Probing axion-like particles with high-energy astrophysics

From radio to high-energy gamma rays

CERN Theory Colloquium — 28/10/2020

Francesca Calore (CNRS/LAPTh)

Outline

- Axions and axion-like particles (ALPs)
- ALPs production mechanisms and couplings
- Signatures of ALP-photon coupling
  - Searches for spectral irregularities in gamma and X rays
  - ALPs and TeV transparency of the Universe
  - Radio searches for DM ALPs
- Conclusion and outlook

Axion & Axion-like particles

- Axion as pseudo-Nambu Goldstone boson predicted by the Peccei-Quinn mechanism

  Peccei Journal of Korean Physical Society 1996

- ALPs as generalization of the QCD axion
  - Very light pseudo-scalar bosons predicted by multiple extensions of the Standard Model

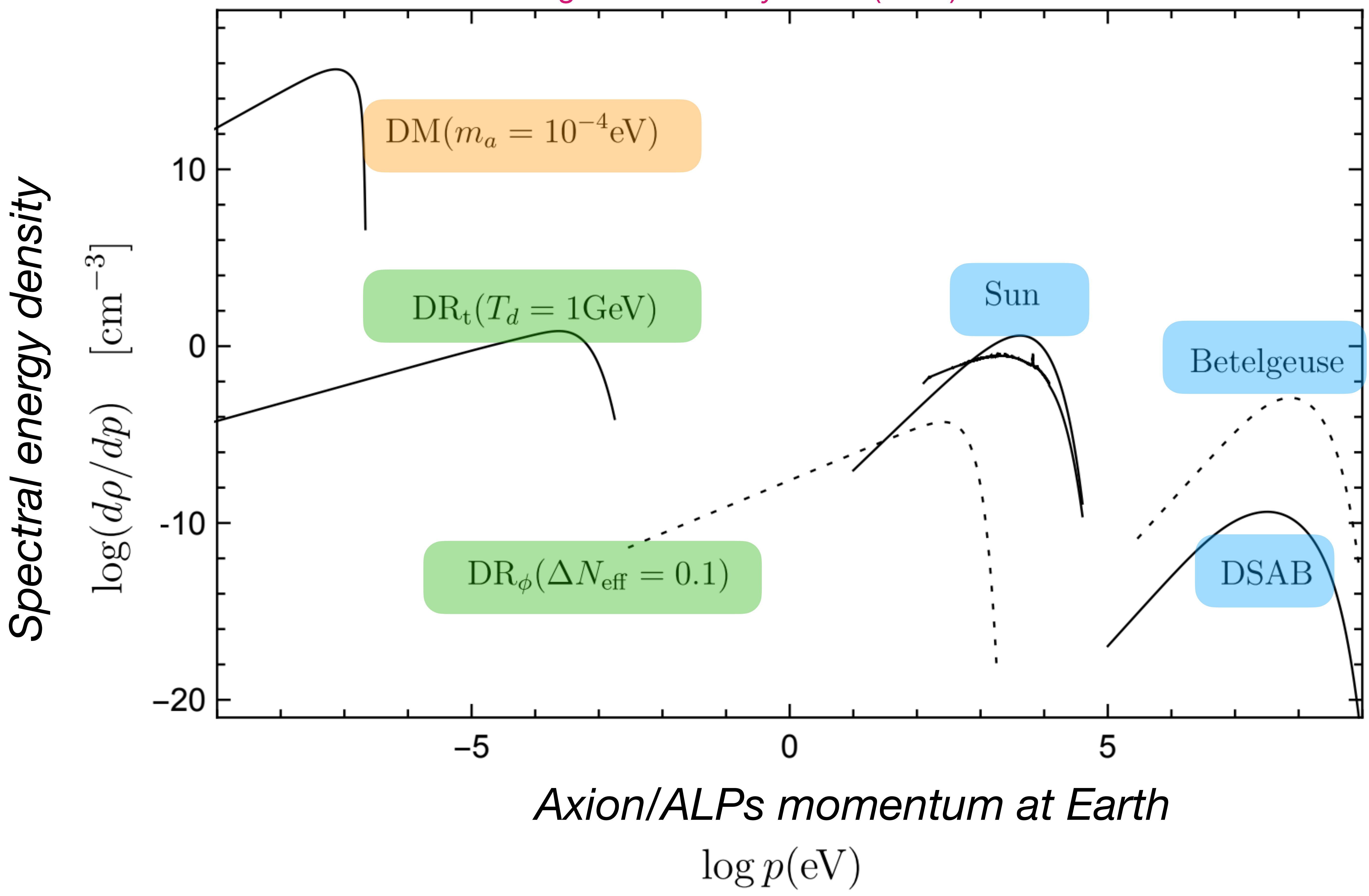
    Chang+ PRD 2000; Turok PRL 1996; Arvanitaki+ PRD'10

  - The mass and the coupling constant of ALPs are completely independent parameters
  - They represent weakly interacting slim (ultralight) particles (**WISPs**)
  - They can be cold dark matter candidates for certain values of mass and coupling

    Preskill+ PLB 1983; Sikivie International Journal of Modern Physics '10

Axion & ALPs sources

Irastorza & Redondo Prog.Part.Nucl.Phys. 102 (2018) 89-159



- Tentative unified ALPs spectrum to realise magnitude of different components
- **Galactic cold DM** from misalignment or topological defect decay
- **Hot DM axion and/or dark radiation** from thermal reactions or moduli decay
- **Stellar axions** above keV energies

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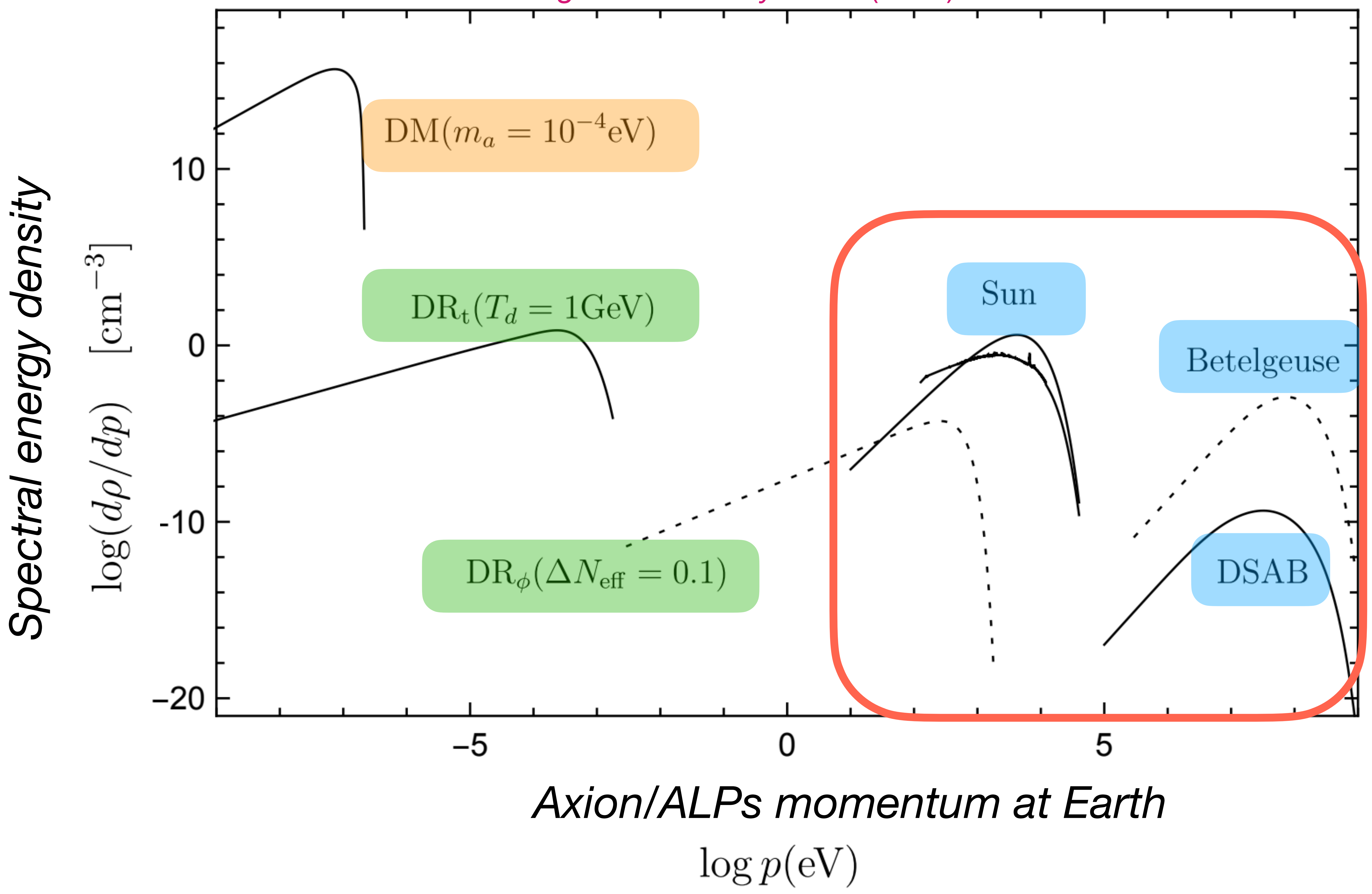

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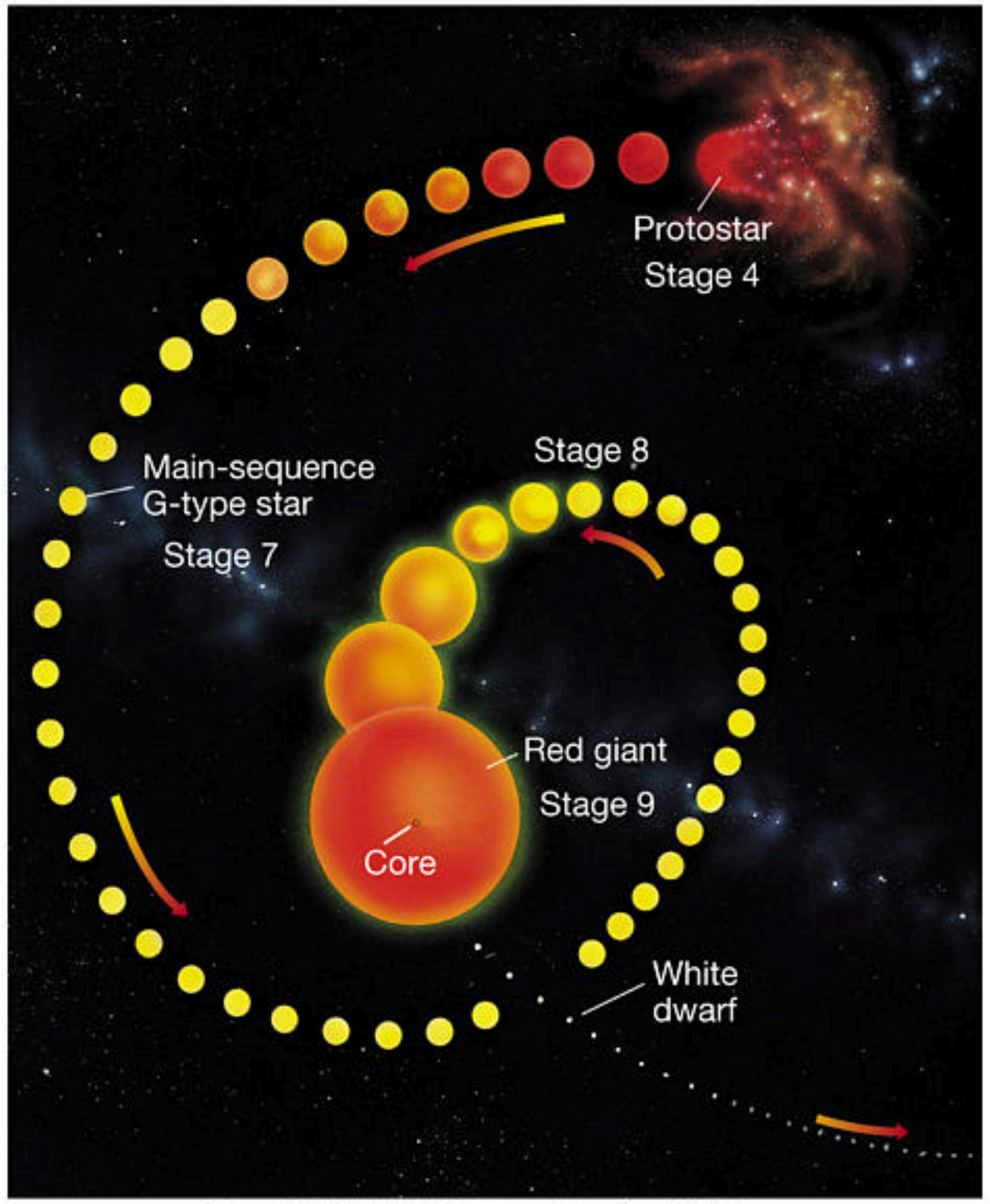
Stellar ALPs main production mechanisms

- ALPs can generally **interact with photons, electrons and nucleons** in stellar plasmas
- As an **additional source of heating/cooling**, they can affect evolutionary stages of stars
- Because of the competition with neutrino production and cooling, systems with relatively low temperature are more relevant for ALPs searches



ALP-photon coupling

Primakoff production $\gamma + Ze \rightarrow Ze + a$

- ALPs produced from thermal photons in the fluctuating electromagnetic fields of the stellar plasma.
- Dominant process for MS stars (like Sun) or HB stars

Raffelt Cambridge U. Press 1996, Lect. Notes. Phys. 2008

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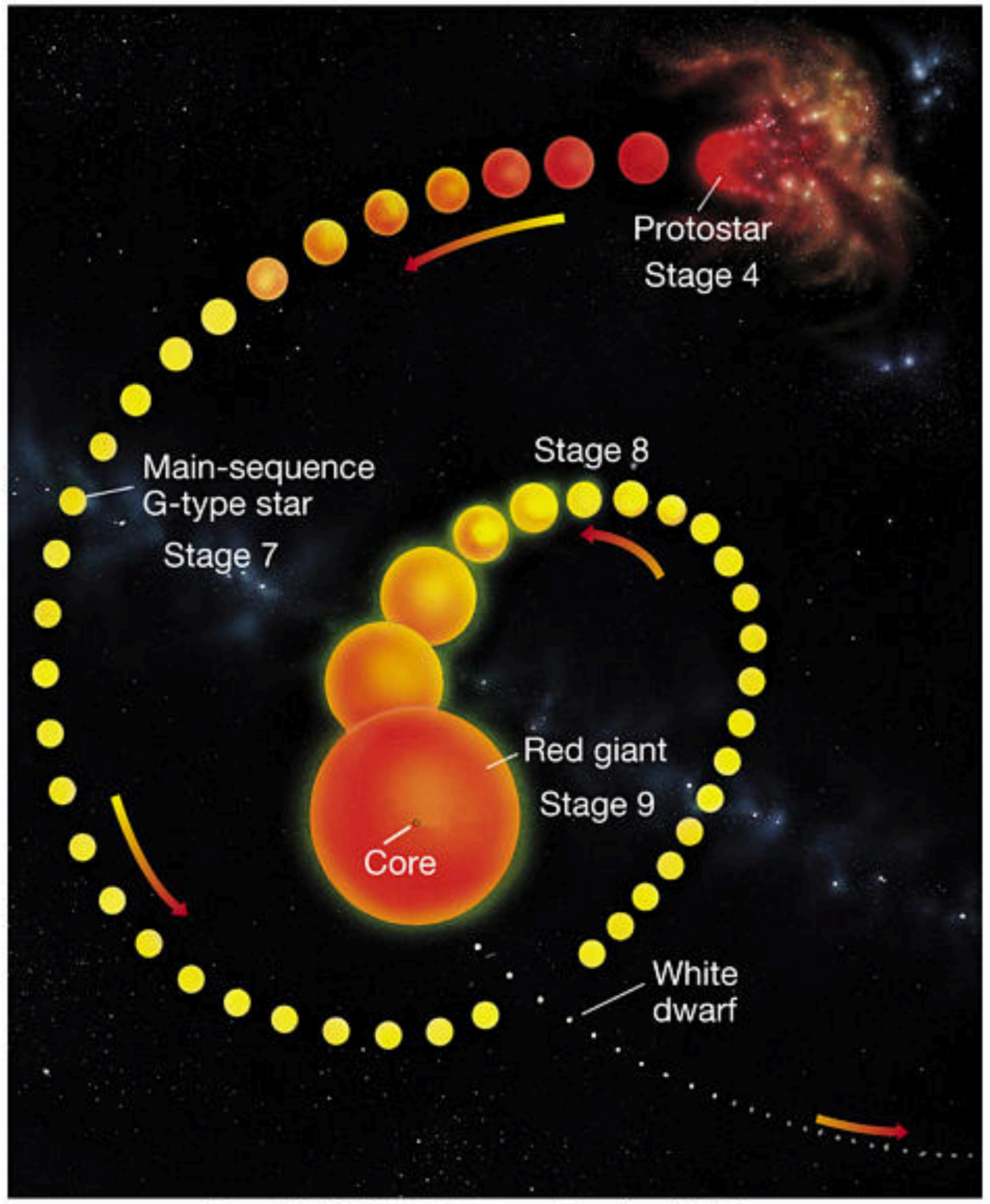

ALP-photon coupling

Primakoff production $\gamma + Ze \to Ze + a$

ALP-electron coupling

Electron bremsstrahlung $e + Ze \to Ze + e + a$

- Thermal production in the stellar plasma
- Dominant process in stars with degenerate electron plasma (helium-burning RGB and white dwarfs)

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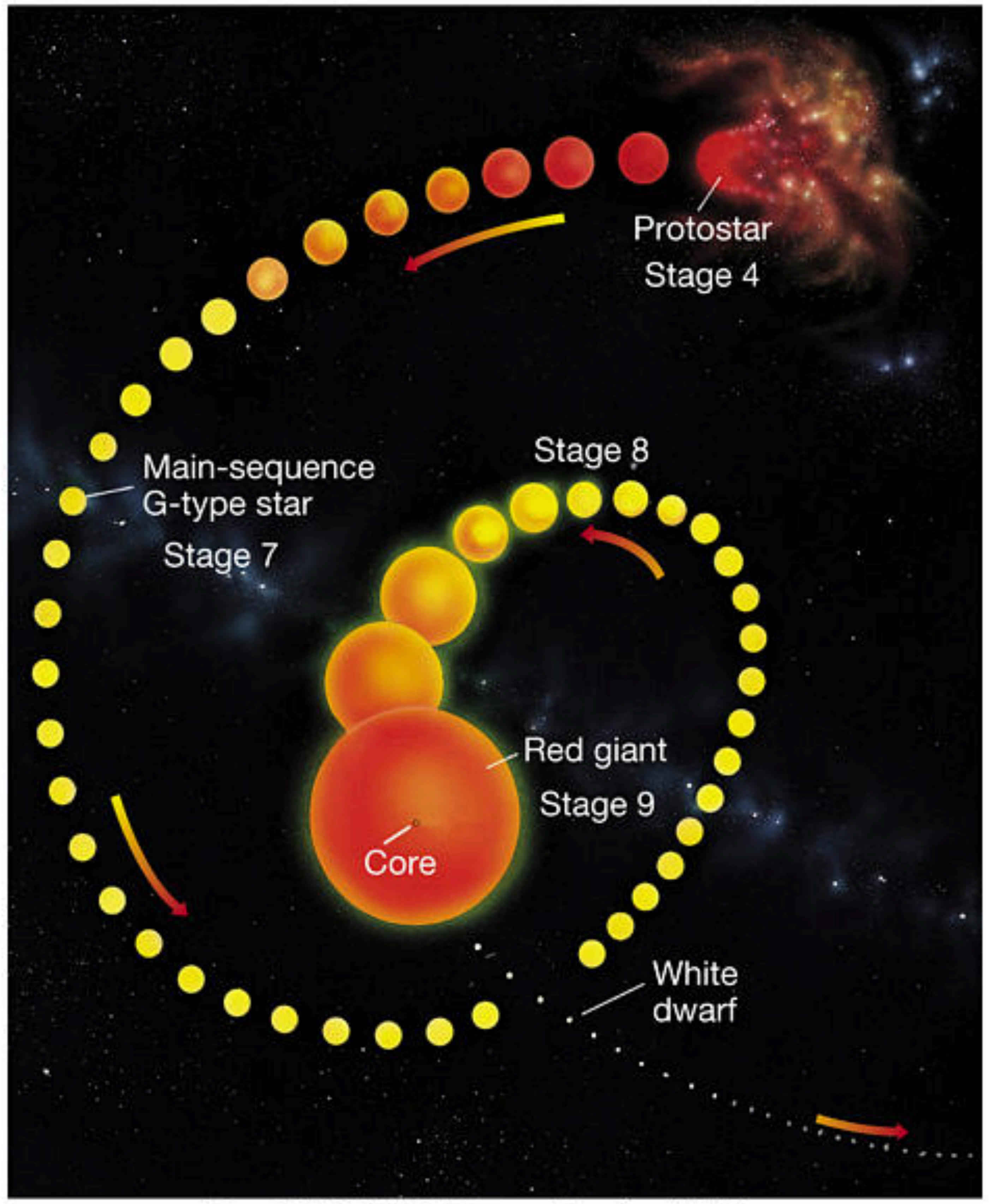

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ALP-electron coupling

Electron bremsstrahlung $e + Ze \to Ze + e + a$

Photo-production (Compton) $\gamma + e \to e + a$

- Important for non-degenerate, non-relativistic electron plasma
- Contribution for HB stars

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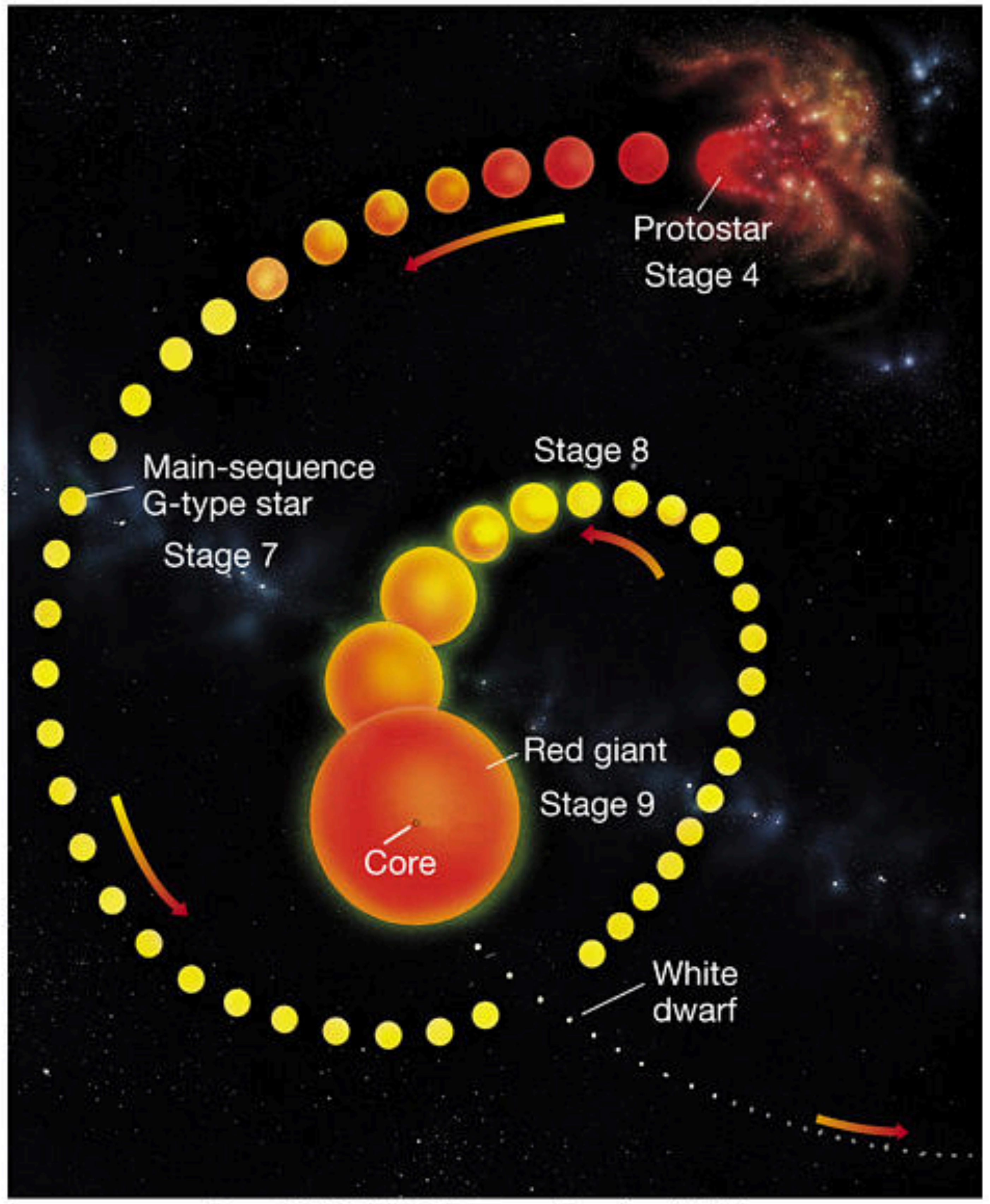

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ALP-nucleon coupling

NN bremsstrahlung $N_1 + N_2 \longrightarrow N_3 + N_4 + a$

- Important for nuclear plasma
- Dominant for neutron stars and supernova

Raffelt Cambridge U. Press 1996, Lect. Notes. Phys. 2008

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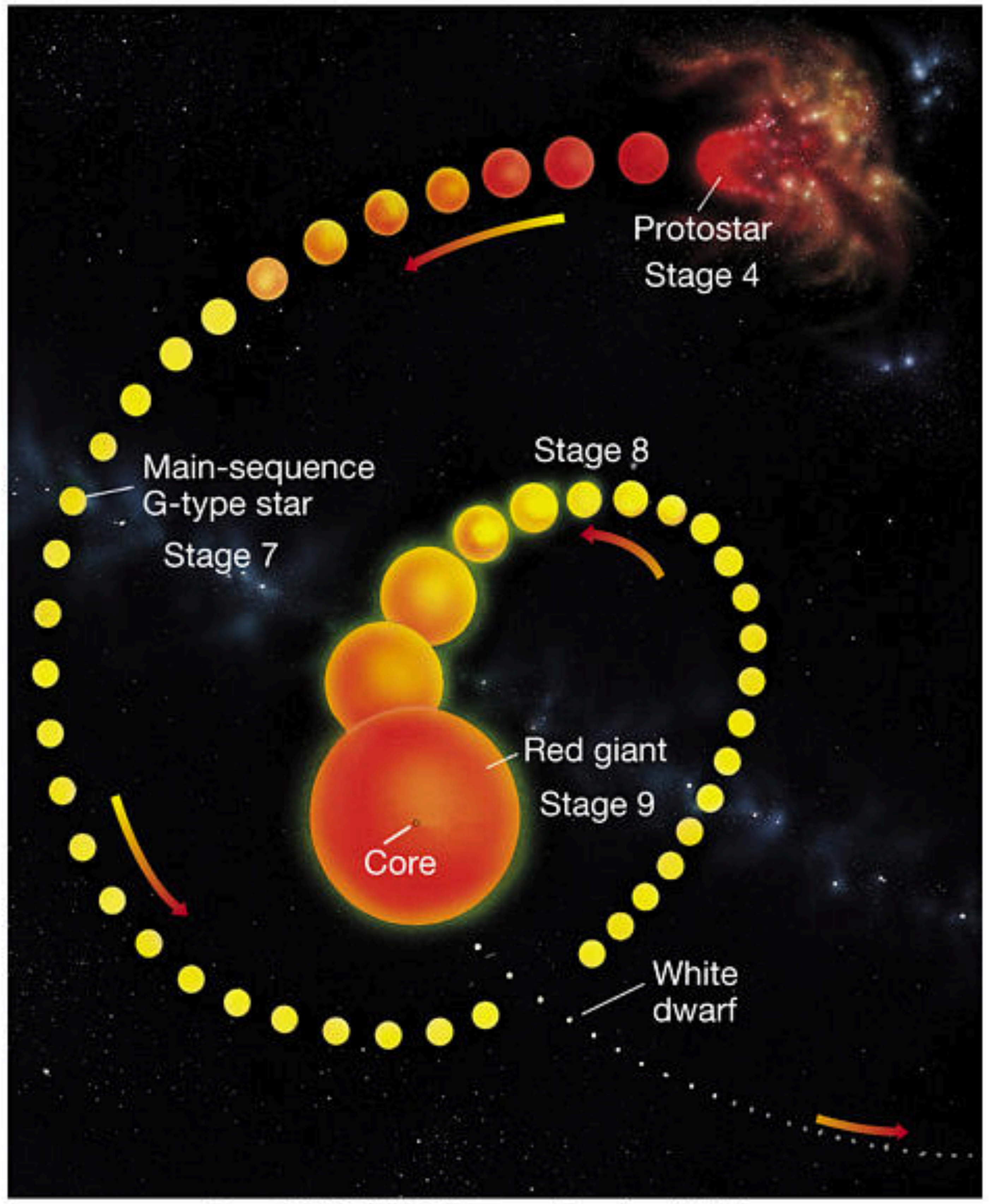

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$g_{ae} < 2.6 \times 10^{-13}$

ALP-nucleon coupling

NN bremsstrahlung $N_1 + N_2 \longrightarrow N_3 + N_4 + a$

$g_{ap} < 0.9 \times 10^{-9}$

$g_{an} < 0.8 \times 10^{-9}$

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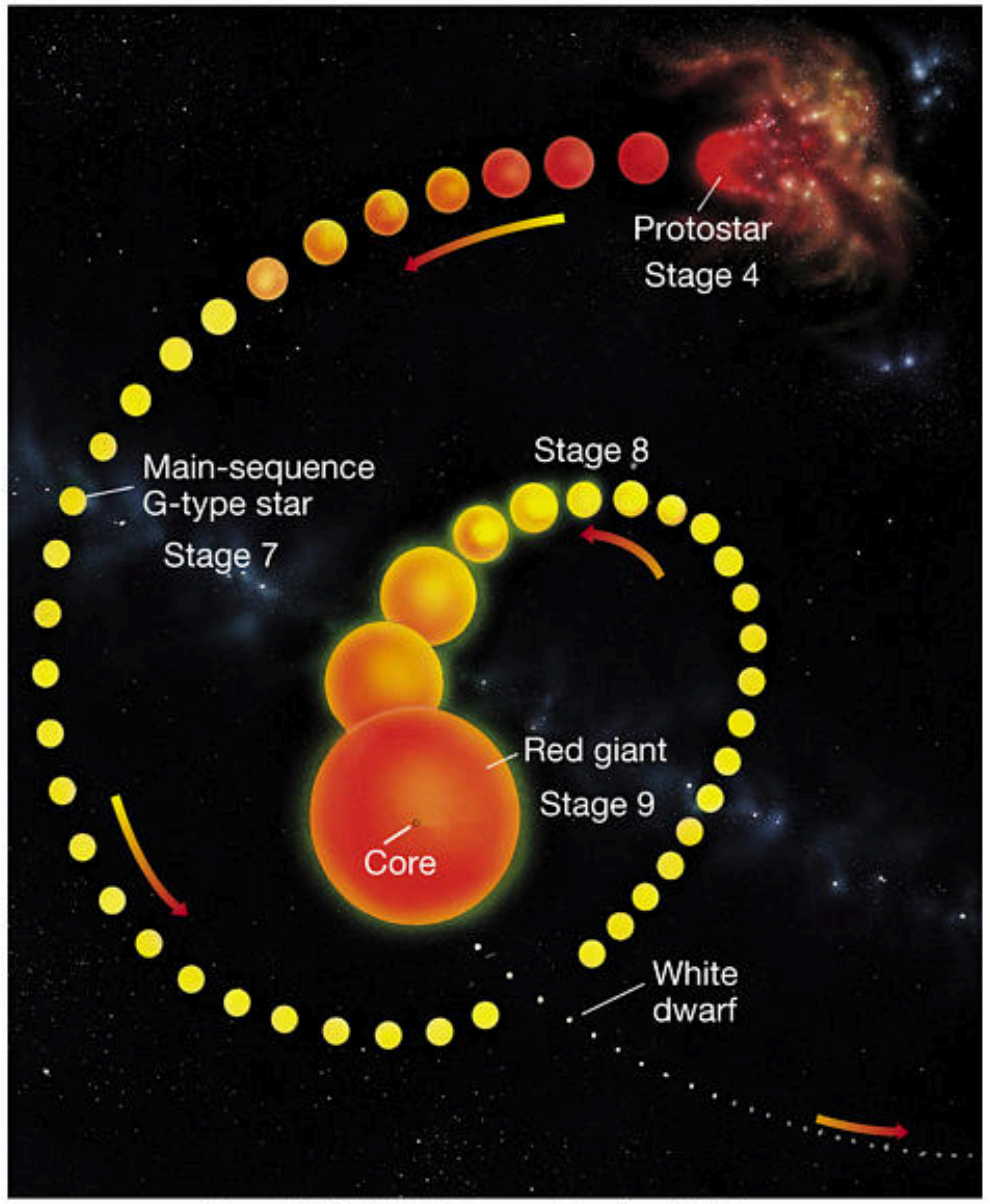

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Phenomenological imprints

1. Alteration of stellar evolutionary time scales and other observables
2. Conversion to photons and/or decay in the interstellar medium

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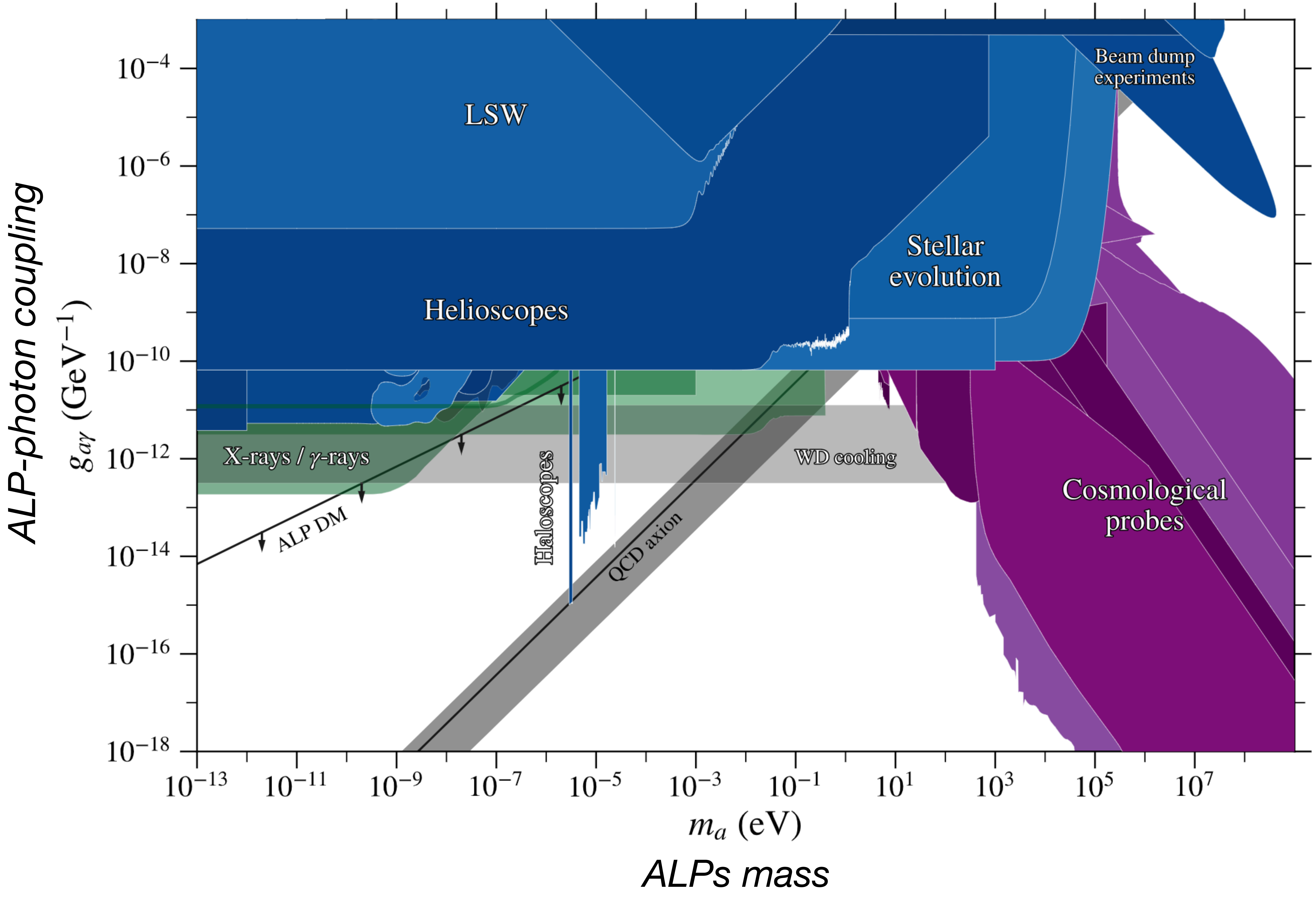
The ALP-photon coupling landscape

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



Credit: M. Meyer @ https://github.com/me-manu/gammaALPsPlot/

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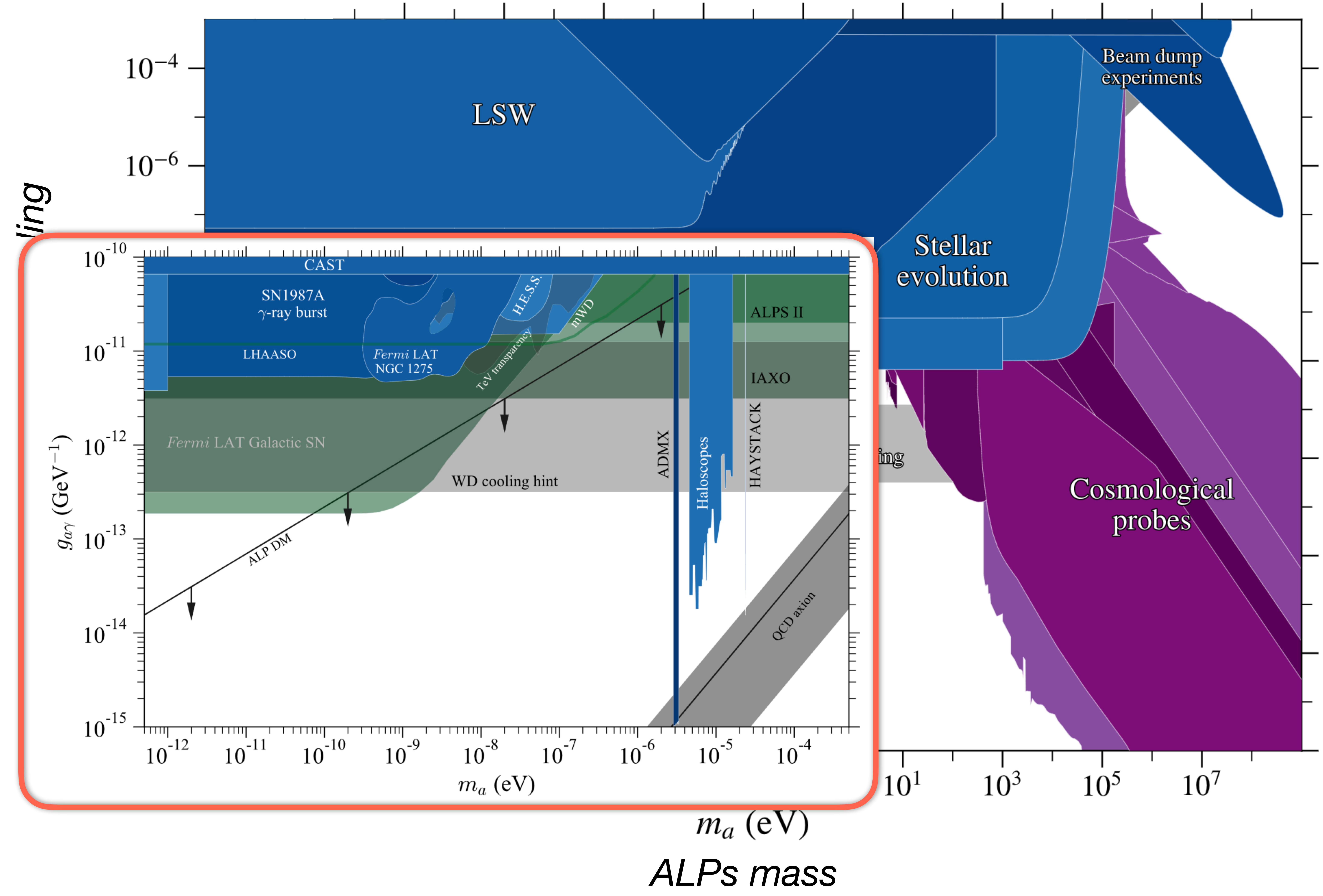

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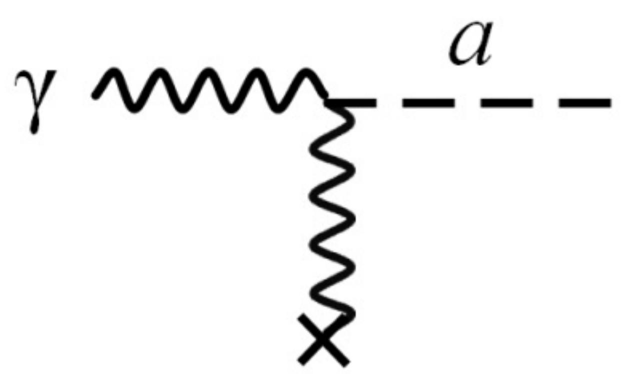
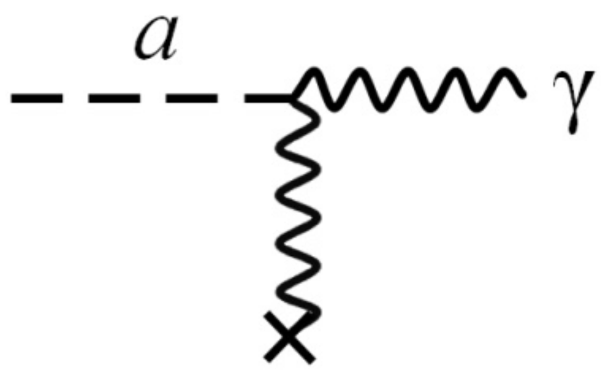


The ALP-photon mixing



For a **monochromatic photon-ALP beam** of energy E propagating along the x_3 axis in a cold plasma within a **homogeneous magnetic field B**:

$$\left(i\frac{\mathrm{d}}{\mathrm{d}x_3} + E + \mathcal{M}_0\right)\begin{pmatrix} A_1(x_3) \\ A_2(x_3) \\ a(x_3) \end{pmatrix} = 0$$

Schrödinger-like equation of motion

$$\mathcal{M}_0 = \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_{||} & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix}$$

$$\Delta_\perp \equiv \Delta_{\rm pl} + \Delta_\perp^{\rm CM}$$

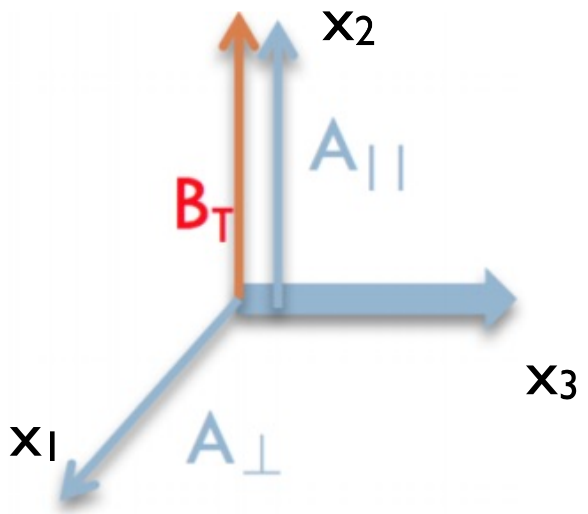
$$\Delta_{||} \equiv \Delta_{\rm pl} + \Delta_{||}^{\rm CM}$$

$$\Delta_{a\gamma} \simeq 7.6\times10^{-2}\left(\frac{g_{a\gamma}}{5\times10^{-11}\mathrm{GeV}^{-1}}\right)\left(\frac{B_T}{10^{-6}\,\mathrm{G}}\right)\mathrm{kpc}^{-1},$$

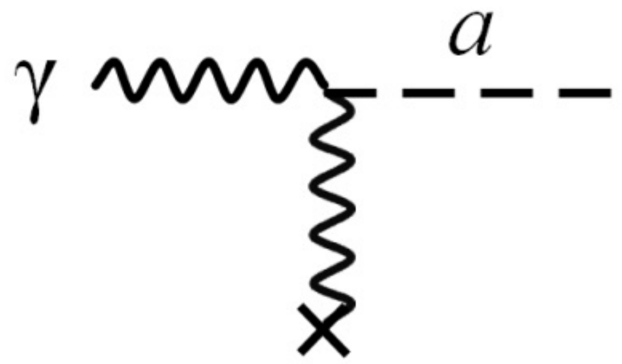
$$\Delta_a \simeq -7.8\times10^{-3}\left(\frac{m_a}{10^{-8}\mathrm{eV}}\right)^2\left(\frac{E}{\mathrm{TeV}}\right)^{-1}\mathrm{kpc}^{-1},$$

$$\Delta_{\rm pl} \simeq -1.1\times10^{-10}\left(\frac{E}{\mathrm{TeV}}\right)^{-1}\left(\frac{n_e}{10^{-3}\,\mathrm{cm}^{-3}}\right)\mathrm{kpc}^{-1},$$

$$\Delta_{\rm QED} \simeq 4.1\times10^{-6}\left(\frac{E}{\mathrm{TeV}}\right)\left(\frac{B_T}{10^{-6}\,\mathrm{G}}\right)^2\mathrm{kpc}^{-1}.$$



Raffelt & Stodolsky PRD'88; Horns+PRD'12; and others



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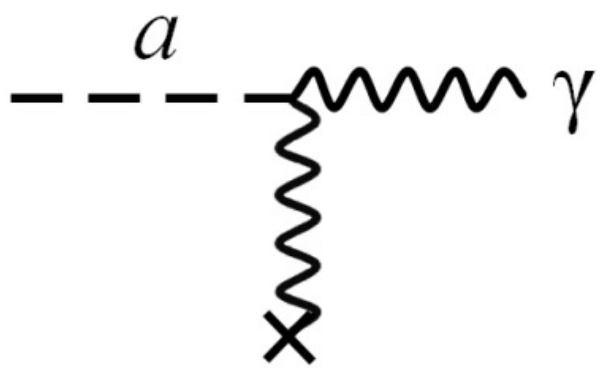


Considering the propagation of photons in a **single magnetic domain d** with a **coherent B-field**, the propagation equations reduce to a 2-dimensional problem:

$$P^{(0)}_{\gamma\to a} = \sin^2 2\theta \, \sin^2\left(\frac{\Delta_{\rm osc}\, d}{2}\right) = (\Delta_{a\gamma} d)^2 \frac{\sin^2(\Delta_{\rm osc} d/2)}{(\Delta_{\rm osc} d/2)^2}$$

Probability for purely polarised photon beam ($A_\parallel$) to oscillate into an ALP after distance d

$$\Delta_{\rm osc} \equiv \left[(\Delta_a - \Delta_{\rm pl})^2 + 4\Delta^2_{a\gamma}\right]^{1/2}$$

Oscillation wave number

$$E_c \equiv \frac{E|\Delta_a - \Delta_{\rm pl}|}{2\Delta_{a\gamma}}$$

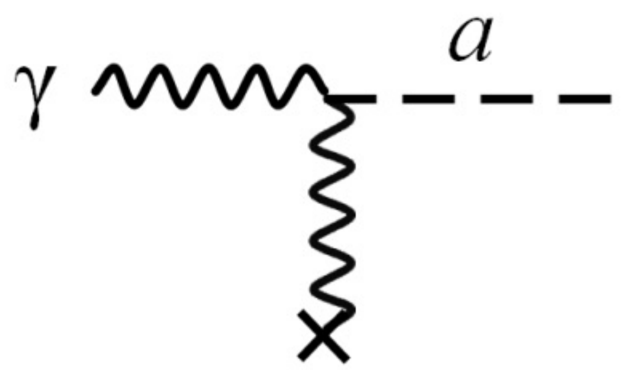
Critical energy

$$\Delta_{\rm osc} = 2\Delta_{a\gamma}\sqrt{1 + \left(\frac{E_c}{E}\right)^2}$$

$E \gg E_c$ → $\Delta_{\rm osc} \simeq 2\Delta_{a\gamma}$ **Strong mixing regime**

$E \simeq E_c$ → **Oscillation regime**

e.g. Mirizzi & Montanino JCAP'09



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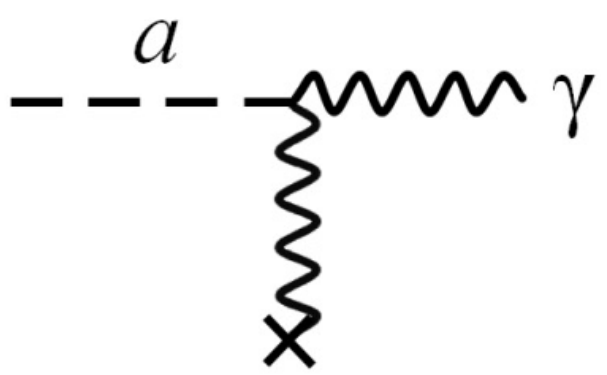
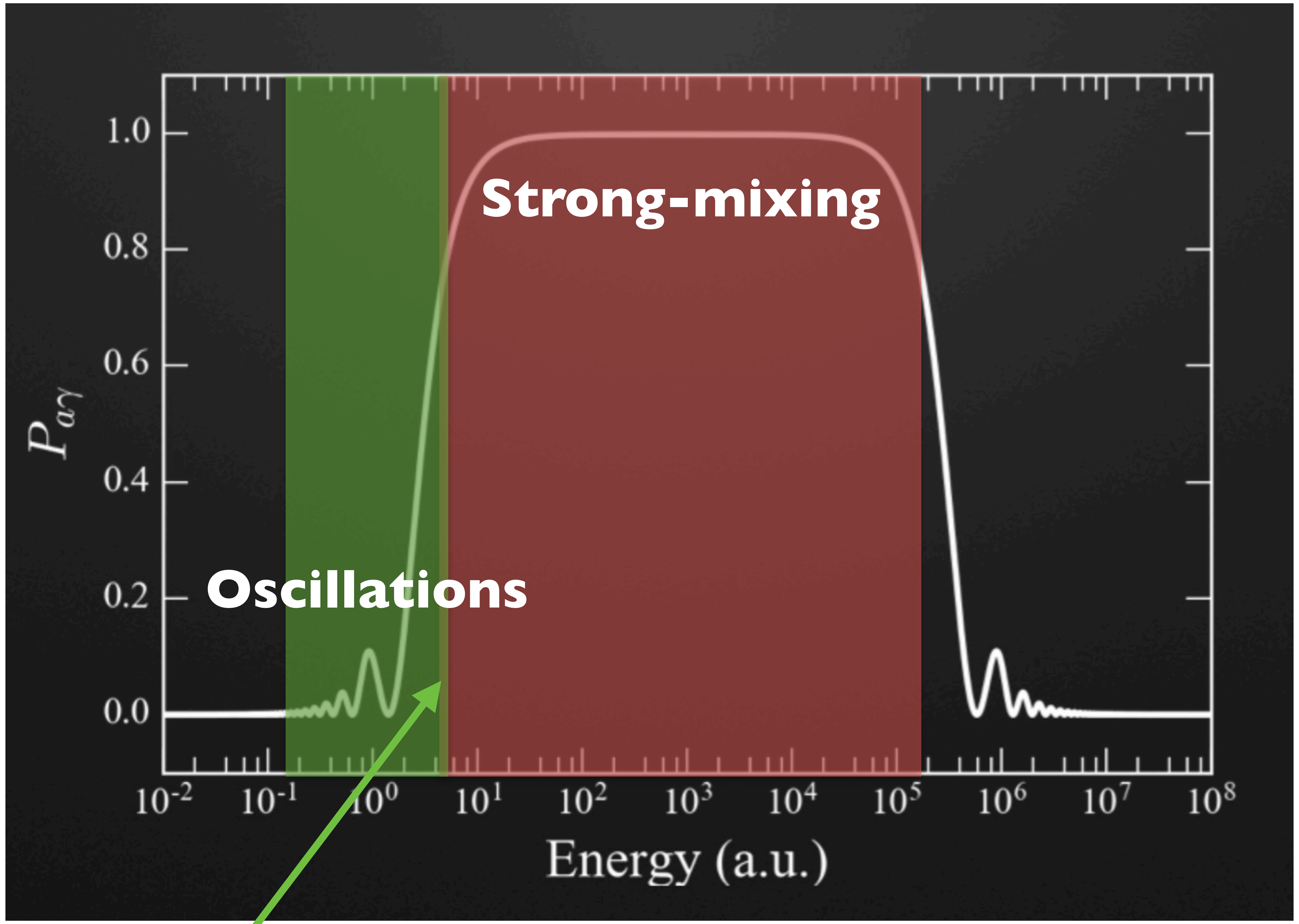
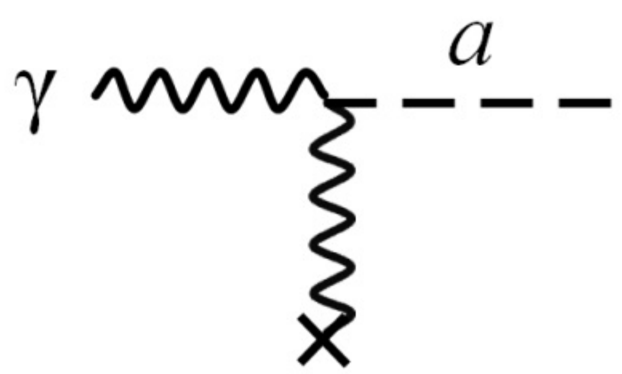




$$E_c \simeq 2.5\ \mathrm{GeV}\frac{|m_a^2 - \omega_{Pl}^2|}{1\,\mathrm{neV}}\left(\frac{B_\perp}{\mu\mathrm{G}}\right)^{-1}\left(\frac{g_{a\gamma\gamma}}{10^{-11}\ \mathrm{GeV}^{-1}}\right)^{-1}$$



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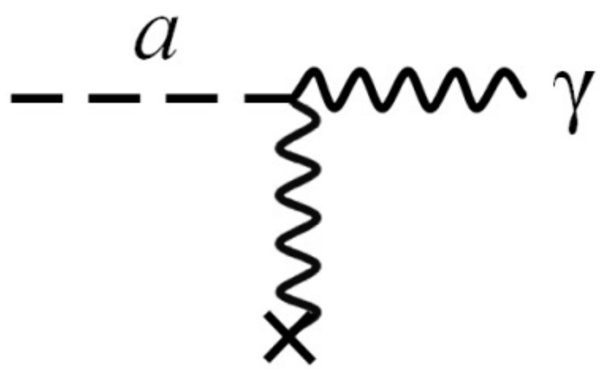

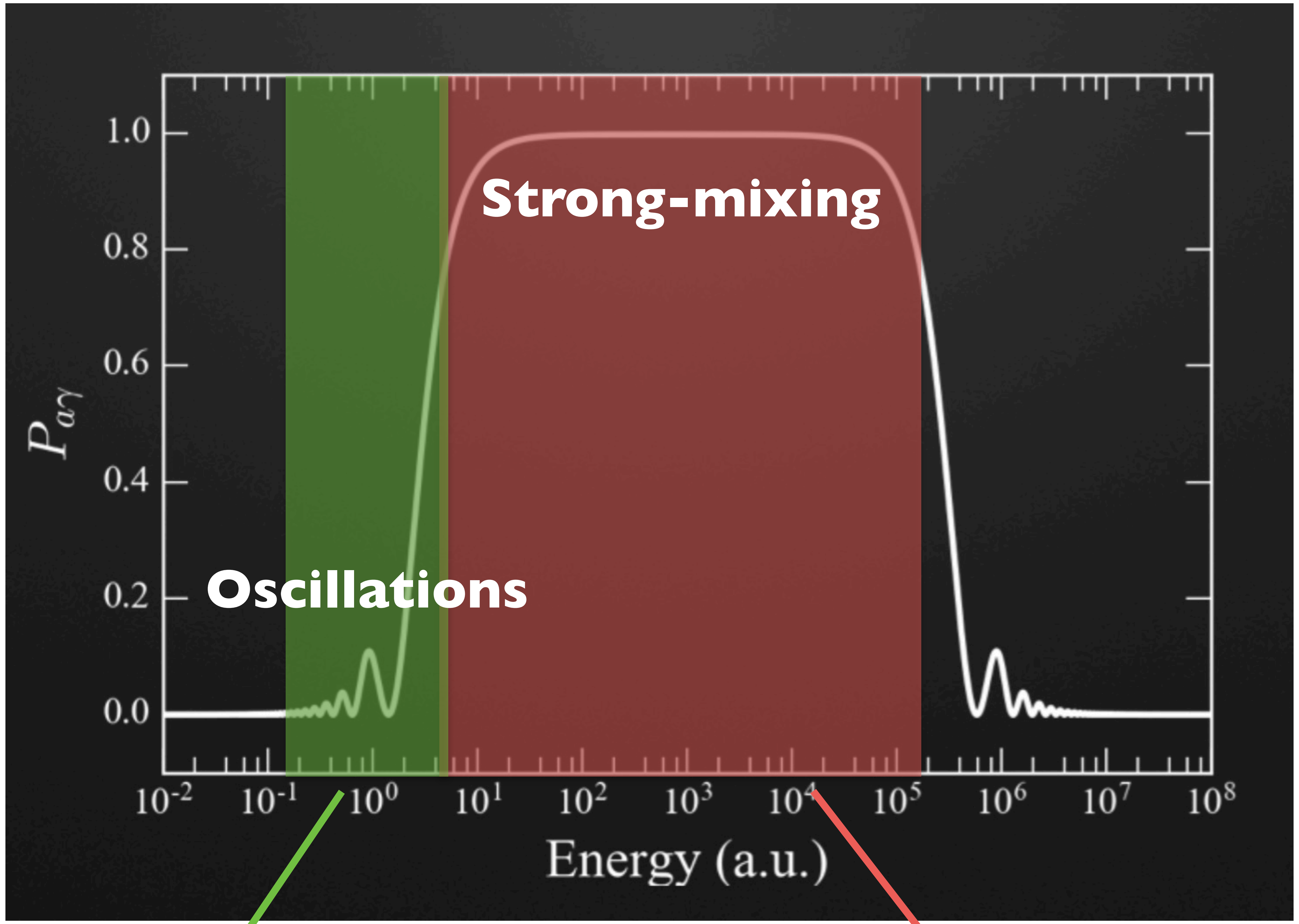

I. Spectral irregularities at $\sim E_c$

II. ALPs do not get absorbed, enhancing the photon flux

Searches for spectral irregularities

$$E_\gamma \simeq E_c$$

$$E_c \simeq 2.5\ \text{GeV}\,\frac{|m_a^2 - \omega_{Pl}^2|}{1\,\text{neV}}\left(\frac{B_\perp}{\mu\text{G}}\right)^{-1}\left(\frac{g_{a\gamma\gamma}}{10^{-11}\ \text{GeV}^{-1}}\right)^{-1}$$

ALPs parameters

m_a

$g_{a\gamma\gamma}$

Astrophysical environment

$$\omega_{Pl} = 0.03\,\text{neV}\sqrt{\text{n}_\text{e}/\text{cm}^{-3}}$$

B_T

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Galaxy cluster

$n_e \sim 0.01\,\mathrm{cm}^{-3}$

$B_0 \sim 1 - 10\,\mu\mathrm{G}$

Milky Way

$n_e \sim 0.1\,\mathrm{cm}^{-3}$

$B \sim 1\,\mu\mathrm{G}$

m_a	E_c
$\sim 10^{-6}\,\mathrm{eV}$	$\sim$ TeV
$\sim 10^{-9}\,\mathrm{eV}$	$\sim$ GeV
$\sim 10^{-12}\,\mathrm{eV}$	$\sim$ keV

Wouters & Brun ApJ'13; Conlon+ JCAP'17

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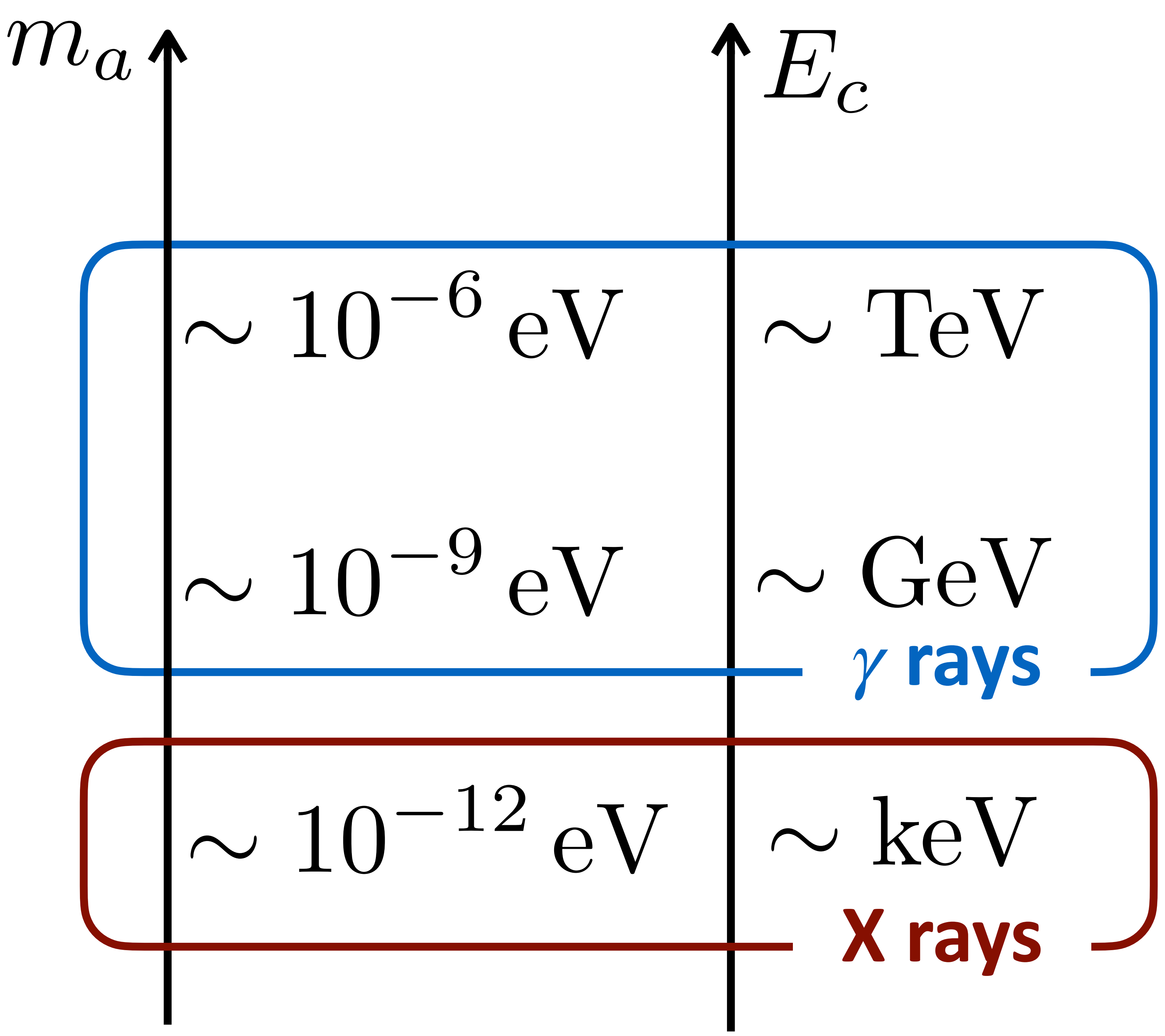

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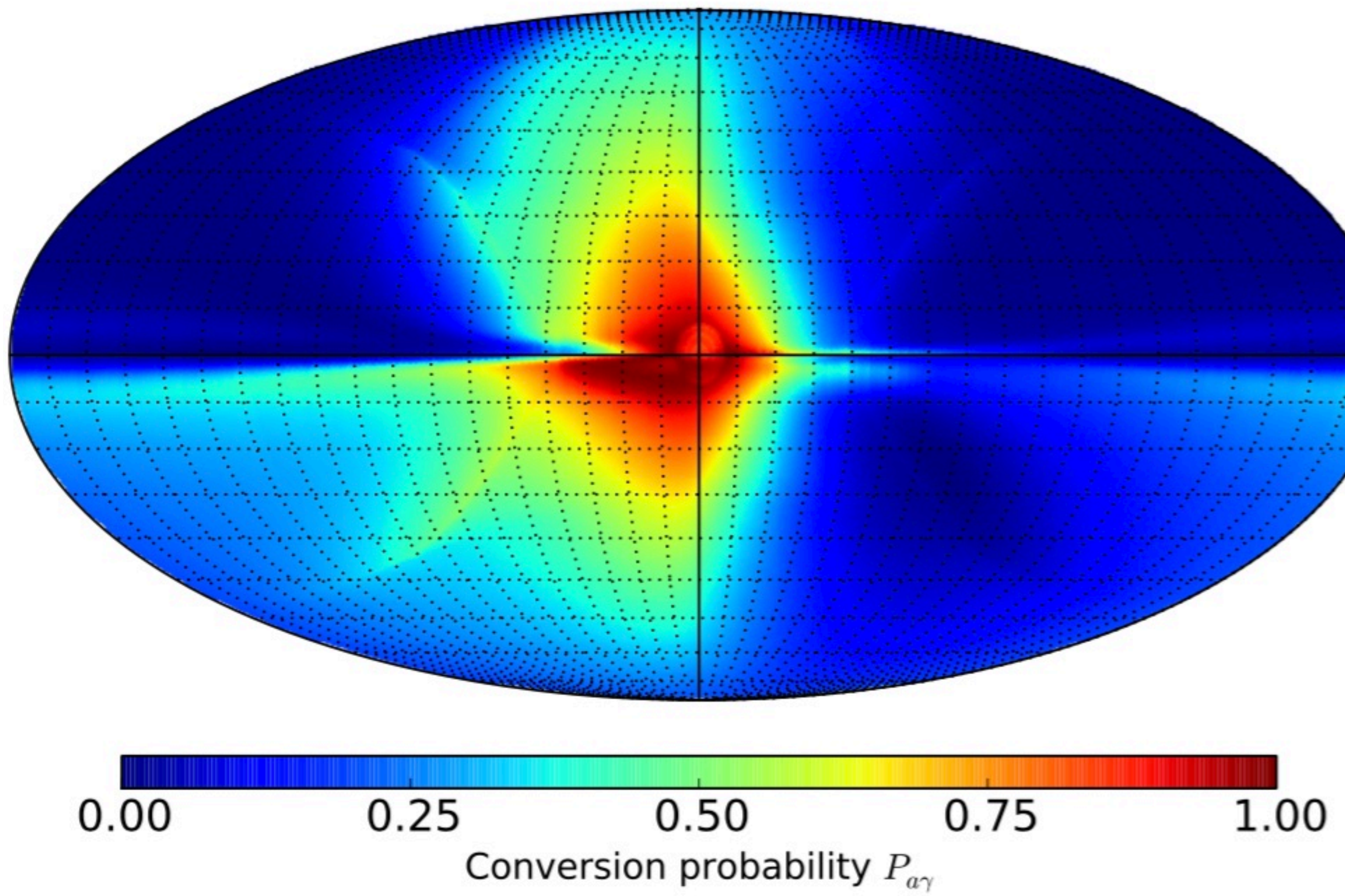
Searches for spectral irregularities

High-energy gamma rays

Some basic requirement:

- Very **bright gamma-ray sources** ⟶ High statistics for a good spectral determination
- Sources far enough and in the **direction of strong transversal B-fields**, e.g. behind or within a galaxy cluster
- Good knowledge of B-field! As ALP searches are sensitive to the product $\mathbf{g_{a\gamma}\,B_T}$, the constraint on $g_{a\gamma}$ is only as good as the knowledge of B_T.

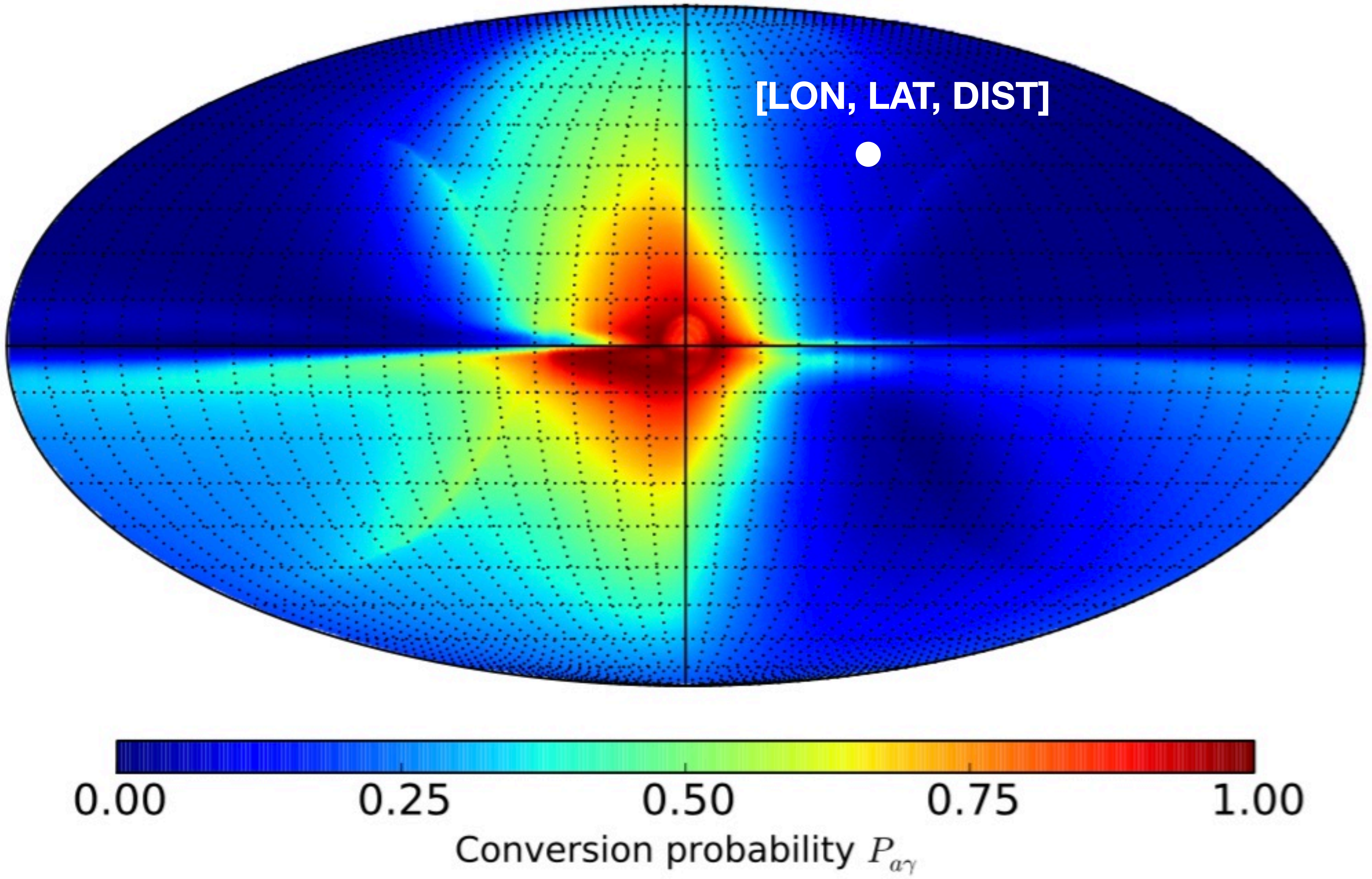


Conversion probability in Galactic B-field

$g_{a\gamma}$ = 5 x 10^{-11} GeV^{-1}
pure ALP beam
propagating through entire Milky Way
[Jansson & Farrar 2012 model]

Searches for gamma-ray spectral irregularities

Galactic and extragalactic targets

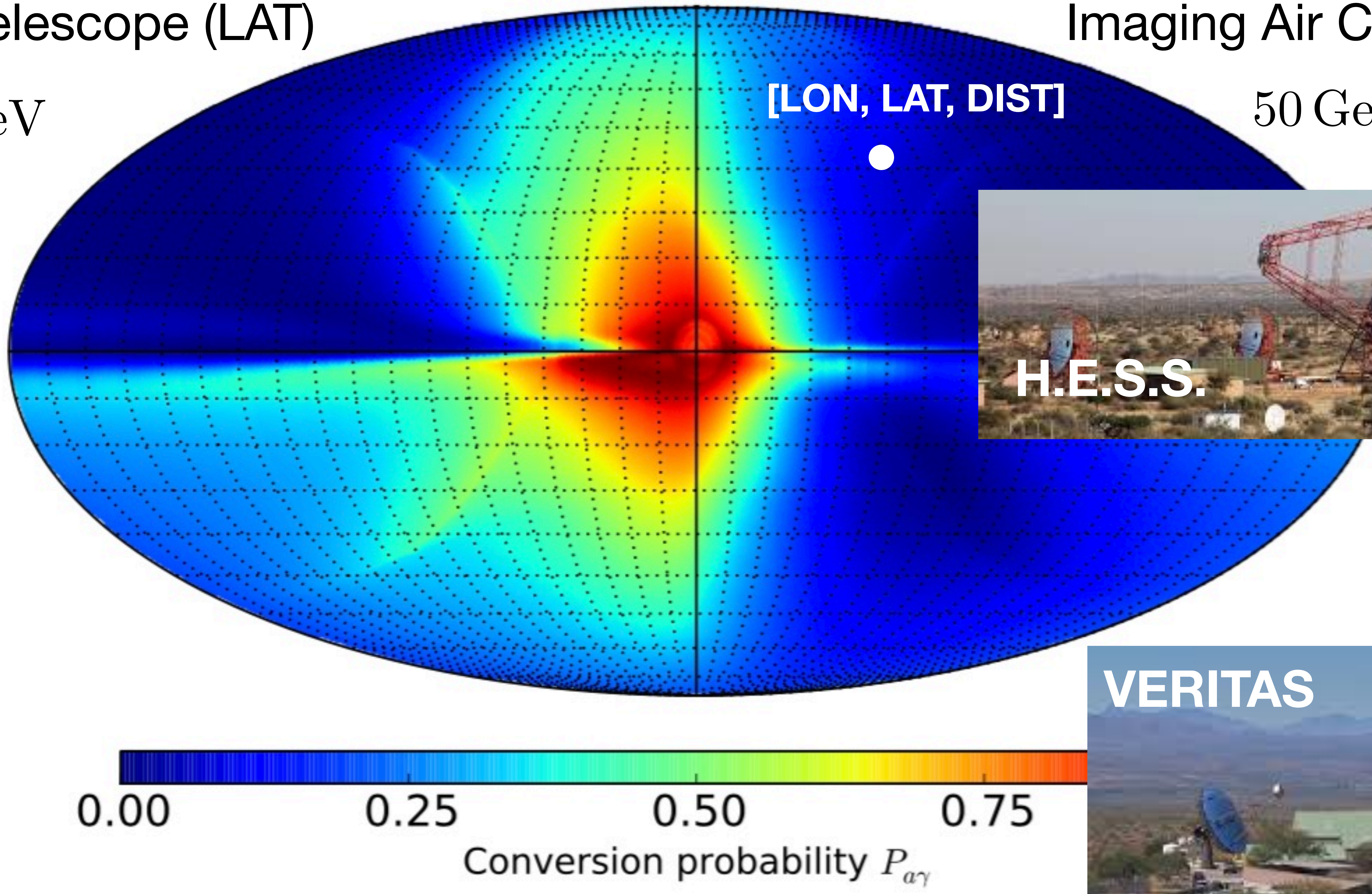


Searches for gamma-ray spectral irregularities

Galactic and extragalactic targets

Fermi Large Area Telescope (LAT)

$30\,\mathrm{MeV} \lesssim \mathrm{E}_\gamma \lesssim 1\,\mathrm{TeV}$

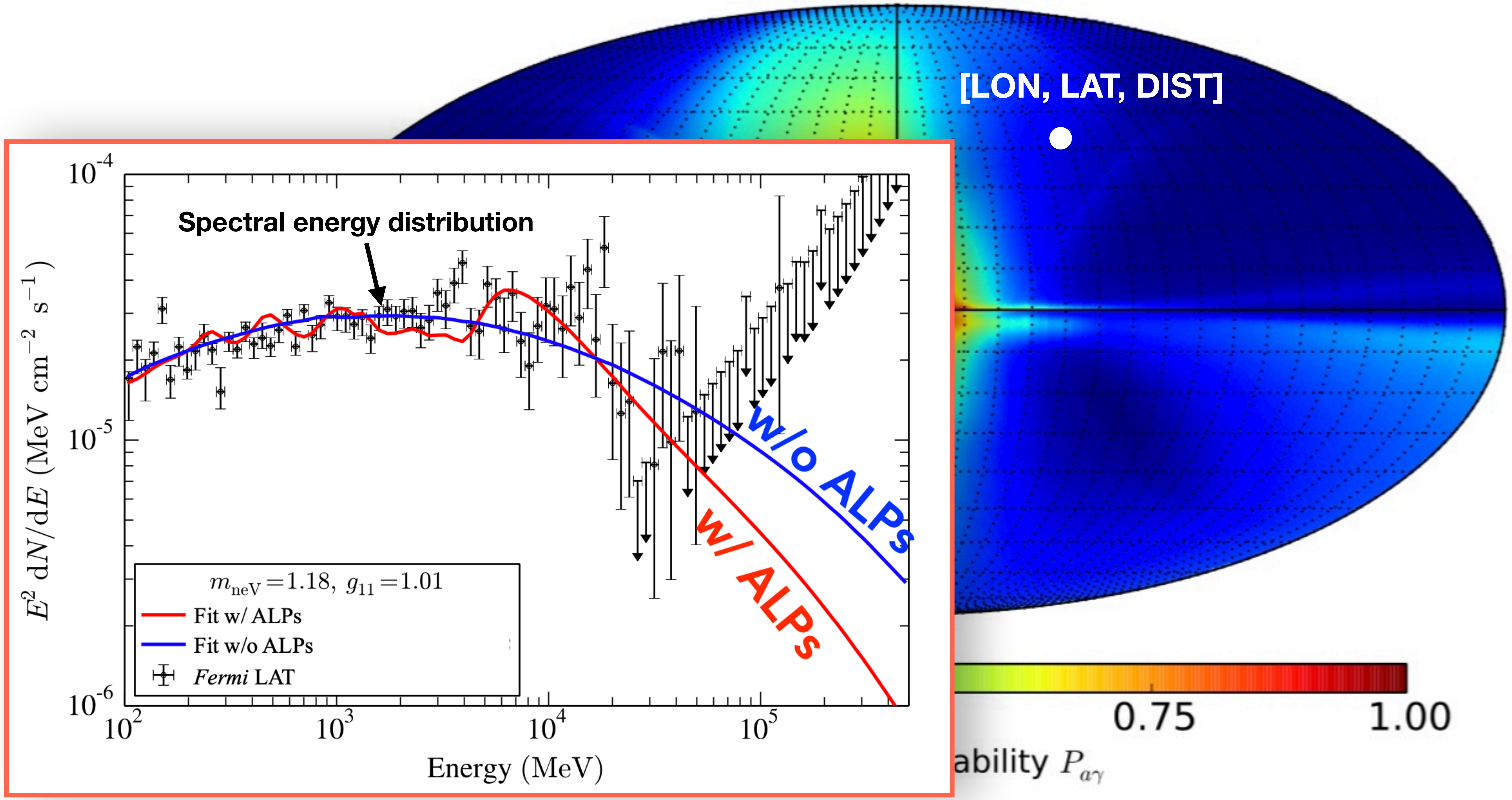


Imaging Air Cherenkov Telescopes

$50\,\mathrm{GeV} \lesssim \mathrm{E}_\gamma \lesssim 100\,\mathrm{TeV}$

Searches for gamma-ray spectral irregularities

Galactic and extragalactic targets

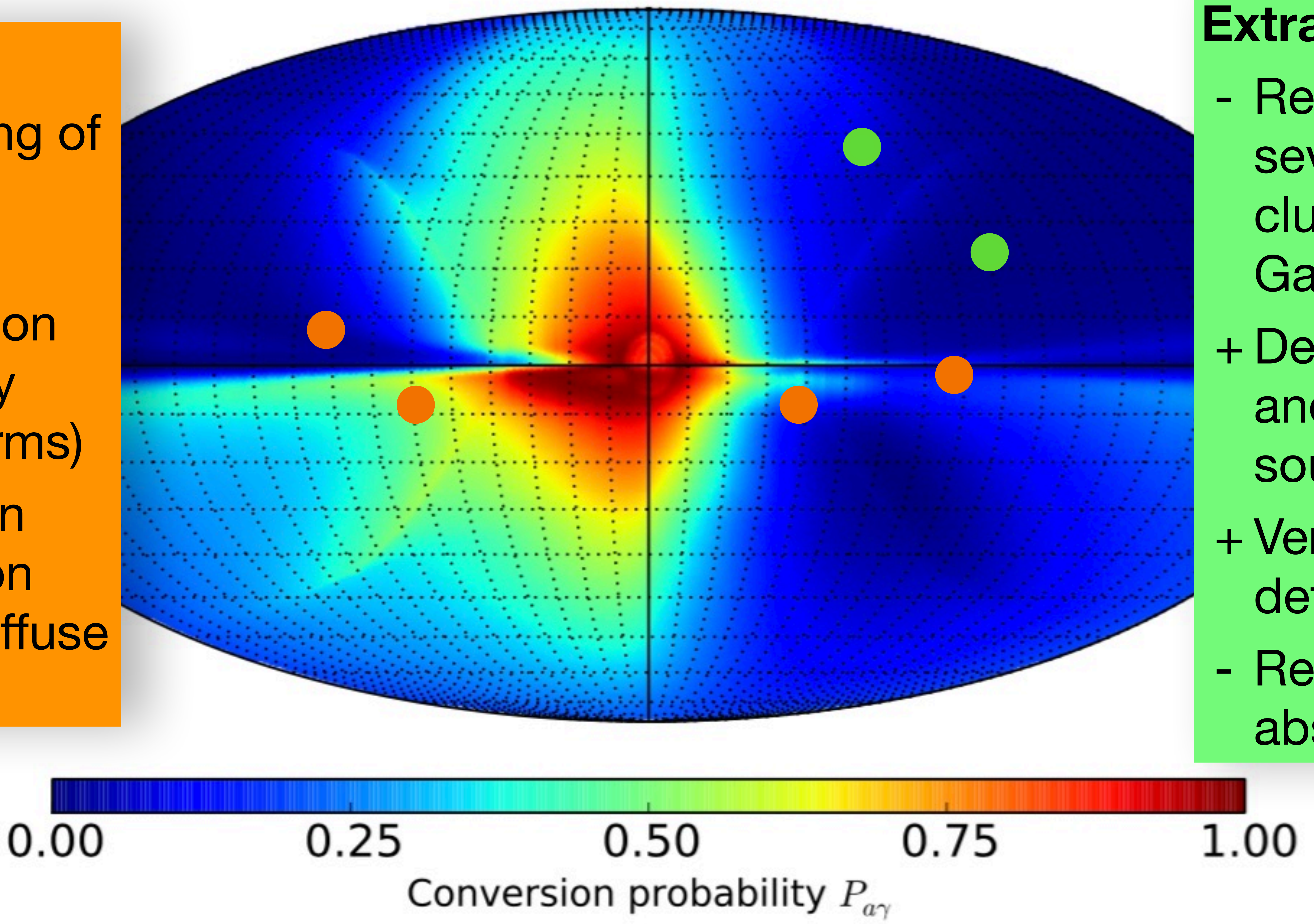


Searches for gamma-ray spectral irregularities

Galactic and extragalactic targets

Galactic targets:

- + Require only modelling of Galactic B field
- - Strength of the conversion depends on position in the Galaxy (e.g. beyond spiral arms)
- - Larger systematics on spectral determination due to gamma-ray diffuse emission foreground



Extragalactic targets:

- - Require modelling of several B fields (intra-cluster, intergalactic, Galactic)
- + Depends only on latitude and longitude of the sources
- + Very accurate spectral determination
- - Require modelling of EBL absorption

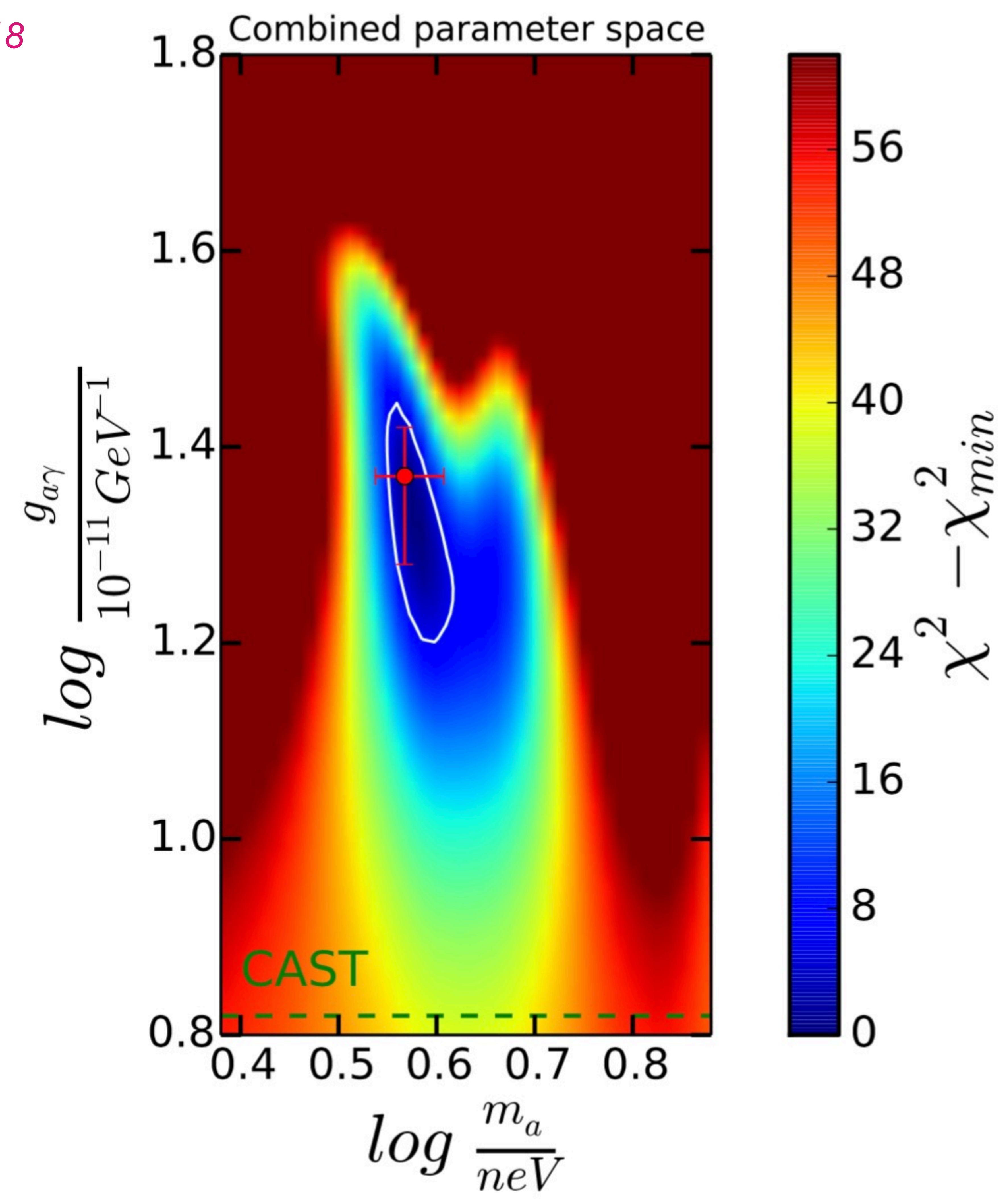
Signal hints for ALP-photon mixing

Search for spectral irregularities in Galactic targets

- Analysis of **6 bright pulsars** with **Fermi-LAT** *Majumdar, FC & Horns JCAP'18*
  - ✓ **4.6σ** significance for common ALP-photon mixing

$$m_a = (3.6^{+0.5_{\rm stat.}}_{-0.2_{\rm stat.}} \pm 0.2_{\rm syst.})\ {\rm neV} \qquad g_{a\gamma\gamma} = (2.3^{+0.3_{\rm stat.}}_{-0.4_{\rm stat.}} \pm 0.4_{\rm syst.}) \times 10^{-10}\ {\rm GeV}^{-1}$$

  - ✓ 20%-40% spectral variation vs ~3% experimental systematic uncertainty
  - ✓ Systematic theoretical uncertainties on transverse B field and distances
- Analysis of **3 bright SNRs** with **Fermi-LAT** and **HESS/MAGIC/VERITAS** *Xia+ PRD'19*
  - ✓ **3σ** significance for only one source (IC443)
  - ✓ Large systematic due to GeV-TeV data calibration
- Analysis of **10 SNRs and pulsars** *Liang+ JCAP'19*
  - ✓ No evidence for common ALP-photon mixing

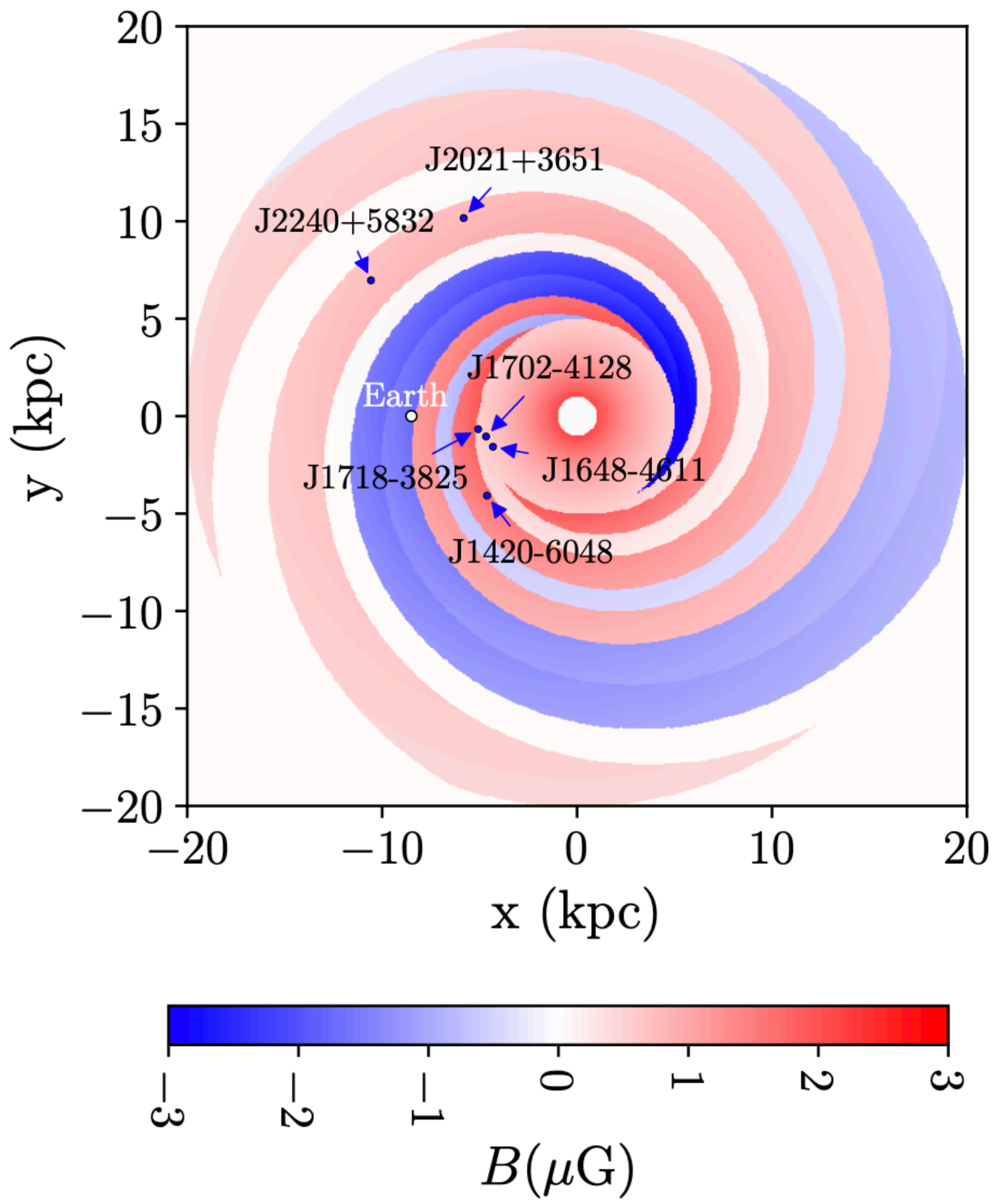


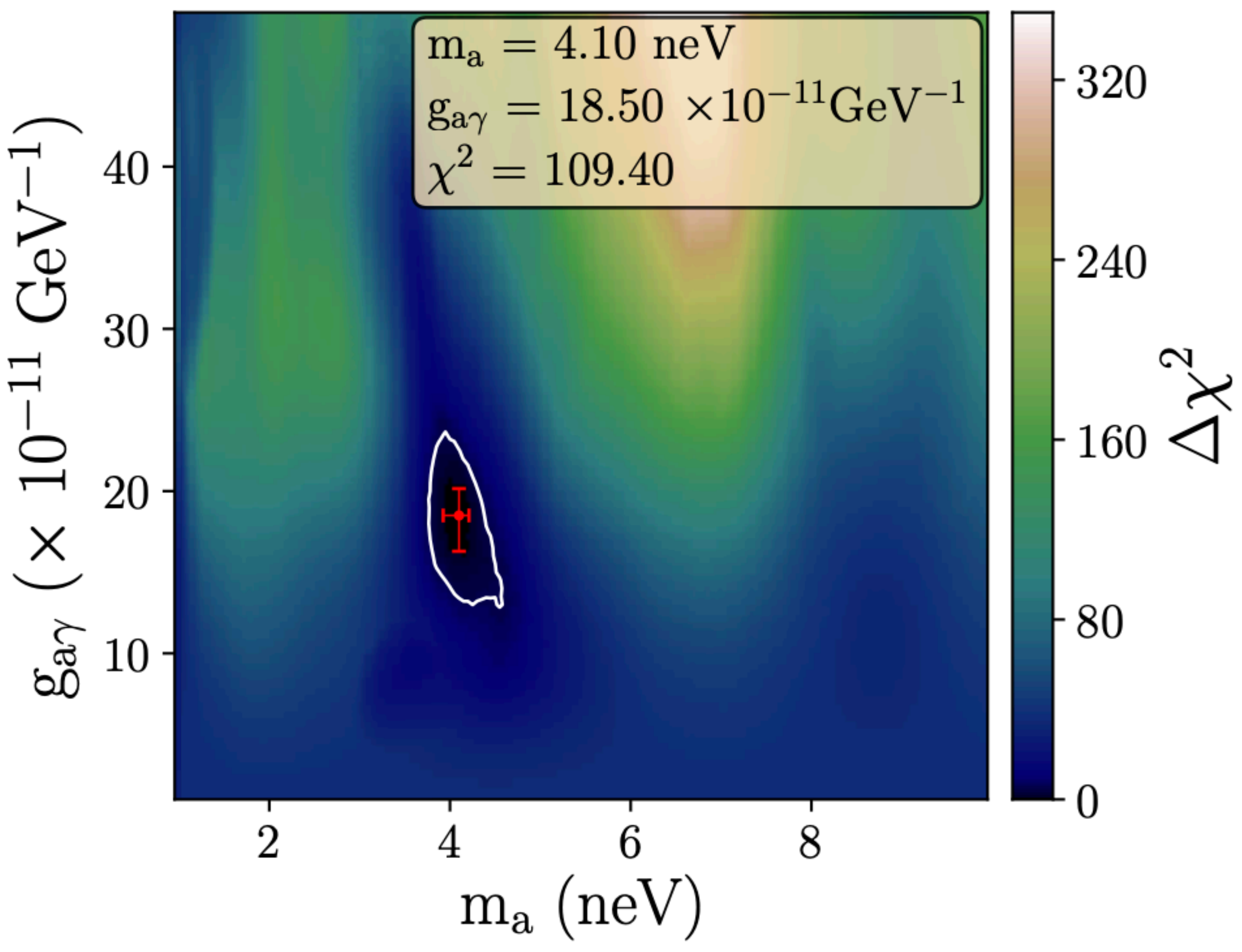
Signal hints for ALP-photon mixing

A recent update of PSR signal region

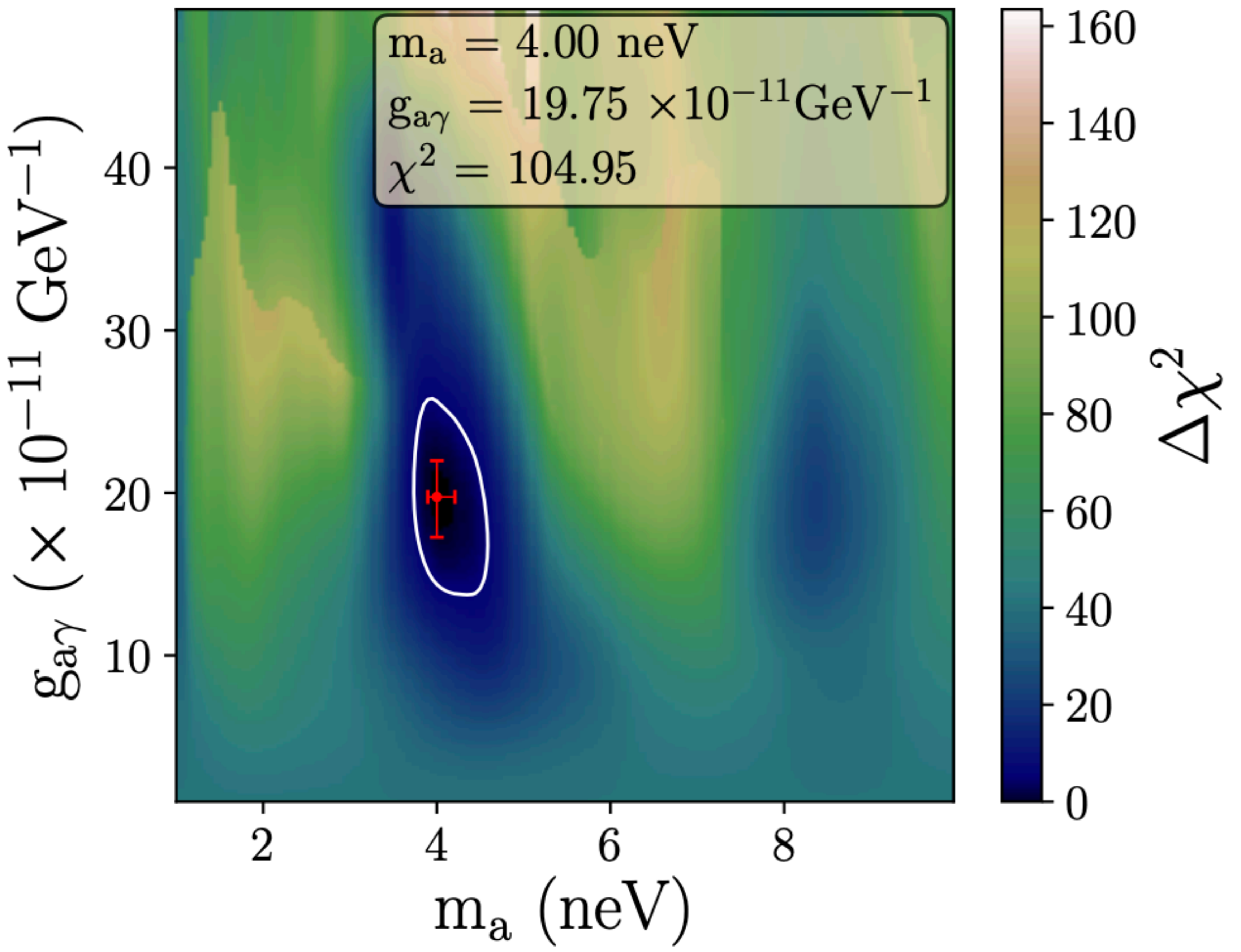
Adamane Pallathadka, FC+ 2008.08100

- Re-analysis of **6 bright pulsar sample**
- Updated B field model (Planck results) and distance measurements
- **Profiling** of the likelihood over **distance and B field uncertainties** adding penalised likelihood terms





Distance uncertainty



B-field uncertainty

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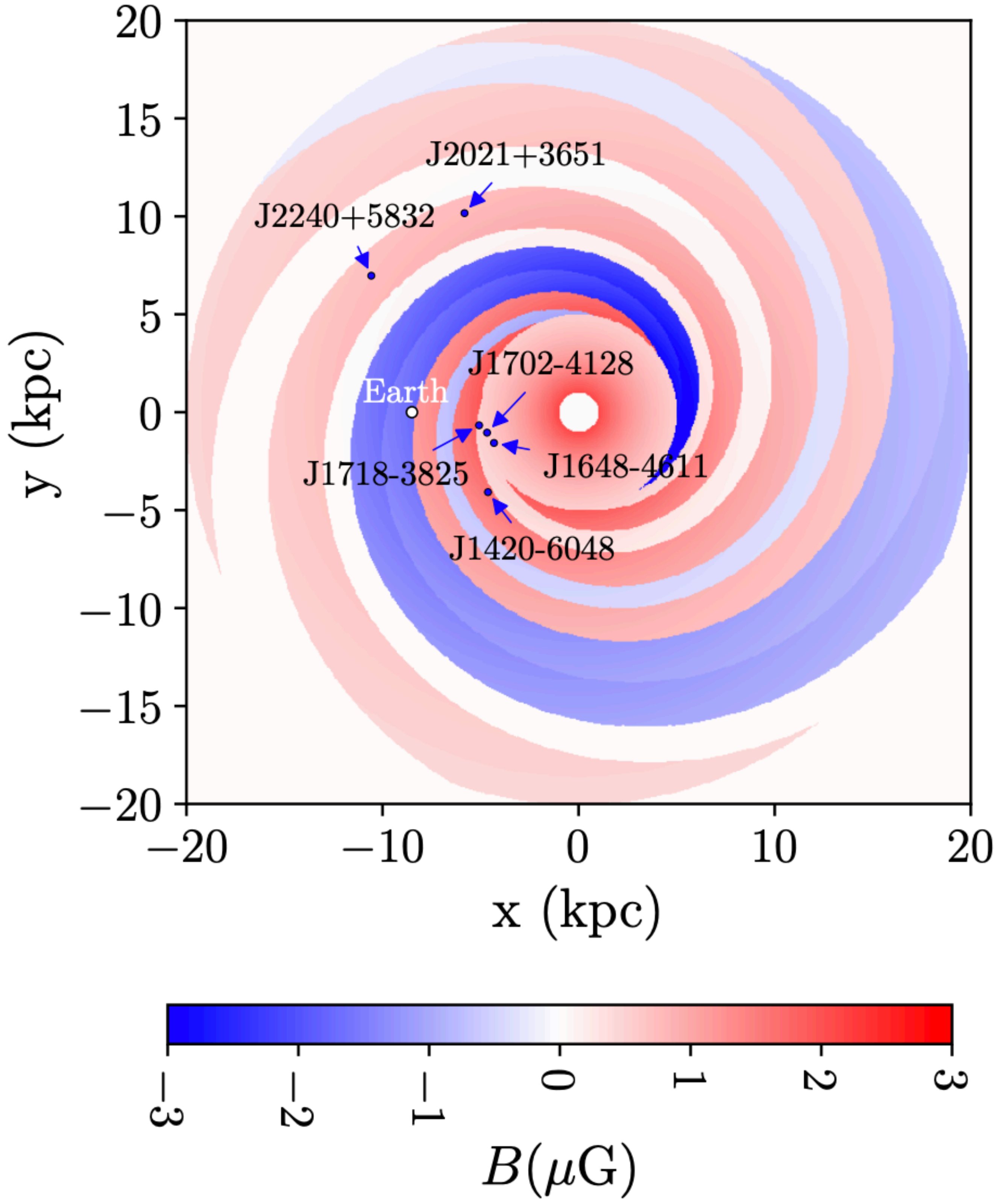

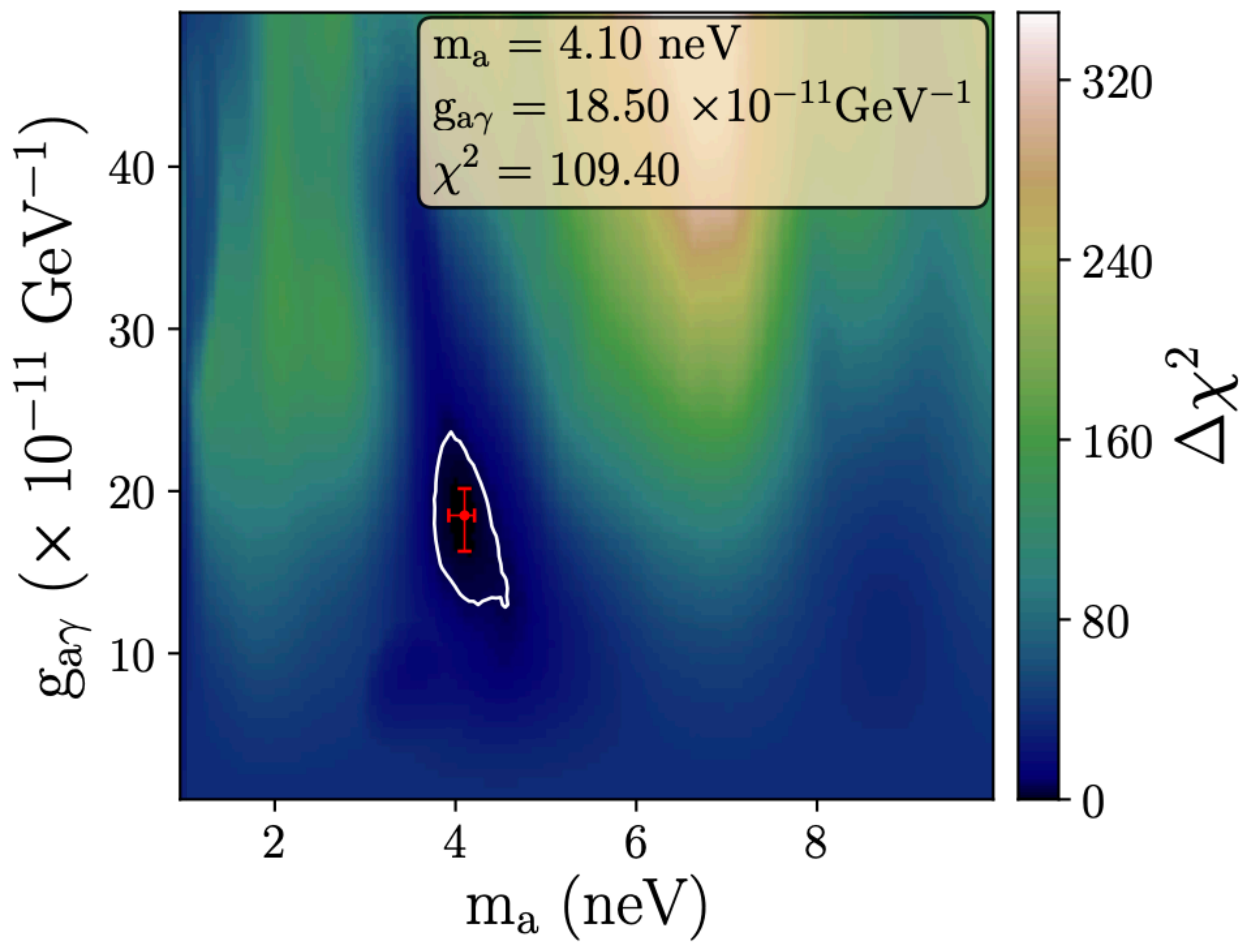

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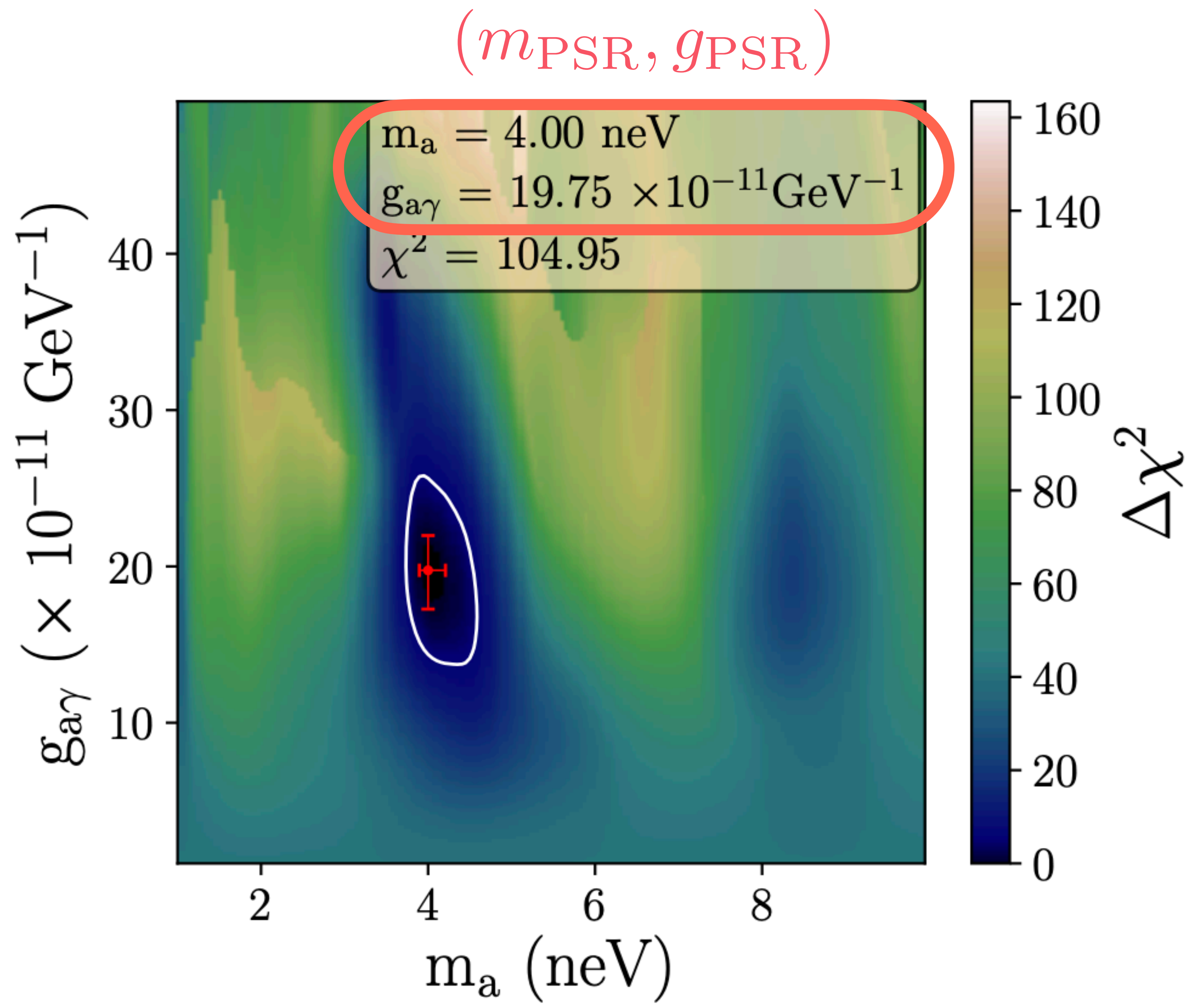
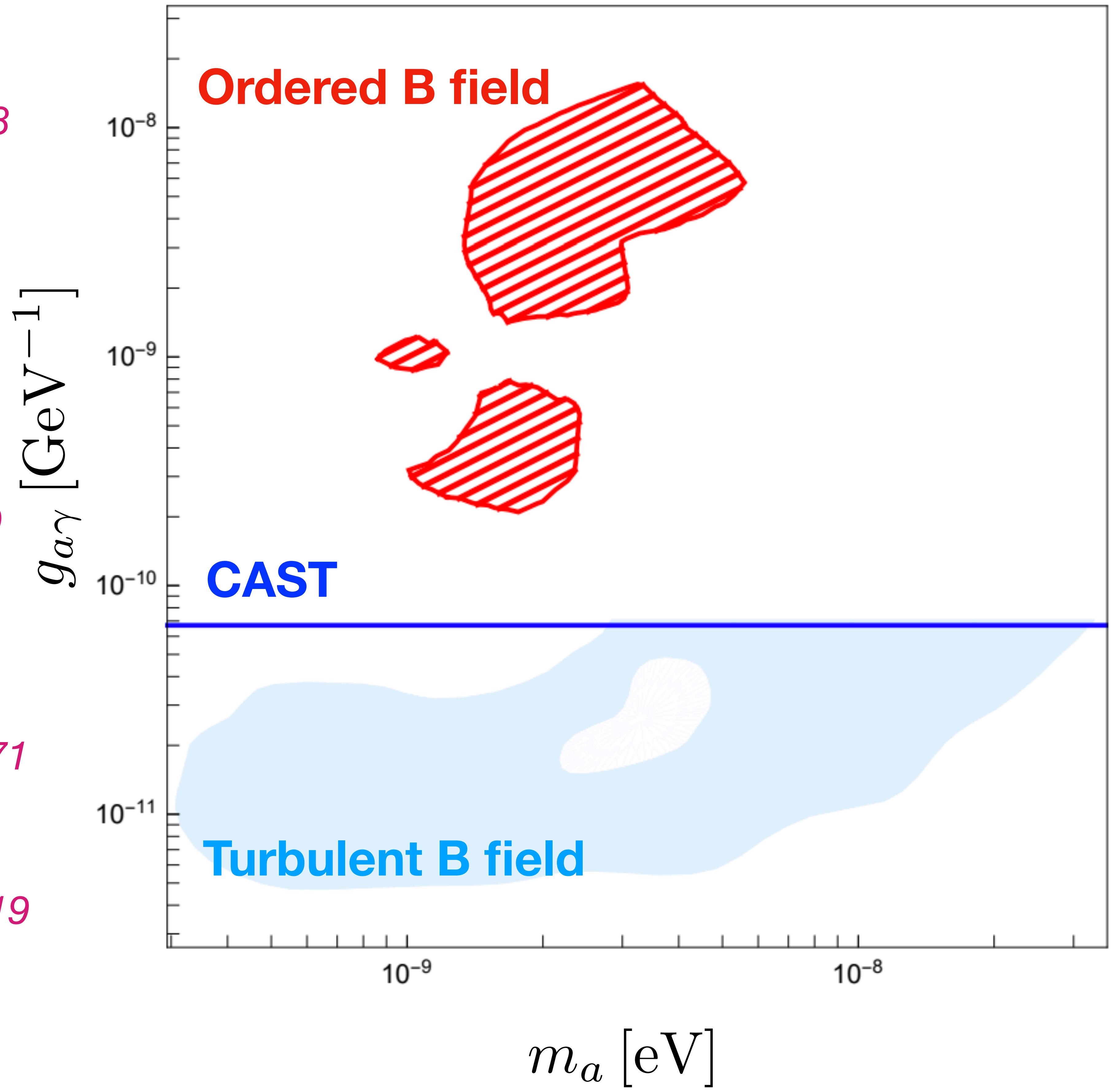


B-field uncertainty

Constraints on ALP-photon mixing
Search for spectral irregularities in extragalactic targets

No evidence for ALP-photon mixing ⟶ Strong but **not very robust upper limits**

- Analysis of radio galaxy **NGC1275** (Perseus cluster) with **Fermi-LAT** and **MAGIC** *Ajello+PRL'16, Malyshev+1805.04388*
  - ✓ Limits very sensitive to modelling of intra-cluster B field
  - ✓ Typically, only turbulent component is modelled
  - ✓ But, there is evidence for large scale ordered component (better match to Faraday rotation measure and others) *Libanov &Troitsky PLB'20*
  - ✓ With a purely ordered B field limits almost vanish
- Analysis of nearby blazar **PKS 2155-304** with **Fermi-LAT** and **HESS** *Abramowski+ PRD'13, Zhang+ PRD'18; Guo+:2002.07571*
  - ✓ Only turbulent component of the intra-cluster B field
  - ✓ Intergalactic B field RMS usually overestimated *Jedamzik & Saveliev, PRL'19*
  - ✓ Limits can be significantly weakened

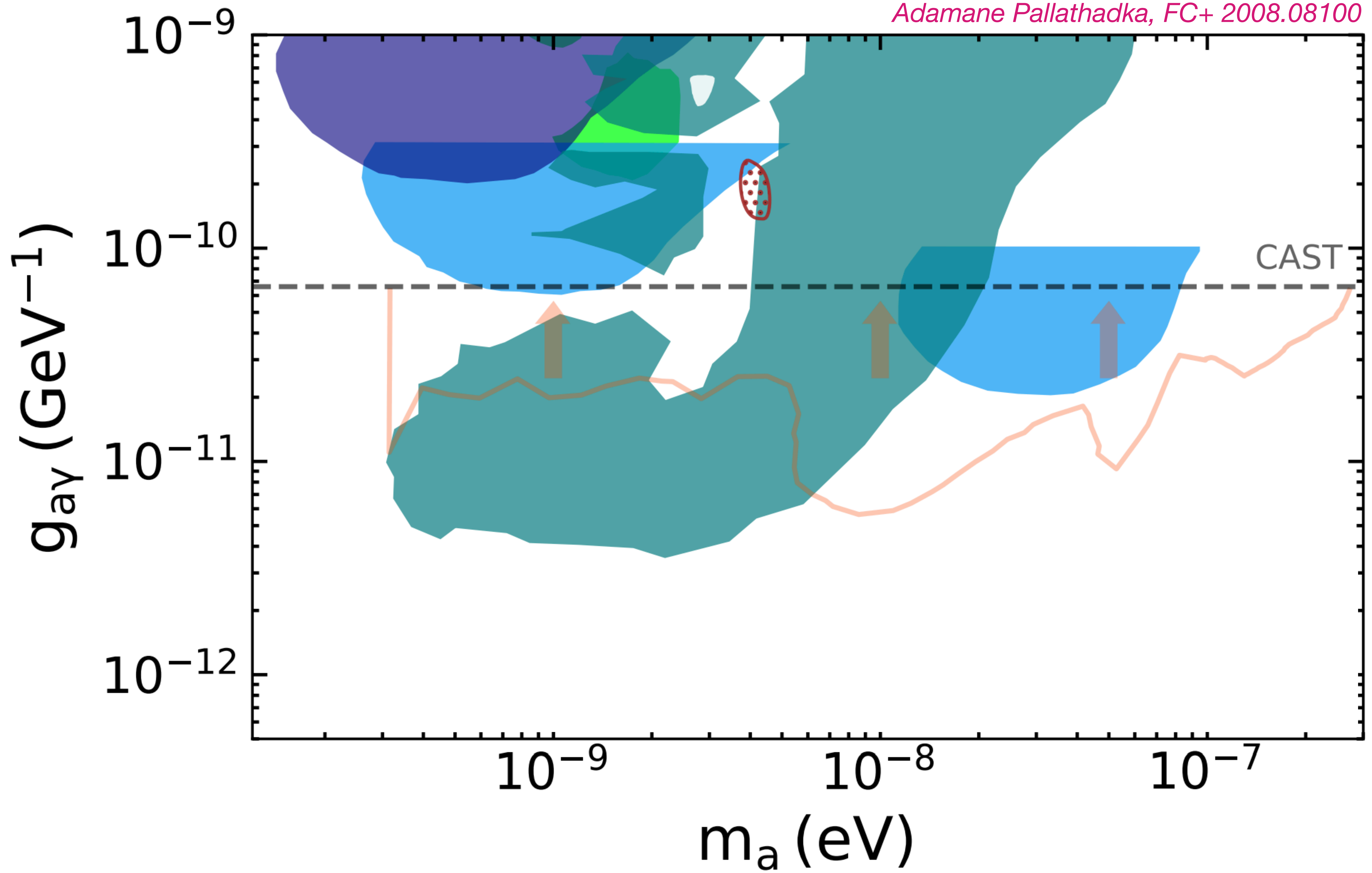


Libanov &Troitsky PLB'20

ALP-photon mixing w/ HE gamma rays

Summary of hints and constraints

Adamane Pallathadka, FC+ 2008.08100



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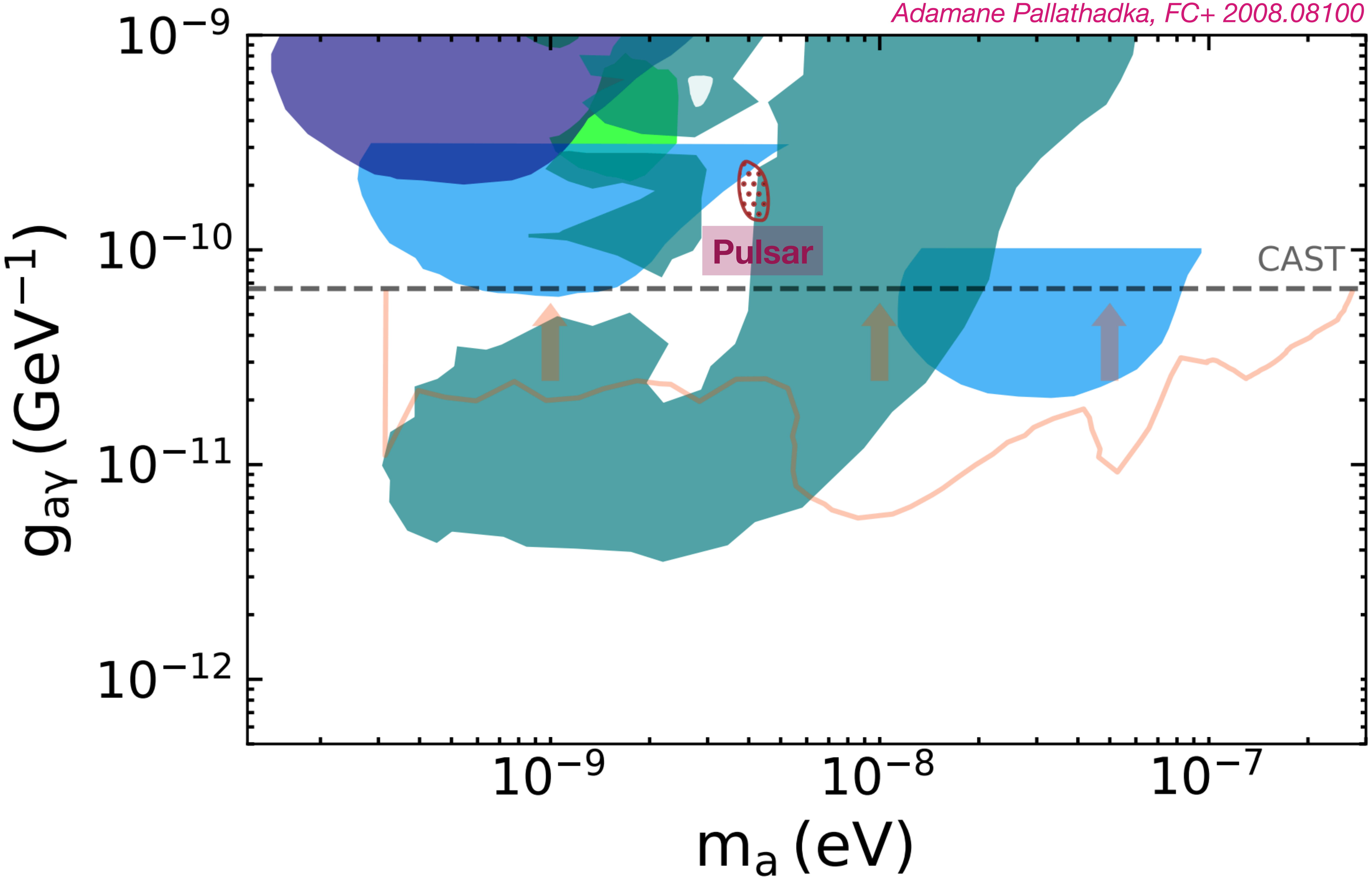

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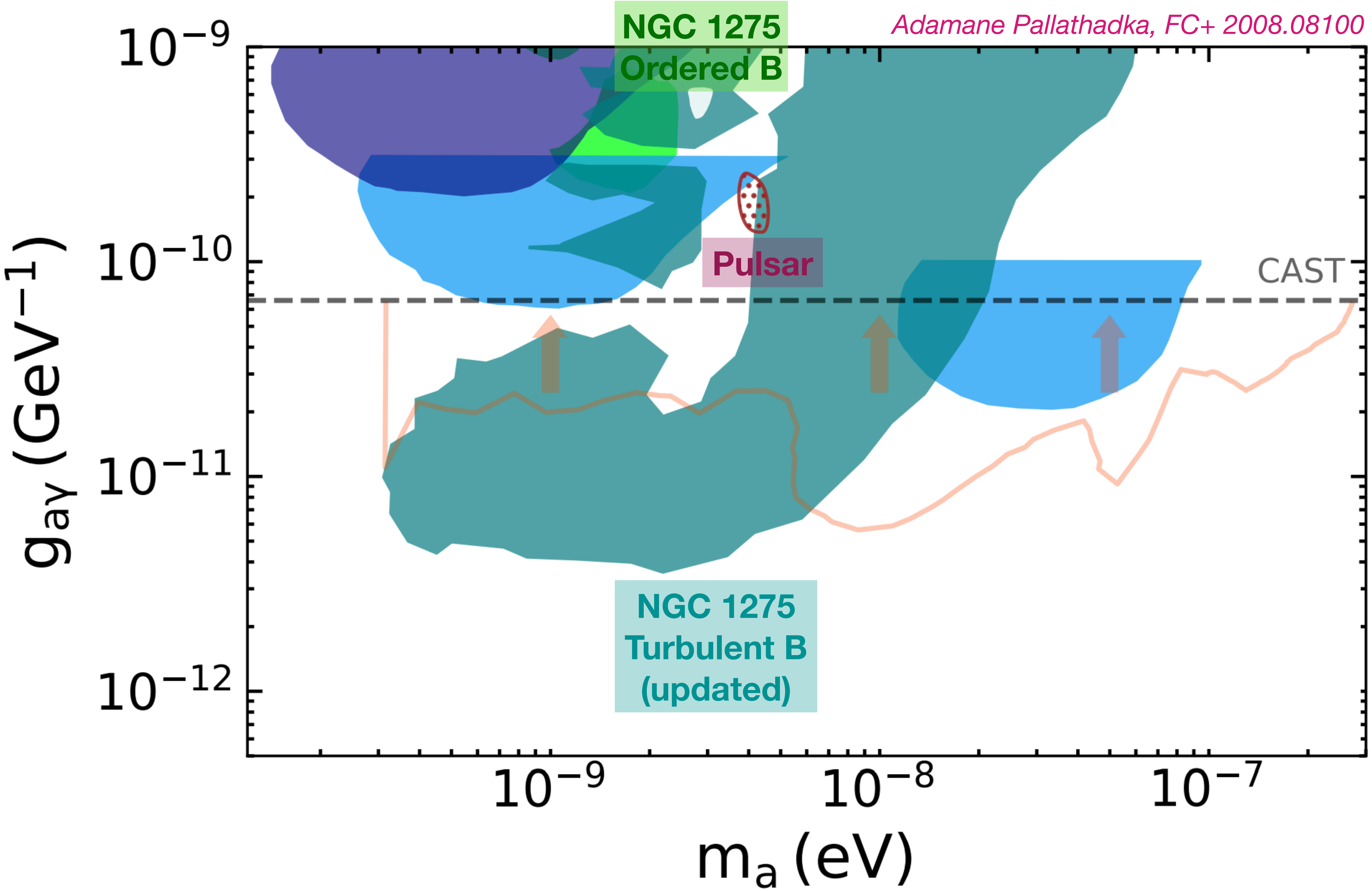

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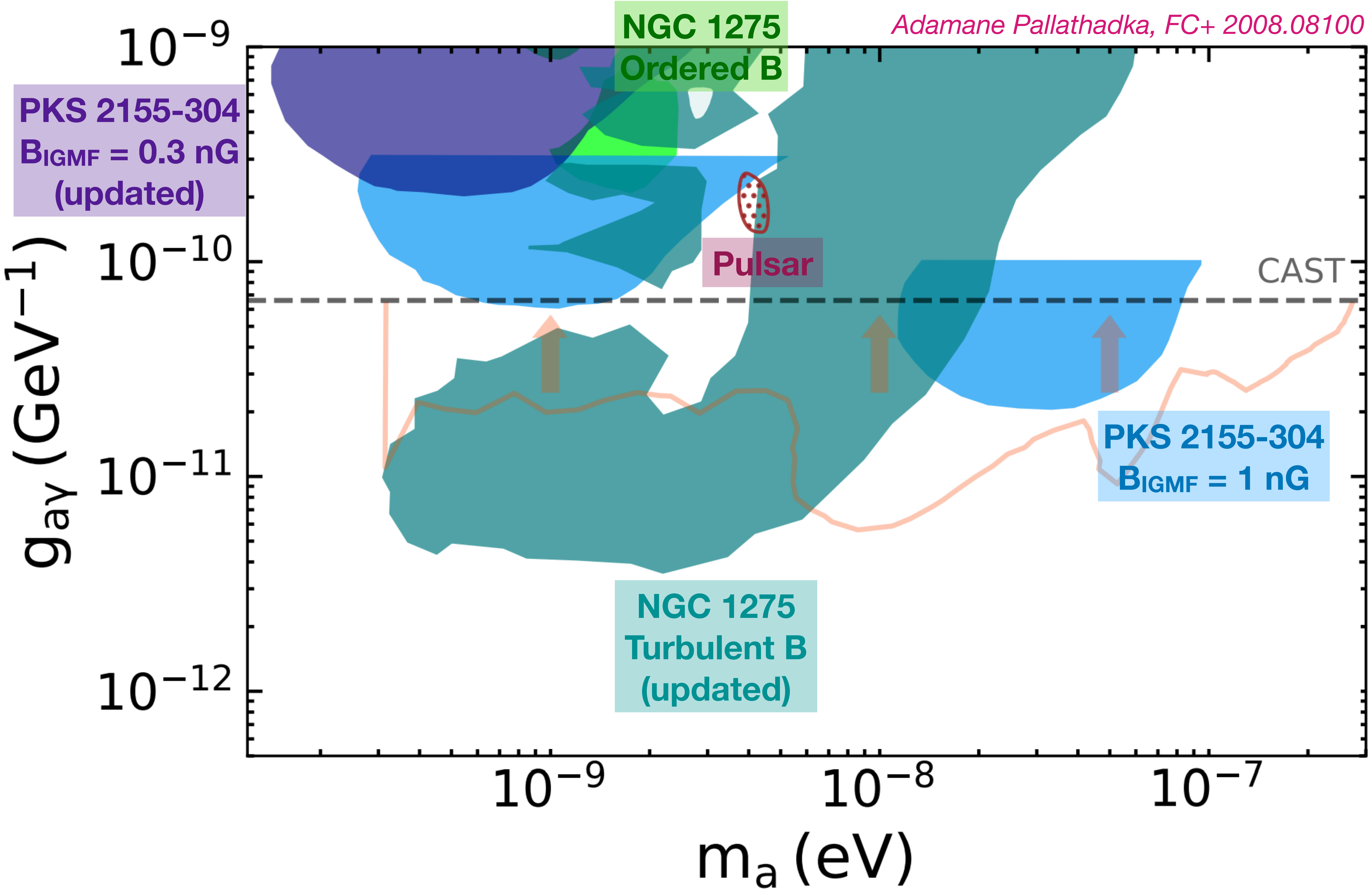

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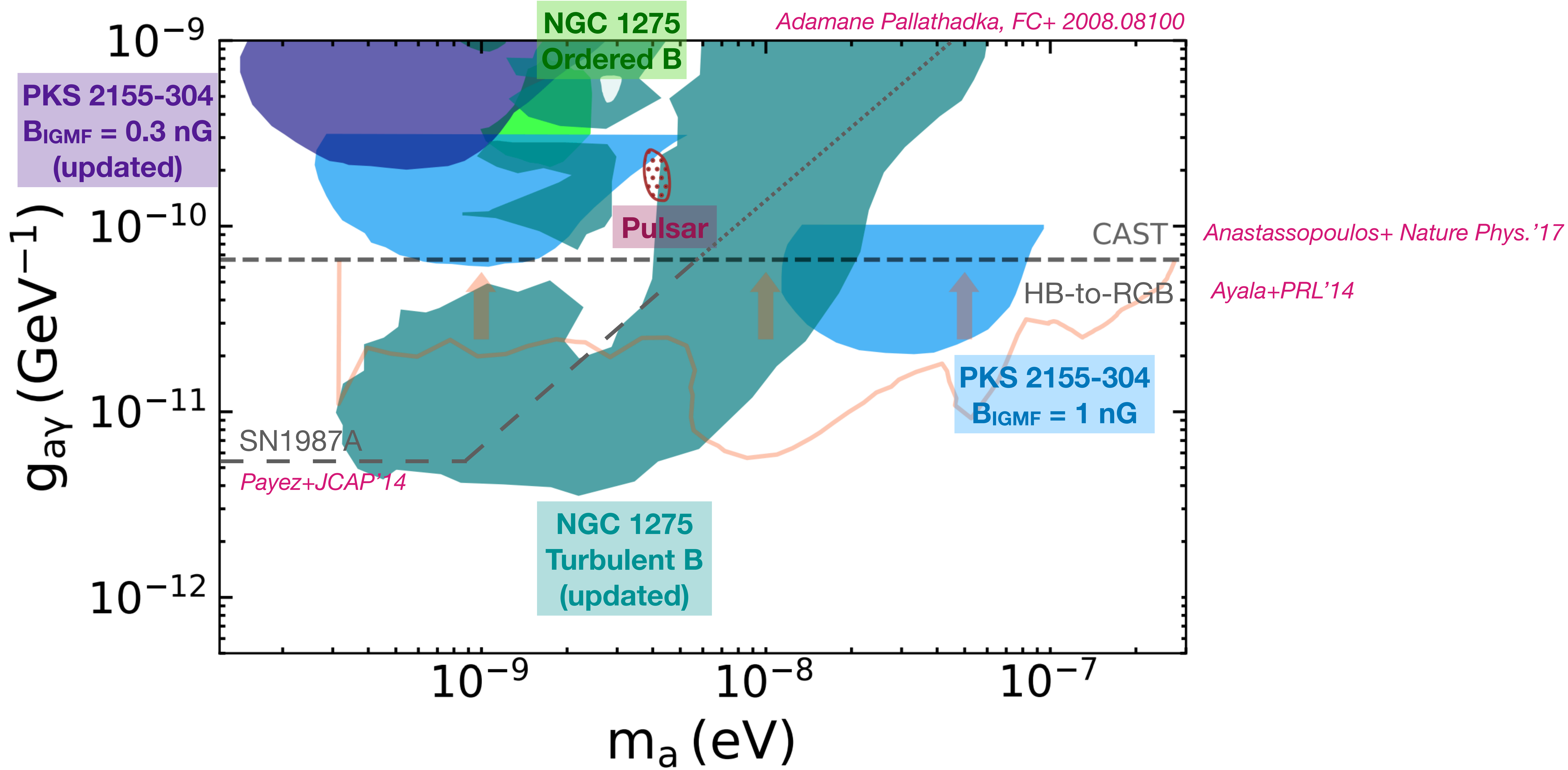


Evading solar and stellar constraints

Adamane Pallathadka, FC+ 2008.08100

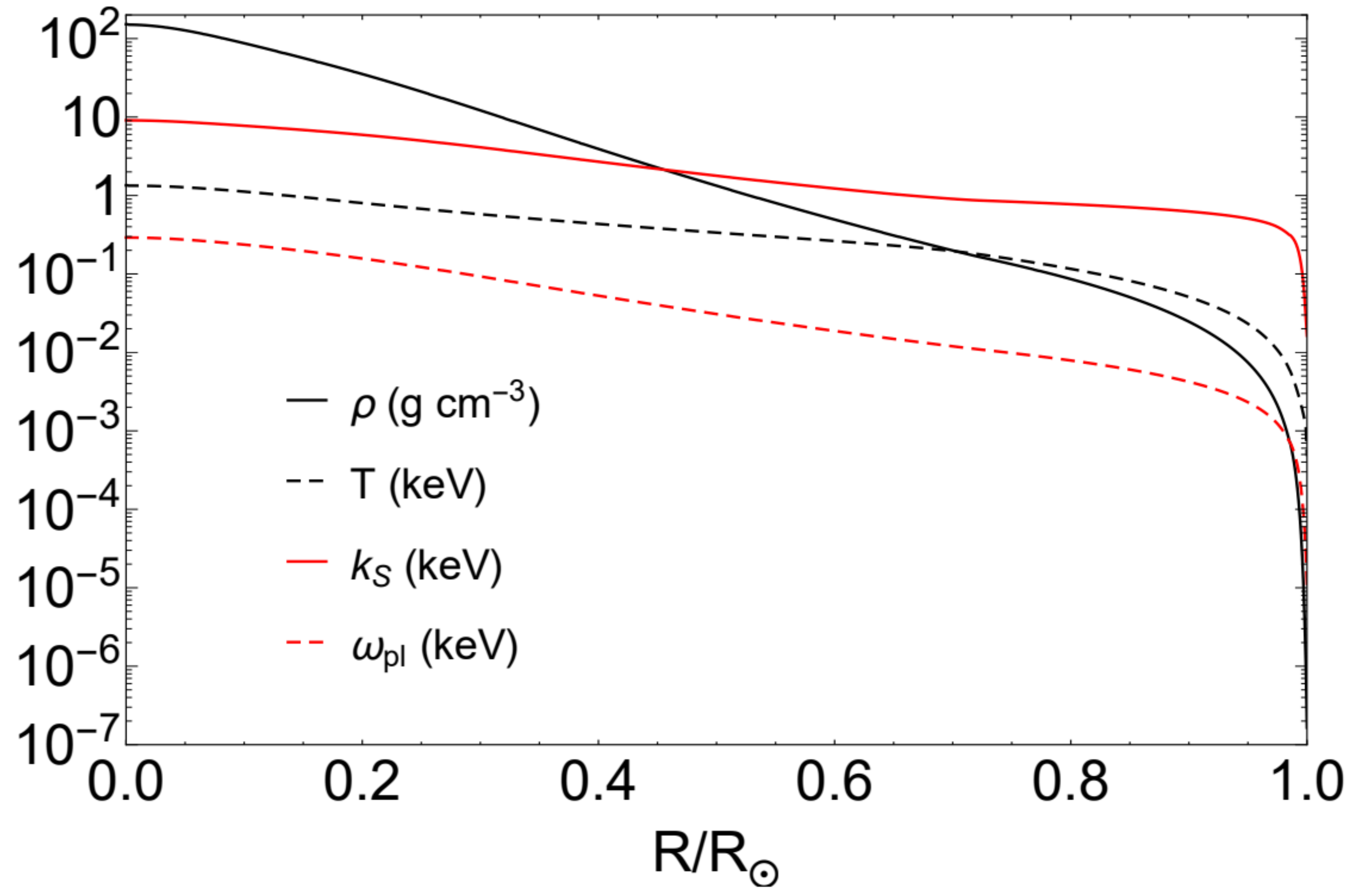
CAST limits from null detection of ALP-photon mixing in the direction of the Sun

Production of ALPs in the Sun mainly by **Primakoff effect** $\gamma + Ze \to Ze + a$

Hp: **ALP-photon coupling** is an **environment-dependent quantity**

Jaeckel+ PRD'07

$$g_{a\gamma} \to g_{a\gamma}(\eta) \qquad \eta = \omega_{pl}, T, \kappa_s^2, \rho, q^2, \ldots \qquad g_{a\gamma}(r, r_c) = g_{\rm PSR}\,\theta(r - r_c)$$



Radial profile of environmental parameters in the Sun

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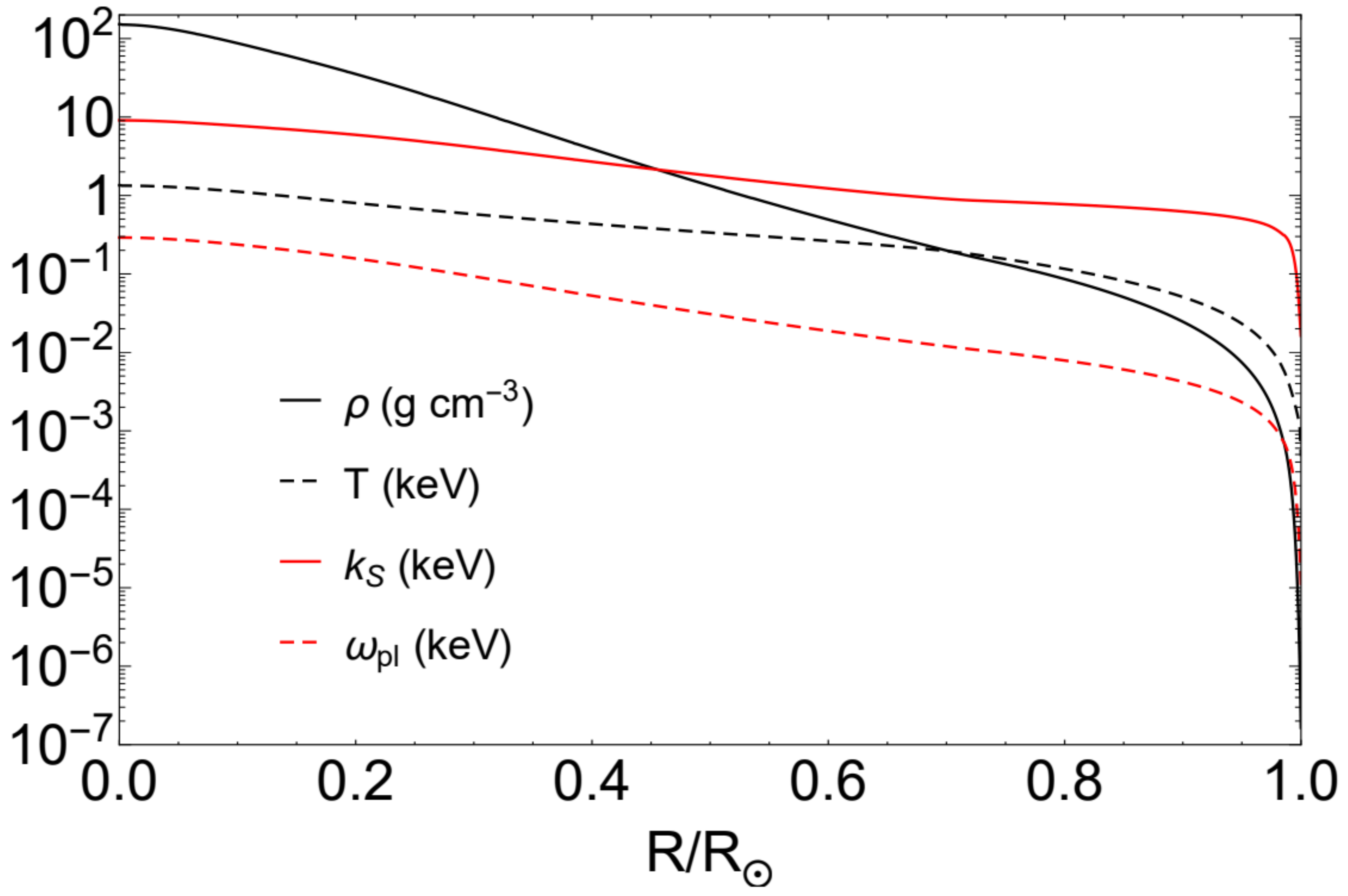

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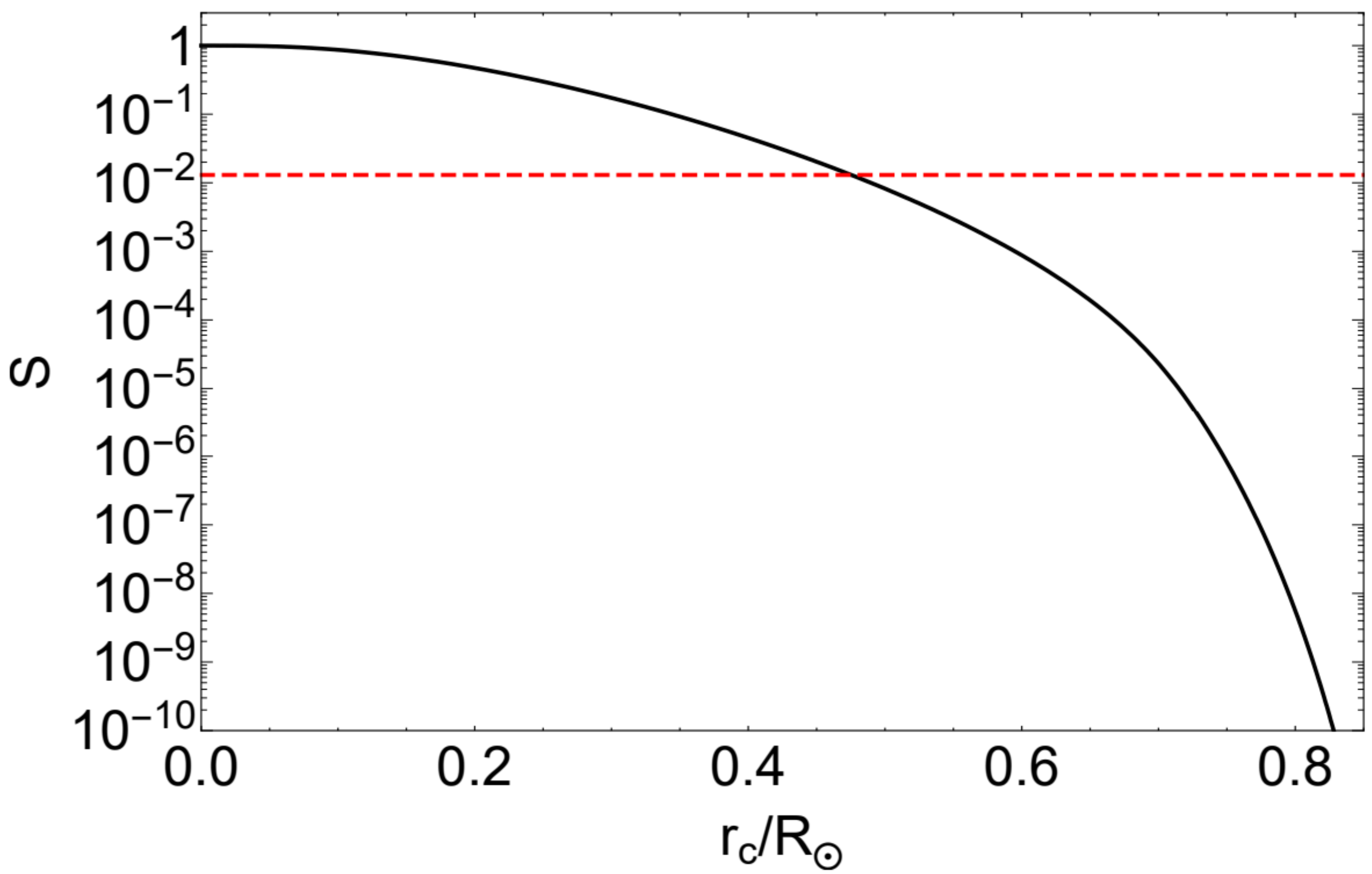

Radial profile of production flux suppression factor

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Adamane Pallathadka, FC+ 2008.08100

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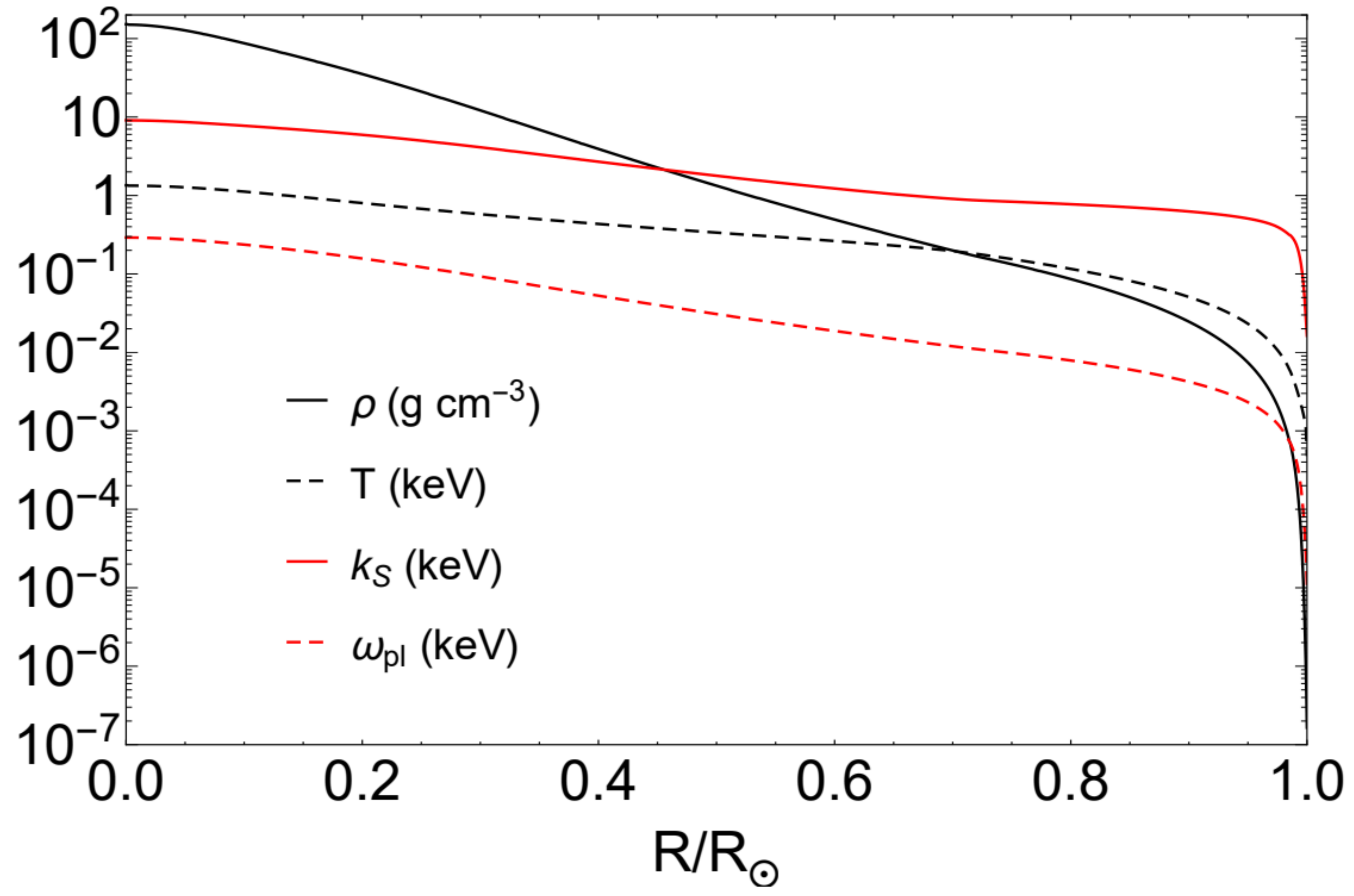

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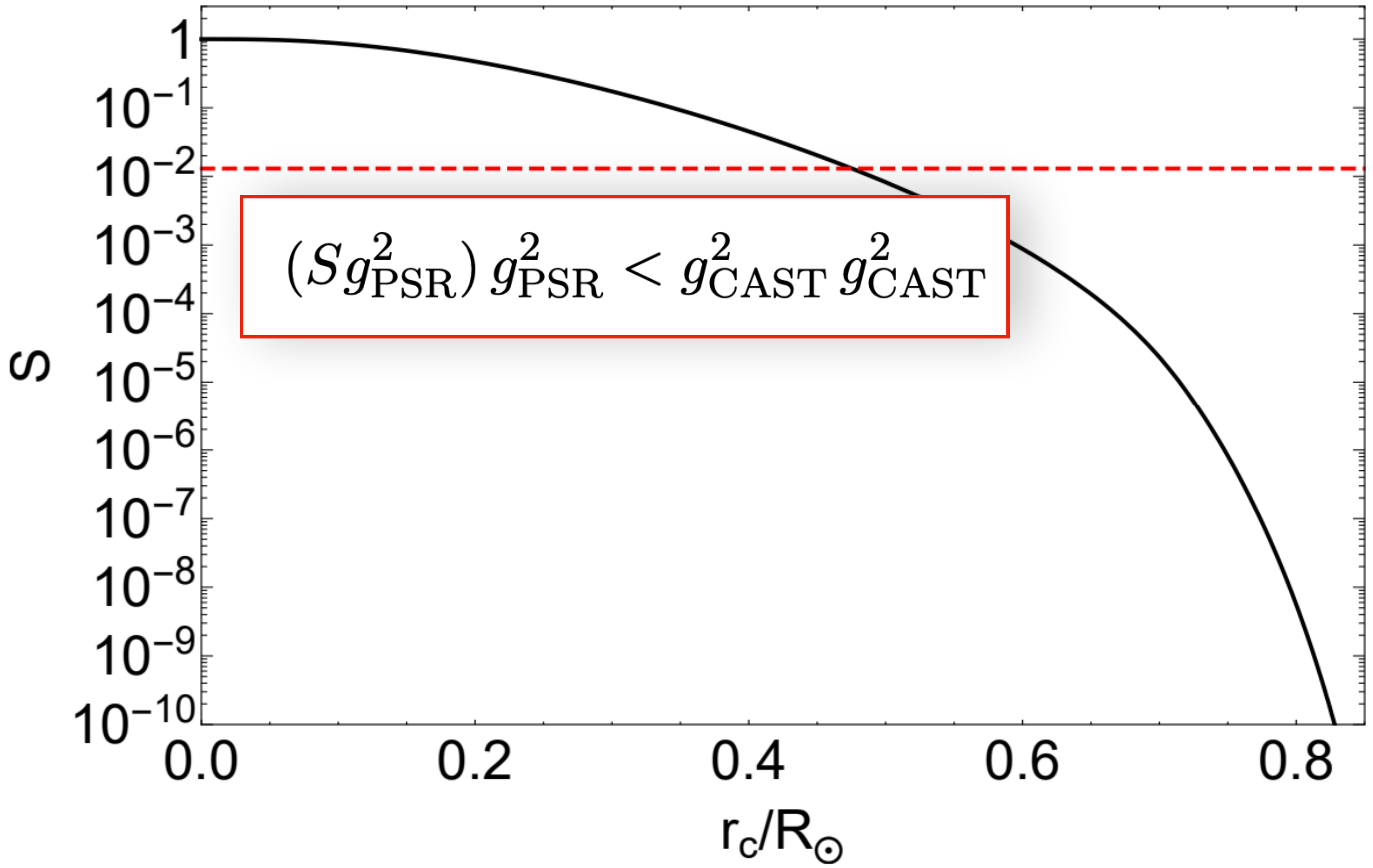

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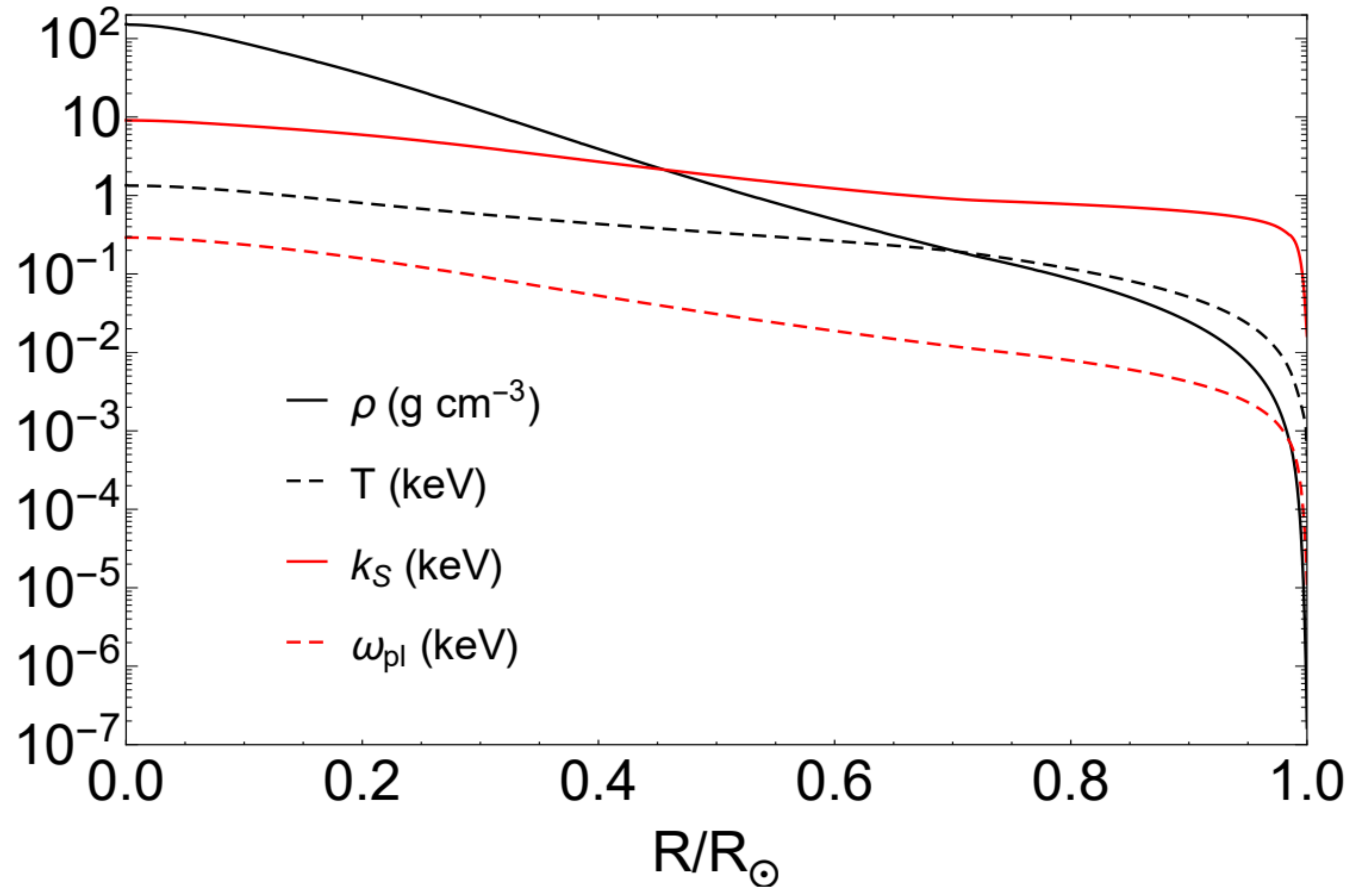

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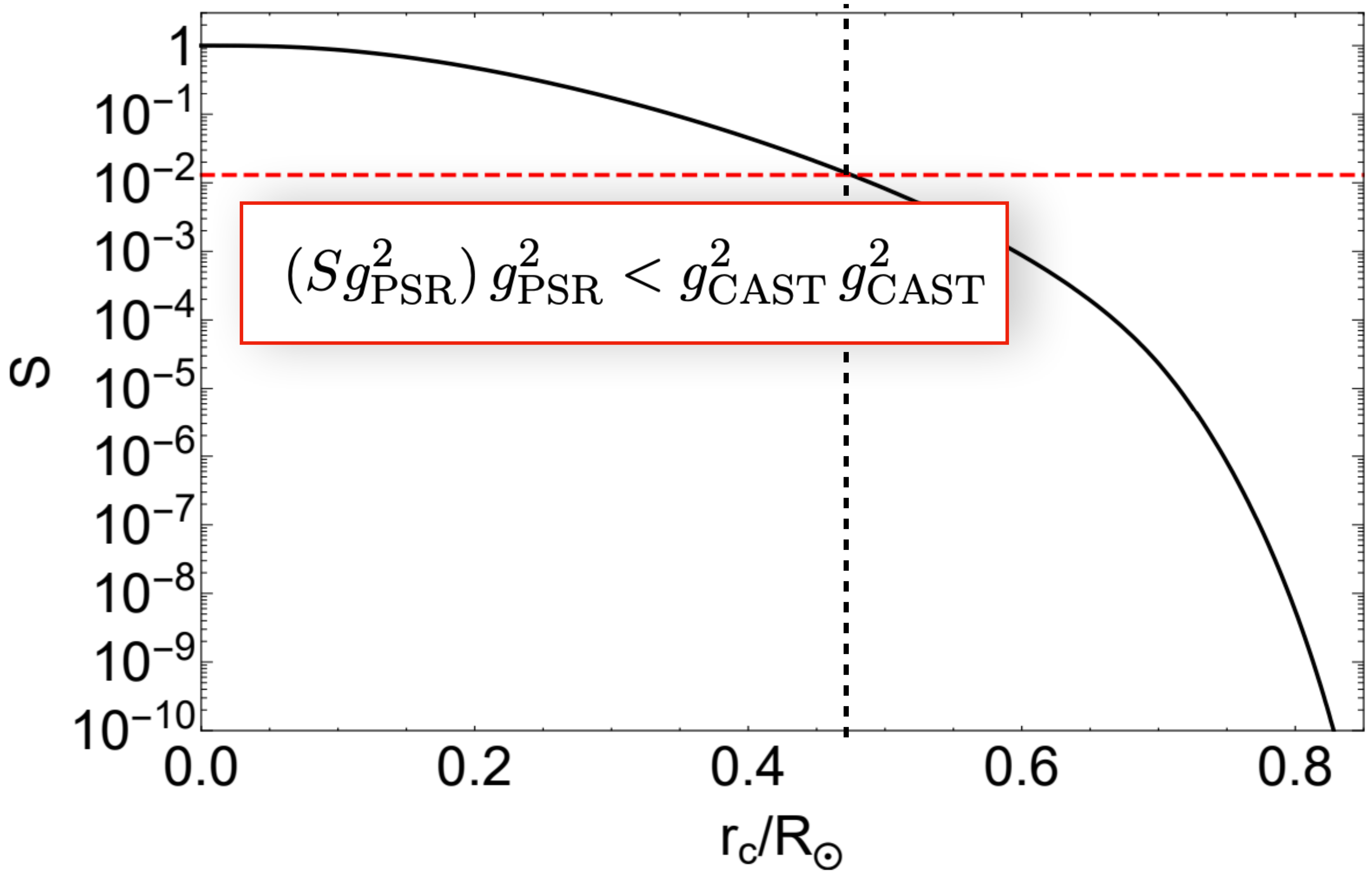

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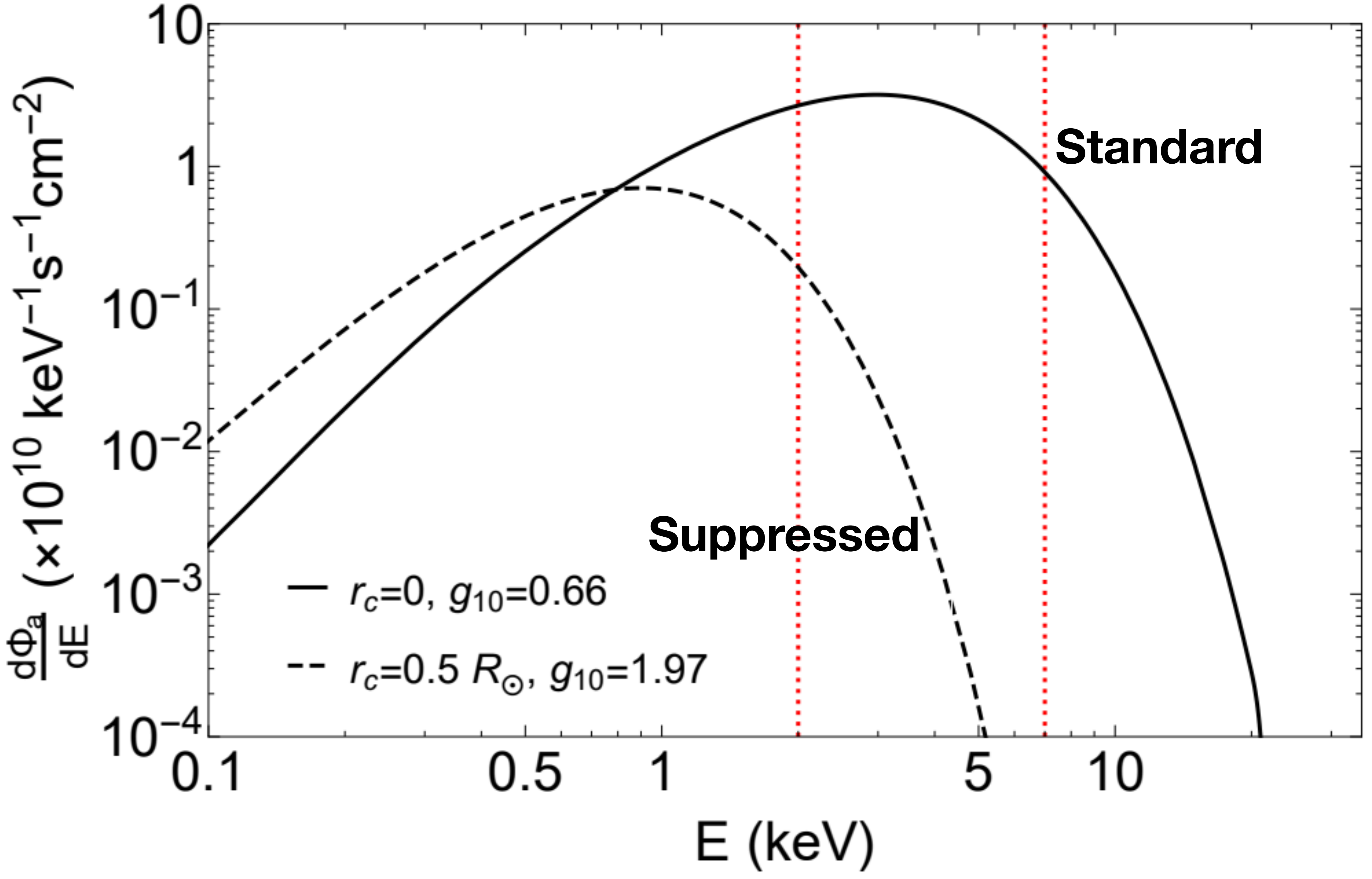
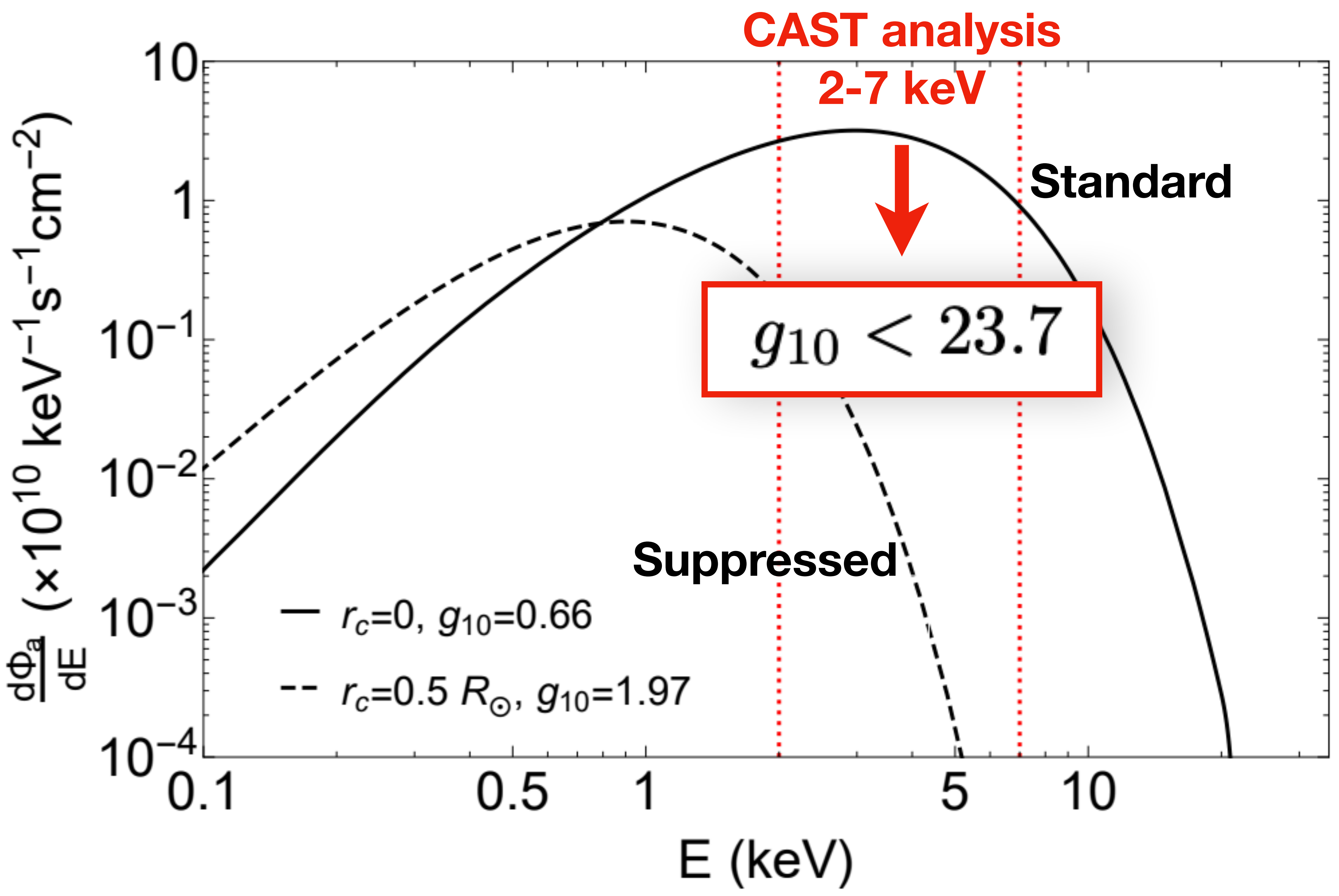


The ALP flux with an environmental dependent coupling is strongly suppressed with respect to the standard case

Evading solar and stellar constraints

Adamane Pallathadka, FC+ 2008.08100



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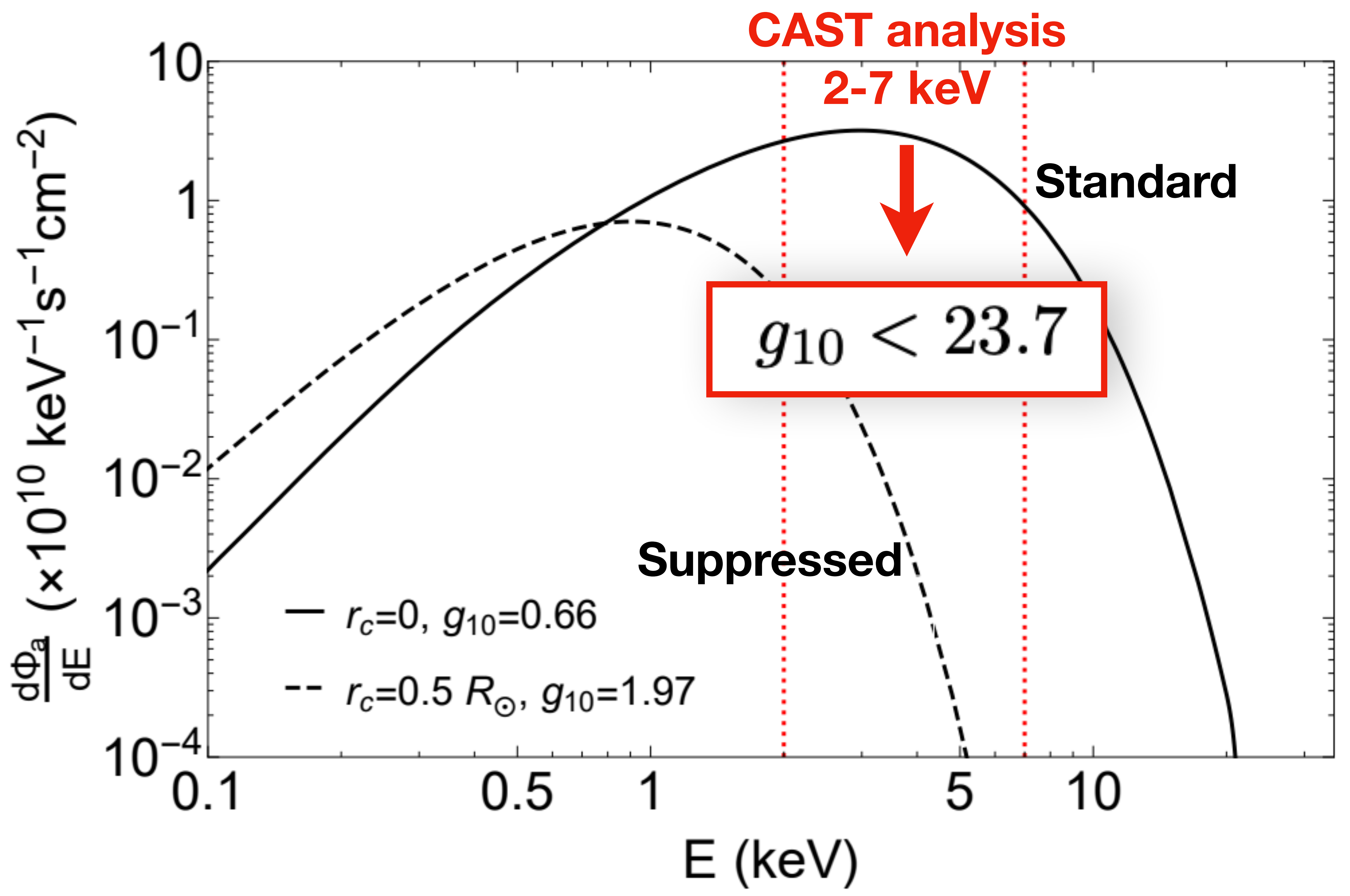

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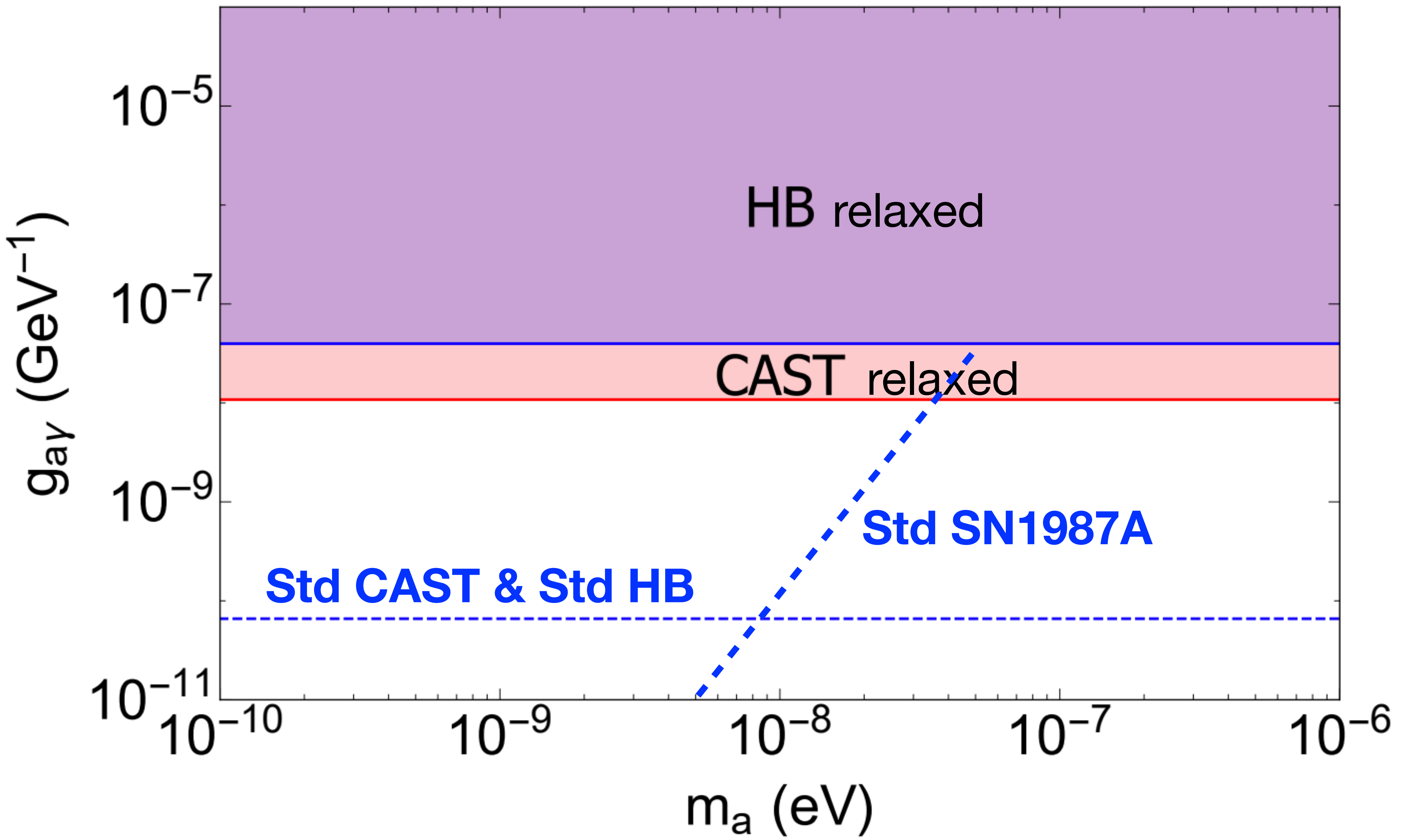

Same argument can be applied to bounds from HB-to-RGB stars and SN1987A

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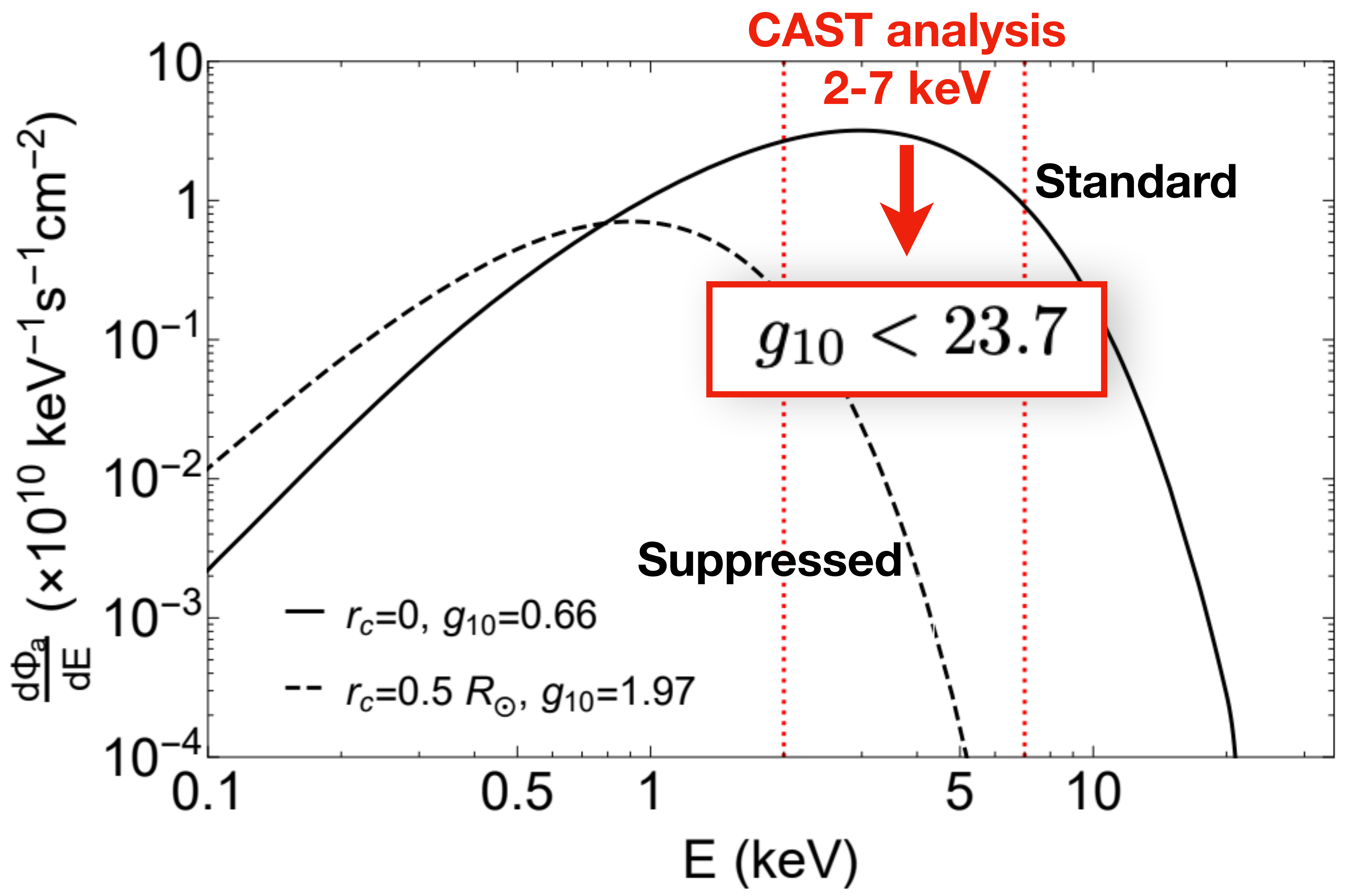

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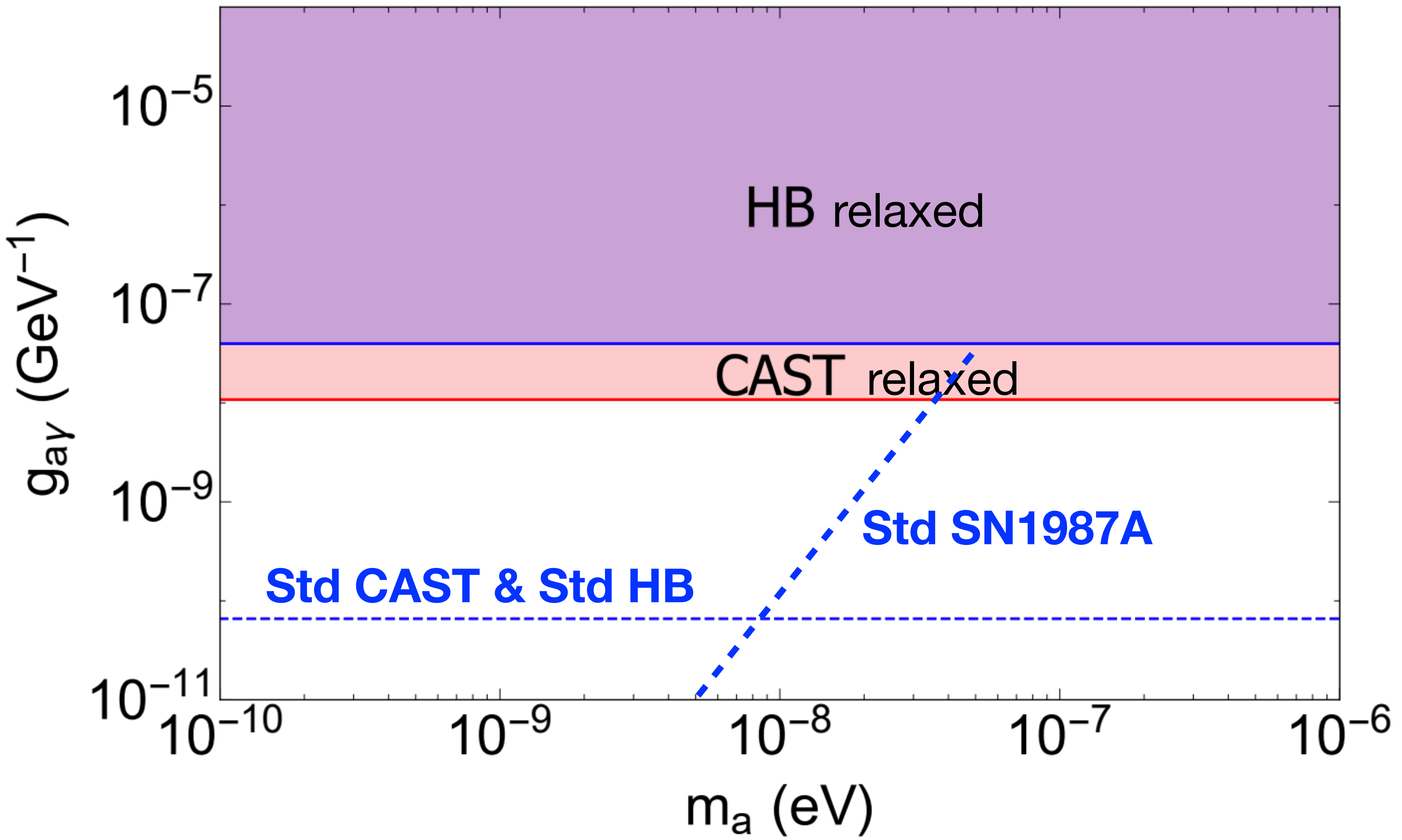

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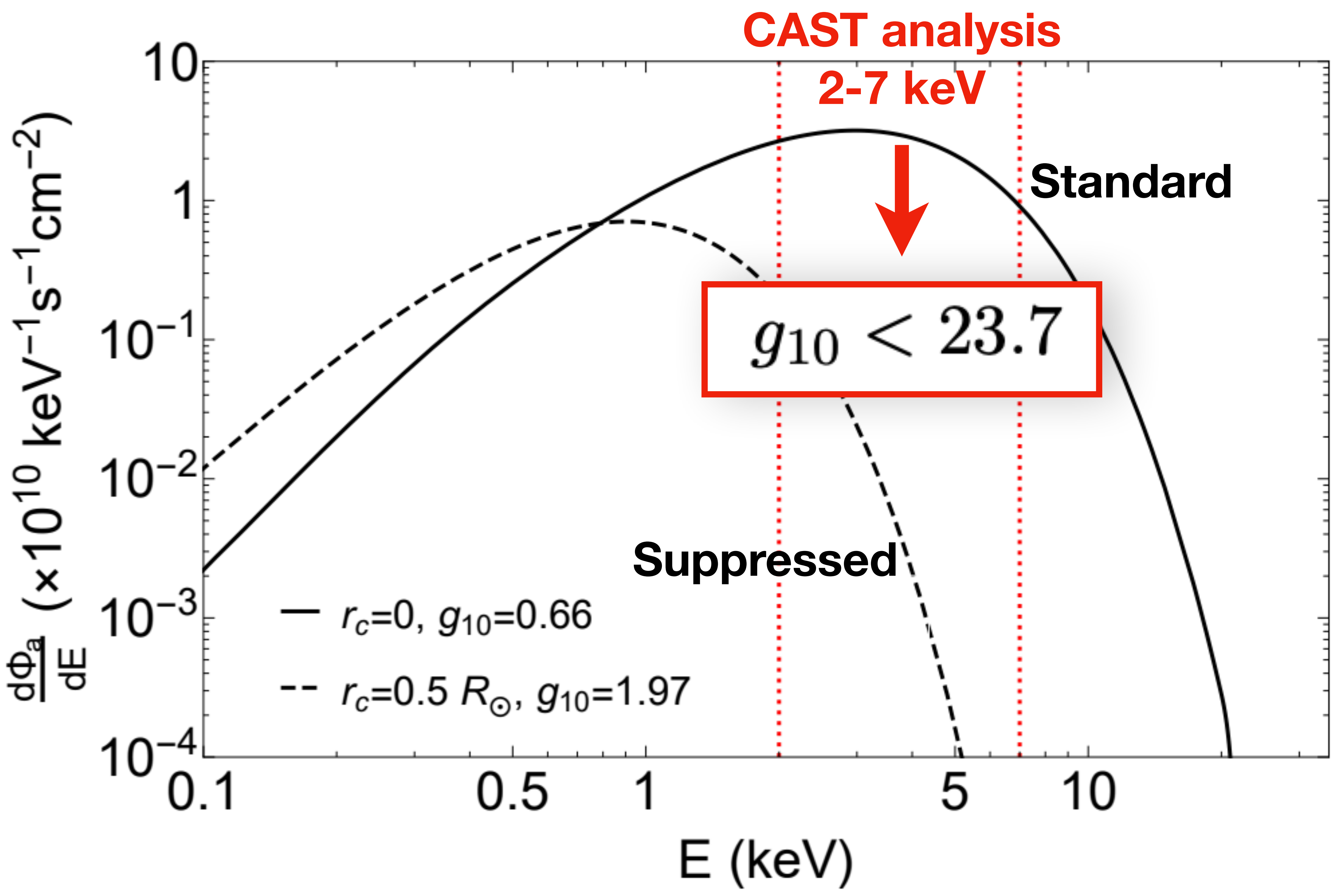
Spectacular signal rate in the pure laboratory experiment ALPS II

Evading solar and stellar constraints

Adamane Pallathadka, FC+ 2008.08100



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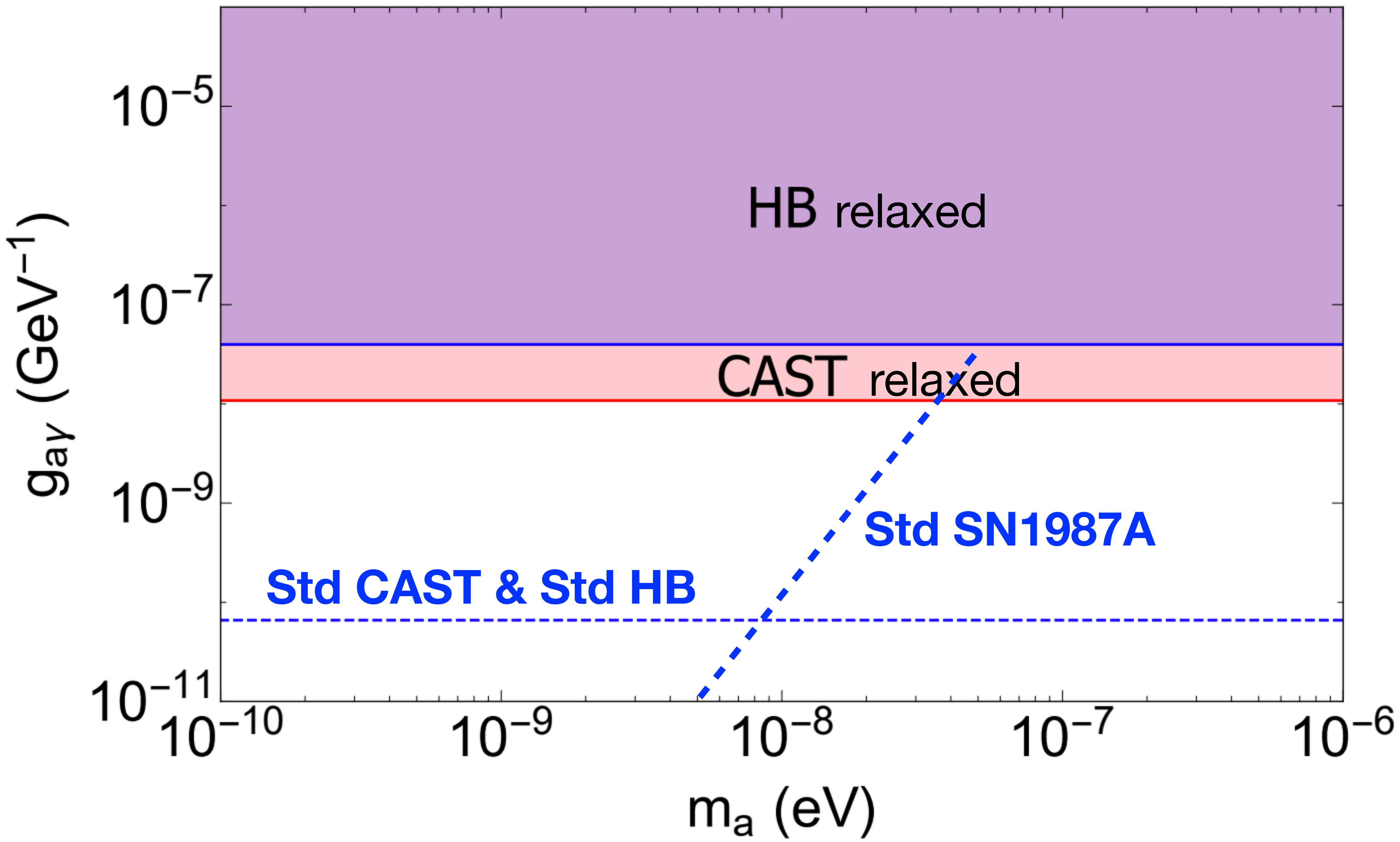

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Spectacular signal rate in the pure laboratory experiment ALPS II

[Axion mediated dark-photon mixing can also explain oscillations and the re-casted limits do not exclude the best-fit region]

Choi+ PRD'20

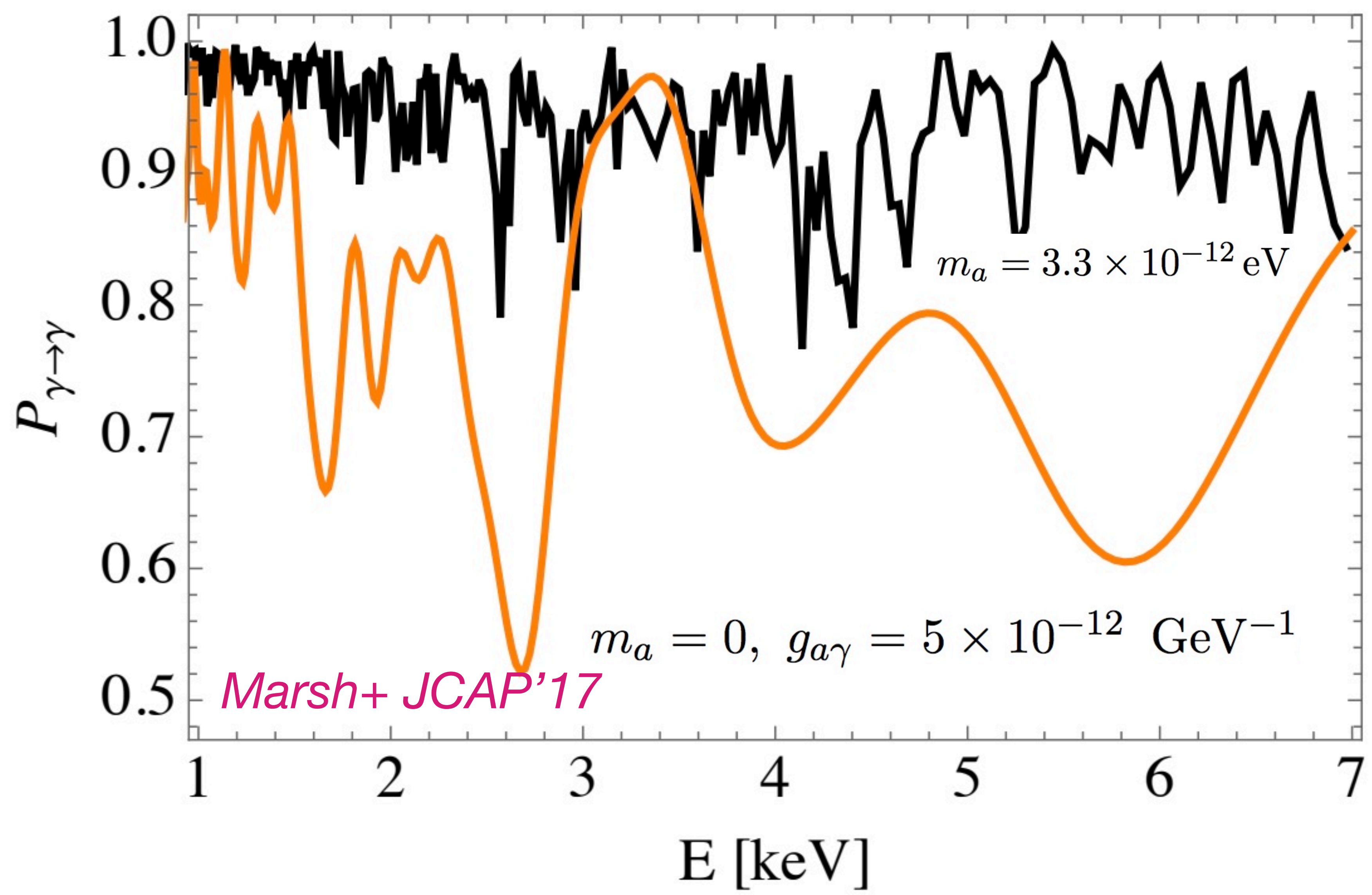
Searches for X-ray spectral irregularities

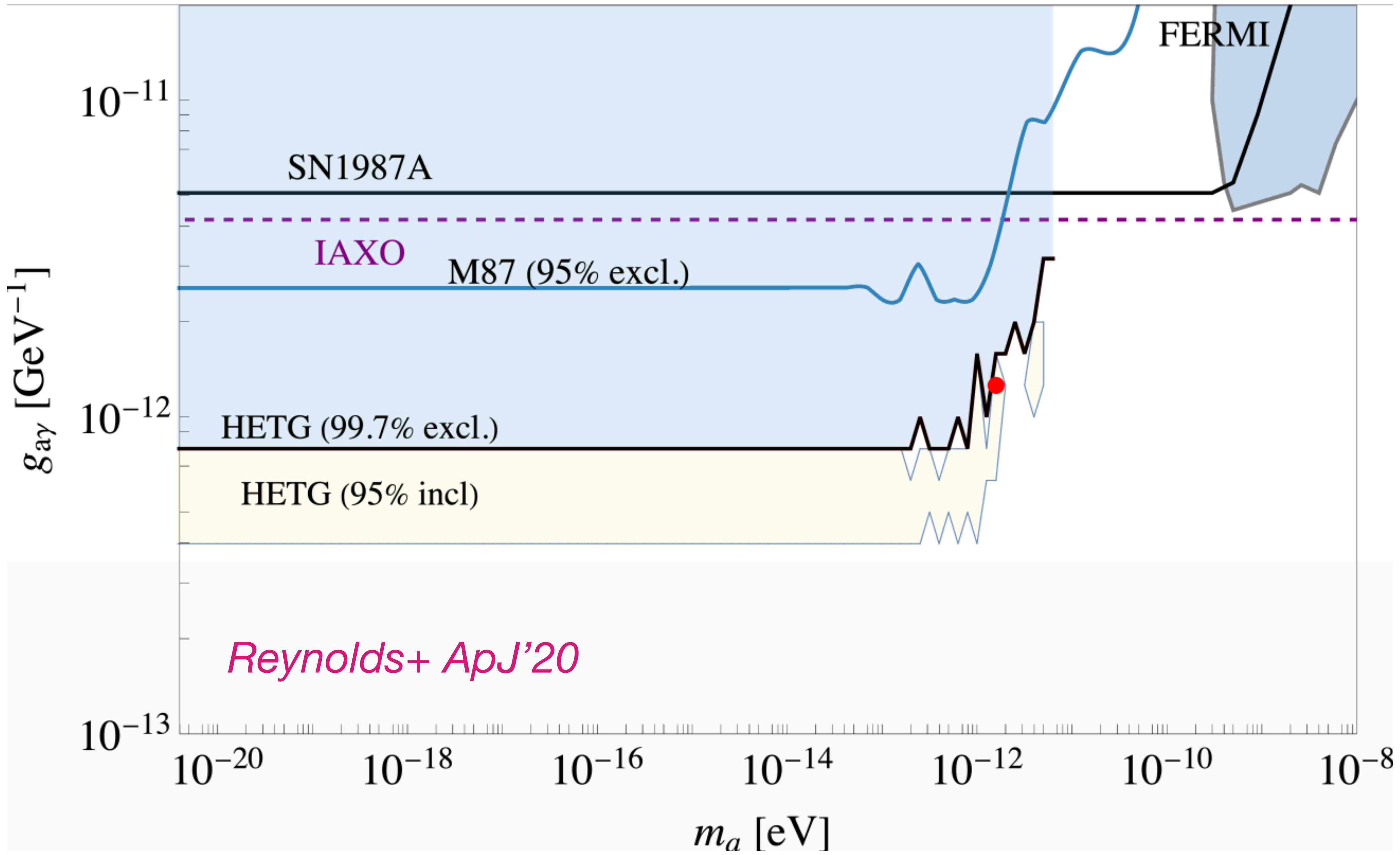
- **Hydra A galaxy cluster**: z = 0.052, 240ks *Chandra* observation *Wouters&Brun ApJ'13*
- **NGC1275** in **Perseus cluster**: *Chandra* and *XMM Newton* observations *Berg+ ApJ'17; Reynolds+ ApJ'20*
- **M87** AGN in the **Virgo cluster** *Marsh+ JCAP'17*
- **7 Quasars/AGN** behind/within **nearby clusters**: *Chandra* archival data *Conlon+ JCAP'17*

➡ All spectra consistent with absorbed power laws

➡ X rays strong emission in low-mass regime **$m_a \sim 10^{-12}$eV**, where the ALP mass is below the plasma frequency of galaxy clusters

[See also: *Schlederer&Sigl JCAP'16; Conlon+PRD'16*]





Searches for gamma-ray core collapse SNe

Production of ALPs in the SNe mainly by **Primakoff effect** $\gamma + Ze \rightarrow Ze + a$

ALPs produced in **O(10) sec bursts**, with an energy spectrum peaked at **60-100 MeV**

➡ Specific **time dependent** and **spectral** signatures

➡ 3% chance to see a Galactic SN with the LAT over 5 years

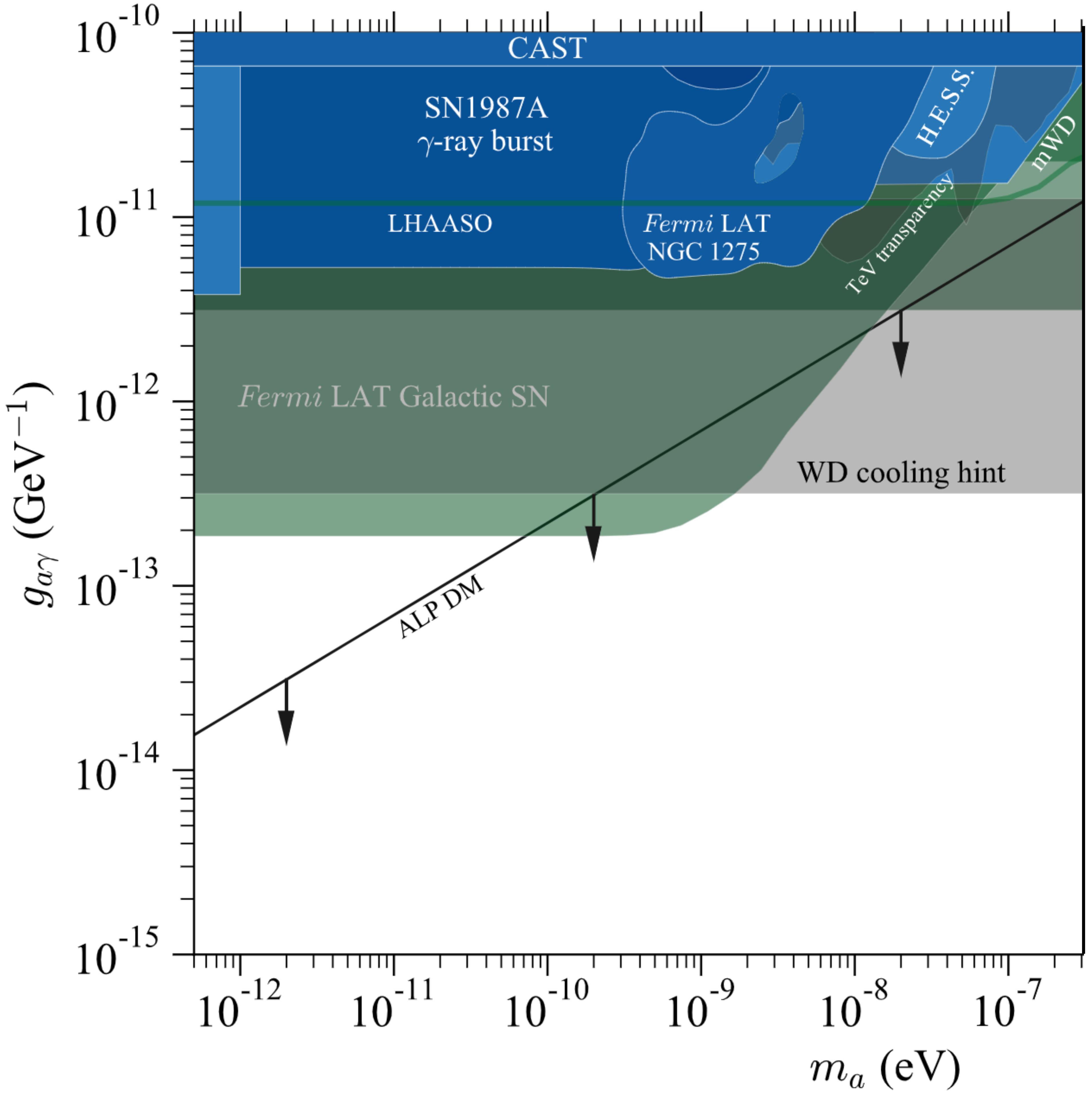
- **SN1987A**: Lack of gamma-ray burst in the Gamma-Ray Spectrometer (GRS) of the Solar Maximum Mission (SMM)

$$g_{a\gamma} \lesssim 5.3 \times 10^{-12}\ \mathrm{GeV}^{-1}, \quad \text{for} \quad m_a \lesssim 4.4 \times 10^{-10}\ \mathrm{eV}$$

Payez+ JCAP'14

- **Future Fermi-LAT Galactic SN**: Projected constraints from observation of short gamma-ray burst from SN explosion with the LAT

Meyer+ PRL'17



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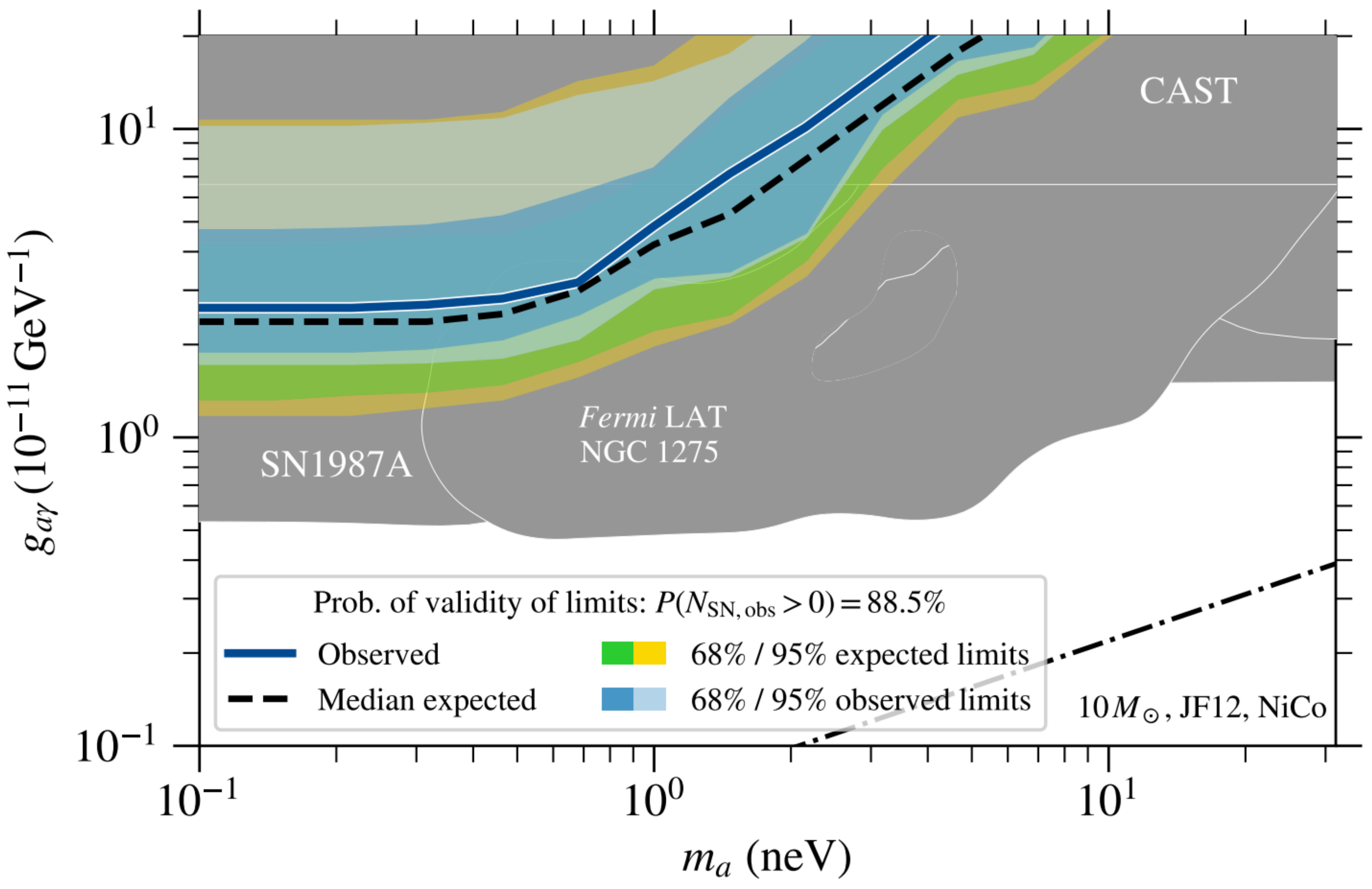
- **Extragalactic SNe**: Search for gamma-ray burst at the time and direction of 20 optically characterised SNe

Meyer & Petrushevska PRL'20



Searches for gamma-ray core collapse SNe

The diffuse SN ALP background (DSNALPB)

FC+ 2008.11741

- The cumulative **axion** emission from past core-collapse SNe in the Universe would lead to a diffuse axion flux comparable with that of neutrinos ⟶ Gamma-ray signal suppressed by Galactic conversion *Raffelt+ PRD'11*
- The same cumulative contribution can be considered for **ALP production in SNe** ⟶ Significant regions in the parameter space where we can have a large ALP production and sizeable photon conversions

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Production of ALPs in the SNe

ALP-photon coupling

Primakoff production $\gamma + Ze \to Ze + a$

ALP-electron coupling

Electron bremsstrahlung $e + Ze \to Ze + e + a$

Photo-production (Compton) $\gamma + e \to e + a$

ALP-nucleon coupling

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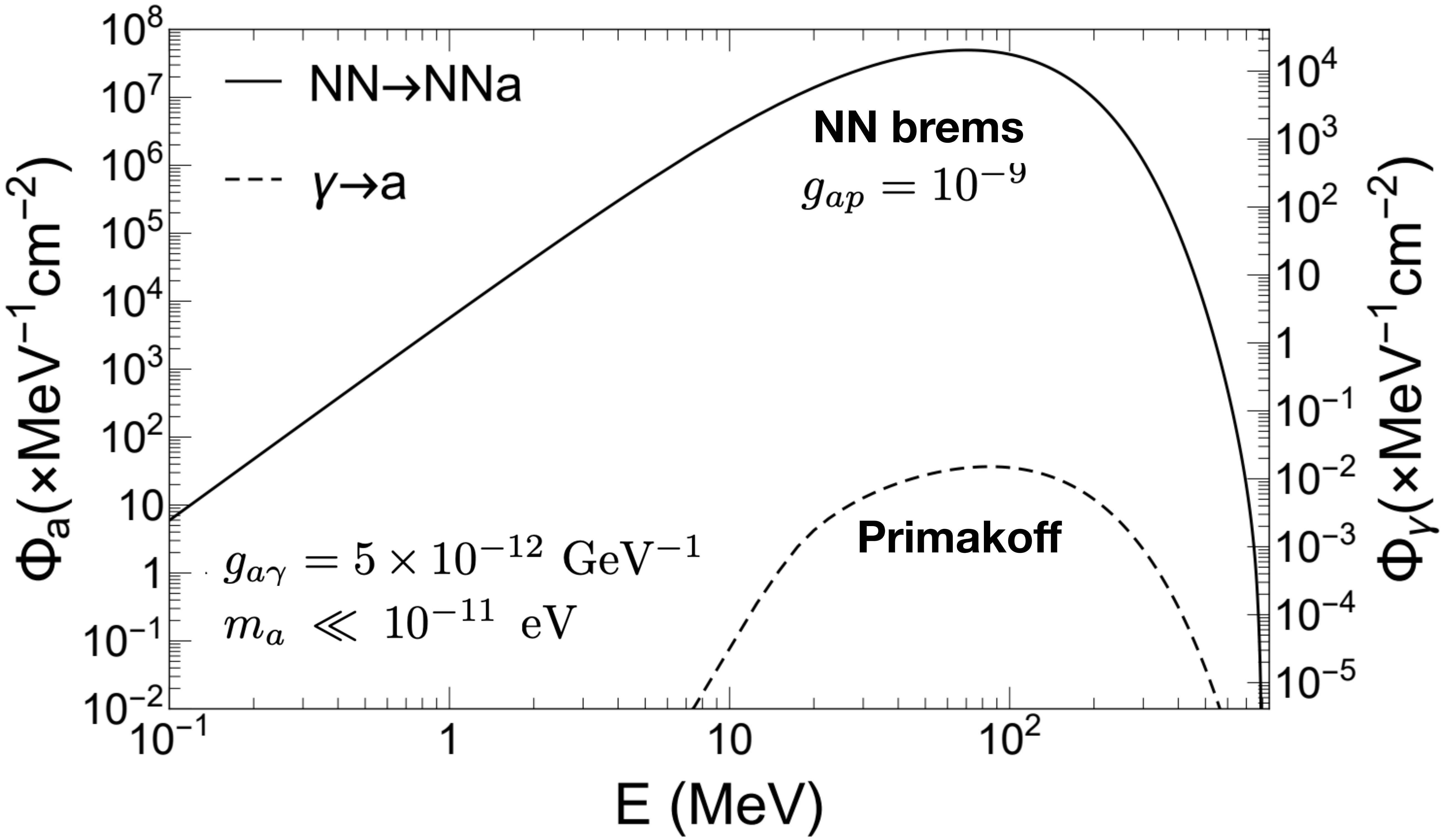
NN bremsstrahlung $N_1 + N_2 \longrightarrow N_3 + N_4 + a$

$g_{ap} < 0.9 \times 10^{-9}$, $g_{an} < 0.8 \times 10^{-9}$ ⟶ Copious ALPs production

Searches for gamma-ray core collapse SNe

ALPs production and gamma-ray flux



ALPs flux at Earth and gamma-ray flux for SN1987A

- NN brems. enhances the ALPs production and final gamma-ray flux
- Gamma-ray spectrum peaked @ 100 MeV, in the sensitivity range of Fermi-LAT

➡ Revisited limits from SN1987A

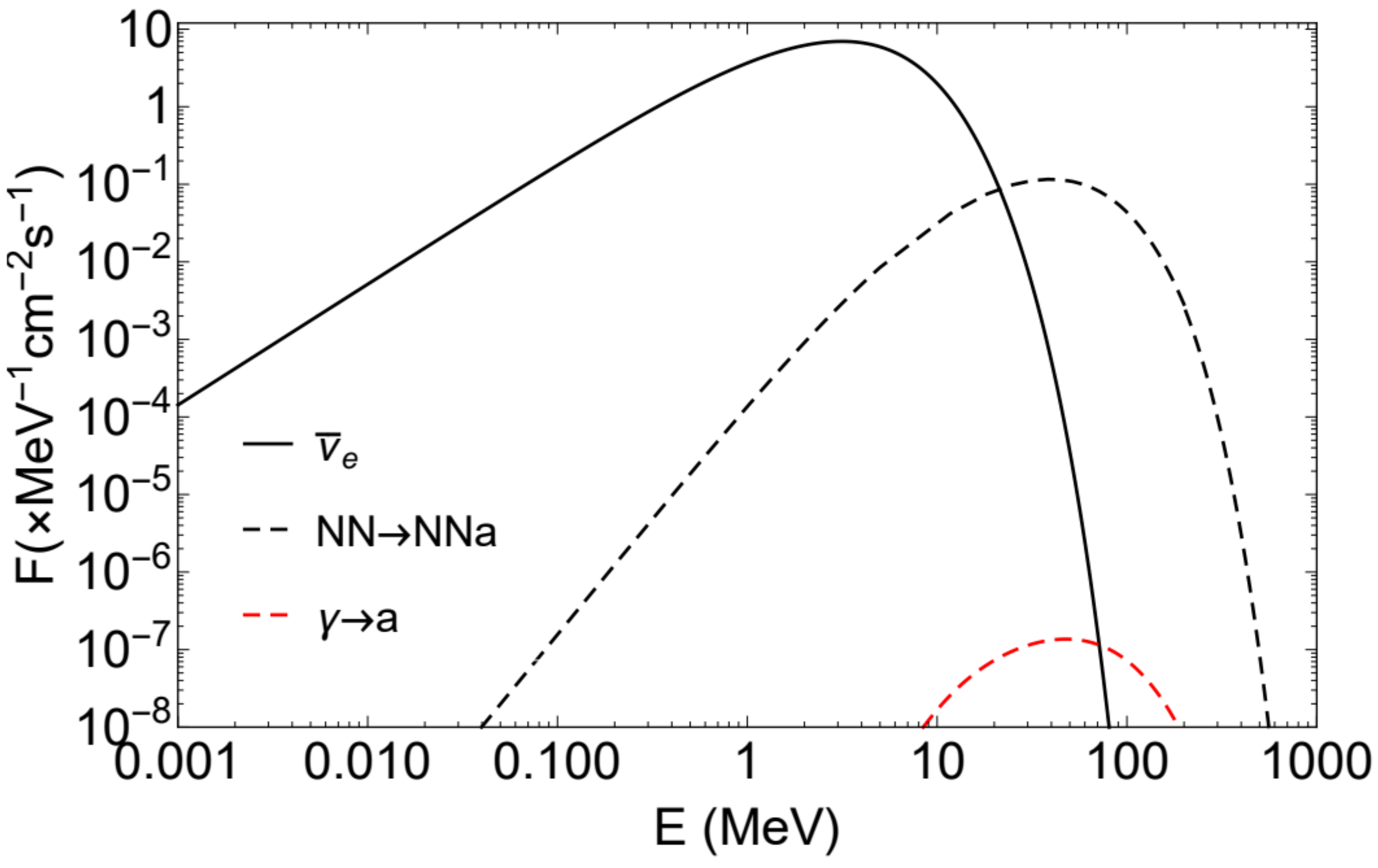
➡ New constraints from DSNALPB

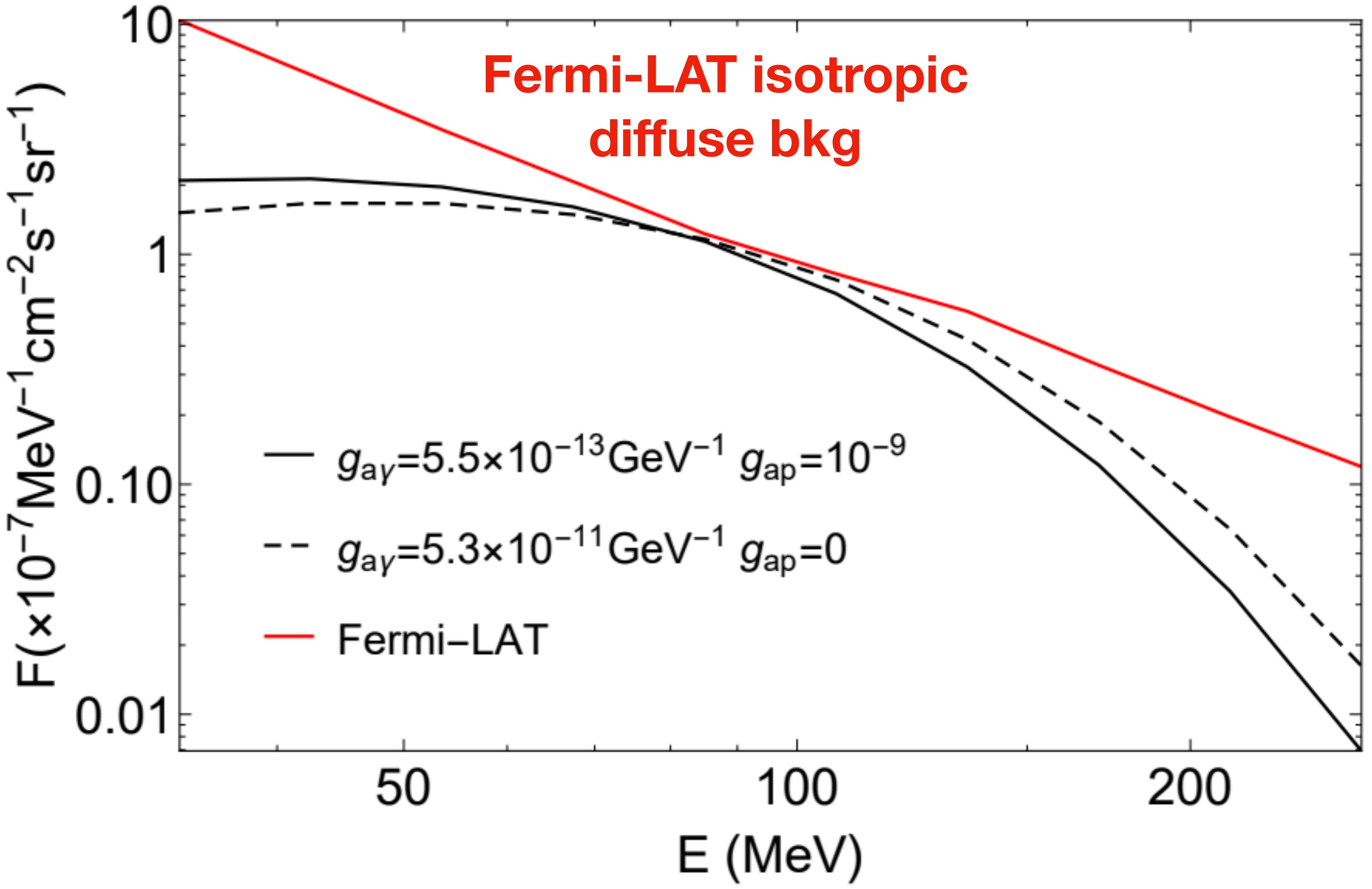
Searches for gamma-ray core collapse SNe

DSNALPB gamma-ray flux

$$\frac{d\phi_a(E_a)}{dE_a} = \int_0^\infty (1+z) \frac{dN_a(E_a(1+z))}{dE_a} [R_{SN}(z)] \left[\left| c\frac{dt}{dz} \right| dz \right]$$

Beacom, Ann. Rev. Nucl. Part. Sci.'10





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Constraints from enhanced NN brems. production

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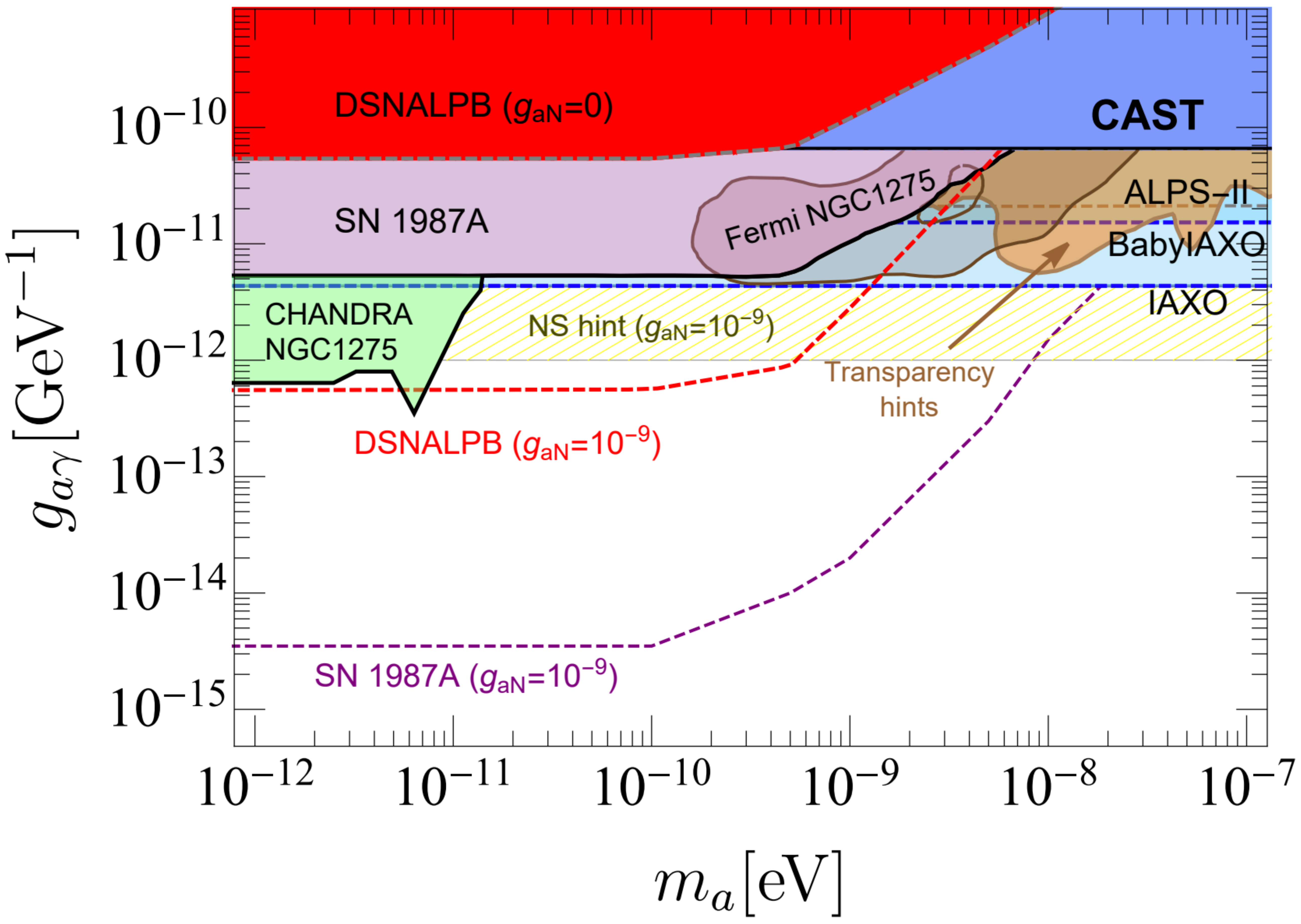

- If coupling only w/ **photons**, DSNALPB constraint:
  - ✓ Comparable with CAST
  - ✓ Less stringent than SN1987A
- If coupling w/ **nucleons**, DSNALPB constraint:
  - ✓ Competitive w/ IAXO sensitivity
  - ✓ Exclude part on the NS hint region
- If coupling w/ **nucleons**, SN1987A constraint:
  - ✓ Improves by O(10^3)

Searches for gamma-ray core collapse SNe

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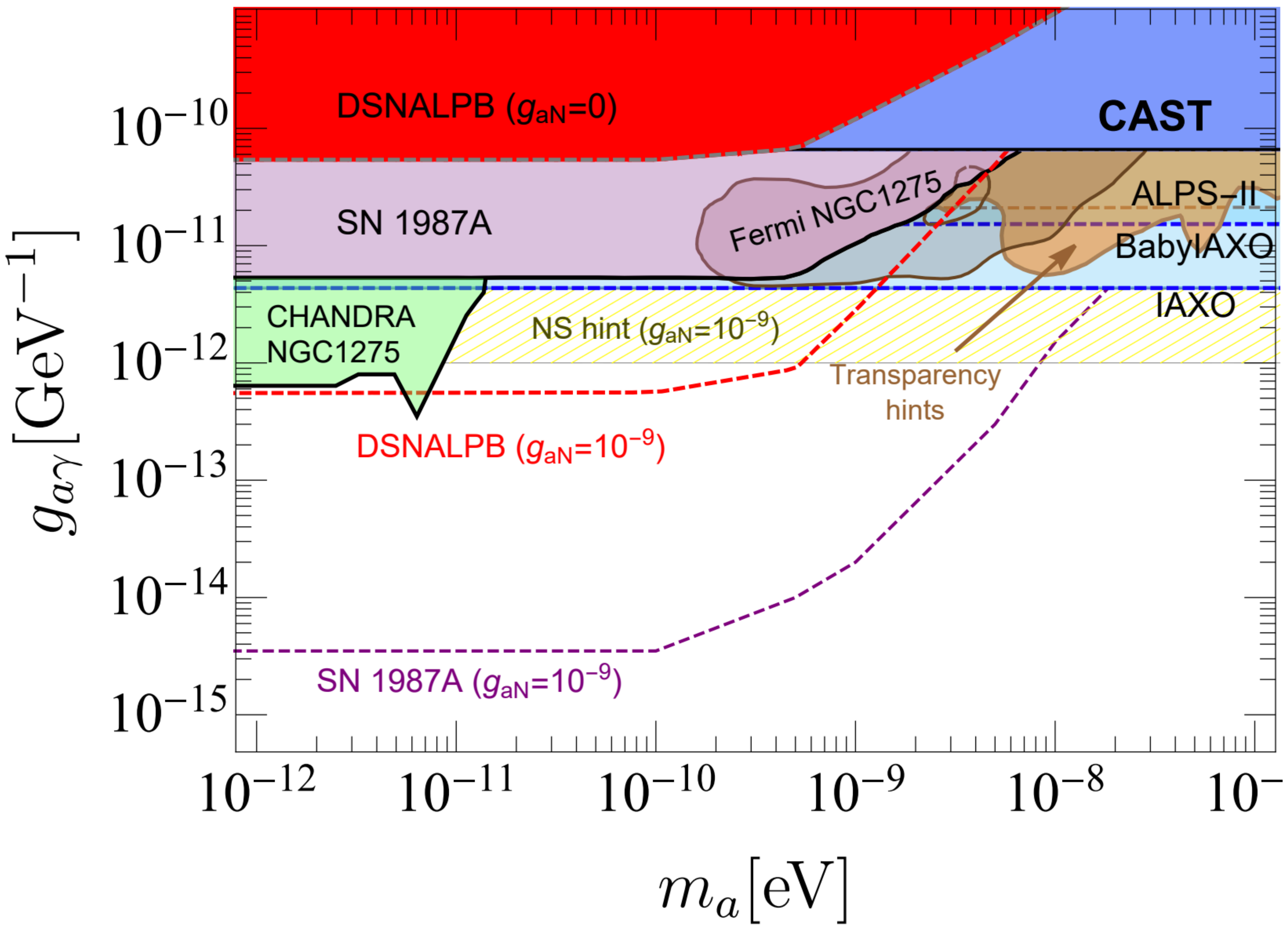
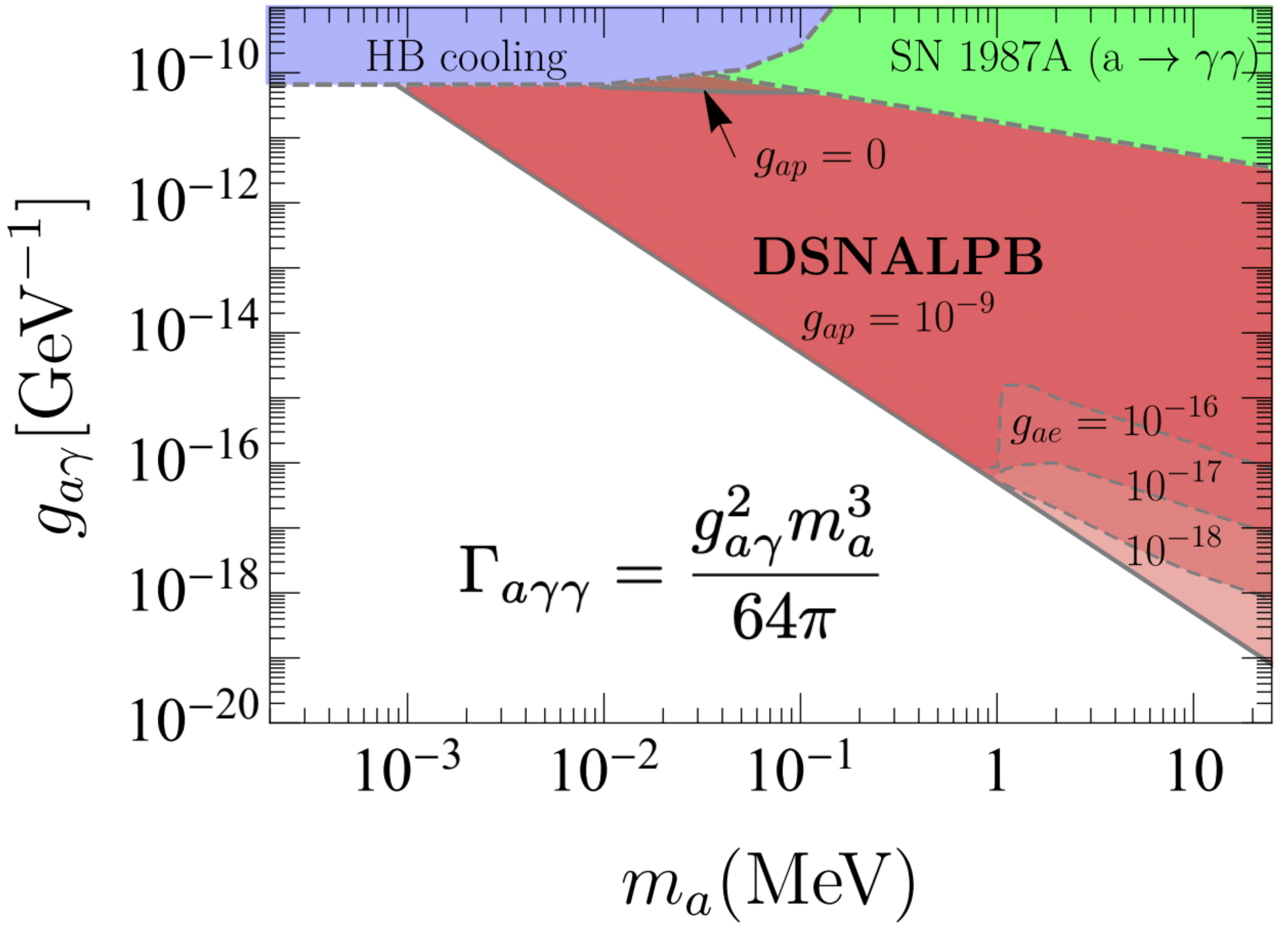


- Using COMPTEL data (< 30 MeV), strong constraints on heavy ALPs (10 - 100 keV) from gamma-ray decay



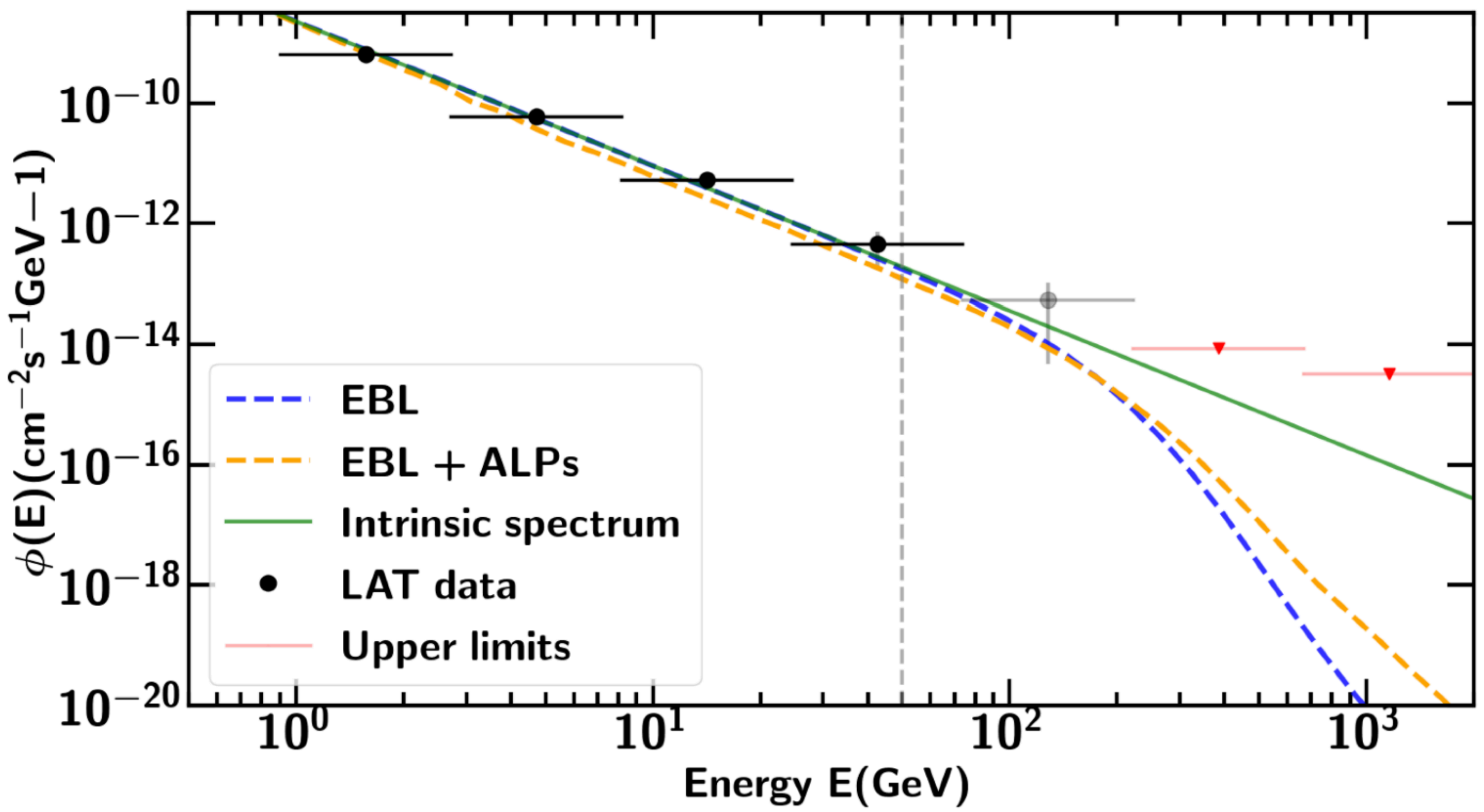
ALPs and the opacity of the Universe

- **VHE photons** from distant sources are **attenuated** by pair production onto the **Extragalactic Background Light (EBL)**

$$\phi_{obs}(E) = \phi_{int}(E) \cdot \exp\left[-\tau(E,z)\right] \qquad \tau = \frac{d}{n(E)\sigma(\gamma\gamma \to e^+e^-)}$$

- The flux of very distant sources and at very high energies should be exponentially suppressed
- In the past, indications of **anomalous cosmic trasparency** from gamma-ray studies interpreted as possible signs of ALPs *De Angelis et al. (2009,2011,2015); Essey & Kusenko (2012); Horns & Meyer (2012); Rubtsov & Troitsky (2014); etc*
- Latest data **consistent with EBL expectations**

Biteau&Williams+ApJ'15; Dominguez&Ajello ApJL'15



➡ Search for ALPs-induced anomalous EBL absorption

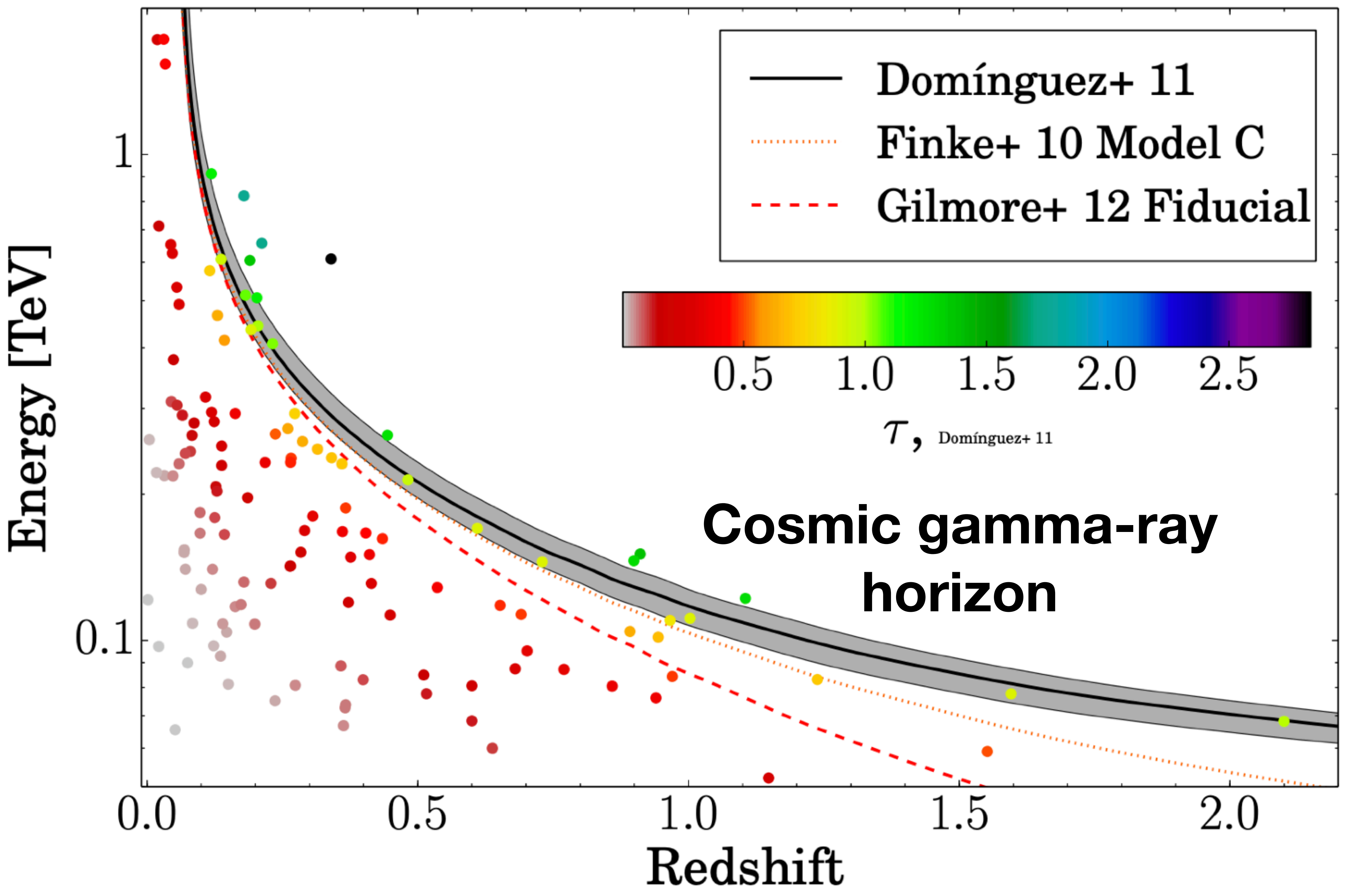
Buehler+ 2004.09396

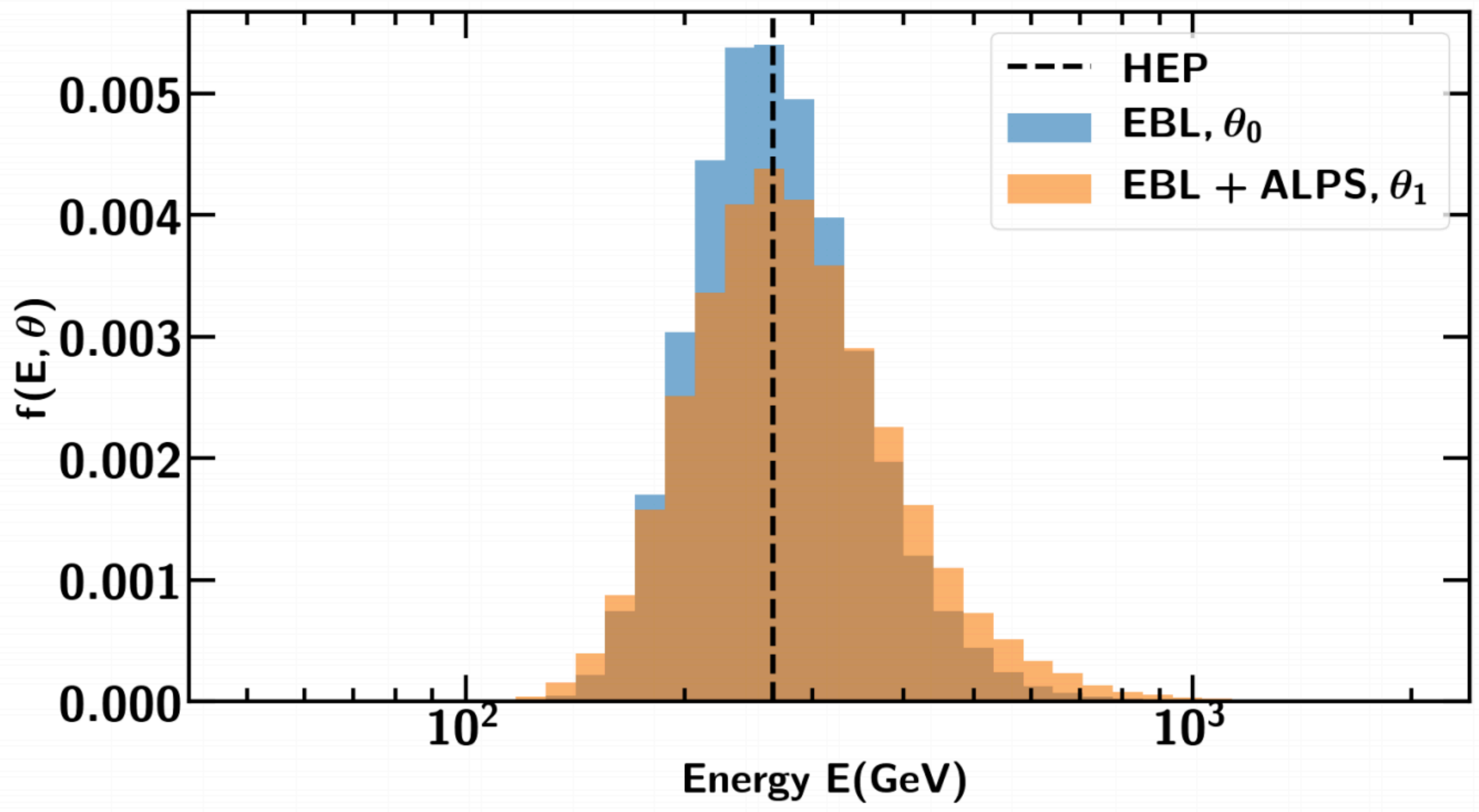
ALPs and the opacity of the Universe

Constraints from the cosmic gamma-ray horizon

Buehler+ 2004.09396

- Search for the imprint of ALPs in the **highest-energy photons** of hard gamma-ray blazars
- No evidence for an increased γ-ray transparency due to ALPs





Distribution of observed highest-energy photons ($z \geq 0.1$) vs theoretical predictions in the presence of ALPs

ALPs and the opacity of the Universe

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Buehler+ 2004.09396

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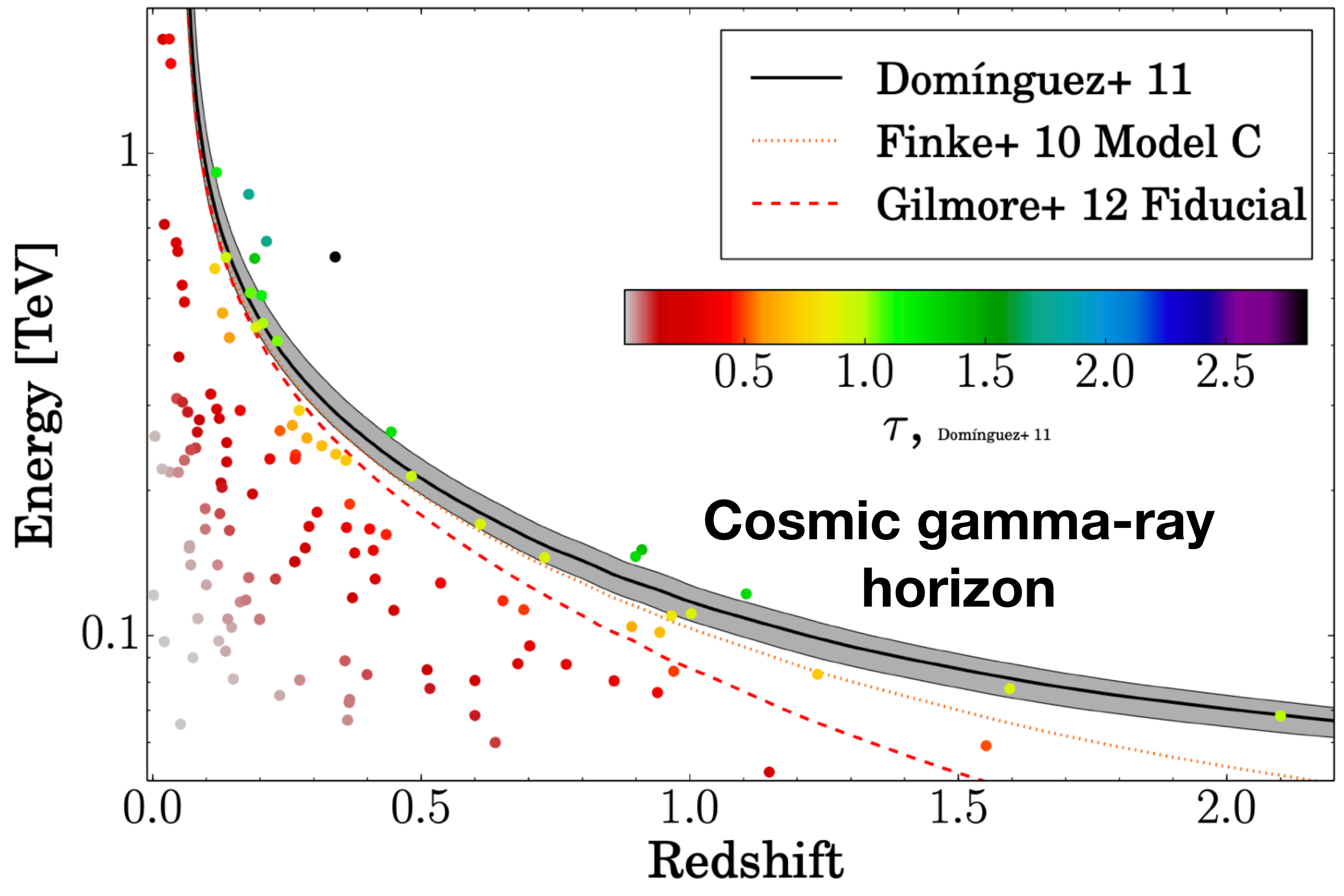
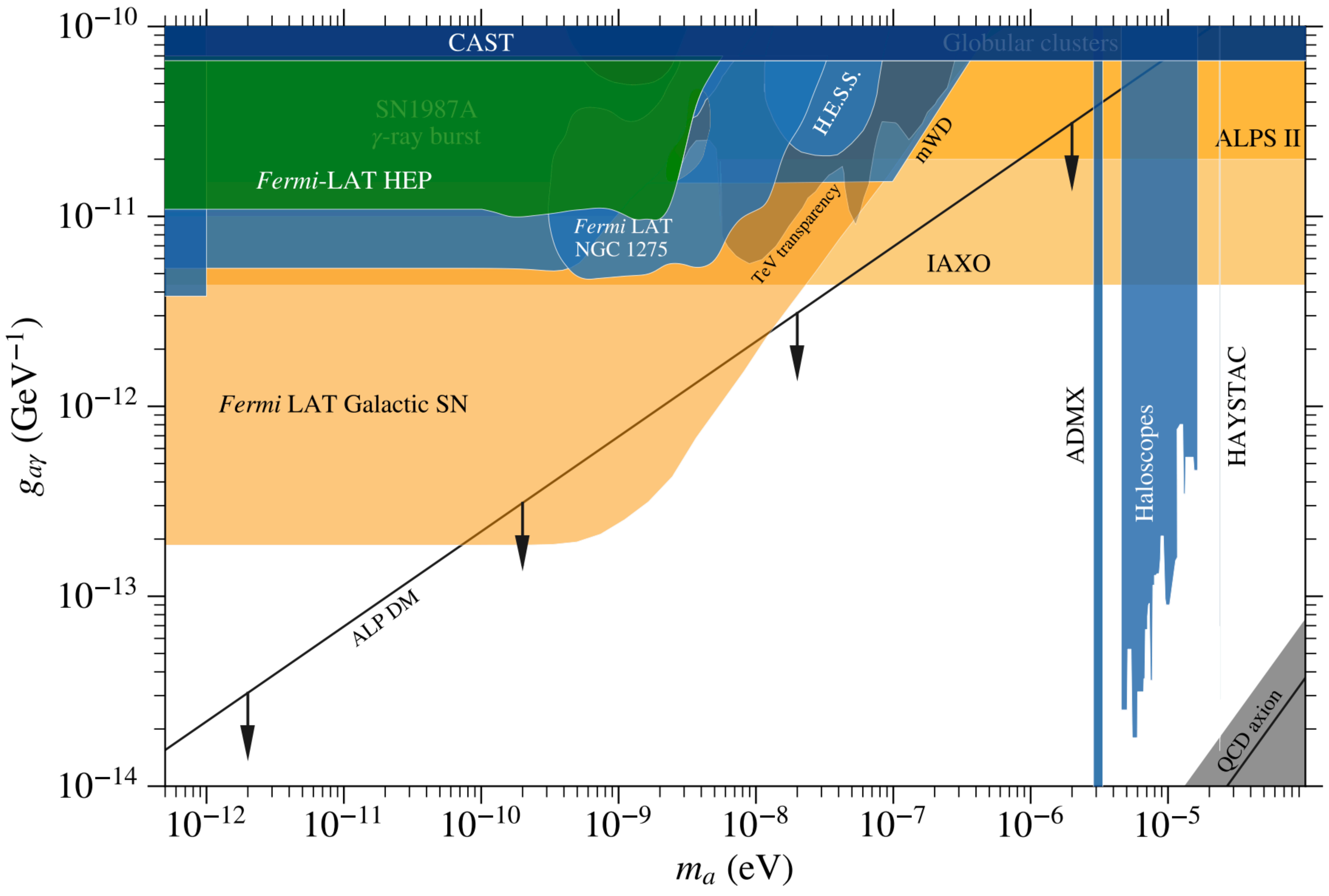
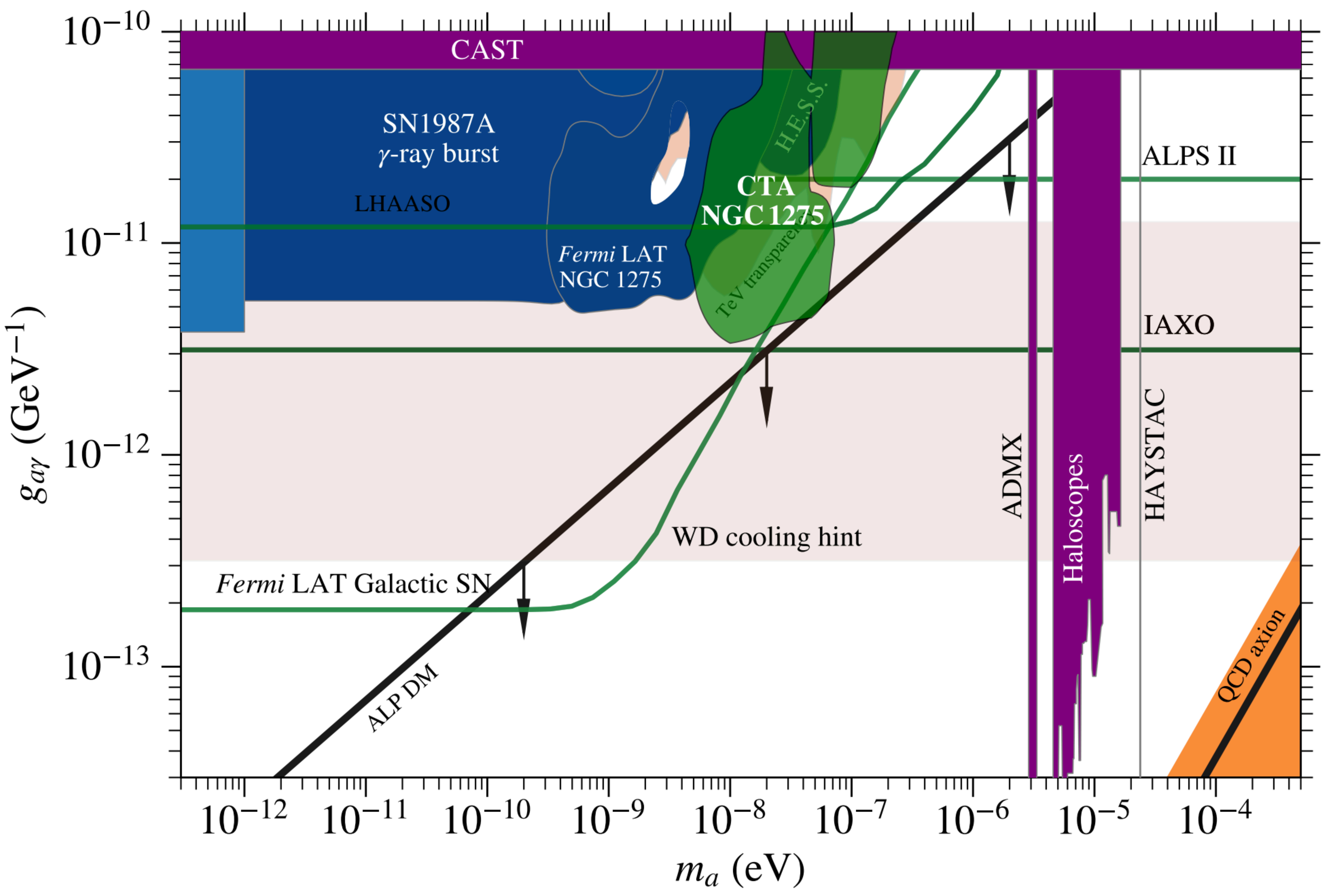




What future for gamma-ray searches?



- DSNALB, SNe and pulsars constraints would benefit by **future MeV missions**, able to **better resolve the diffuse gamma-ray background** and provide **accurate spectra in the MeV** energy range
- Galaxy clusters (e.g. NGC1275) limits would be improved by **CTA** touching ALP DM region *CTA Consortium 2010.01349*
- Search for SNe bursts opens exciting complementarity with **optical transient facilities** (**LSST**).

Radio searches for axion/ALPs DM

In strongly magnetised astrophysical objects, the axion/ALP-photon conversion (**Primakoff effect**) can lead to **monochromatic radio emission** (MHz — GHz):

(a) Resonant conversions in homogeneous magnetic fields around neutron stars

Pshirkov JETP'09; Huang+2018; Hook+PRL'18

(b) Non-resonant transitions in the vicinity of the Galactic center and/or of discrete astrophysical objects

Kelley&Quinn ApJ'17; Sigl PRD'17

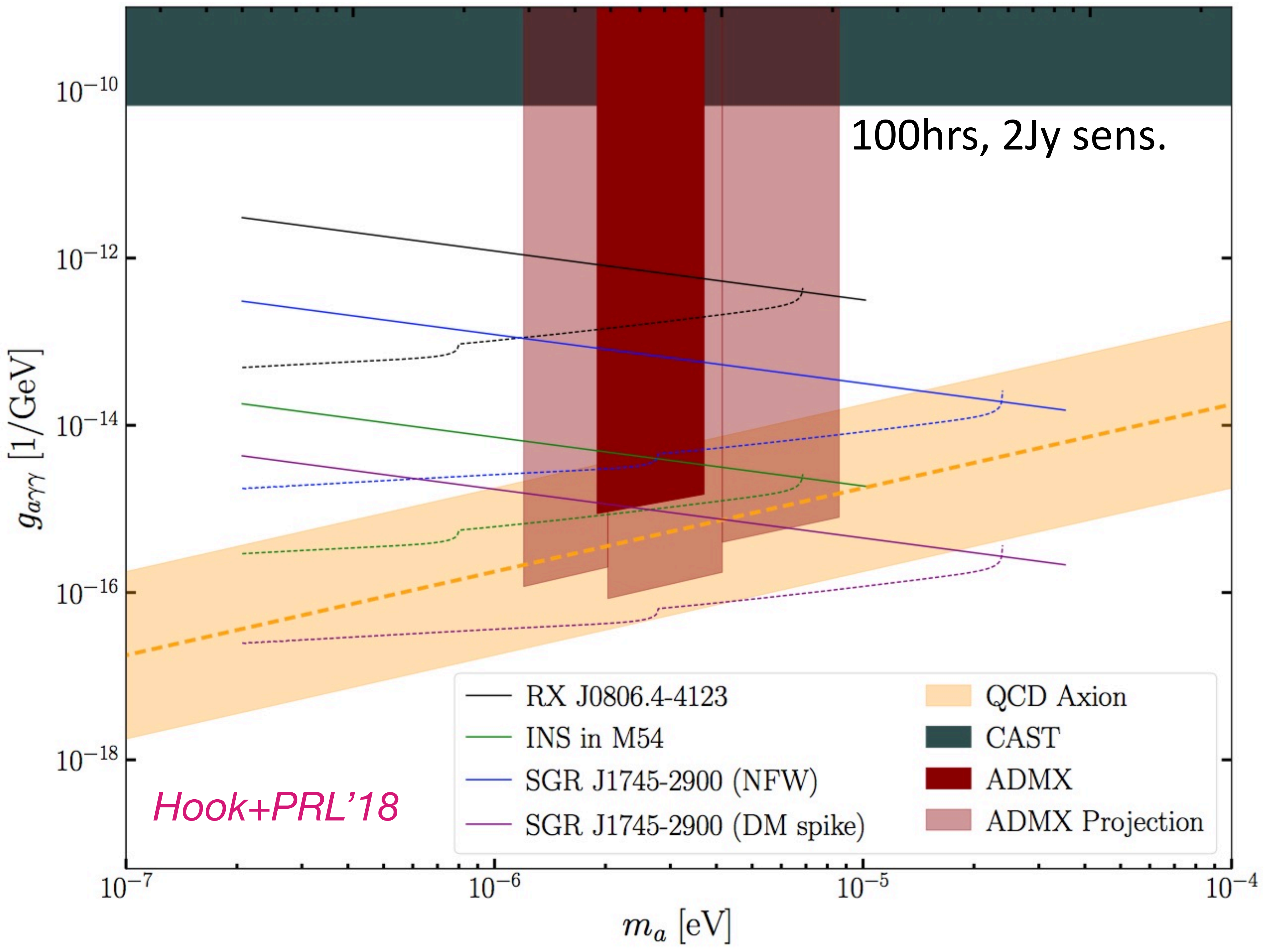
Future telescopes (LOFAR, SKA):

✓ Can probe QCD axion 0.2 - 40 μeV

Hook+ PRL'18

✓ Will be sensitive to 0.1 — 100 μeV ALP masses and $g_{a\gamma} > 10^{-13}$ GeV^{-1} from observation of strongly magnetized stellar winds

Sigl PRD'17



Radio searches for axion/ALPs DM

Radio lines from neutron stars

- **Galactic center magnetar** PSR J1745-2900 with VLA

$$m_a \sim 10 - 100\,\mu\mathrm{eV} \qquad g_{a\gamma}^{\mathrm{UL}} \sim 10^{-12} - 10^{-13}\,\mathrm{GeV}^{-1}$$

Darling PRL'20, ApJL'20

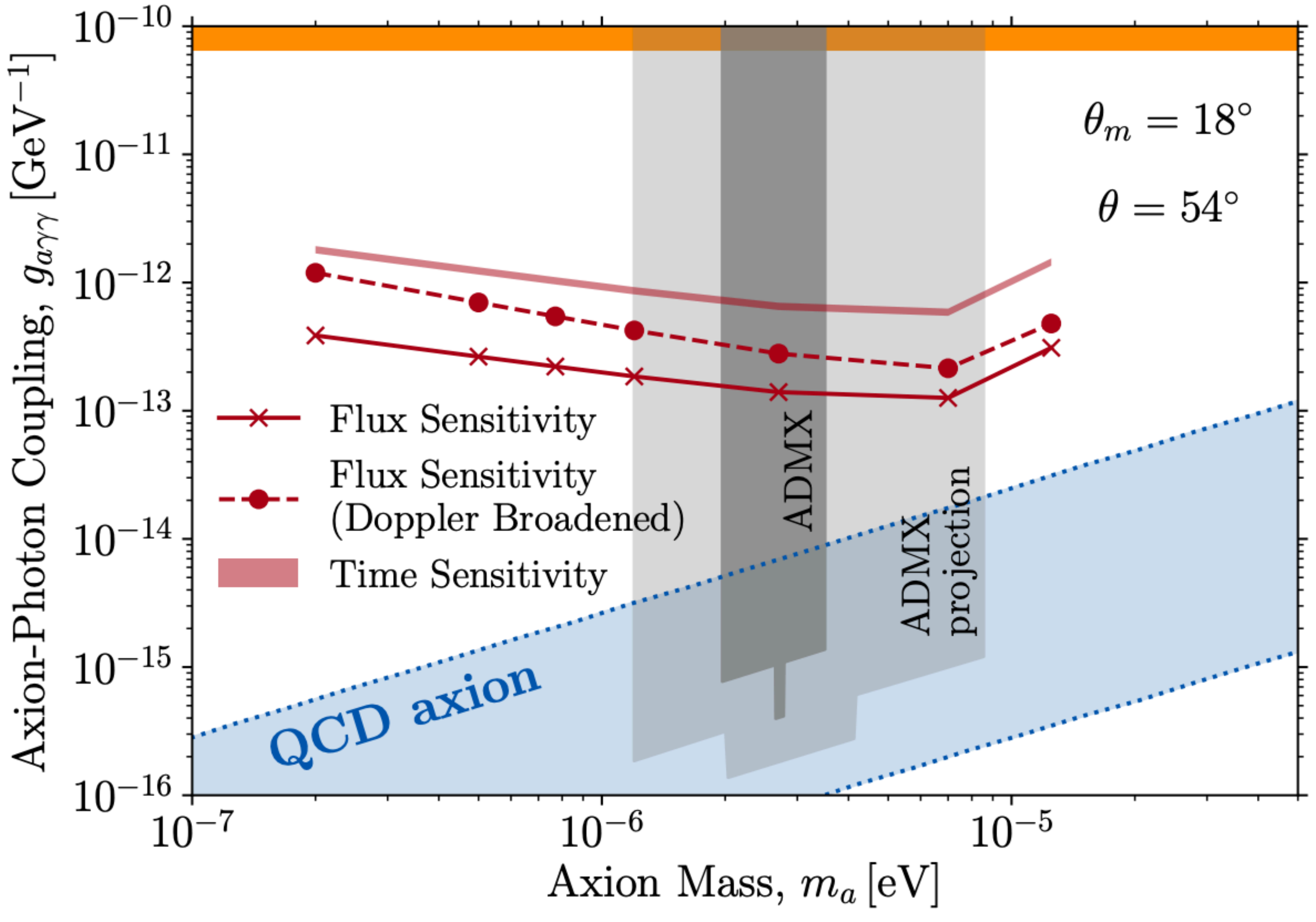
- **Galactic center** and **two nearby isolated neutron stars** with GBT and Effelsberg

$$m_a \sim 5 - 10\,\mu\mathrm{eV} \qquad g_{a\gamma}^{UL} \sim 10^{-11} - 10^{-12}\,\mathrm{GeV}^{-1}$$

Foster+ PRL'20

Still large **limitations** in **model predictions**:

- ALPs electrodynamics in magnetised plasma and 3D effects (vs 1D mixing equations) *Battye+ PRD'20*
- Detailed treatment of what happens to photons when they escape NS (ray tracing) *Leroy+ PRD'20*



Leroy+ PRD'20

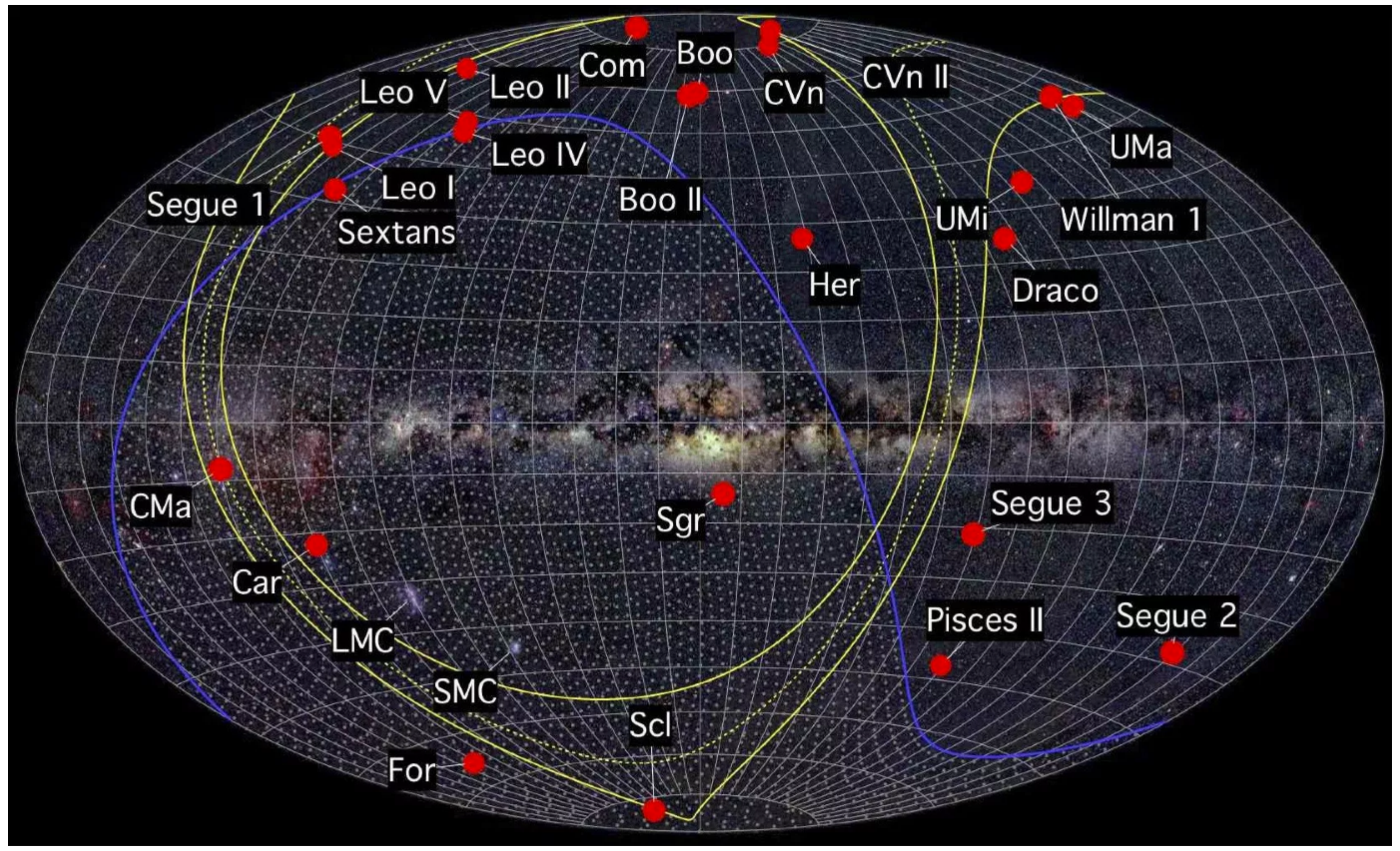
Radio searches for axion/ALPs DM

Radio lines from dwarf galaxies

Axion/ALP can also spontaneously **decay into two photons**

$$\tau_a = \frac{64\pi}{m_a^3 g^2} \qquad S_{\rm sd} = \frac{m_a}{4\pi\Delta\nu}\int d\Omega\, d\ell\, \frac{n(\ell,\Omega)}{\tau_a}$$

Blout+ ApJ'01



Signal: Spectral line from axion decays in halos of dwarf spheroidal galaxies (axion DM hypothesis)

Search: Narrow lines in radio power spectrum, with Doppler broadening proportional to the line-of-sight velocity dispersion

Radio searches for axion/ALPs DM

Radio lines from dwarf galaxies

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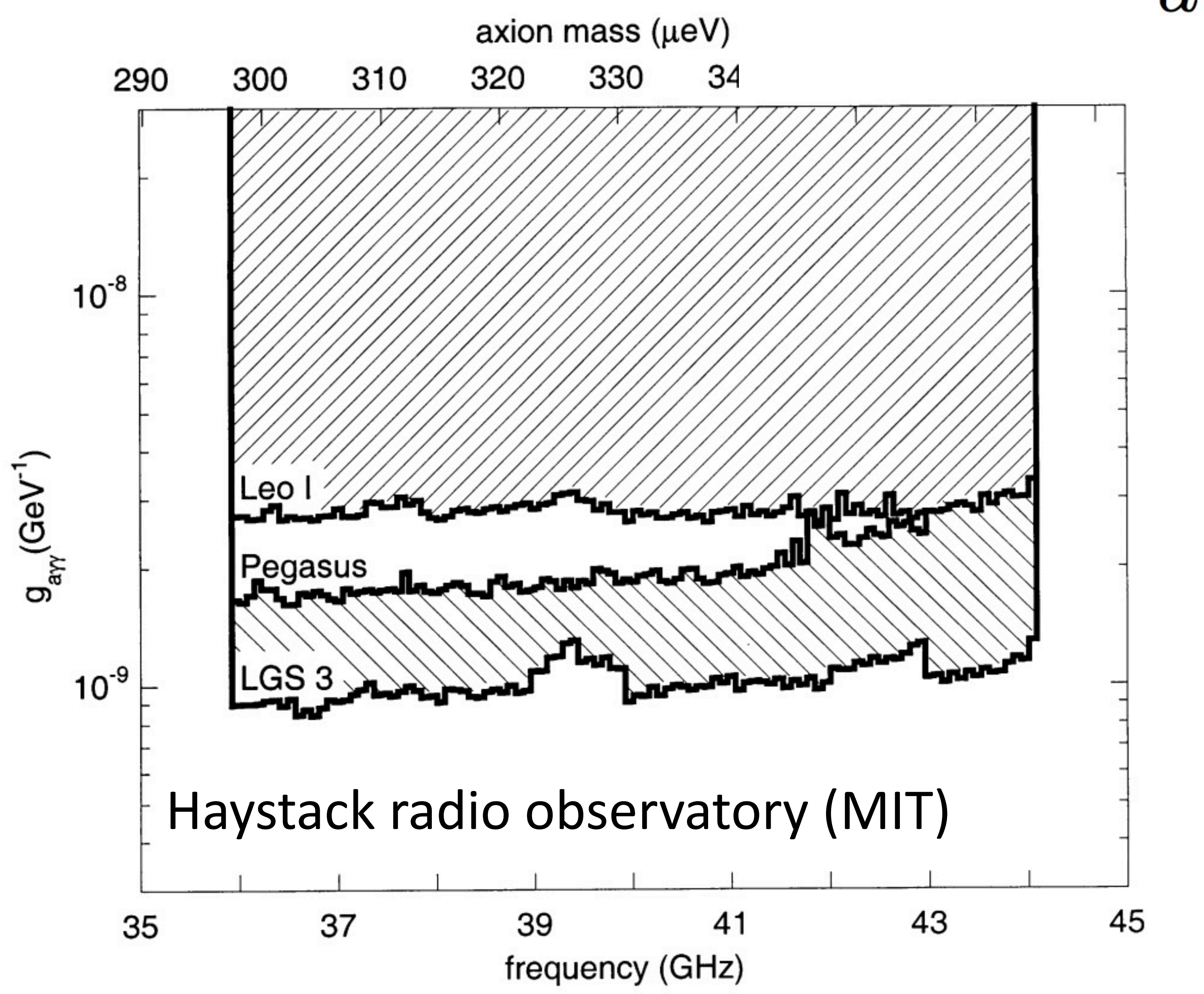
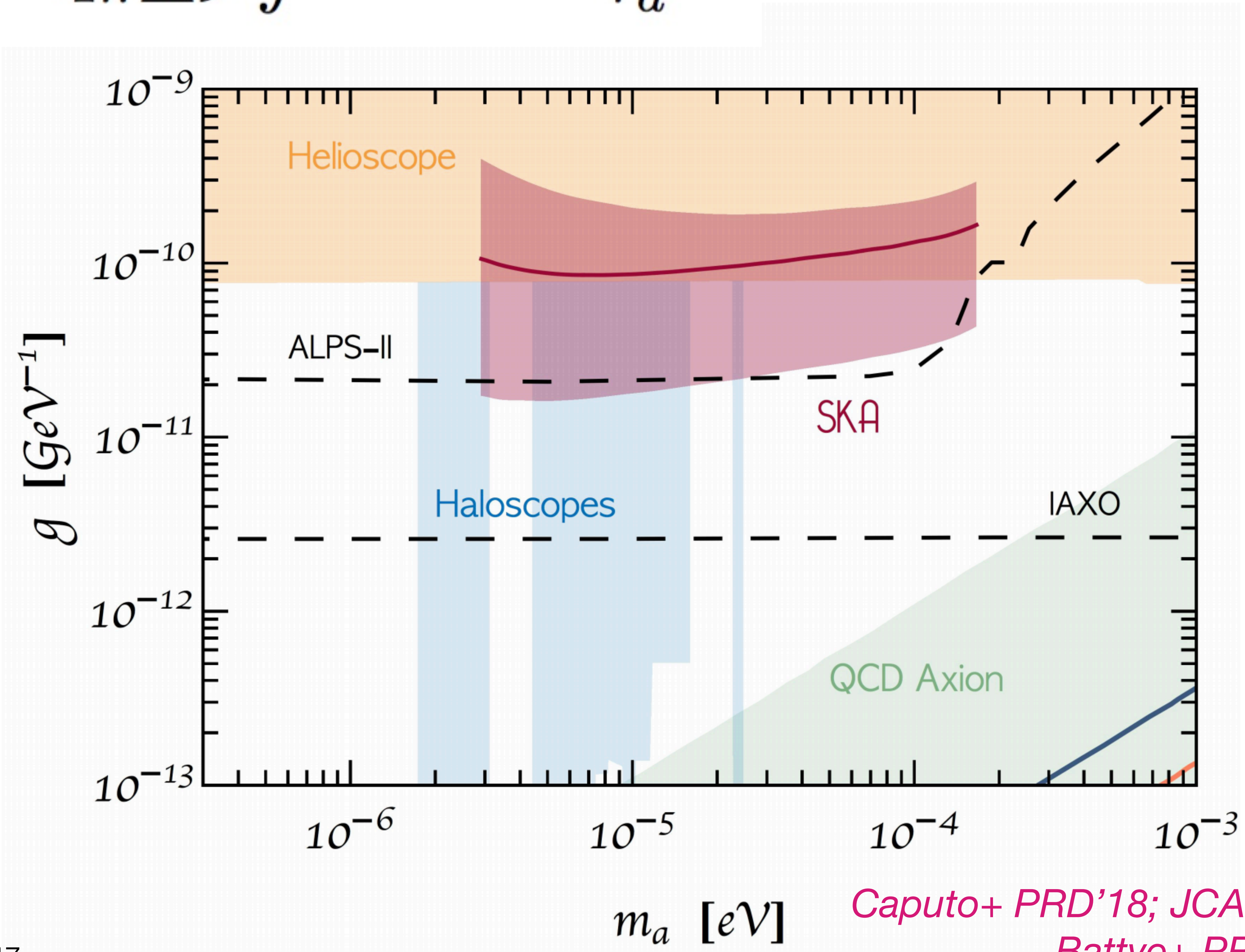


Blout+ ApJ'01



Caputo+ PRD'18; JCAP'19; Battye+ PRD'20

Conclusions & Outlook

- Probes for axion/ALP-photon coupling in astrophysics are truly **multi-wavelength** (radio, X-rays, gamma rays)
- From HE gamma-ray astrophysics **few hints exist** (TeV trasparency, Galactic pulsar search), challenged however by **several constraints**
- Future gamma-ray telescopes at high and low energies — **CTA, HAWC, future MeV missions** — will improve by far the sensitivity to ALPs
- Other future missions — **SKA** (radio), **Athena** (X-ray) — can further constrain the ALP mass/coupling parameter space
- Fundamental **degeneracy** with knowledge of **B-field configuration**