
Credit: ESO (eso0708a)

Axion-sourced fireballs from compact objects

YOUNGST@RS - Interacting dark sectors in astrophysics, cosmology, and the lab
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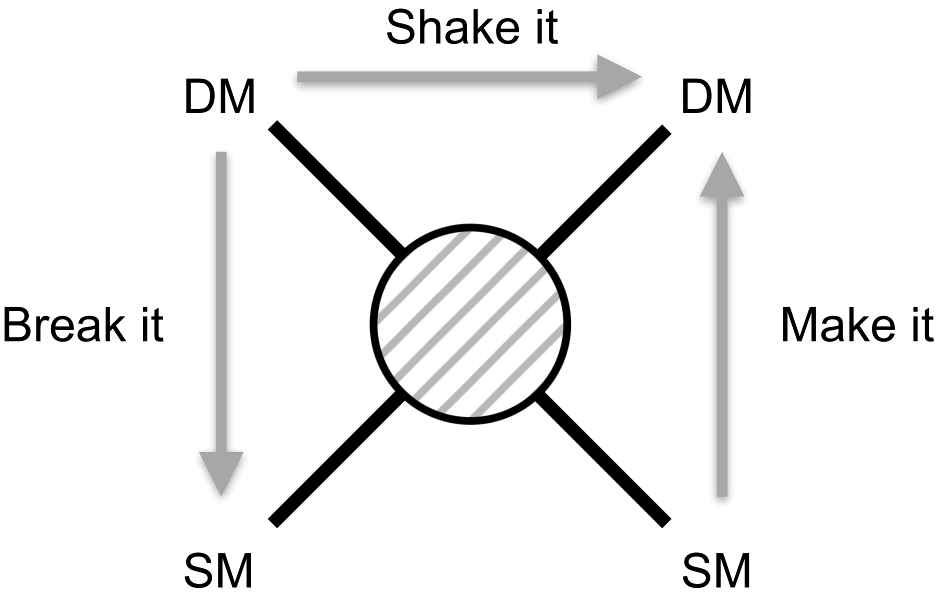
Based on work with M.Diamond, D.Fiorillo, G.Marques-Tavares, I.Tamborra

Motivations for heavy axions

The WIMP paradigm



Shake it

DM

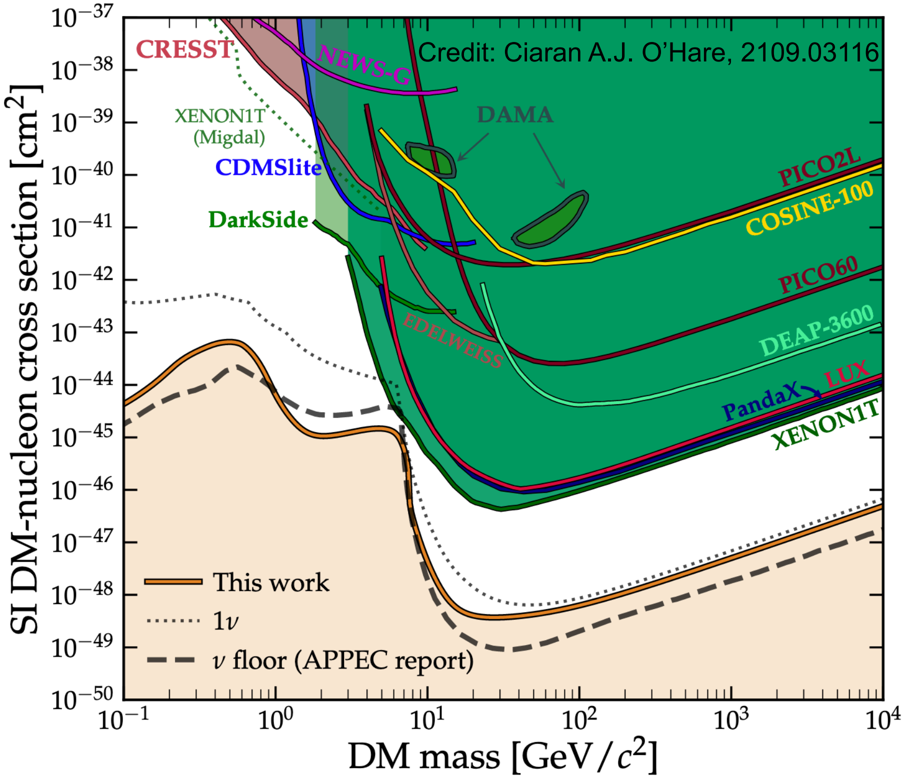
DM

Break it

Make it

SM

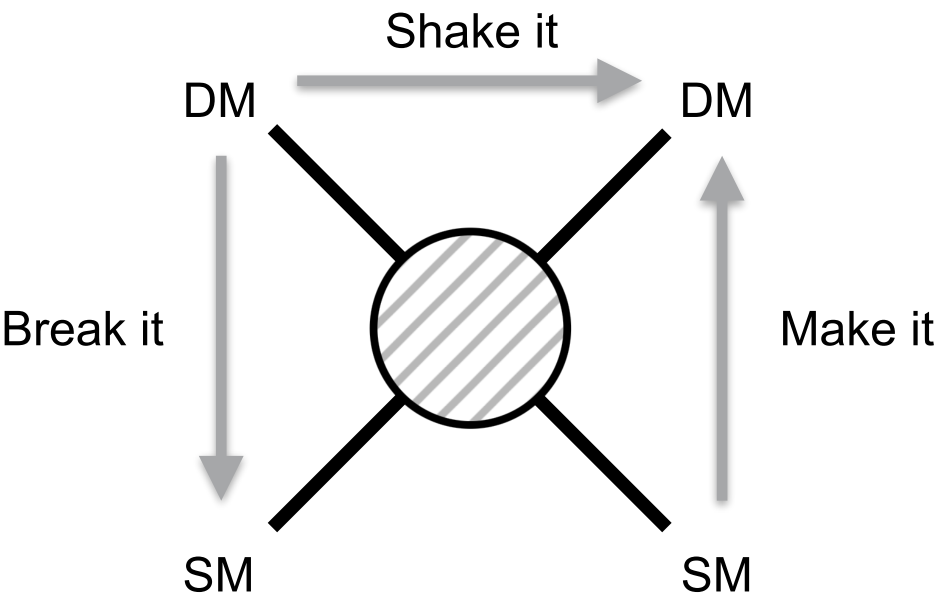
SM

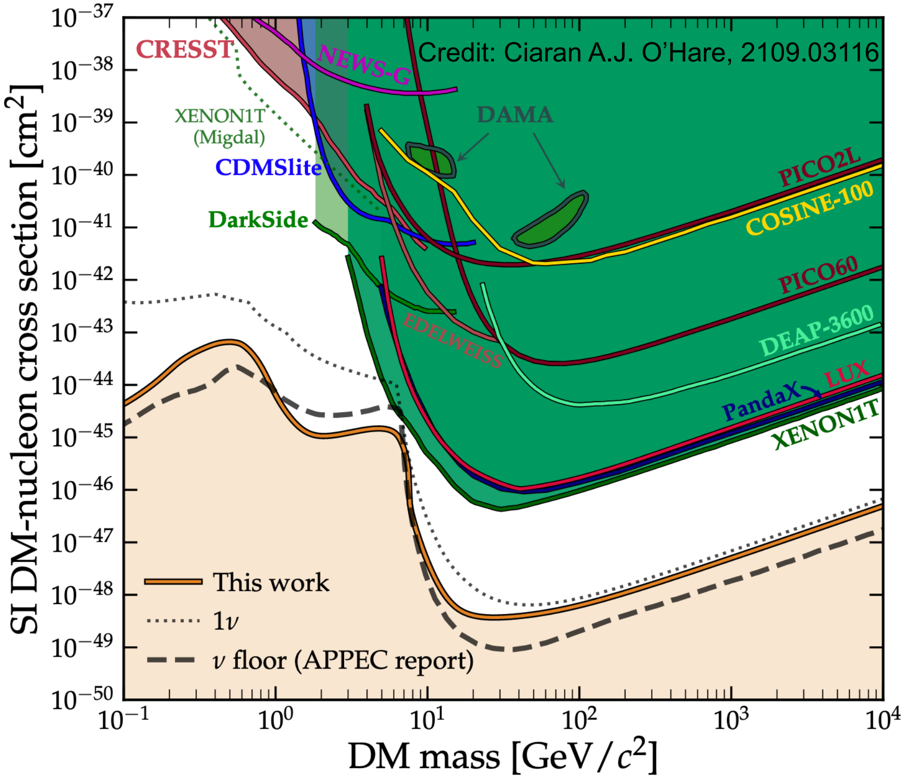

Credit: Ciaran A.J. O'Hare, 2109.03116

Improvement in sensitivity in shake-it searches faster than Moore's law from '80s to '00s

Where is the DM?

The WIMP paradigm




Credit: Ciaran A.J. O'Hare, 2109.03116

Improvement in sensitivity in shake-it searches faster than Moore's law from '80s to '00s

Where is the DM?

How about searching under different lampposts?

Beyond the WIMP paradigm

According to the Snowmass proceeding, different directions to go:

- Ultralight DM (sub-keV)
- Light DM (keV-GeV)
- WIMPzilla, PBHs…

Beyond the WIMP paradigm

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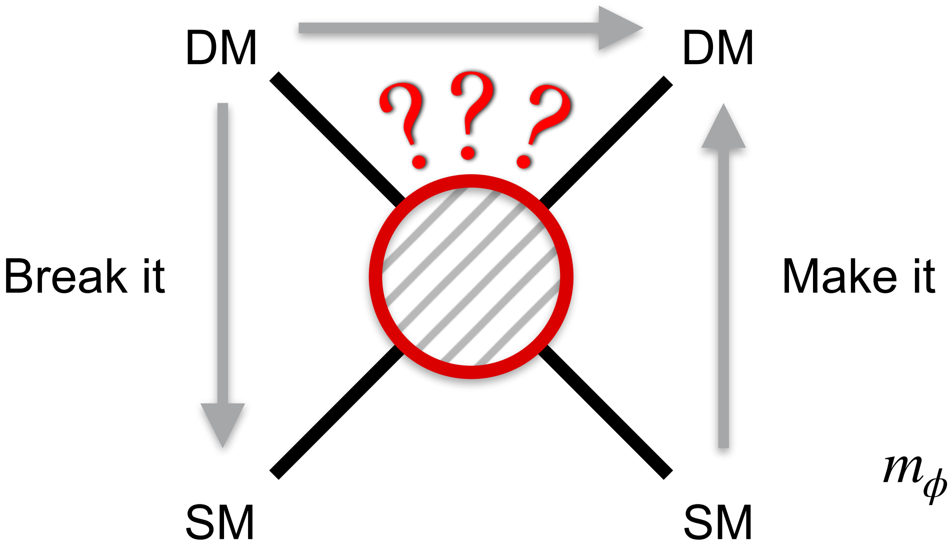
What about mediators ϕ of heavier DM?



$$\sim \left[\frac{1}{p^2 - m_\phi^2}\right]^2$$

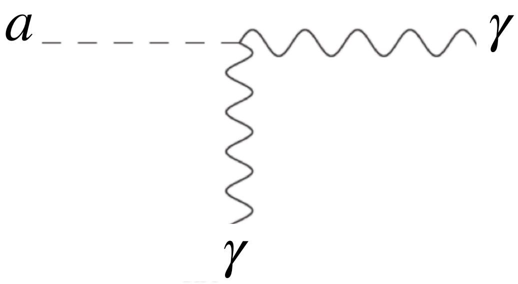
$m_\phi \gg 1\,\mathrm{GeV}$ colliders very constraining.

What about light mediators?

Beyond the WIMP paradigm

3 examples of detection possibilities for lightish feebly interacting particles

- Long range interactions ($m_\phi \lesssim 1\,\mathrm{eV}$)
- Oscillations (e.g. dark photons with a coupling $\epsilon F F^{\mathrm{Dark}}$)
- Decay e.g. $\mathscr{L}_{\mathrm{I}} \sim \frac{1}{4} G_{a\gamma} a F \tilde{F}$



Call it an axion, might be a QCD axion with some imagination

Hook et al. *Phys.Rev.Lett.* 124 (2020) 22, 221801

Lifetime: d5 operator, $\Gamma = \underbrace{G_{a\gamma}^2 m_a^3}_{\text{Dimensional analysis}} \underbrace{\frac{1}{64\pi}}_{\text{Phase Space}} \underbrace{\frac{m_a}{\omega}}_{\text{Lorentz Factor}}$

In other words: we can solve the strong CP problem and have the portal between DM and SM at the same time with a heavy axion

How to constrain heavy axions

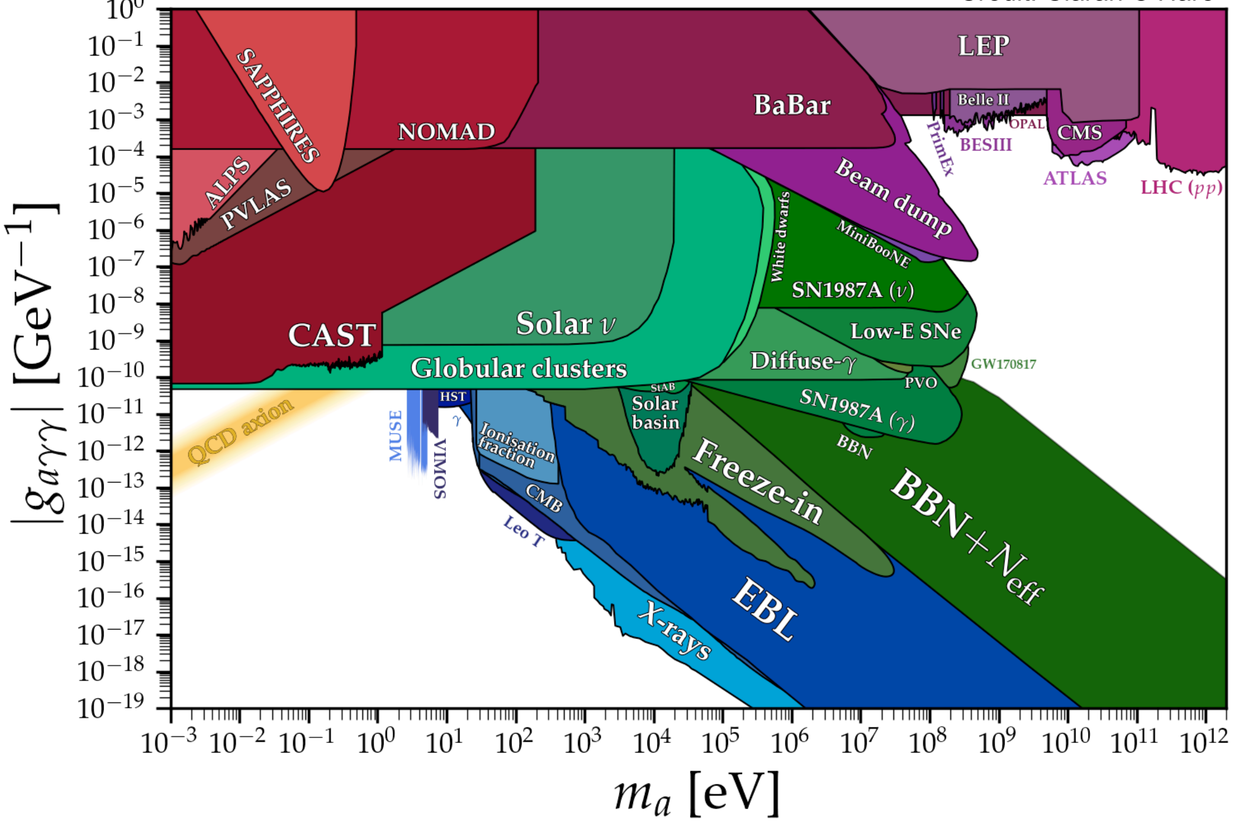
Axions with photon coupling

Searching for heavy axions:

- Beam dumps
- Astrophysical transients
- Cosmology—goes away for low T_{RH}

(see Langhoff, Outmezguine, Rodd *Phys.Rev.Lett.* 129 (2022) 24, 241101)

Credit: Ciaran O'Hare



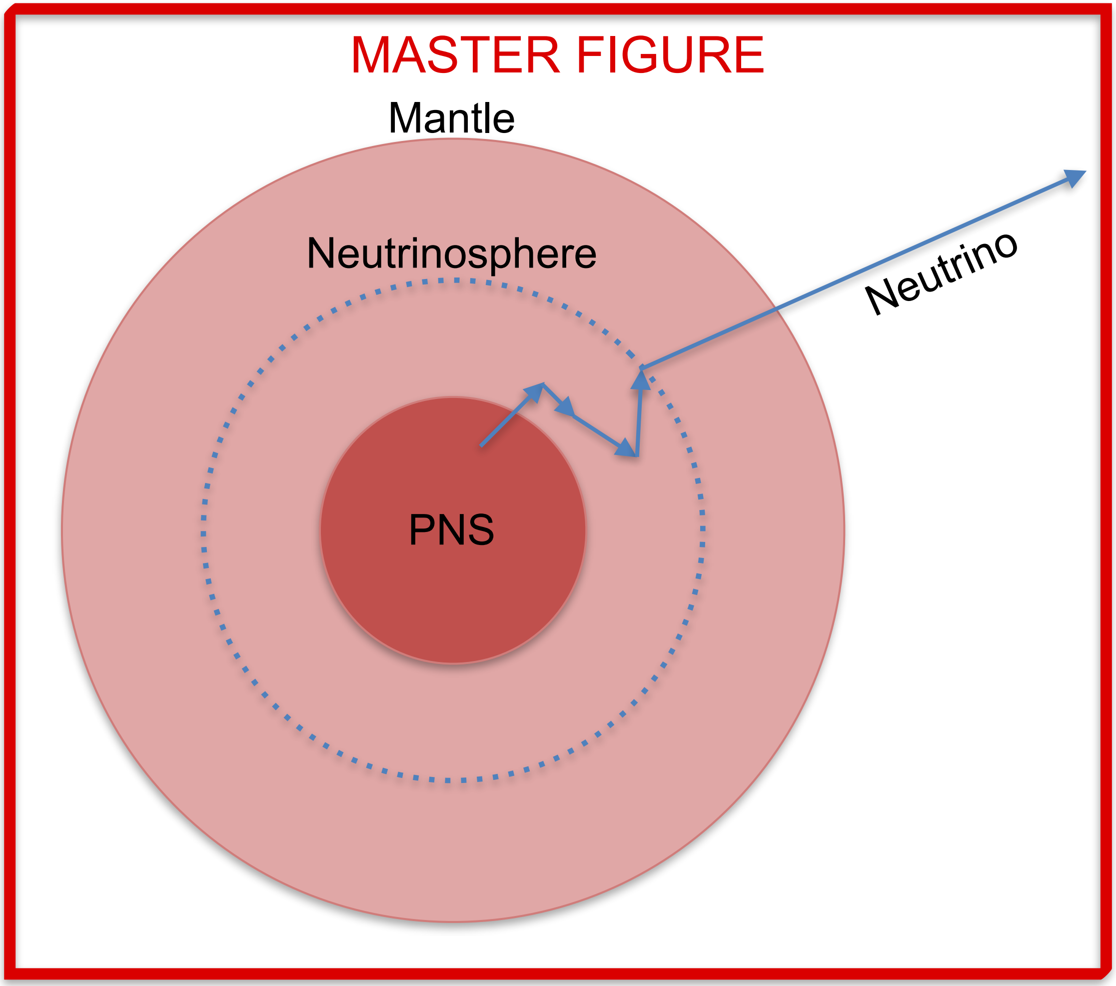
Stellar collapse

Protoneutron star, it has

- $T = \mathcal{O}(100\,\mathrm{MeV})$ in the core, $T = \mathcal{O}(10\,\mathrm{MeV})$ at the surface
- $\rho = 3 \times 10^{14}\mathrm{g/cm}^3$
- $R_{\mathrm{PNS}} = 20\,\mathrm{km}$
- $R_{\mathrm{Mantle}} \gtrsim 10^7\,\mathrm{km}$

And produce many neutrinos,

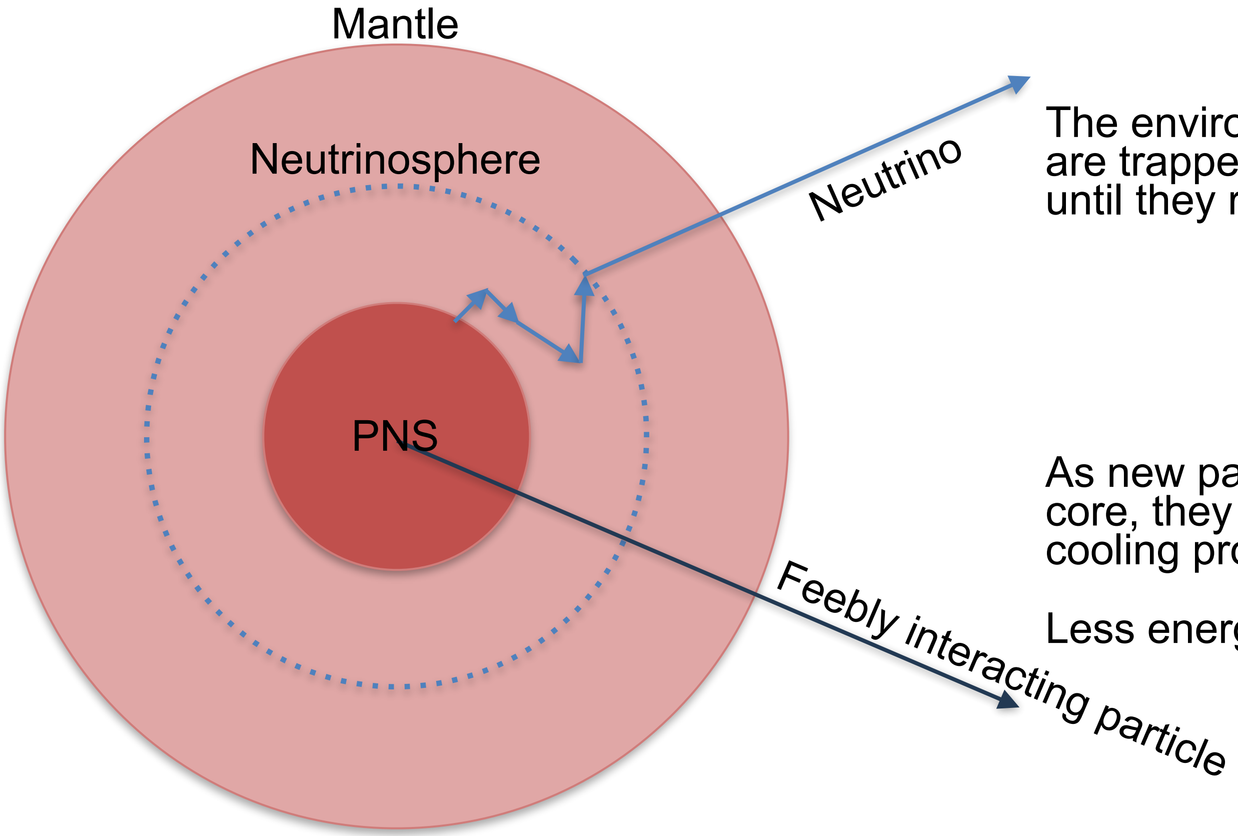
- $L_\nu = 3 \times 10^{53}\mathrm{erg/3s}$
- Energy deposited: 1%



(Analogous to photons in the Sun)

Raffelt bound (SN 1987A cooling)

The existence of a feebly interacting particle can affect the duration of the neutrino signal of a supernova



The environment is so dense neutrinos are trapped and cannot escape freely, until they reach the neutrinosphere

As new particles are produced in the core, they take away energy from the cooling proto-neutron star

Less energy available to neutrinos!

Raffelt bound (SN 1987A cooling)

- The emission of new particles affect the cooling time of the protoneutron star
- Several papers in the 1980s (1D simulations with an energy sink) found the relative cooling time (right figure, axion-nucleon coupling). **Observable: duration of the neutrino signal at IMB and KII**
- All simulations on a common footing: new particle emission should not exceed $\epsilon_a = 10^{19} \mathrm{erg\,g^{-1} s^{-1}}$, or in terms of the total energy

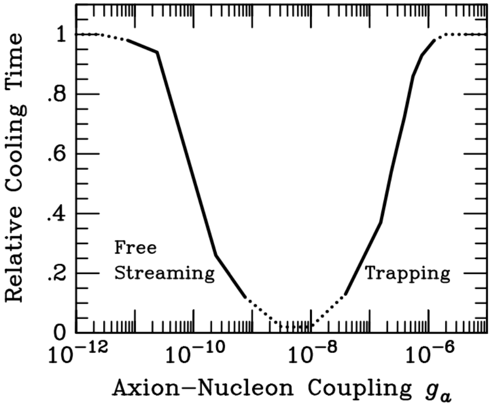


Fig. 13.1. Relative duration of neutrino cooling of a SN core as a function of the axion-nucleon Yukawa coupling g_a. In the free-streaming limit axions are emitted from the entire volume of the protoneutron star, in the trapping limit from the “axion sphere” at about unit optical depth. The solid line is according to the numerical cooling calculations (case B) of Burrows, Turner, and Brinkmann (1989) and Burrows, Ressell, and Turner (1990); the dotted line is an arbitrary completion of the curve to guide the eye. The signal duration is measured by the quantity $\Delta t_{90\%}$ discussed in the text; an average for the IMB and Kamiokande detectors was taken.

Raffelt (1994)

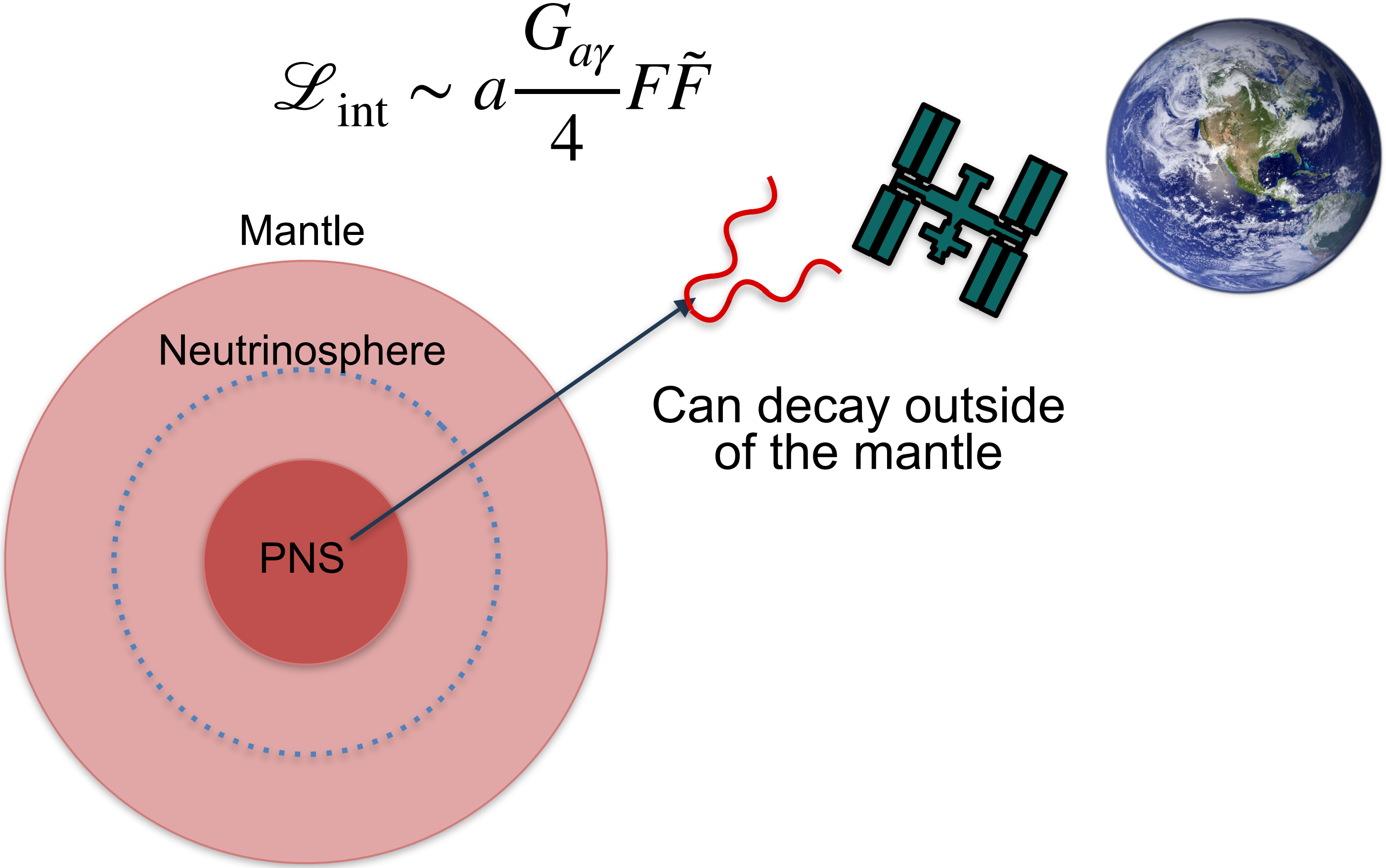
$$L_\phi \lesssim L_\nu(1\mathrm{s}) = 3 \times 10^{52}\,\mathrm{erg\,s^{-1}}$$

Computed at $T = 30\,\mathrm{MeV}$ and $\rho = 3 \times 10^{14}\,\mathrm{g\,cm^{-3}}$

Look for different observables

Supernovae (and other transients) are far (a long baseline for **conversion** or **decay**) and **hot/dense** (they can produce **heavy feebly interacting particles**)

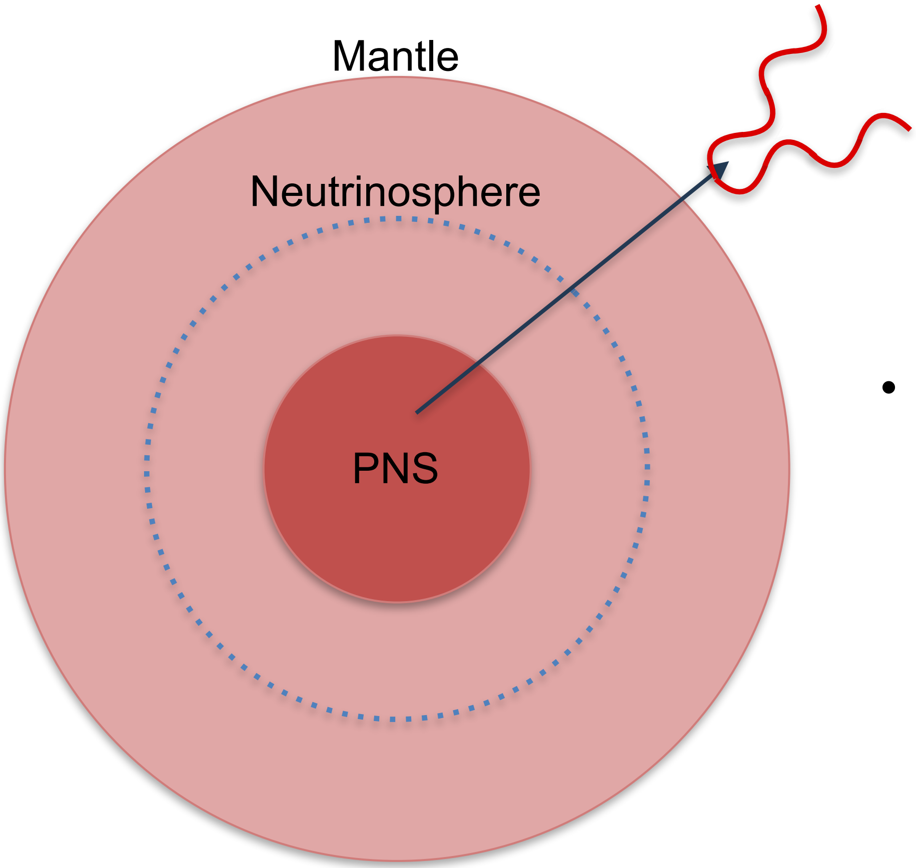
$$\mathscr{L}_{\text{int}} \sim a\frac{G_{a\gamma}}{4}F\tilde{F}$$



Can decay outside of the mantle

Look for different observables

Supernovae (and other transients) are far (a long baseline for **conversion** or **decay**) and **hot/dense** (they can produce **heavy feebly interacting particles**)



- **Gamma-ray decay** observed by the Gamma-Ray Spectrometer (GRS) on board the Solar Maximum Mission (SMM) satellite that operated 02/1980–12/1989

Oberauer et al. *Astropart.Phys.* 1 (1993) 377-386
Chupp et al. *Phys.Rev.Lett.* 62 (1989) 505-508
Jaeckel et al., *Phys.Rev.D* 98 (2018) 5, 055032
Caputo, Raffelt, **Vitagliano**, *Phys.Rev.D* 105 (2022) 3, 035022
Hoof and Schulz (2022)

- They also create a **diffuse** from all the SNe in the history of the universe

Calore et al. *Phys. Rev. D* 102 (2020) 123005
Caputo, Raffelt, **Vitagliano**, *Phys.Rev.D* 105 (2022) 3, 035022

Gamma rays from SN 1987A

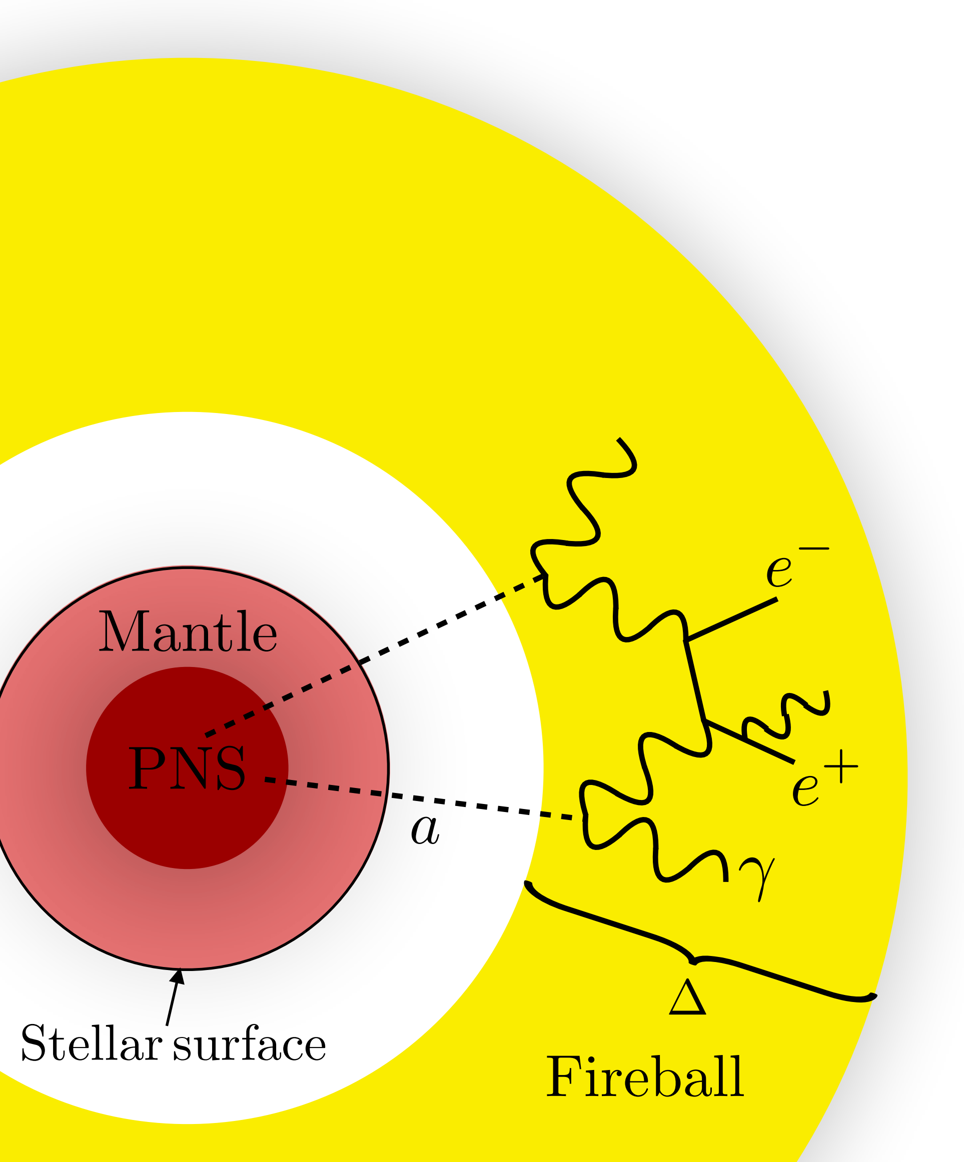
- If particles decay outside of the mantle [$\Gamma \lesssim (c/R_{\rm mantle})$] bounds from the Solar Maximum Mission at SN 1987A **could** apply
- They were looking for $25 - 100\,{\rm MeV}$ photons, fluence of $\dfrac{dN}{dA} \lesssim 1\,{\rm cm}^{-2}$
- For couplings at the Raffelt bound, $10^{53}\,{\rm erg},\, 15\,{\rm MeV},\, {\rm distance}\; 50\,{\rm kpc},$

$$\frac{dN}{dA} \simeq 10^{10}\,{\rm cm}^{-2}$$

Are we sure it applies?

Axion-sourced fireballs

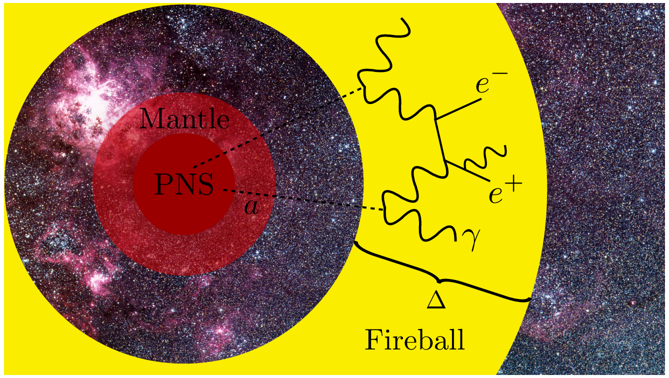
Axion-sourced fireballs



- Consider ALPs with a coupling to photons $a\tilde{F}F$
- They are produced in the hot and dense core of proton-neutron stars through coalescence and Primakoff effect with energies $E \simeq 100\,\mathrm{MeV}$
- The ALPs decay back to photons outside
- Daughter photons interact with each other, **unavoidably** creating a fireball
- Photons will eventually have energy $E \lesssim 1\,\mathrm{MeV}$
- We can detect these photons with X-ray telescopes

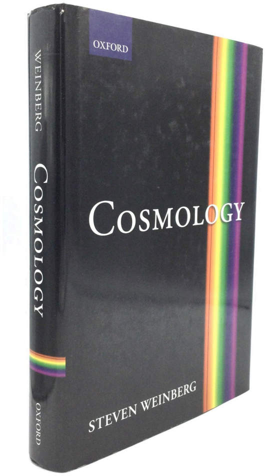
Axion-sourced fireballs

Let us consider the axion frame. They decay isotropically. In the lab-frame, they are boosted, but NOT to c.



There are therefore 3 phases in the evolution of the fireball:

- Decay of axions into photons
- Onset of photons thermalization/Evolution towards equilibrium of the electron-positron pairs and photon plasma
- Decoupling of the products (the density reduces as the fireball gets farther from the source)



Similar to cosmology!

- Decay of heavy relics to SM particles
- Evolution towards equilibrium
- Decoupling of the products (Hubble expansion eventually dominates over the interaction rate)

Relativistic fluid dynamics

Anticipating fireballs are characterized by many interactions among the particles, we use fluid dynamics of a perfect fluid ($p = \rho/3$)

$\partial_\mu T^{\mu\nu} = 0$ where $T^{\mu\nu}$ is the stress-energy tensor

Which reduce to 2 equations in spherical symmetry: momentum and energy conservation

There are 3 quantities to be determined: temperature T, chemical potential μ_γ, and Lorentz boost of the plasma γ

The additional equation is

$$\partial_\mu N^\mu = 0$$

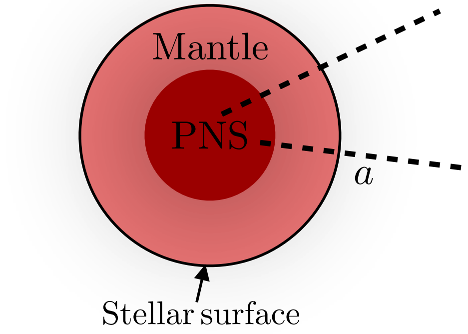
When number-changing processes are slow

$$\Gamma(ee \to ee\gamma) = \Gamma(ee\gamma \to ee)$$

When number-changing processes are fast

3 equations, 3 variables!

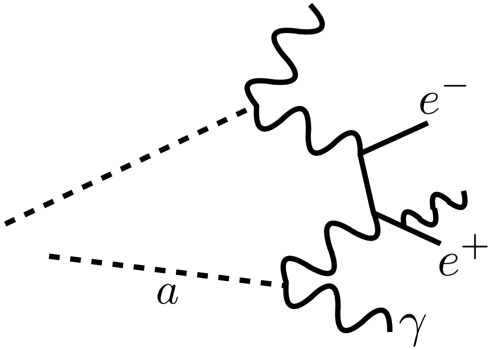
Thermalization



From axion production in the core…

$$\frac{dN_a}{d\omega_a} = \frac{1}{2\pi^2}\int dV\,dt\,\frac{1}{e^{\omega_a/T}-1}$$
$$\times\left(\Gamma_{\rm P}\omega_a\sqrt{\omega_a^2-\omega_{\rm P}^2}+\Gamma_{\rm c}\omega_a\sqrt{\omega_a^2-m_a^2}\right)$$

Primakoff production Coalescence



…to photons outside…

$$\frac{dN_\gamma^i}{d\omega_\gamma} = 2\int_{\omega_\gamma}^{\infty}\frac{dN_a}{d\omega_a}\frac{d\omega_a}{\omega_a}$$

…which have a density in the lab-frame

$$n_0' = 2\mathcal{N}/4\pi r^2\Delta$$

Thermalization

First condition for thermalization: produce $e^{\pm}$

$$n_0' \sigma_{\gamma\gamma\to e^+e^-} \Delta \gg 1 \qquad \sigma_{\gamma\gamma\to e^+e^-} = \frac{\pi\alpha^2}{E_\gamma^2}$$

(Akin to $\Gamma > H$ in cosmology)

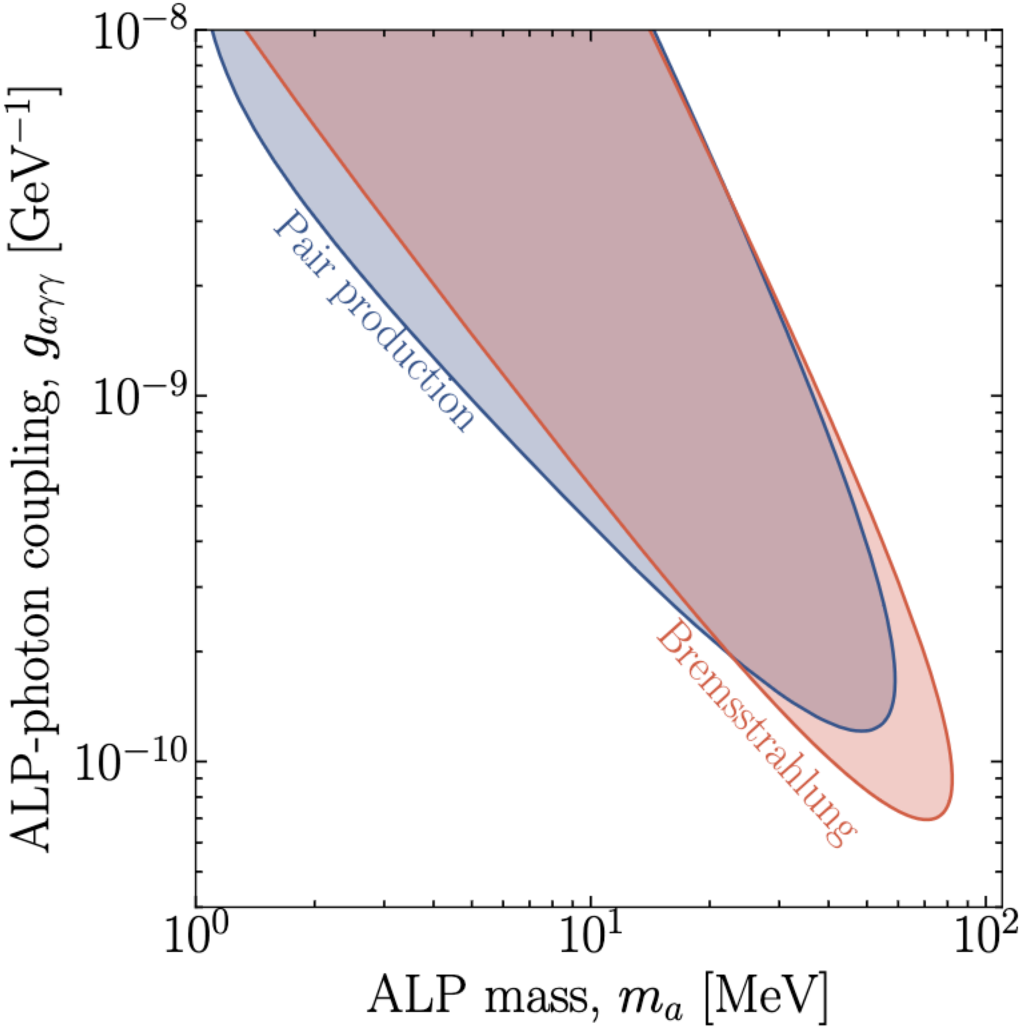
Second condition for thermalization: number changing processes

$$\gamma n_e(T_\gamma, \mu_\gamma) v_{\rm th} \sigma_{ee\to ee\gamma} \Delta = 1$$

Lorentz factor of the fireball Electron density Thermal velocity Bremsstrahlung cross section

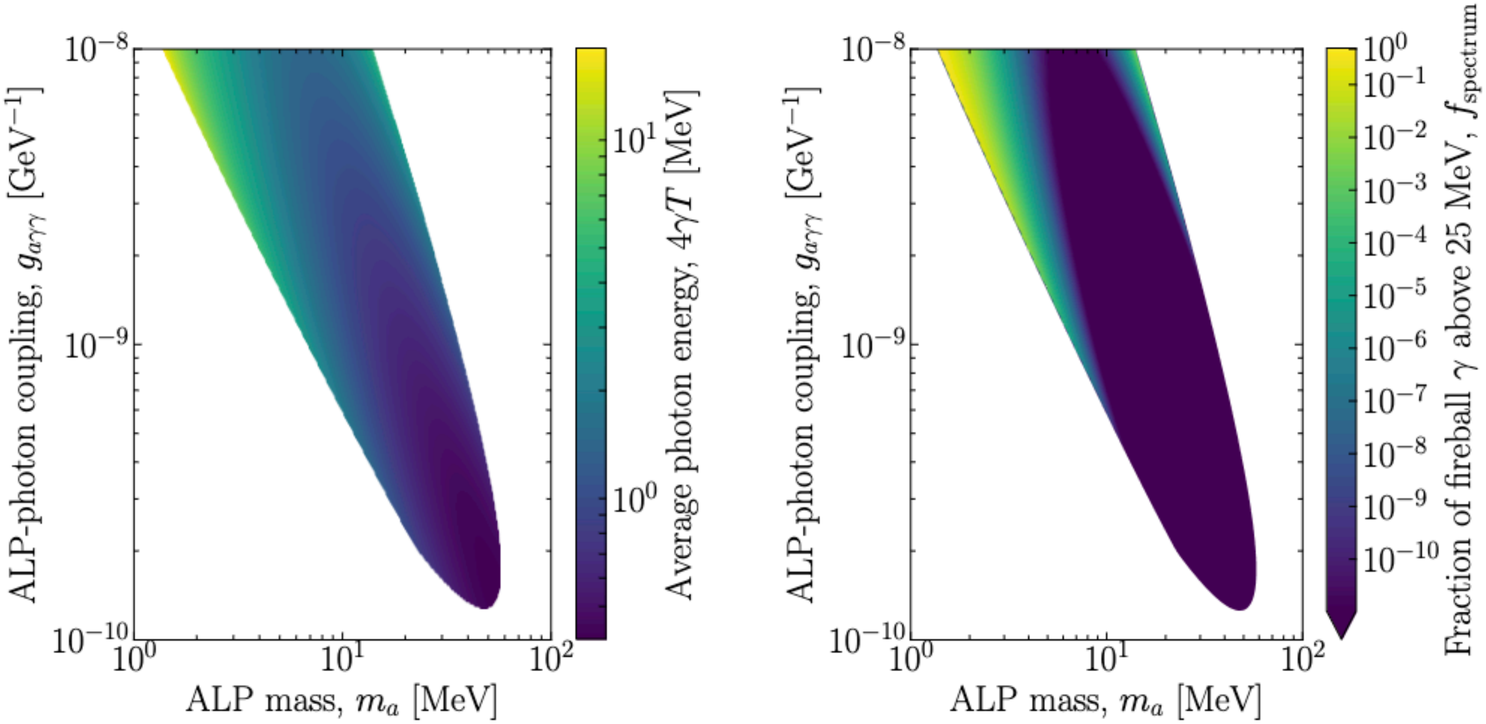
(NB at some point pair annihilation become relevant)

Thermalization



Decoupling

After decoupling, the average energy in the lab-frame is $4\gamma T$



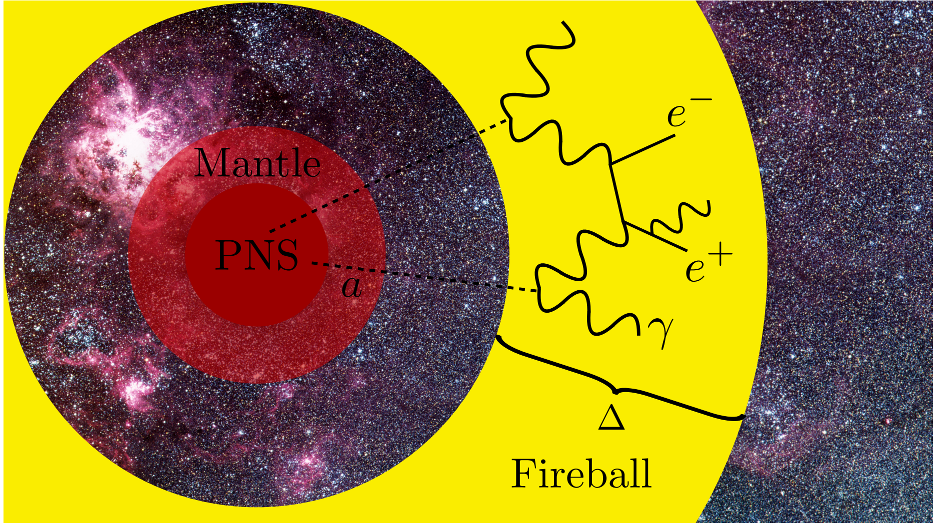
The energy of the photons is now out of SMM window used in gamma-ray searches ($\gtrsim 25\,\mathrm{MeV}$)

Revisited gamma-ray bounds

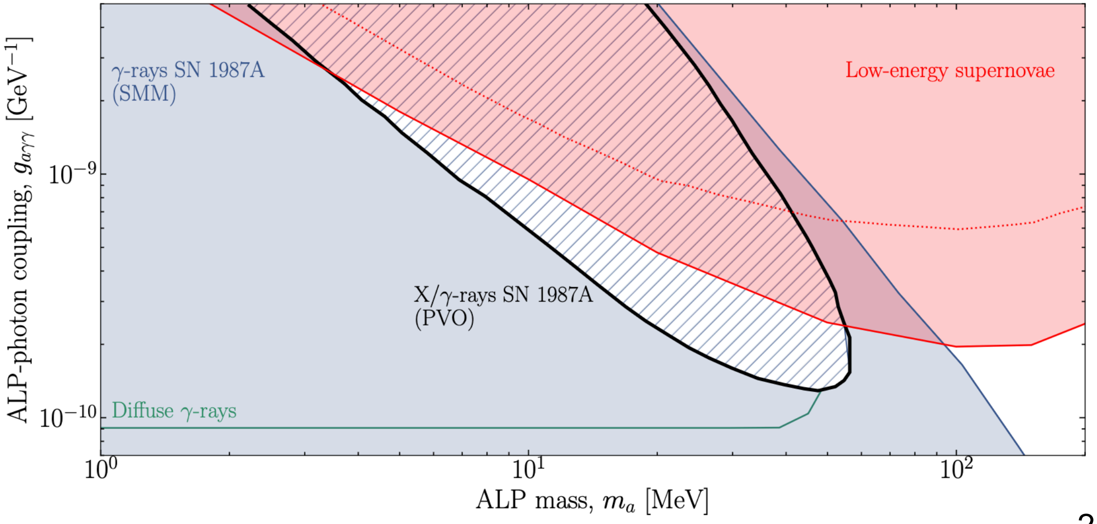
Brand new!

Editors' Suggestion

Diamond, Fiorillo, Marques-Tavares, **Vitagliano**, *Phys.Rev.D* 107 (2023) 10, 103029

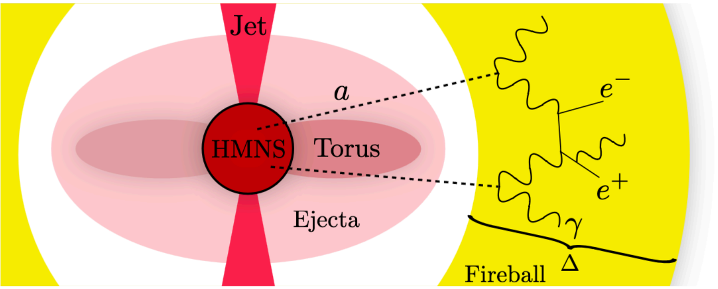


- The bounds from decay to gamma-rays do not apply everywhere
- For a large region of masses and couplings, axions form a fireball
- The expected flux is at much smaller frequencies
- New bounds from Pioneer Venus Observatory



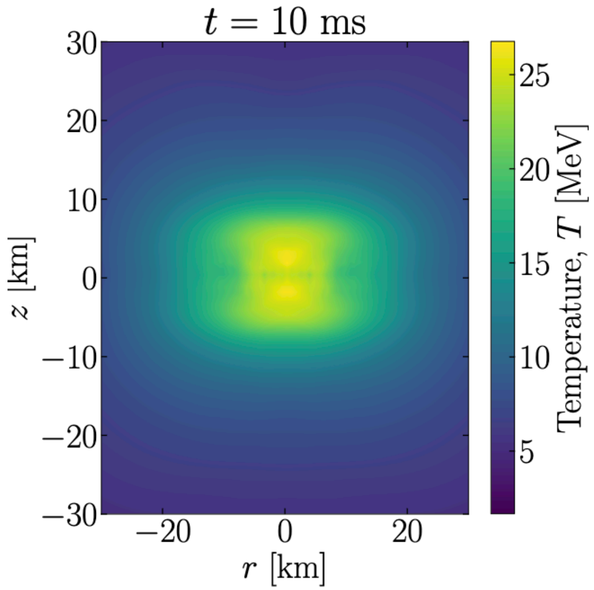
Neutron star mergers: a new bound

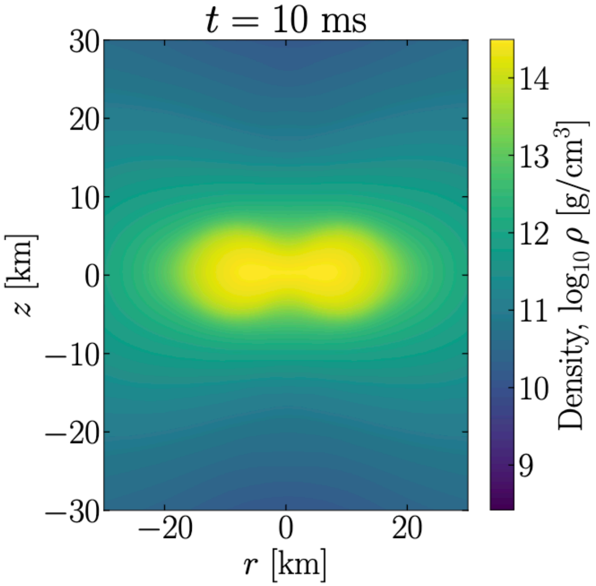
Brand new!



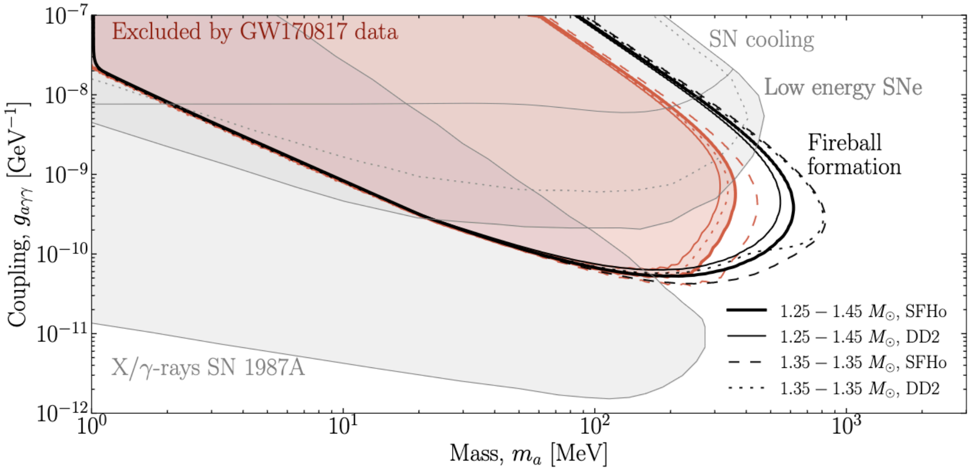
- We have observed a NS merger, GW 170817
- When two neutron stars merge, a heavy mass neutron star forms
- The one-zone model parameters are similar to a CCSN: $\rho \simeq 10^{14}\,\mathrm{g/cm^3}$, $T \simeq 18\,\mathrm{MeV}$, $\delta t \simeq 1\,\mathrm{s}$
- However, no mantle

Diamond, Fiorillo, Marques-Tavares, Tamborra, **Vitagliano**, e-Print: 2305.10327

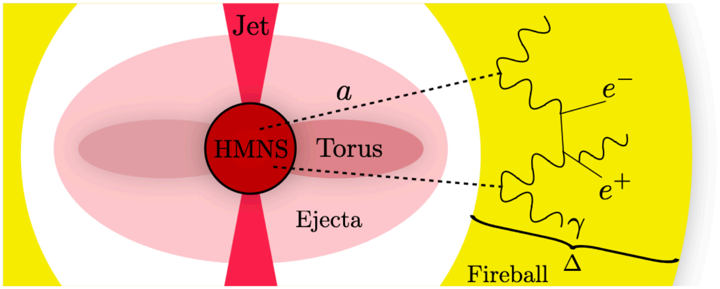


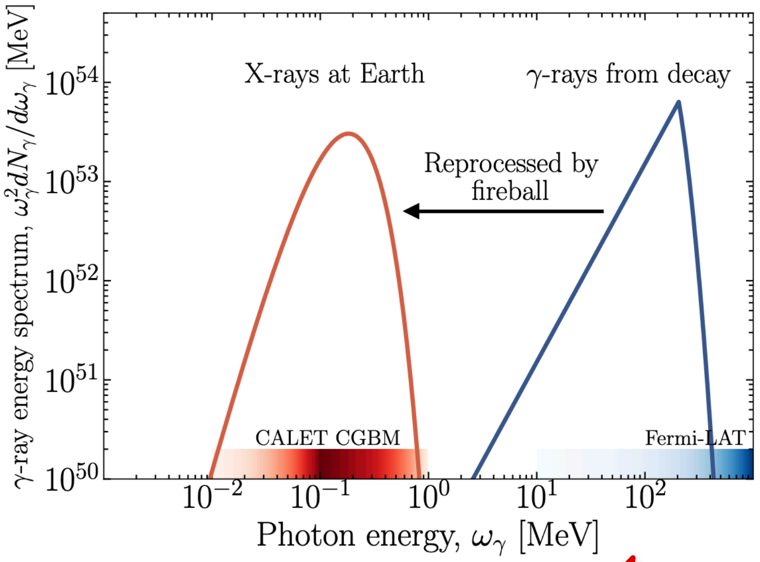


Bounds from GW170817



Diamond, Fiorillo, Marques-Tavares, Tamborra, **Vitagliano**, e-Print: 2305.10327





- Neutron star mergers produce a heavy mass NS remnant without a mantle! So we can probe $\Gamma \gtrsim c/R_{\rm mantle}$
- Huge temperature and densities
- Extremely sensitive measurements by X-ray detectors of GW 170817 (energy injected $\lesssim 10^{46}\,\mathrm{erg}$)
- Fresh bounds on $m_a > 1\,\mathrm{MeV}$ axions

Brand new!

Conclusions

Conclusions

- Cooling bounds still useful for QCD axion hadronic couplings, look for other observables in other cases—decays!
- Need fluid dynamics, fireballs can form so simple bounds on gamma-ray daughter do not apply
- Particle physics: best bounds on new feebly interacting particles for “heavy” bosons from decay to photon
- Astrophysics: rule-out decaying bosons as supernova explosions catalyzers
- Cosmology: strongly constraining DM mediators

Credit: ESO (eso0708a)

Thank you

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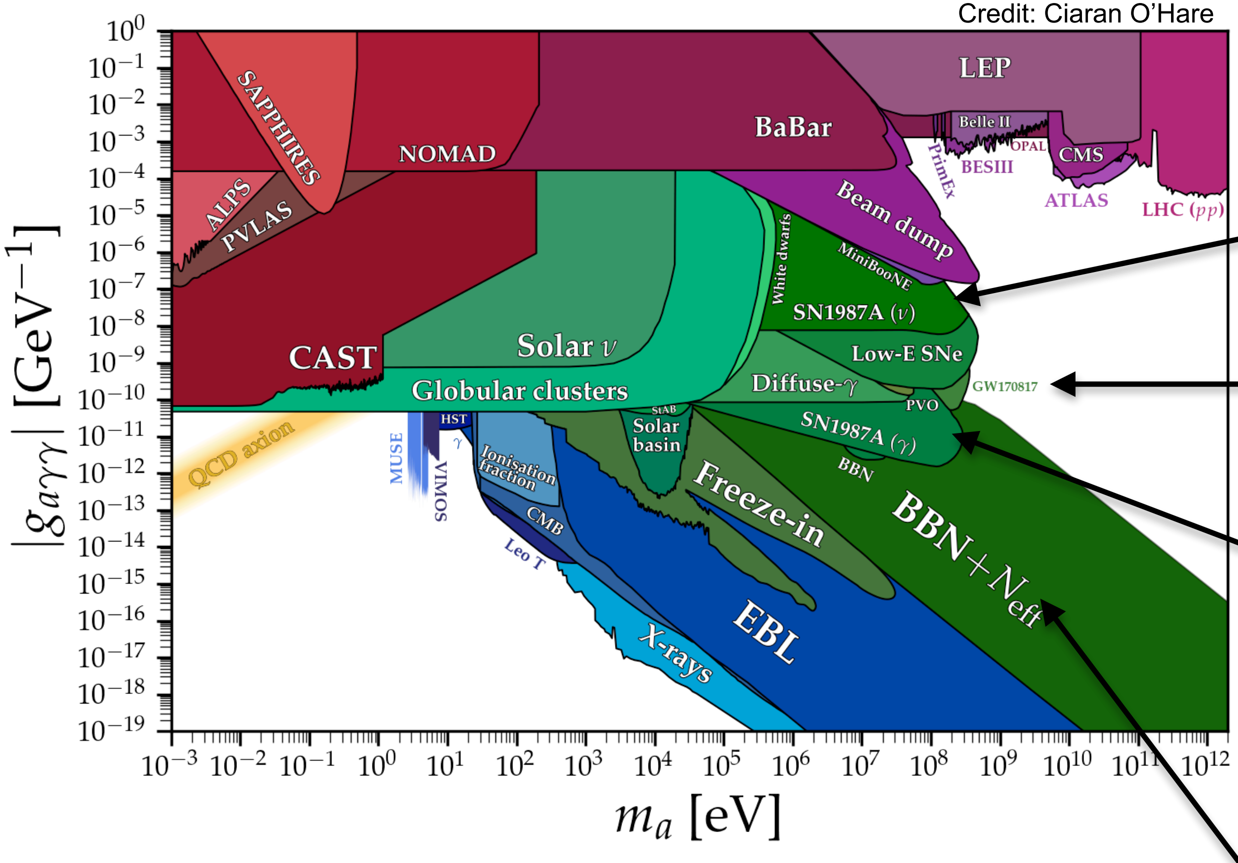
Axion-like particles with photon coupling



Credit: Ciaran O'Hare

Heats up the mantle of low-energy SNe

(see Caputo, Raffelt, Janka, **Vitagliano**, *Phys.Rev.Lett.* 128 (2022) 22, 221103)

GW170817 bounds

(see Diamond, Fiorillo, Marques-Tavares, Tamborra, **Vitagliano** (2023))

Gamma-ray from SN 1987A at SMM and PVO

(see Diamond, Fiorillo, Marques-Tavares, **Vitagliano**, *Phys.Rev.D* 107 (2023) 10, 103029)

Goes away for low $T_{\rm RH}$

(see Langhoff, Outmezguine, Rodd *Phys.Rev.Lett.* 129 (2022) 24, 241101)

Resonant production and subsequent decay for some specific couplings and masses

see e.g. Axions from Hypernovae,
Caputo, Carenza, Lucente, **Vitagliano** et al. *Phys.Rev.Lett.* 127 (2021) 18, 181102