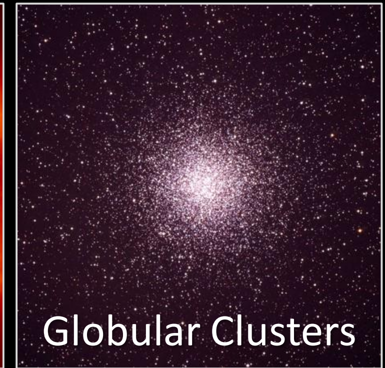
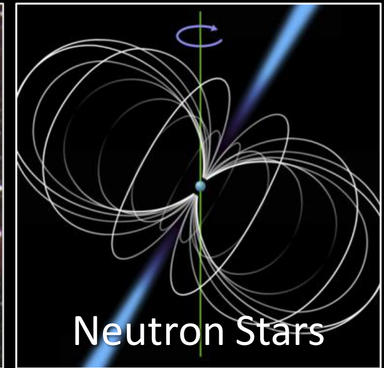
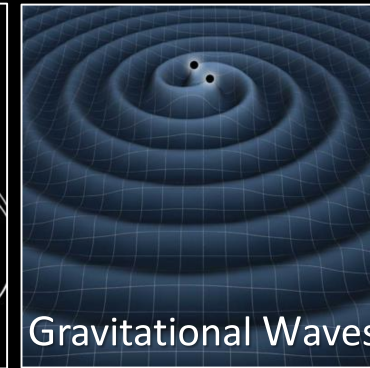






Axions from Supernovae

Old Ideas and New Developments

ORIGINS Excellence Cluster

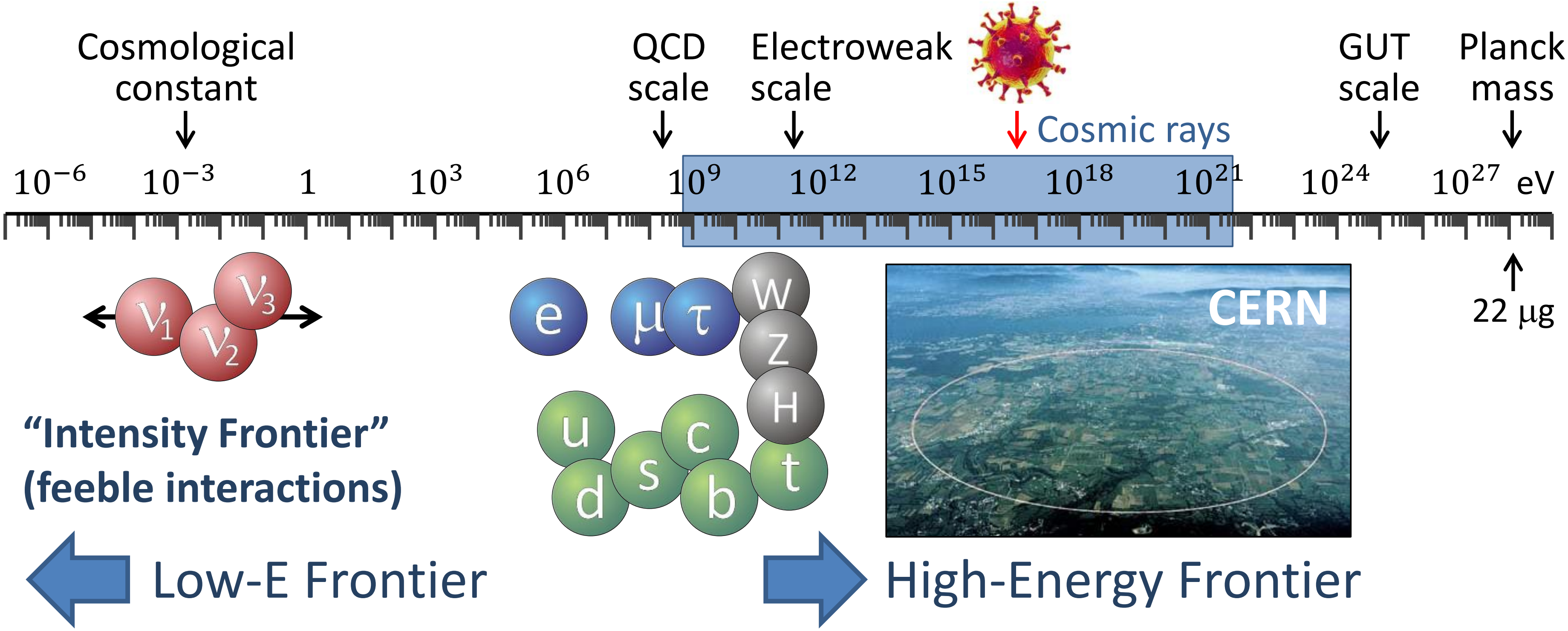
MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

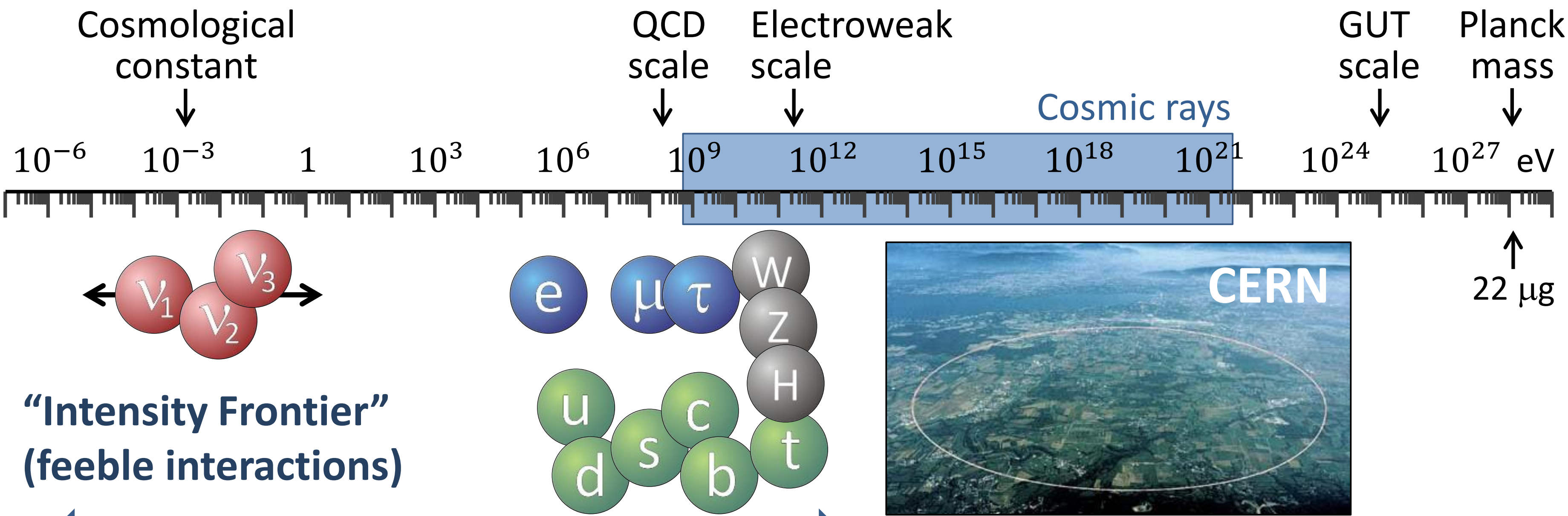
SFB 1258 | Neutrinos Dark Matter Messengers

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

High- and Low-Energy Frontiers in Particle Physics



High- and Low-Energy Frontiers in Particle Physics



Low-E Frontier

High-Energy Frontier

Neutrinos (active & sterile)
Axions & friends
Dark photons, fuzzy dark matter,
muon-philic bosons, …

} Feebly-interacting particles (FIPs) (e.g. CERN 2020 workshop report arXiv:2102.12143)

Some Early Papers on Stellar Particle Physics

Neutrinos

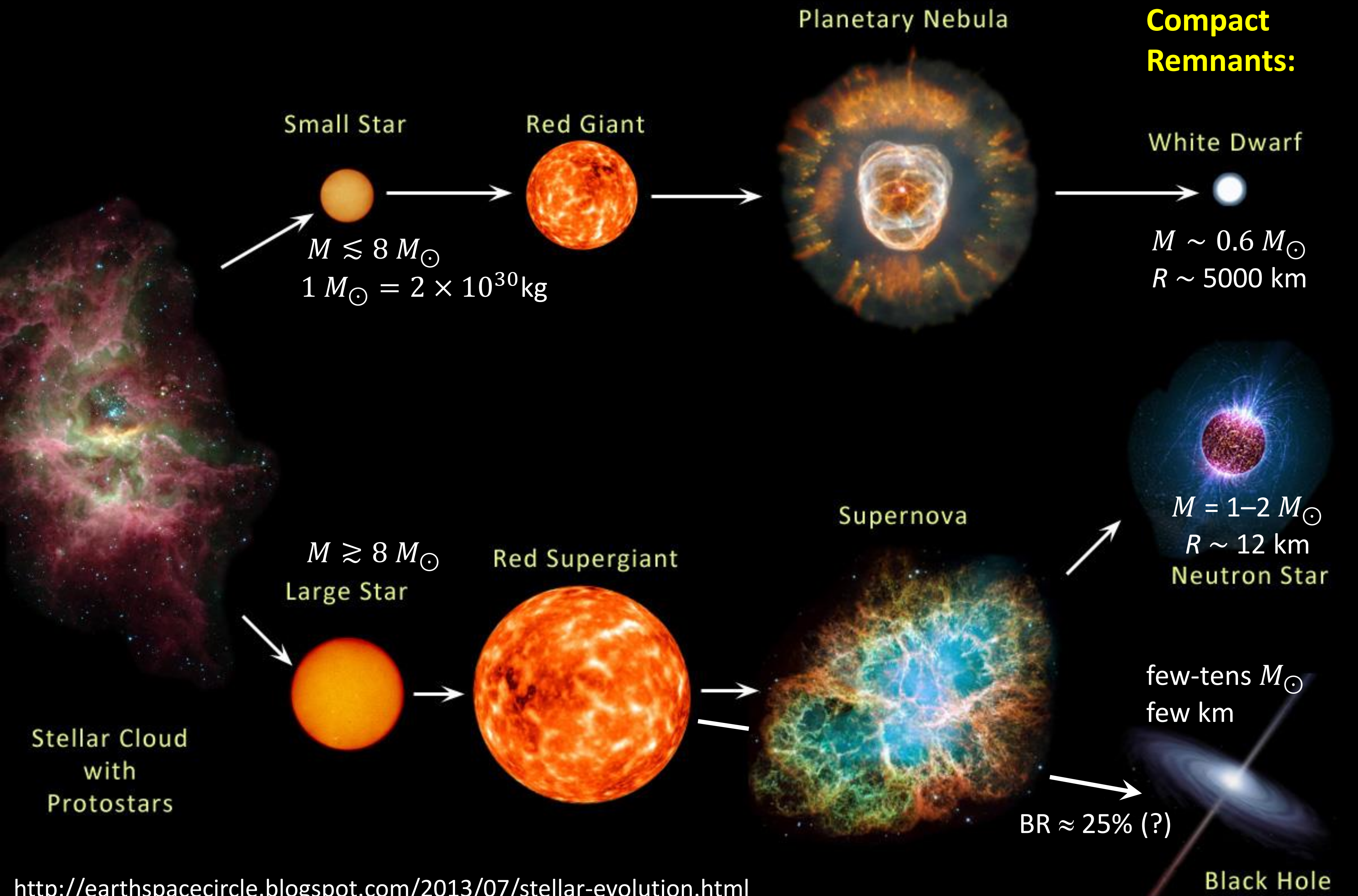
- Bernstein, Ruderman & Feinberg:
  Electromagnetic properties of the neutrino, Phys. Rev. 132 (1963) 1227
- Gribov & Pontecorvo:
  Neutrino astronomy and lepton charge, PLB 28 (1969) 493
- Cowsik:
  Limits on the radiative decay of neutrinos, PRL 39 (1978) 511
- Falk & Schramm:
  Limits from supernovae on neutrino radiative lifetimes, PLB 79 (1978) 511

Flavor oscillations!

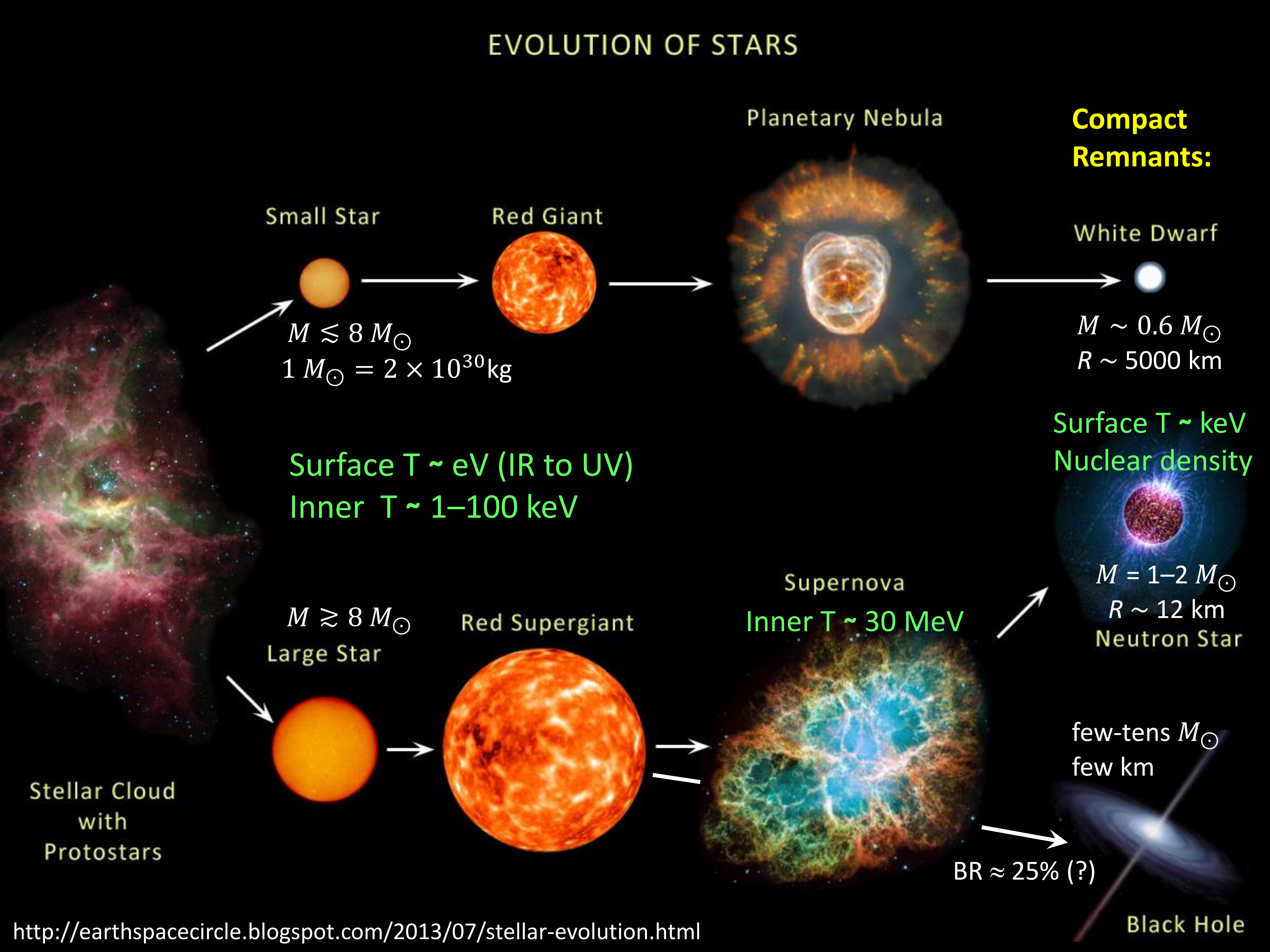
Axions & light Higgs (ca 1978)

- Vysotsky, Zeldovich, Khlopov & Chechetkin:
  Some astrophysical limitations on the axion mass,
  Pisma Zh. Eksp. Teor. Fiz. 27 (1978) 533 [JETP Lett. 27 (1978) 502]
- Dicus, Kolb, Teplitz & Wagoner:
  Astrophysical bounds on the masses of axions and Higgs particles, PRD 18 (1978) 1829
- K. O. Mikaelian: Astrophysical implications of new light Higgs bosons, PRD 18 (1978) 3605
- K. Sato: Astrophysical constraints on the axion mass and the number of quark flavors,
  Prog. Theor. Phys. 60 (1978) 1942

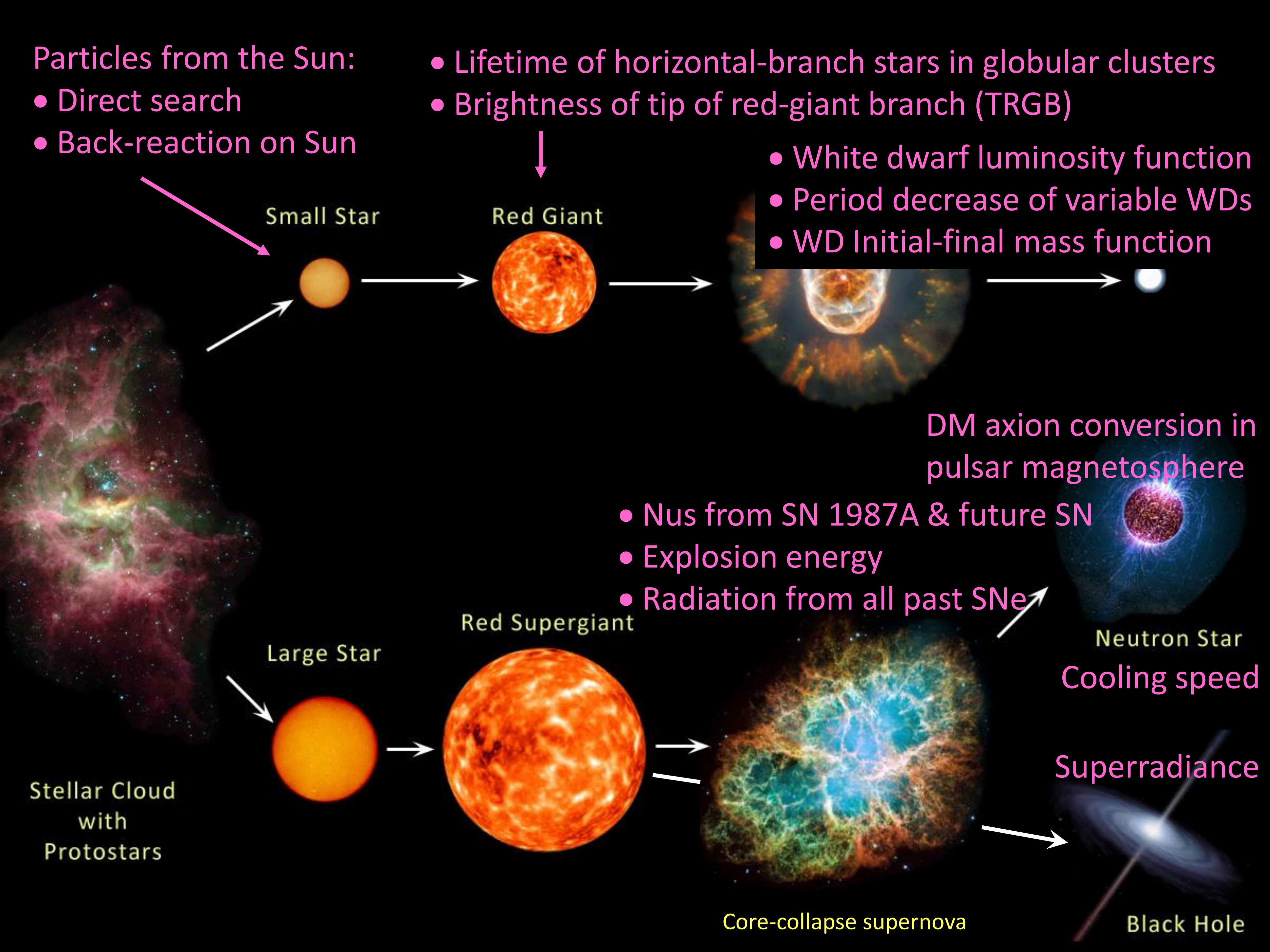
EVOLUTION OF STARS



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

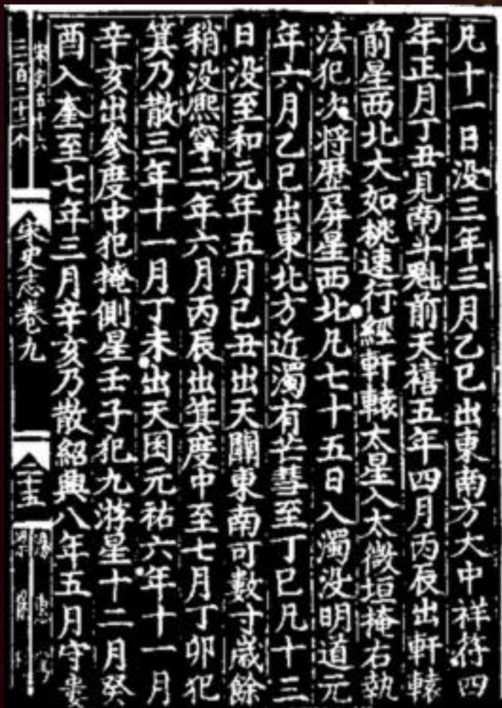


EVOLUTION OF STARS
Planetary Nebula
Compact Remnants:
Small Star
Red Giant
White Dwarf
$M \lesssim 8\ M_\odot$
$1\ M_\odot = 2 \times 10^{30}$kg
$M \sim 0.6\ M_\odot$
$R \sim 5000$ km
Surface T ~ keV
Nuclear density
Surface T ~ eV (IR to UV)
Inner T ~ 1–100 keV
Supernova
$M = 1–2\ M_\odot$
$R \sim 12$ km
Neutron Star
$M \gtrsim 8\ M_\odot$
Large Star
Red Supergiant
Inner T ~ 30 MeV
few-tens $M_\odot$
few km
Stellar Cloud with Protostars
BR ≈ 25% (?)
Black Hole
http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html



Particles from the Sun:
• Direct search
• Back-reaction on Sun
• Lifetime of horizontal-branch stars in globular clusters
• Brightness of tip of red-giant branch (TRGB)
• White dwarf luminosity function
• Period decrease of variable WDs
• WD Initial-final mass function
Small Star
Red Giant
DM axion conversion in pulsar magnetosphere
• Nus from SN 1987A & future SN
• Explosion energy
• Radiation from all past SNe
Red Supergiant
Large Star
Neutron Star
Cooling speed
Superradiance
Stellar Cloud with Protostars
Core-collapse supernova
Black Hole

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


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斿星十二月癸
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

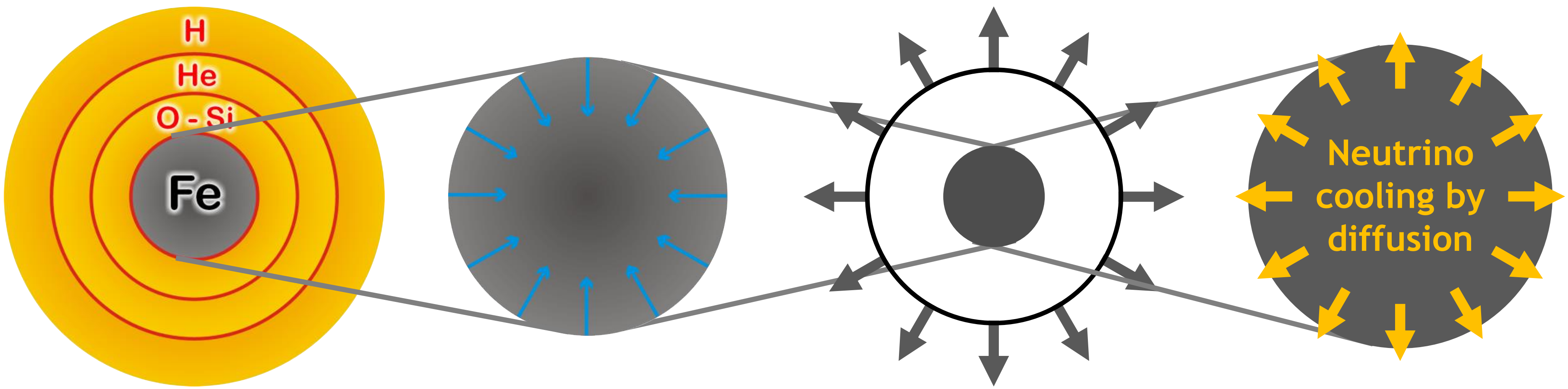
Core-Collapse Supernova Explosion

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

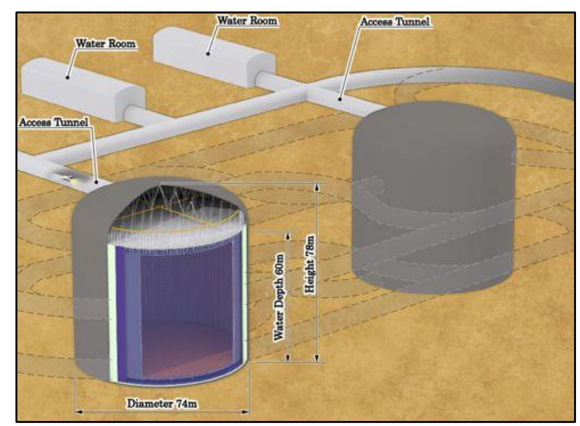
Collapse of degenerate core

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



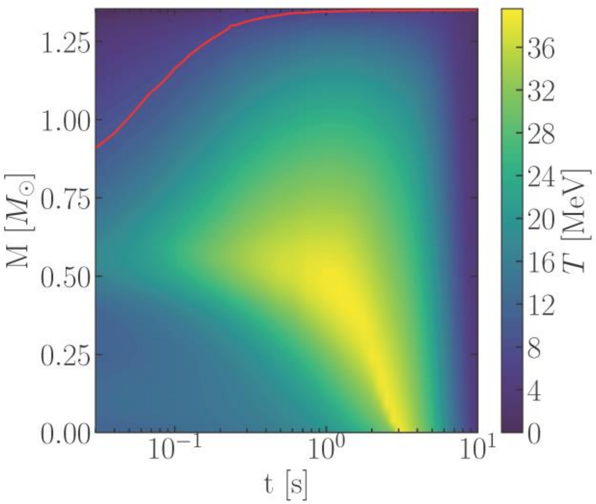
- Huge rate of low-E neutrinos (tens of MeV) over few seconds in large-volume detectors
- A few core-collapse SNe in our galaxy per century
- Once-in-a-lifetime opportunity



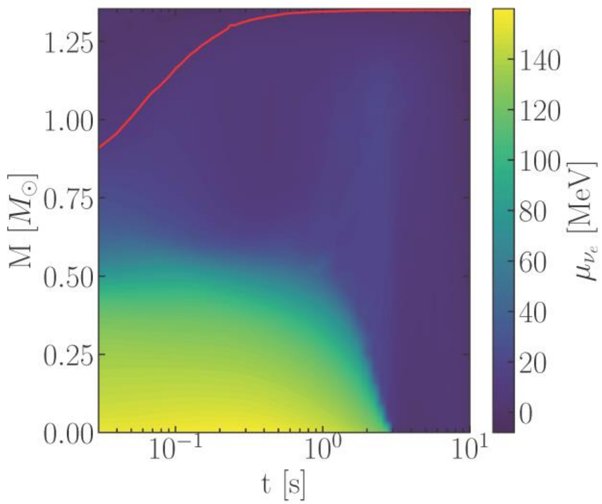
Inner Structure of a Typical Supernova Model

Muonic SN model from Garching group, used in [2005.07141]() and [2109.03244]()

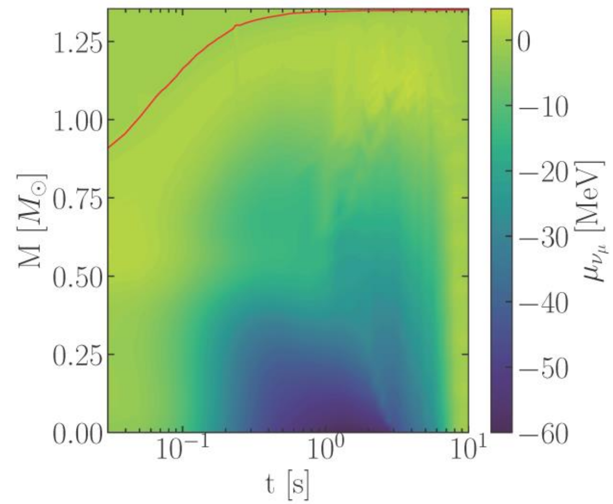
Temperature



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]())

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

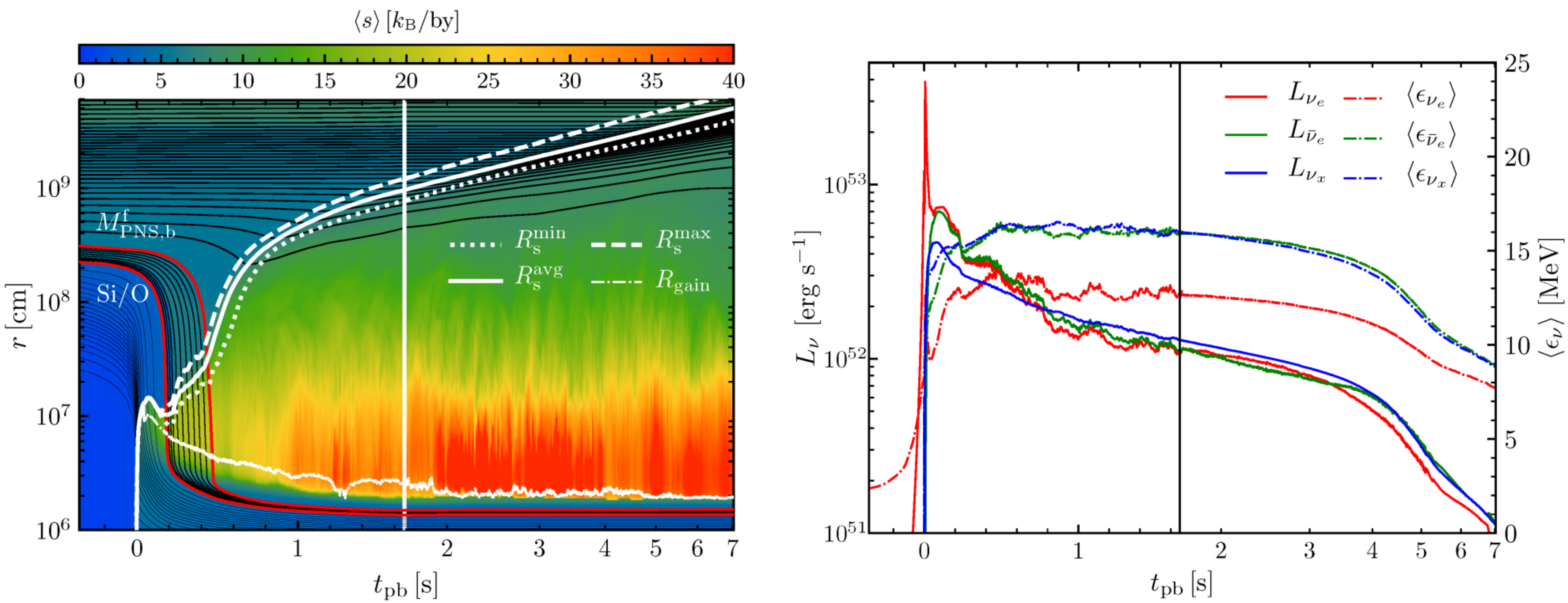
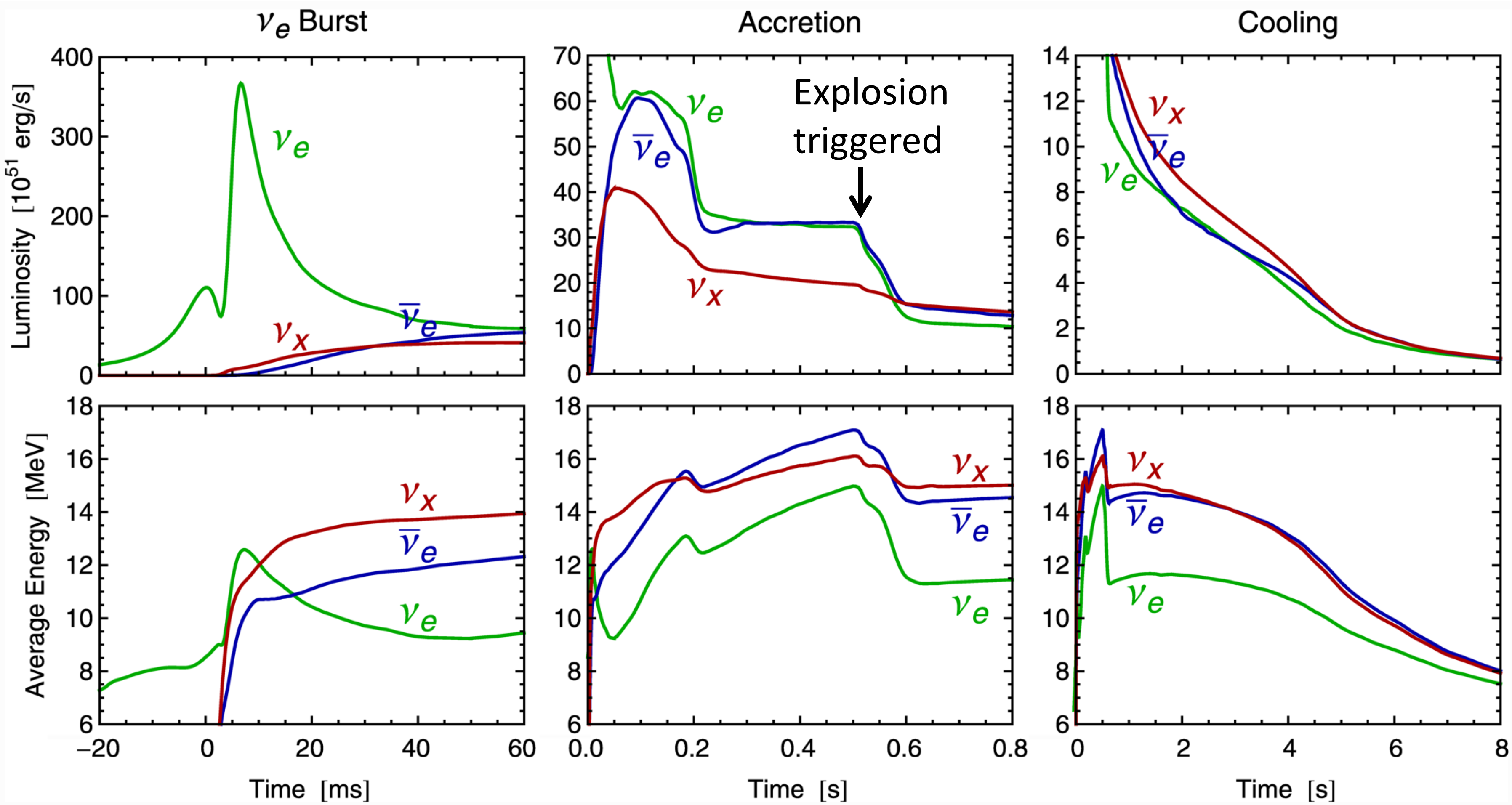


Figure 1. Explosion dynamics and neutrino emission of model `M_P3D_LS220_m−` and its extension `M_P3D_LS220_m−HC`. The time axes are chosen for optimal visibility. *Left:* Mass shells with entropy per nucleon color-coded. Maximum, minimum, and average shock radii, gain radius, and the mass shells of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

Three Phases of Neutrino Emission

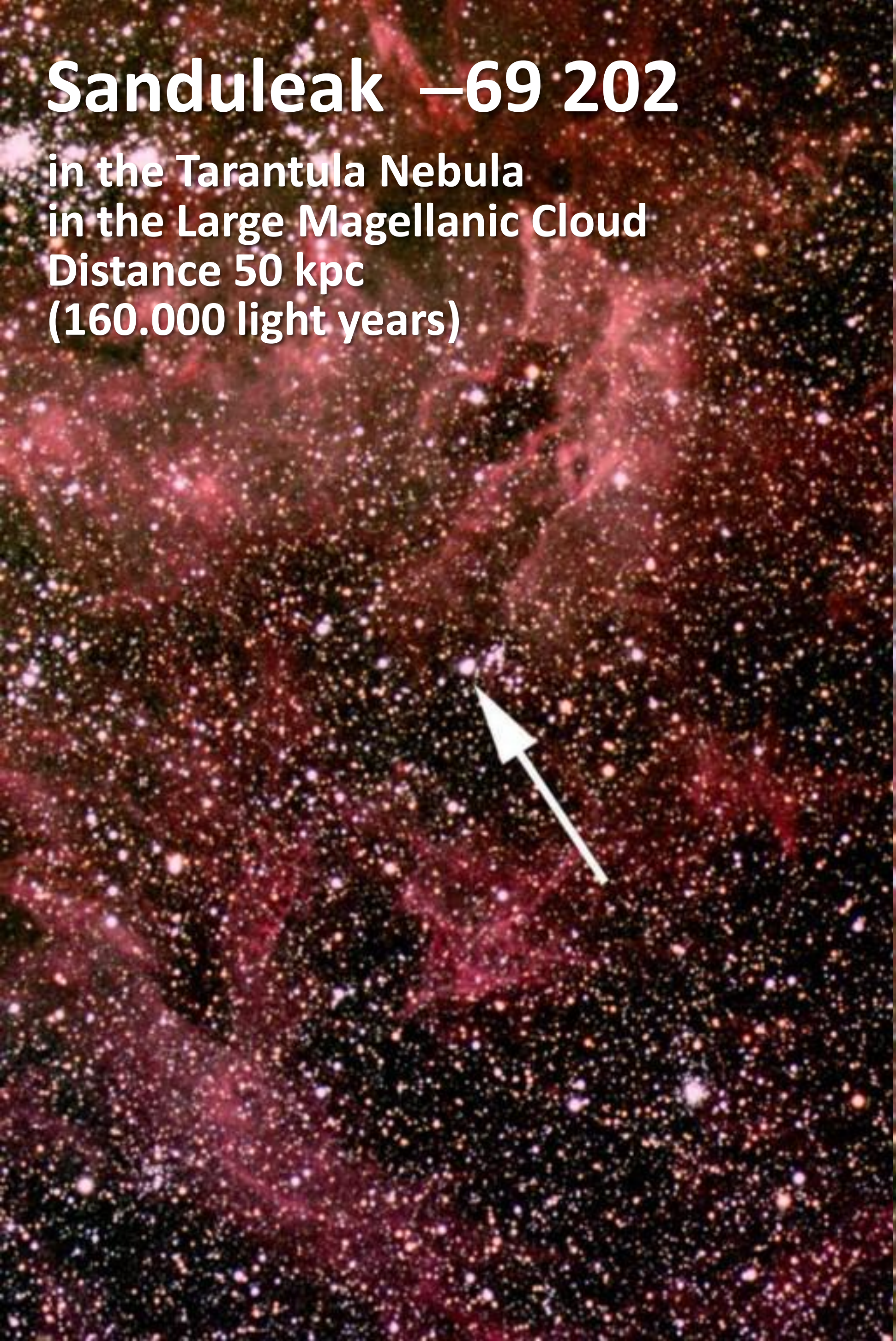


- Shock breakout
- De-leptonization of outer core layers

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

Cooling on neutrino diffusion time scale

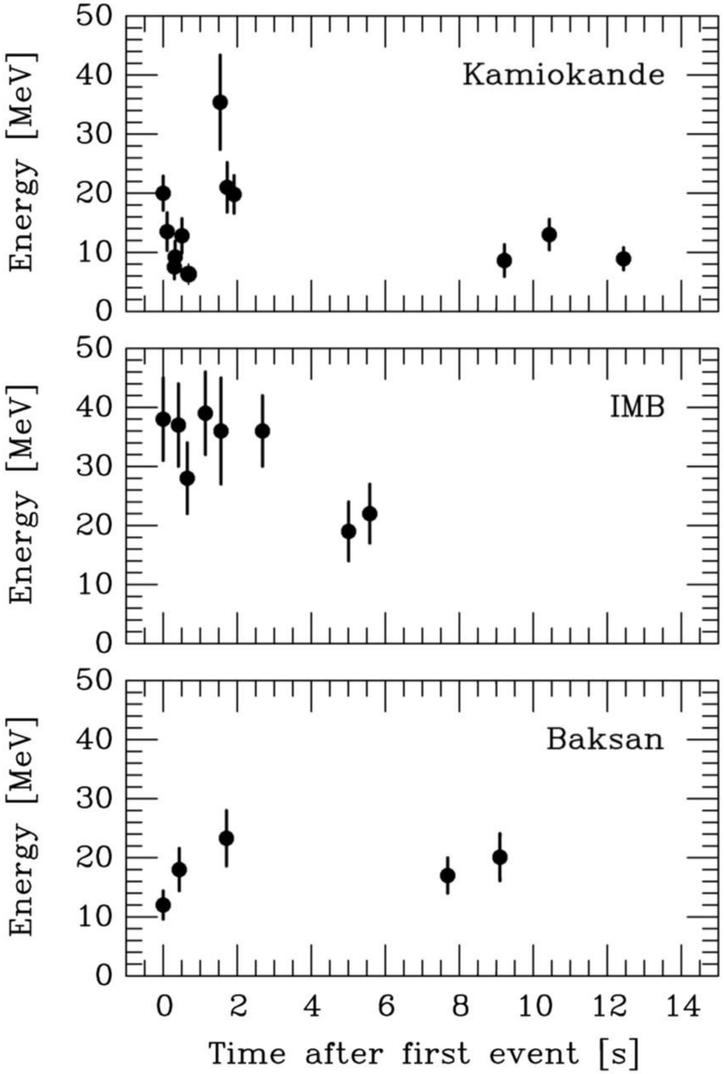
Spherically symmetric Garching model (25 $M_\odot$) with Boltzmann neutrino transport

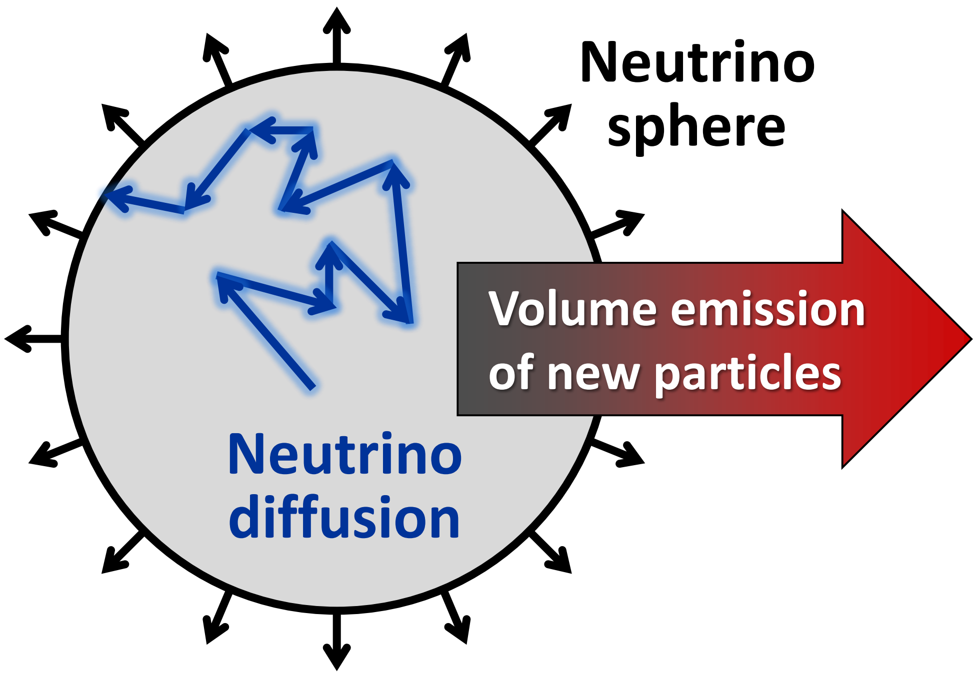

Sanduleak –69 202
in the Tarantula Nebula
in the Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)


Supernova 1987A
23 February 1987

Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal





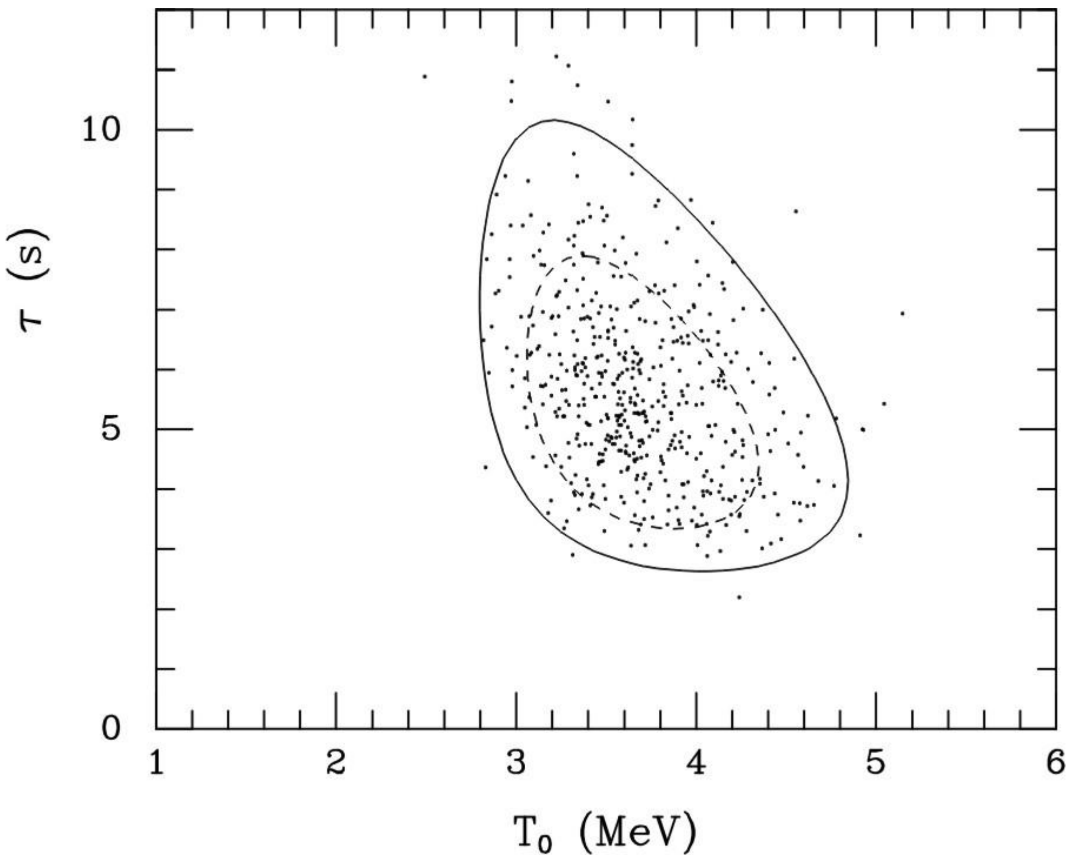
Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

Cooling Time Scale

Exponential cooling model: $T = T_0\, e^{-t/4\tau}$, constant radius, $L = L_0\, e^{-t/\tau}$

Fit parameters are T_0, τ, radius, 3 offset times for KII, IMB & BST detectors



Loredo and Lamb, Bayesian analysis
astro-ph/0107260

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Bounds on Exotic Particle Intera

https://inspirehep.net/

INSPIRE HEP Help

literature

Bounds on Exotic Particle Interactions from SN 1987a

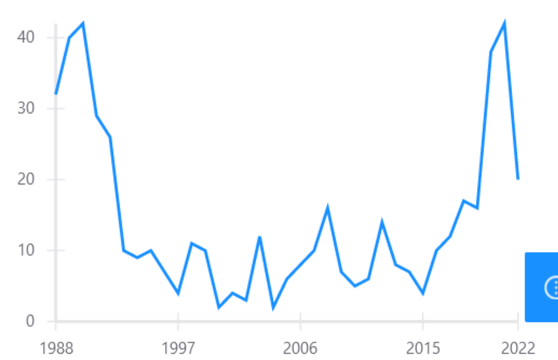
Georg Raffelt (UC, Berkeley, Astron. Dept. and LLNL, Livermore), David Seckel (UC, Santa Cruz)

Sep, 1987

10 pages
Published in: *Phys.Rev.Lett.* 60 (1988) 1793
DOI: 10.1103/PhysRevLett.60.1793
Report number: SCIPP-87/107
View in: OSTI Information Bridge Server

cite claim

Citations per year



Abstract: (APS)
The observation of a neutrino pulse from the supernova

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Axions from SN 1987a - INSPIRE

https://inspirehep.net/lite

INSPIRE HEP Help

literature

Axions from SN 1987a

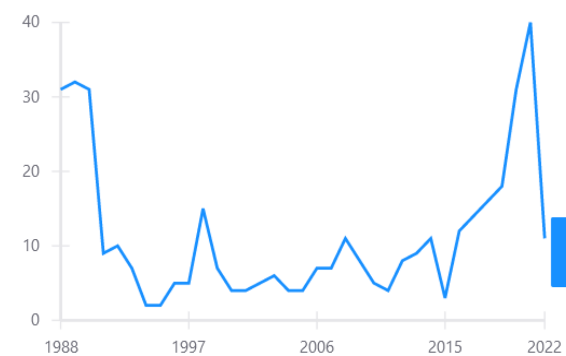
Michael S. Turner (Fermilab and Chicago U., EFI and Chicago U., Astron. Astrophys. Ctr.)

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

pdf links cite claim

Citations per year



Abstract: (APS)

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Constraints on Axions from SN 1

https://inspirehep.net/

INSPIRE HEP Help

literature

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

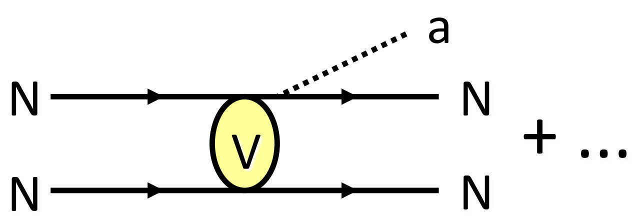
9 pages
Published in: *Phys.Lett.B* 203 (1988) 188-196
Published: 1988
DOI: 10.1016/0370-2693(88)91595-X
Report number: FERMILAB-PUB-87-225-A, EFI-87-104-CHICAGO, UMN-TH-637-87, CERN-TH-4887-87
View in: CERN Document Server

pdf links cite claim

Citations per year

Axion Emission from a Nuclear Medium

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



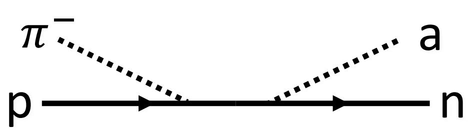
Nucleon-Nucleon
Bremsstrahlung

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:1906.11844v3 (28 May 2020)

Thermal π^- contribute significantly (dominantly?)



→ For latest discussion see Carenza et al. arXiv:2010.02943 (06 Oct 2020)

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 [1906.11844v3]
  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 [arXiv: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)

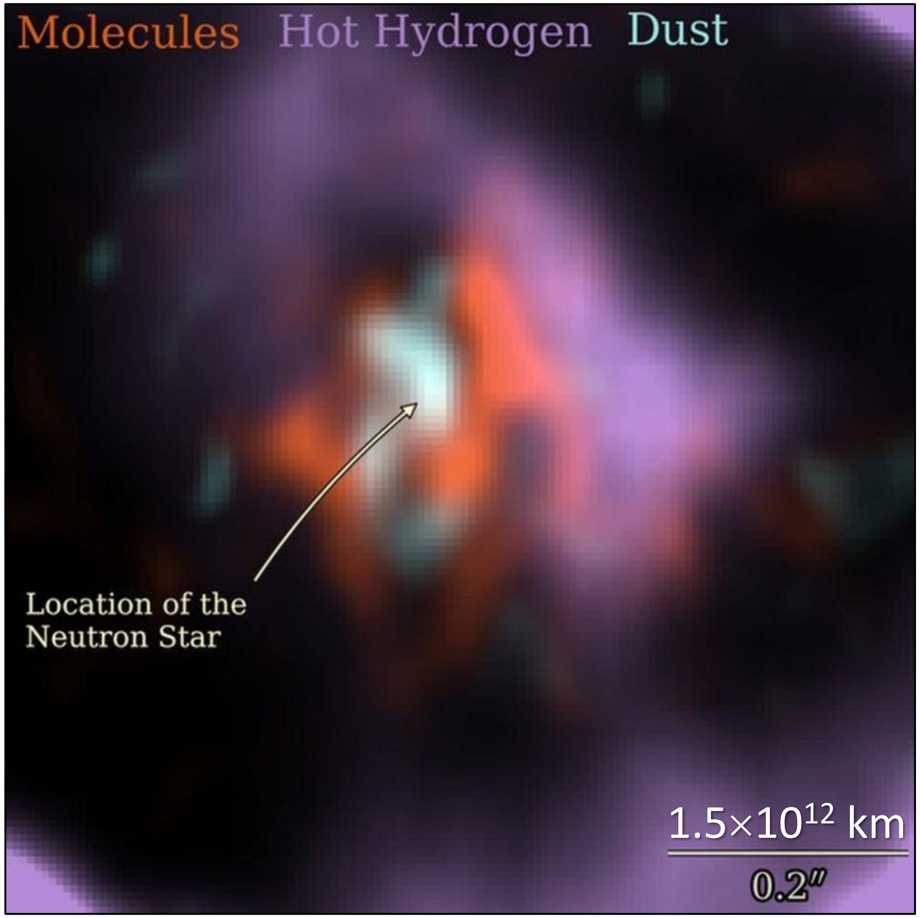
- Bar, Blum & D'Amico, Is there a supernova bound on axions? [1907.05020]
  Alternative picture of SN explosion (thermonuclear event)
  Observed signal not PNS cooling. SN1987A neutron star (or pulsar) not yet found.
  (but see "NS 1987A in SN 1987A", Page et al. arXiv:2004.06078)

Where is the Neutron Star of SN 1987A?

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

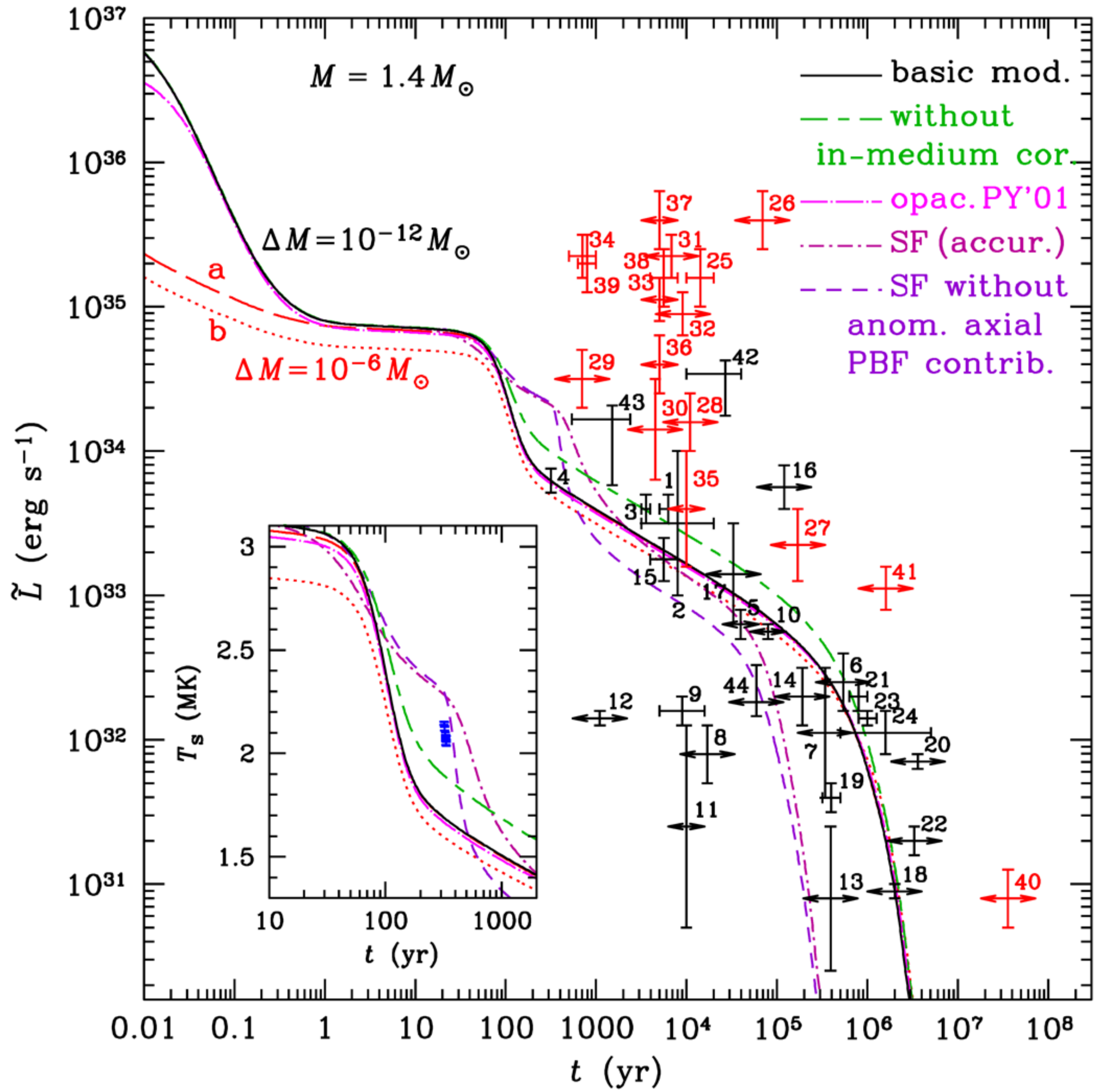
- Infra-red excess observed by ALMA: In “the blob” strong indication for NS
  Expected position, remnant hidden by dust [Cigan+ arXiv:1910.02960]
- Most plausible model: Thermally cooling non-pulsar NS [Page+ arXiv:2004.06078]

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



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

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
- 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 $C_n m_a \lesssim 2\ \mathrm{meV}$
  $g_{an}^2 < 1.1 \times 10^{-19}$

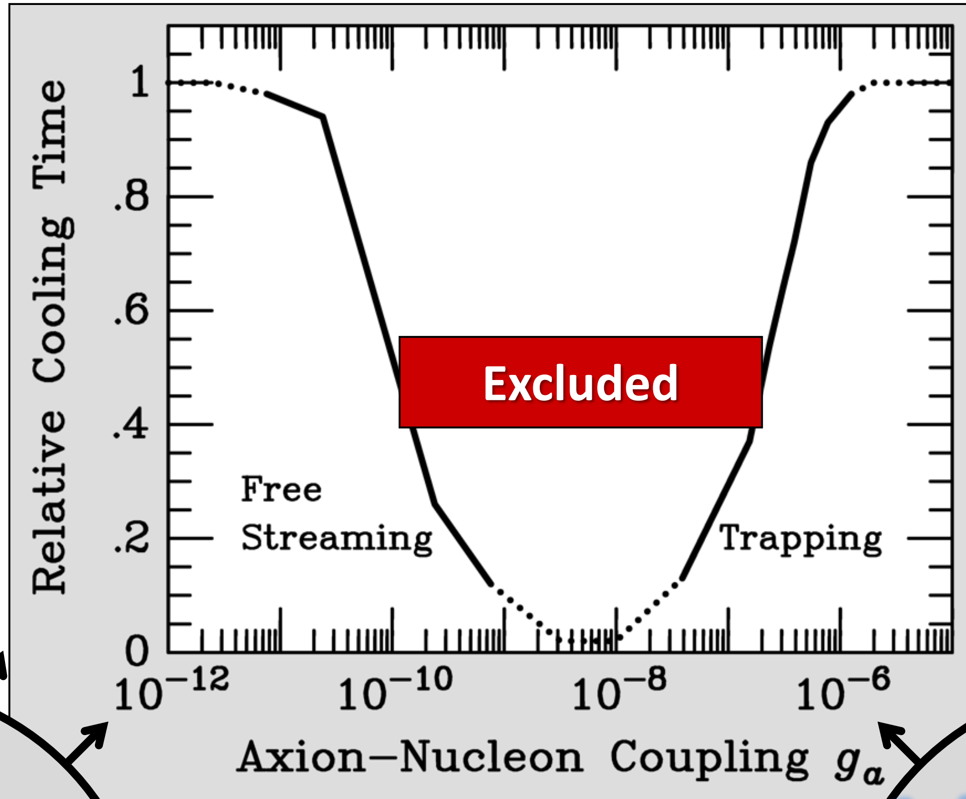
Magnificent Seven & PSR J0659 (ages $> 10^5$ years)

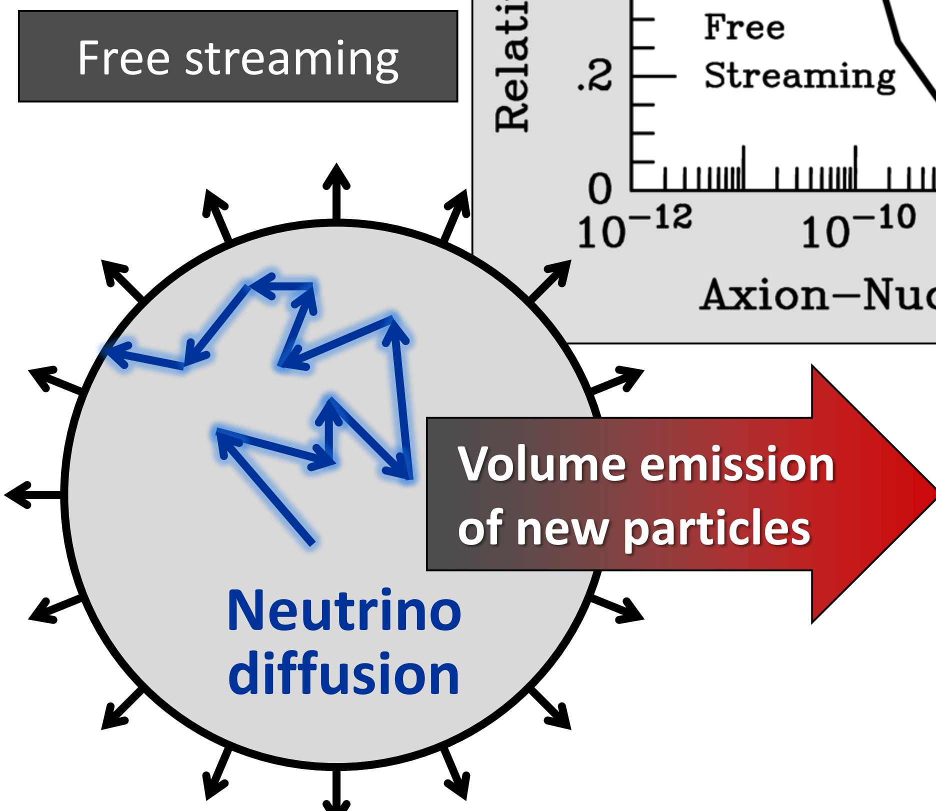
- Buschmann et al. arXiv:2111.09892
  $m_a < 16\ \mathrm{meV}$ (95% CL) for KSVZ axions

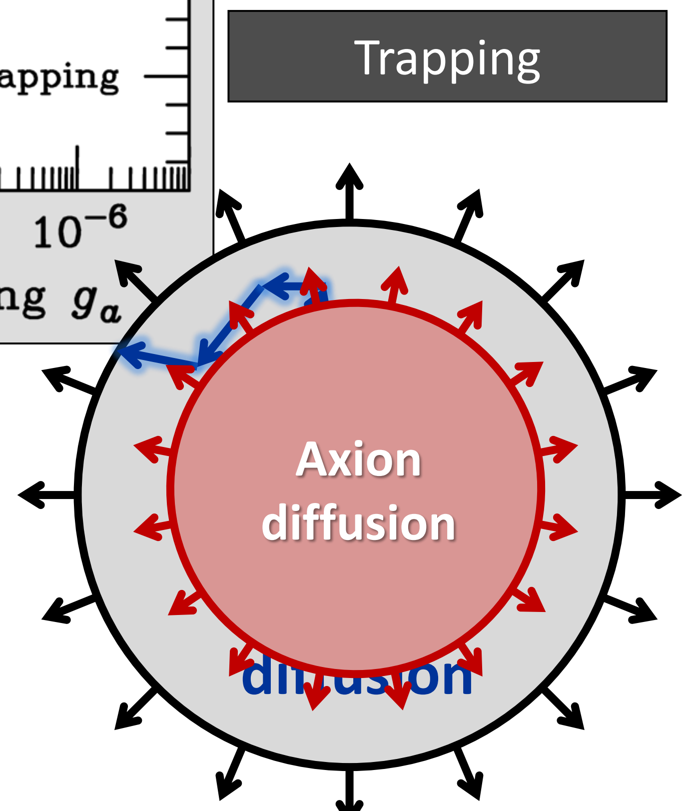
Limits broadly comparable to SN 1987A bounds (m_a tens of meV range) with different systematics

SN 1987A Axion Limits

Based on numerical simulations of
Burrows, Turner & Brinkmann
PRD 39 (1989) 1020
Burrows, Ressell & Turner
PRD 42 (1990) 3297





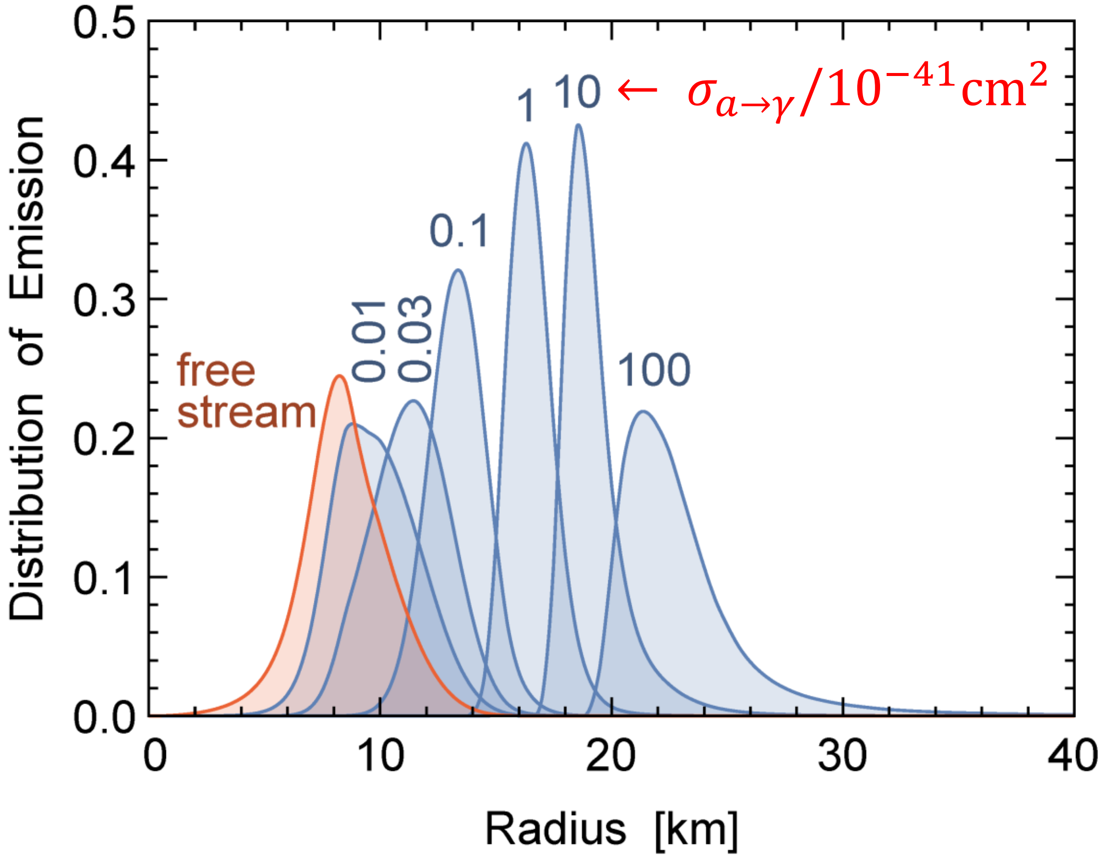


Radiative Transfer in Stars by Feebly Interaction Bosons

Brand New

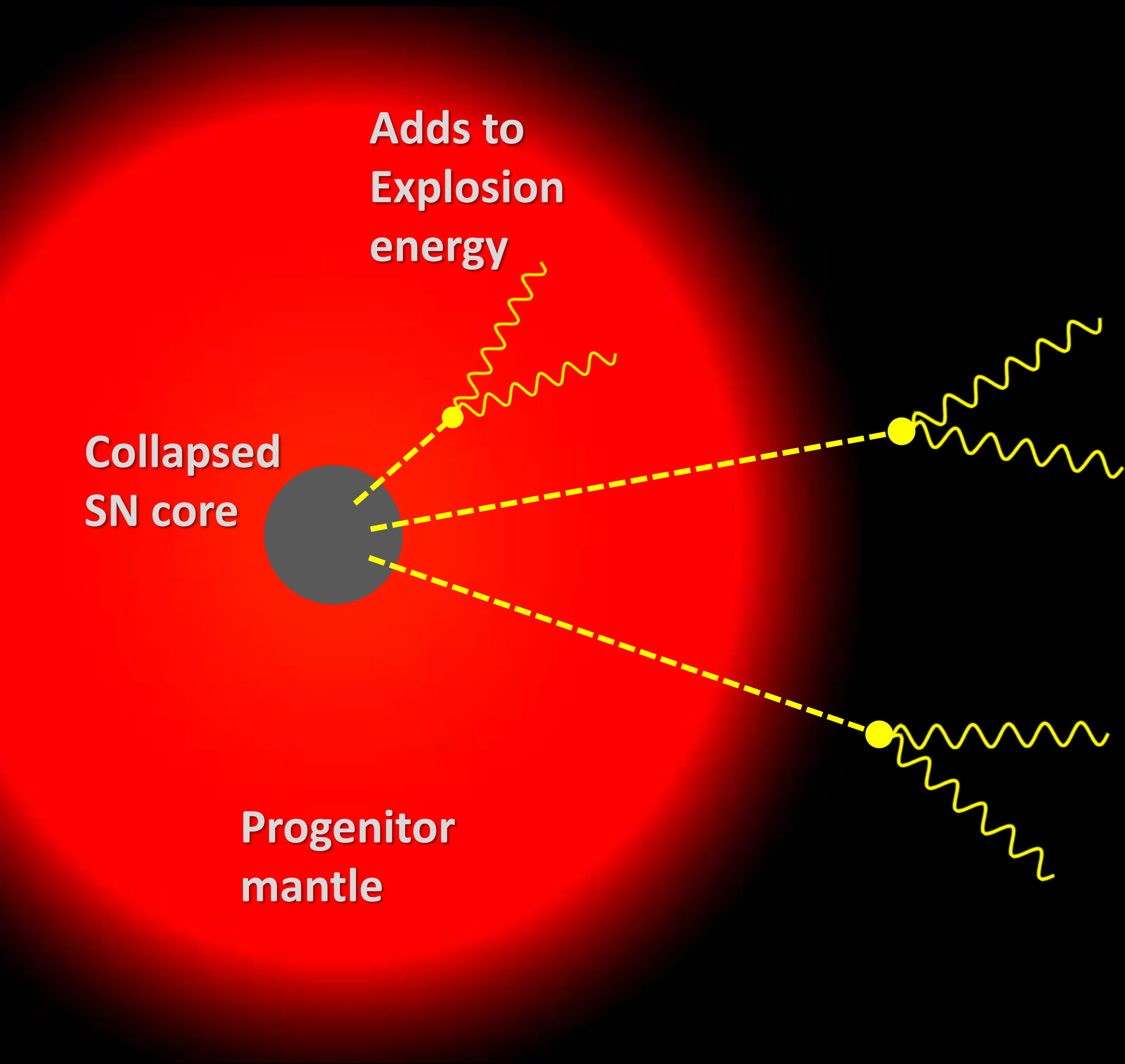
Caputo, Raffelt & Vitagliano, [2204.11862](https://arxiv.org/abs/2204.11862), JCAP 2022

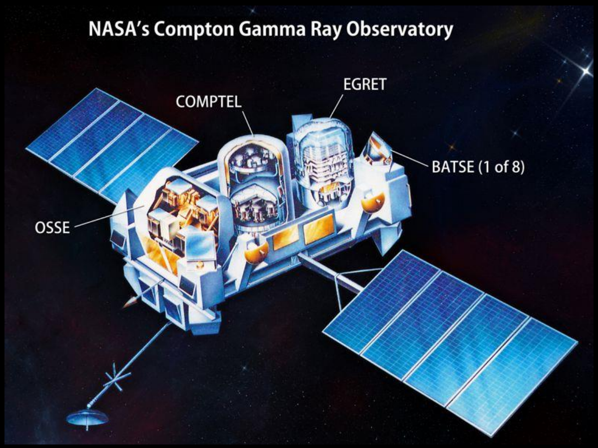
- Bosons that are emitted or absorbed (no scattering)
- Integral kernels for spherical (not only plane parallel) geometry
- Connection between "volume emission" and "axion sphere"
- Specifically ALPs, Primakoff process $a + Ze \leftrightarrow Ze + \gamma$



Trapping limit:
volume emission from thick surface layers well approximated by Stefan-Boltzmann Law from "axion sphere"

Supernova Bounds on Radiative Particle Decays





Cosmic gamma ray background from all past supernovae

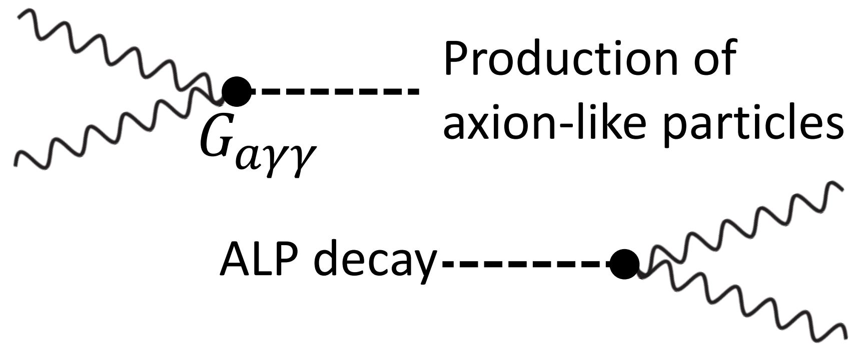
Solar Maximum Mission

No excess gamma rays @ SN 1987A neutrino burst

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

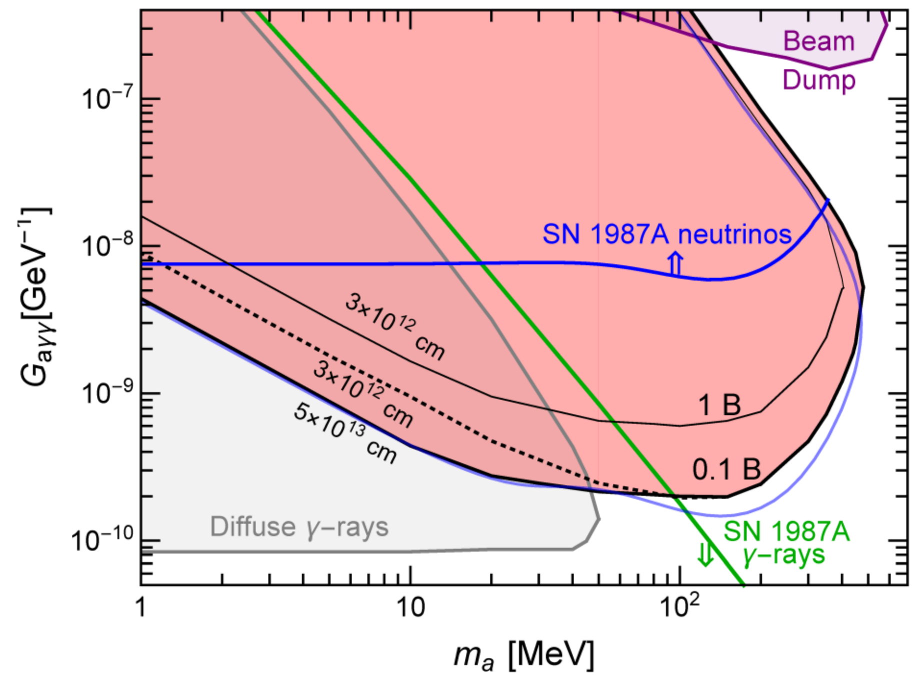


Typical SN explosion energy 1–2 B

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–$0.22\ M_{SUN}$)

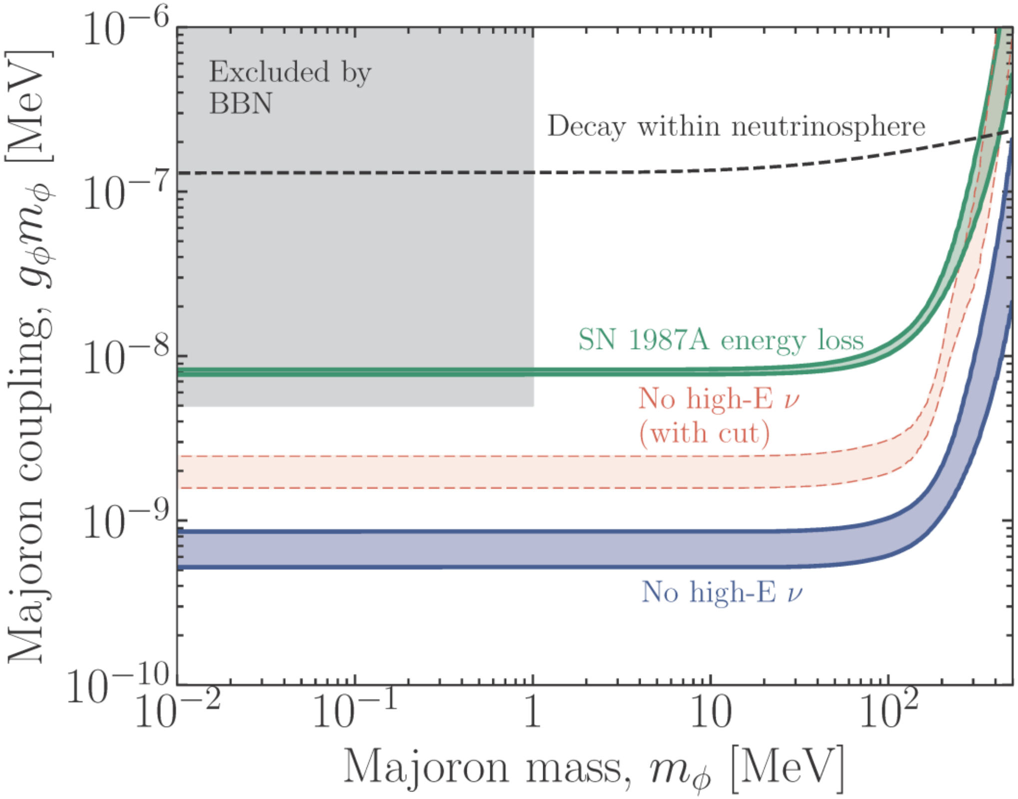


Strong Supernova 1987A Constraints on Bosons Decaying to Neutrinos

Brand New

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

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

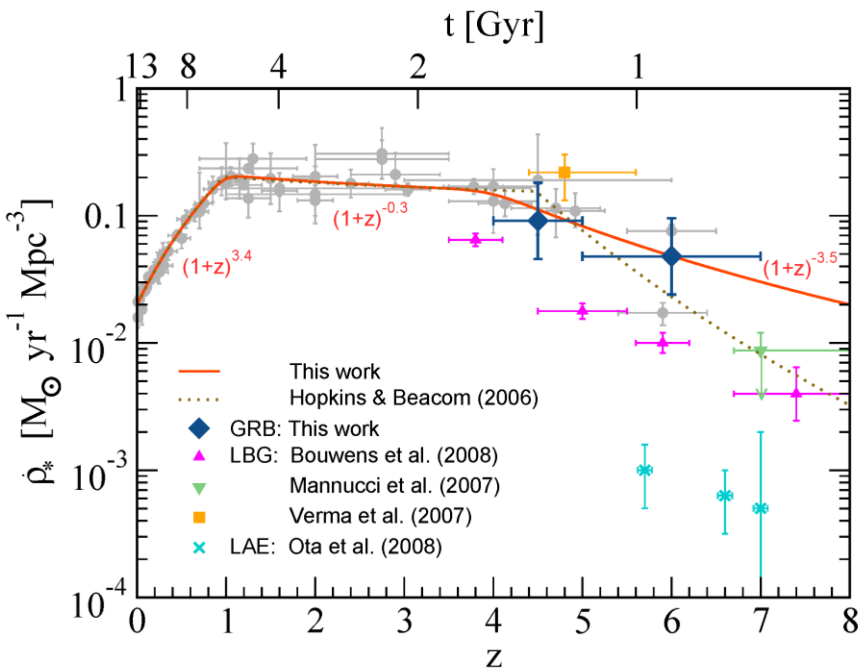
- Production by coalescence

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

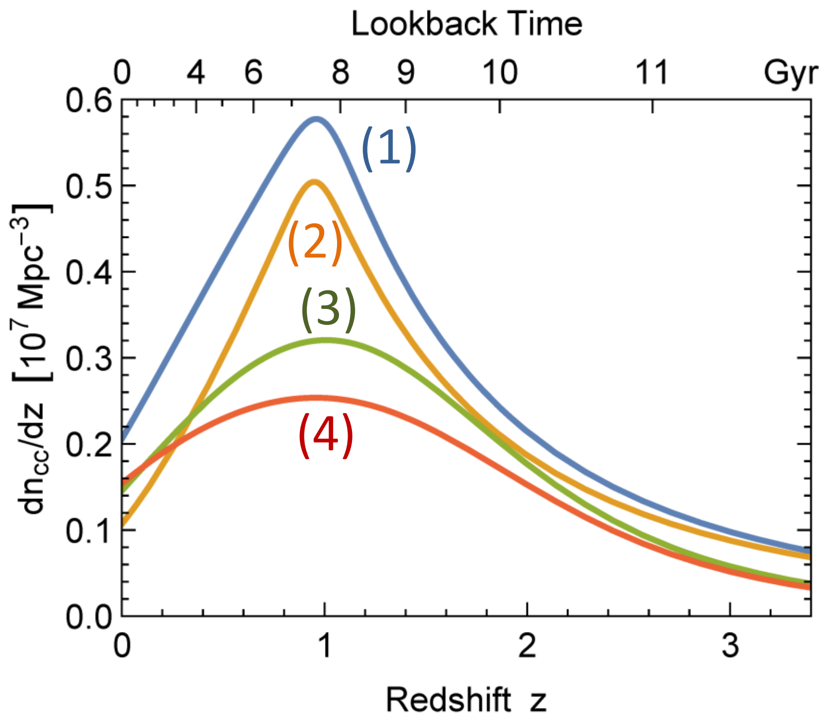
- Decay outside SN to all flavors

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

Star-formation rate (1)



Core-collapse distribution



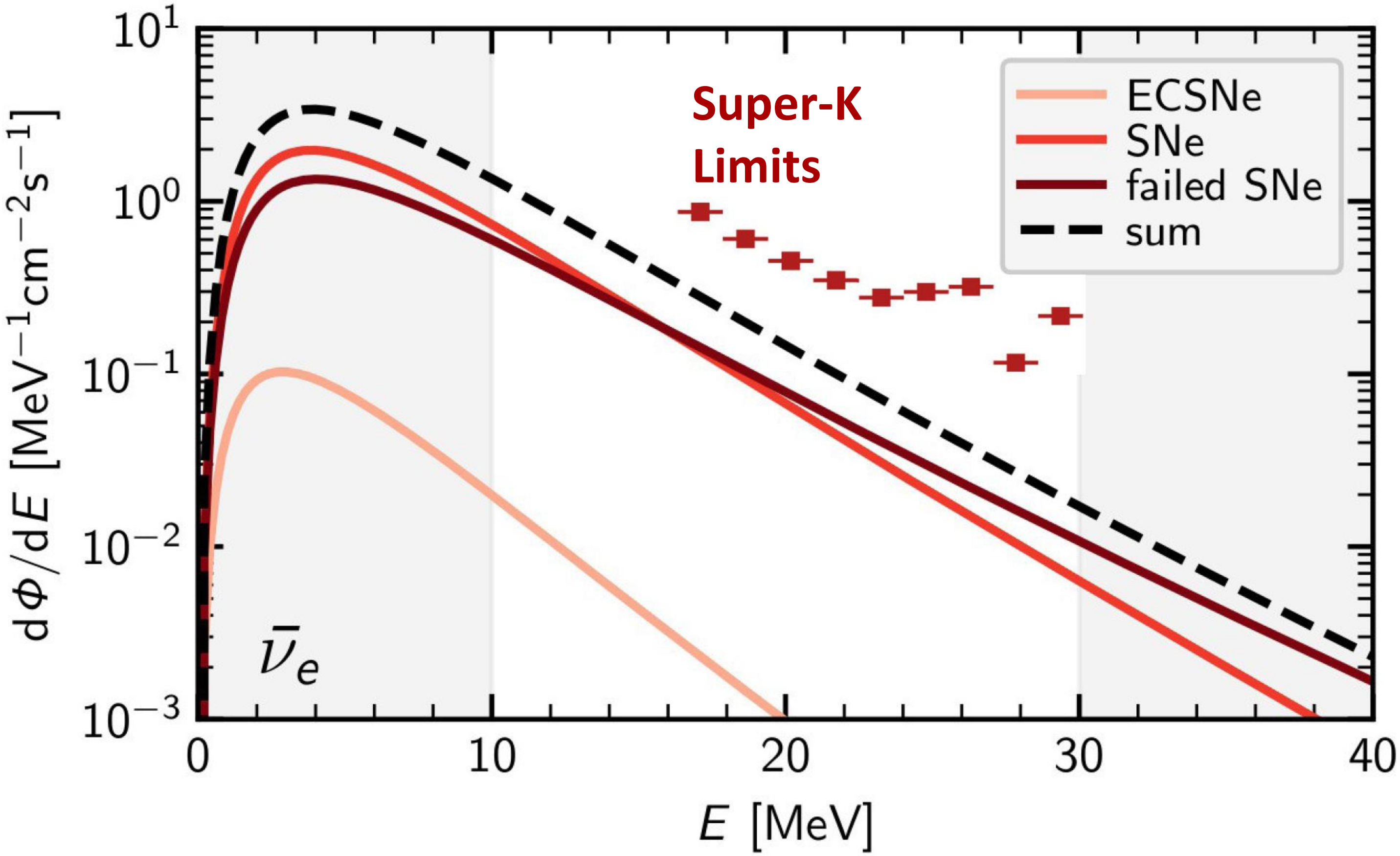
(1) Yüksel+ arXiv:0804.4008
(2) Mathews+ arXiv:1405.0458
(3) Robertson+ arXiv:1502.02024
(4) Madau+ arXiv:1403.0007

Total core collapse density
$0.6 - 1 \times 10^7\ \mathrm{Mpc}^{-3}$

DSNB Prediction

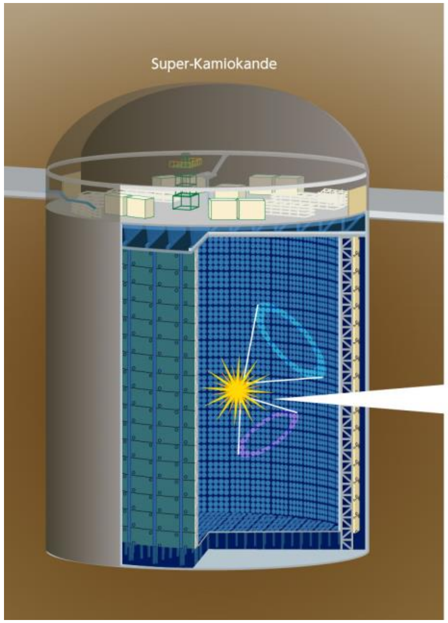
Kresse+, arXiv:2010.04728

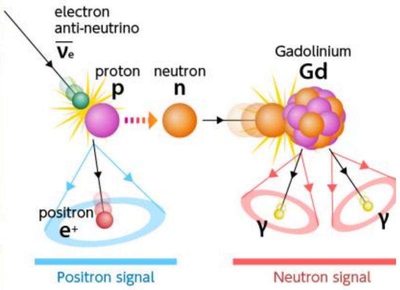
For latest Super-K limits see arXiv:2109.11174



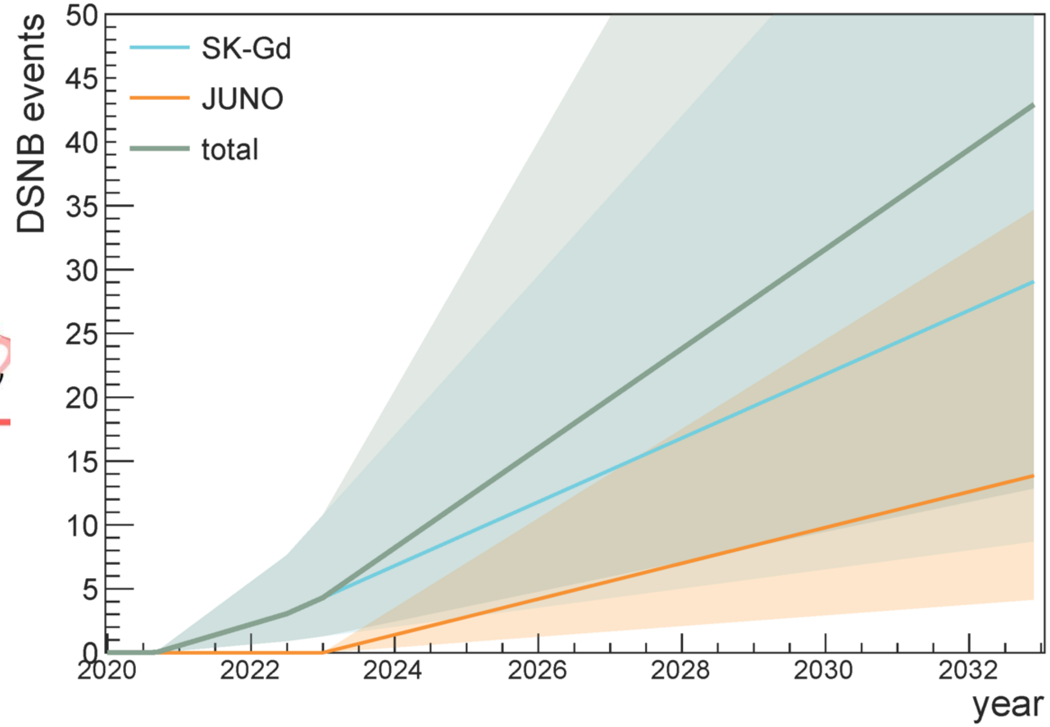
In the detection window, essentially $\frac{d\Phi}{dE} \propto e^{-E/E_0}$

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

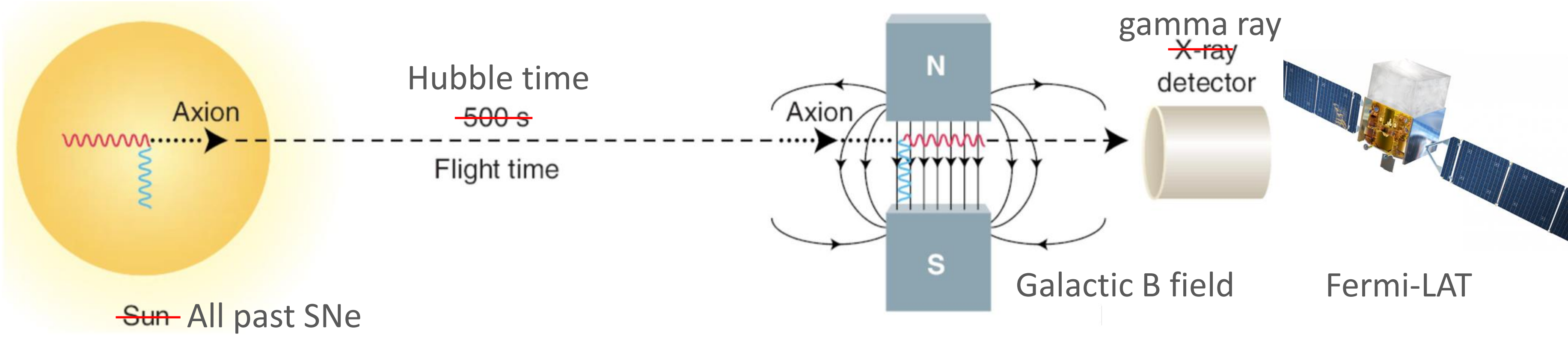
JUNO
Liquid Scintillator
17 kt fiducial
Data taking 2023

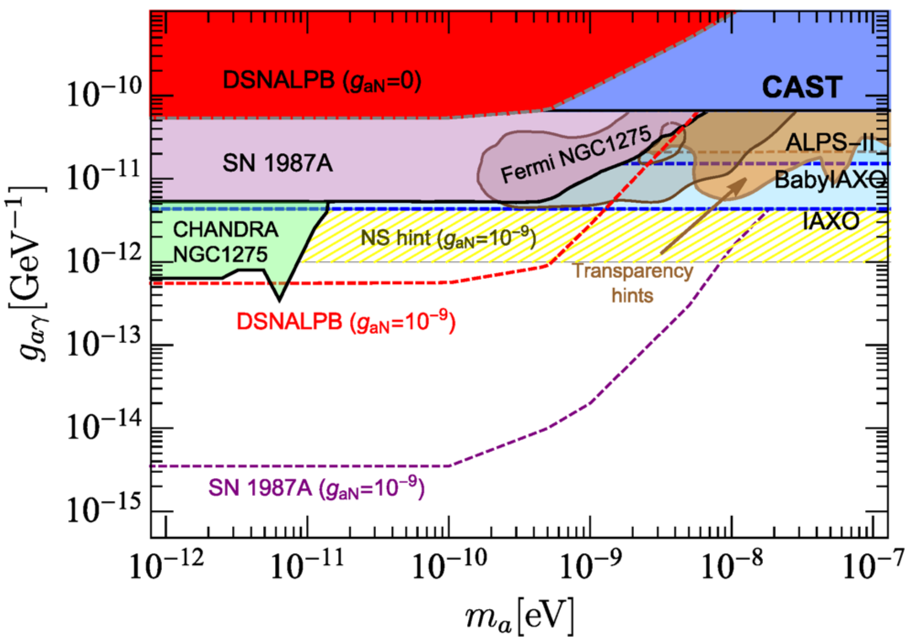
PHYSICAL REVIEW D **102**, 123005 (2020)

arXiv:2008.11741
2110.03679

Bounds on axionlike particles from the diffuse supernova flux

Francesca Calore,[1,*] Pierluca Carenza,[2,3,†] Maurizio Giannotti,[4,‡] Joerg Jaeckel,[5,§] and Alessandro Mirizzi[2,3,∥]





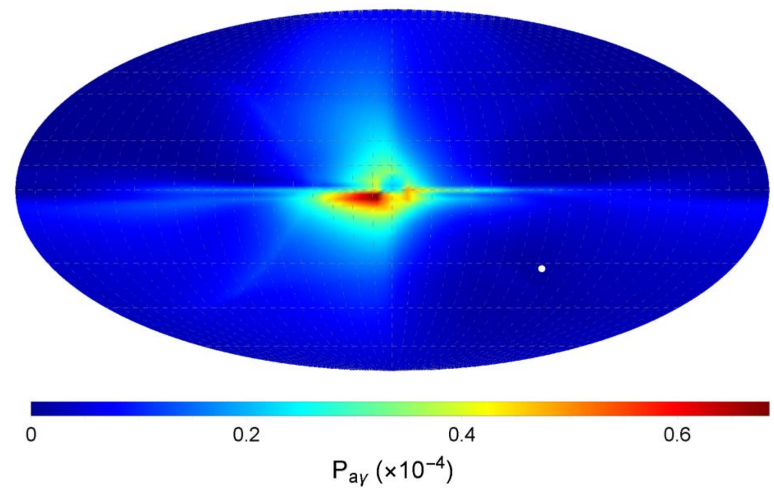


FIG. 3. Sky map in Galactic coordinates of the $a \to \gamma$ conversion probability, starting from a pure ALPs beam at the outside boundary of the Galaxy, for the Jansson and Farrar magnetic field model derived in [36]. We have taken the energy to be $E = 50$ MeV, the coupling $g_{a\gamma} = 3 \times 10^{-13} \mathrm{GeV}^{-1}$

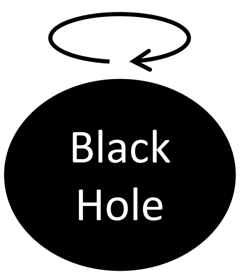
Axion Detection Opportunities from Stars

m_{Planck} ↓

f_a 10^{18} 10^{15} 10^{12} 10^{9} 10^{6} GeV

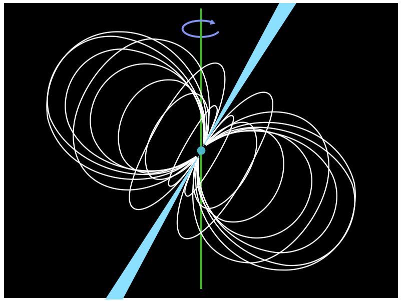
peV neV μeV meV eV m_a

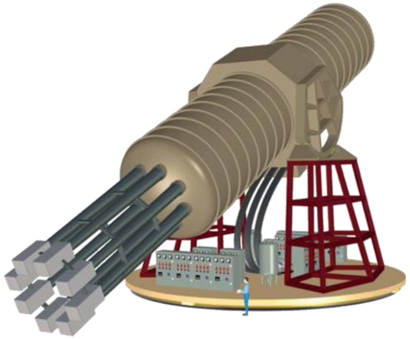
Super Radiance



Opportunities for detection

Astrophysical Bounds (Energy loss of stars)





IAXO Solar Axion Telescope

Axion conversion in neutron star magnetospheres