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

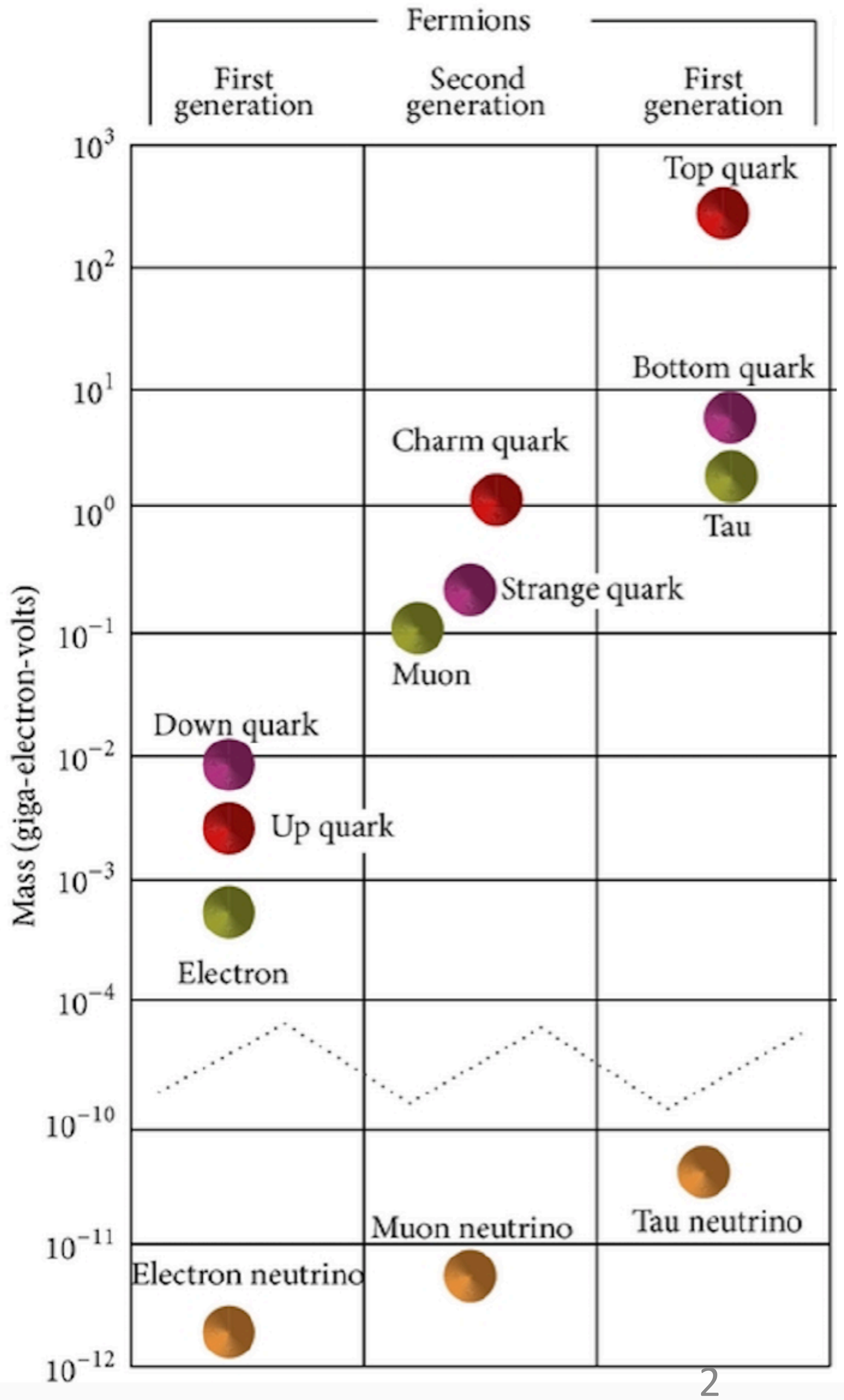
Andrea Caputo

Annecy, 21 March 2023

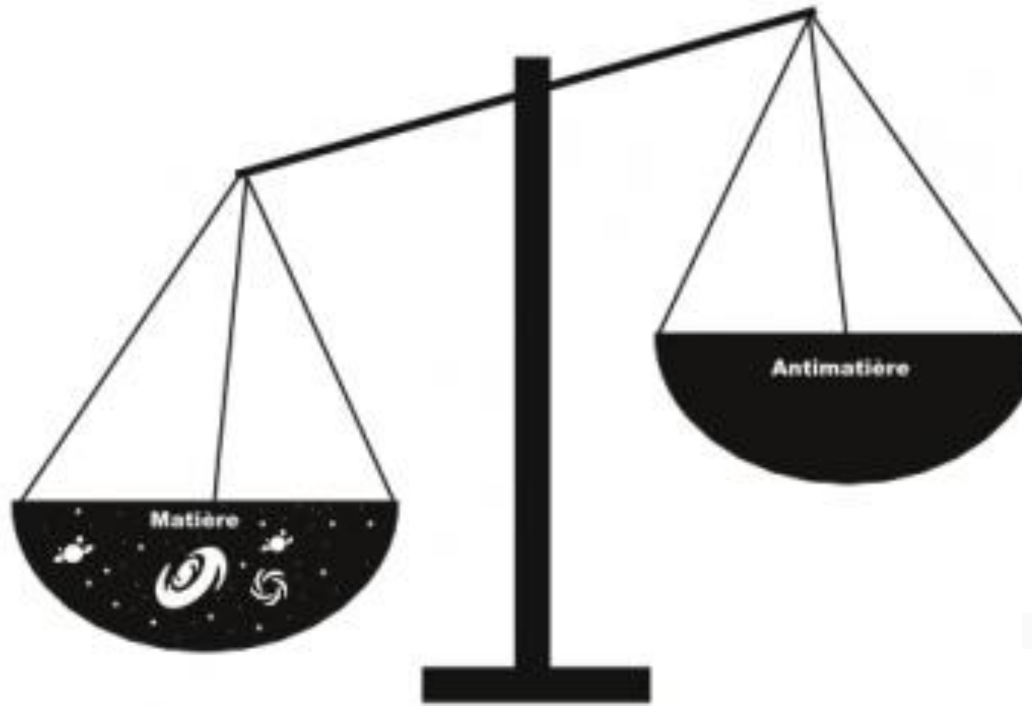
We have a lot of evidences for physics beyond the Standard Model

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

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

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

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

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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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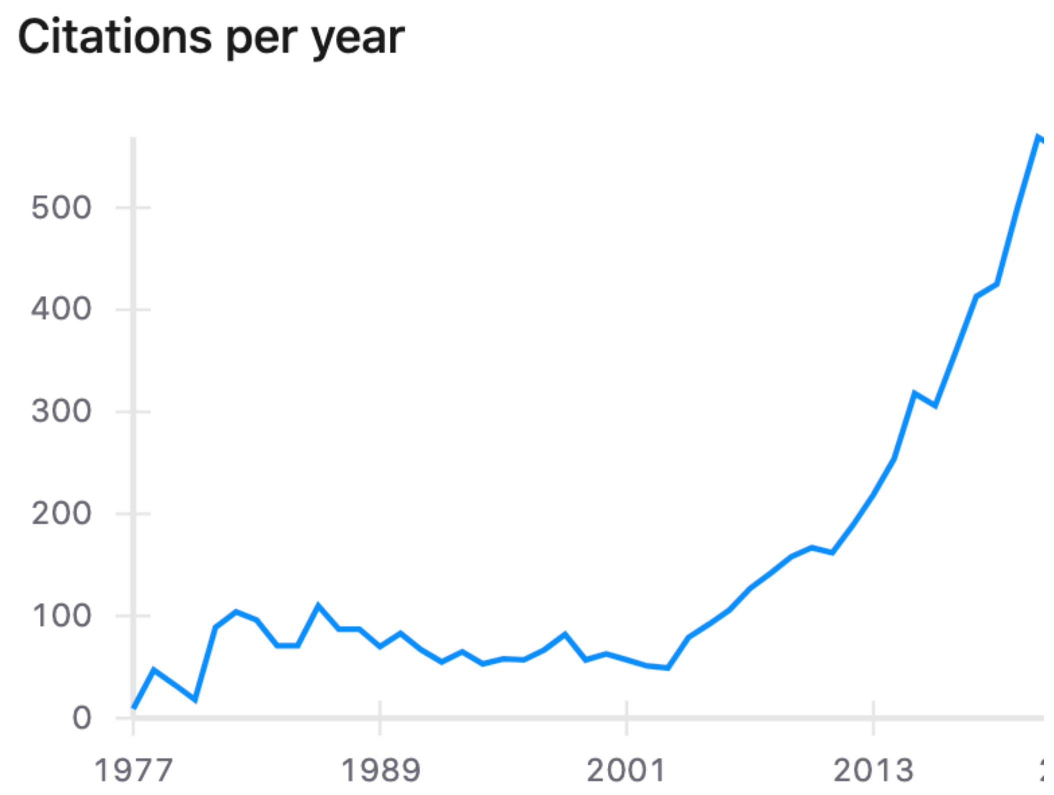
CP Conservation in the Presence of Instantons

R.D. Peccei (Stanford U., ITP), Helen R. Quinn (Stanford U., ITP)
Mar, 1977

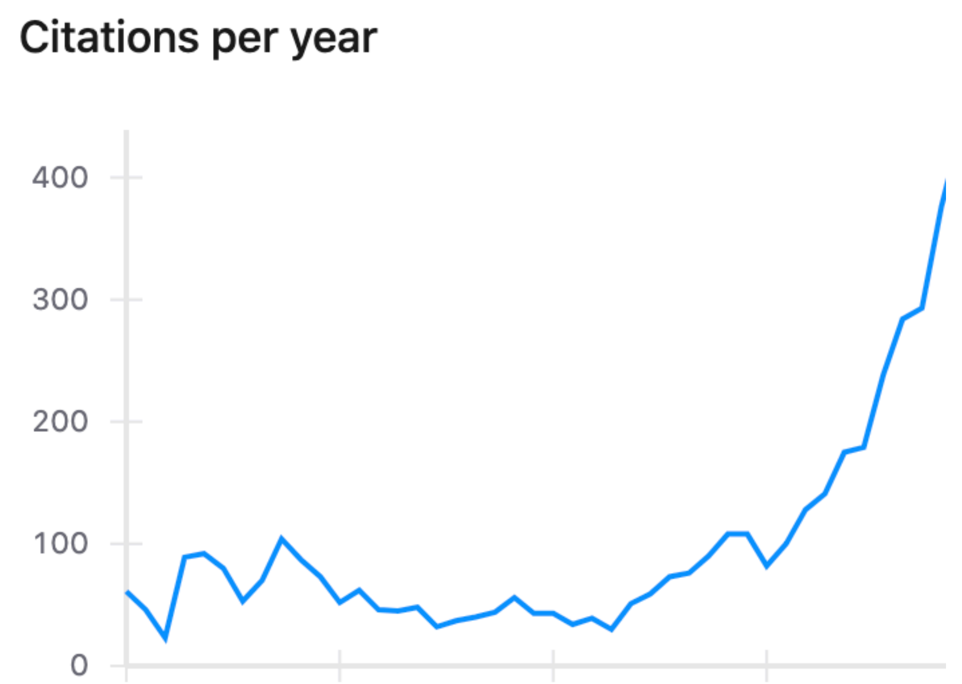
8 pages
Part of Gauge models of CP violation, 1440-1443
Published in: *Phys.Rev.Lett.* 38 (1977) 1440-1443
DOI: 10.1103/PhysRevLett.38.1440
Report number: ITP-568-STANFORD
View in: OSTI Information Bridge Server, ADS Abstract Service



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



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In a theory with the quarks charged under electromagnetism one gets a coupling to the photon performing a *chiral* (and *anomalous*) transformation

$$\Rightarrow \quad \mathcal{L}_{a\gamma\gamma} = -\frac{1}{4}g_{a\gamma}a\tilde{F}^{\mu\nu}F_{\mu\nu}$$

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Axions In String Theory

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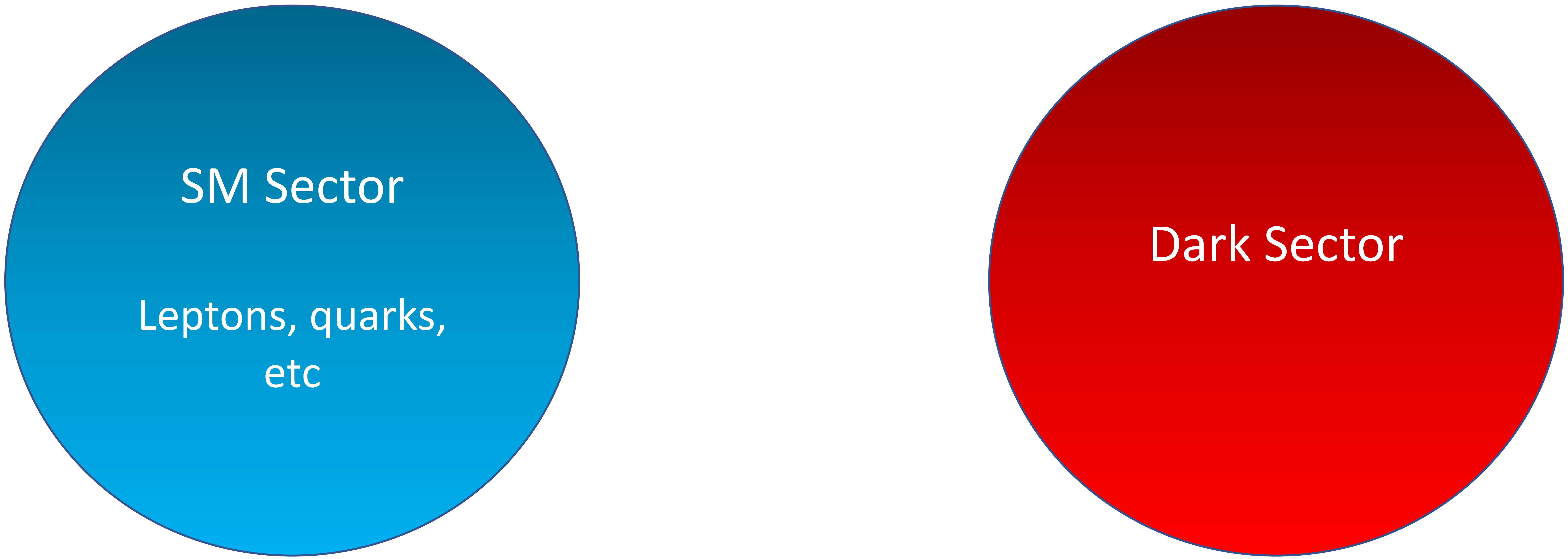
String Axiverse

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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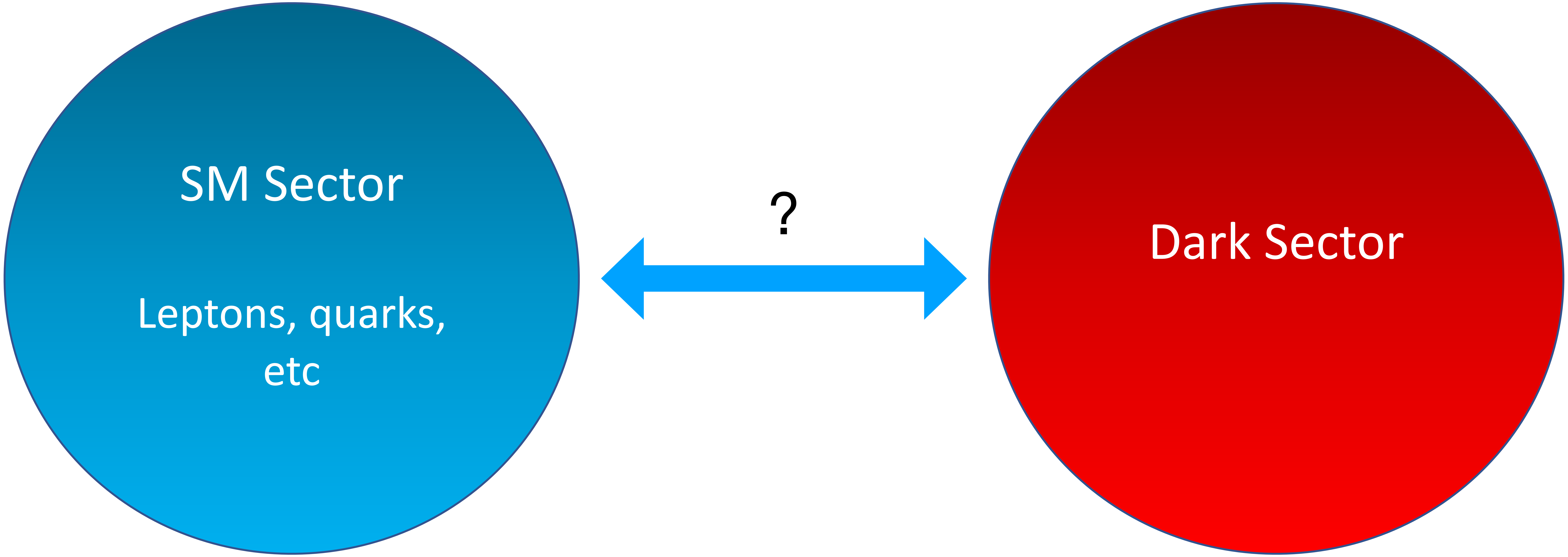
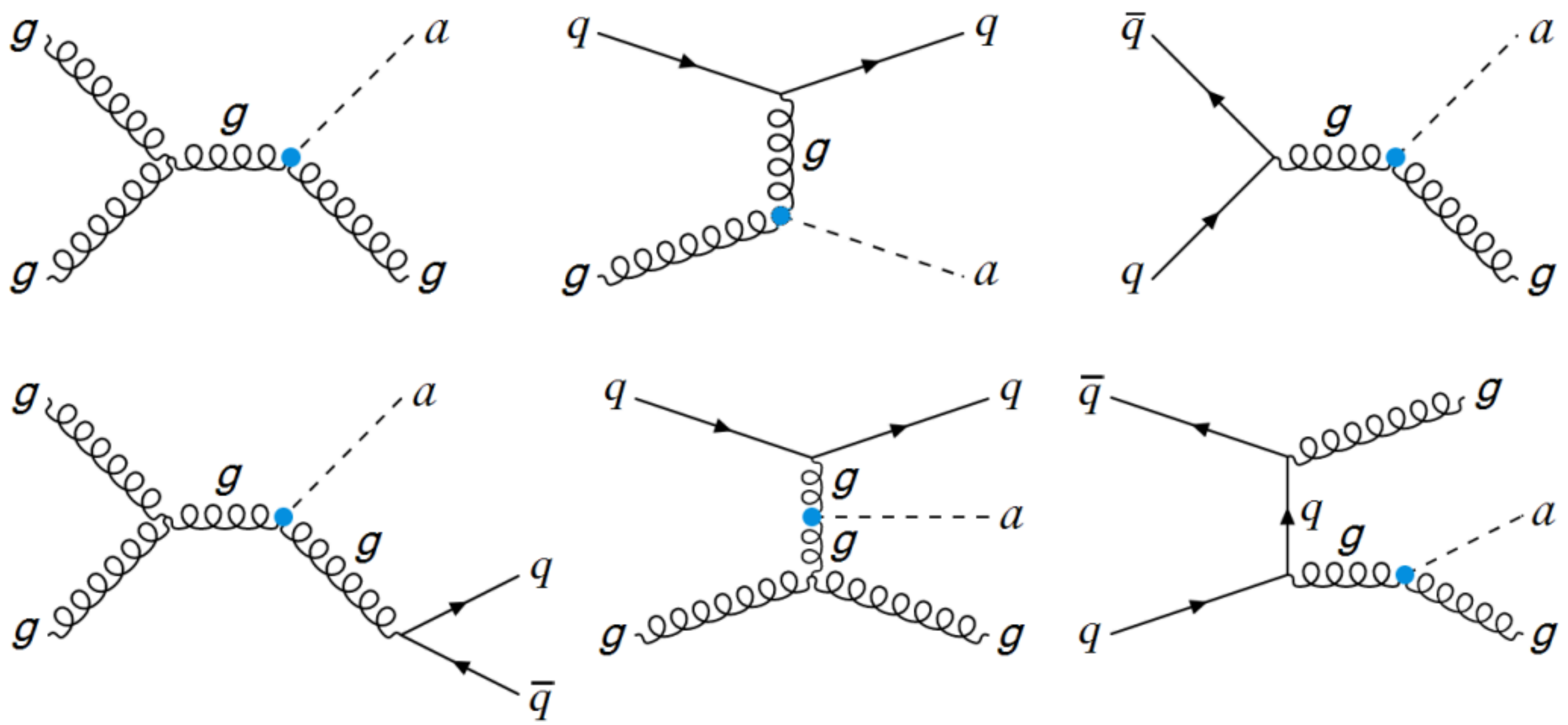


How to look for these new particles?

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?

Zel'dovich

"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)

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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

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Dark Matter and other indirect probes

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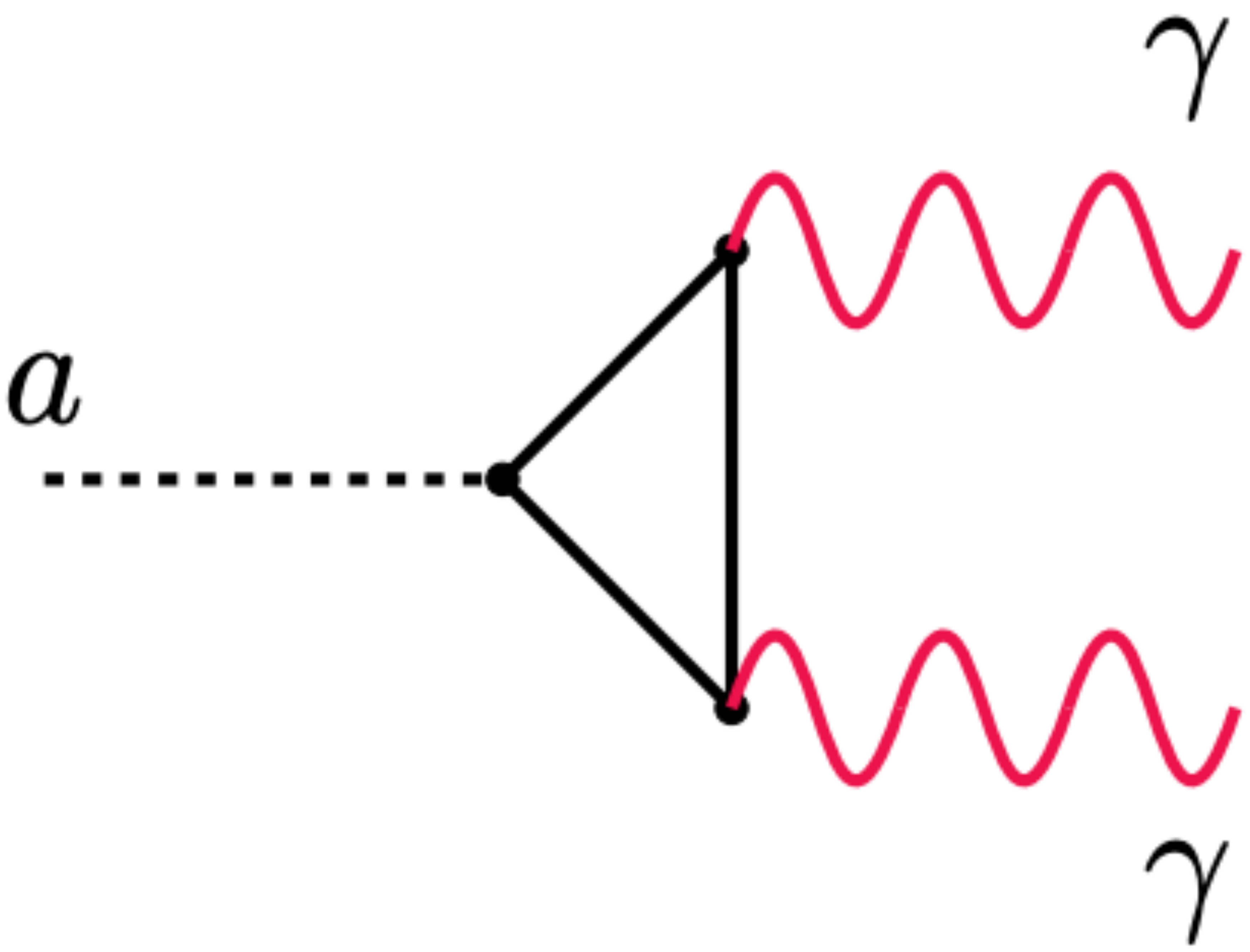
However the ideas will be further more generic, applying to sterile neutrinos DM, dipole DM, scalar DM, hidden photino DM, etc..

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

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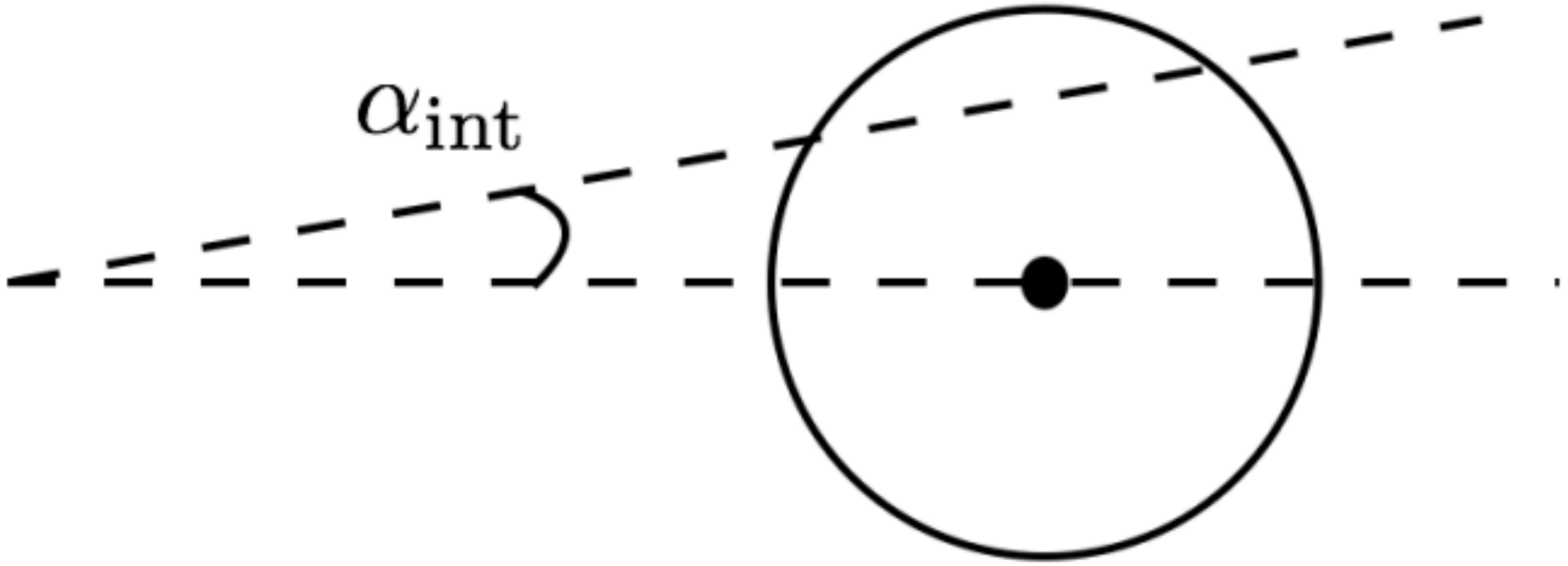
Where?

A) Which astrophysical targets?

Galactic center, clusters of galaxies, Dwarf galaxies

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



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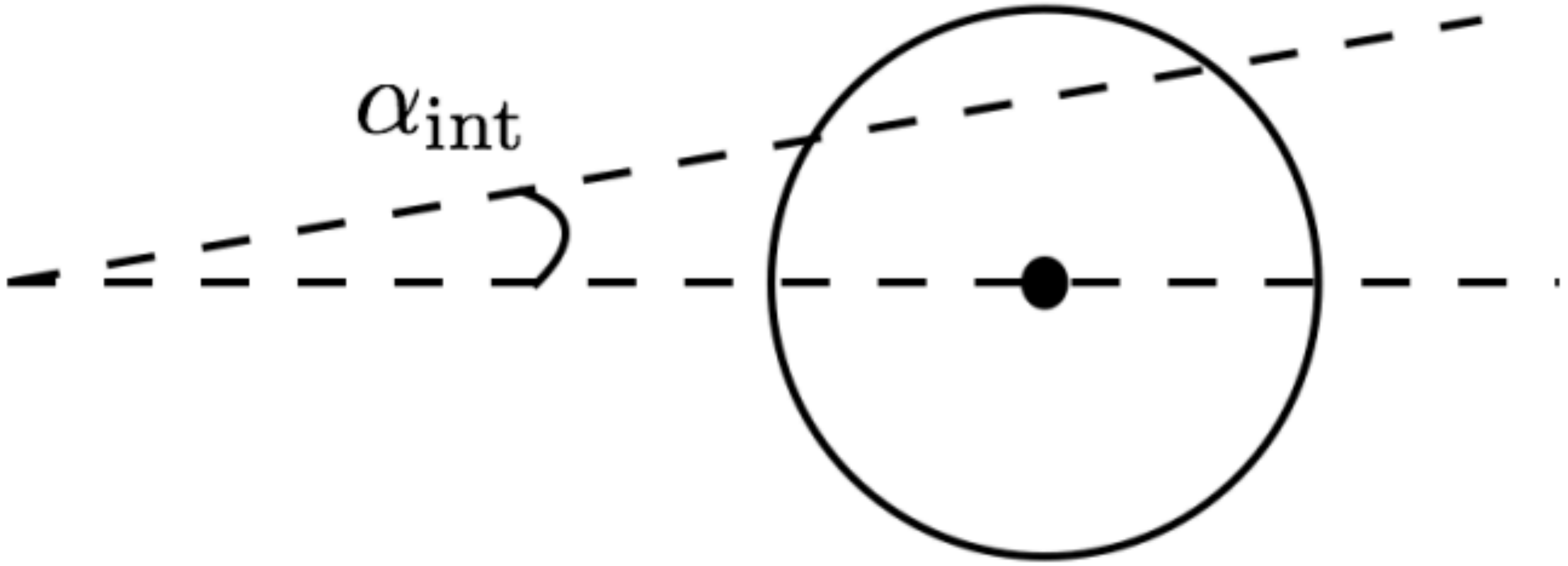

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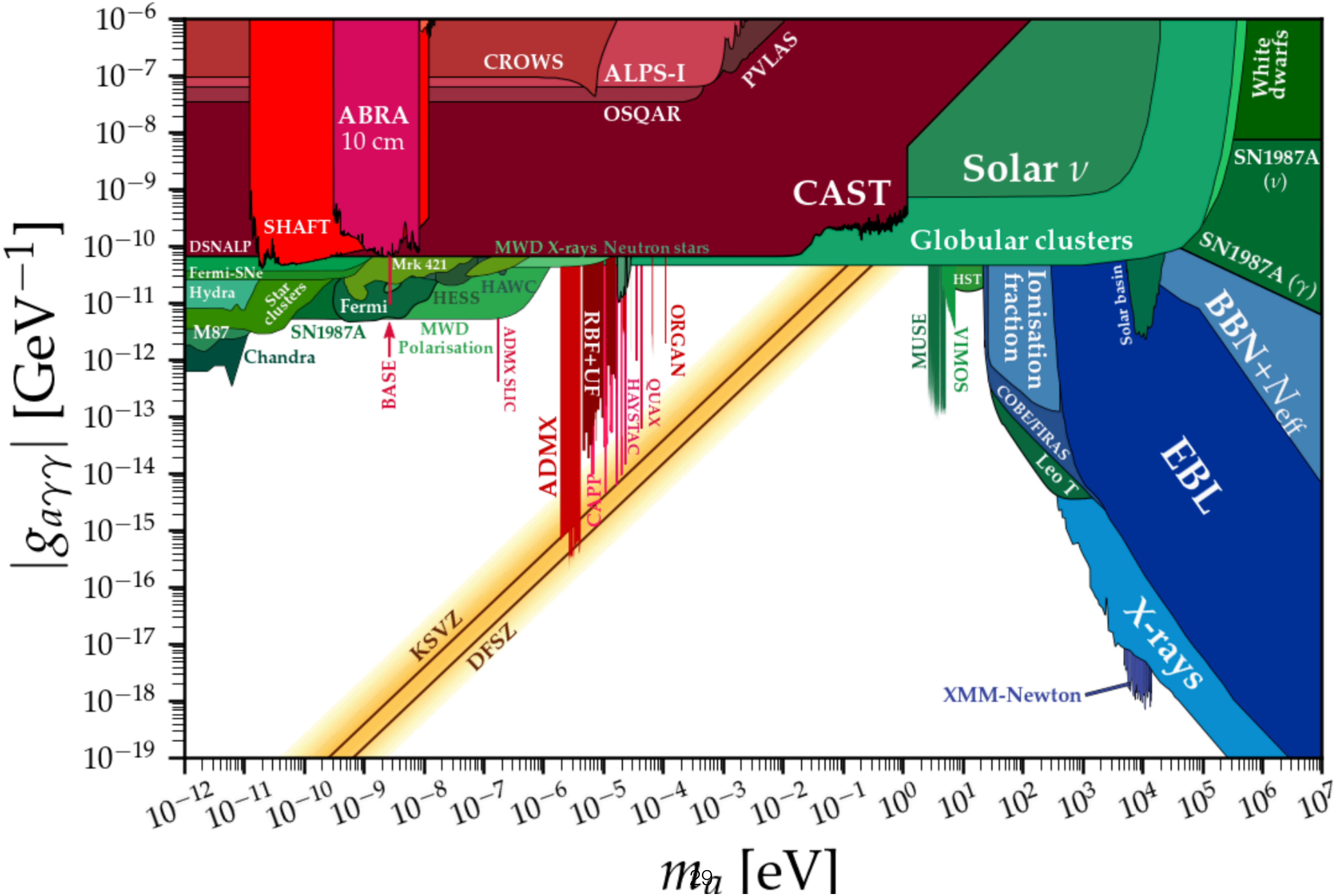
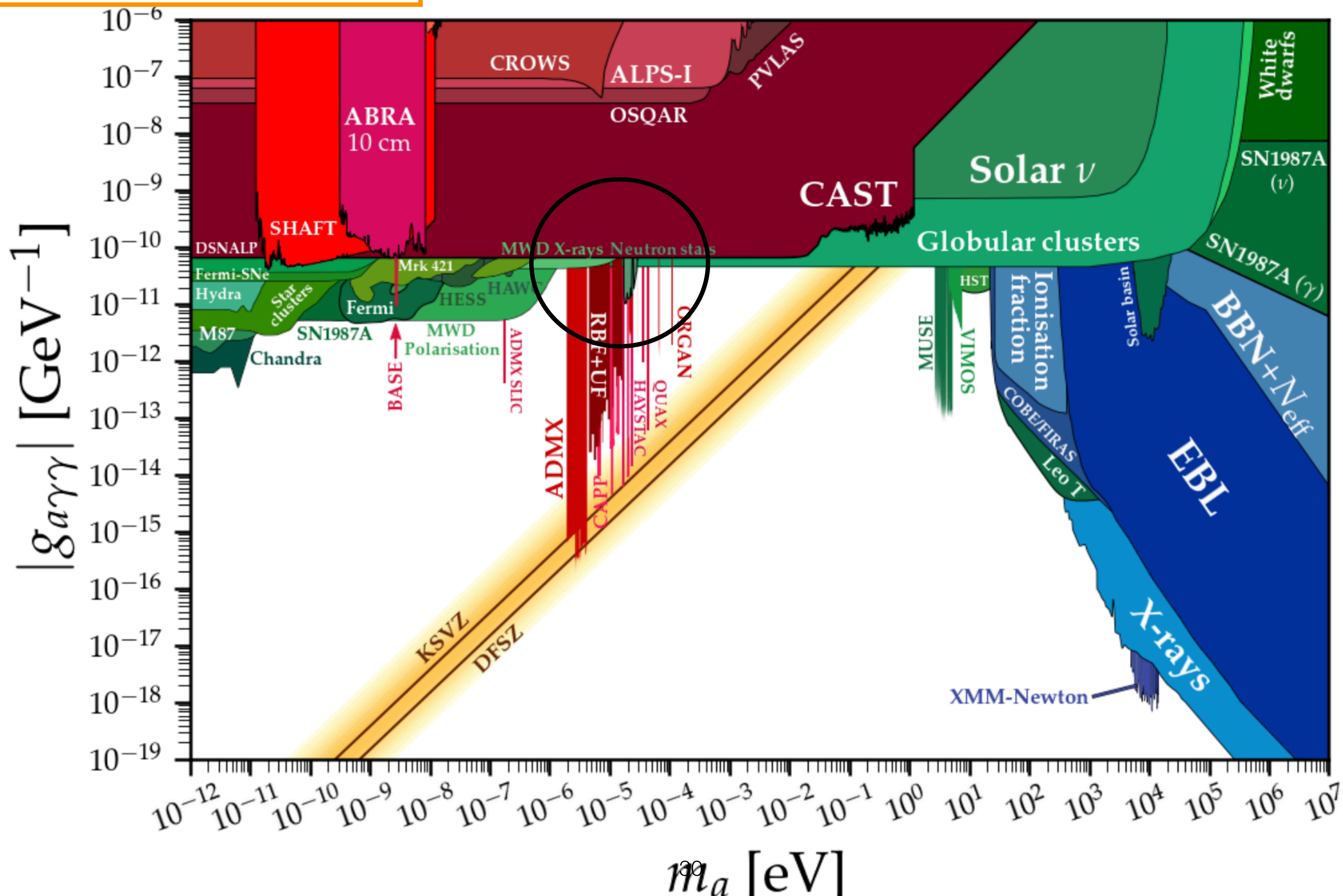
B) Which energy range?

https://github.com/cajohare/AxionLimits



micro-eV (radio)

https://github.com/cajohare/AxionLimits



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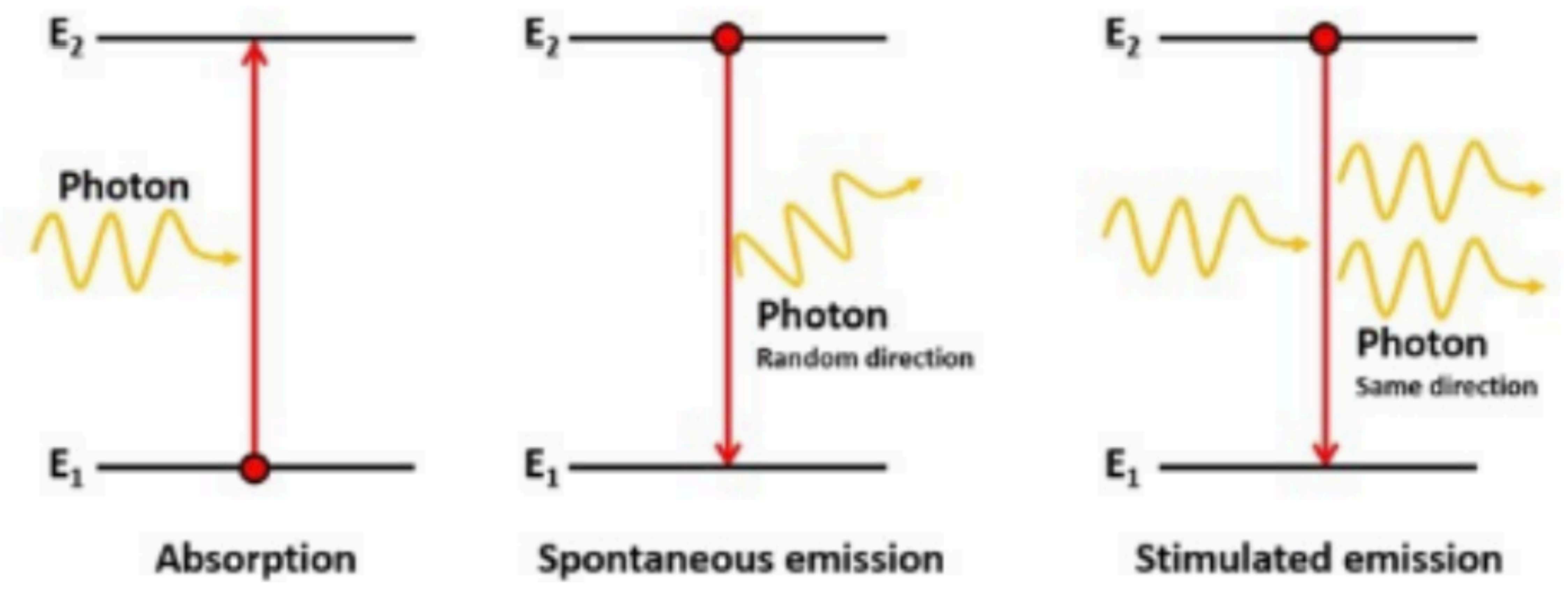
Stimulated decay



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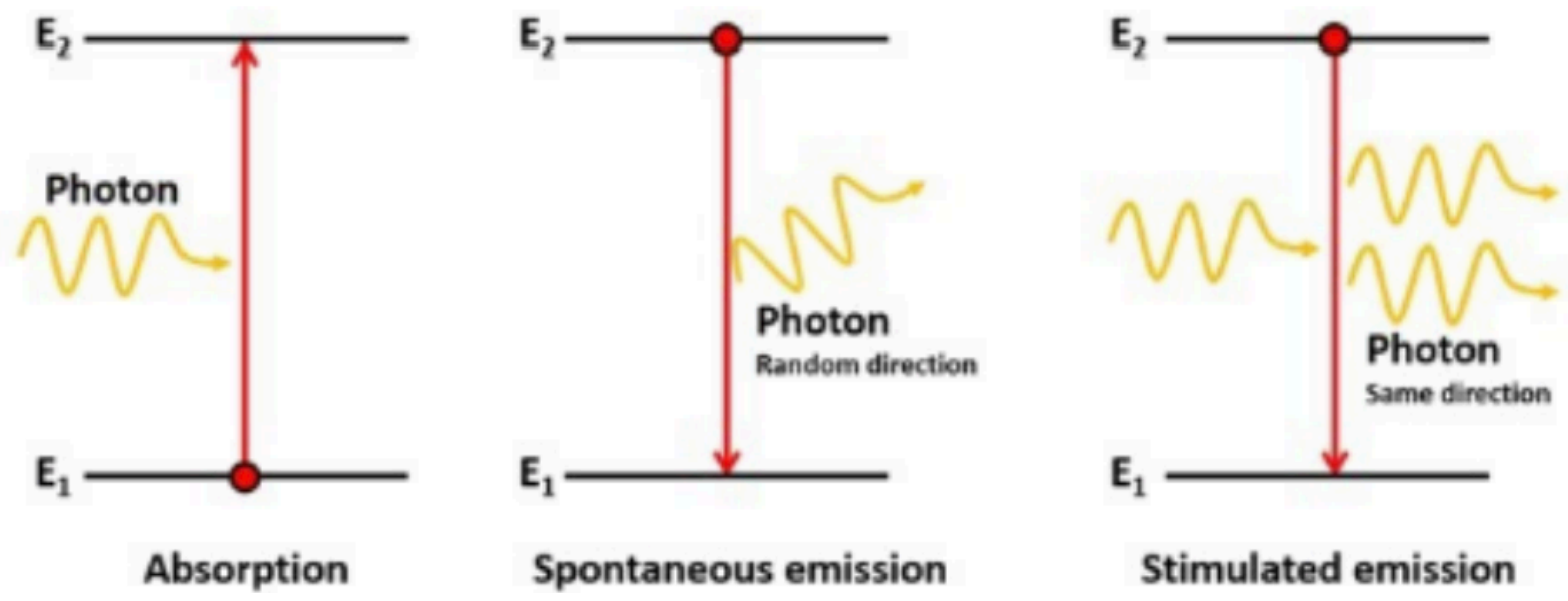


$$S_{\rm decay} = \frac{\Gamma_a}{4\pi\Delta\nu} \int d\Omega\, d\ell\, \rho_a(\ell,\Omega)\,[1 + 2 f_\gamma(\ell,\Omega,m_a)]$$

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

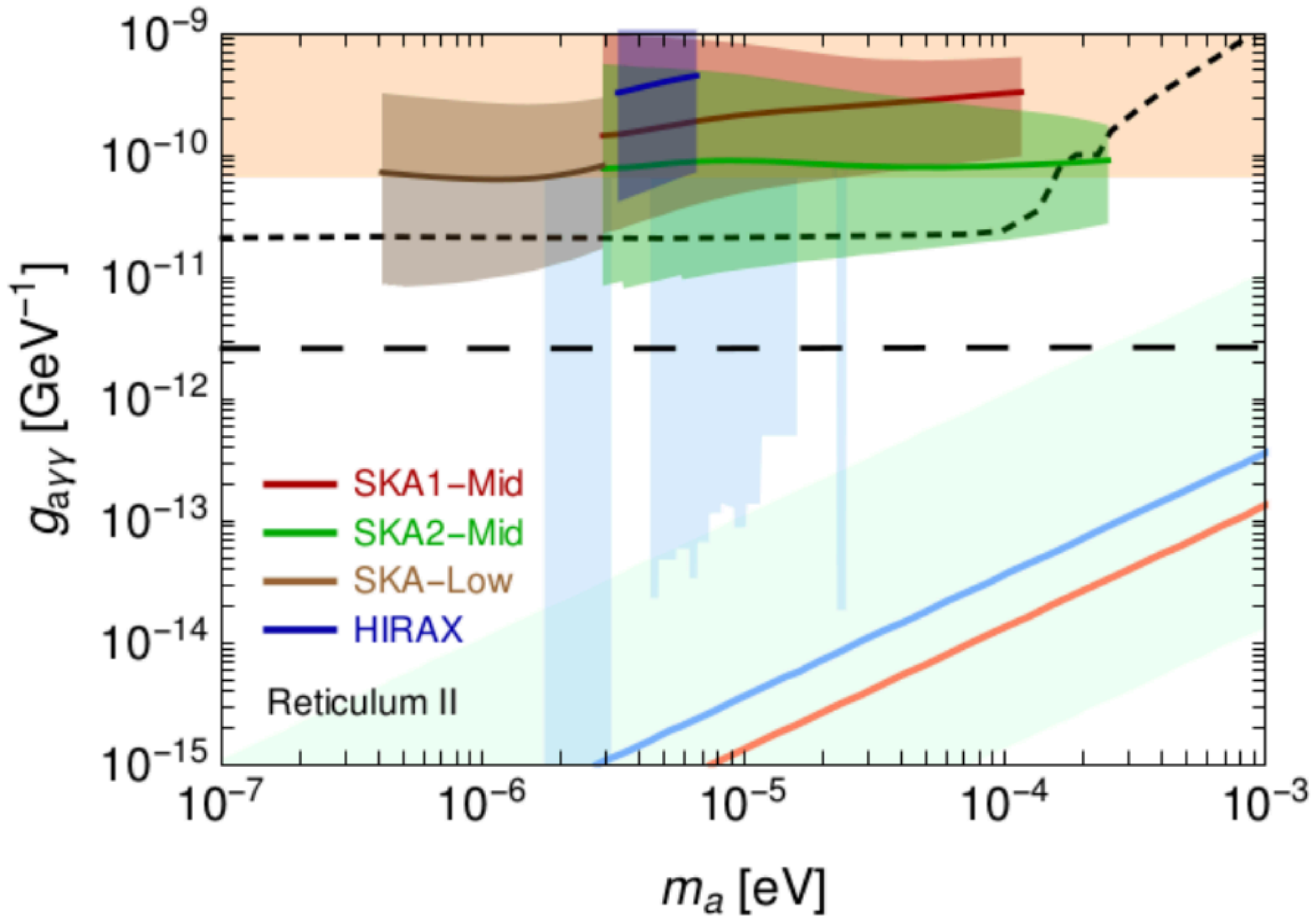
A golden era has started for radio astronomy with SKA and its precursors.

SKA1-Low: 100 hours of observation;

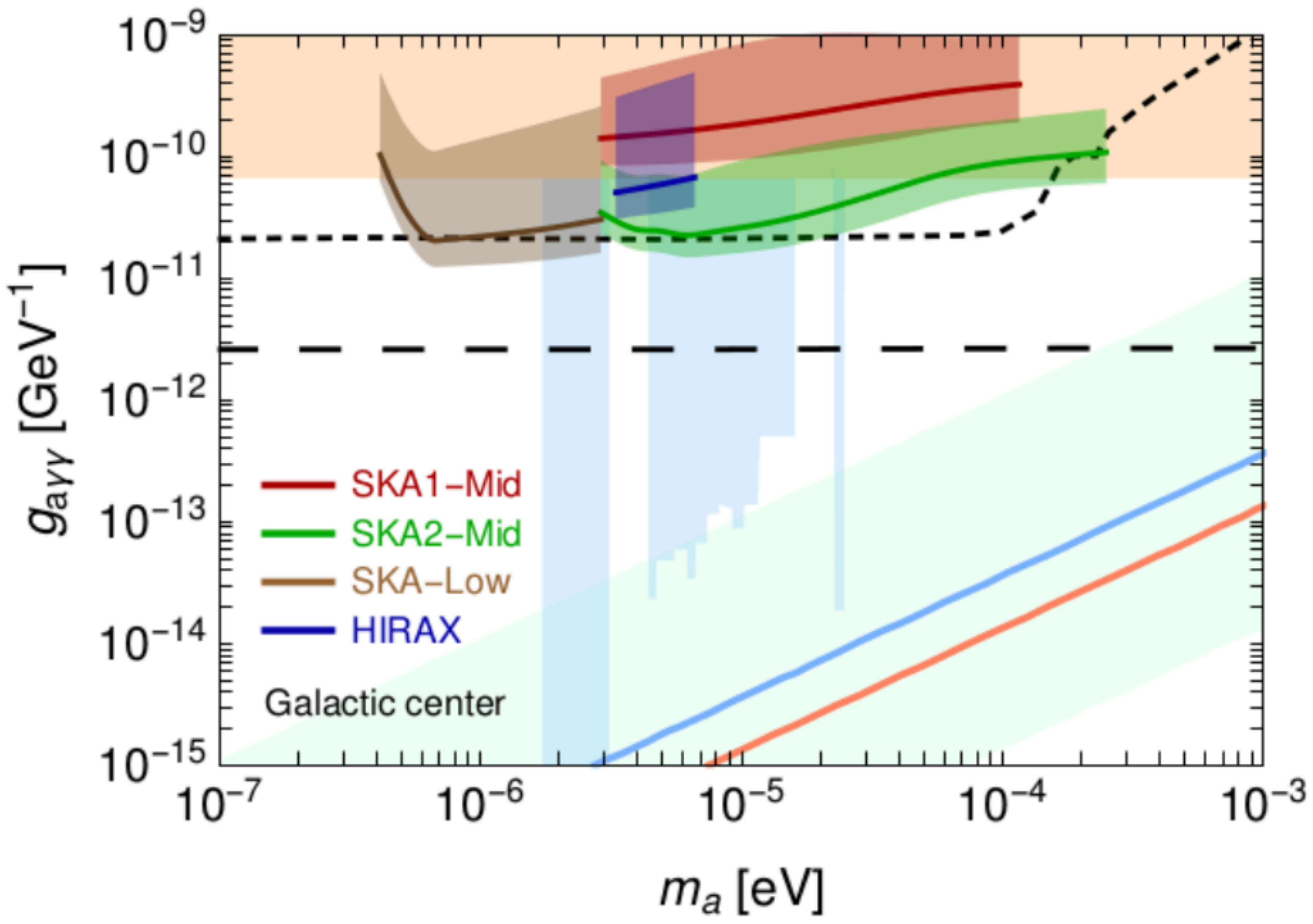
sensitivity of $180\mu Jy/beam$

$\Delta\nu/\nu = 10^{-4}$

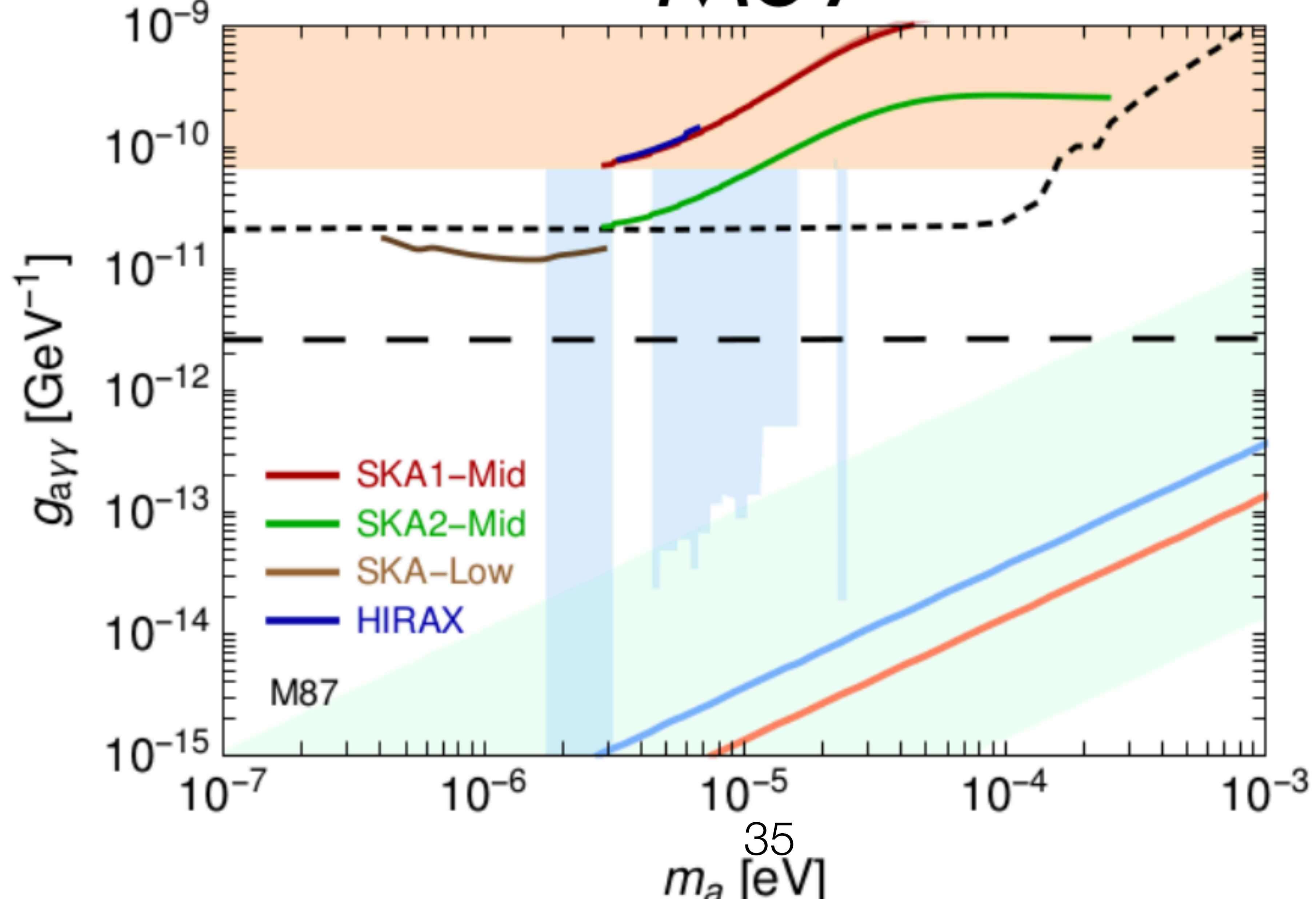
Dwarf spheroidal galaxy



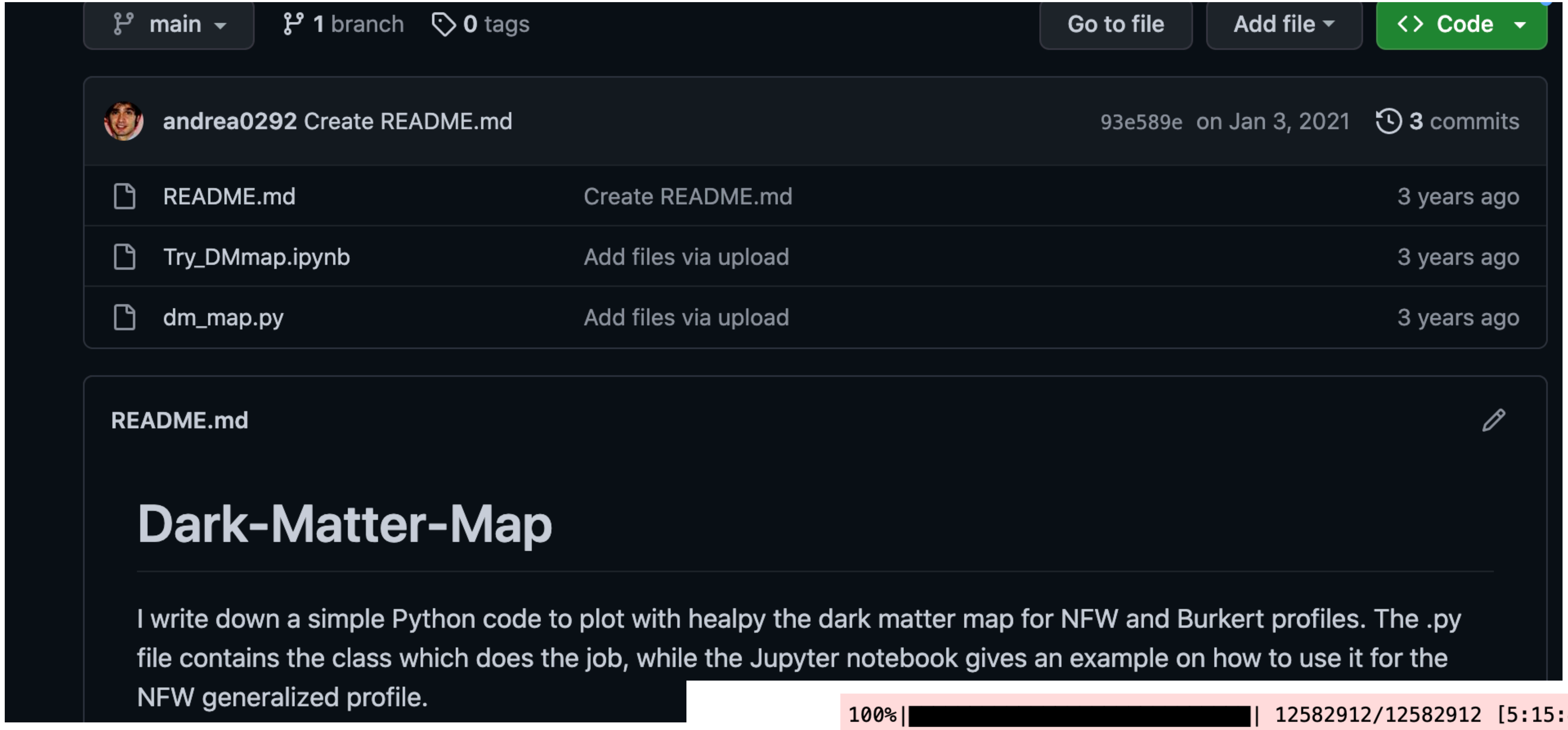
Galactic Center



M87



Caputo, M.Regis, M. Taoso, S. Witte,
JCAP 03 (2019) 027


main 1 branch 0 tags Go to file Add file Code

andrea0292 Create README.md 93e589e on Jan 3, 2021 3 commits

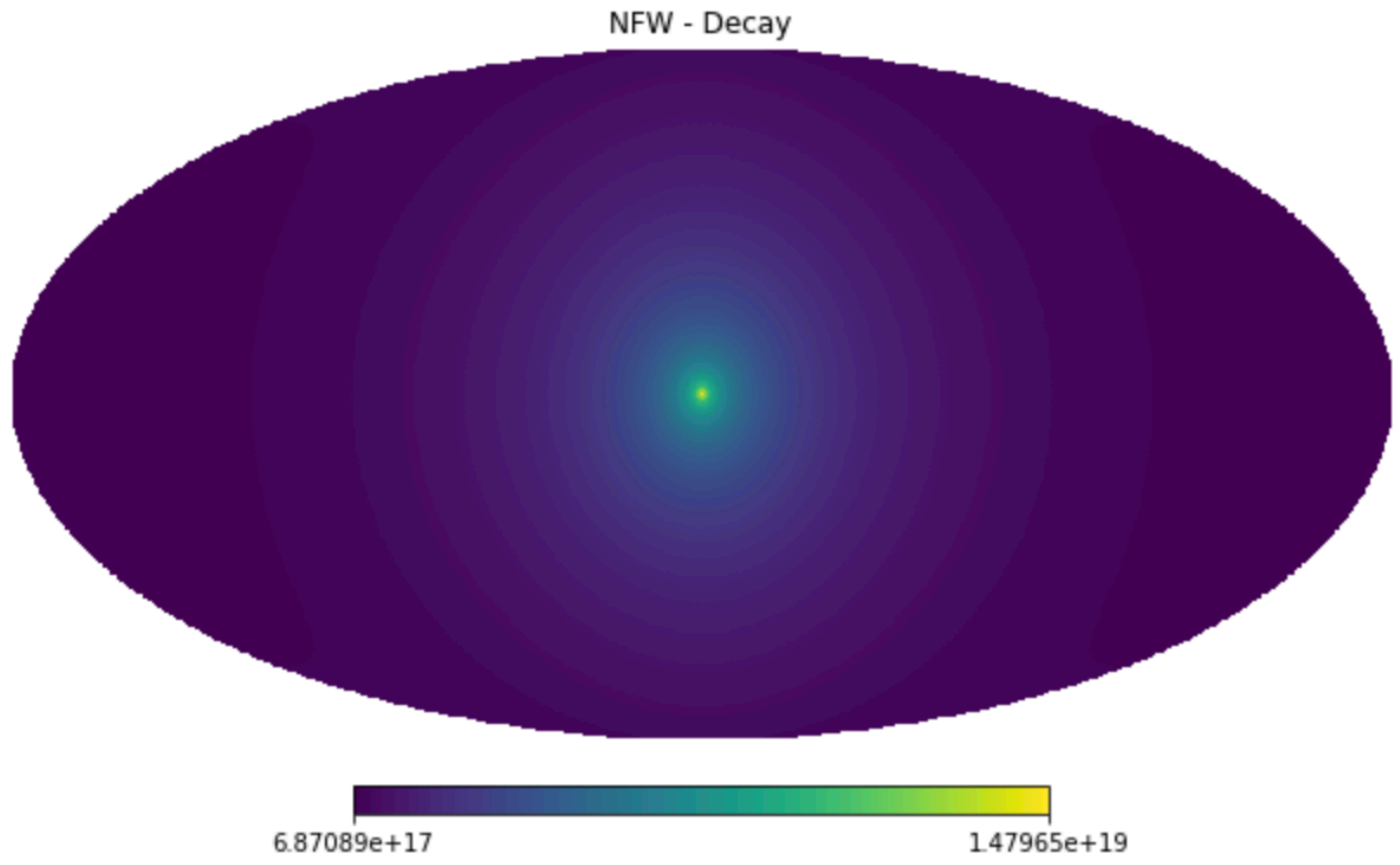
README.md	Create README.md	3 years ago
Try_DMmap.ipynb	Add files via upload	3 years ago
dm_map.py	Add files via upload	3 years ago

README.md

Dark-Matter-Map

I write down a simple Python code to plot with healpy the dark matter map for NFW and Burkert profiles. The .py file contains the class which does the job, while the Jupyter notebook gives an example on how to use it for the NFW generalized profile.

```
100%|████████████████████| 12582912/12582912 [5:15:47<00:00, 664.08it/s]
...done!
```



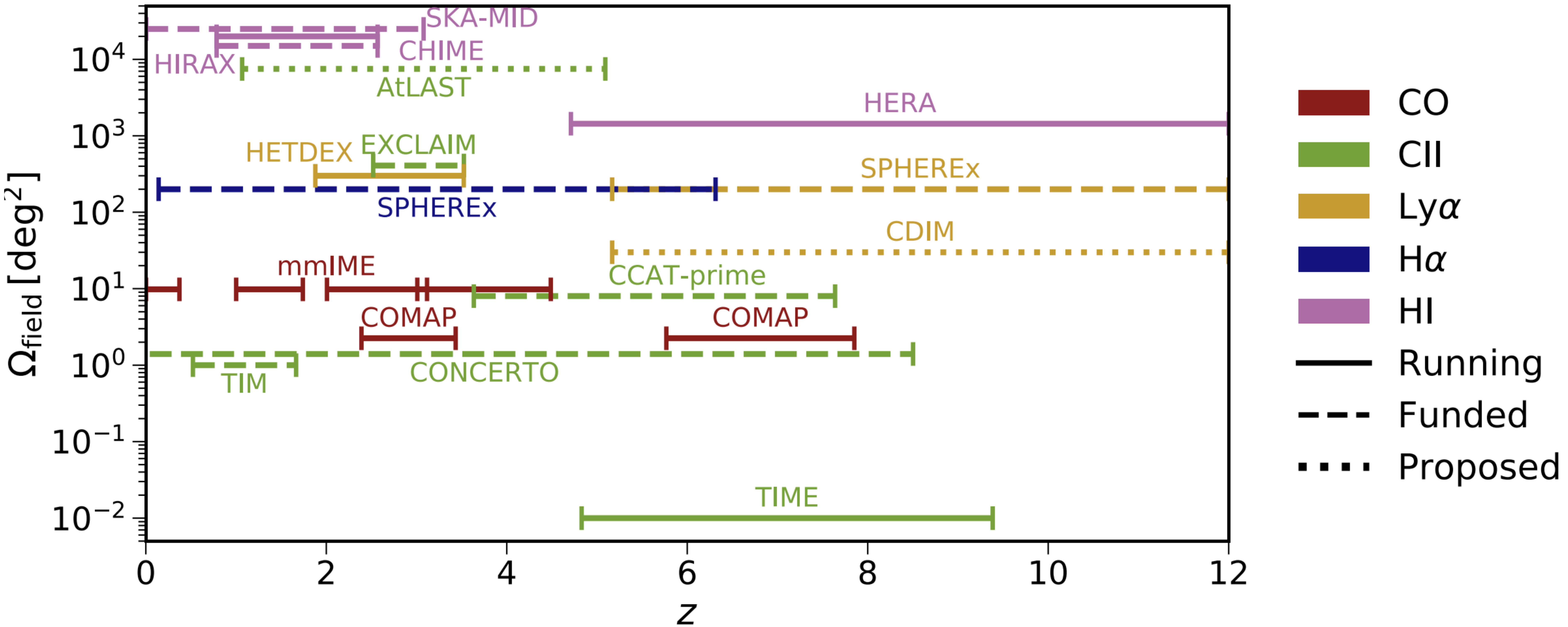
In this case we have targeted specific objects..however there is another possibility

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!

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



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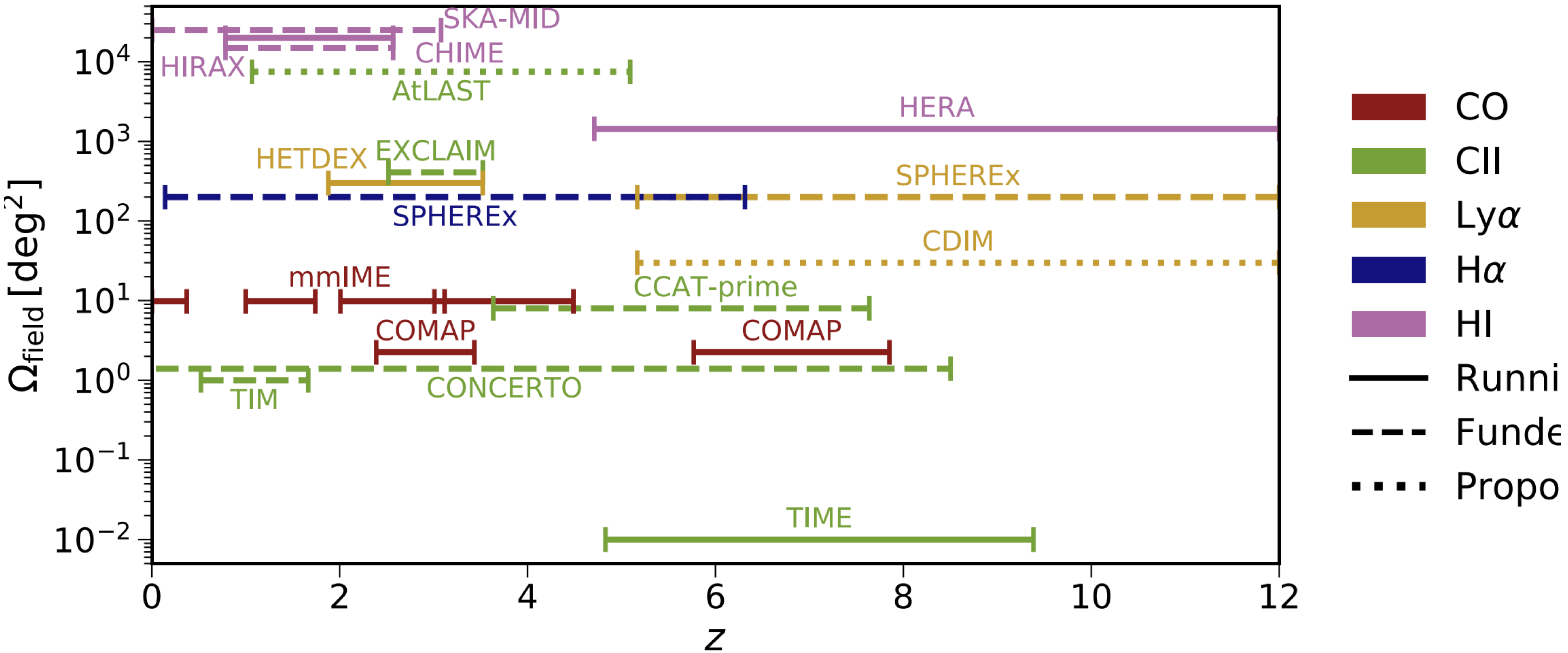
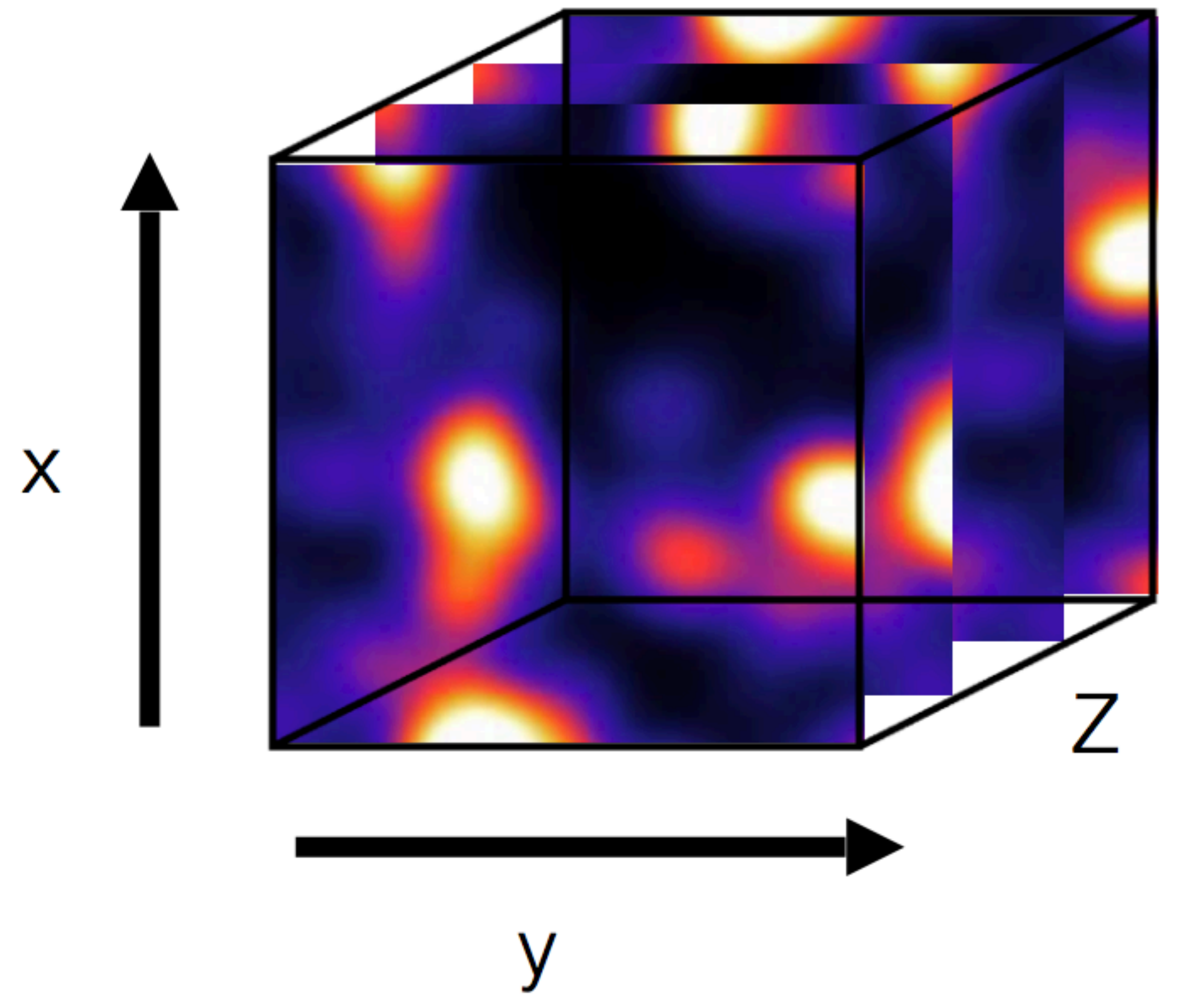
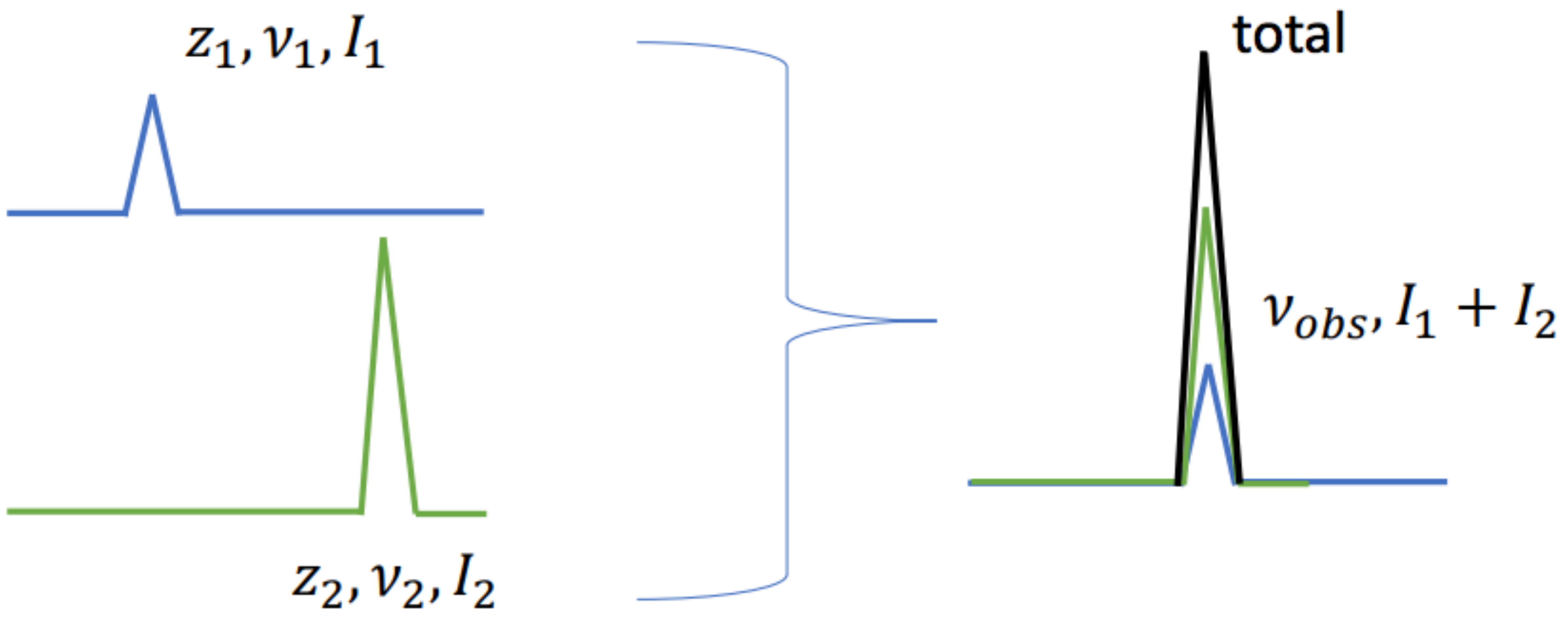




Contamination of intensity maps

- 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}



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

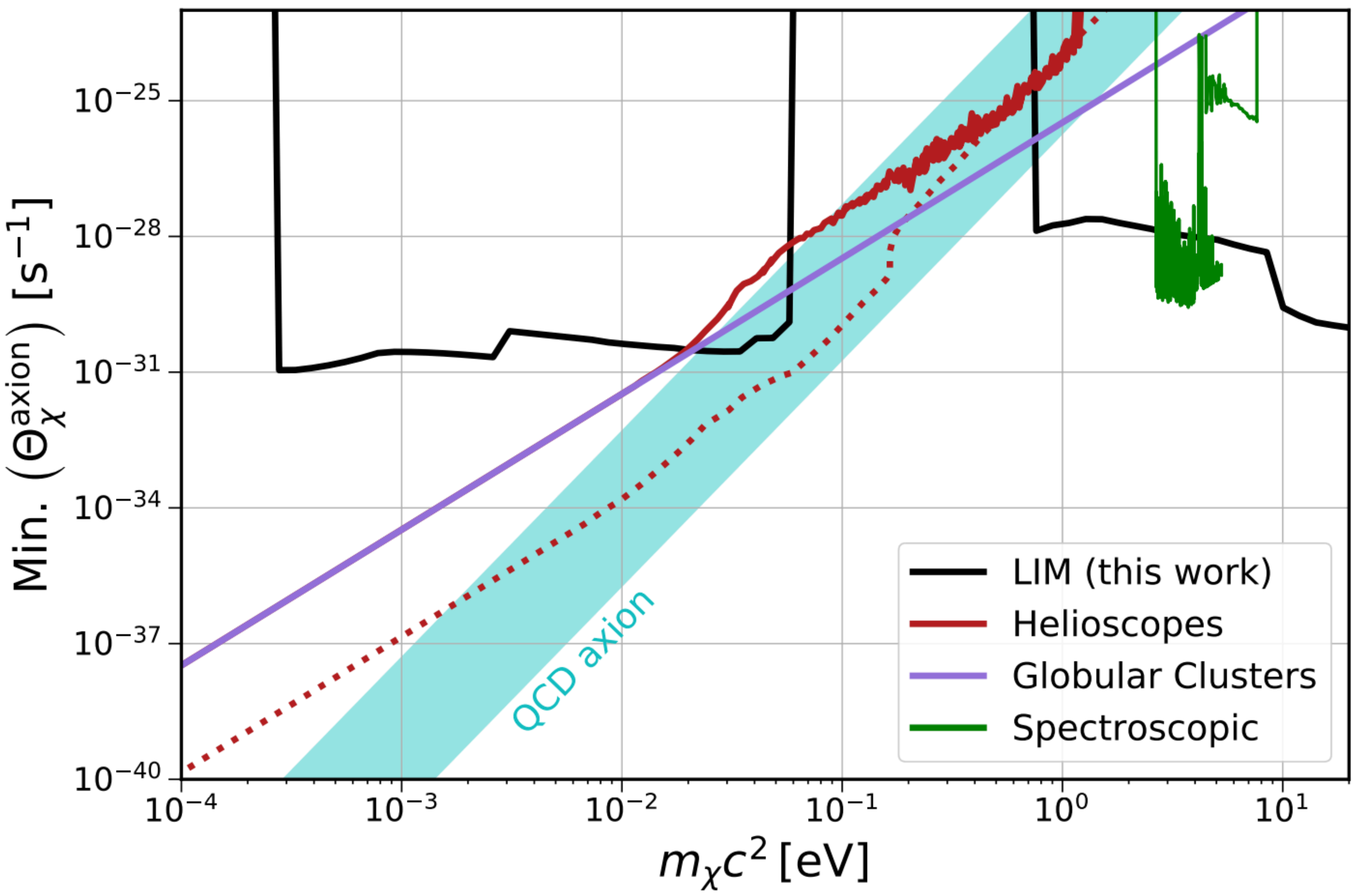
Exotic radiative decays would be inadvertently detected as a line interloper!!

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)

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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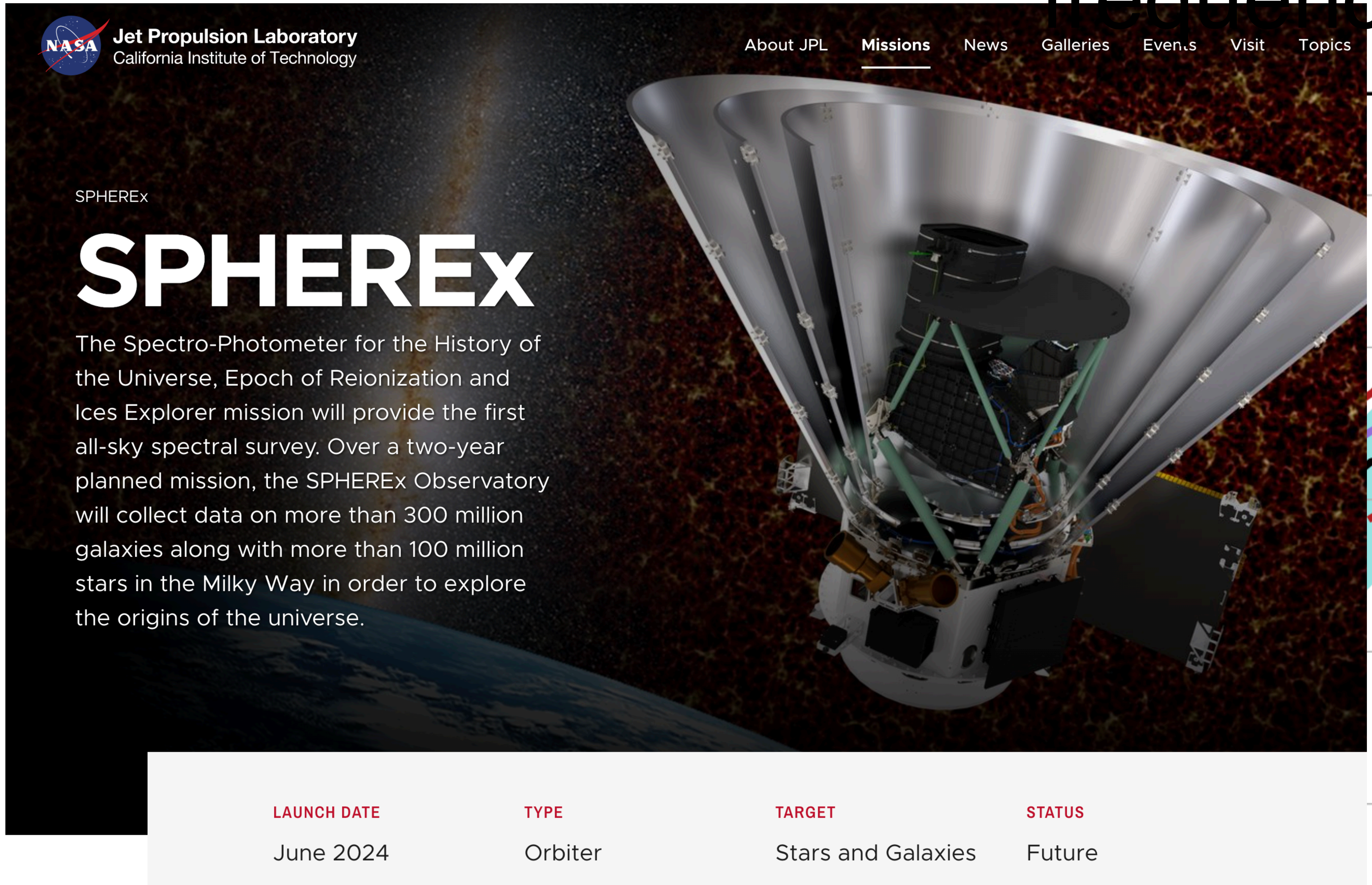

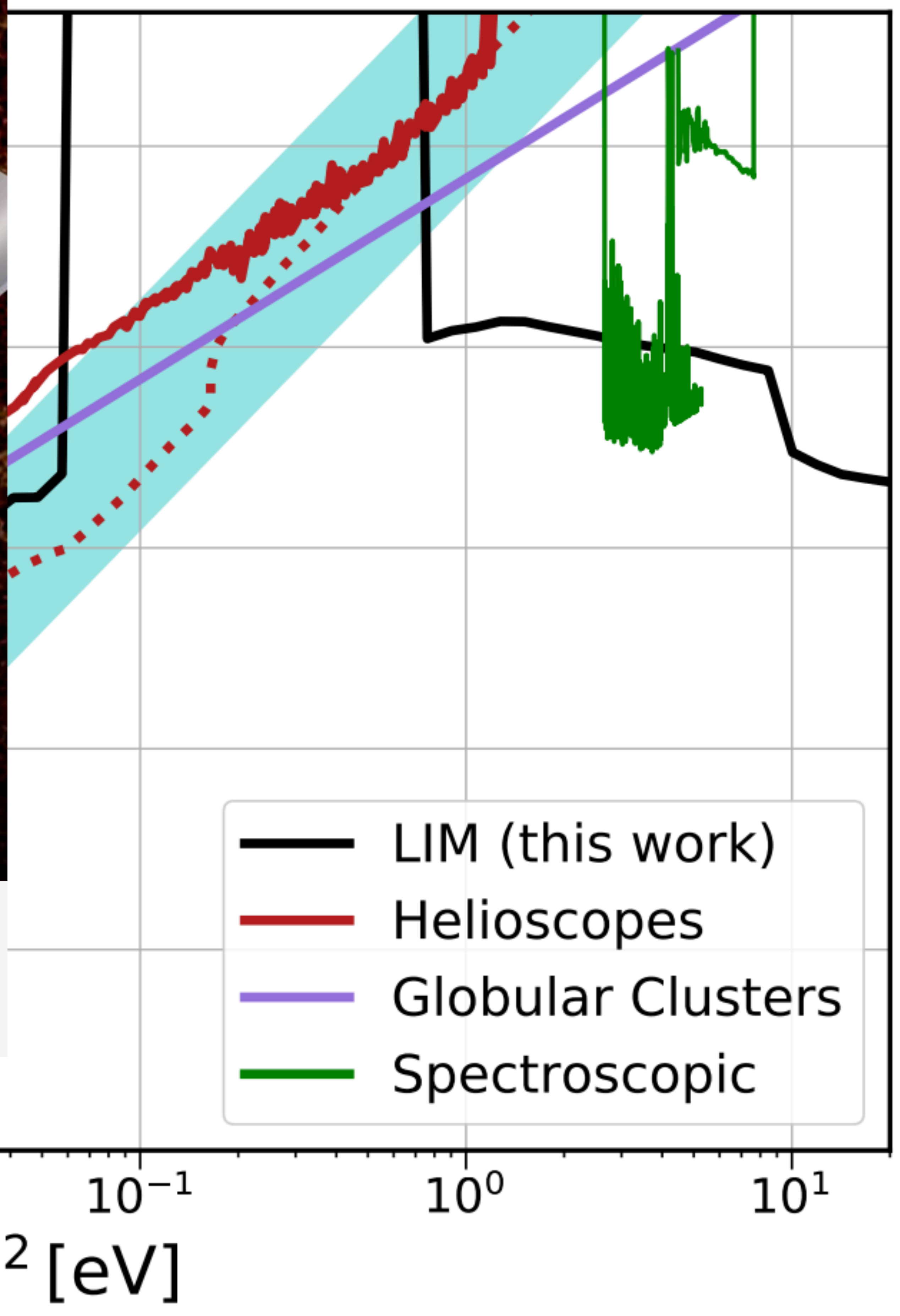

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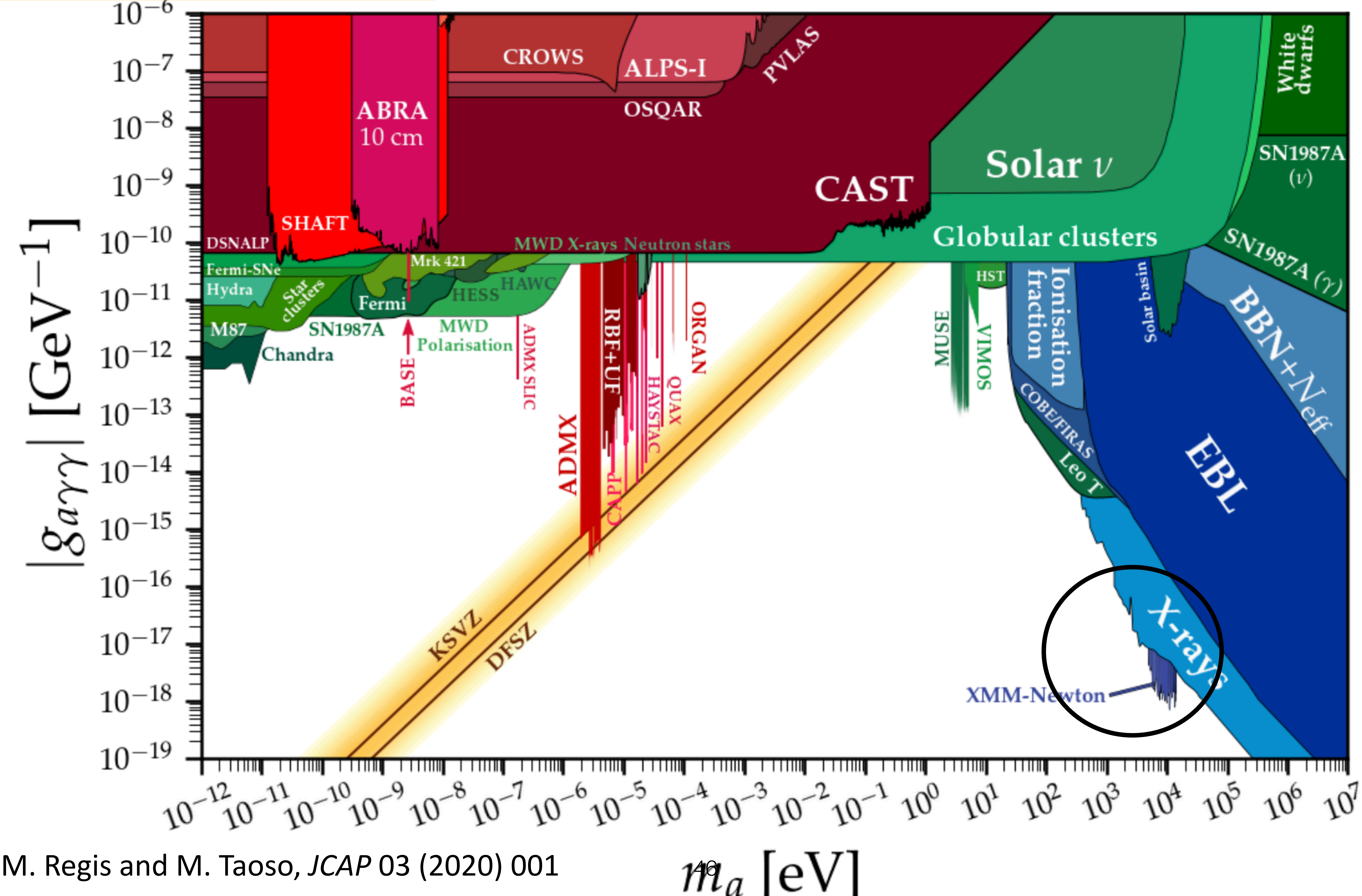

Caputo, M. Regis and M. Taoso, *JCAP* 03 (2020) 001

MeV (gamma-rays)

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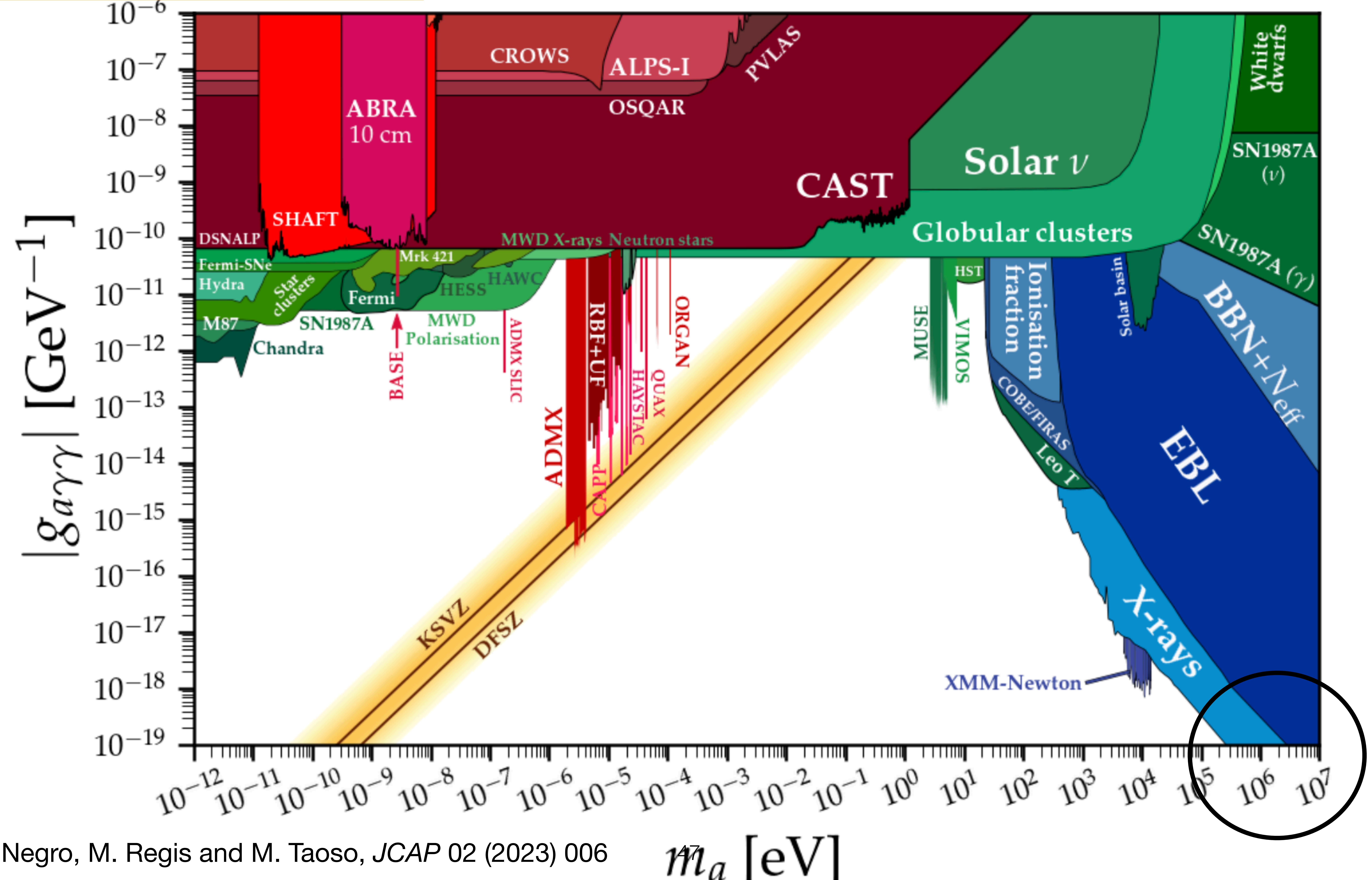

Caputo, M. Negro, M. Regis and M. Taoso, *JCAP* 02 (2023) 006

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**.

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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)

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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

Caputo et al., *JCAP* 03 (2019) 027 (radio)
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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
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D. Barducci, E. Bertuzzo, Caputo, P. Hernandez, *JHEP* 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)

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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)

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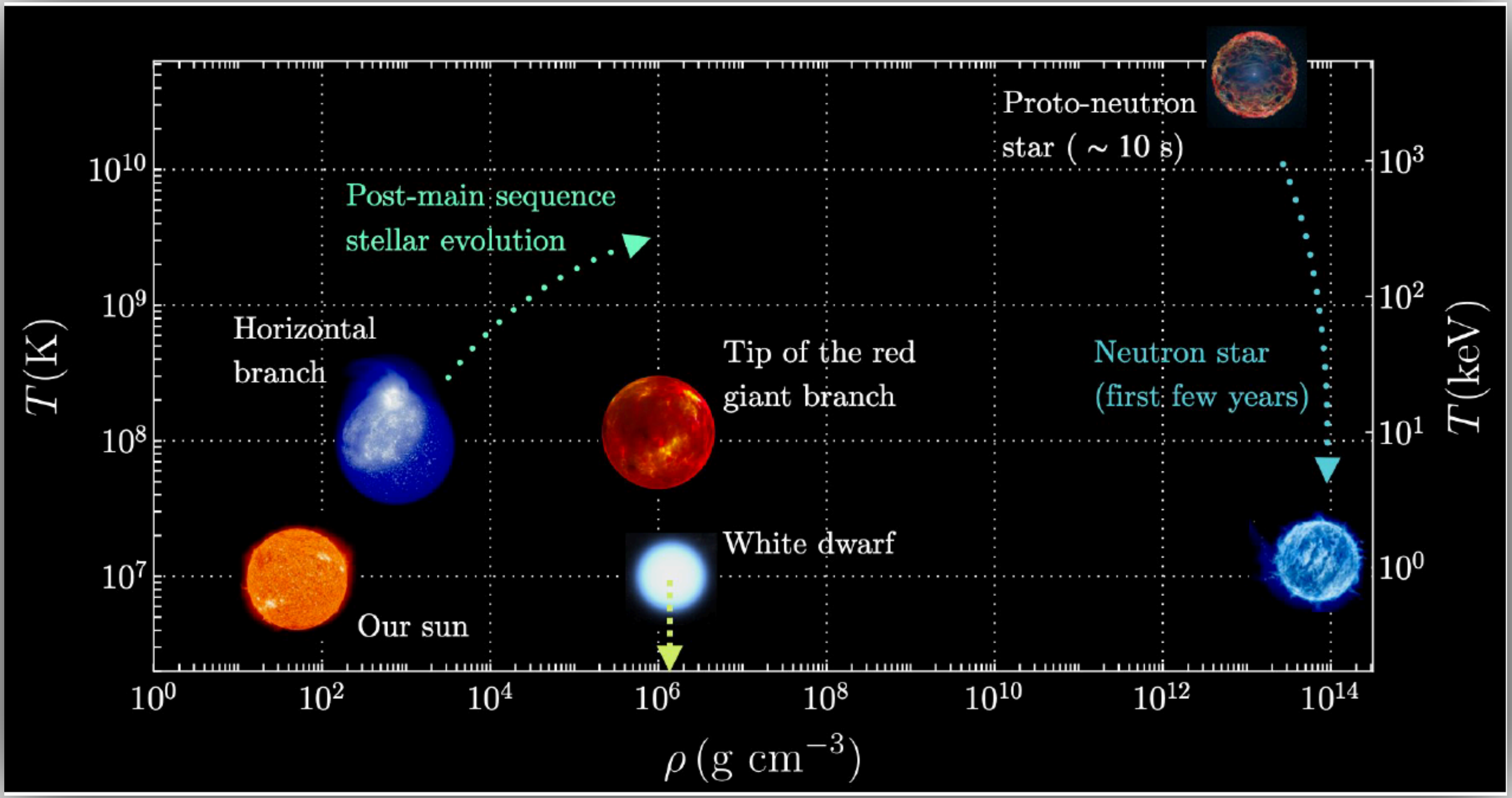
Caputo, T.H. Janka, G. Raffel, E.Vitagliano, *Phys.Rev.Lett.* 128 (2022) 22, 221103



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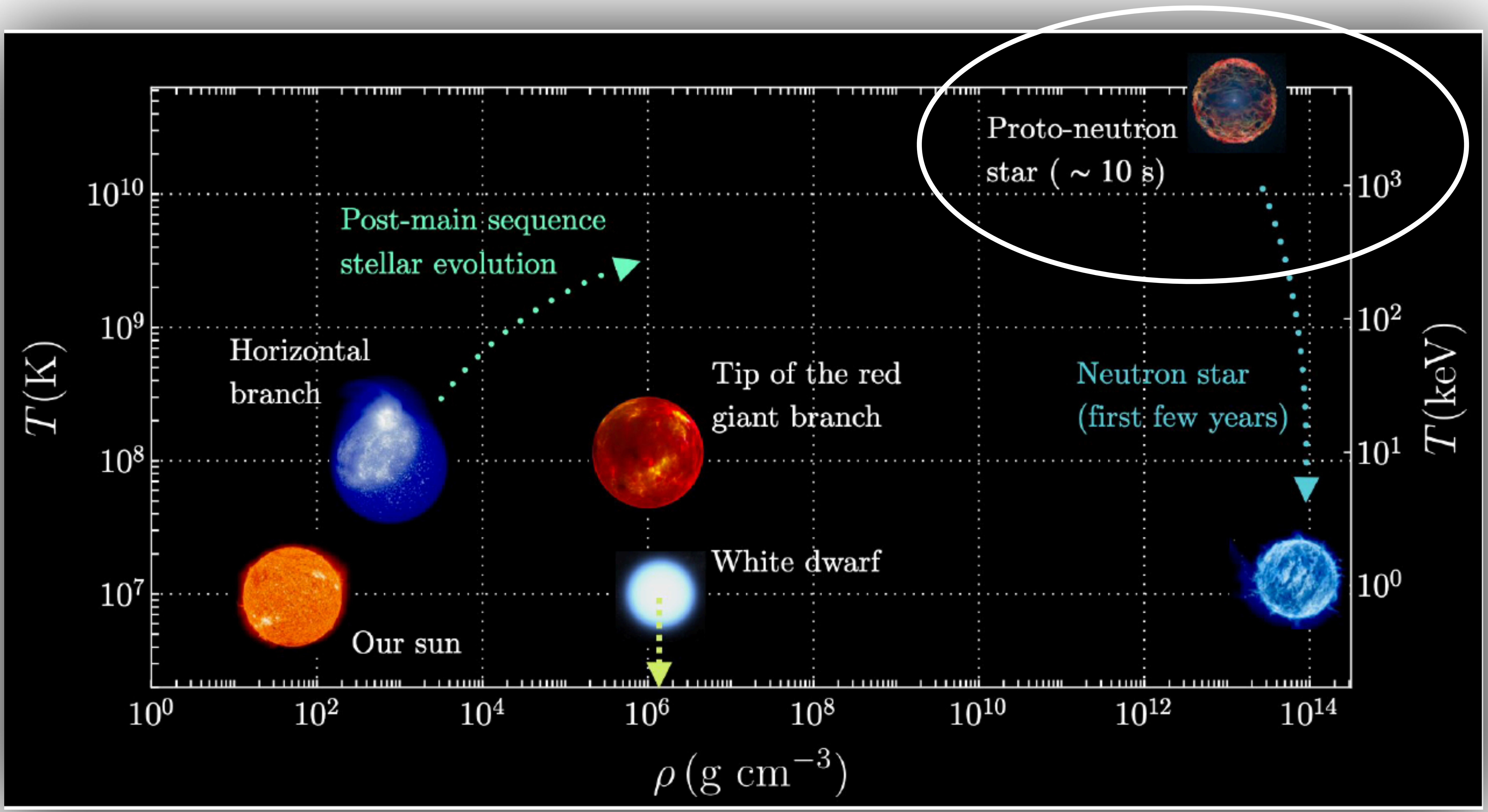

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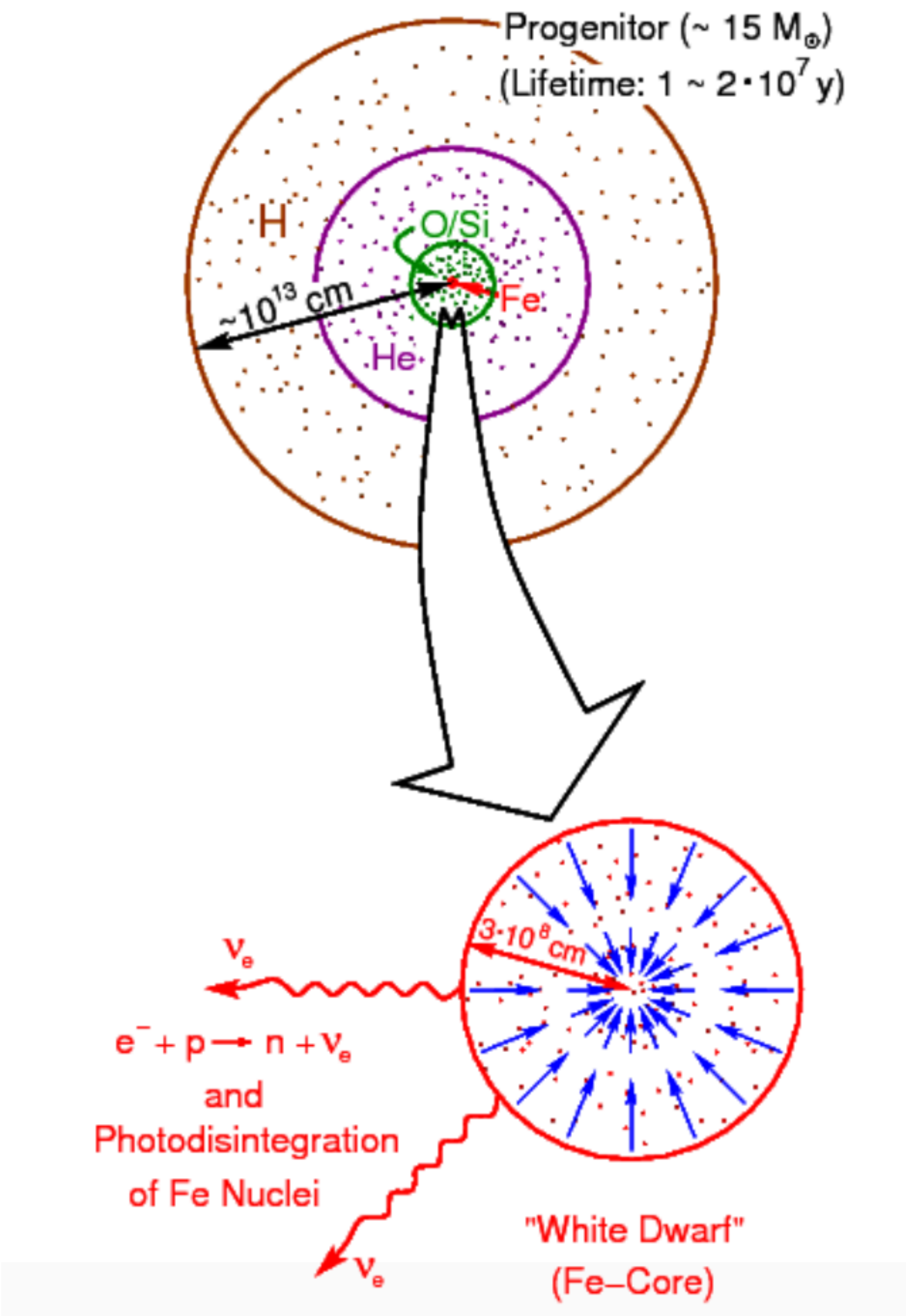
Caputo, P.Carenza, G.Lucente, E.Vitagliano, et al., *Phys.Rev.Lett.* 127 (2021) 18, 181102

Crash-course on Supernovae (SNe)

A little bit of SN Physics



See T. Janka Cern Colloquium
https://indico.cern.ch/event/1037035/

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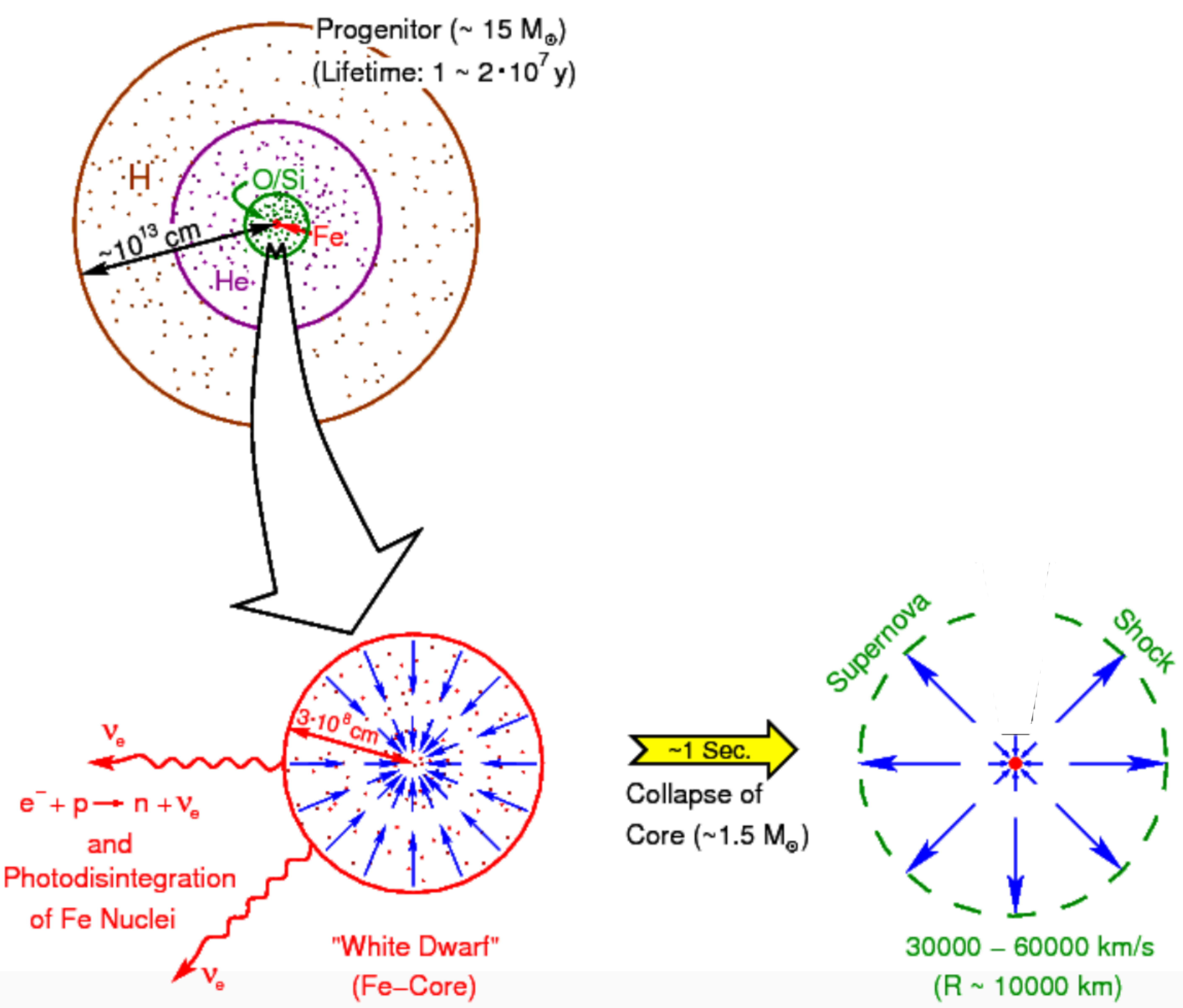

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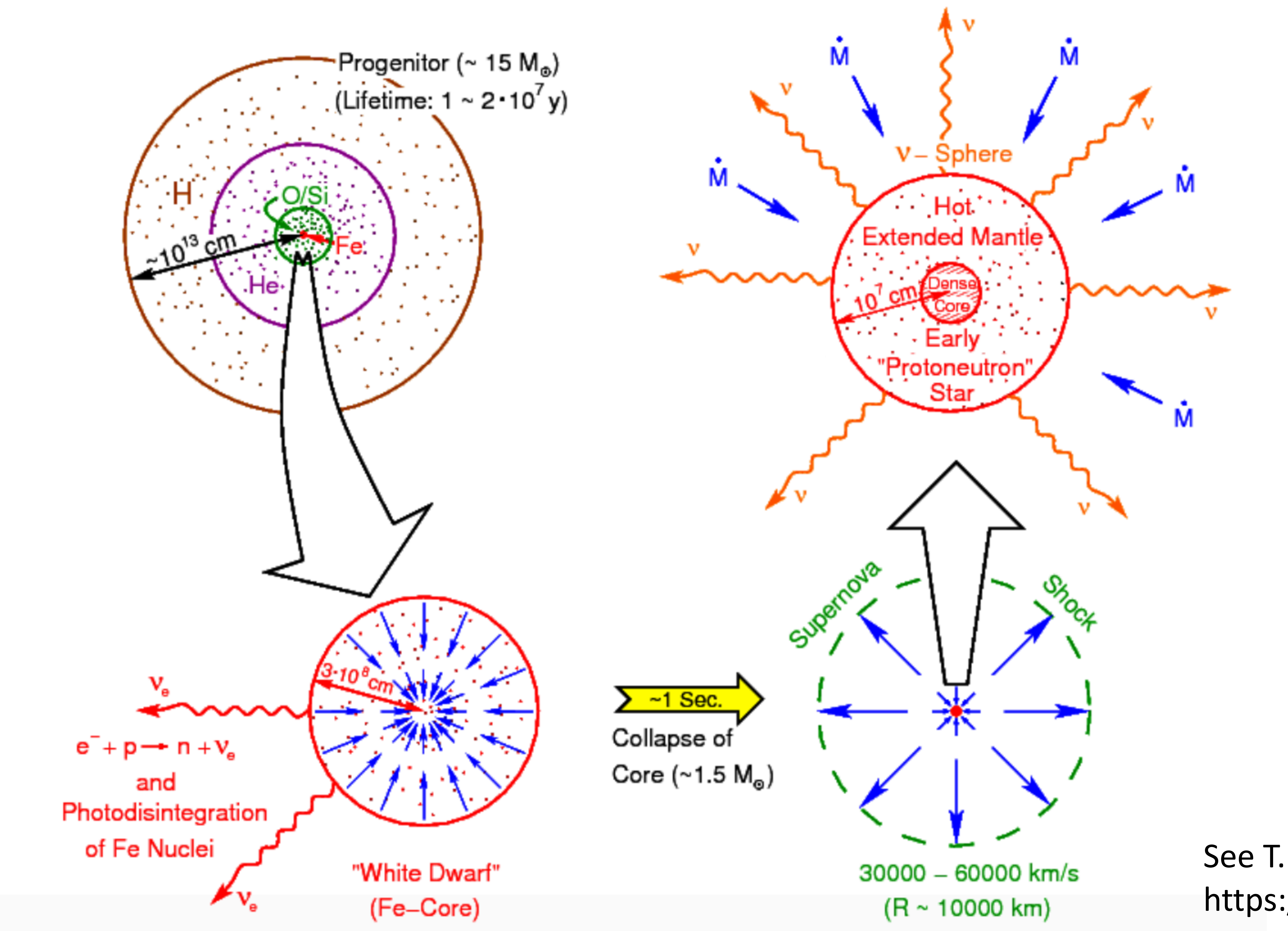

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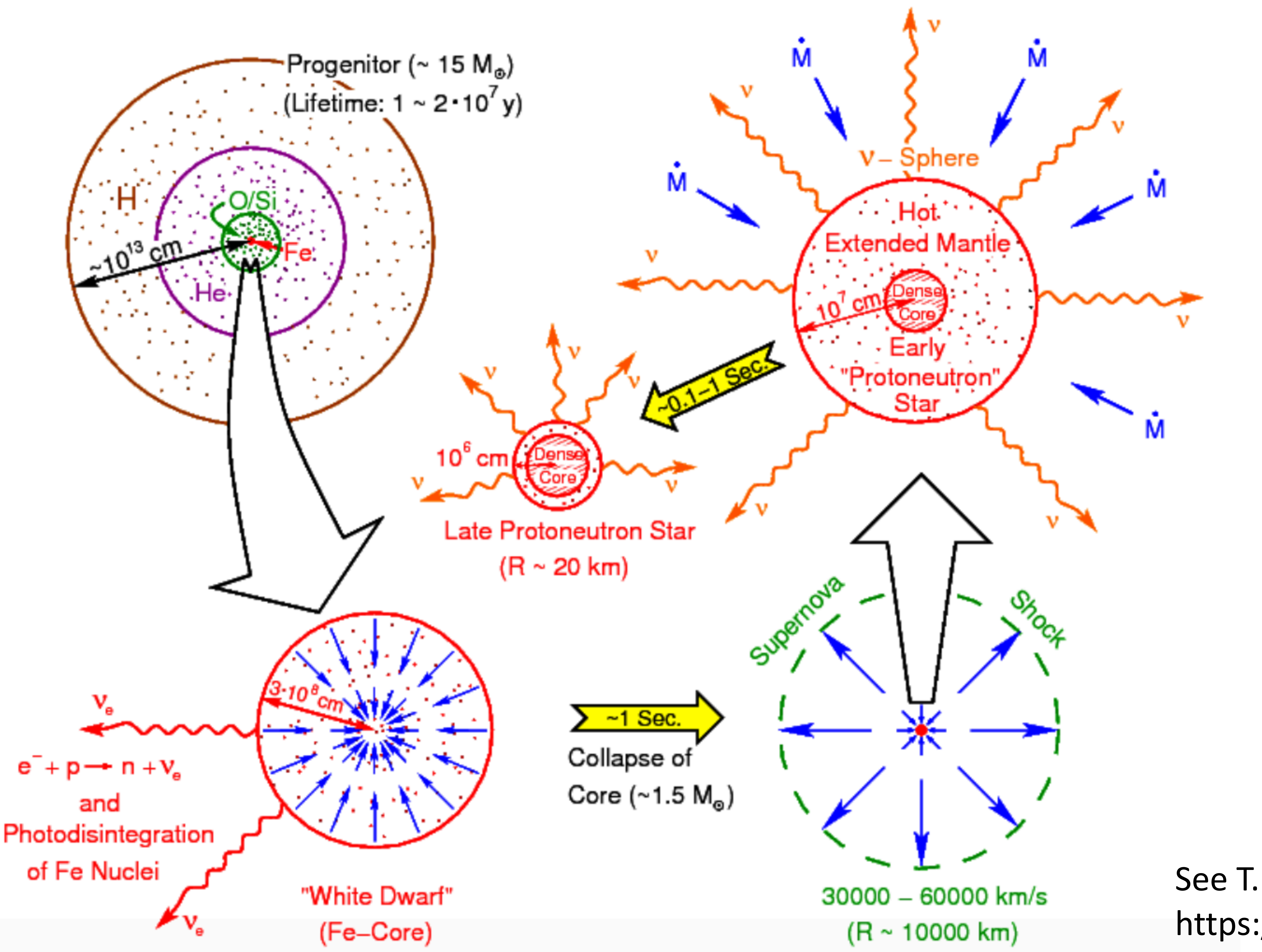

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PNS: protoneutron star

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

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

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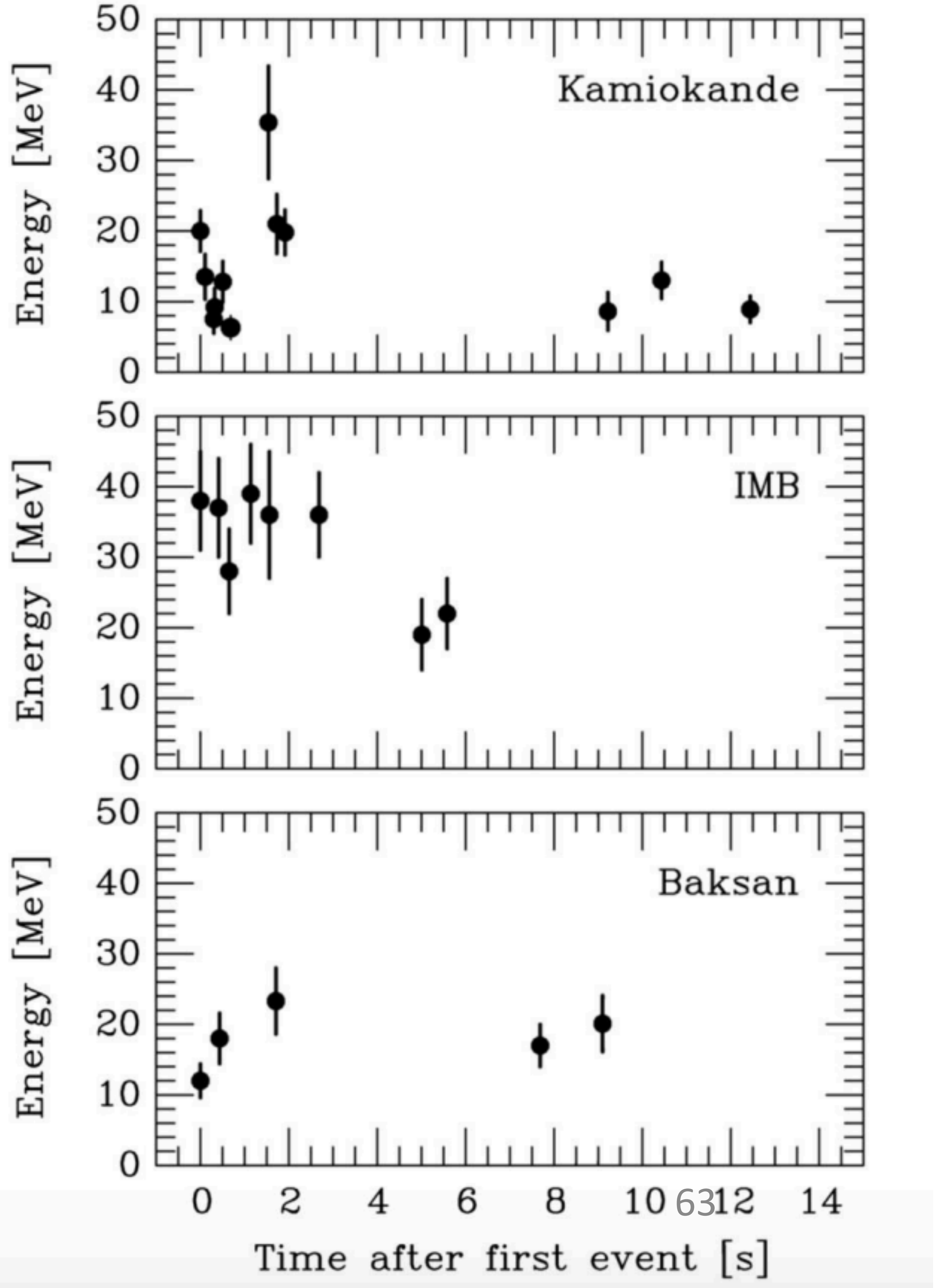
$$T = \tfrac{2}{3}\langle E_{\text{kin}}\rangle \approx 17\,\text{MeV}$$

$$t_{\text{diff}} \approx R^2/\lambda$$

SN 1987A neutrino signal



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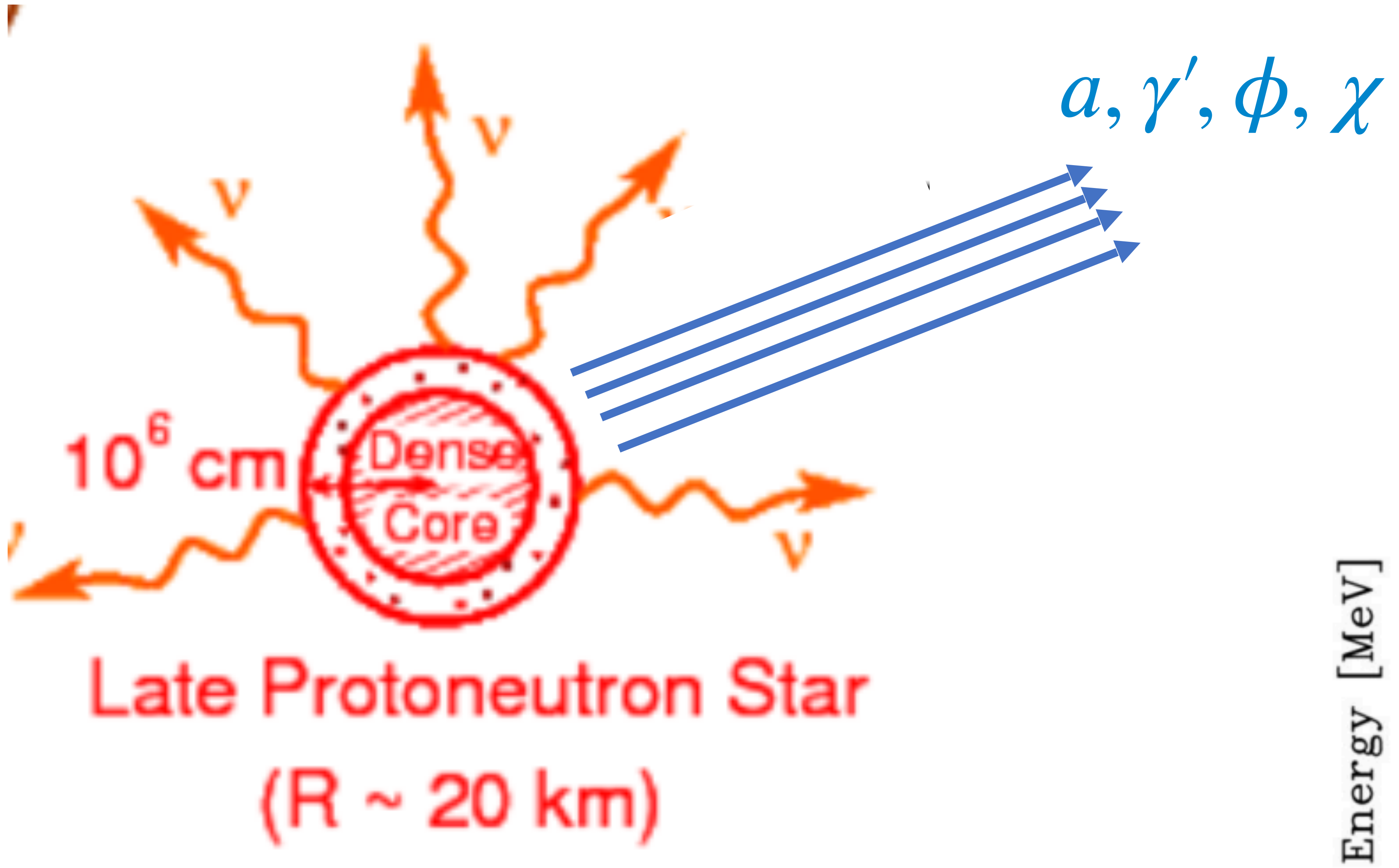

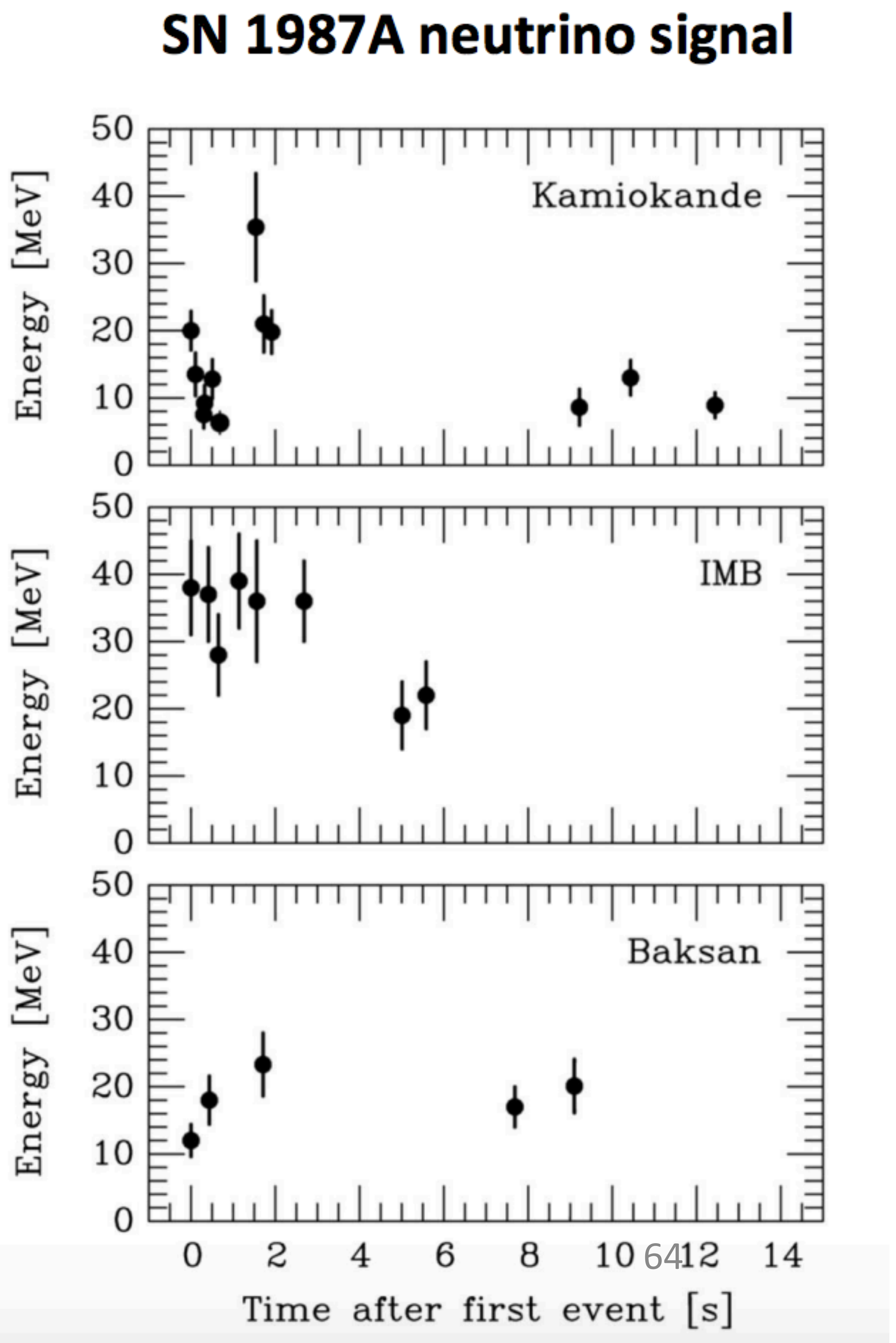

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Limits on right-handed interactions from SN 1987A observations

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

Implications of the supernova SN1987A neutrino signals

I. Goldman, Y. Aharonov, G. Alexander, and S. Nussinov
Phys. Rev. Lett. **60**, 1789 – Published 2 May 1988

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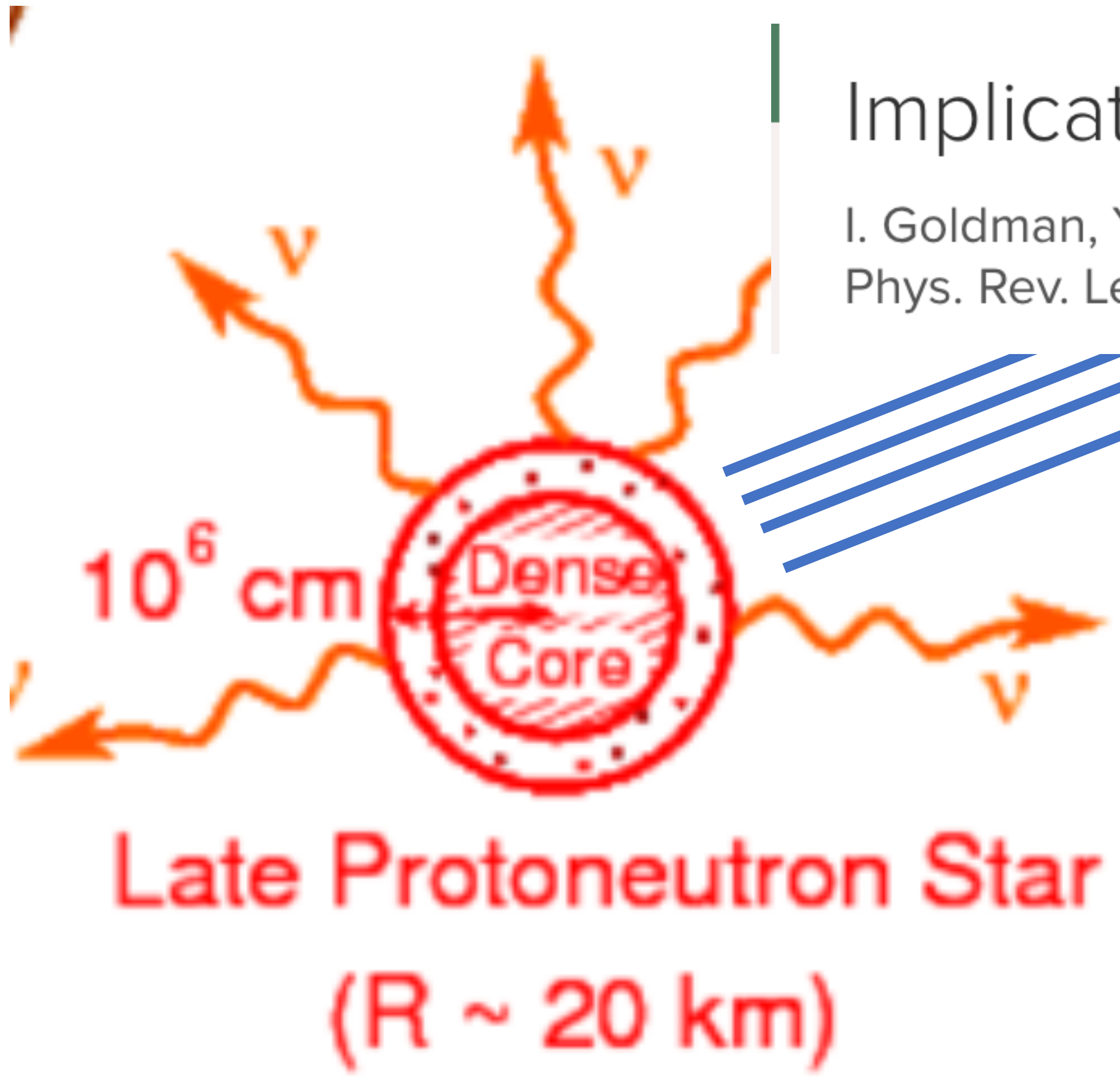

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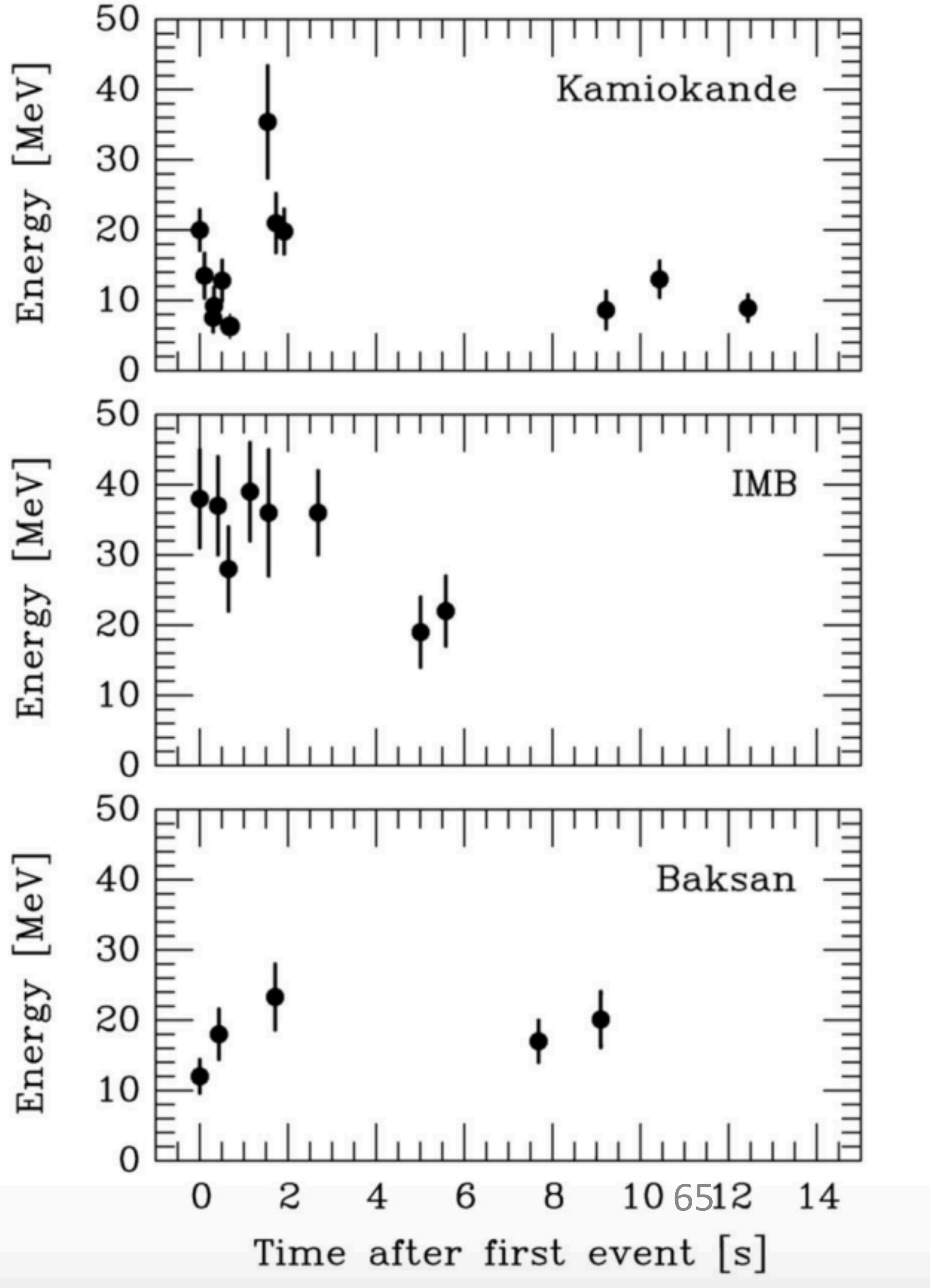

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Example model: axion coupling to photons

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

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

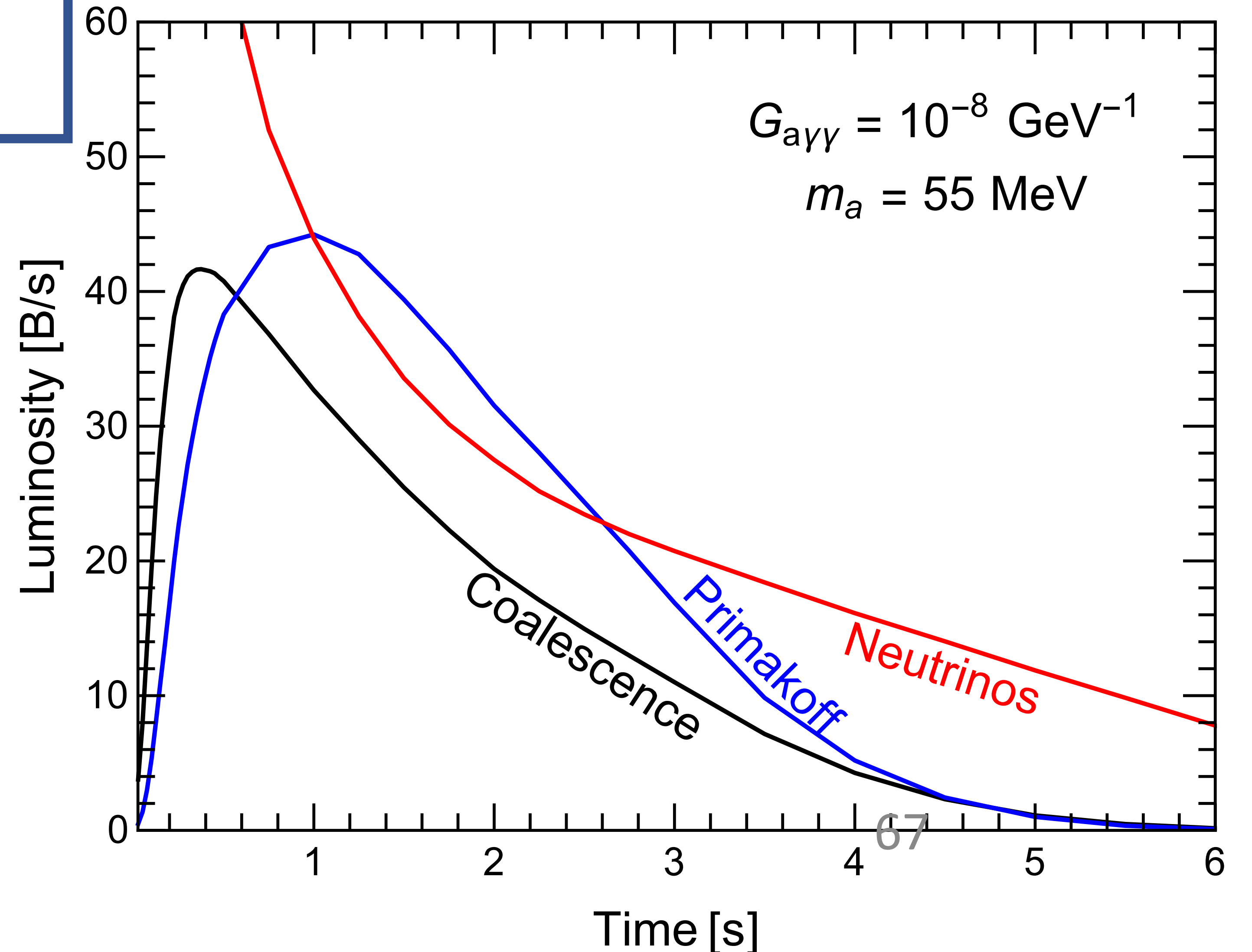
$$= \hat{n}\, \alpha G_{a\gamma\gamma}^2 \frac{\pi^2 T^4}{30} \langle f_{\rm P} \rangle, \qquad \langle f_{\rm P} \rangle = 20 \frac{m_a^2 + 3m_a T + 3T^2}{\pi^4 T^2} e^{-m_a/T}$$

Primakoff

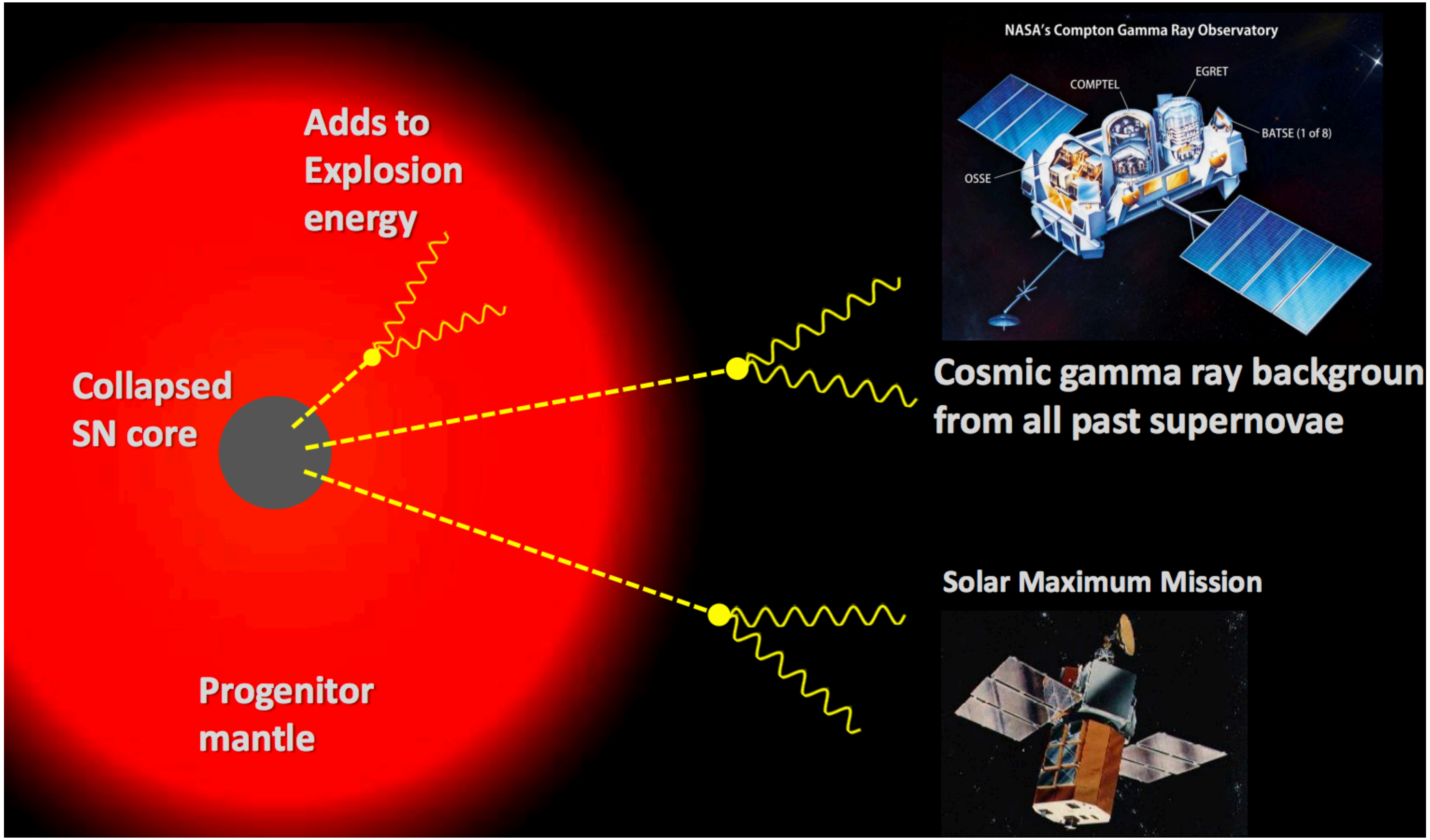
$$Q_a = \int \frac{d^3\mathbf{p}}{(2\pi)^3} \omega\, e^{-\omega/T} \Gamma_{\rm A} = \frac{G_{a\gamma\gamma}^2 T^3 m_a^4}{128\pi^3} F(m_a/T)$$

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

Coalescence



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



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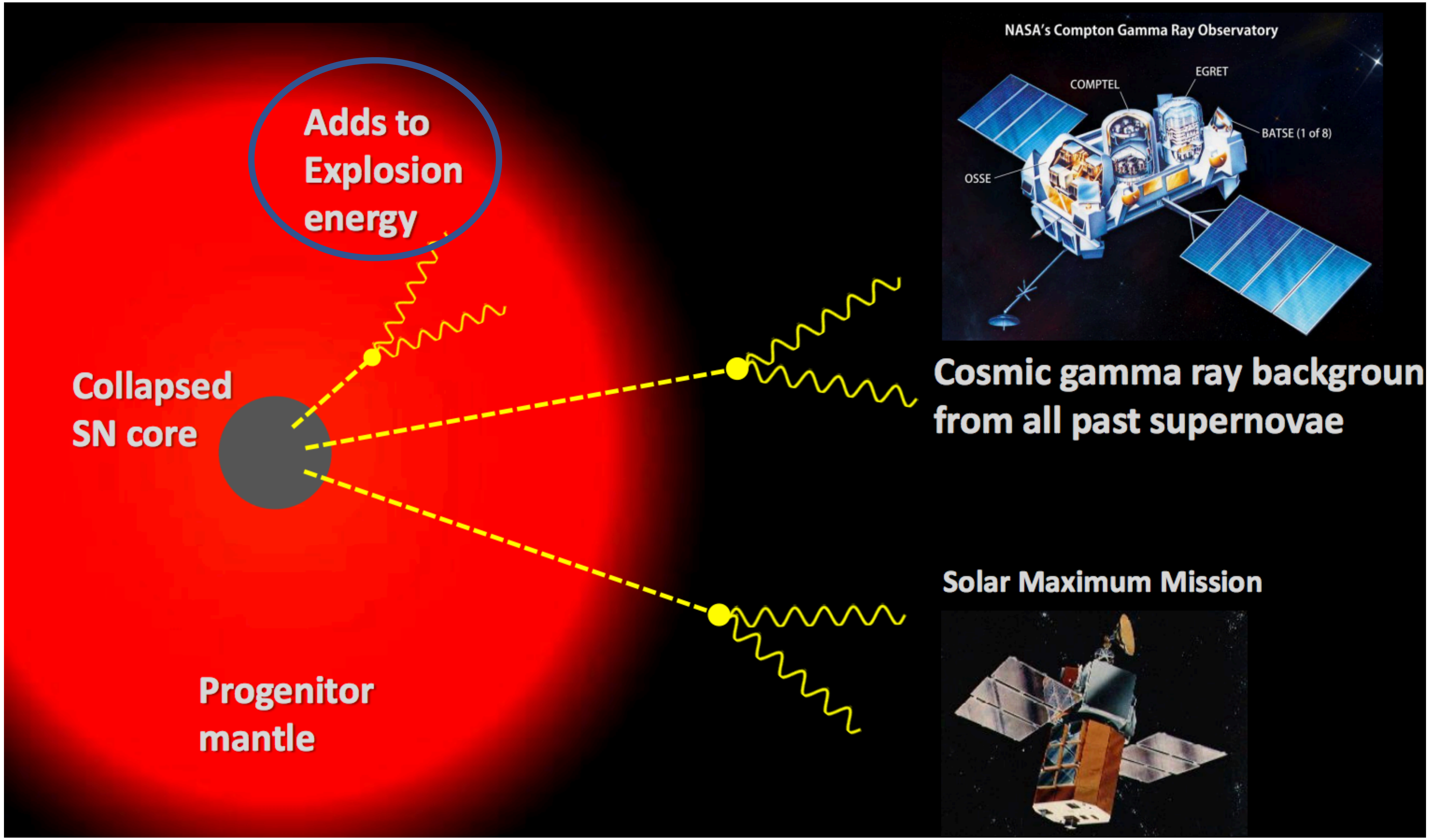

The axions get produced and then can decay back into photons!

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

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

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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

Low-luminosity Type II supernovae: spectroscopic and photometric evolution

A. Pastorello,[1,2,5★] L. Zampieri,[2] M. Turatto,[2] E. Cappellaro,[3]
S. Benetti,[2] D. Branch,[5] E. Baron,[5] F. Patat,[6] M. Armstrong,[7] C
M. Salvo[8] and M. Riello[2,1]

[1]*Dipartimento di Astronomia, Università di Padova, Vicolo dell' Osservatorio 2, I-35122 Padova, Italy*
[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 2BZ*
[5]*Department of Physics and Astronomy, University of Oklahoma, 440 W. Brooke St., Norman, OK 73019, USA*
[6]*European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748, Garching bei Munchen, Germany*
[7]*UK Supernova Patrol, British Astronomical Association, Rolvenden, Kent*
[8]*Australian National University, Mount Stromlo Observatory, Cotter Road, Weston ACT 2611, Australia*

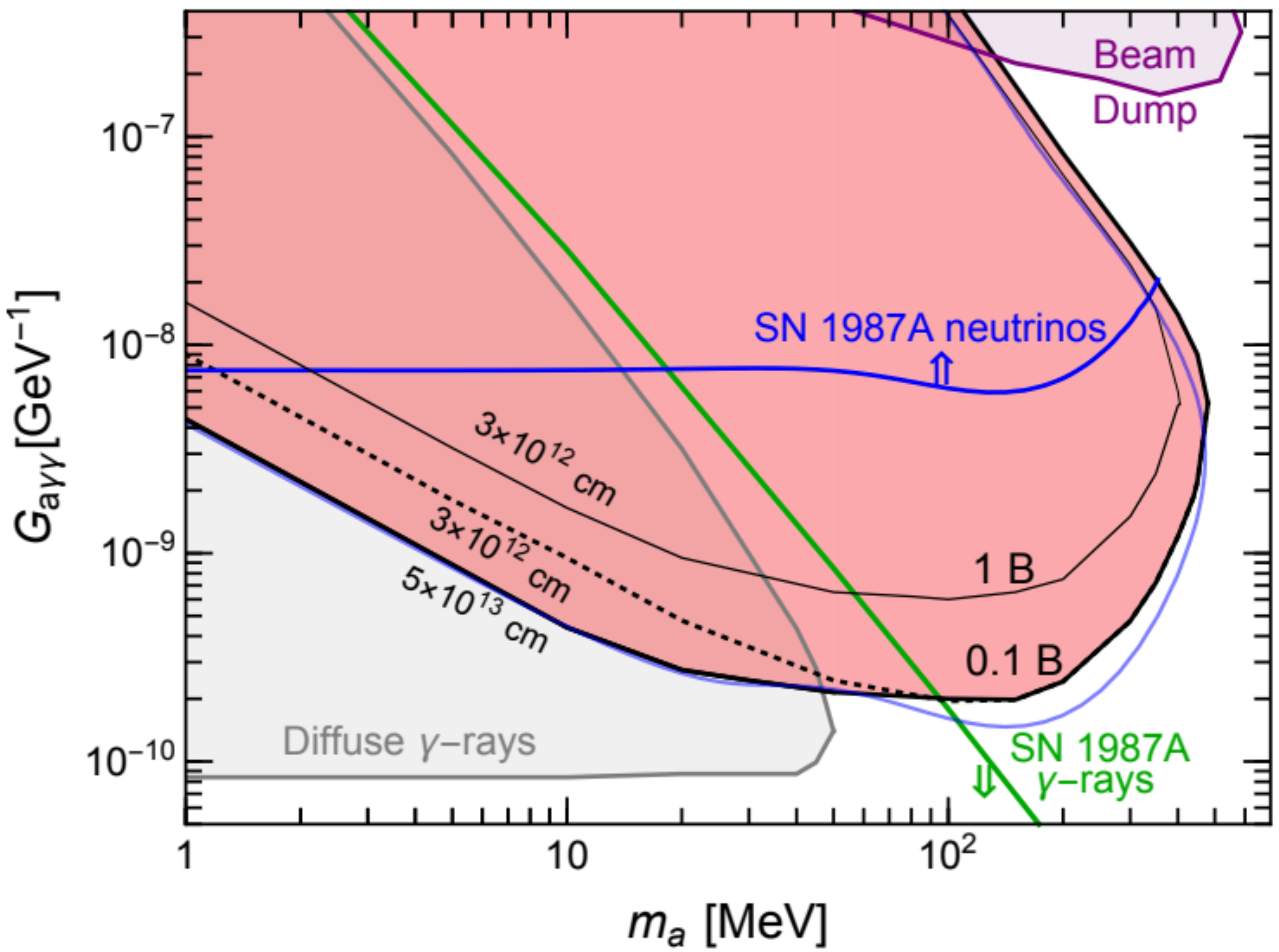
Monthly Notices *of the* ROYAL ASTRONOMICAL SOCIETY

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

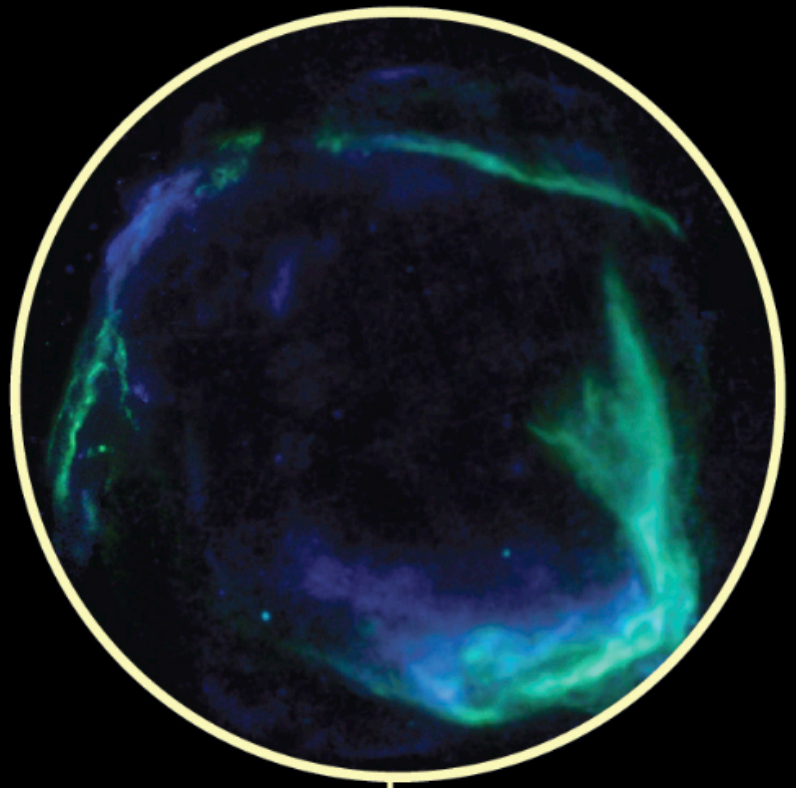
S. Spiro,[1★] A. Pastorello,[1] M. L. Pumo,[1,2] L. Zampieri,[1] M. Turatto,[1] S. J. Smartt,[3]
S. Benetti,[1] E. Cappellaro,[1] S. Valenti,[4,5] I. Agnoletto,[1] G. Altavilla,[6] T. Aoki,[7]
E. Brocato,[8] E. M. Corsini,[1,9] A. Di Cianno,[10] N. Elias-Rosa,[11] M. Hamuy,[12]
K. Enya,[13] M. Fiaschi,[9] 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

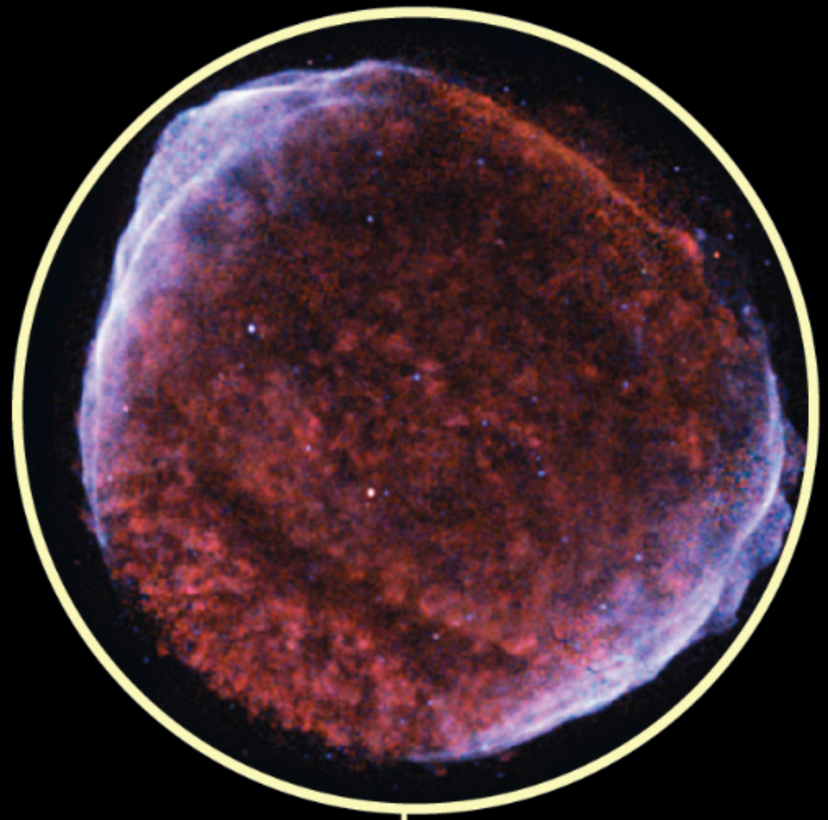
RCW 86

Historical Observers: Chinese

Likelihood of Identification: Possible

Distance Estimate: 8,200 light years

Type: Core collapse of massive star



A.D. 393

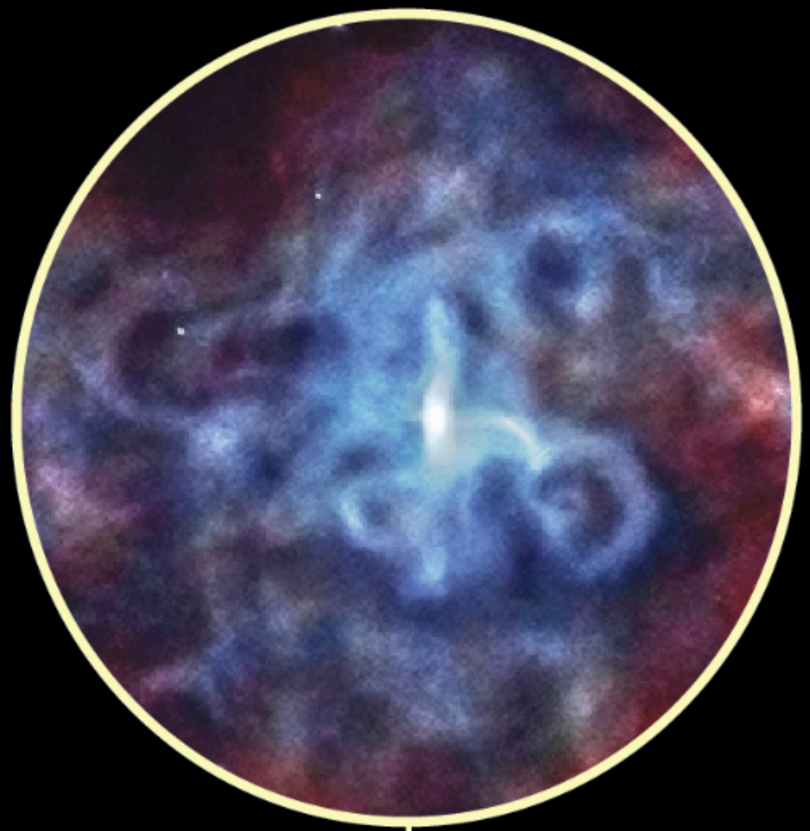
SN 1006

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

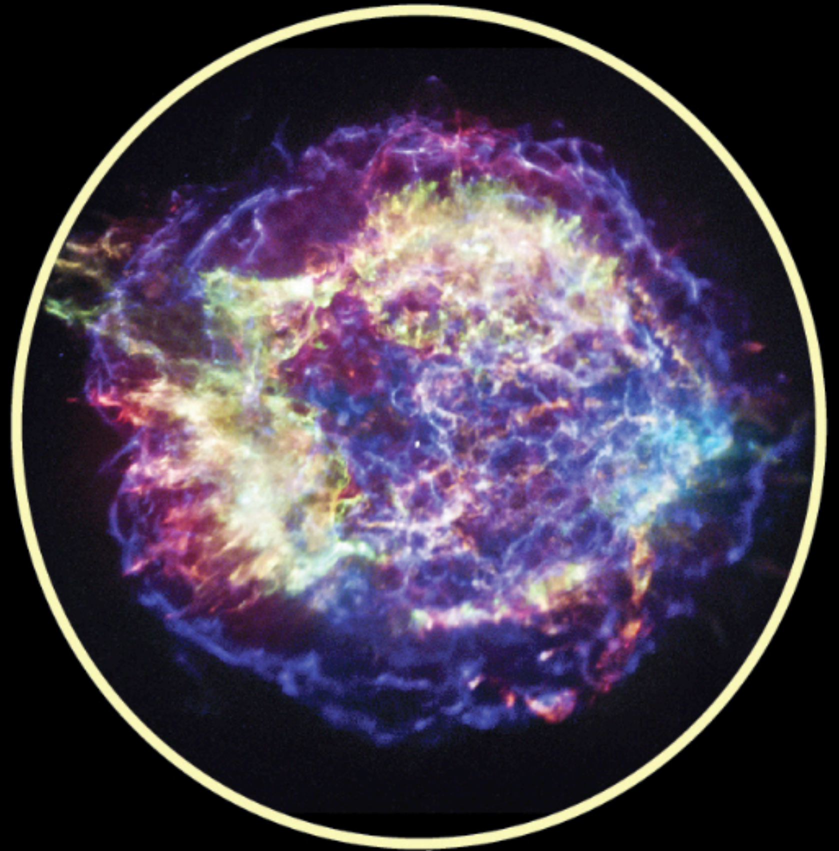
3C58

Historical Observers: Chinese, Japanese

Likelihood of Identification: Possible

Distance Estimate: 10,000 light years

Type: Core collapse of massive star



A.D. 1680

Cassiopeia A

Historical Observers: European?

Likelihood of Identification: Unlikely

Distance Estimate: 10,000 light years

Type: Core collapse of massive star

A.D. 386

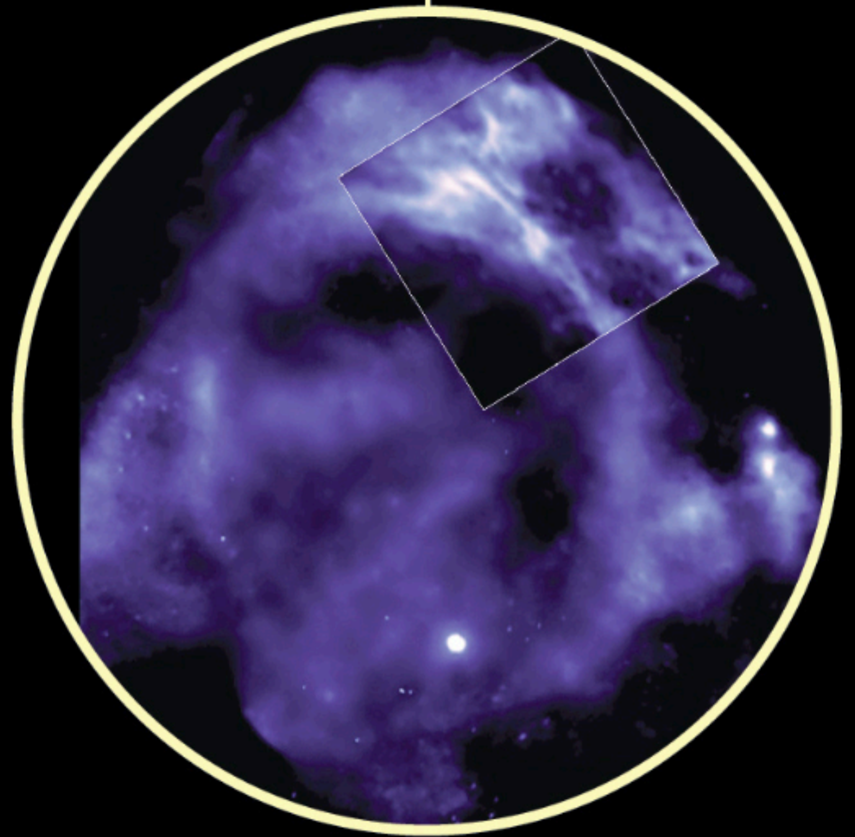
G347.3-0.5

Historical Observers: Chinese

Likelihood of Identification: Possible

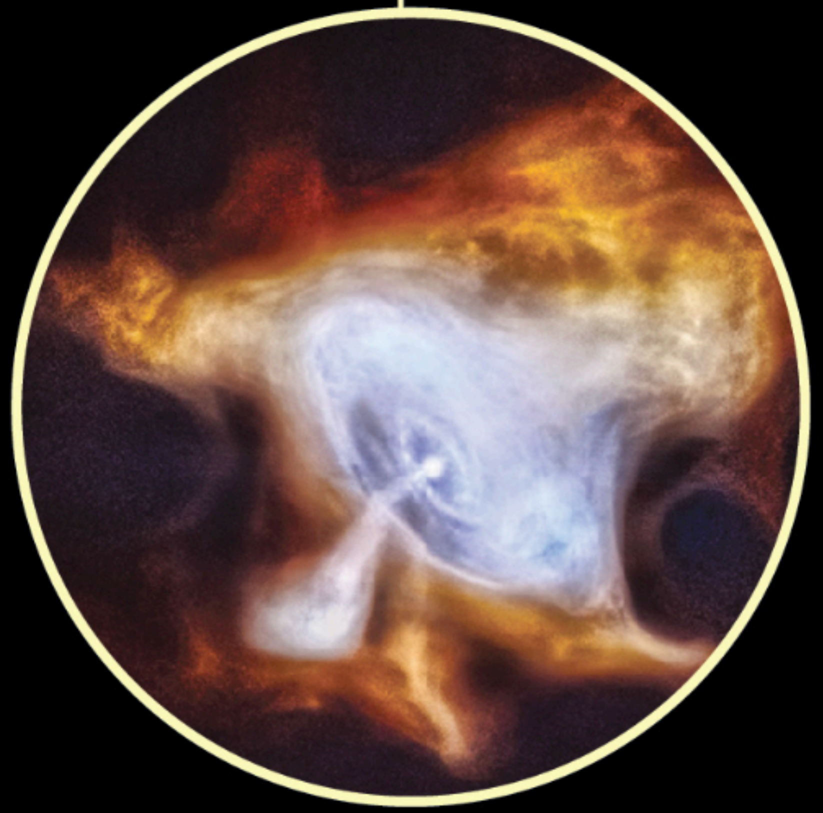
Distance Estimate: 3,000 light years

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. 1572

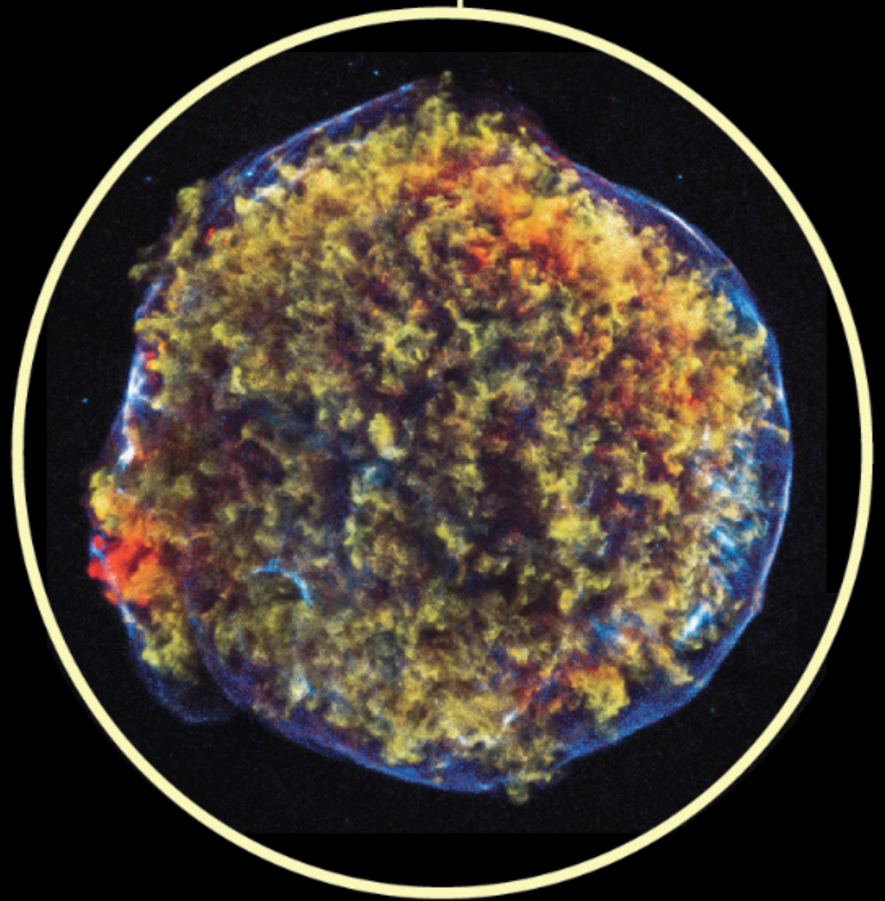
Tycho's SNR

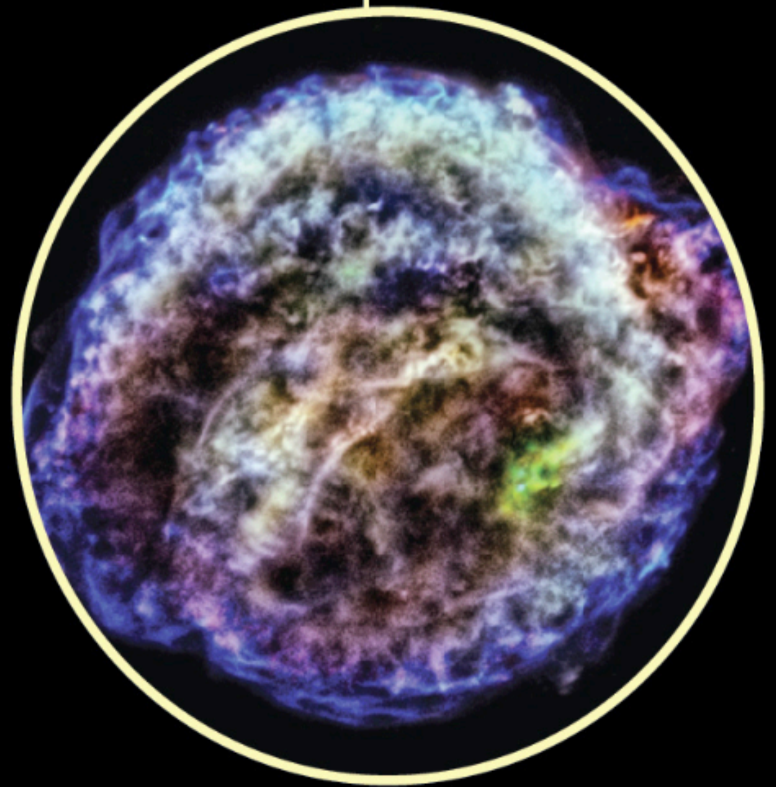
Historical Observers: European, Chinese, Korean

Likelihood of Identification: Definite

Distance Estimate: 7,500 light years

Type: Thermonuclear explosion of white dwarf





A.D. 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?

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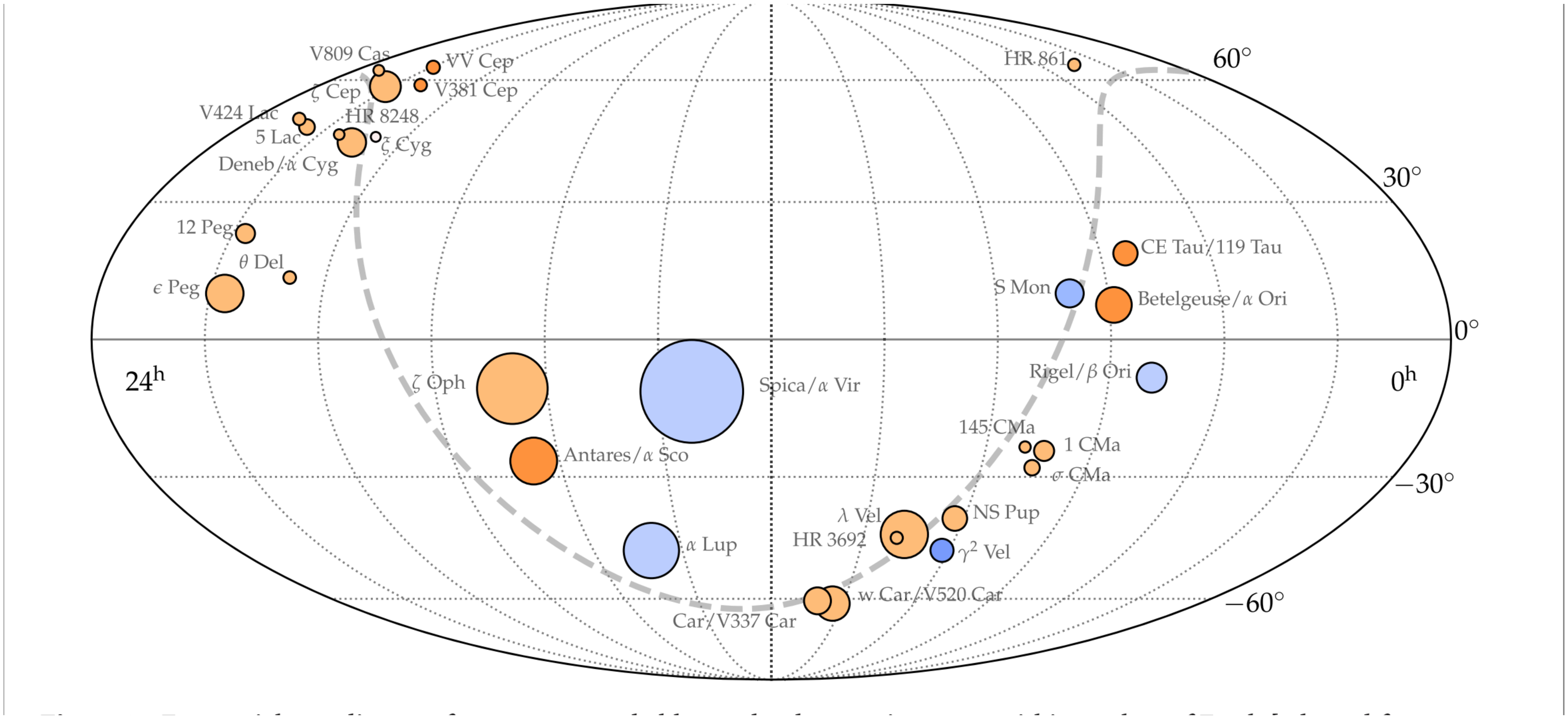
NEWS FEATURE | 21 February 2022

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

Next SN candidates within 1 kpc from us



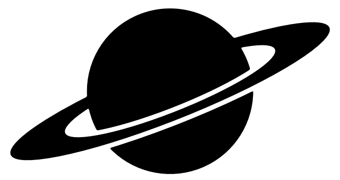
Plans for the future

- Detailed simulations and output from radiative transport simulations in supernovae;
- Extension of the LESN criterion to other relevant models;
- Cross-correlation studies for line intensity mapping + foreground analysis + extension to other dark matter models;
- Study dark matter impact on star formation (JWT is taking data, amazing opportunity).


Thanks for the attention!

Back-up slides

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

Caputo et al., *JCAP* 03 (2019) 027 (radio)
Caputo et al., *Phys.Rev.D* 98 (2018) 8, 083024 (radio)

Caputo et al., *JCAP* 03 (2020) 001 (X-rays)

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

Bernal, Caputo, et al., *Phys.Rev.D* 103 (2021) 6, 063523 (optic)
Bernal, Caputo, et al., *Phys.Rev.Lett.* 127 (2021) 13, 131102 (optic)

Gravitational Waves

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

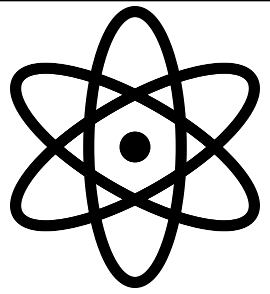
Toubiana, Sberna, Caputo, et al.,
Phys.Rev.Lett. 126 (2021) 10, 101105

My research

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, *JHEP* 06 (2020) 185
D. Barducci, E. Bertuzzo, Caputo, P. Hernandez, B. Mele,
JHEP 03 (2021) 117

Dark Matter direct detection

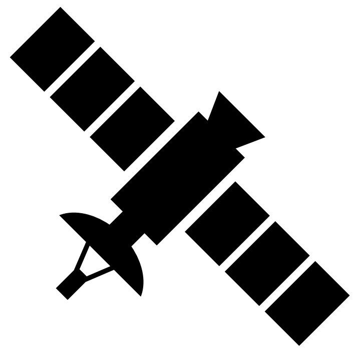


Caputo et al., *Phys.Rev.D* 100 (2019) 11, 116007 (sub-GeV DM)
Caputo et al., *Phys.Lett.B* 802 (2020) 135258 (sub-GeV DM)
Caputo et al., *Phys.Rev.D* 103 (2021) 5, 055017 (sub-GeV DM)

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)

Caputo et al., *Phys.Rev.D* 100 (2019) 6, 063515 (pulsars)
Caputo et al., Phys.Dark Univ. 19 (2018) 1-11 (pulsars)

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D. Barducci, E. Bertuzzo, Caputo, P. Hernandez, B. Mele, *JHEP* 03 (2021) 117

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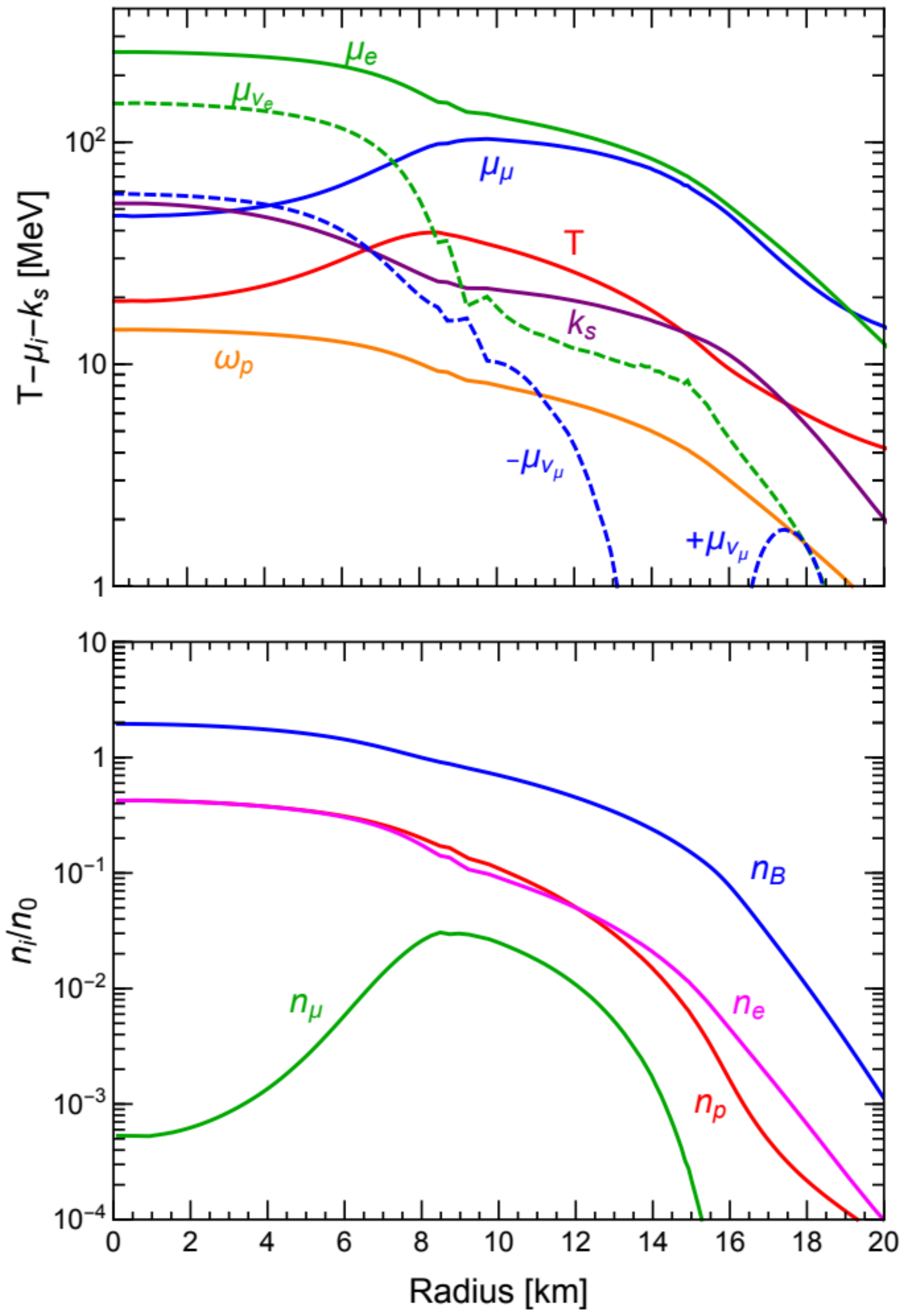
Caputo et al., *Phys.Rev.D* 100 (2019) 6, 063515 (pulsars)
Caputo et al., Phys.Dark Univ. 19 (2018) 1-11 (pulsars)

Garching SN model



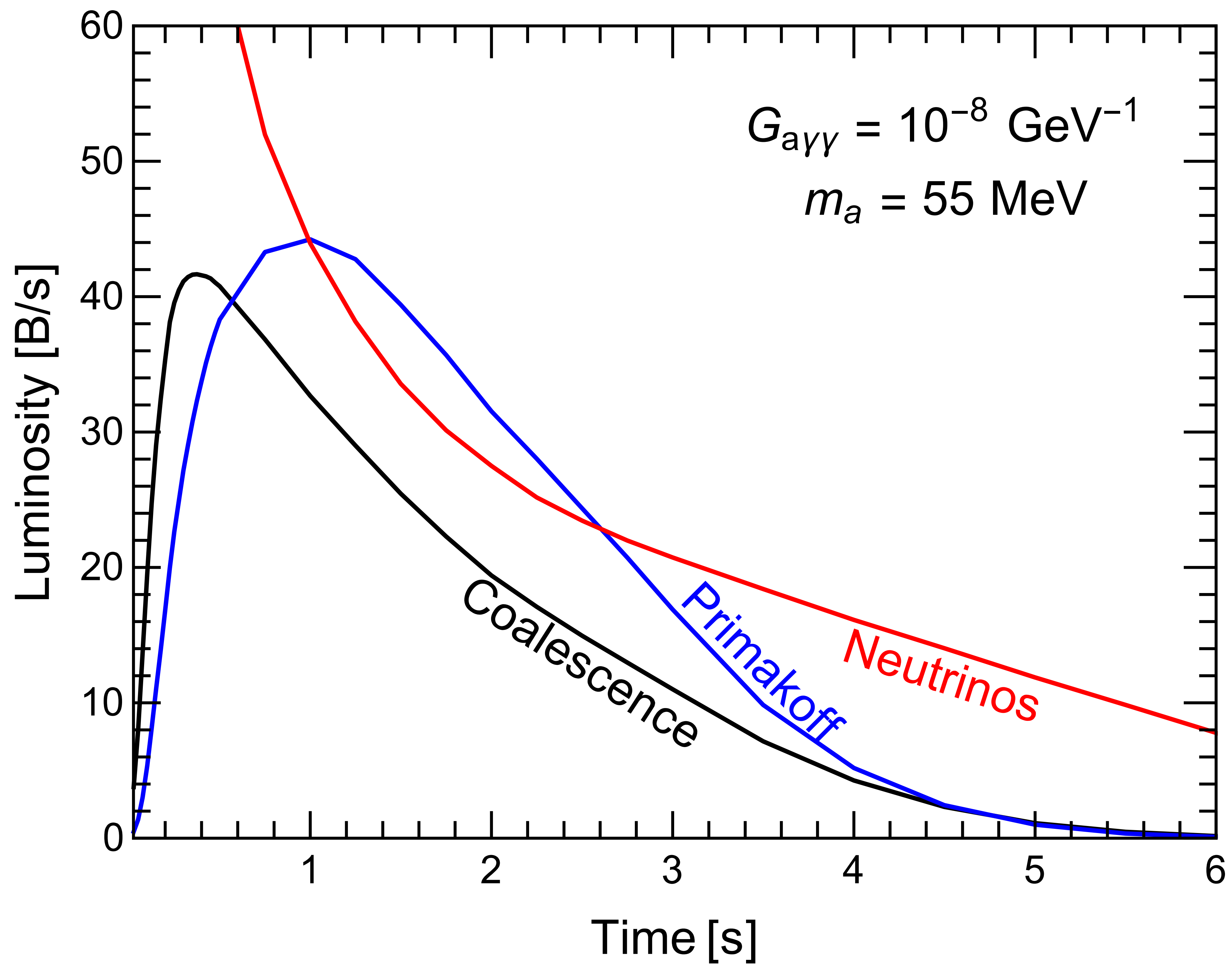
Primakoff and Coalescence calculation

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

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

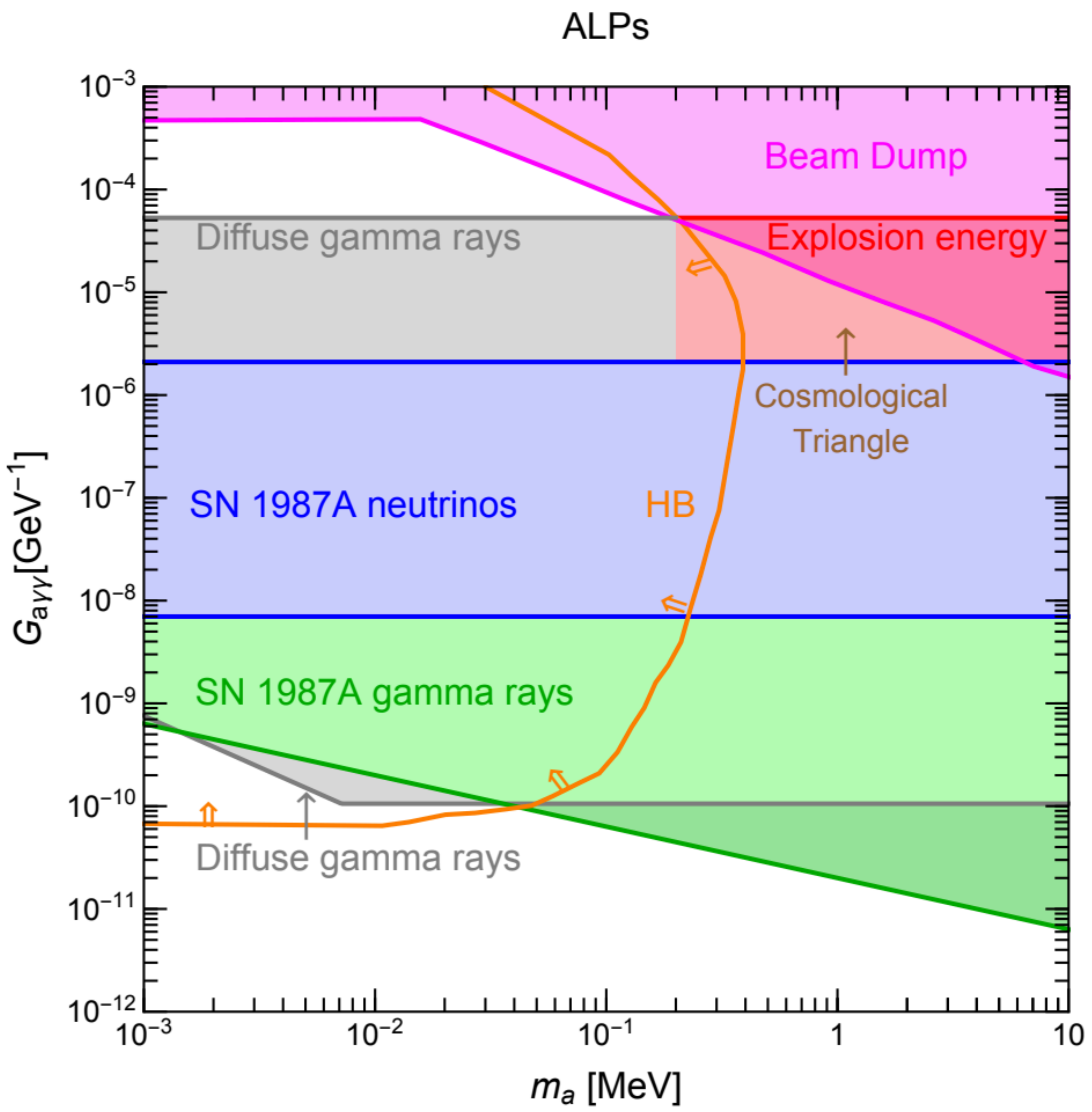
$$Q_a = \int \frac{d^3\mathbf{p}}{(2\pi)^3} \omega\, e^{-\omega/T} \Gamma_{\mathrm{A}} = \frac{G_{a\gamma\gamma}^2 T^3 m_a^4}{128\pi^3} F(m_a/T)$$

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

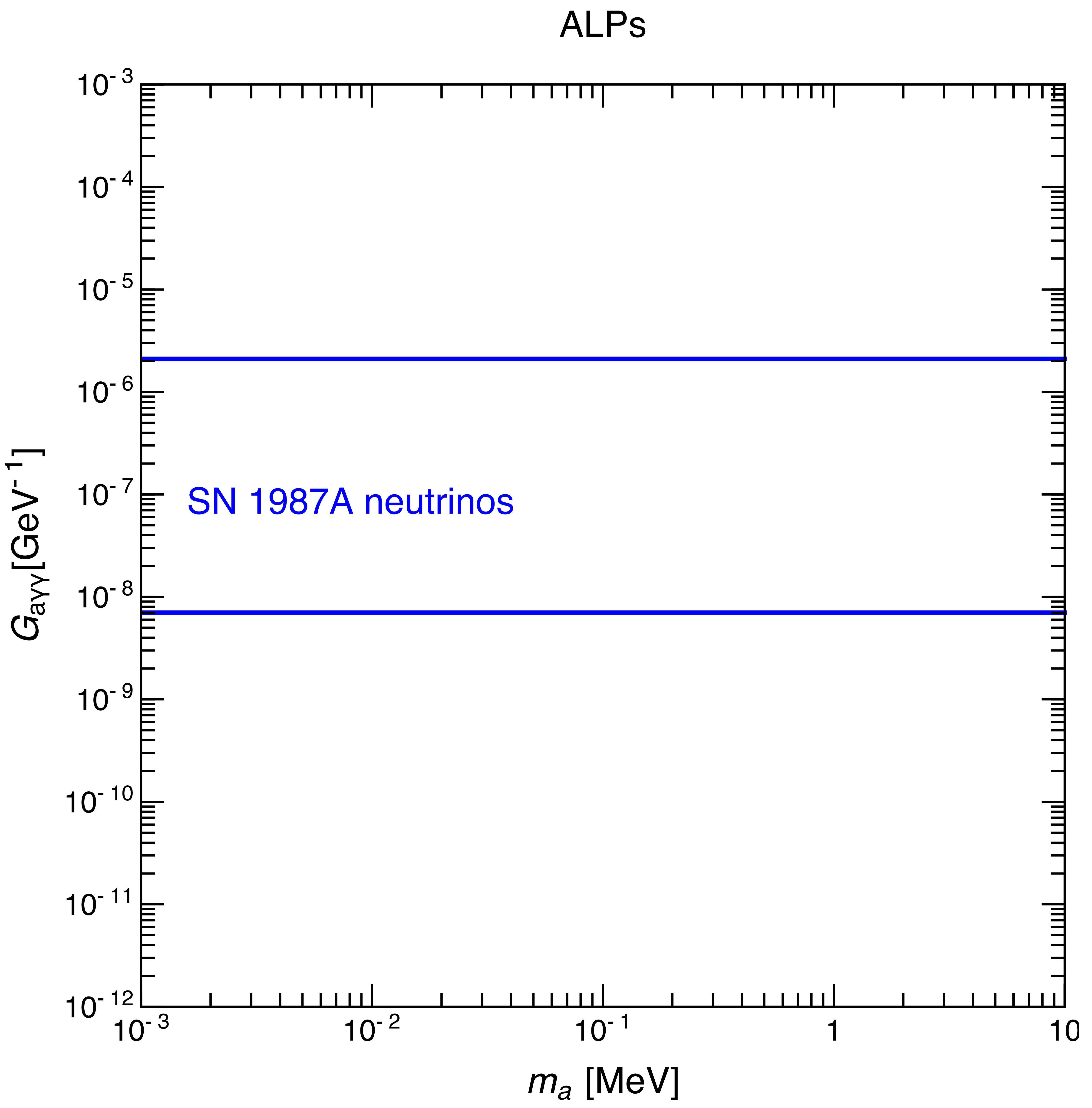


Other bounds

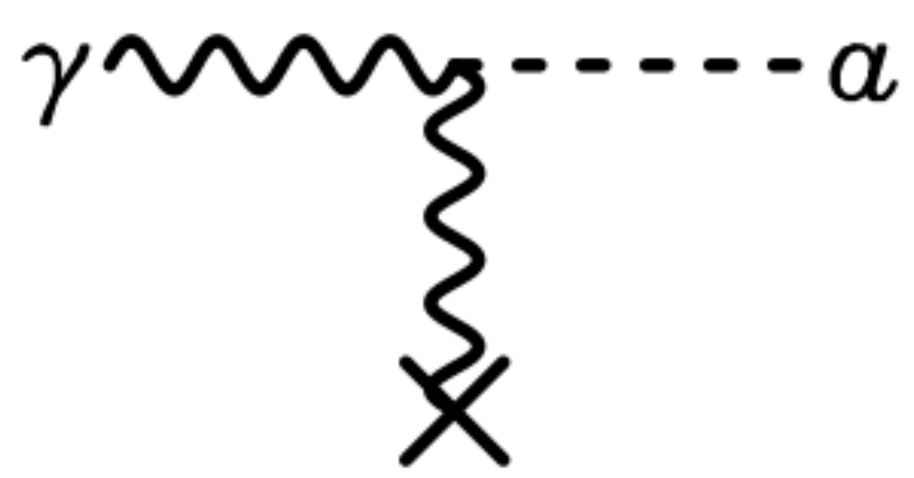
For masses above 1–10 MeV, muonphilic particles can also be efficiently probed at colliders. In particular, electron beam-dump experiments, such as the SLAC E137 experiment or the planned Jefferson Lab BDX experiment provide an excellent source of secondary muons, which can then be used to look for muonic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



Cooling bounds from SN1987A (free streaming)



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)

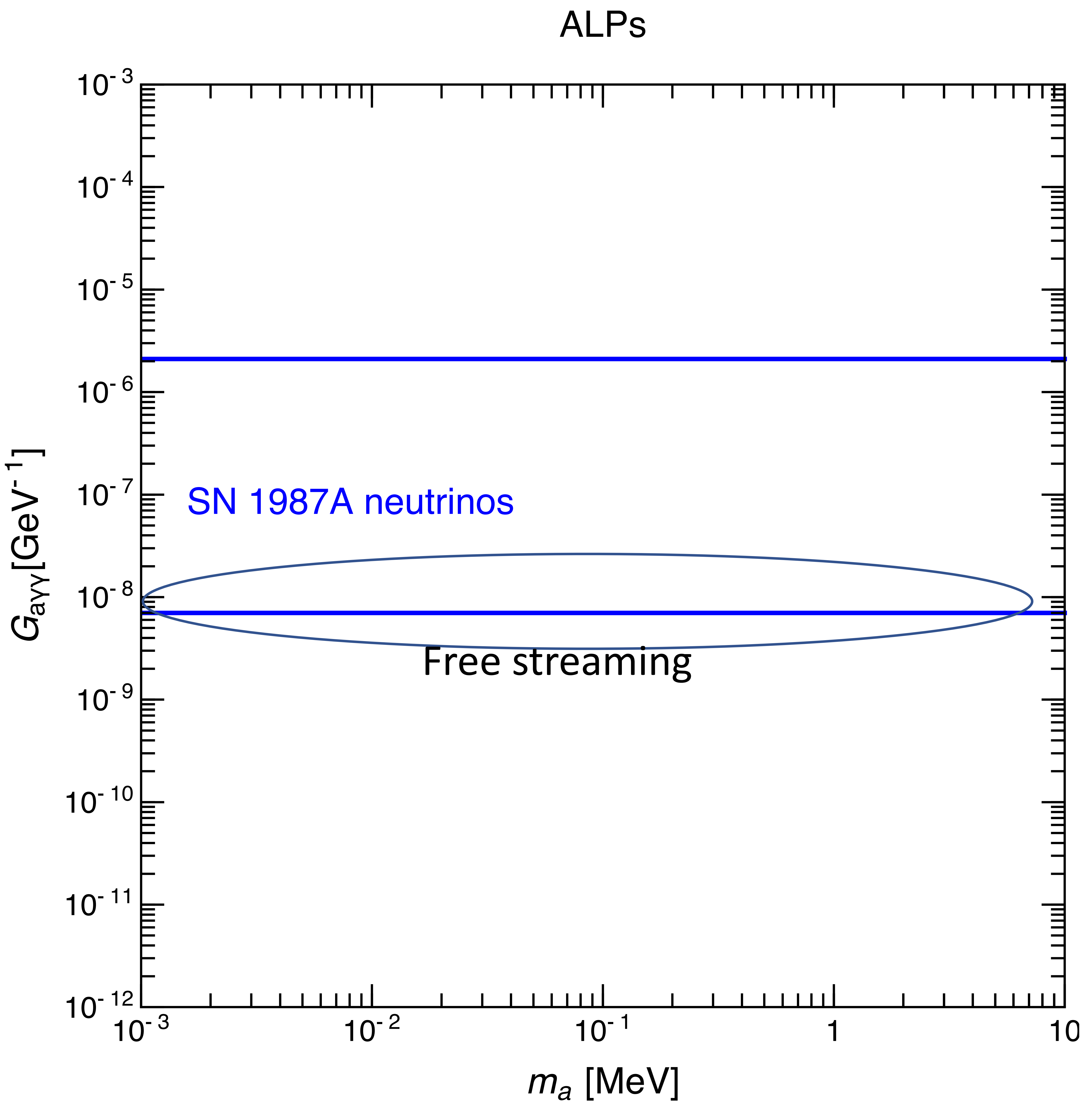


$$Q_{\rm P} \simeq \hat{n}\frac{2\alpha G_{a\gamma\gamma}^2}{3\pi^2}\left(m_a^2 + 3m_aT + 3T^2\right)T^2 e^{-m_a/T}$$

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

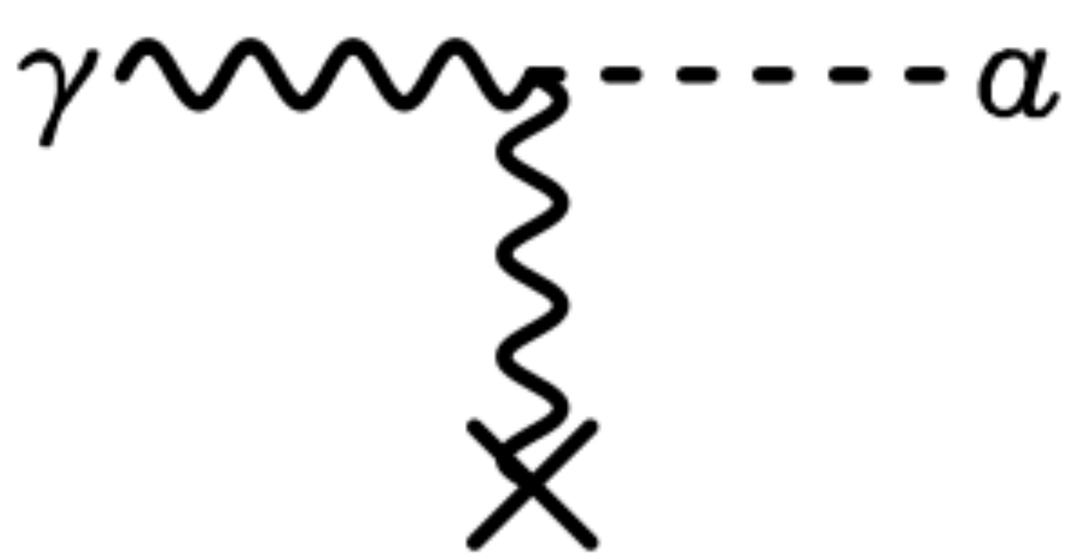
A.C, G. Raffelt and E. Vitagliano, arXiv 2109.03244 (PRD in press)

Cooling bounds from SN1987A



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

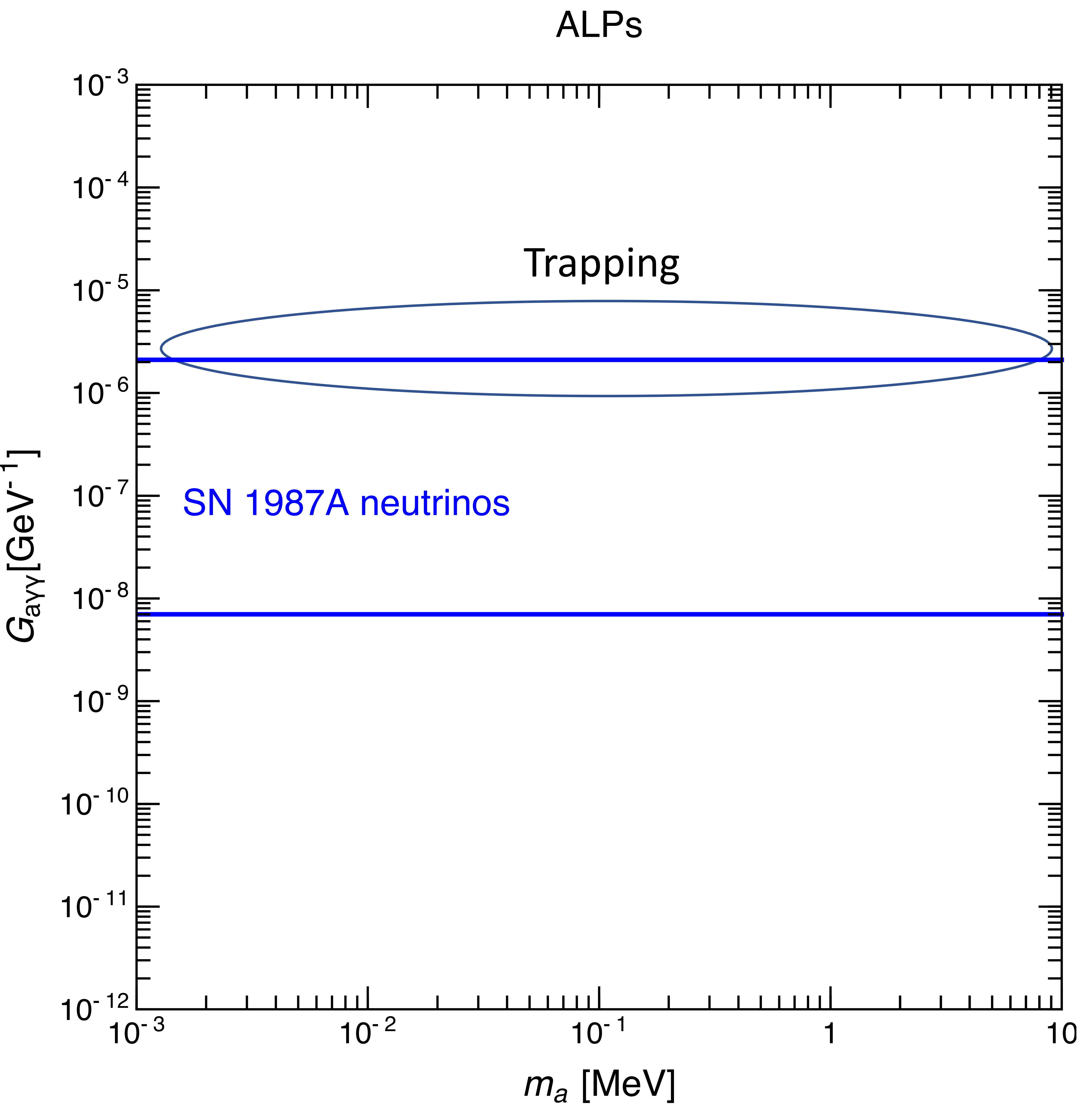
The duration of several seconds of the SN 1987A neutrino signal is incompatible with excessive energy loss in hypothetical new forms of radiation.
The main emission process in this case is photo-production on charged particles (aka Primakoff)



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

Raffelt's criterion

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

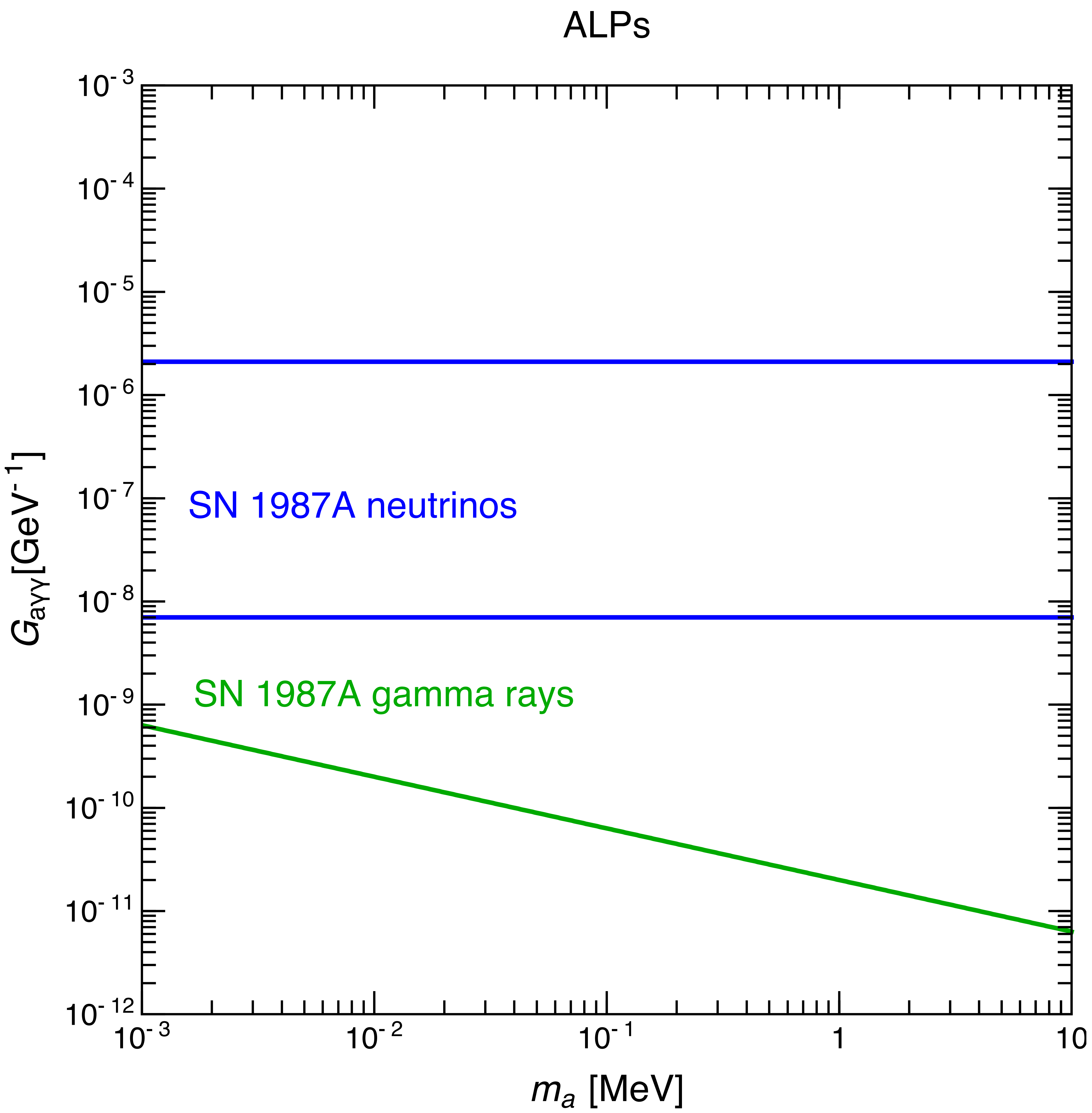
$$L_\phi = 4\pi R_\phi^2 \, \frac{\pi^2}{120} \, T^4(R_\phi)$$

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

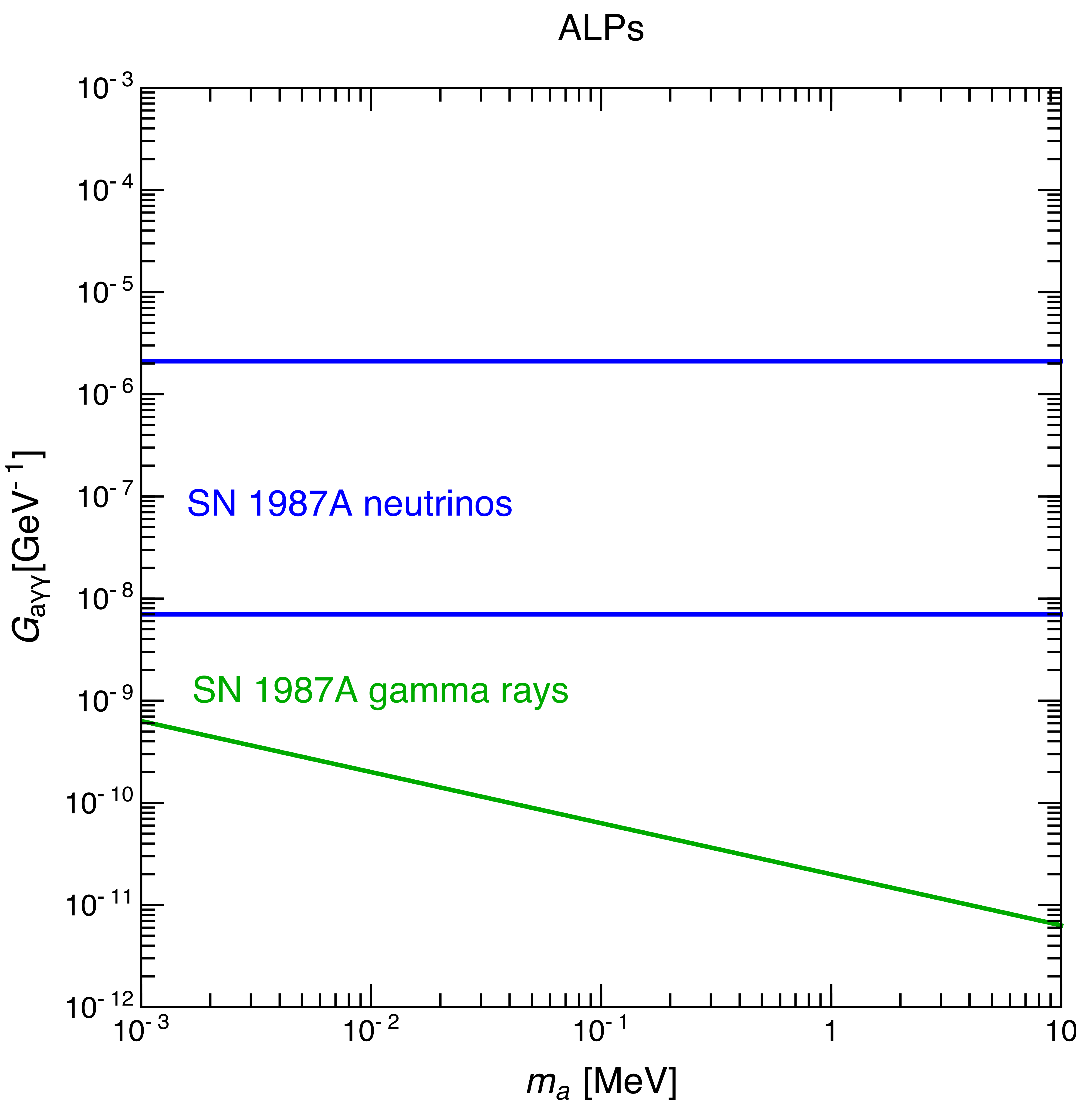


The (putative) produced bosons from 1987A could have decayed into photons, which would have been picked up by the Gamma-Ray Spectrometer (GRS) on board the Solar Maximum Mission (SMM) satellite that operated 02/1980–12/1989 .

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

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

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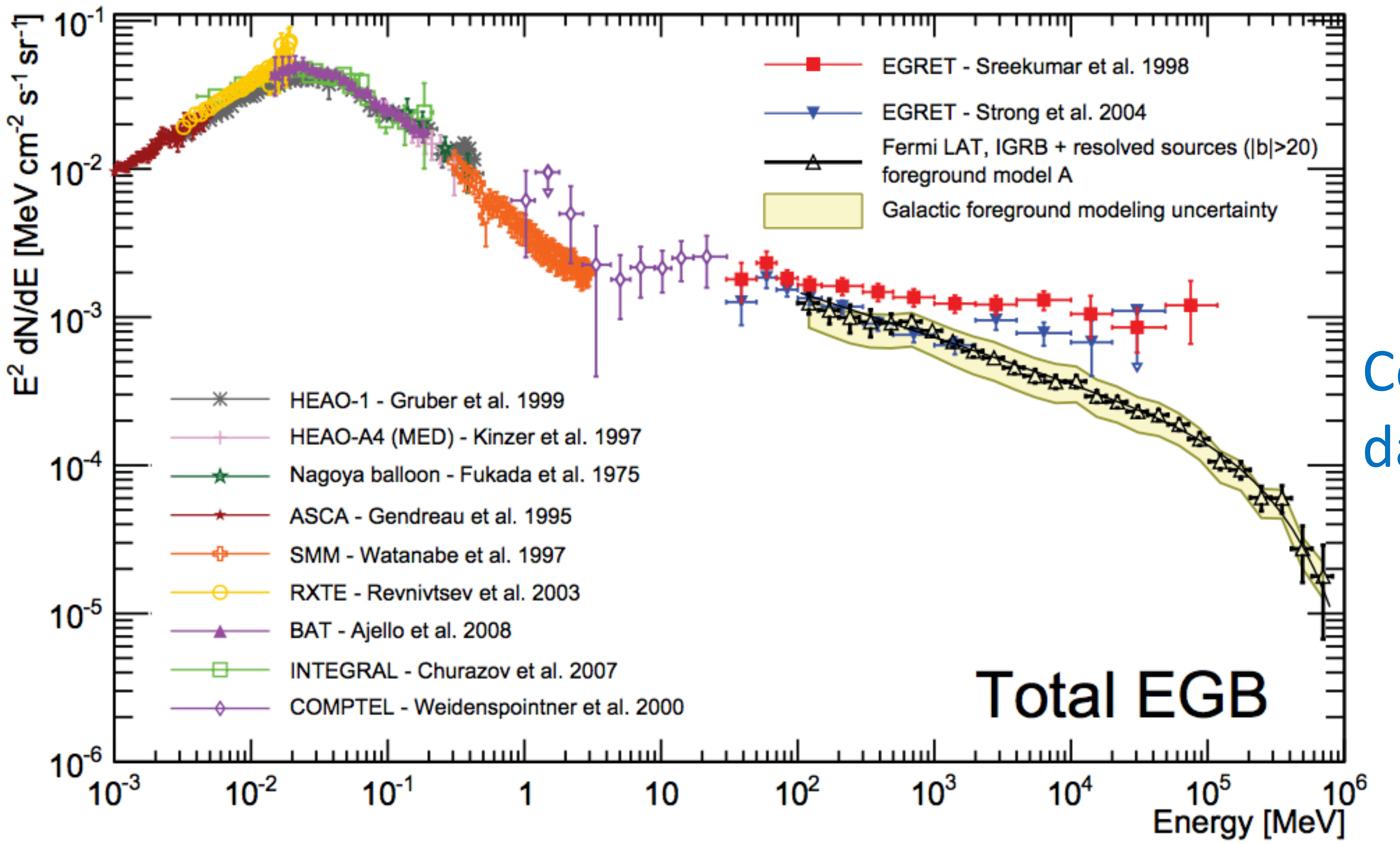
rest-frame boson lifetime

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

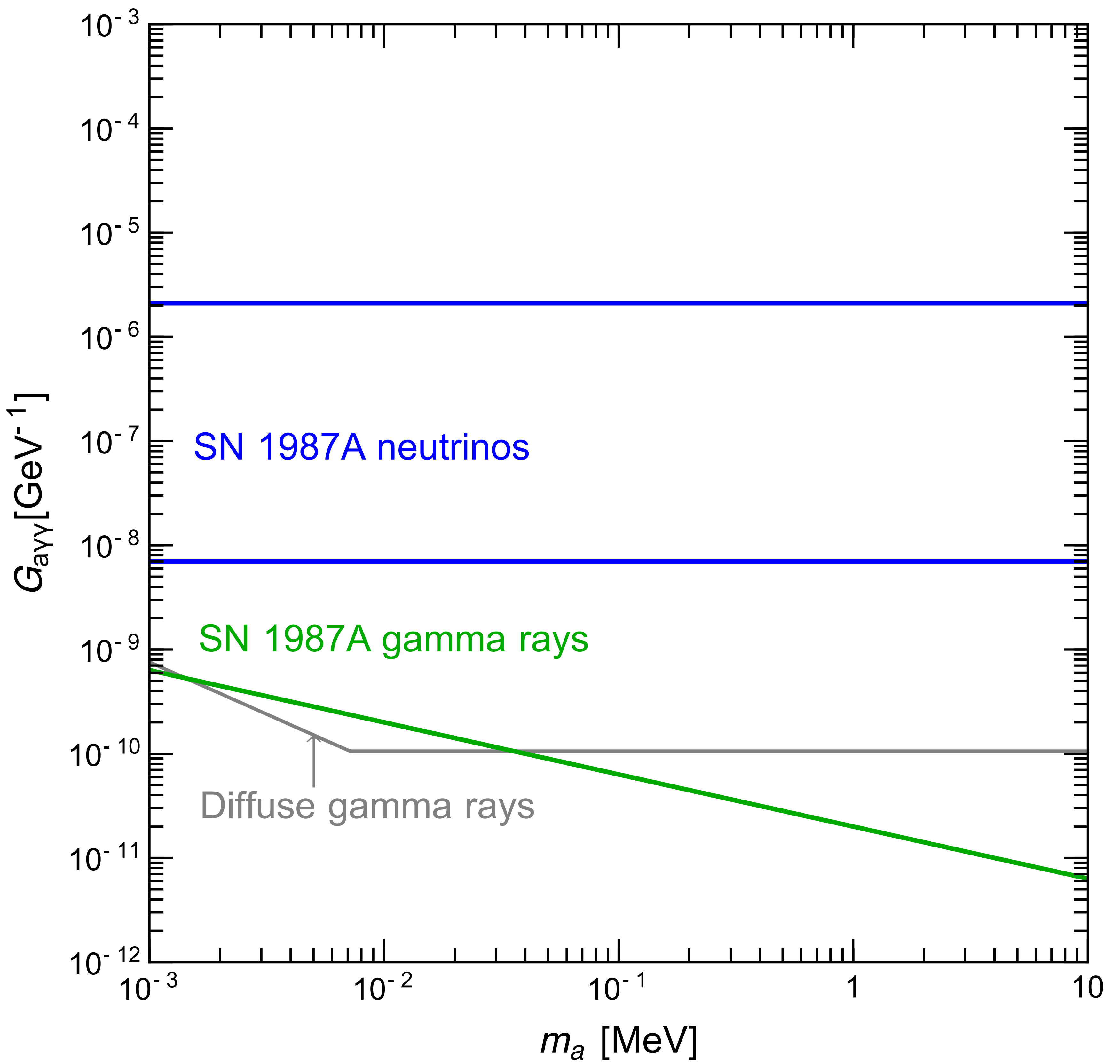
The scalar boson emission from all past SNe creates a cosmic background density in analogy to the diffuse SN neutrino background (DSNB). The radiative decays of these particles contribute to the diffuse cosmic γ-ray background and thus can be constrained.

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



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

Compare with data!



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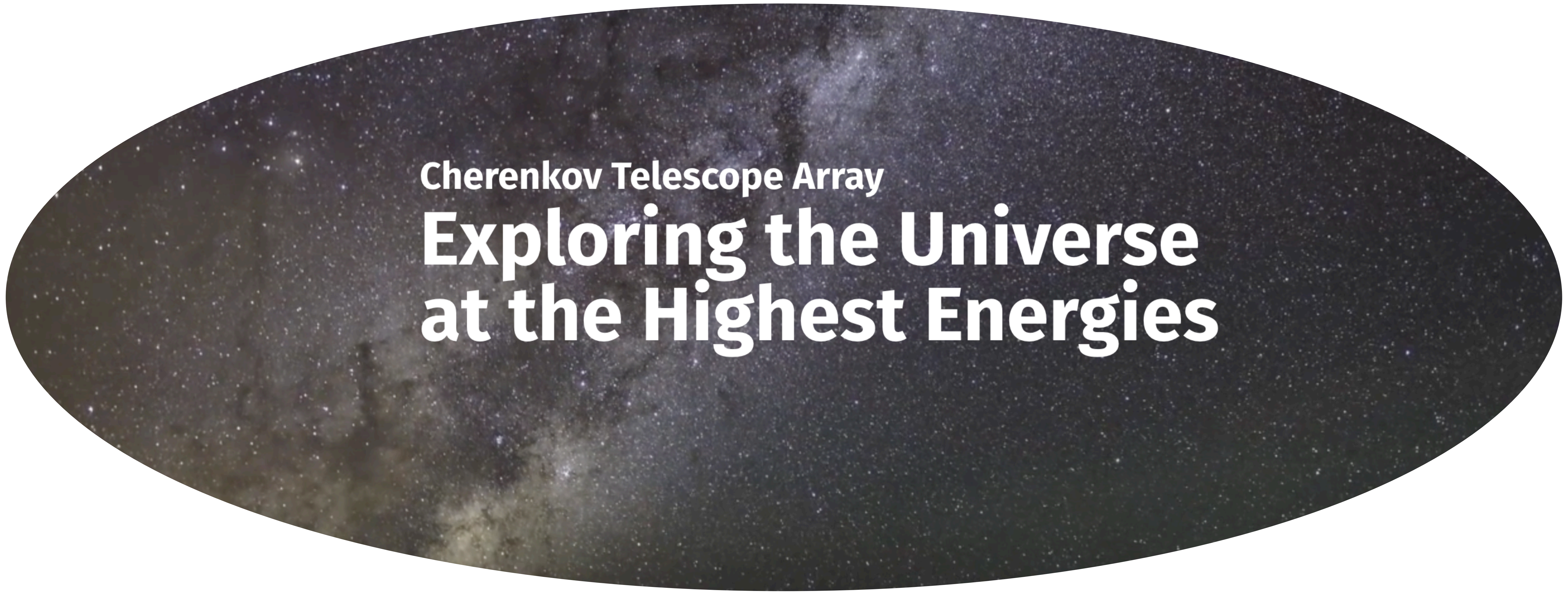
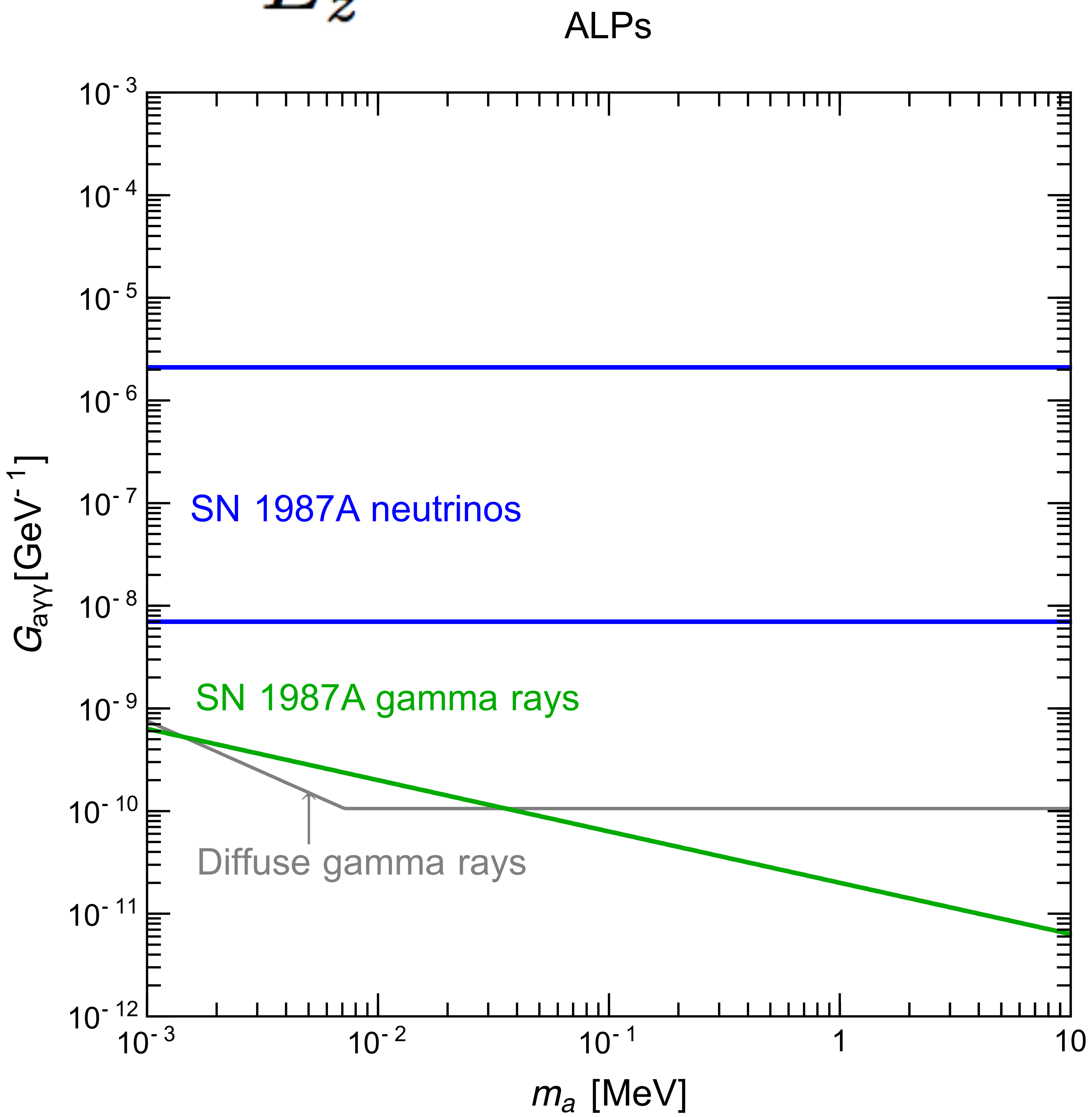
Future is exciting! Gamma-ray astronomy!





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

Galaxy surveys

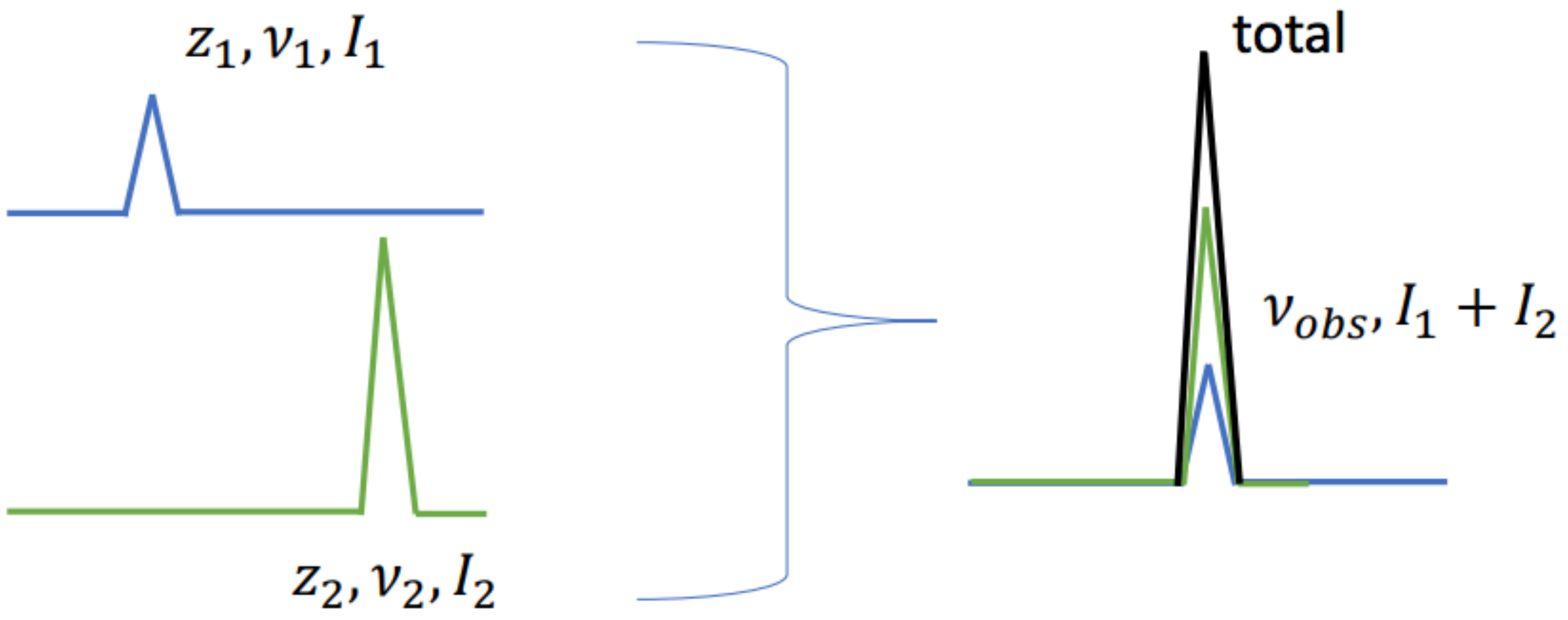
	2MPZ	SDSS	DES	DESI	Euclid	LSST
# of galaxies	6.7×10^5	1.5×10^7	2×10^8	3.5×10^7	2×10^9	3.6×10^9
Sky coverage	0.66	0.26	0.12	0.34	0.36	0.49
z-range	0-0.08	0.08-0.8	0.08-2	0-2	0-2	0-3
# of z-bins	1	4	6	132*	7	8

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: $\chi \rightarrow \gamma + \gamma$

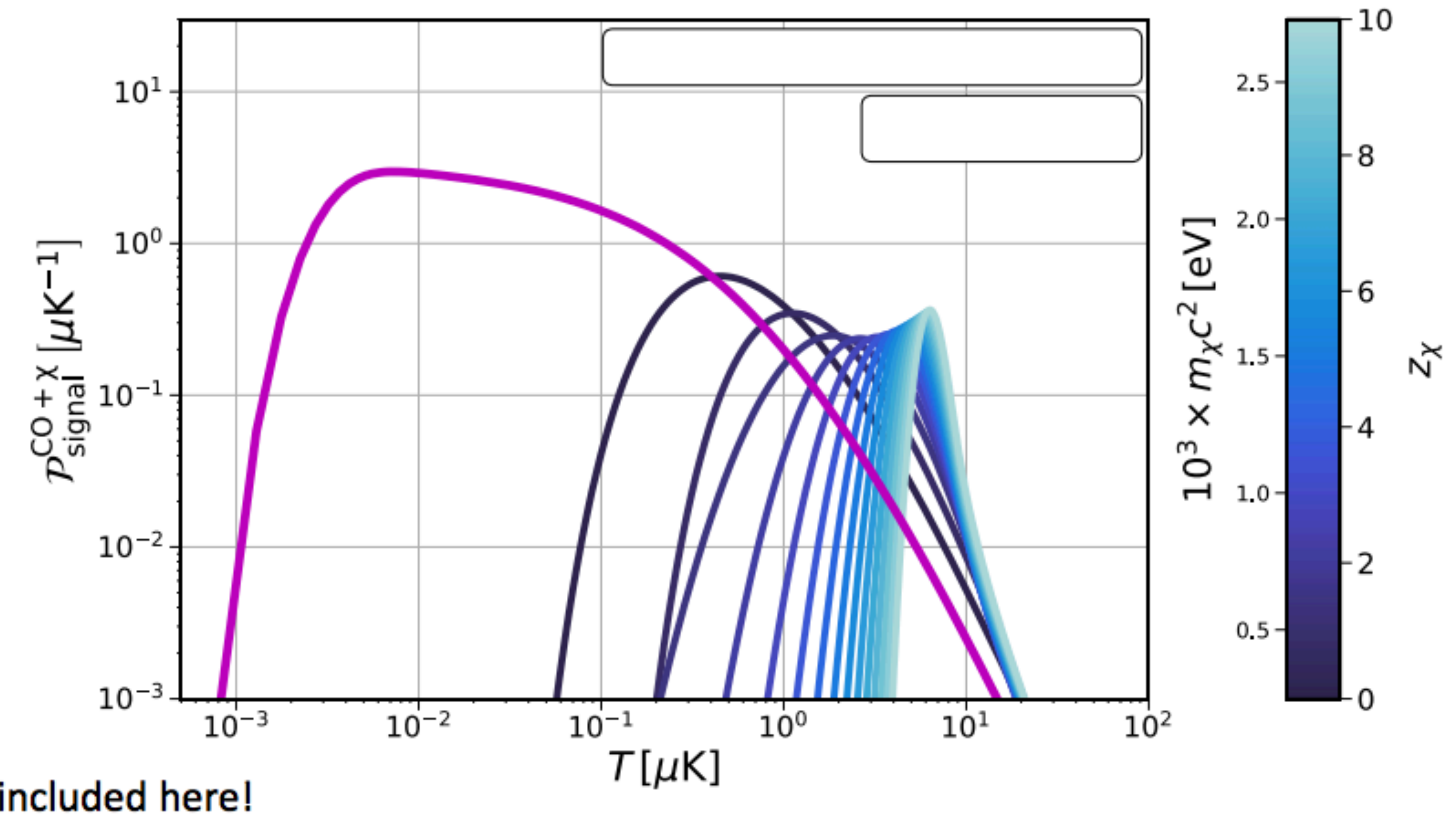
$$\nu_\gamma = m_\chi c^2 / 2h_P \qquad \rho_L^\chi(\boldsymbol{x}, z) = \rho_\chi(\boldsymbol{x}, z) c^2 \underbrace{\Gamma_\chi f_\chi f_{\gamma\gamma} f_{esc}}_{\Theta_\chi} (1 + 2\mathcal{F}_\gamma)$$

- Traces directly the DM density field

Effect in VID

- Each voxel receives contributions from both emissions:

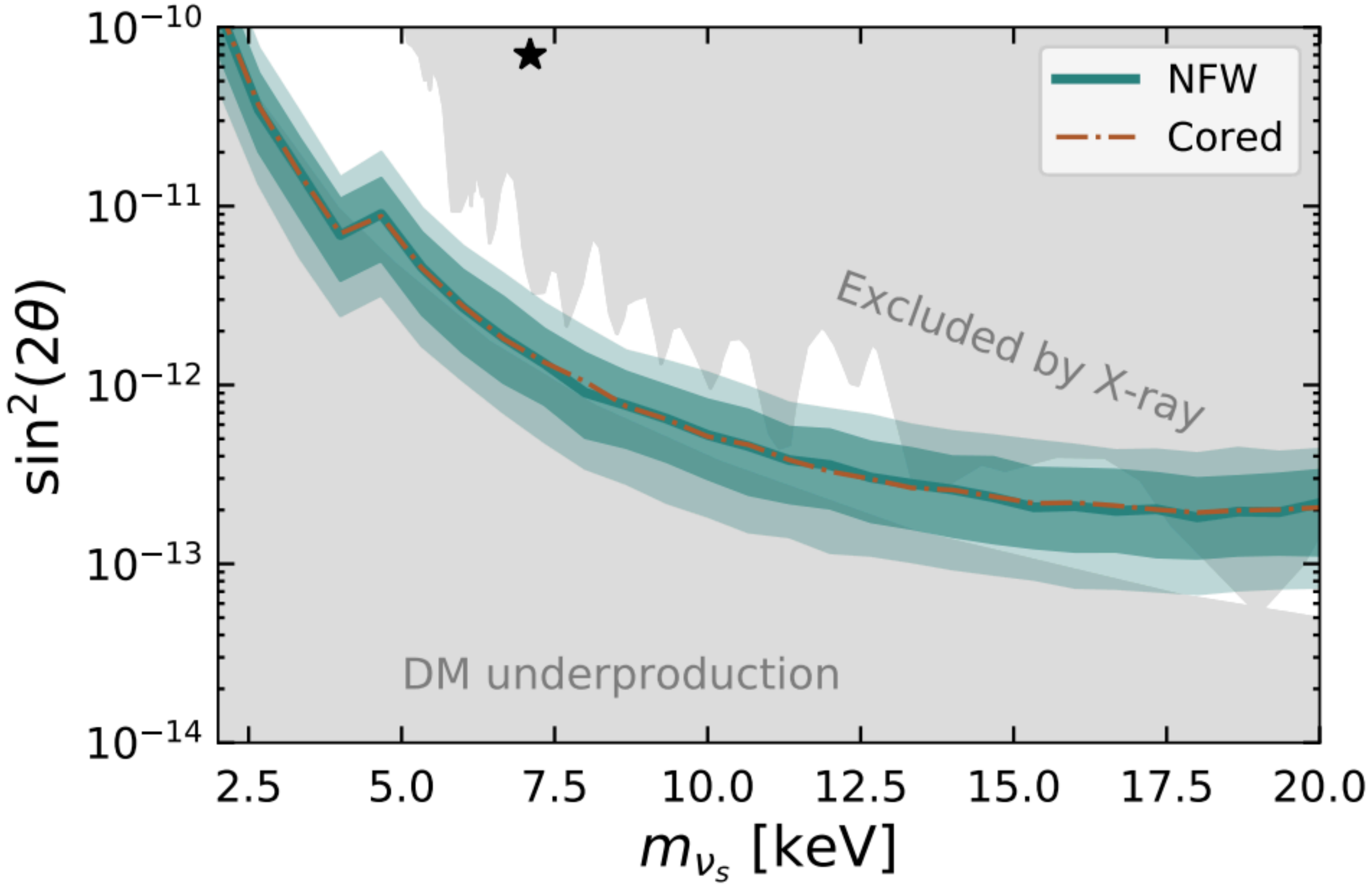
$$\mathcal{P}_{tot+\chi}(T) = \left((\mathcal{P}_l * \mathcal{P}_\chi) * \mathcal{P}_{noise} \right)(T); \qquad \mathcal{P}_\chi = \mathcal{P}_{\tilde{\rho}} / \langle T_\chi \rangle$$



No noise contribution included here!

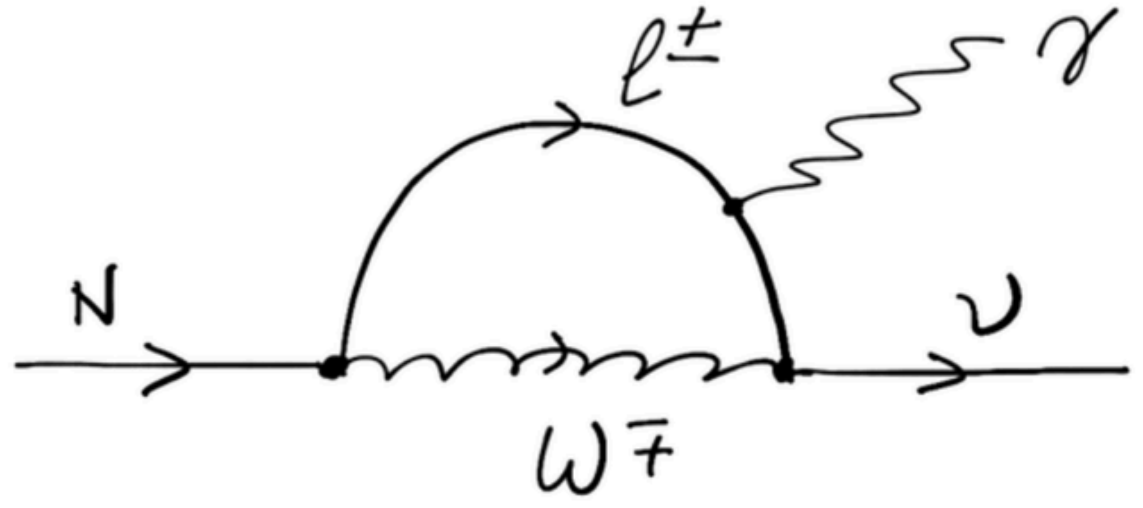
Sterile neutrinos X-ray

Point towards the galactic center and use



A. Dekker, at al (2021)

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

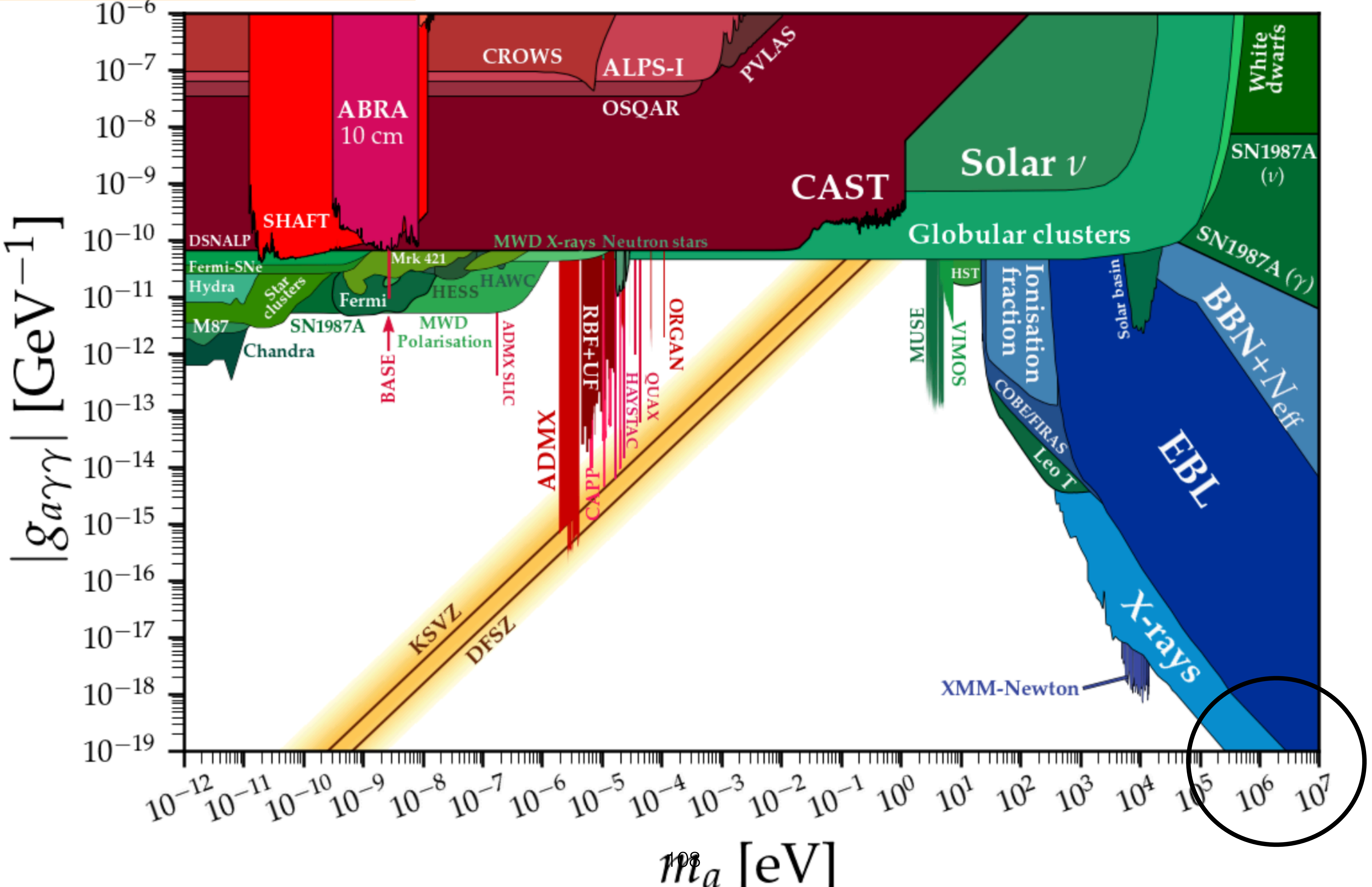


eROSITA [0.2 - 8 keV]

Launched in 2019, Russian-German mission

MeV (gamma-rays)

https://github.com/cajohare/AxionLimits



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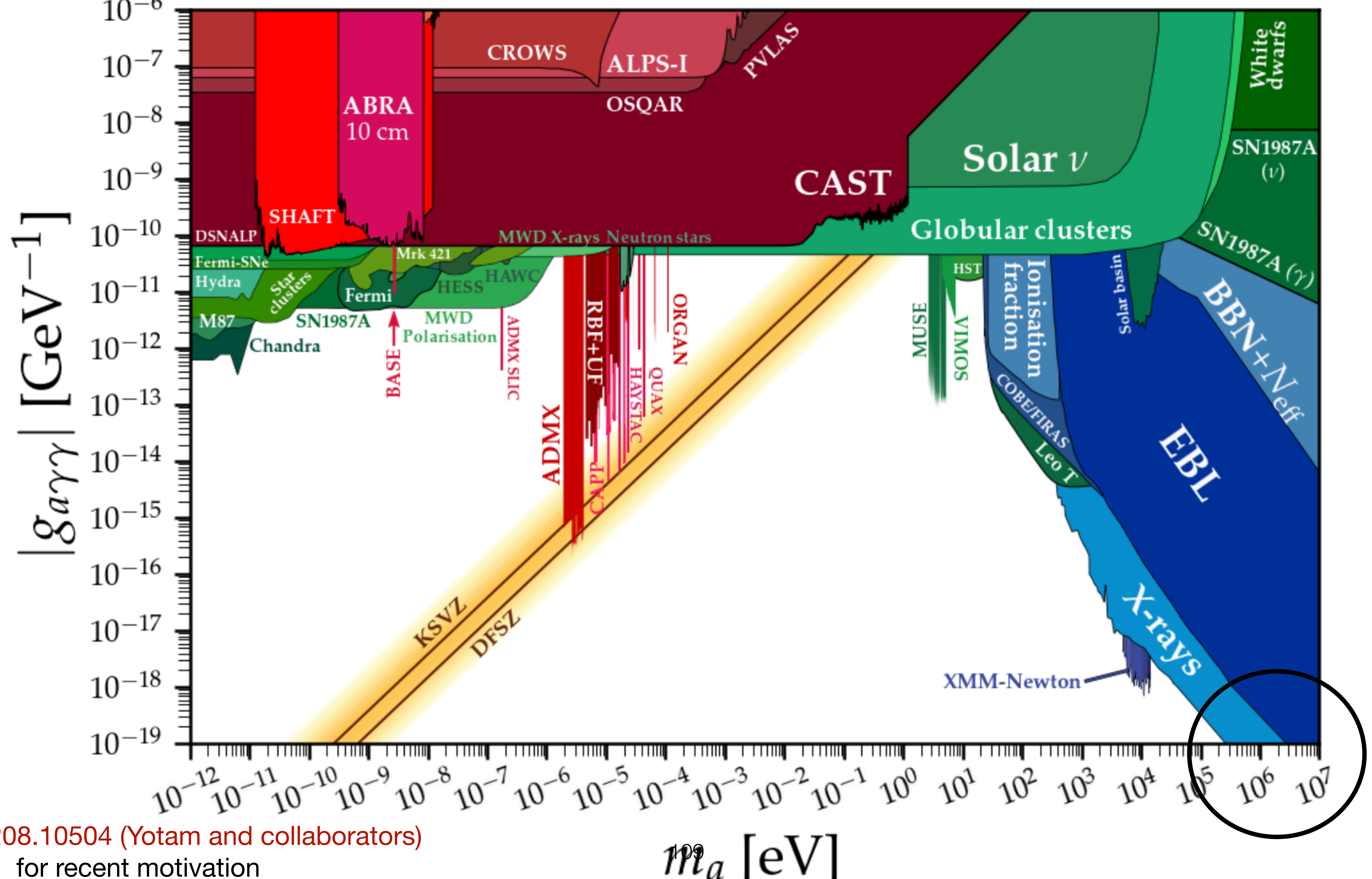

See arXiv 2208.10504 (Yotam and collaborators) for recent motivation

Oct 18, 2021

RELEASE 21-134

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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

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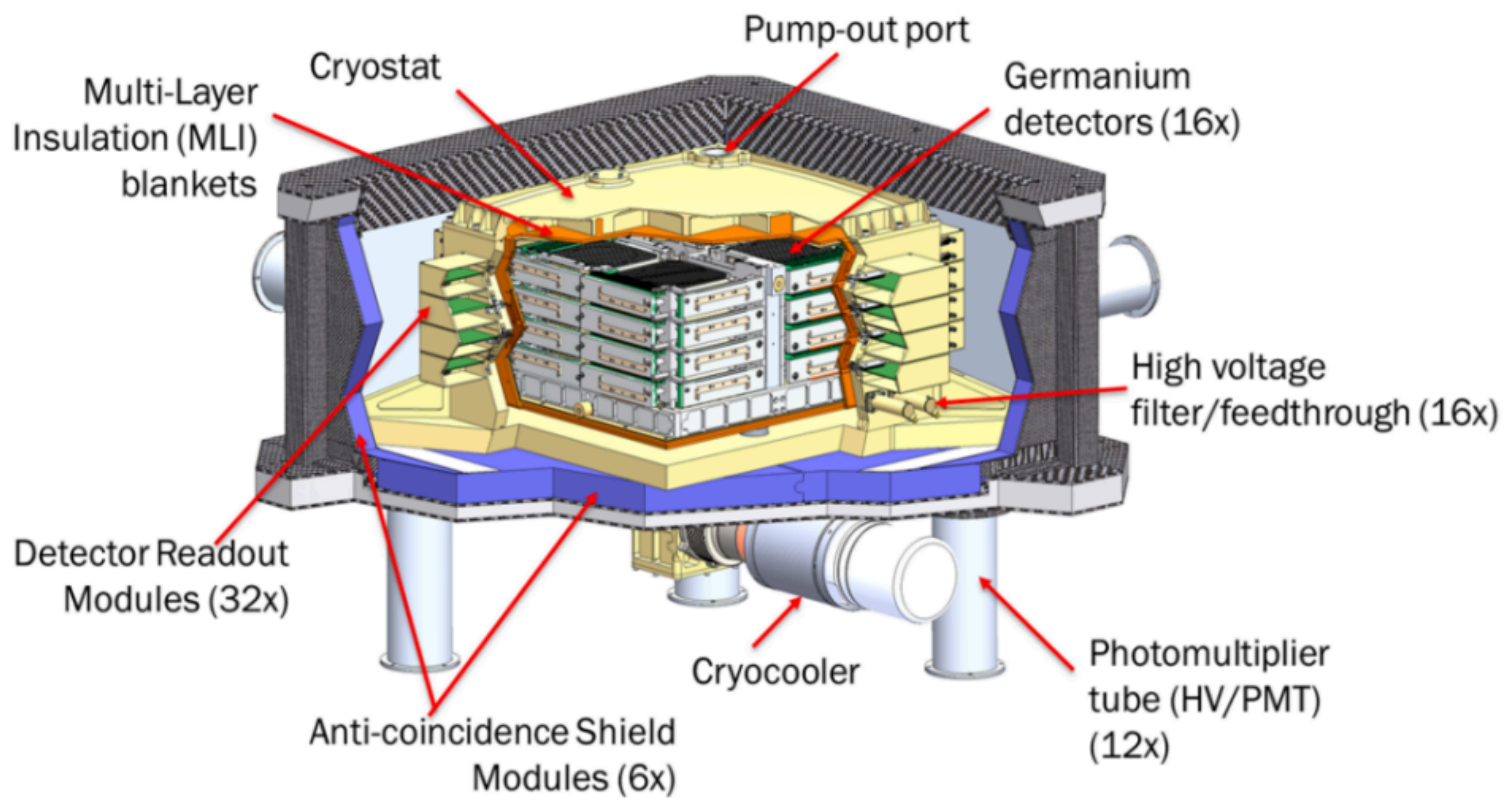

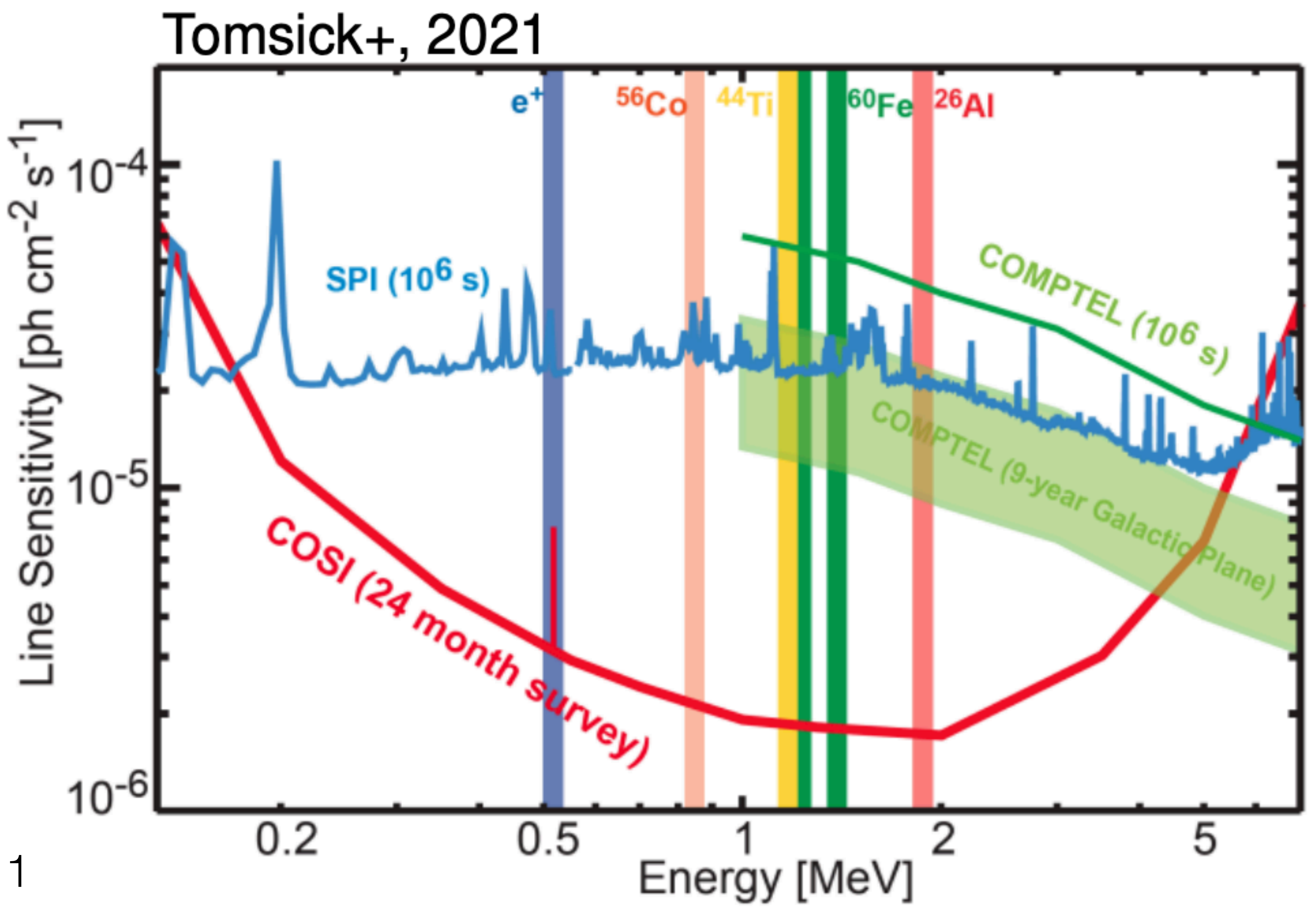

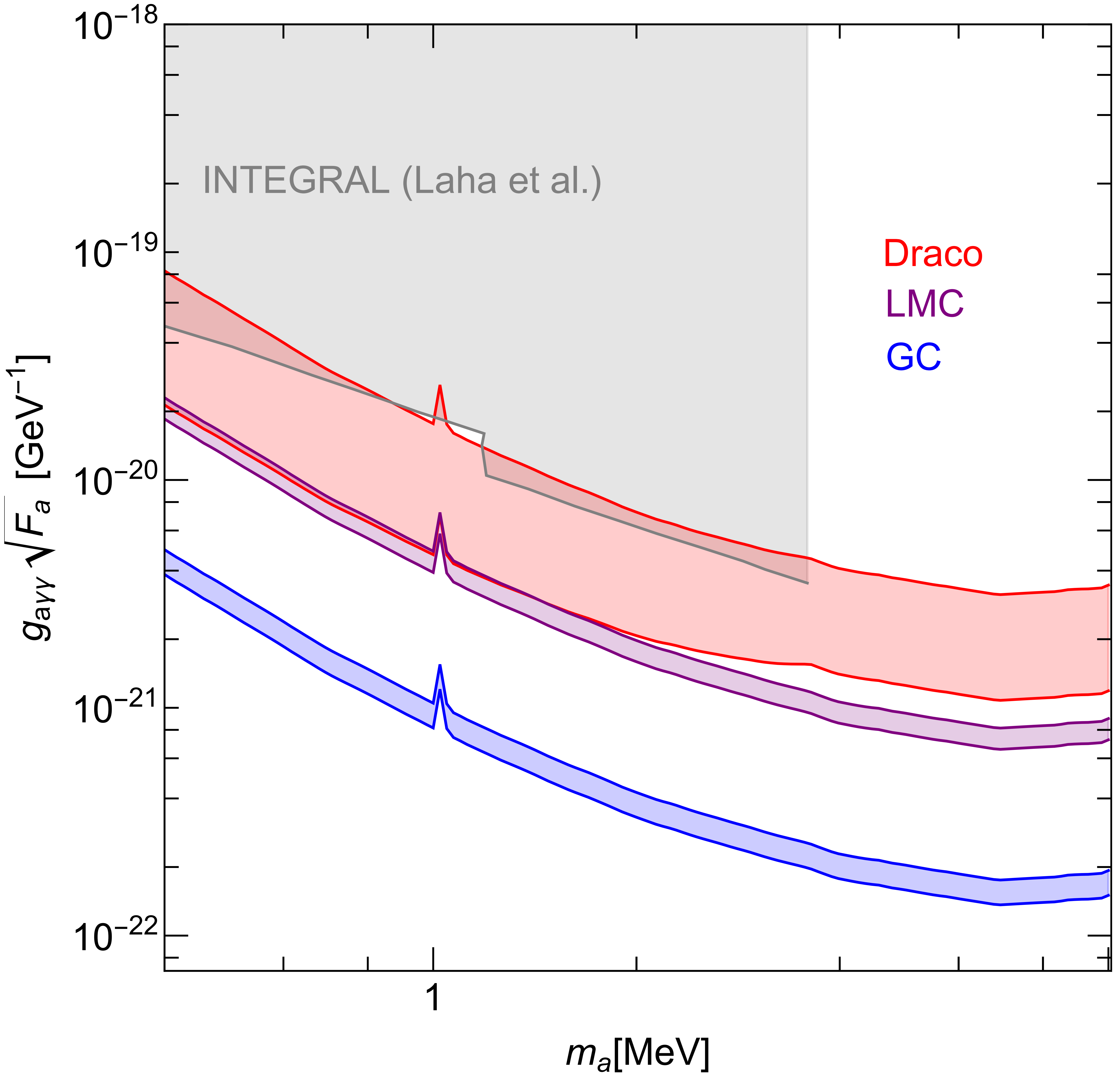

Caputo, M. Negro, M. Regis and M. Taoso, arXiv 2210.09310 (accepted JCAP)