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Compact stars as laboratories for fundamental physics

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Light bosons

Light bosons emerge in many extensions of Standard Model:

- Compelling candidates for DM
- Possible solutions to theoretical problems

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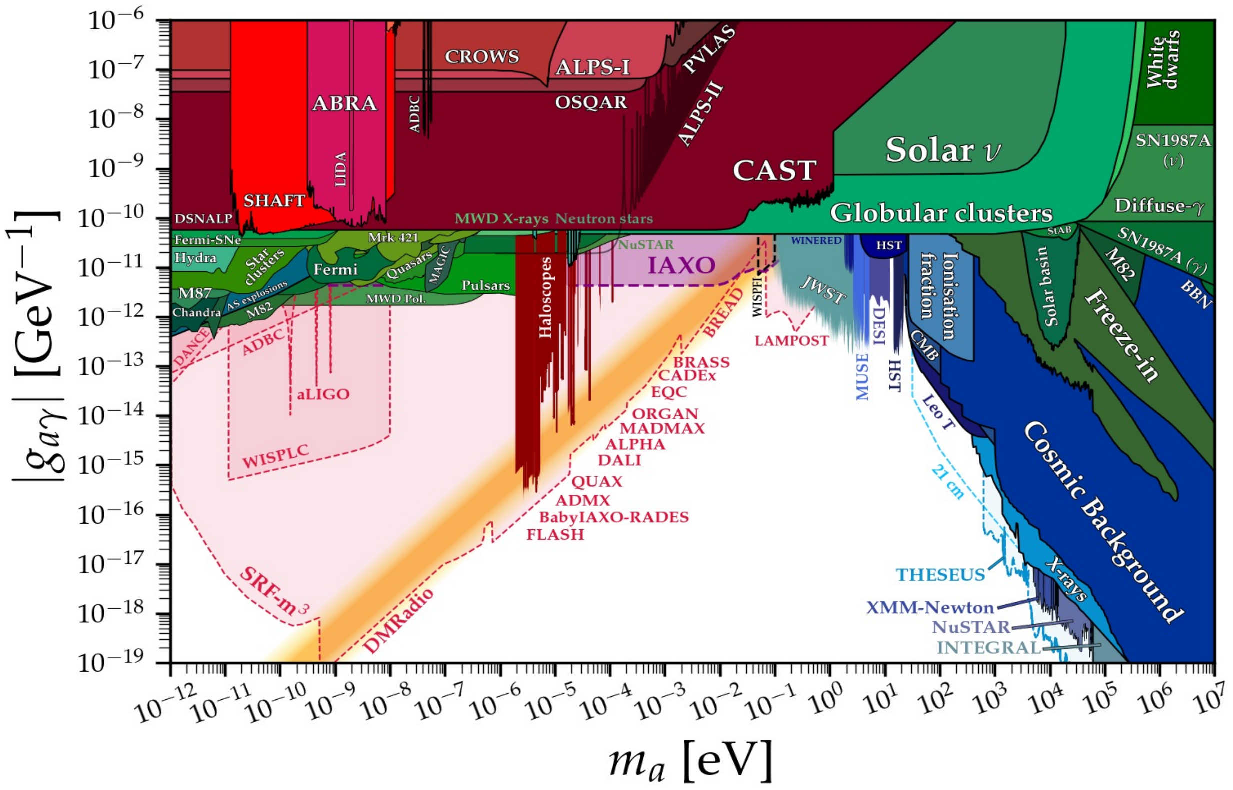

QCD axion and pseudoscalars

cajohare.github.io/AxionLimits/

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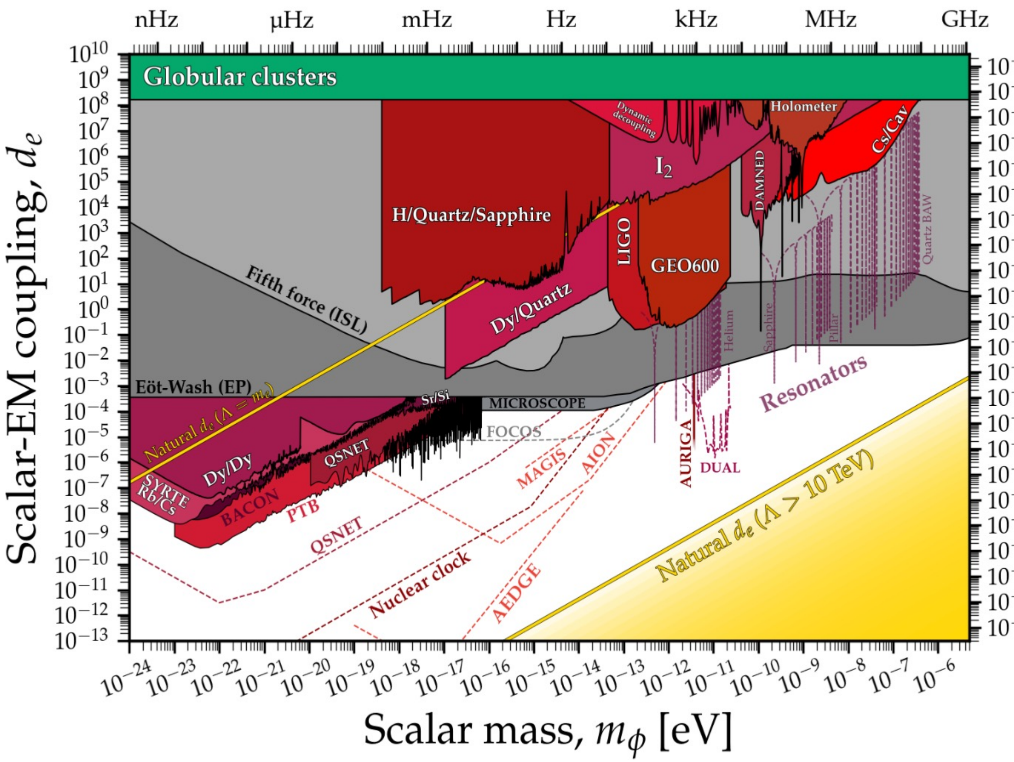
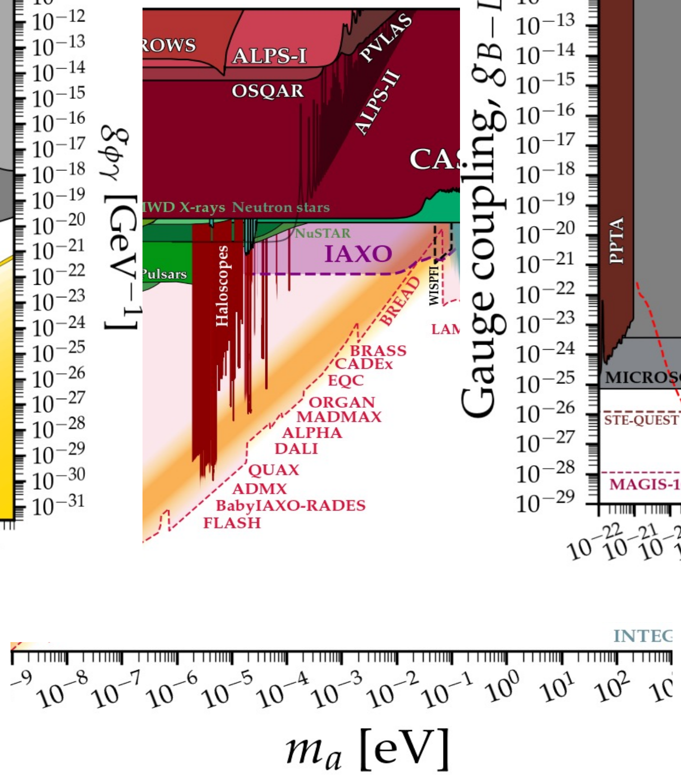


Scalars



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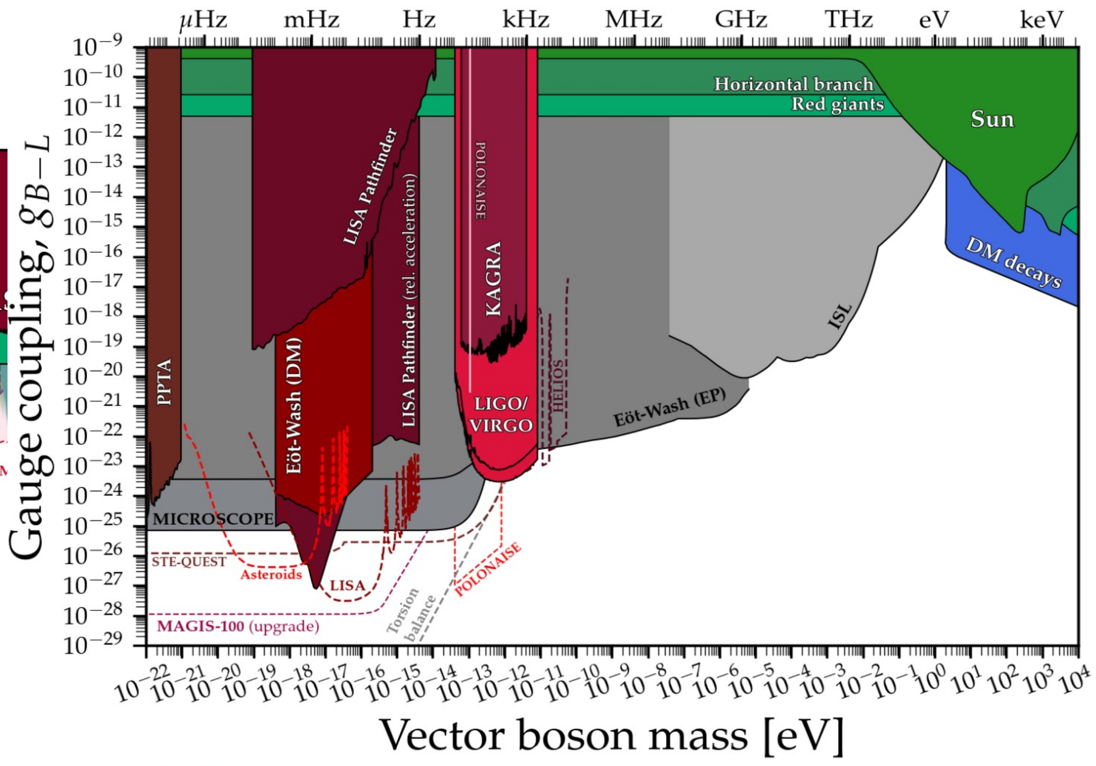

Gauge bosons

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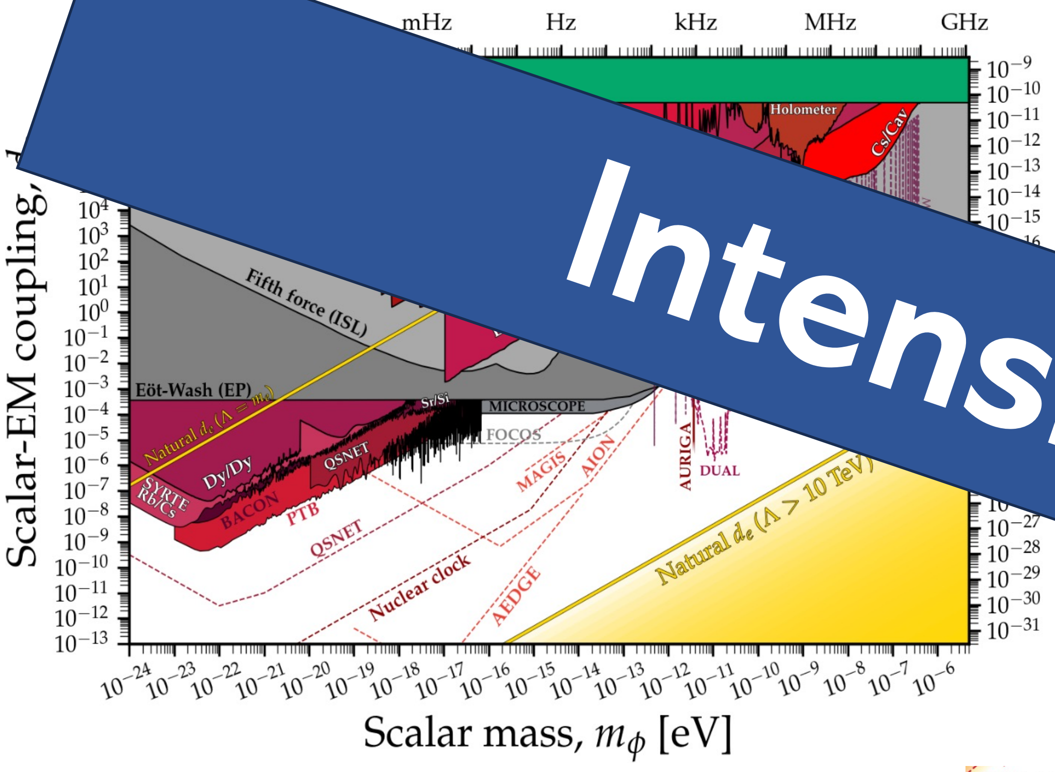
Light bosons

Light bosons emerge in many extensions of Standard Model:

Intensity Frontier



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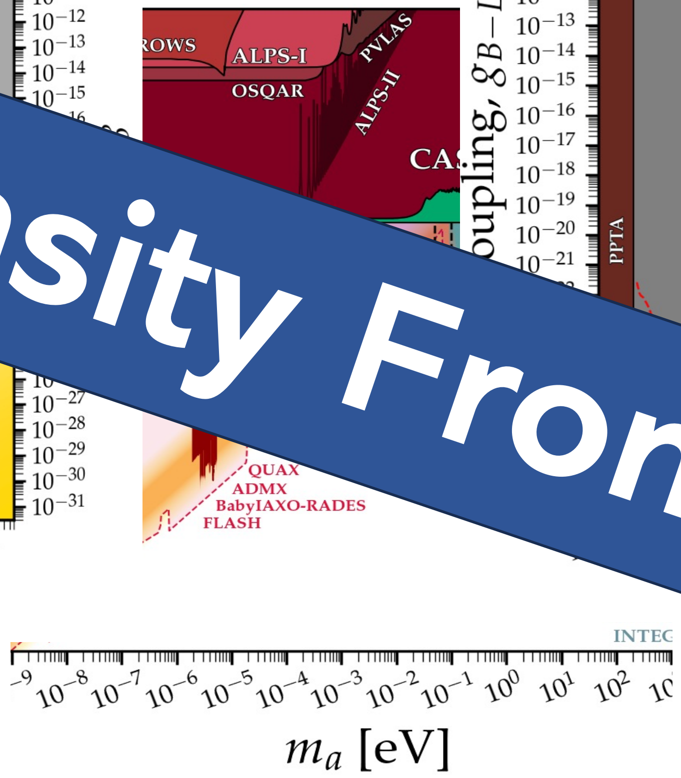

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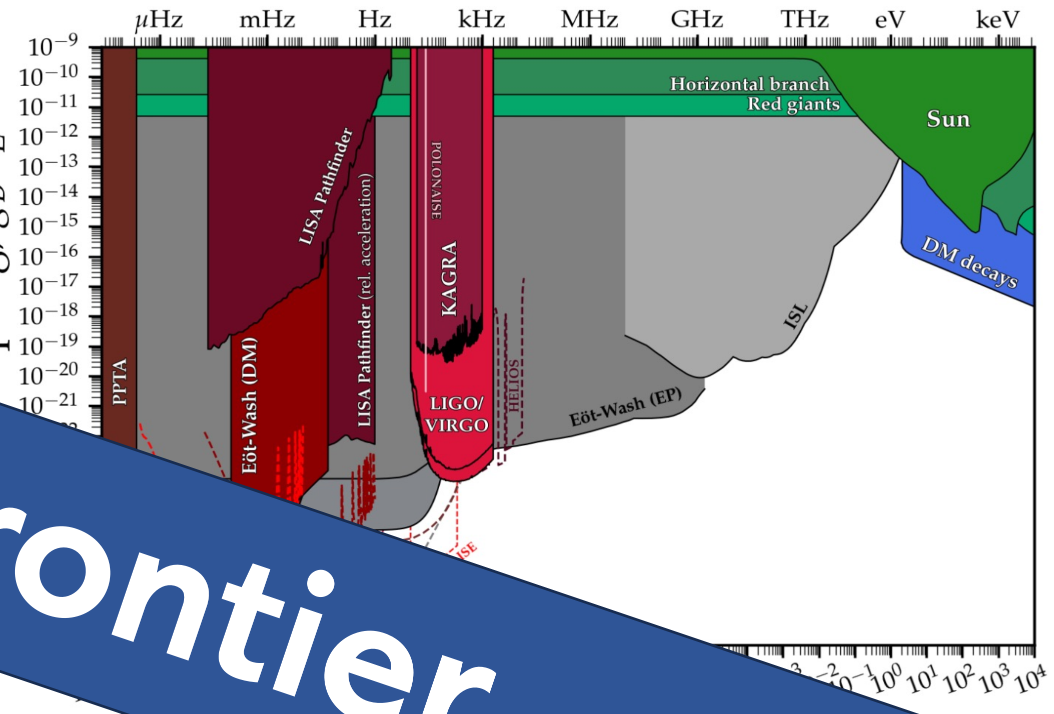

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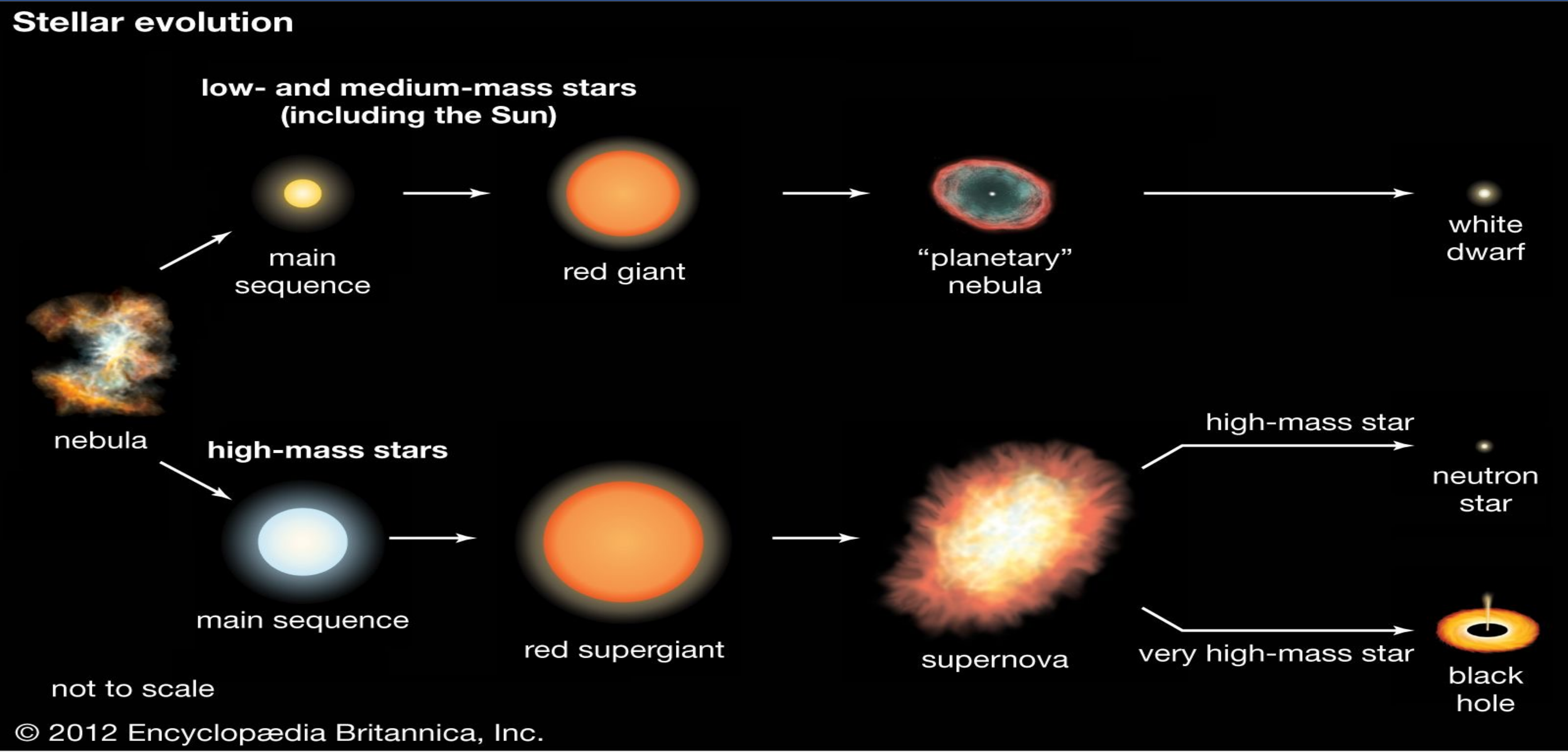
Stars: Life and Death



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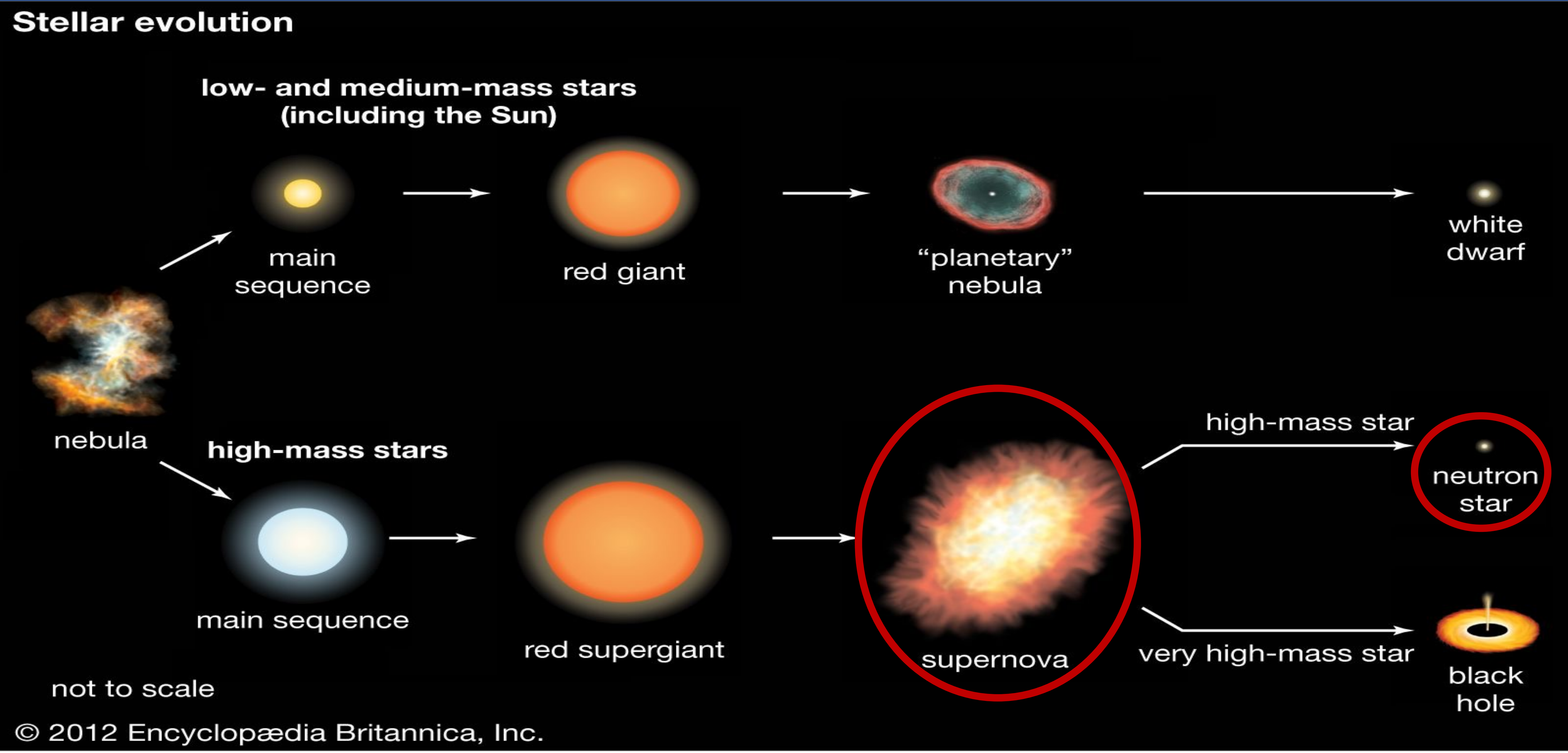


Core-collapse SNe

Core-Collapse Supernovae

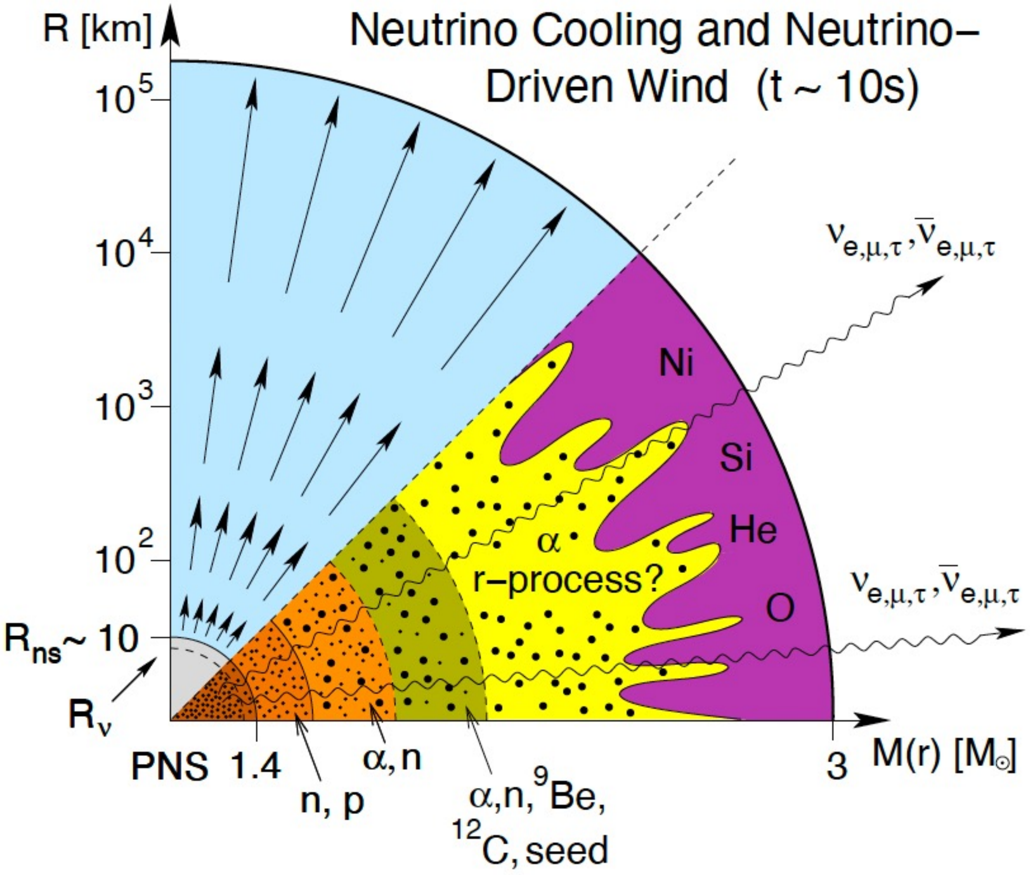
A Supernova is the terminal phase of a massive star $[\mathrm{M} \geq 8\, M_{\odot}]$.
Gravitational collapse triggered by the formation of a degenerate iron core.

[H.T. Janka & al., Phys.Rept. 442 (2007)]

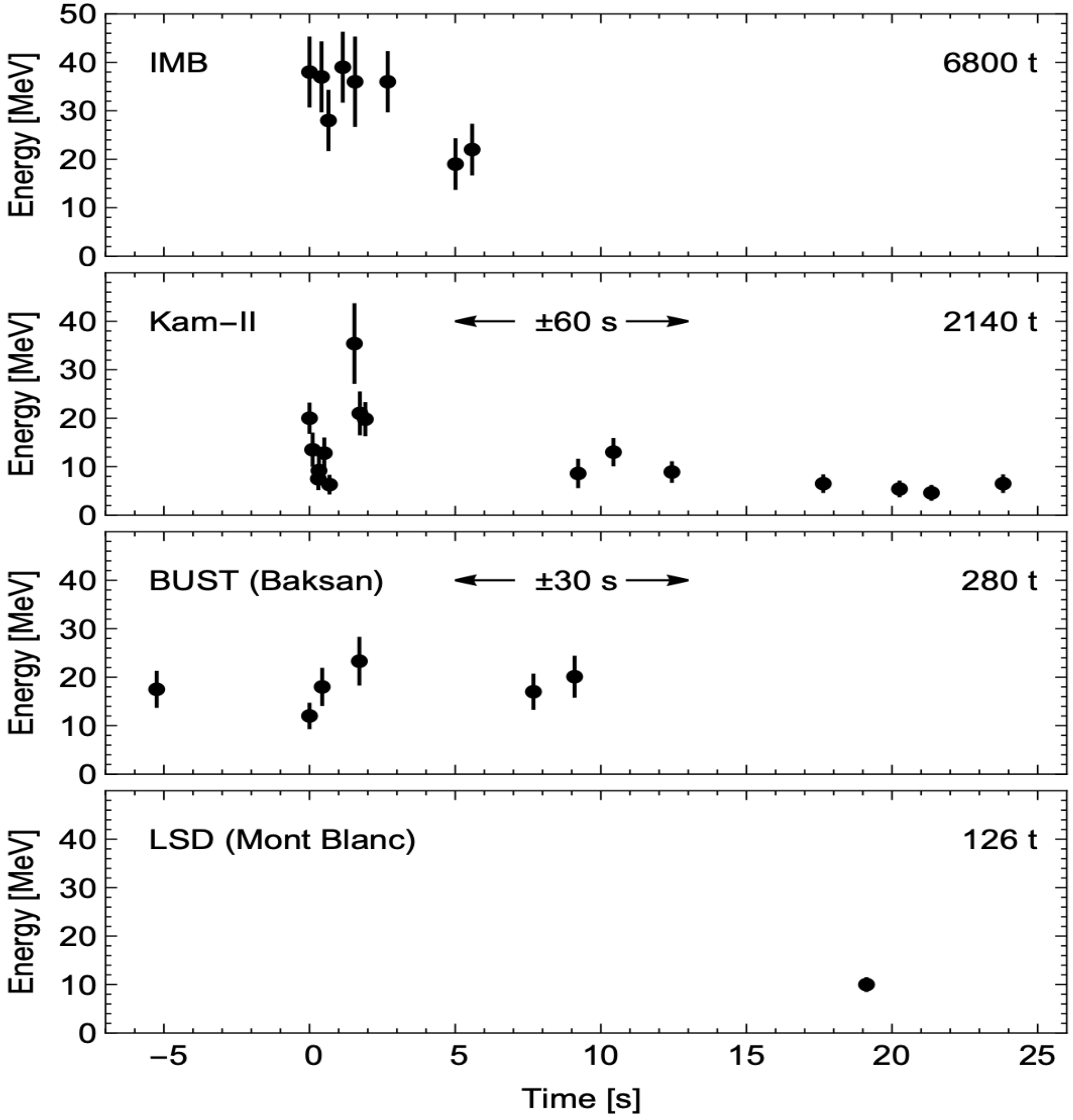
- Incompressible nuclear matter in the core
  → shock-wave driven explosion

- Formation of a Proto-Neutron star at the centre ($\mathrm{T} \sim 30$ MeV, $\rho \sim 3{\times}10^{14}$ g/cm^{-3}).

- Cooling via neutrino emission of all species (99% of total energy)
  - $E \sim 10^{53}$ erg , $t \sim 10$ s.



SN 1987A



SN 1987A was the first and only SN event allowing for the observation of the associated neutrino burst so far.

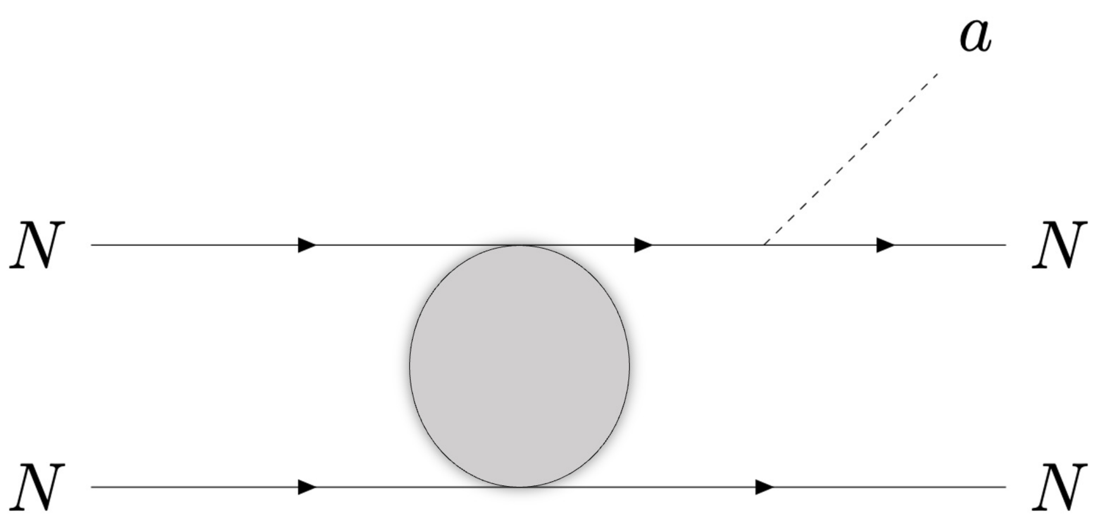
- From SN 1987A neutrino burst observations:
  - Duration of the burst ~ 10 s.
  - $< E_\nu > \approx 15$ MeV.

- Standard picture confirmed by SN 1987A observation.

Recent re-analysis showed that late time events are in tension with SN simulations.
[Fiorillo et al., Phys. Rev. D 108 (2023)]

ALP production in SNe

Nucleon-Nucleon bremsstrahlung



[Carenza & al., JCAP 10 (2019) 10,
Raffelt & Seckel, Phys. Rev. D 52 (1995),
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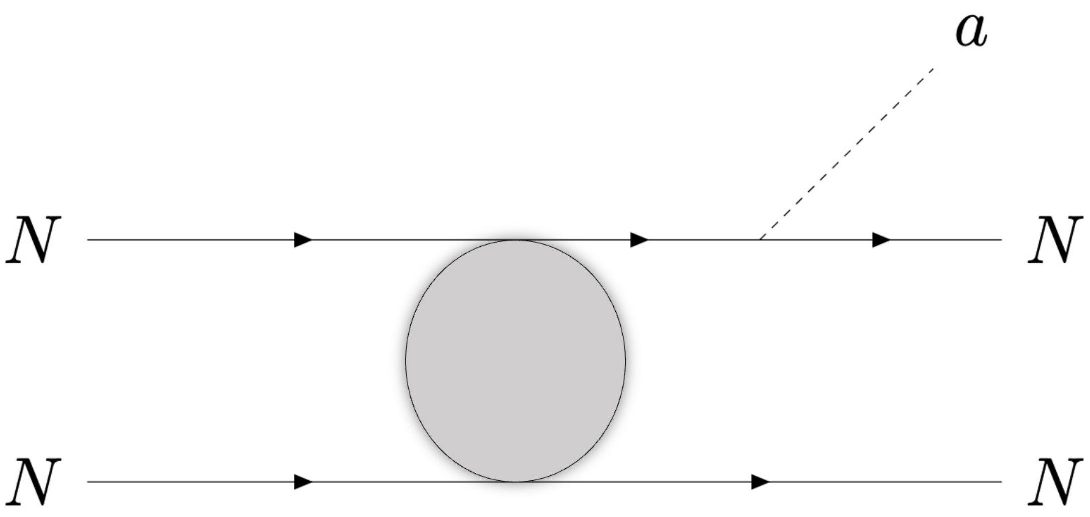

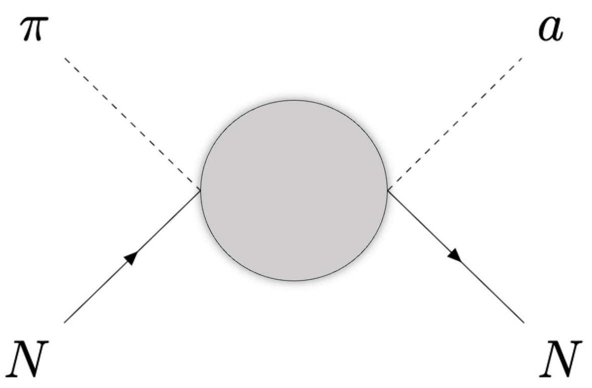

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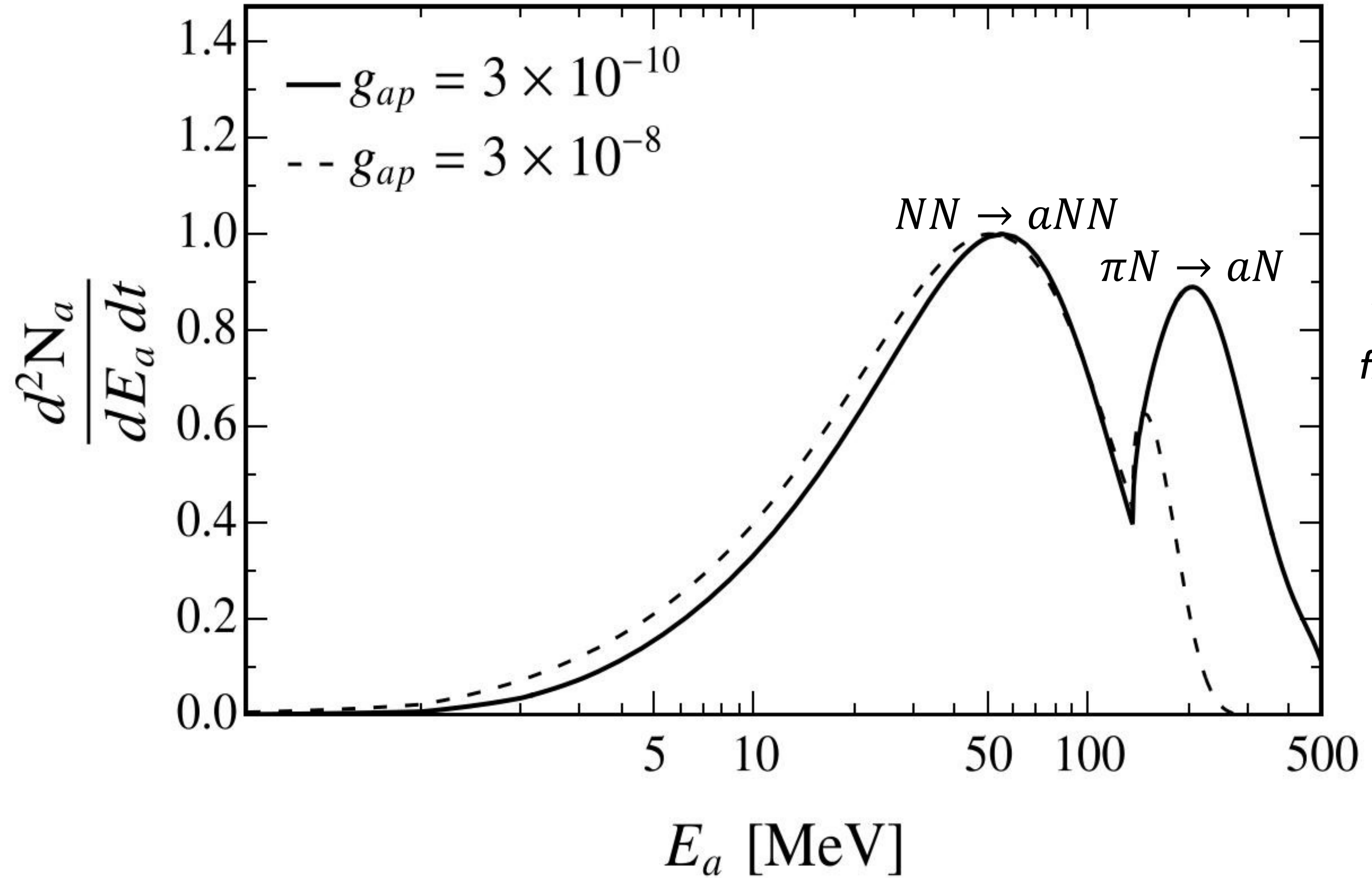
Uncertainties in the computation of the emission rates

- Modelling of the nuclear interaction potential
- In-medium effects are important!
- Pion conversions? *[Carenza & al., Phys.Rev.Lett. 126 (2021)]*

ALP emission spectra

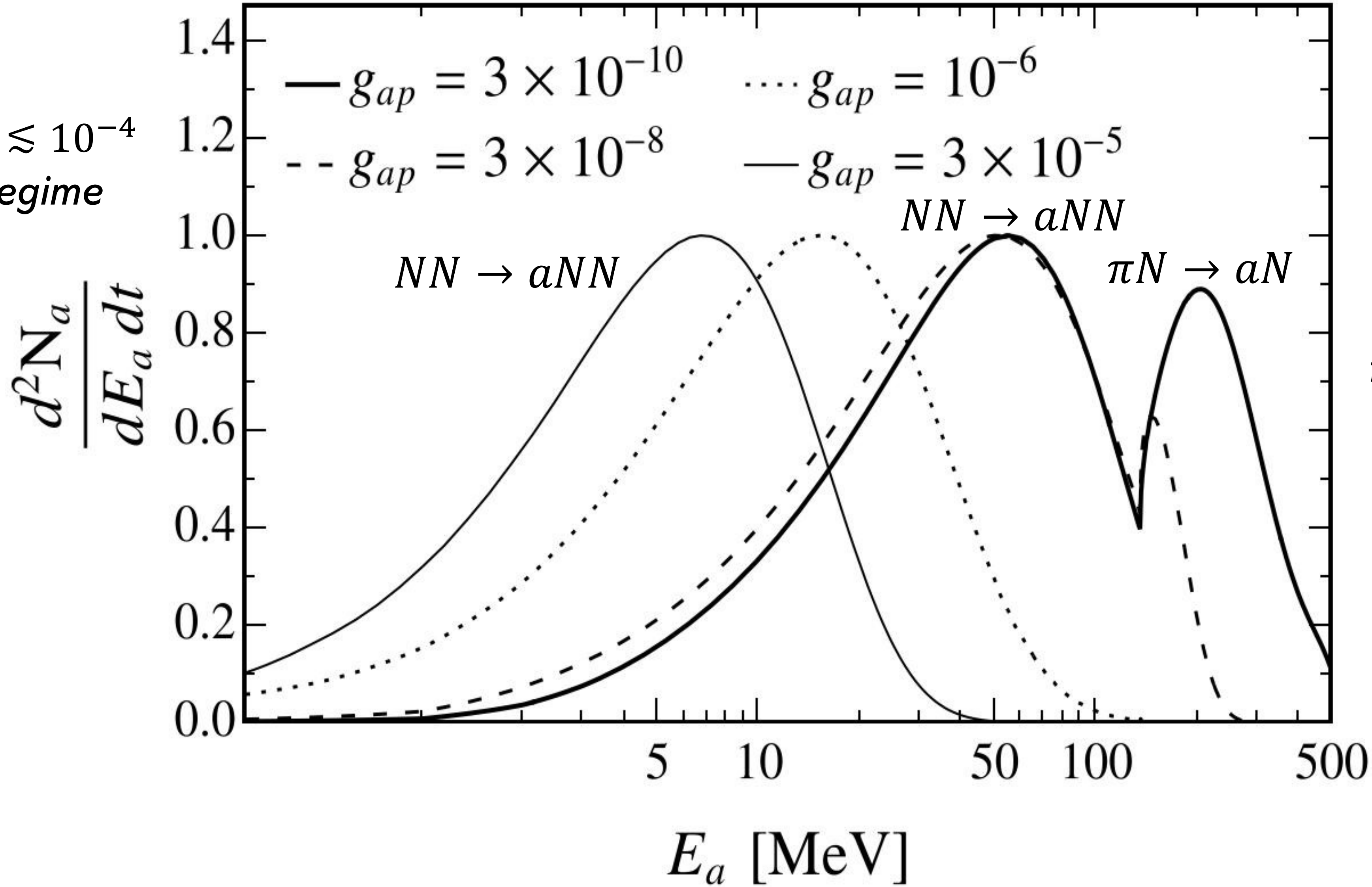


$10^{-10} \lesssim g_{ap} \lesssim 10^{-7}$

free-streaming regime

ALP emission spectra

$10^{-7} \lesssim g_{ap} \lesssim 10^{-4}$
trapping regime



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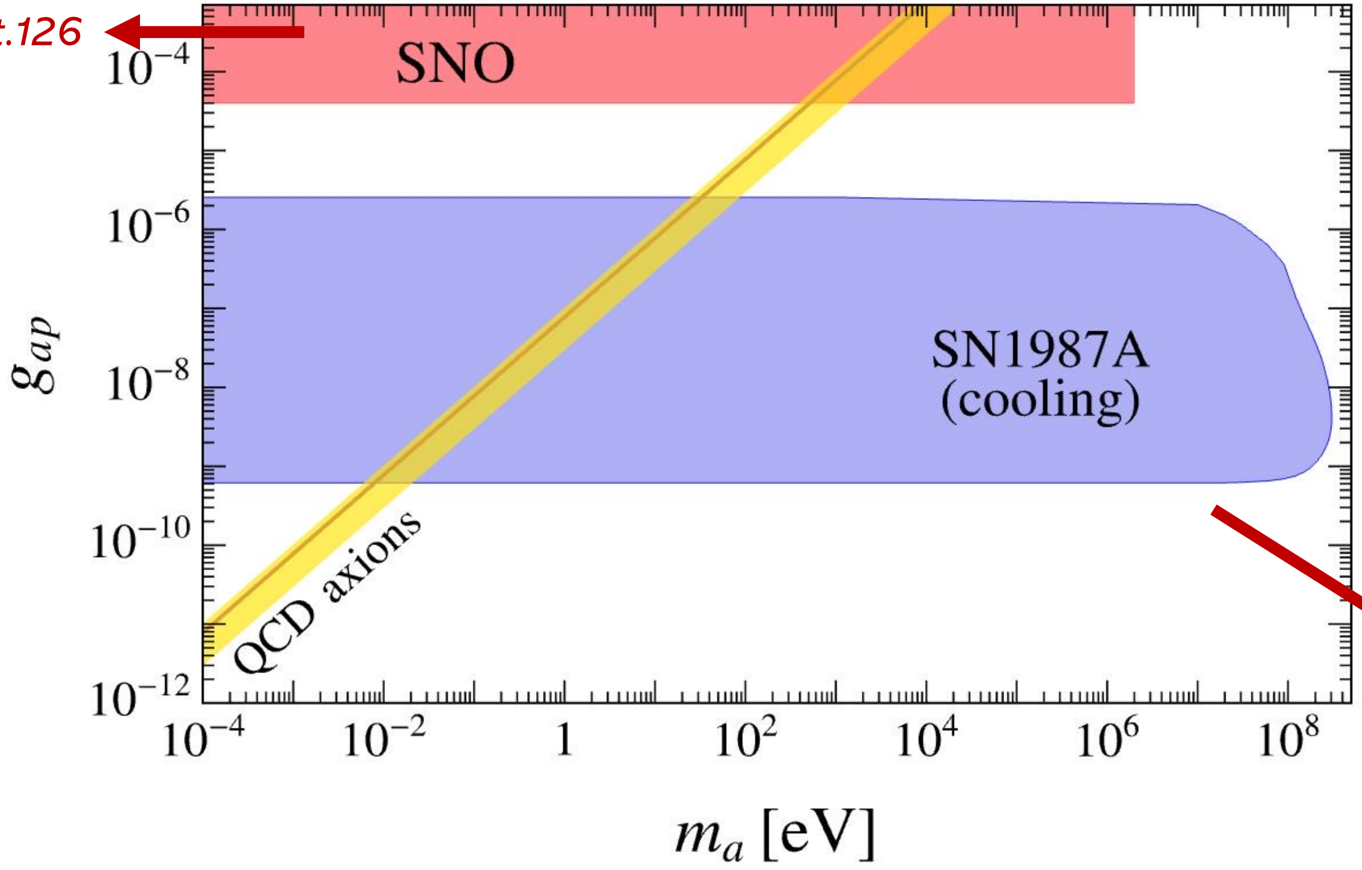
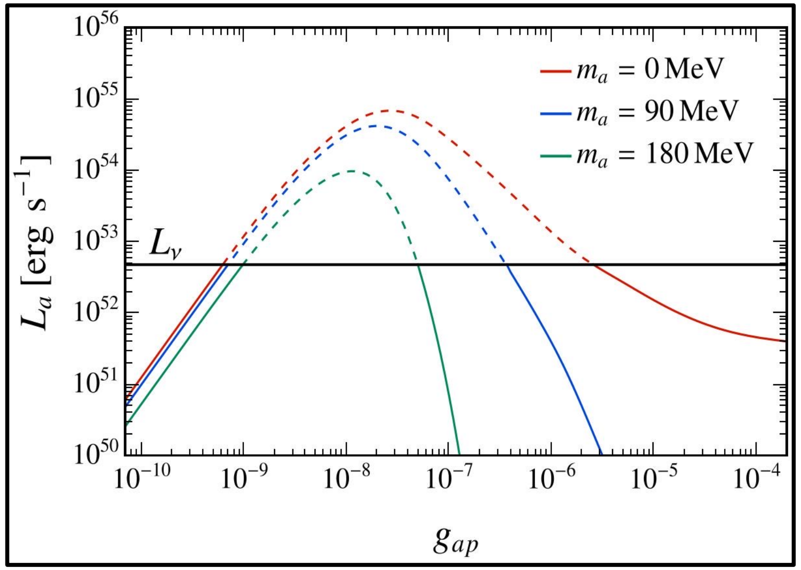
The energy-loss argument

Assuming that ALP emission did not shorten the duration of the neutrino burst more than ~ 1/2, we require that *[Raffelt, Phys. Rept. 198 (1990)]* :

$$L_a \lesssim L_\nu \quad \text{at } t_{\rm pb} = 1 \text{ s}$$

[Bhusal et al., Phys. Rev. Lett.126 (2021)]





[AL & al., Phys. Rev. D 109 (2024) 2]

Similar limits from NS cooling

[Buschmann et al., Phys.Rev.Lett. 128 (2022) 9]

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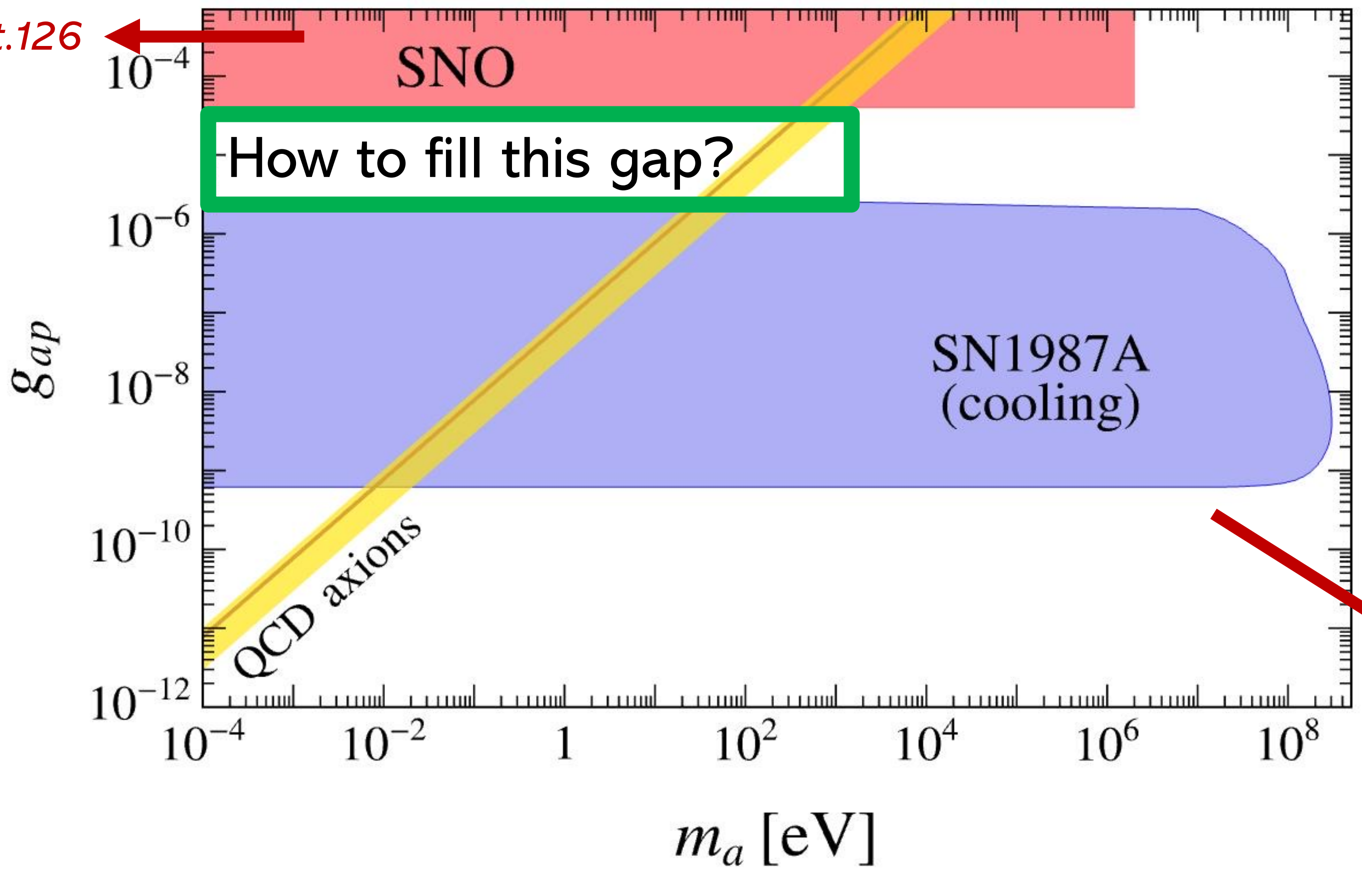

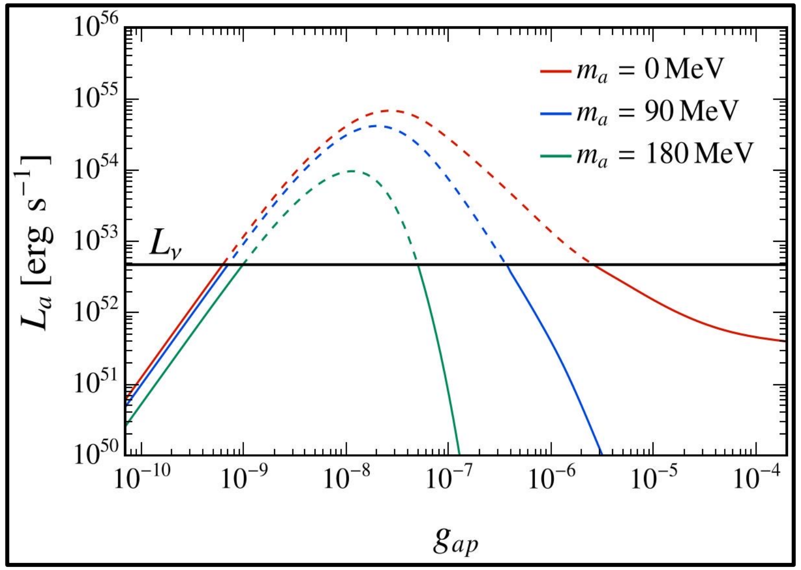

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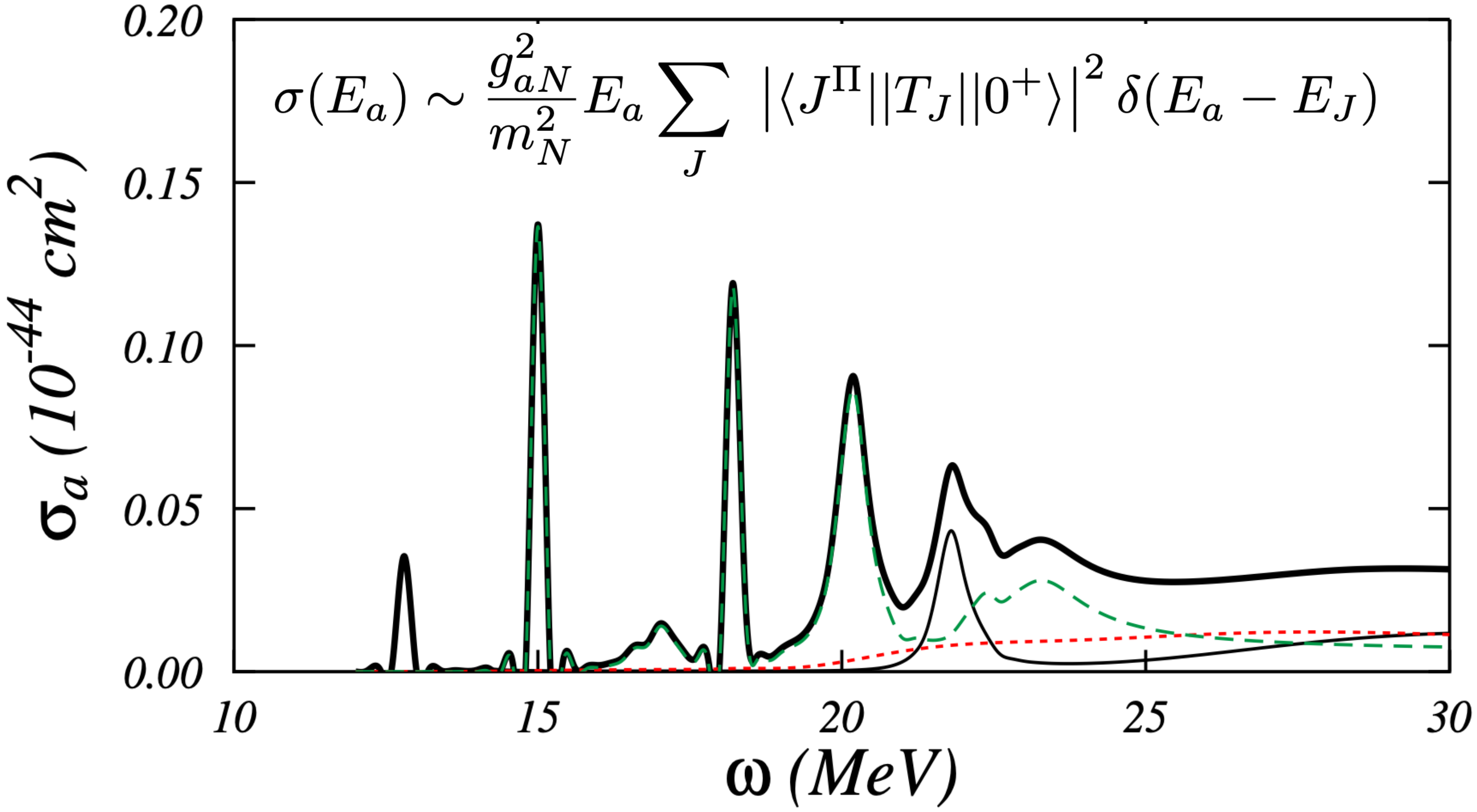
Axion signal in Kamiokande-II

In case of strong couplings the ALP flux would have produced a signal in Kamiokande II: look for axion-induced excitation of oxygen nuclei! *[Engel et al., Phys. Rev. Let. 65 (1990)]* .

$$a + {}^{16}\mathrm{O} \to {}^{16}\mathrm{O}^* \to {}^{16}\mathrm{O} + \gamma$$

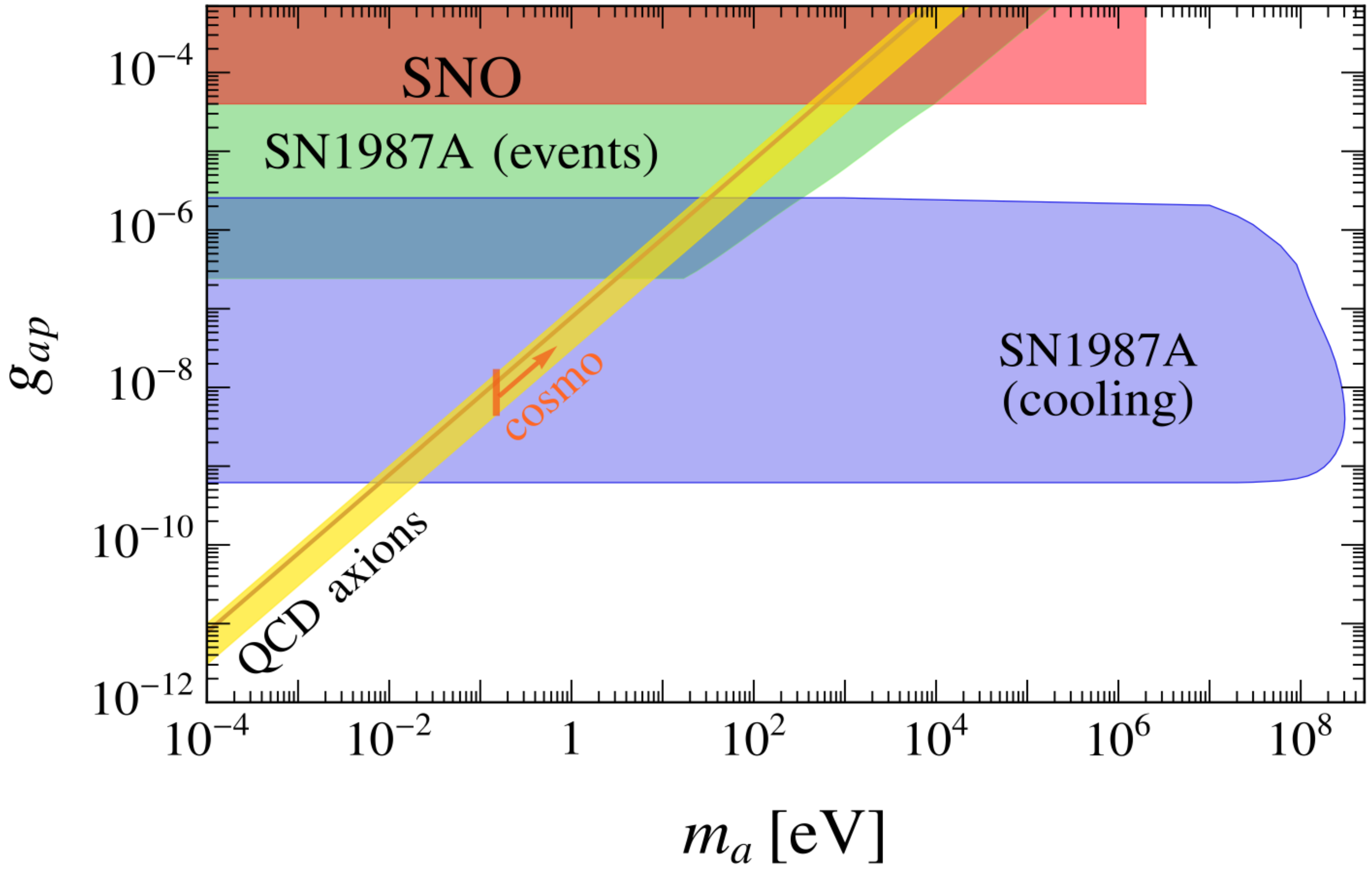


[P. Carenza, G. Co', M. Giannotti, AL, G. Lucente, A. Mirizzi, T. Rauscher, Phys. Rev. C 109 (2024) 1]

Axion events from SN 1987A

No excess in the background of K-II around SN 1987A event ($\bar{n}_{bkg} \simeq 0.02$ events/s)

[Kamiokande Coll., Phys. Rev. Lett. 58 (1987) 1490].



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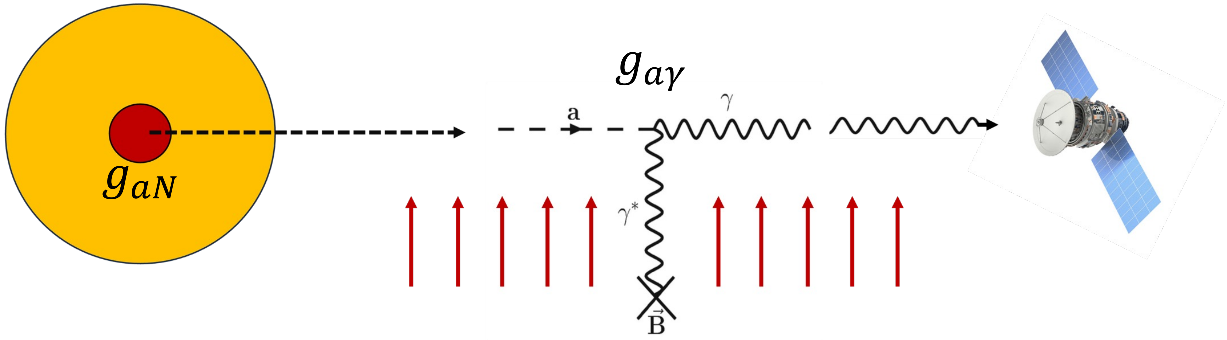
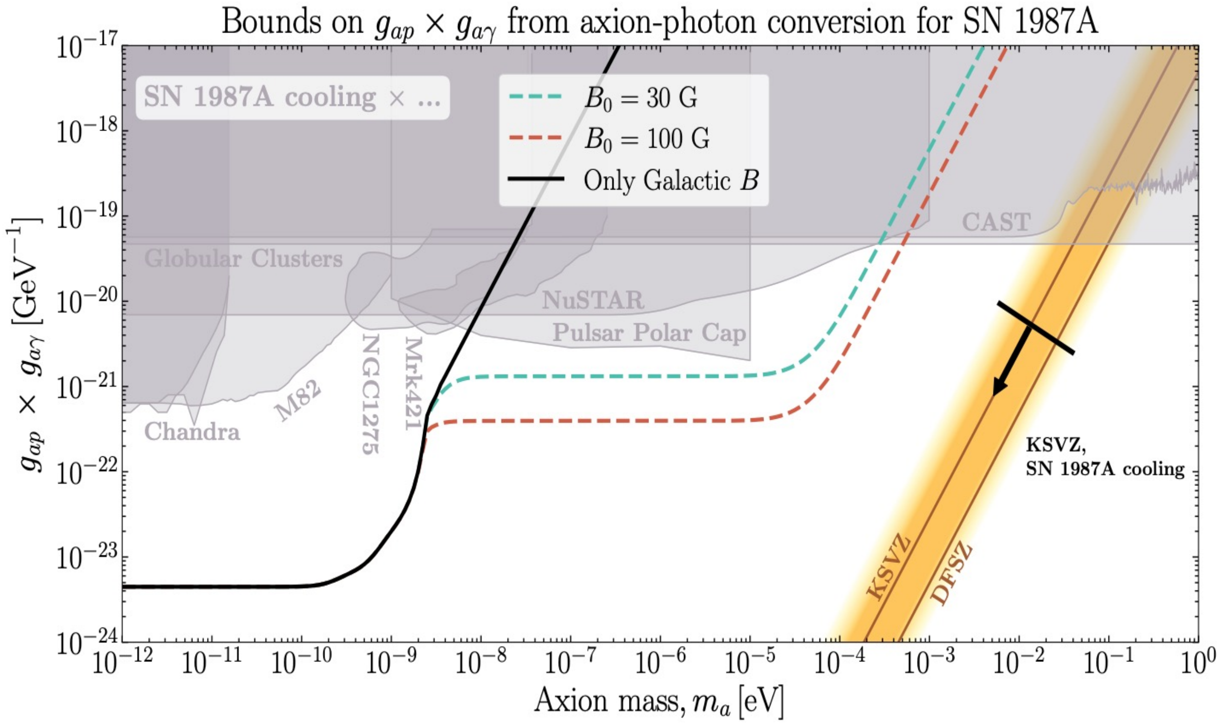
Gamma-ray glow from axion conversion

ALPs emitted from cc SNe may convert in photons in astrophysical magnetic fields along their path



[Fiorillo et al., JCAP 03 (2026) 053]



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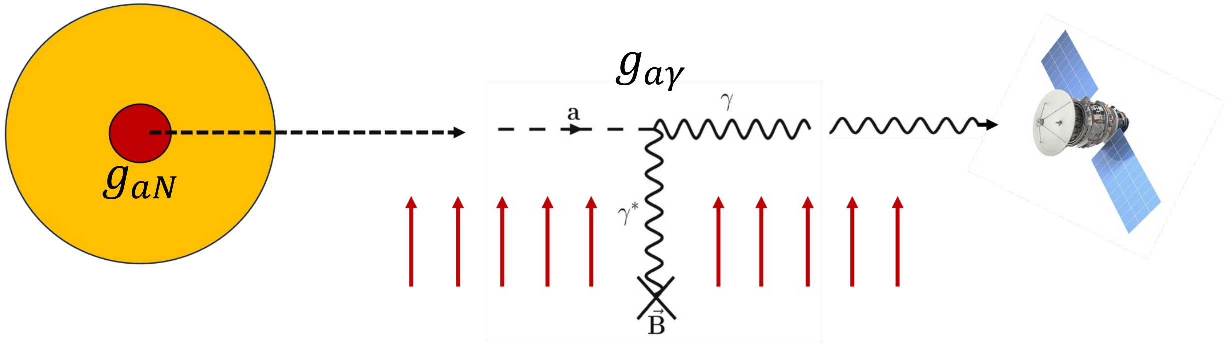

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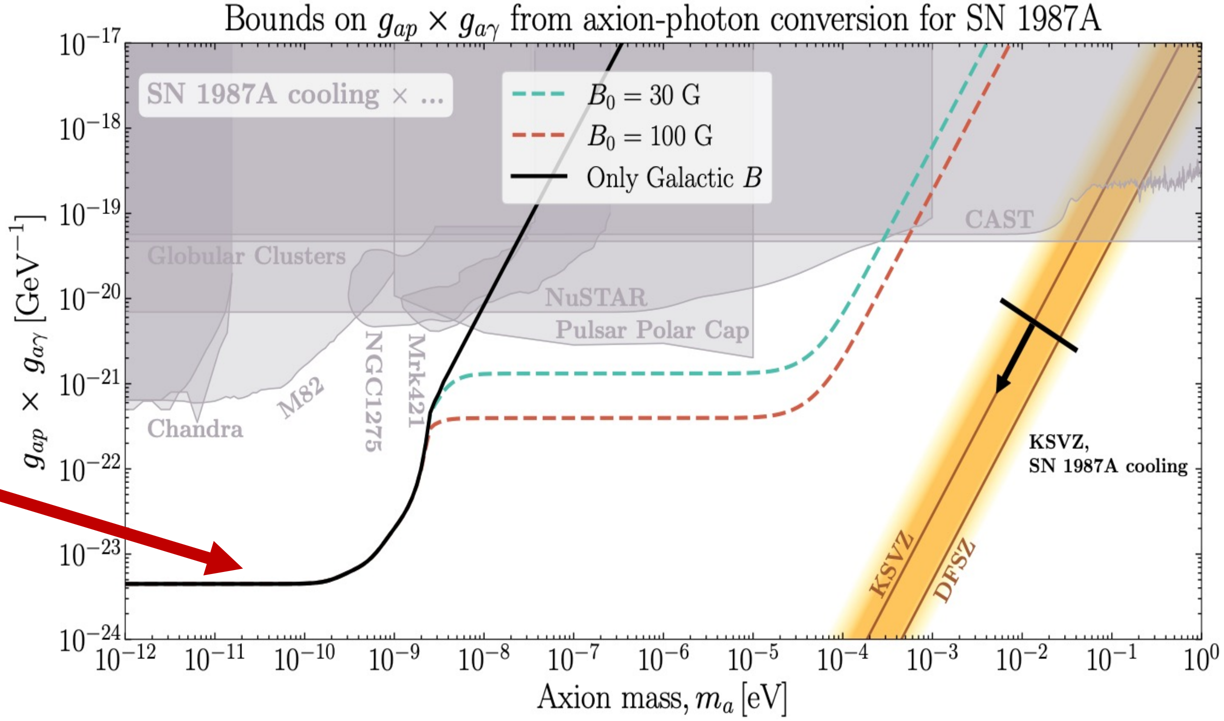

- Conversions in the galactic magnetic field ($m_a < 10^{-9}$ eV)
  [Payez et al., JCAP 02 (2015) 006]
  - $B \sim 10^{-6}$ G   L $\sim$ 10 kpc

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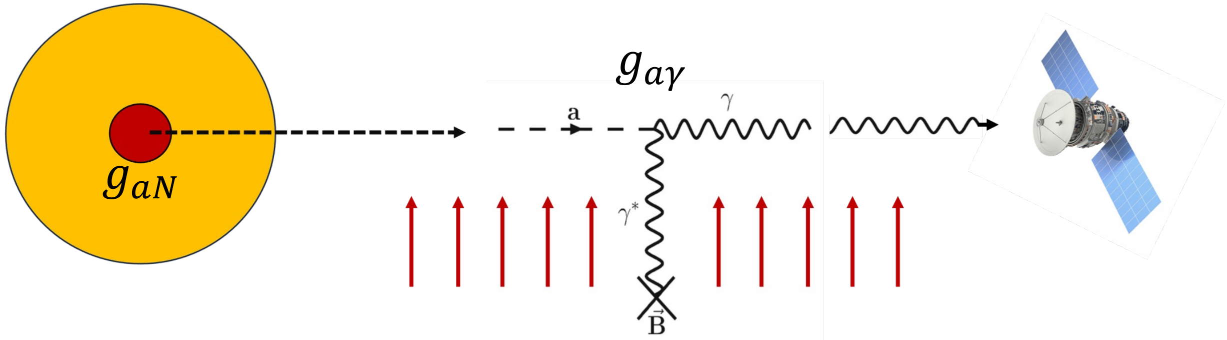

[Fiorillo et al., JCAP 03 (2026) 053]

- Conversions in the progenitor magnetic field
  $(10^{-8}\ \mathrm{eV} < m_a < 10^{-5}\ \mathrm{eV})$
  [Manzari et al., Phys.Rev.Lett. 133 (2024) 21]
  - $B \sim 1 - 100$ G $\mathrm{L} \sim 30\, R_\odot$

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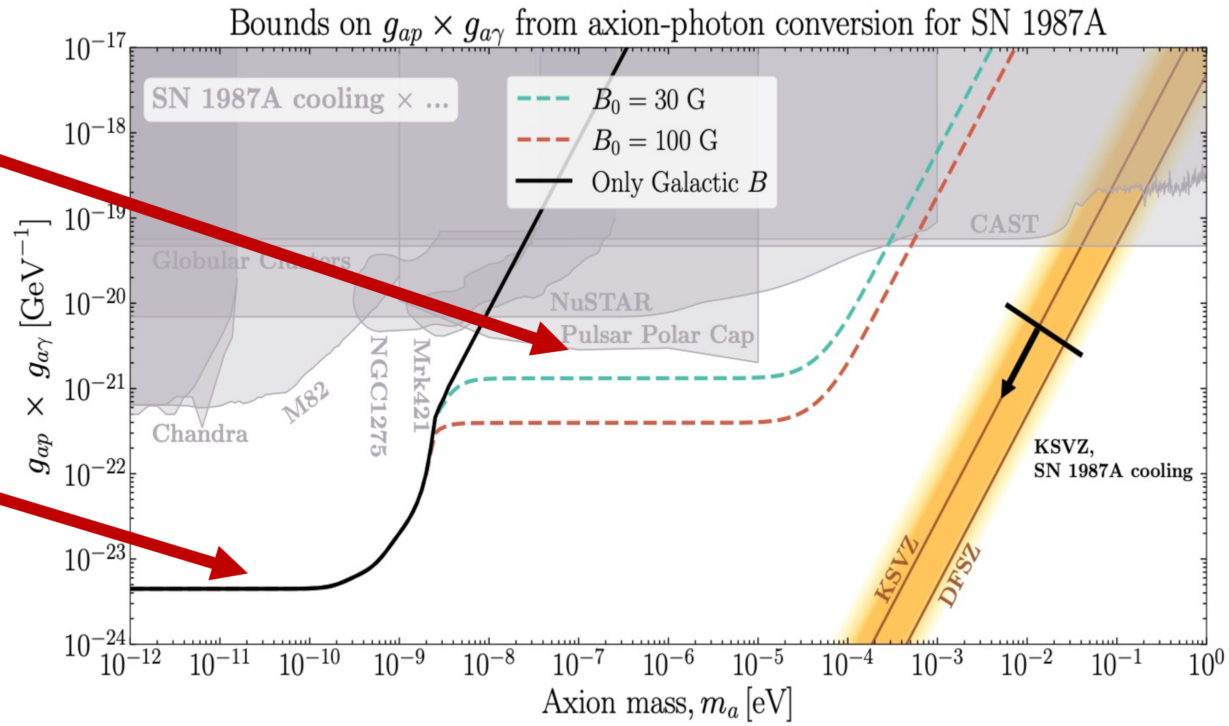
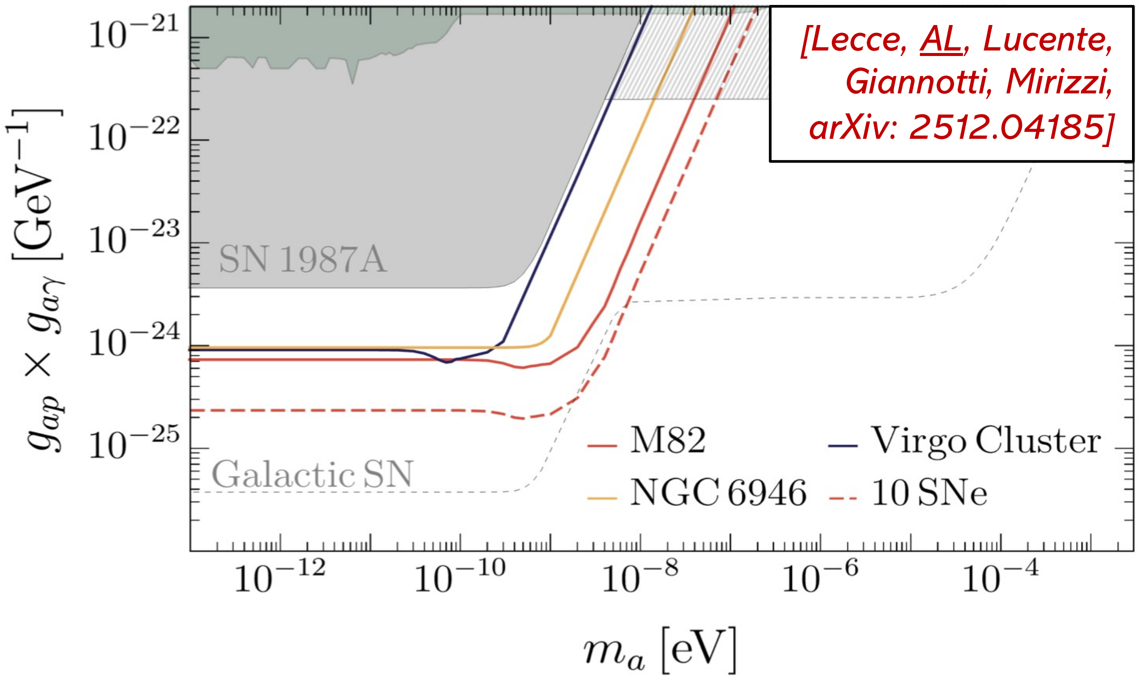


Gamma-ray glows from axion conversion

New perspectives:

- **Extra-galactic SNe:**
  - 1-7 SN per year within 20 Mpc
  - Strong magnetic fields in host galaxies
  - Need for an external time trigger: GWs?



[Lecce, AL, Lucente, Giannotti, Mirizzi, arXiv: 2512.04185]

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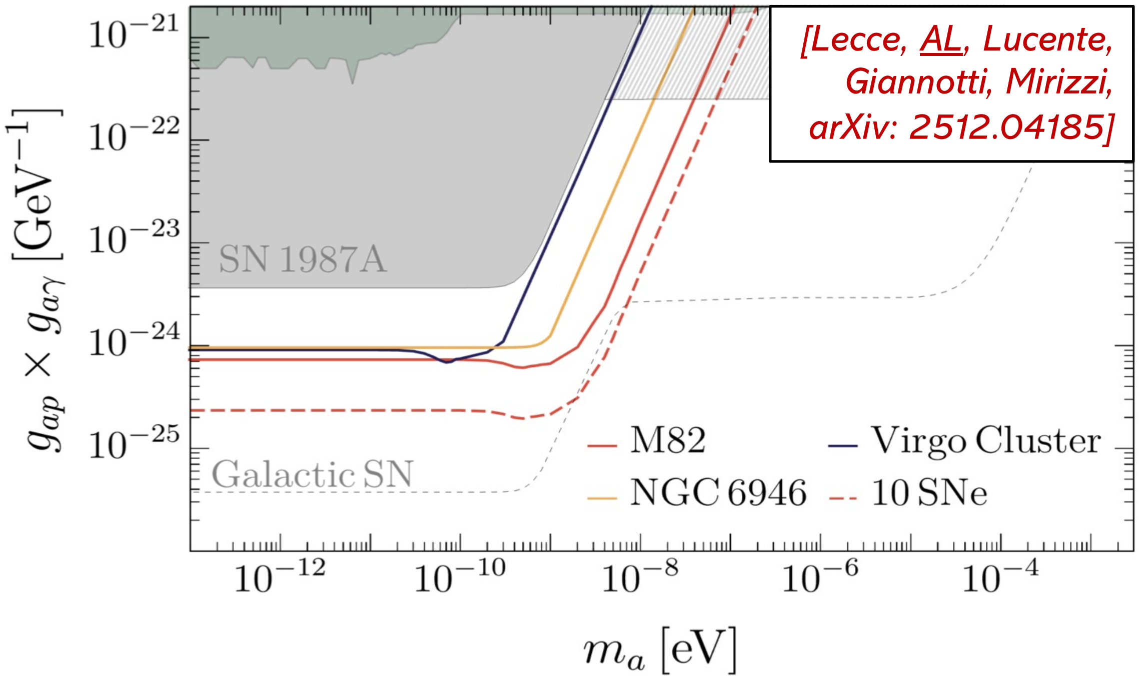
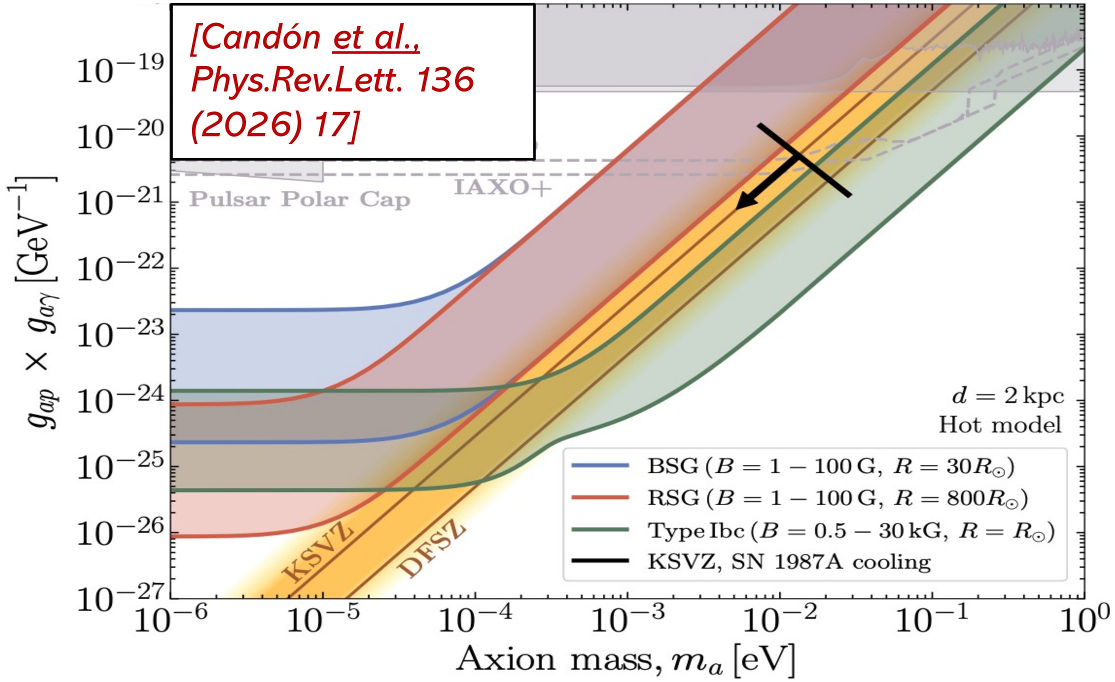


[Candón et al., Phys.Rev.Lett. 136 (2026) 17]

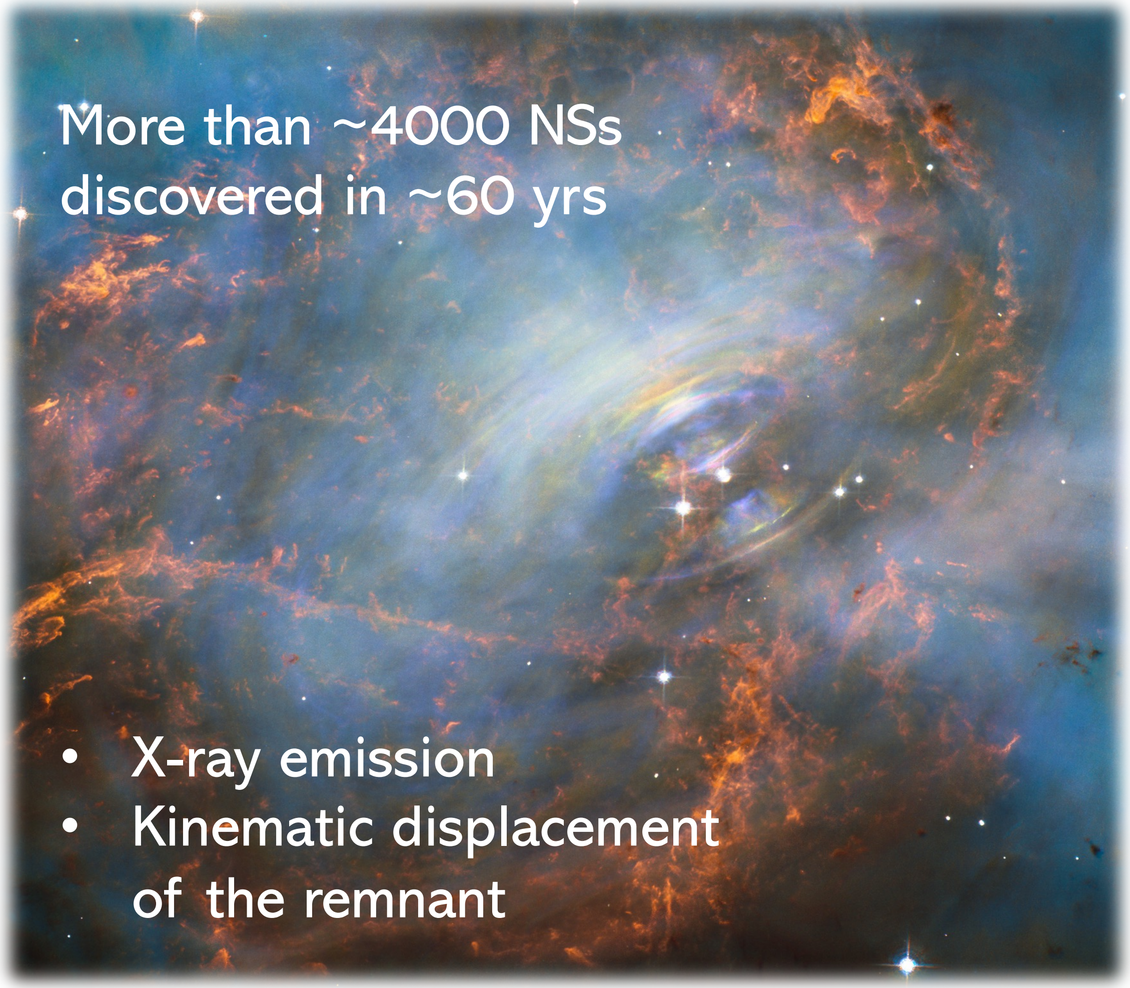


- **Type Ib/c SNe:**
  - 30% of the total SN population
  - Envelope ejected
  - Strong progenitor magnetic fields

Cold Isolated Neutron stars

Neutron stars

Neutron stars are the cold remnants of the explosion of massive stars $\mathrm{M} \sim 1-2\, M_{\odot}$



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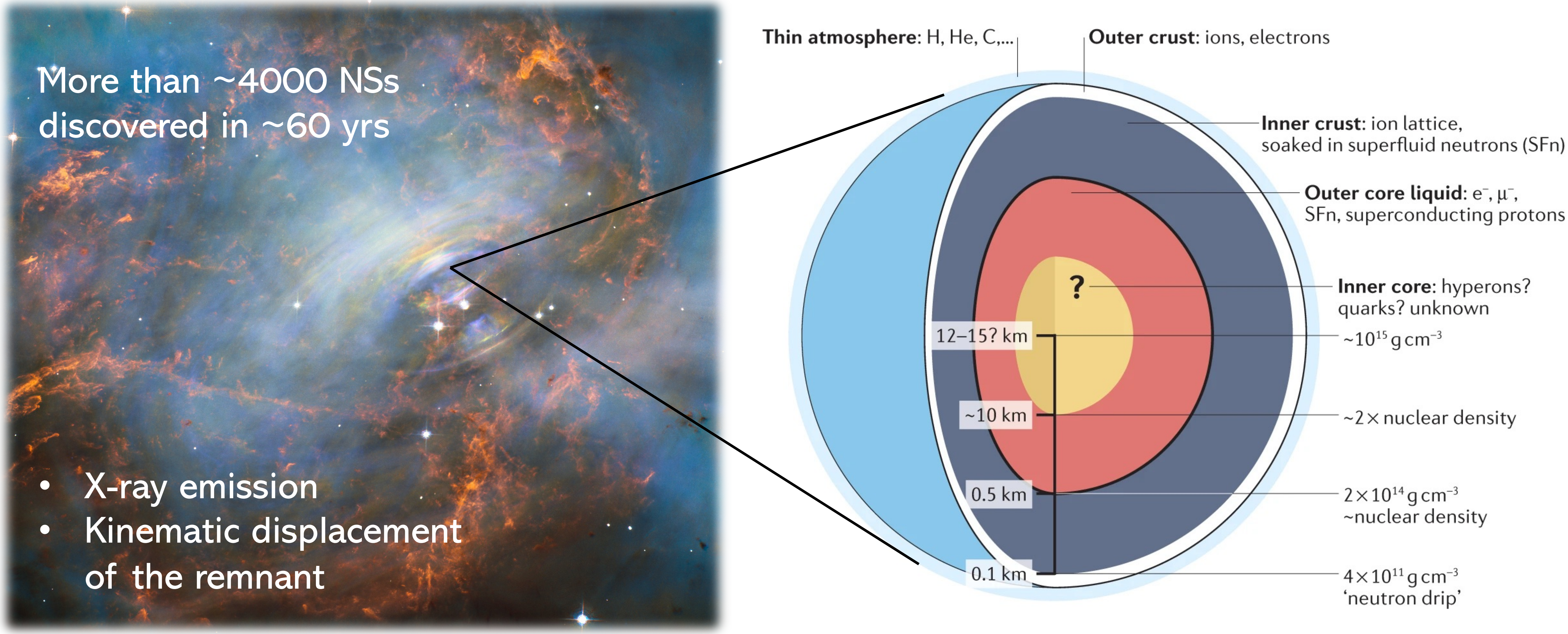
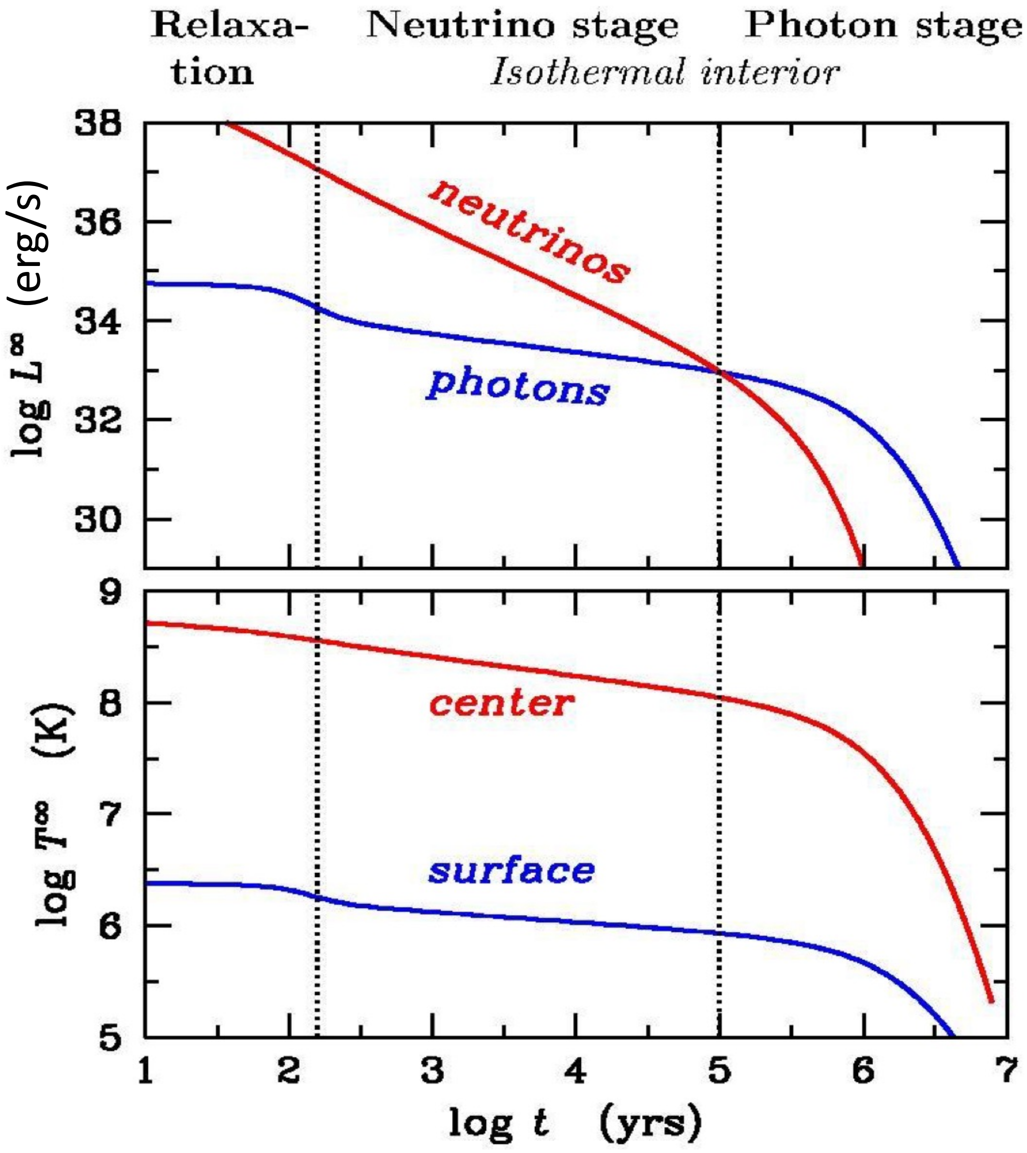


Alessandro Lella

SLAC, 2026/07/17

Basics of NS cooling



- **Neutrino-dominated phase**

➢ $t \sim 1 - 10^5$ yrs, $T_{\rm core} \sim 100 - 10$ keV.

➢ Main production channels:

$n \to p + e^- + \bar{\nu}_e$ Urca $Q_\nu \sim T^6$

$n + n \to p + n + e + \bar{\nu}_e$ Murca $Q_\nu \sim T^8$

$n + n \to n + n + \nu + \bar{\nu}$ NN bremsstrahlung $Q_\nu \sim T^8$

$B \to B + \nu + \bar{\nu}$ CP breaking $Q_\nu \sim T^7$

[Yakovlev et al., Phys.Rept. 354 (2001)]

- **Photon-dominated phase**

➢ $t > 10^5$ yrs, $T_{\rm core} < 10$ keV.

➢ Thermal emission from NS surface

The energy loss argument: SNe VS NSs

Cooling argument

If an exotic energy sink becomes competitive with the dominant channel in standard evolution, stellar cooling would proceed faster than observed

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$\boldsymbol{\rho \gtrsim 10^{14}\ \mathrm{g\ cm^3}}$

Core-Collapse SNe

$T_{\rm SN} \sim 30 - 40\ \mathrm{MeV},\ t \sim 10\ s$

Probe Emission processes
highly-sensitive to Temperature

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Core-Collapse SNe

$T_{\rm SN} \sim 30 - 40\ \mathrm{MeV},\ t \sim 10\ s$

Probe Emission processes
highly-sensitive to Temperature

Cold isolated NSs

$T_{\rm NS} \sim 10\ \mathrm{keV},\ t \sim 10^5\ \mathrm{yrs}$

Probe Emission processes
mildly-sensitive to Temperature

The energy loss argument: SNe VS NSs

Let's simplify things!

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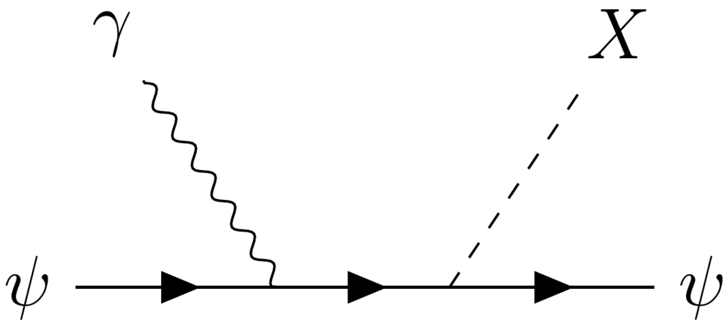
Let's simplify things!

~~$2 \to 3$~~ $2 \to 2$



Non-relativistic

The energy loss argument: SNe VS NSs

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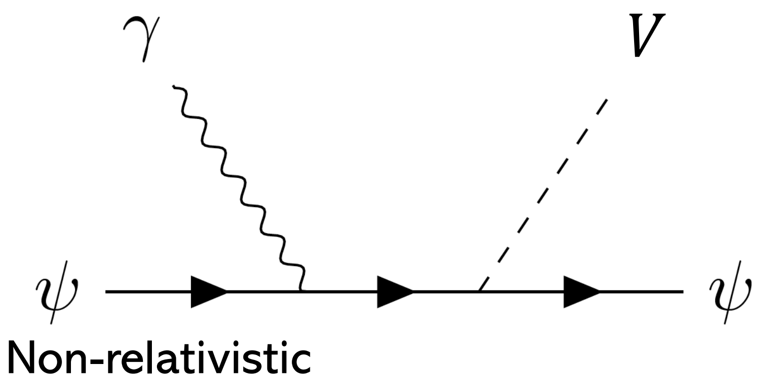

Vectors → $\sigma_V \sim \frac{\alpha_{\rm em}\alpha_V}{m_\psi^2}$

The energy loss argument: SNe VS NSs

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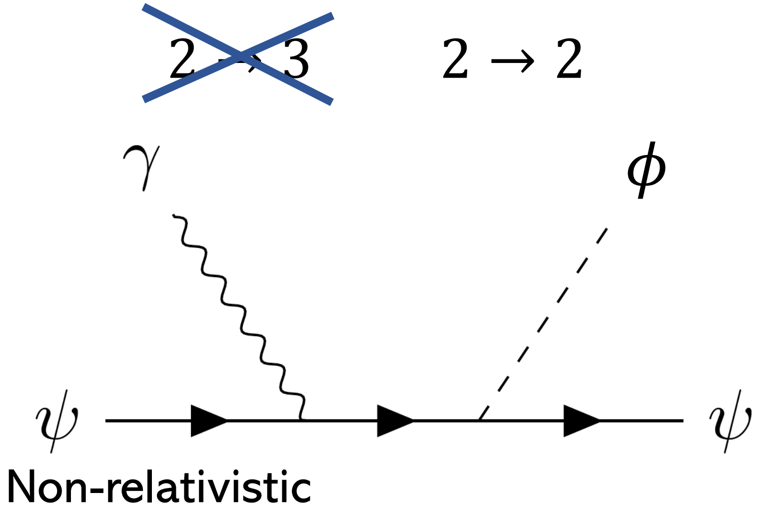

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Scalars → $\sigma_\phi \sim \frac{1}{2}\frac{\alpha_{\rm em}\alpha_\phi}{m_\psi^2}$

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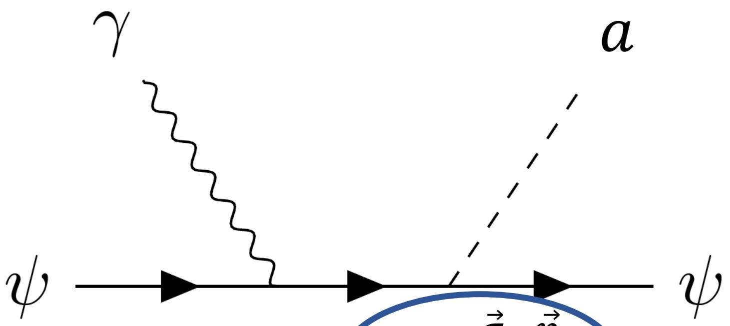

Non-relativistic $\gamma_5 \sim \frac{\vec{\sigma} \cdot \vec{p}_a}{m_\psi}$

- Vectors → $\sigma_V \sim \frac{\alpha_{\rm em}\alpha_V}{m_\psi^2}$
- Scalars → $\sigma_\phi \sim \frac{1}{2}\frac{\alpha_{\rm em}\alpha_\phi}{m_\psi^2}$
- Pseudoscalars → $\sigma_a \sim \frac{\alpha_{\rm em}\alpha_a}{m_\psi^2}\left(\frac{\omega}{m_\psi}\right)^2 \sim \frac{\alpha_{\rm em}\alpha_a}{m_\psi^2}\left(\frac{T}{m_\psi}\right)^2$

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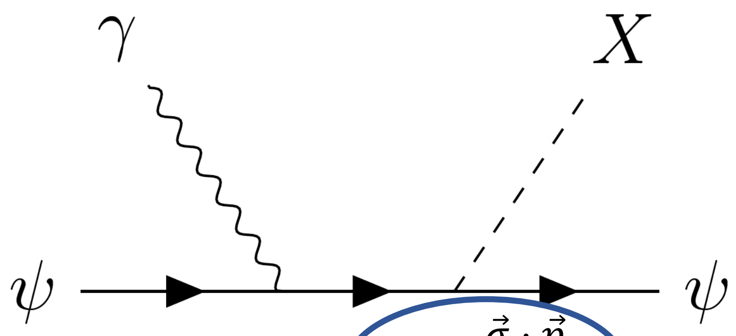

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Once integrating over the phase space for $2 \to 3$ in degenerate environments

Pseudoscalars → $Q_a \sim T^6$

Scalars → $Q_\phi \sim T^4$

Vectors → $Q_V \sim T^4$

The energy loss argument: SNe VS NSs

Let's simplify things!

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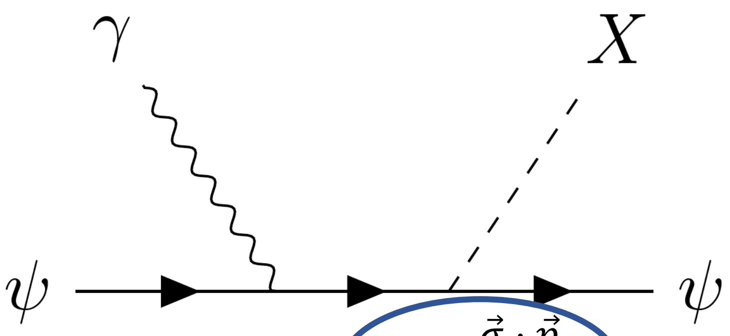

Non-relativistic $\quad \gamma_5 \sim \dfrac{\vec{\sigma}\cdot\vec{p}_a}{m_\psi}$

- Vectors $\longrightarrow$ $\sigma_V \sim \dfrac{\alpha_{\rm em}\alpha_V}{m_\psi^2}$
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Vectors $\longrightarrow$ $Q_V \sim T^4$

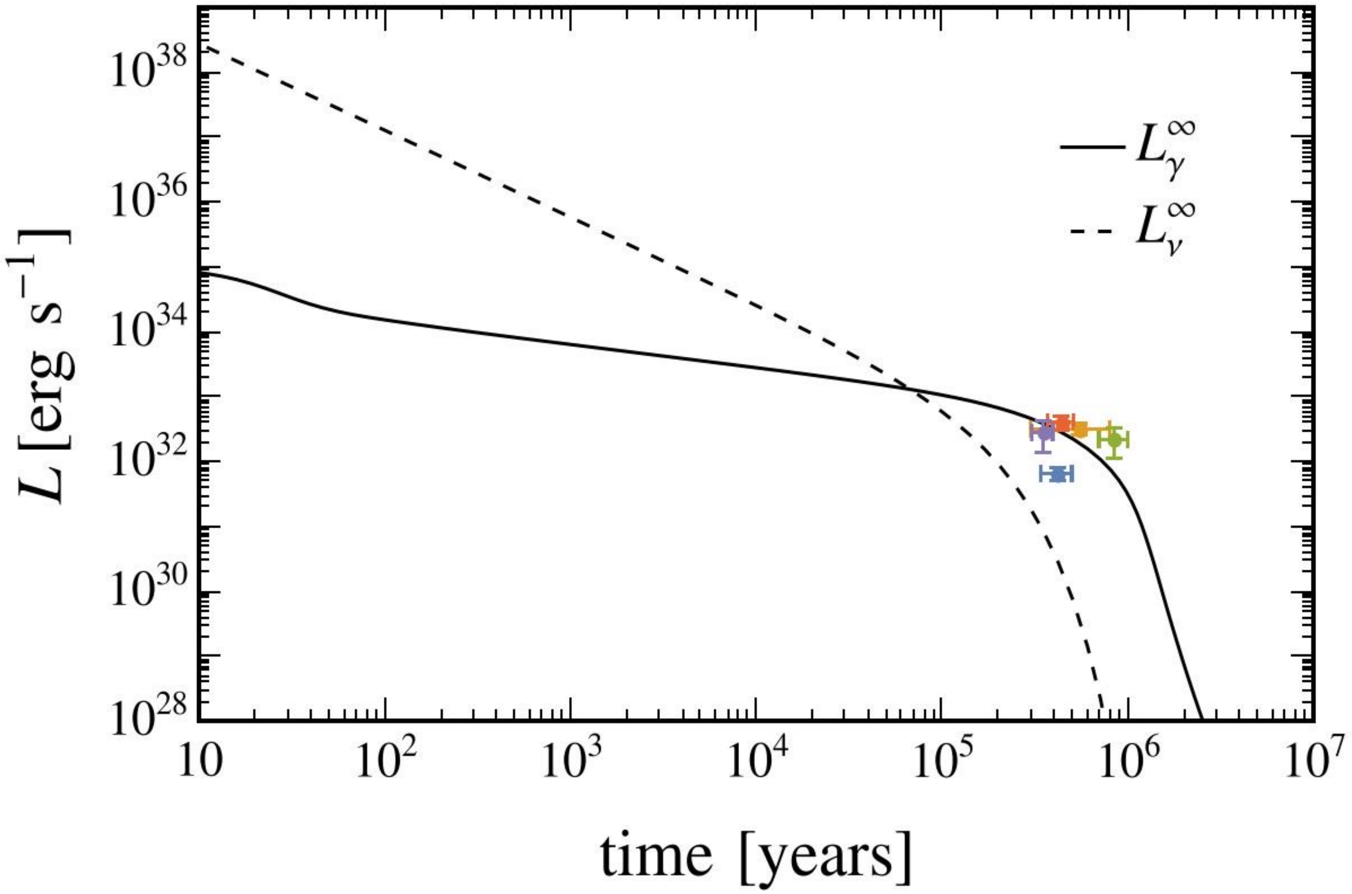
Axion NS bounds comparable to SNe…

[Buschmann et al., Phys.Rev.Lett. 128 (2022) 9]

…for other bosons,
NSs must do much better than SNe!

Modelling standard NS cooling

Analysis of the evolution of a sample of five isolated neutron stars with ages around $\sim 10^5$ yrs.



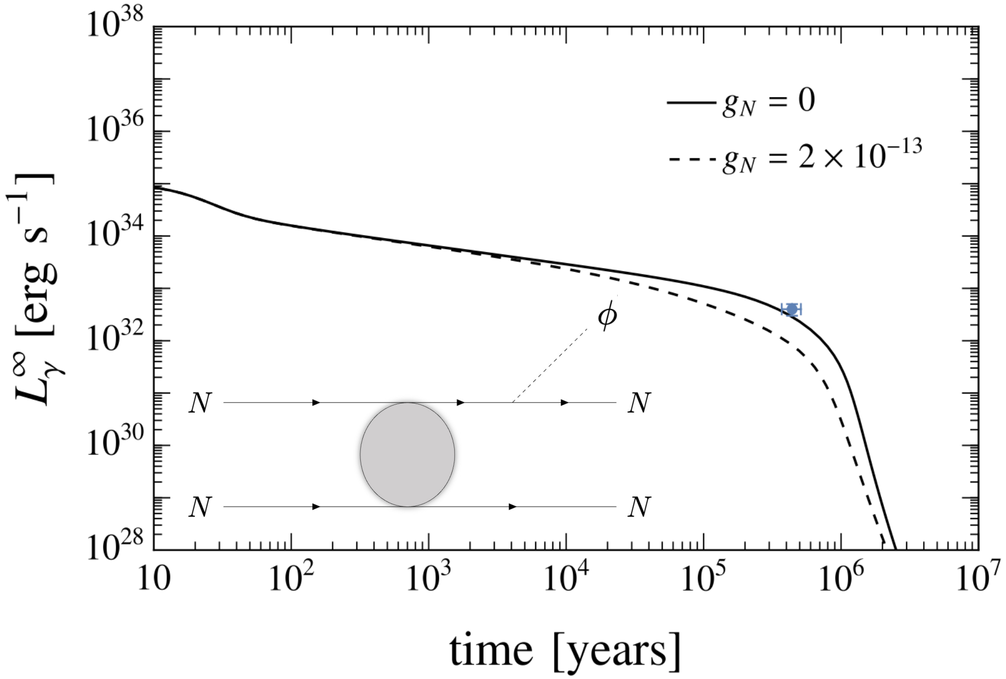
[Buschmann et al., Phys.Rev.Lett. 128 (2022) 9]

Name	L_γ^∞ [10^{33} erg/s]	Age [Myr]
J1856[a]	0.065 ± 0.015	0.42 ± 0.08
J1308[b]	0.32 ± 0.06	0.55 ± 0.25
J0720[c]	0.22 ± 0.11	0.85 ± 0.15
J1605[d]	0.4 ± 0.1	0.44 ± 0.07
J0659[e]	0.28 ± 0.14	0.35 ± 0.044

Cooling lightcurves simulated through the open-source code `NSCool`

- NS cooling models depends on NS properties (mass, fraction of light elements, superfluidity…)

Impact of scalar emission



Upper limits from a joint likelihood analysis…

$$q(g_N; m_\phi) = \begin{cases} -2\ln \frac{\mathcal{L}\left(\boldsymbol{d}|m_\phi, g_N, \hat{\boldsymbol{\theta}}\right)}{\mathcal{L}\left(\boldsymbol{d}|m_\phi, \hat{g}_N, \hat{\boldsymbol{\theta}}\right)} & g_N \geq \hat{g}_N\,, \\ 0 & g_N < \hat{g}_N\,, \end{cases}$$

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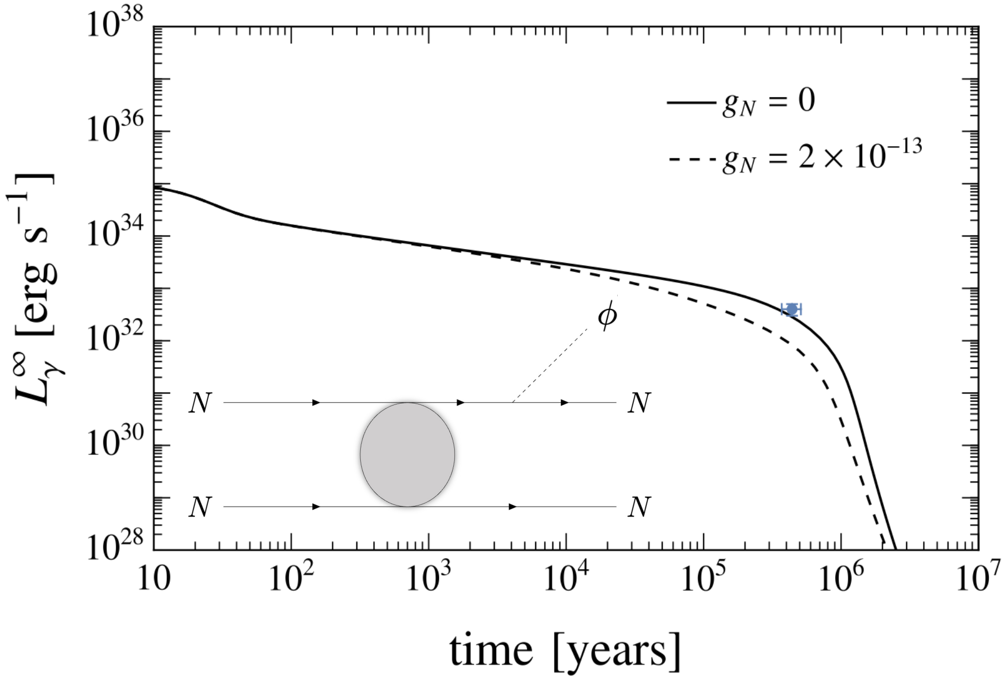

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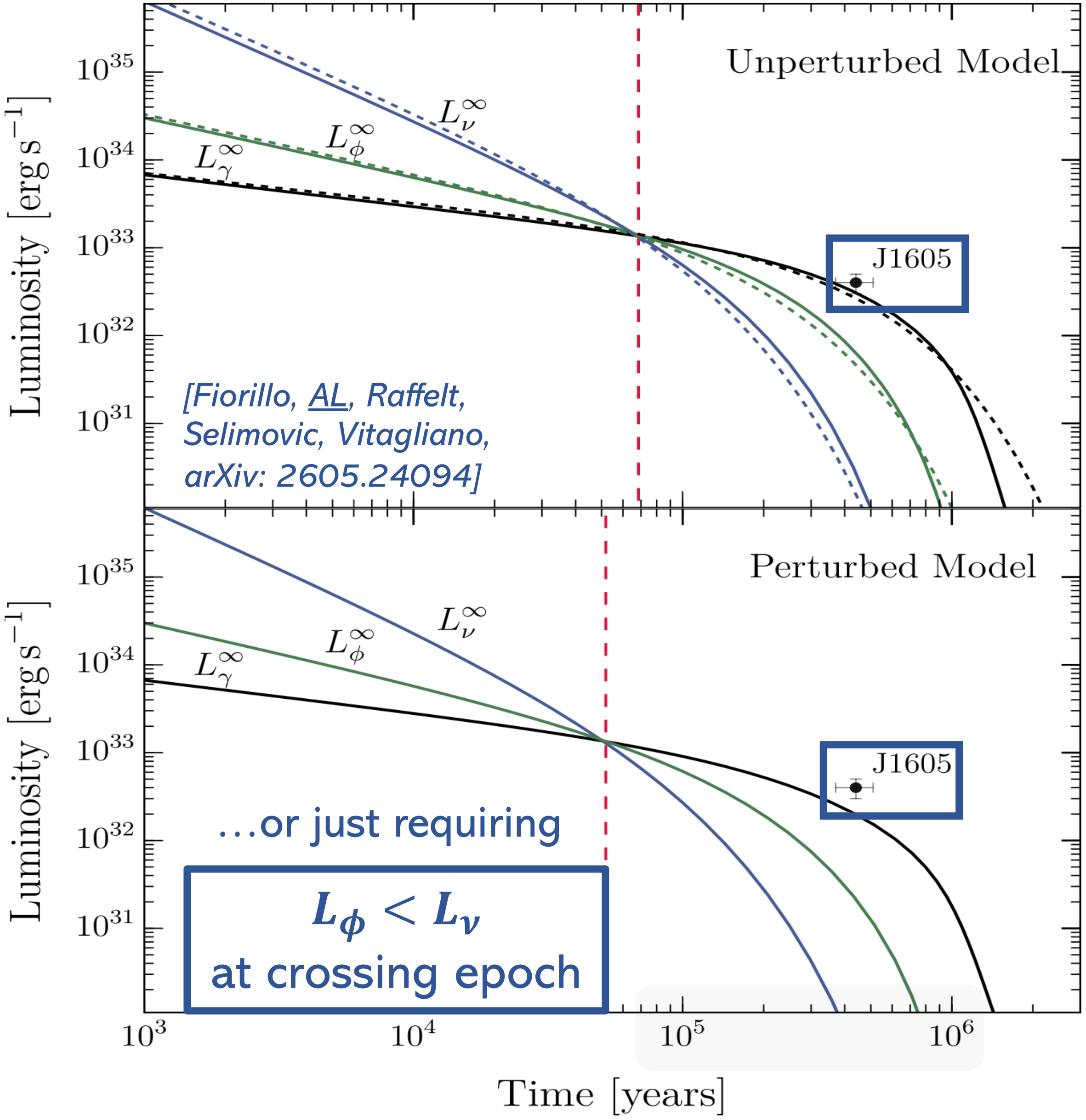


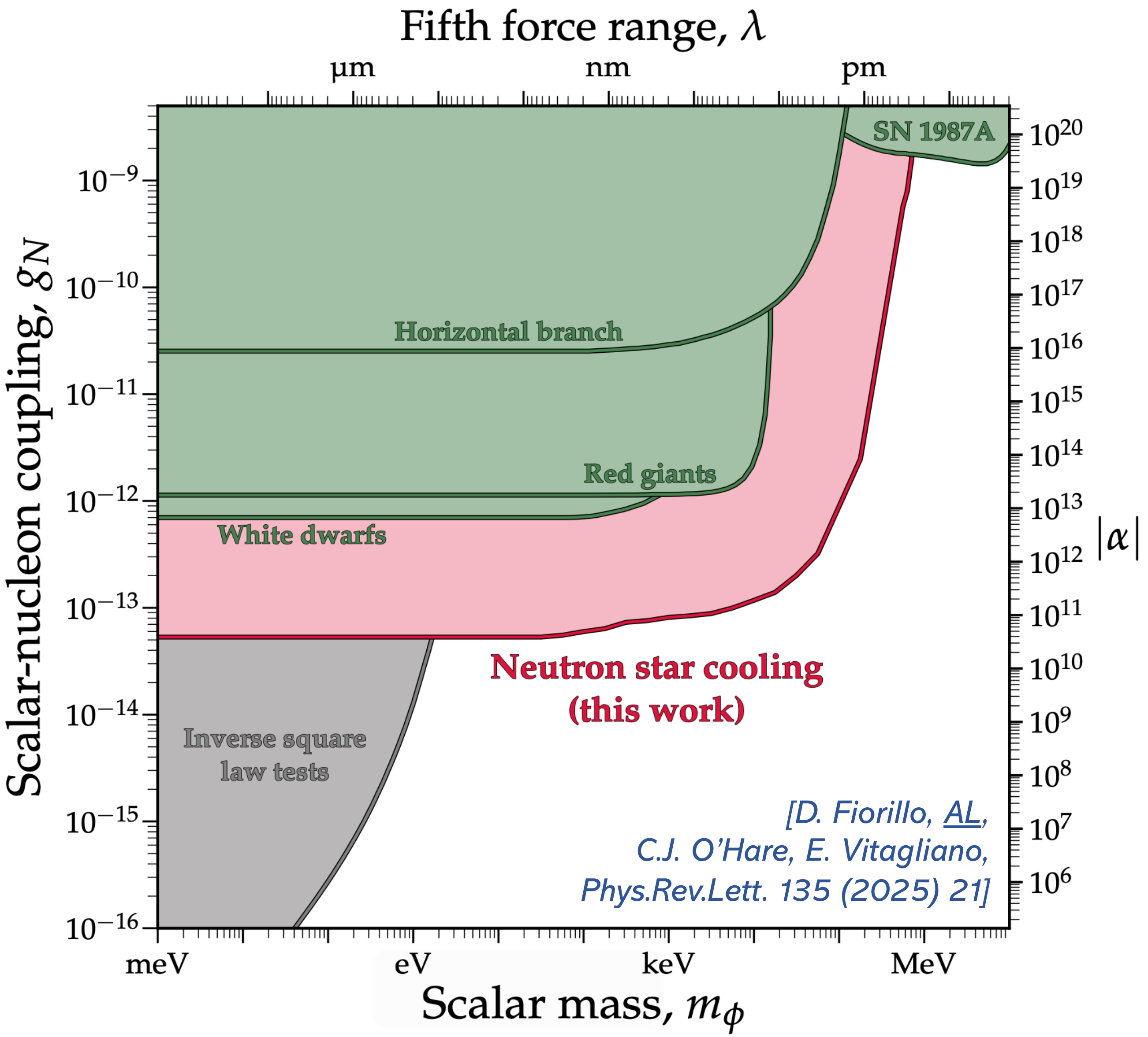
[Fiorillo, AL, Raffelt, Selimovic, Vitagliano, arXiv: 2605.24094]

…or just requiring

$L_\phi < L_\nu$ at crossing epoch

NS cooling bounds

- Most stringent astrophysical limits on exotic scalars with masses $m_\phi < \mathrm{MeV}$.

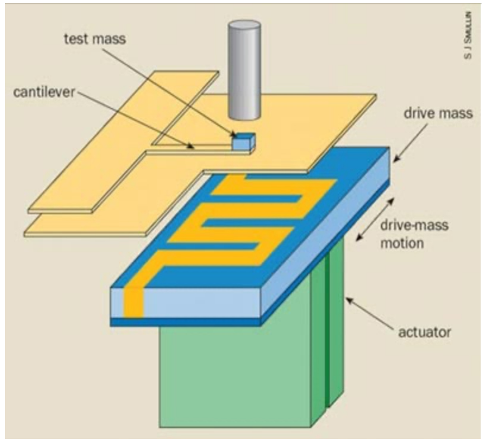


NS cooling bounds

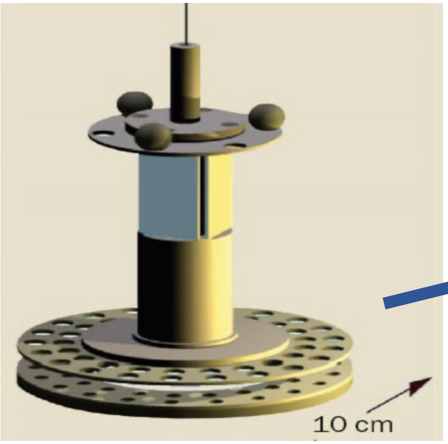
- Most stringent astrophysical limits on exotic scalars with masses $m_\phi < \mathrm{MeV}$.

- Leading limits on pico- to micrometer fifth forces.

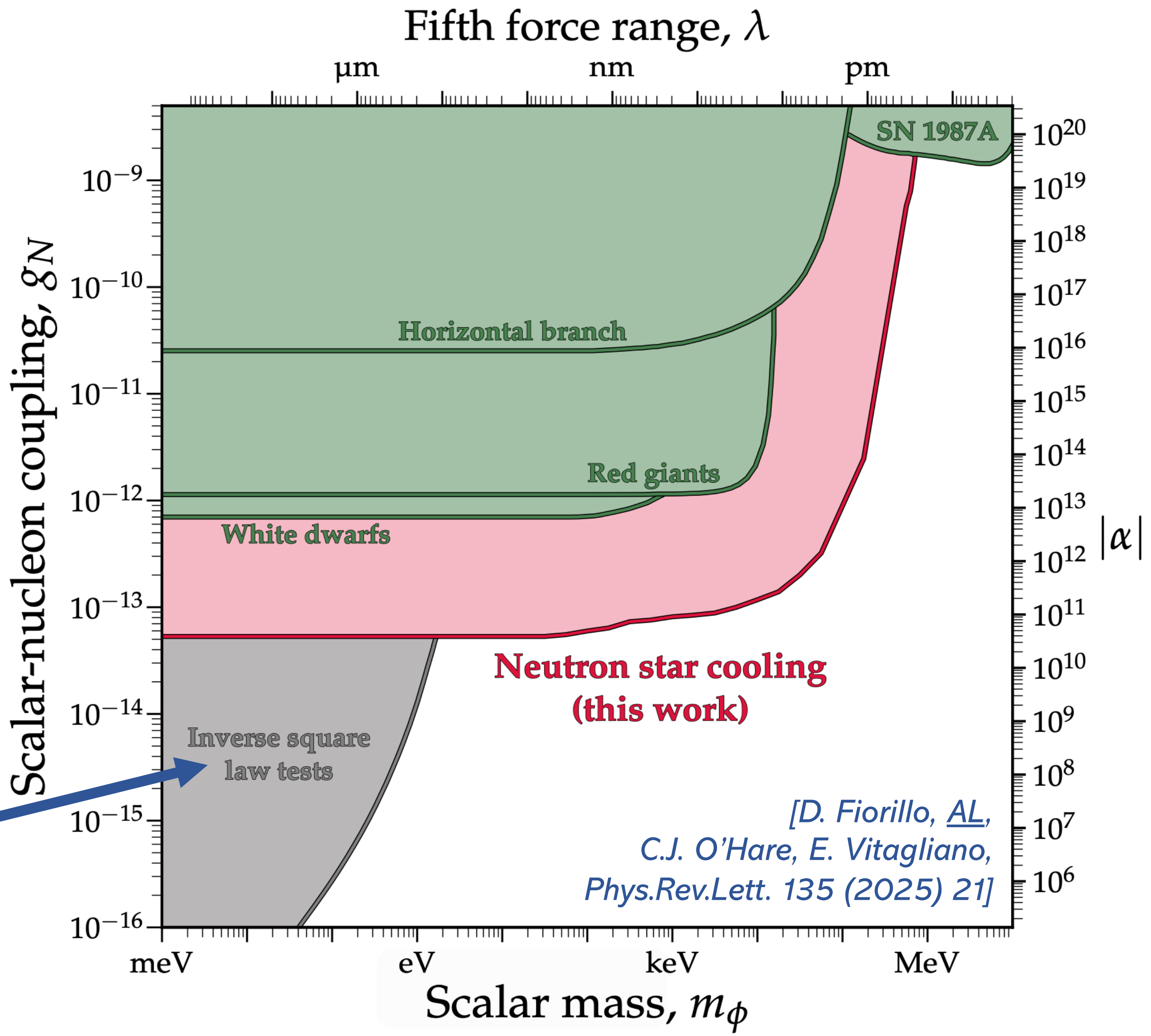
$$V(r) = -G_\infty \frac{m_i m_j}{r_{ij}}(1+\alpha e^{-r/\lambda}) \qquad \frac{1}{\lambda} \propto m_\phi$$



Microcantilevers



Torsion pendulum



Muonic bosons from NSs

Due to the extremely large fermion chemical potential, CC SNe and NSs may host large muon populations

PNS $\left\{\begin{matrix} e^- + e^+ \longrightarrow \mu^- + \mu^+ \\ \gamma + \gamma \longrightarrow \mu^- + \mu^+ \end{matrix}\right\}$

$$n \to p + \mu + \bar{\nu}_\mu$$
$$\mu + p \to n + \nu_\mu$$

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$$n + p + \mu \to n + n + \nu_\mu$$

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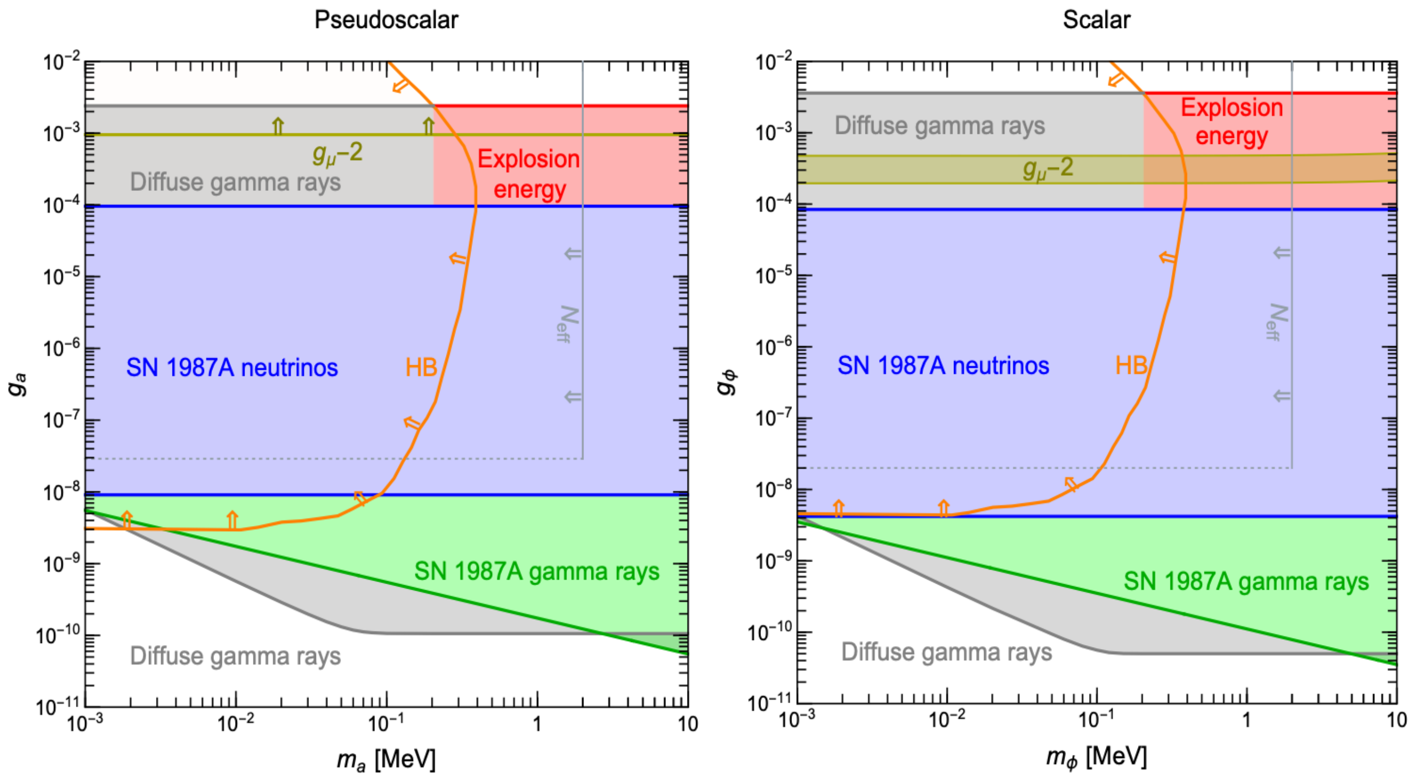
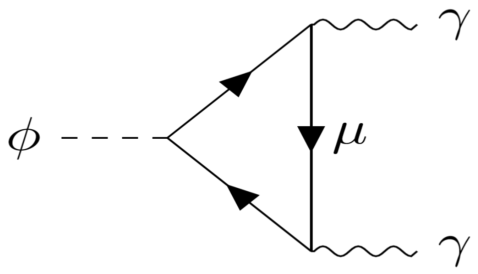


[Caputo et al., Phys.Rev.D. 105 (2022) 21]

SNe as testbeds for novel bosons coupling to muons

[Chang et al., JHEP 09 (2018) 051]

[Bollig et al., Phys.Rev.Let. (2020) 5]



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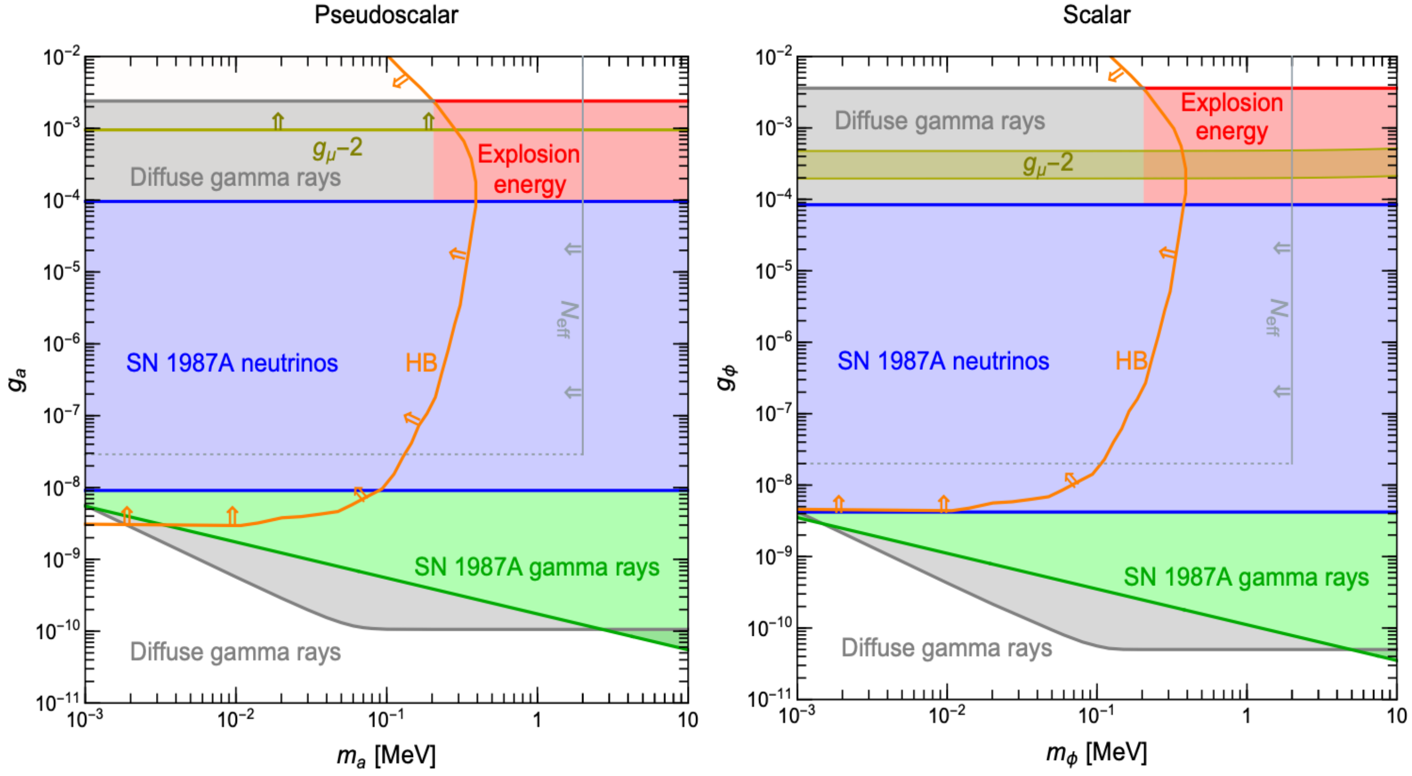

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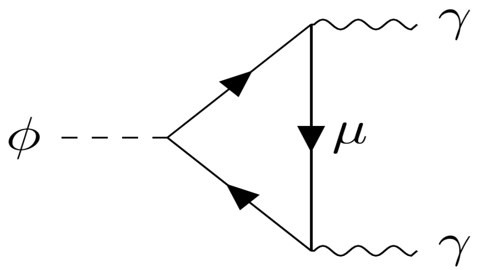
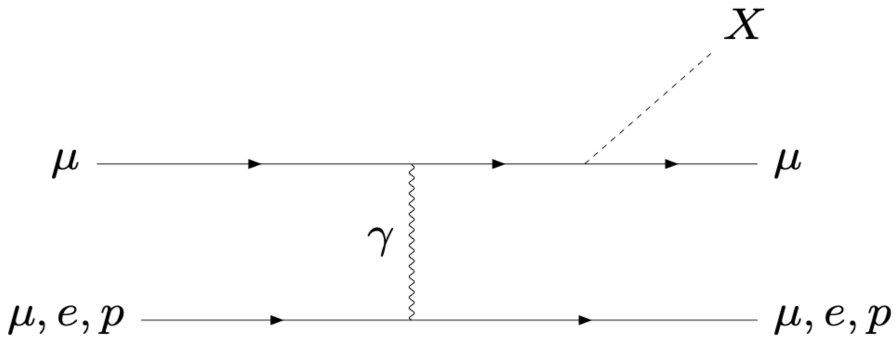


What about Neutron stars?

NS bounds on muonic bosons

- An excessive emission of novel particles would fasten the NS cooling process



[Fiorillo, AL, Raffelt, Selimovic, Vitagliano, arXiv: 2605.24081]

$$L_X \lesssim L_\nu \quad \text{at} \;\; L_\gamma = L_\nu$$

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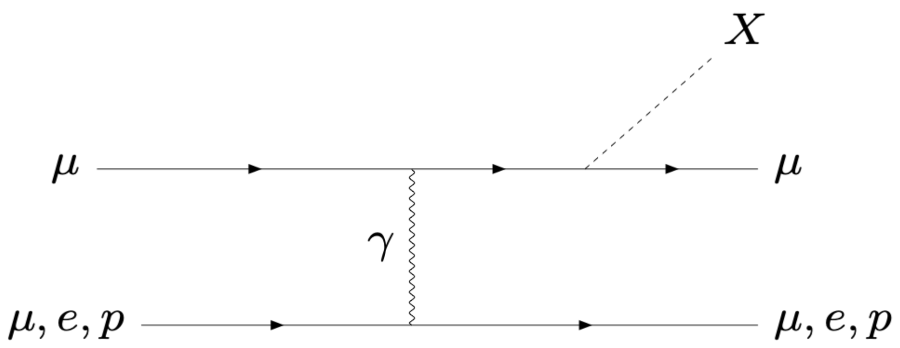


[Fiorillo, AL, Raffelt, Selimovic, Vitagliano, arXiv: 2605.24081]

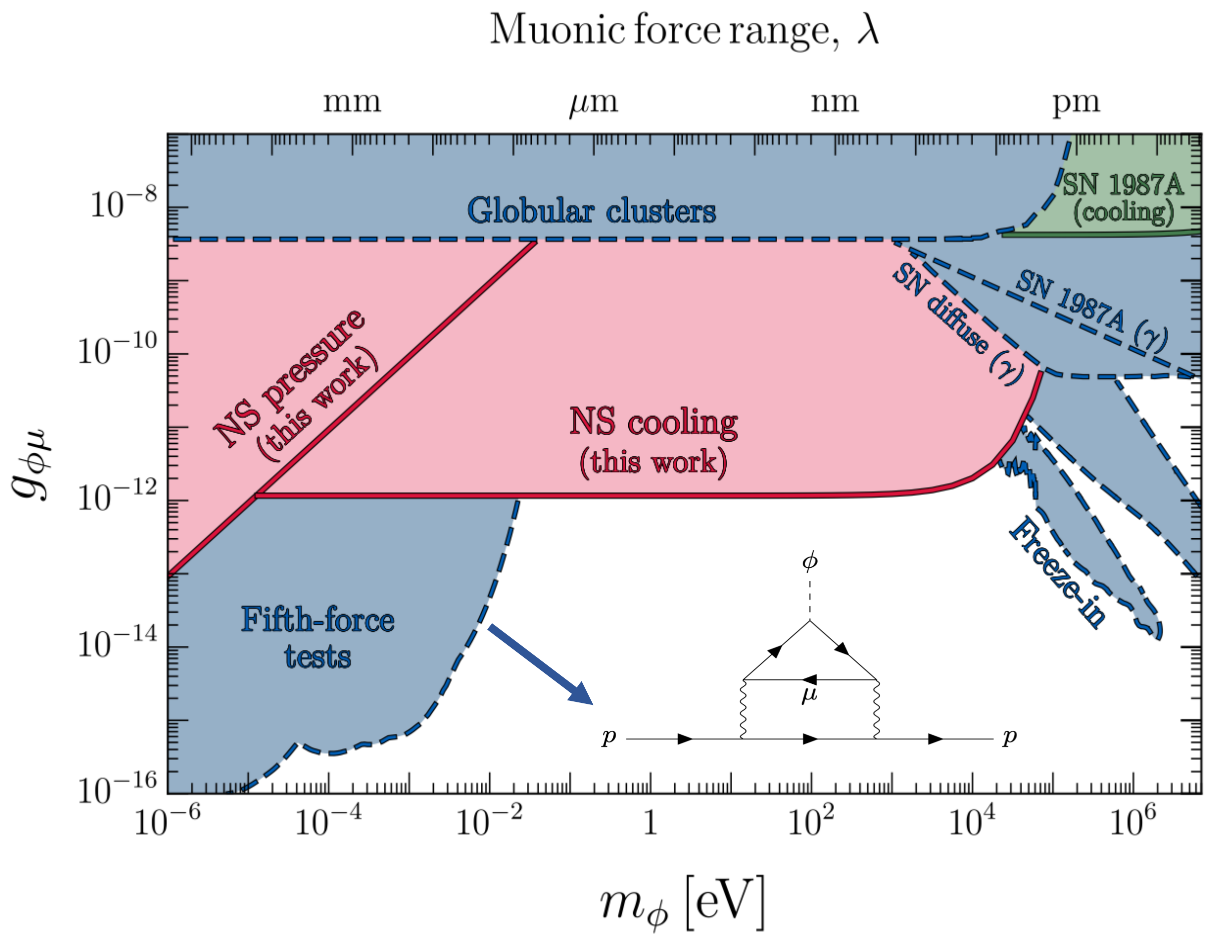
$$L_X \lesssim L_\nu \quad \text{at } L_\gamma = L_\nu$$

- Muon interactions mediated by novel bosons would generate additional pressure on the NS structure.

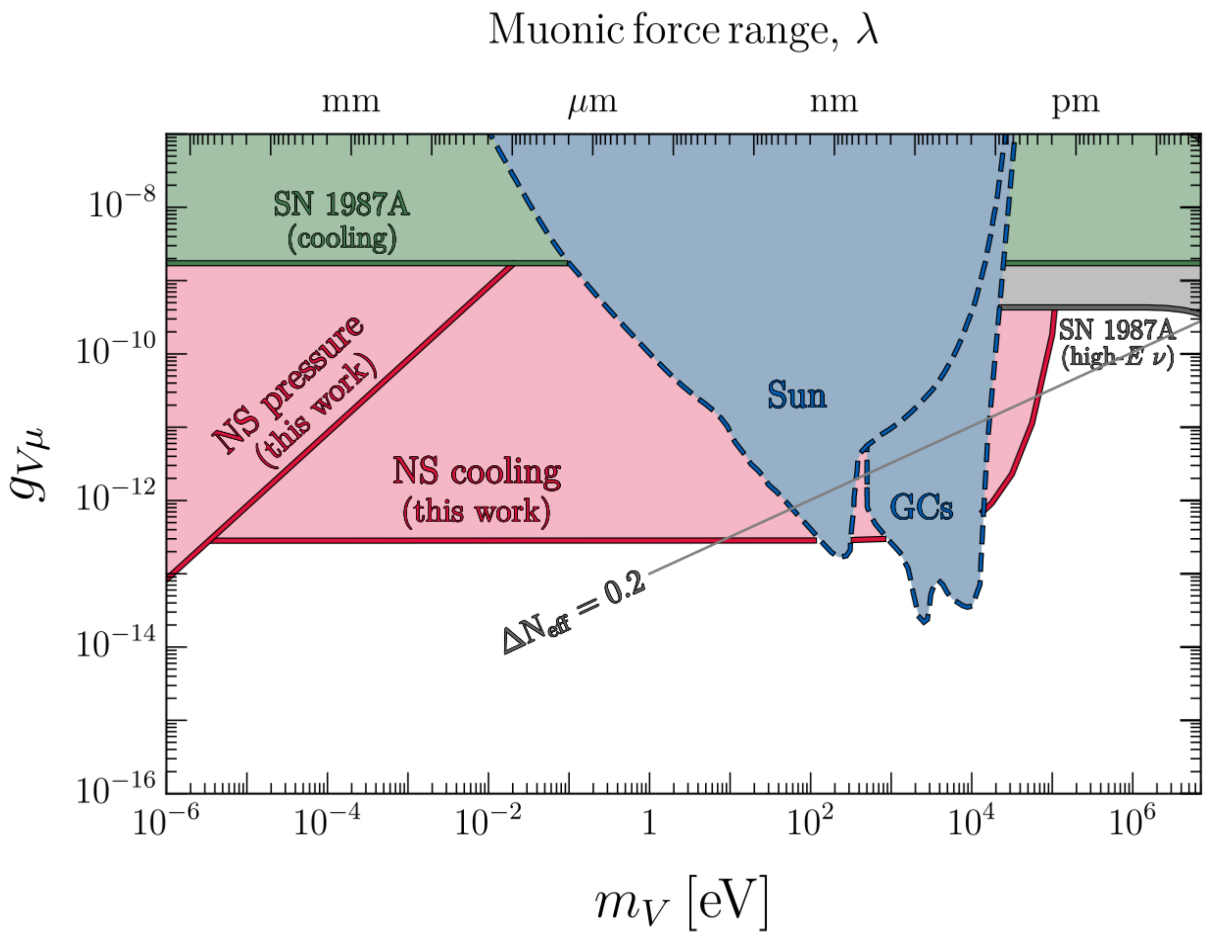
$$P_\mu \sim 4\pi g_{X\mu}^2 \frac{n_\mu^2}{m_X^2} \lesssim G_N \frac{M_{\rm NS}^2}{R^4}$$

NS bounds on muonic bosons

Scalars



Vectors



[Fiorillo, AL, Raffelt, Selimovic, Vitagliano, arXiv: 2605.24094]

Take-home messages

- Compact Objects are powerful astrophysical laboratories for novel light bosons
- The microphysics of the BSM determines the best astrophysical laboratory.
- Core-collapse SNe are powerful astrophysical laboratories for QCD axions and pseudascalars.
- NS are the most constraining astro probe for bosons $Q_X \sim T^p$ with $p < 6$.

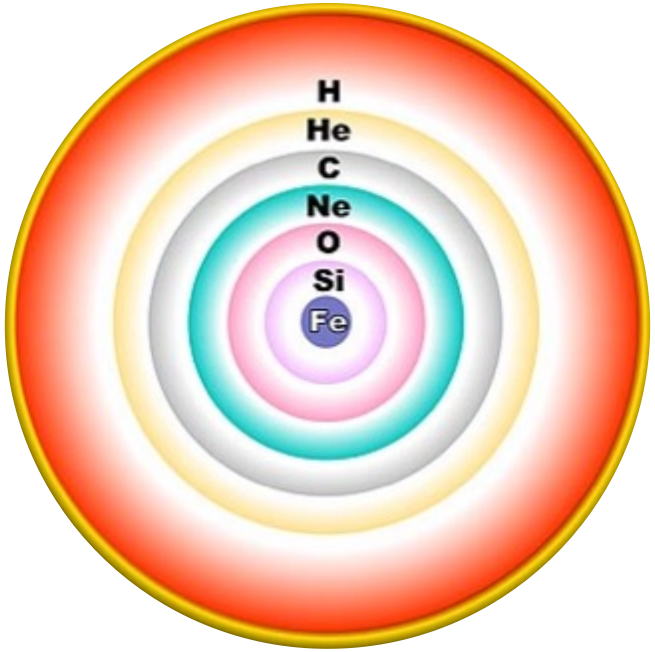
Thank you for your attention

This work is supported by the Italian Ministero dell'Università e della Ricerca through the FIS 2 project FIS-2023-01577 (DD n. 23314 10-12-2024, CUP C53C24001460001)

Massive stars and gravitational collapse

Stars with masses $\mathrm{M} \geq 8\, M_\odot$ can induce the ignition of heavy elements, up to Silicon.

Burning Phase	Dominant Process	T_c [keV]	ρ_c [g/cm^3]	L_γ [10^4 L_{sun}]	L_ν/L_γ	Duration [years]
Hydrogen	$H \to He$	3	5.9	2.1	–	1.2×10^7
Helium	$He \to C, O$	14	1.3×10^3	6.0	1.7×10^{-5}	1.3×10^6
Carbon	$C \to Ne, Mg$	53	1.7×10^5	8.6	1.0	6.3×10^3
Neon	$Ne \to O, Mg$	110	1.6×10^7	9.6	1.8×10^3	7.0
Oxygen	$O \to Si$	160	9.7×10^7	9.6	2.1×10^4	1.7
Silicon	$Si \to Fe, Ni$	270	2.3×10^8	9.6	9.2×10^5	6 days

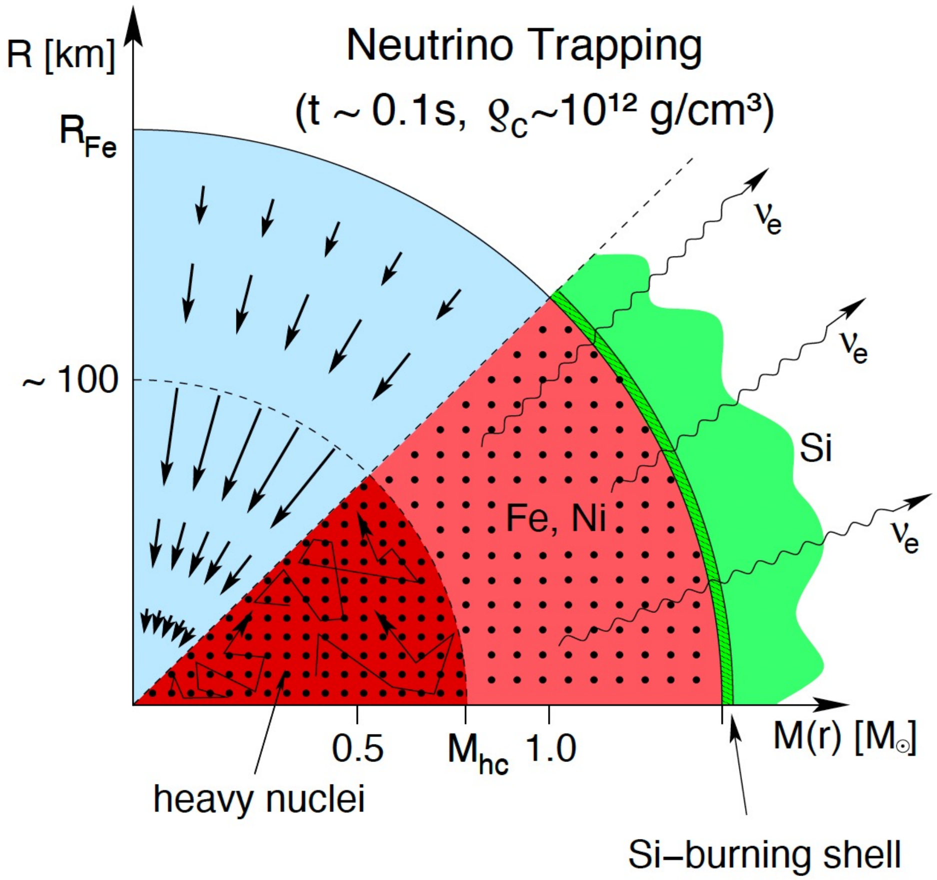


Heavy elements collected in an "onion" structure with shells of burning elements around a degenerate iron core.

CC SNe: explosion mechanism

A core-collapse Supernova is the terminal phase of a massive star ($\mathrm{M} \geq 8\, M_{\odot}$).

- Formation of a degenerate Iron core
  - → e^-captures reduces electron degeneracy pressure
- Onset of the gravitational collapse
  - → Keeps going on until inner core becomes uncompressible ($\rho \sim 10^{14}\ \mathrm{g/cm^3}$)
- Core bounce and formation of a shock-wave
  - → Converts the implosion into an explosion



CC SNe: explosion mechanism

During shock-wave propagation

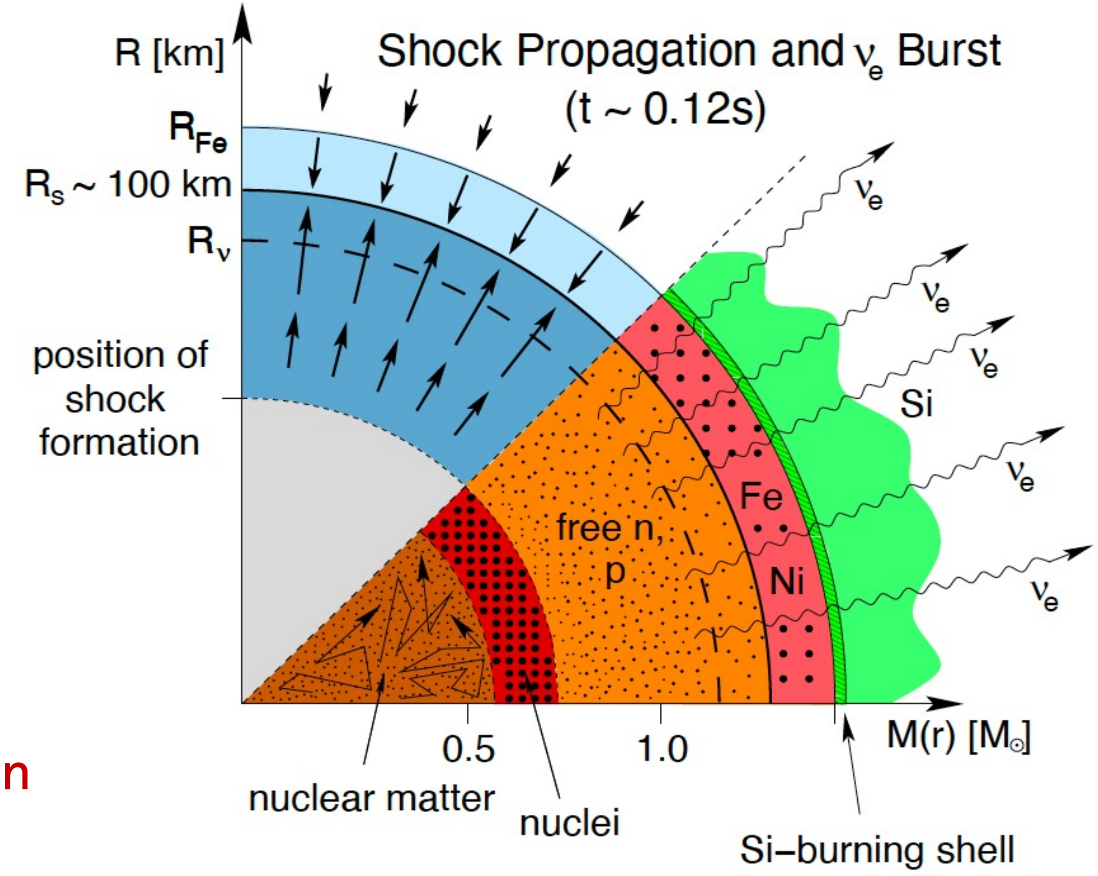
➢ Matter infalling (accretion) from above forms a PNS

⟶ $R \sim 10$ km, T ~ 30 MeV

⟶ Cooling via neutrino emission of all species
$E \sim 10^{53}$ erg , $t \sim 10$ s.

➢ The shock-wave loses energy dissociating heavy nuclei.

⟶ ν-heating+hydro-instability aided delayed explosion



CC SNe: explosion mechanism

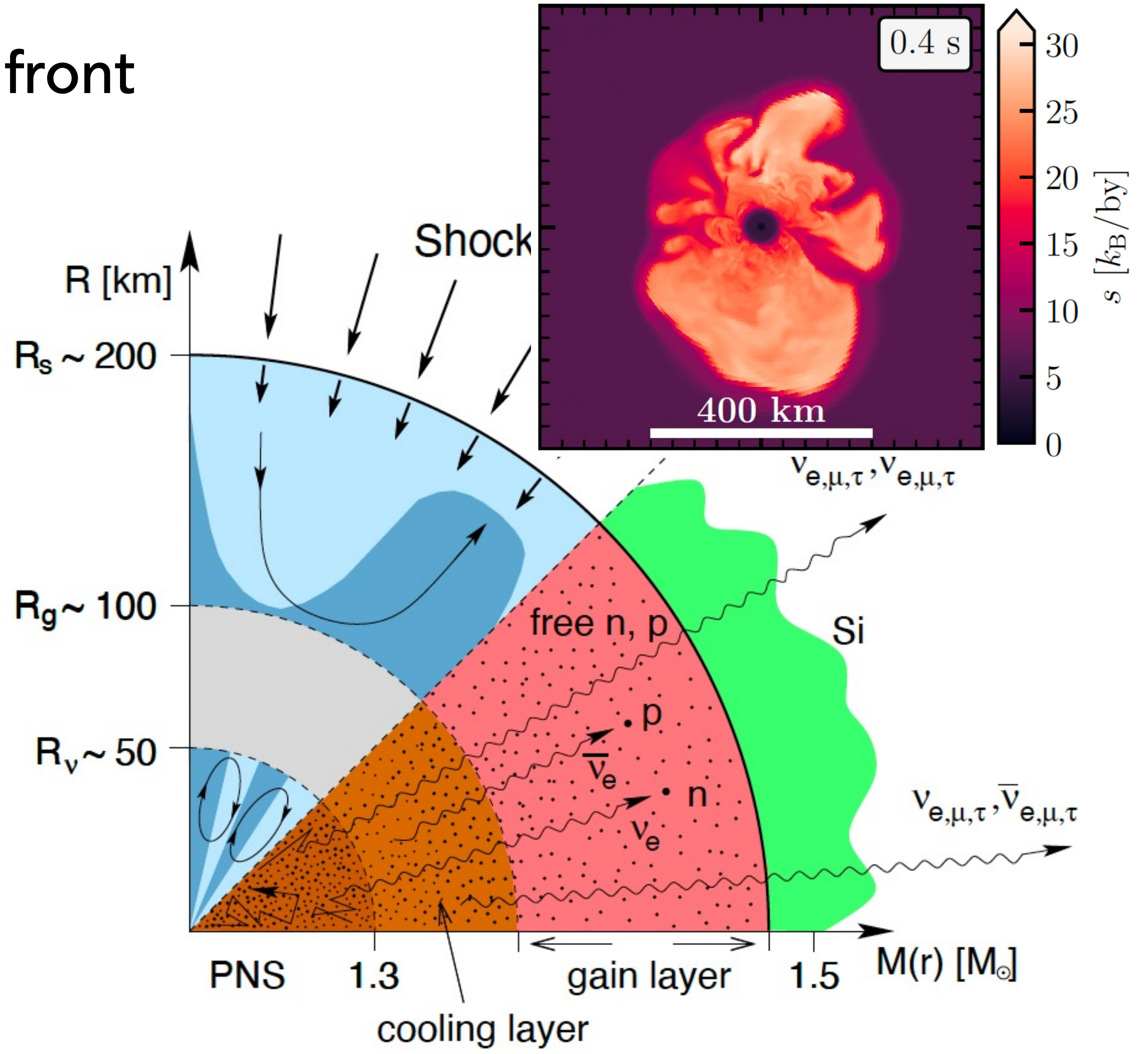
- Neutrinos deposit energy behind the shock front (ν- heating)

- Neutrinos heat high-entropy material at the PNS surface

⟶ Post-shock convection

- Dynamical deformation of the shock surface

⟶ Standing accretion shock instabilities (SASI)



Supernova neutrinos

Neutronization burst

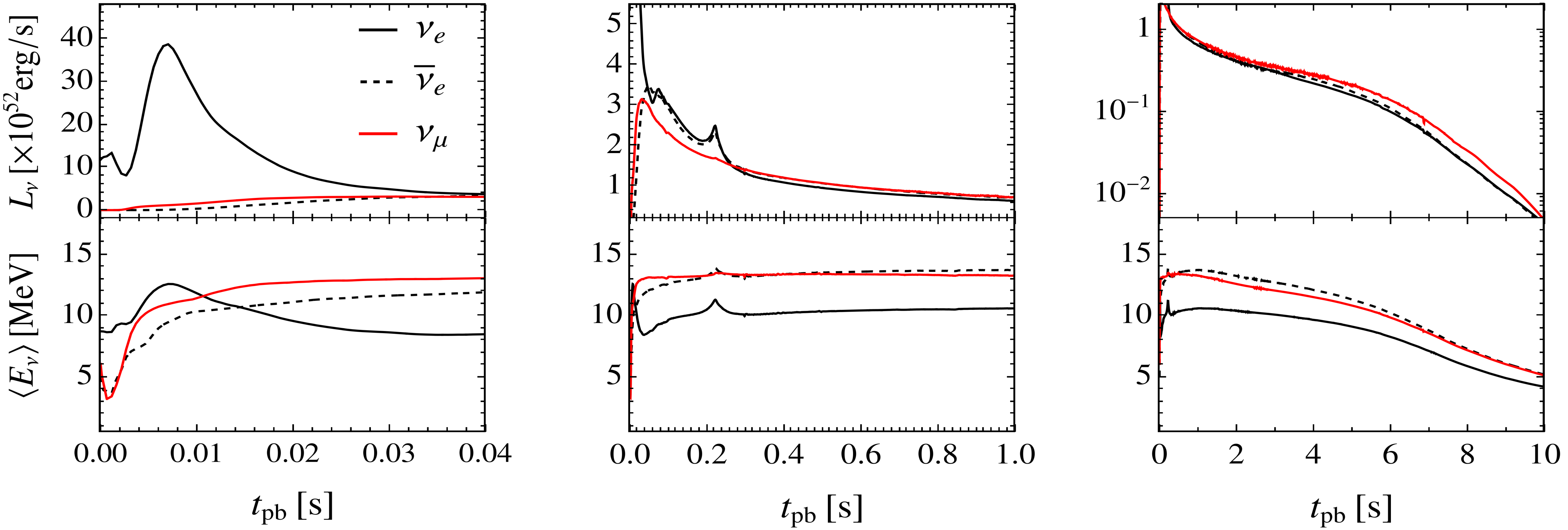
- Electron capture in the inner core

Accretion

- When shock stalls, ν powered by infalling matter

Cooling

- Cooling on ν diffusion time scale



https://www.mpa-garching.mpg.de/ccsnarchive//

ALP emission spectra

- If axions interact weakly with nuclear matter, they can *free-stream* through the SN volume

$$\frac{d^2 N_a}{dE_a\, dt} = \int_0^\infty 4\pi r^2 dr \frac{d^2 n_a}{dE_a\, dt}$$

- In case of strongly coupled axions, they could enter the *trapping regime* *[Caputo & al., Phys. Rev. D 105 (2022)]*

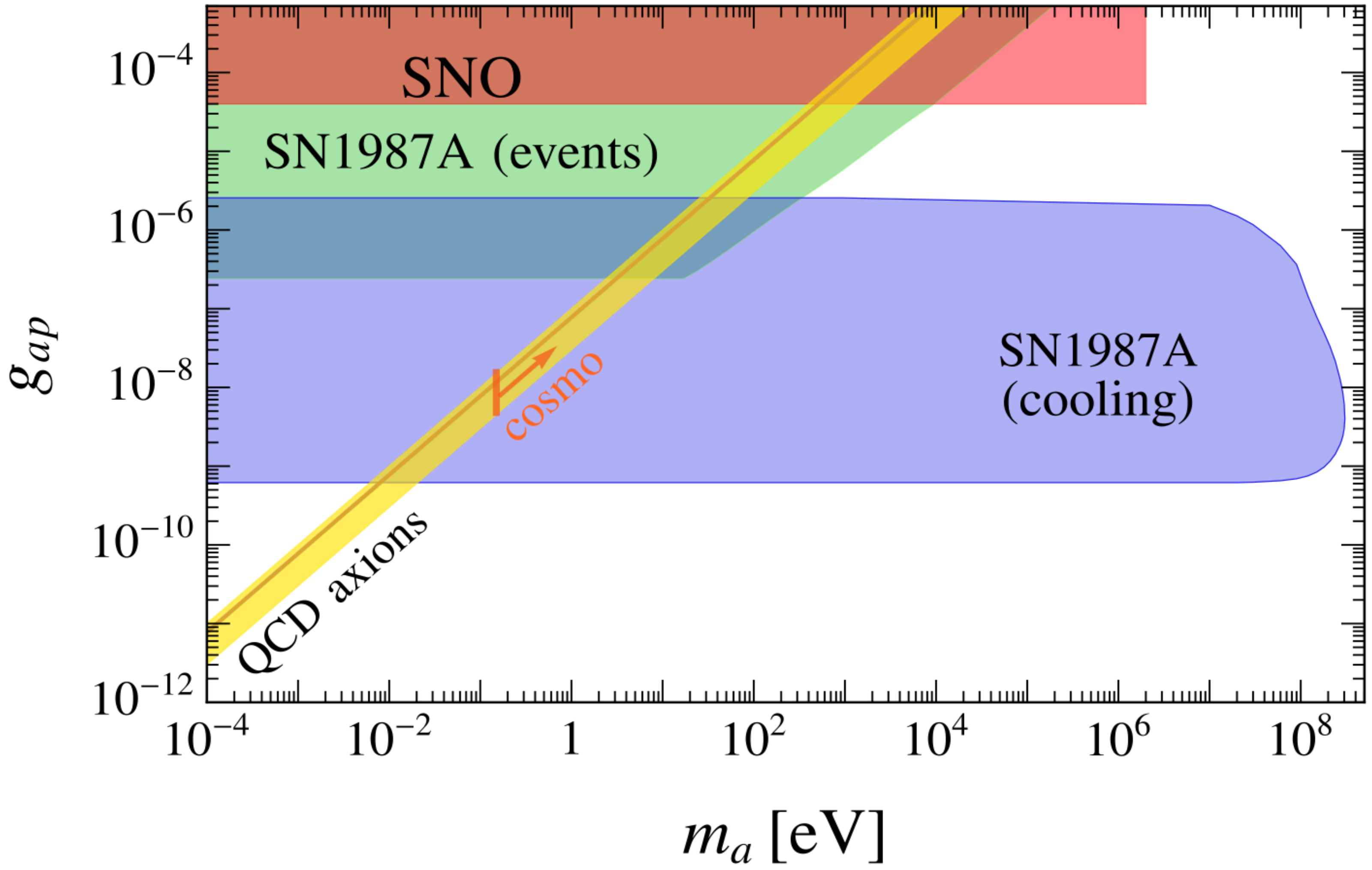
$$\frac{d^2 N_a}{dE_a\, dt} = \int_0^\infty 4\pi r^2 dr \left\langle e^{-\tau(E_a, r)} \right\rangle \frac{d^2 n_a}{dE_a\, dt}$$

$\tau \sim \int_0^\infty dr\, \lambda_a^{-1}$ optical depth for nuclear processes

Axion events from SN 1987A

No excess in the background of K-II around SN 1987A event ($\bar{n}_{bkg} \simeq 0.02$ events/s)

[Kamiokande Coll., Phys. Rev. Lett. 58 (1987) 1490].

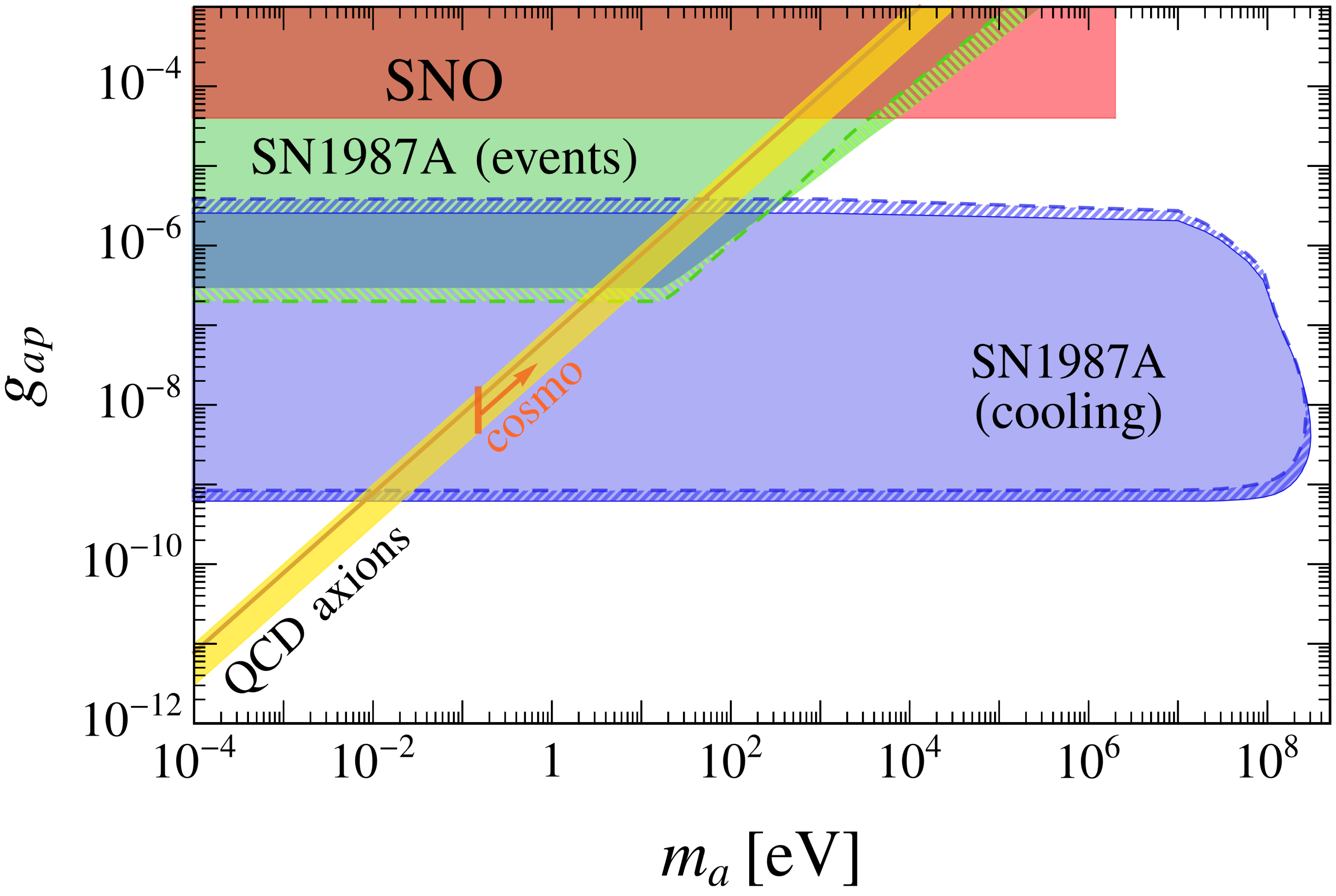


[AL & al., Phys. Rev. D 109 (2024) 2]

[P. Carenza, G. Co', M. Giannotti, AL, G. Lucente, A. Mirizzi, T. Rauscher, Phys. Rev. C 109 (2024) 1]

Uncertainties on SN bounds

Different SN models from same progenitors ($\sim 18\, M_\odot$) show different temperature and density profiles.



AGILE BOLTZTRAN

[Mezzacappa & al., Astrophys. J. 405 (1993) 669]
[Liebendoerfer & al., Astrophys. J. Suppl. 150 (2004) 263]

Similar impact over standard and new physics → Similar bounds

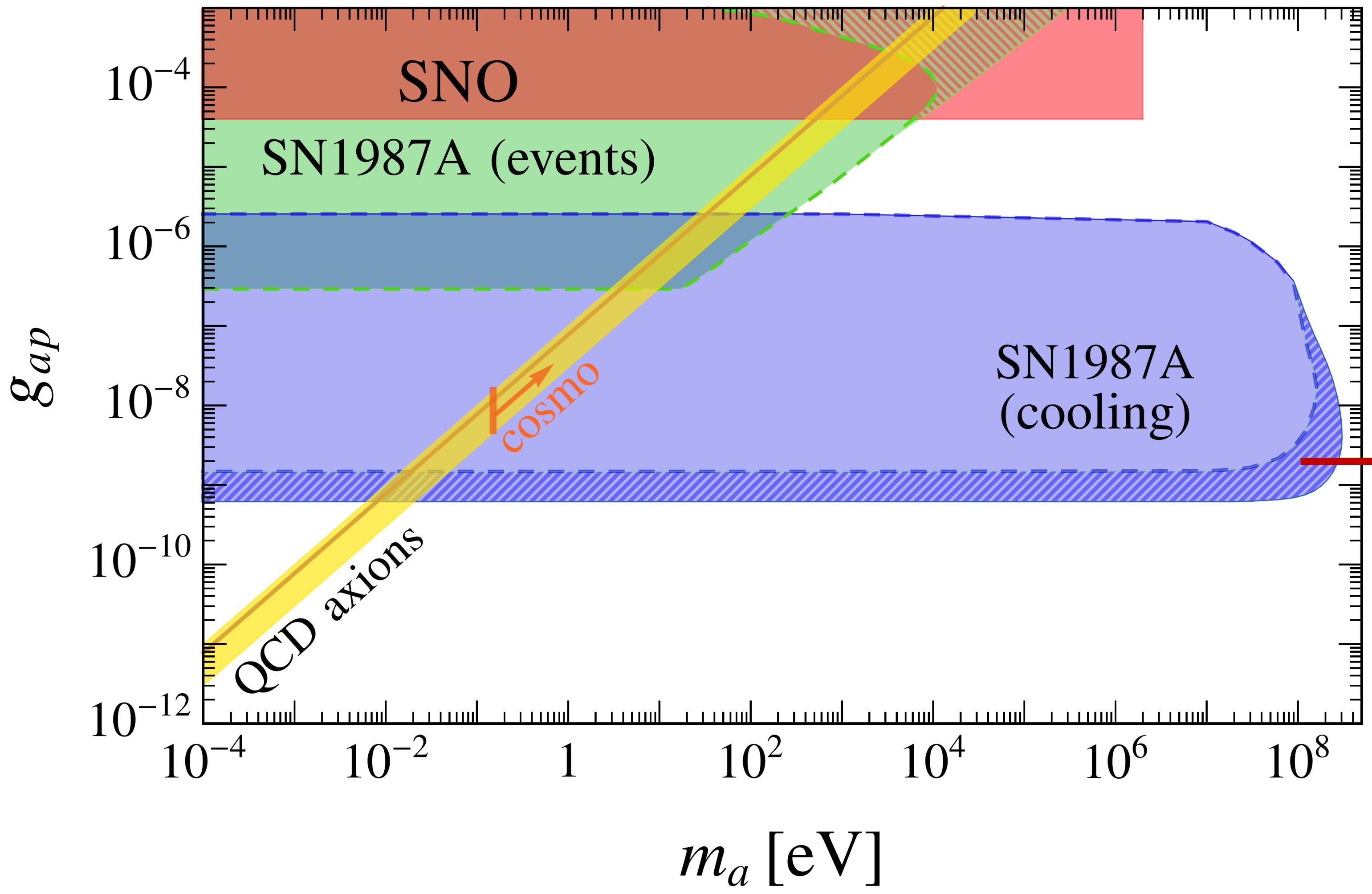
GARCHING

[Sukhobold & al., Astrophys. J. 860 (2018) 93]
[Rampp & Janka, Astron. Astrophys. 396 (2002) 361]

Uncertainties on SN bounds

Strong interactions can enhance the pion fraction in the SN core

[Fore & Reddy, Phys.Rev.C 101 (2020) 3]



Pions still not self-consistently included in SN simulations

[Fore & Reddy , Phys.Rev.C 110 (2024) 2]

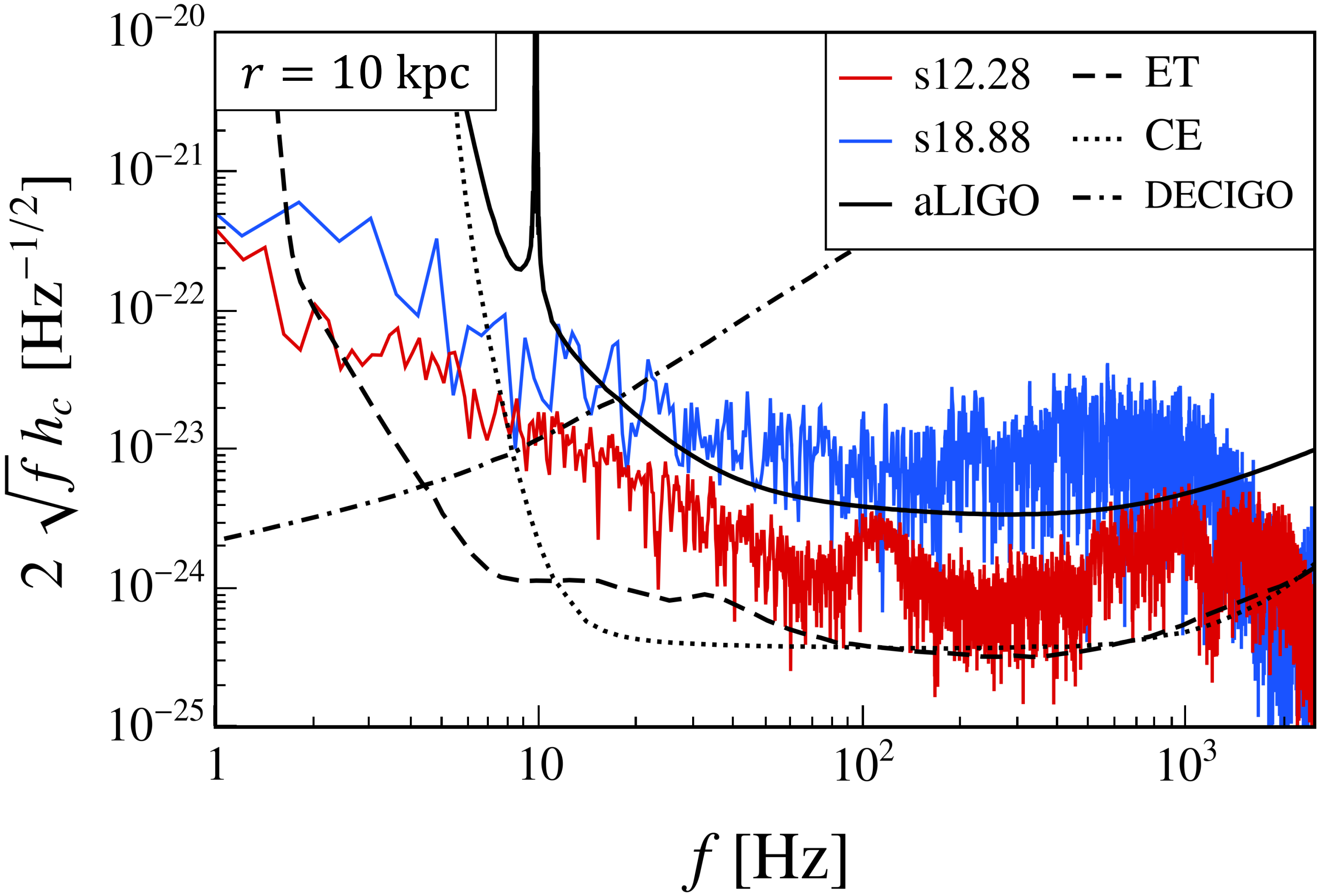
Without pions, cooling bound relaxes by a factor ~ 2

[Fiorillo et al., e-Print: 2509.13322 [hep-ph]]

Detection prospects for SN GWs

- Current detectors like aLIGO able to capture high-frequency modes.
- Future detectors as ET and CE able to detect both neutrino and matter GWs
- DECIGO able to capture the full memory components (Detection of SN events up to ~10-100 Mpc) *[Mukhopadhyay et al., Phys.Rev.D 106 (2022) 4]*

[AL & al., Phys. Rev. D 113 (2026) 8]



How to test fifth forces?

The emergence of a fifth interaction is predicted in many theories including a dark scalar sector, extra dimensions, etc... **But how to probe it?**

Putting … **to the test!**

PHYSICAL REVIEW LETTERS

VOLUME 56 6 JANUARY 1986

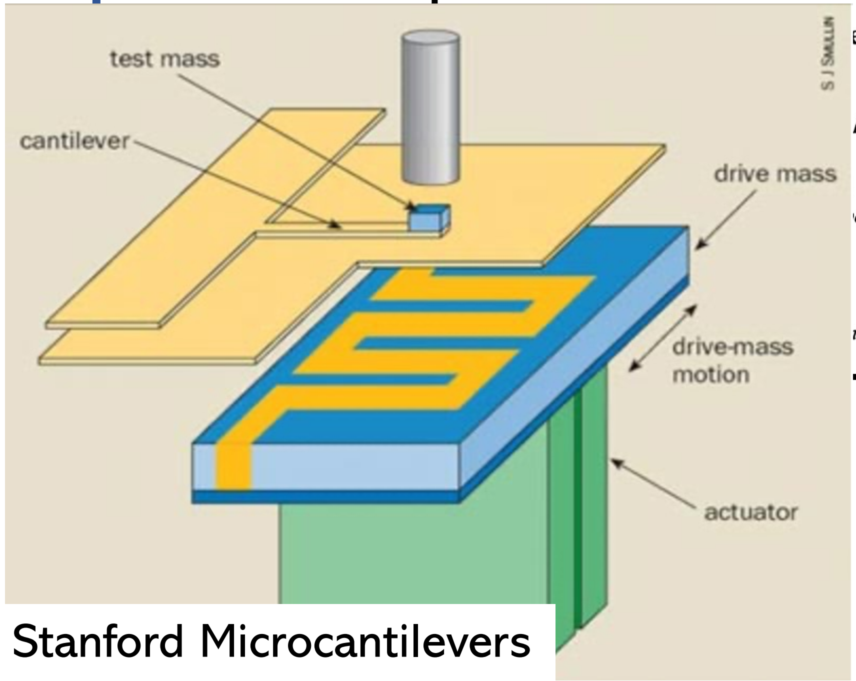
eanalysis of the Eötvös Experiment

Ephraim Fischbach[a]
Department of Physics, University of Washington, Seattle

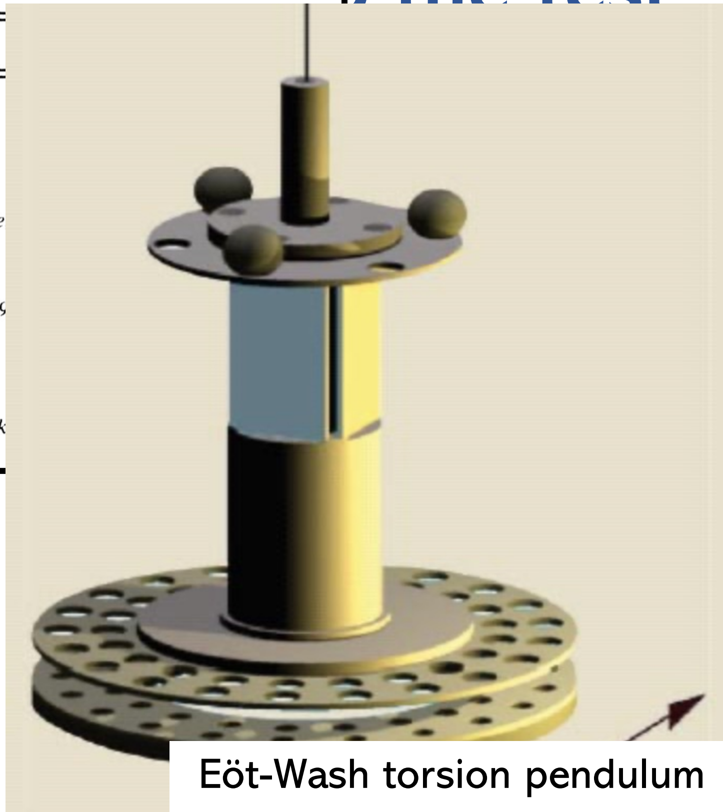
Sudarsky, Aaron Szafer, and Carrick Talmadge
artment, Purdue University, West Lafayette, Indiana 479

and

S. H. Aronson
ment, Brookhaven National Laboratory, Upton, New York
(Received 7 November 1985)

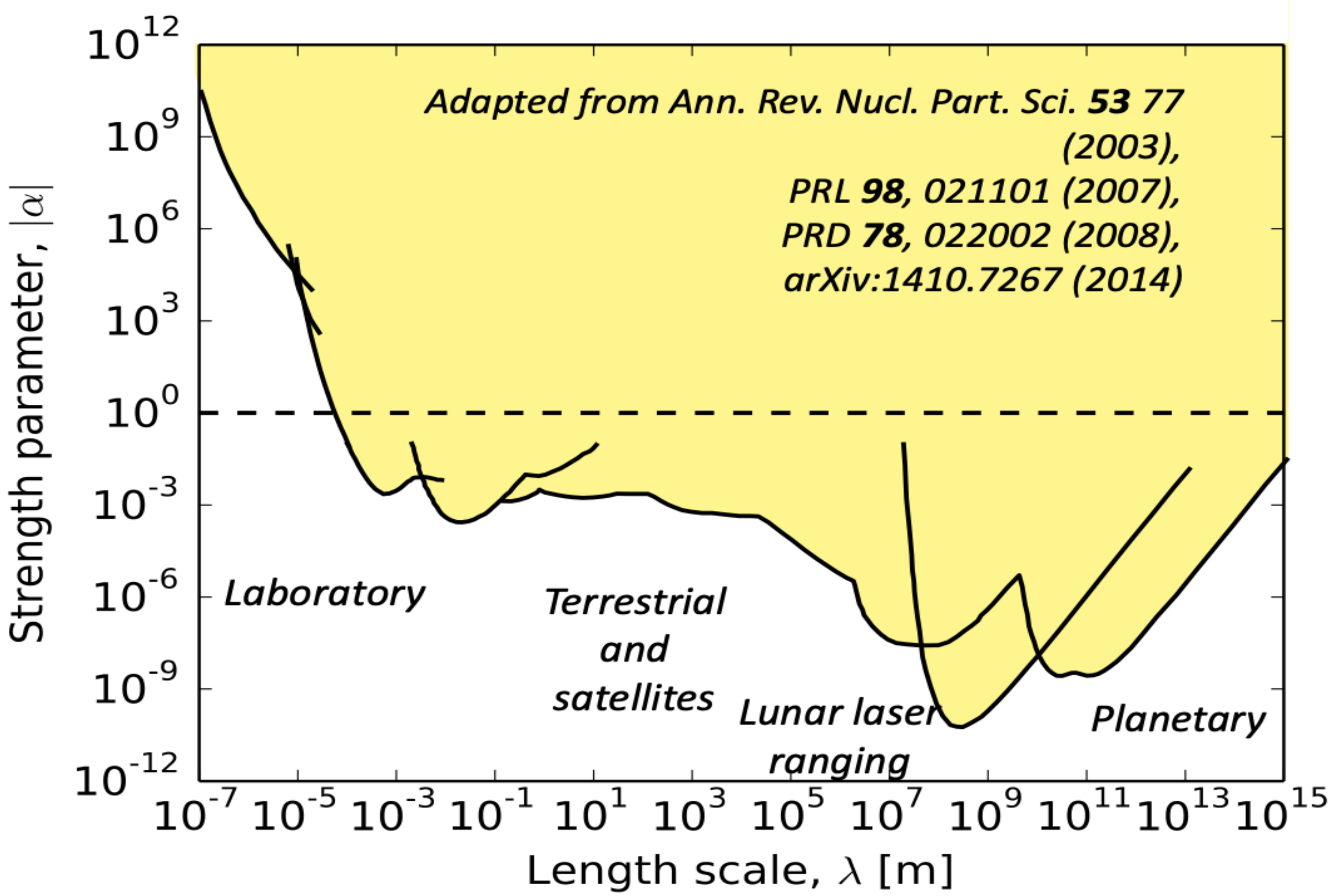


Stanford Microcantilevers


Eöt-Wash torsion pendulum

How to test fifth forces?

Laboratory and astrophysical tests of the inverse-square low rule out fifth forces even weaker than gravity and acting on scales $\lambda \gtrsim \mu\mathrm{m}$



Details on scalar emissivities

$$V(\mathbf{k}) = f + f'\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 + g\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + g'_{\mathbf{k}}\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2\,\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + h'_{\mathbf{k}}(\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{k}})(\boldsymbol{\sigma}_2 \cdot \hat{\mathbf{k}})\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$$

$$\{f, f', g, G\} = \frac{\pi^2}{2\, m_{\rm N}\, p_{\rm F}(n)}\{F_0, F_0', G_0, G_0'\}$$

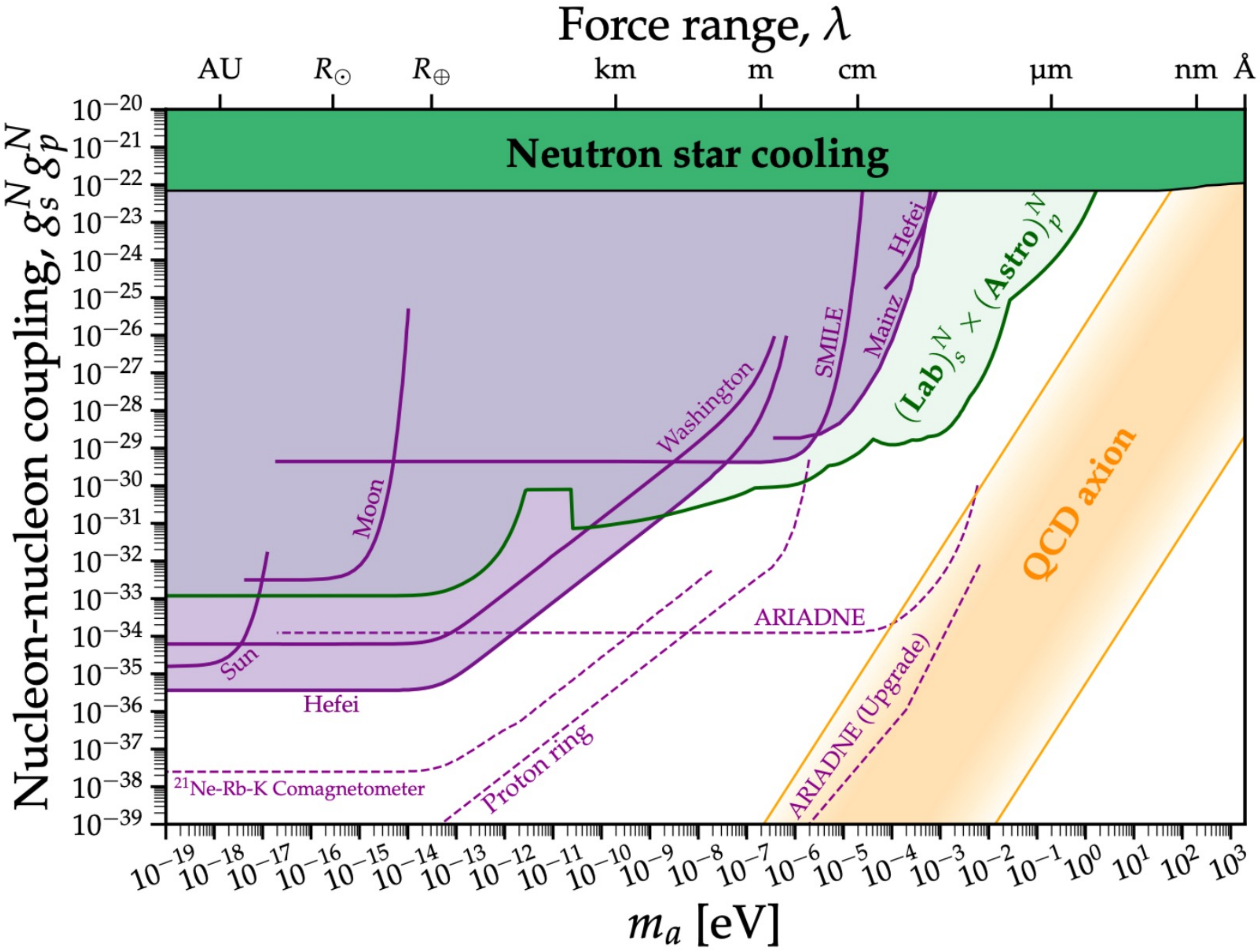
$$\frac{dN_s}{dtdVd\omega} = \frac{\omega|\mathbf{q}|}{2\pi^2}\prod_i \int \frac{d^3\mathbf{p}_i}{(2\pi)^3}\frac{1}{2\omega}(2\pi)^4\delta^3\left(\sum_i \mathbf{p}_i\right)\delta\left(\varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4 - \omega\right) S f_1 f_2 (1 - f_3)(1 - f_4)|\mathcal{M}|^2$$

$$\mathcal{N}_S = \frac{|\mathbf{q}|m_N(m_N T)^{7/2} J(\tilde{\omega})}{32\pi^8}\frac{4g_N^2 m_N^2 T^2}{15 m_N^4 \omega^2}\left[C_0 I_0 + \sum_{i=k,l}\sum_{\mu=\pi,\rho} C_\mu^i I_i(\alpha_\mu) + \sum_{i,j=k,l}\sum_{\mu,\nu=\pi,\rho} C_{\mu\nu}^{ij} I_{ij}(\alpha_\mu, \alpha_\nu)\right]$$

$$I_0 = \int \frac{d\tilde{k}d\tilde{l}}{\sqrt{4\tilde{p}_F^2 - \tilde{k}^2 - \tilde{l}^2}}\tilde{k}^2\tilde{l}^2,\; I_k(\alpha) = \int \frac{d\tilde{k}d\tilde{l}}{\sqrt{4\tilde{p}_F^2 - \tilde{k}^2 - \tilde{l}^2}}\tilde{k}^2\tilde{l}^2\frac{\tilde{k}^2}{(\tilde{k}^2 + \alpha)},\quad I_l(\alpha) = \int \frac{d\tilde{k}d\tilde{l}}{\sqrt{4\tilde{p}_F^2 - \tilde{k}^2 - \tilde{l}^2}}\tilde{k}^2\tilde{l}^2\frac{\tilde{l}^2}{(\tilde{l}^2 + \alpha)},\; I_{kk}(\alpha, \beta) = \int \frac{d\tilde{k}d\tilde{l}}{\sqrt{4\tilde{p}_F^2 - \tilde{k}^2 - \tilde{l}^2}}\tilde{k}^2\tilde{l}^2\frac{\tilde{k}^4}{(\tilde{k}^2 + \alpha)(\tilde{k}^2 + \beta)},$$

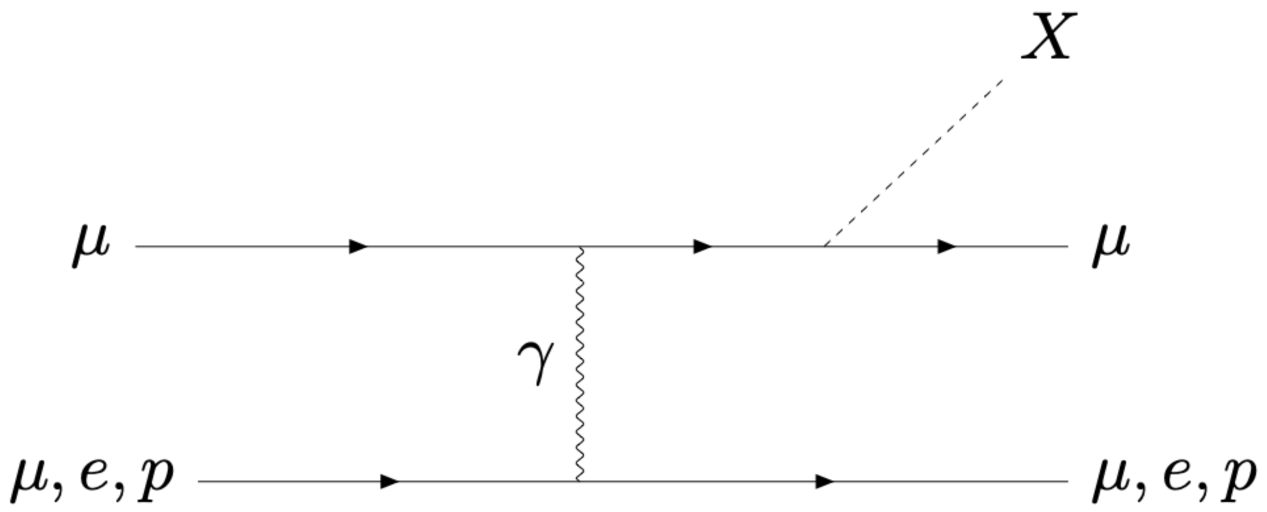
$$I_{ll}(\alpha, \beta) = \int \frac{d\tilde{k}d\tilde{l}}{\sqrt{4\tilde{p}_F^2 - \tilde{k}^2 - \tilde{l}^2}}\tilde{k}^2\tilde{l}^2\frac{\tilde{l}^4}{(\tilde{l}^2 + \alpha)(\tilde{l}^2 + \beta)}, I_{kl}(\alpha, \beta) = \int \frac{d\tilde{k}d\tilde{l}}{\sqrt{4\tilde{p}_F^2 - \tilde{k}^2 - \tilde{l}^2}}\tilde{k}^2\tilde{l}^2\frac{\tilde{k}^2\tilde{l}^2}{(\tilde{k}^2 + \alpha)(\tilde{l}^2 + \beta)}.$$

Limits on CP-violating axions



Muonic bosons from NSs

Muonic bosons are mainly emitted via bremsstrahlung of muons over charged particles



Strongly degenerate plasma of relativistic charged fermions

Treatment for electromagnetic interactions in the NS core medium is highly non-trivial

$$D^{\alpha\beta}(q) = \frac{P_{\rm T}^{\alpha\beta}}{Q^2 - \Pi_{\rm T}} + \frac{P_{\rm L}^{\alpha\beta}}{Q^2 - \Pi_{\rm L}}$$

- Electric currents are screened
- Magnetic currents are either screened (superconductive medium) or dumped

Muonic bosons from NSs

Scalars

$$Q_{\phi,0}^{(\mu)} = \frac{11\alpha^2 g_{\phi\mu}^2 m_\mu^2 T^4}{720\pi^2}\left[\frac{\pi^2}{3(1-\beta_\mu^2)^2}\left(\frac{2}{m_D}+\frac{\beta_\mu^4}{m_T}\right)-\left(\frac{K_0}{2m_D}-2\beta_\mu^2\frac{K_1}{m_D+m_T}+\beta_\mu^4\frac{K_2}{2m_T}\right)\right],$$

$$Q_{\phi,0}^{(X)} = \frac{11\alpha^2 g_{\phi\mu}^2 m_\mu^2 T^4}{2160(1-\beta_\mu^2)^2}\left(\frac{\varepsilon_X}{\varepsilon_\mu}\right)^2\left[\frac{2}{m_D}+\frac{\beta_\mu^2\beta_X^2}{m_T}\right].$$

Vectors

$$Q_V^{(X)} = \frac{11\alpha^2 \hat{g}_{V\mu}^2 \varepsilon_X^2 T^4}{720\pi^2}\left[\frac{M_0}{2m_D}+\frac{\beta_\mu^2\beta_X^2 M_2}{2m_T}-\frac{m_\mu^2}{\varepsilon_\mu^2}\left(\frac{J_0}{2m_D}+\frac{\beta_\mu^2\beta_X^2 J_2}{2m_T}\right)\right].$$

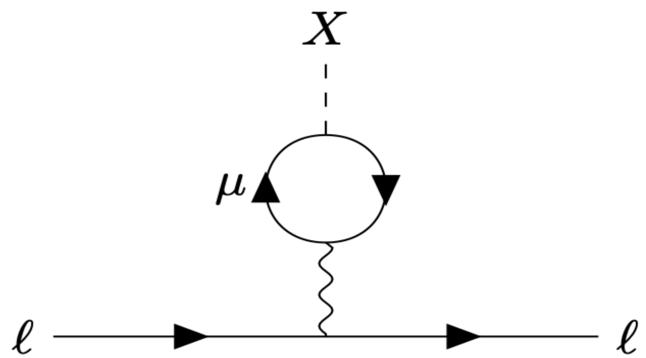
Pseudoscalars

$$Q_{a,0}^{(\mu)} = \frac{31\pi^2 g_{a\mu}^2\alpha^2 T^6}{1890(1-\beta_\mu^2)}\left[\frac{1}{2m_T}\left(2\beta_\mu^2-1+\frac{1-\beta_\mu^2}{\beta_\mu}\mathrm{ArcTanh}\,\beta_\mu\right)+\frac{1}{m_D}\left(\frac{1}{\beta_\mu^2}-\frac{1-\beta_\mu^2}{\beta_\mu^3}\mathrm{ArcTanh}\,\beta_\mu\right)\right],$$

$$Q_{a,0}^{(X)} = \frac{31\pi^2 g_{a\mu}^2\alpha^2 T^6}{1890(1-\beta_\mu^2)}\left(\frac{\varepsilon_X}{\varepsilon_\mu}\right)^2\left[\frac{1}{2m_T}\frac{\beta_e^2}{\beta_X^2}\left(2\beta_\mu^2-1+\frac{1-\beta_\mu^2}{\beta_\mu}\mathrm{ArcTanh}\,\beta_\mu\right)+\frac{1}{m_D}\left(\frac{1}{\beta_\mu^2}-\frac{1-\beta_\mu^2}{\beta_\mu^3}\mathrm{ArcTanh}\,\beta_\mu\right)\right],$$

Muonic bosons from NSs

In-medium renormalization of the coupling required



- Vectors got an effective electron coupling $\hat{g}_{Ve} \sim 0.3 g_{V\mu}$

$$\hat{g}_{Ve} = -g_{V\mu} \frac{\Pi_{\mathrm{T},\mu}}{\Pi_{\mathrm{T},\mu} + \Pi_{\mathrm{T},e}} \,.$$

- For scalars, corrections at the order of ~5%

$$\mathcal{M} = g_{\phi\mu} - 2e^2\gamma^0 \frac{\sum_j g_{\phi j} m_j^* \xi_j}{\Omega^2 - \sum_k \frac{\omega_{\mathrm{P},k}^2}{1-\beta_k^2}\left[1 - G\left(\beta_k^2\right)\right]} \,.$$