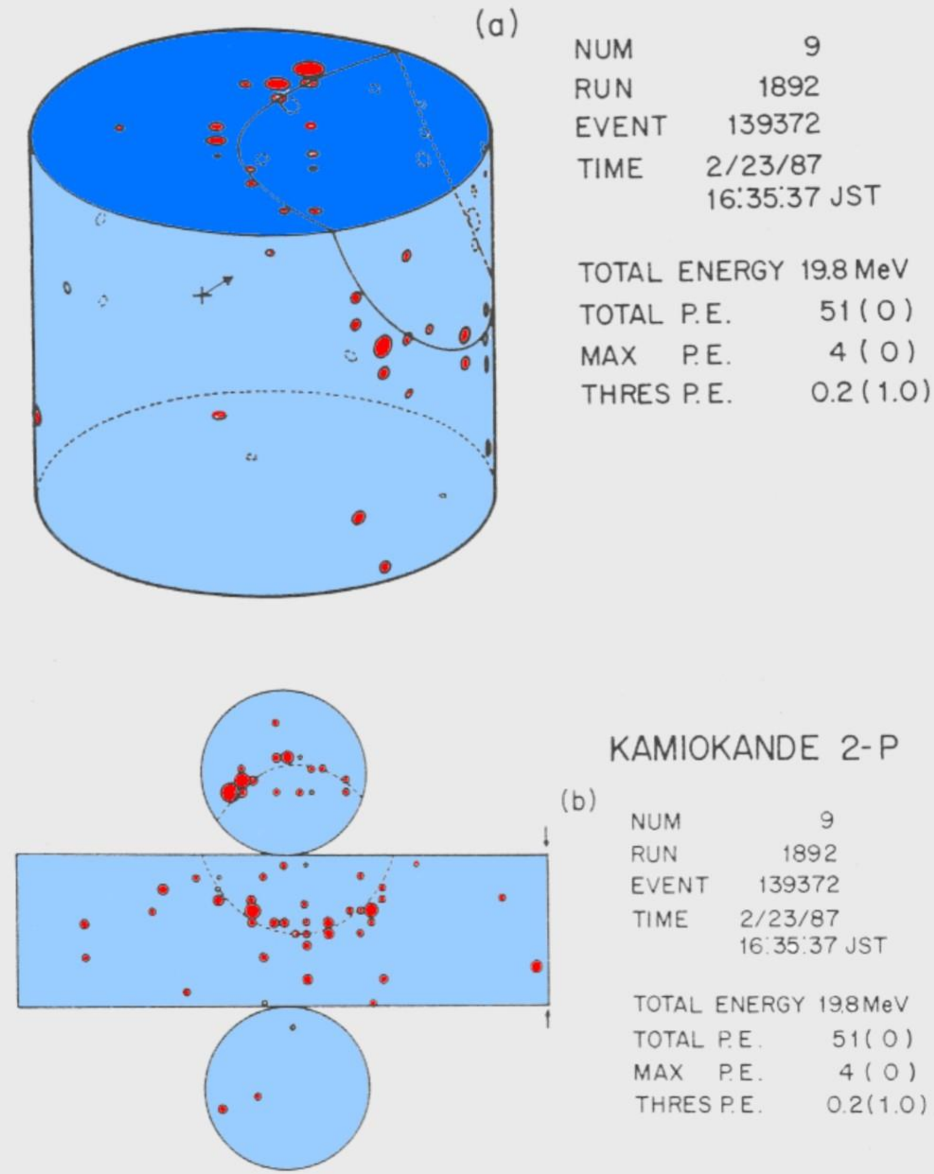


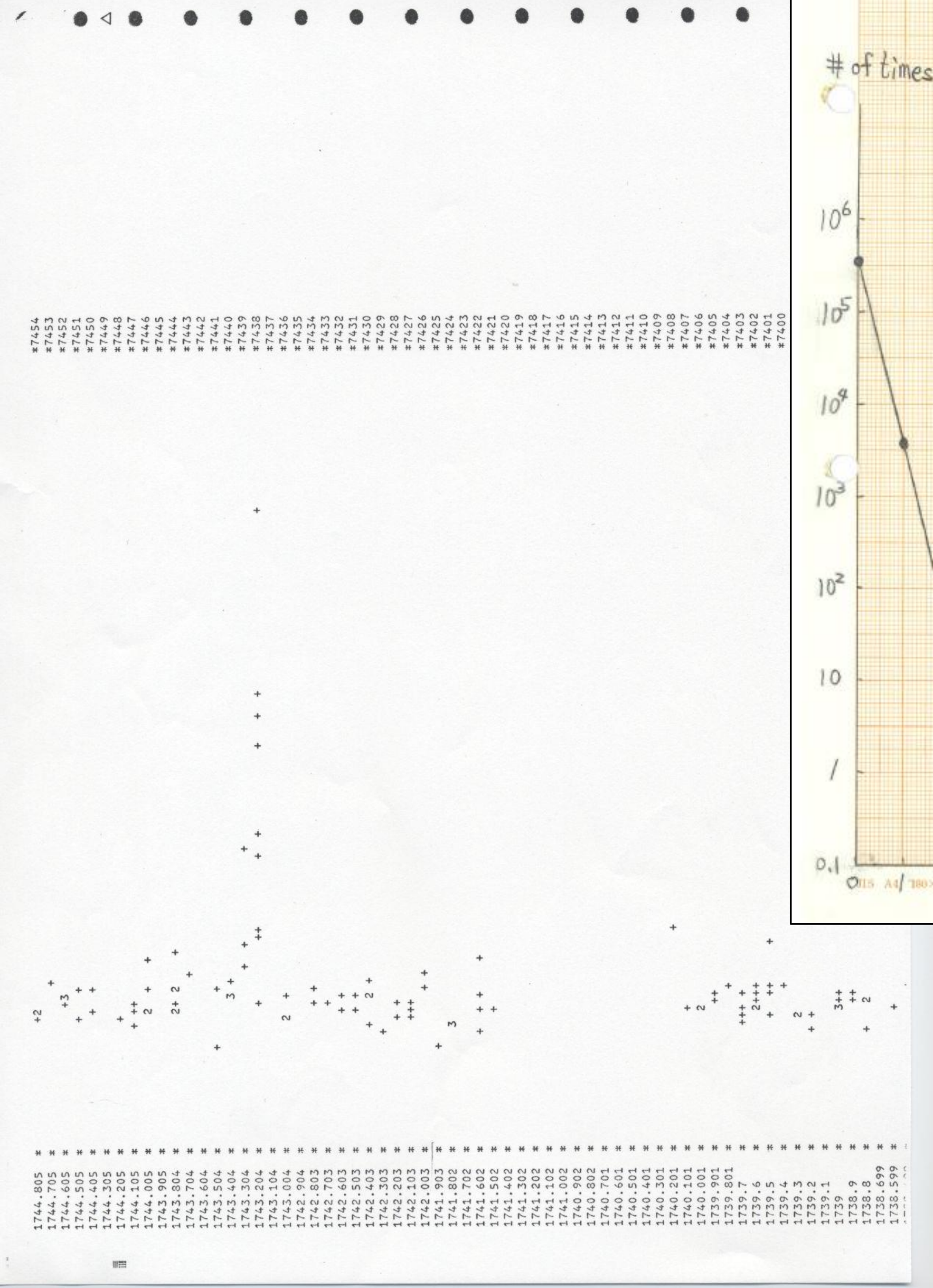
SN 1987A Event No.9 in Kamiokande

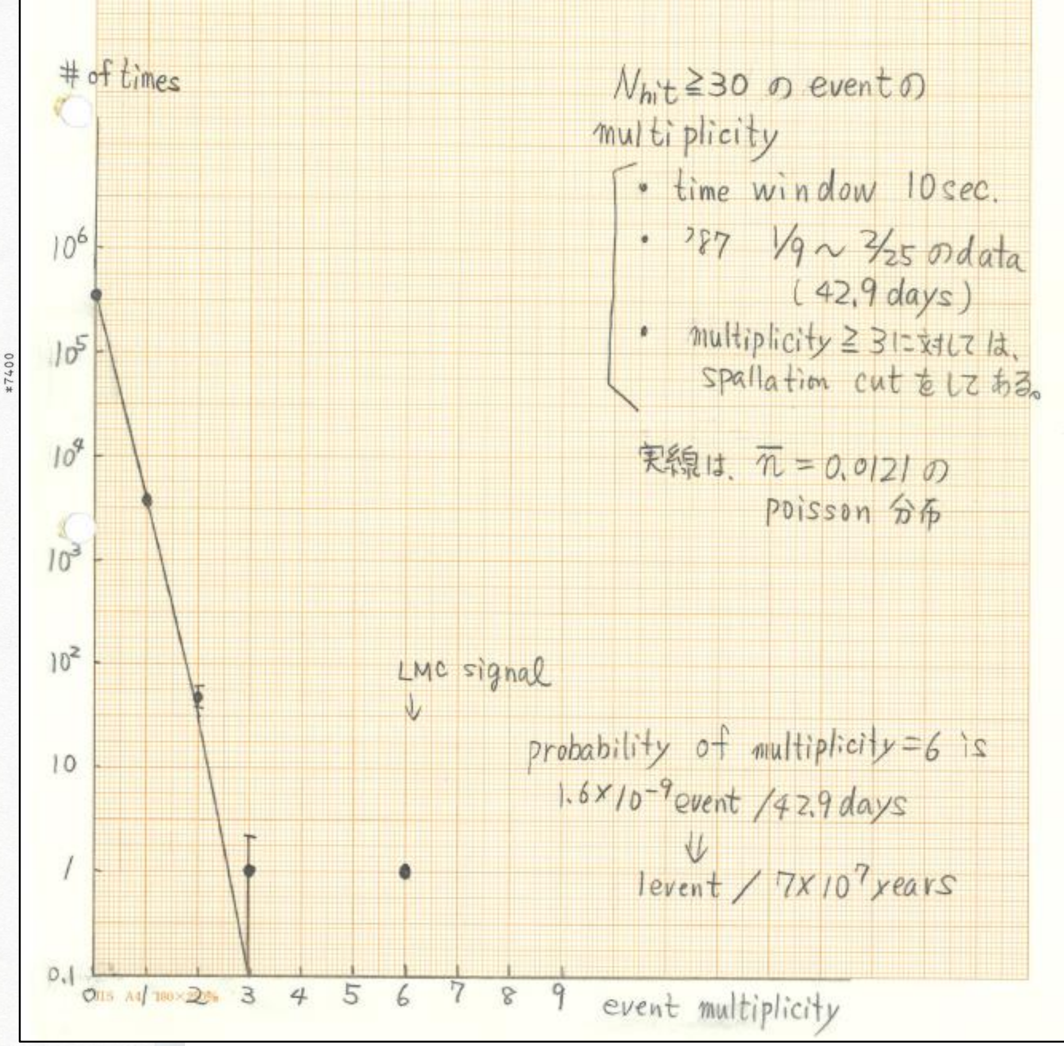
Kamiokande-II Detector
(2140 tons of water)



Hirata et al., PRD 38 (1988) 448

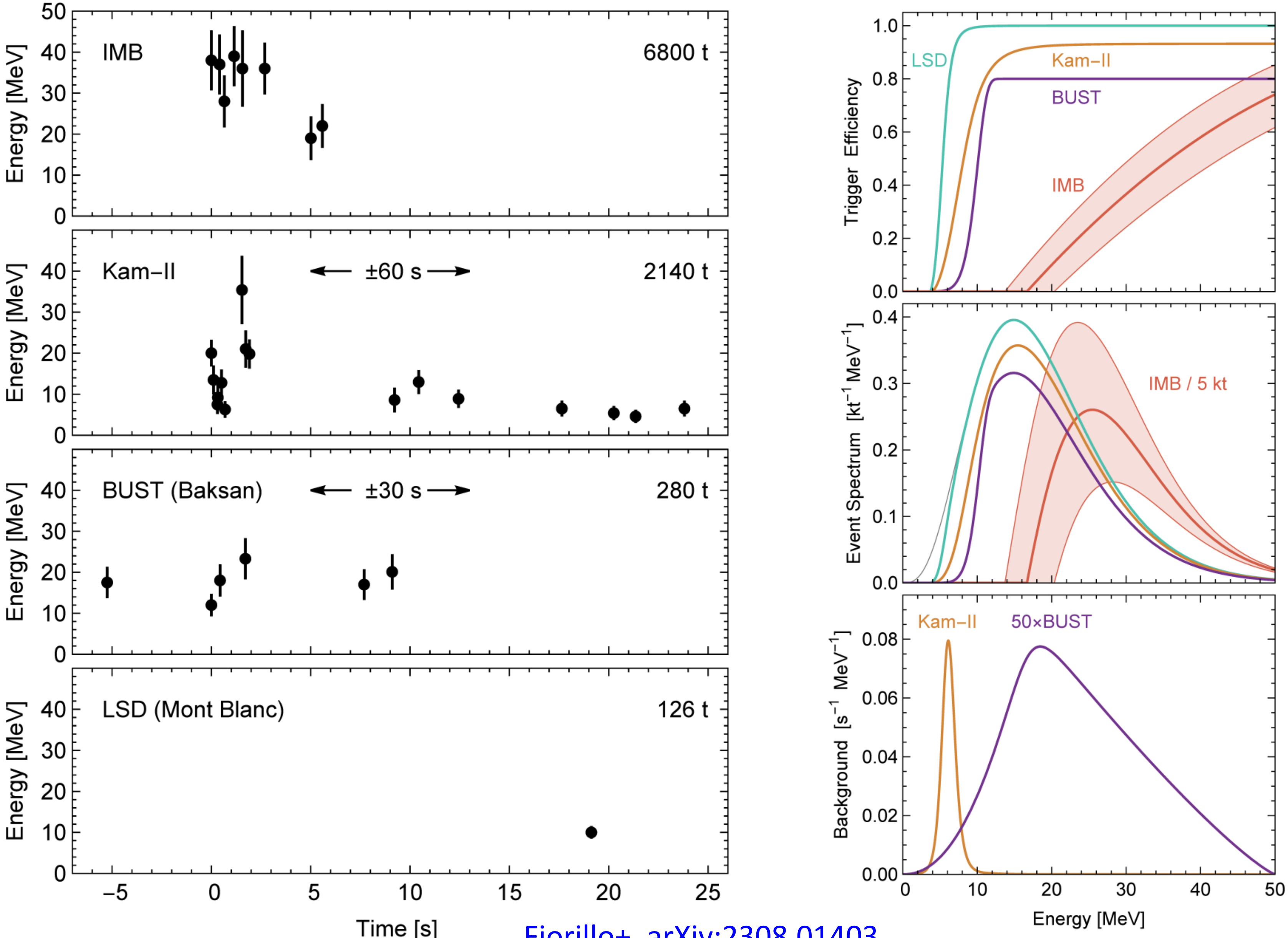






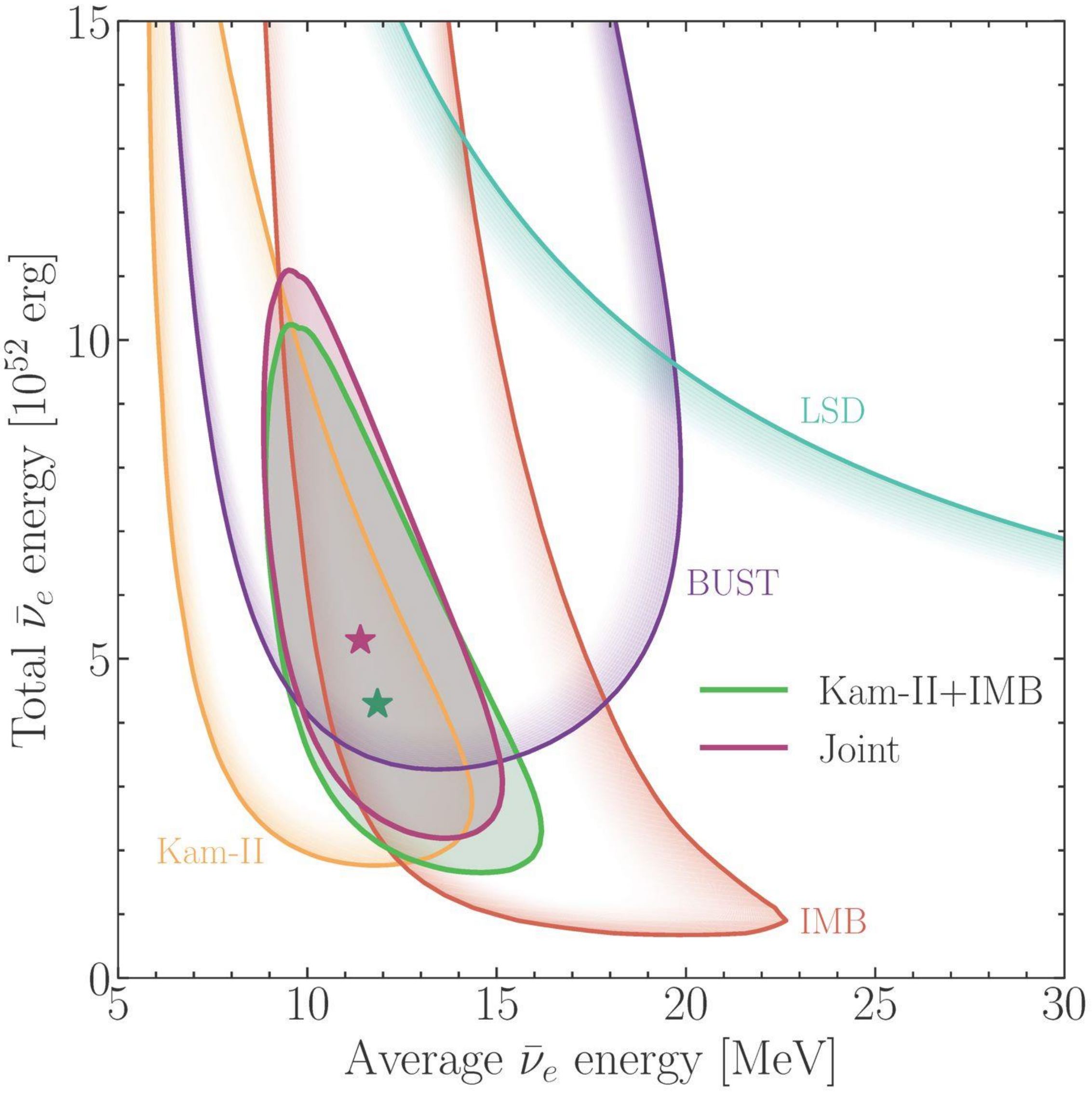
Masayuki Nakahata's notes after the analysis
(since April 2022 director of
ICRR at University of Tokyo)

Neutrino Signal of Supernova 1987A



Fiorillo+, arXiv:2308.01403

Generic Time-Integrated Analysis



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

(Maxwell-Boltzmann spectrum)

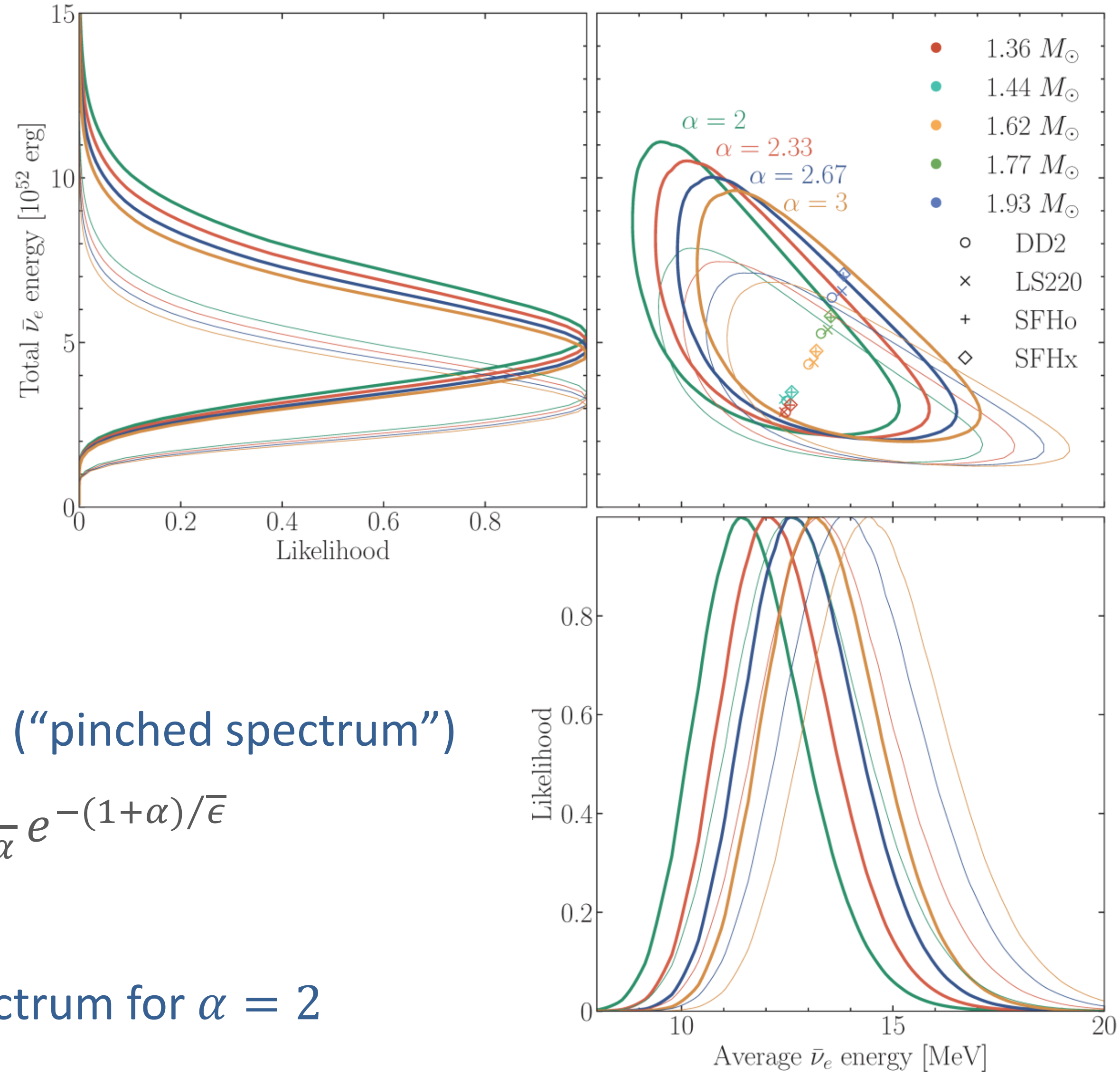
Distance 50 kpc

Likelihood fit with parameters

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

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

Time-Integrated Analysis with Pinched Spectra



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

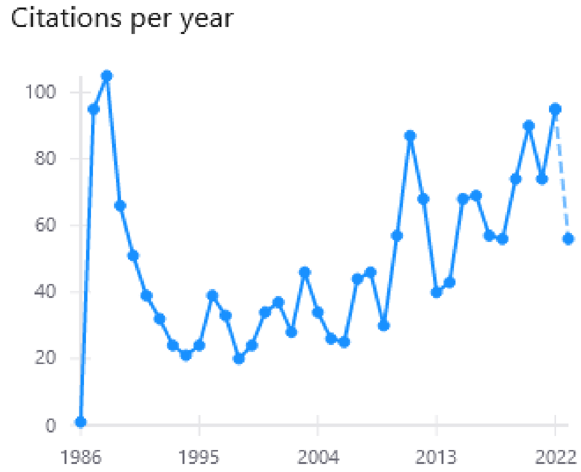
IMB and Kam-II SN 1987A Neutrino Observations

Observation of a Neutrino Burst in Coincidence with Supernova SN 1987a in the Large Magellanic Cloud

R.M. Bionta, G. Blewitt, C.B. Bratton, D. Casper, A. Ciocio Show All(37)
Mar, 1987

10 pages
Published in: *Phys.Rev.Lett.* 58 (1987) 1494
DOI: 10.1103/PhysRevLett.58.1494
Report number: UCI-NEUTRINO-87-10
Experiments: IMB
View in: OSTI Information Bridge Server, ADS Abstract Service

cite claim reference search 1,858 citations

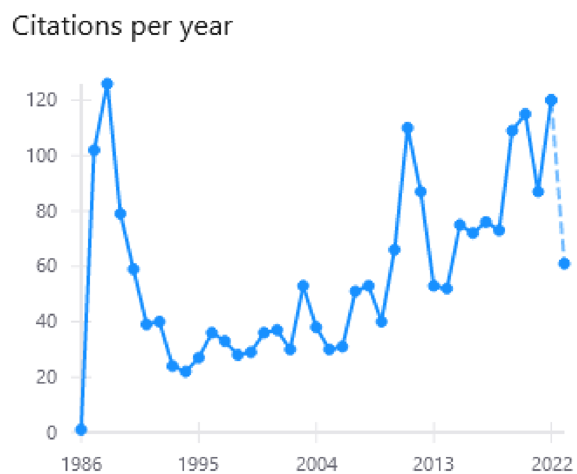


Observation of a Neutrino Burst from the Supernova SN 1987a

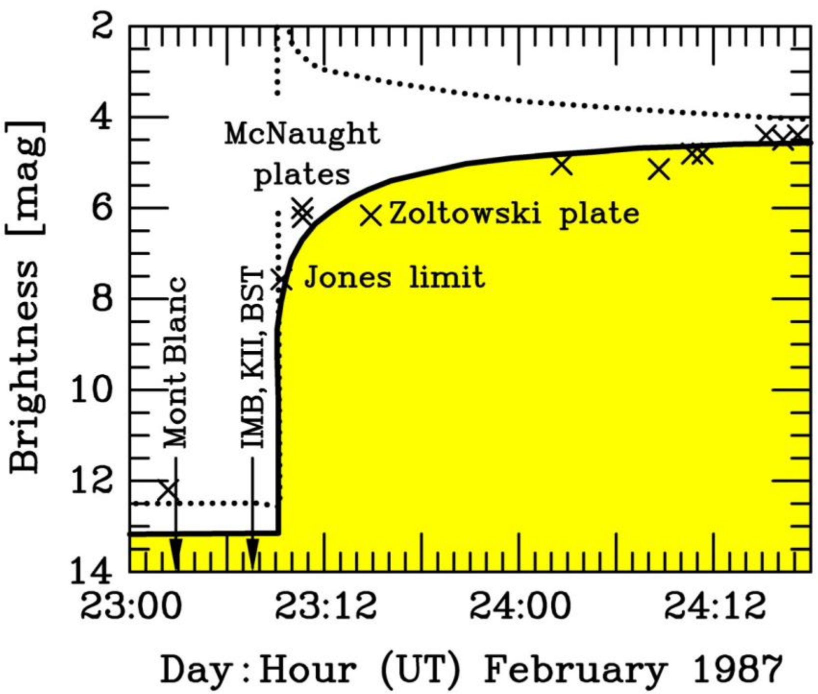
Kamiokande-II Collaboration • K. Hirata (Tokyo U., ICEPP) Show All(21)
Mar, 1987

14 pages
Part of GRAND UNIFICATION. PROCEEDINGS, 8TH WORKSHOP, SYRACUSE, USA, APRIL 16-18, 1987, 1490-1493
Published in: *Phys.Rev.Lett.* 58 (1987) 1490-1493
Contribution to: Eighth Workshop on Grand Unification, 22nd Rencontres de Moriond: Electroweak Interactions and Unified Theories, 727-734
DOI: 10.1103/PhysRevLett.58.1490
Report number: UT-ICEPP-87-01, UPR-142E
Experiments: KAMIOKANDE
View in: OSTI Information Bridge Server, ADS Abstract Service

pdf cite claim reference search 2,200 citations



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,

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

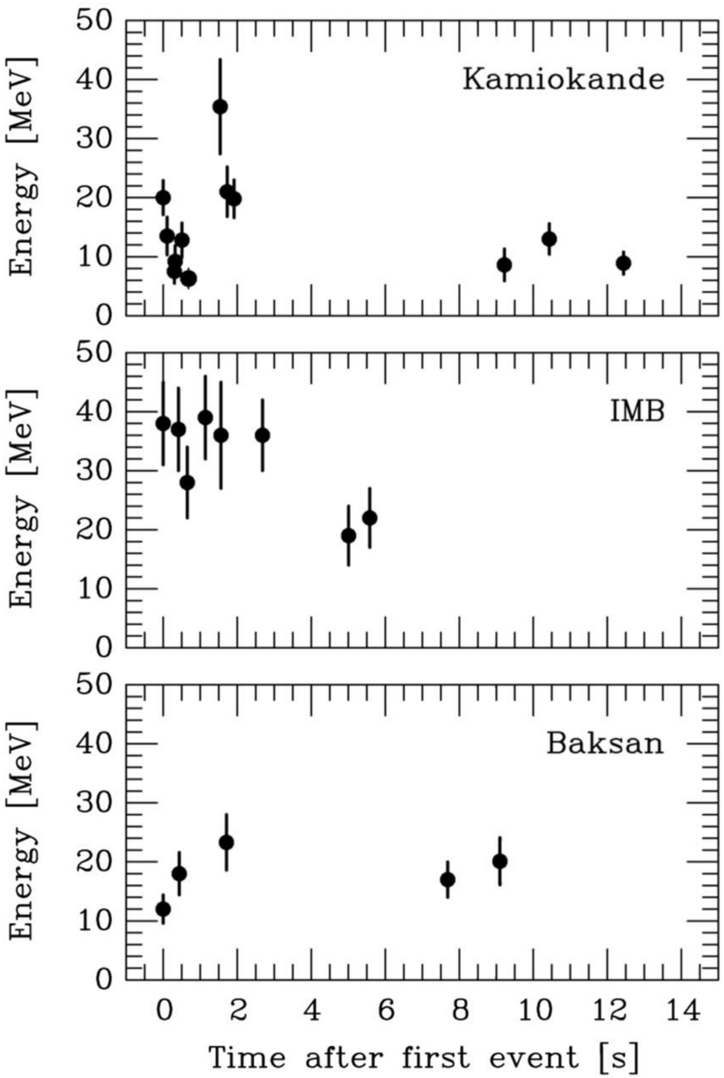
Neutrinos and photons respond to gravity the same to within

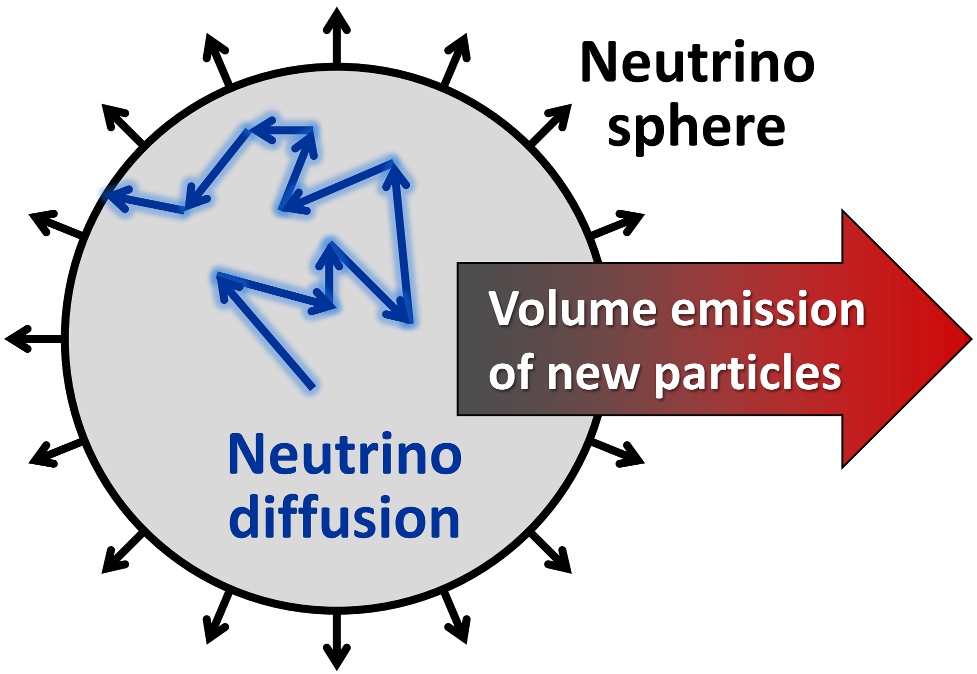
$$1\text{–}4 \times 10^{-3}$$

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

Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal

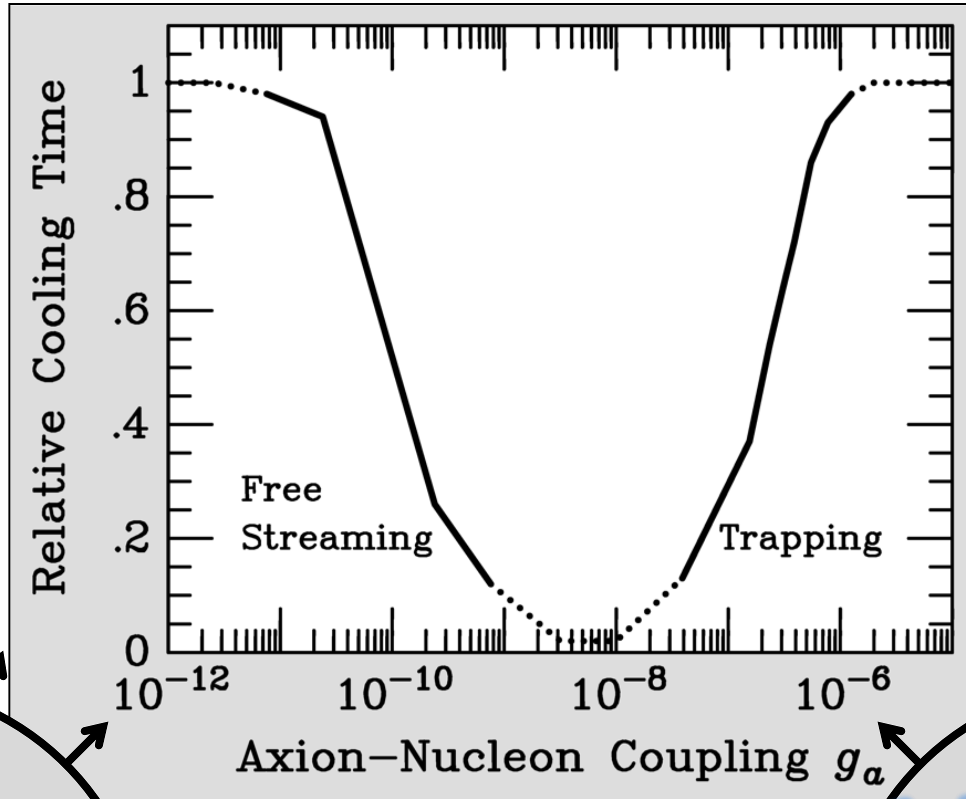


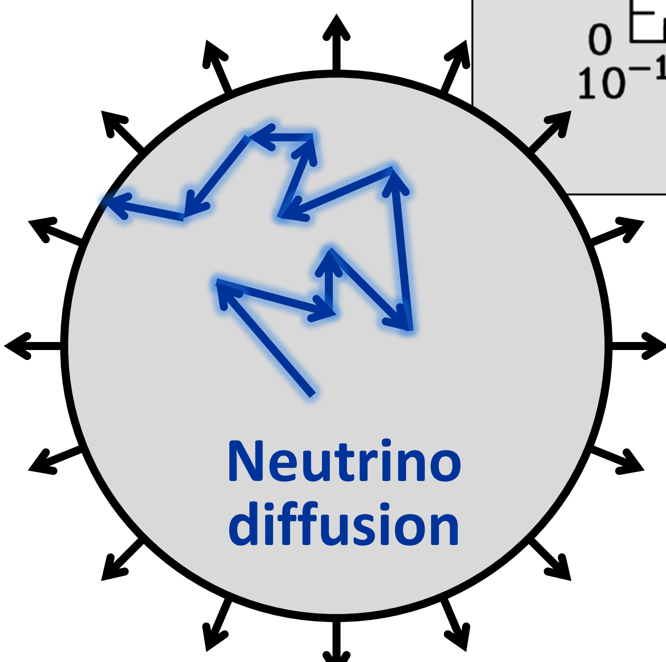


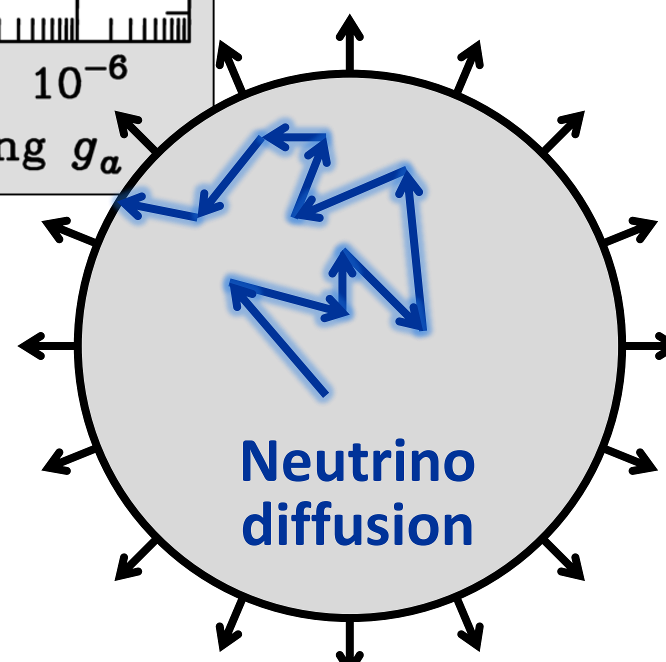
Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

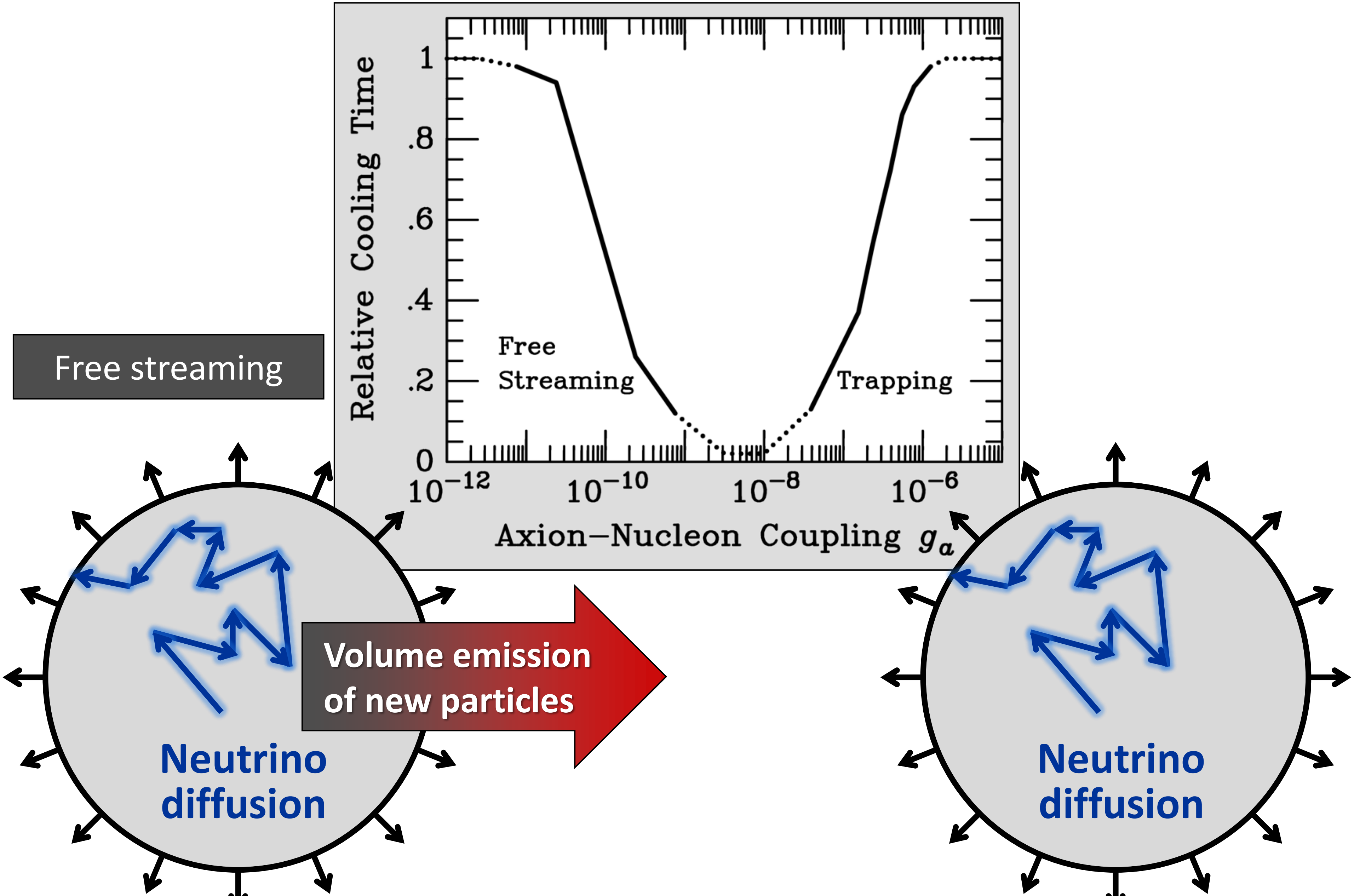
SN 1987A Axion Limits



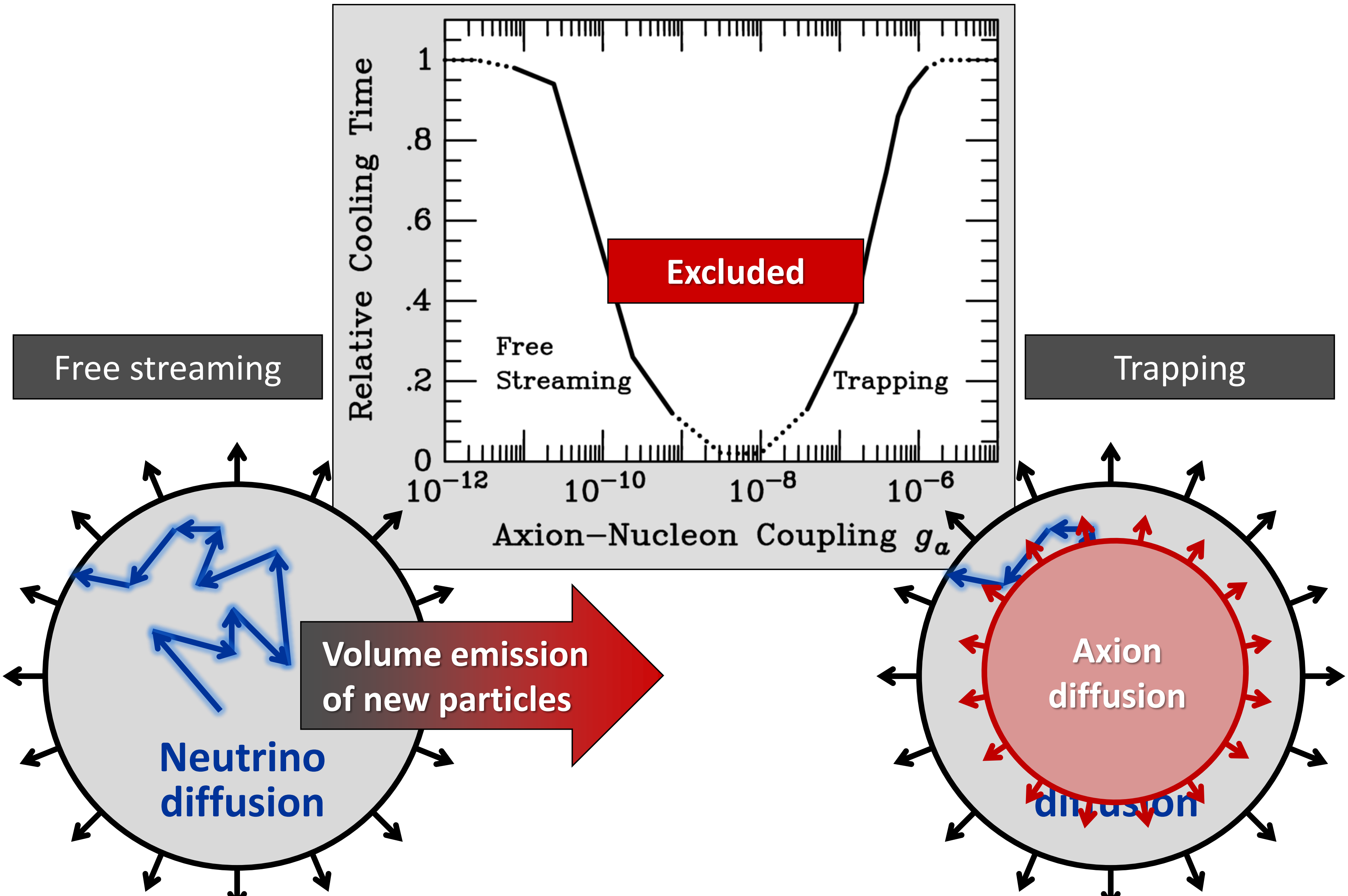




SN 1987A Axion Limits

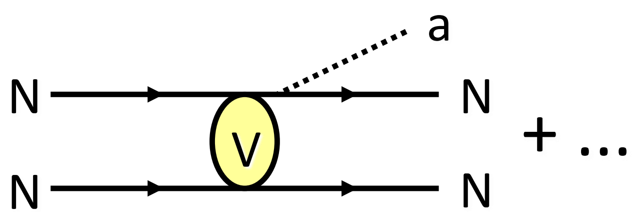


SN 1987A Axion Limits



Axion Emission from a Nuclear Medium

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



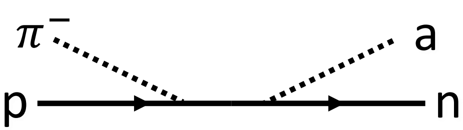
Nucleon-Nucleon Bremsstrahlung

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?)



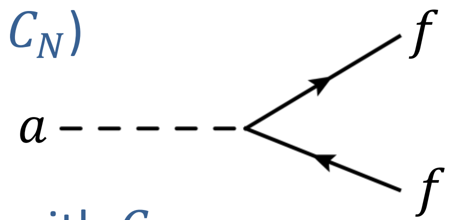
→ For latest discussion see Carenza et al. arXiv:2010.02943

Axion-Nucleon Couplings

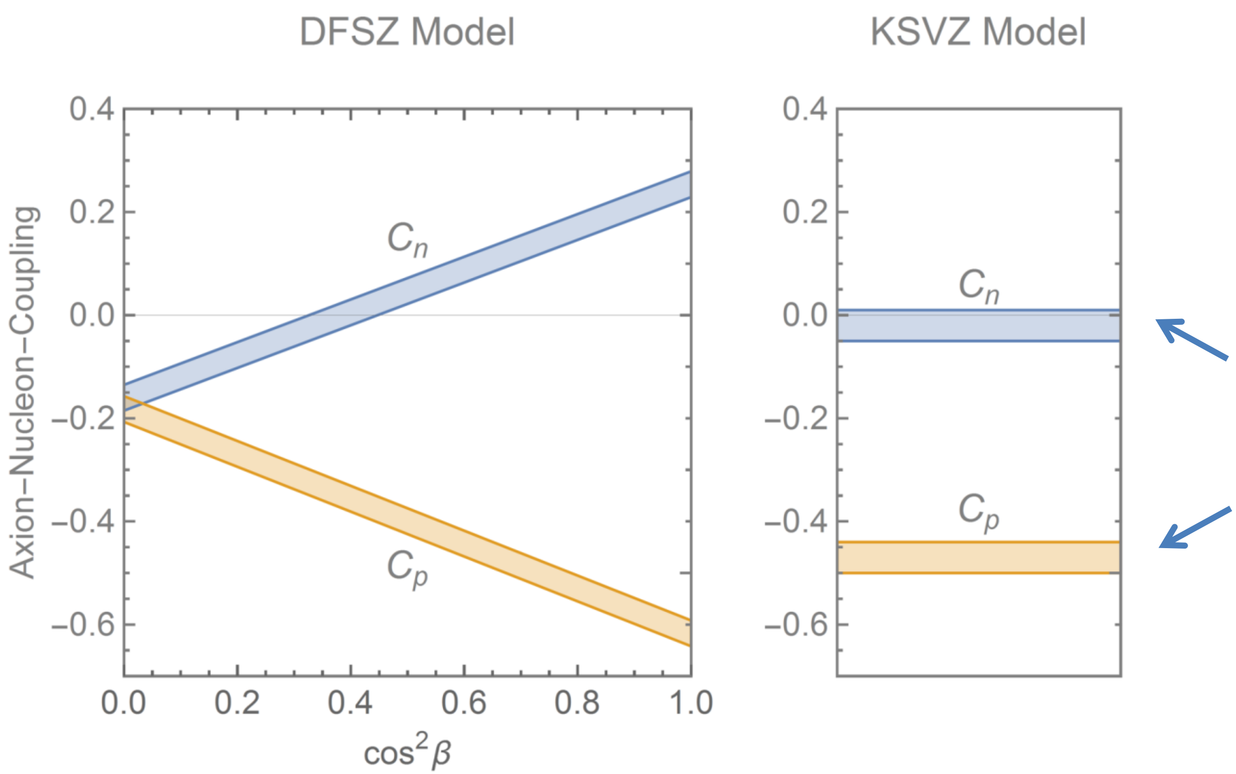
Axion-nucleon coupling (model-dependent numerical factors C_N)

$$\mathcal{L}_{aN} = C_N\,\overline{\Psi}_N\gamma^\mu\gamma_5\Psi_N\,\frac{\partial_\mu a}{2f_a}$$

- Axial-vector current
- Spin-dependent int'n



Axion-electron coupling in non-hadronic models is analogous with C_e



Values from Grilli di Cortona et al. arXiv:1511.02867

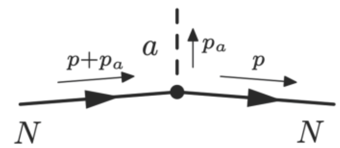
Coupling to neutron could be very small!

Brand New

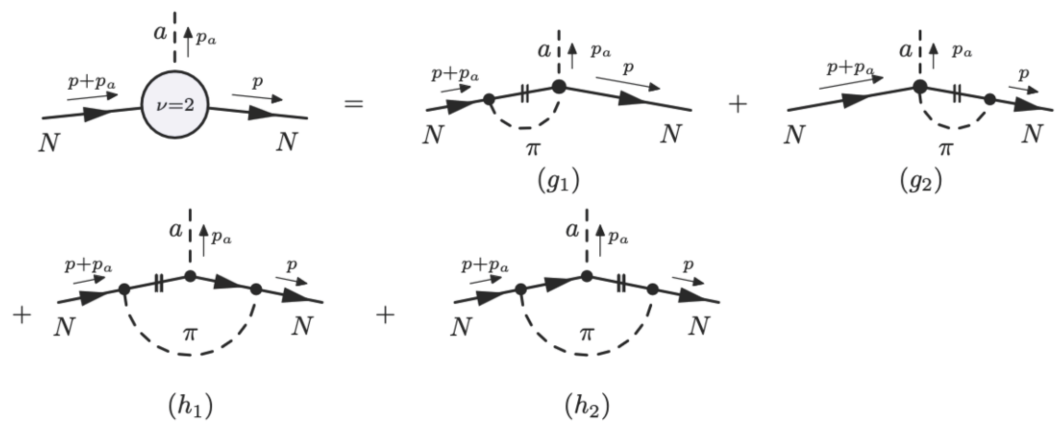
QCD axion couplings at finite density

Systematic expansion in nucleon momenta: $\left(\frac{k}{4\pi f_\pi}\right)^\nu \rightarrow \left(\frac{k_f}{4\pi f_\pi}\right)^\nu$

$\left(\frac{k_f}{4\pi f_\pi}\right)^0$



$\left(\frac{k_f}{4\pi f_\pi}\right)^2$



Naively this is suppressed in the chiral expansion…

… but due to $\Delta(1232)$ resonances some corrections are large!

This happens the first time at $\nu = 3$

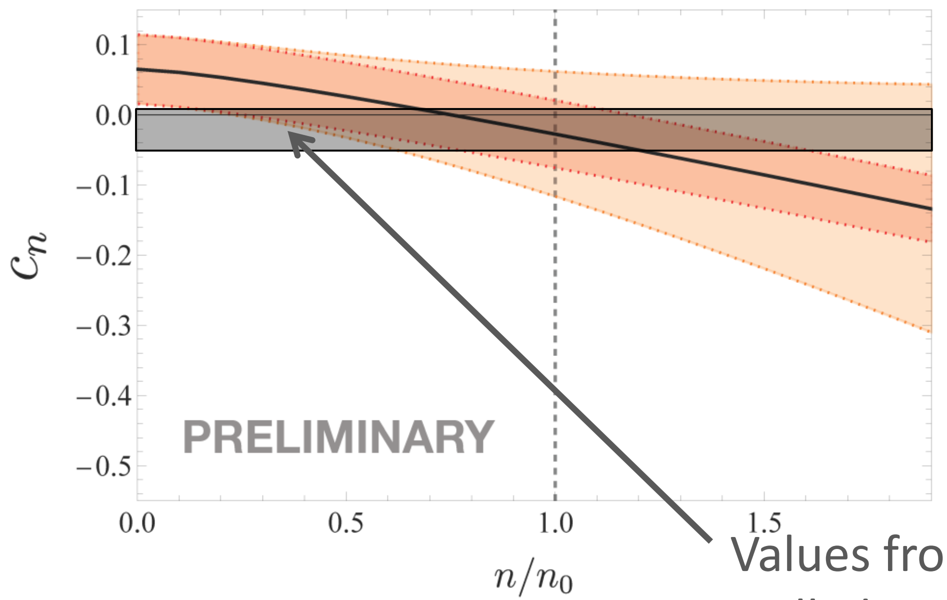
S. Stelzl, Cosmic Wispers Workshop, Bari

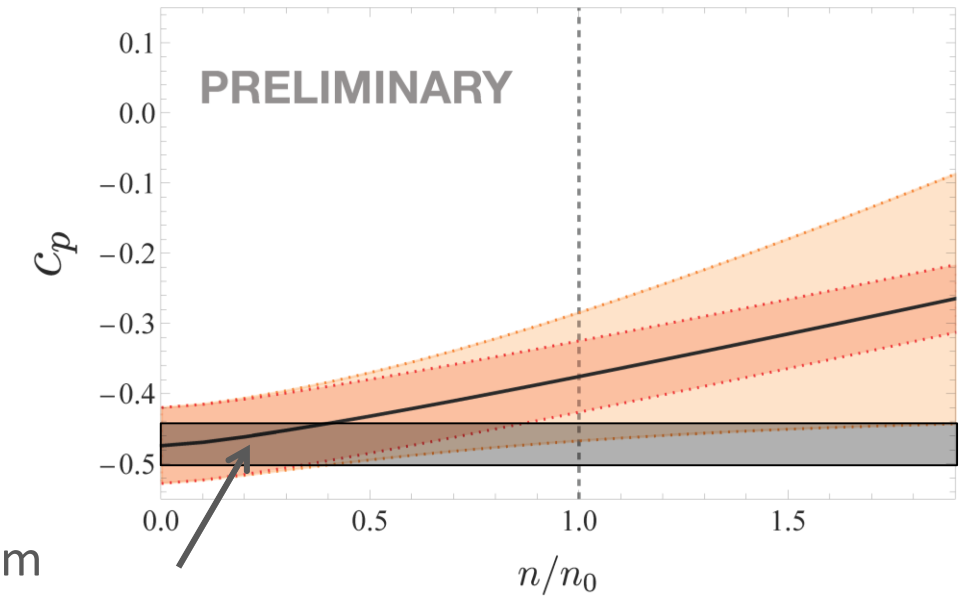
Work in preparation, Balkin, Serra, Springmann, Stadlbauer, Stelzl & Weiler

Axion Couplings in Dense Nuclear Medium

Brand New

KSVZ Axions





Values from
Grilli di Cortona et al.
arXiv:1511.02867

S. Stelzl, Cosmic Wispers Workshop, Bari

Work in preparation, Balkin, Serra, Springmann, Stadlbauer, Stelzl & Weiler

SN 1987A Axion Limits from Burst Duration

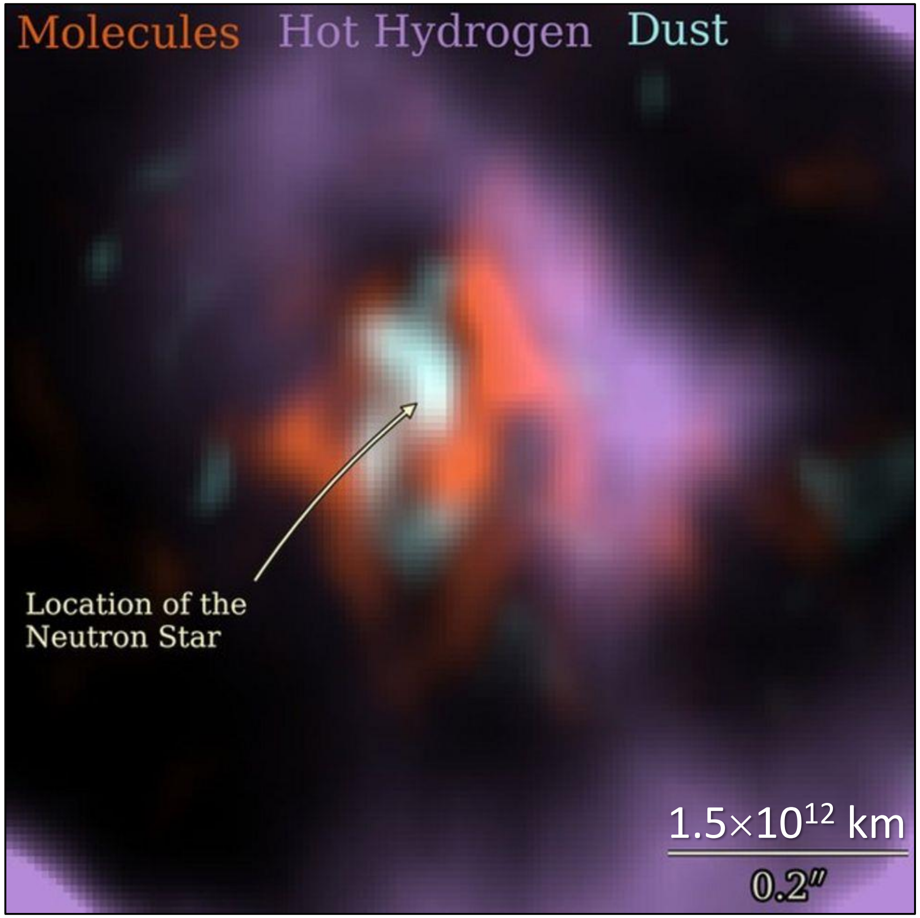
- Raffelt, Lect. Notes Phys. 741 (2008) 51 hep-ph/0611350
  Burst duration calibrated by early numerical studies
  "Generic" emission rates inspired by OPE rates
  $f_a \gtrsim 4 \times 10^8$ GeV and $m_a \lesssim 16$ meV (KSVZ, based on proton coupling)
- Chang, Essig & McDermott, JHEP 1809 (2018) 051 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

New Interest in SN 1987A as Particle Lab

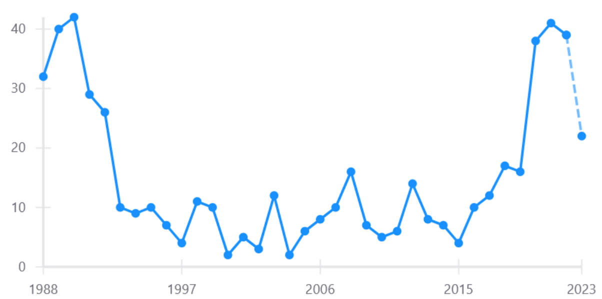
Bounds on Exotic Particle Interactions from SN 1987a

Georg Raffelt (UC, Berkeley, Astron. Dept. and LLNL, Livermore), David Seckel (UC, Santa Cruz)

Sep, 1987

10 pages
Published in: *Phys.Rev.Lett.* 60 (1988) 1793
DOI: 10.1103/PhysRevLett.60.1793
PDG: Invisible A0 (Axion) MASS LIMITS from Astrophysics and Cosmology
Report number: SCIPP-87/107
View in: OSTI Information Bridge Server

Citations per year



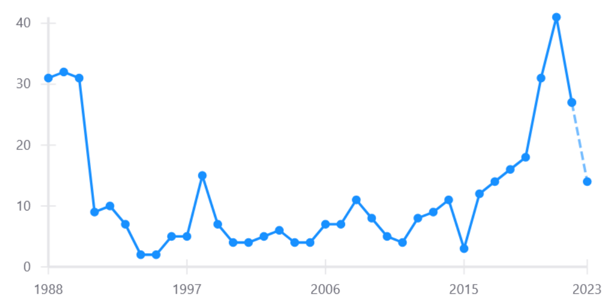
Axions from SN 1987a

Michael S. Turner (Fermilab and Chicago U., EFI and Chicago U., Astron. Astrophys. Ctr.)

Nov, 1987

9 pages
Published in: *Phys.Rev.Lett.* 60 (1988) 1797
DOI: 10.1103/PhysRevLett.60.1797
Report number: FERMILAB-PUB-87-202-A
View in: OSTI Information Bridge Server, ADS Abstract Service, KEK scanned document

Citations per year



Constraints on Axions from SN 1987a

Ron Mayle (LLNL, Livermore), James R. Wilson (LLNL, Livermore), John R. Ellis (CERN), Keith A. Olive (Minnesota U.), David N. Schramm (Chicago U., Astron. Astrophys. Ctr. and Fermilab) Show All(6)

Dec, 1987

9 pages
Published in: *Phys.Lett.B* 203 (1988) 188-196
Published: 1988
DOI: 10.1016/0370-2693(88)91595-X
Report number: FERMILAB-PUB-87-225-A, EFI-87-104-CHICAGO, UMN-TH-637-87, CERN-TH-4887-87
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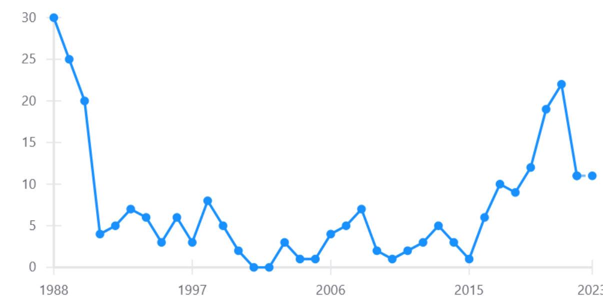
Citations per year



arXiv:2308.01403

Supernova Simulations Confront SN 1987A Neutrinos

Damiano F. G. Fiorillo [1] Malte Heinlein [2,3] Hans-Thomas Janka [2] Georg Raffelt [4] and Edoardo Vitagliano [5]

[1] *Niels Bohr International Academy, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark*
[2] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85748 Garching, Germany*
[3] *Technische Universität München, TUM School of Natural Sciences, Physics Department, James-Franck-Str. 1, 85748 Garching, Germany*
[4] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany*
[5] *Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem 91904, Israel*

(Dated: August 4, 2023)

We return to interpreting the historical SN 1987A neutrino data from a modern perspective. To this end, we construct a suite of spherically symmetric supernova models with the Prometheus-Vertex code, using four different equations of state and five choices of final baryonic neutron-star (NS) mass in the 1.36–1.93 $M_\odot$ range. Our models include muons and proto-neutron star (PNS) convection by a mixing-length approximation. The time-integrated signals of our 1.44 $M_\odot$ models agree reasonably well with the combined data of the four relevant experiments, IMB, Kam-II, BUST, and LSD, but the high-threshold IMB detector alone favors a NS mass of 1.7–1.8 $M_\odot$, whereas Kam-II alone prefers a mass around 1.4 $M_\odot$. The cumulative energy distributions in these two detectors are well matched by models for such NS masses, and the previous tension between predicted mean neutrino energies and the combined measurements is gone, with and without flavor swap. Generally, our predicted signals do not strongly depend on assumptions about flavor mixing, because the PNS flux spectra depend only weakly on antineutrino flavor. While our models show compatibility with the events detected during the first seconds, PNS convection and nucleon correlations in the neutrino opacities lead to short PNS cooling times of 5–9 s, in conflict with the late event bunches in Kam-II and BUST after 8–9 s, which are also difficult to explain by background. Speculative interpretations include the onset of fallback of transiently ejected material onto the NS, a late phase transition in the nuclear medium, e.g. from hadronic to quark matter, or other effects that add to the standard PNS cooling emission and either stretch the signal or provide a late source of energy. More research, including systematic 3D simulations, is needed to assess these open issues.

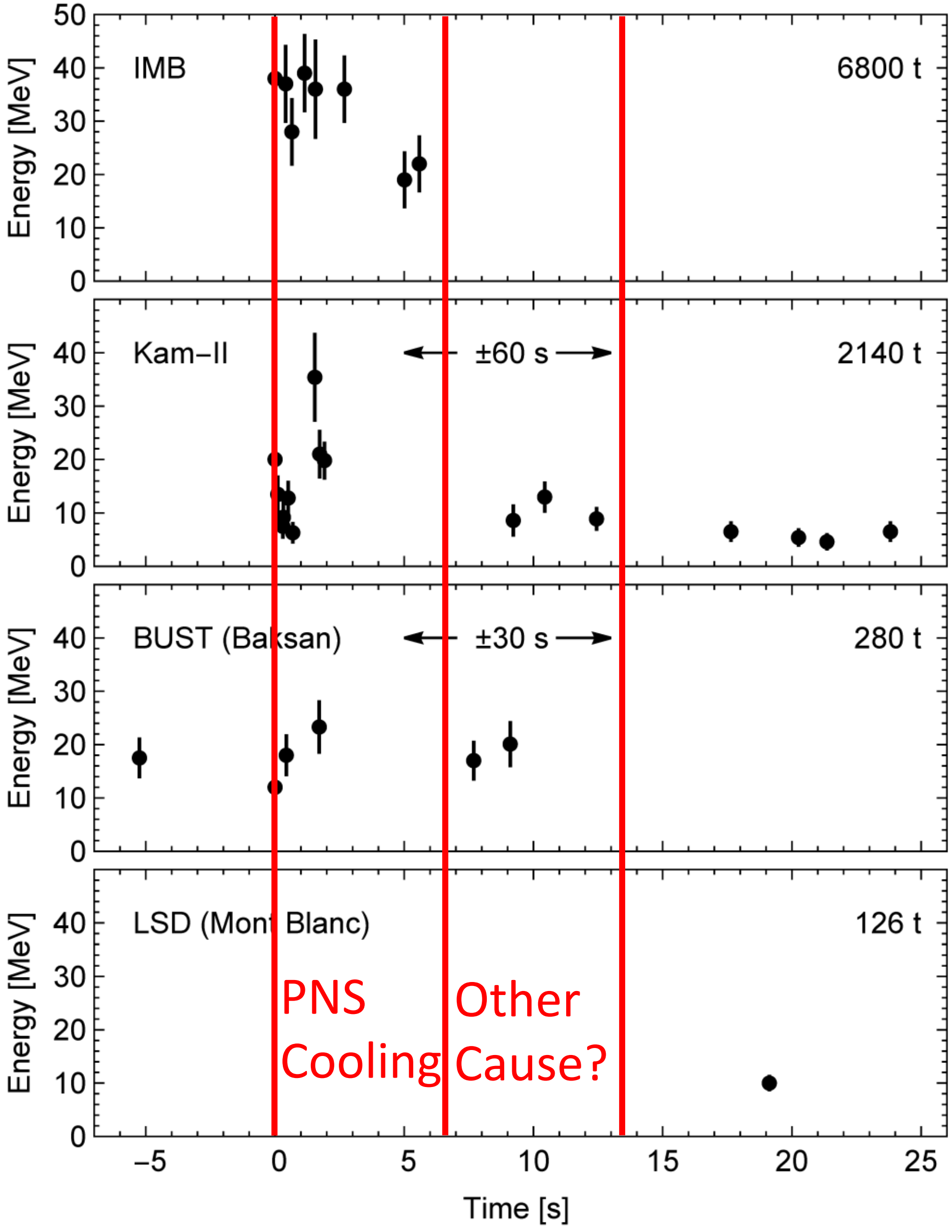
CONTENTS

I. INTRODUCTION

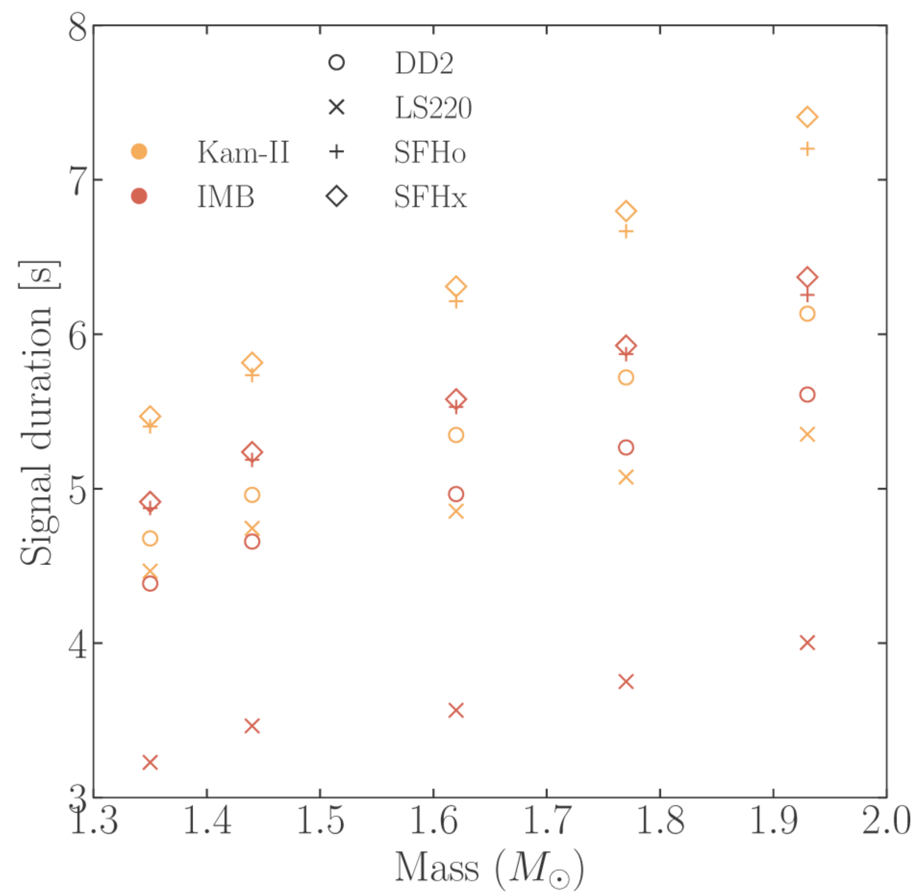
After almost four decades, the historical SN 1987A of 23$^{\rm rd}$ February 1987 remains the only case of a measured neutrino signal from stellar core collapse. Today, many large-scale detectors are running or in preparation so that the neutrino signal from the next nearby supernova (SN) will provide a bonanza of high-statistics information on the dynamics of core collapse (CC) and SN explosion, on neutrinos and their flavor-dependent interaction and propagation, the nuclear equation of state, and hypothetical feebly interacting particles. Also multi-messenger information including gravitational waves will yield new insights. Standard and nonstandard astrophysical and particle-physics ideas will be put to the test [1–27].

Until that time, however, the SN 1987A legacy data remain the only direct test of such questions. Broadly, the data agree with expectations, but at that time, theoretical understanding and numerical SN modeling were in their infancy, and after almost four decades of progress, this question deserves a fresh look, a sentiment also shared by other recent authors [28–30]. How well do modern SN models agree with the old data and are there open issues? One motivation to return to this subject is the role of SN 1987A as a particle-physics laboratory, a topic that has gained a fresh boost of activity over the past few years [14, 18, 31–44]. However, here we do not delve into question of new physics, but simply ask about the match between new models with old data.

Signal Duration of Suite of Garching Models

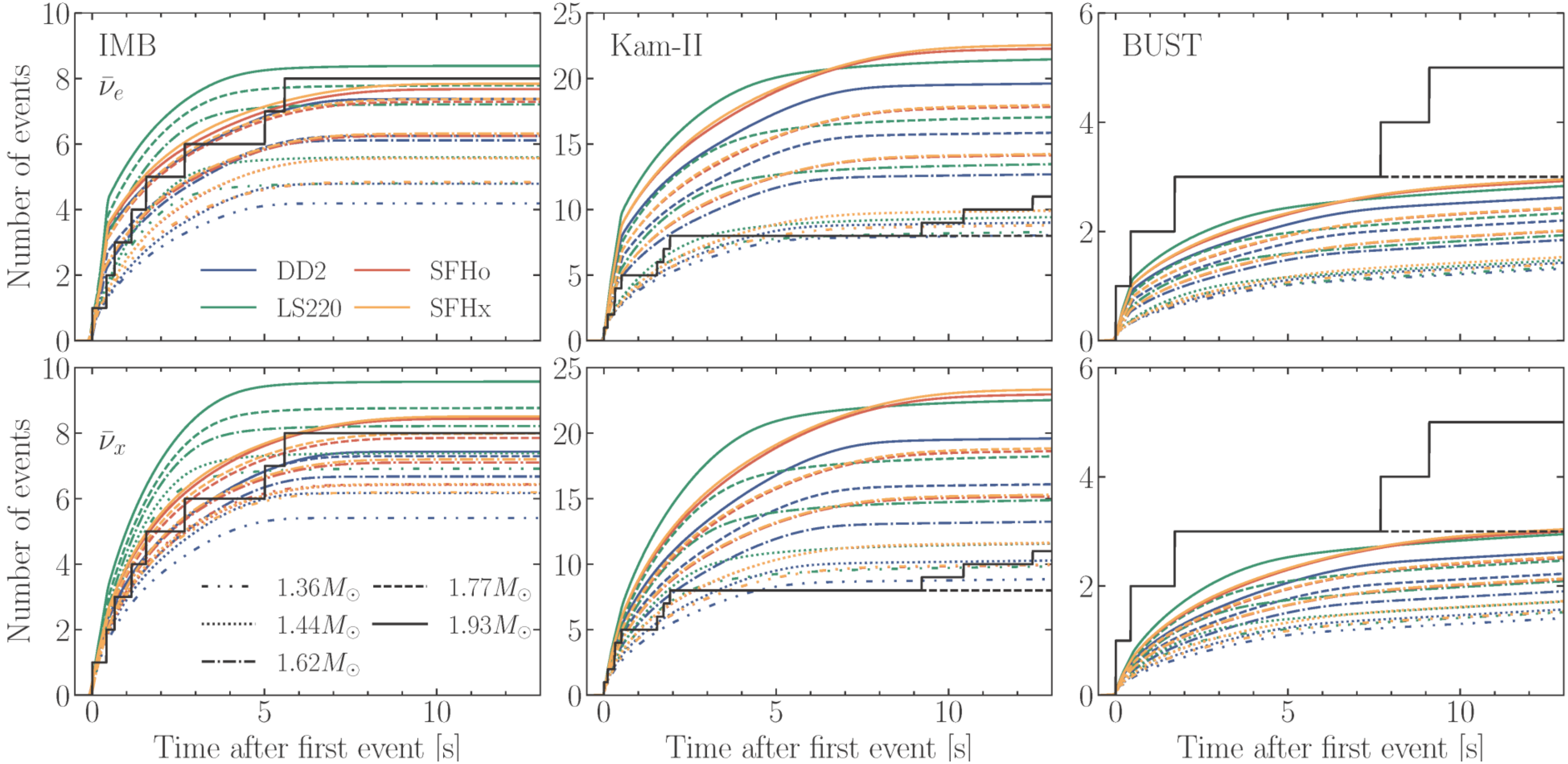


Signal duration (95% expected events) for 20 Garching models



Fiorillo+ arXiv:2308.01403

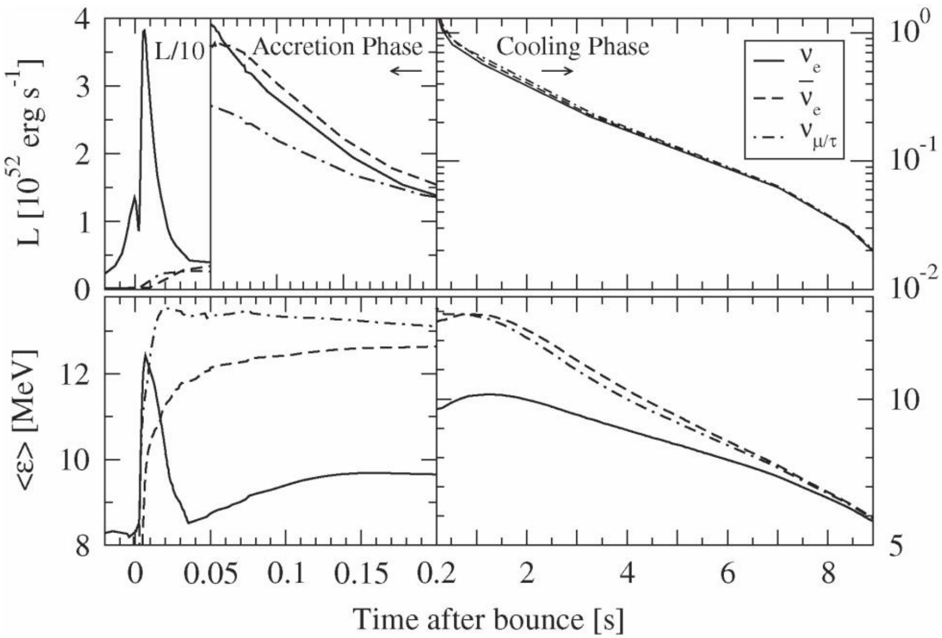
Cumulative Event Distributions



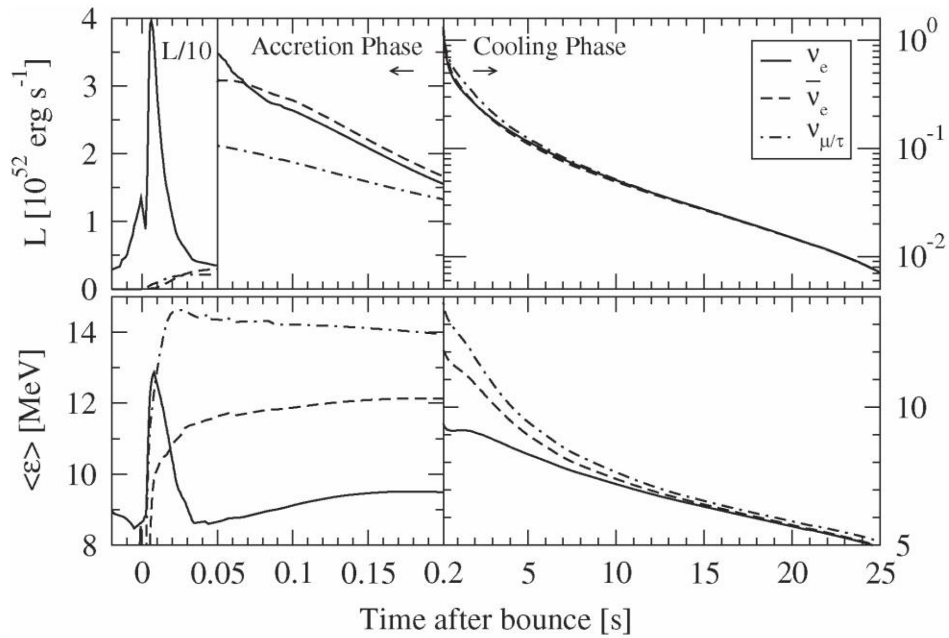
Fiorillo, Heinlein, Janka, Raffelt, Vitagliano & Bollig, arXiv:2308.01403

Long-Term Cooling of EC SN (Garching 2009)

Neutrino opacities with strong NN correlations and nucleon recoil in neutrino-nucleon scattering.



Neutrino opacities without these effects
Much longer cooling times



L. Hüdepohl et al. (Garching Group), arXiv:0912.0260

Proto-Neutron Star Convection

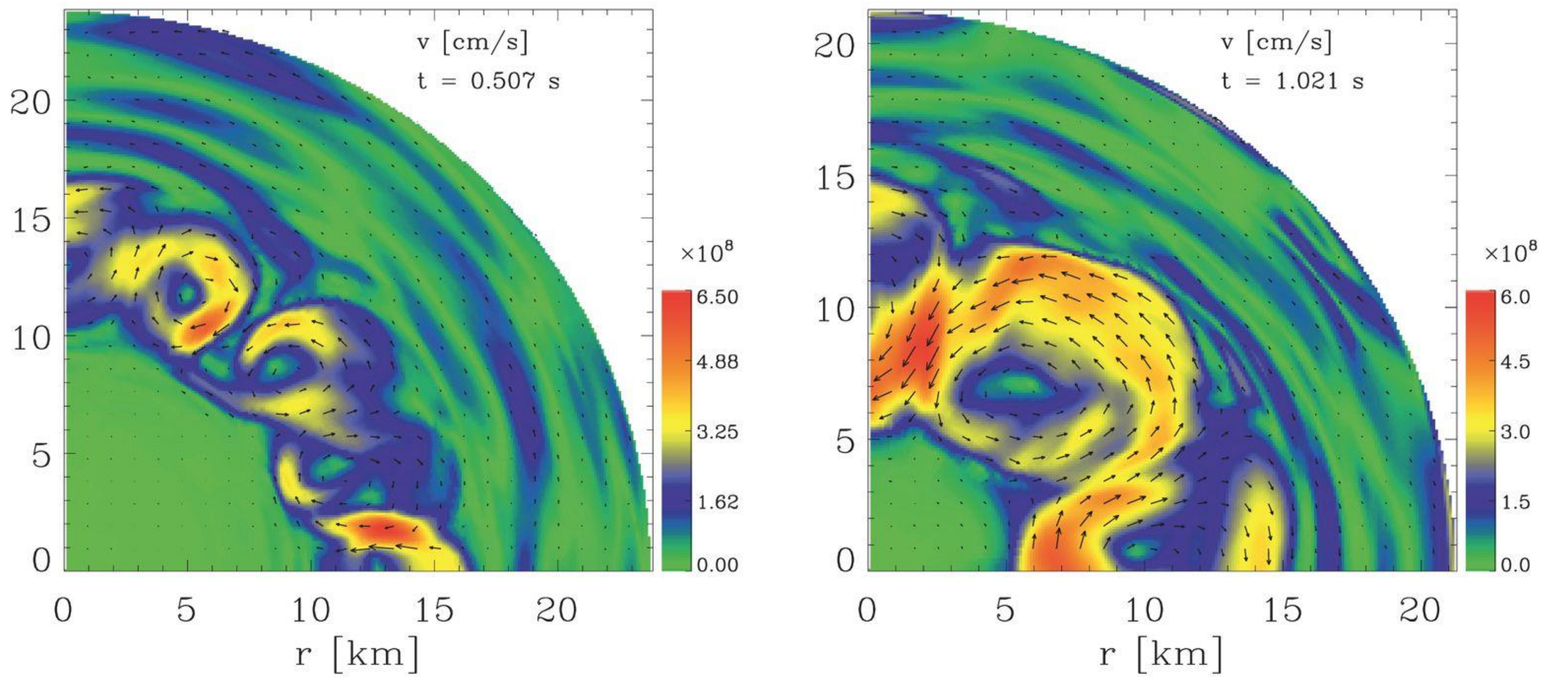


Fig. 11. Absolute values of the convective velocity in the proto-neutron star for two instants (about 0.5 s (left) and 1 s (right) after core bounce) as obtained in a two-dimensional, hydrodynamical simulation. The arrows indicate the direction of the velocity field. Note that the neutron star has contracted from a radius of about 60 km initially to little more than 20 km. The growth of the convective region can be seen. Typical velocities of the convective motions are several 10^8 cm/s.

H.-Th. Janka, K. Kifonidis, M. Rampp, arXiv:astro-ph/0103015

PRL 108, 061103 (2012) PHYSICAL REVIEW LETTERS week ending 10 FEBRUARY 2012

Protoneutron Star Cooling with Convection: The Effect of the Symmetry Energy

L. F. Roberts,[1] G. Shen,[2] V. Cirigliano,[2] J. A. Pons,[3] S. Reddy,[2,4] and S. E. Woosley[1]

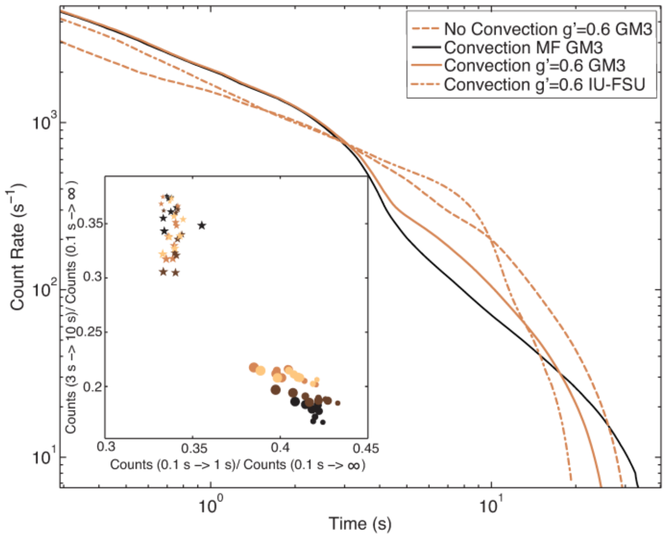
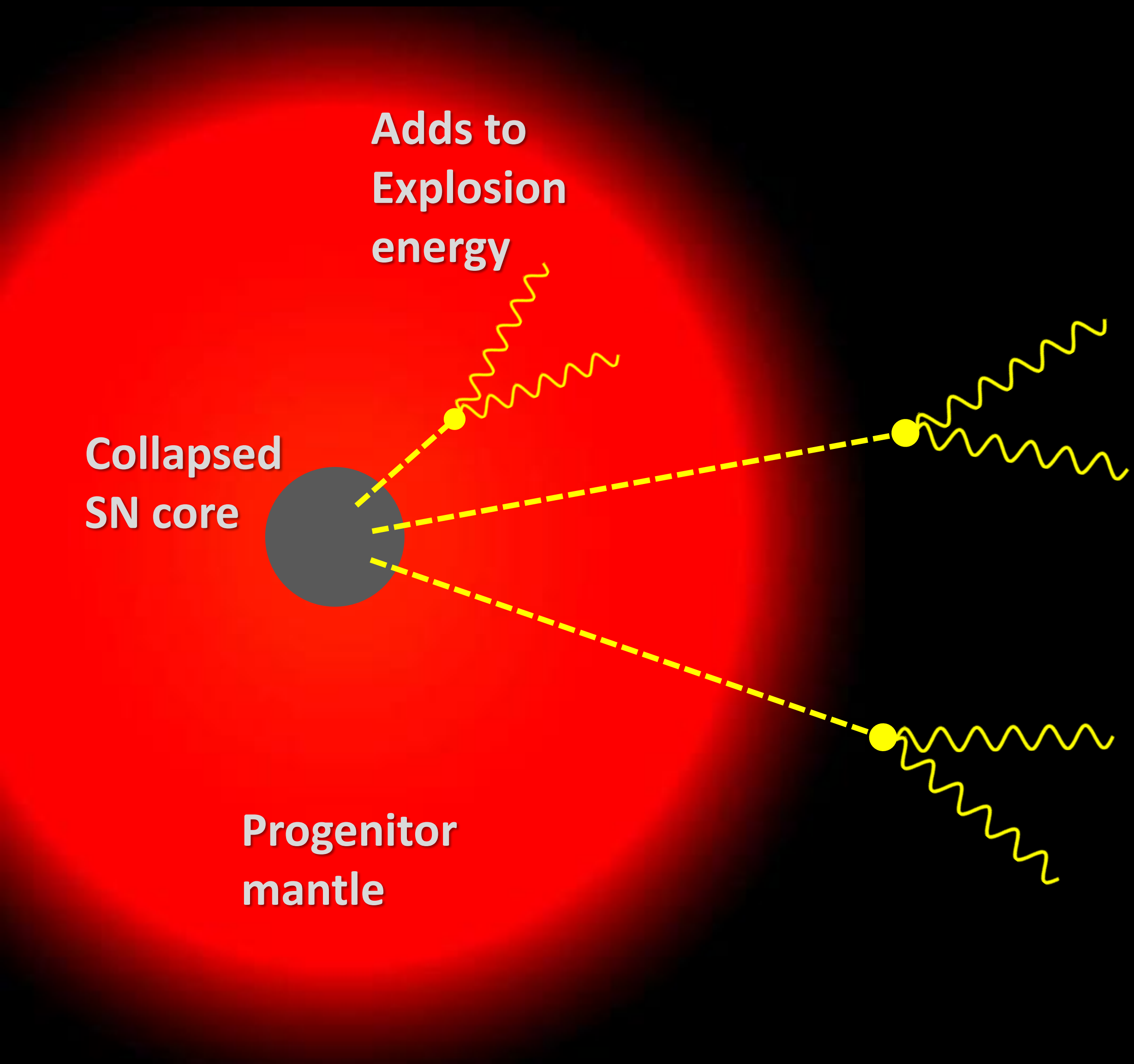
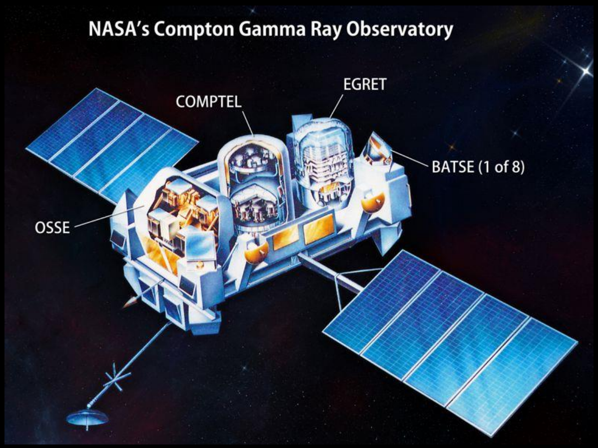


FIG. 3: Count rates as a function of time for a number of $1.6M_\odot$ PNS models with and without convection. The black line is for neutrino opacities calculated in the mean field approximation, while all the other lines are for models that use RPA opacities with $g' = 0.6$. The inset plot shows the integrated number of counts from 0.1 s to 1 s divided by the total number of counts for $t > 0.1$ second on the horizontal axis, and the number of counts for $t > 3$ seconds on divided by the total number of counts for $t > 0.1$ second. The stars correspond to the IU-FSU EoS and the circles to the GM3 EoS. Symbol sizes correspond to various neutron star rest masses ranging from $1.2M_\odot$ to $2.1M_\odot$. Colors correspond to different values of the Migdal parameter, g'.

Count rate in a detector like Kamiokande, 50 kt

Supernova Bounds on Radiative Particle Decays





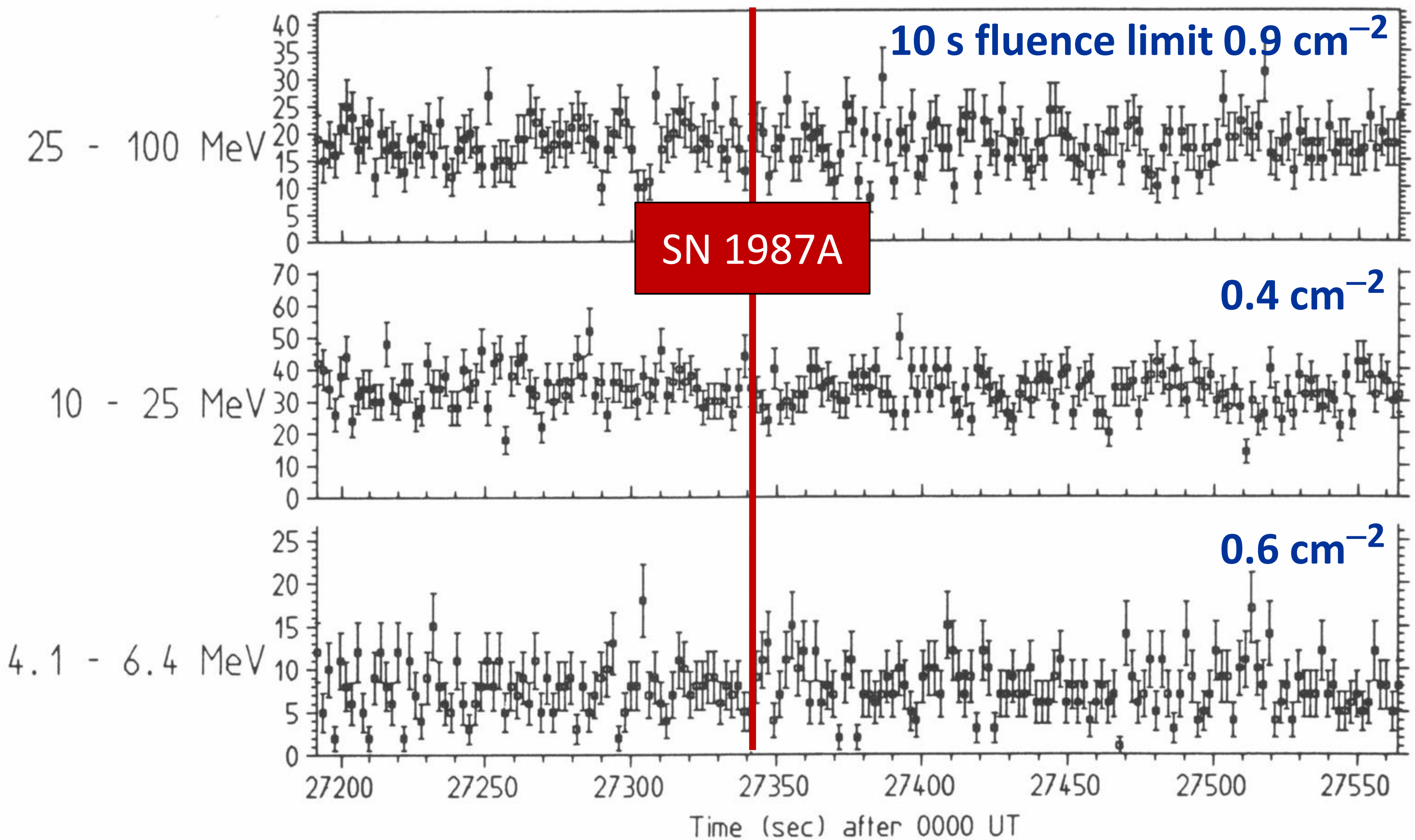
Cosmic gamma ray background from all past supernovae

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 $\sim 10^{10} \mathrm{cm}^{-2}$

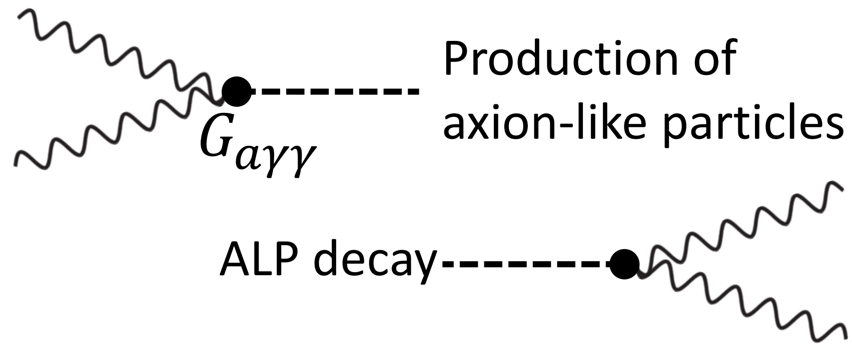
$< 10^{-10}$ of neutrinos have decayed to photons on their way to Earth

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)

Brand New

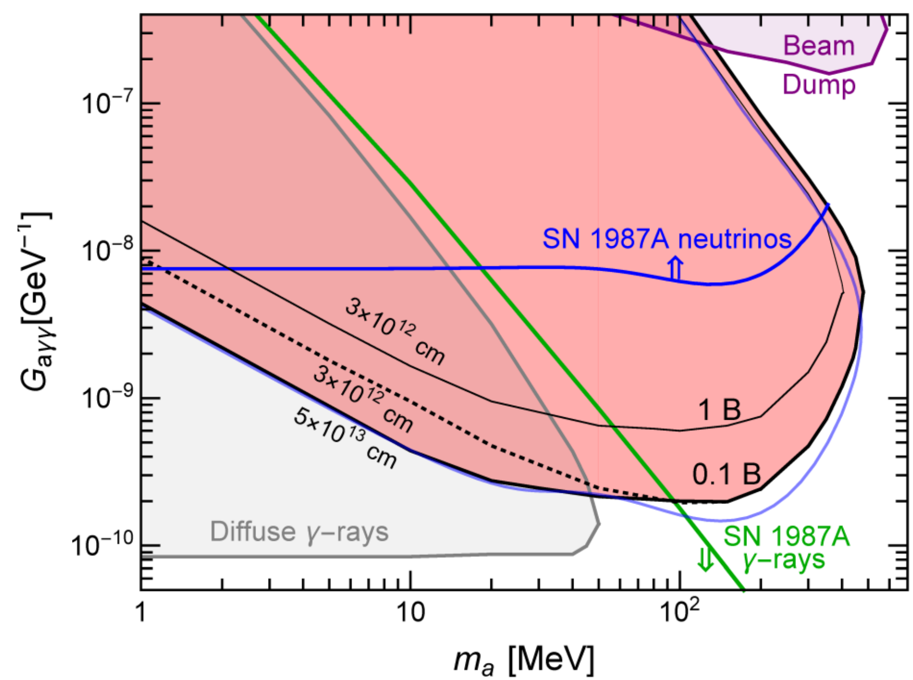


Typical SN explosion energy 1–2 B

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!

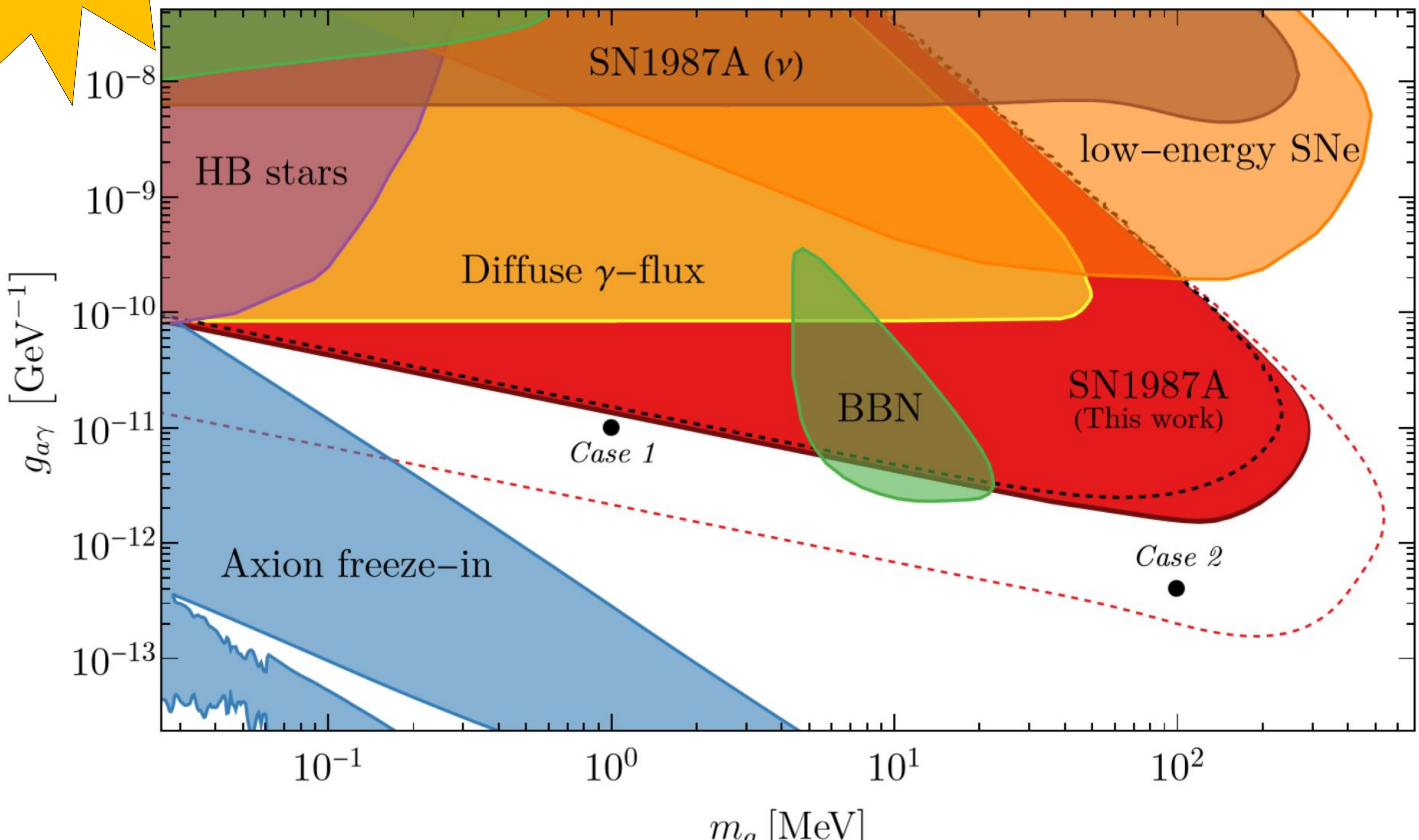
1 B (bethe) = 10^{51} erg
Neutron-star binding energy 200–400 B
(0.11–0.22 M_{SUN})



Brand New

Investigating the gamma-ray burst from decaying MeV-scale axion-like particles produced in supernova explosions [2304.01060](2304.01060)

E.Müller, F.Calore, P.Carenza, C.Eckner & M.C.D.Marsh

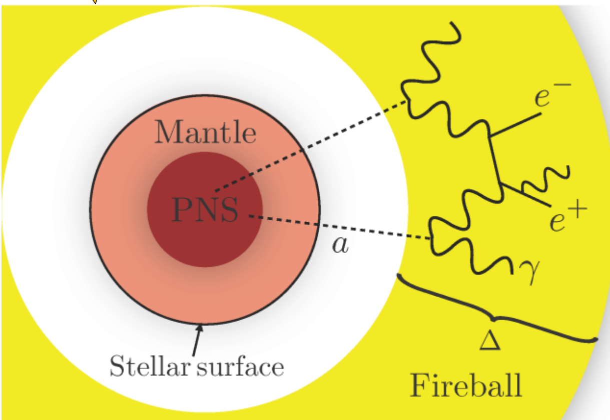


Brand New

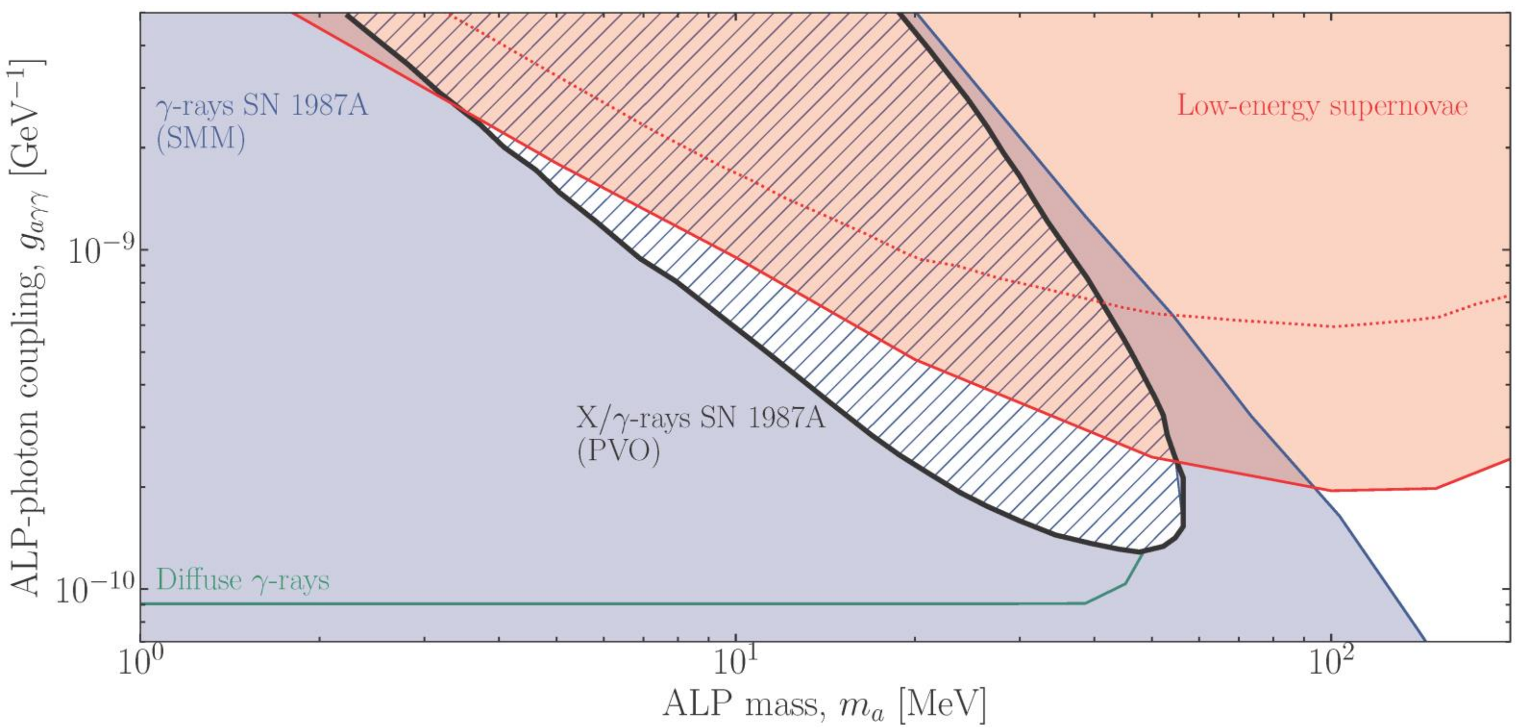
Axion-sourced fireballs from supernovae

[2303.11395](2303.11395)

Diamond [1] Damiano F. G. Fiorillo [2] Gustavo Marques-Tavares [3] and Edoardo Vitagliano [4]



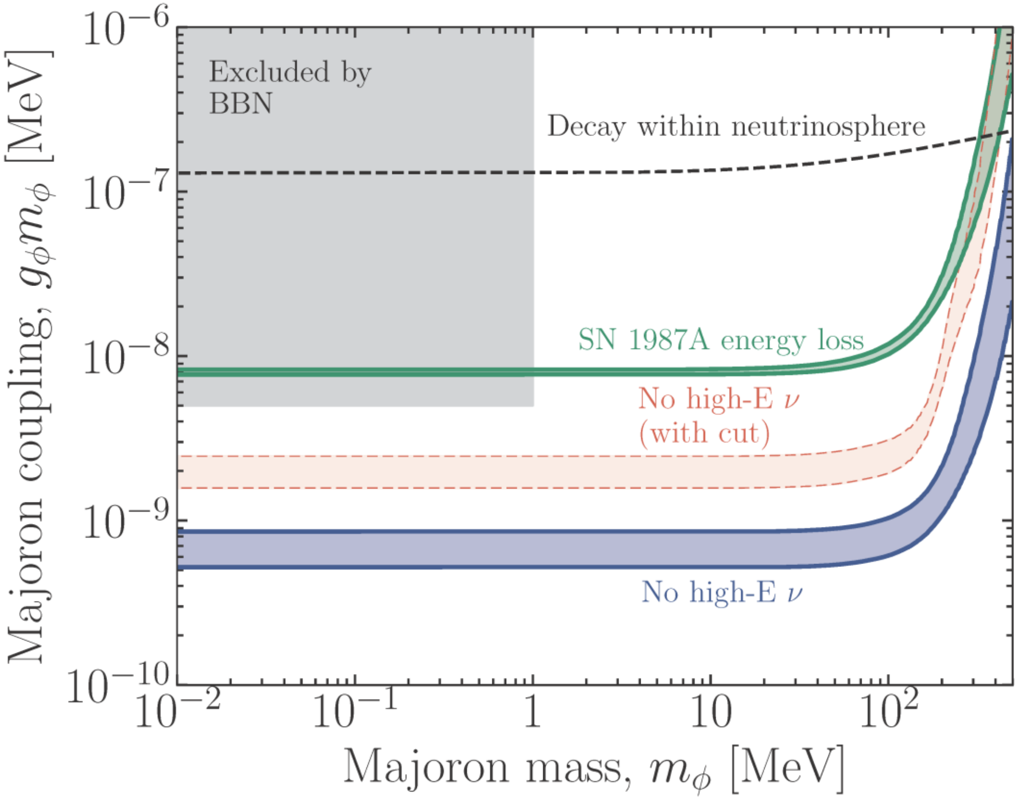
- Massive ALPs form a fireball outside progenitor star
- Downgrades photons, conserves total energy
- sub-MeV photons would have been seen by Pioneer Venus Orbiter (PVO) from SN 1987A
- Exclusion window remains



Strong Supernova 1987A Constraints on Bosons Decaying to Neutrinos

Fiorillo, Raffelt & Vitagliano, arXiv.2209.11773

- BSM particles escaping from inner SN core
- Decay to active neutrinos, 100 MeV range
- No such events in the detectors



- Majoron-like particles ϕ

$$\mathcal{L}_{\rm int} = g\phi\, \psi_\nu^T \sigma_2 \psi_\nu$$

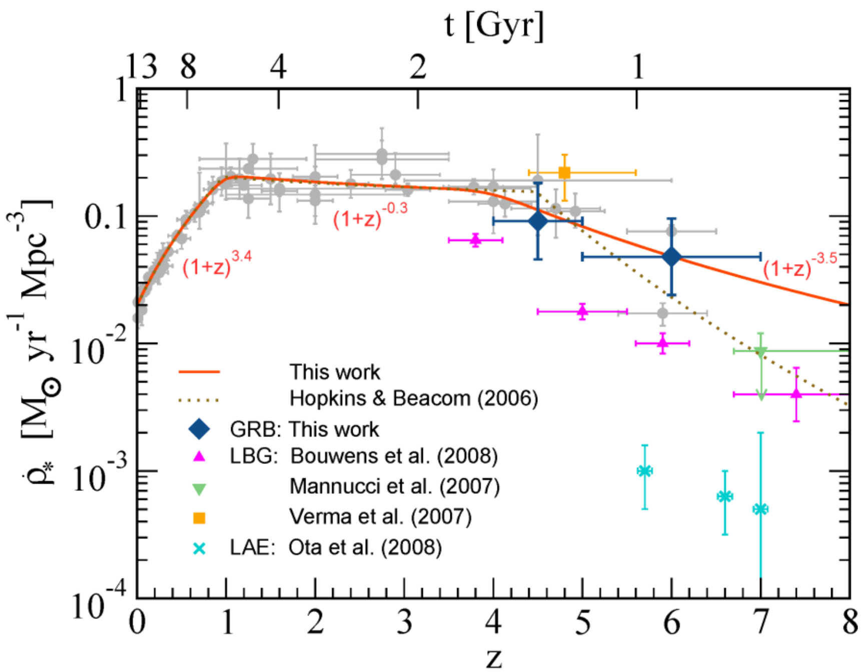
- Production by coalescence

$$\nu_e + \nu_e \to \phi$$

- Decay outside SN to all flavors

$$\phi \to \nu\nu \text{ or } \overline{\nu}\,\overline{\nu}$$

Star-formation rate (1)



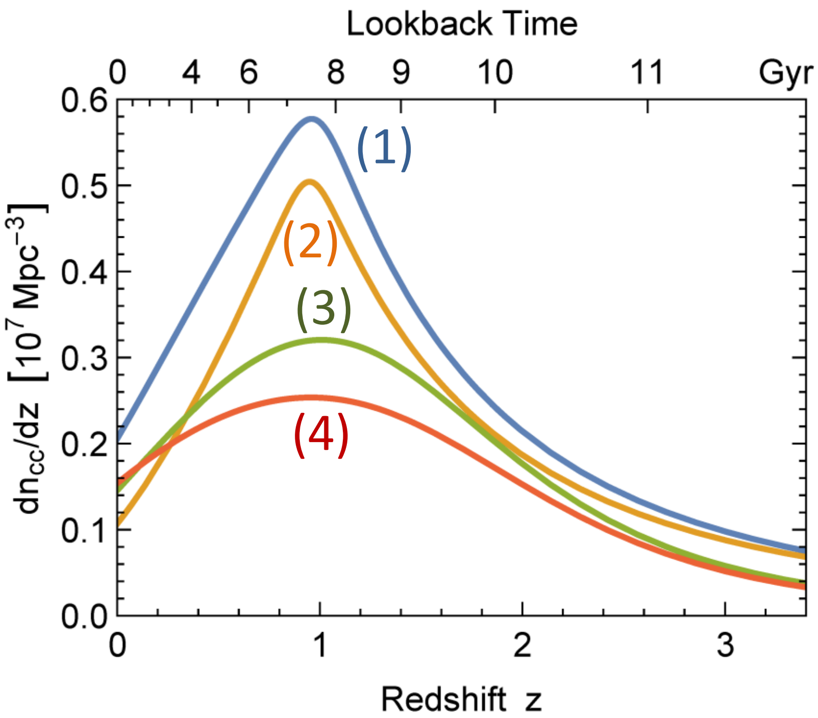
(1) Yüksel+ arXiv:0804.4008

(2) Mathews+ arXiv:1405.0458

(3) Robertson+ arXiv:1502.02024

(4) Madau+ arXiv:1403.0007

Core-collapse distribution



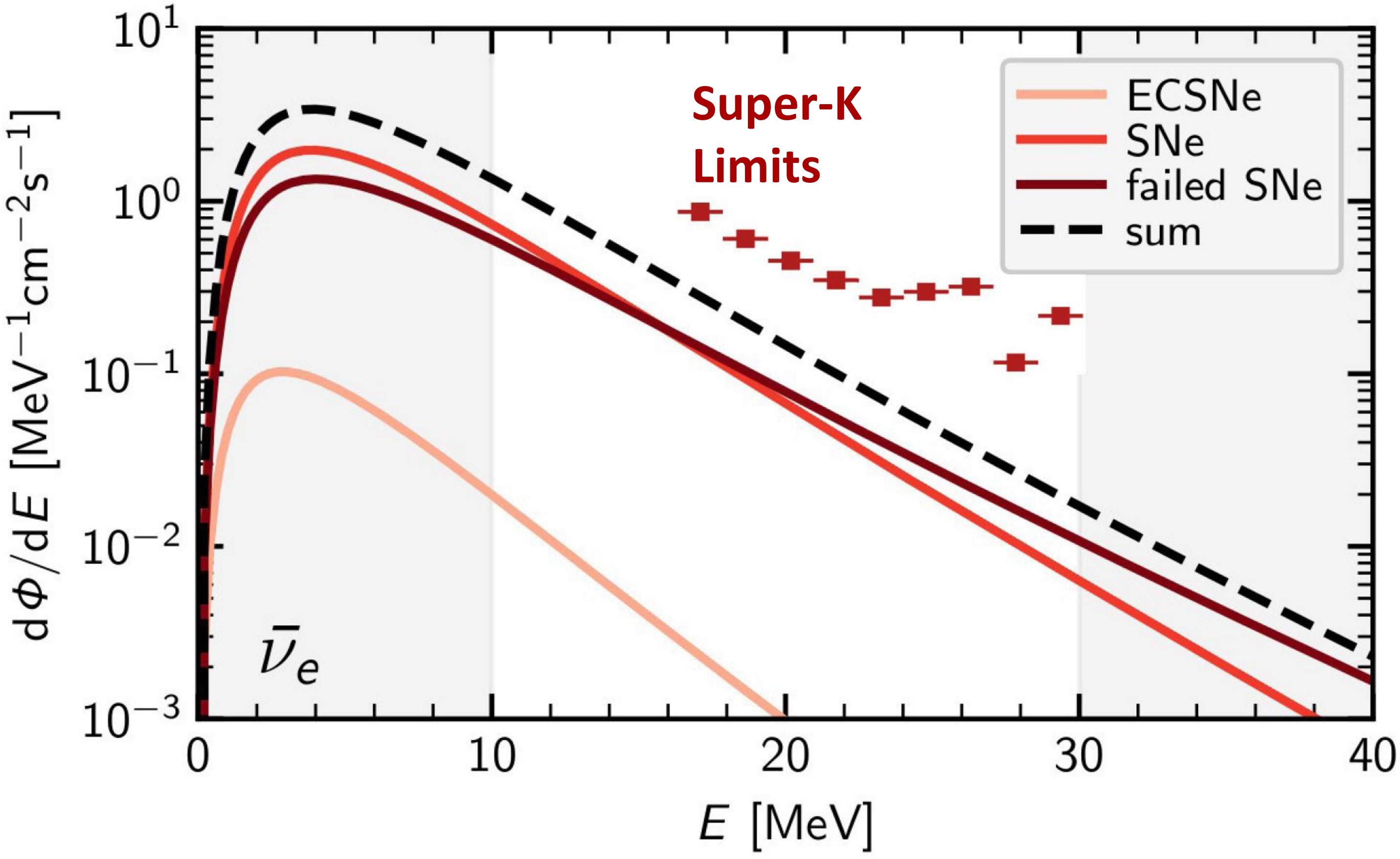
Total core collapse density

$0.6 - 1 \times 10^7\ \mathrm{Mpc}^{-3}$

DSNB Prediction

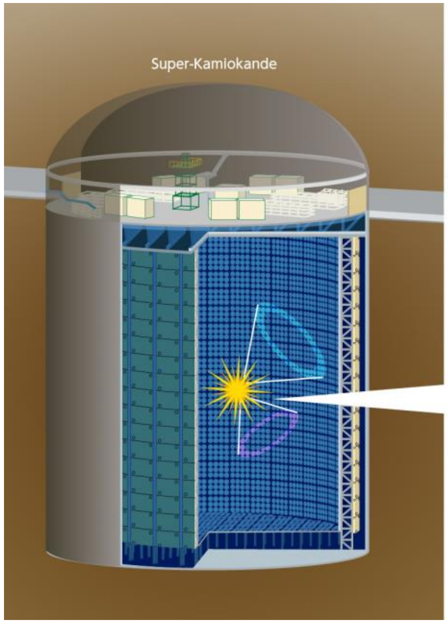
Kresse+, arXiv:2010.04728

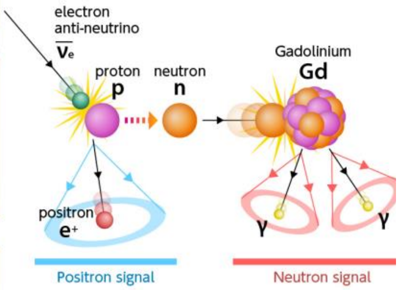
For latest Super-K limits see arXiv:2109.11174



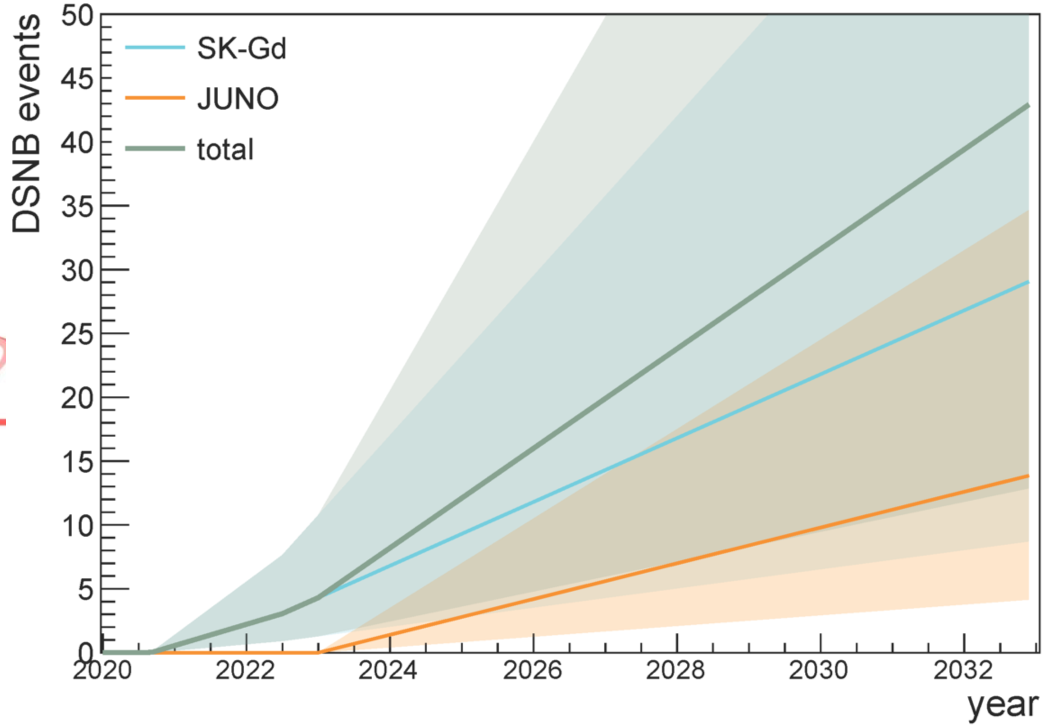
In the detection window, essentially $\frac{d\Phi}{dE} \propto e^{-E/E_0}$

Search for the Diffuse SN Neutrino Background





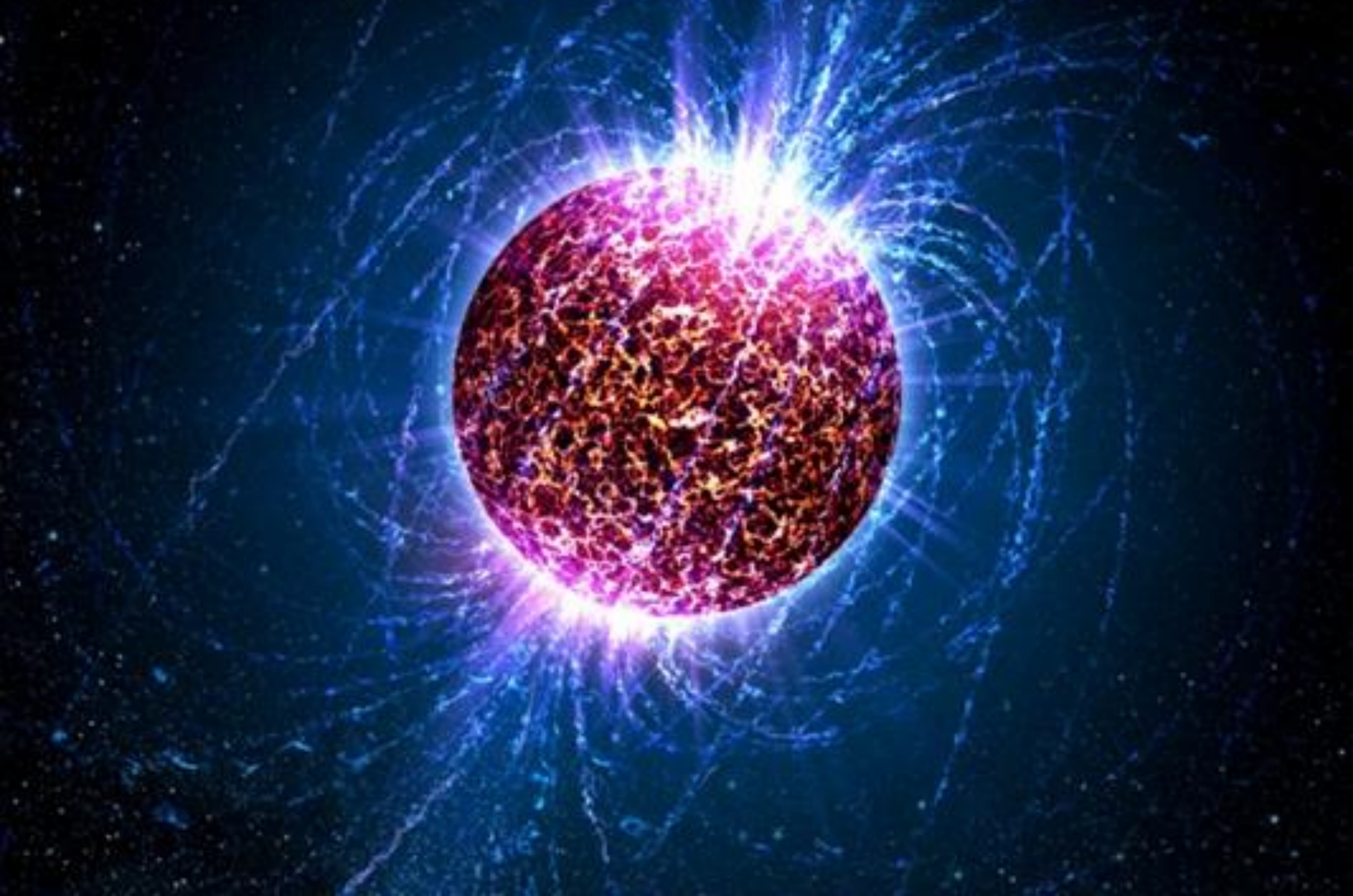
Water Cherenkov
22.5 kt fiducial
Sk-Gd since 2020

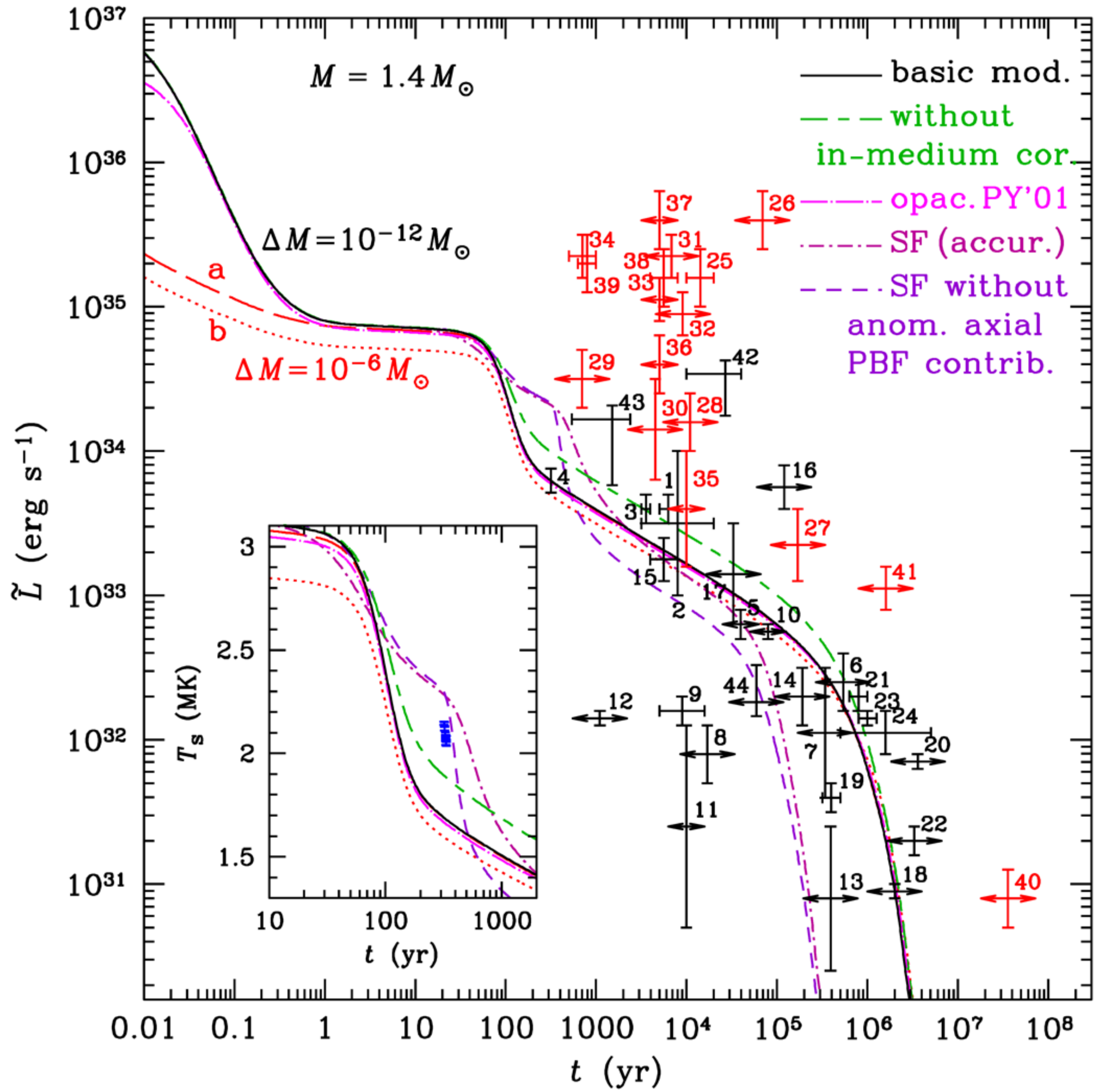


Li, Vagins & Wurm:
Prospects for the detection of the DSNB with the experiments SK-Gd and JUNO
arXiv:2201.12920

JUNO
Liquid Scintillator
17 kt fiducial
Commissioning 2024

Neutron Star Cooling





Potekhin & Chabrier: Magnetic neutron star cooling and microphysics [1711.07662]

Axion Limits from Neutron Star Cooling

Selection of pulsars at different age:

- Umeda, Iwamoto, Tsuruta, Qin & Nomoto, astro-ph/9806337
- A. Sedrakian, arXiv:1512.07828 (hadronic axions)
- A. Sedrakian, arXiv:1810.00190 (non-hadronic axions)

Supernova Remnant Cas A (320 years)

- Leinson, arXiv:1405.6873, 2105.14745
- Hamaguchi, Nagata, Yanagi & Zheng, arXiv:1806.07151

Supernova Remnant HESS J1731-347 (27 kyears)

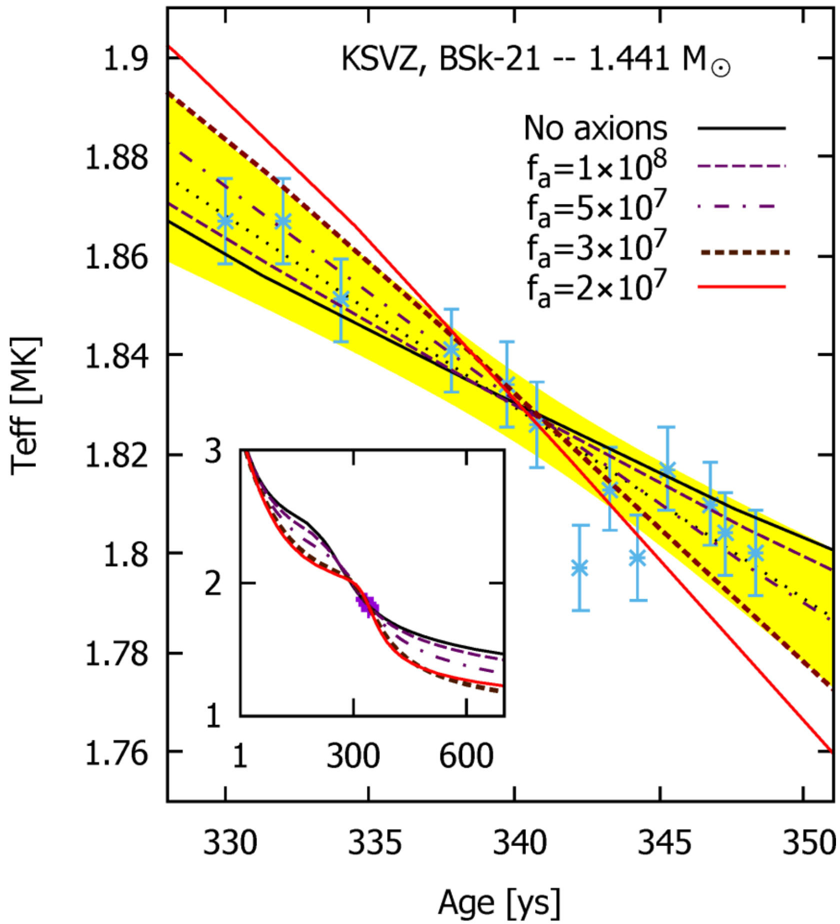
- Beznogov, Rrapaj, Page & Reddy, arXiv:1806.07991
  $g_{an}^2 < 0.77 \times 10^{-19}$
- Leinson, arXiv:1909.03941
  $g_{an}^2 < 1.1 \times 10^{-19}$

$$C_n m_a \lesssim 2\ \mathrm{meV}$$

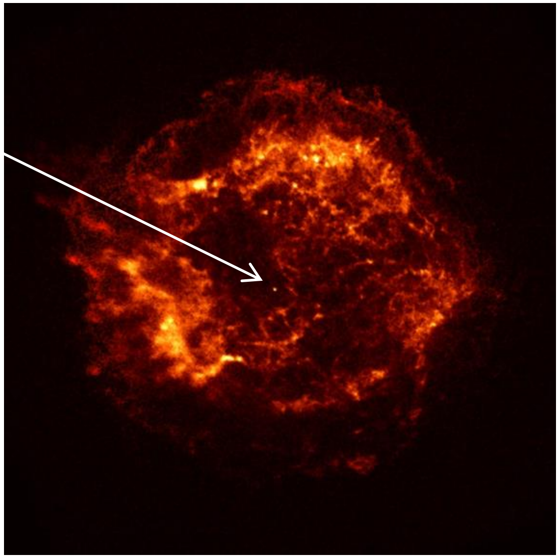
Limits broadly comparable to SN 1987A bounds (m_a tens of meV range)

- Protons can be superconducting – bremsstrahlung from neutrons
- Neutron-axion coupling can be very small or vanish

Cooling of Neutron Star in Cas A



Chandrax-ray image of non-pulsar compact remnant



Limiting value
$C_n m_a \sim 4\ \mathrm{meV}$

Measured surface temperature over 20 years reveals unusually fast cooling rate

- Neutron Cooper pair breaking and formation (PBF) as neutrino emission process?
- Evidence for extra cooling (by axions)?

Leinson, 2105.14745

Cooling Simulations of Five Neutron Stars

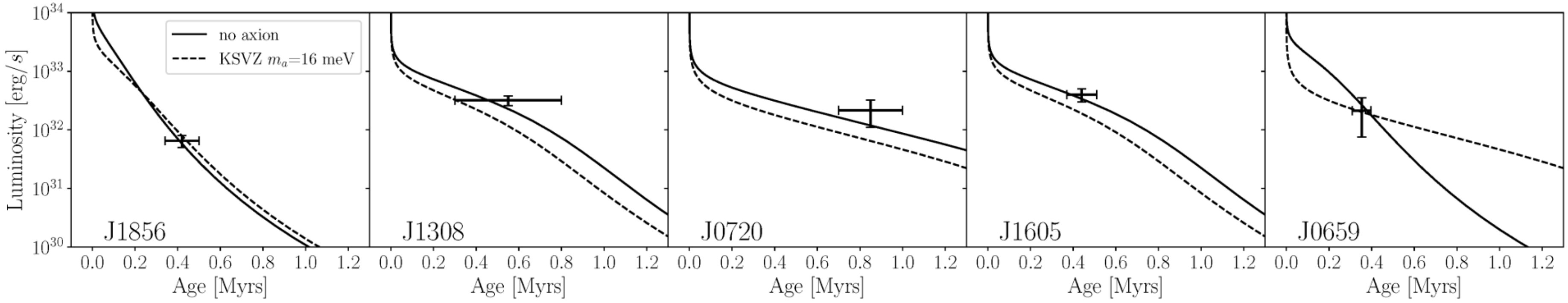
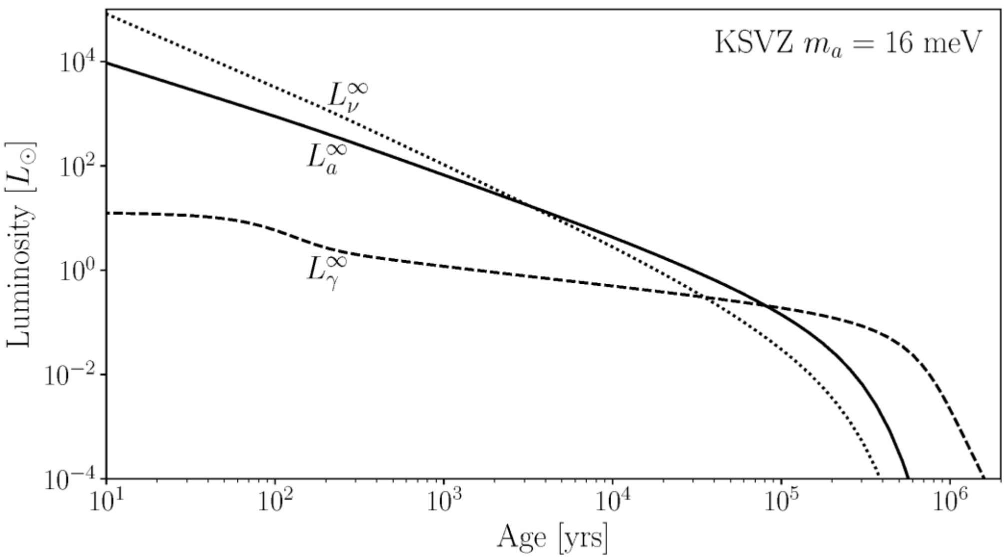


Figure 1. The luminosity and age data for each of the NSs considered in this work (see Tab. I). We show the best-fit cooling curves computed in this work for each of these NSs under the null hypothesis and with the axion mass fixed to $m_a = 16$ meV, which is our 95% upper limit on the QCD axion mass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

Neutron-Star Cooling Bounds

DFSZ Axions

$$\mathcal{L}_{af} = C_f \, \overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_f \frac{\partial_\mu a}{2 f_a}$$

$$C_n = -0.160 \pm 0.025 + 0.414 \cos^2\beta$$

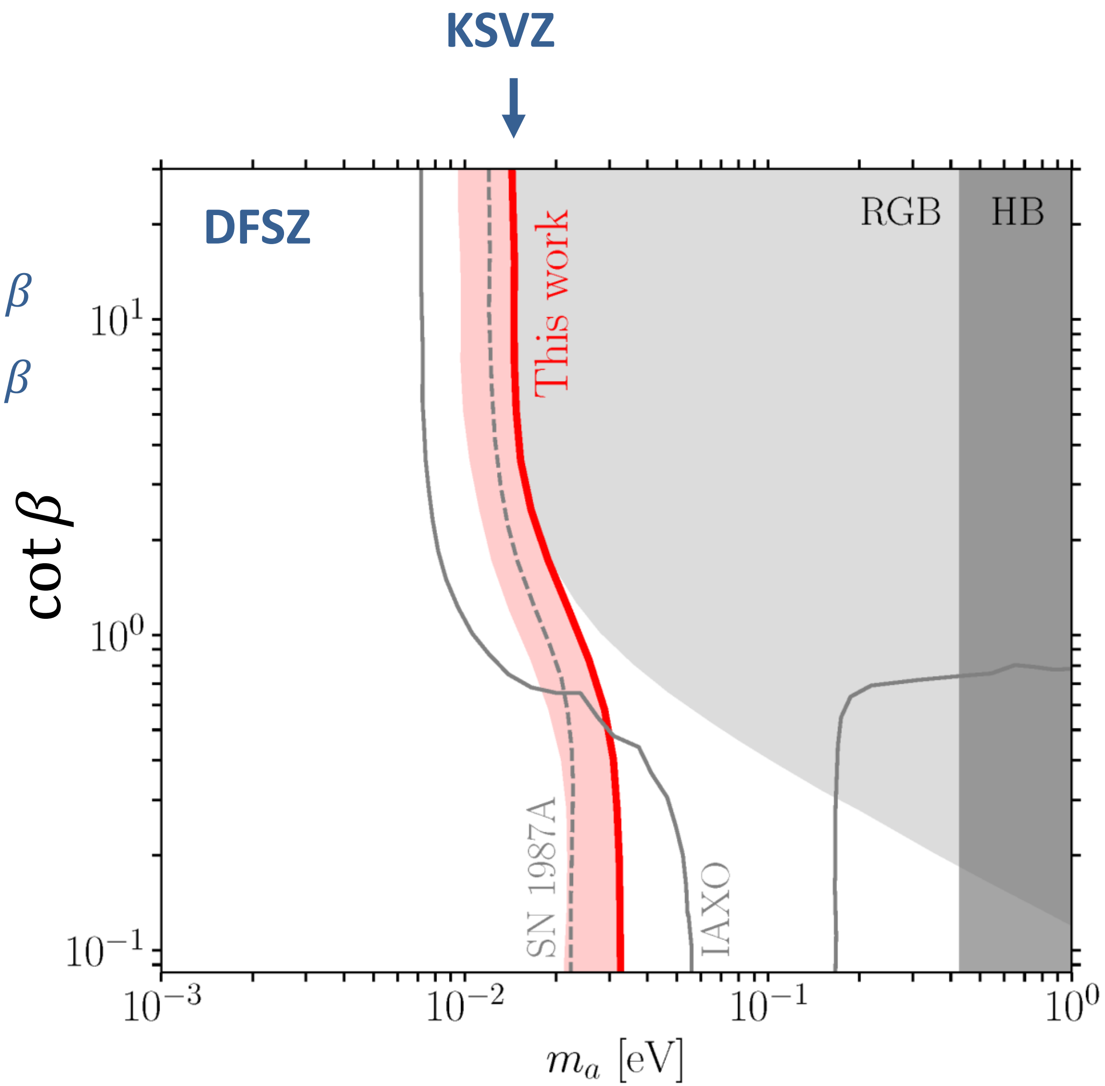
$$C_p = -0.182 \pm 0.025 - 0.435 \cos^2\beta$$

$$C_e = \tfrac{1}{3} \cos^2\beta$$

Notice that in this paper a different convention is used where

$\tan\beta \to \cot\beta$

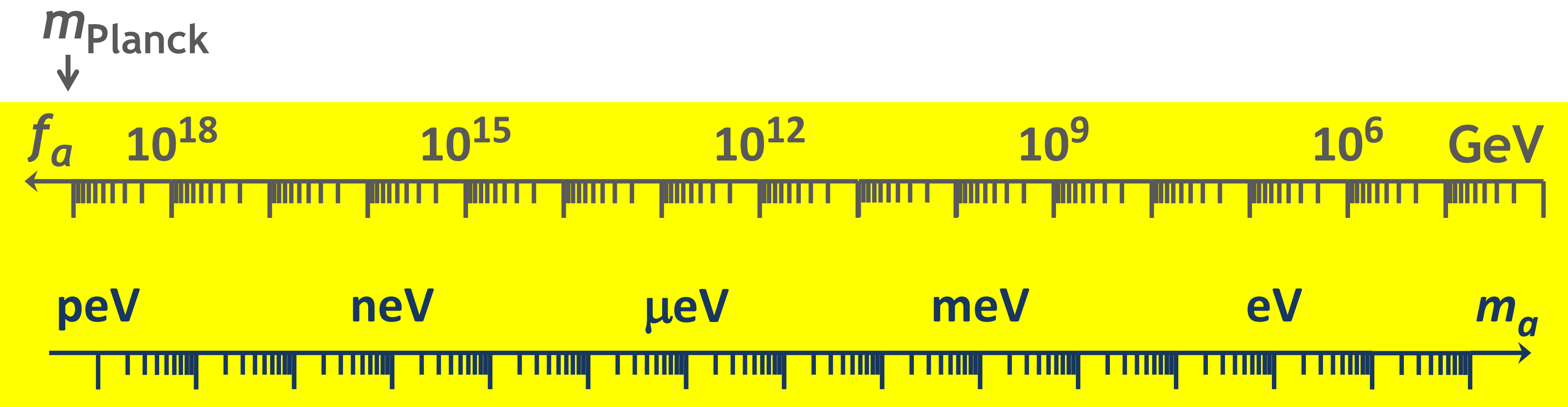
as advocated by the PDG



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

Buschmann, Dessert, Foster, Long & Safdi, 2111.09892

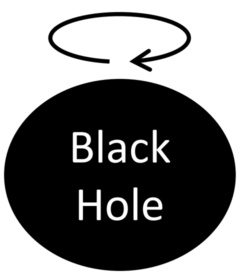
Astrophysical Axion Bounds and Opportunities

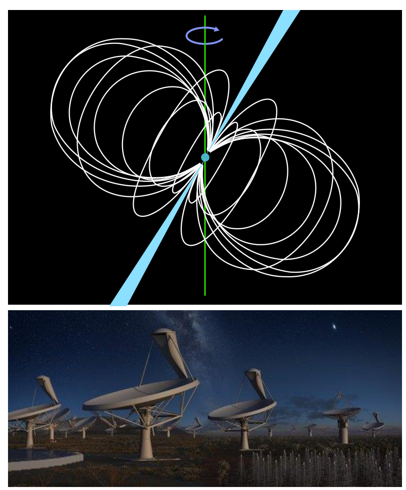


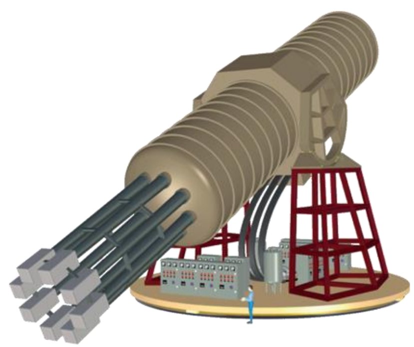
Super Radiance

Opportunities for detection

Astrophysical Bounds (Energy loss of stars)







IAXO Solar Axion Telescope

Axion conversion in neutron star magnetospheres

Particles from Stars: What to expect?

- 😀 New Ideas ...
- 😀 Extension & refinements of existing arguments
(ordinary stars, Red Giants, (variable) white dwarfs, neutron star cooling, ...)
- 😀 Search for solar axions: (baby) IAXO, XENON n tonne, ...
- 😀 Search for magnetically converted ALPs
from magnetic white dwarfs & neutron stars (x-ray satellites)
- 😀 Radio search for axion dark matter conversion in neutron star magnetospheres
(new detetectors SKA, ...)
- 😀 Next galactic supernova observation **(3% chance every year!)**
- 😀 Theoretical developments in collective neutrino flavor evolution
- 😀 Diffuse Supernova Neutrino Background observation
- 😀 Gravitational-wave evidence for superradiance from black holes

Some Literature

Axion Reviews: Theory & Cosmology

- **Axion Dark Matter (Snowmass 2021 White Paper), 2203.14923**
  C.B. Adams, et al.
- **Axion dark matter: What is it and why now? 2105.01406**
  F. Chadha-Day, J. Ellis & D.J.E. Marsh
- **Recent Progress in the Physics of Axions and Axion-Like Particles, 2012.05029**
  K. Choi, S.H. Im & C.S. Shin
- **The Landscape of QCD Axion Models, 2003.01100**
  L. Di Luzio, M. Giannotti, E. Nardi & L. Visinelli
- **Small-Scale Structure of Fuzzy and Axion-Like Dark Matter, 1912.07064**
  J.C. Niemeyer
- **Axion Cosmology, 1510.07633**
  D.J.E. Marsh
- **Axions: Theory and Cosmological Role, 1301.1123**
  M. Kawasaki & K. Nakayama
- **Axions and the Strong CP Problem, 0807.3125**
  J.E. Kim & G. Carosi

Axion Reviews: Experiments & Searches

- **The Search for Ultralight Bosonic Dark Matter,** doi:10.1007/978-3-030-95852-7
  D.F. Jackson Kimball & K. van Bibber (eds.), (Springer, 2023, open access)

- **Invisible Axion Search Methods,** 2003.02206
  P. Sikivie

- **New Experimental Approaches in the Search for Axion-Like Particles,** 1801.08127
  I.G. Irastorza & J. Redondo

- **Experimental Searches for the Axion and Axion-Like Particles,** 1602.00039
  P.W. Graham, I.G. Irastorza, S.K. Lamoreaux, A. Lindner & K.A. van Bibber

- **Searches for astrophysical and cosmological axions,**
  doi:10.1146/annurev.nucl.56.080805.140513
  S.J. Asztalos, L.J. Rosenberg, K. van Bibber, P. Sikivie & K. Zioutas (2006)

- **Microwave cavity searches for dark-matter axions,** doi:10.1103/RevModPhys.75.777
  R. Bradley, J. Clarke, D. Kinion, L.J. Rosenberg, K. van Bibber, S. Matsuki,
  M. Mück & P. Sikivie (2003)

- **Searches for invisible axions,** doi:10.1016/S0370-1573(99)00045-9
  L.J. Rosenberg & K.A. van Bibber (2000)

Axion Reviews: Astrophysical Methods

Stellar Evolution

- **White Dwarfs as Physics Laboratories: Lights and Shadows,** 2202.02052
  J. Isern, S. Torres & A. Rebassa-Mansergas

- **Stellar Evolution Confronts Axion Models,** 2109.10368
  L. Di Luzio, M. Fedele, M. Giannotti, F. Mescia & E. Nardi

- **Astrophysical axion bounds,** hep-ph/0611350
  G. Raffelt

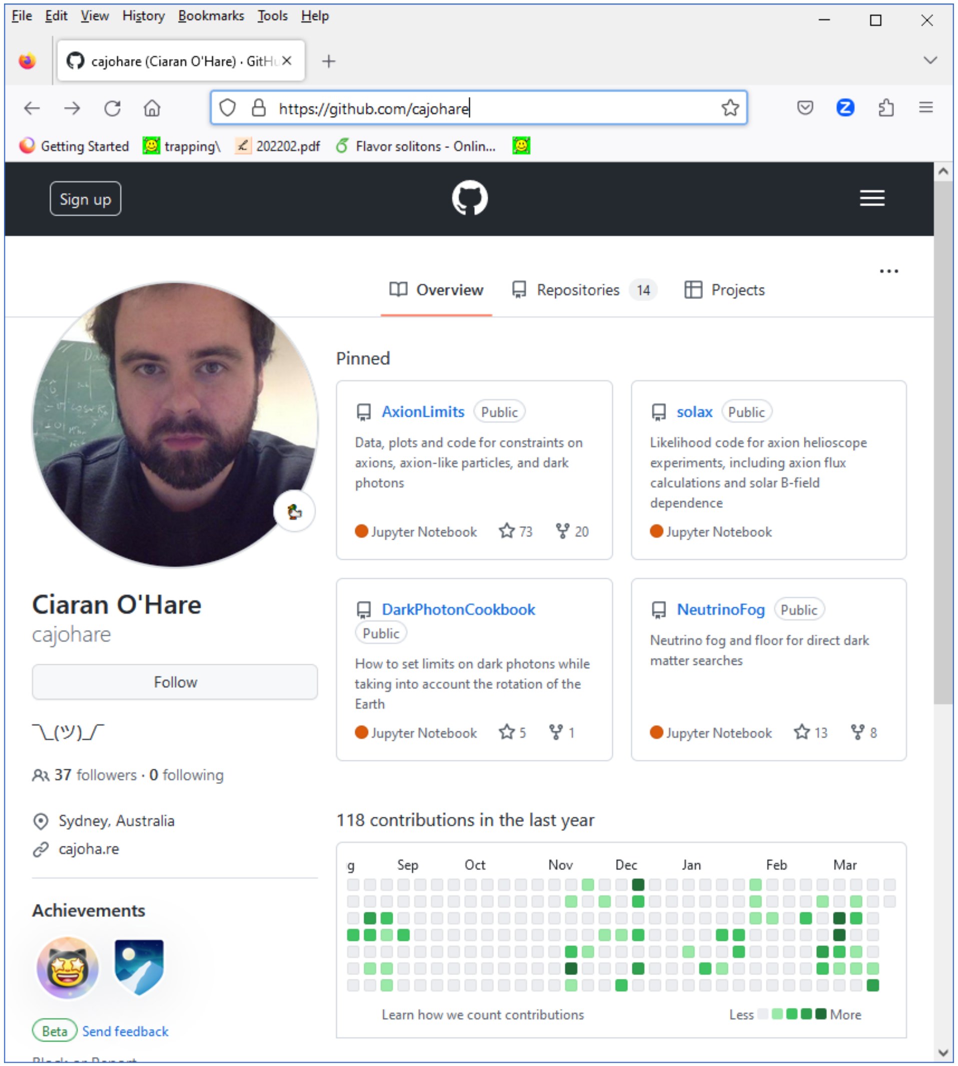
- **Stars as Particle Physics Laboratories, (Univ. Chicago Press, 1996)**
  G. Raffelt

CAST in the Sky (Axion-Photon Conversion in B-fields)

- **Axion-Like Particles Implications for High-Energy Astrophysics,** 2205.00940
  G. Galanti & M. Roncadelli

- **Axion-Like Particle Searches with IACTs,** 2106.03424
  I. Batković, A. De Angelis, M. Doro & M. Manganaro

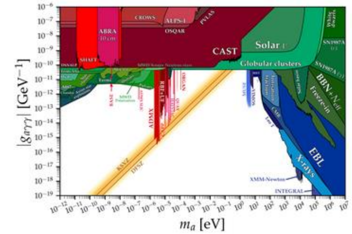
Bounds on Low-Mass Bosons



https://github.com/cajohare

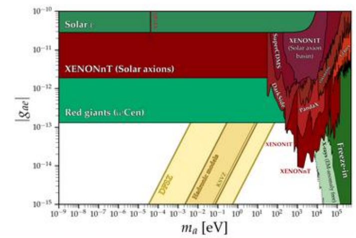
Axion-photon coupling

Data files
Plot (pdf, png)
Plot with projections (pdf, png)
Plot of dimensionless coupling (pdf, png)
Plot of dimensionless coupling with projections (pdf, png)



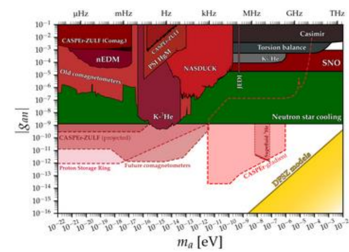
Axion-electron coupling

Data files
Plot (pdf, png)
Plot with projections (pdf, png)



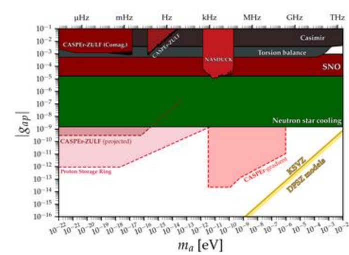
Axion-neutron coupling

Data files
Plot (pdf, png)
Plot with projections (pdf, png)



Axion-proton coupling

Data files
Plot (pdf, png)
Plot with projections (pdf, png)



Many constraint plots and the latest references

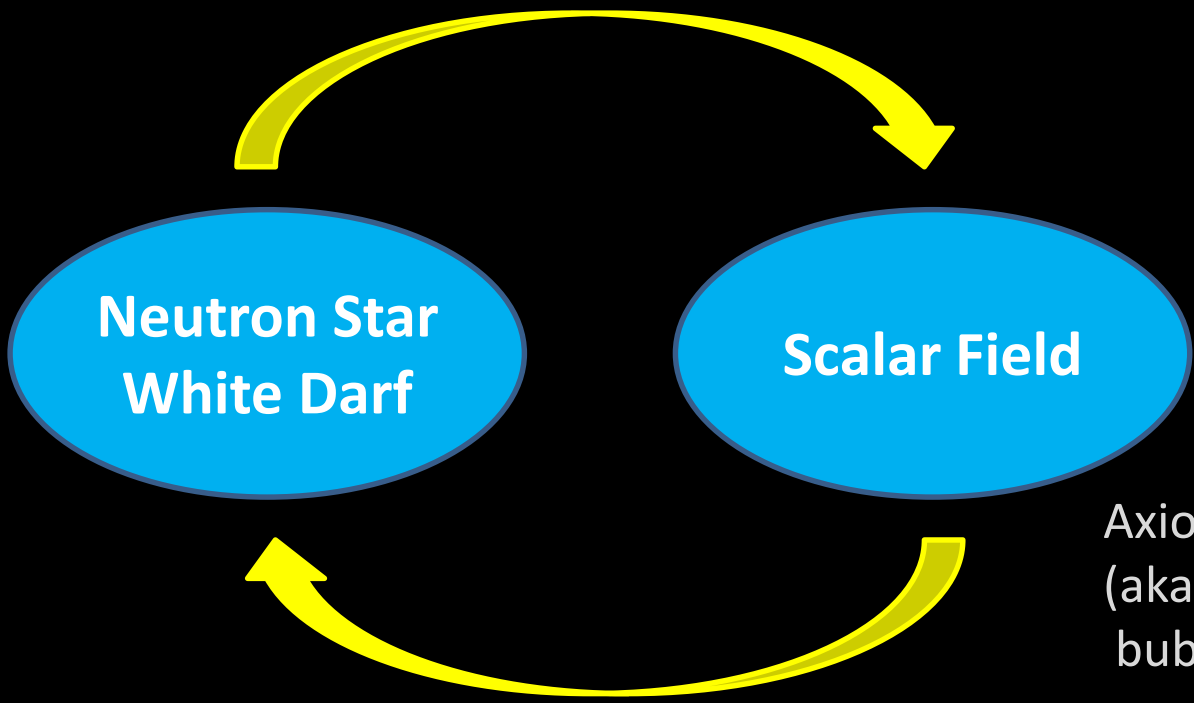
Some Reviews on Supernova Neutrinos

- Mirizzi, Tamborra, Janka, Saviano & Scholberg:
  Supernova Neutrinos: Production, Oscillations and Detection
  → arXiv:1508.00785
- Burrows & Vartanyan: **Core-Collapse Supernova Explosion Theory**
  → arXiv:2009.14157
- Janka: **Neutrino Emission from Supernovae**
  → arXiv:1702.08713
- Beacom: **The Diffuse Supernova Neutrino Background**
  → arXiv:1004.3311
- Himmel & Scholberg: **Supernova Neutrino Detection**
  → arXiv:1205.6003

Bonus Topics

Axions and Stellar Structure

Coupled systems are coupled:
Stars destabilize axions, axions destabilize stars



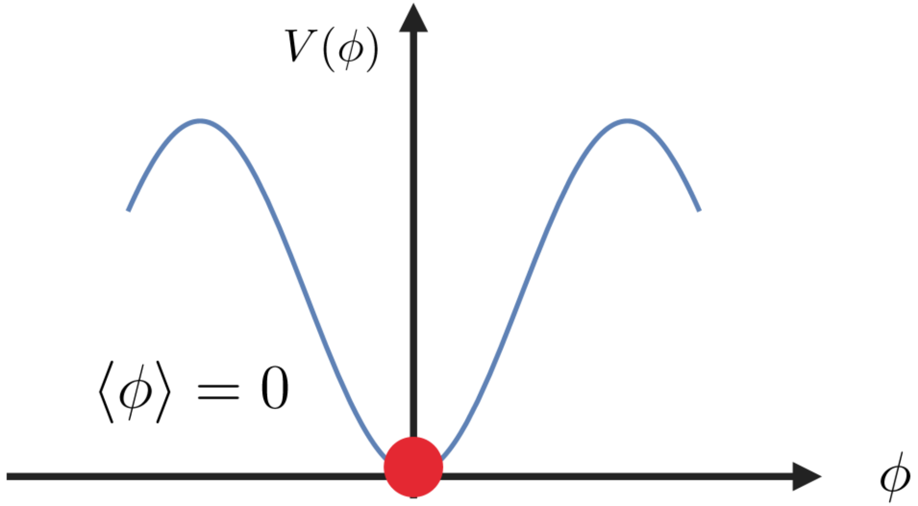
Axion condensation
(aka axion sourcing,
bubble formation)

Adapted from Andi Weiler

Axion Potential in Vacuum

Non-perturbative effects generate Λ_{QCD}

UV $\quad \dfrac{g_s^2}{32\pi^2}\dfrac{\phi}{f_a}\, G\tilde{G}$



IR $\quad V(\phi) = -m_\pi^2 f_\pi^2 \sqrt{1 - \dfrac{4 m_u m_d}{(m_u + m_d)^2}\sin^2\left(\dfrac{\phi}{2f_a}\right)}$

$$\simeq -\underbrace{\frac{m_\pi^2 f_\pi^2}{4}}_{m_a^2 f_a^2}\left[\cos\left(\frac{\phi}{f_a}\right) - 1\right]$$

$2\pi f_a$ periodic potential

Axion Potential in Dense Medium

Nuclear chiral perturbation theory with QCD axion

$$\mathcal{L}_{\text{chiral}} = \text{Tr}\left[U\, M_q e^{i\phi/f_a} + \text{h.c.}\ \right] \bar{N}N + \cdots$$

Leads to non-derivative nucleon couplings

$$\mathcal{L} \supset -\left[m_N + \sigma_{\pi N}\left(\cos\frac{\phi}{f_a} - 1\right)\right]\bar{N}N \qquad \sigma_{\pi N} \simeq 50\ \text{MeV}$$

For nonvanishing nucleon density $n_N = \langle \bar{N}N \rangle$ an axion potential

$$V(\phi) = -\frac{m_\pi^2 f_\pi^2}{4}\left(1 - \underbrace{\frac{4\sigma_{\pi N} n_N}{m_\pi^2 f_\pi^2}}\right)\left(\cos\frac{\phi}{f_a} - 1\right)$$

$\mathcal{O}(1)$ at nuclear density

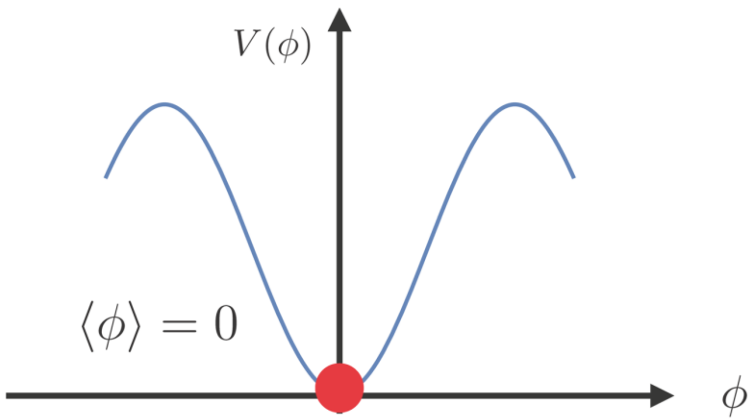
Hook & Huang 1708.08464, Balkin+ 2105.13354

Light QCD Axions at Finite Density

$$V(\phi) = -\frac{m_\pi^2 f_\pi^2}{4}\left(\epsilon - \frac{4\sigma_{\pi N} n_N}{m_\pi^2 f_\pi^2}\right)\left(\cos\frac{\phi}{f_a} - 1\right)$$

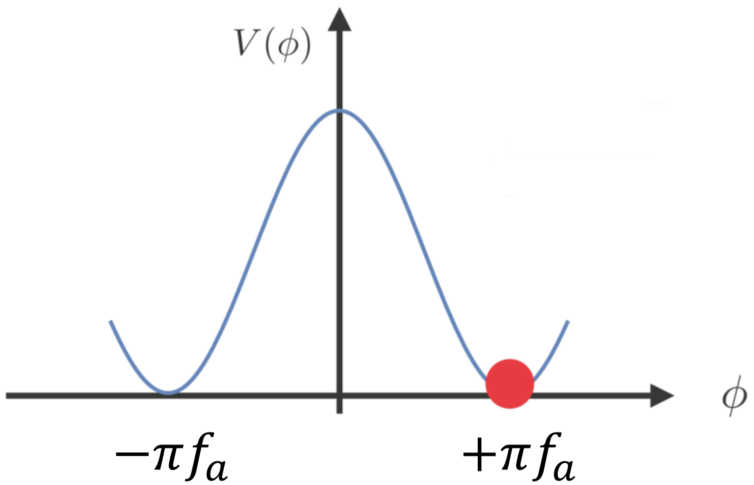
Axions with smaller mass

$$n < n_c = \epsilon \underbrace{\frac{m_\pi^2 f_\pi^2}{4\sigma_{\pi N}}}_{(2.1\ \mathrm{fm})^{-3}}$$



New minima appear at large density

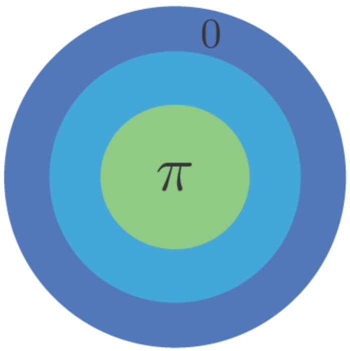
$$n > n_c = \epsilon \frac{m_\pi^2 f_\pi^2}{4\sigma_{\pi N}}$$

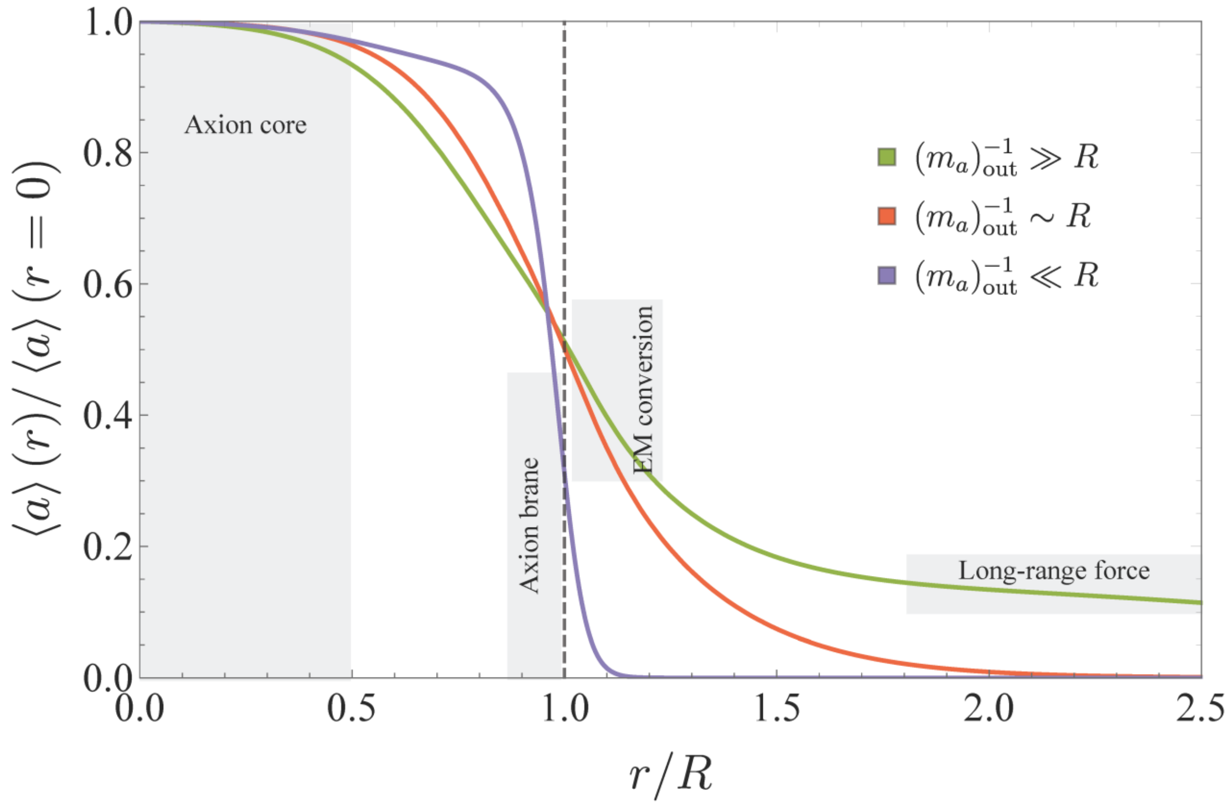


Hook & Huang 1708.08464, Balkin+ 2105.13354

Axion Profile of a Neutron Star

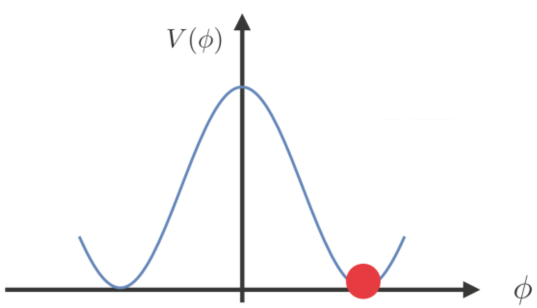
$\phi = \theta f$

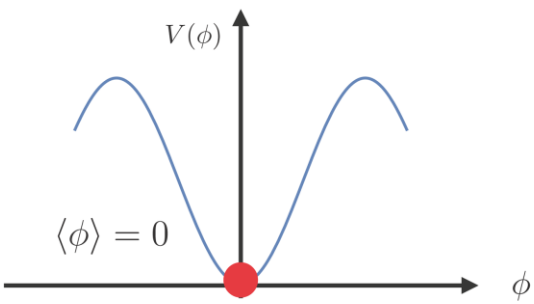




Nucleon mass shifted

$m_N \to m_N - \sigma_{\pi N}$



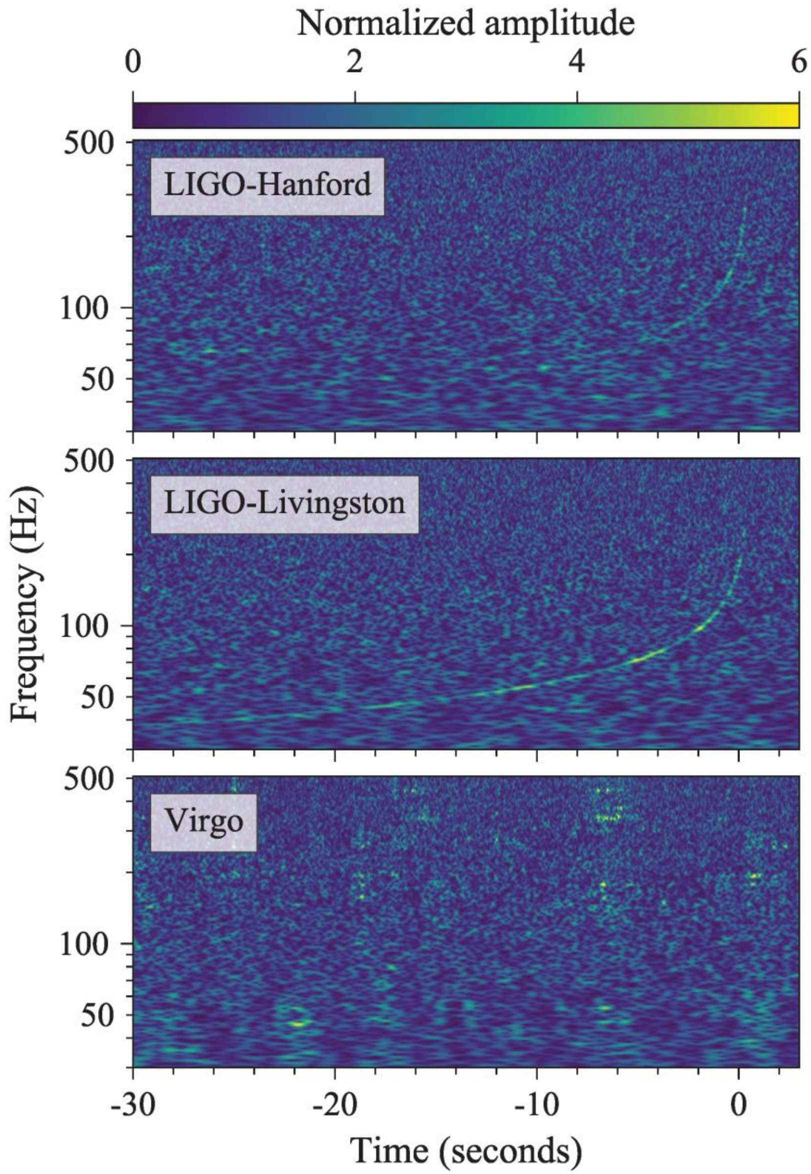


Hook & Huang 1708.08464
Balkin+ 2105.13354

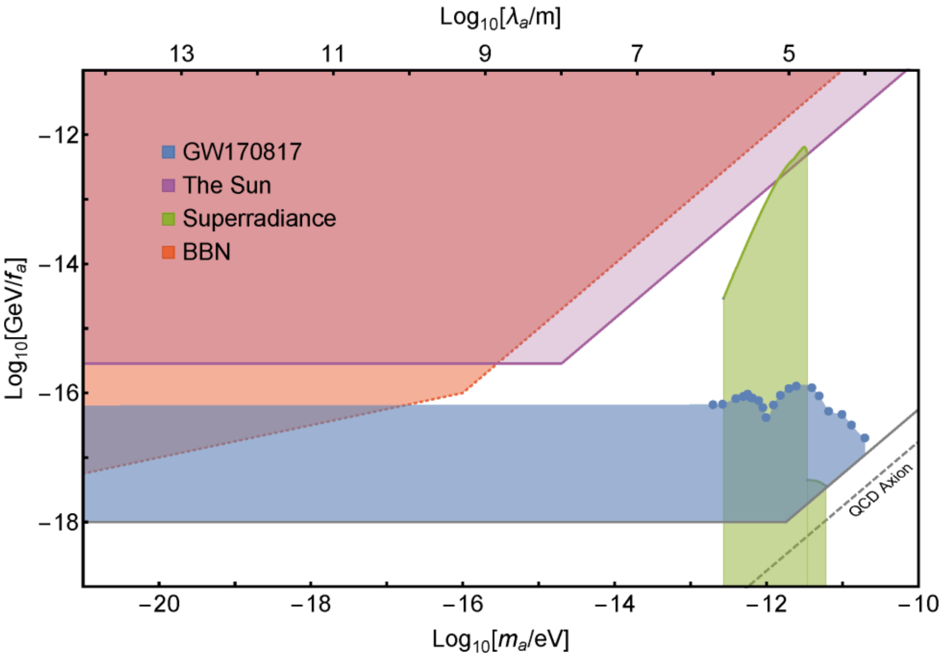
Binary Neutron Star Merger GW 170817

https://physics.aps.org/articles/v10/114

Binary Neutron Star Merger GW 170817



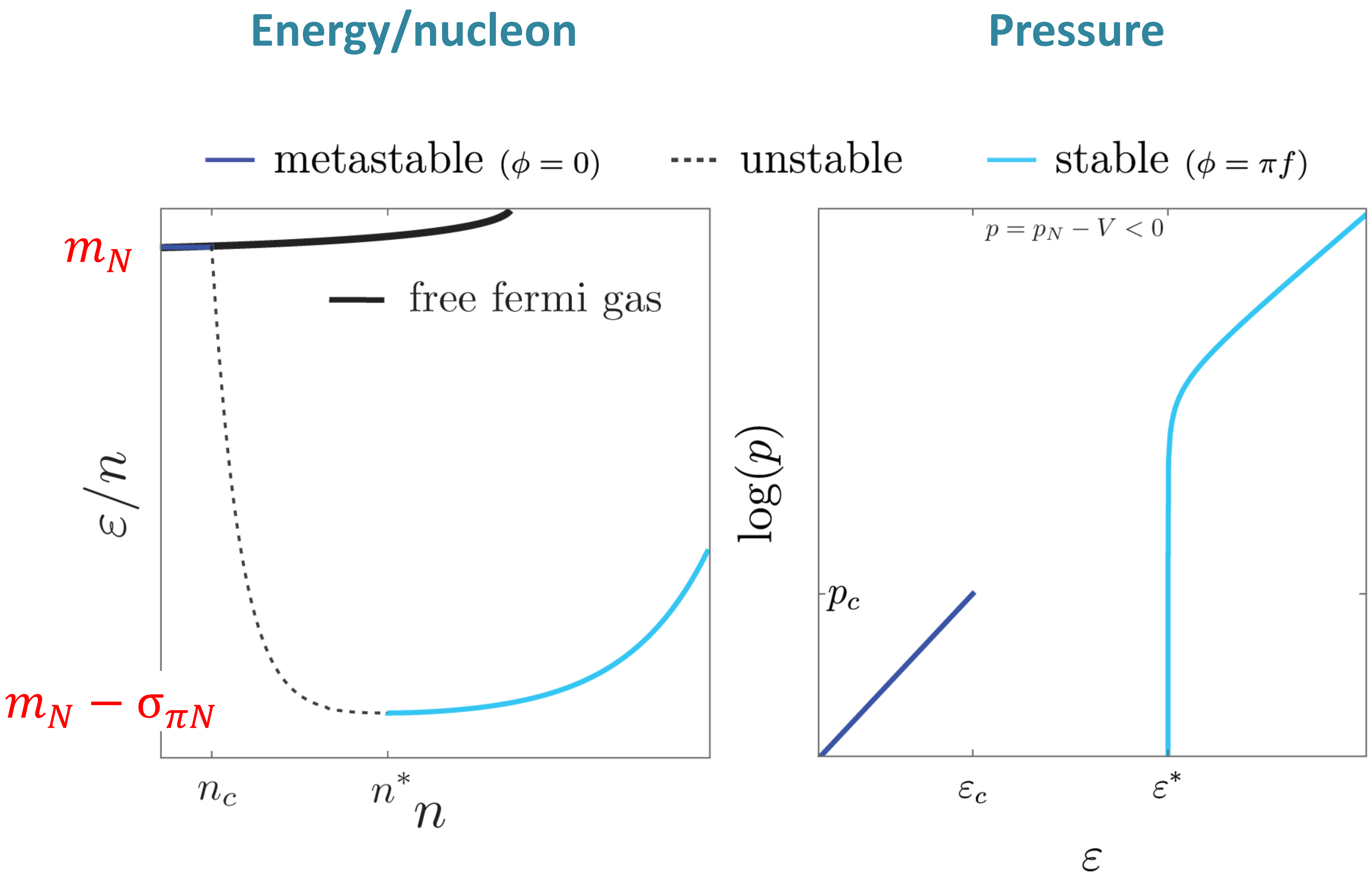
LIGO & Virgo, [1710.05832](https://arxiv.org/abs/1710.05832)



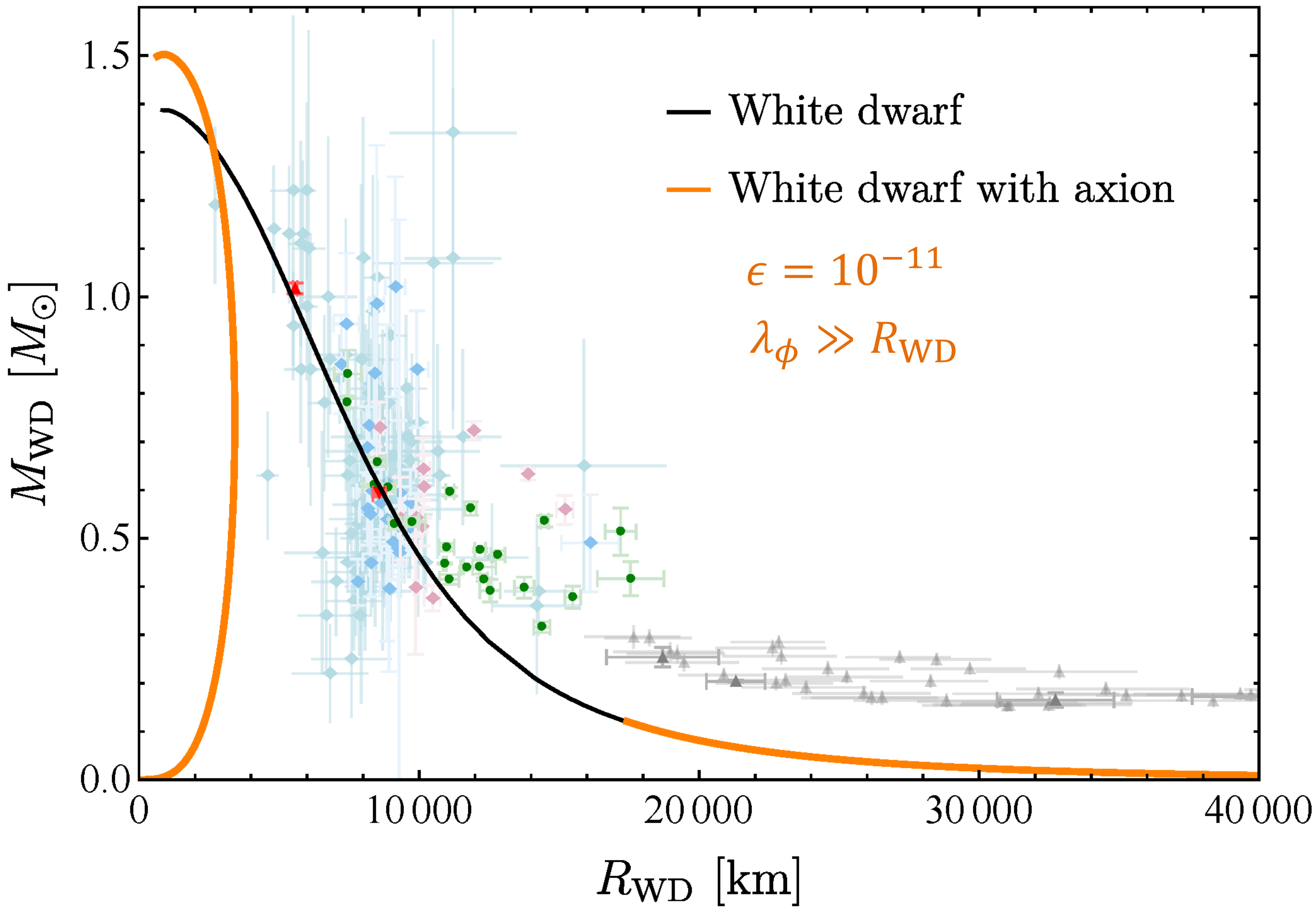
First Constraints on Nuclear Coupling of Axionlike Particles from the Binary Neutron Star Gravitational Wave Event GW 170817

J.Zhang+, [2105.13963](https://arxiv.org/abs/2105.13963)

Changed Equation of State (EoS)

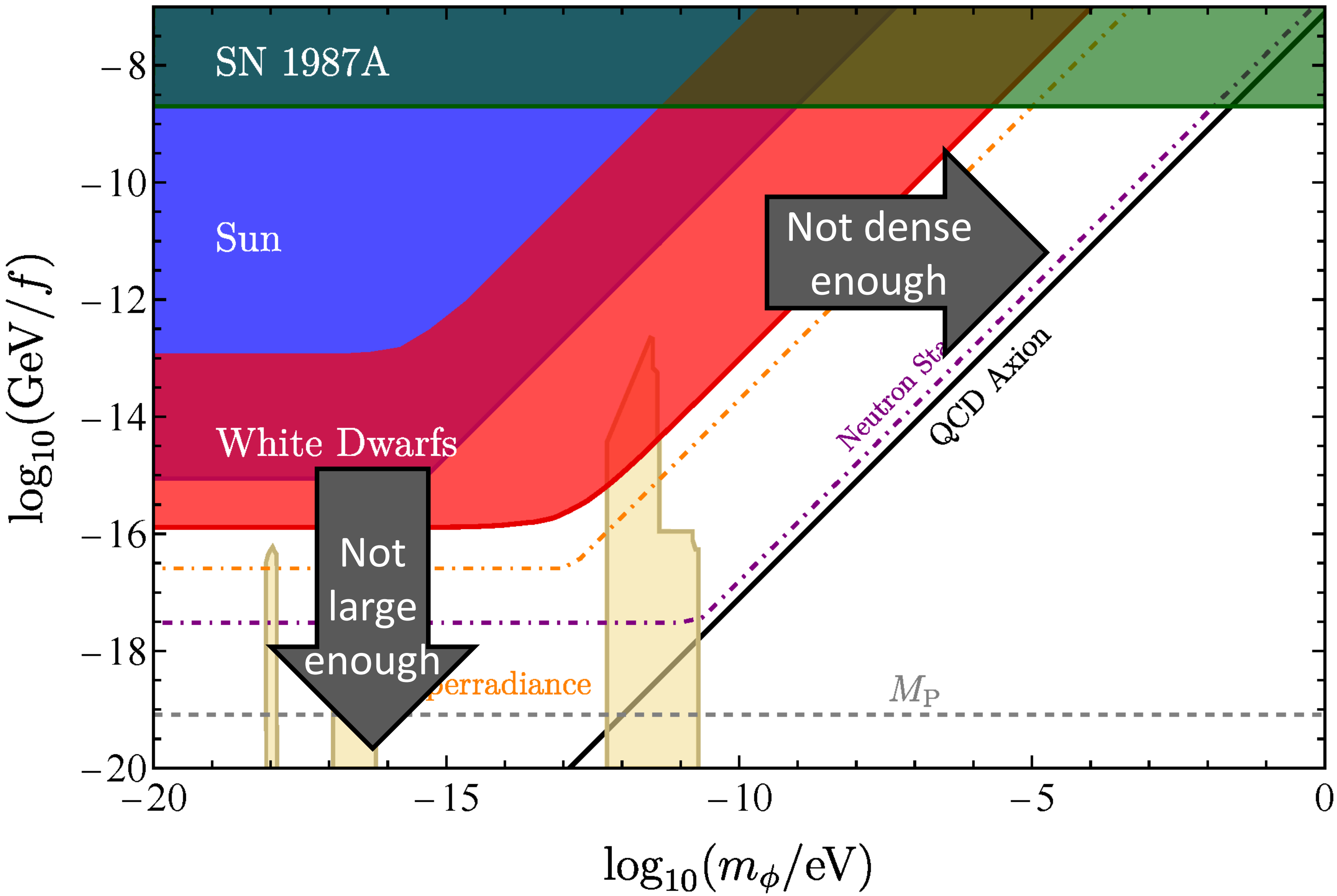


White-Dwarf Mass-Radius Relation



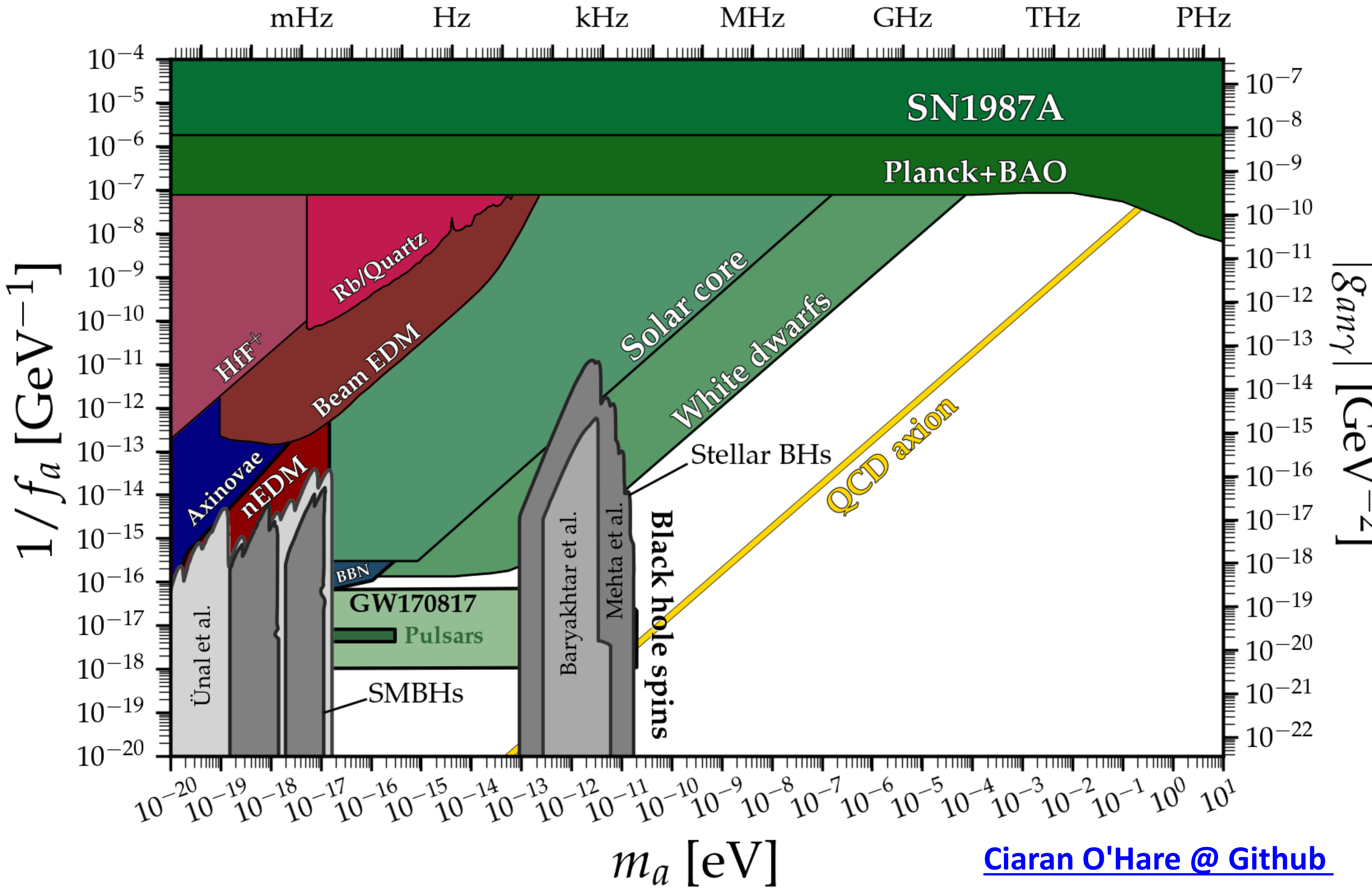
R. Balkin, J. Serra, K. Springmann, S. Stelzl & A. Weiler, 2211.02661

Axion Bounds from Stellar Structure



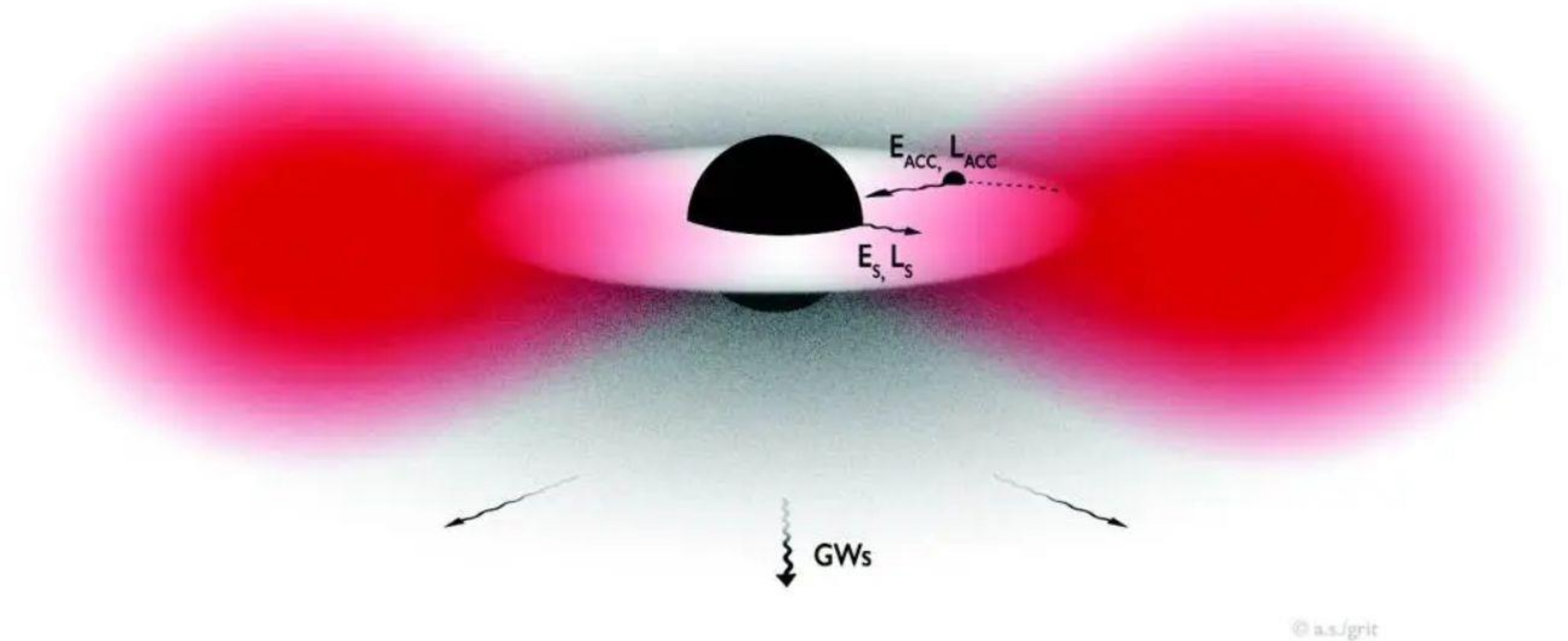
R. Balkin, J. Serra, K. Springmann, S. Stelzl & A. Weiler, [2211.02661](2211.02661)

Peccei-Quinn Scale vs. Axion Mass



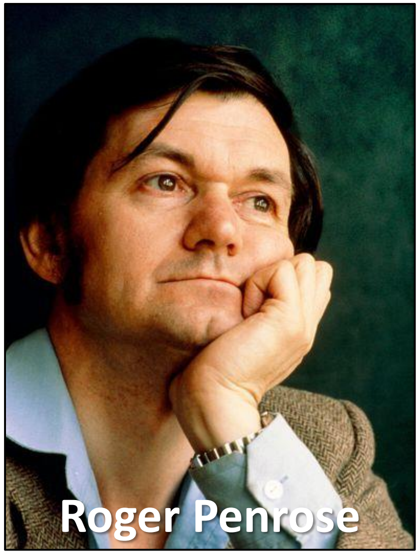
Ciaran O'Hare @ Github

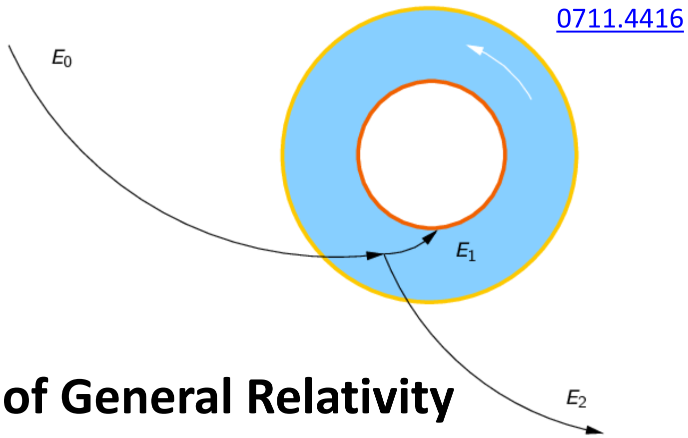
Superradiance



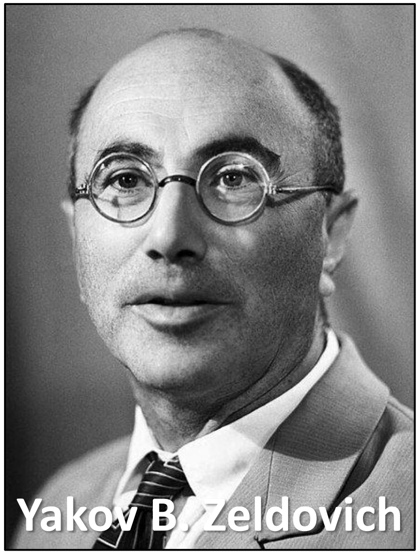
Superradiance: New Frontiers in Black Hole Physics (2020 edition)
R. Brito, V. Cardoso & P. Pani, 1501.06570v8 (8 Jan 2021)

Rotational Superradiance





Gravitational Collapse: The Role of General Relativity
Riv. Nuovo Cim., Num. Spez. 1 (1969) 257
Reprinted in Gen. Rel. Grav. 34 (2002) 1141

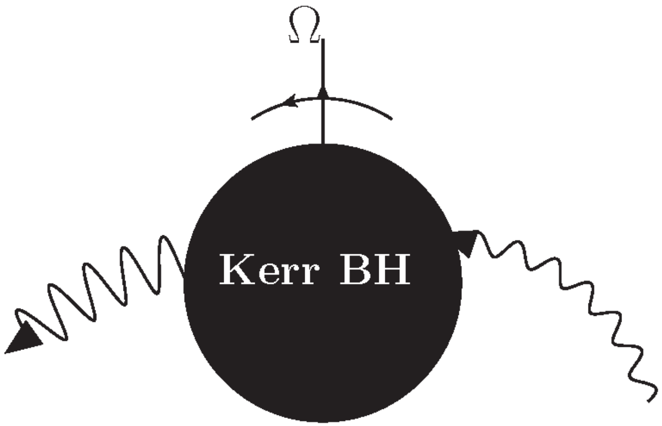


Generation of Waves by a Rotating Body
JETP Lett. 14 (1971) 180

Amplification of Cylindrical Electromagnetic Waves Reflected from a Rotating Body
Zh. Eksp. Teor. Fiz. 62 (1972) 2076

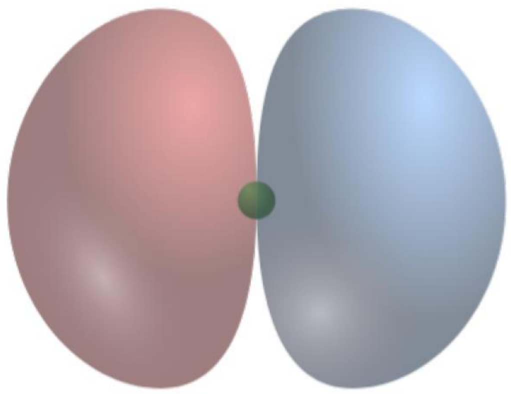
Superradiance

Extraction of rotational energy from spinning object by low-frequency modes $\omega < \Omega$ of an external bosonic field



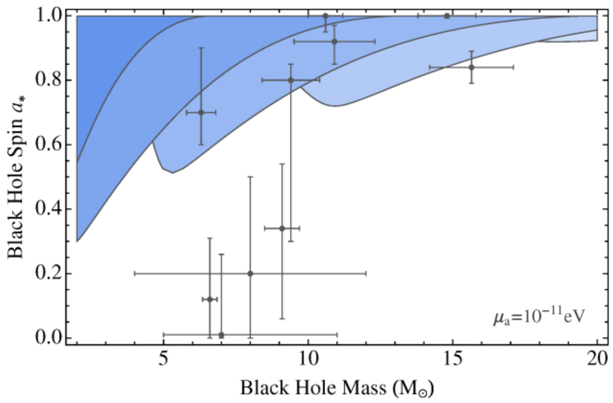
$m\Omega > \omega$

- **Bosons with mass get gravitationally bound**
- **Superradiant run-away mode** $\phi = Y_{lm}(\theta,\phi)\psi_{lmn}(r)e^{\Gamma t}$
- **"Bosonic atom"**
- **Transitions → Gravitational waves**



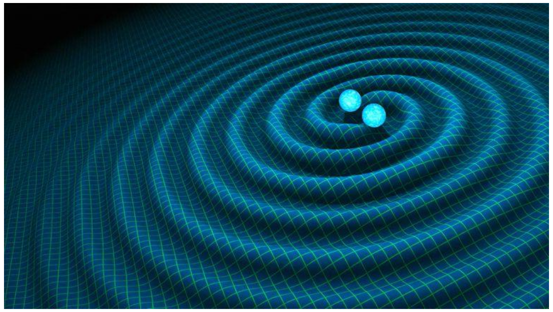
Superradiance: New Frontiers in Black Hole Physics (2020 edition)

R. Brito, V. Cardoso & P. Pani, 1501.06570v8 (8 Jan 2021)



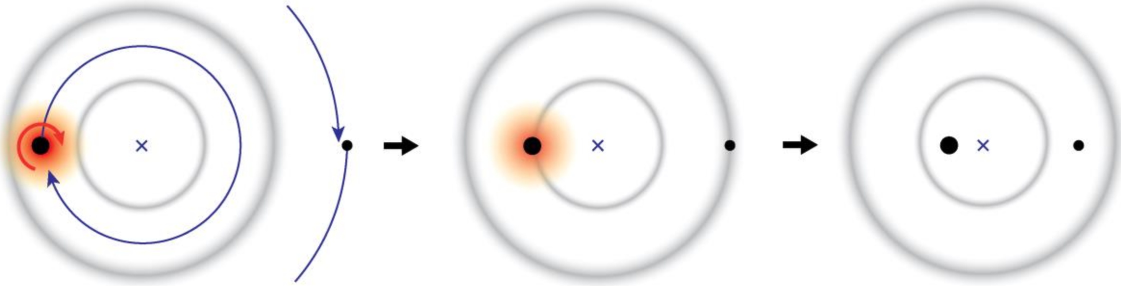
- **Constraints on light particles from BH spin**

Exploring the string axiverse with precision black hole physics
Arvanitaki & Dubovsky, 1004.3558
Discovering the QCD axion with black holes and gravitational waves, Arvanitaki, Baryakhtar & Huang, 1411.2263



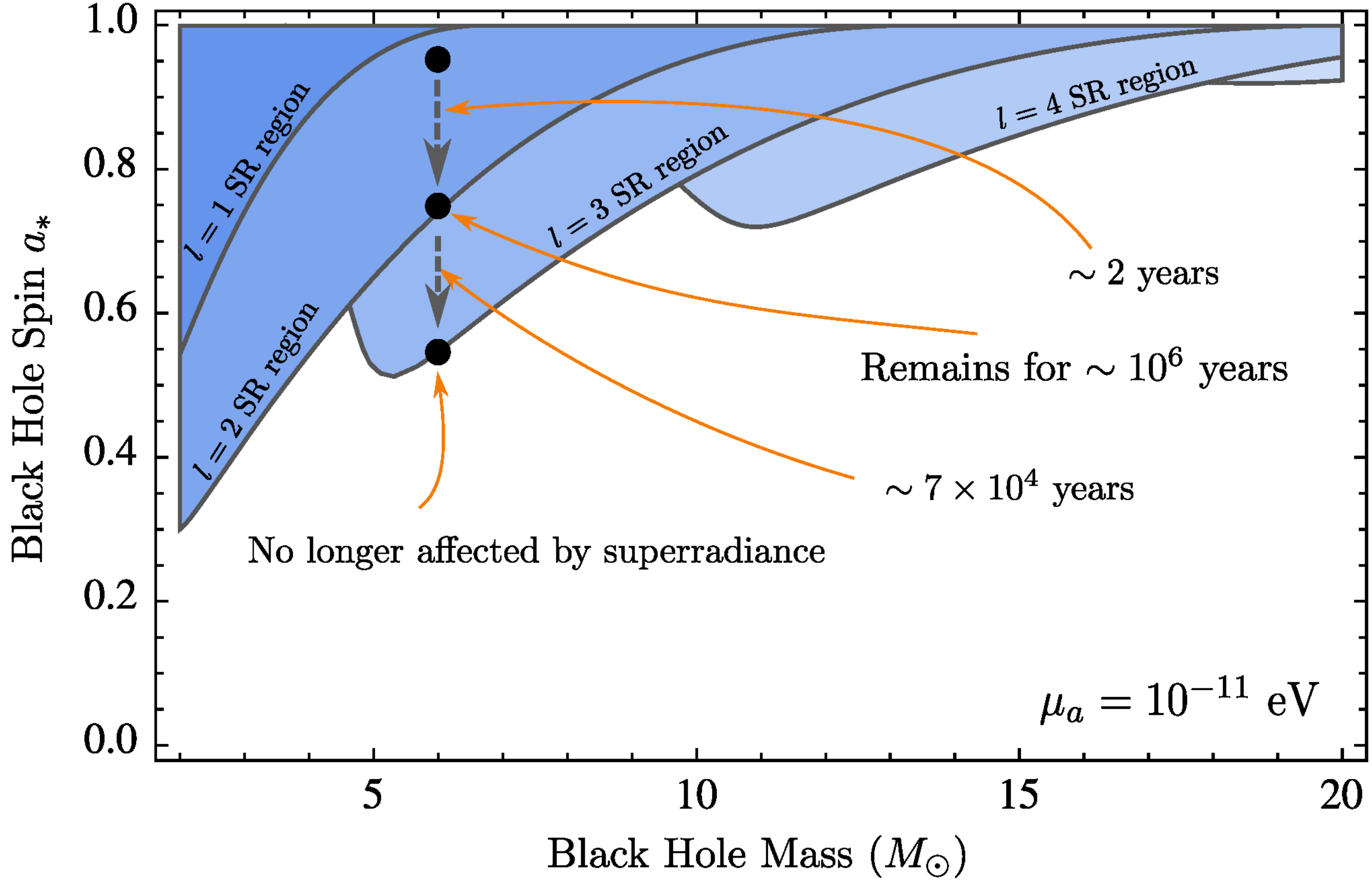
- **Gravitational waves from "atomic transitions"**

- **Effects on binaries**



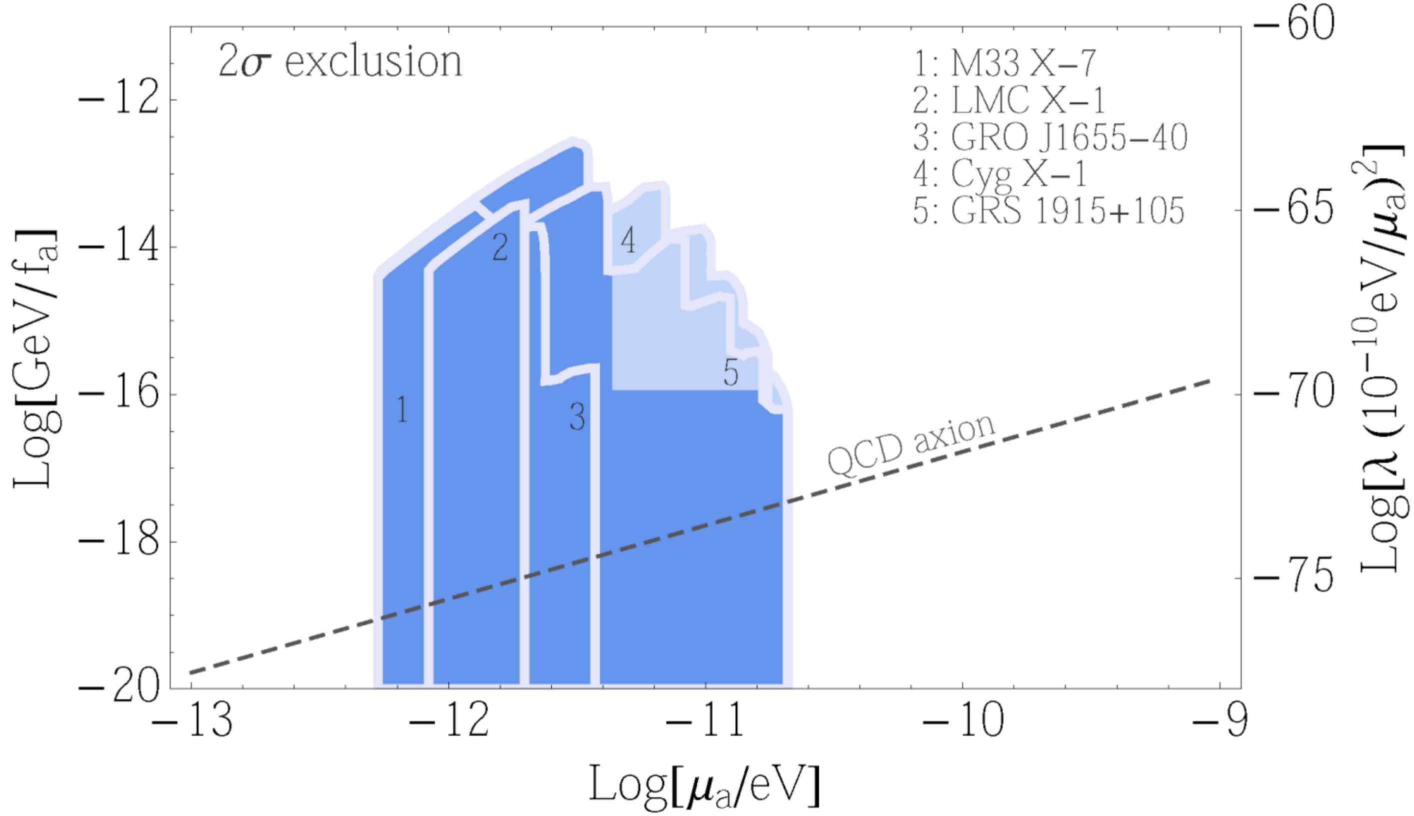
Probing Ultralight Bosons with Binary Black Holes
Baumann, Chia & Porto, 1804.03208

Impact on Black Hole Spins



Discovering the QCD axion with black holes and gravitational waves
Arvanitaki, Baryakhtar & Huang, 1411.2263

Constraints from Black Hole Spins

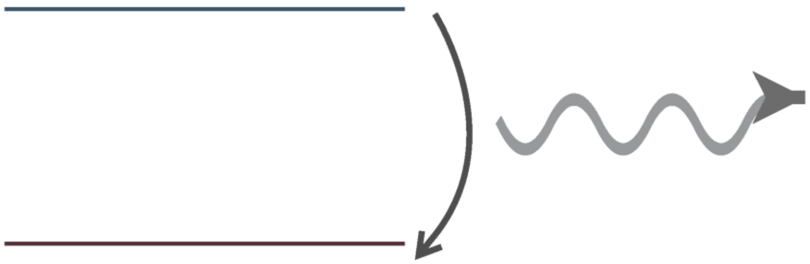


#	Object	Mass ($M_\odot$)	Spin	Age (yrs)	Period (days)	$M_{\mathrm{comp.\,star}}$ ($M_\odot$)	$\dot{M}/\dot{M}_E$
1	M33 X-7	15.65 ± 1.45	$0.84^{+.10}_{-.10}$[51]	3×10^6 [52]	3.4530 [53]	$\gtrsim 20$ [53]	$\gtrsim 0.1$[53]
2	LMC X-1	10.91 ± 1.4	$0.92^{+.06}_{-.18}$ [54]	5×10^6 [52]	3.9092 [55]	31.79±3.48 [55]	0.16 [55]
3	GRO J1655-40	6.3 ± 0.5	$0.72^{+.16}_{-.24}$ [51]	3.4×10^8 [56]	2.622 [56]	2.3 - 4 [56]	$\lesssim 0.25$ [57]
4	Cyg X-1	14.8 ± 1.0	> 0.99 [58]	4.8×10^6[59]	5.599829 [52]	17.8 [52]	0.02[52]
5	GRS1915+105	10.1 ± 0.6	> 0.95 [51, 60]	4×10^9 [61]	33.85 [62]	0.47 ± 0.27 [62]	$\gtrsim 1$ [62].

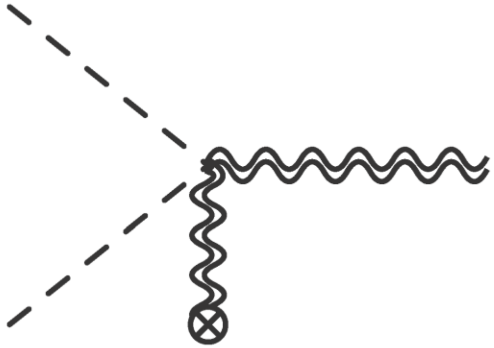
Arvanitaki, Baryakhtar & Huang, 1411.2263

Gravitational Wave Signals

- Transitions between levels



- Annihilations to gravitons



Arvanitaki, Baryakhtar, Dimopoulos, Dubovsky & Lasenby, arXiv:1604.03958

Direct Constraints on the Ultralight Boson Mass from Searches of Continuous Gravitational Waves

C. Palomba,[1] S. D'Antonio,[2] P. Astone,[1] S. Frasca,[3,1] G. Intini,[3,1] I. La Rosa,[4] P. Leaci,[3,1] S. Mastrogiovanni,[5] A. L. Miller,[3,1,6] F. Muciaccia,[3] O. J. Piccinni,[3,1] L. Rei,[7] and F. Simula[1]

Superradiance limits from LIGO O2 all-sky search for periodic GWs

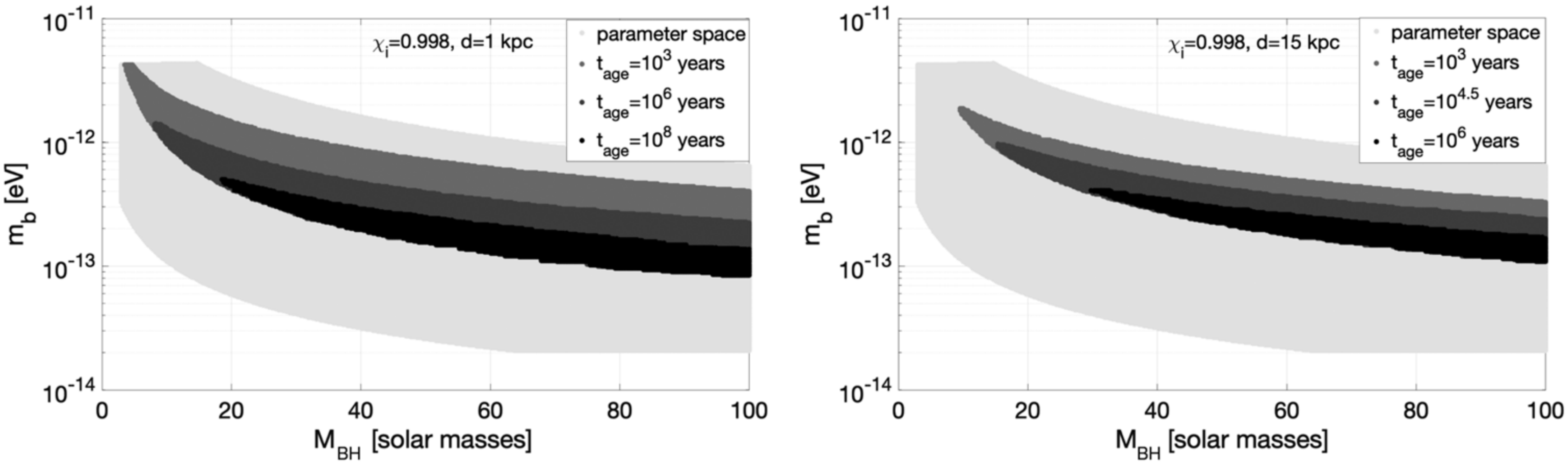
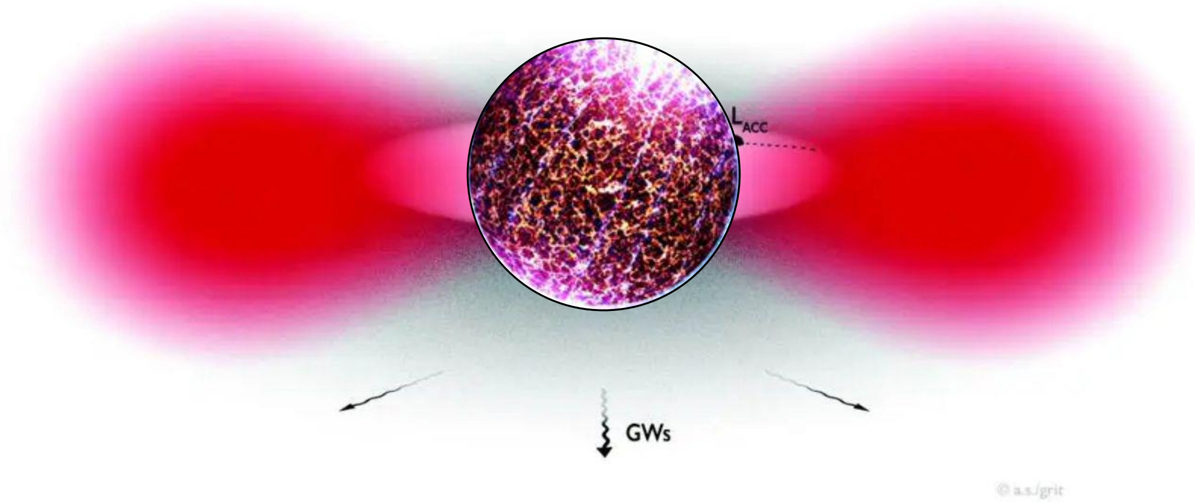


FIG. 2. 95% C.L. exclusion regions in the plane $m_b - M_{BH}$ assuming a maximum distance $d = 1$ kpc (left plot) and $d = 15$ kpc (right plot), a black hole initial adimensional spin $\chi_i = 0.998$, and three possible values for t_{age}: 10^3, 10^6, 10^8 yr (left plot) and 10^3, $10^{4.5}$, 10^6 yr (right plot). The larger light gray area is the accessible parameter space. As expected, the extension of the excluded region decreases for increasing t_{age} (corresponding to darker color).

See also:
Search for ultralight bosons in Cygnus X-1 with Advanced LIGO, arXiv:1909.11267

Superradiance in Neutron Stars

- Crucial issue is absorption of bosons within neutron star
- Not enough absorption for axions in nuclear matter?

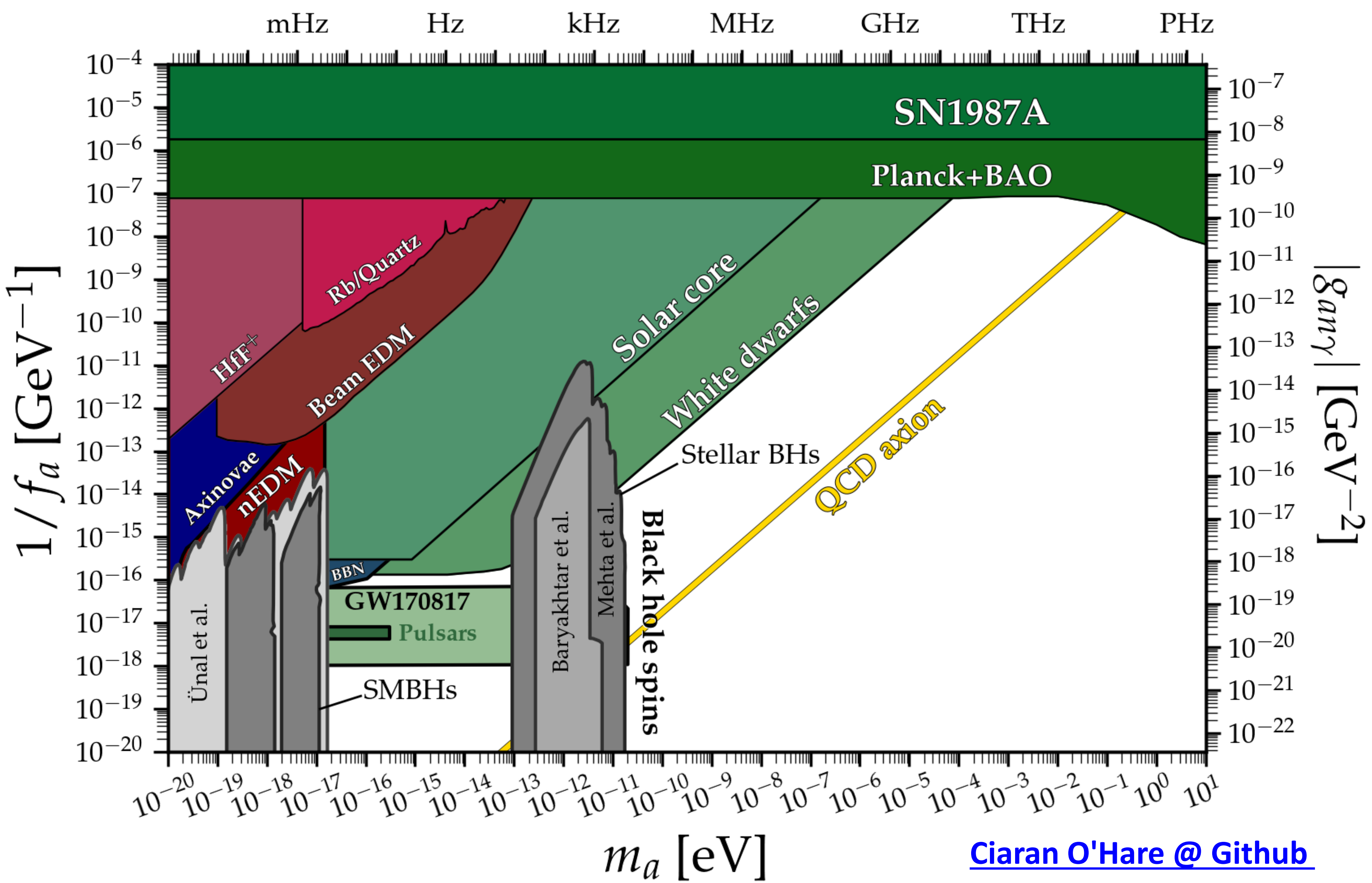


Superradiance in rotating stars and pulsar-timing constraints on dark photons
V.Cardoso, P.Pani & T.-T.Yu, 1704.06151

Axion superradiance in rotating neutron stars
F.V.Day & J.I.McDonald, 1904.08341

Superradiance in stars: non-equilibrium approach to damping of fields in stellar media
F.Chadha-Day, B.Garbrecht & J.I.McDonald, 2207.07662

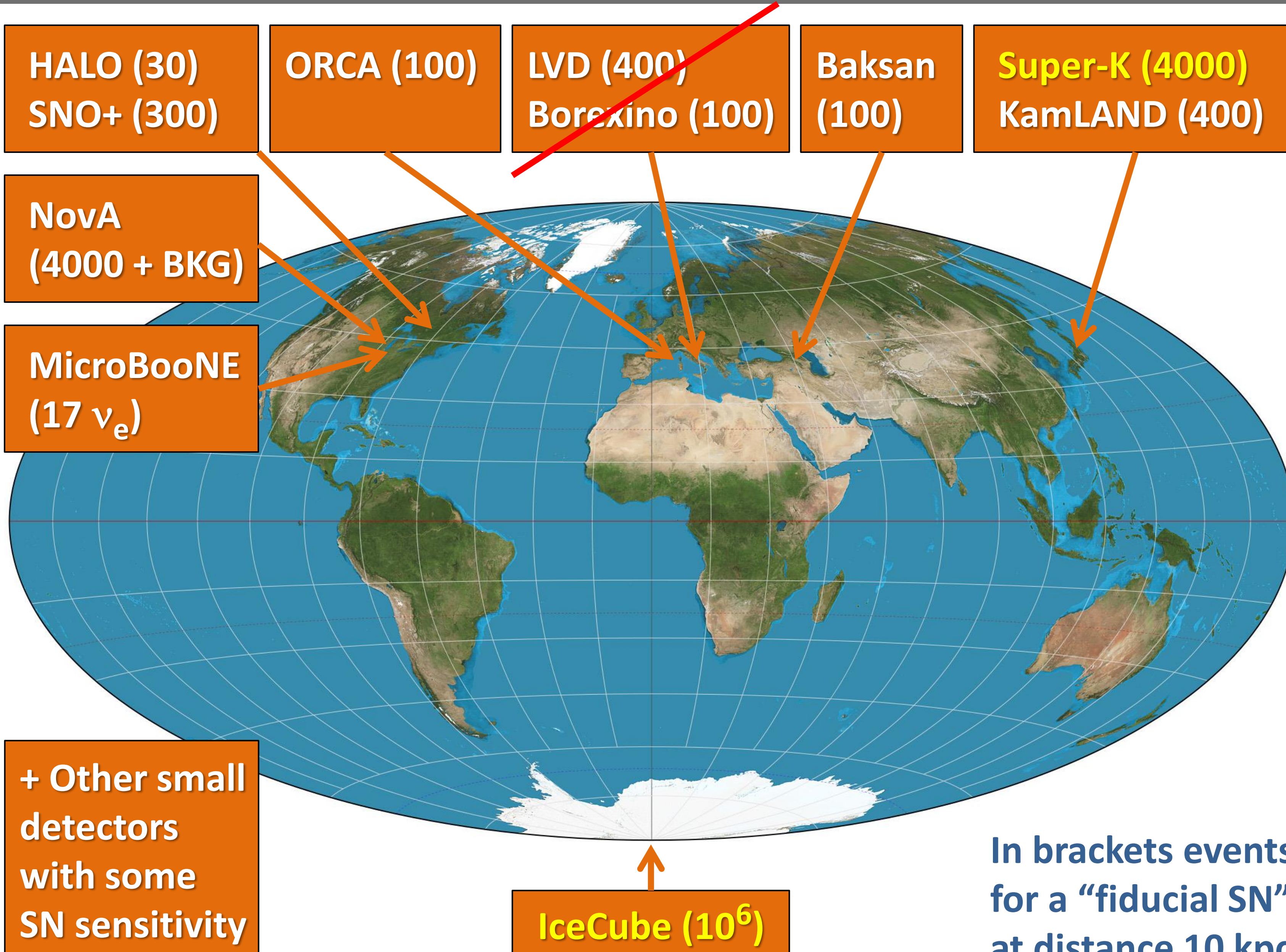
Peccei-Quinn Scale vs. Axion Mass



Ciaran O'Hare @ Github


Neutrinos from the Next Galactic Supernova

Operational Detectors for Supernova Neutrinos

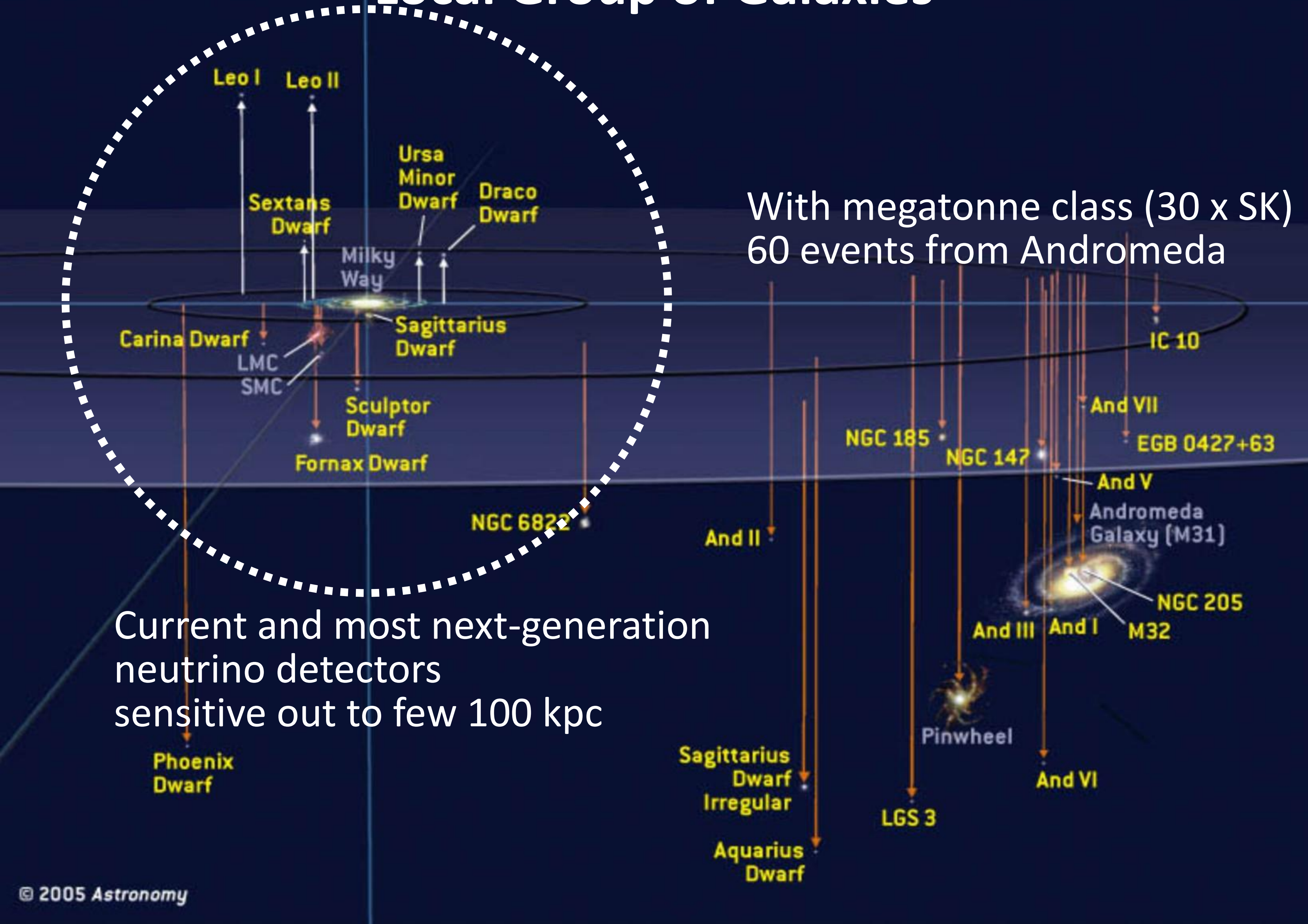


In brackets events for a “fiducial SN” at distance 10 kpc

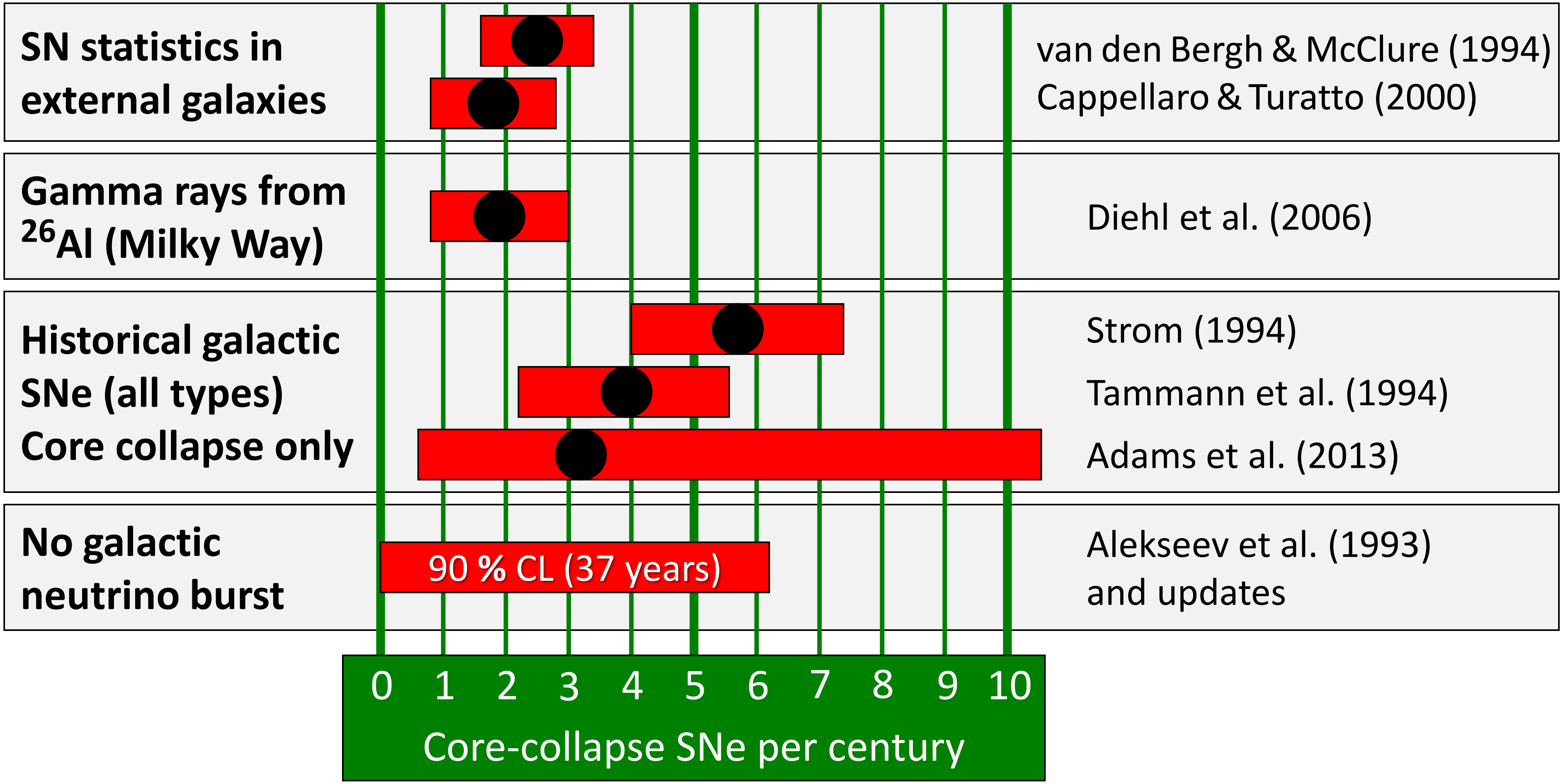
Local Group of Galaxies

With megatonne class (30 x SK)
60 events from Andromeda

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

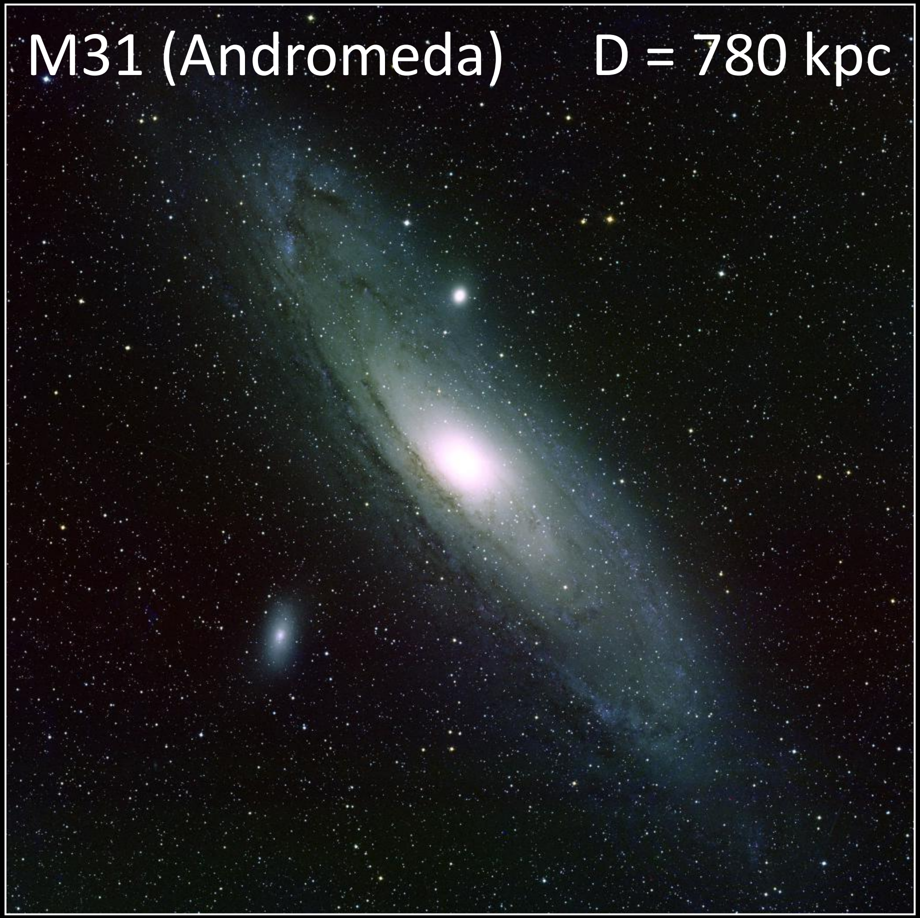


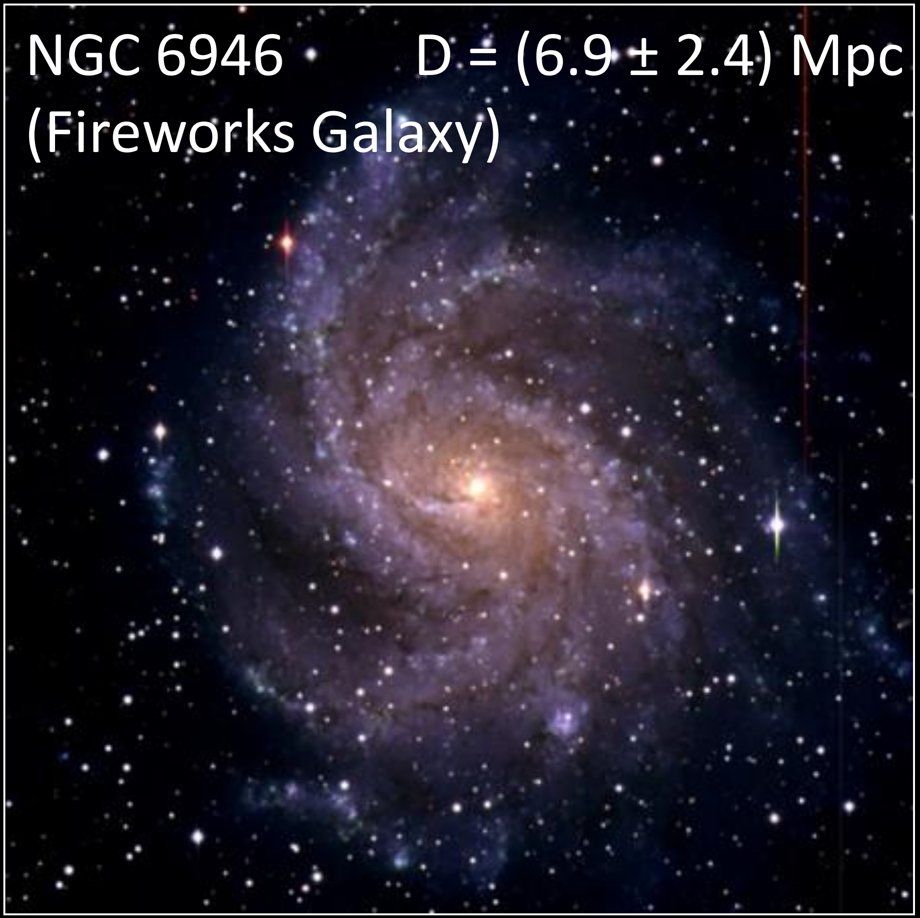
Core-Collapse SN Rate in the Milky Way



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.

High and Low Supernova Rates in Nearby Galaxies



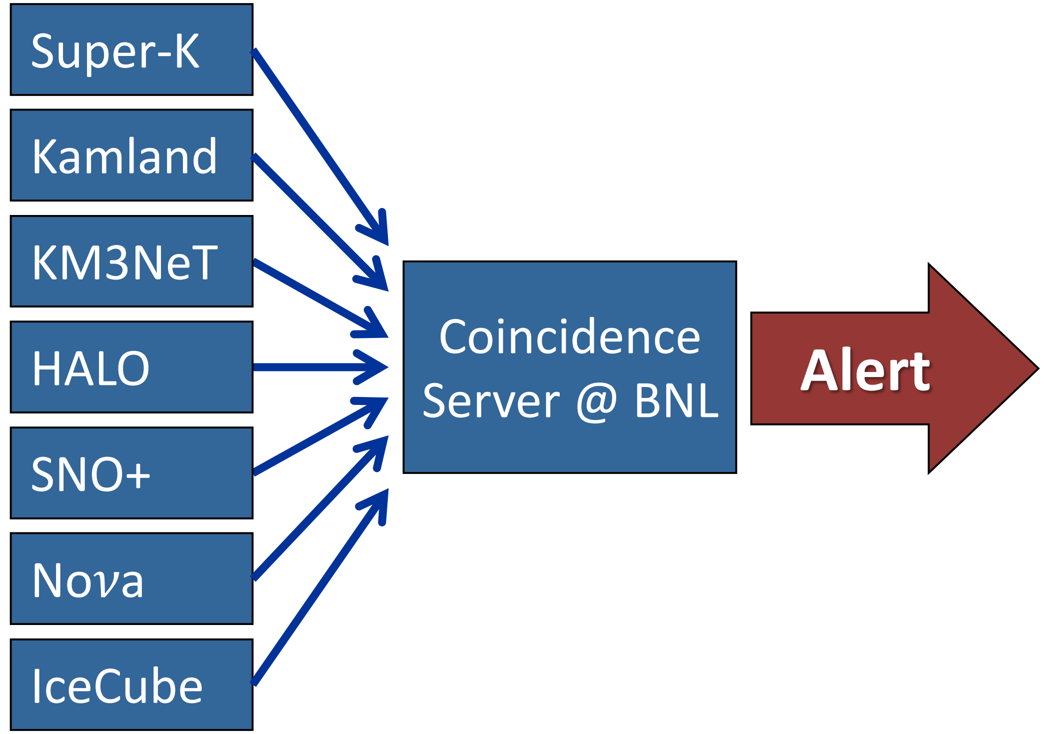


Last Observed Supernova: 1885A

Observed Supernovae:
1917A, 1939C, 1948B, 1968D, 1969P,
1980K, 2002hh, 2004et, 2008S, 2017eaw
N6946-BH1 (failed SN 2009/10)

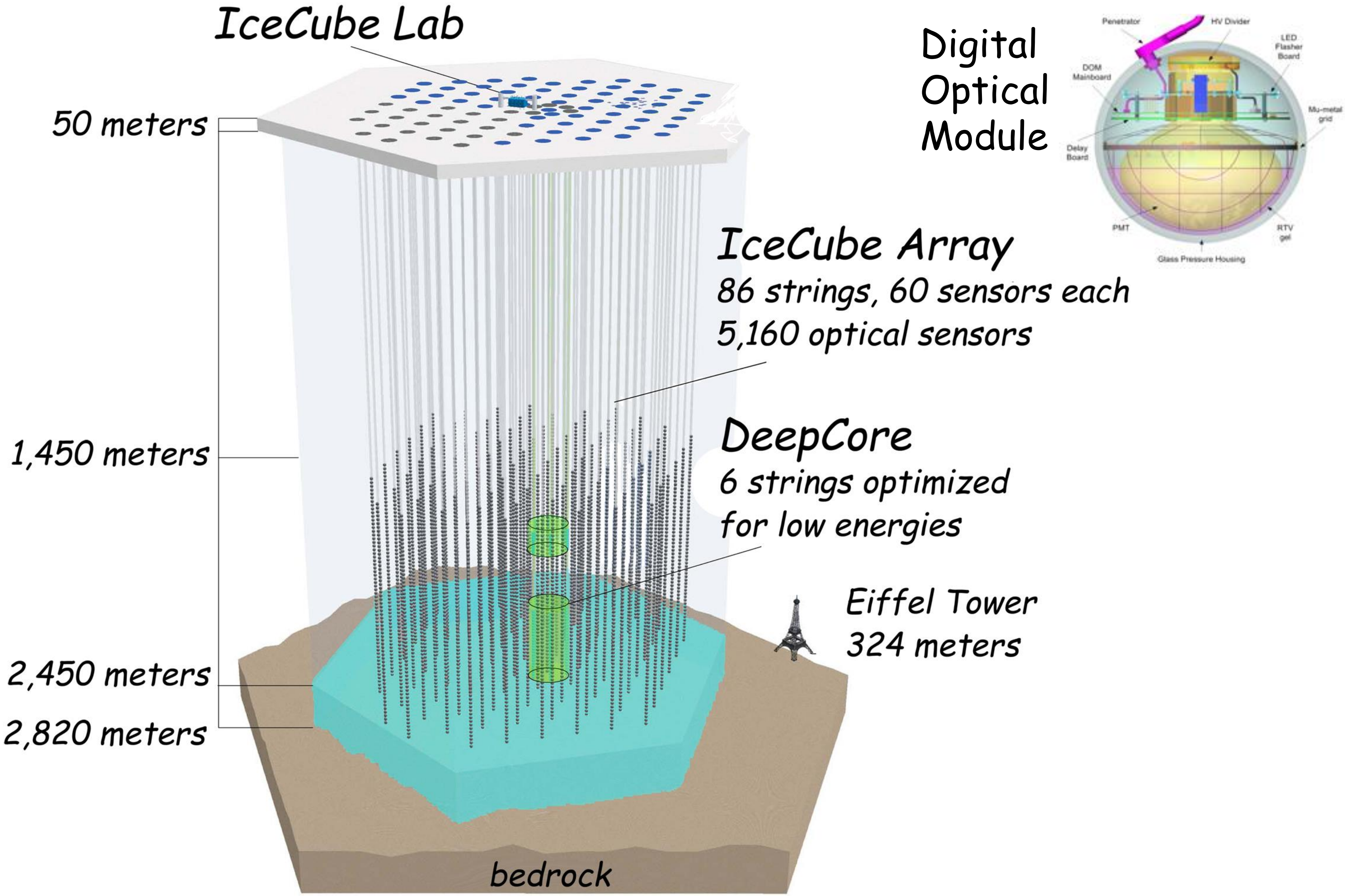
SuperNova Early Warning System (SNEWS)

https://snews2.org/

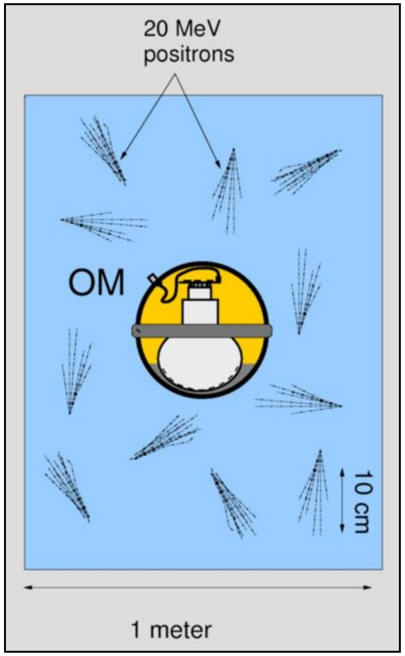


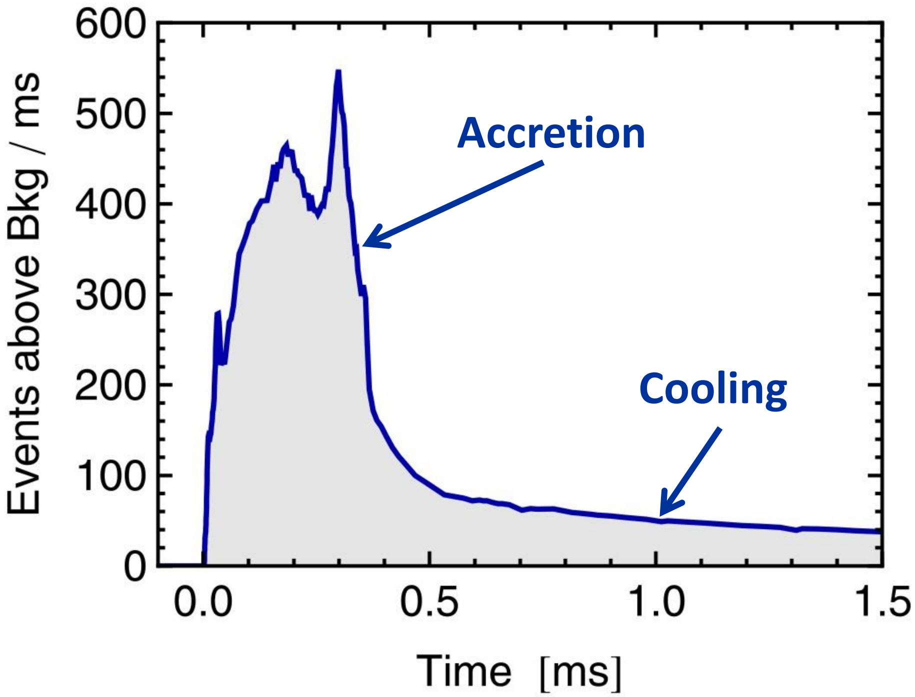
- Neutrinos arrive several hours before optical outburst
- Issue an alert to astronomical community
- Trigger to LIGO, NOvA, GCN

IceCube Neutrino Telescope at the South Pole



IceCube as a Supernova Neutrino Detector



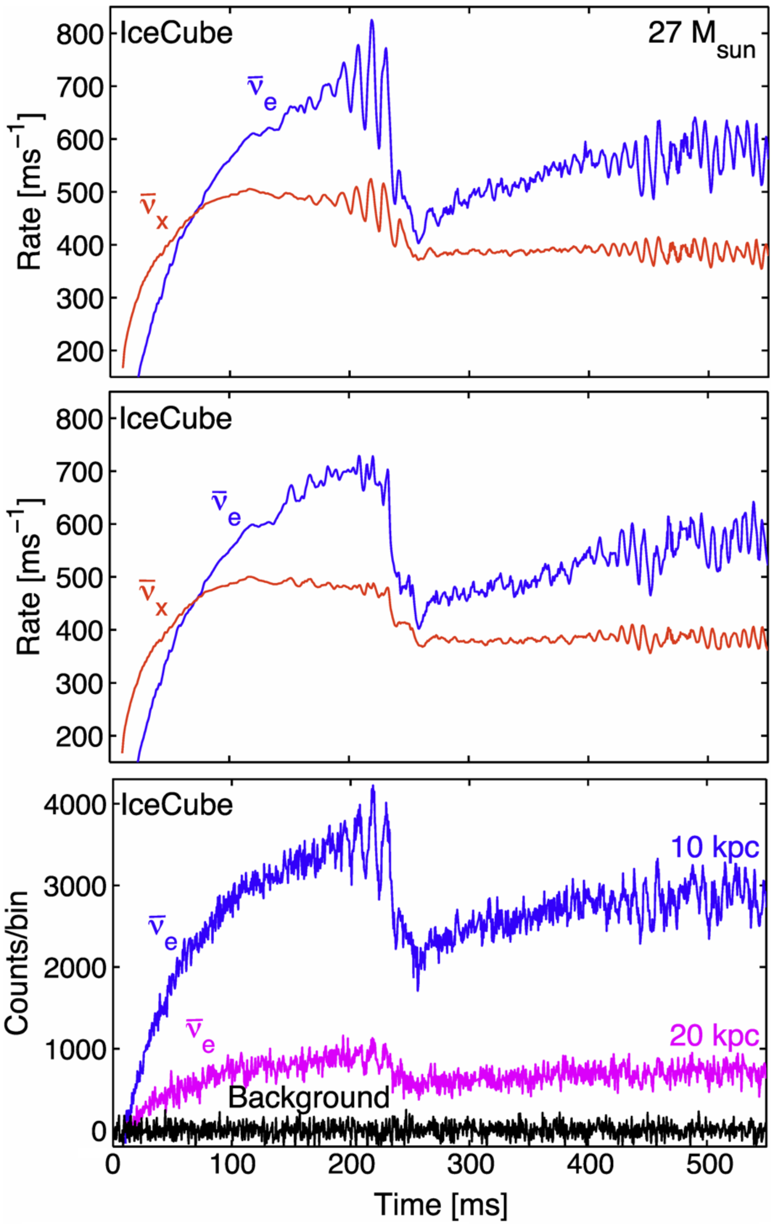


SN signal at 10 kpc
10.8 M_{sun} simulation of Basel group
[arXiv:0908.1871]

- 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

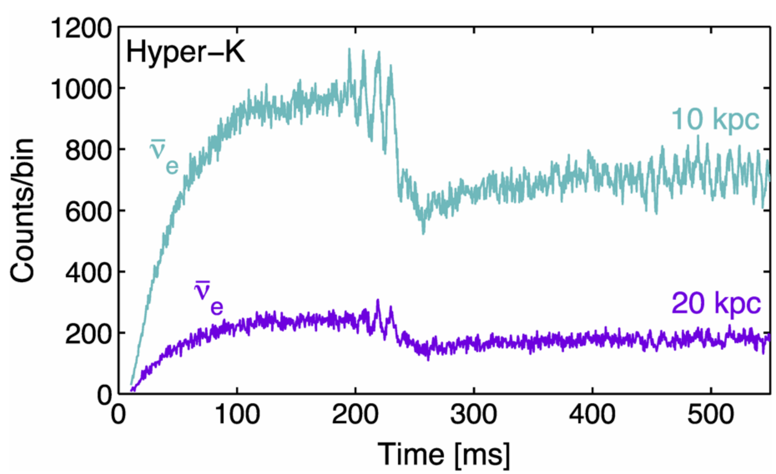
Pryor, Roos & Webster, ApJ 329:355, 1988. Halzen, Jacobsen & Zas, astro-ph/9512080.
Demirörs, Ribordy & Salathe, arXiv:1106.1937.

SASI Detection Perspectives (27 M_{SUN} Model)



Optimistic Observer Direction (along SASI dipole)

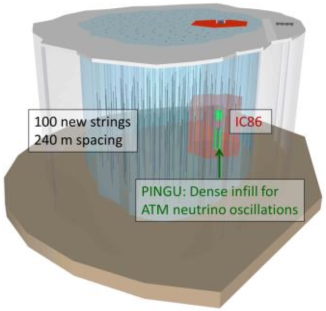
Pessimistic Observer Direction



With shot noise

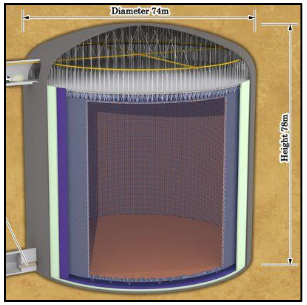
Tamborra, Hanke, Müller, Janka & Raffelt, arXiv:1307.7936. See also Lund, Marek, Lunardini, Janka & Raffelt, arXiv:1006.1889

Next Generation Very-Large-Scale Detectors (2020+)



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

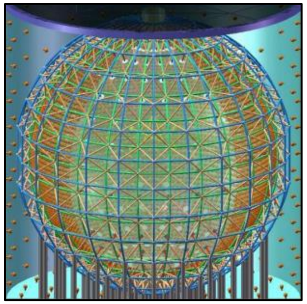
Doubling the number of optical modules



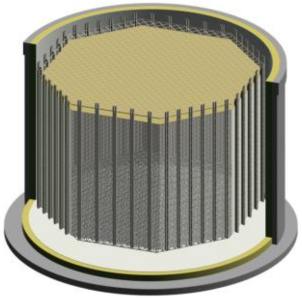
Megaton-class water Cherenkov detector

Notably Hyper-Kamiokande

SN neutrino statistics comparable to IceCube, but with event-by-event energy information



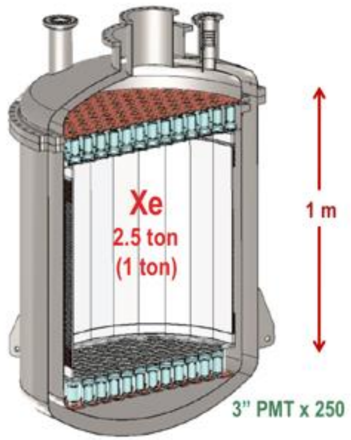
Scintillator detectors (20 kilotons)
- JUNO in China for reactor nus (construction)
- RENO-50 in Korea for reactor nus (plans)
- Baksan Large Volume Scintillator Detector (discussions in Russia)

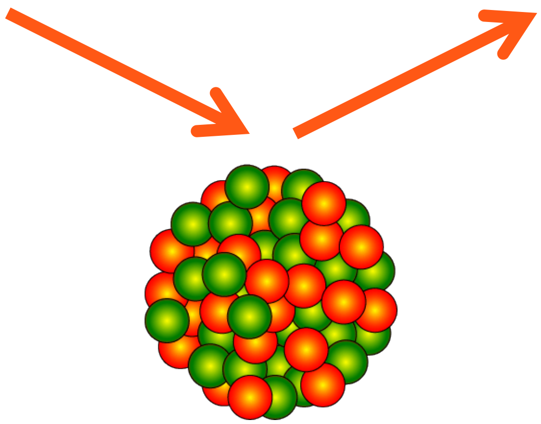


Liquid argon time projection chamber

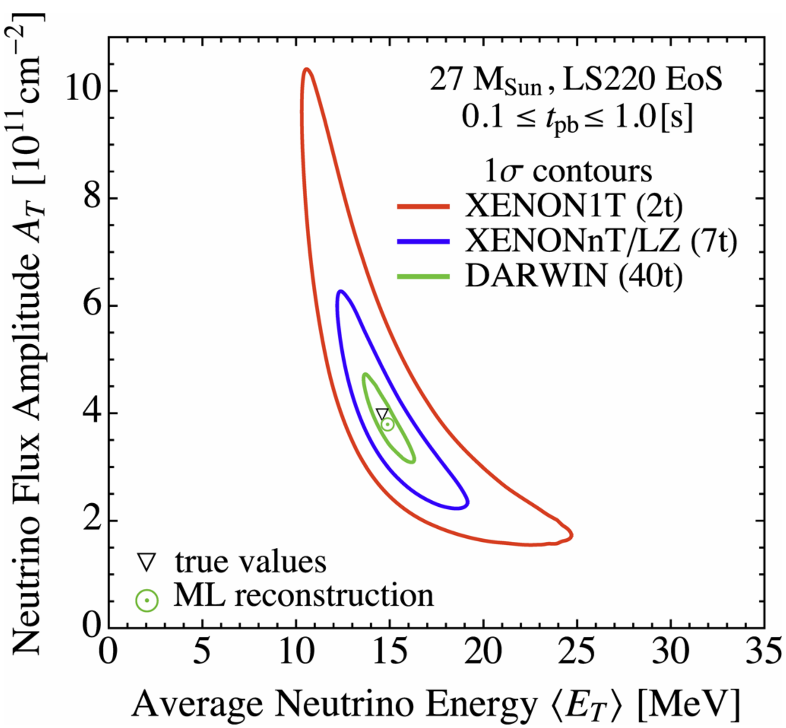
For long-baseline oscillation experiment DUNE
- Unique SN capabilities (CC ν_e signal)
- But cross sections poorly known

Xenon Dark Matter Detectors





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

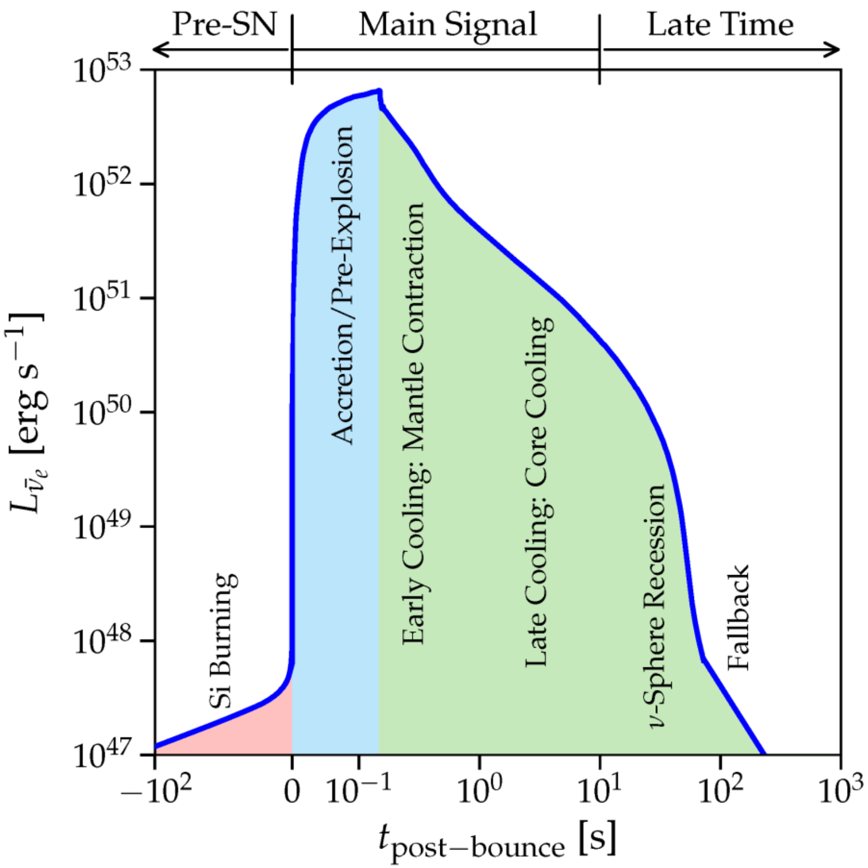


Pinning down SN neutrino flux and average energy

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)

Five Phases – Yet More 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.

Shifting Targets

Important questions circa 1987

- How many neutrino flavors? (Z decay width early 1990s)
- What are neutrino masses?
- Do neutrinos oscillate? (MSW effect 1985)
- How do core-collapse SNe explode? (Bethe-Wilson 1982–1985)

Status circa 2022

- Mass: restrictive cosmo limits, measurement “in the sky” foreseen
- KATRIN: sub-eV limit, new experiments foreseen
- Large mixing between three flavors (θ_{13} not small, 2012)
- Mass ordering and CP violation foreseen in the lab (JUNO, ...)
- Collective flavor conversion needs to be fully understood
- Modern SN models now in 3D, explosions probably ok
- Significant fraction of black-hole formation
- Huge amount of relevant astro observations