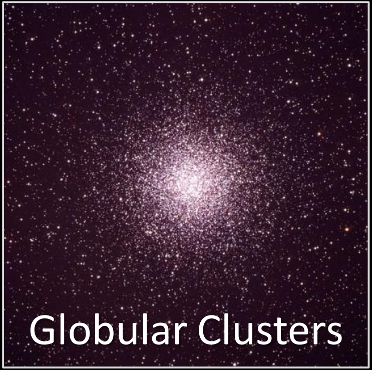
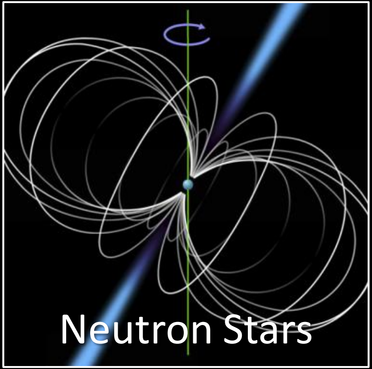
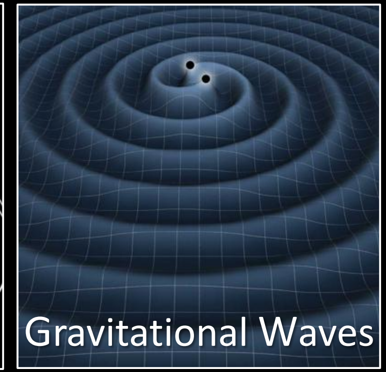


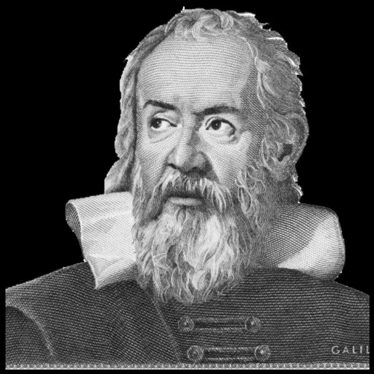




Axions and the Stars

Old Ideas and New Developments

GGI, Florence, April 2023



ORIGINS Excellence Cluster

COSMIC WISPERS CA21106

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

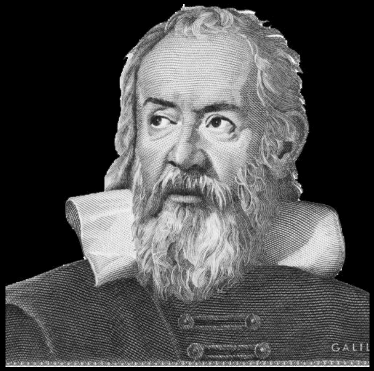
SFB 1258 Neutrinos Dark Matter Messengers

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

Axions and the Stars

Old Ideas and New Developments

GGI, Florence, April 2023

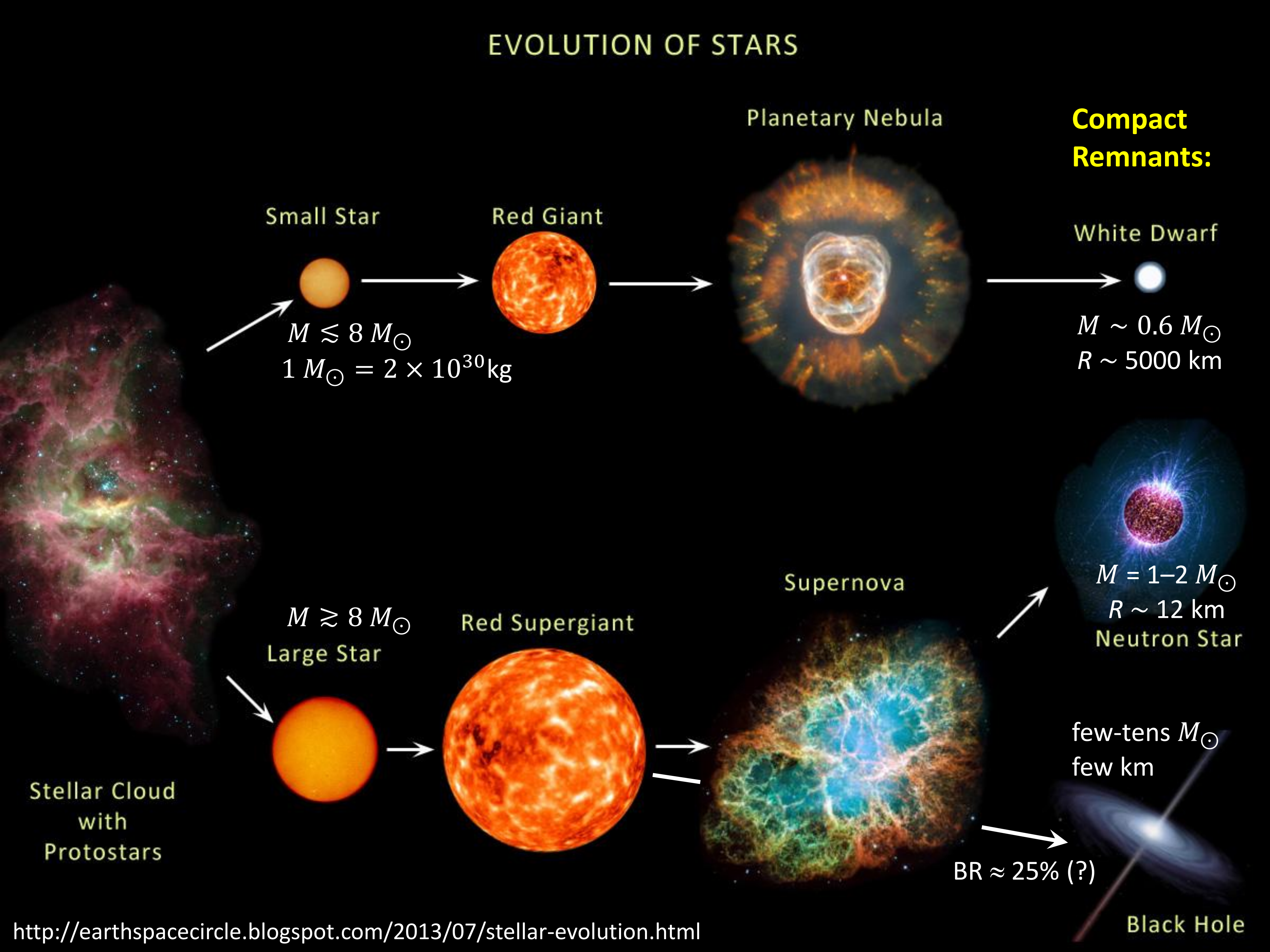


Lecture I: Axions and ordinary stars

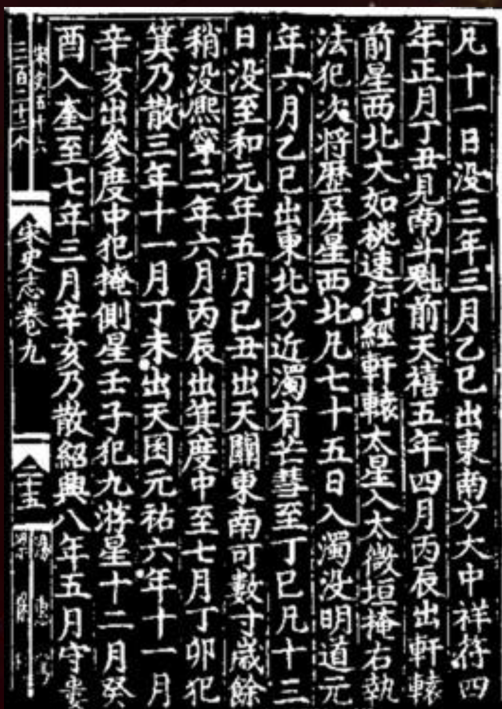
- Detection opportunity from the Sun
- Photon-axion oscillations in astronomy
- Globular Clusters & White Dwarfs

Lecture II: Compact Stars

- SN 1987A and Neutron Stars
- Equation of State in Compact Stars
- Dark matter axions & radiowaves from pulsars
- Superradiance


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
Supernova
$M = 1\text{–}2\ M_\odot$
$R \sim 12$ km
Neutron Star
$M \gtrsim 8\ M_\odot$
Large Star
Red Supergiant
few-tens $M_\odot$
few km
Stellar Cloud with Protostars
BR ≈ 25% (?)
Black Hole
http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html

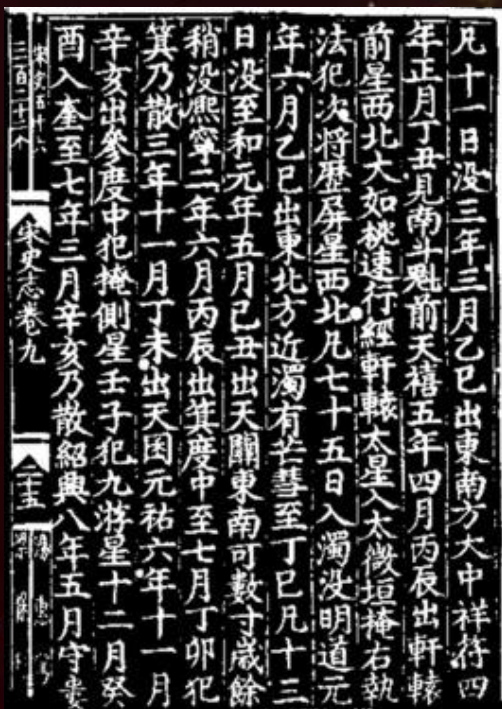
Crab Nebula – Remnant of SN 1054



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

宋史志卷九

Crab Nebula – Remnant of SN 1054



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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 Pulsar
Chandra X-ray composite image

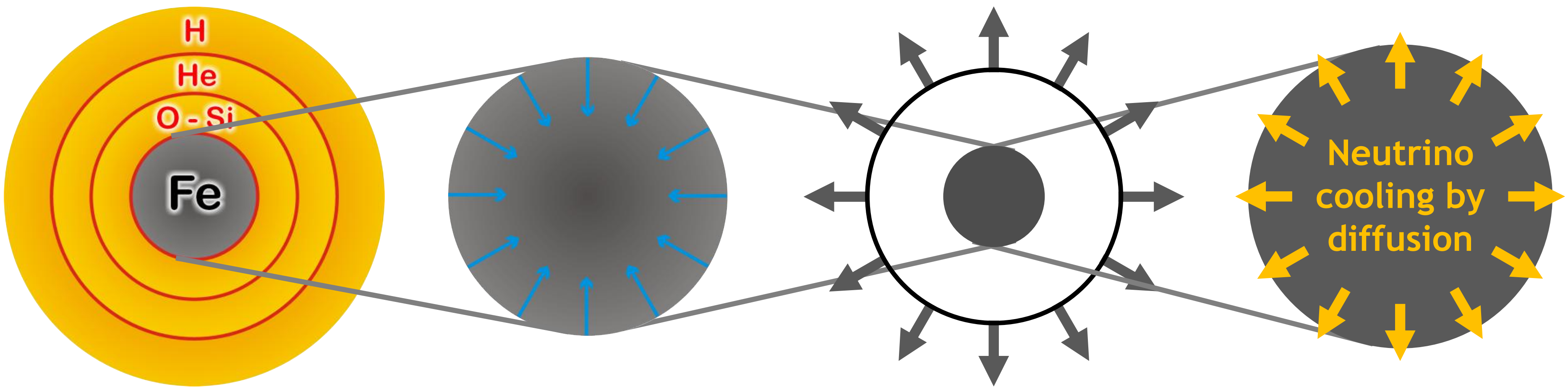
Core-Collapse Supernova Explosion

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

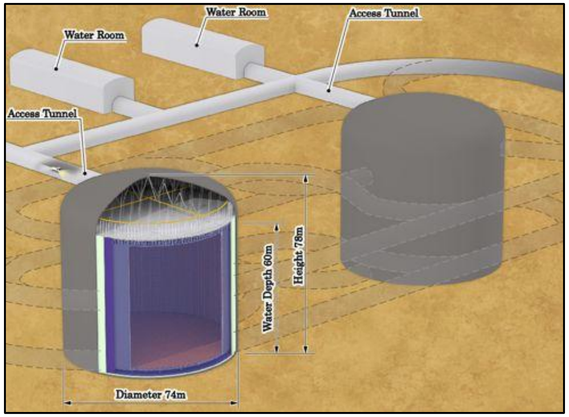
Collapse of degenerate core

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

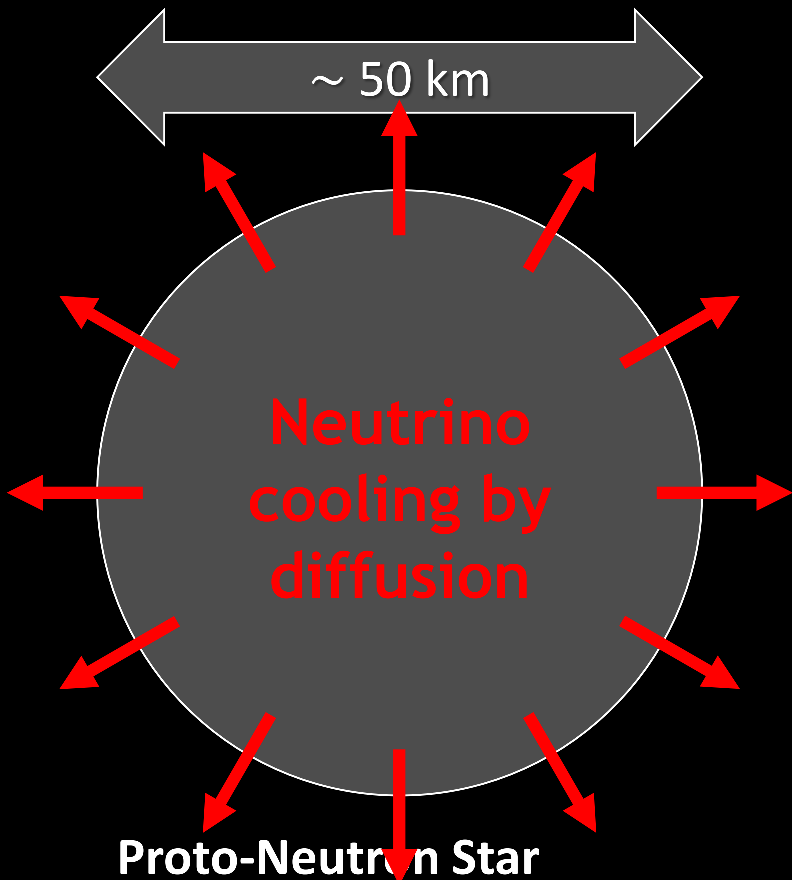


- Huge rate of low-E neutrinos (tens of MeV) over few seconds in large-volume detectors
- A few core-collapse SNe in our galaxy per century
- Once-in-a-lifetime opportunity



Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

$T \sim 10$ MeV

Gravitational binding energy

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

This shows up as

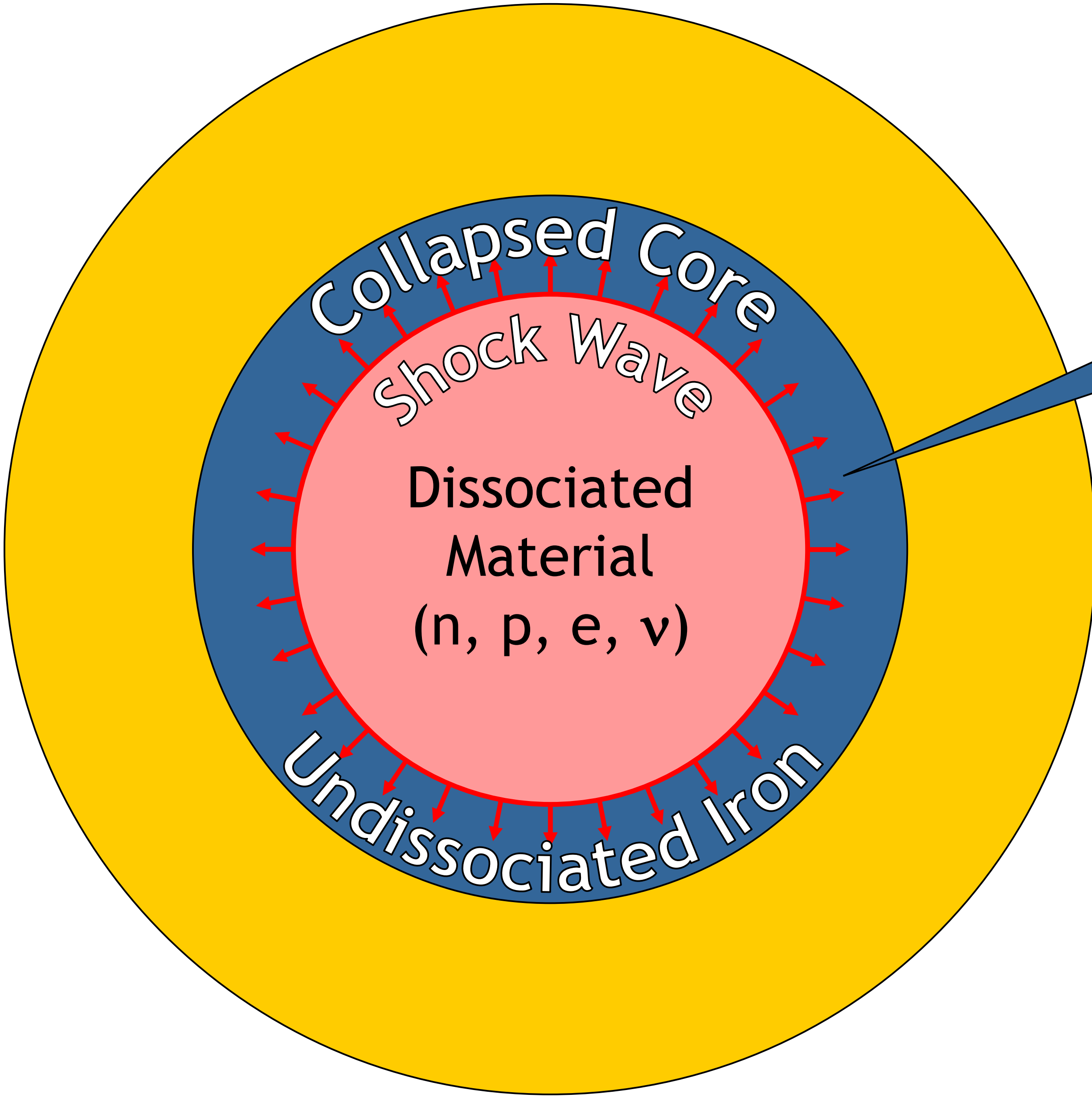
- 99% Neutrinos
- 1% Kinetic energy of explosion
- 0.01% Photons, outshine host galaxy

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

Why No Prompt Explosion?



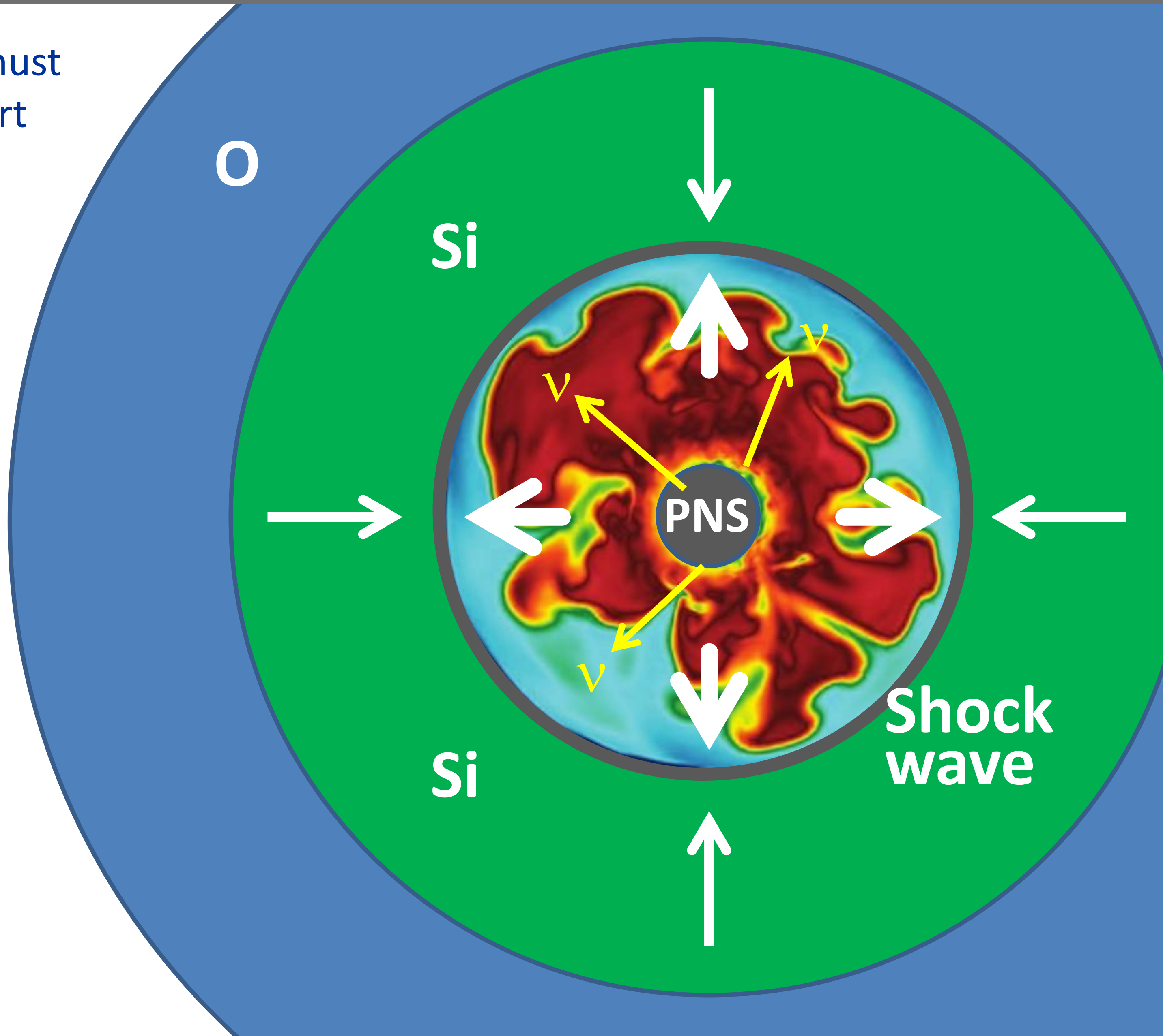
- 0.1 M_{sun} of iron has a nuclear binding energy $\approx 1.7 \times 10^{51}$ erg
- Comparable to explosion energy

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

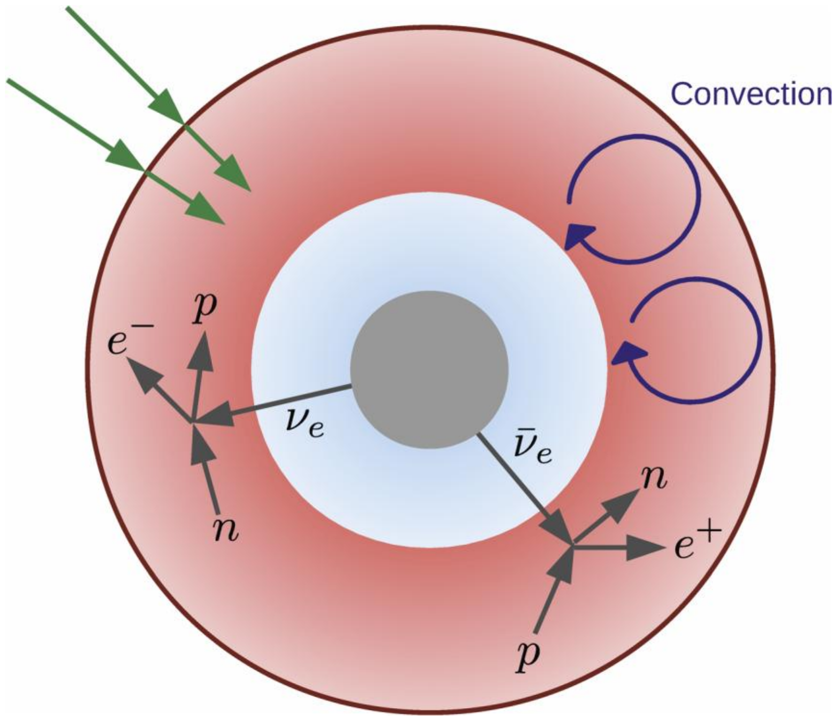
Shock Revival by Neutrinos

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

Shock can receive fresh energy from neutrinos!

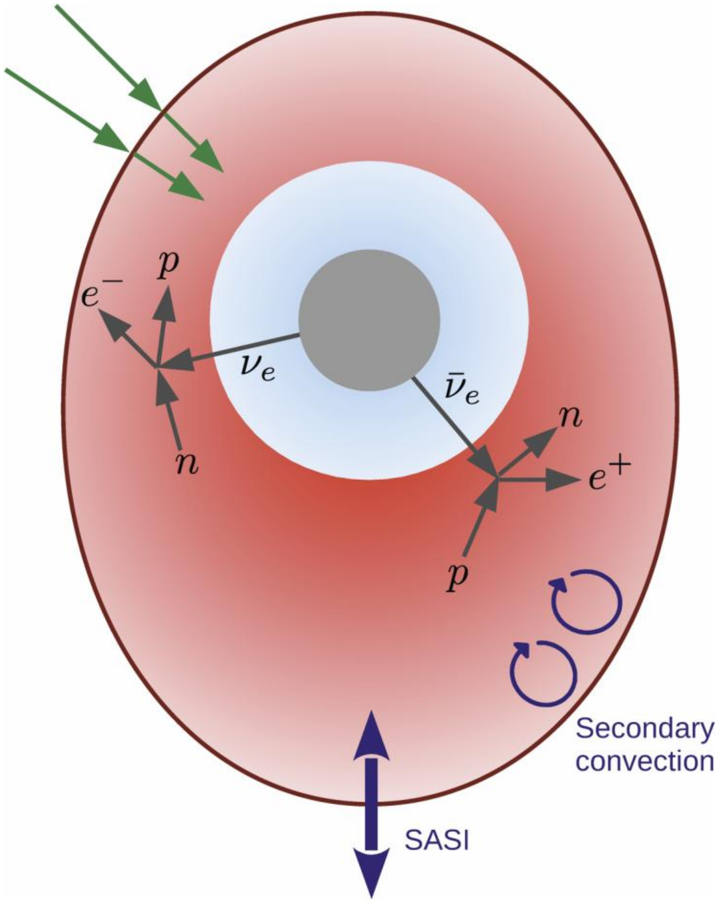


Convection



SASI

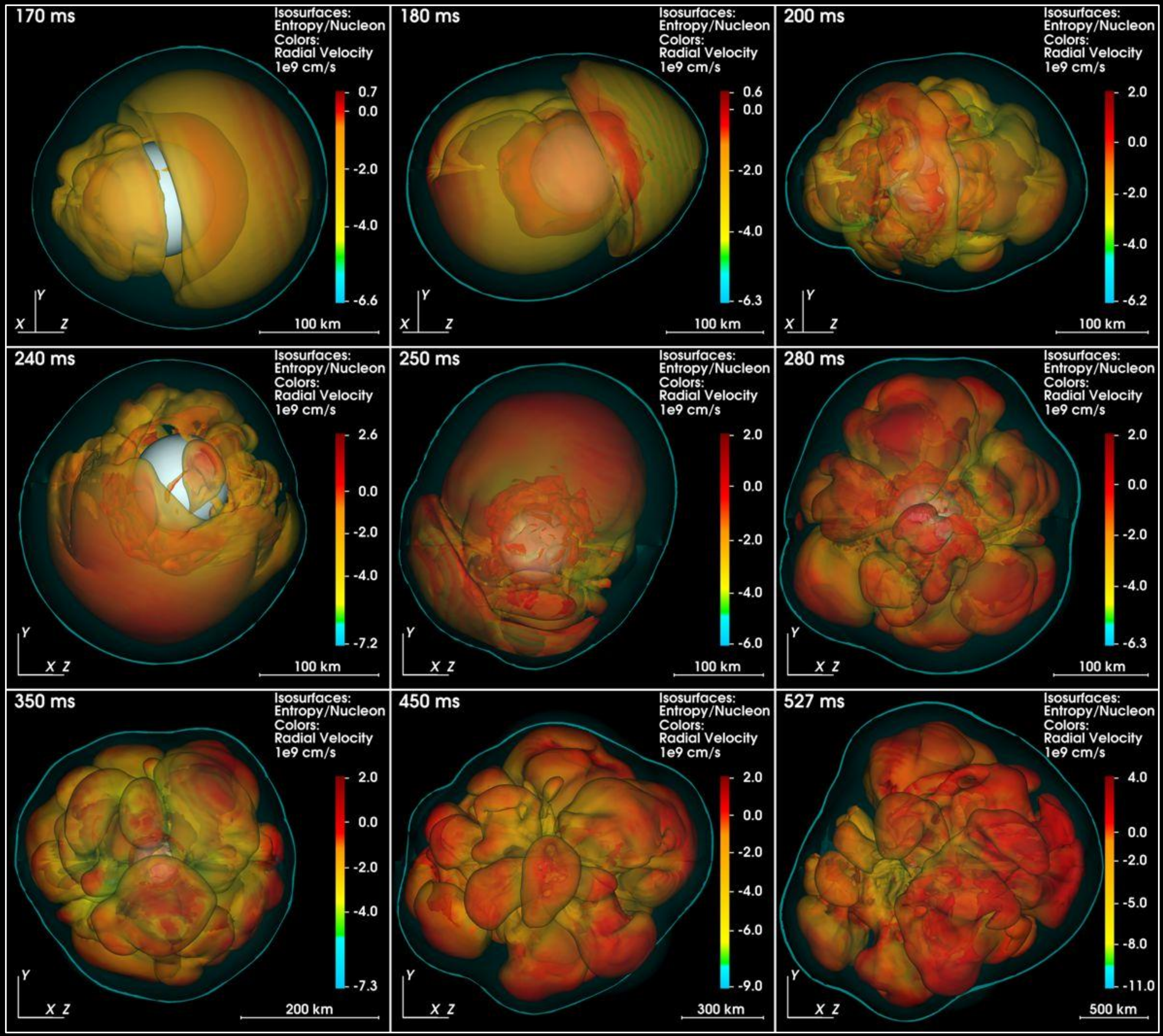
Standing accretion shock instability



Images: Tobias Melson

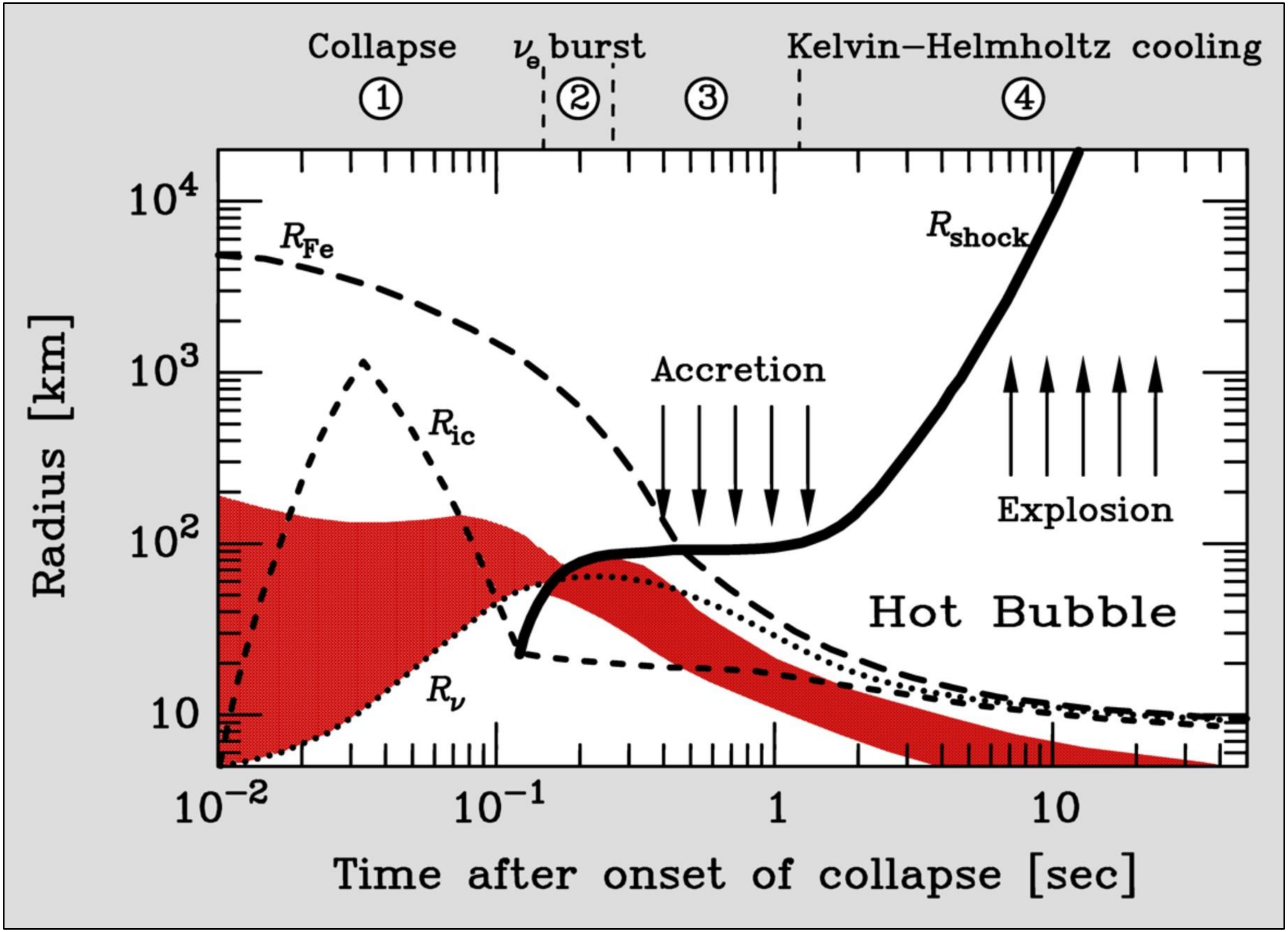
→ 3D Model of Princeton Group: https://youtu.be/i-Ly8aCoF7E

Breaking Spherical Symmetry (3D Effects)



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

Supernova Delayed Explosion Scenario



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

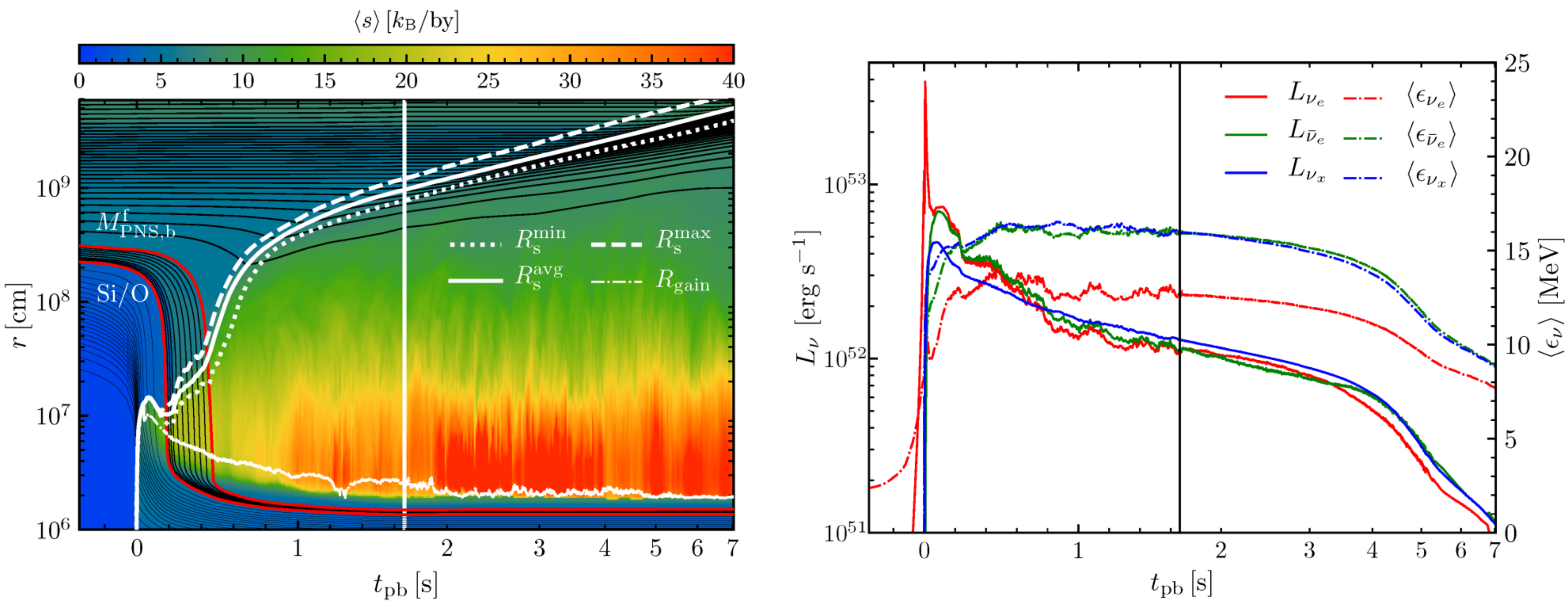
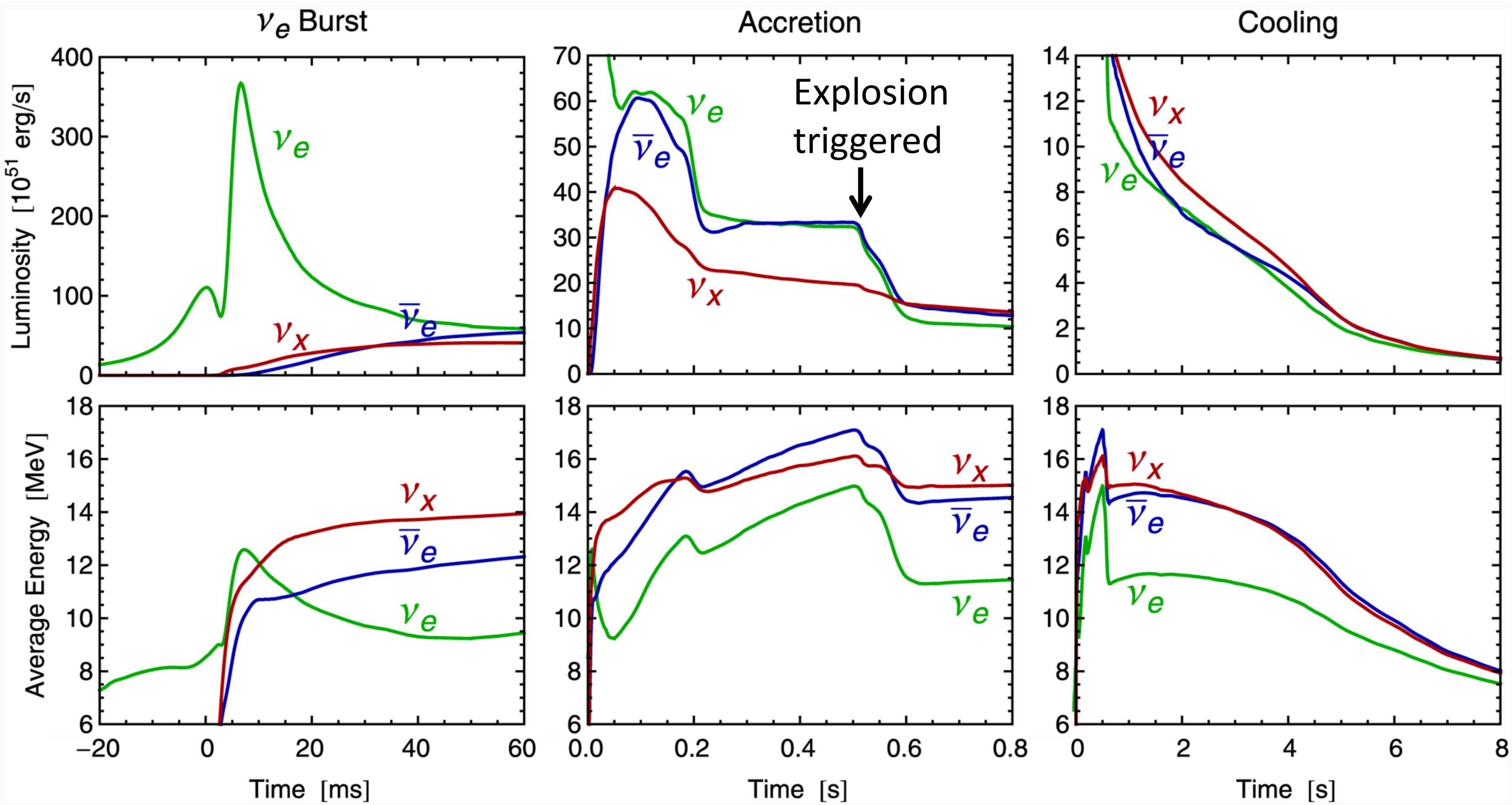


Figure 1. Explosion dynamics and neutrino emission of model M_P3D_LS220_m− and its extension M_P3D_LS220_m−HC. The time axes are chosen for optimal visibility. *Left:* Mass shells with entropy per nucleon color-coded. Maximum, minimum, and average shock radii, gain radius, and the mass shells of Si/O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



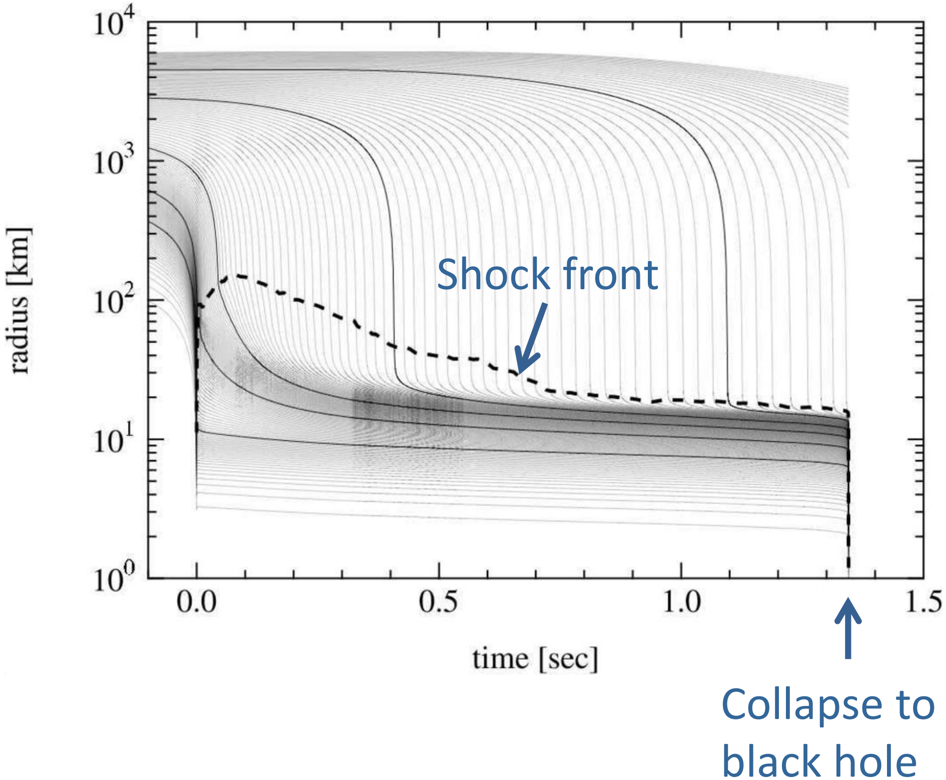
- Shock breakout
- De-leptonization of outer core layers

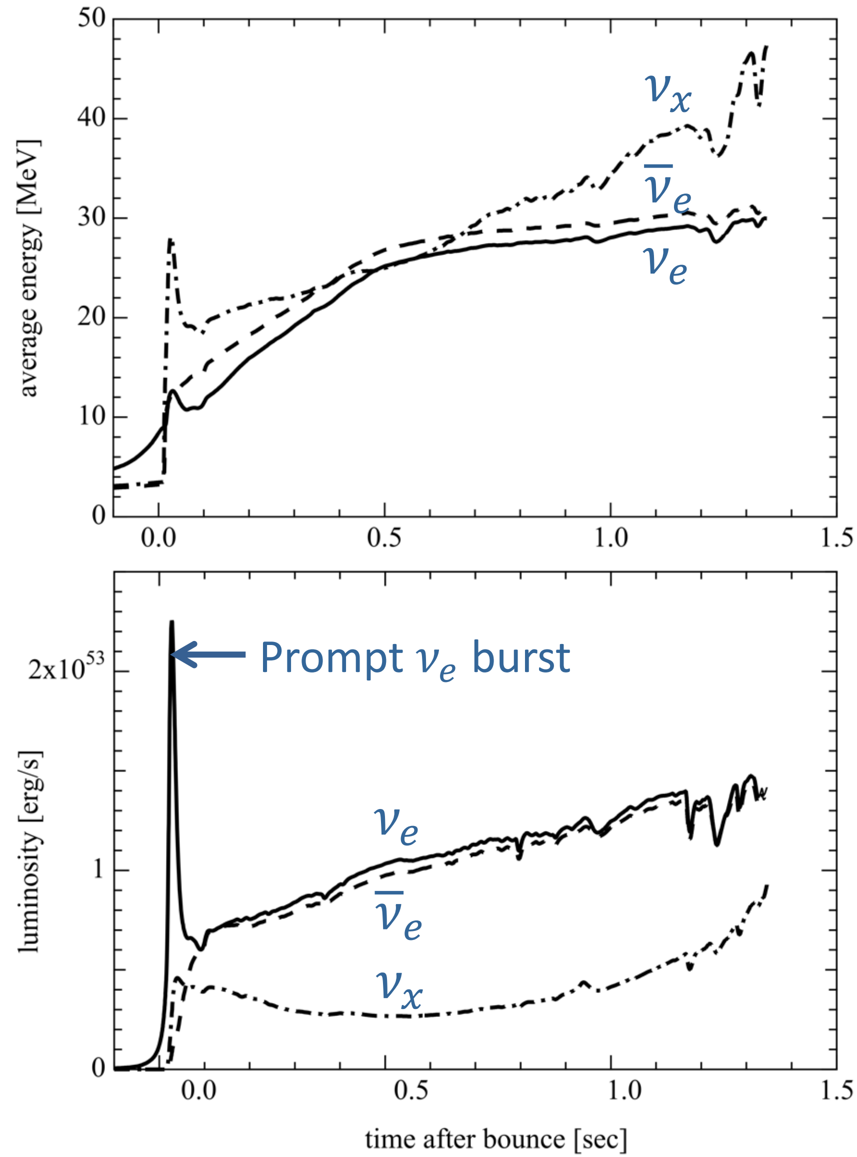
- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling on neutrino diffusion time scale

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

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





Sumiyoshi, Yamada & Suzuki, arXiv:0706.3762

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 $\overline{\nu}_\tau + N \leftrightarrow N + \overline{\nu}_\tau$)

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

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

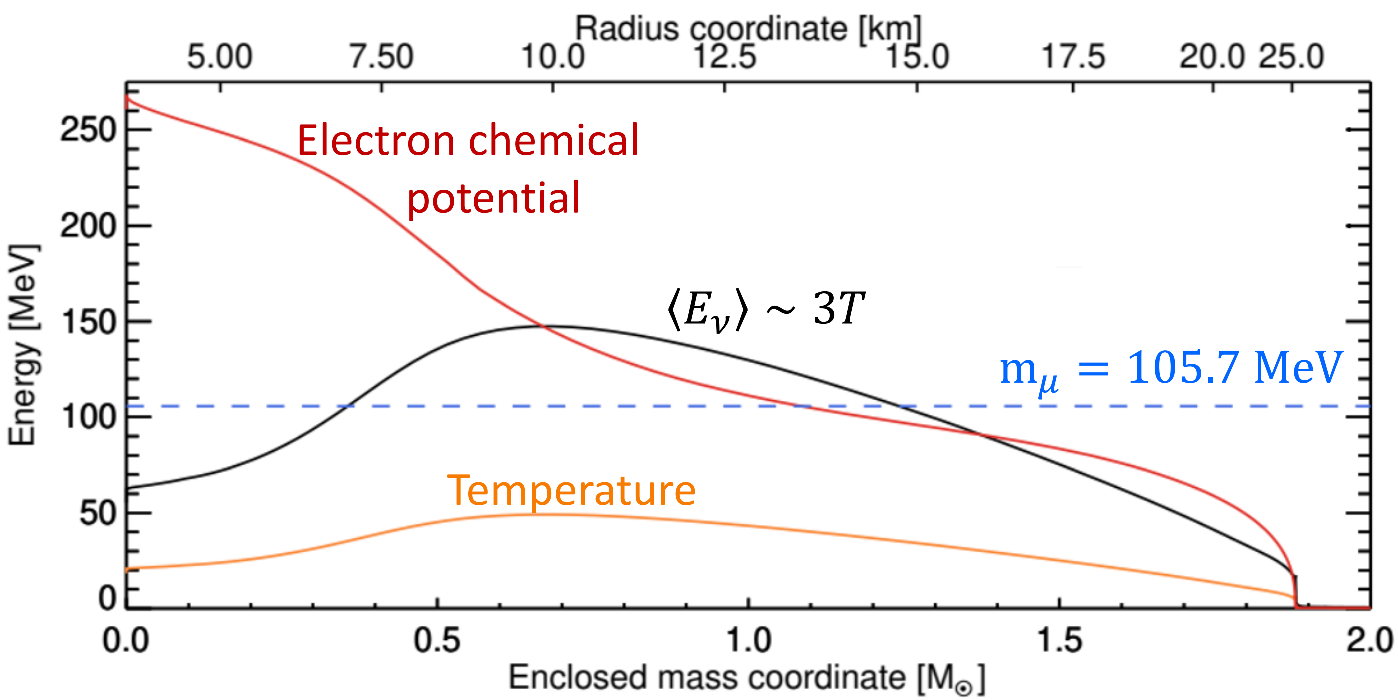
Flavor oscillations:

Typically studied in 2-flavor limit

(But anyway not included in numerical SN simulations)

Muonisation of a Supernova Core

- Muon production energetically favored ($m_\mu = 105.7$ 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])



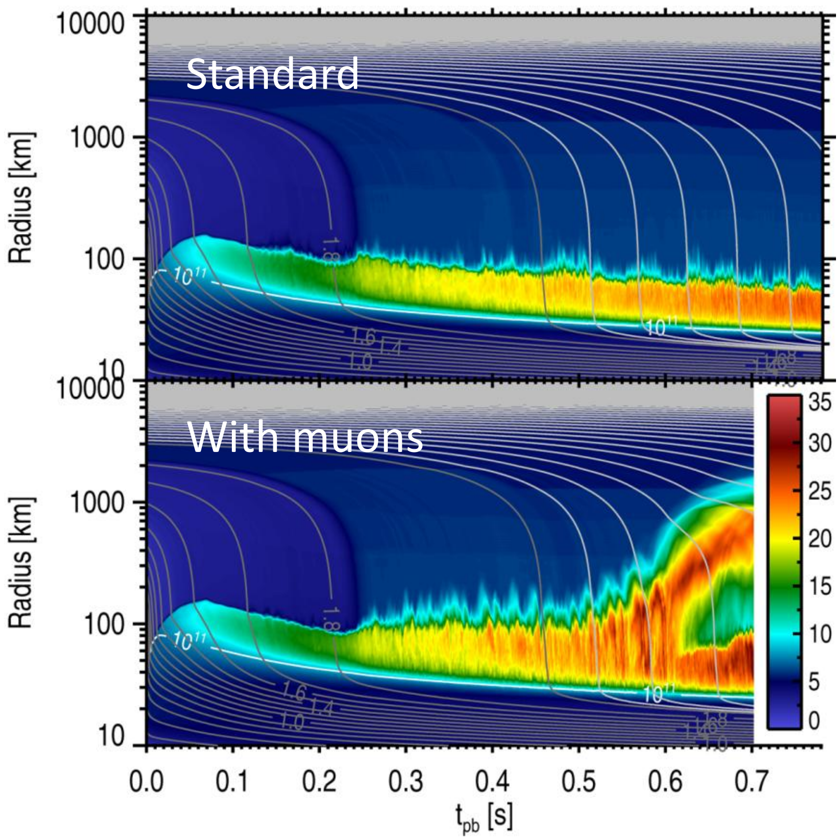
Proto neutron star (PNS) profile
350 ms postbounce

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

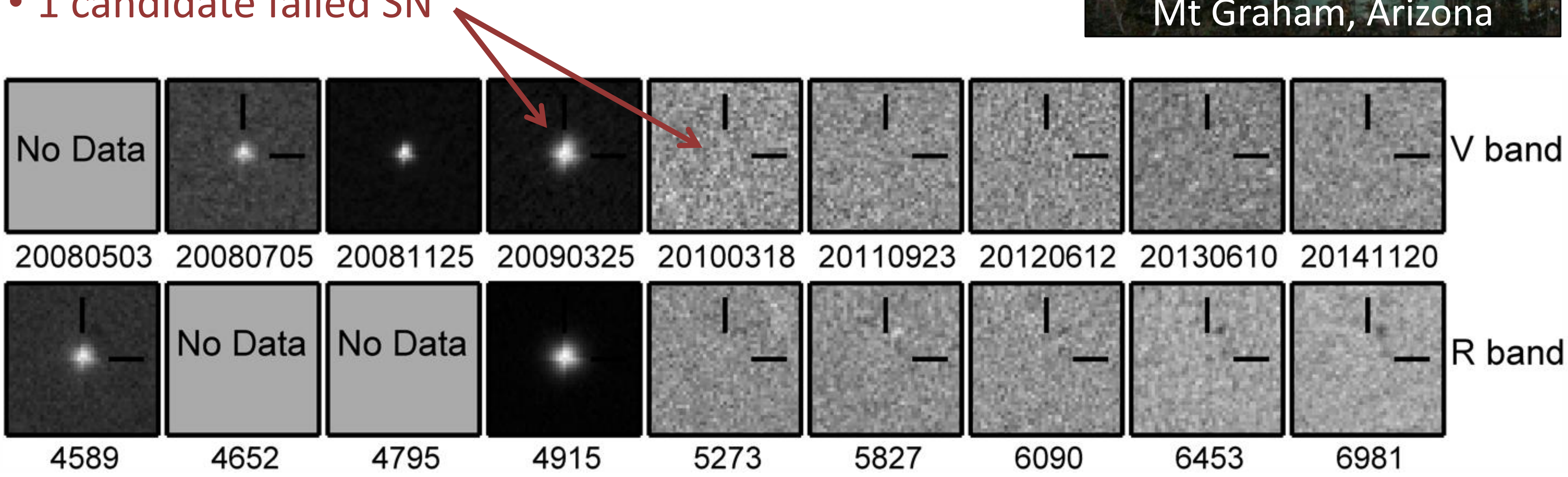
- Facilitate neutrino-driven explosion
- Affect compactness of hot NSs
- Change neutrino emission
- May affect ν oscillations / nucleosynthesis
- Affect grav. instability of hot NS → BH
- Should be included in SN and NS-NS/BH merger simulations
- Require six-species neutrino transport with coupling of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

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



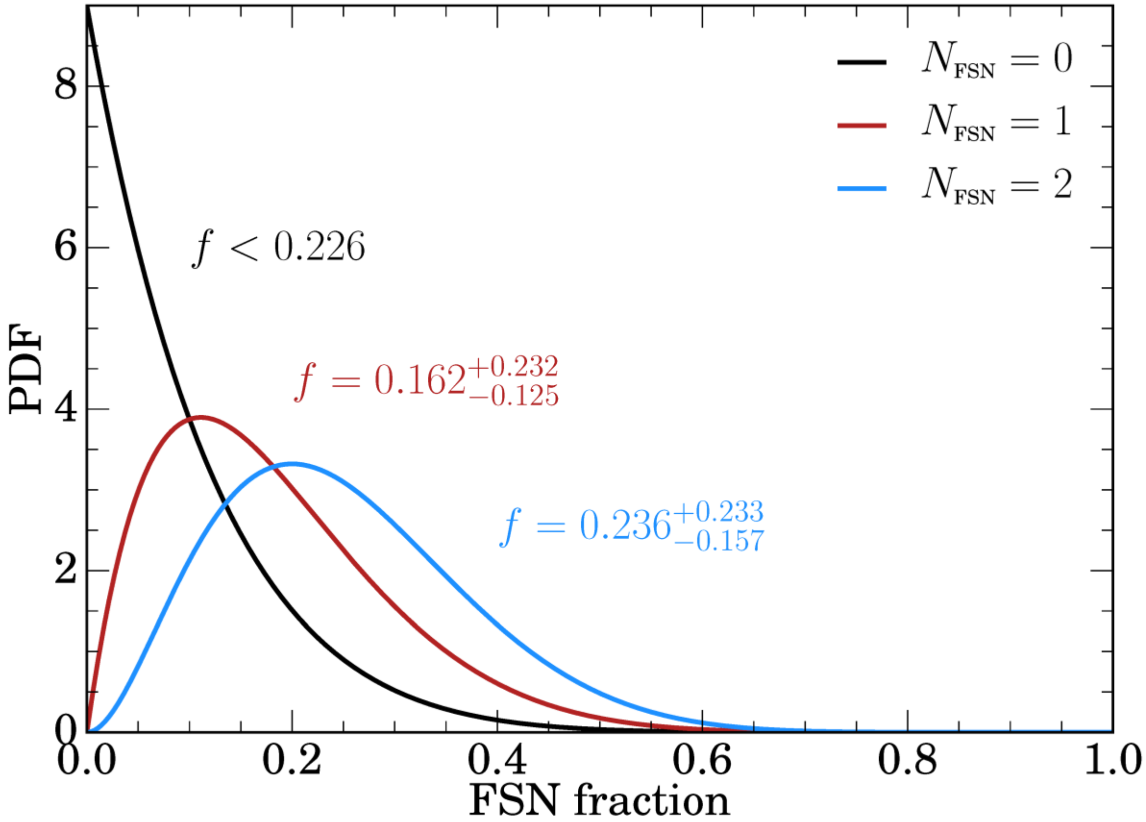
Gerke, Kochanek & Stanek, arXiv:1411.1761

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

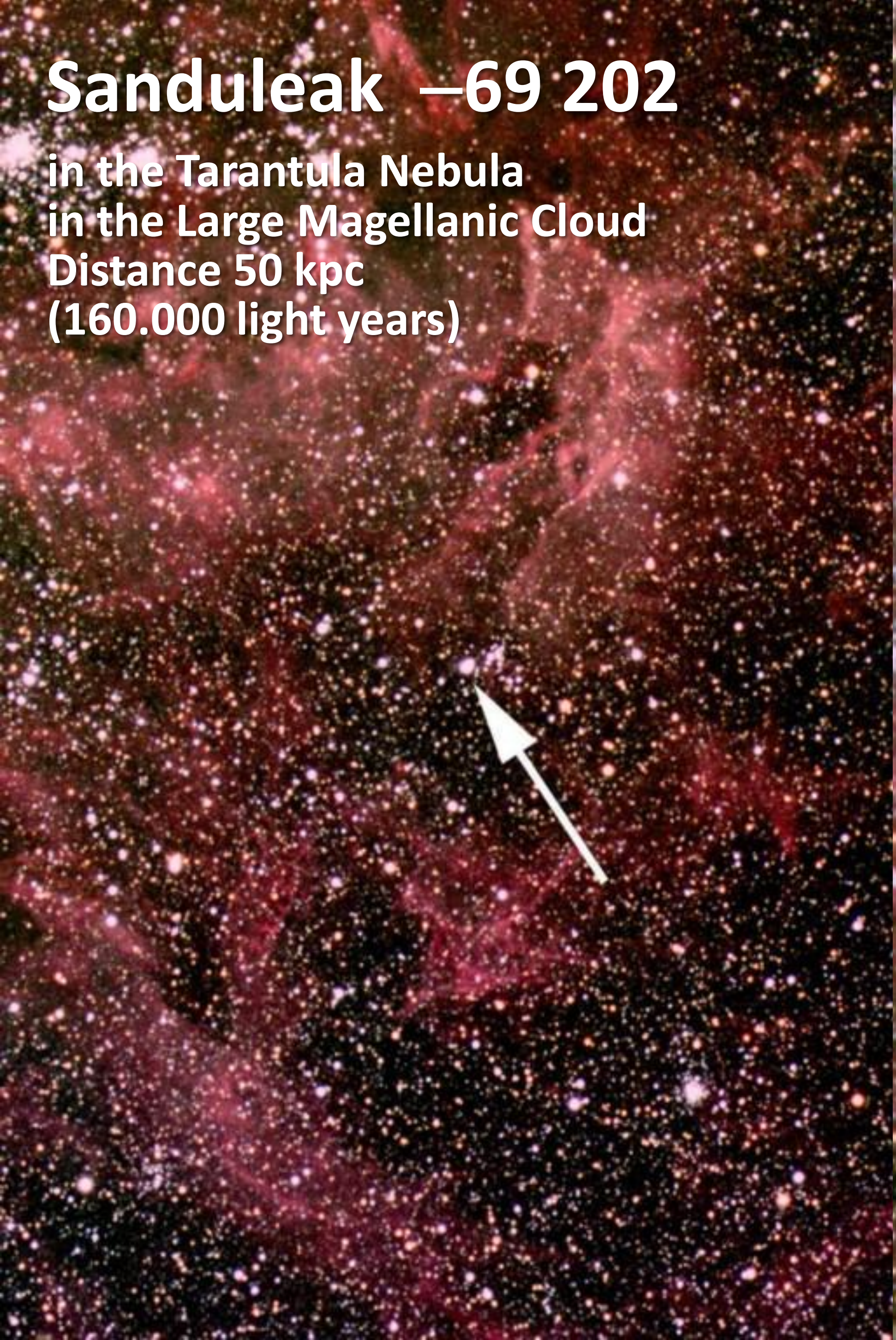
Empirical Fraction of Black-Hole Formation

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

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

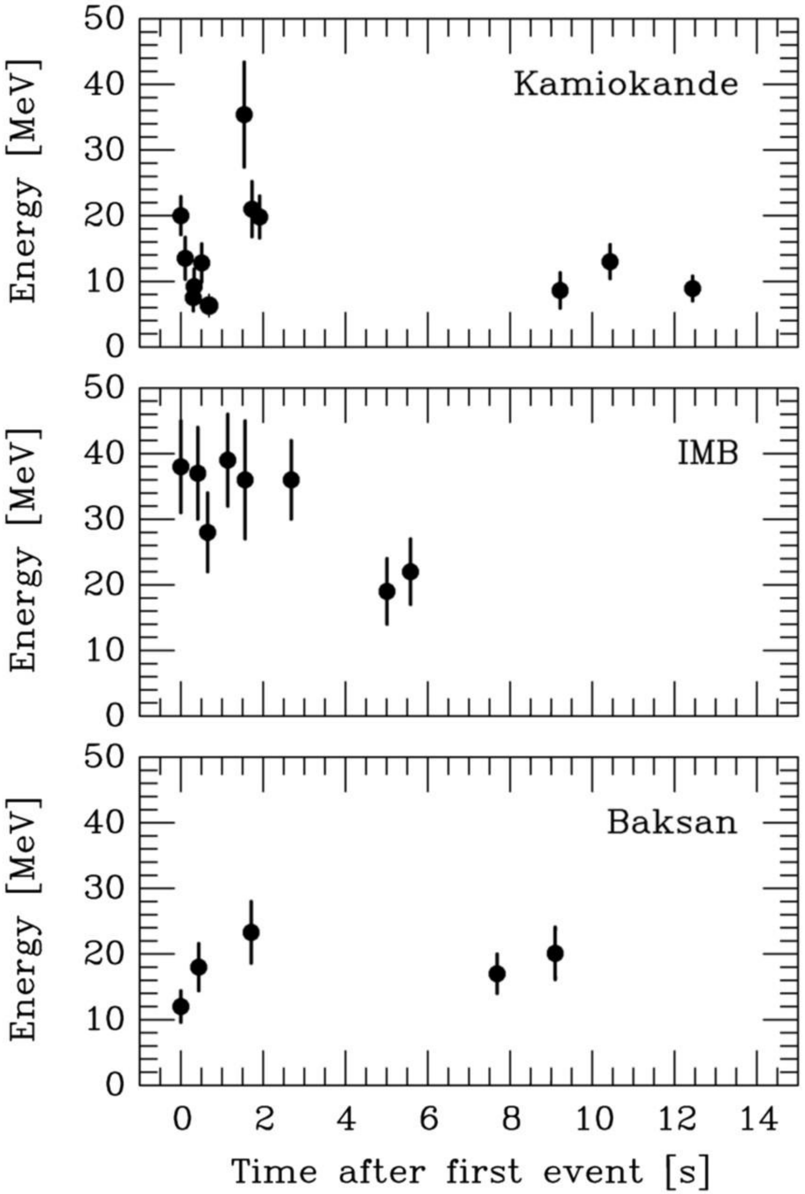


Roughly a quarter of all core-collapses could lead to BH formation, in agreement with theory estimates!


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


Supernova 1987A
23 February 1987

Neutrino Signal of Supernova 1987A



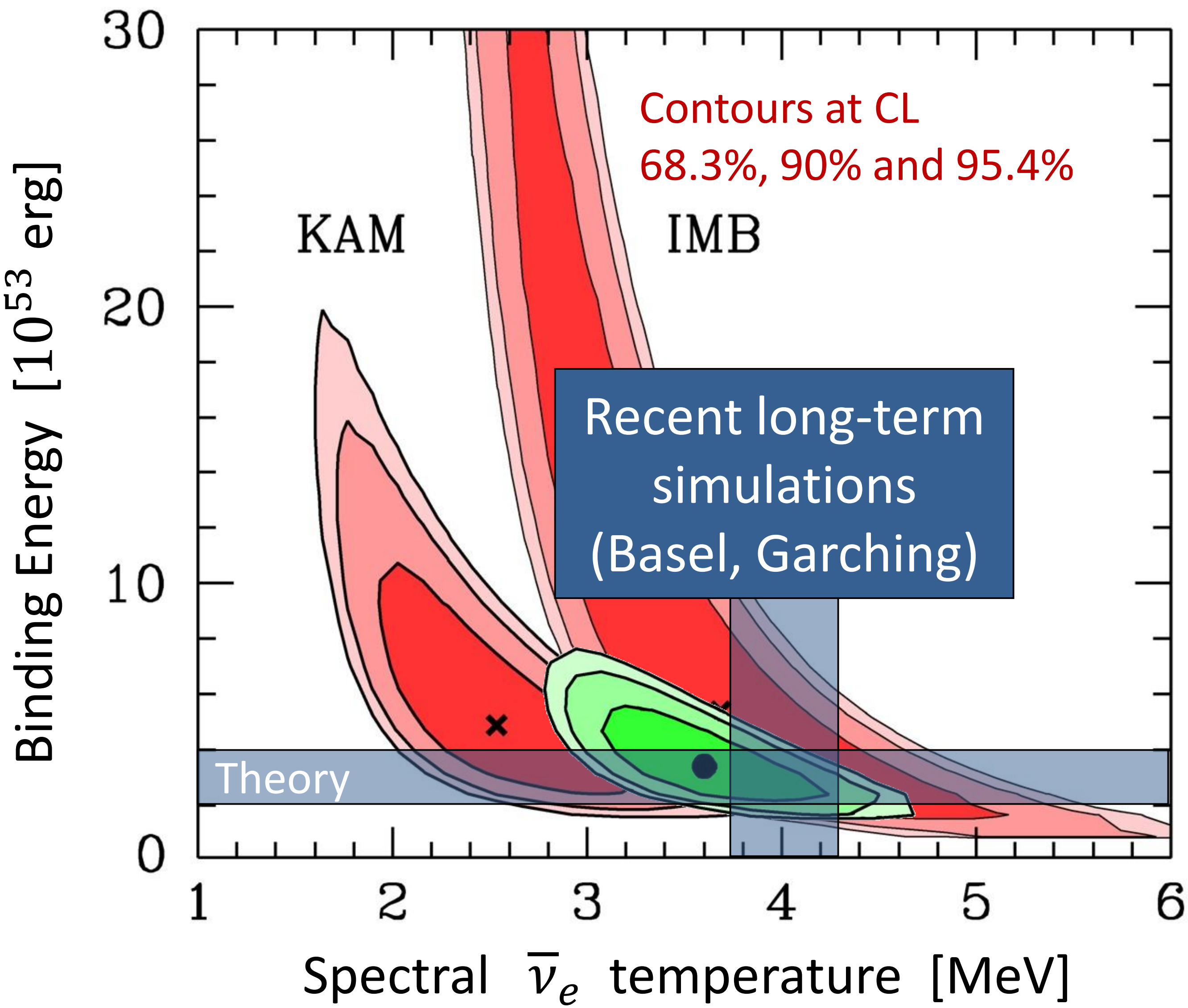
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty $\pm$1 min

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

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster $\sim$ 0.7/day
Clock uncertainty +2/–54 s

Within clock uncertainties,
all signals are contemporaneous

Interpreting SN 1987A Neutrinos



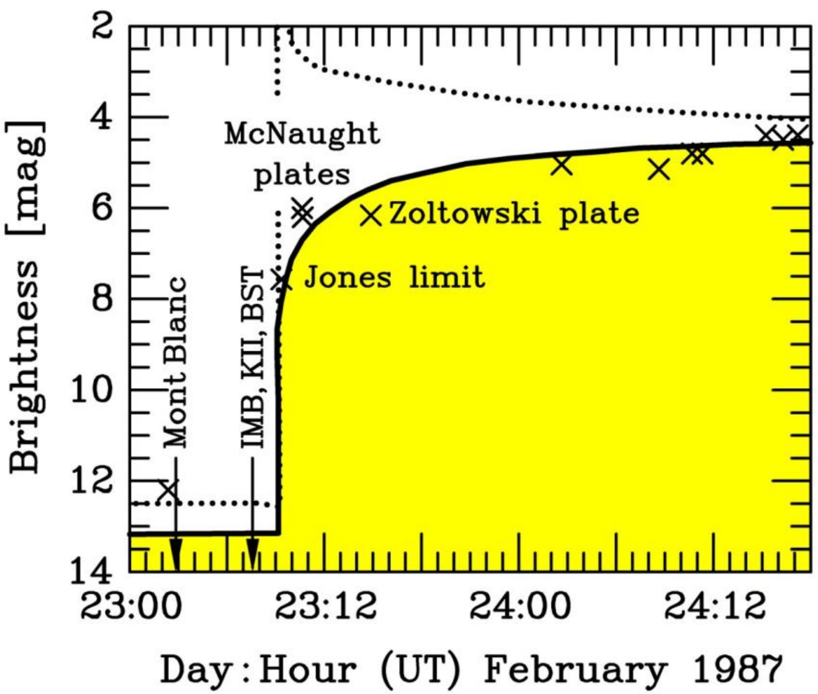
Assume

- Thermal spectra
- Equipartition of energy between $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau$ and $\bar{\nu}_\tau$

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

Do Neutrinos Gravitate?

Early light curve of SN 1987A



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

Shapiro time delay for particles moving in a gravitational potential

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

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

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

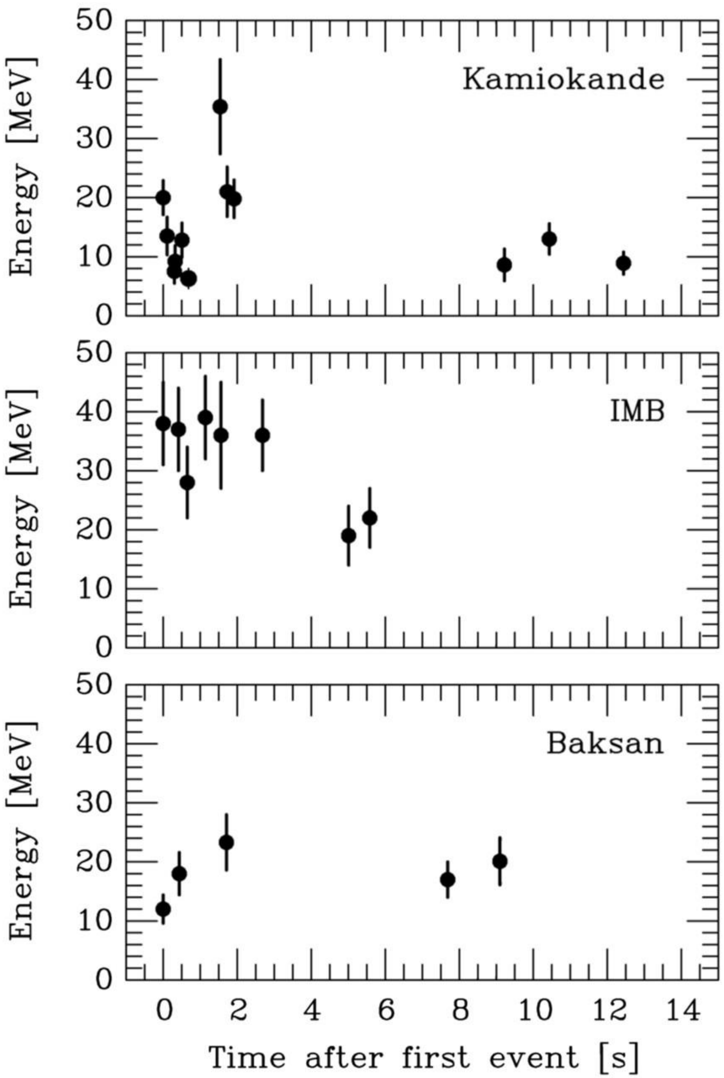
Neutrinos and photons respond to gravity the same to within

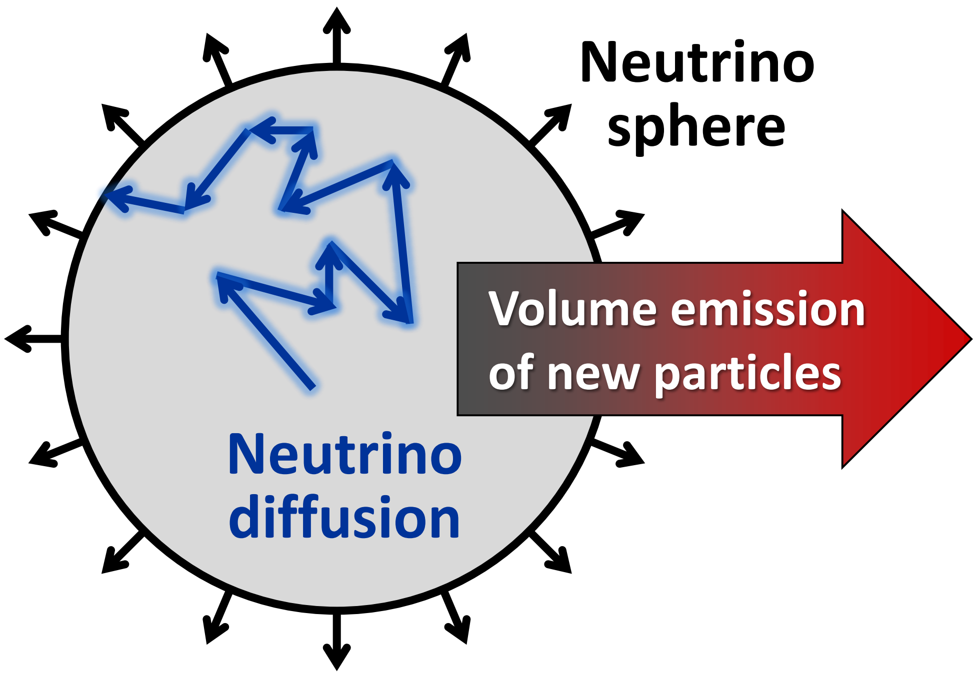
$$1\text{–}4 \times 10^{-3}$$

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

Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal

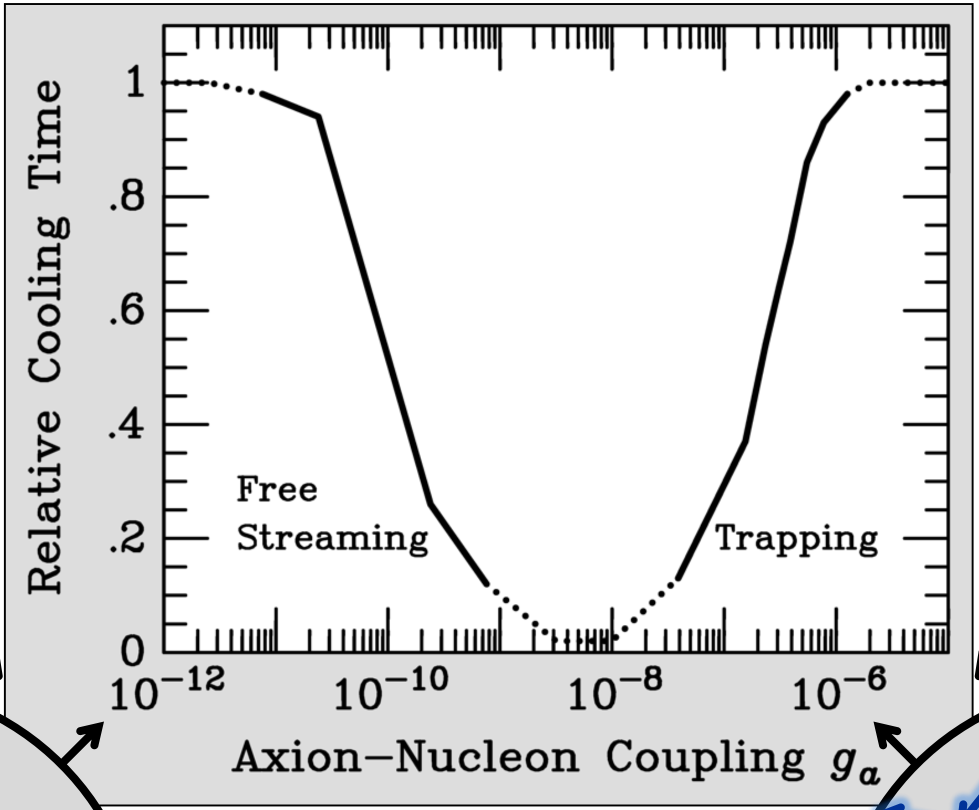


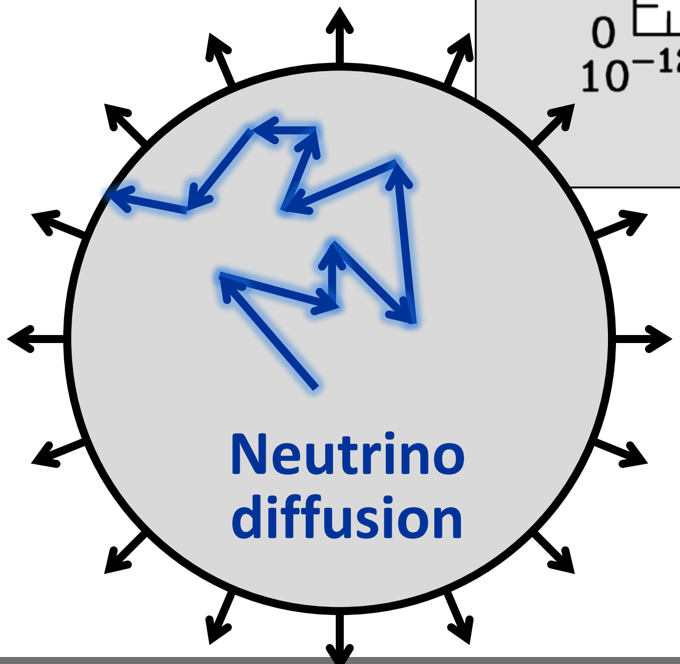


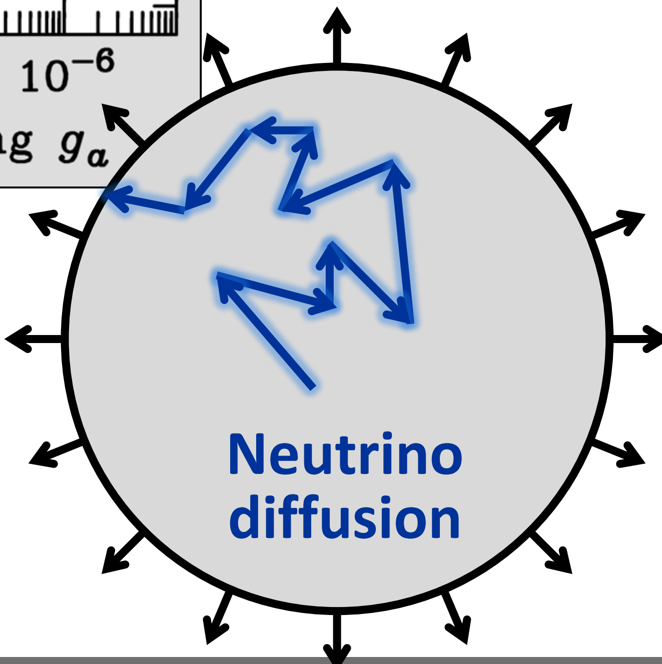
Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

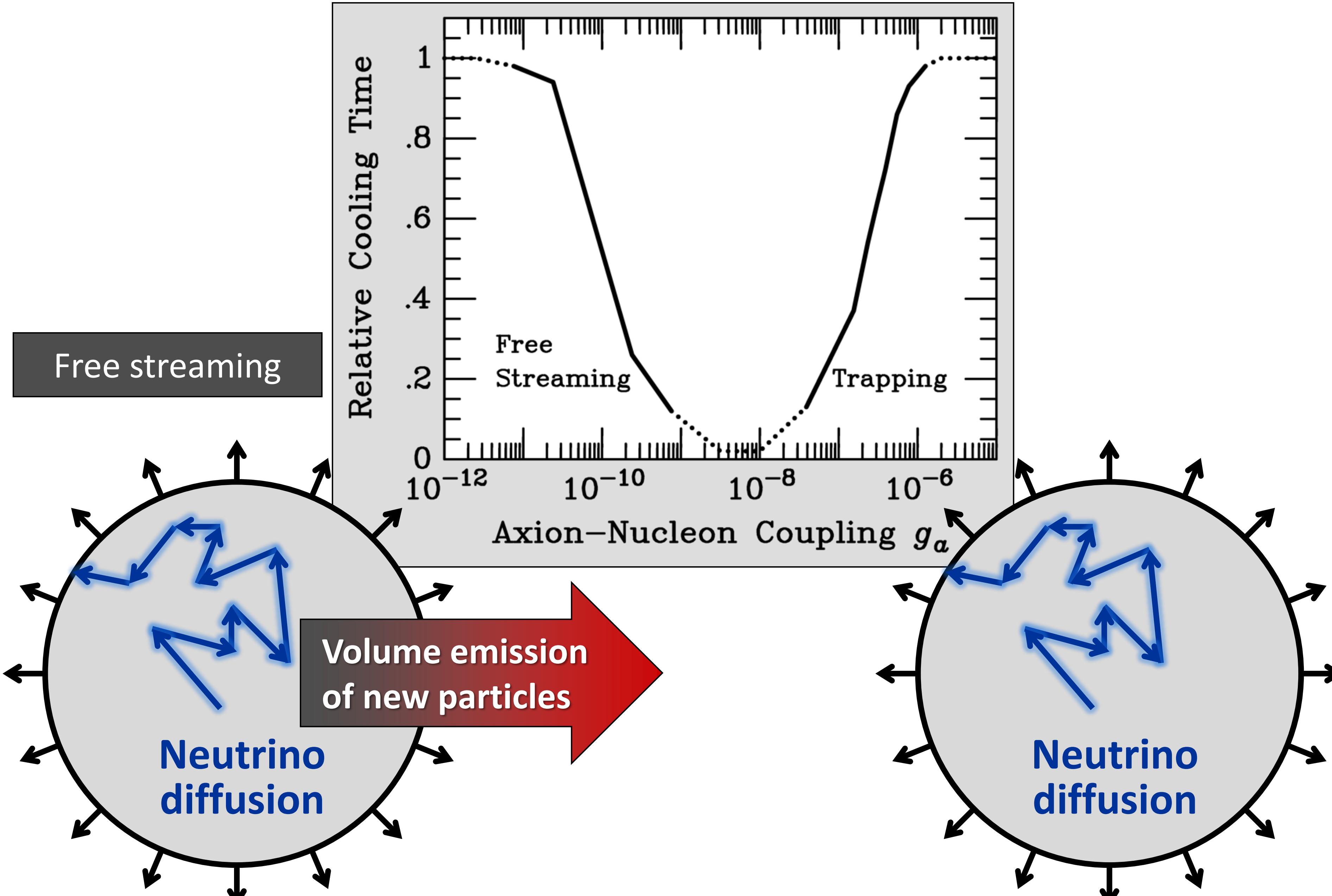
SN 1987A Axion Limits



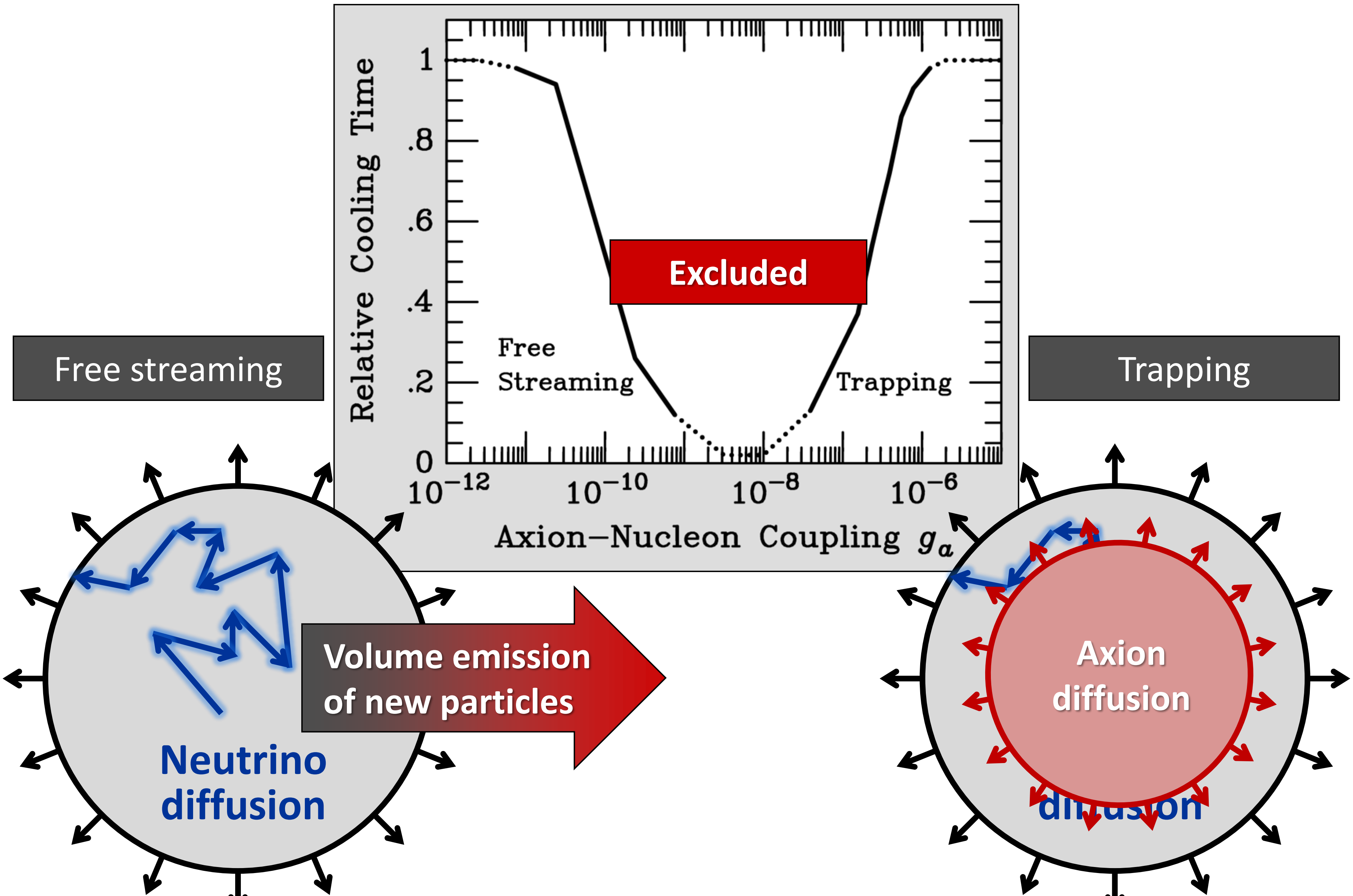




SN 1987A Axion Limits



SN 1987A Axion Limits



New Interest in SN 1987A as Particle Lab

File Edit View History Bookmarks Tools Help

Bounds on Exotic Particle Intera ×

https://inspirehep.net/literature 110%

Bounds on Exotic Particle Interactions from SN 1987a

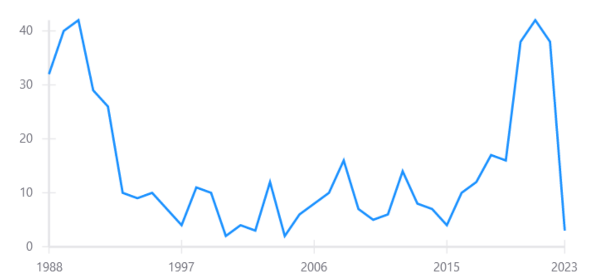
Georg Raffelt (UC, Berkeley, Astron. Dept. and LLNL, Livermore), David Seckel (UC, Santa Cruz)

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

cite claim reference search 520 citations

Citations per year



Abstract: (APS)
The observation of a neutrino pulse from the supernova SN1987A constrains the production of light exotic particles in the proto neutron star. We derive a new bound on the axion decay constant, fa≳1010 GeV. If right-handed (RH) neutrinos exist, the "RH Fermi constant" is GRH≲10−4GF, 2 orders of magnitude below laboratory bounds. The Dirac mass of νμ can be constrained below laboratory limits.

NEUTRINO: COSMIC RADIATION | COSMIC RADIATION: PARTICLE SOURCE | N: MATTER | POSTULATED PARTICLE: AXION | DECAY: AXION | AXION: DECAY

File Edit View History Bookmarks Tools Help

Axions from SN 1987a - INSPIRE ×

https://inspirehep.net/literature 110%

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

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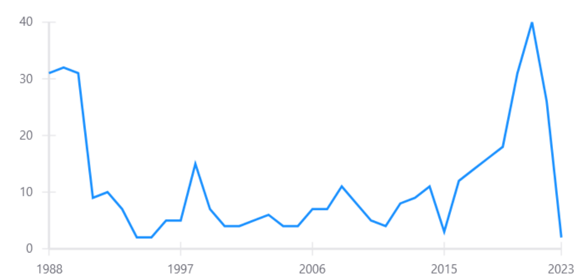

Abstract: (APS)
Axion emission from SN1987A by nucleon-nucleon axion bremsstrahlung is considered. On the basis of the neutrino observations the axion luminosity must be ≲1053 erg s−1. This occurs if (1) axions couple very weakly: ma≲0.75×10−3 eV; or (2) axions couple strongly enough to be "trapped" and radiated from an "axion sphere" with Ta≲8 MeV: ma≳2.2 eV. In general, "axion trapping" occurs for ma≳0.016 eV. Our mass constraints are at best reliable to within a factor of ≃3.

COSMIC RADIATION: PARTICLE SOURCE | NEUTRINO: COSMIC RADIATION

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Constraints on Axions from SN ×

https://inspirehep.net/literature 110%

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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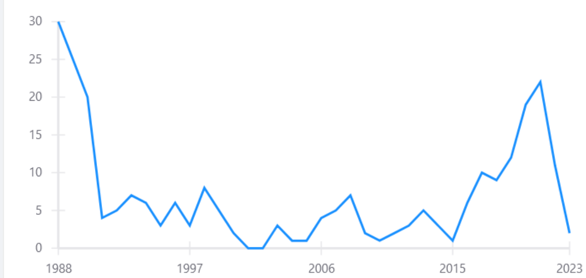
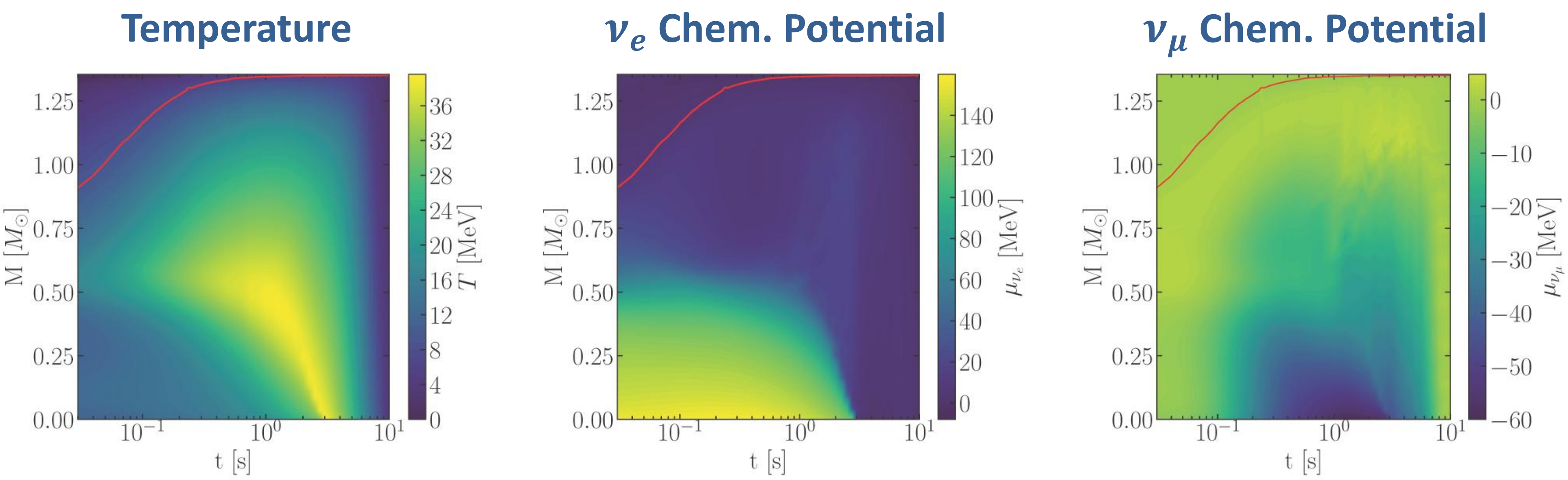


Abstract: (Elsevier)
We argue that the detection of neutrinos from SN 1987A implies that axion emission from the collapsing star must not have been significant. The best axion supernova limits come from nucleon bremsstrahlung processes which involve axion-quark couplings rather than the electron or photon couplings used in obtaining axion limits from red giants. The axion-quark couplings are less sensitive

Inner Structure of a Typical Supernova Model

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



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

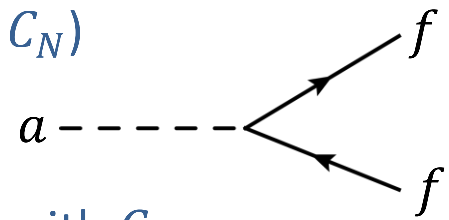
Fiorillo, Raffelt & Vitagliano (arXiv:2209.11773)

Axion-Nucleon Couplings

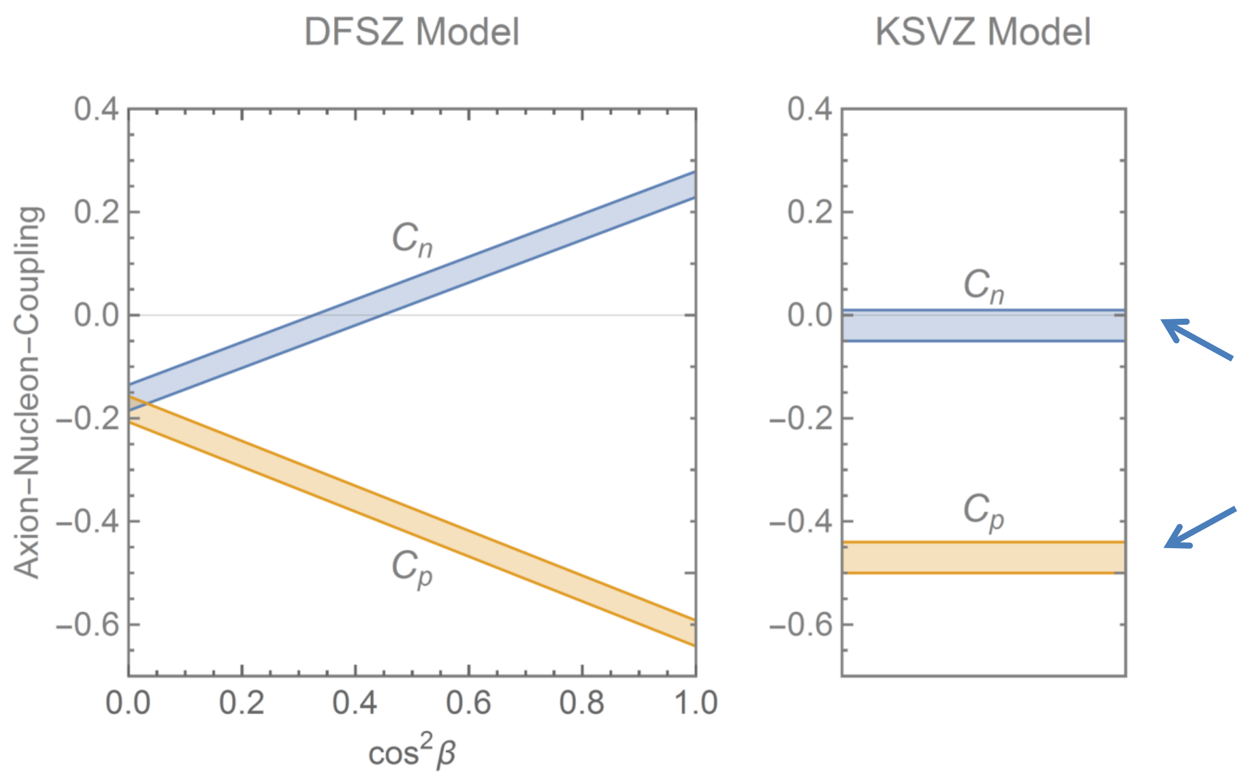
Axion-nucleon coupling (model-dependent numerical factors C_N)

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

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



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

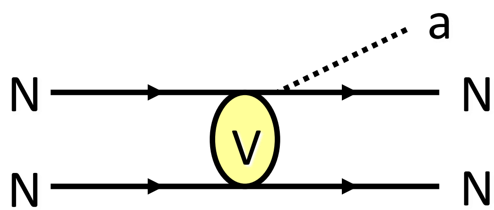


Values from Grilli di Cortona et al. arXiv:1511.02867

Coupling to neutron could be very small!

Axion Emission from a Nuclear Medium

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



+ ...

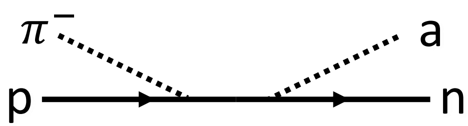
Nucleon-Nucleon
Bremsstrahlung

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:1906.11844**

Thermal π^- contribute significant (dominant?)



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

SN 1987A Axion Limits from Burst Duration

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

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

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

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

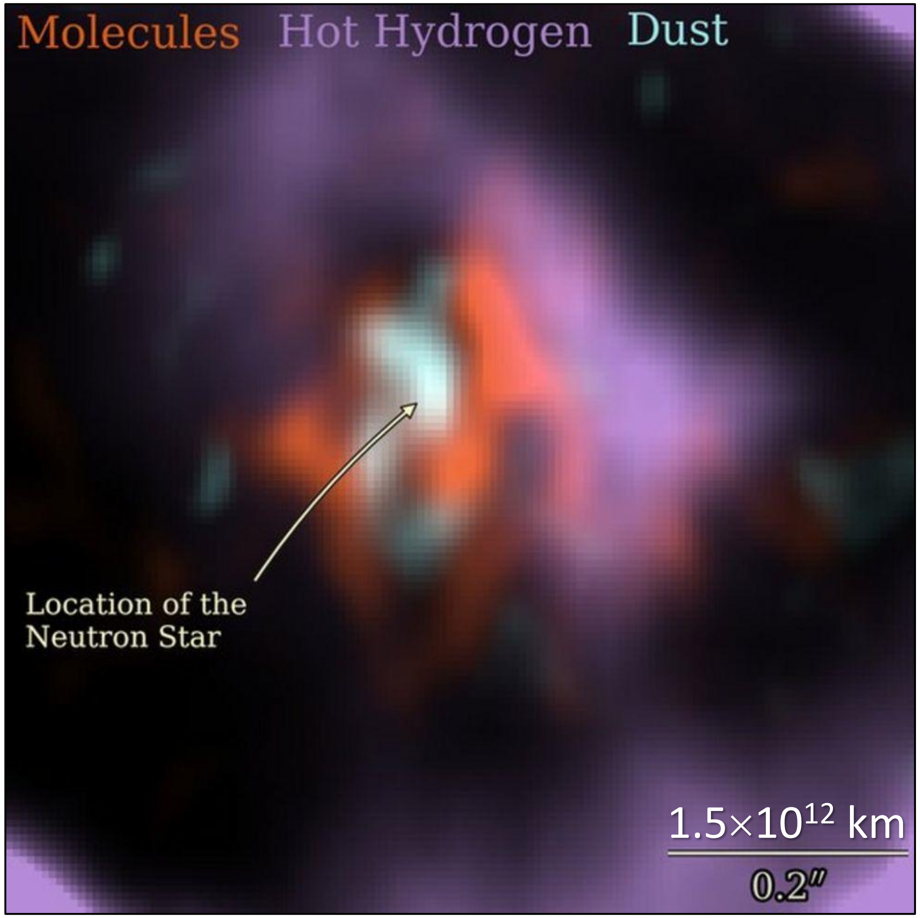
- Bar, Blum & D'Amico, Is there a supernova bound on axions? 1907.05020
  Alternative picture of SN explosion (thermonuclear event)
  Observed signal not PNS cooling. SN1987A neutron star (or pulsar) not yet found.
  (but see "NS 1987A in SN 1987A", Page et al. arXiv:2004.06078)

Where is the Neutron Star of SN 1987A?

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

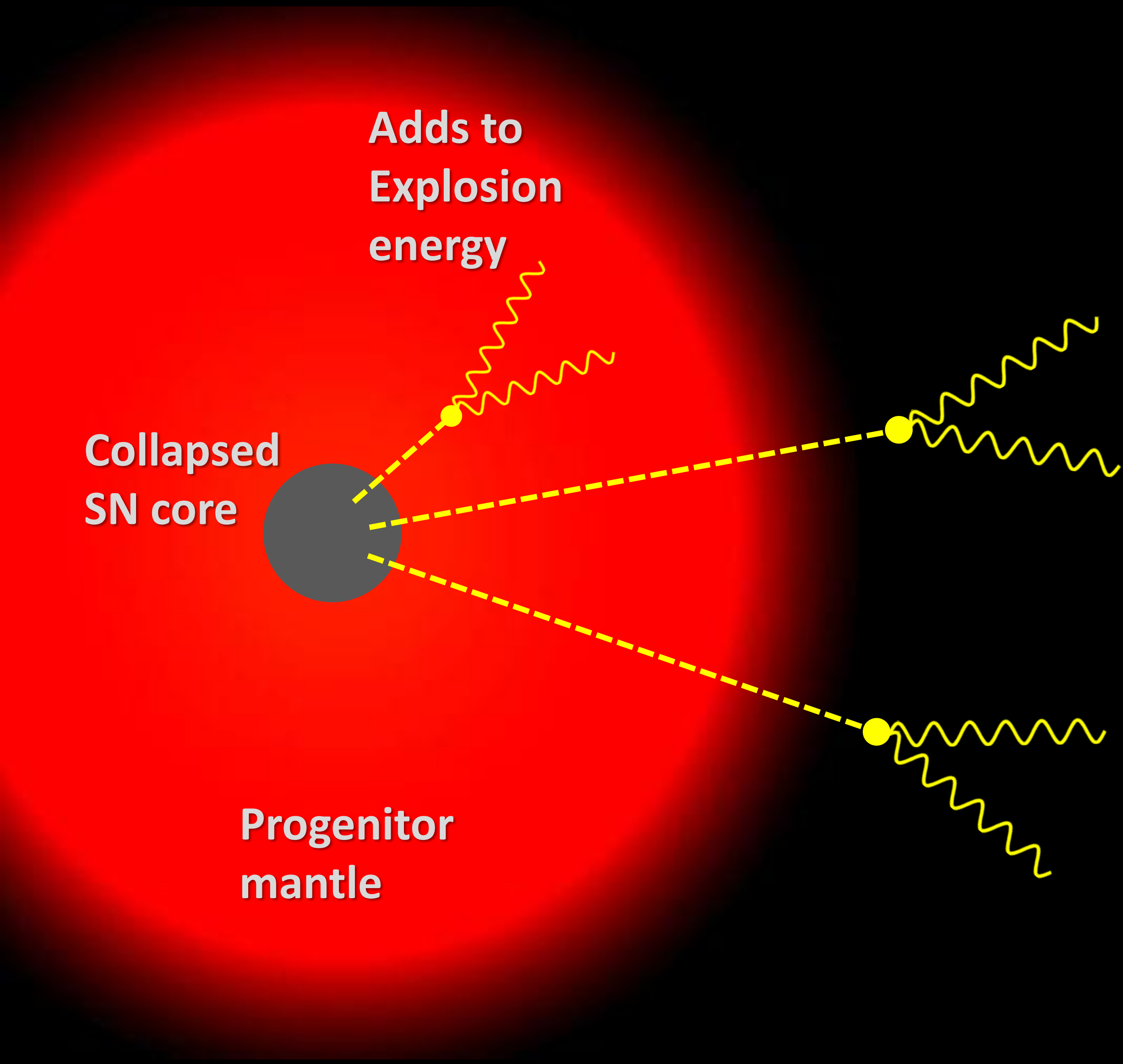
- Infra-red excess observed by ALMA: In “the blob” strong indication for NS
  Expected position, remnant hidden by dust [Cigan+ arXiv:1910.02960]
- Most plausible model: Thermally cooling non-pulsar NS [Page+ arXiv:2004.06078]

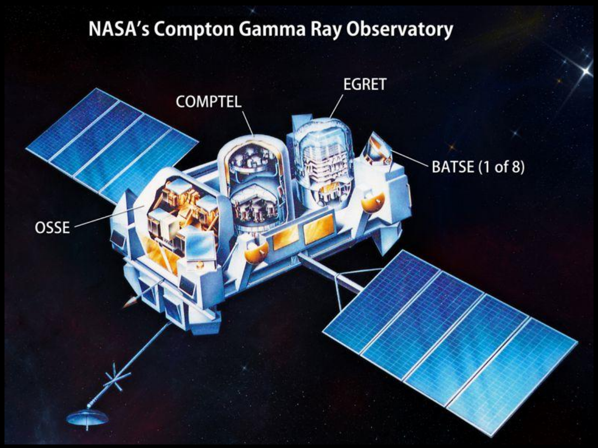
https://www.bbc.com/news/science-environment-50473482



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

Supernova Bounds on Radiative Particle Decays





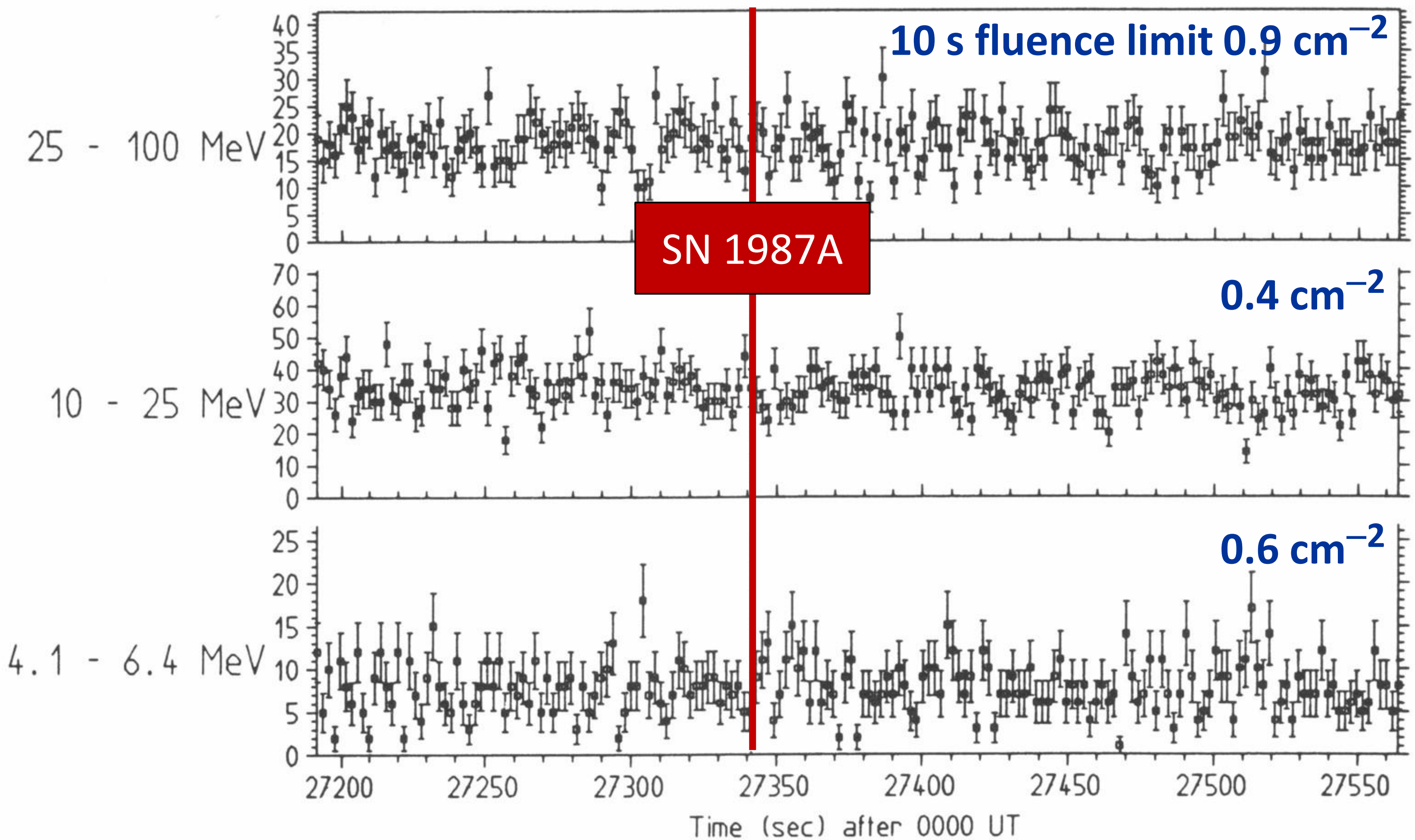
Cosmic gamma ray background
from all past supernovae

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

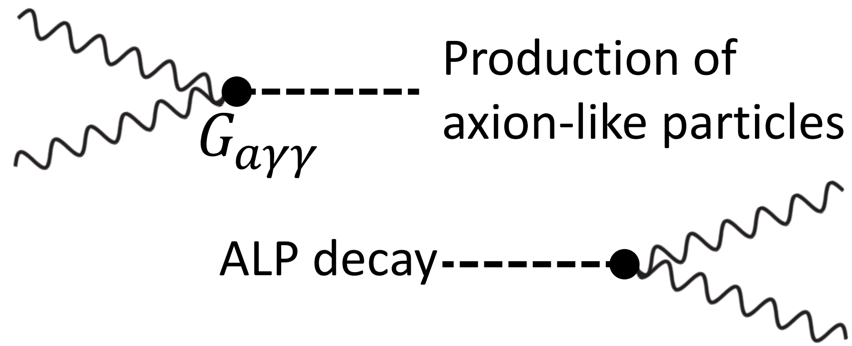
$< 10^{-10}$ of neutrinos have decayed to photons on their way to Earth

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

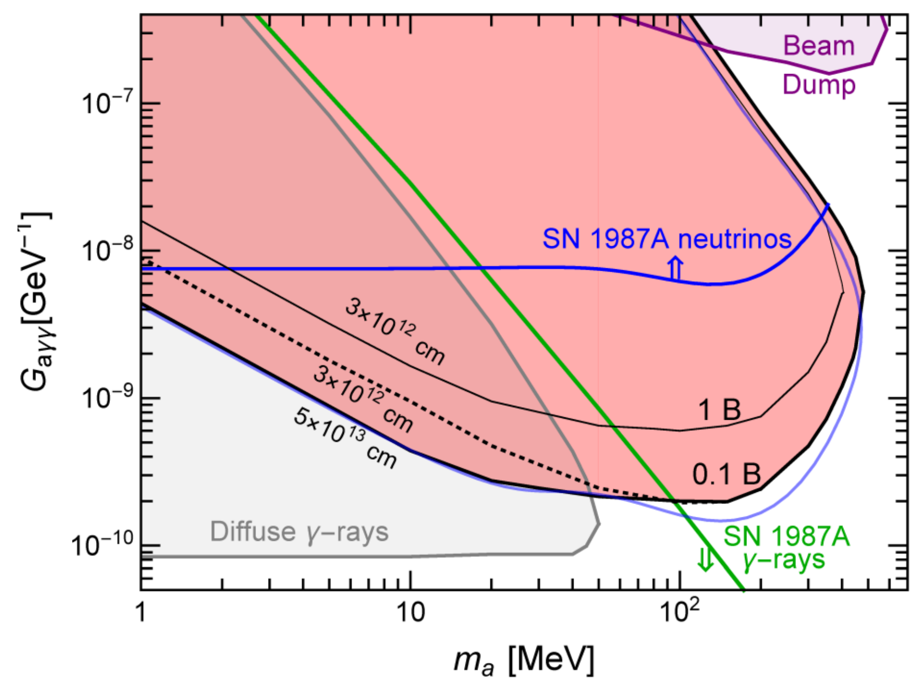


Typical SN explosion energy 1–2 B

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–$0.22\ M_{SUN}$)

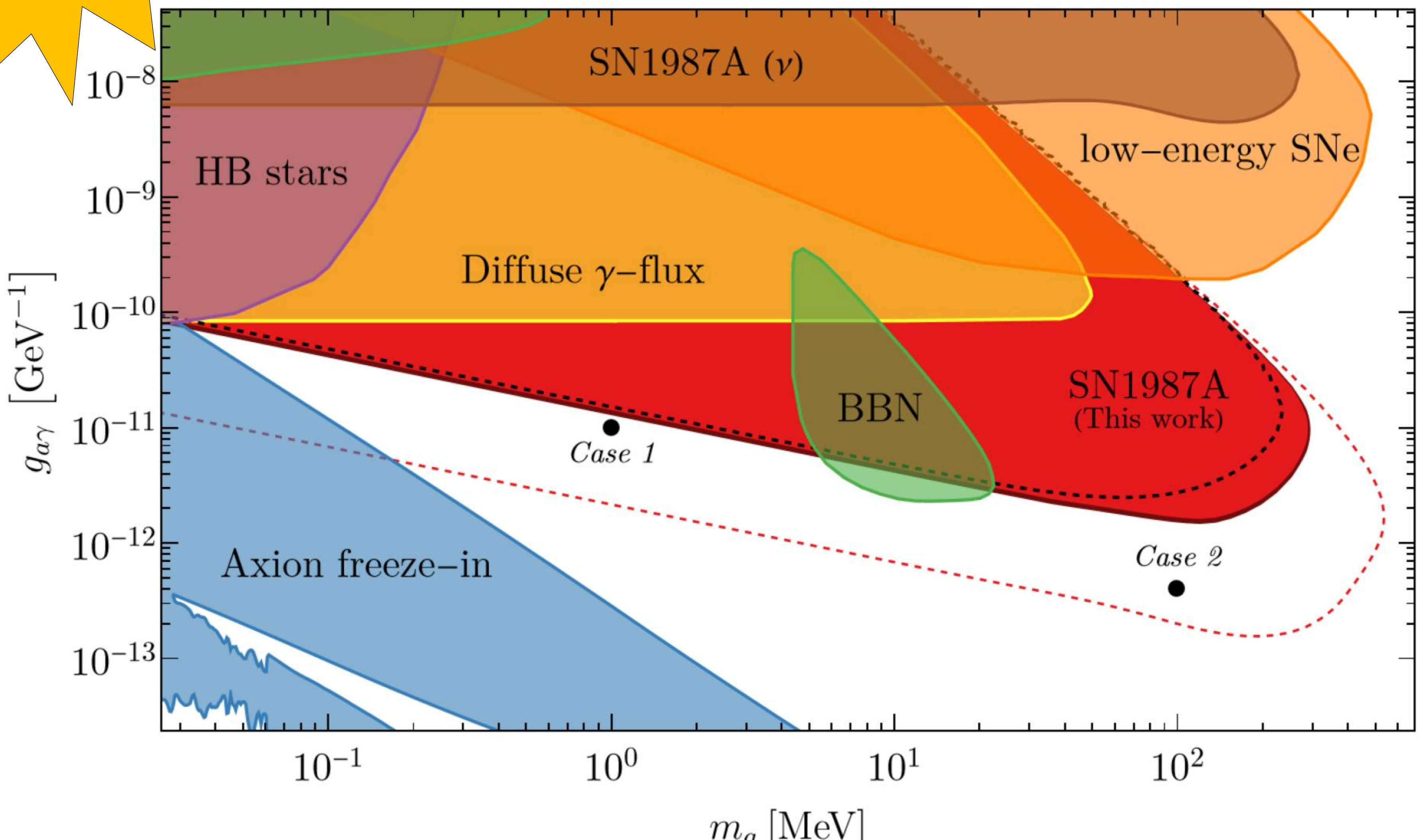


Constraints on Massive ALPs

Brand New

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

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

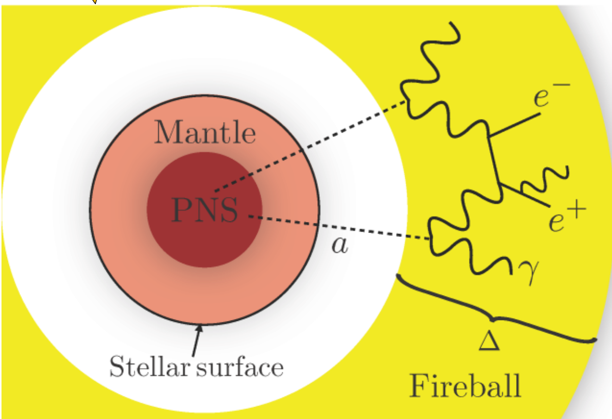


Brand New

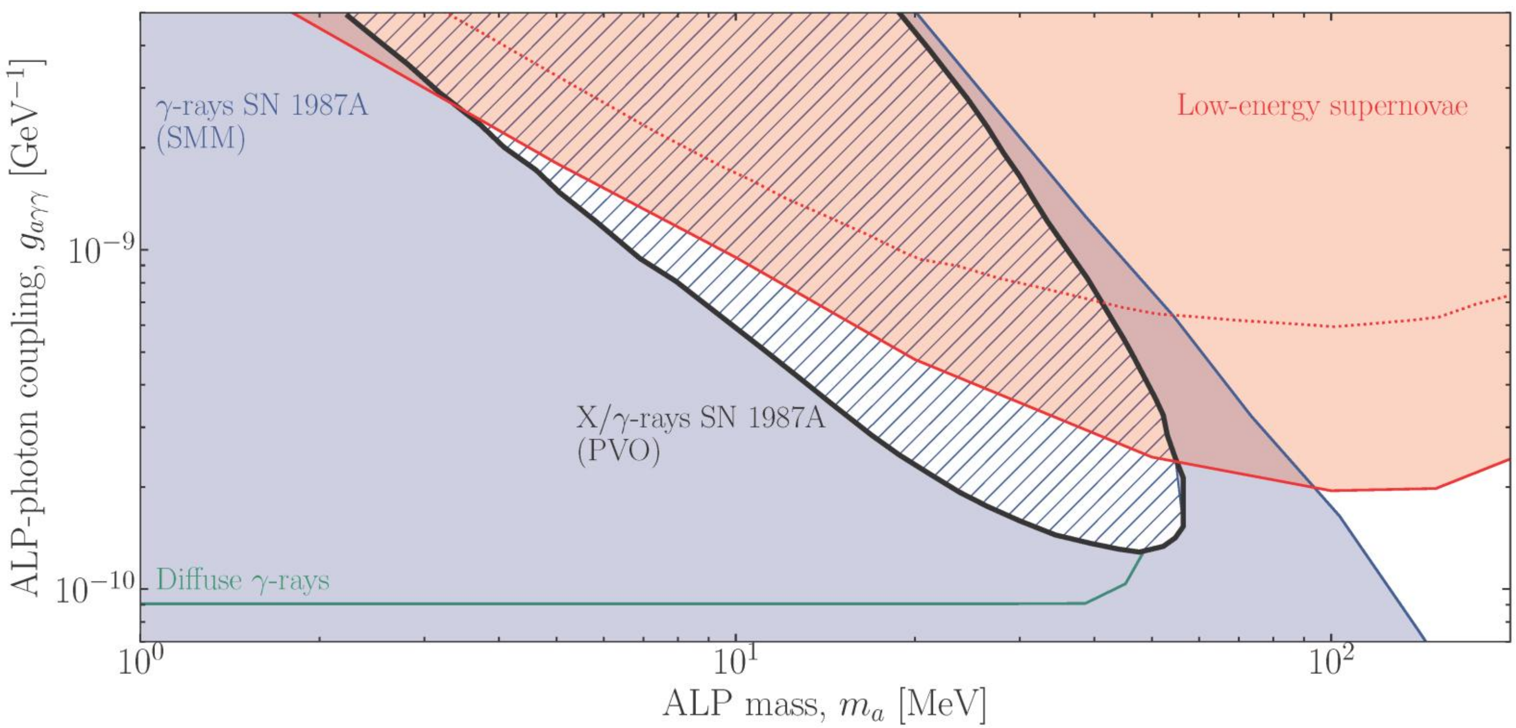
Axion-sourced fireballs from supernovae

2303.11395

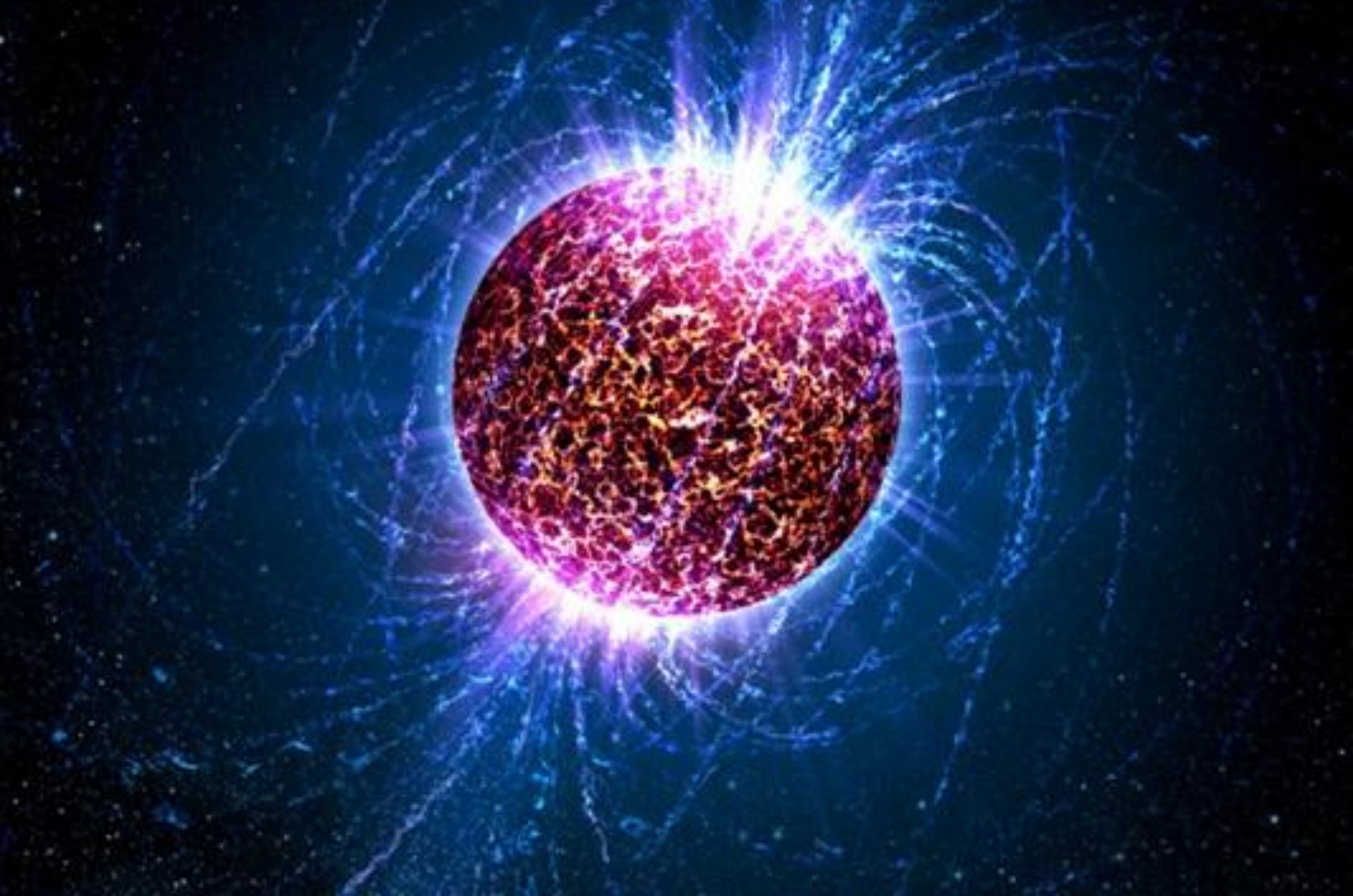
Diamond[1] Damiano F. G. Fiorillo[2] Gustavo Marques-Tavares[3] and Edoardo Vitagliano[4]



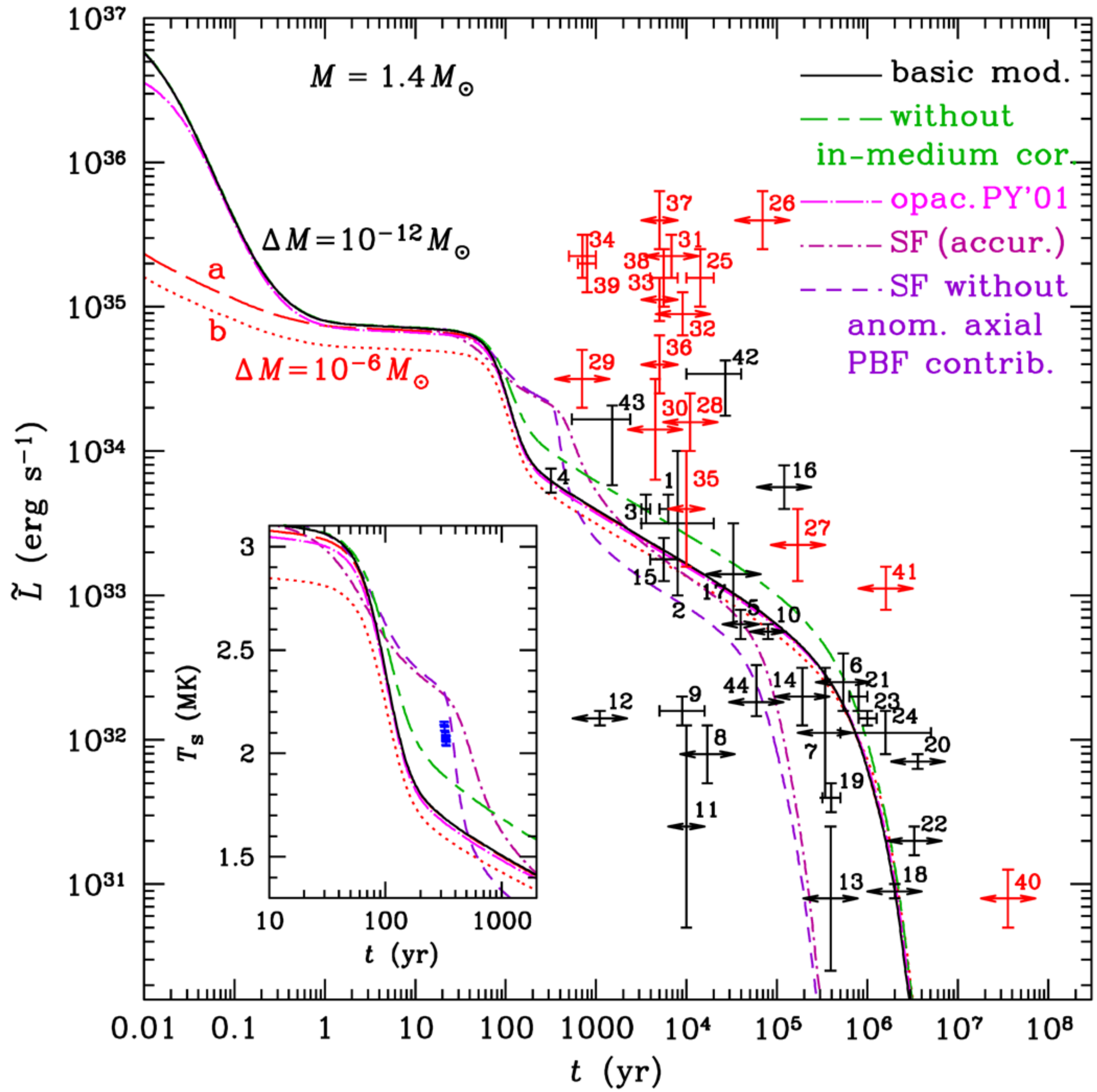
- Massive ALPs form a fireball outside progenitor star
- Downgrades photons, conserves total energy
- sub-MeV photons would have been seen by Pioneer Venus Orbiter (PVO) from SN 1987A
- Exclusion window remains



Neutron Star Cooling



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)

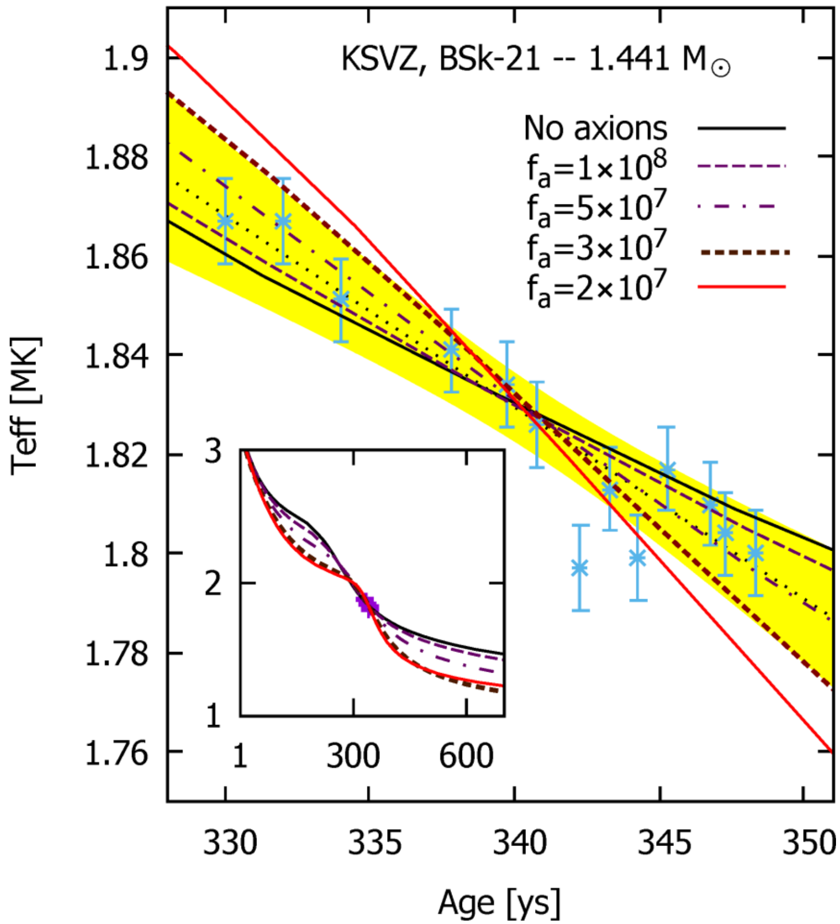
- Beznogov, Rrapaj, Page & Reddy, arXiv:1806.07991
  $g_{an}^2 < 0.77 \times 10^{-19}$
- Leinson, arXiv:1909.03941
  $g_{an}^2 < 1.1 \times 10^{-19}$

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

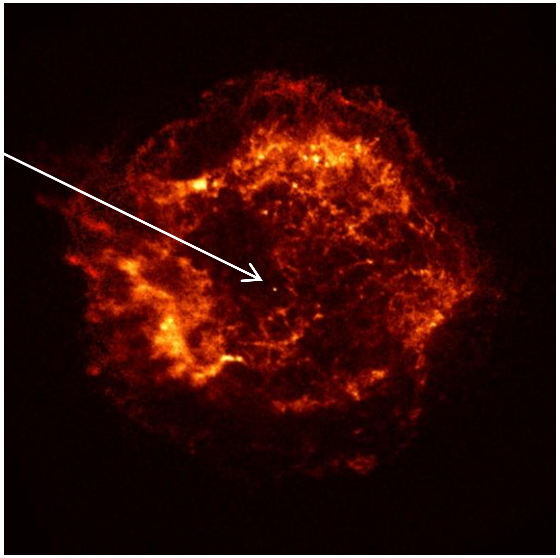
Limits broadly comparable to SN 1987A bounds (m_a tens of meV range)

- 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

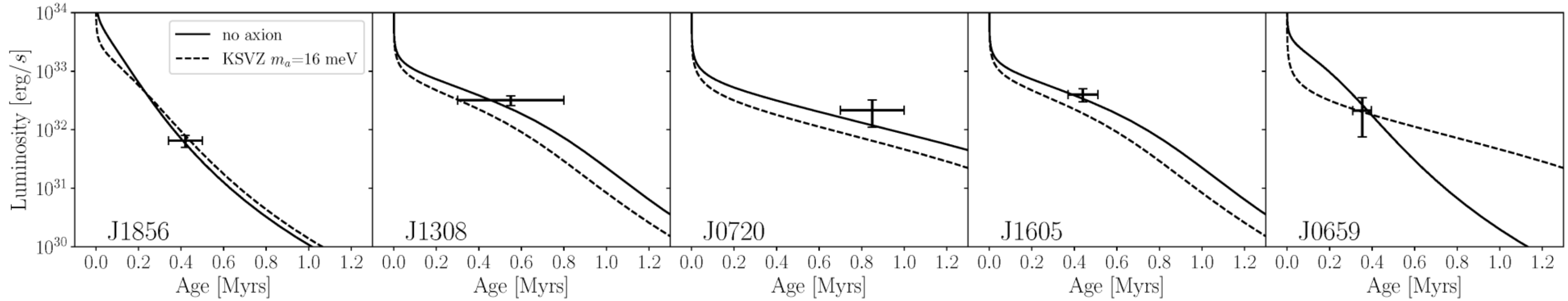
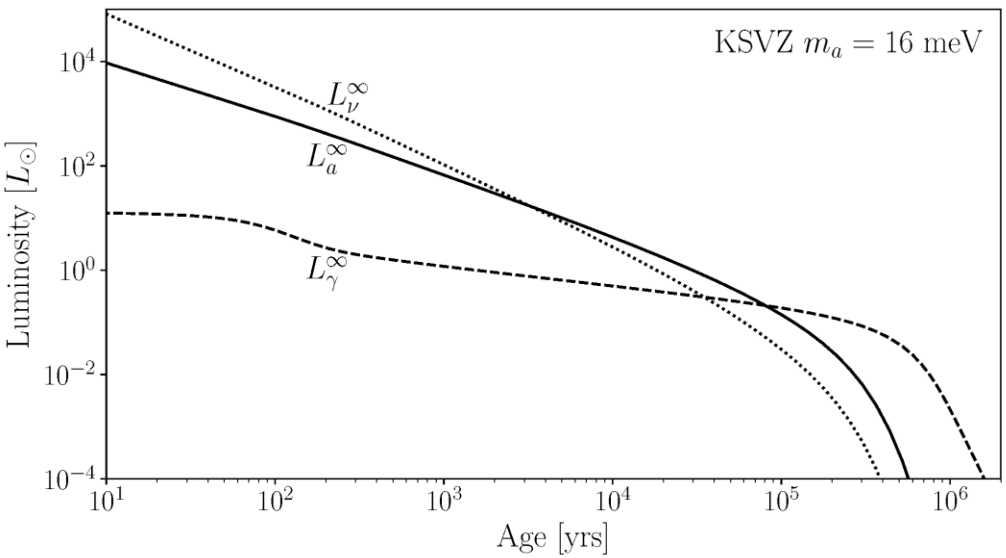


Figure 1. The luminosity and age data for each of the NSs considered in this work (see Tab. I). We show the best-fit cooling curves computed in this work for each of these NSs under the null hypothesis and with the axion mass fixed to $m_a = 16$ meV, which is our 95% upper limit on the QCD axion mass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

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

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

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

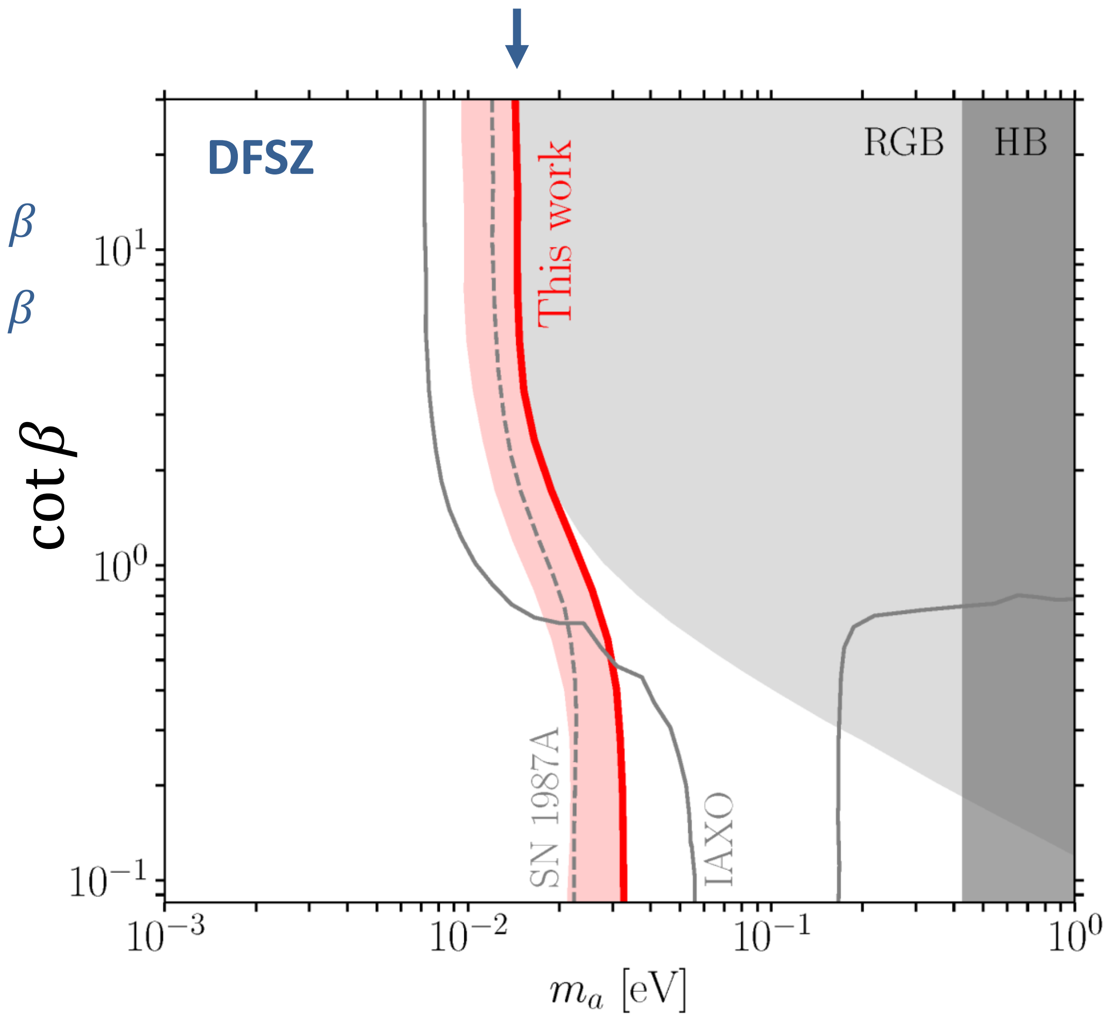
$$C_e = \tfrac{1}{3}\cos^2\beta$$

Notice that in this paper a different convention is used where

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

as advocated by the PDG

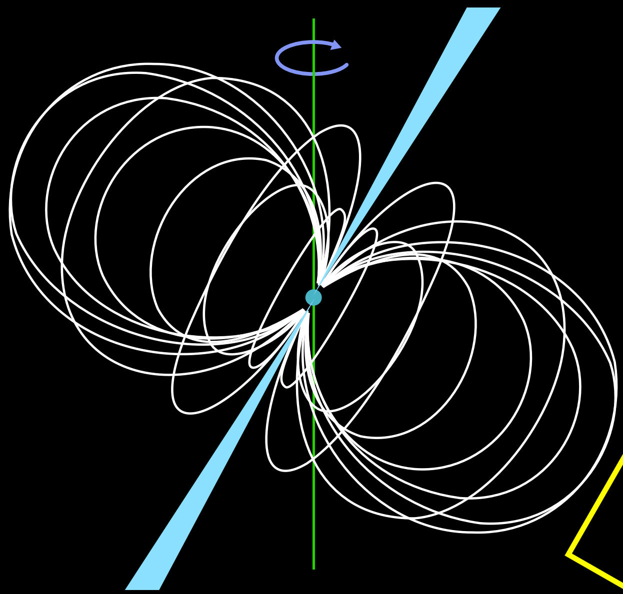
KSVZ



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

Buschmann, Dessert, Foster, Long & Safdi, 2111.09892

Dark Matter Axion-Photon Conversion in Neutron Star Magnetospheres



Dark matter axions
$m_a \sim \mu\text{eV},\ v_a \sim 10^{-3}c$

Very narrow radio line

Pshirkov & Popov 2007
arXiv:0711.1264
Many papers recently

Axion mass and plasma frequency
Degenerate near NS surface
→ Resonant conversion

Dark-Matter-Axion Radiowaves from Pulsars

Conversion of Dark matter axions to photons in magnetospheres of neutron stars

M.S. Pshirkov (ITAE, Moscow), S.B. Popov (ITAE, Moscow)
Nov, 2007

10 pages
Published in: *J.Exp.Theor.Phys.* 108 (2009) 384-388
e-Print: 0711.1264 [astro-ph]
DOI: 10.1134/S1063776109030030
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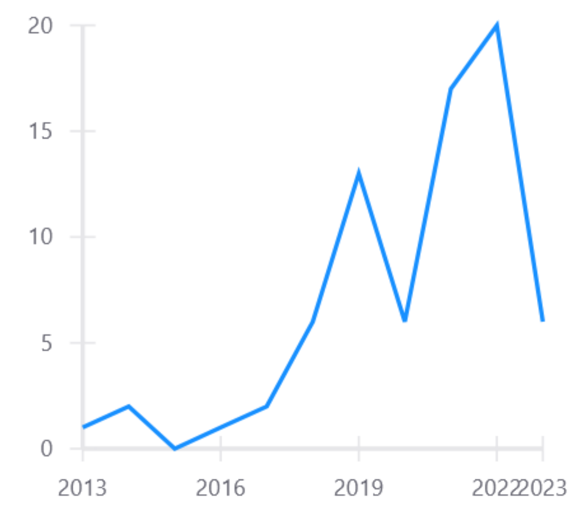
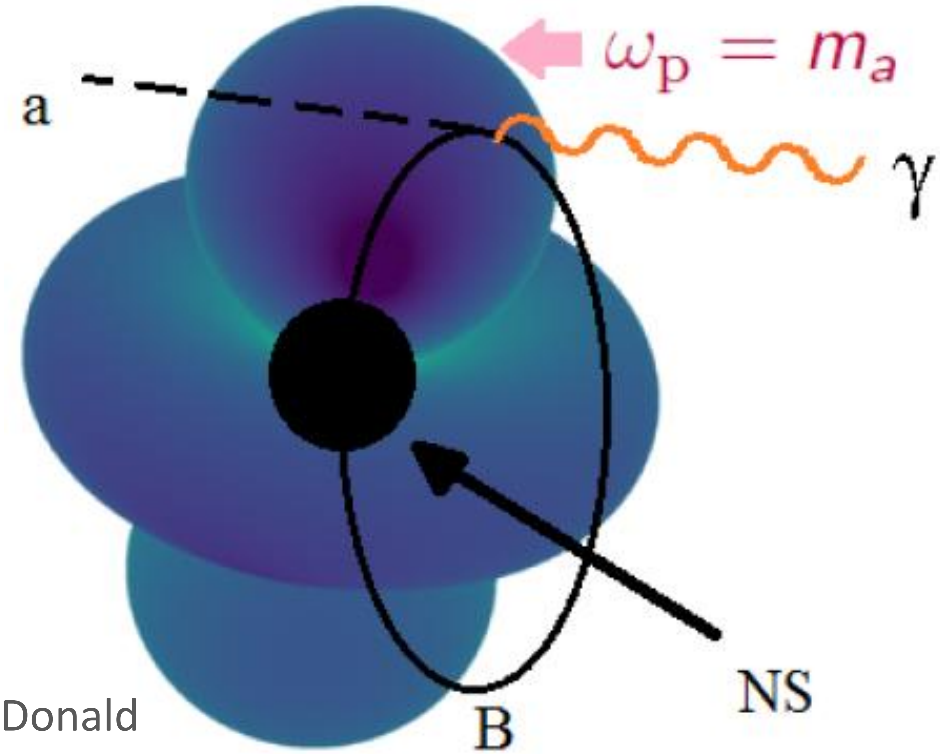
Citations per year



Abstract: (arXiv)
A new method is suggested for search of the axions constituting Dark Matter that utilizes observations of neutron stars (NS) in radio-frequency region. It uses the conversion of axions to photons in strong magnetic fields of NS. The observations of Magnificent Seven objects are proposed. Whether the conversion takes place, the radio spectrum of the object would have a very distinctive feature -- a narrow spike at a frequency corresponding to the rest mass of the axions. For example, if the coupling constant of the photon-axion interaction is M=10^10 GeV, the density of DM axions is \rho=10^(-24)*g*cm^(-3) and the NS is located at a distance of 300 pc from the Solar system, then the flux density of excess signal for axions with the rest mass of 1 \mu eV will be as large as several mJy at the frequency 240 MHz in the bandwidth 0.5 MHz.

14.80.Mz | 97.60.Gb | 95.35.+d | 95.85.Bh | axion: dark matter | photon axion: transition | neutron star | magnetic field: high | axion: mass | axion: density | Show all (11)



J.McDonald

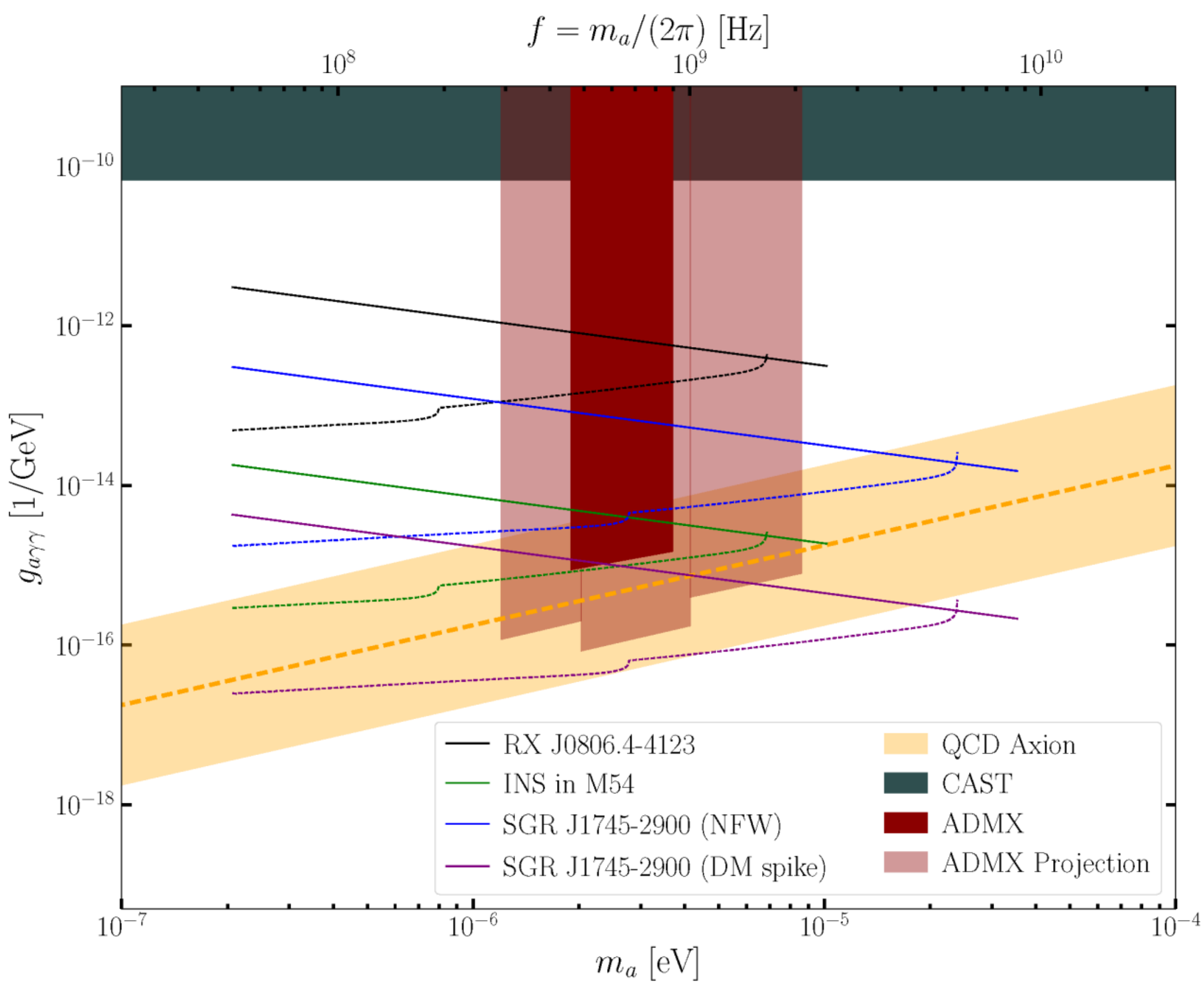
$$P_{a\to\gamma} \simeq \frac{g_{a\gamma}^2 B^2}{\frac{d}{dz}\omega_{\rm plas}(z_{\rm res})}$$

- **Conversion of dark matter axions to photons in magnetospheres of neutron stars,** 0711.1264
  M.S. Pshirkov & S.B. Popov
- **The radio telescope search for the resonant conversion of cold dark matter axions from the magnetized astrophysical sources** 1803.08230
  F.P. Huang, K. Kadota, T. Sekiguchi & H. Tashiro
- **Radio Signals from Axion Dark Matter Conversion in Neutron Star Magnetospheres,**
  A. Hook, Y. Kahn, B.R. Safdi & Z. Sun 1804.03145

Radio Signals from Axion Dark Matter Conversion in Neutron Star Magnetospheres

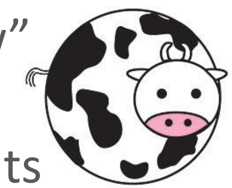
[1804.03145](1804.03145)

Anson Hook,[1,*] Yonatan Kahn,[2,†] Benjamin R. Safdi,[3,‡] and Zhiquan Sun[3,§]



Optimistically,
QCD DM Axions reachable

But "spherical cow" approximation



- Radial axion orbits
- Radio line width $\approx 10^{-6}$ (galactic virial velocity 10^{-3})

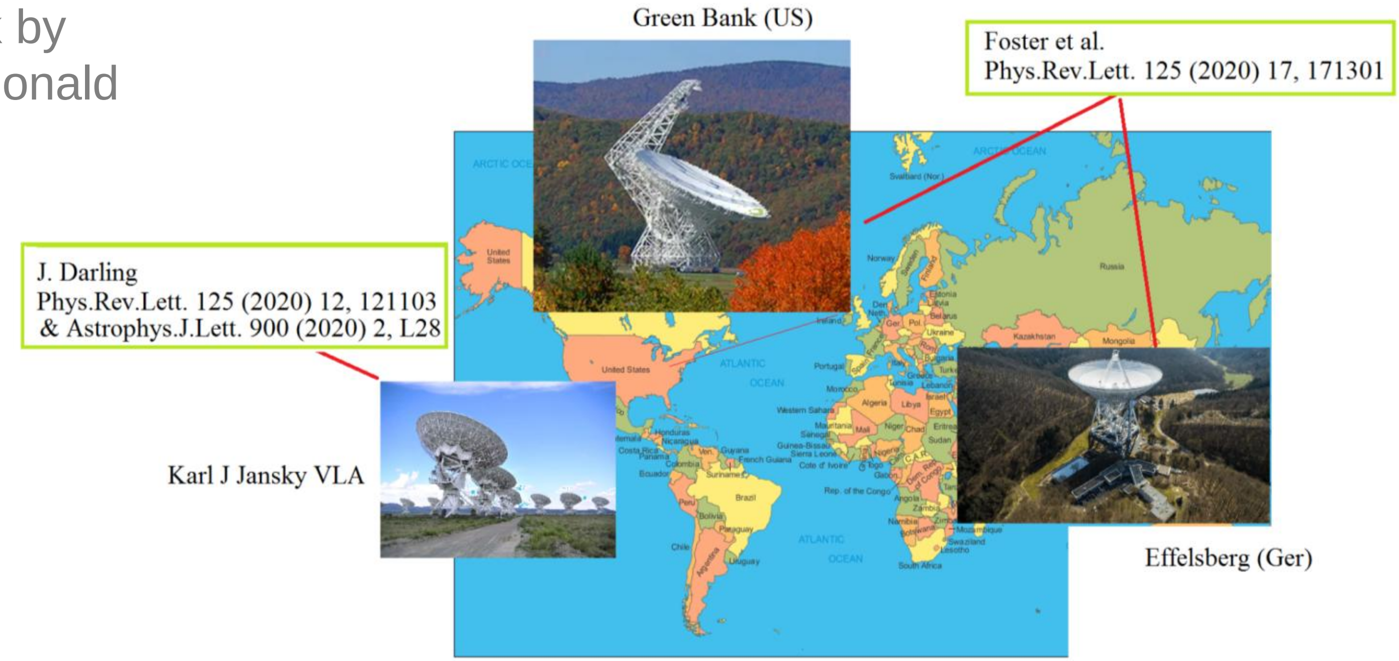
Galactic Center Magnetar
SGR (PSR) J1745–2900

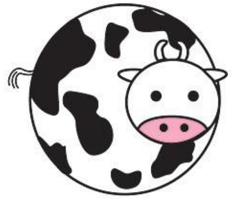
$P = 3.76$ s

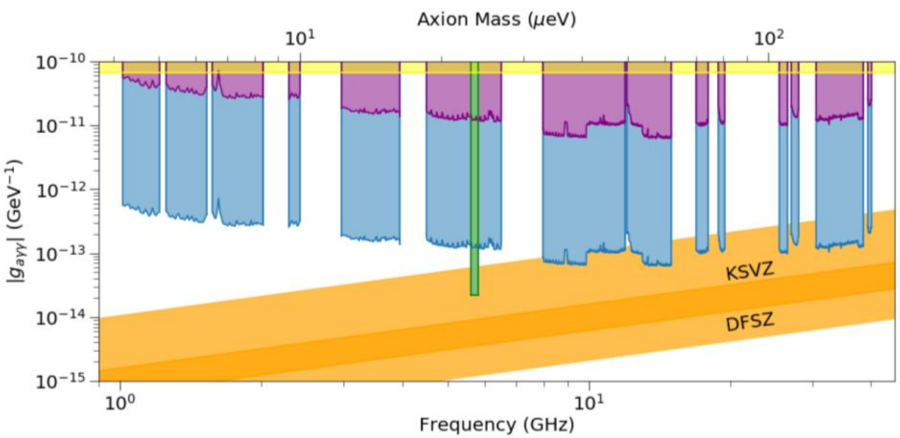
$B_0 = 1.6 \times 10^{14}$ G

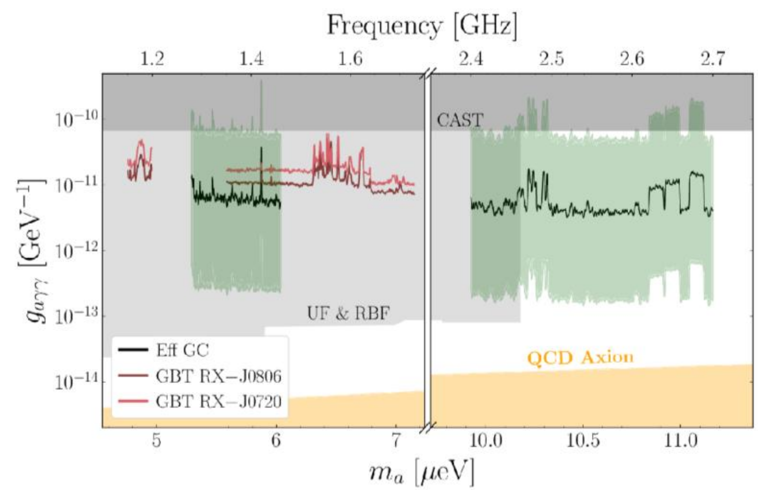
Early Constraints (Simplified Signal Prediction)

From a talk by
Jamie McDonald

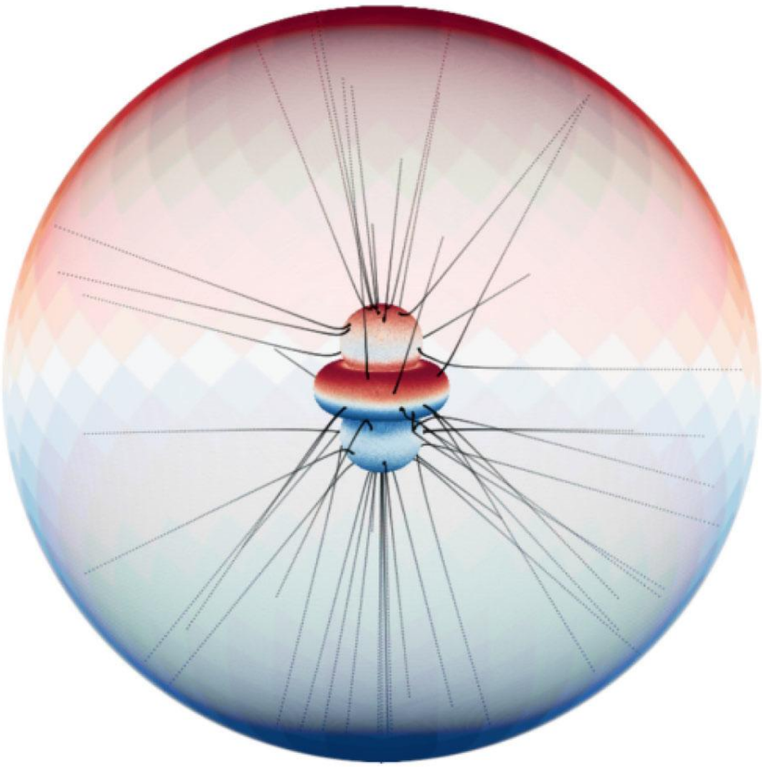


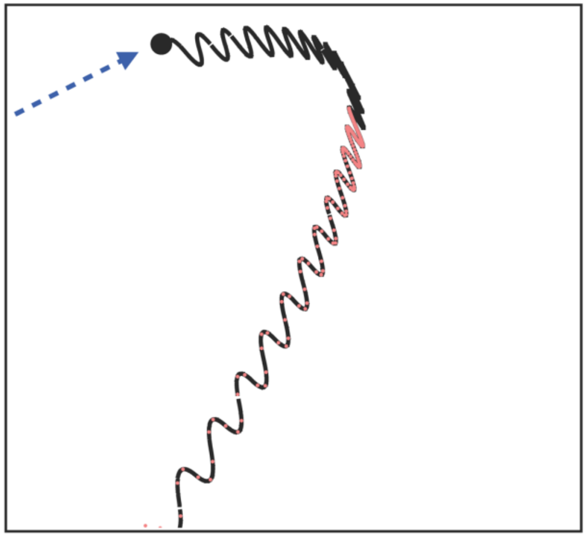


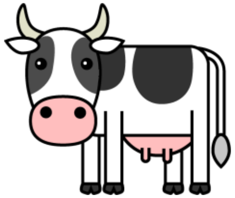




Signal Modeling with Ray Tracing







Ray tracing allows for:

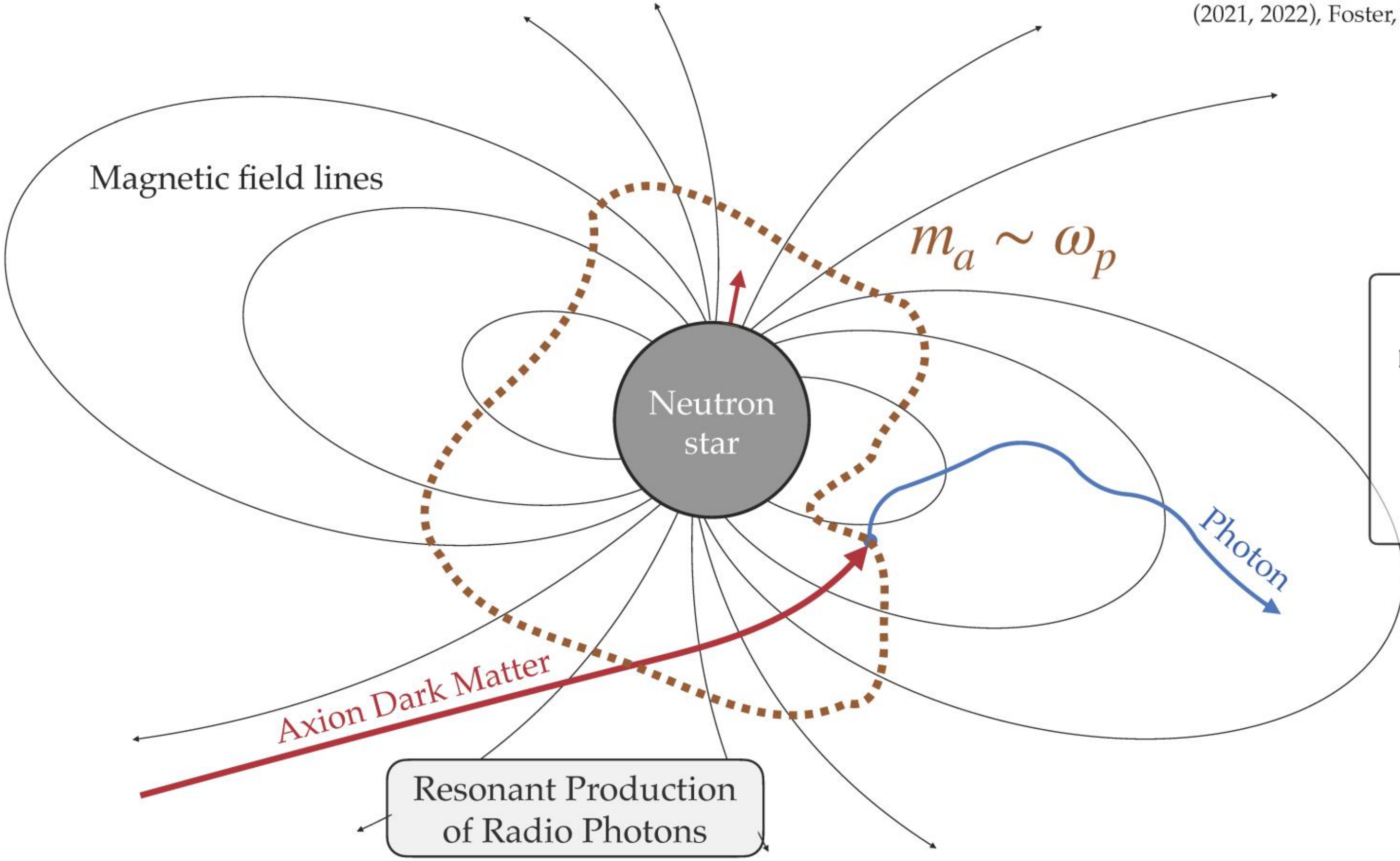
- Accurate mapping of radio flux
- Back-reaction on axion phase space
- Line broadening effects (Doppler)
- Path-dependent absorption

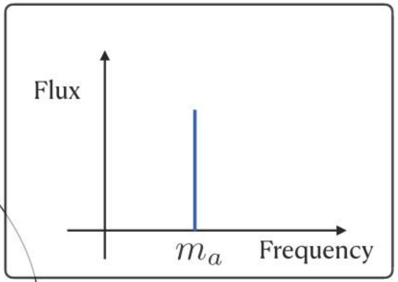
(following a talk by Sam Witte)

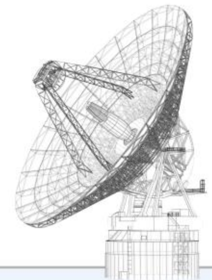
Leroy+ 1912.08815, Witte+ 2104.07670, 2212.08079, Battye+ 2104.08290, 2107.01225

Neutron stars as axion labs

Spectral Lines from Axion Dark Matter:
See e.g.: Pshirkov & Popov (2009), Hook et al. (2018), Safdi et al. (2018), Battye et al. (2019, 2021), **SJW** et al. (2021, 2022), Foster, **SJW** et al (2022), …







Radio Line Properties of Axion Dark Matter Conversion in Neutron Stars

R. A. Battye,[1,*] B. Garbrecht,[2,†] J. I. McDonald,[3,‡] and S. Srinivasan[1,§] 2104.08290

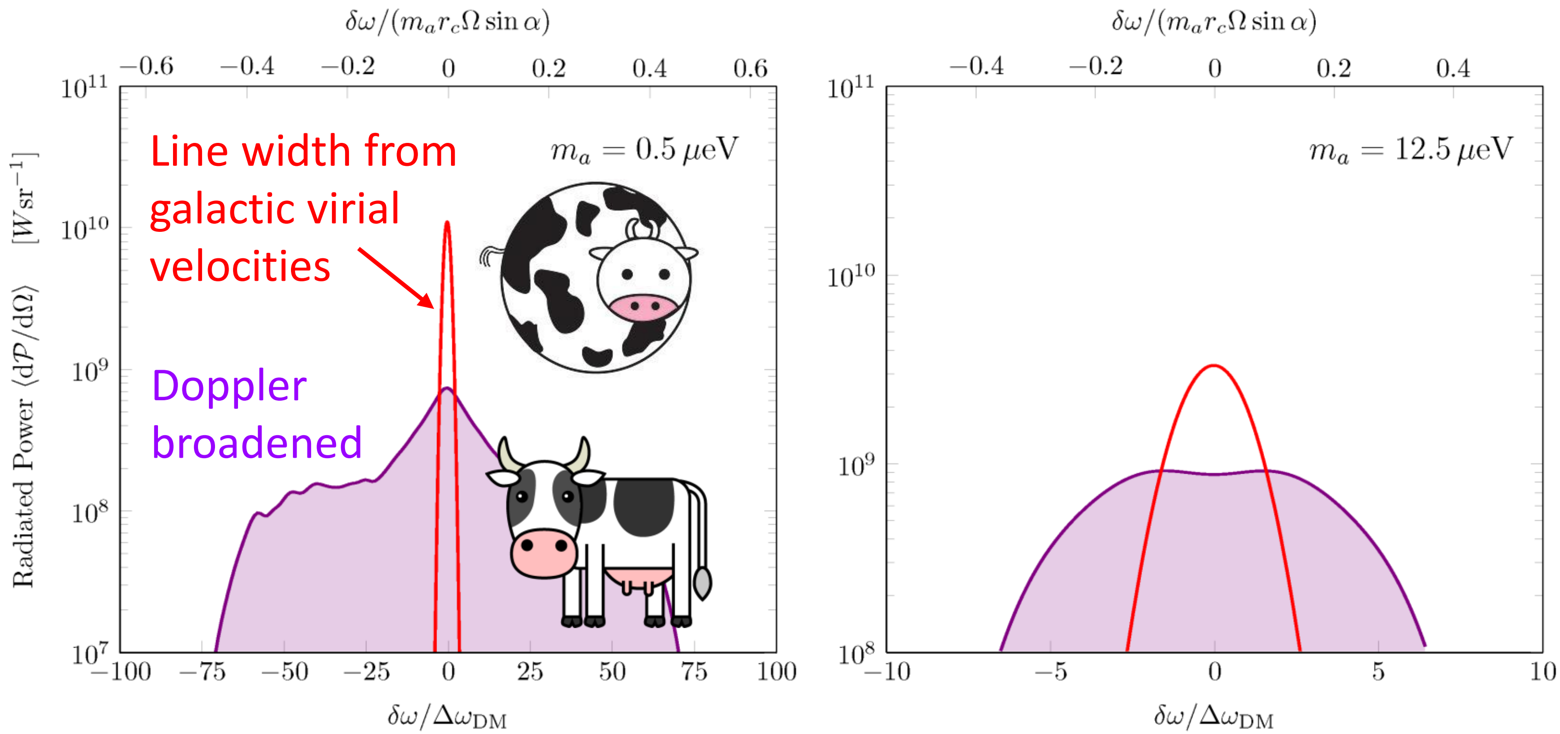


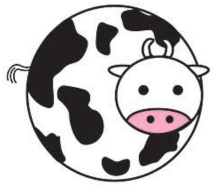
FIG. 5. **Pulse-averaged line shapes.** Line profile (purple) of the Doppler broadened radio line computed via evolving eq. (24) along rays. We took an observing angle $\theta = 36°$. Other model parameters are as for Fig. 3. The bottom axis shows the width relative to that set by velocity dispersion of dark matter $\Delta\omega_{\rm DM} = \frac{1}{2}v_0^2 m_a$ with $v_0 = 6 \times 10^{-4}$ corresponding to a dark matter velocity $v_0 = 200\,\mathrm{km\,sec}^{-1}$. The top axis compares the width to the analytic estimate (43). We display the original un-broadened Gaussian line signal in red.

Searching for axion dark matter with MeerKAT Radio Telescope

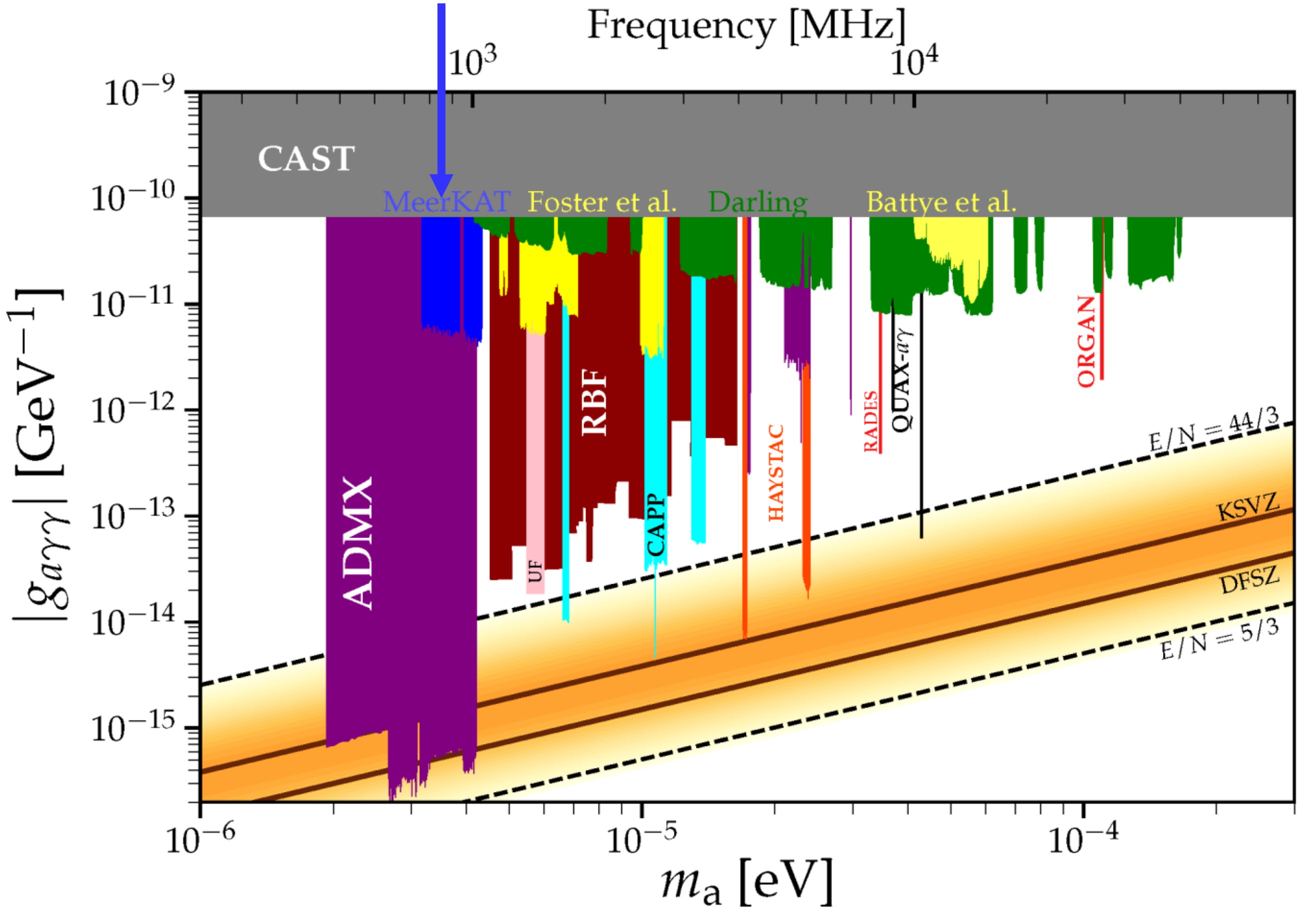
[2209.09695](2209.09695)

Yun-Fan Zhou[1,2], Nick Houston[3], Gyula I. G. Józsa[4,5,6], Hao Chen[7,1,8], Yin-Zhe Ma[9,10,11,1*], Qiang Yuan[12,2†], Tao An[13], Yogesh Chandola[1], Ran Ding[14], Fujun Du[1,2], Shao-Guang Guo[13], Xiaoyuan Huang[12,2], Mengtian Li[12,2], Chandreyee Sengupta[1]

Isolated Neutron Star J0806.4−4123
10h with MeerKAT Radio Telescope
Polar B field $B_0 = 2.5 \times 10^{13}$ Gauss



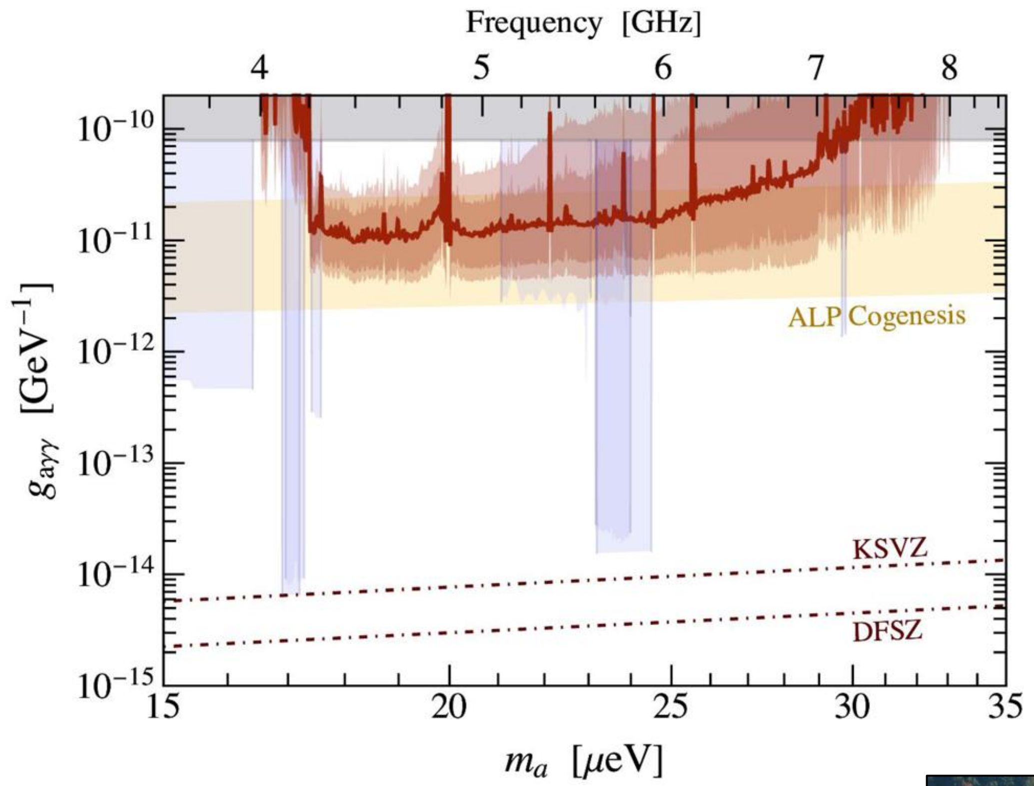
No ray tracing



Extraterrestrial Axion Search with the Breakthrough Listen Galactic Center Survey

Joshua W. Foster,[1,*] Samuel J. Witte,[2,†] Matthew Lawson,[3,4] Tim Linden,[3]
Vishal Gajjar,[5] Christoph Weniger,[2] and Benjamin R. Safdi[6,7,‡]

2202.08274

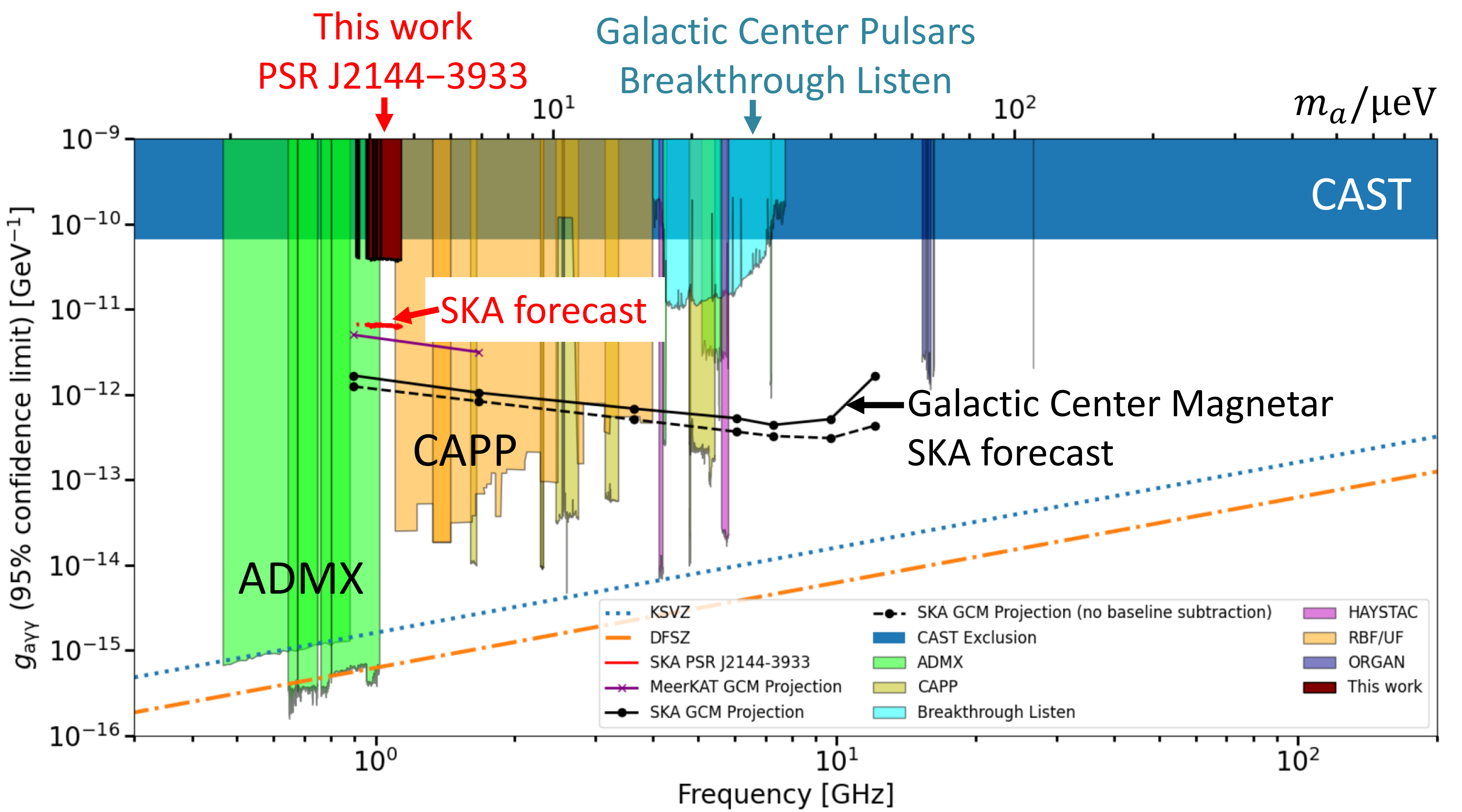


- Green Bank Telescope Archival Data
- Breakthrough Listen Project (Search for ET Life)
- State-of-the-art ray tracing simulations
- Galactic Center Region
  - Many pulsars
  - Enhanced dark matter density

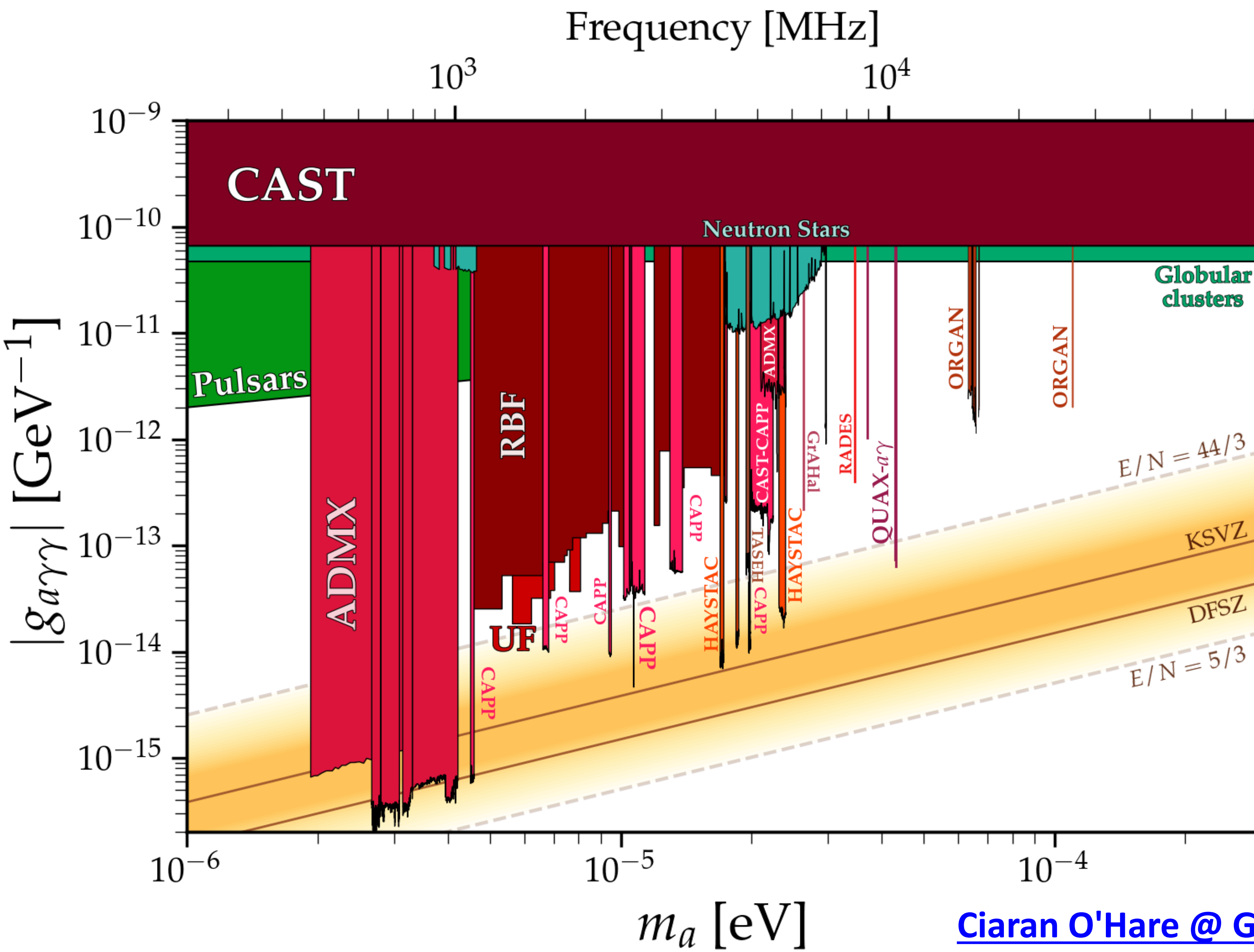
Searching for Time-Dependent Axion Dark Matter Signals in Pulsars

R. A. Battye,[1,*] M. J. Keith,[1,†] J. I. McDonald,[2,‡] S. Srinivasan,[1,§] B. W. Stappers,[1,¶] and P. Weltevrede[1,**]

2303.11792



ALP Scape – Dark Matter Search Closeup



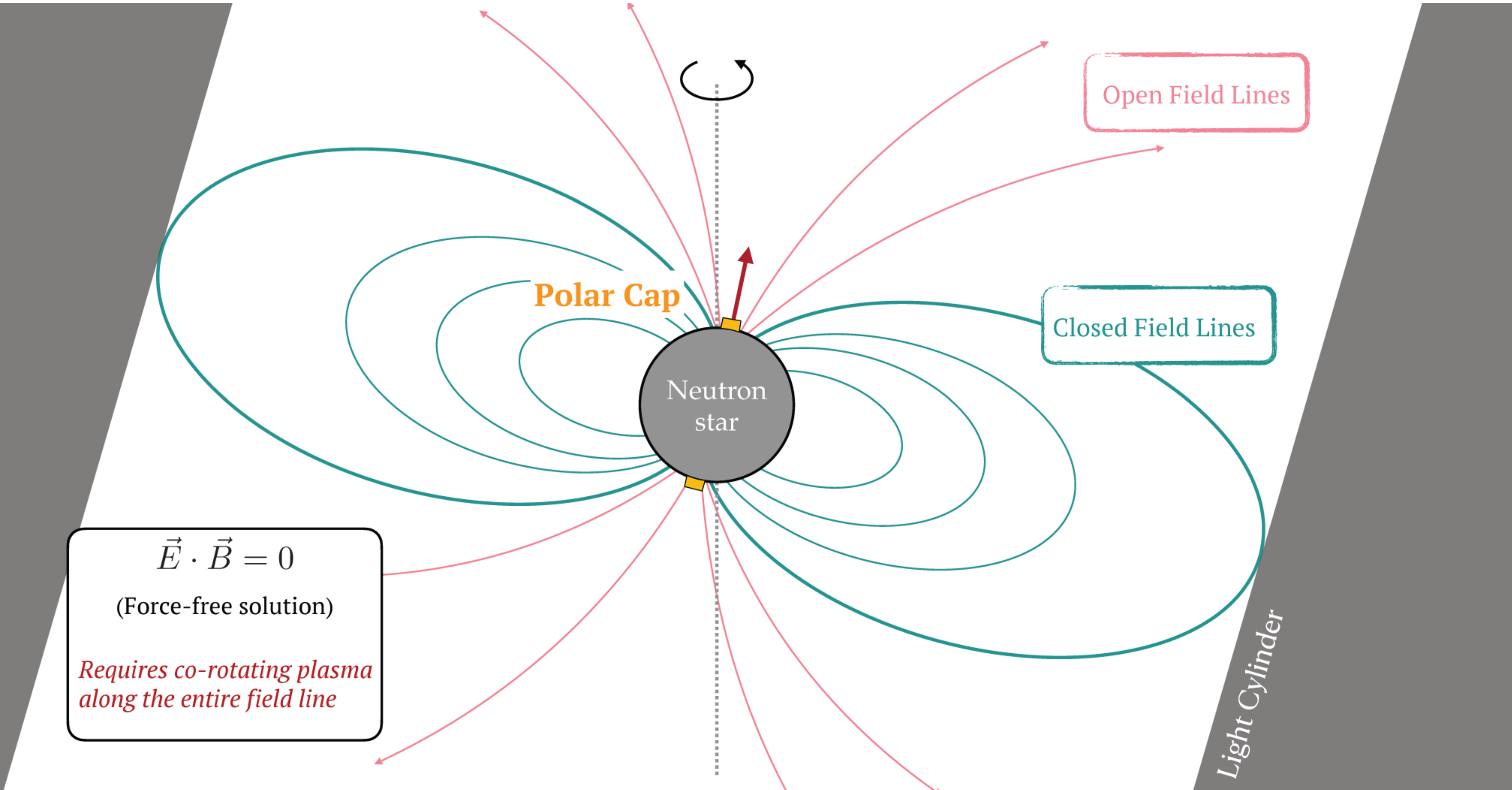
[Ciaran O'Hare @ Github](#)

Novel Constraints on Axions Produced in Pulsar Polar Cap Cascades

Dion Noordhuis,[1,*] Anirudh Prabhu,[2,3,*] Samuel J. Witte,[1,*]
Alexander Y. Chen,[4] Fábio Cruz,[5,6] and Christoph Weniger[1]

arXiv: 2209.09917

From a talk by Sam Witte



Novel Constraints on Axions Produced in Pulsar Polar Cap Cascades

Dion Noordhuis,[1,*] Anirudh Prabhu,[2,3,*] Samuel J. Witte,[1,*]
Alexander Y. Chen,[4] Fábio Cruz,[5,6] and Christoph Weniger[1]

[arXiv: 2209.09917](https://arxiv.org/abs/2209.09917)

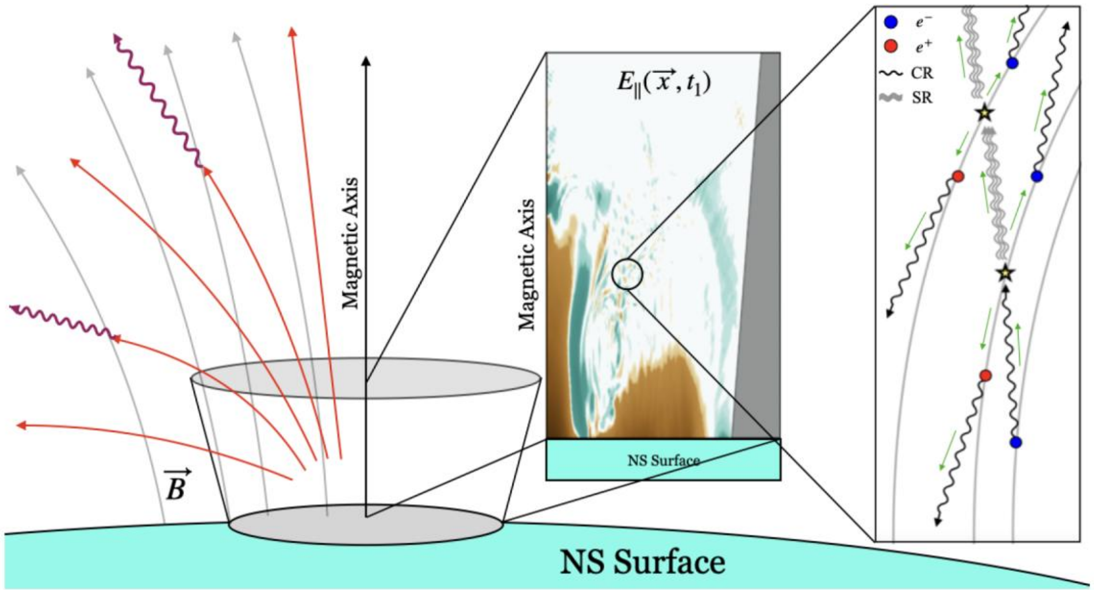


FIG. 1. Schematic figure showing axion production in neutron star vacuum gaps. The vacuum gap is depicted by a truncated cone on the neutron star surface. The left inset shows a time snapshot of $E_\parallel$ (as computed in the simulations of [67]), with the brown/green coloring reflecting negative/positive values of $E_\parallel$. The right inset depicts the microphysical processes responsible for the pair cascade, with green arrows indicating the direction the cascade flows with time. Axions (red) are emitted from the gap and periodically convert to photons (purple) in the presence of the neutron star's magnetic field, $\vec{B}$ (grey).

- E-field extracts charges
- QED cascade
- Shuts off E-field
- Cascade stops

...

- Peridioc E modulation
- Peridioc **E.B**
- Sources ALPs

Coherent emission from QED cascades in pulsar polar caps
Fábio Cruz+ arXiv:2108.11702, Animation https:/youtu.be/wHSw5kp7Ik4

Novel Constraints on Axions Produced in Pulsar Polar Cap Cascades

Dion Noordhuis,[1,*] Anirudh Prabhu,[2,3,*] Samuel J. Witte,[1,*]
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arXiv: 2209.09917

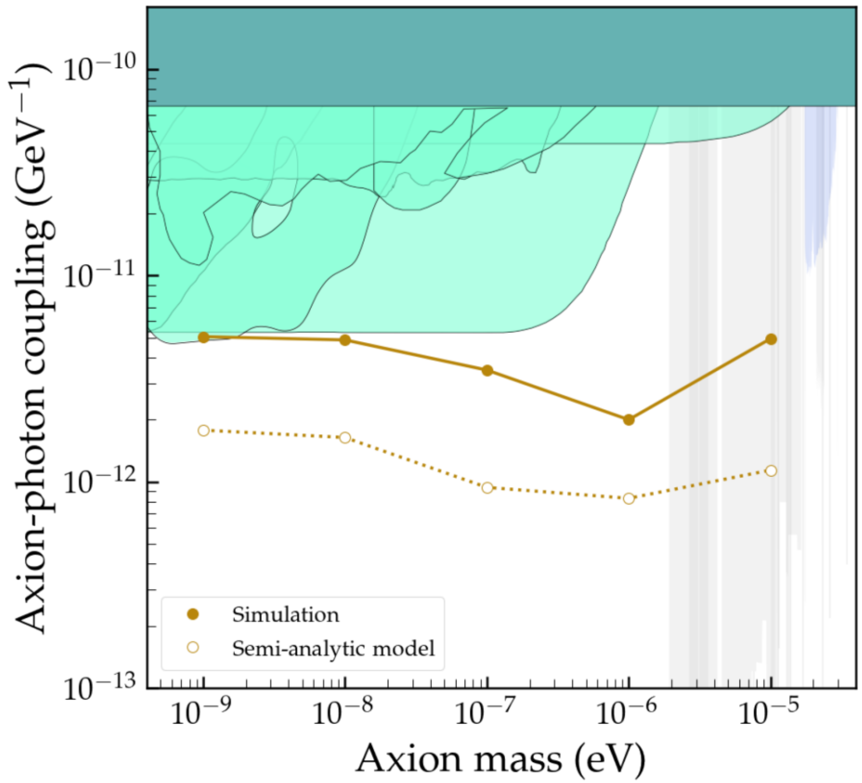


FIG. 2. Upper limits on the axion-photon coupling derived in this work, using both the simulation (solid) and semi-analytic model (dotted). We compare to existing constraints from neutron stars [49] (shown in blue), haloscopes [8–24, 94] (grey), helioscopes [30] (teal), and astrophysics [34–43, 95, 96] (light green). The former two have been drawn with reduced opacity to highlight that they rely on axions being dark matter.

Current search:

- Uses only 27 well-studied pulsars!

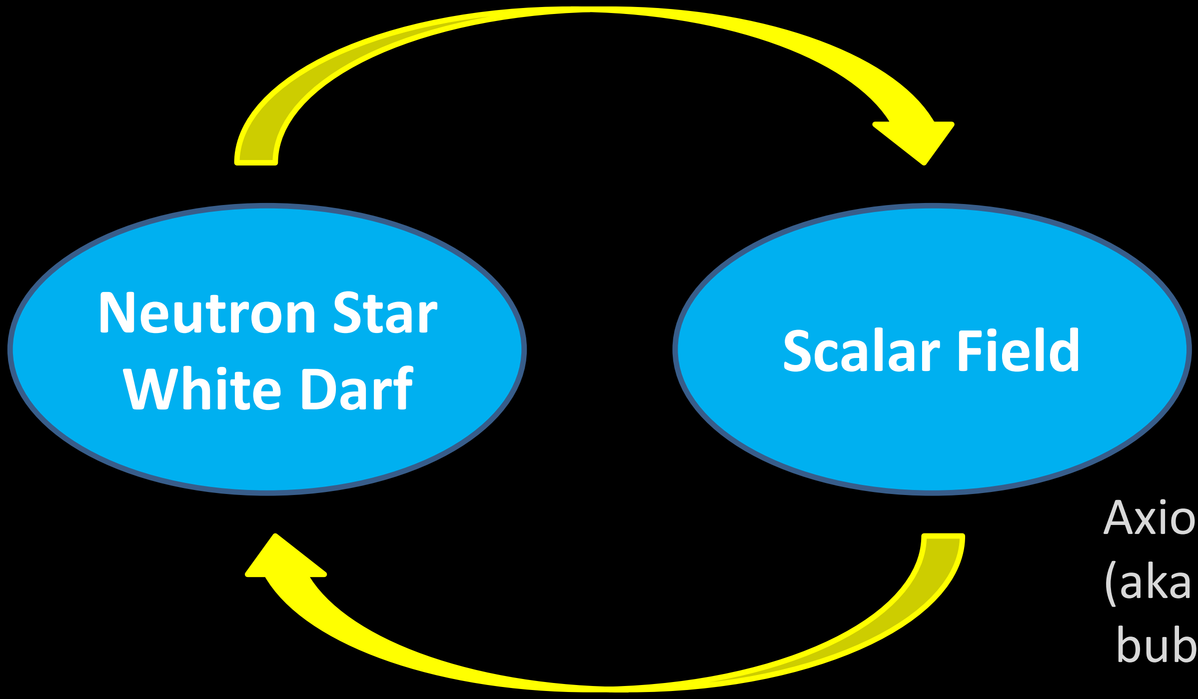
Future outlook:

- Wider frequency observations
- Full population in ATNF pulsar catalogue
- 3D PIC simulations

(from a talk by Sam Witte)

Axions and Stellar Structure

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



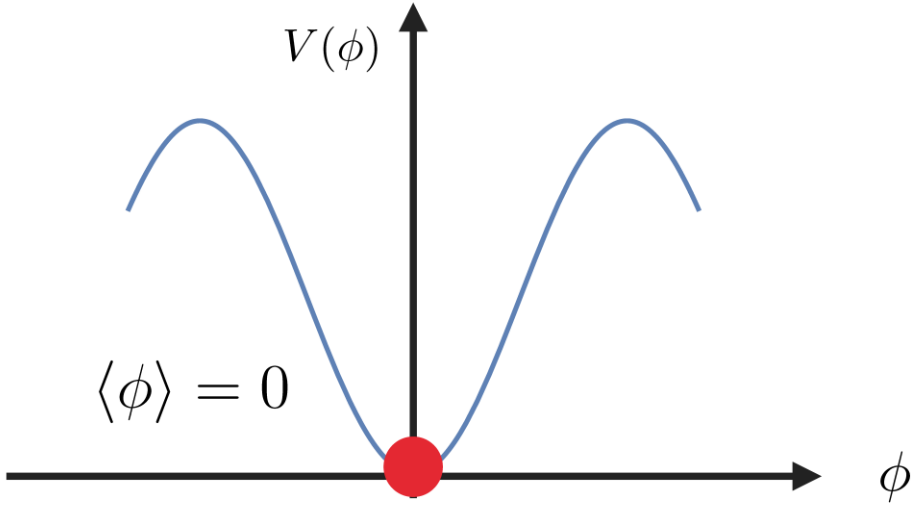
Axion condensation
(aka axion sourcing,
bubble formation)

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

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

$2\pi f_a$ 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

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

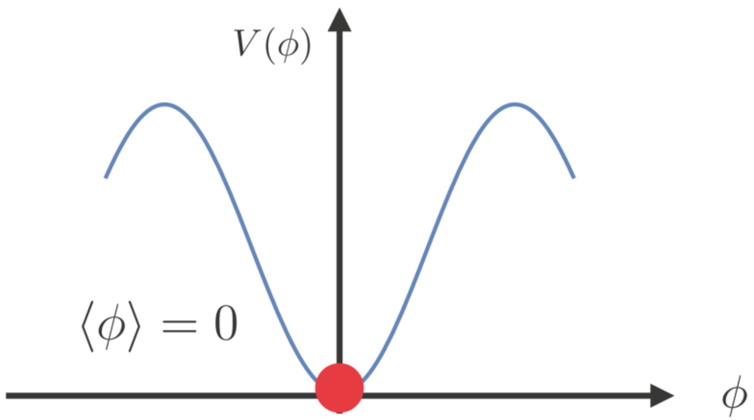
$\mathcal{O}(1)$ at nuclear density

Hook & Huang 1708.08464, Balkin+ 2105.13354

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

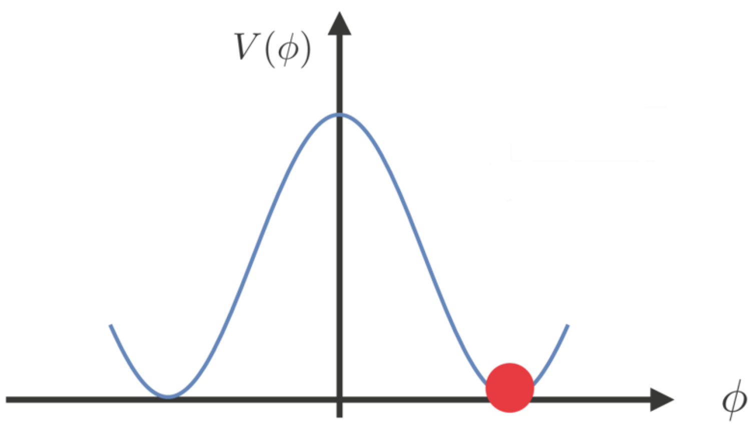
Axions with smaller mass

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



New minima appear at large density

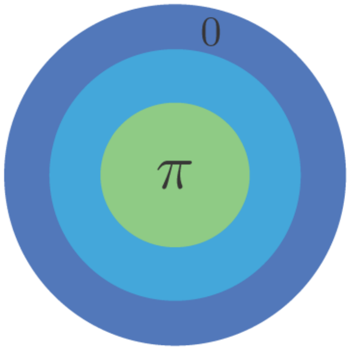
$$n > n_c = \epsilon\, \frac{m_\pi^2 f_\pi^2}{4\sigma_{\pi N}}$$

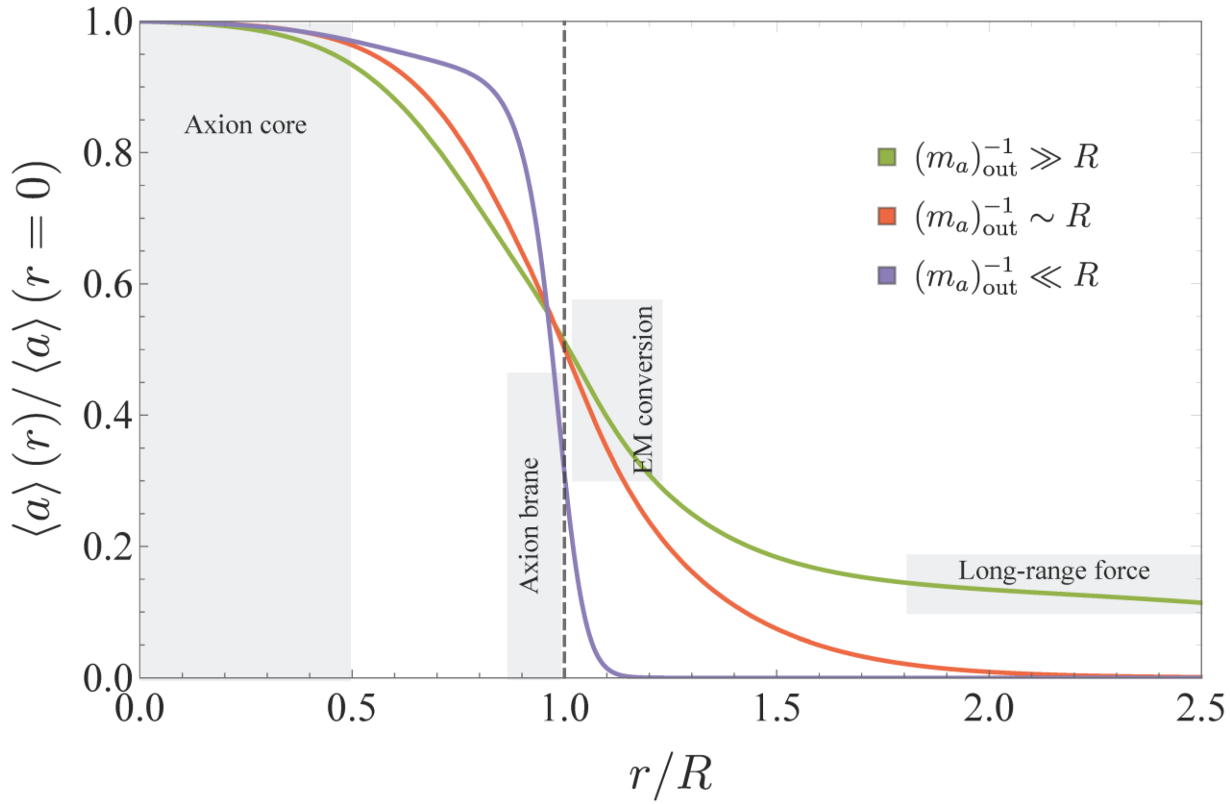


Hook & Huang 1708.08464, Balkin+ 2105.13354

Axion Profile of a Neutron Star

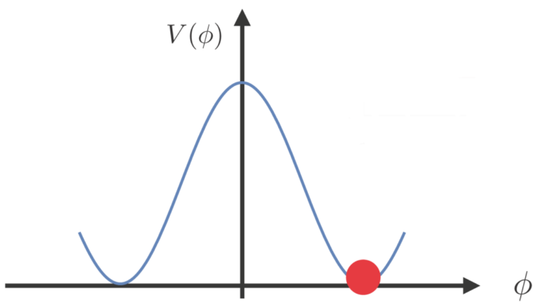
$\phi = \theta f$

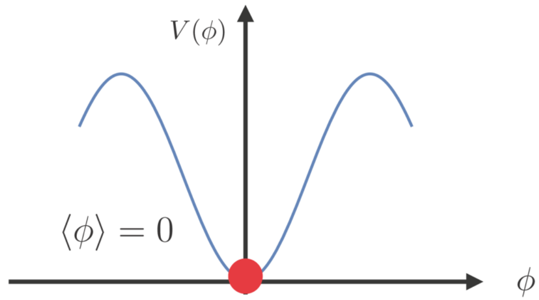




Nucleon mass shifted

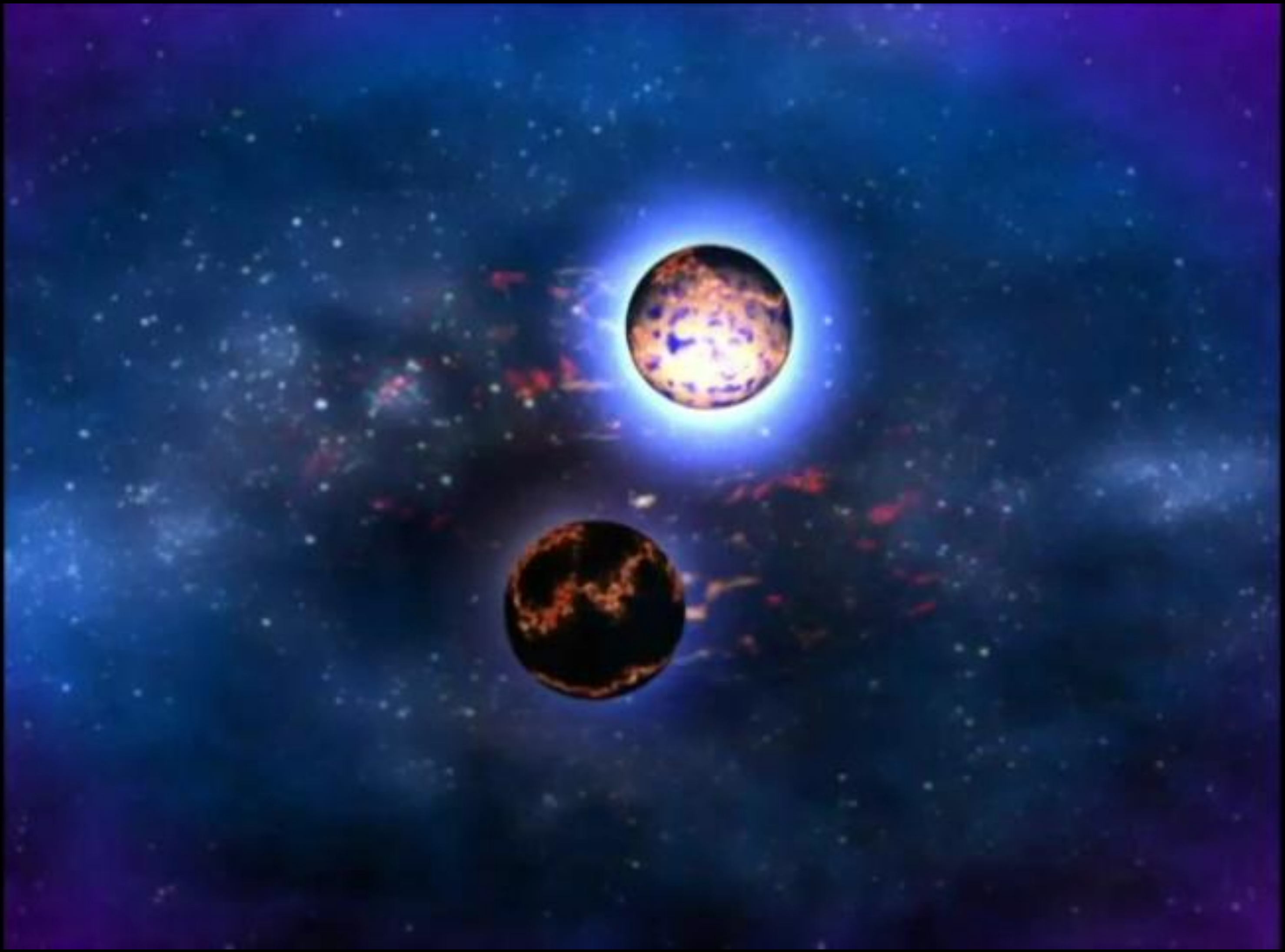
$m_N \rightarrow m_N - \sigma_{\pi N}$





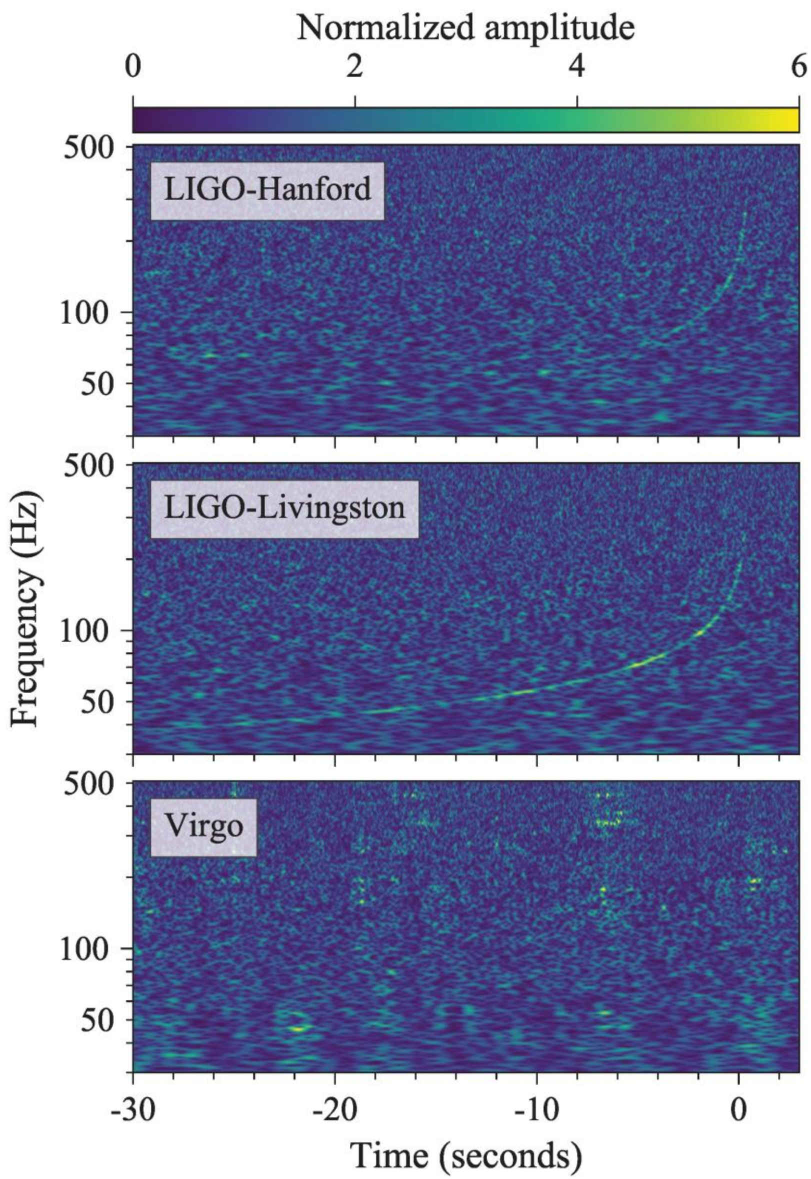
Hook & Huang 1708.08464
Balkin+ 2105.13354

Binary Neutron Star Merger GW 170817

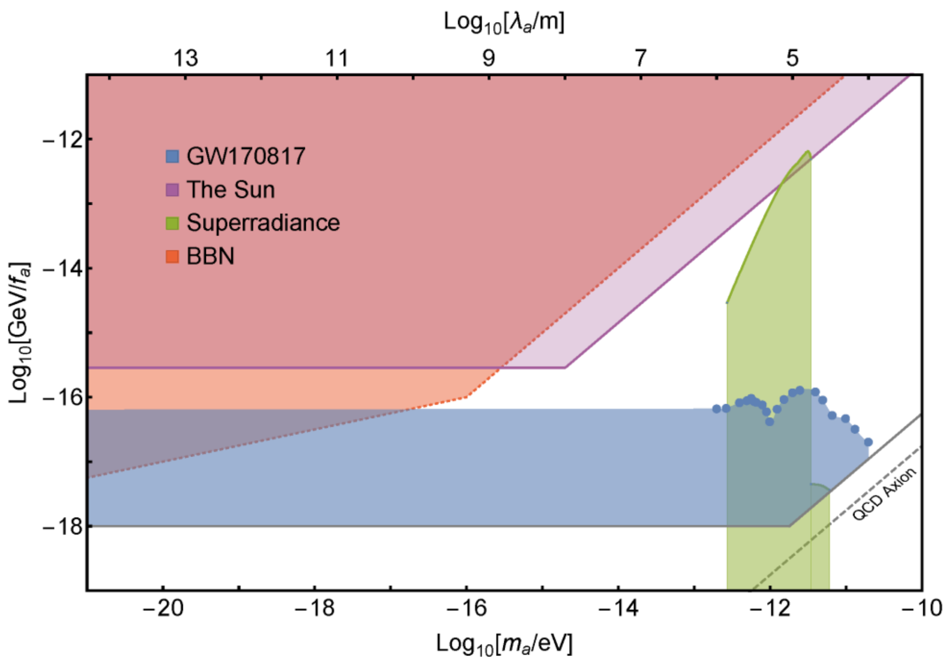


https://physics.aps.org/articles/v10/114

Binary Neutron Star Merger GW 170817



LIGO & Virgo, [1710.05832]

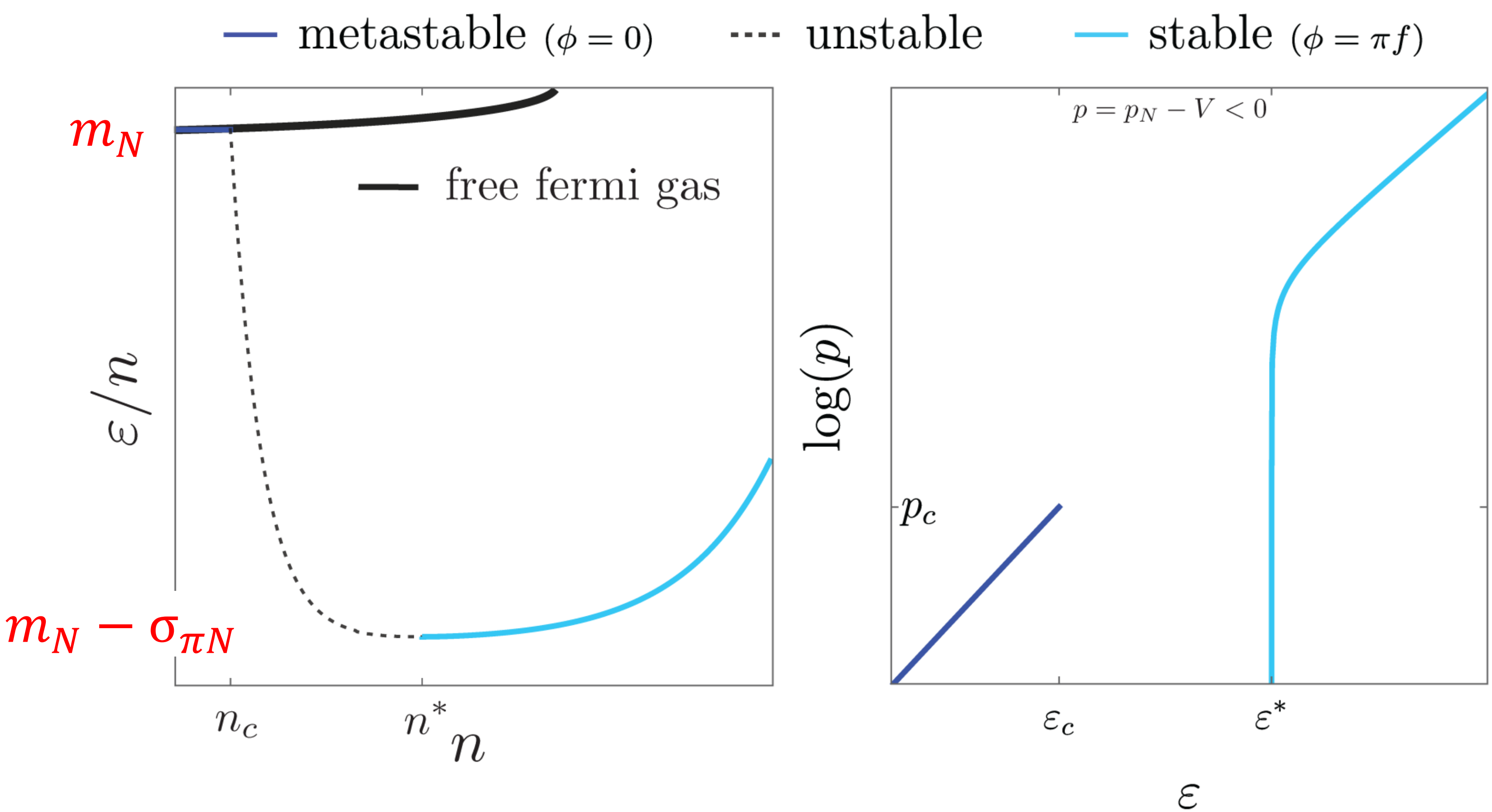


First Constraints on Nuclear Coupling of Axionlike Particles from the Binary Neutron Star Gravitational Wave Event GW 170817

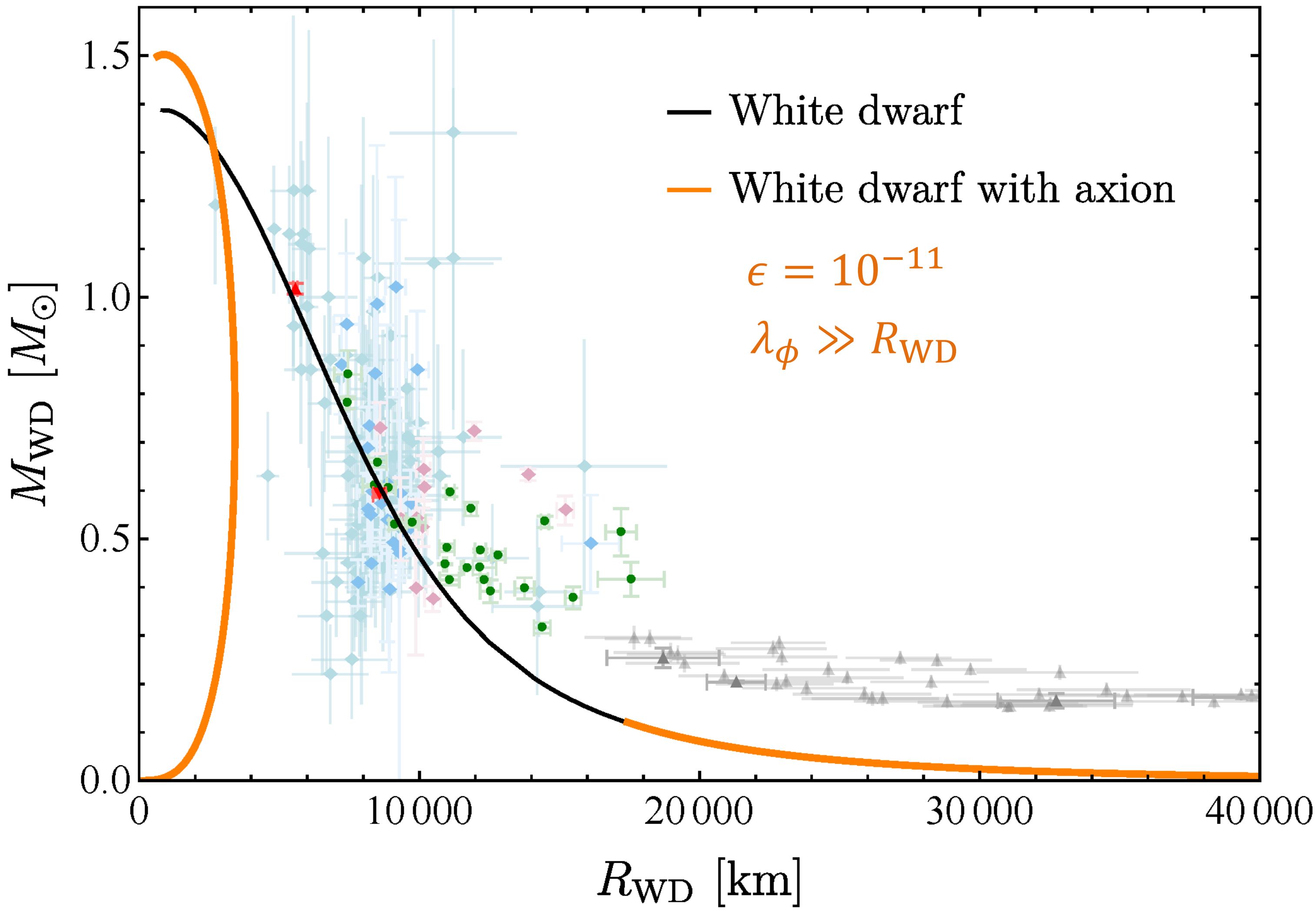
J.Zhang+, [2105.13963]

Changed Equation of State (EoS)

Energy/nucleon — Pressure

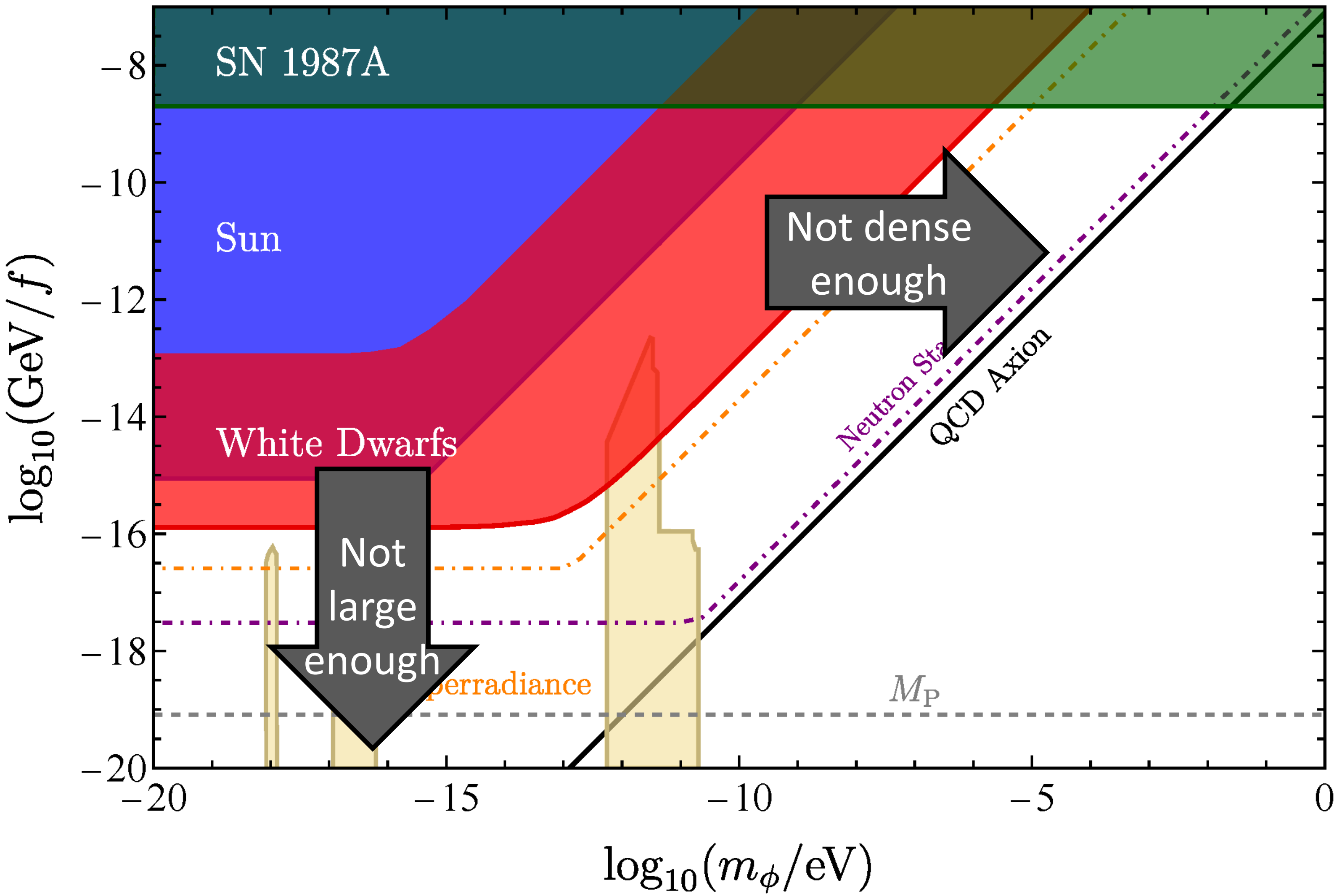


White-Dwarf Mass-Radius Relation



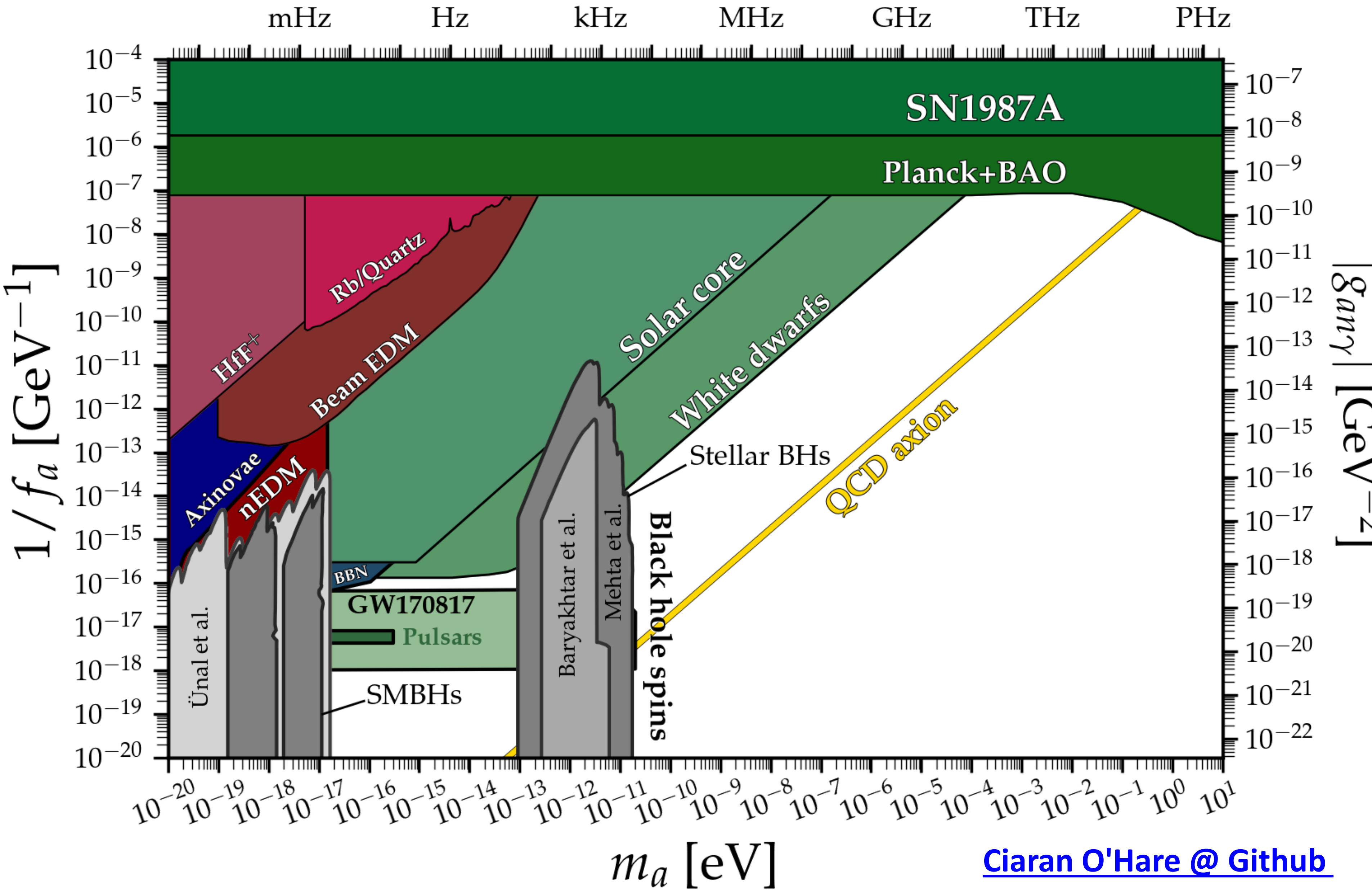
R. Balkin, J. Serra, K. Springmann, S. Stelzl & A. Weiler, 2211.02661

Axion Bounds from Stellar Structure



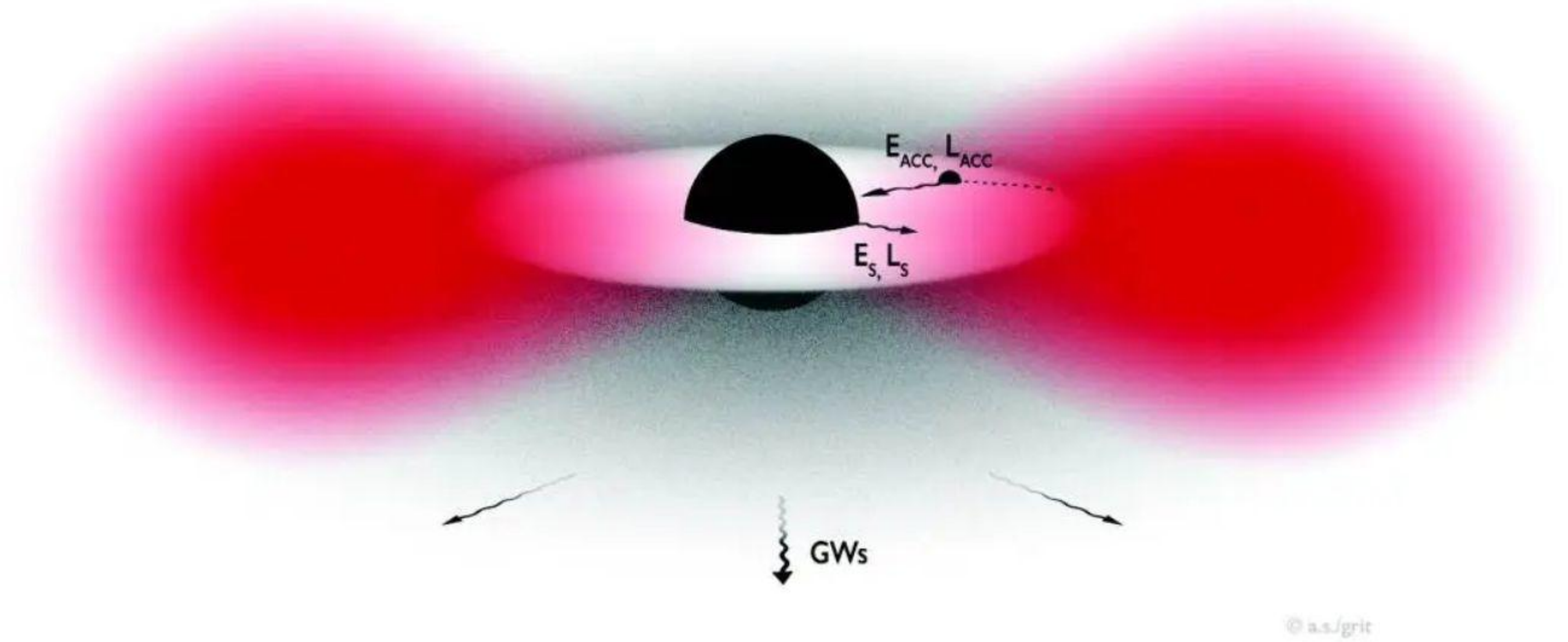
R. Balkin, J. Serra, K. Springmann, S. Stelzl & A. Weiler, [2211.02661](https://arxiv.org/abs/2211.02661)

Peccei-Quinn Scale vs. Axion Mass



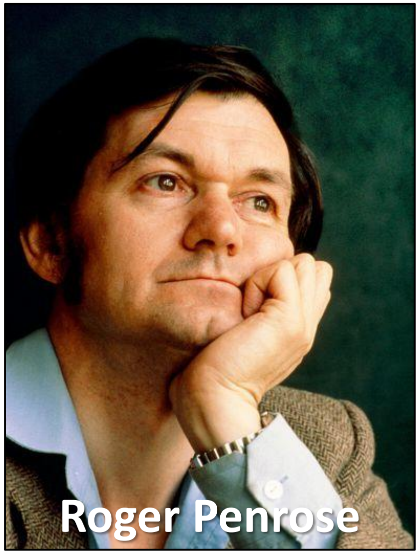
Ciaran O'Hare @ Github

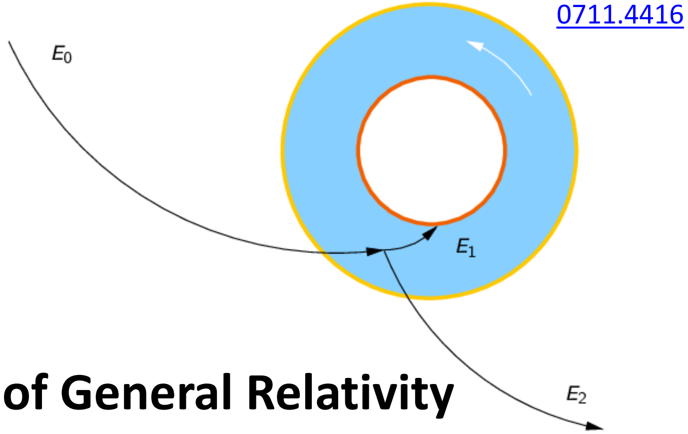
Superradiance



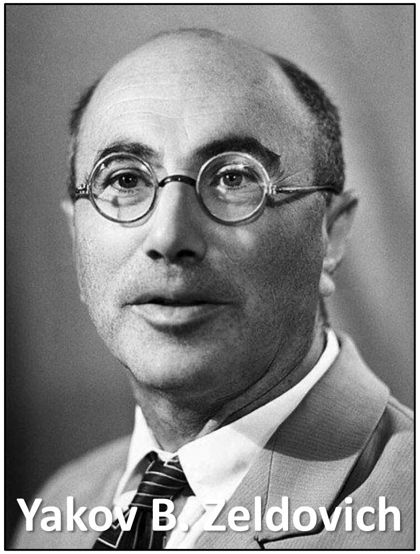
Superradiance: New Frontiers in Black Hole Physics (2020 edition)
R. Brito, V. Cardoso & P. Pani, [1501.06570v8] (8 Jan 2021)

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

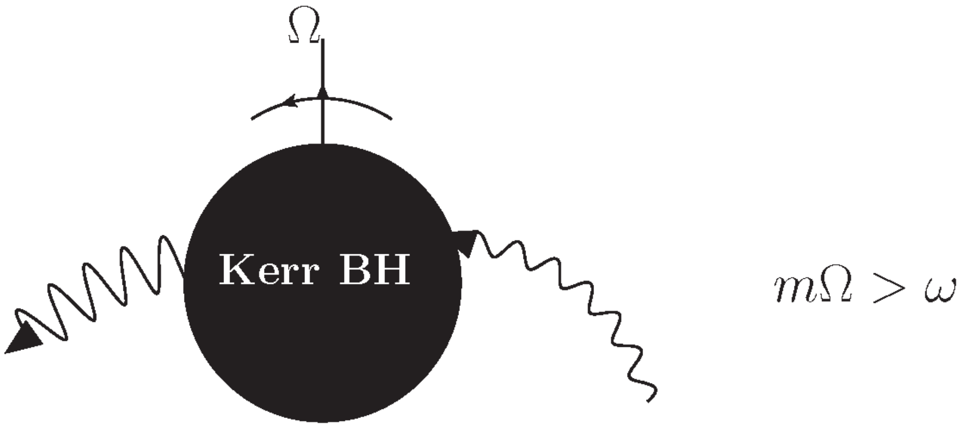


Generation of Waves by a Rotating Body
JETP Lett. 14 (1971) 180

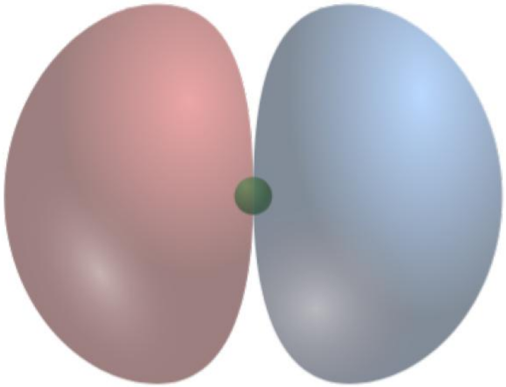
Amplification of Cylindrical Electromagnetic Waves Reflected from a Rotating Body
Zh. Eksp. Teor. Fiz. 62 (1972) 2076

Superradiance

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



- 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

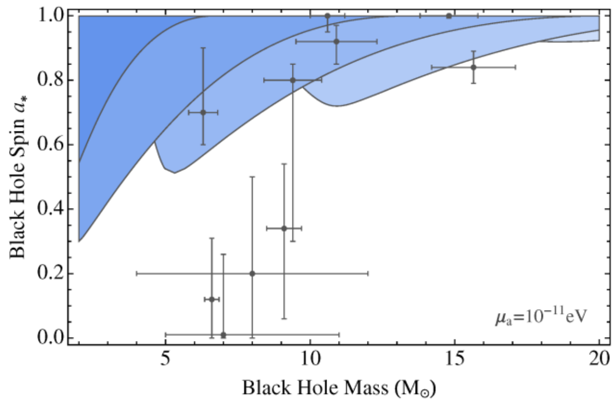


Superradiance: New Frontiers in Black Hole Physics (2020 edition)
R. Brito, V. Cardoso & P. Pani, 1501.06570v8 (8 Jan 2021)

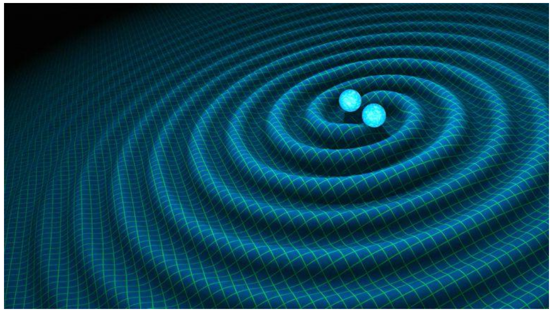
Signatures

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

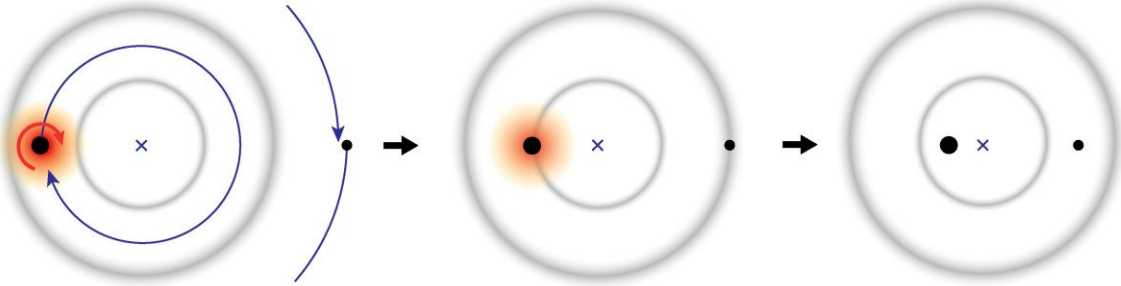
  Exploring the string axiverse with precision black hole physics
  Arvanitaki & Dubovsky, [1004.3558]()
  Discovering the QCD axion with black holes and gravitational waves, Arvanitaki, Baryakhtar & Huang, [1411.2263]()



- **Gravitational waves from “atomic transitions”**

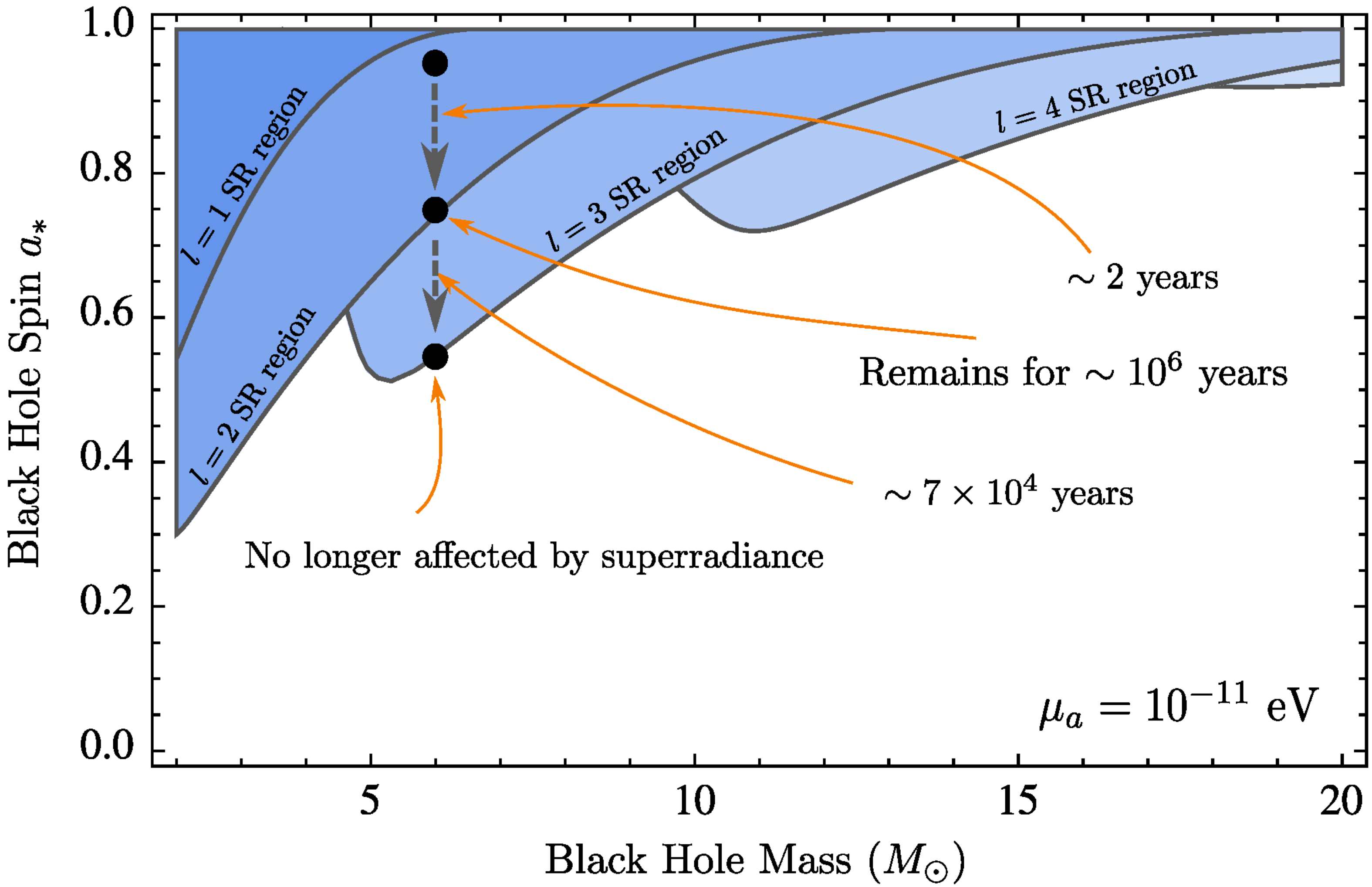


- **Effects on binaries**



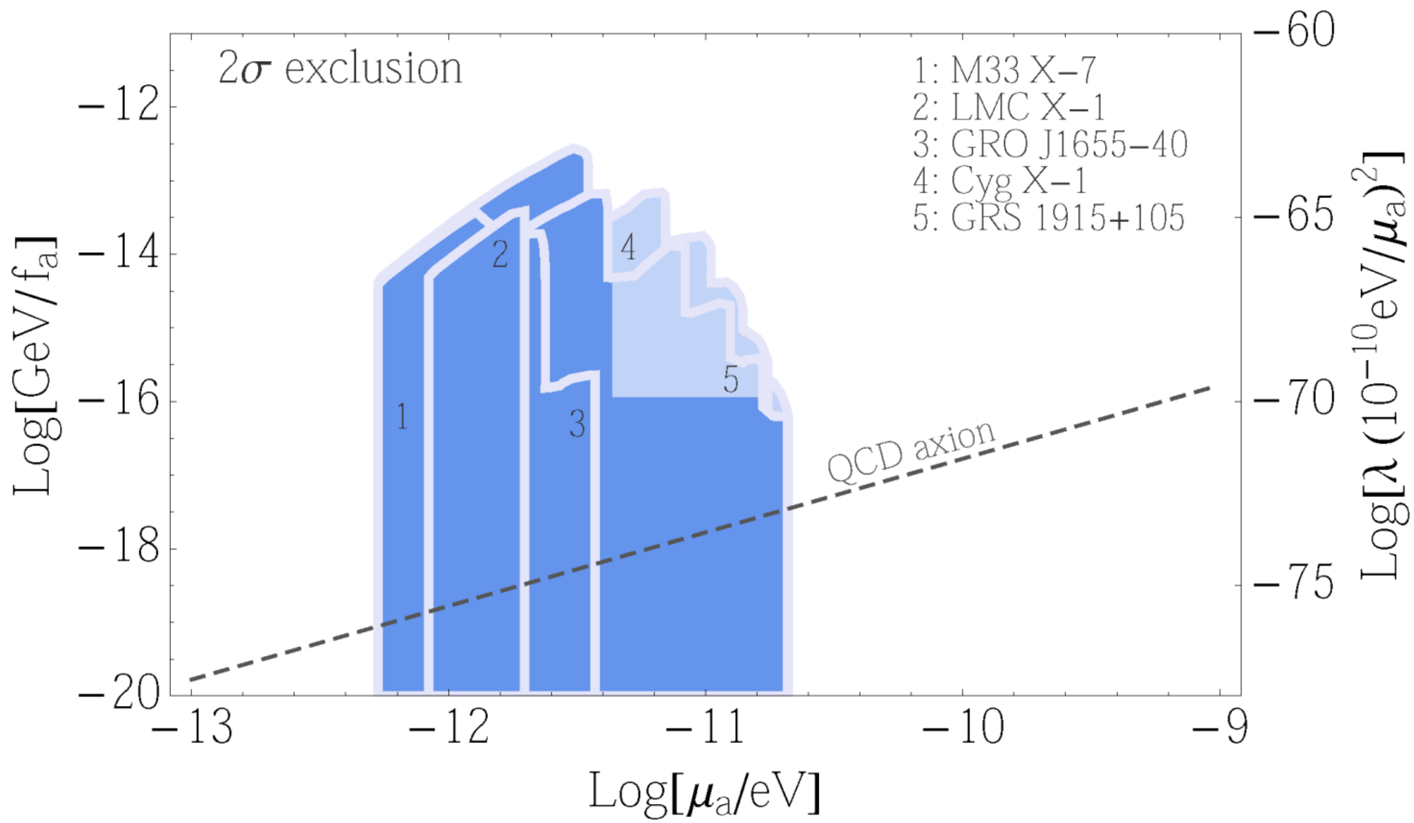
Probing Ultralight Bosons with Binary Black Holes
Baumann, Chia & Porto, [1804.03208]()

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

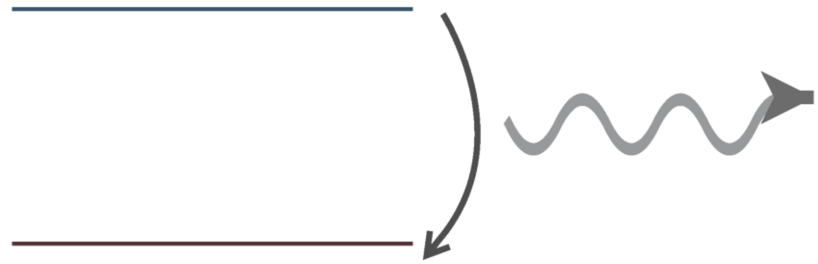


#	Object	Mass ($M_\odot$)	Spin	Age (yrs)	Period (days)	$M_{\mathrm{comp.\,star}}$ ($M_\odot$)	$\dot{M}/\dot{M}_E$
1	M33 X-7	15.65 ± 1.45	$0.84^{+.10}_{-.10}$[51]	3×10^6 [52]	3.4530 [53]	$\gtrsim 20$ [53]	$\gtrsim 0.1$[53]
2	LMC X-1	10.91 ± 1.4	$0.92^{+.06}_{-.18}$ [54]	5×10^6 [52]	3.9092 [55]	31.79±3.48 [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].

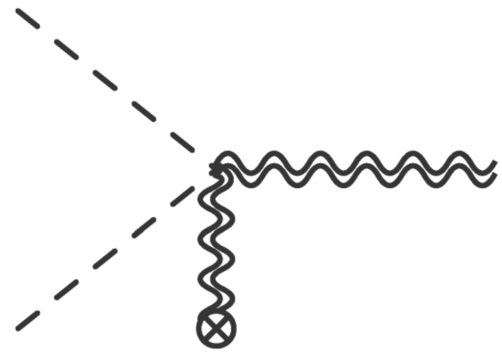
Arvanitaki, Baryakhtar & Huang, 1411.2263

Gravitational Wave Signals

- Transitions between levels



- Annihilations to gravitons



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

Masha Baryakhtar, Talk at Invisibles 2016, https://indico.cern.ch/event/464402/

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

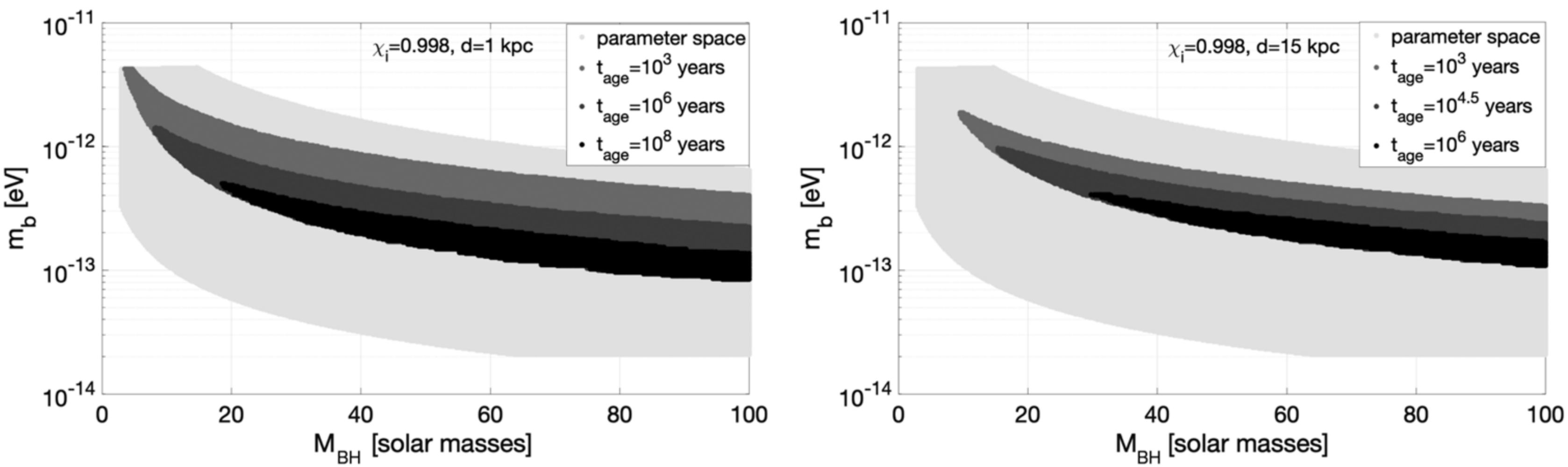
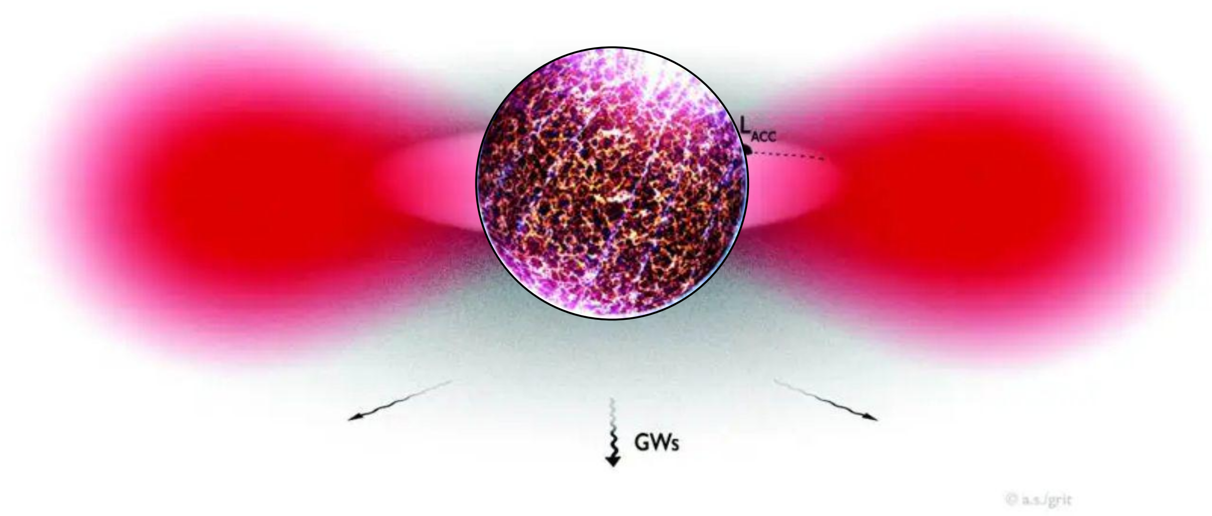


FIG. 2. 95% C.L. exclusion regions in the plane $m_b - M_{BH}$ assuming a maximum distance $d = 1$ kpc (left plot) and $d = 15$ kpc (right plot), a black hole initial adimensional spin $\chi_i = 0.998$, and three possible values for t_{age}: 10^3, 10^6, 10^8 yr (left plot) and 10^3, $10^{4.5}$, 10^6 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?

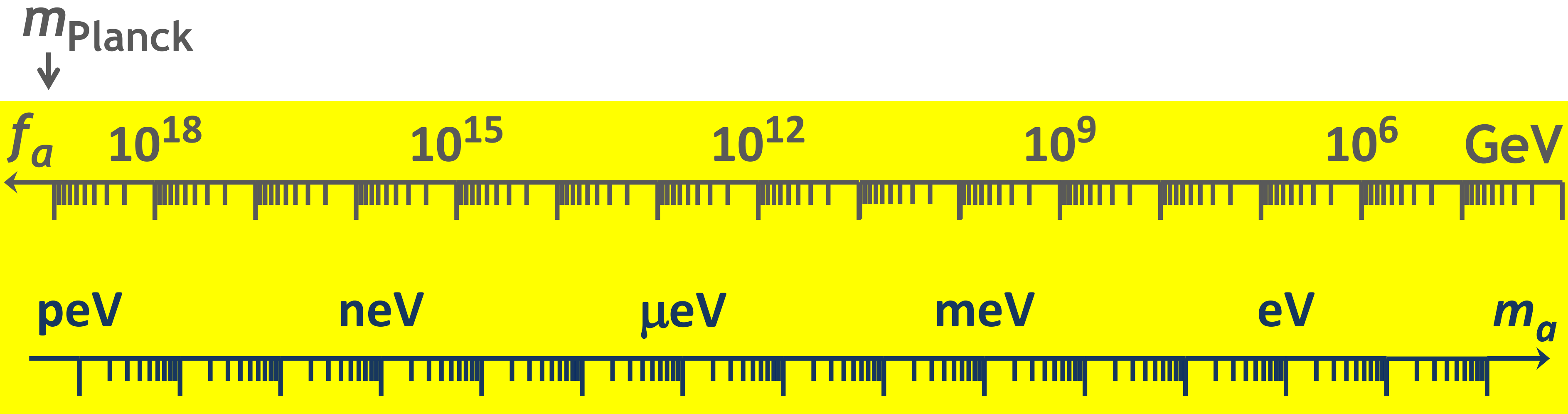


Superradiance in rotating stars and pulsar-timing constraints on dark photons
V.Cardoso, P.Pani & T.-T.Yu, 1704.06151

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

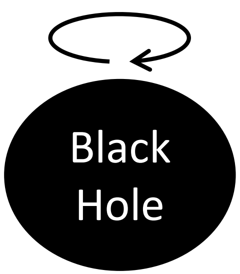
Astrophysical Axion Bounds and Opportunities

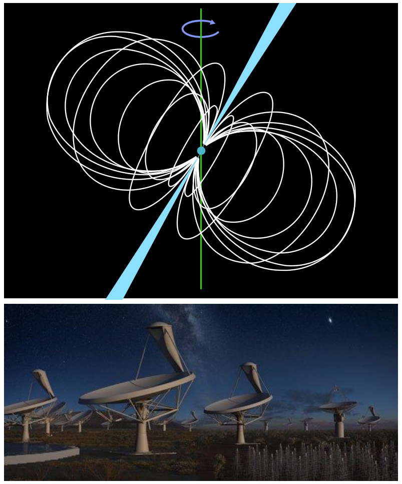


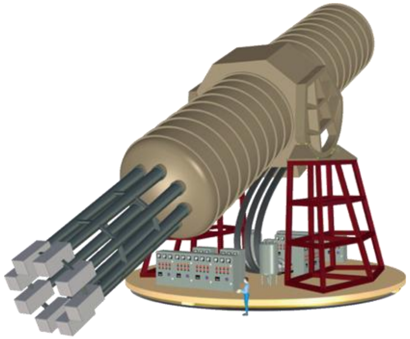
Super Radiance

Opportunities for detection

Astrophysical Bounds (Energy loss of stars)







IAXO Solar Axion Telescope

Axion conversion in neutron star magnetospheres

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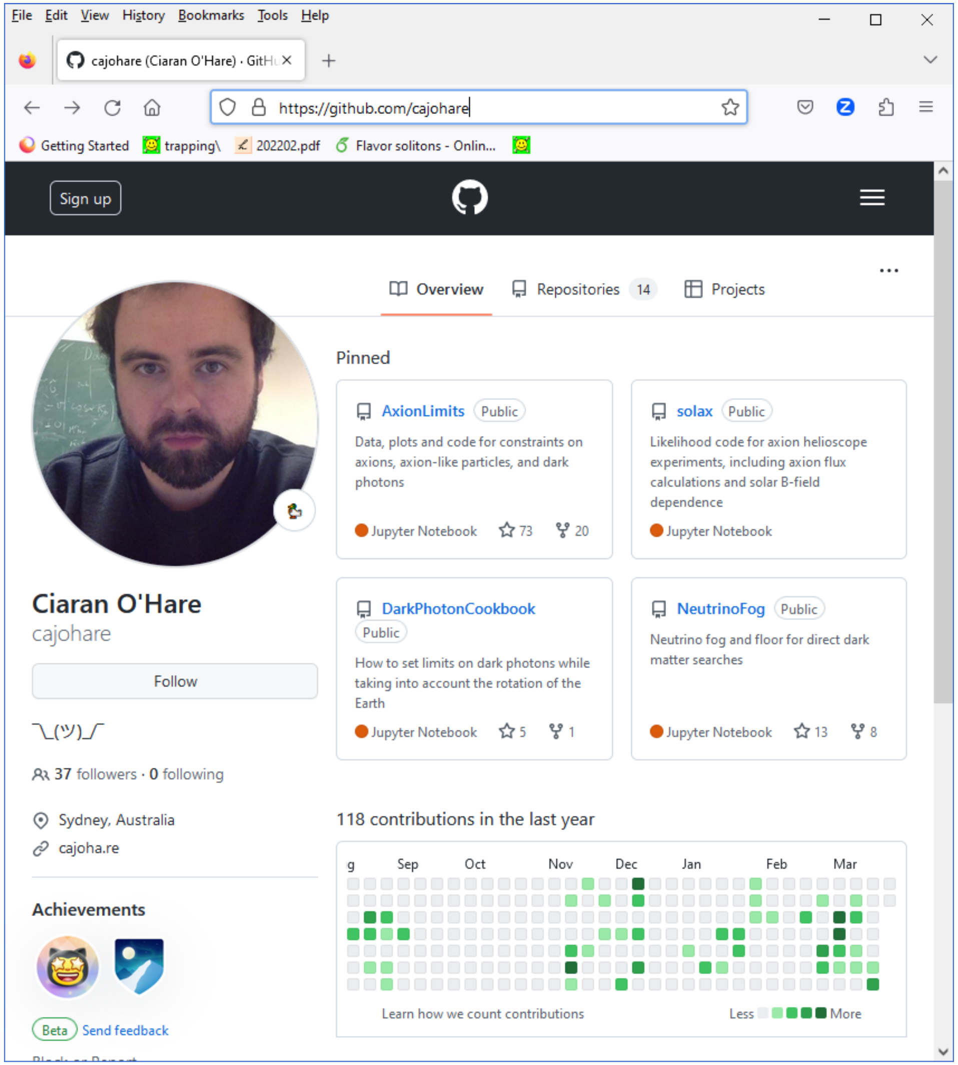
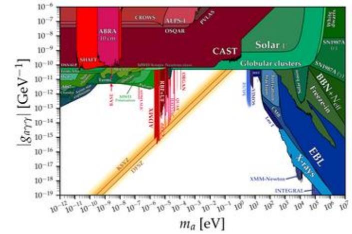
Bounds on Low-Mass Bosons



https://github.com/cajohare

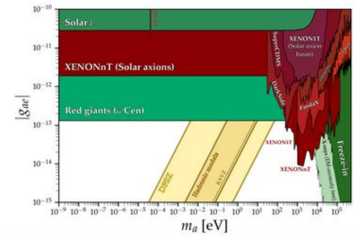
Axion-photon coupling

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



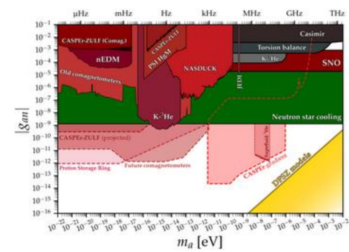
Axion-electron coupling

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



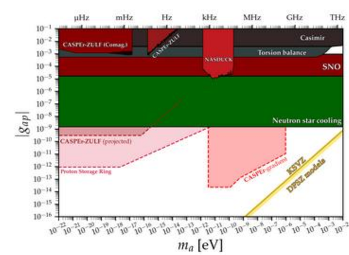
Axion-neutron coupling

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