
Oskar Klein centre

Stockholm University

DMAP
Dark Matter Astroparticle Physics

Fermi
Gamma-ray Space Telescope

# SEARCHES FOR AXIONLIKE PARTICLES WITH THE FERMI LARGE AREA TELESCOPE

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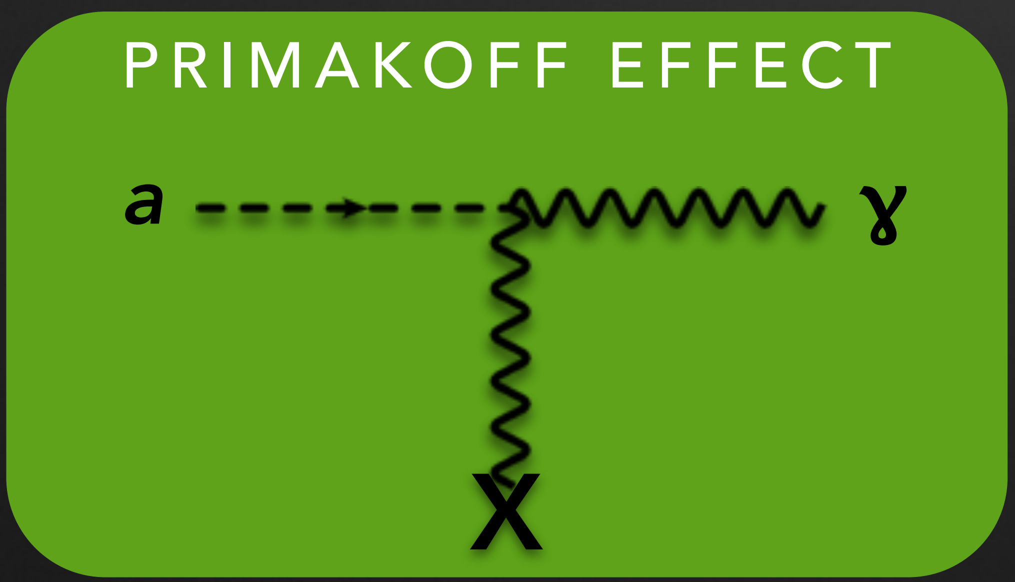
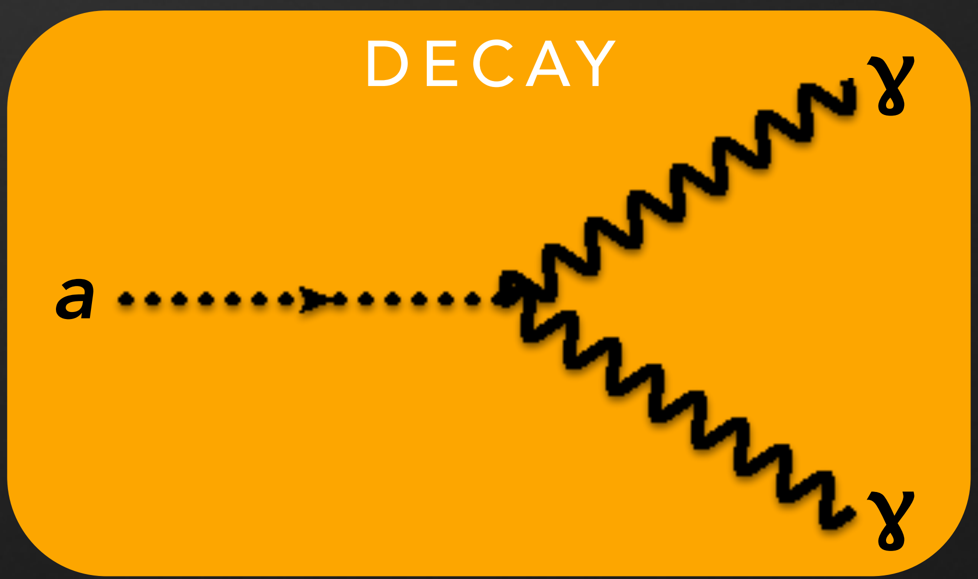
FOR THE FERMI-LAT COLLABORATION

# DETECTING AXIONS/ALPs WITH PHOTONS

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



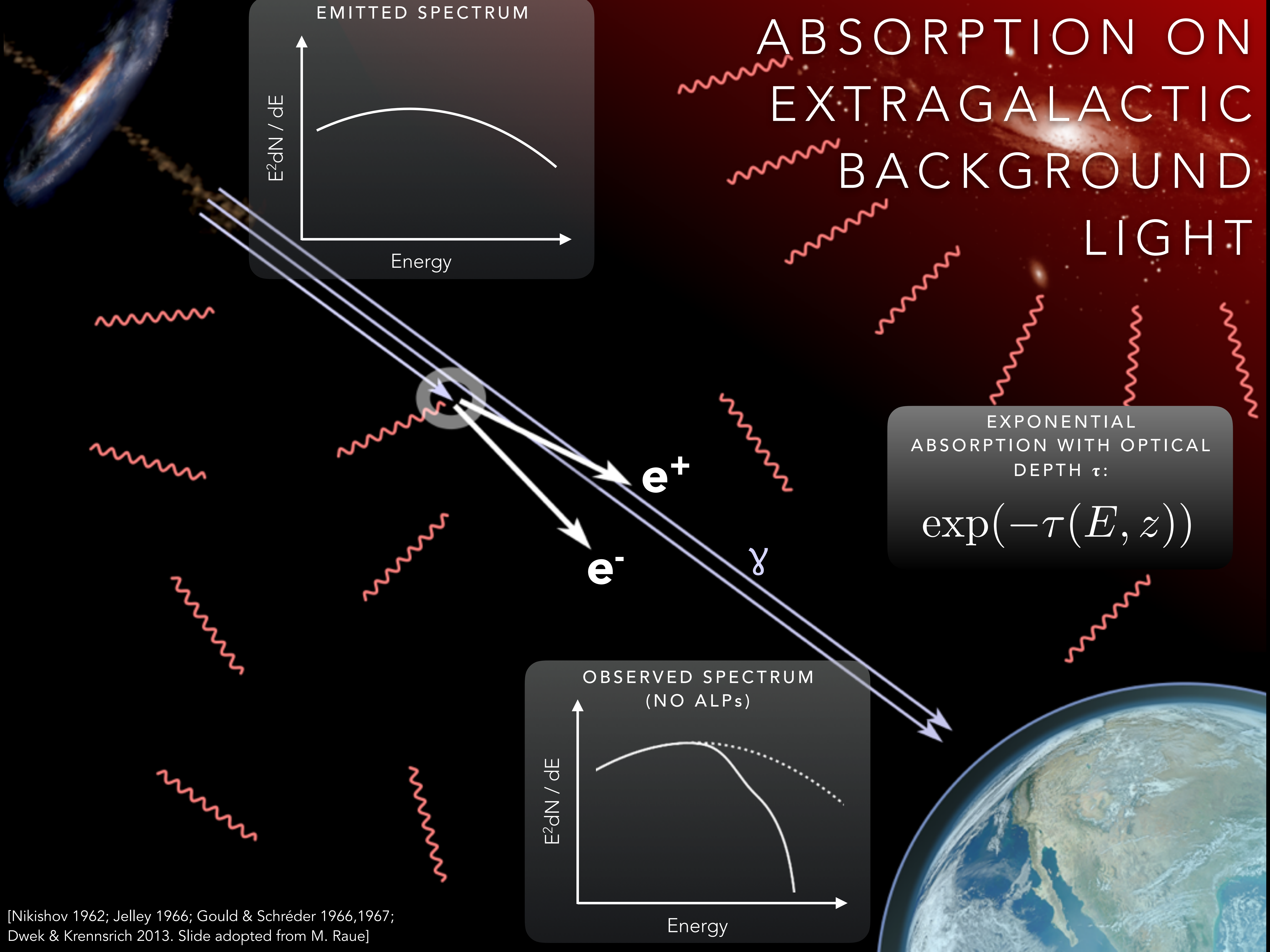




$$\tau_{a\gamma\gamma} \sim 10^{25}\,\mathrm{s} \left( \frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}} \right)^{-2} \left( \frac{m_a}{\mathrm{eV}} \right)^{-3}$$

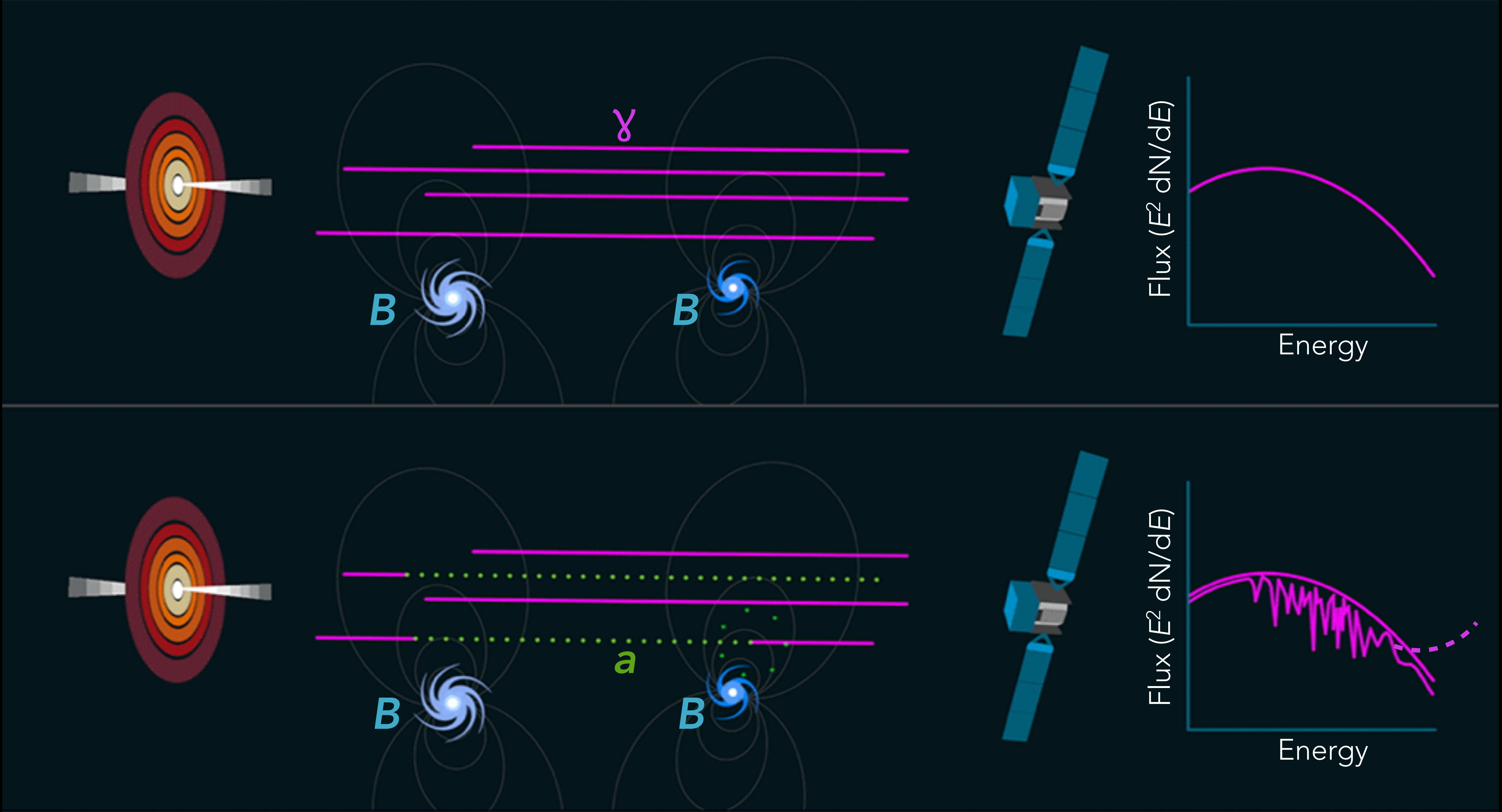
QCD Axion: $m_a \approx 0.3\,\mathrm{eV} \frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}} = 0.3\,\mathrm{eV}\, g_{10}$



[Birenji, Gaskins, Meyer 2016]


ABSORPTION ON EXTRAGALACTIC BACKGROUND LIGHT
EMITTED SPECTRUM
E²dN / dE
Energy
e+
e-
γ
EXPONENTIAL ABSORPTION WITH OPTICAL DEPTH τ:
$\exp(-\tau(E, z))$
OBSERVED SPECTRUM (NO ALPs)
E²dN / dE
Energy
[Nikishov 1962; Jelley 1966; Gould & Schréder 1966,1967; Dwek & Krennsrich 2013. Slide adopted from M. Raue]

# PHOTON-ALP MIXING IN GALAXY CLUSTER & MILKY WAY




[Credit: SLAC National Accelerator Laboratory/Chris Smith]

[Hooper & Serpico 2007; Fairbairn et al. 2011;Horns et al. 2012; Wouters & Brun 2012,2013; Abramowski et al. 2013; MM et al. 2014, MM & Conrad 2014; Ajello et al. 2016; Berg et al. 2016]

# PHOTON-ALP MIXING IN GALAXY CLUSTER & MILKY WAY

$$E_{\mathrm{crit}} \sim 2.5\,\mathrm{GeV}\,\frac{|m^2_{a,\mathrm{neV}} - \omega^2_{\mathrm{pl,\,neV}}|}{g_{11}B_{\mu\mathrm{G}}}$$


National Accelerator Laboratory/Chris Smith]

[Hooper & Serpico 2007; Fair
2012; Wouters & Brun 2012,2
MM et al. 2014, MM & Conrad 2014; Ajello et al. 2016;
Berg et al. 2016]

# SEARCHES FOR REDUCED OPACITY

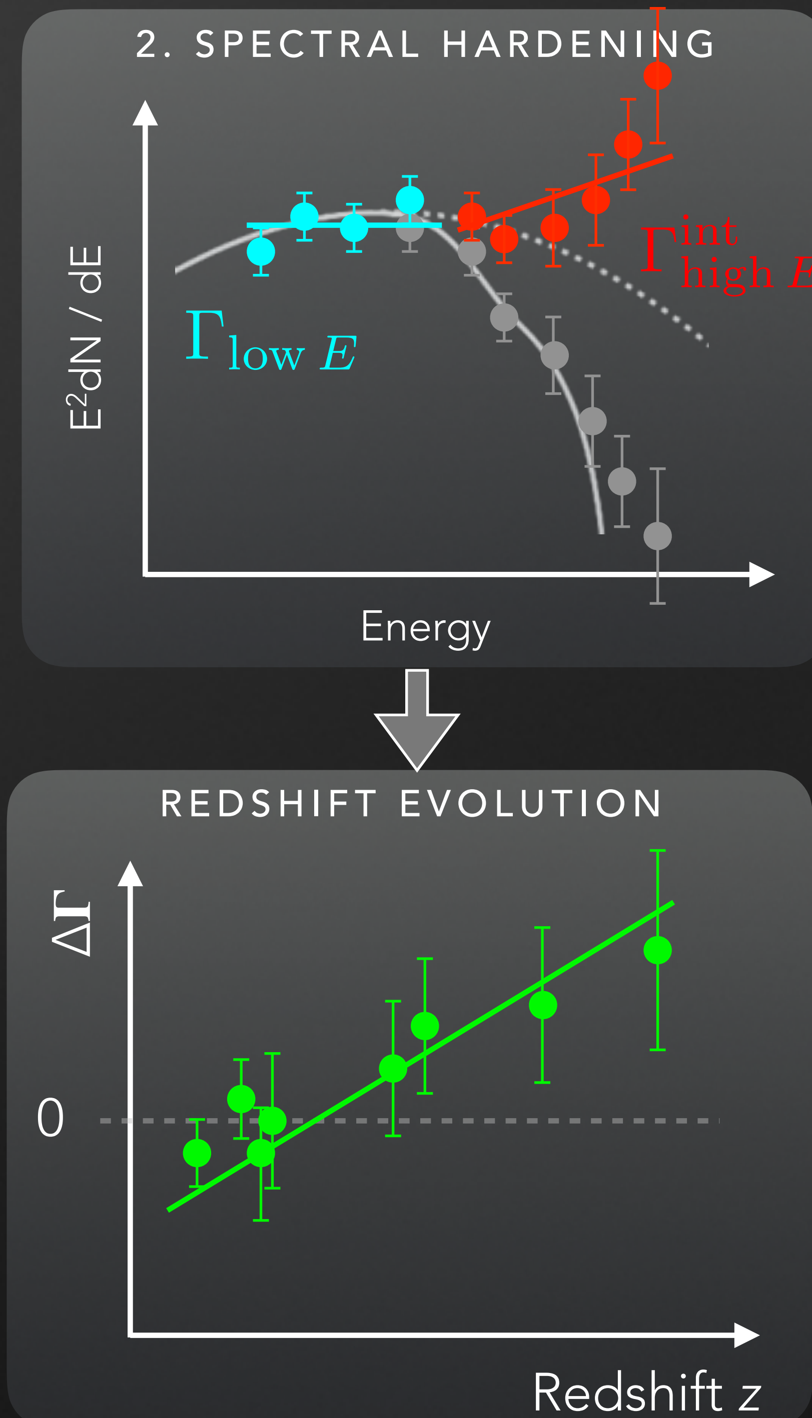
- Expectations **if opacity lower** than EBL model predictions:

    1. We should **detect ɣ rays** from blazars at energies corresponding to **high values of τ and positive residuals at highest energies**

    2. Correcting measured blazar spectra for EBL absorption should give a **spectral hardening at high values of τ — or very hard intrinsic spectra**

    3. **Absorption corrected spectral indices** should become **harder (lower) with increasing redshift ⇔ Difference in Spectral Indices** at low and high energies should be **> 0 and evolve with redshift**

$$\Delta\Gamma = \Gamma_{\mathrm{low}\ E} - \Gamma^{\mathrm{int}}_{\mathrm{high}\ E} \sim mz + b > 0$$



# SEARCHES FOR REDUCED OPACITY

- Expectations **if opacity lower** than EBL model predi...

1.

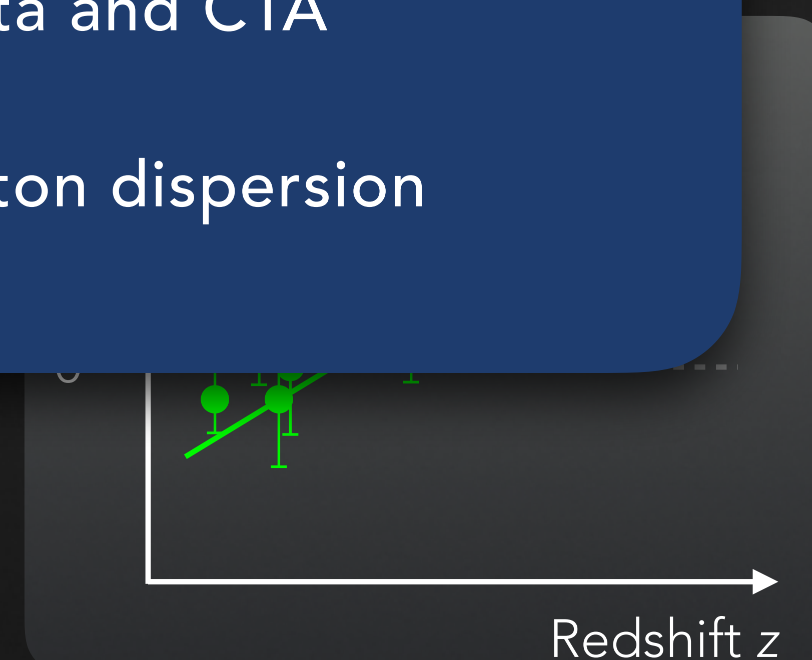
2.

3.


**CURRENT STATUS:**

- Many analyses found hints / evidences [e.g. De Angelis et al. 2009,2011,2015; Essey & Kusenko 2012, Horns & MM 2012, Rubtsov & Troitsky 2014]
- Recent analyses (Fermi-LAT / IACT) are consistent with EBL only [Sanchez et al. 2013; Biteau & Williams 2015; Dominguez & Ajello 2015]
- Dedicated Future (re-) analysis of IACT data and CTA observations will settle the Issue
- Analyses w/ ALPs did not account for photon dispersion [Kartavtsev, Raffelt, Vogel 2016]

become **harder (lower) with increasing redshift** ⇔ **Difference in Spectral Indices** at low and high energies should be **> 0 and evolve with redshift**




$$\Delta\Gamma = \Gamma_{\mathrm{low}\ E} - \Gamma^{\mathrm{int}}_{\mathrm{high}\ E} \sim mz + b > 0$$

# SEARCH FOR IRREGULARITIES WITH FERMI LAT FROM NGC 1275

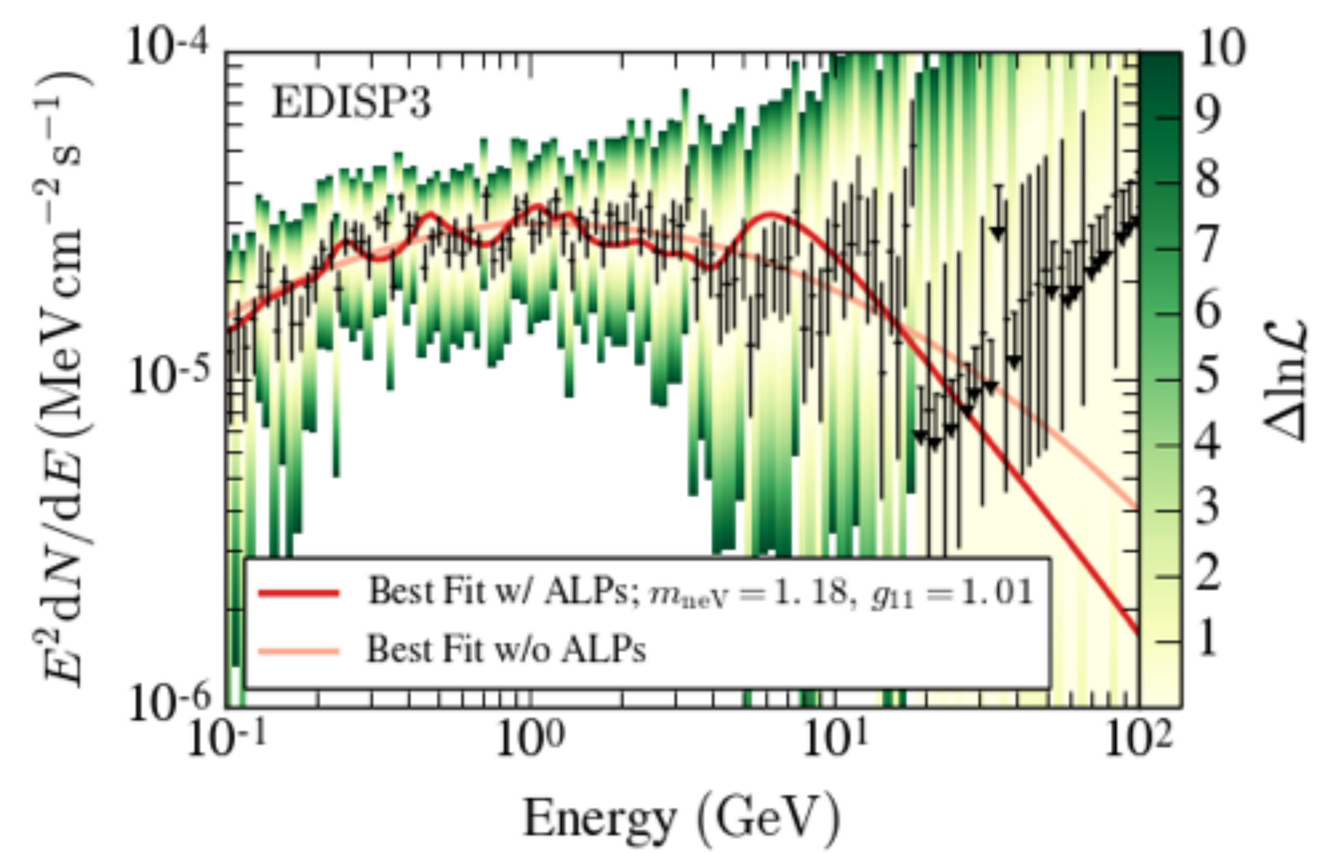
- **Radio galaxy NGC 1275**, **bright *Fermi* source** [e.g. Abdo et al. 2009]
- In the center of **cool-core** Perseus cluster
- Rotation measures: **central** B field ~**25μG** [Taylor+ 2006]
- **B ≳ 2 μG from non-observation of ɣ rays** [Aleksic et al. 2012]

Hubble image of NGC 1275
http://hubblesite.org/newscenter/archive/releases/2008/28/image/a/

[Ajello et al. (*Fermi*-LAT Collaboration) 2016]

# FERMI-LAT DATA ANALYSIS

- **6 years** of LAT data
- Split into analysis **EDISP event types**
- Method: **log-likelihood ratio test** for no-ALP and ALP hypothesis
- Hypothesis test **calibrated with Monte-Carlo simulations**




ALP HYPOTHESIS: $P_{\gamma\gamma}(E, m_a, g_{a\gamma}, \mathbf{B})F(E)$

Photon. surv. prob.; incl. EBL — Intrinsic spectrum

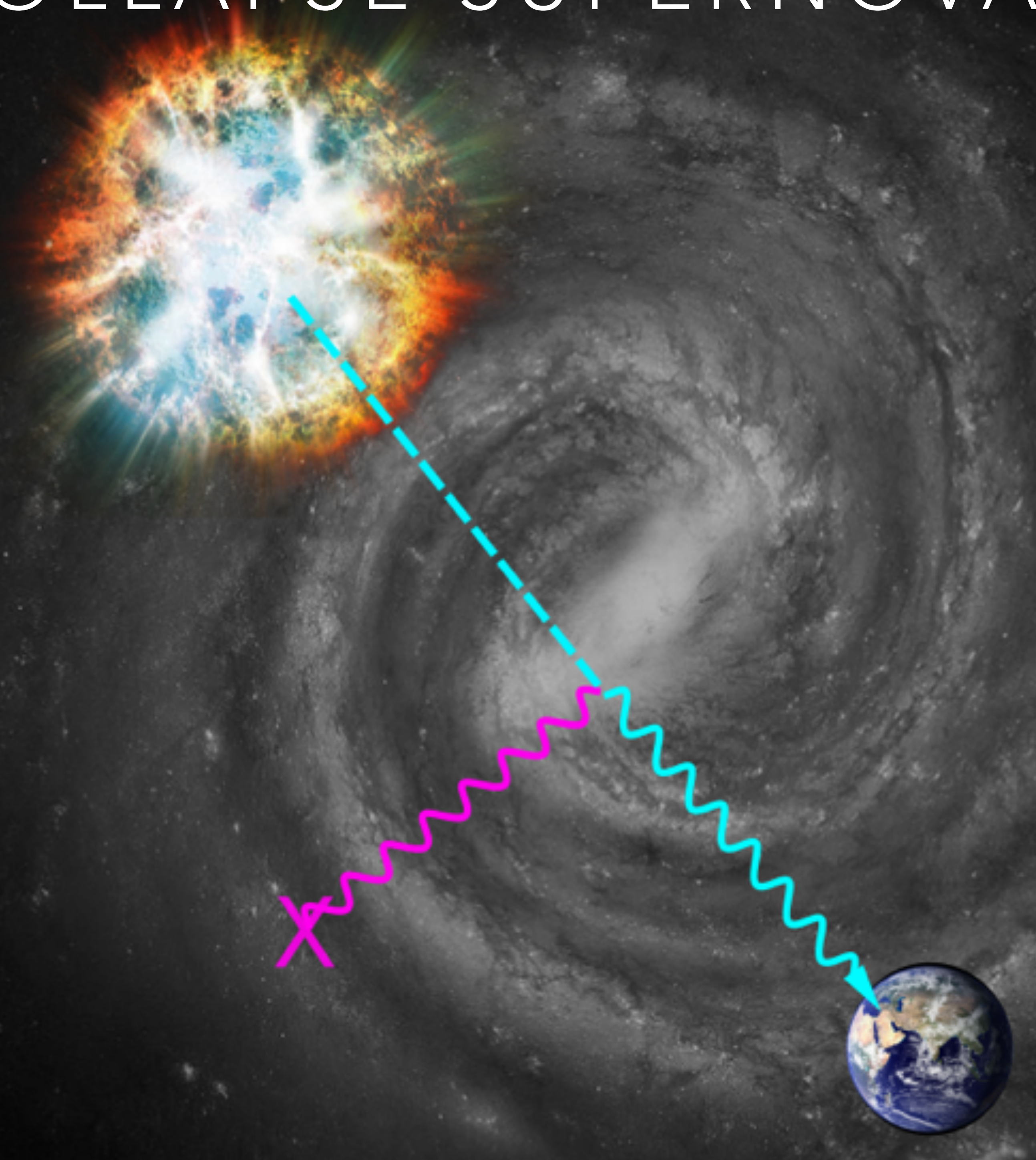
NO-ALP HYPOTHESIS: $\exp(-\tau)F(E)$

EBL attenuation only — Intrinsic spectrum

No axions observed, constraints

[Ajello et al. (*Fermi*-LAT Collaboration) 2016]

# AXIONLIKE PARTICLES FROM CORE COLLAPSE SUPERNOVAE

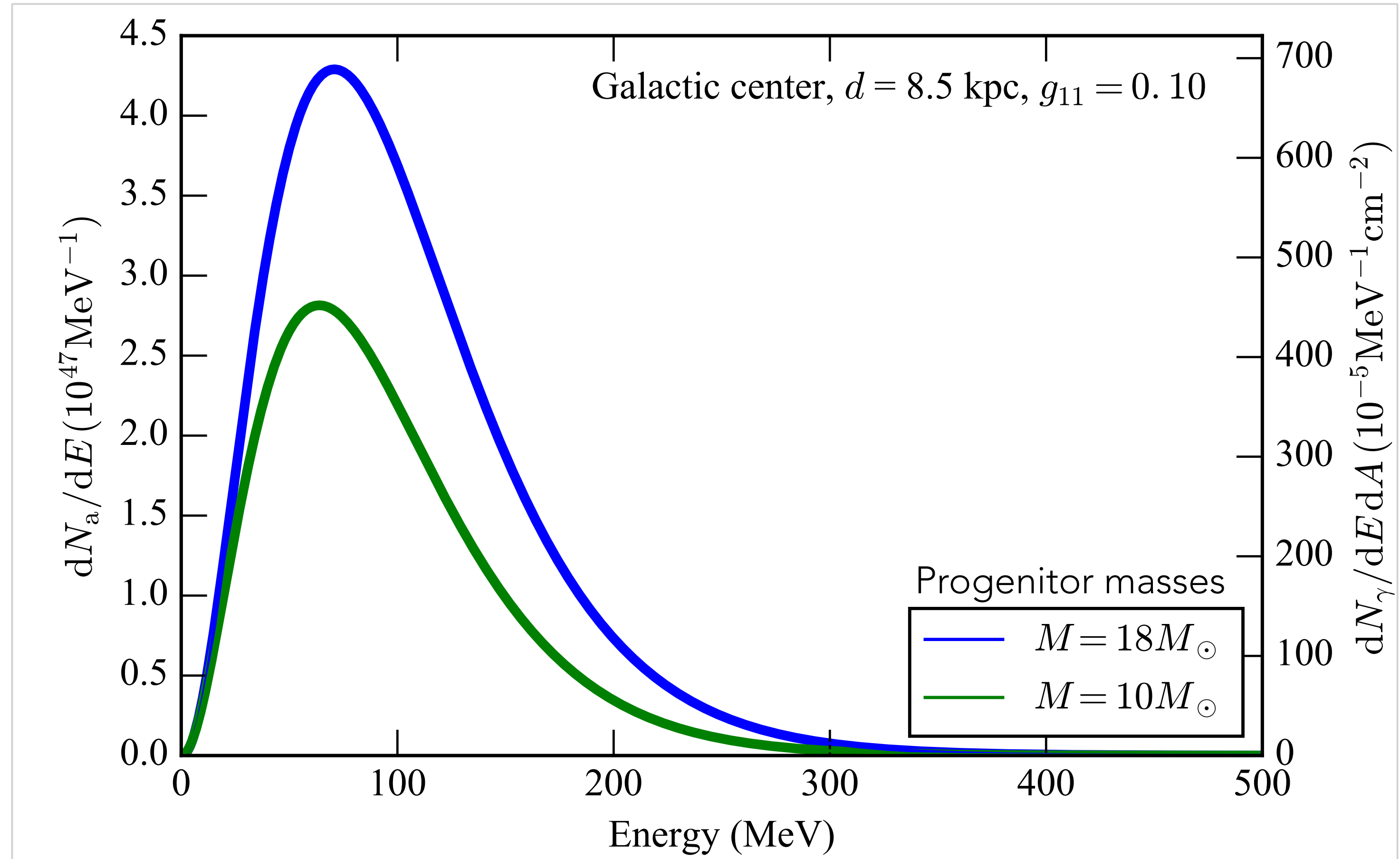


- ALPs would be **produced in a core-collapse SN** explosion via Primakoff process
- Could **convert into gamma-rays in Galactic magnetic field**

# EXPECTED ALP SIGNAL

- ALPs produced in SN core within ~10 s after explosion and escape core ➜ **short burst**
- **Spectrum** has thermal-like shape, **peaks at ~50 MeV**
- **Gamma rays would arrive co-incident with SN neutrinos** (provides time tag)

ALP / ɣ-ray flux integrated over explosion time




Better **gamma-ray sensitivity and large FoV** of *Fermi* LAT promise **unparalleled sensitivity** for ALPs in case of a Galactic core-collapse SN within *Fermi*-LAT lifetime and FoV

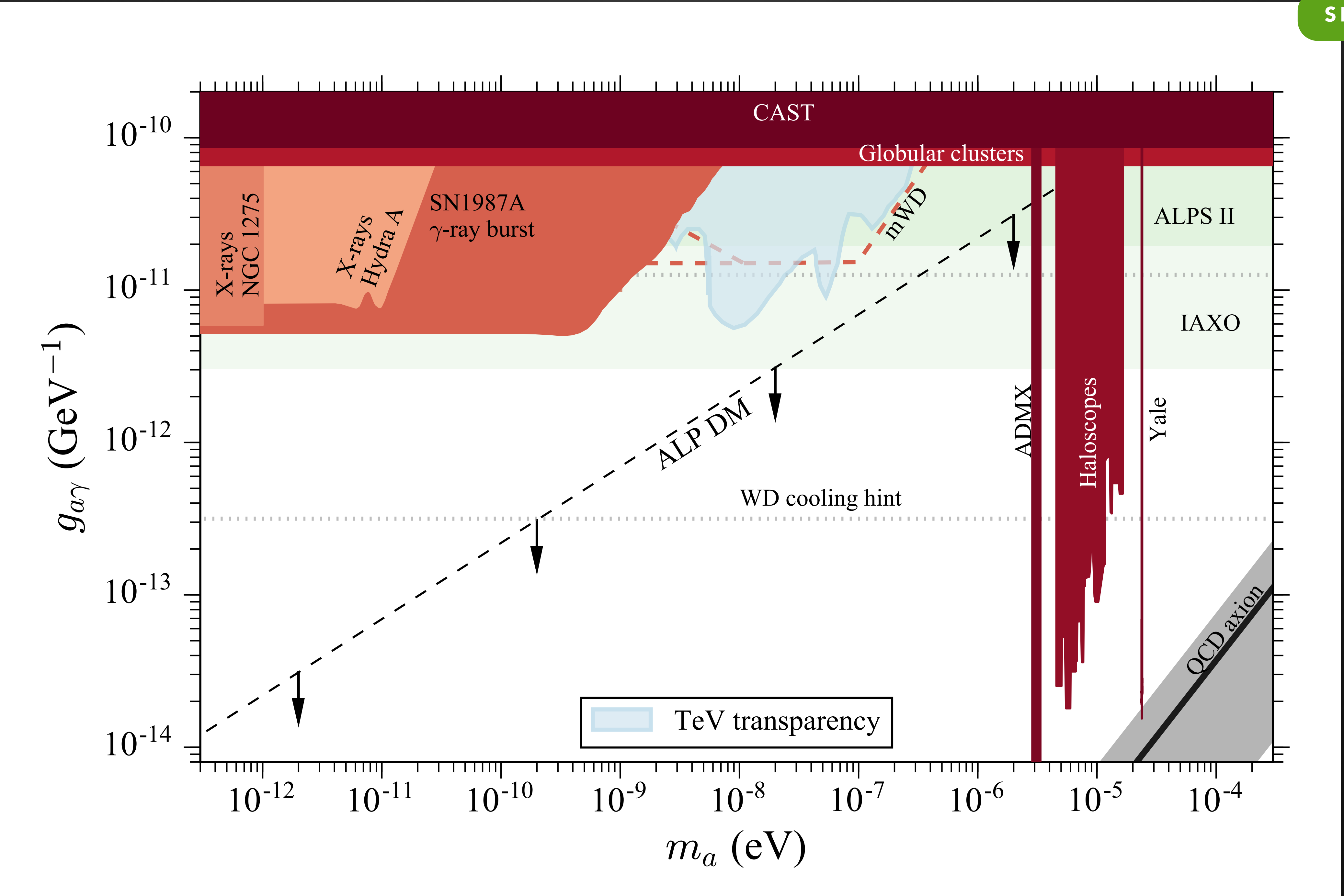


[Payez et al. 2015]

# CONSTRAINTS & SENSITIVITIES

LIMITS

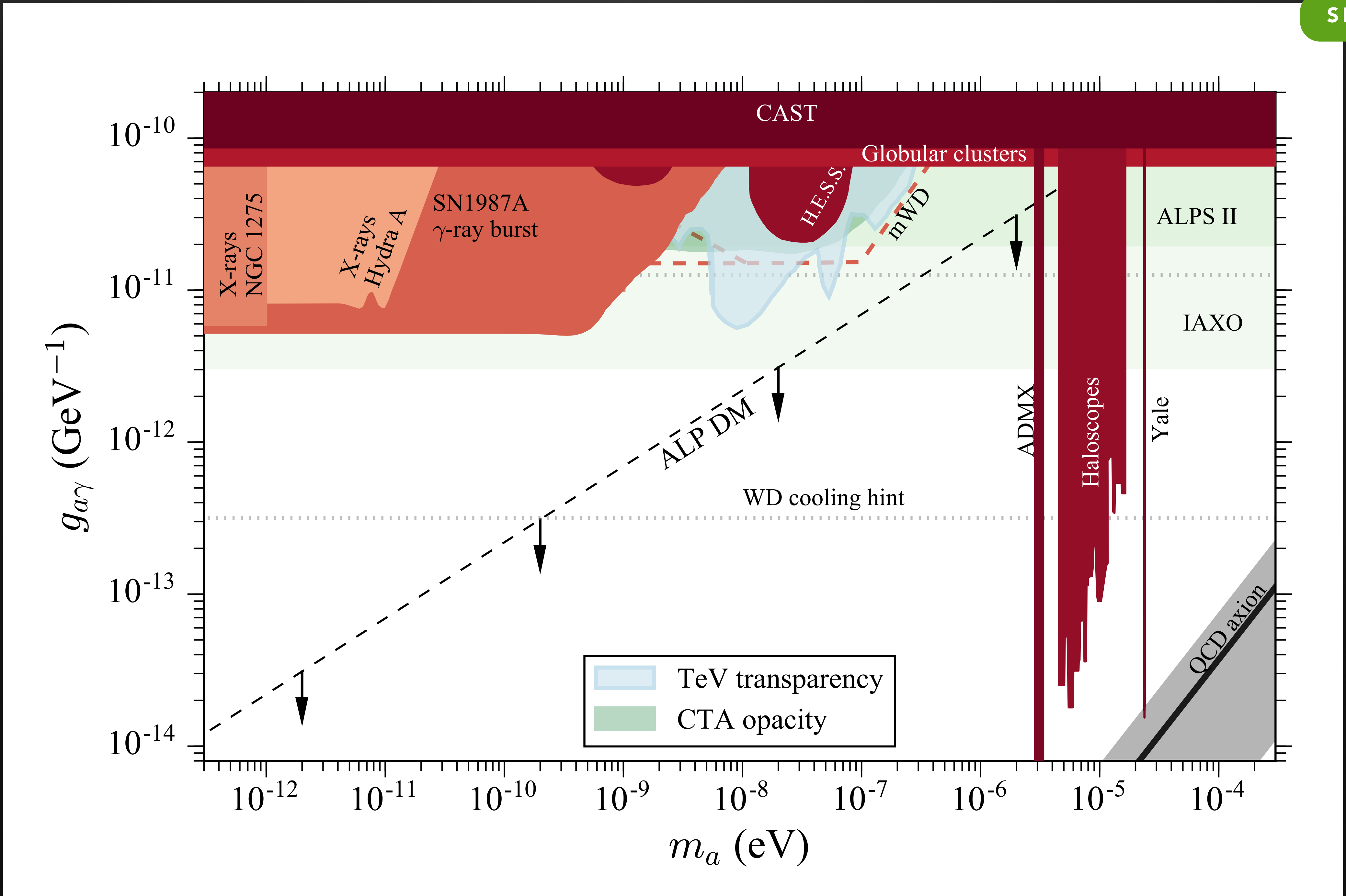
SENSITIVITIES




[MM, Horns, Raue 2013]

# CONSTRAINTS & SENSITIVITIES

LIMITS
SENSITIVITIES

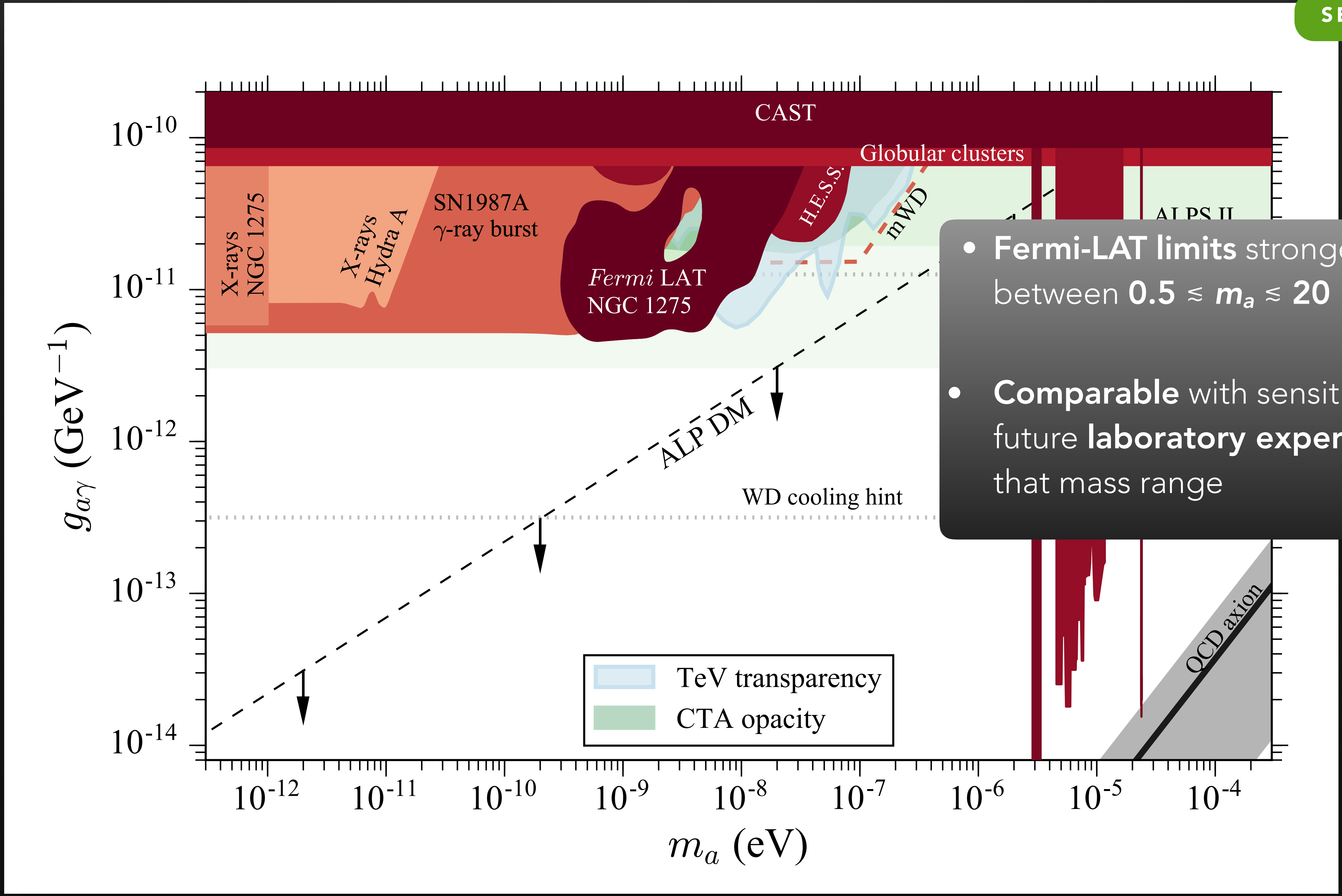



[Abramowksi et al. (H.E.S.S. Collaboration) 2013]

# CONSTRAINTS & SENSITIVITIES

LIMITS

SENSITIVITIES



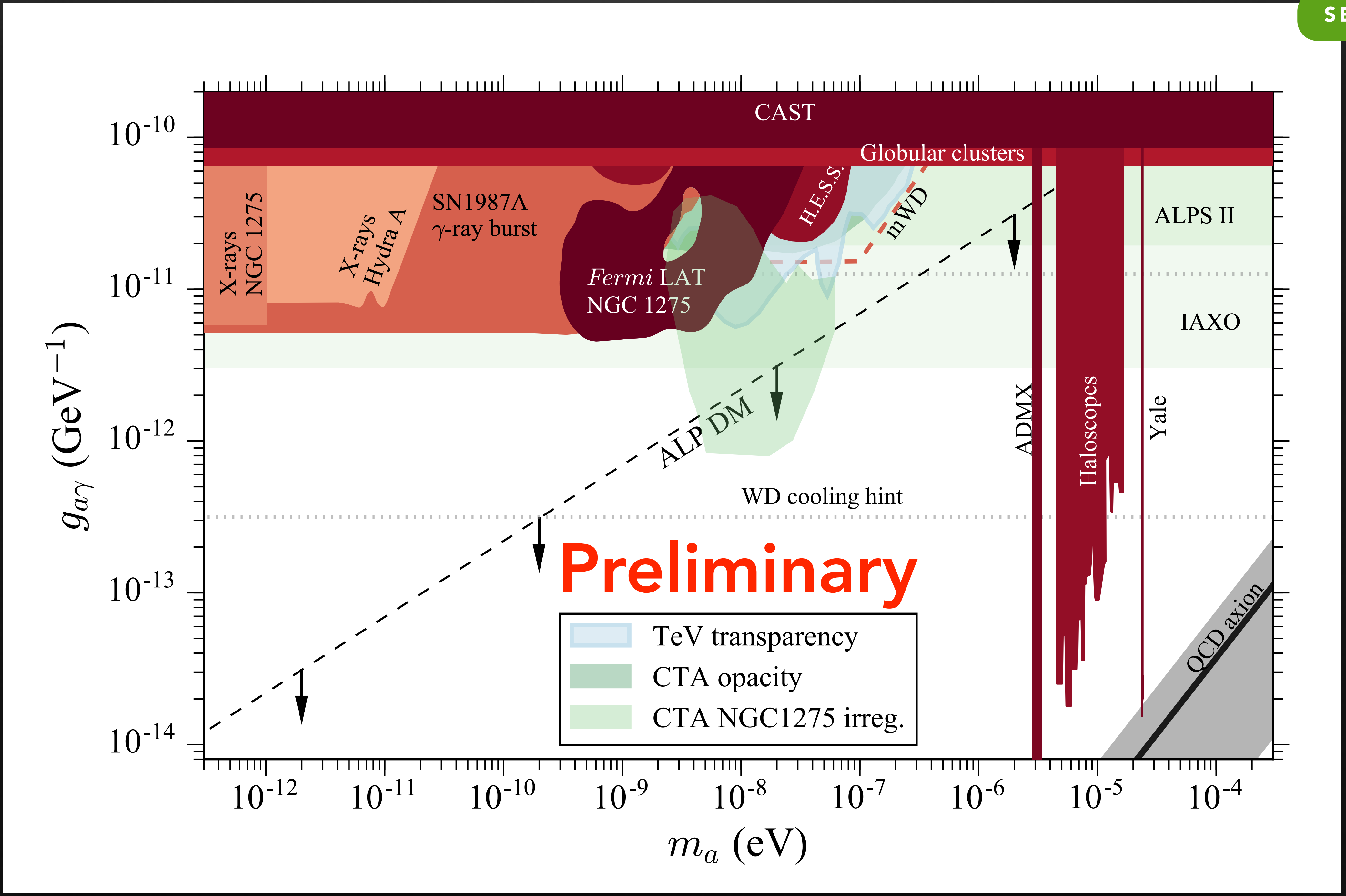

- **Fermi-LAT limits** strongest to date between **0.5 ≲ $m_a$ ≲ 20 neV**
- **Comparable** with sensitivity of future **laboratory experiments** in that mass range

[Ajello et al. 2016]

# CONSTRAINTS & SENSITIVITIES

LIMITS

SENSITIVITIES




[Wood & MM 2014, preliminary]

# CONSTRAINTS & SENSITIVITIES

LIMITS

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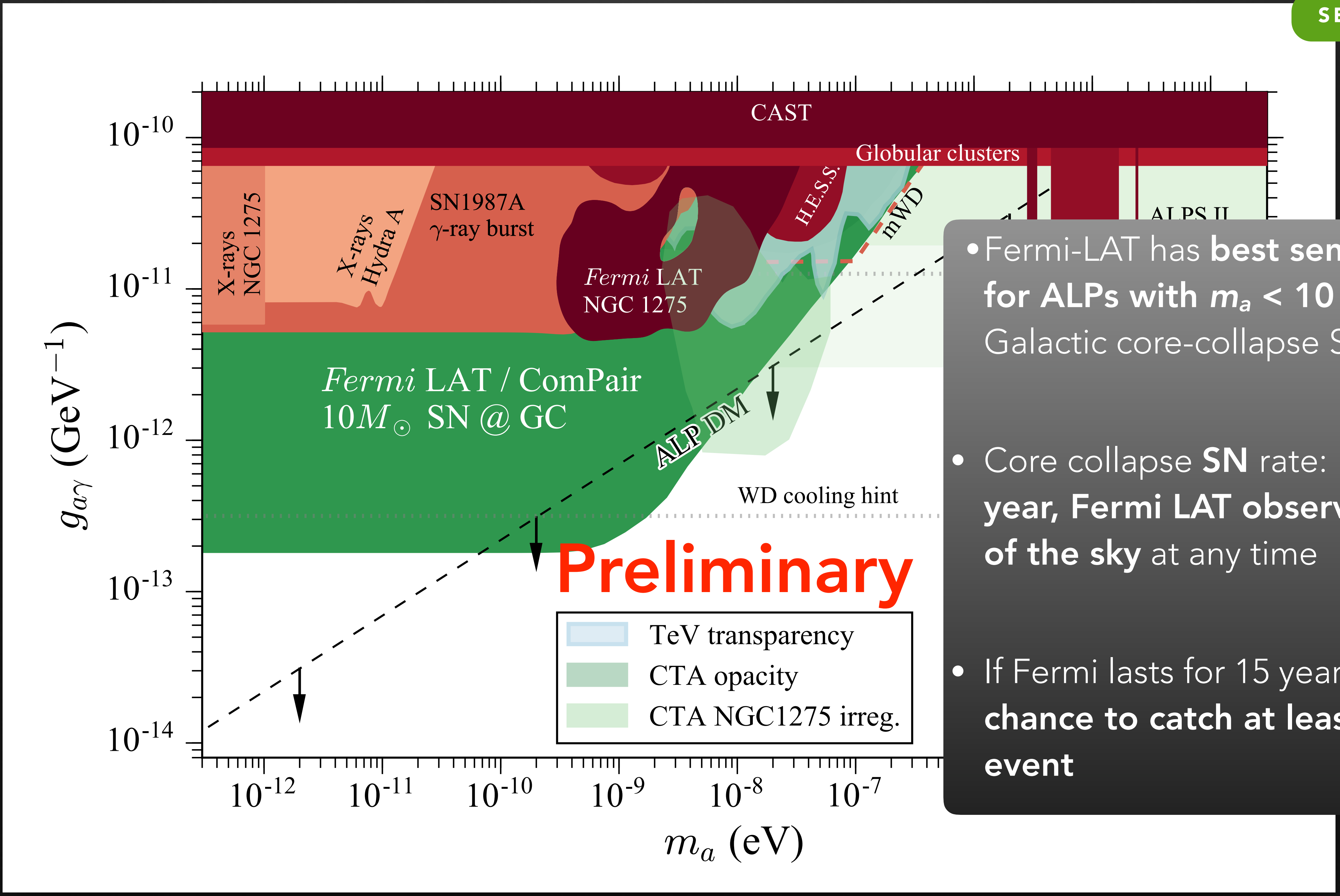



- Fermi-LAT has **best sensitivity for ALPs with $m_a$ < 10 neV** from a Galactic core-collapse SN
- Core collapse **SN** rate: **~2–3% per year, Fermi LAT observes ~20% of the sky** at any time
- If Fermi lasts for 15 years **~ 3% chance to catch at least one such event**

[MM; M. Giannotti; A. Mirizzi; J. Conrad; M. Sanchez-Conde, accepted in PRL. ArXiv:1609.02350]

# Extra Slides

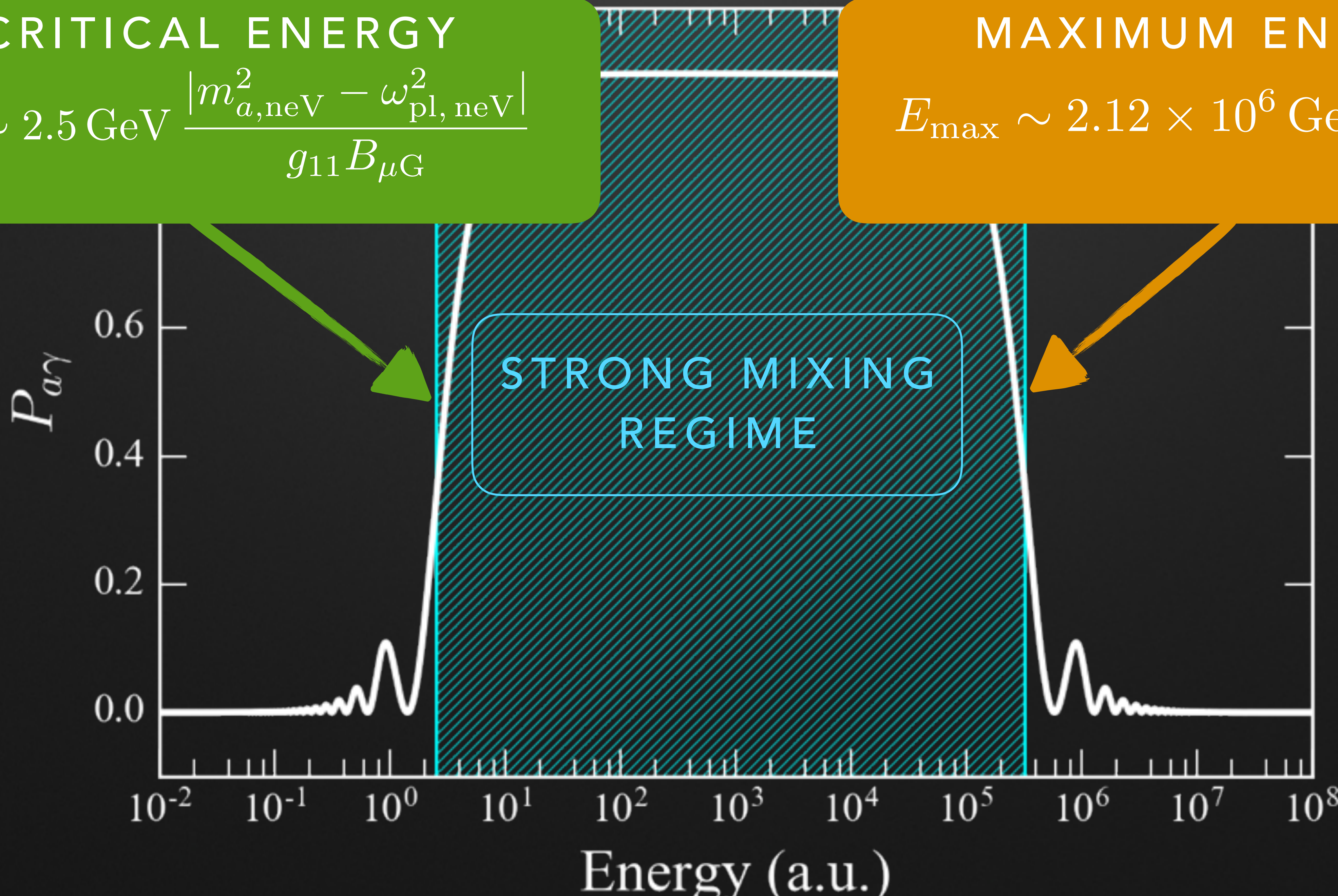
# PHOTON-AXION/ALP MIXING

**CRITICAL ENERGY**

$$E_{\rm crit} \sim 2.5\,{\rm GeV}\,\frac{|m^2_{a,{\rm neV}} - \omega^2_{\rm pl,\,neV}|}{g_{11} B_{\mu{\rm G}}}$$

**MAXIMUM ENERGY**

$$E_{\rm max} \sim 2.12 \times 10^6\,{\rm GeV}\,g_{11} B^{-1}_{\mu{\rm G}}$$

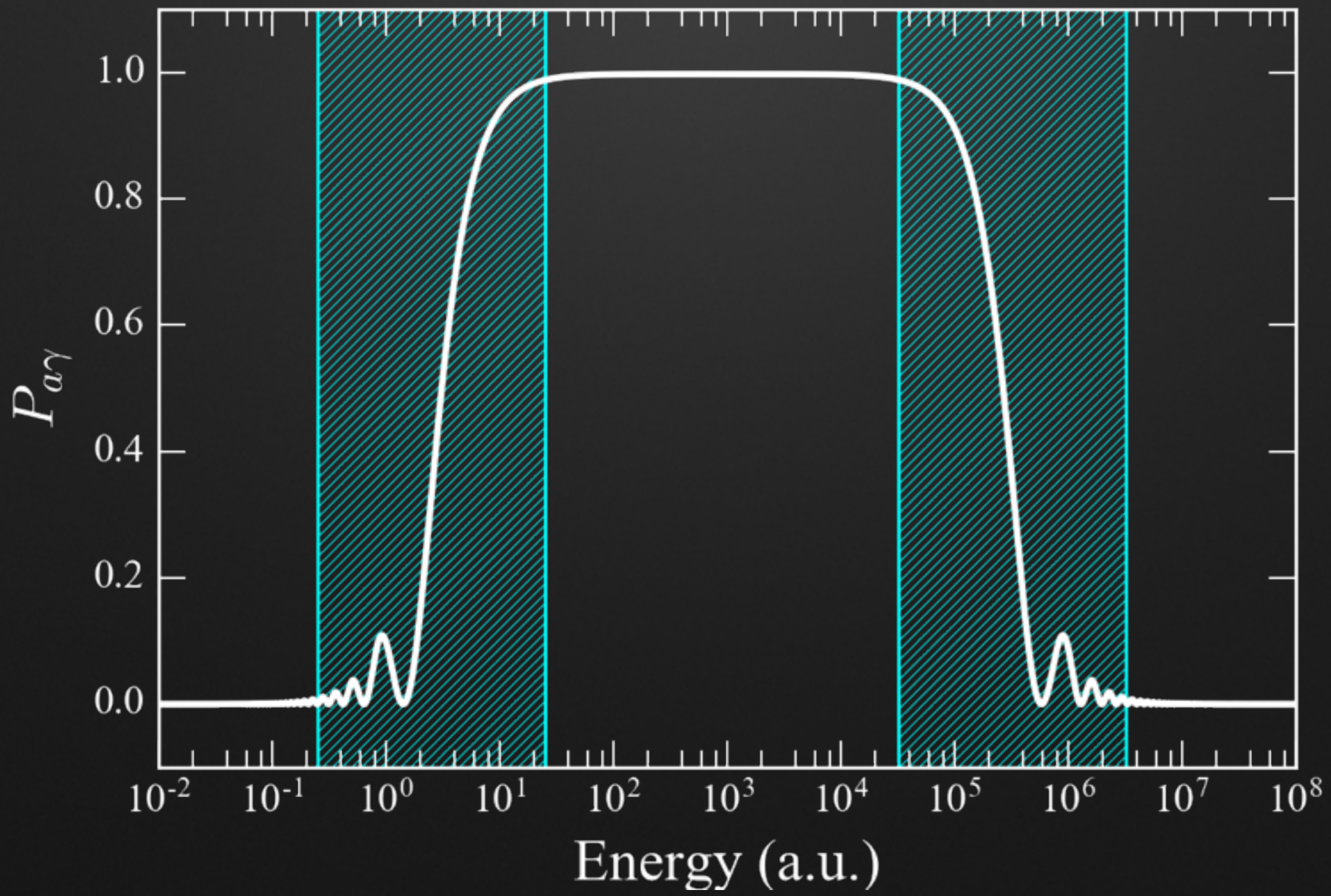





[Raffelt & Stodolsky 1988]

# PHOTON-AXION/ALP MIXING

**2nd Observable:** irregularities in energy spectrum around $E_{crit}$ and $E_{max}$




[Östman & Mörtsell 2005; Hooper & Serpico 2007; Mirizzi et al 2007; Hochmuth & Sigl 2007
De Angelis et al. 2008; Wouters & Brun 2012,2013; Abramowski et al. 2013; Ajello et al. 2016