Stars and Galaxies: a pathway to the Dark Side of Fundamental Physics

Andrea Caputo

IFIC, 31 October 2023

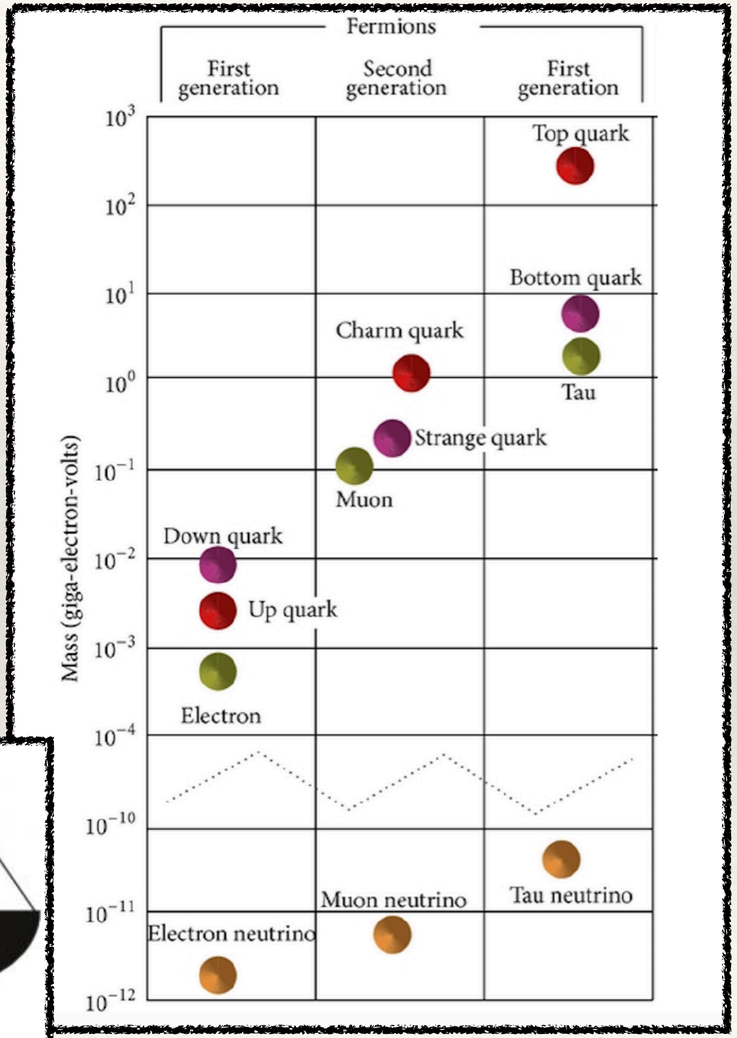


We have a lot of evidences for physics beyond the Standard Model

Dark Matter



Neutrino Masses



Matter Antimatter asymmetry



The strong CP problem

We know that QCD suffers from the fact one can add to the Lagrangian the following term



$$\mathscr{L} \supset -\theta \frac{g^2}{16\pi} Tr(G\tilde{G})$$

$$G_{\mu\nu} = G^a_{\mu\nu} T^a$$

$$\tilde{G}_{\mu\nu} = \epsilon_{\mu\nu\rho\sigma} G^{\rho\sigma}$$

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It leads to a dipole moment for the neutron

$$\theta < 10^{-9}$$

The axion

(Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978)

The idea is simple and consists on promoting the dimensionless parameter θ to a *dynamical field*

$$\mathscr{L} \supset -\frac{a(x)}{f_a}\frac{g^2}{16\pi}Tr(G\tilde{G})$$

- (pseudo) Goldstone Boson associated to $U(1)_{PQ}$
- Good dark matter candidate

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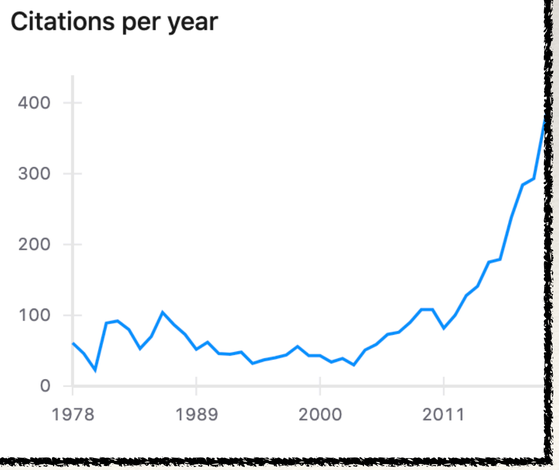
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A New Light Boson?

Steven Weinberg (Harvard U.)
Dec, 1977

12 pages
Published in: *Phys.Rev.Lett.* 40 (1978) 223-226
DOI: 10.1103/PhysRevLett.40.223
Report number: HUTP-77/A074
View in: OSTI Information Bridge Server, ADS Abstract Service, KEK scanned document

pdf cite claim reference search 4,855 citations



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Peter Svrcek, Edward Witten

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String Axiverse

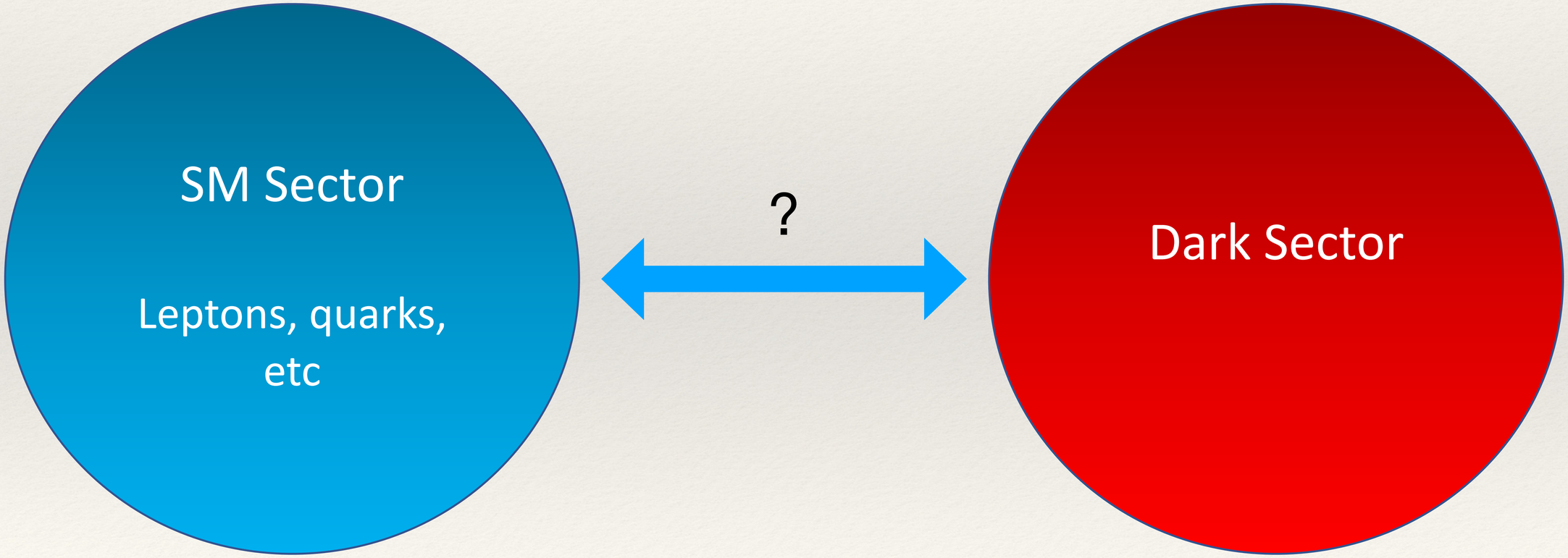
Asimina Arvanitaki, Savas Dimopoulos, Sergei Dubovsky, Nemanja Kaloper, John March-Russell

More generally we can have a rich Dark Sector, that is to say new particles which can be connected in different ways to the SM particles



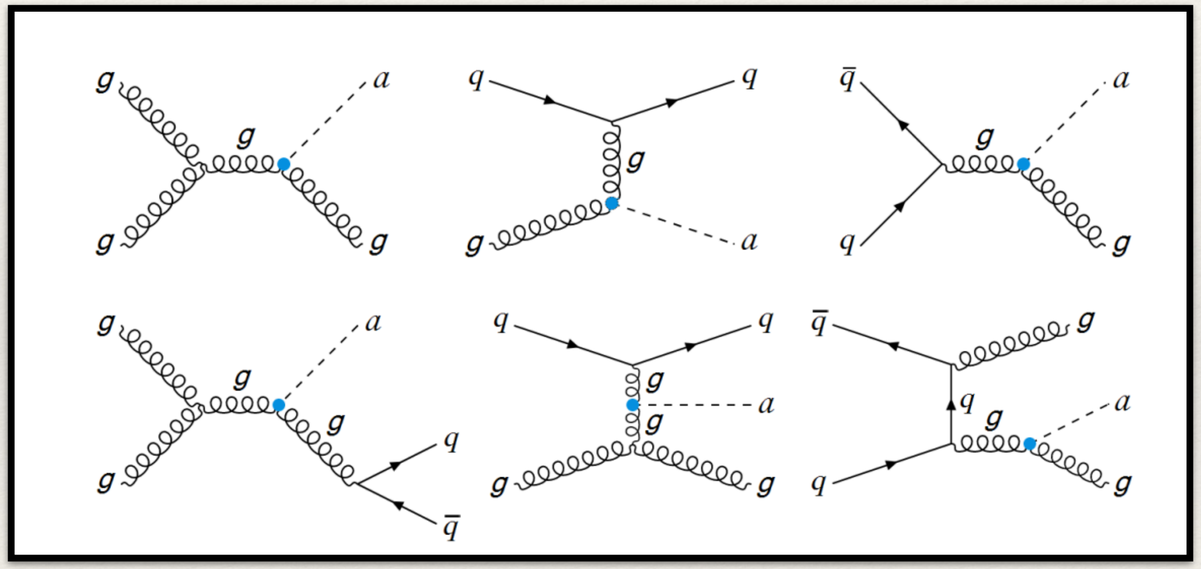


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How to look for these new particles?

Collider searches. We have been doing this successfully for decades, however it is more and more difficult to reach high energies



Caputo, P. Hernandez, M. Kekic, J. Lopez-Pavon, J.Salvado, *Eur.Phys.J.C* 77 (2017) 4, 258
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D. Barducci, E. Bertuzzo, Caputo, P. Hernandez, J*HEP* 06 (2020) 185
D. Barducci, E. Bertuzzo, Caputo, P. Hernandez, B. Mele, *JHEP* 03 (2021) 117

How to look for these new particles?



“The Universe is a “poor man” accelerator” Zel’dovich

Be creative and use astrophysical objects and the universe!

Two parts

- Dark Matter particles

- New particles which are NOT Dark Matter

I. Looking for dark matter



My research

Stars and new physics



Caputo et al., *JCAP* 08 (2022) 08, 045

Caputo et al., *Phys.Rev.Lett.* 128 (2022) 22, 221103 (CCSNe)
Caputo et al., *Phys.Rev.D* 105 (2022) 3, 035022 (CCSNe)

Caputo et al., *Phys.Rev.Lett.* 127 (2021) 18, 181102 (Hypernovae)

Caputo et al., *Phys.Rev.D* 101 (2020) 12, 123004 (Sun)
O'Hare, Caputo, et al., *Phys.Rev.D* 102 (2020) 4, 043019 (Sun)

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Bernal, Caputo, et al., *Phys.Rev.D* 103 (2021) 6, 063523 (optic)
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Gravitational Waves

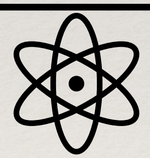
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Toubiana, Sberna, Caputo, et al.,
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Dark Matter direct detection



Caputo et al., *Phys.Rev.D* 100 (2019) 11, 116007 (sub-GeV DM)
Caputo et al., *Phys.Lett.B* 802 (2020) 135258 (sub-GeV DM)
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Dark Matter and other indirect probes



Caputo et al., *Phys.Rev.Lett.* 127 (2021) 1, 011102 (21 cm)
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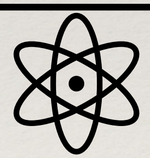
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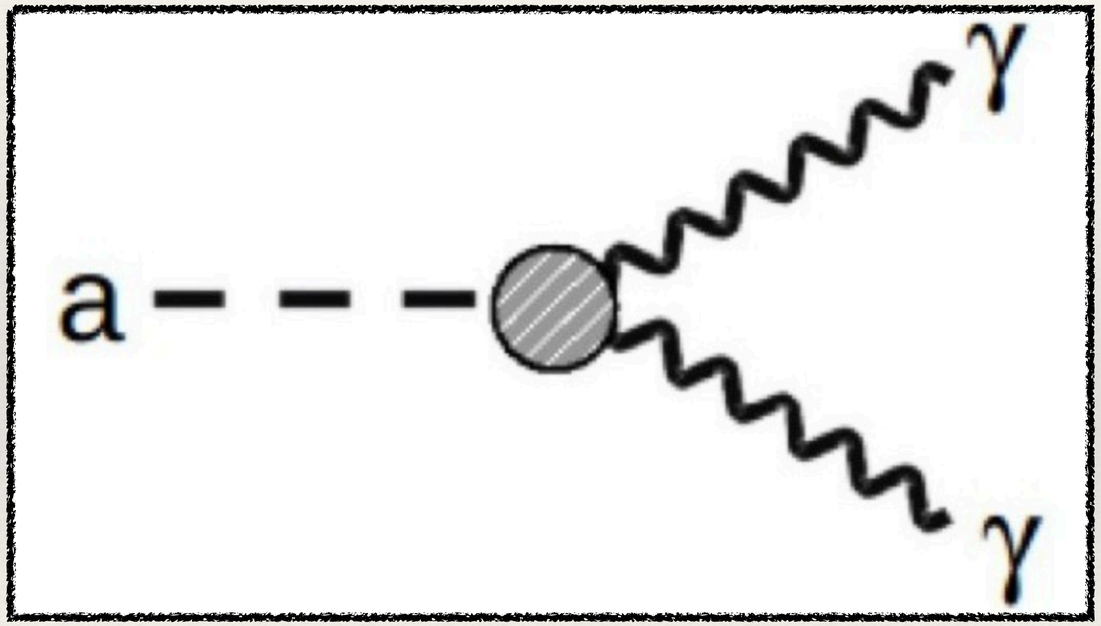
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However the ideas will be further more generic, applying to sterile neutrinos DM, dipole DM, scalar DM, hidden photino DM, etc..

Constraining light dark matter with diffuse X-ray and gamma-ray observations

Rouven Essig, Eric Kuflik, Samuel D. McDermott ✉, Tomer Volansky & Kathryn M. Zurek

Axion dark matter decaying into photons



$$\tau_a = \frac{64\,\pi}{m_a^3 g_{a\gamma\gamma}^2}$$

General strategy

A good story should answer few basic questions

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What?

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Looking for a photon monochromatic emission at $E_\gamma = m_a/2$
given by ALP decay from regions with high dark-matter density

General strategy

A good story should answer few basic questions

Where?

General strategy

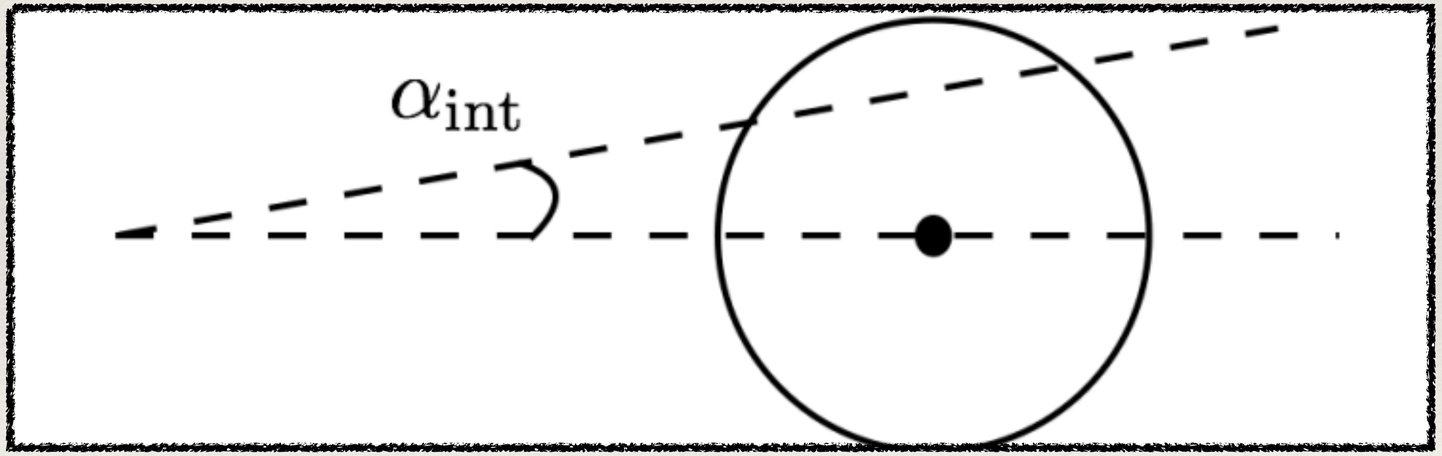
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Where?

A) Which astrophysical targets?

Galactic center, clusters of galaxies, Dwarf galaxies

$$S_{\rm sd} \propto \int d\Omega\, dl\, \frac{\rho_a(\Omega, l)}{\tau_a}$$



General strategy

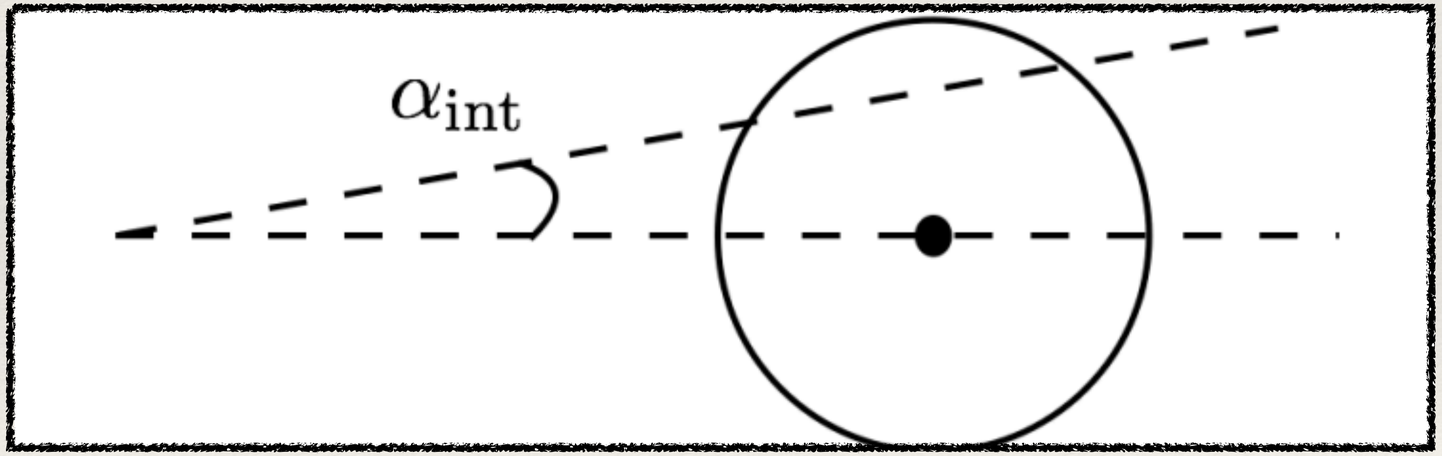
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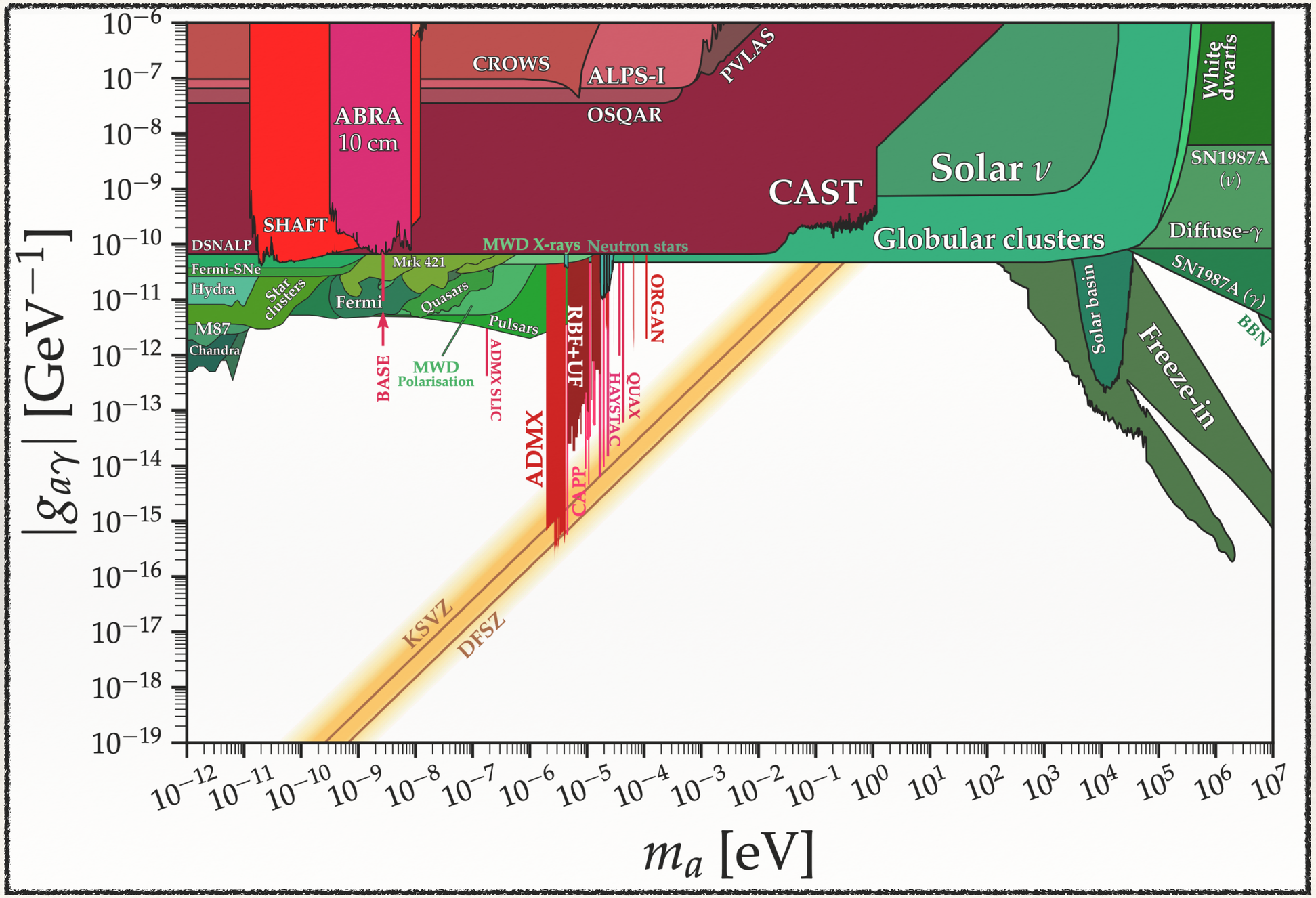
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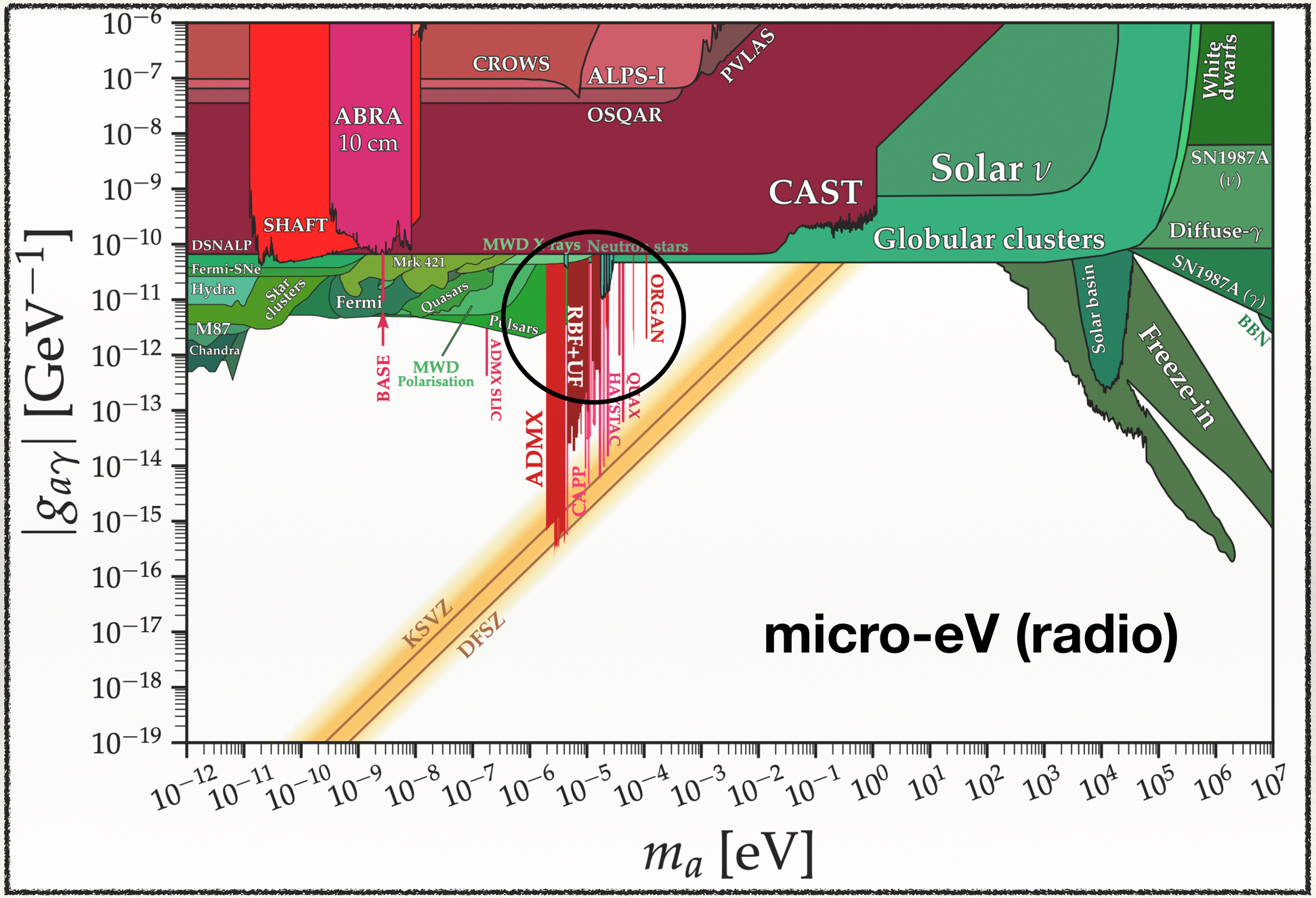
$$S_{\rm sd} \propto \int d\Omega\, dl\, \frac{\rho_a(\Omega, l)}{\tau_a}$$



B) Which energy range?



https://github.com/cajohare/AxionLimits

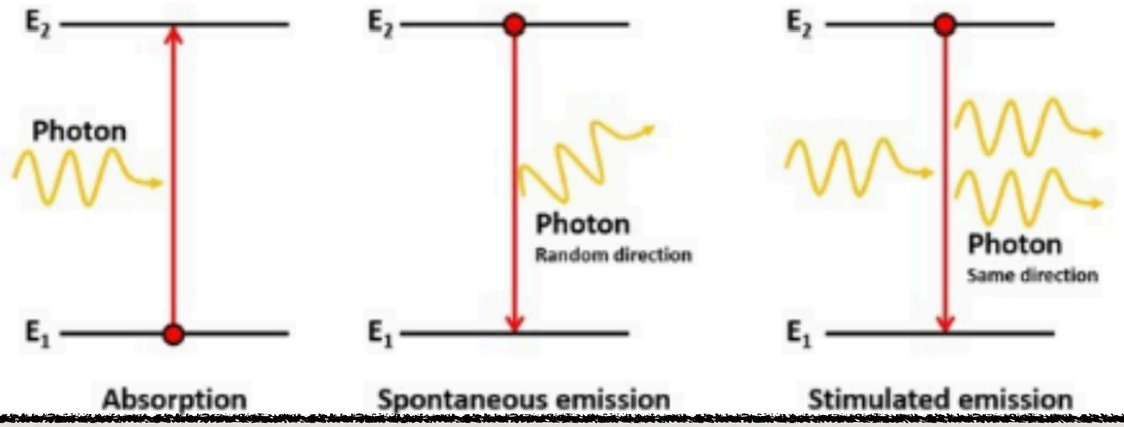


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In this energy range we realised that stimulated emission is important, the ALP decay is not happening in vacuum!

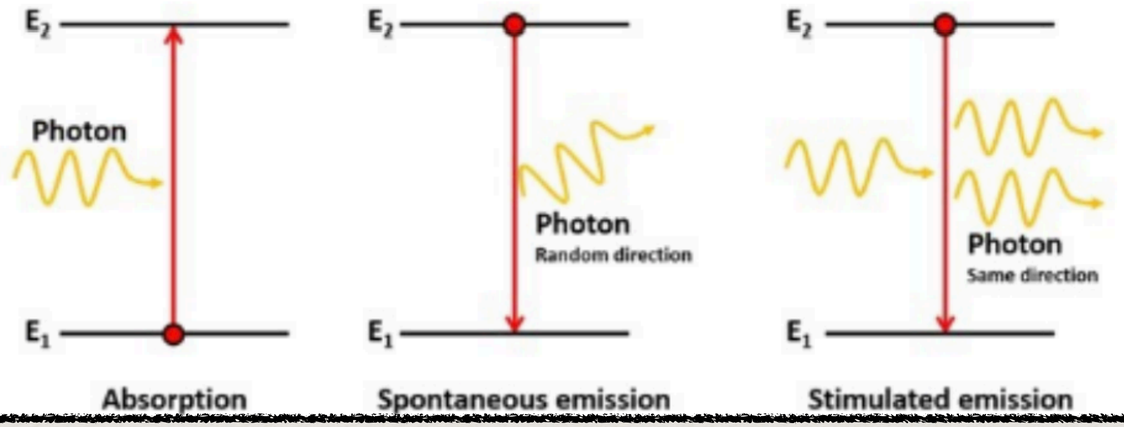
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Stimulated decay

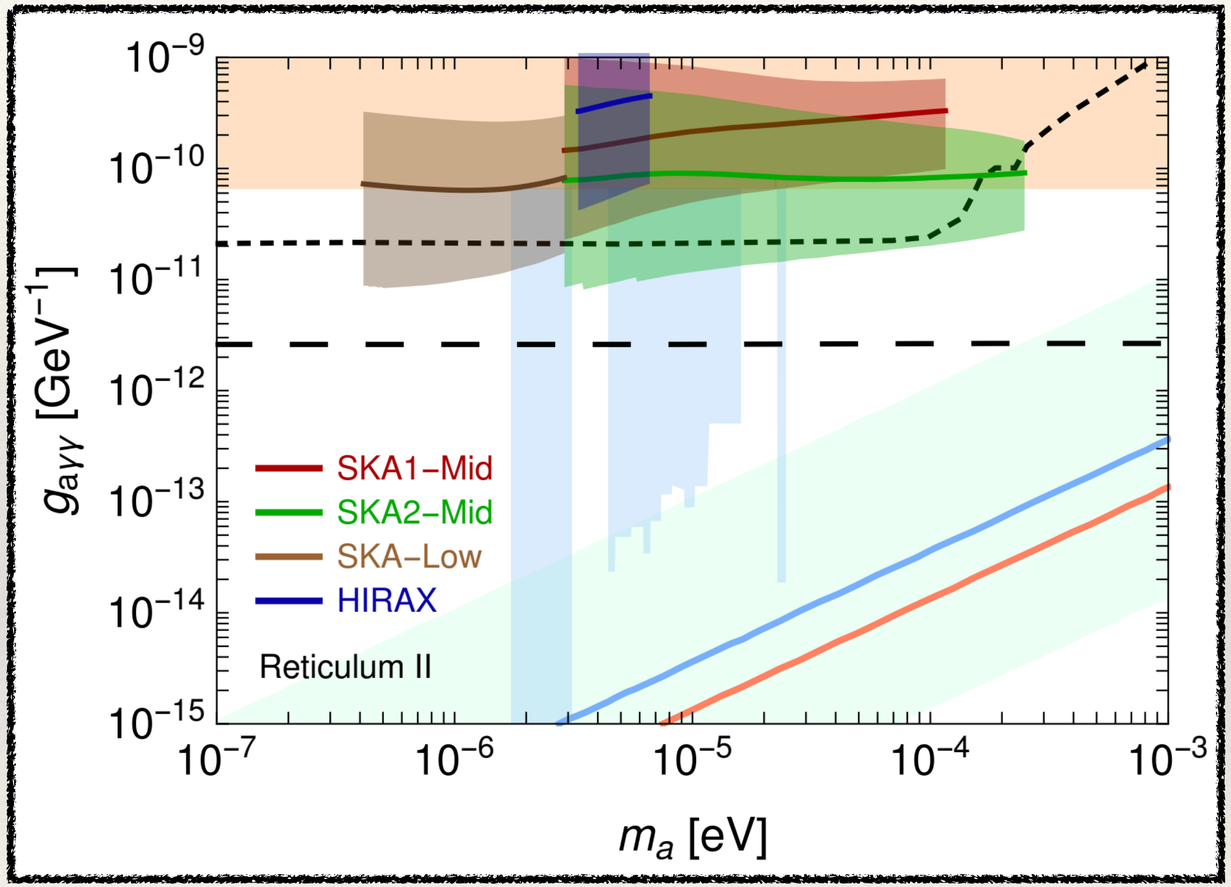


$$S_{\text{decay}} = \frac{1}{4\,\pi\,\Delta\nu} \int d\Omega\, dl\, \frac{\rho_a(\Omega, l)}{\tau_a} \left(1 + 2 f_\gamma(\Omega, l, m_a)\right)$$

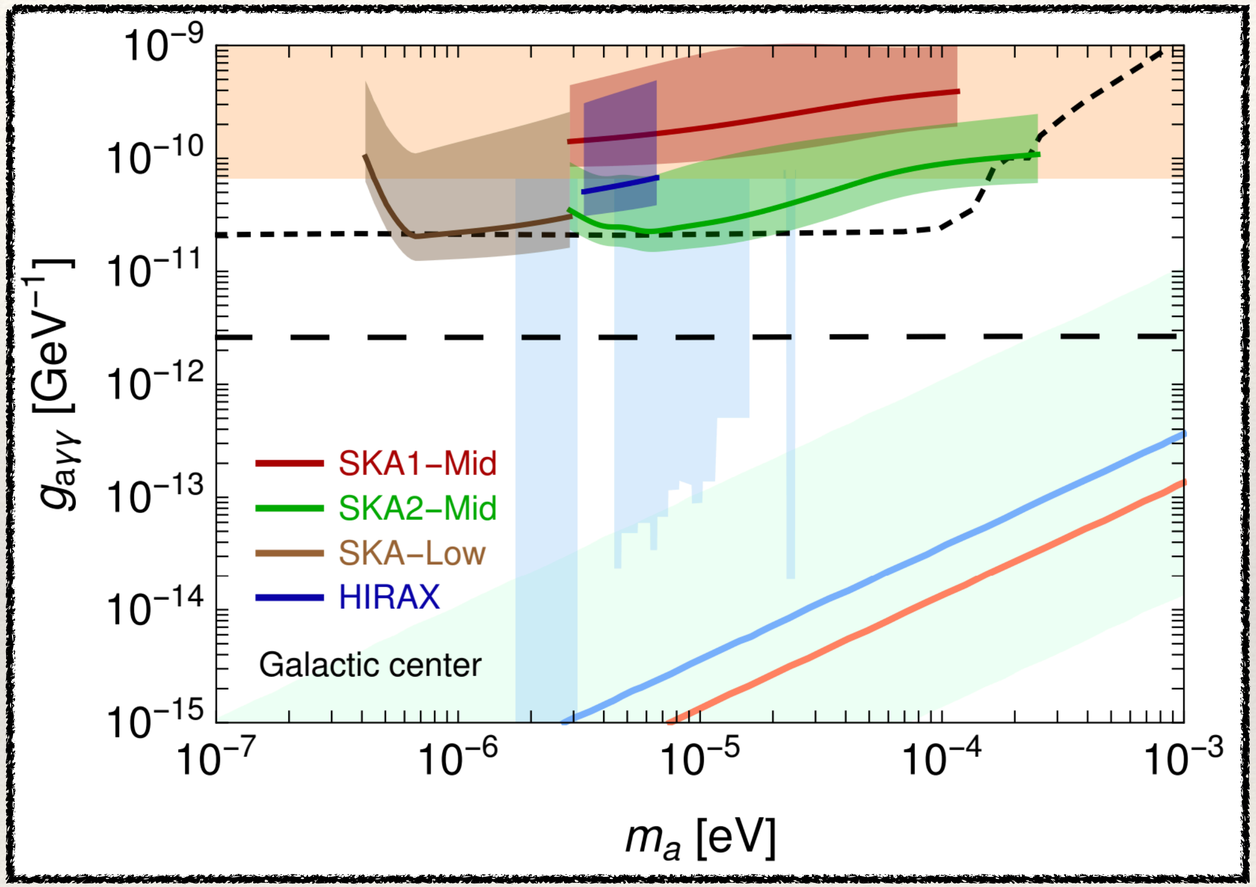
$$f_\gamma = \frac{\pi^2 \rho_\gamma}{E_\gamma^3}$$


A golden era has started for radio astronomy with SKA and its precursors.
SKA1-Low: 100 hours of observation;
sensitivity of $180\mu Jy/beam$
$\Delta\nu/\nu = 10^{-4}$

Dwarf Spheroidal Galaxies



Galactic Center



A.C, M.Regis, M. Taoso, S. Witte, *JCAP* 03 (2019) 027

In this case we have targeted specific objects..however there is another possibility

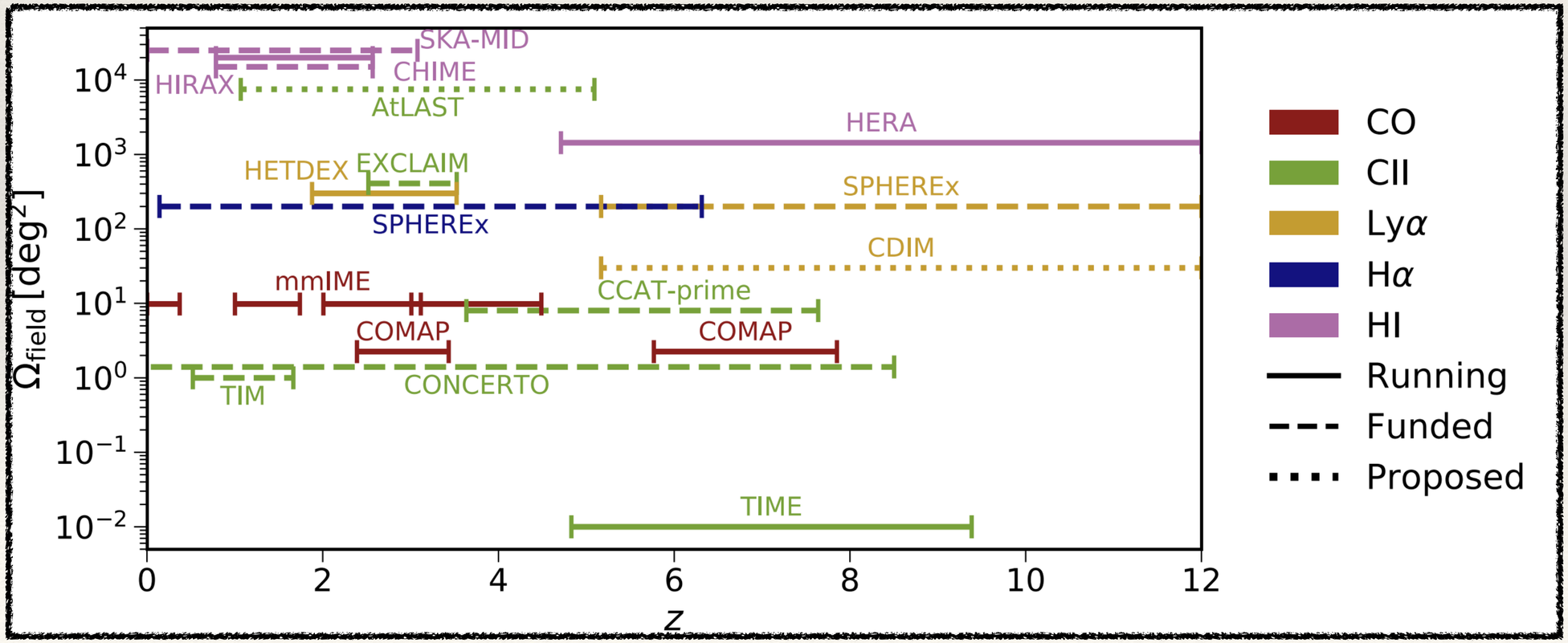
Using the integrated signal from all galaxies in the past (**line intensity mapping**) with

$$E_{\rm obs} = m_a/2/(1+z_e)$$

People already do this for atomic and molecular spectral lines!

$$\nu_{\rm obs} = \nu_0/(1+z)$$

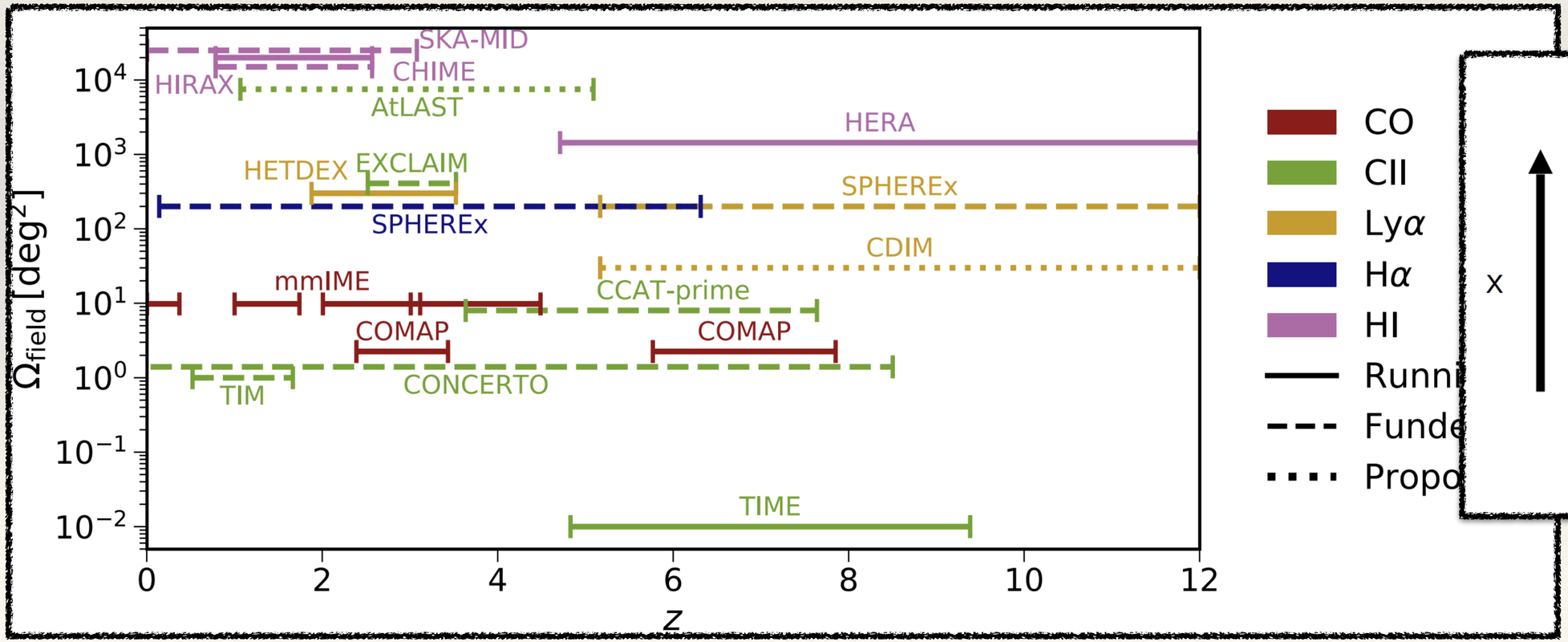


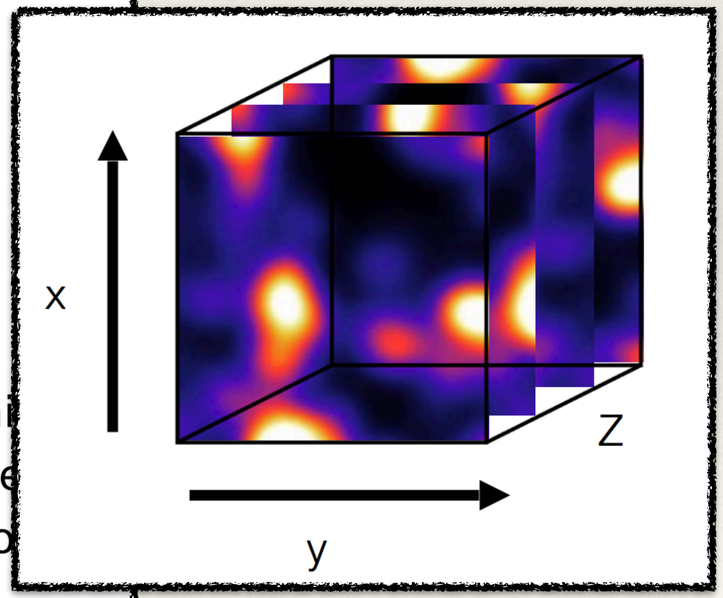


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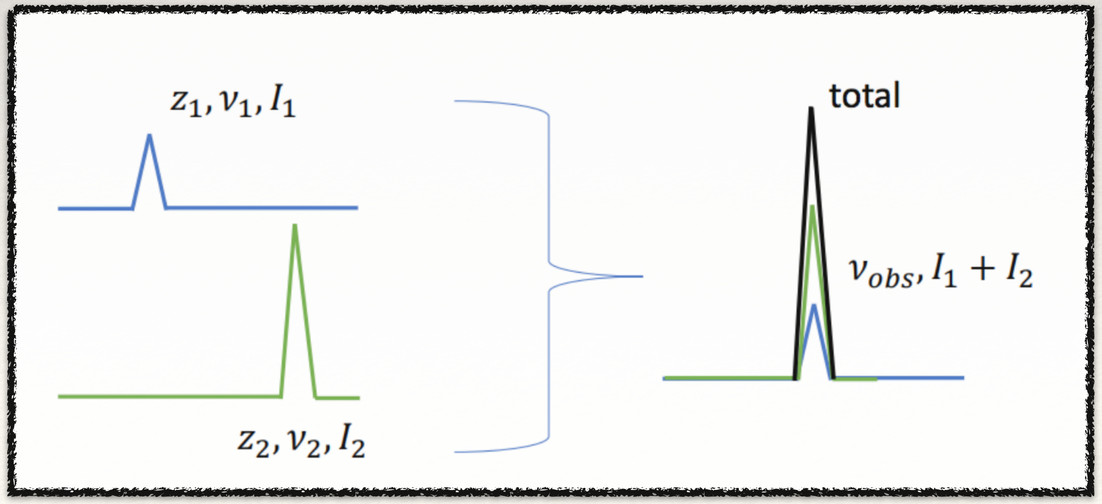


Contamination of intensity maps

1) Continuous foregrounds: problem especially for HI surveys

2) Line interlopers, other lines redshifted to the same bin: main problem for higher frequency LIM surveys

$$\nu_{\rm obs} = \nu/(1+z) = \nu'/(1+z')$$



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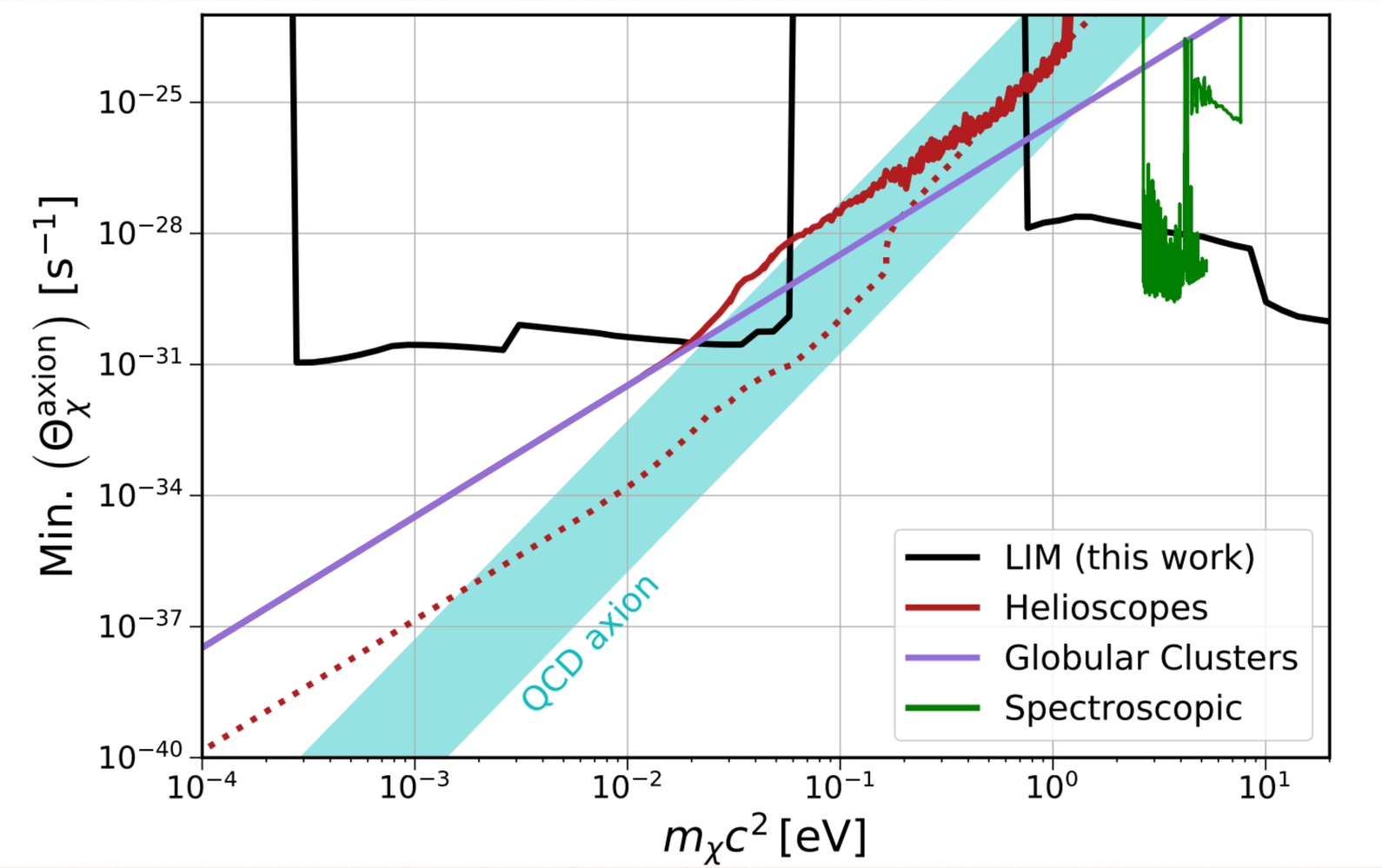
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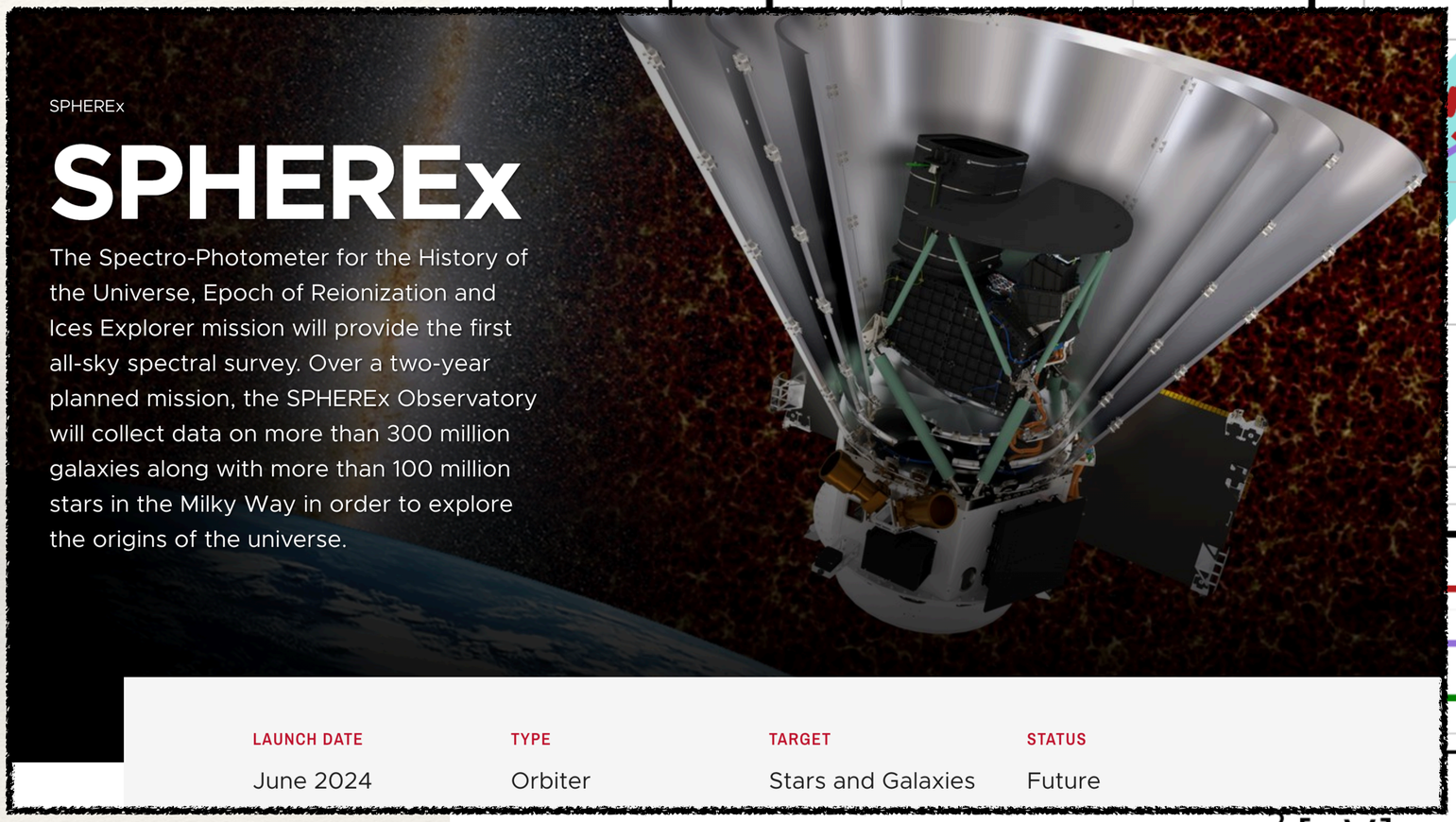
“Exotic” decay, for example from axions, would act like interlopers!

Line-intensity mapping is a promising avenue at different frequencies

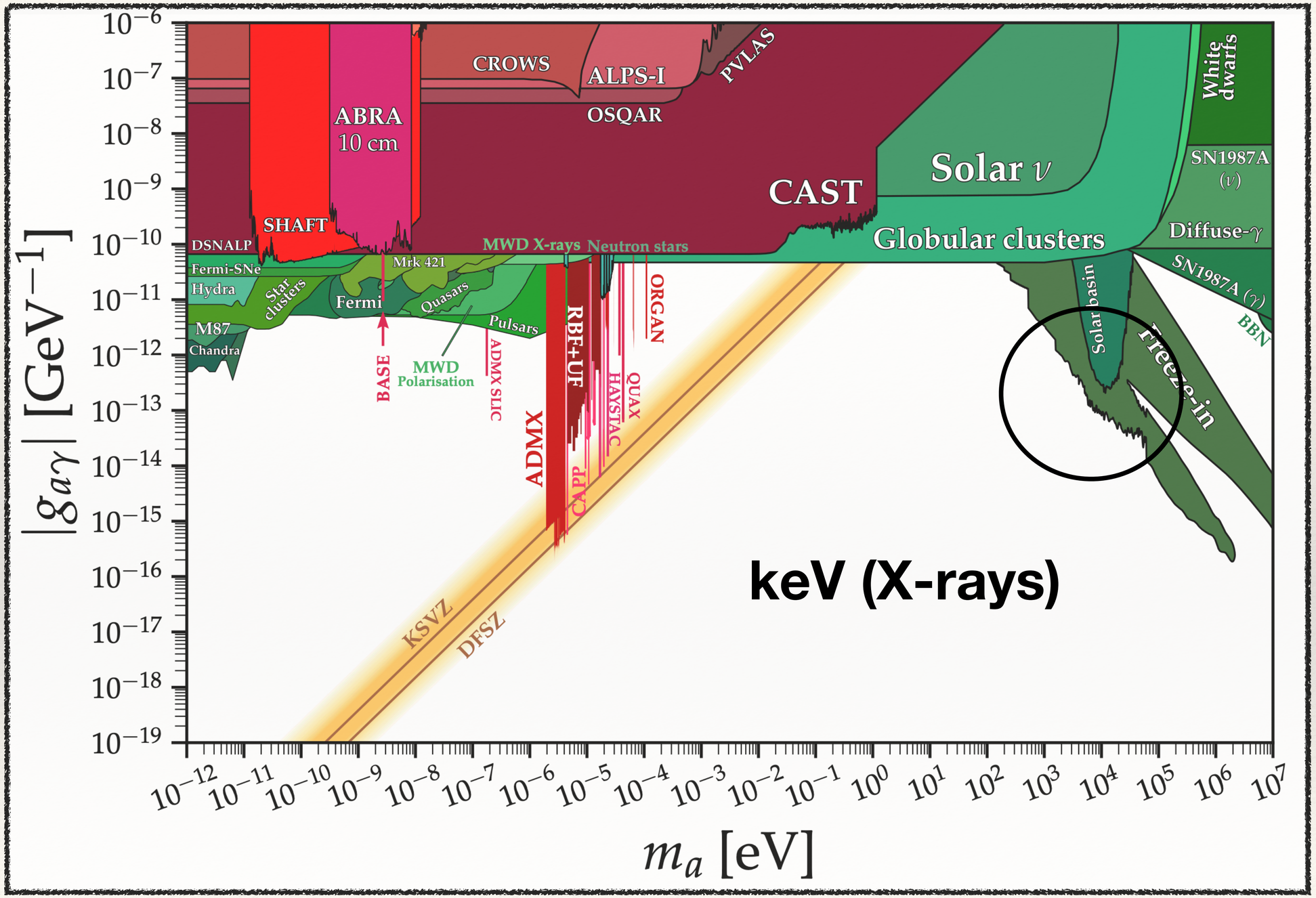


J. Bernal, Caputo, M. Kamionkowski, *Phys.Rev.D* 103 (2021) 6, 063523
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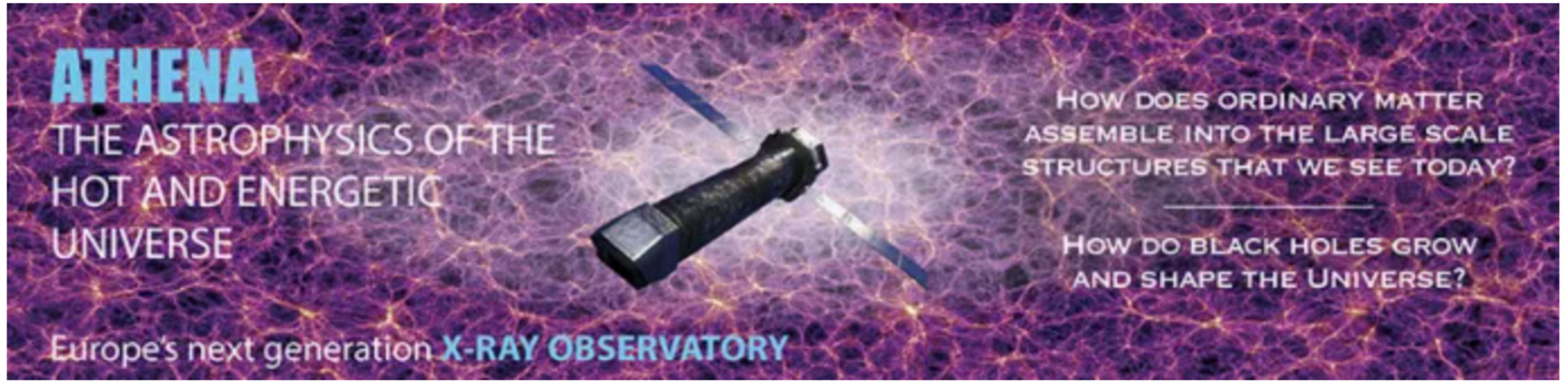


Caputo, M. Regis and M. Taoso, *JCAP* 03 (2020) 001

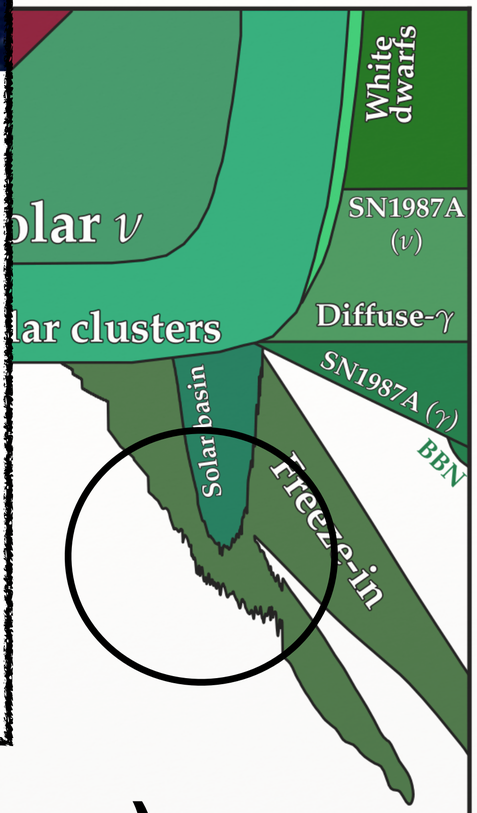
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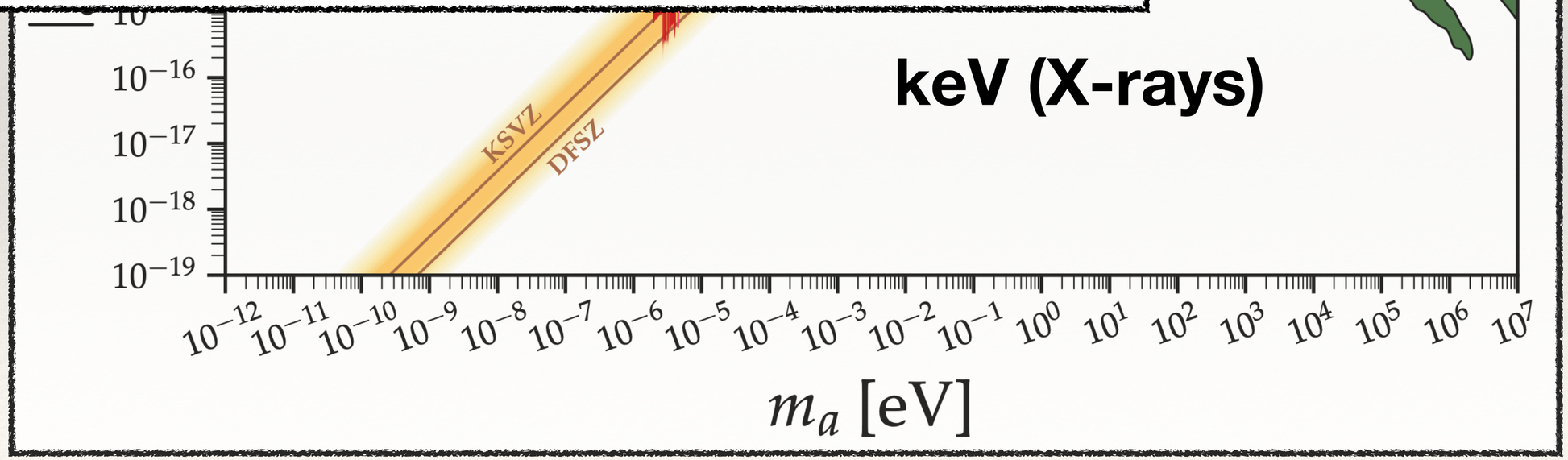
Osservatorio Astronomico di Roma > Attività scientifica > Progetti > Athena

Athena



Athena (Advanced Telescope for High ENergy Astrophysics) is the **future large-class X-ray Observatory** selected by ESA to **study the Hot and Energetic Universe**. It is due for launch in 2028.

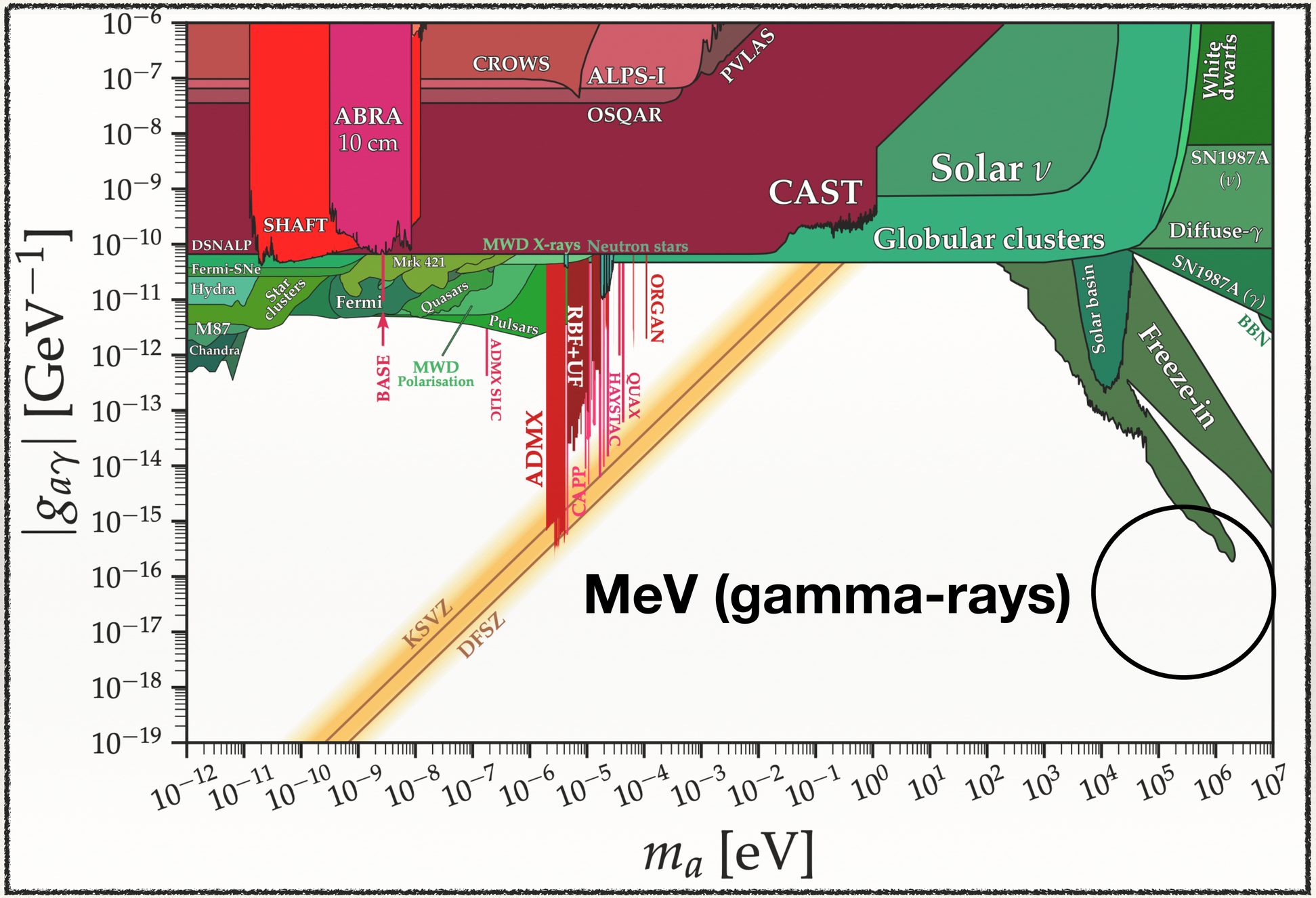




keV (X-rays)

Caputo, M. Regis and M. Taoso, *JCAP* 03 (2020) 001

https://github.com/cajohare/AxionLimits



Caputo, M. Negro, M. Regis and M. Taoso, *JCAP* 02 (2023) 006

https://github.com/cajohare/AxionLimits

Oct 18, 2021
RELEASE 21-134

NASA Selects Gamma-ray Telescope to Chart Milky Way Evolution

COSI-Telescope (approved by NASA)

Compton Spectrometer and Imager (COSI) wide-FOV telescope designed to survey the gamma-ray sky at 0.2-5 MeV → Imaging with high-resolution spectroscopy

Caputo, M. Negro, M. Regis and M. Taoso, *JCAP* 02 (2023) 006

General strategy

A good story should answer few basic questions.

We considered **what** and **where**.

General strategy

A good story should answer few basic questions.

We considered **what** and **where**. **When?** Very soon! All the missions I talked about will operate in the next 5-6 years.

II. Looking for new particles (not to be dark matter)



My research

Stars and new physics



Caputo et al., *JCAP* 08 (2022) 08, 045

Caputo et al., *Phys.Rev.Lett.* 128 (2022) 22, 221103 (CCSNe)
Caputo et al., *Phys.Rev.D* 105 (2022) 3, 035022 (CCSNe)

Caputo et al., *Phys.Rev.Lett.* 127 (2021) 18, 181102 (Hypernovae)

Caputo et al., *Phys.Rev.D* 101 (2020) 12, 123004 (Sun)
O'Hare, Caputo, et al., *Phys.Rev.D* 102 (2020) 4, 043019 (Sun)

Dark Matter and telescopes



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Caputo et al., *Phys.Rev.D* 98 (2018) 8, 083024 (radio)

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Caputo et al., *JCAP* 05 (2021) 046 (IR)

Bernal, Caputo, et al., *Phys.Rev.D* 103 (2021) 6, 063523 (optic)
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Gravitational Waves

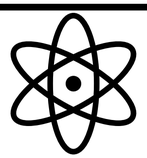
Caputo et al., *JAstrophys.J.* 892 (2020) 2, 90

Toubiana, Sberna, Caputo, et al.,
Phys.Rev.Lett. 126 (2021) 10, 101105

Colliders phenomenology

Caputo, P. Hernandez, M. Kekic, J. Lopez-Pavon, J.Salvado,
Eur.Phys.J.C 77 (2017) 4, 258
Caputo, P. Hernandez, J. Lopez-Pavon, J.Salvado, *JHEP* 06 (2017) 112
D. Barducci, E. Bertuzzo, Caputo, P. Hernandez, J*HEP* 06 (2020) 185
D. Barducci, E. Bertuzzo, Caputo, P. Hernandez, B. Mele,
JHEP 03 (2021) 117

Dark Matter direct detection



Caputo et al., *Phys.Rev.D* 100 (2019) 11, 116007 (sub-GeV DM)
Caputo et al., *Phys.Lett.B* 802 (2020) 135258 (sub-GeV DM)
Caputo et al., *Phys.Rev.D* 103 (2021) 5, 055017 (sub-GeV DM)

Bloch, Caputo et al., *JHEP* 01 (2021) 178 (sub-GeV DM)

Caputo et al., *Phys.Rev.D* 104 (2021) 9, 095029 (Dark Photon DM)

Dark Matter and other indirect probes



Caputo et al., *Phys.Rev.Lett.* 127 (2021) 1, 011102 (21 cm)
Bolton, Caputo, et al., *Phys.Rev.Lett.* 129 (2022) 21, 211102
(Ly-alpha)

Caputo et al., *Phys.Rev.Lett.* 125 (2020) 22, 221303 (CMB)

Bernal, Caputo, et al., *arXiv* 2208.13794 (blazars data)

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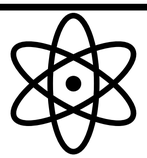
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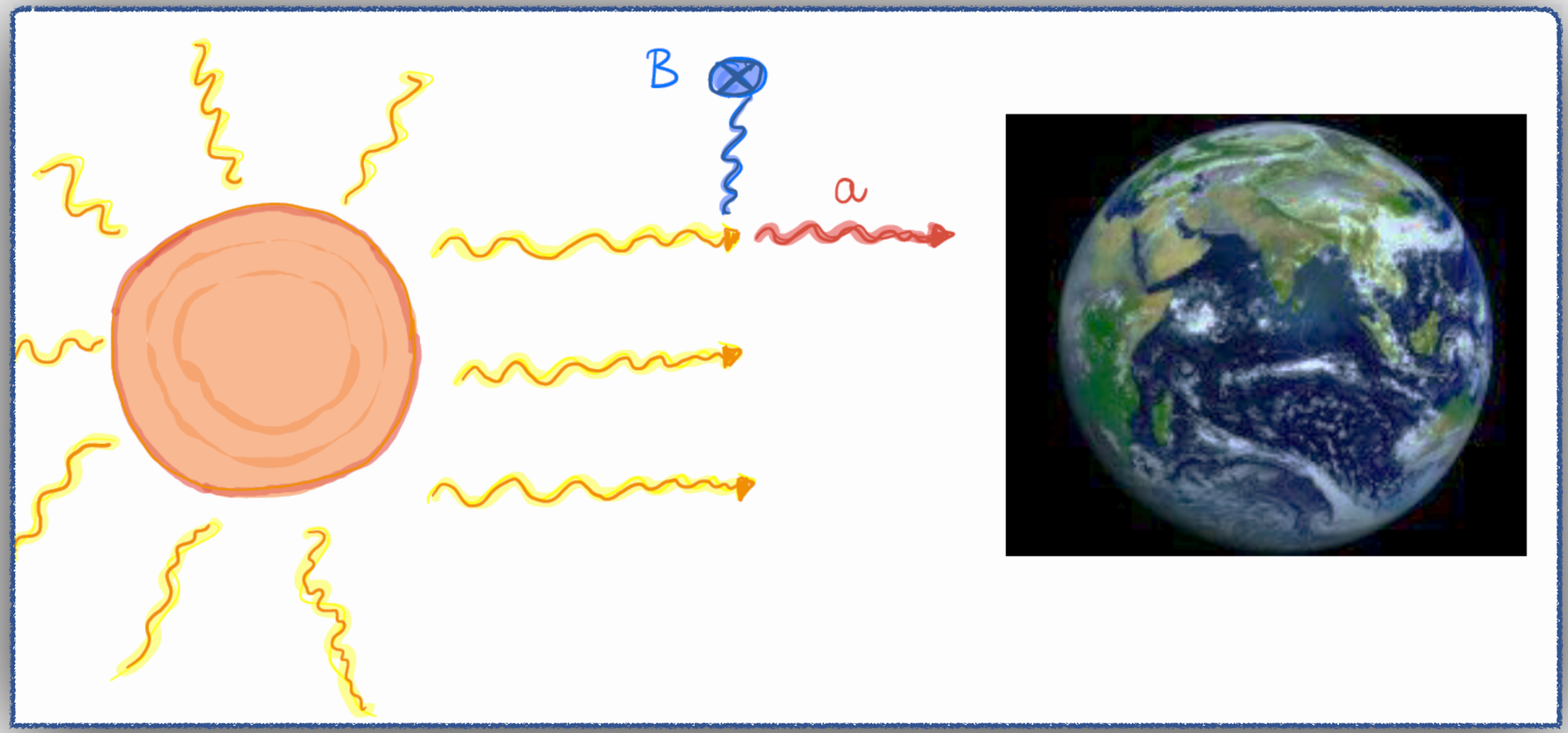
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In general, stars can be used to study fundamental physics in different ways:

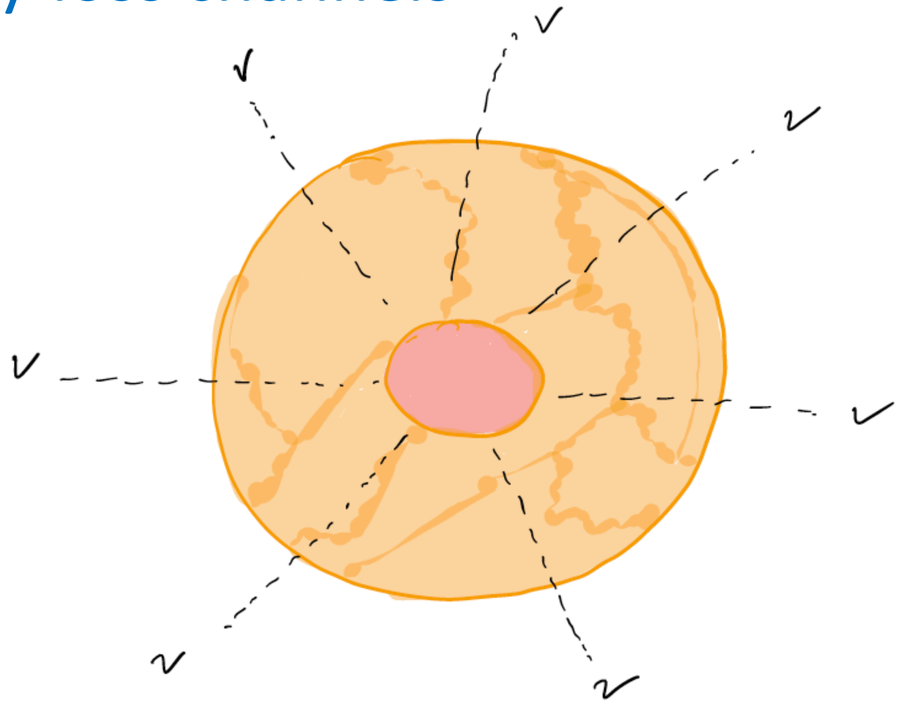
- First, modifications of the measured signal due to new physics (e.g photon-axion oscillation in magnetic fields).



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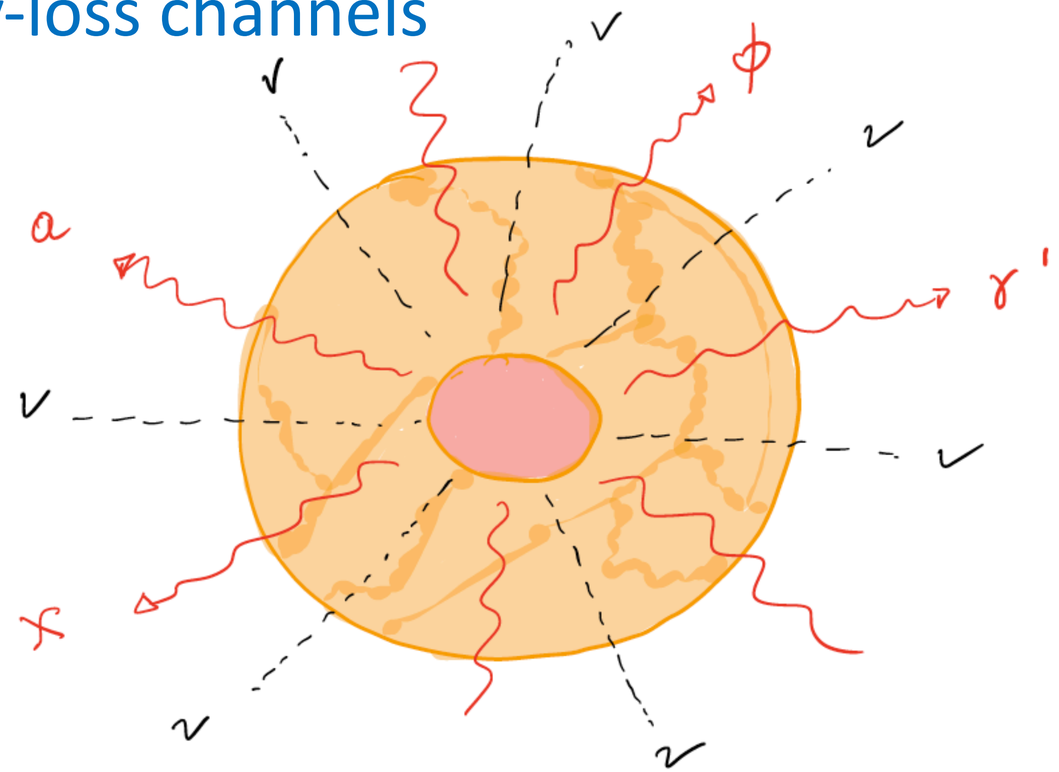
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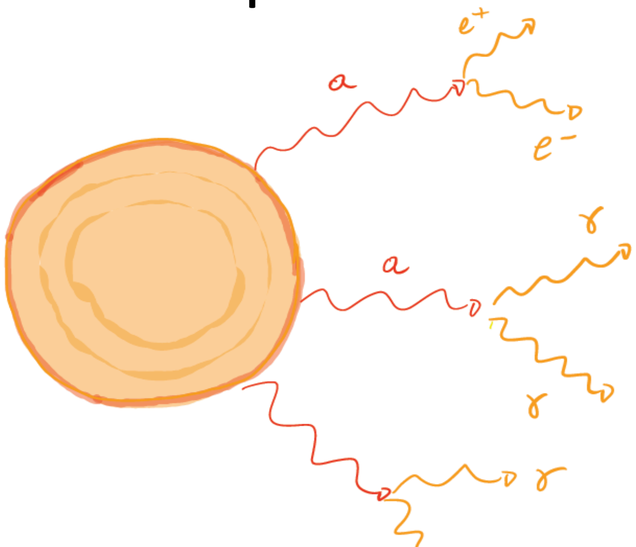


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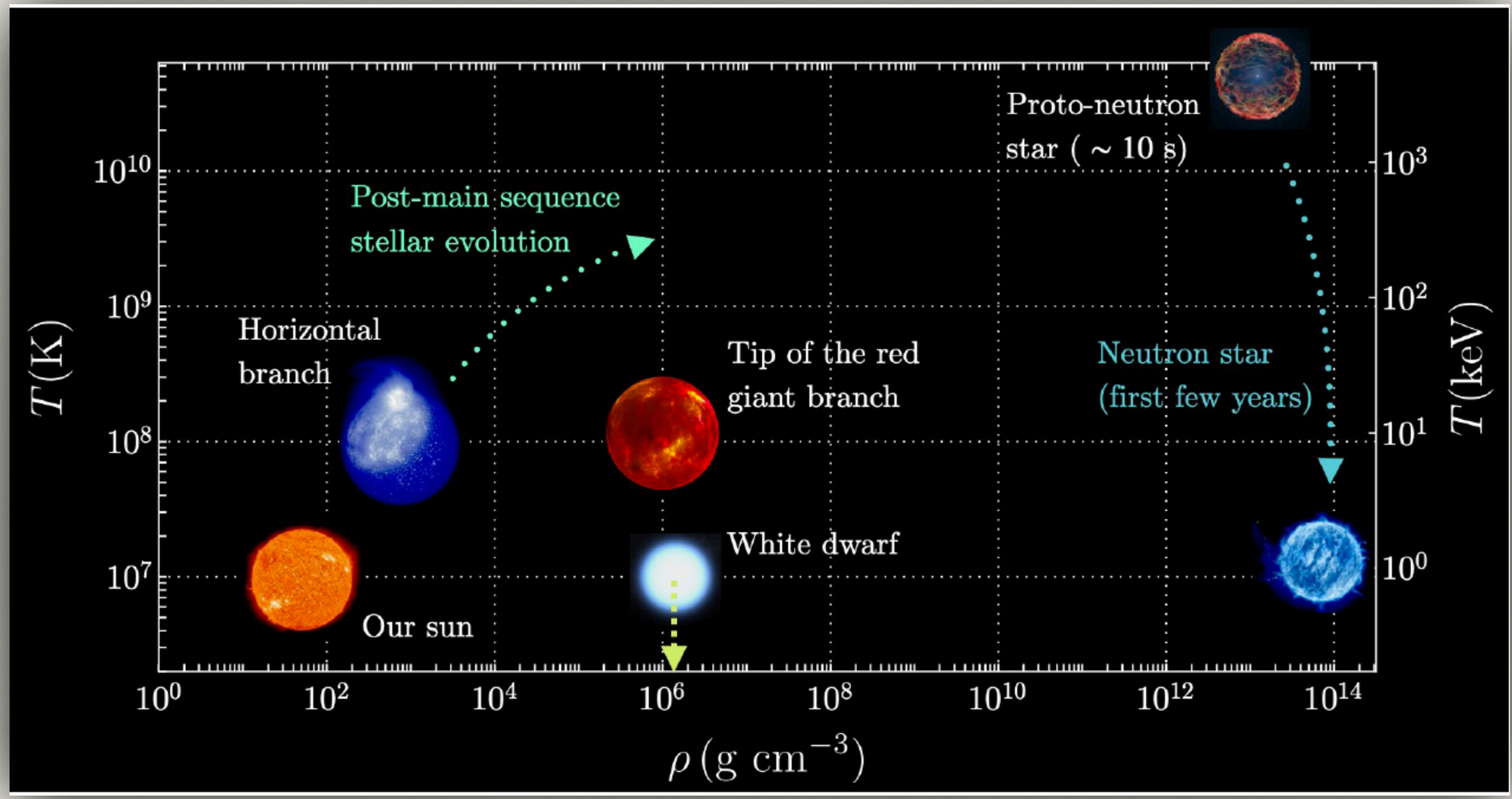
- Third, new produced particles can produce SM decay products.





Stars as a laboratory

Caputo, G. Raffel, E.Vitagliano, *Phys.Rev.D* 105 (2022) 3, 035022
Caputo, T.H. Janka, G. Raffel, E.Vitagliano, *Phys.Rev.Lett.* 128 (2022) 22, 221103

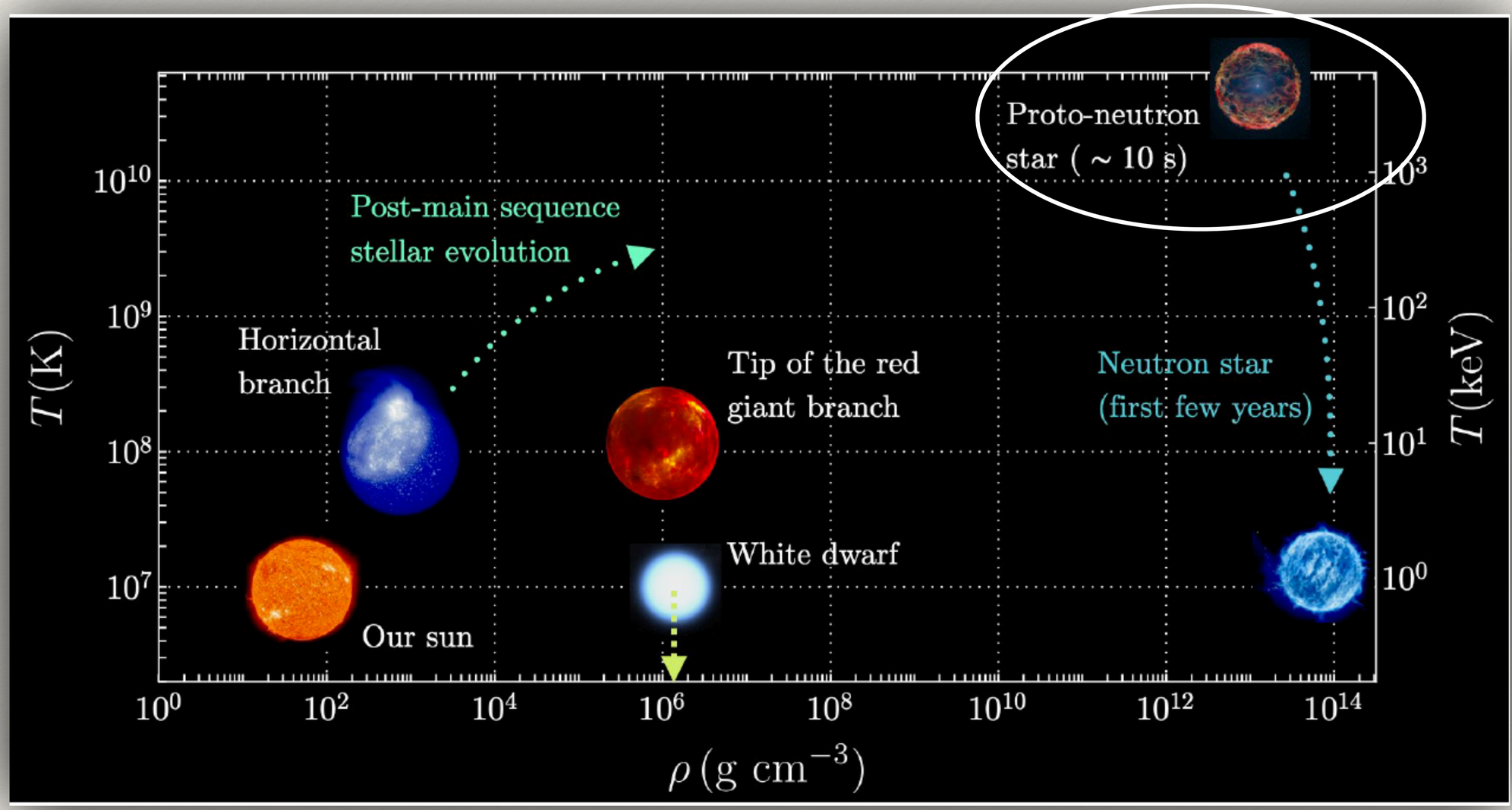


Caputo, A. Millar, E.Vitagliano, *Phys.Rev.D* 101 (2020) 12, 123004
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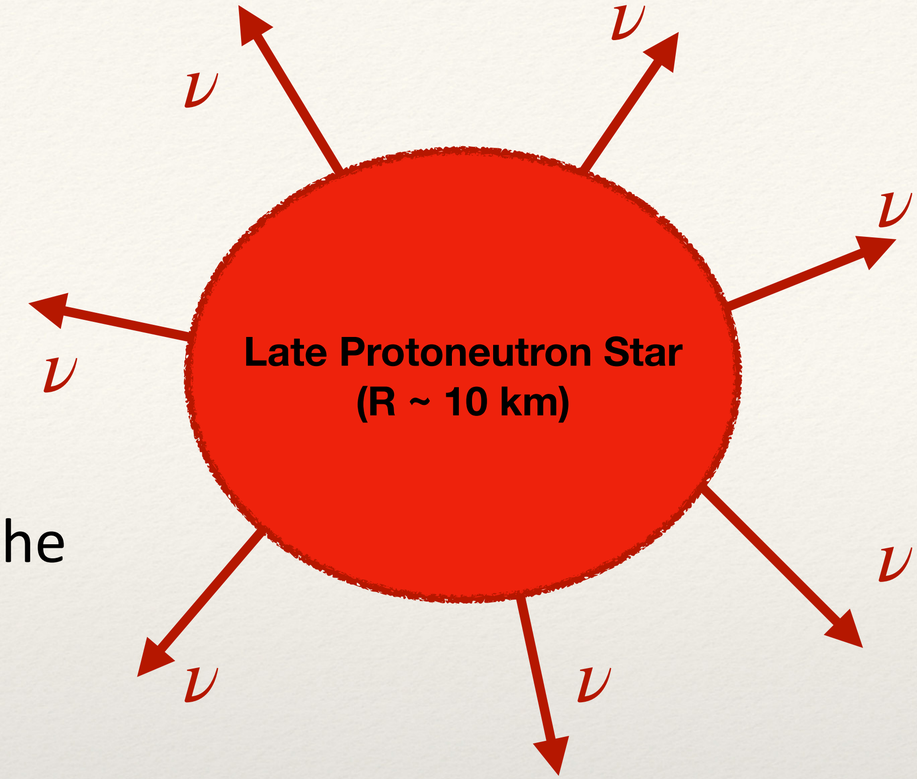
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One target example: Supernovae

PNS: protoneutron star

- $r \approx 10\ km$
- T $\approx 40\ MeV$
- Nuclear density

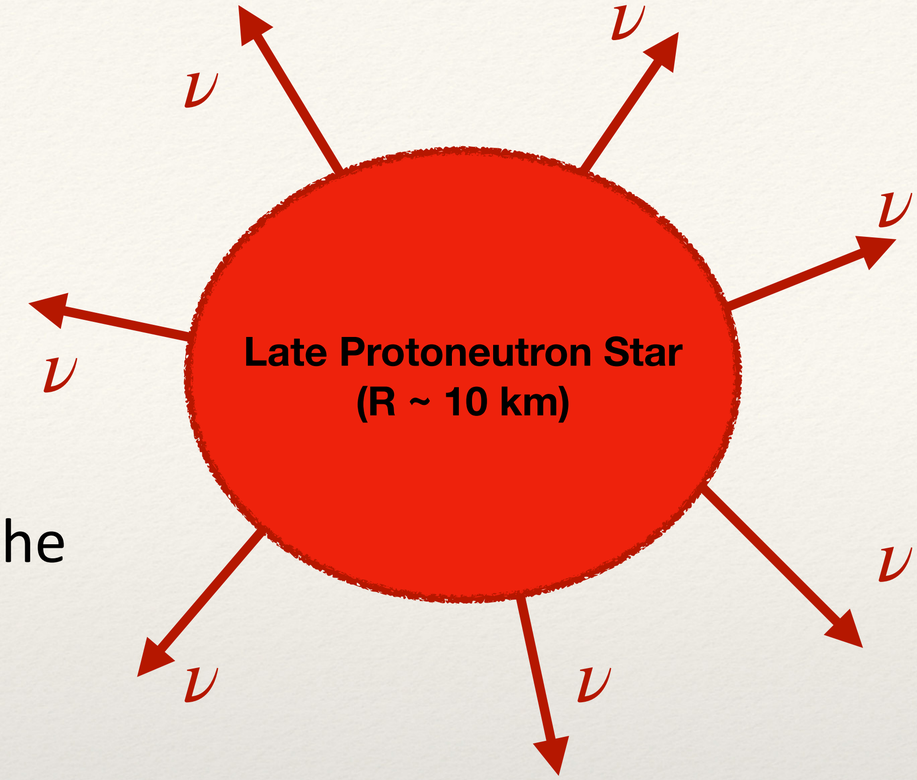
Neutrino emitted from the “neutrino sphere”, cooling the PNS in $\sim 10s$



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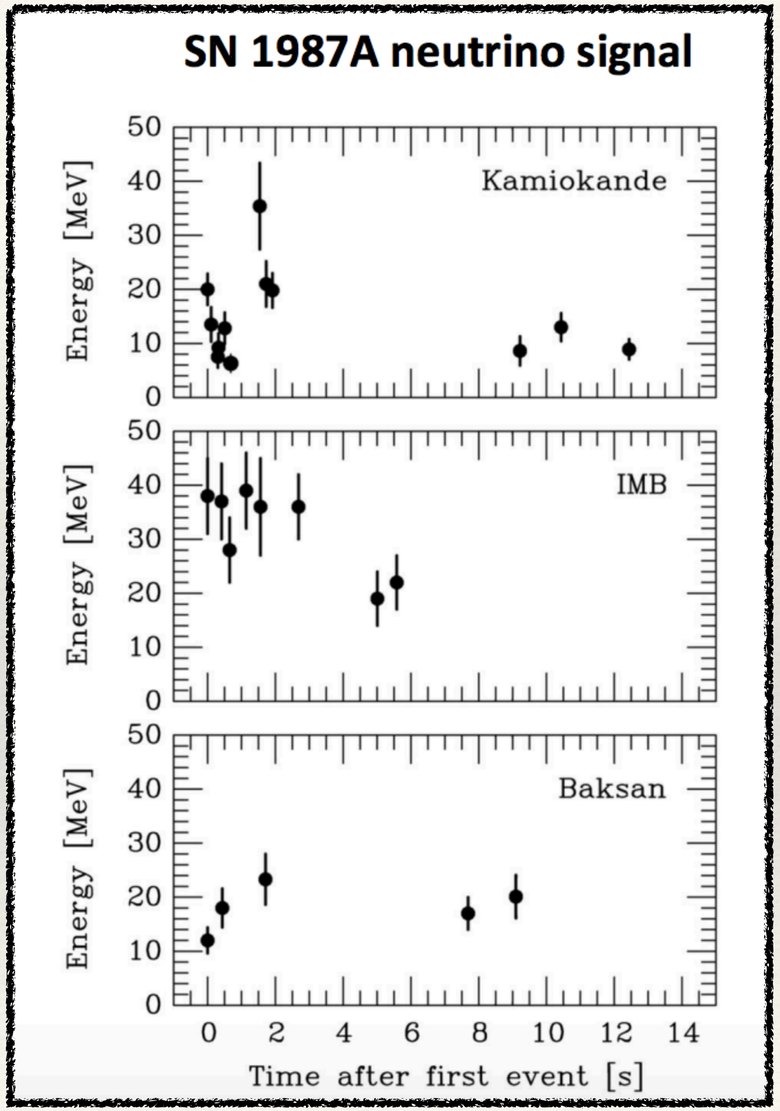


$$E_b \sim \frac{3}{5}\frac{G_N M^2}{R} = 1.6 \times 10^{53}\,\mathrm{erg}\left(\frac{\mathrm{M}}{\mathrm{M}_\odot}\right)^2\left(\frac{10\,\mathrm{km}}{\mathrm{R}}\right)$$

$$T = \frac{2}{3} < E_{\mathrm{kin}} > \sim 17\,\mathrm{MeV}$$

$$t_{\mathrm{diff}} \sim R^2/\lambda$$

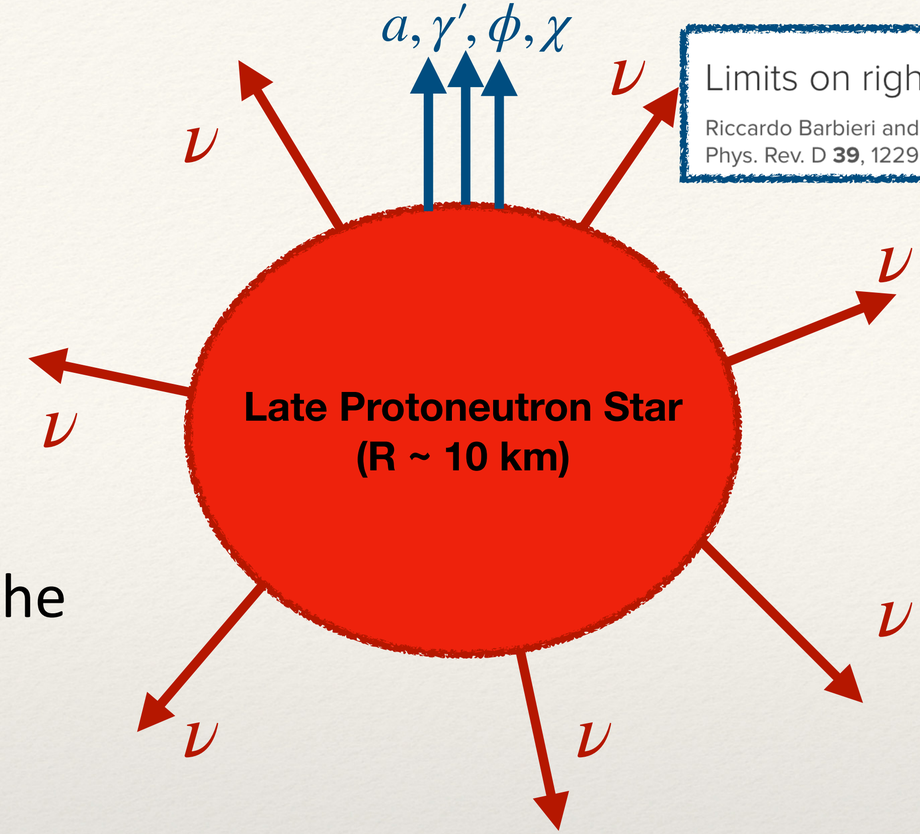




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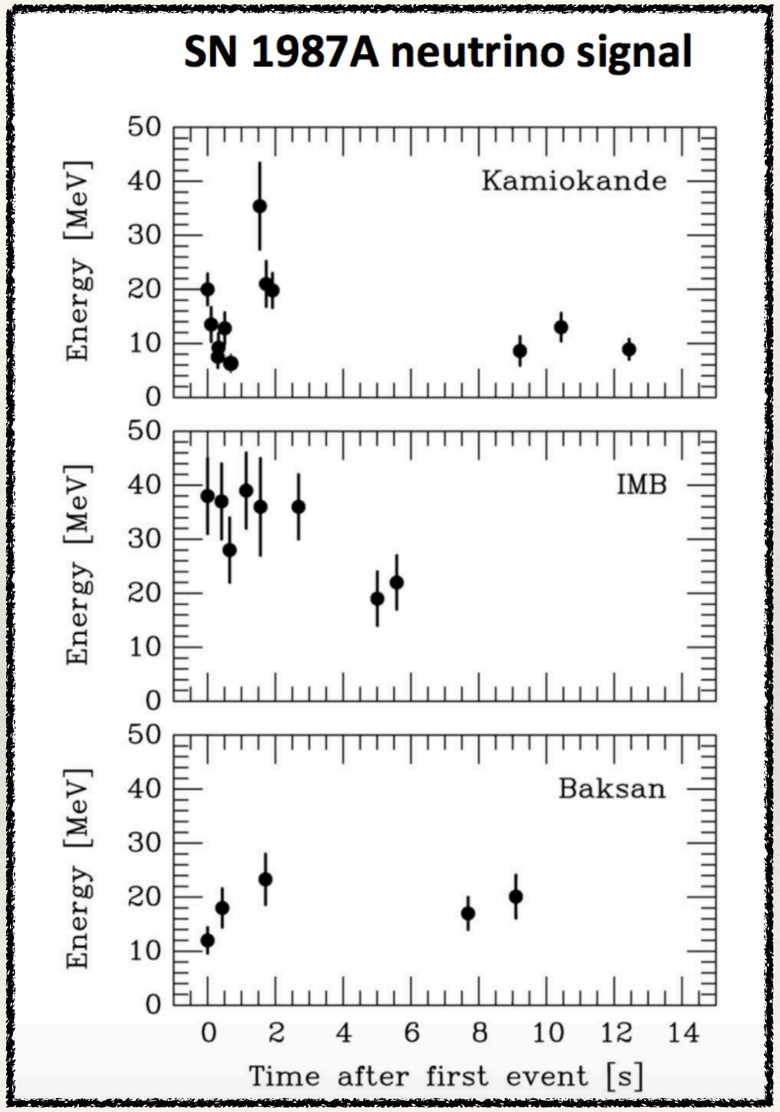
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Limits on right-handed interactions from SN 1987A observations

Riccardo Barbieri and Rabindra N. Mohapatra
Phys. Rev. D **39**, 1229 – Published 15 February 1989



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Example model: axion coupling to photons

$$L_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma} \tilde{F}^{\mu\nu} F_{\mu\nu}$$

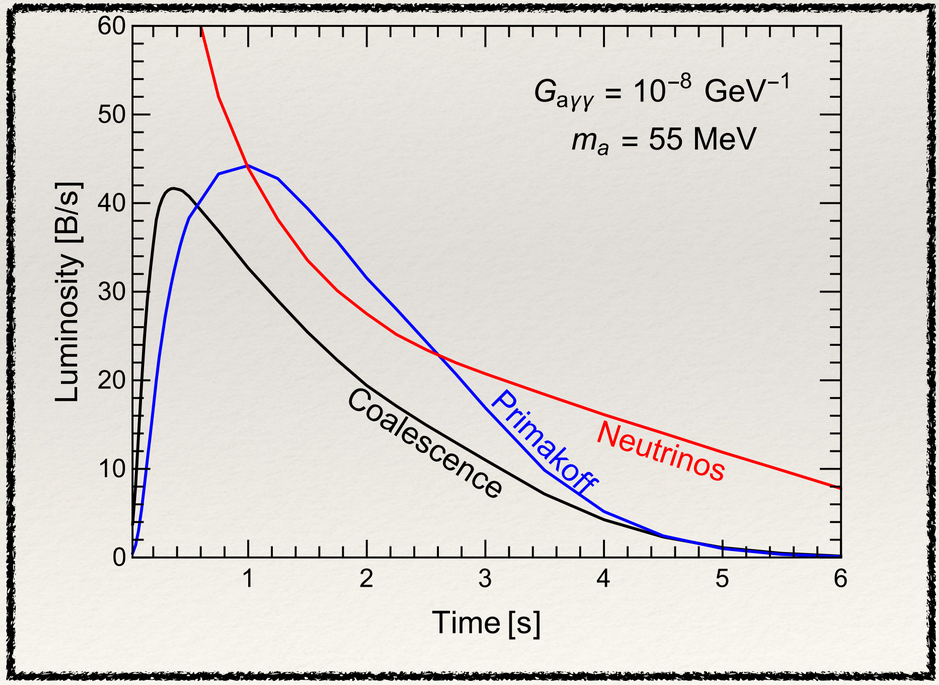
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$$Q_a = \int \frac{2d^3\mathbf{k}}{(2\pi)^3} \frac{\omega}{e^{\omega/T} - 1} \hat{n}\sigma_{\rm P}$$

$$= \hat{n}\,\alpha G_{a\gamma\gamma}^2 \frac{\pi^2 T^4}{30} \langle f_{\rm P} \rangle,$$

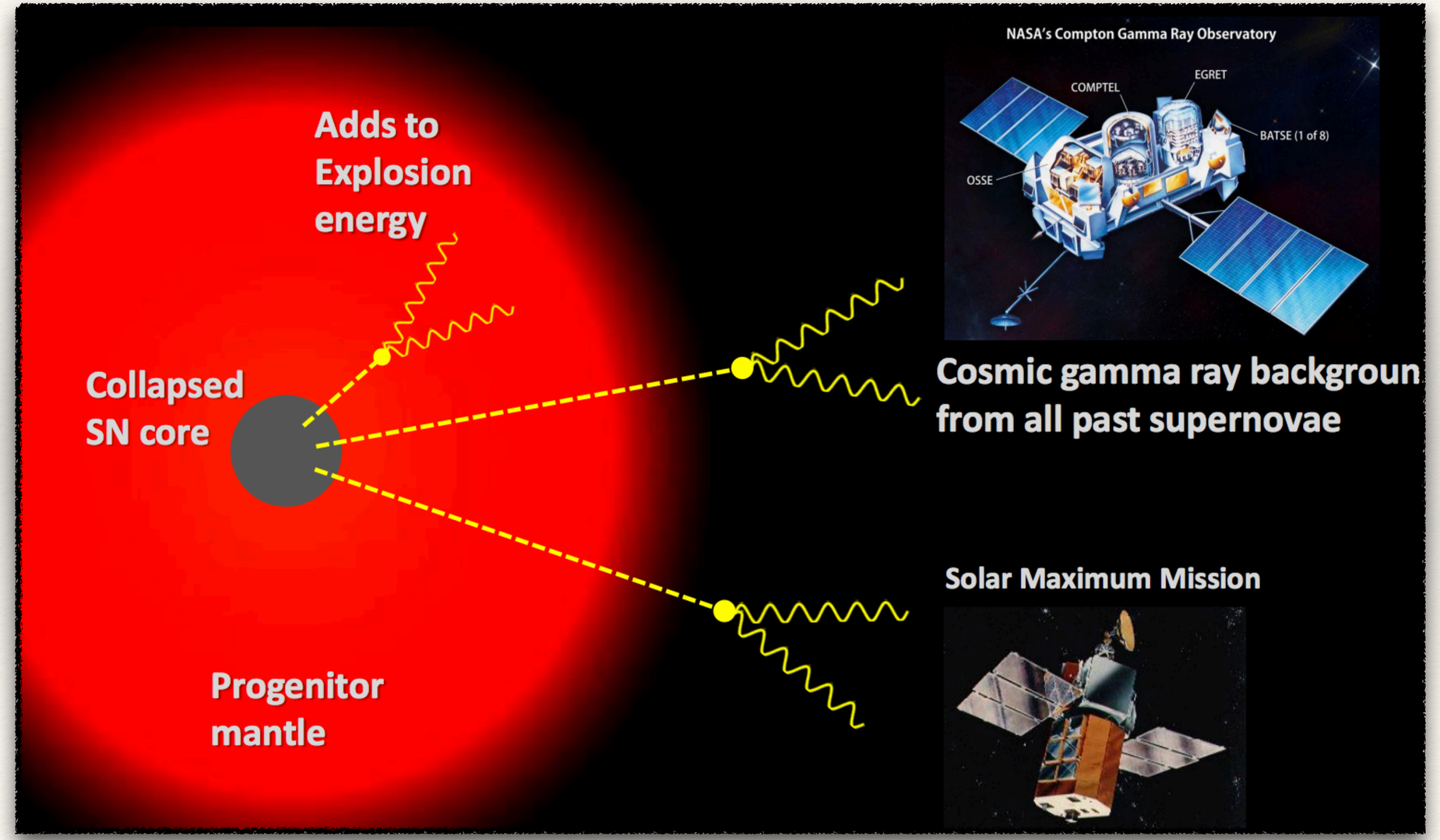
Primakoff



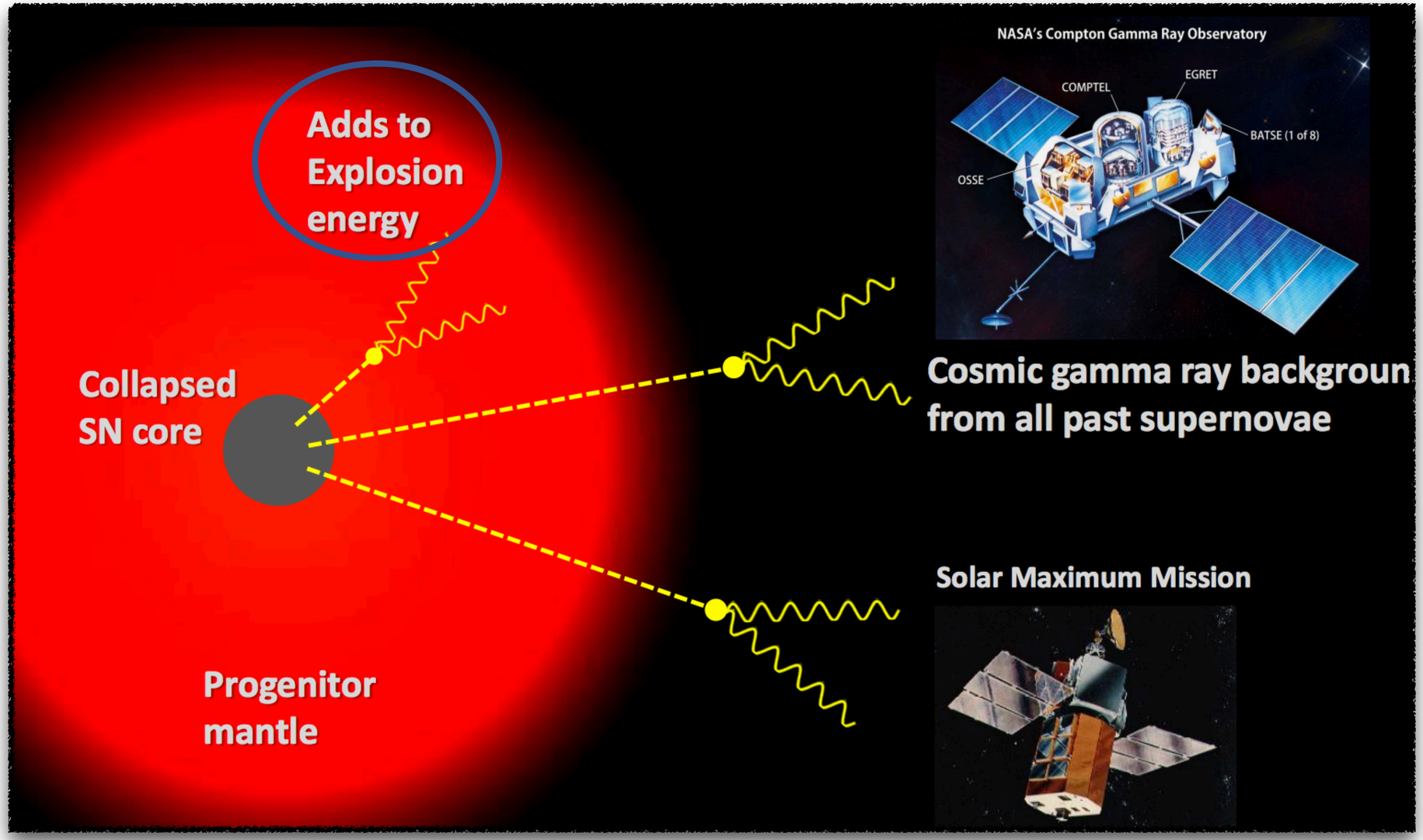
$$Q_a = \int \frac{d^3\mathbf{p}}{(2\pi)^3}\, \omega\, e^{-\omega/T} \Gamma_{\rm A} = \frac{G_{a\gamma\gamma}^2 T^3 m_a^4}{128\pi^3} F(m_a/T)$$

Coalescence

Use these SNe to get a bound on exotic particles which decay into SM relics



Use these SNe to get a bound on exotic particles which decay into SM relics



The axions get produced and then can decay back into photons!

$$\lambda_{a\to 2\gamma} = \frac{64\pi}{G_{a\gamma\gamma}^2}\,\frac{\sqrt{E_a^2 - m_a^2}}{m_a^4} \simeq \frac{4.0\times 10^{13}\,\mathrm{cm}}{G_9^2}\,\frac{E_{100}}{m_{10}^4}$$

Gamma ray photons **quickly absorbed** by pair production on nuclei and electrons

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So axions are produced in the SN core and they then **decay in the SN mantle**, they can **dump energy** which should then show up either in **kinetic energy or radiation energy**.

$$E_{\mathrm{mantle}} = \int dt \int_0^{R_{\mathrm{NS}}} dR \int_{m_a'(R)}^{\infty} dE_a\, \frac{dL_a(R, E_a, t)}{dR\, dE_a}$$
$$\times \left\{\exp[-(R_{\mathrm{NS}} - R)/\lambda_a] - \exp[-(R_* - R)/\lambda_a]\right\},$$

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Neutron star radius

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Neutron star radius

Progenitor radius

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Neutron star radius — Progenitor radius — Axion MFP

Low-energy Supernovae (LESNe)

- 10–100 times dimmer than normal core-collapse SNe (CCSNe)
- 2–3 times lower photospheric expansion velocities
- Observations point to **0.1 B** (or smaller) explosion energies

nature

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nature › letters › article

Published: 04 June 2009

A low-energy core-collapse supernova without a hydrogen envelope

S. Valenti ✉, A. Pastorello, E. Cappellaro, S. Benetti, P. A. Mazzali, J. Manteca, S. Taubenberger, N. Elias-Rosa, R. Ferrando, A. Harutyunyan, V. P. Hentunen, M. Nissinen, E. Pian, M. Turatto, L. Zampieri & S. J. Smartt

Mon. Not. R. Astron. Soc. **347,** 74–94 (2004)

Low-luminosity Type II supernovae: spectrosc and photometric evolution

A. Pastorello,[1,2,5★] L. Zampieri,[2] M. Turatto,[2] E. Capp
S. Benetti,[2] D. Branch,[5] E. Baron,[5] F. Patat,[6] M. Arms
M. Salvo[8] and M. Riello[2,1]

[1]*Dipartimento di Astronomia, Università di Padova, Vicolo dell' Osservatorio 2, I-35122 Padova,*
[2]*INAF – Osservatorio Astronomico di Padova, Vicolo dell' Osservatorio 5, I-35122 Padova, Italy*
[3]*INAF – Osservatorio Astronomico di Capodimonte, Via Moiariello 16, I-80131 Napoli, Italy*
[4]*Astrophysics Group, Blackett Laboratory, Imperial College, Prince Consort Road, London SW7*
[5]*Department of Physics and Astronomy, University of Oklahoma, 440 W. Brooke St., Norman, OK*
[6]*European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748, Garching bei Munche*
[7]*UK Supernova Patrol, British Astronomical Association, Rolvenden, Kent*
[8]*Australian National University, Mount Stromlo Observatory, Cotter Road, Weston ACT 2611, Au*

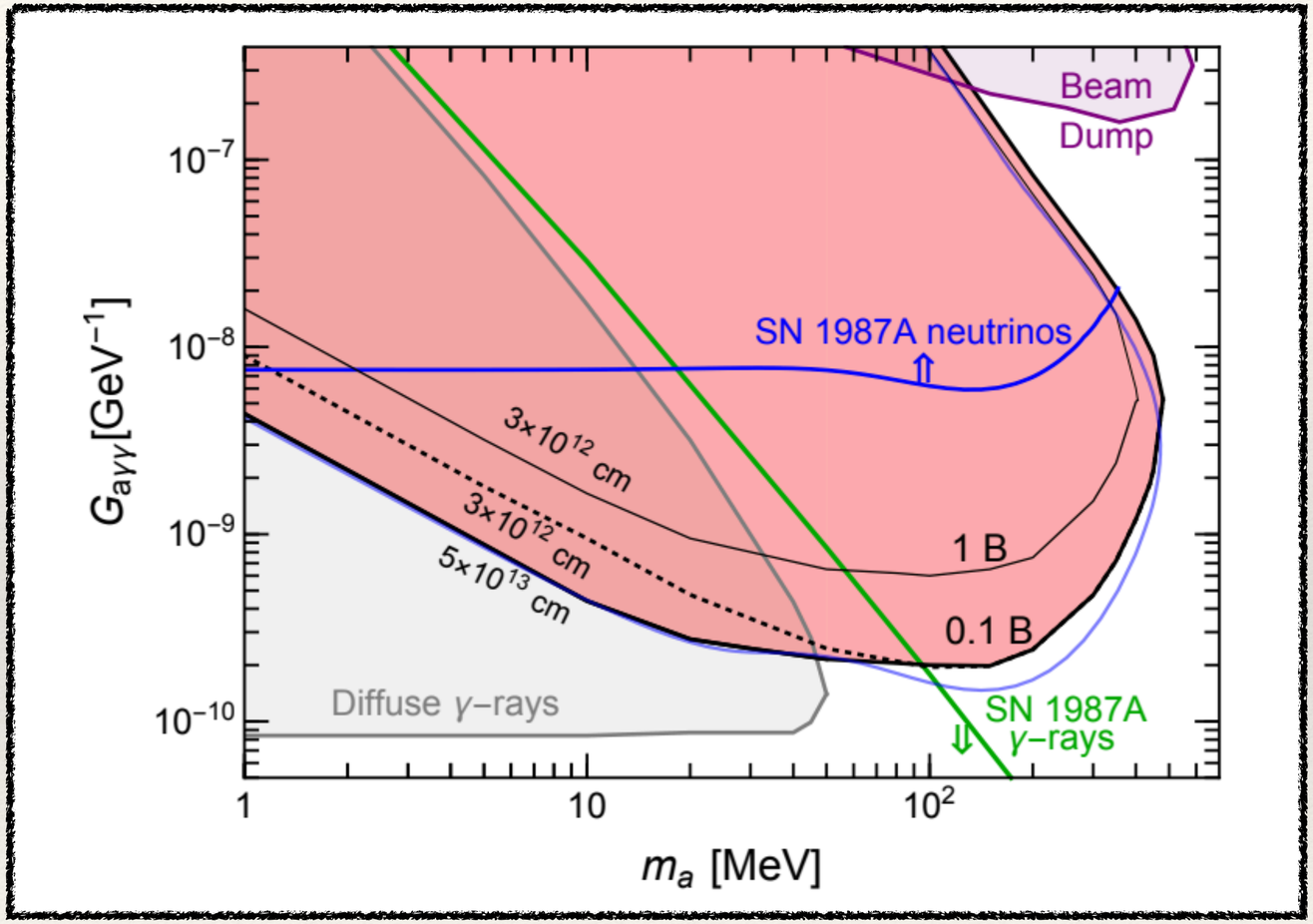
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **439,** 2873–2892 (2014) doi:10.1093/mnras/stu156
Advance Access publication 2014 February 21

Low luminosity Type II supernovae – II. Pointing towards moderate mass precursors

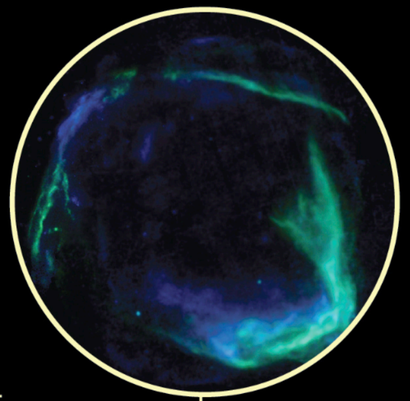
S. Spiro,[1★] A. Pastorello,[1] M. L. Pumo,[1,2] L. Zampieri,[1] M. Turatto,[1] S. J. Smartt,[3]
S. Benetti,[1] E. Cappellaro,[1] S. Valenti,[4,5] I. Agnoletto,[1] G. Altavilla,[6] T. Aoki,[7]
E. Brocato,[8] E. M. Corsini,[1,9] A. Di Cianno,[10] N. Elias-Rosa,[11] M. Hamuy,[12]
K. Enya,[13] M. Fiaschi,[9] G. Folatelli,[14] S. Desidera,[1] A. Harutyunyan,[15]
D. A. Howell,[4,5] A. Kawka,[16] Y. Kobayashi,[17] B. Leibundgut,[18] T. Minezaki,[7]
H. Navasardyan,[1] K. Nomoto,[19,20] S. Mattila,[21] A. Pietrinferni,[10] G. Pignata,[22]
G. Raimondo,[10] M. Salvo,[23] B. P. Schmidt,[23] J. Sollerman,[24] J. Spyromilio,[18]
S. Taubenberger,[25] G. Valentini,[10] S. Vennes[16] and Y. Yoshii[7]

Imposing the energy deposit in the mantle is not too big gives very strong bounds.



Caputo, H.T. Janka, G. Raffelt, E. Vitagliano, *Phys.Rev.Lett.* 128 (2022) 22, 221103

Why this is exciting to me?



A.D.185

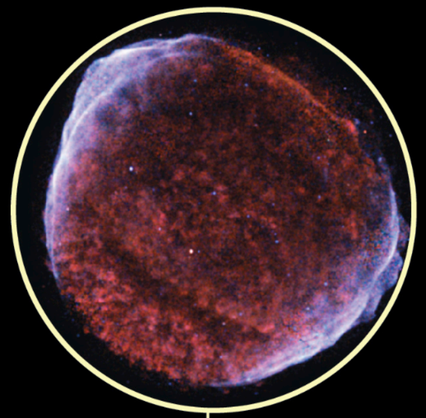
RCW 86

Historical Observers: Chinese

Likelihood of Identification: Possible

Distance Estimate: 8,200 light years

Type: Core collapse of massive star



A.D. 386

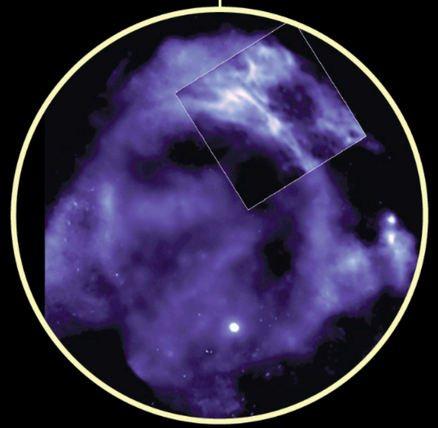
G347.3-0.5

Historical Observers: Chinese

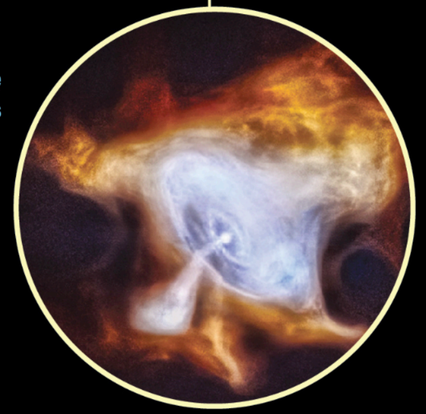
Likelihood of Identification: Possible

Distance Estimate: 3,000 light years

Type: Core collapse of massive star



LIGHT YEAR: the distance hat light, moving at a onstant speed of 300,000 m/s, travels in one year. One light year is just under 0 trillion kilometers.



A.D. 1006

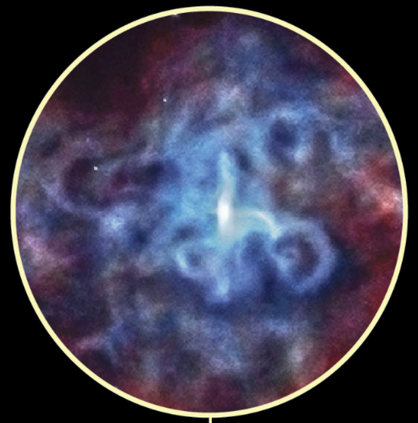
Crab Nebula

Historical Observers: Chinese, Japanese, Arabic, Native American

Likelihood of Identification: Definite

Distance Estimate: 6,000 light years

Type: Core collapse of massive star



A.D. 393

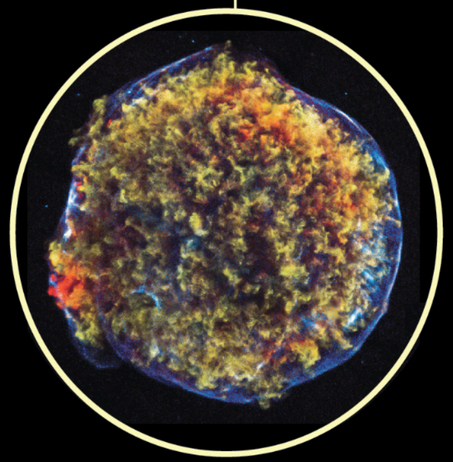
SN 1006

Historical Observers: Chinese, Japanese, Arabic, European

Likelihood of Identification: Definite

Distance Estimate: 7,000 light years

Type: Thermonuclear explosion of white dwarf



A.D. 1054

3C58

Historical Observers: Chinese, Japanese

Likelihood of Identification: Possible

Distance Estimate: 10,000 light years

Type: Core collapse of massive star

A.D. 1572

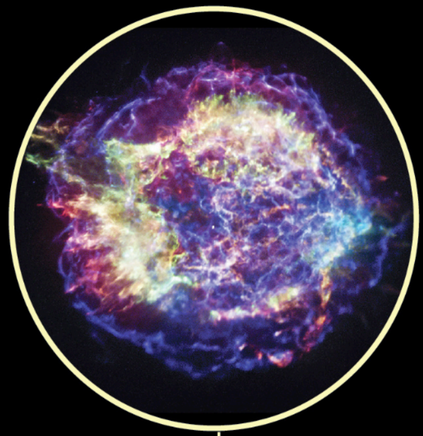
Tycho's SNR

Historical Observers: European, Chinese, Korean

Likelihood of Identification: Definite

Distance Estimate: 7,500 light years

Type: Thermonuclear explosion of white dwarf



A.D. 1680

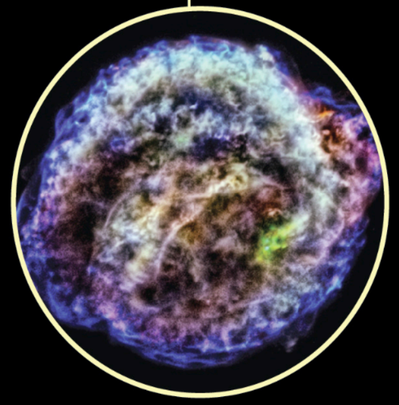
Cassiopeia A

Historical Observers: European?

Likelihood of Identification: Unlikely

Distance Estimate: 10,000 light years

Type: Core collapse of massive star



A.D. 1604

Kepler's SNR

Historical Observers: European, Chinese, Korean

Likelihood of Identification: Definite

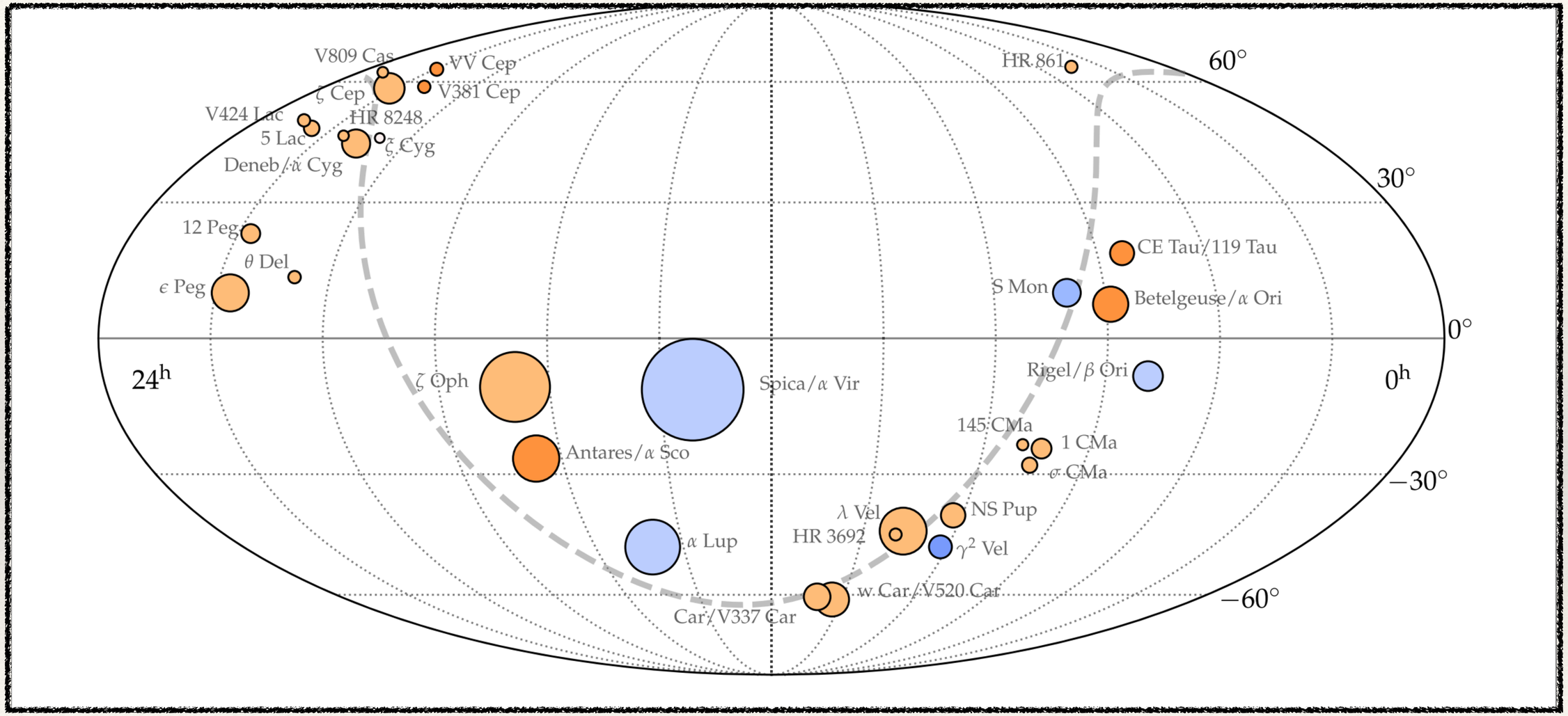
Distance Estimate: 13,000 light years

Type: Thermonuclear explosion of white dwarf?

NEWS FEATURE | 21 February 2022

A supernova could light up the Milky Way at any time. Astronomers will be watching

Next SN candidates within 1 kpc from us



Plans for the future

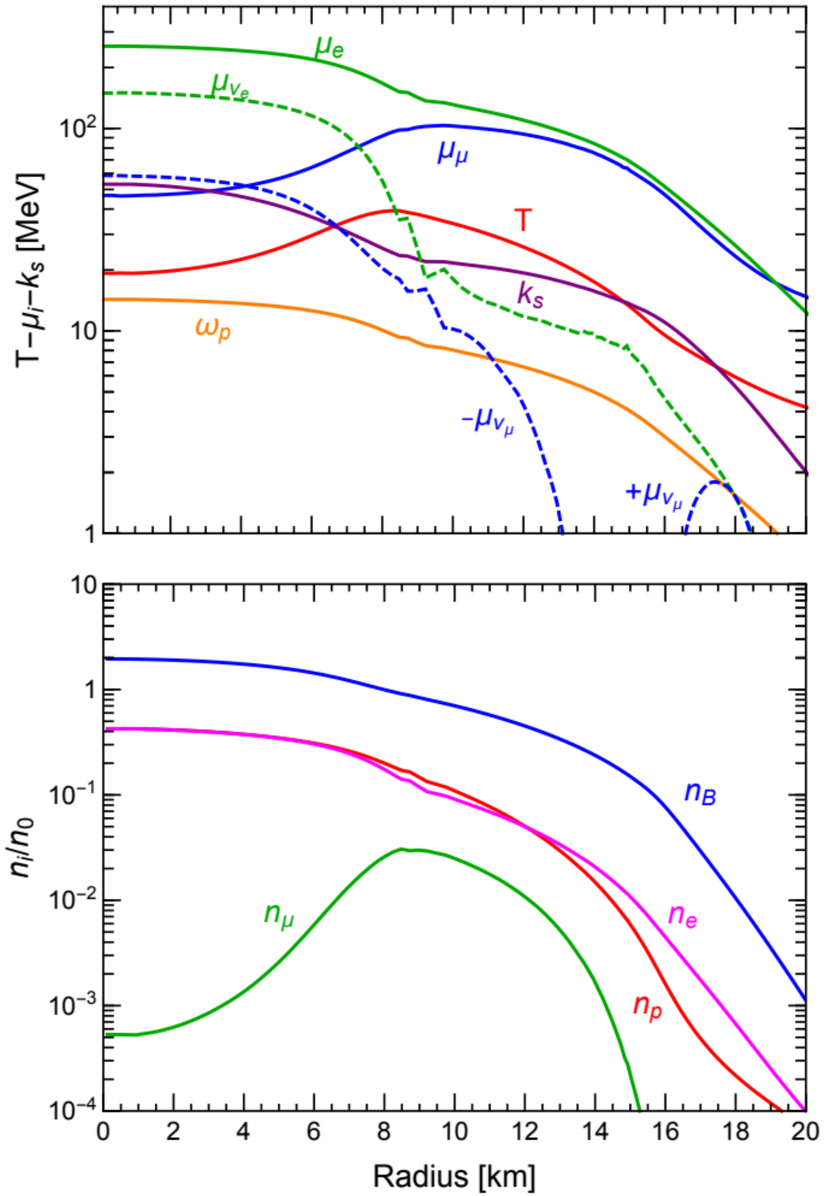
- Detailed simulations and output from radiative transport simulations in supernovae;
- Extension of the LESN criterion to other relevant models;
- Investigate better neutrino opacities in SN (Standard Model Physics);
- Cross-correlation studies for line intensity mapping + foreground analysis + extension to other dark matter models.

Thanks for the attention!



Back-up slides

Garching SN model



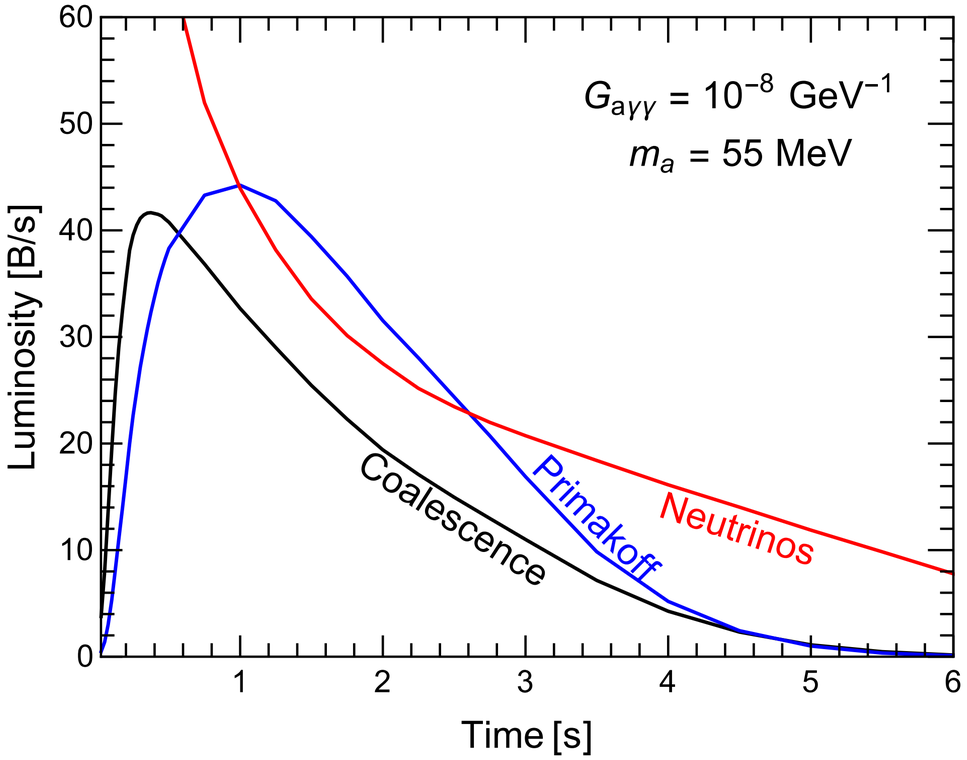
Primakoff and Coalescence calculation

$$Q_a = \int \frac{2d^3\mathbf{k}}{(2\pi)^3} \frac{\omega}{e^{\omega/T}-1} \hat{n}\sigma_{\rm P} \qquad \sigma_{\rm P} = \frac{Z^2\alpha G_{a\gamma\gamma}^2}{2} f_{\rm P}$$

$$= \hat{n}\,\alpha G_{a\gamma\gamma}^2 \frac{\pi^2 T^4}{30} \langle f_{\rm P}\rangle, \qquad \langle f_{\rm P}\rangle = 20 \frac{m_a^2 + 3m_a T + 3T^2}{\pi^4 T^2} e^{-m_a/T}$$

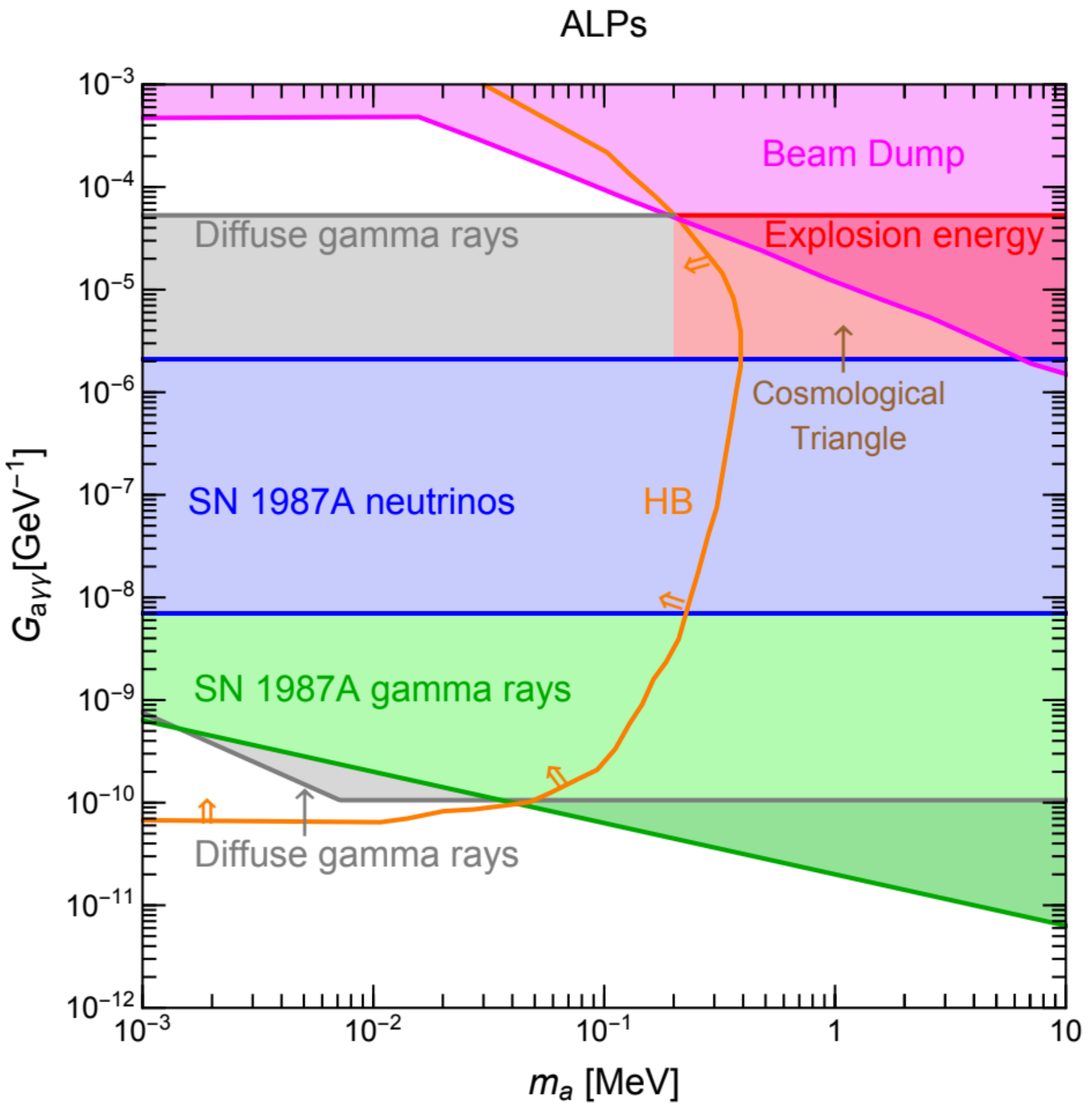
$$Q_a = \int \frac{d^3\mathbf{p}}{(2\pi)^3} \omega\, e^{-\omega/T} \Gamma_{\rm A} = \frac{G_{a\gamma\gamma}^2 T^3 m_a^4}{128\pi^3} F(m_a/T)$$

$$F(\mu) = \int_\mu^\infty dx\, x\sqrt{x^2-\mu^2}\, e^{-x} f_{\rm B}$$

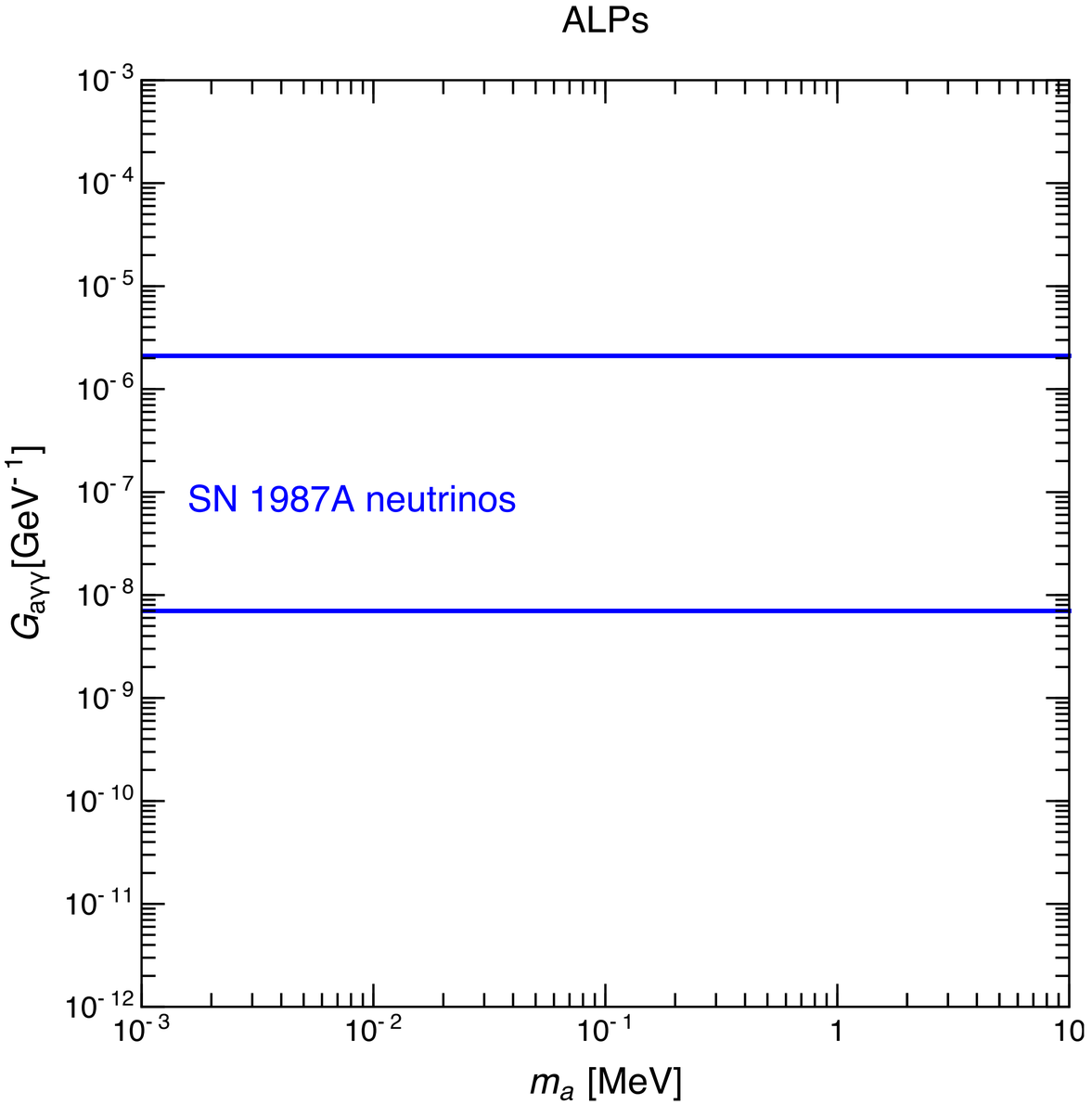


Other bounds

For masses above 1–10 MeV, muonphilic particles can also be efficiently probed at colliders. In particular, electron beam-dump experiments, such as the SLAC E137 experiment or the planned Jefferson Lab BDX experiment provide an excellent source of secondary muons, which can then be used to look for muonic (pseudo)scalars.

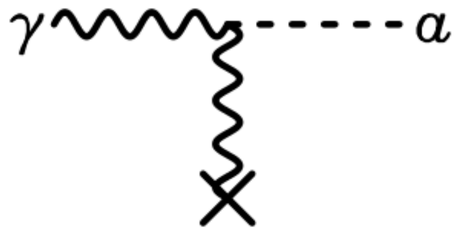


Cooling bounds from SN1987A (free streaming)



A.C, G. Raffelt and E. Vitagliano, arXiv 2109.03244 (PRD in press)

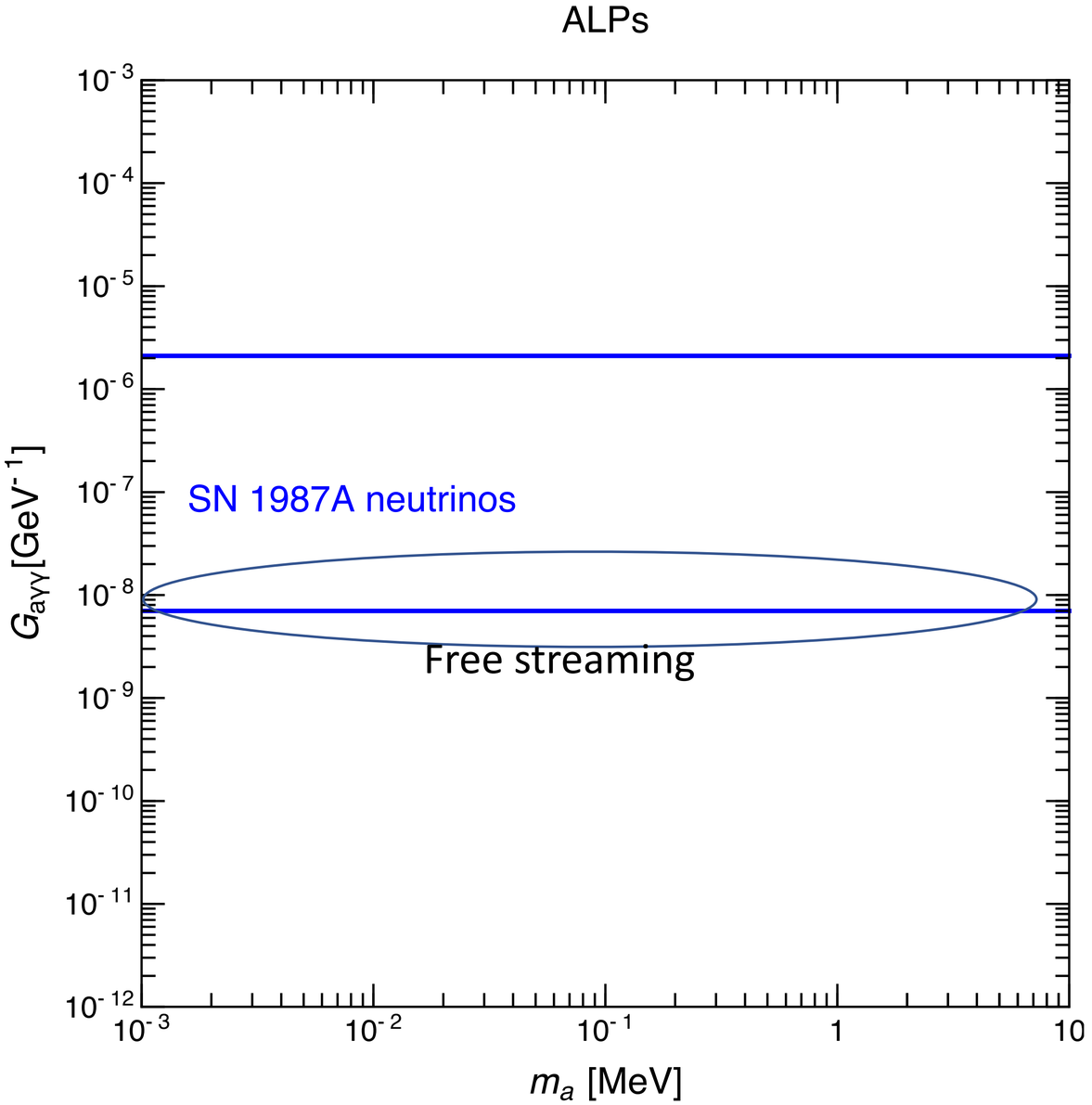
The duration of several seconds of the SN 1987A neutrino signal is incompatible with excessive energy loss in hypothetical new forms of radiation.
The main emission process is photo production on charged particles (aka Primakoff)



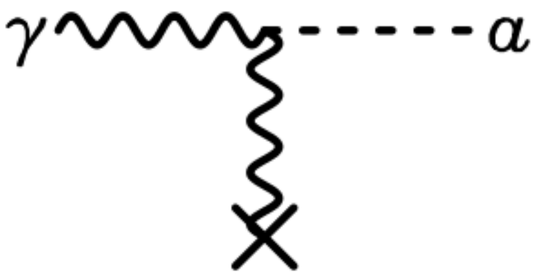
$$Q_{\rm P} \simeq \hat{n}\frac{2\alpha G_{a\gamma\gamma}^2}{3\pi^2}\left(m_a^2+3m_aT+3T^2\right)T^2e^{-m_a/T}$$

A.C, T. Janka, G. Raffelt and E. Vitagliano, in preparation

Cooling bounds from SN1987A



The duration of several seconds of the SN 1987A neutrino signal is incompatible with excessive energy loss in hypothetical new forms of radiation.
The main emission process in this case is photo-production on charged particles (aka Primakoff)

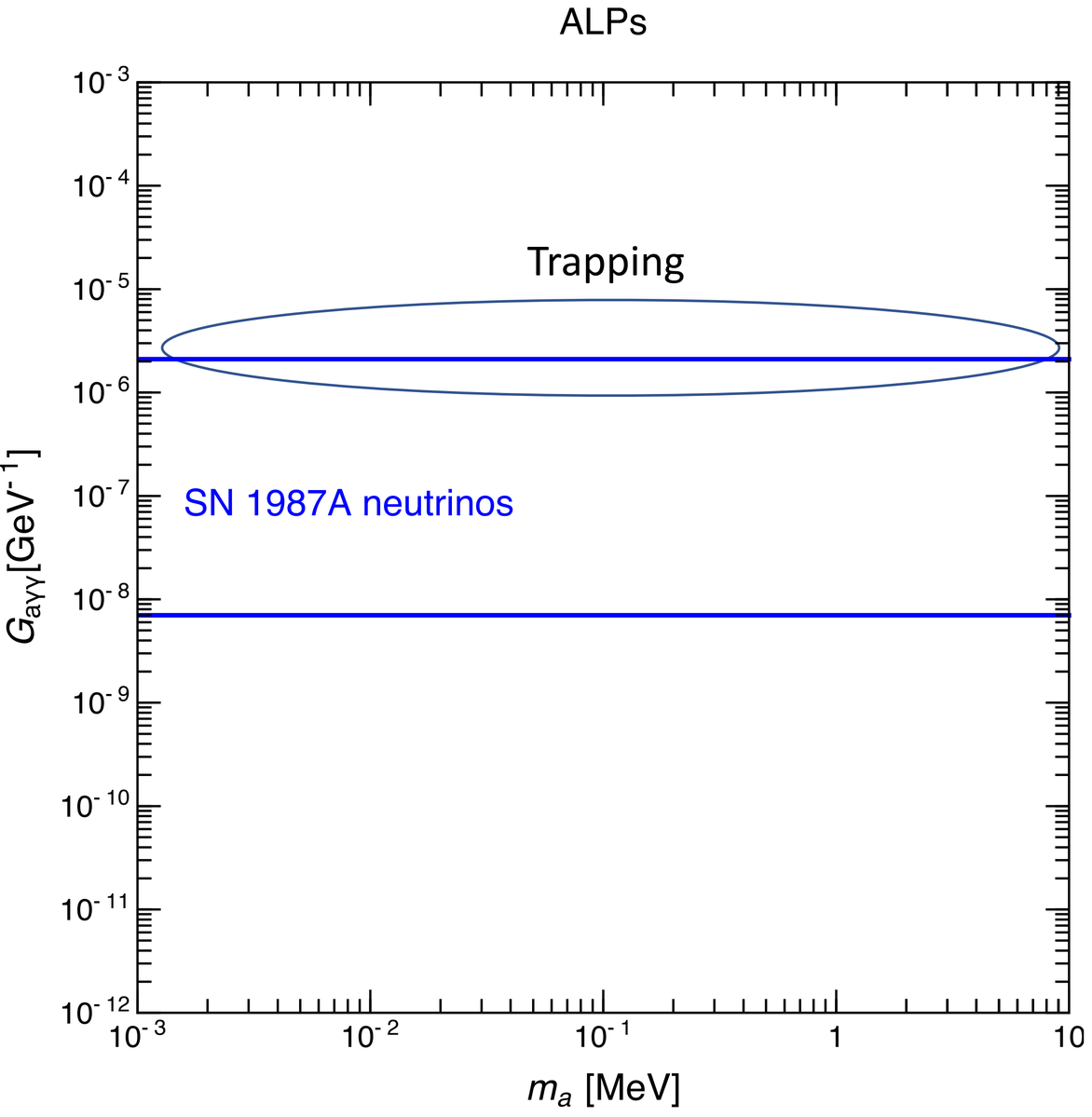


$$\epsilon_a < 10^{19} erg\ g^{-1} s^{-1}$$

Raffelt's criterion

A.C, G. Raffelt and E. Vitagliano, arXiv 2109.03244 (PRD in press)

Cooling bounds from SN1987A (trapping)



A.C, G. Raffelt and E. Vitagliano, arXiv 2109.03244 (PRD in press)

In the trapping limit, our bosons emerge from a region near the PNS surface whence they escape without being reabsorbed on their way out, in analogy to the neutrino sphere

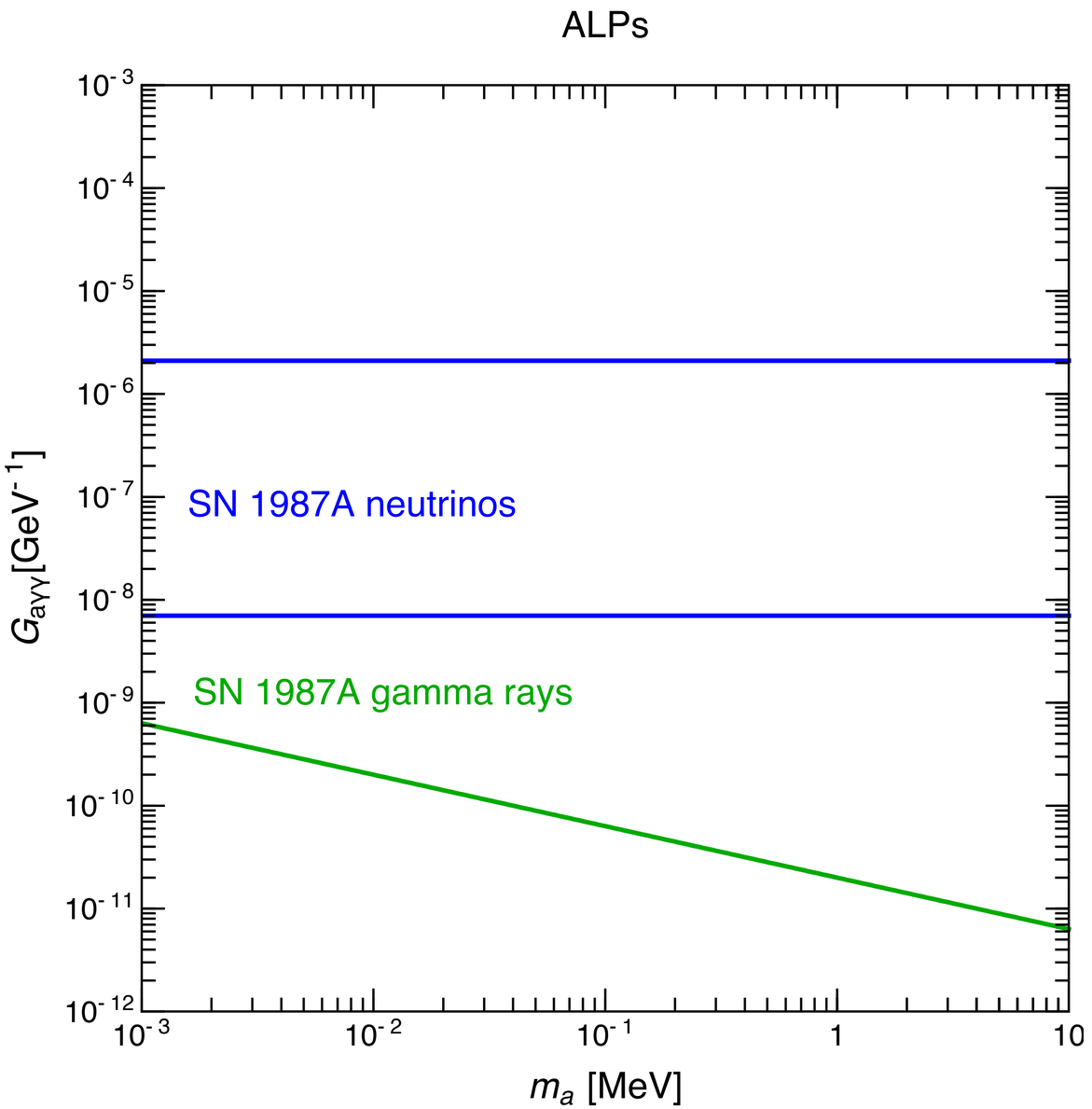
$$L_\phi = 4\pi R_\phi^2 \, \frac{\pi^2}{120} \, T^4(R_\phi)$$

The radius of emission is determined by the optical depth becoming of order one

$$\tau(r) = \int_r^\infty dr' \, \Gamma(r')$$

where in natural units the interaction rate is the same as the inverse mfp.

Bounds from Gamma-ray signals from SN1987A

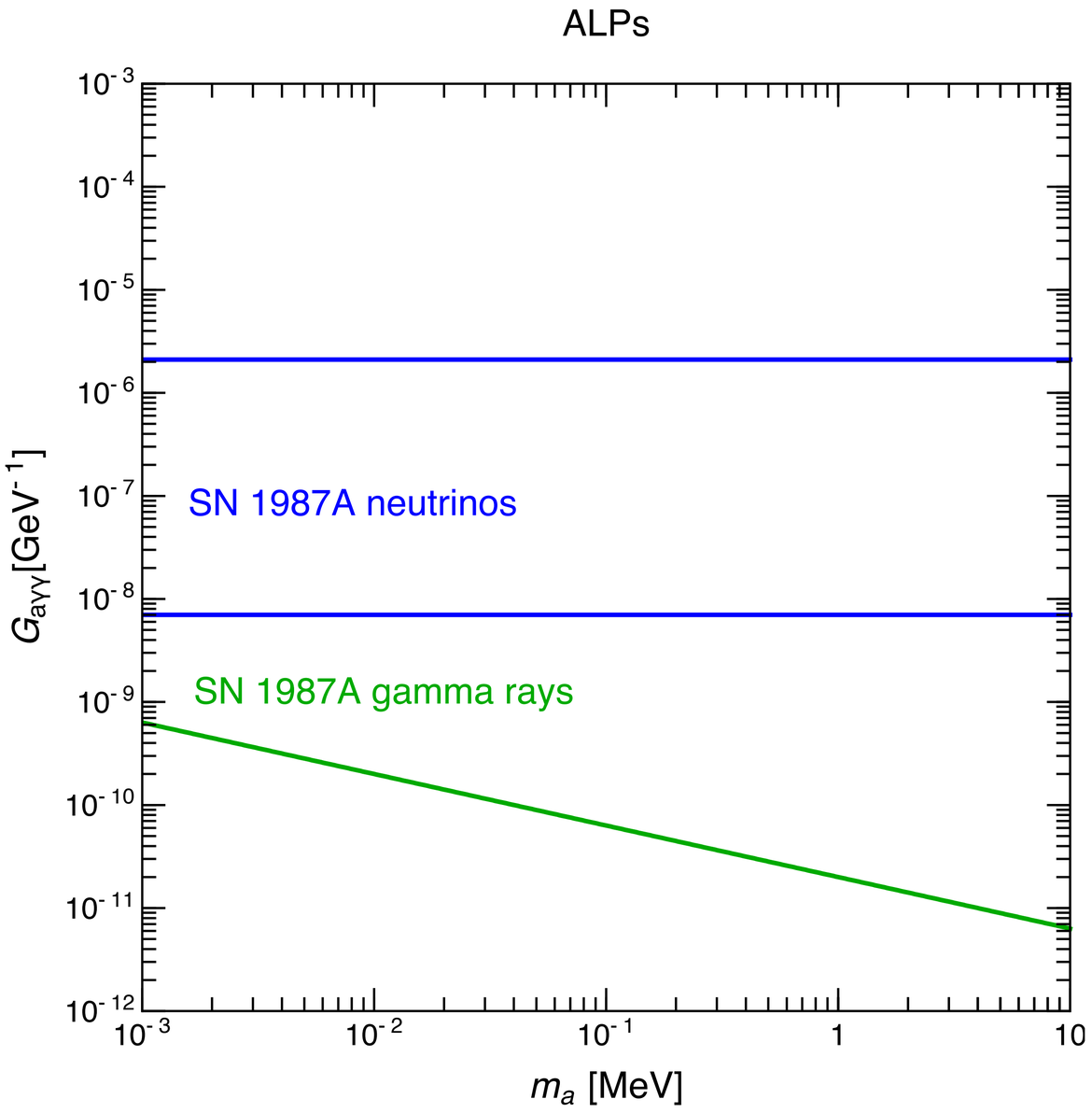


The (putative) produced bosons from 1987A could have decayed into photons, which would have been picked up by the Gamma-Ray Spectrometer (GRS) on board the Solar Maximum Mission (SMM) satellite that operated 02/1980–12/1989 .

$$\frac{dF_\gamma}{dE_\gamma dt} = 2\,\frac{2E_\gamma}{m_a\tau_a}\,e^{-2E_\gamma t/m_a\tau_a}\int_{E_\gamma}^{\infty} dE_a\,\frac{\Phi_a(E_a)}{E_a}$$

A.C, G. Raffelt and E. Vitagliano, arXiv 2109.03244 (PRD in press)

Bounds from Gamma-ray signals from SN1987A



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fluence

$$\frac{dF_\gamma}{dE_\gamma dt} = 2\,\frac{2E_\gamma}{m_a\tau_a}\,e^{-2E_\gamma t/m_a\tau_a}\int_{E_\gamma}^{\infty} dE_a\,\frac{\Phi_a(E_a)}{E_a}$$

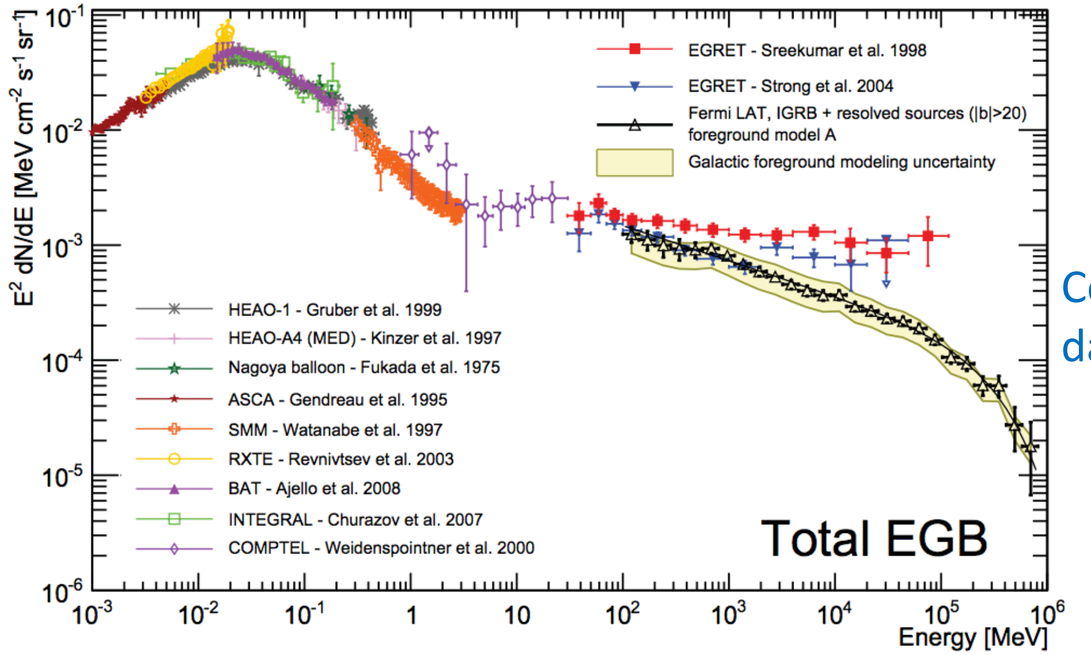
rest-frame boson lifetime

Good agreement with J. Jaeckel, P. C. Malta and J. Redondo, Phys. Rev. D 98 (2018) 055032, although we have been able to provide simple analytical expressions.

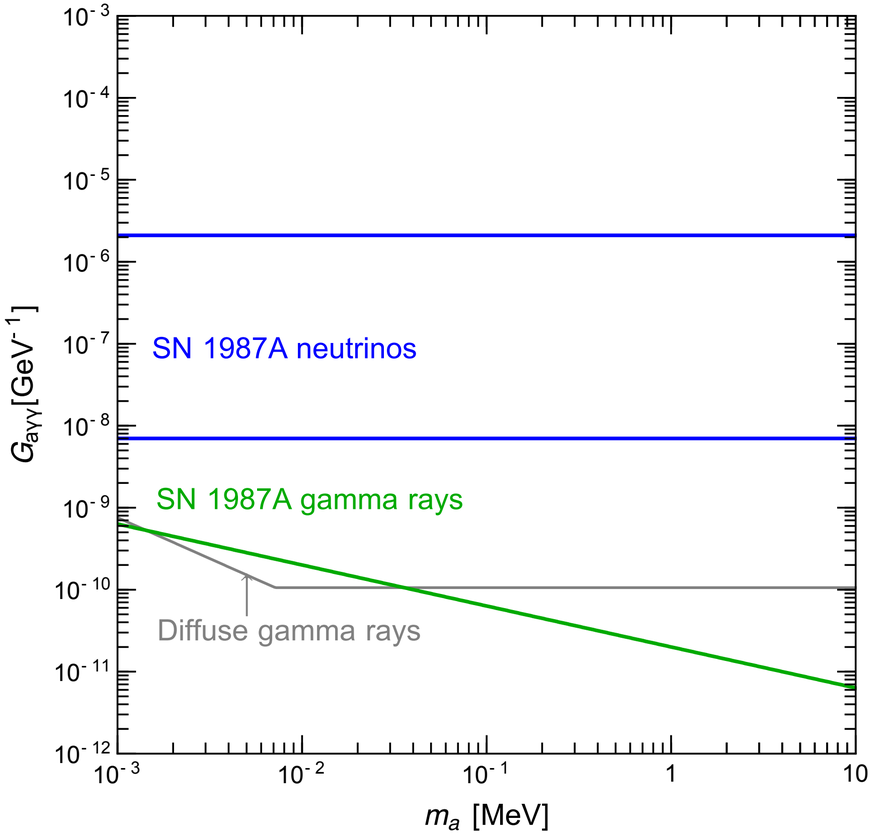
Diffuse SNe Gamma-rays

The scalar boson emission from all past SNe creates a cosmic background density in analogy to the diffuse SN neutrino background (DSNB). The radiative decays of these particles contribute to the diffuse cosmic γ-ray background and thus can be constrained.

$$\frac{dn_\gamma}{d\omega} = \int_0^\infty dz(1+z)n'_{\rm cc}(z)\int_{\omega_z}^\infty dE_z f_{\rm D}(E_z)\,\frac{2}{E_z}\,F_a(E_z)$$



Compare with data!



Fermi-LAT Collaboration, M. Ackermann et al, Astrophys. J. 799 (2015) 86

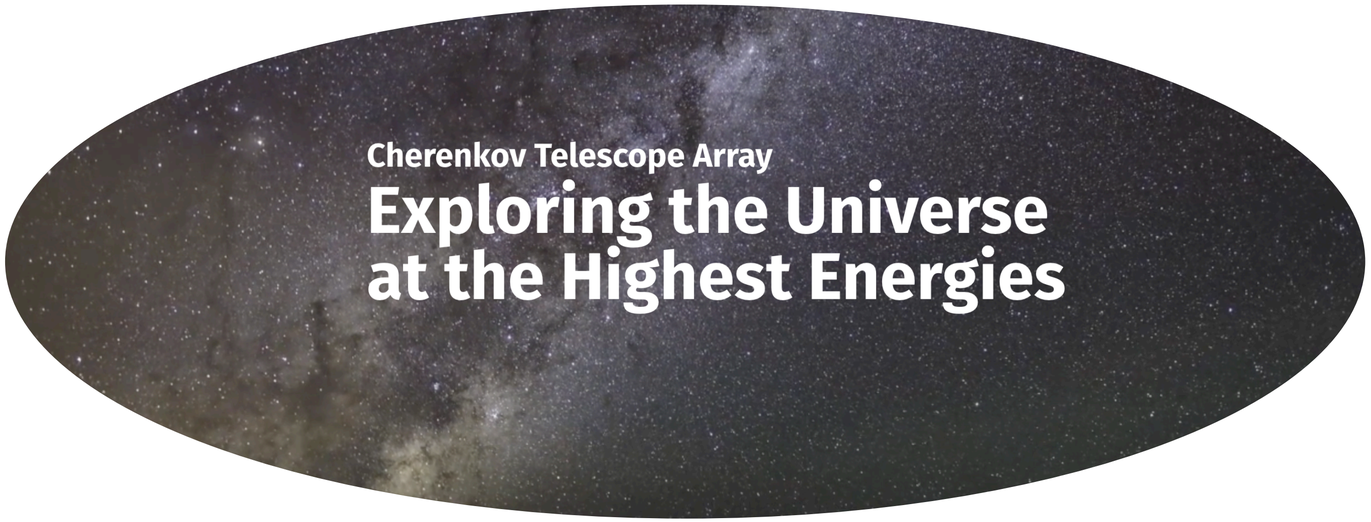
Diffuse SNe Gamma-rays

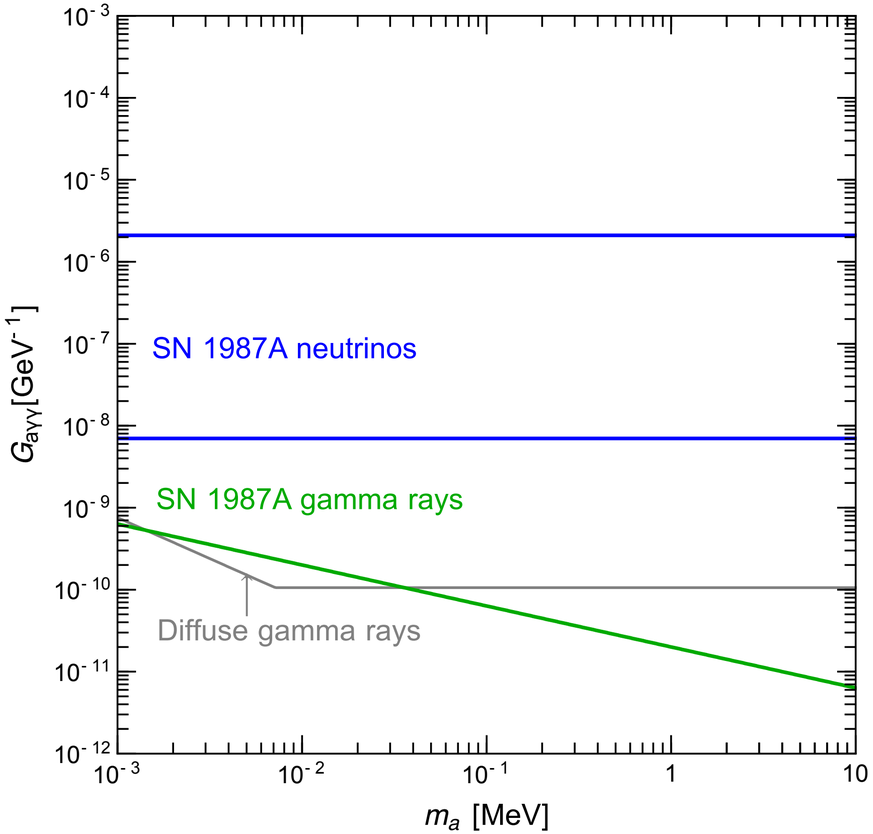
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ALPs

Future is exciting! Gamma-ray astronomy!





See also *JCAP* 02 (2015) 006 for a small axion masses and conversion in the MW magnetic field

X-rays cross-correlation

X-ray telescopes

	eROSITA	Athena WFI	Athena X-IFU
Energy range [keV]	0.3-10	0.1-12	0.3-12
$A_{\rm eff}$ at 3 keV [$\rm m^2$]	0.03	0.79	0.68
Ω_{FoV} [$\rm deg^2$]	0.66	0.69	0.014
HEW [arcsec]	28	5	5
Spectral resolution (FWHM) at 7 keV [eV]	138	138	2.5
$F_{\rm sens}$ [$\rm erg\ cm^{-2}\ s^{-1}$]	1.1×10^{-14}	2.4×10^{-17}	2.4×10^{-17}
Particle bkg [$\rm counts\ keV^{-1}\ s^{-1}\ sr^{-1}$]	1.2×10^{3}	1.2×10^{3}	5.8×10^{3}

Galaxy surveys

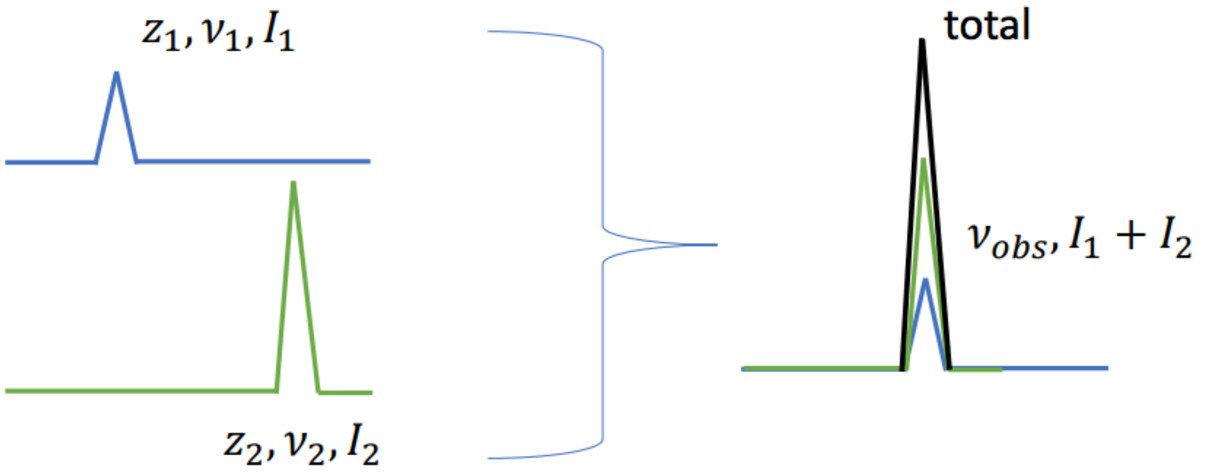
	2MPZ	SDSS	DES	DESI	Euclid	LSST
# of galaxies	6.7×10^5	1.5×10^7	2×10^8	3.5×10^7	2×10^9	3.6×10^9
Sky coverage	0.66	0.26	0.12	0.34	0.36	0.49
z-range	0-0.08	0.08-0.8	0.08-2	0-2	0-2	0-3
# of z-bins	1	4	6	132*	7	8

Line intensity mapping

Contamination of intensity maps

- Continuous foregrounds: problem for HI surveys, less severe at higher frequencies

- **Line interlopers**: Main problem for higher freq. LIM surveys
  - $\nu_{obs} = \nu/(1+z) = \nu'/(1+z') \rightarrow$ other lines redshifted to same ν_{obs}



Contamination of intensity maps

- Continuous foregrounds: problem for HI surveys, less severe at higher frequencies

- **Line interlopers**: Main problem for higher freq. LIM surveys
  - $\nu_{obs} = \nu/(1+z) = \nu'/(1+z') \rightarrow$ other lines redshifted to same ν_{obs}
  - Two approaches:

    - Masking: targeted (external data) and blind (contaminated voxels are expected to be brighter)

    - Model the effect of known interlopers in the likelihood and analyses

Exotic radiative decays would be inadvertently detected as a line interloper!!

Observables

- Clustering anisotropy parametrized by monopole, dipole, quadrupole, hexadecapole in angle wrt LOS
  - Clustering along line of sight
  - Angular clustering

- Voxel-intensity distribution (VID) (one-point PDF)

Exotic radiative decays

- Decaying dark matter: $\chi \rightarrow \gamma + \gamma$

$$\nu_\gamma = m_\chi c^2 / 2h_P$$

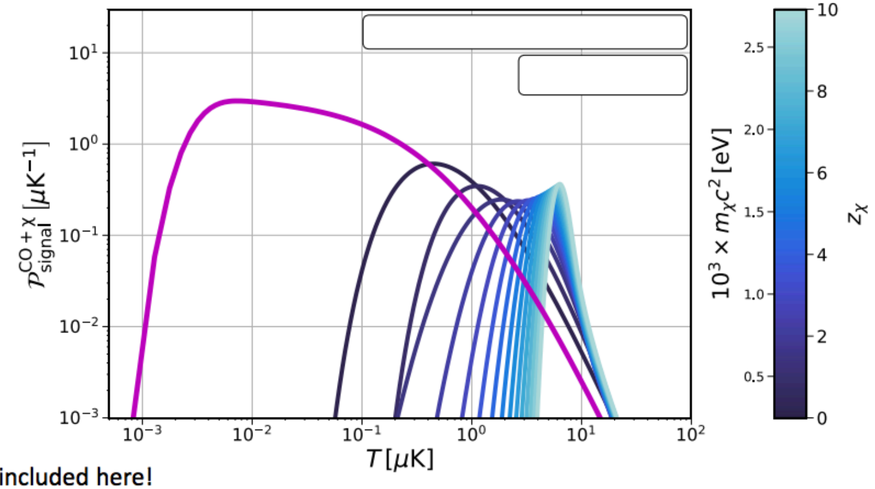
$$\rho_L^\chi(\boldsymbol{x}, z) = \rho_\chi(\boldsymbol{x}, z) c^2 \overbrace{\Gamma_\chi f_\chi f_{\gamma\gamma} f_{esc}}^{\Theta_\chi} \left(1 + 2\mathcal{F}_\gamma\right)$$

- Traces directly the DM density field

Effect in VID

- Each voxel receives contributions from both emissions:

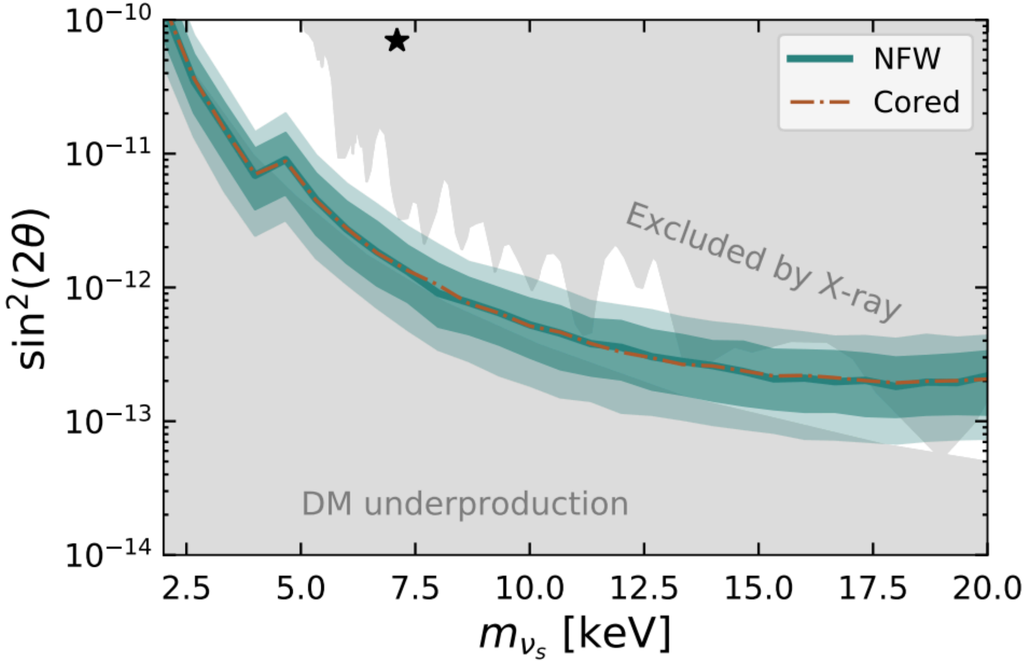
$$\mathcal{P}_{tot+\chi}(T) = \left(\left(\mathcal{P}_l * \mathcal{P}_\chi\right) * \mathcal{P}_{noise}\right)(T); \qquad \mathcal{P}_\chi = \mathcal{P}_{\tilde{\rho}} / \langle T_\chi \rangle$$



No noise contribution included here!

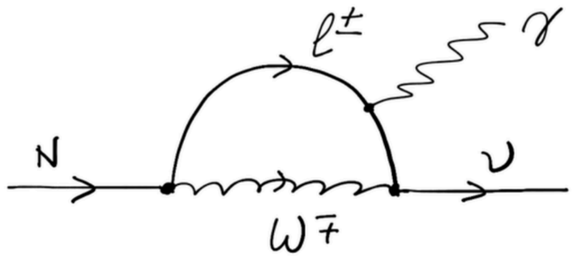
Sterile neutrinos X-ray

Point towards the galactic center and use



A. Dekker, at al (2021)

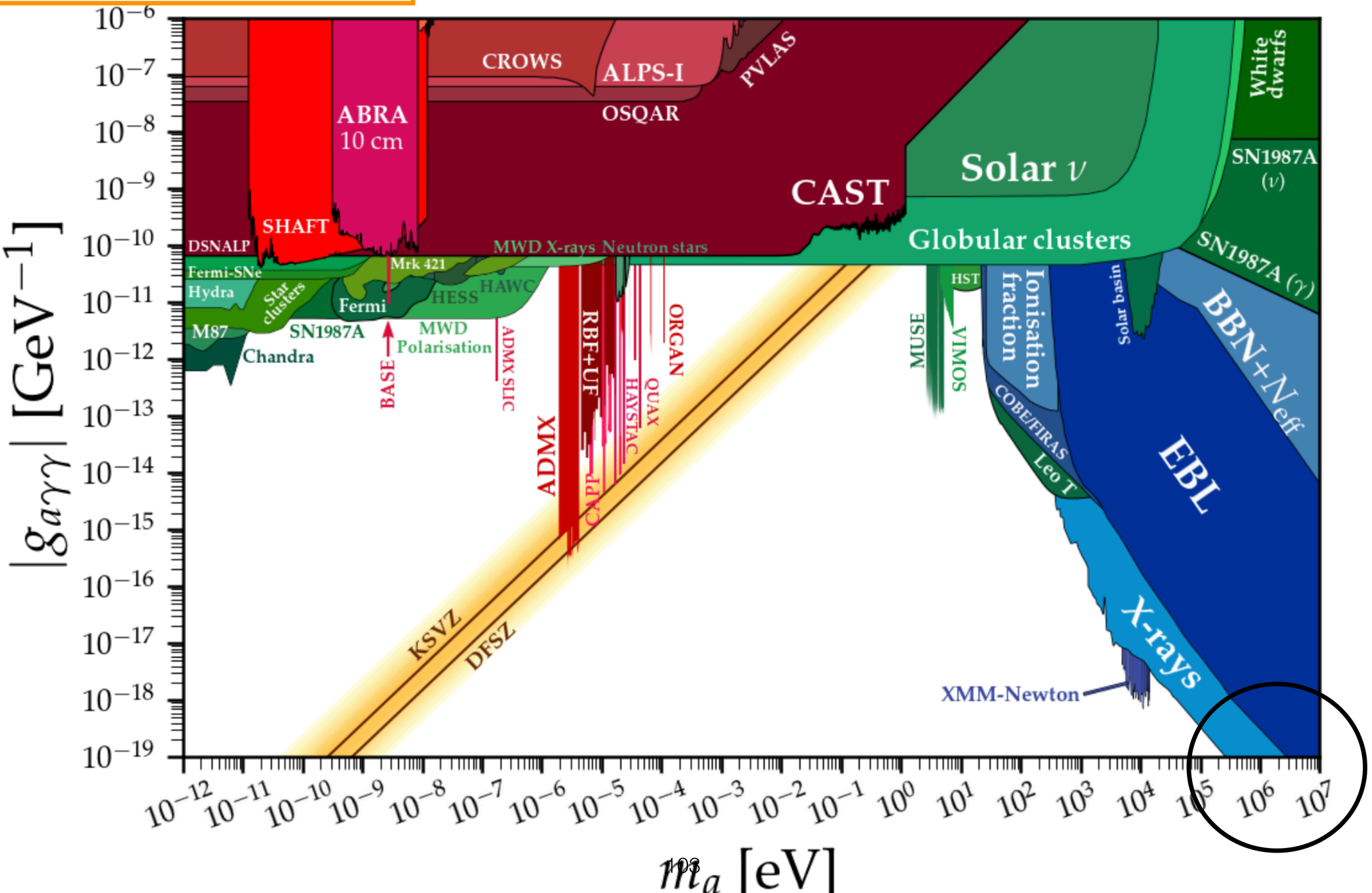
$$\mathscr{L} = \mathscr{L}_{SM} - \sum_{\alpha,i} \bar{L}^{\alpha} Y^{\alpha i} \tilde{\Phi} N_R^i - \sum_{i,j} \frac{1}{2} \bar{N}_R^{ic} M^{ij} N_R^j + h.c$$



eROSITA [0.2 - 8 keV]
Launched in 2019, Russian-German mission

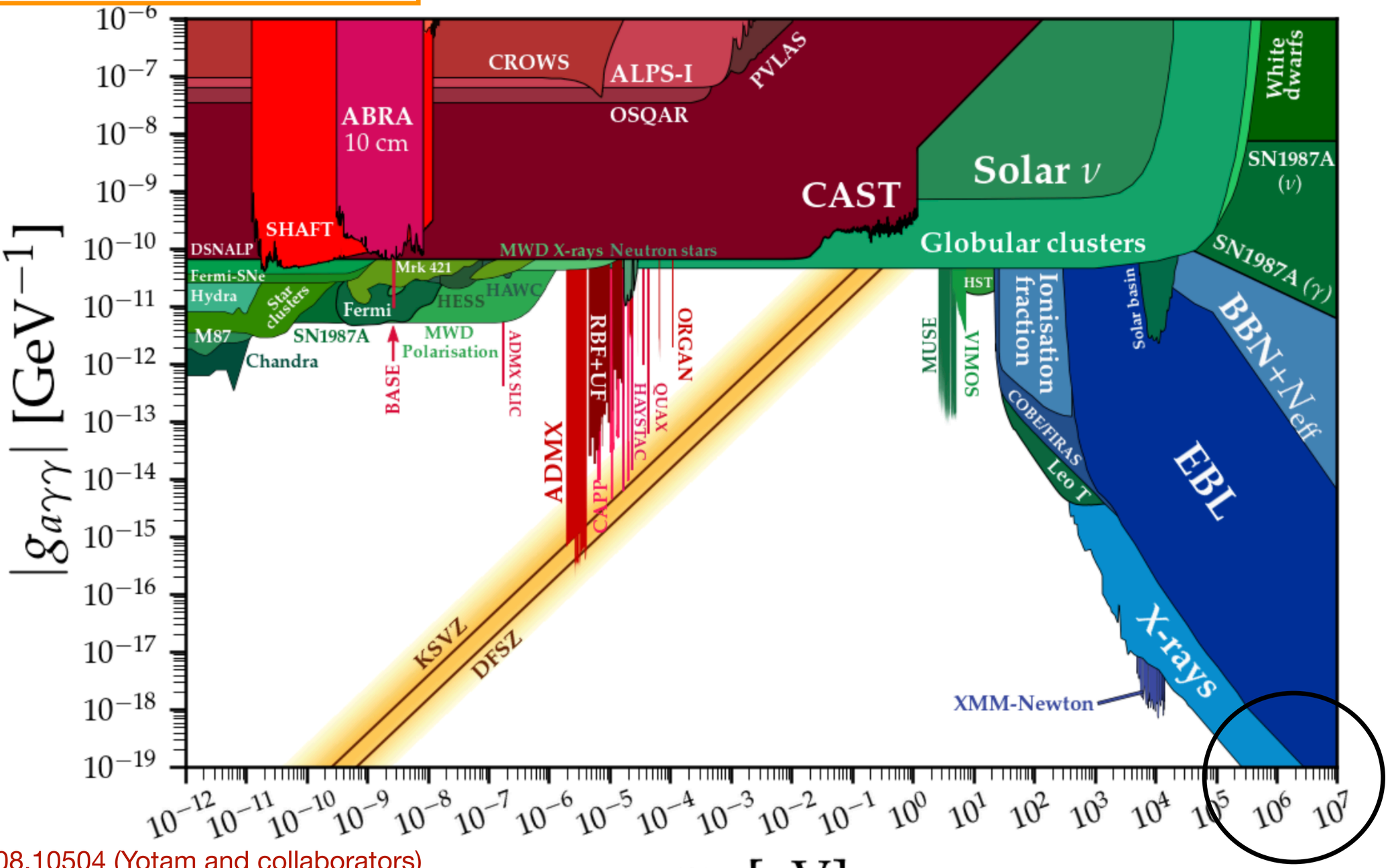
MeV (gamma-rays)

https://github.com/cajohare/AxionLimits



MeV (gamma-rays)

https://github.com/cajohare/AxionLimits



See arXiv 2208.10504 (Yotam and collaborators) for recent motivation

Oct 18, 2021
RELEASE 21-134

NASA Selects Gamma-ray Telescope to Chart Milky Way Evolution

COSI-Telescope (approved by NASA)

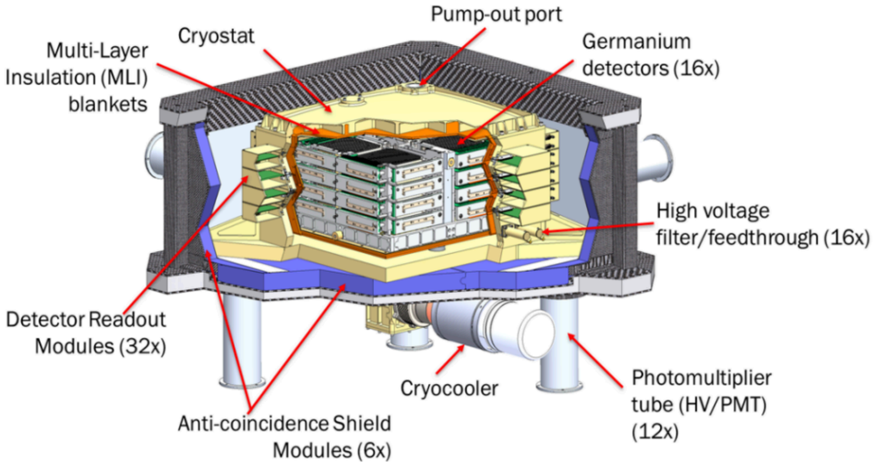
Compton Spectrometer and Imager (COSI) wide-FOV telescope designed to survey the gamma-ray sky at 0.2-5 MeV → Imaging with high-resolution spectroscopy

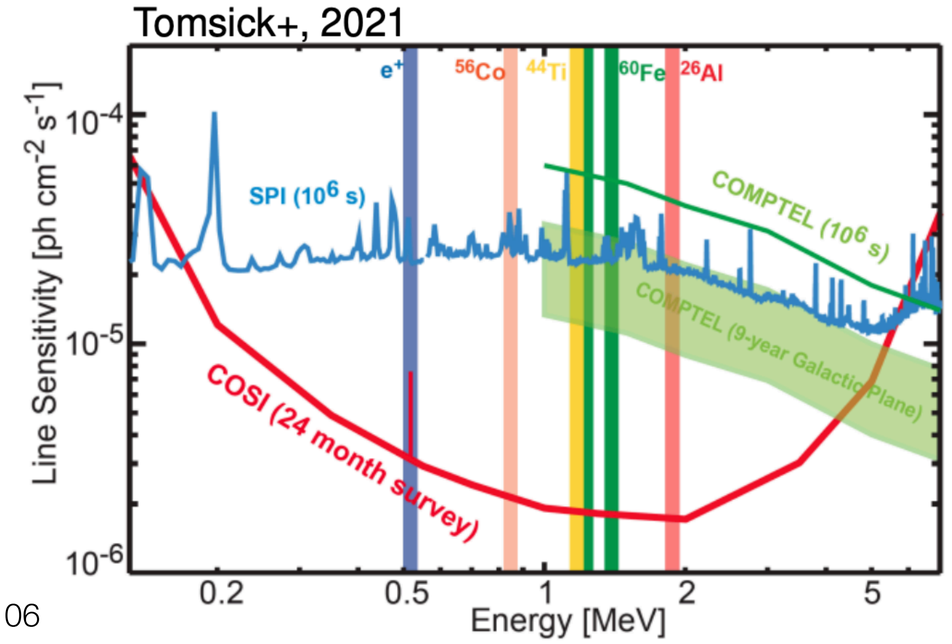
Oct 18, 2021
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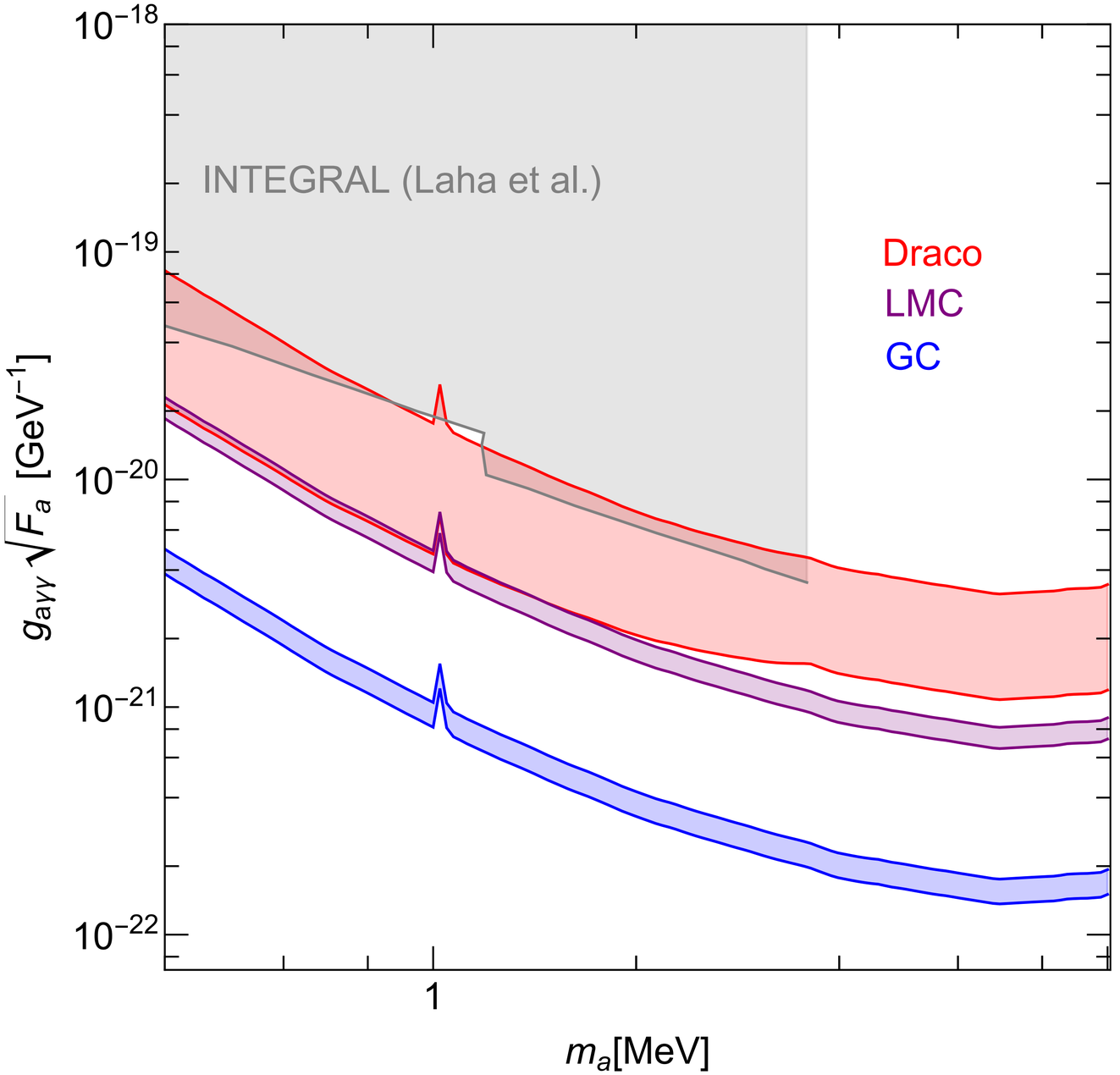
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Caputo, M. Negro, M. Regis and M. Taoso, arXiv 2210.09310 (accepted JCAP)