AN OVERVIEW

GAMMA-RAY CONSTRAINTS ON AXION-LIKE PARTICLES

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ON BEHALF OF THE FERMI-LAT COLLABORATION
MAY 4, 2016
PERSPECTIVES ON THE EXTRAGALACTIC FRONTIER
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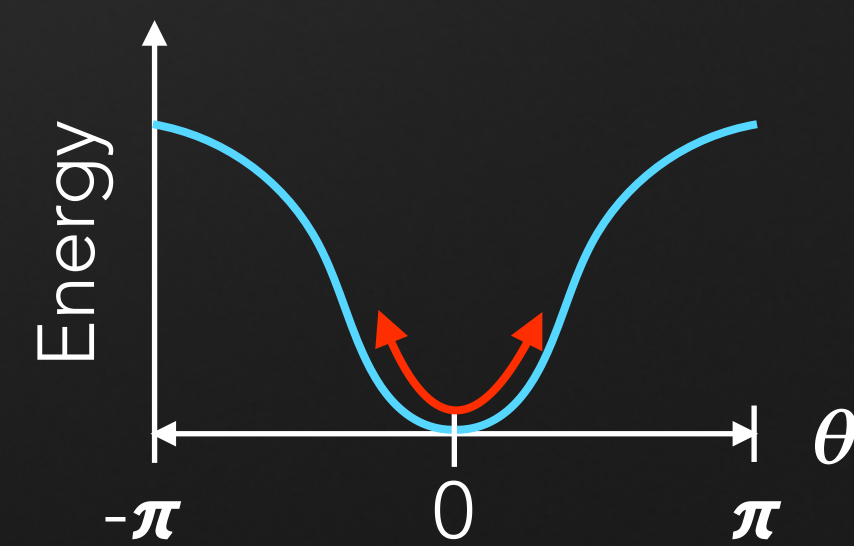
OUTLINE

1. Axions and Axion-like Particles and their detection with ɣ rays
2. Hints, Future and Current constraints
3. Summary

AXIONS AND AXION-LIKE PARTICLES

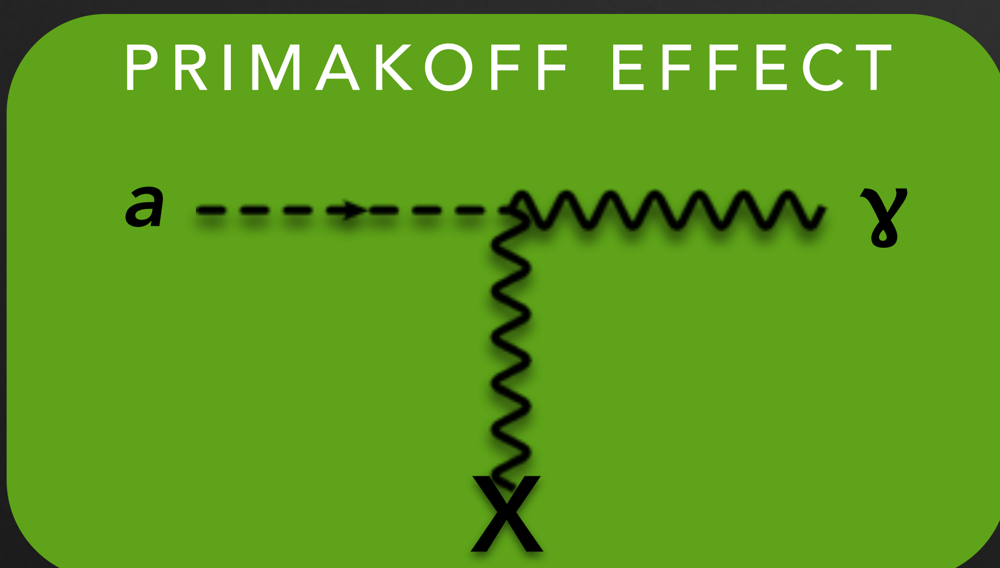
- QCD: has CP violating term with strength $\boldsymbol{\theta}$, measurement: $|\boldsymbol{\theta}| < 10^{-10}$
- Introduce symmetry, $\boldsymbol{\theta}$ is a dynamical field, relaxes to zero in potential
- Symmetry broken at scale $f_a \Rightarrow$ **new particle: the axion!** (similar to Higgs mechanism)
- Axion mass $\boldsymbol{m_a \sim f_a^{-1}}$
- Oscillations around minimum: act like **cold dark matter**
- **Axion-like particles (ALPs)**:
    - arise in similar way, also **dark-matter candidate**
    - plethora of **ALPs predicted in string theory** (axiverse) and other standard model extensions
    - **ALP mass independent of f_a**

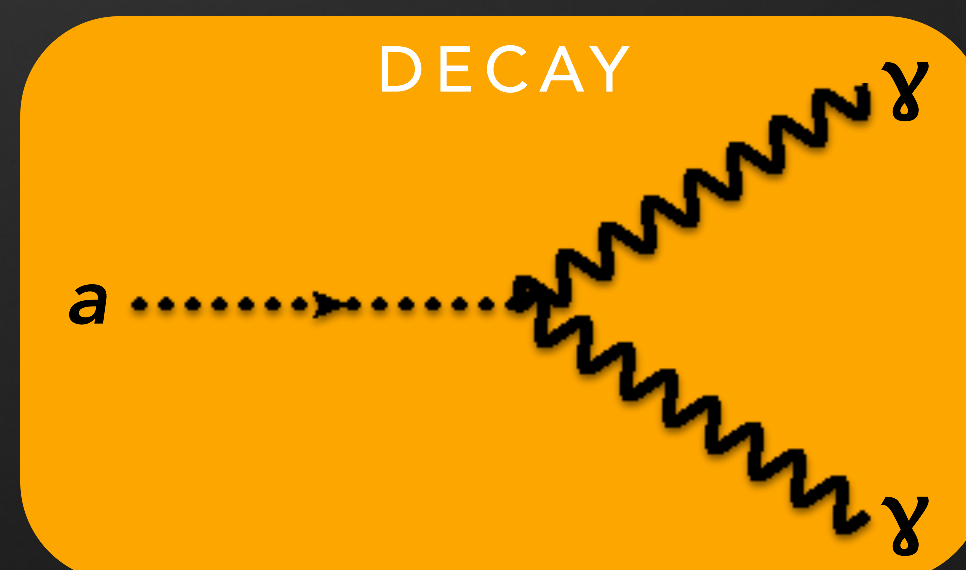


[Peccei & Quinn 77; Wilczek 78; Weinberg 78; Preskill et al. 83; Abbott & Sikivie 83; Witten 84; e.g. Arvanitaki et al. 09; Cicoli et al. 12; Arias et al. 2012]

DETECTING AXIONS/ALPs WITH PHOTONS

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





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

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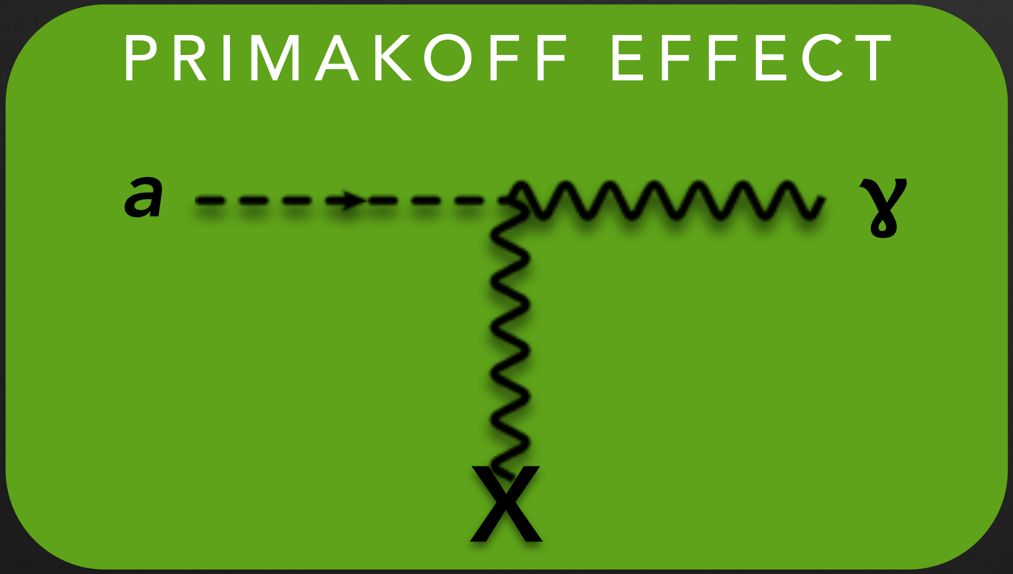

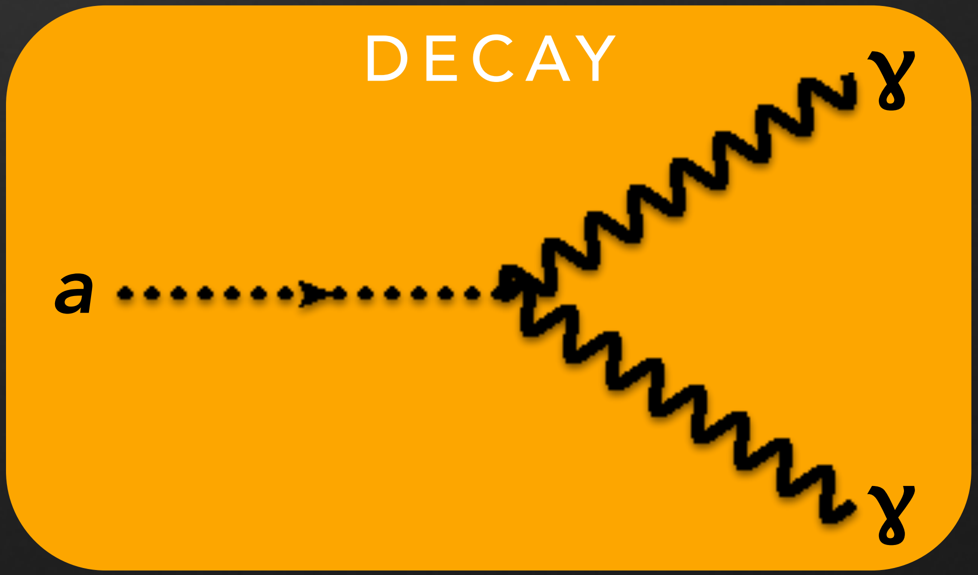

$$\tau_{a\gamma\gamma} \sim 10^{25}\,\mathrm{s} \left(\frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^{-2} \left(\frac{m_a}{\mathrm{eV}}\right)^{-3}$$

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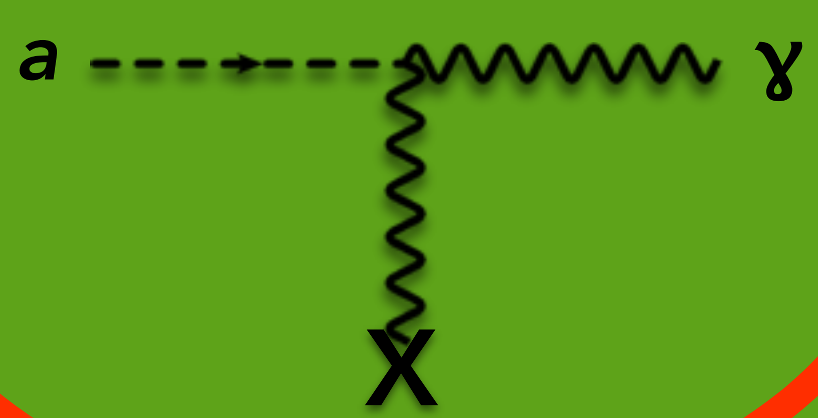
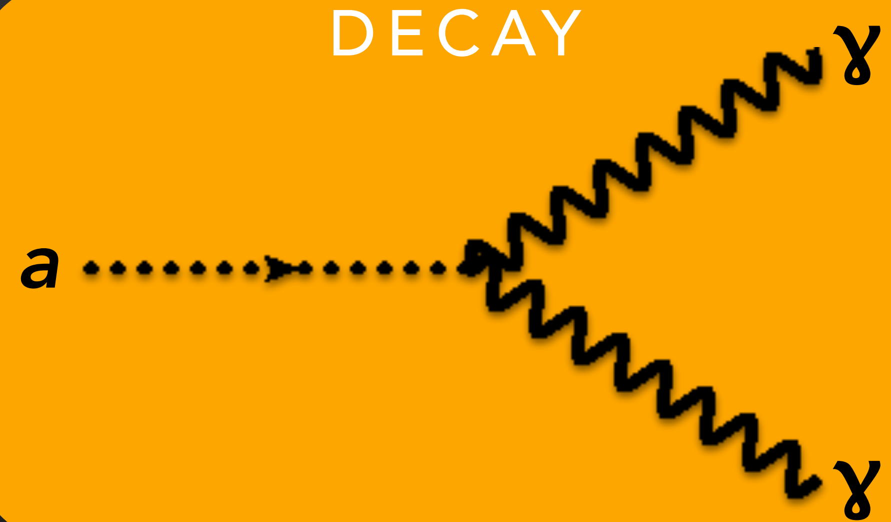
PRIMAKOFF EFFECT



DECAY



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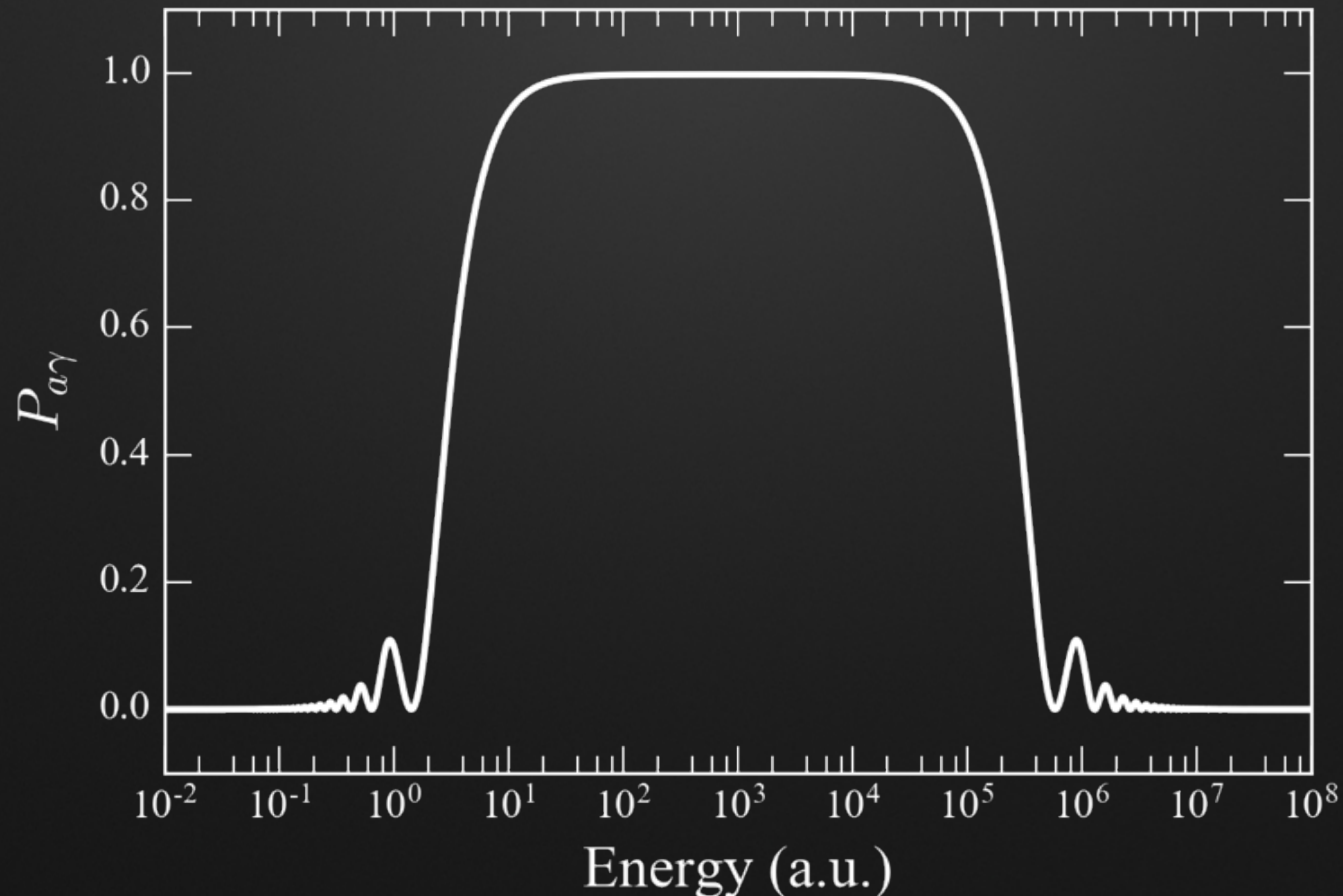
PHOTON-AXION/ALP OSCILLATIONS IN MAGNETIC FIELDS

PHOTON-AXION/ALP MIXING
IN A COHERENT MAGNETIC FIELD



[Raffelt & Stodolsky 1988]

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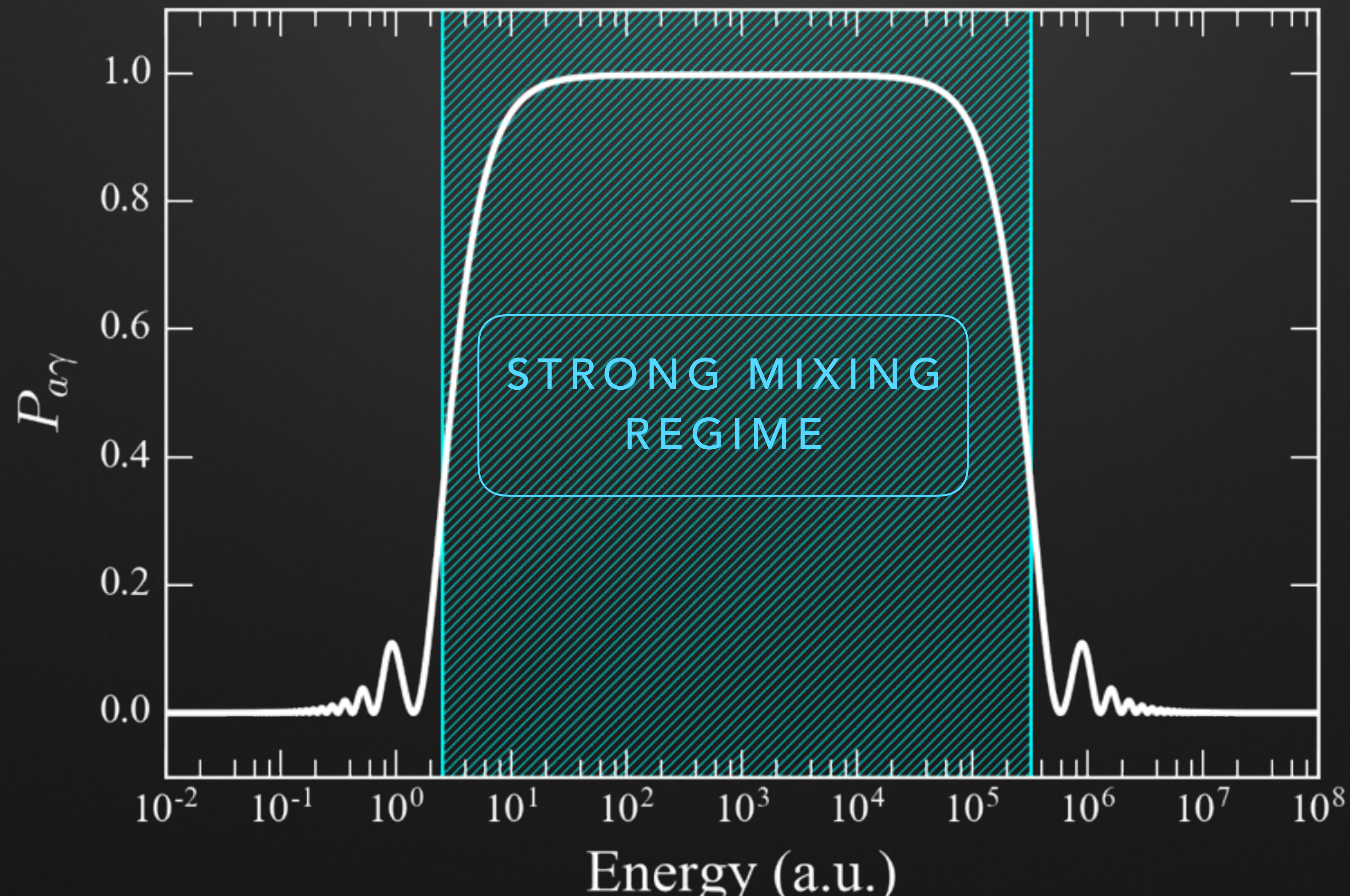


[Raffelt & Stodolsky 1988]

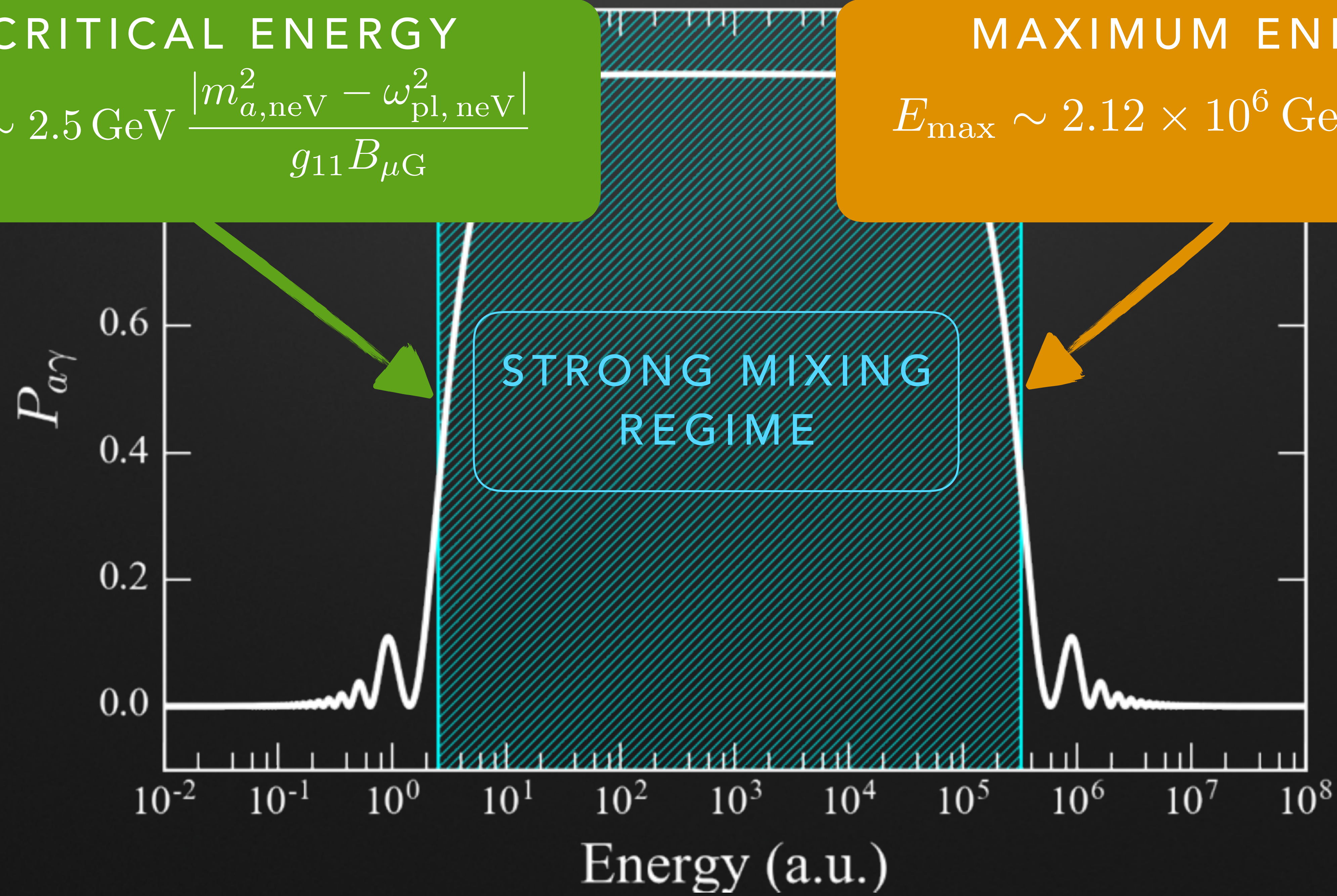
PHOTON-AXION/ALP MIXING

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

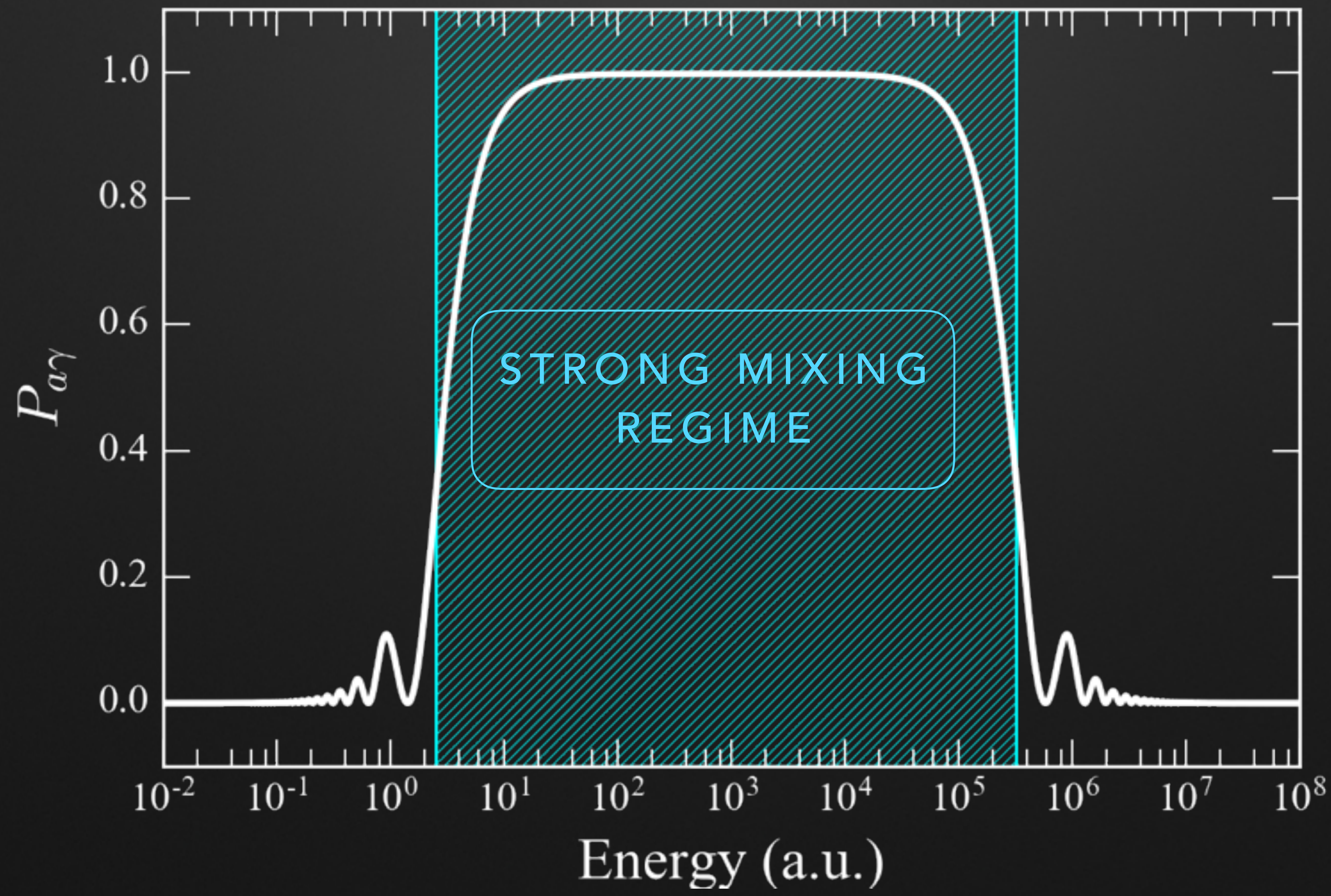
$$E_{\rm max} \sim 2.12 \times 10^6\,{\rm GeV}\,g_{11} B^{-1}_{\mu \rm G}$$



[Raffelt & Stodolsky 1988]

PHOTON-AXION/ALP MIXING

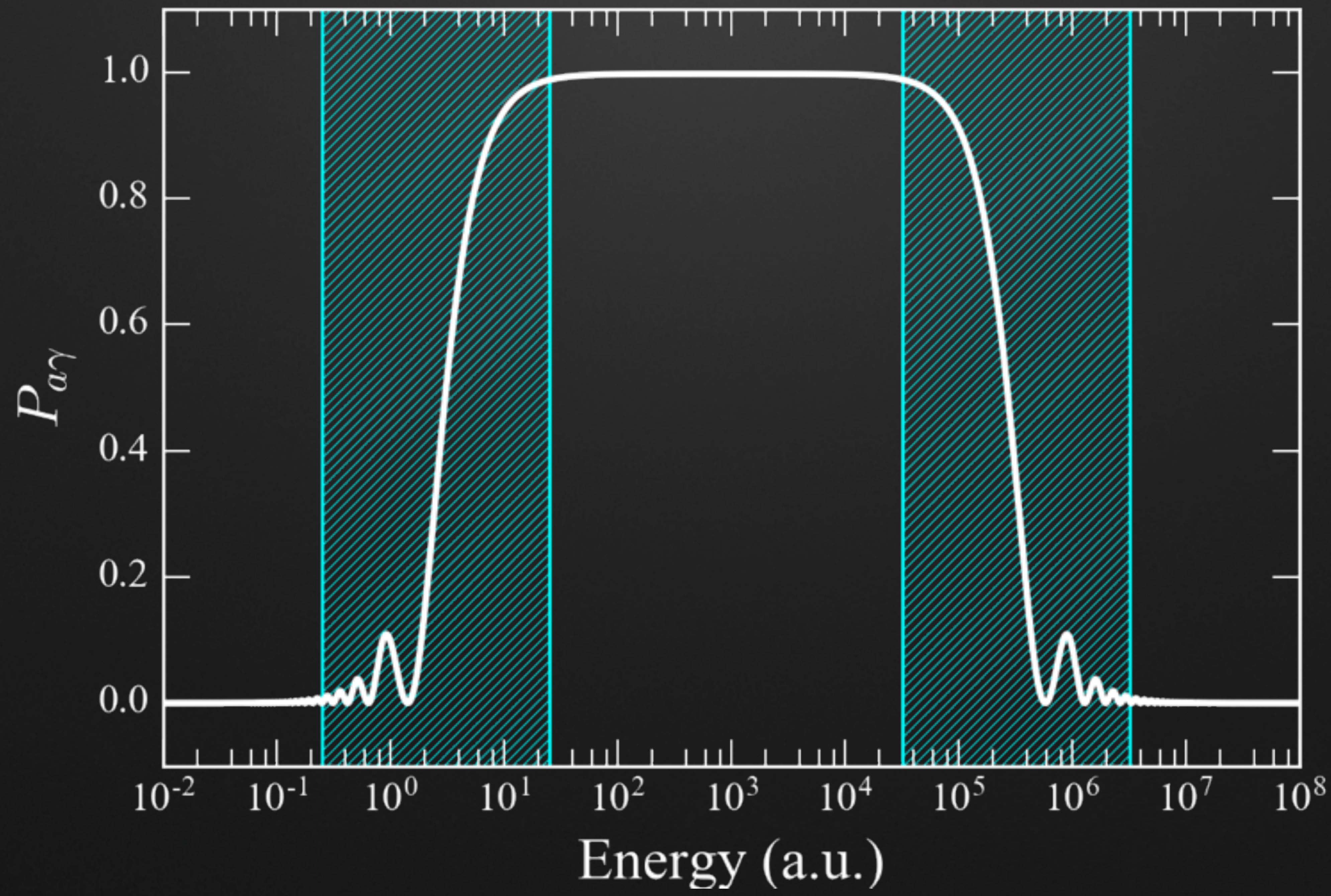
1st Observable: axions/ALPs do not get absorbed during propagation, might lead to a boost in photon flux



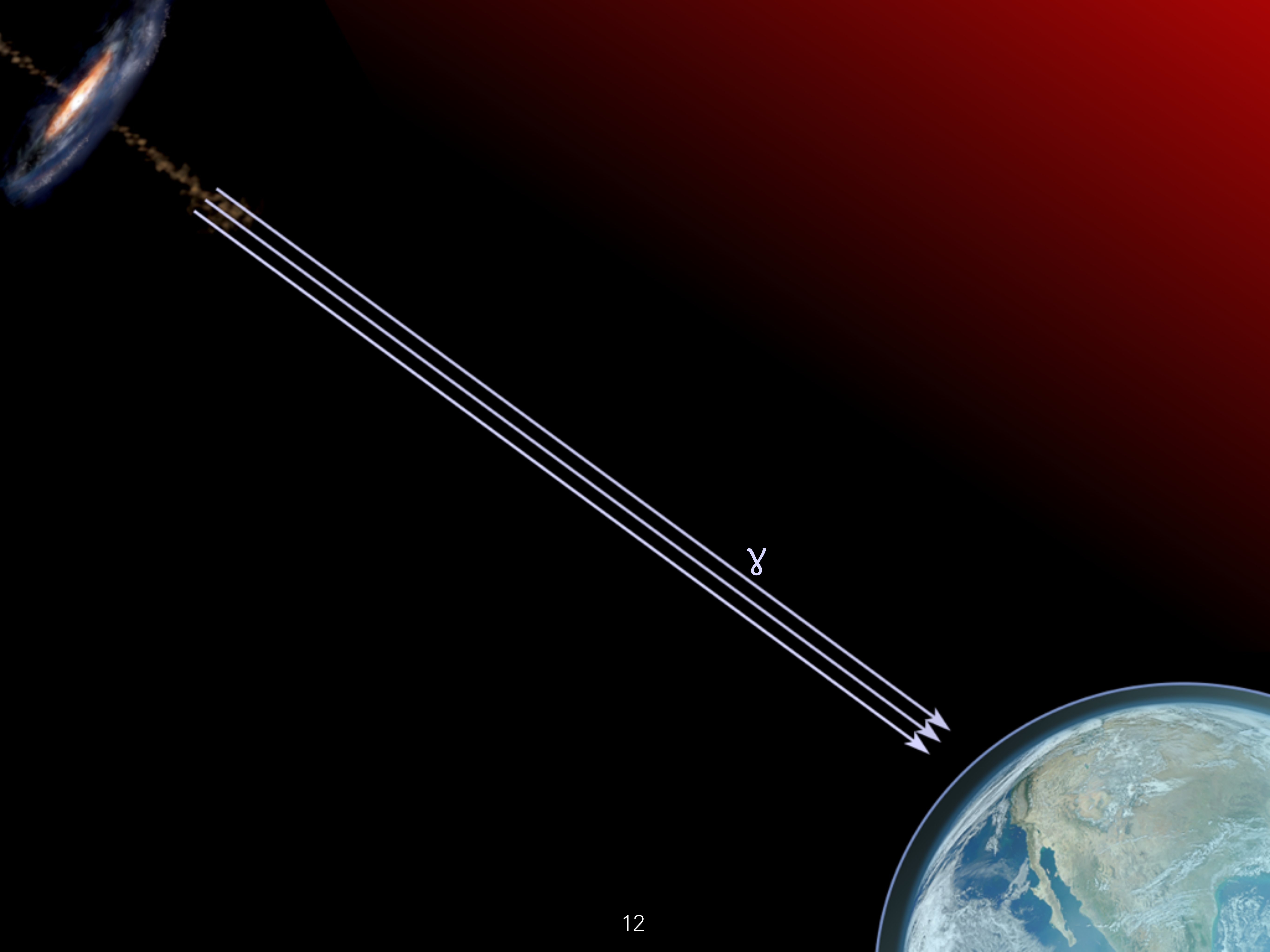
[De Angelis et al. 2007,2011; Simet et al. 2008; Mirizzi & Montanino 2009; Sánchez-Conde et al. 2009; Domínguez & Sánchez-Conde 2011; MM et al. 2013; MM & Conrad 2014]

PHOTON-AXION/ALP MIXING

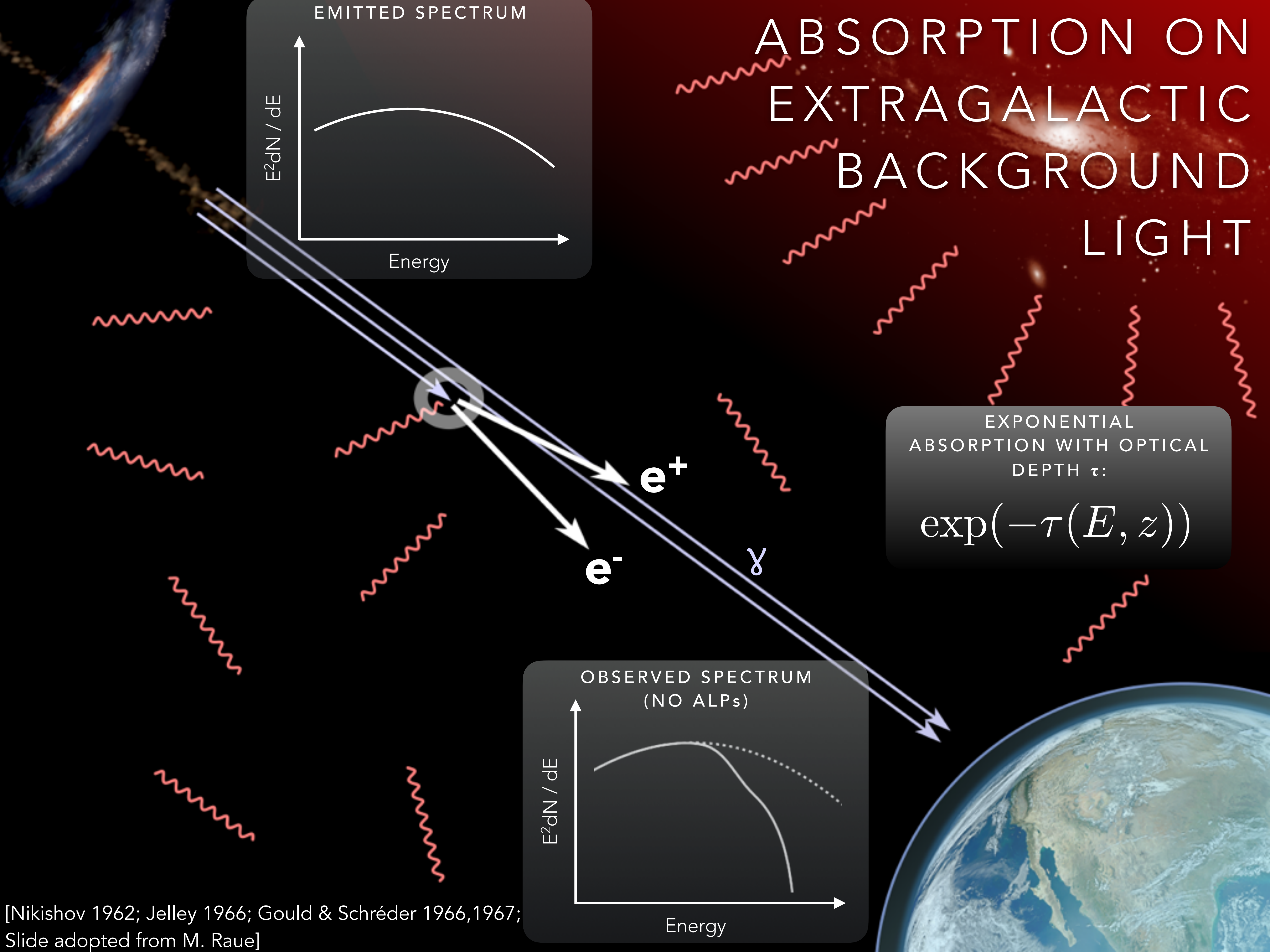
2nd Observable: irregularities in energy spectrum around E_{crit} and E_{max}



[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]

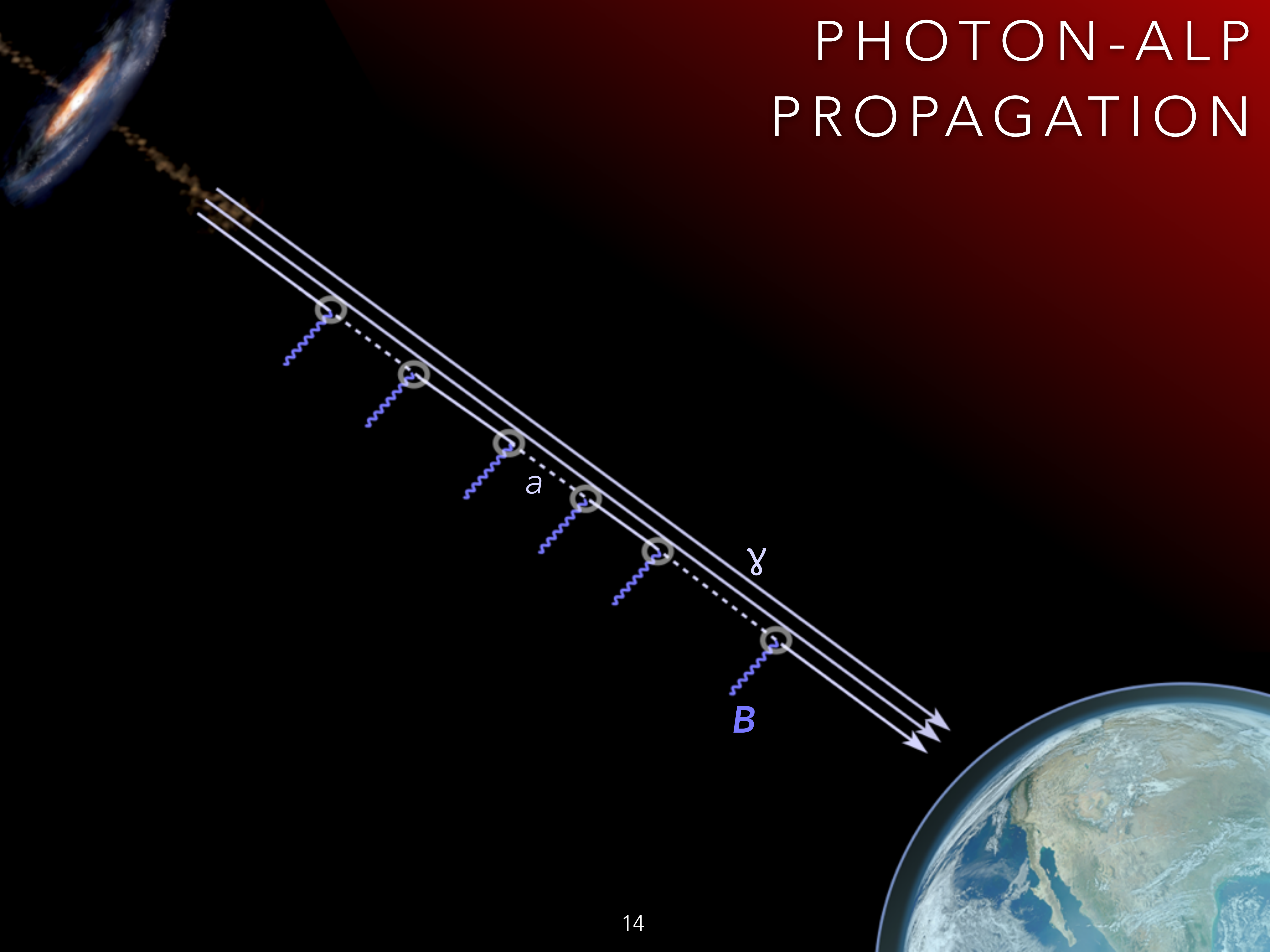

γ

ABSORPTION ON EXTRAGALACTIC BACKGROUND LIGHT

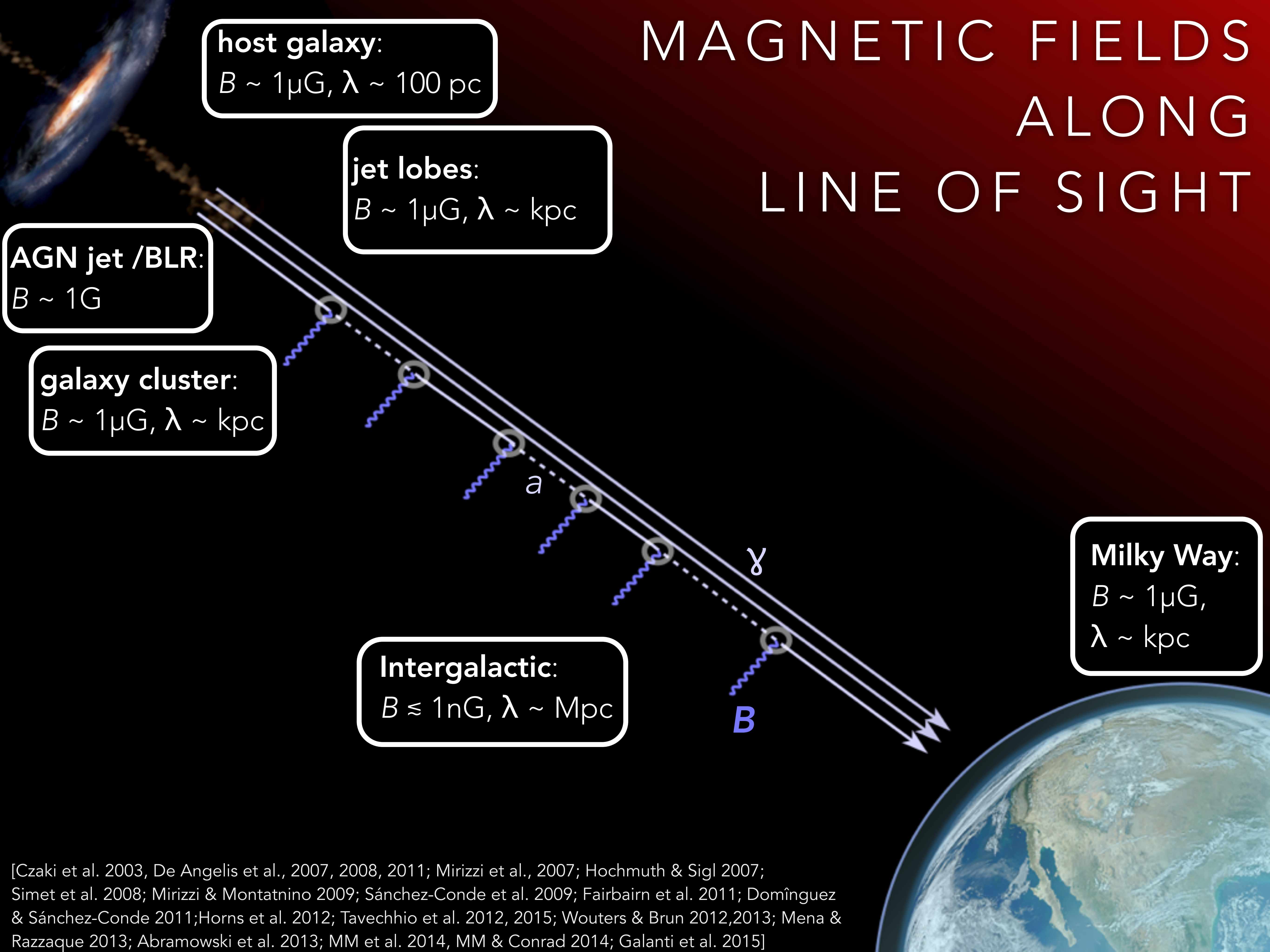


[Nikishov 1962; Jelley 1966; Gould & Schréder 1966,1967; Slide adopted from M. Raue]

PHOTON-ALP PROPAGATION



MAGNETIC FIELDS ALONG LINE OF SIGHT



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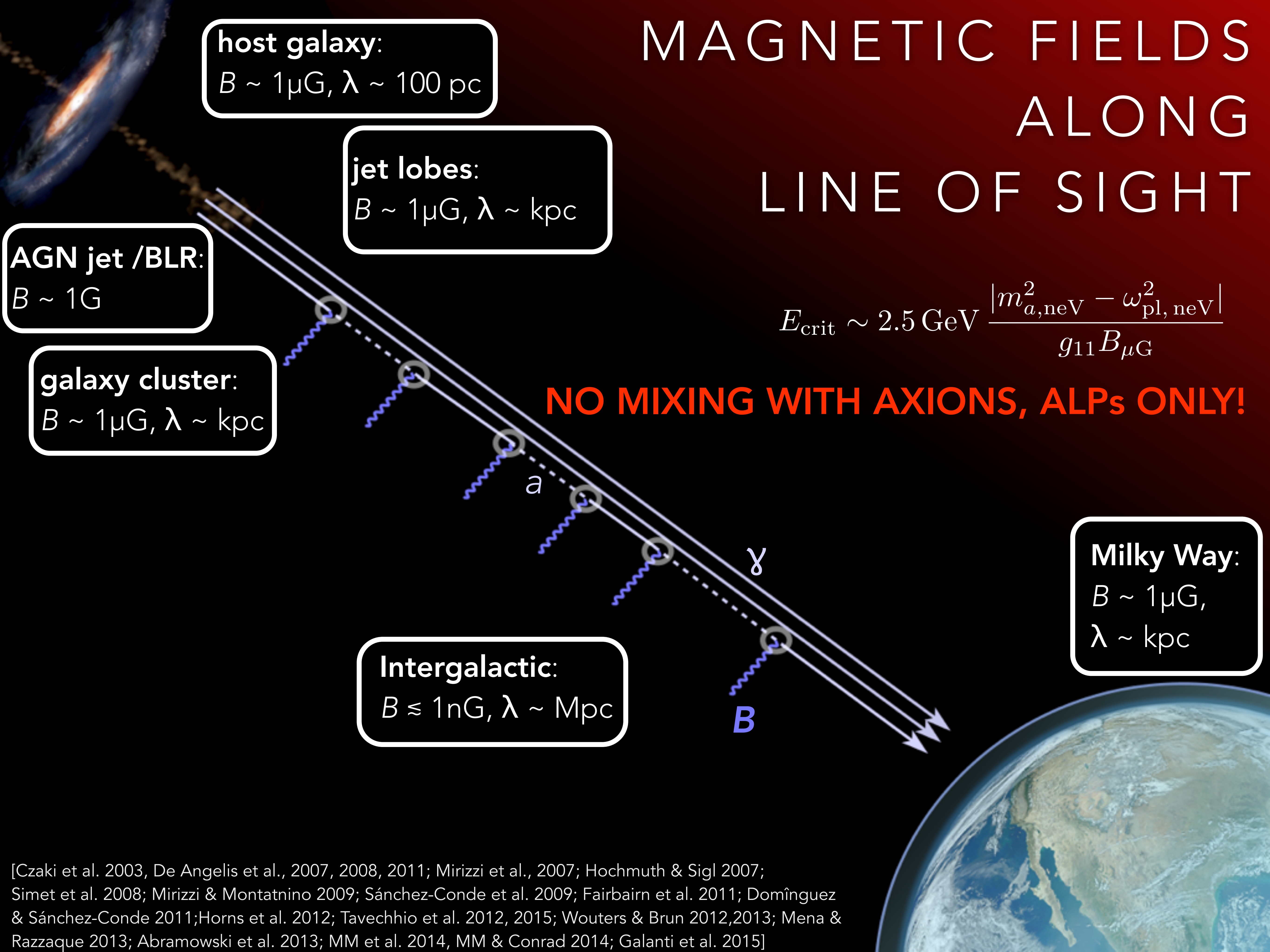

$$E_{\rm crit} \sim 2.5\,{\rm GeV}\,\frac{|m^2_{a,{\rm neV}} - \omega^2_{\rm pl,\,neV}|}{g_{11} B_{\mu{\rm G}}}$$

NO MIXING WITH AXIONS, ALPs ONLY!

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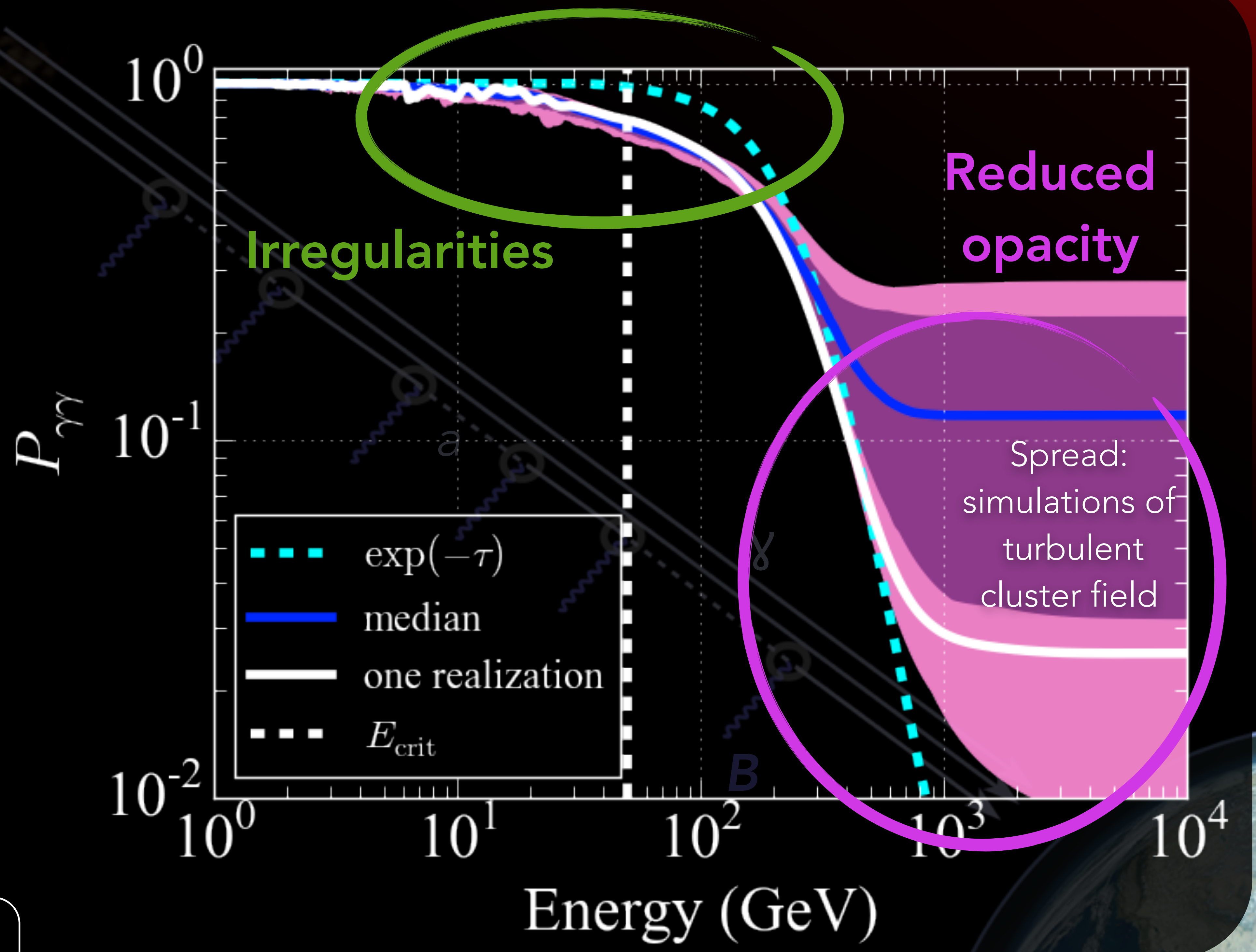
EXAMPLE: MIXING IN GALAXY CLUSTER & MILKY WAY

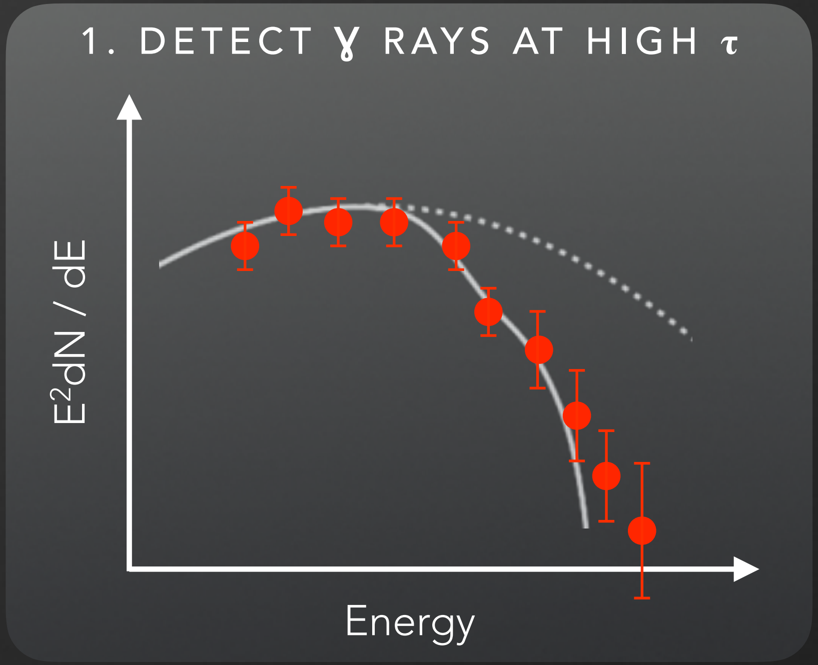


$z = 0.4$
$g_{11} = 5$
$m_{neV} = 10$

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**



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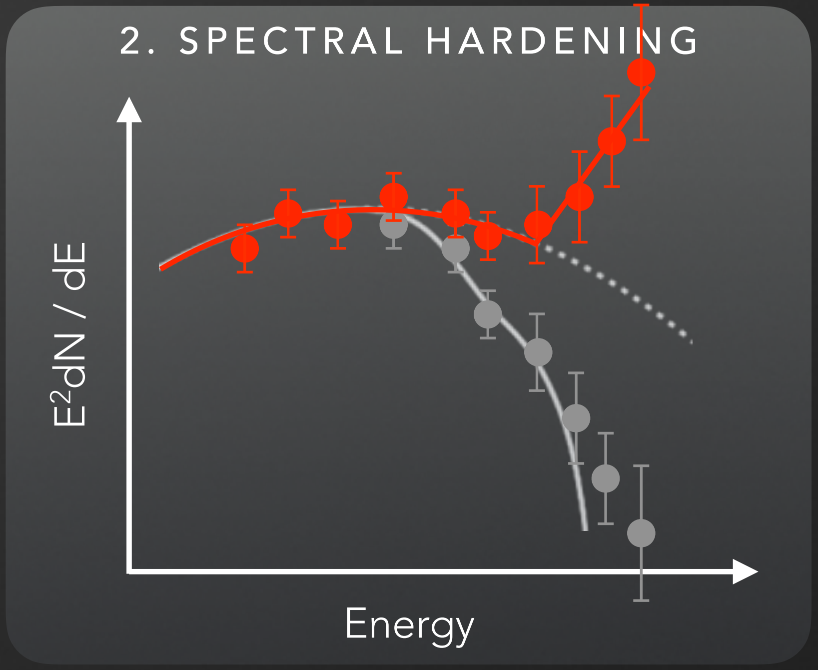

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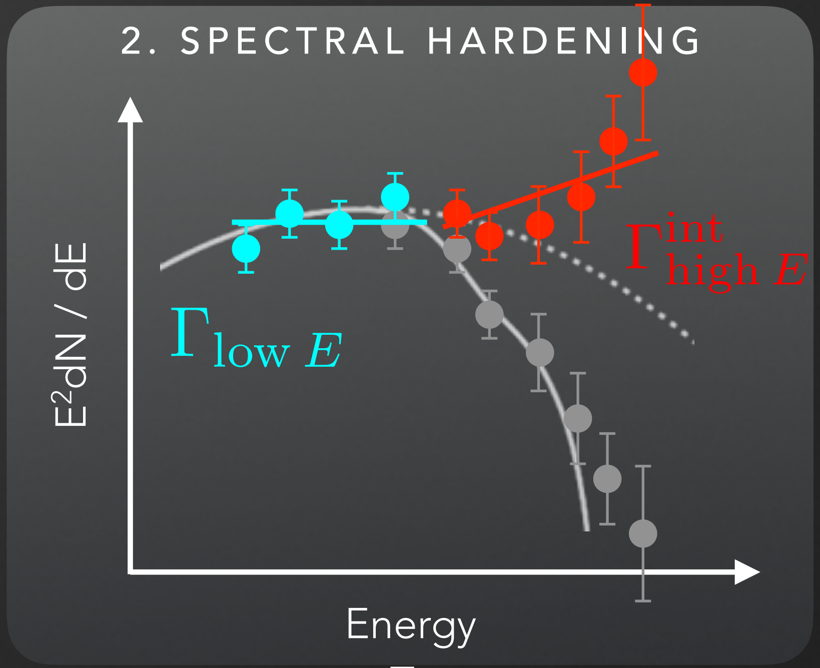
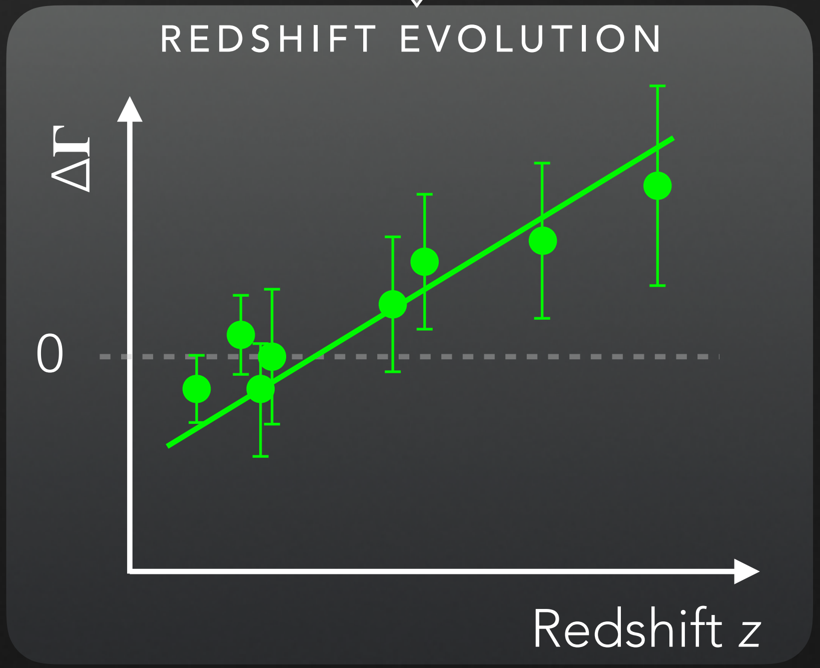
    3. **Absorption corrected spectral indices** should become **harder (lower) with increasing redshift ⇔ Difference in Spectral Indices** at low and high energies should be **> 0 and evolve with redshift**

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





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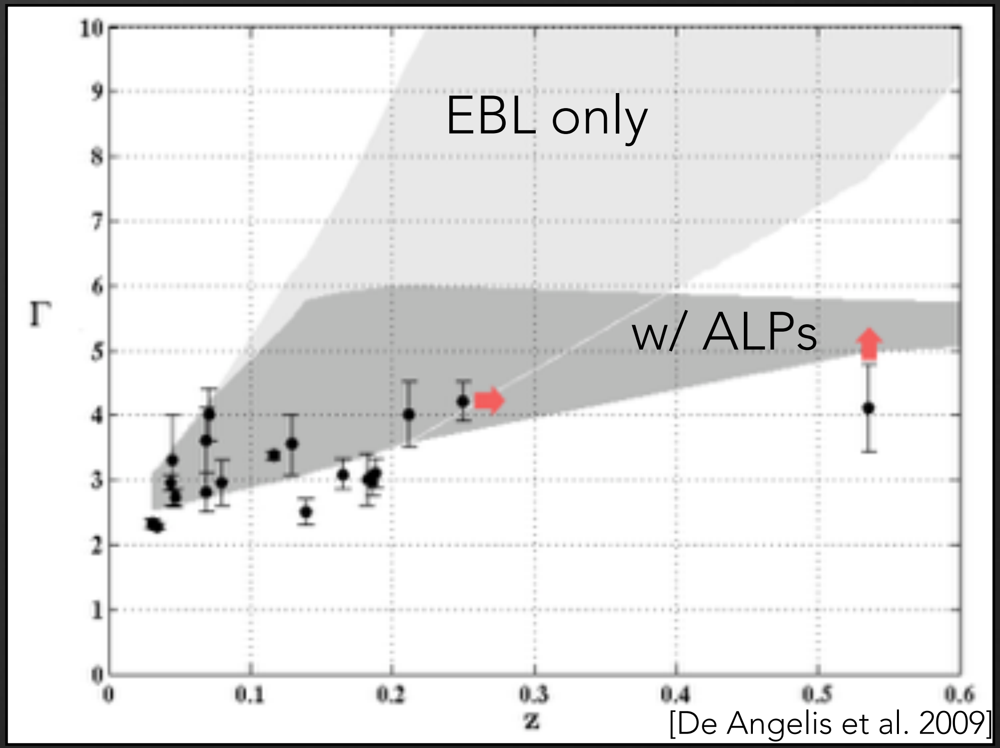

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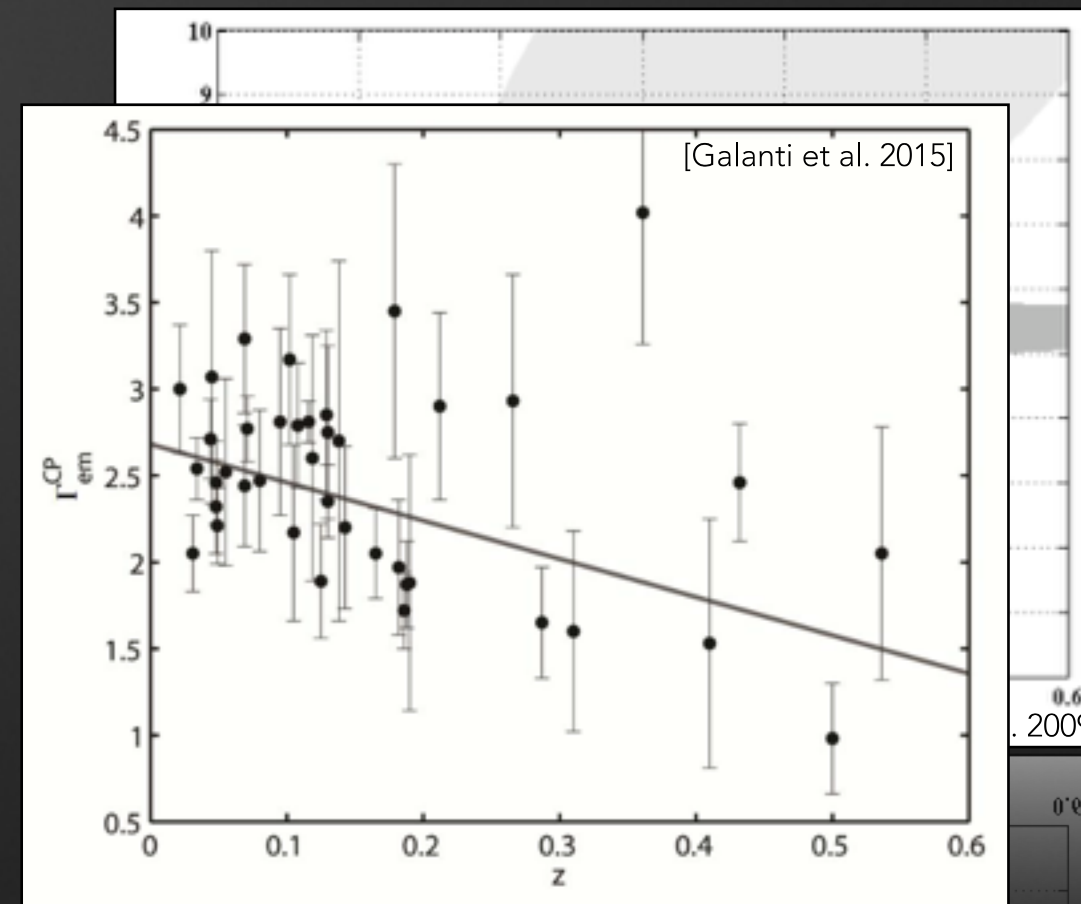

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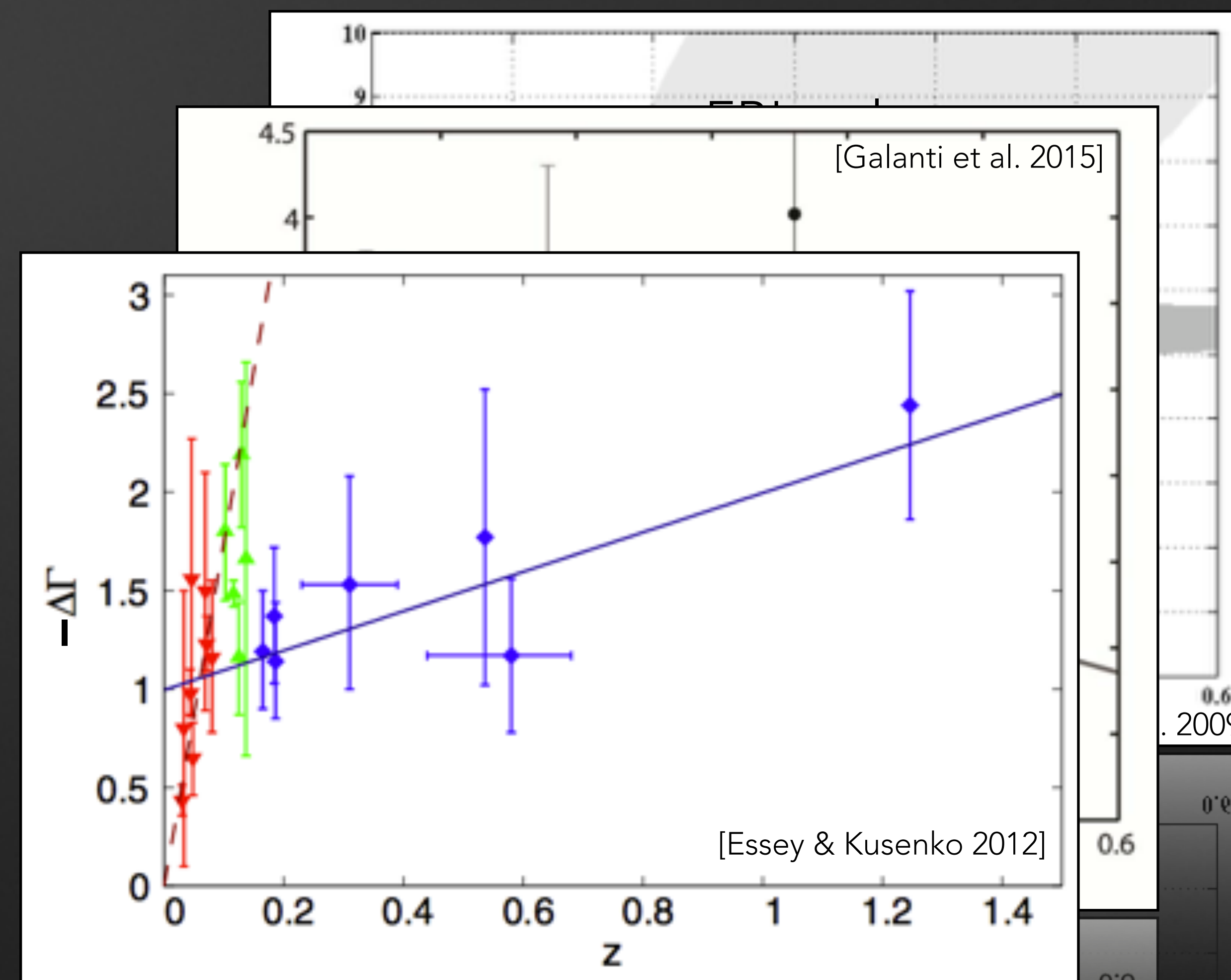

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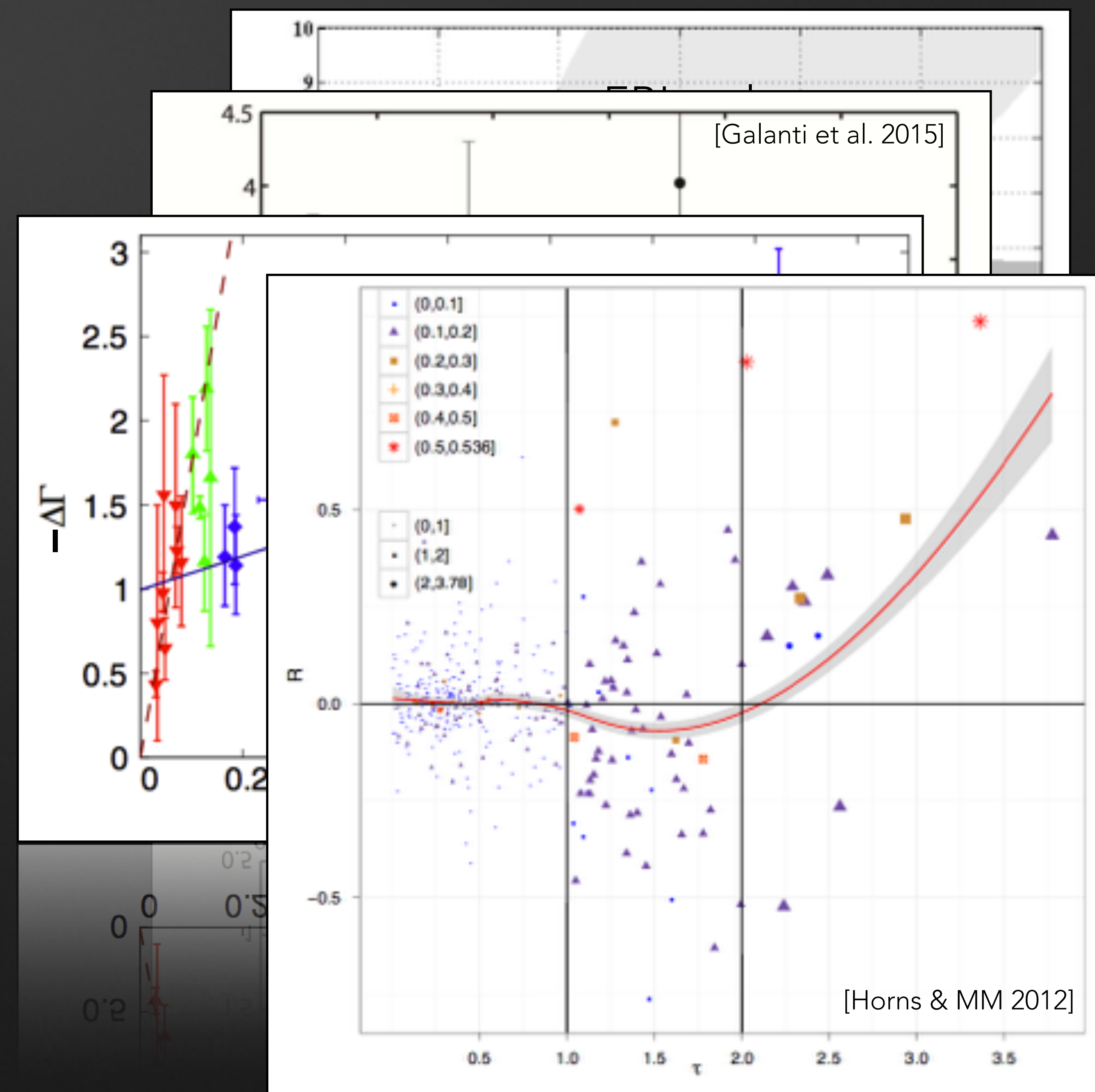
- Horns & MM (2012): evolution of spectral residuals / flux with optical depth, significant at ~4σ level



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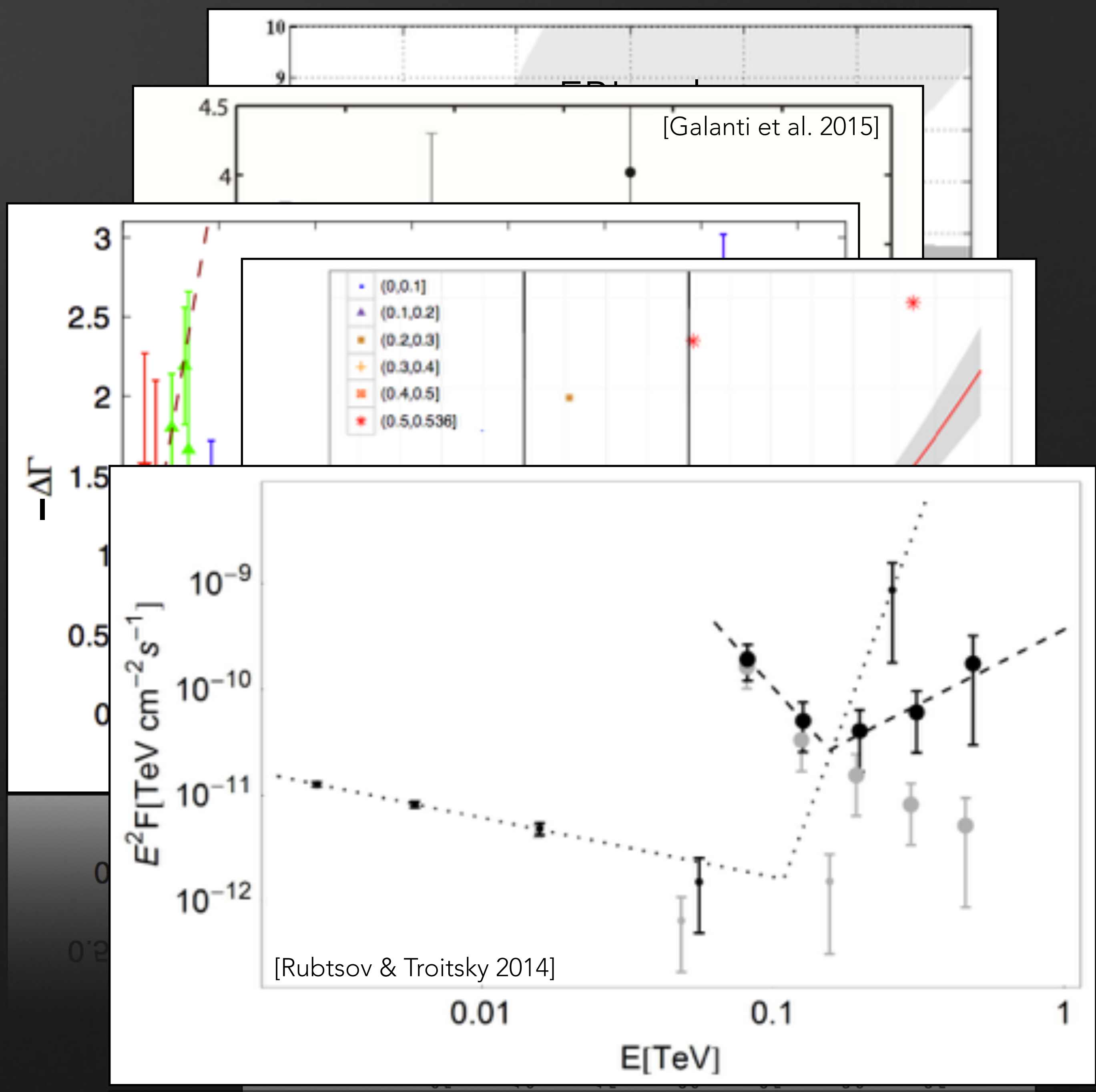

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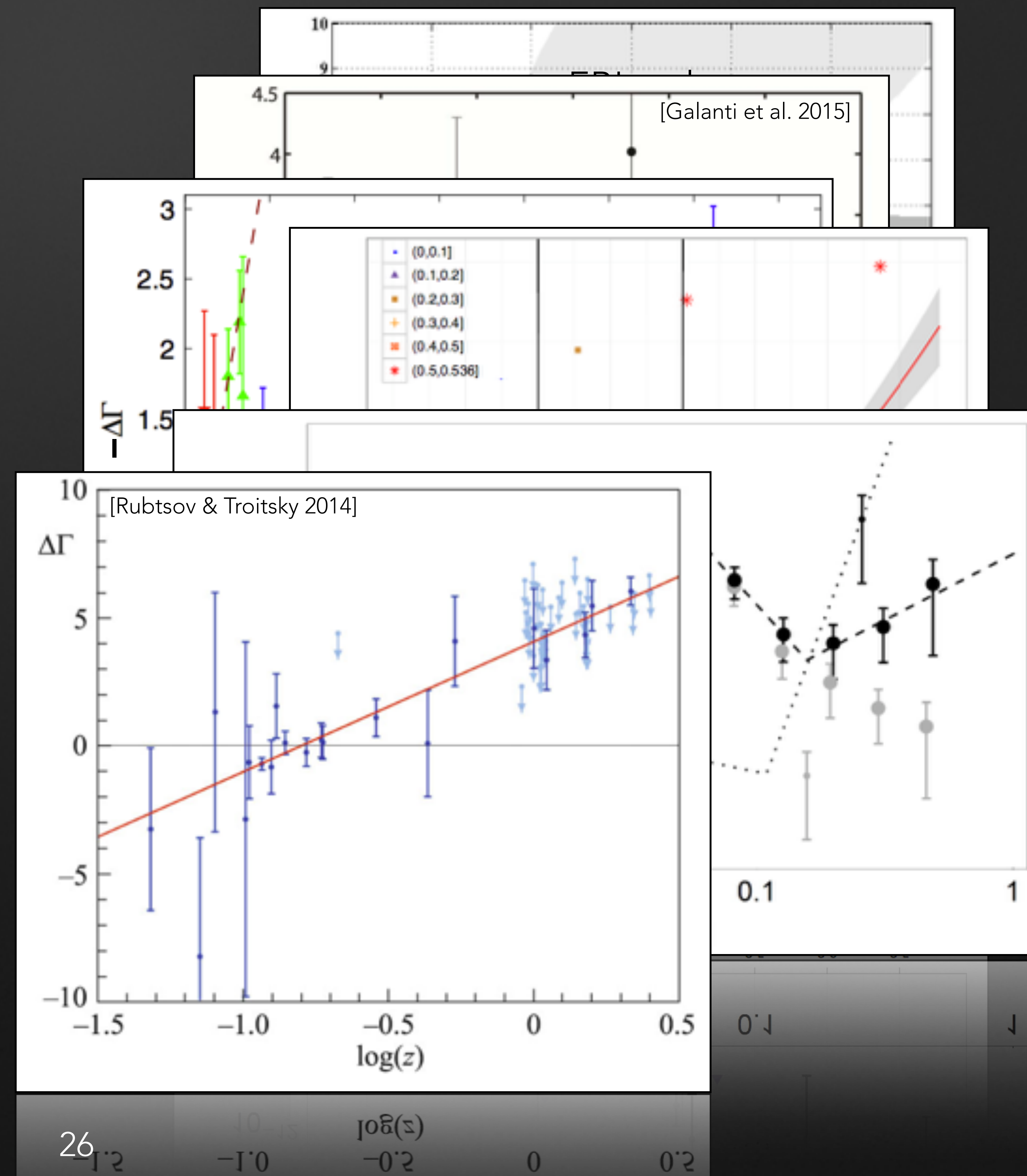
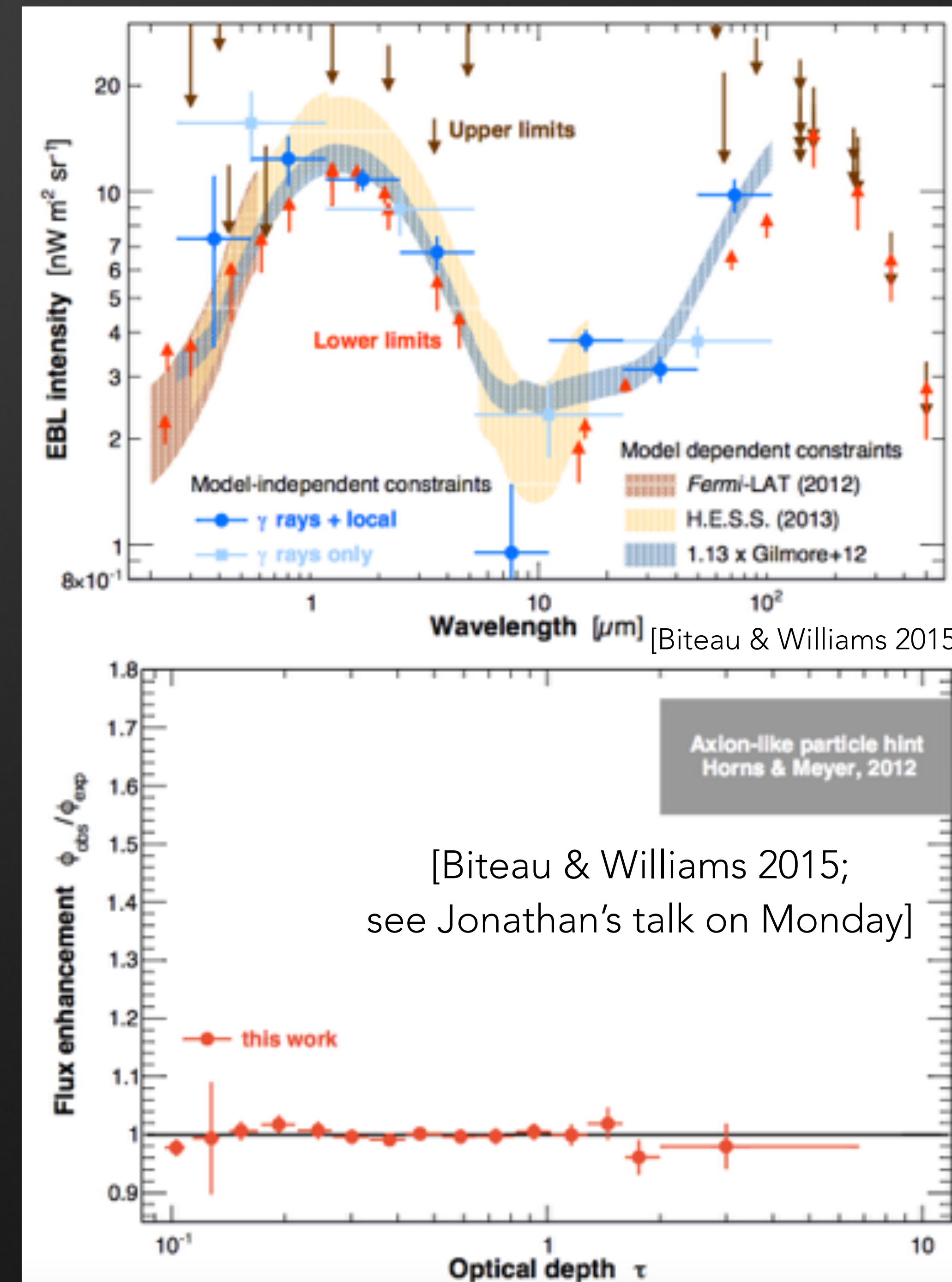


RECENT ANALYSES DO NOT FIND HINT

- Biteau & Williams (2015):
  - Used large set γ-ray observations + direct observations to derive EBL intensity
  - Do not find evolution of flux / residuals with τ



[Biteau & Williams 2015]

[Biteau & Williams 2015;
see Jonathan's talk on Monday]

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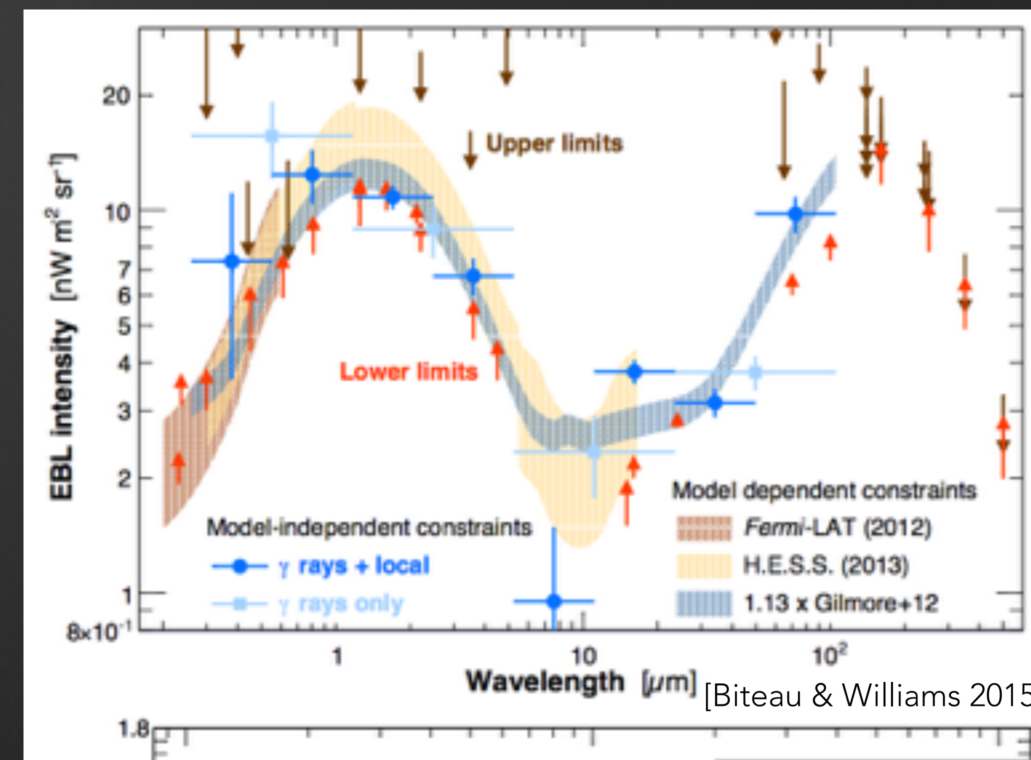
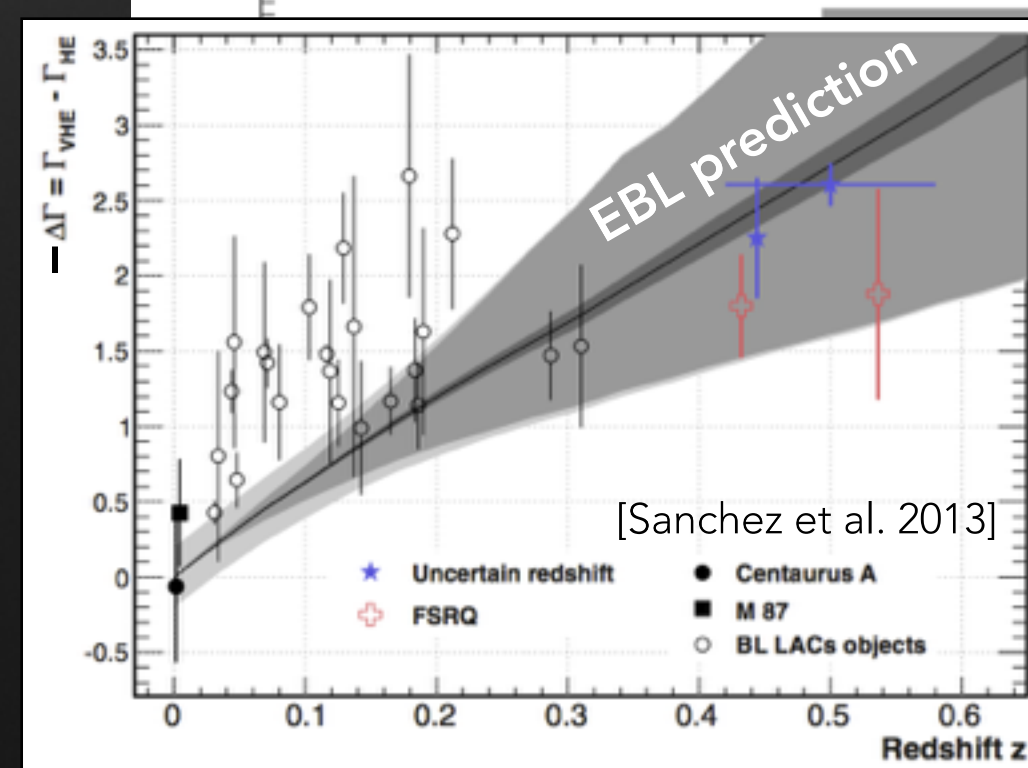
    - Bayesian analysis: data consistent with EBL expectations





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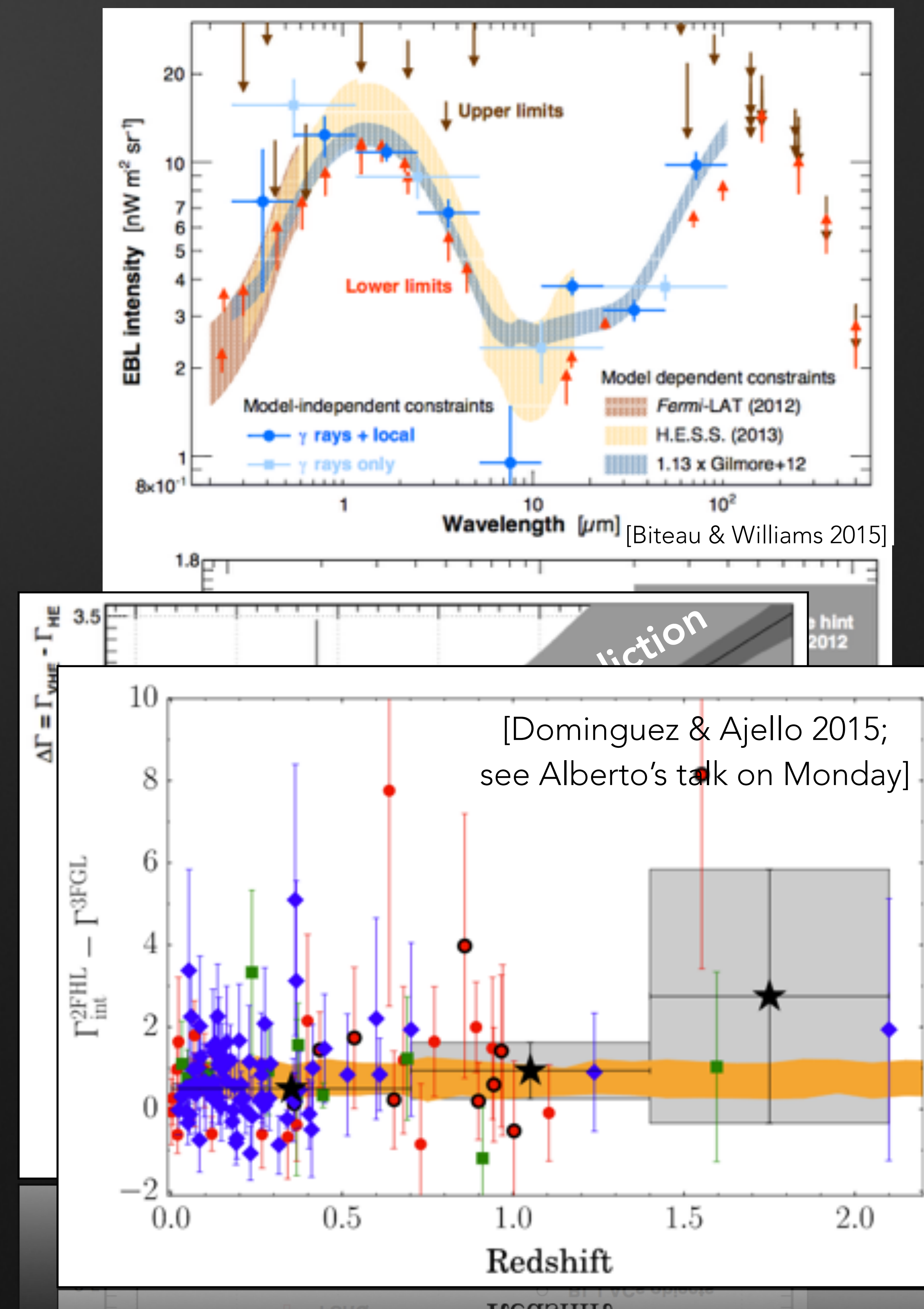
- Domínguez & Ajello (2015):
  - Derive intrinsic spectra for 2FHL sources
  - Do not find evolution of spectral break with redshift
  - Consistent with expectations from EBL only, tested with simulations

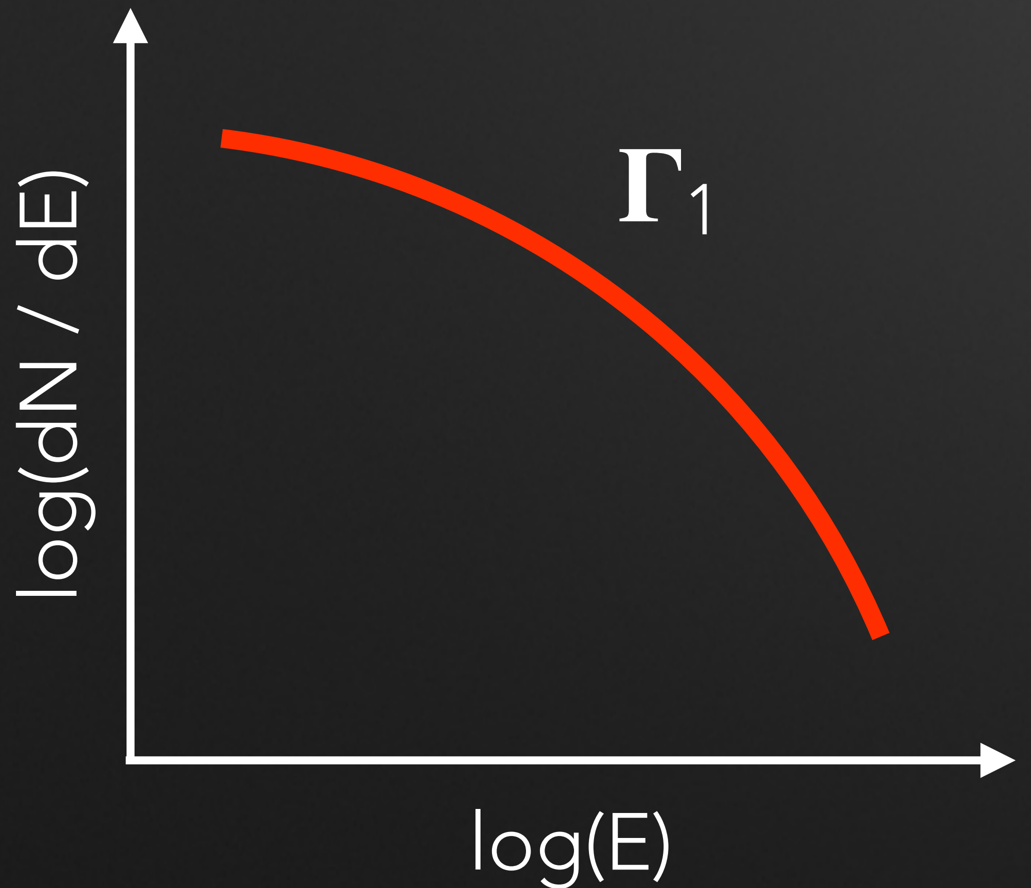


[Biteau & Williams 2015]

[Dominguez & Ajello 2015; see Alberto's talk on Monday]

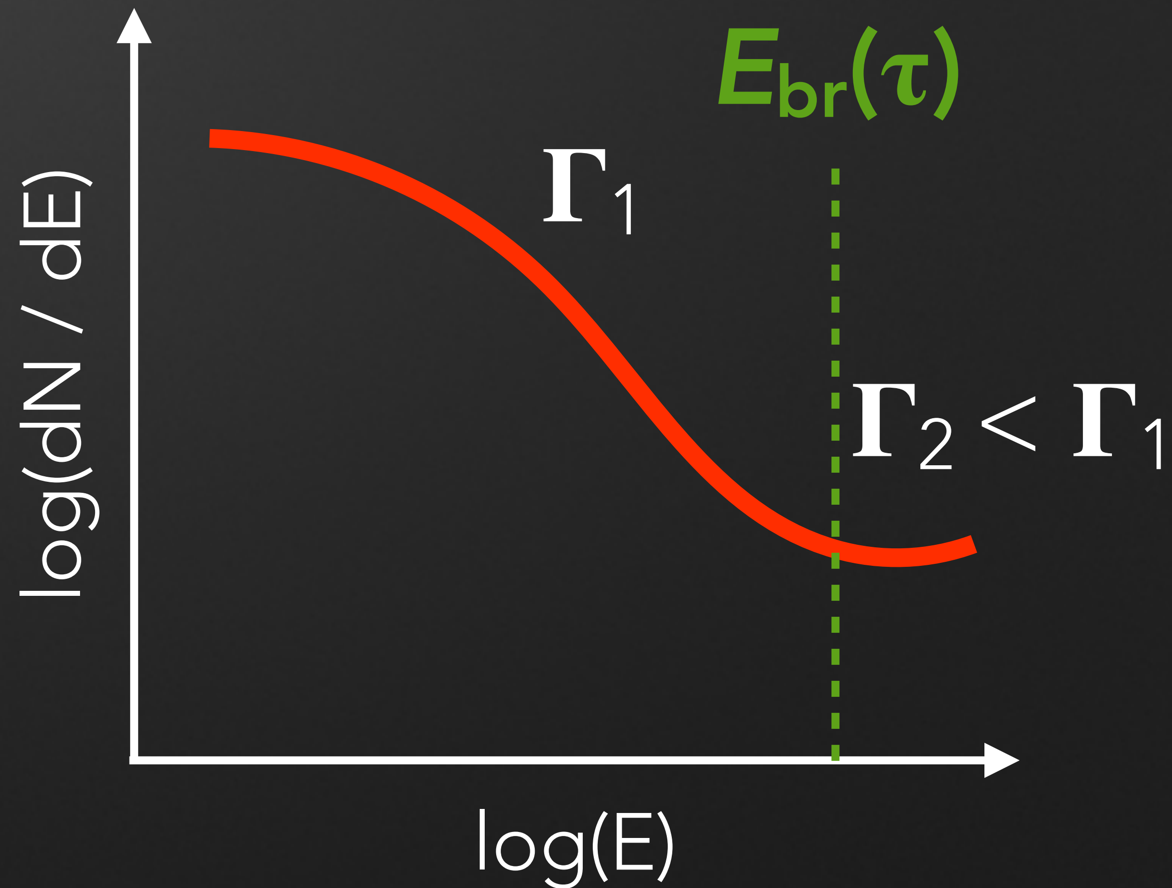
FUTURE: COMBINED LIKELIHOOD ANALYSIS WITH ALL IACTs?

PL + EBL absorption



vs

BPL + EBL absorption

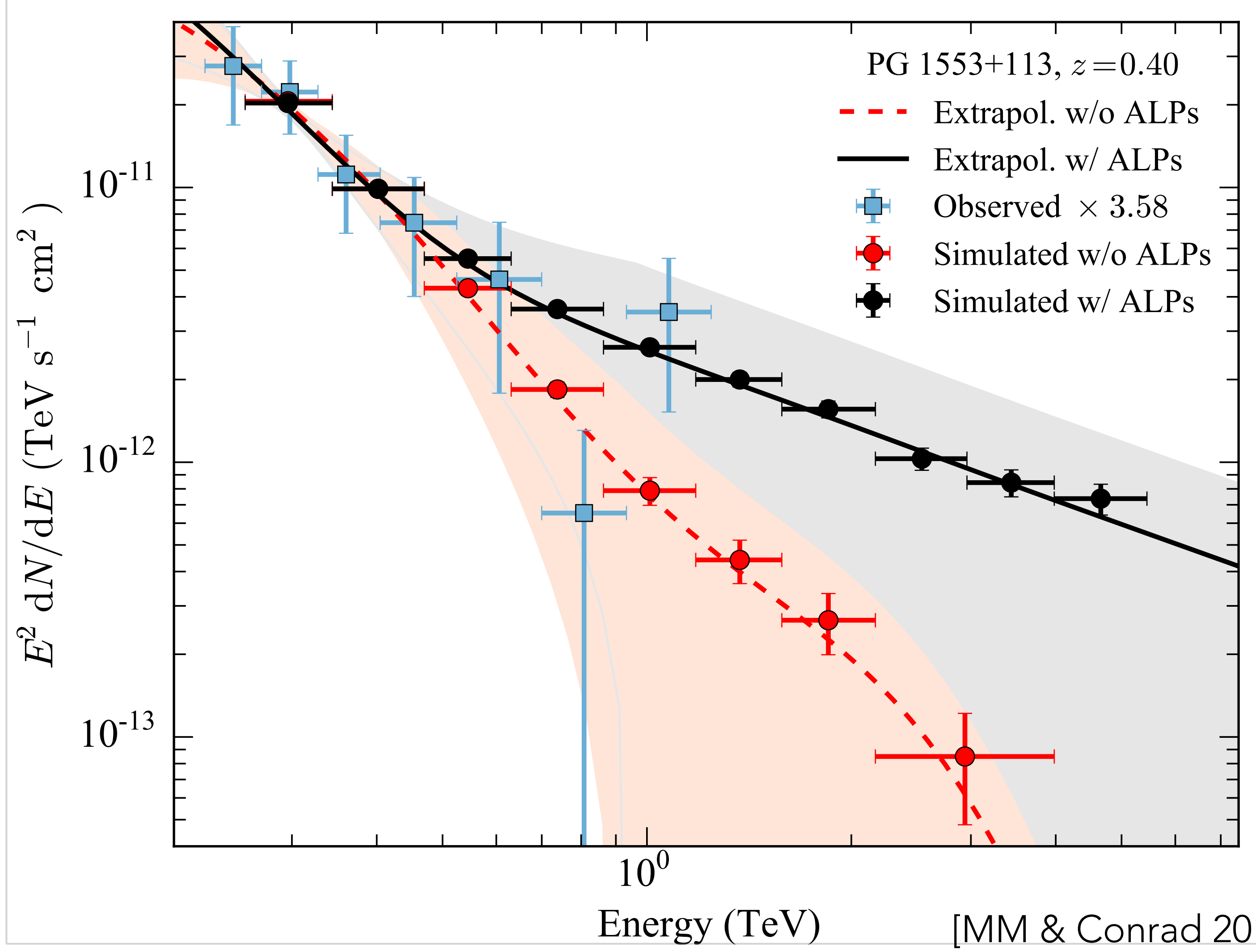


- Analyses so far relied on published data points — difficult to assess **possible pile up** at highest energies
- Release of likelihood curves to easy combine results

[Similar to Rubtsov & Troitsky 2014]

POTENTIAL WITH CTA

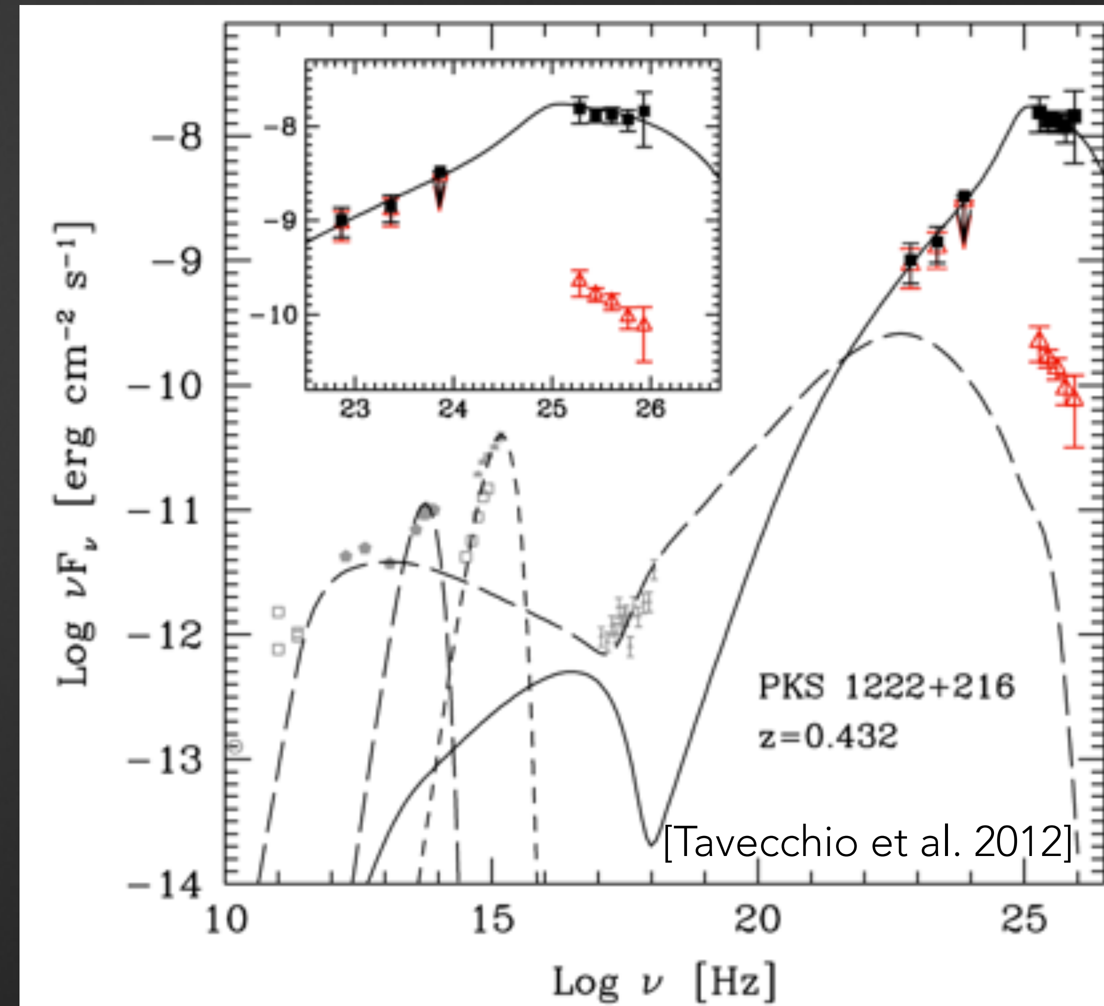
- CTA will have **~10 times the sensitivity** of current IACTs [see David's talk tomorrow]
- **Wide energy range** allows to probe intrinsic spectrum and attenuated spectrum simultaneously
- **Would detect ALPs that could explain low opacity hints**

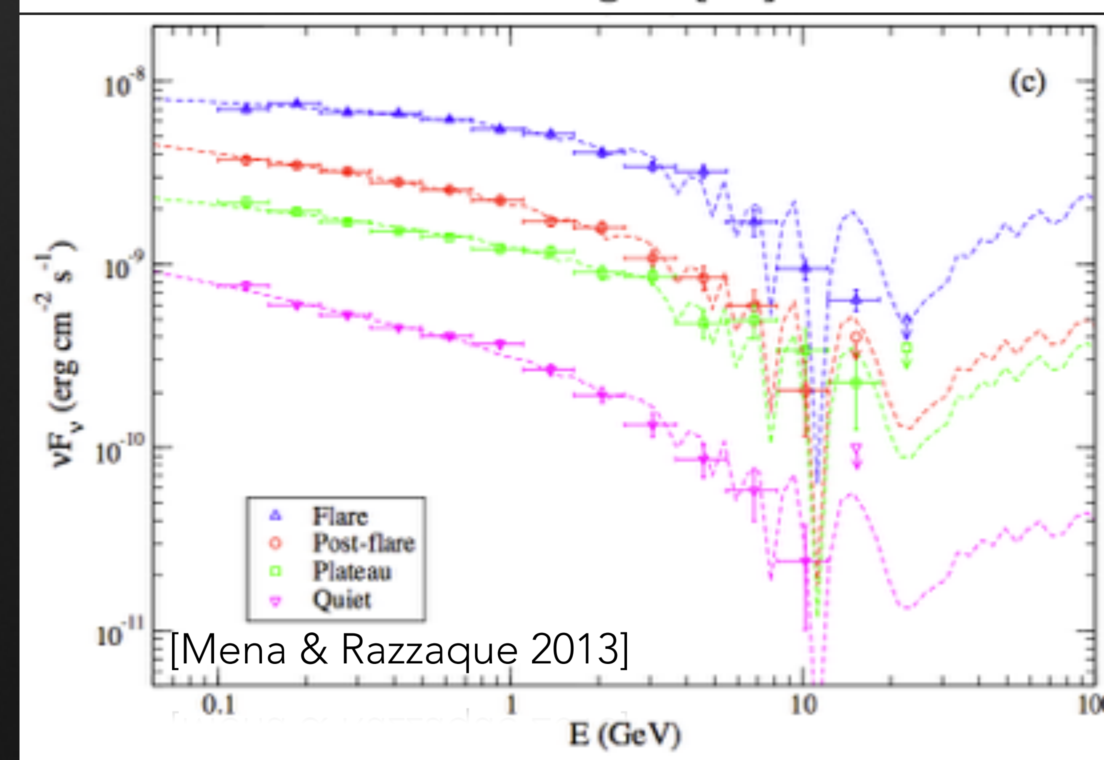


[MM & Conrad 2014]

PHOTON-ALP MIXING IN FSRQs

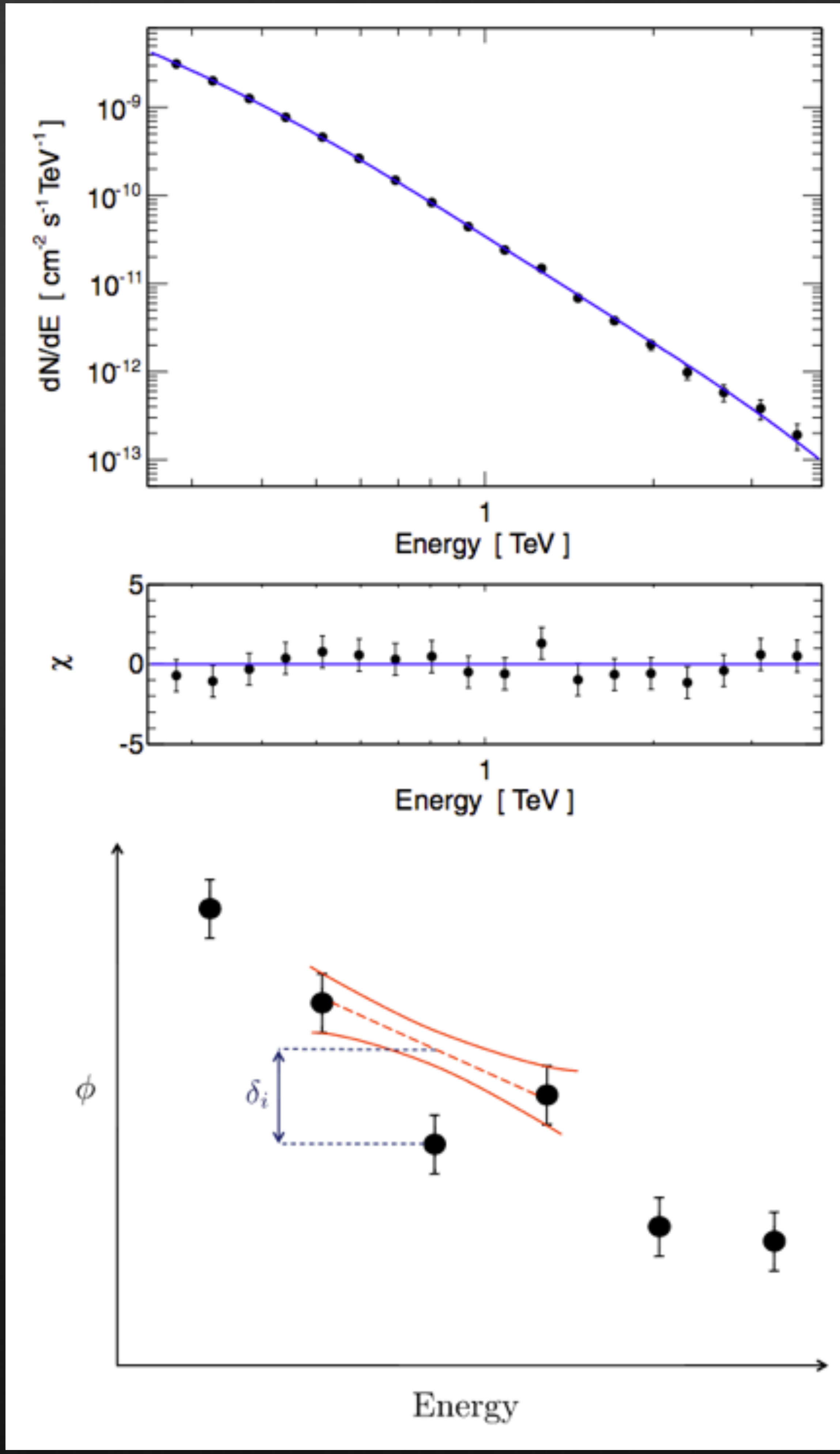
- **ALPs** would also evade pair production in **broad line region of FSRQs**
- Could help to **explain short time variability** of PKS1222+216 for ɣ rays produced close to central engine [Tavecchio et al. 2012]
- ALPs could also explain **spectral breaks in FSRQ spectra** (could also be caused by ɣɣ absorption) [Mena & Razzaque 2013] with spectral irrgularities





CONSTRAINTS FROM SEARCHES FOR SPECTRAL IRREGULARITIES

- Searches require **high signal-to-noise spectra** and **good energy resolution**
- First constraints from **H.E.S.S. observations of PKS2155-304** during flare
- Looked for **local deviations from power law**
- Deviations should be larger if ALPs with certain mass and photon coupling existed



[Abramowski et al. 2013]

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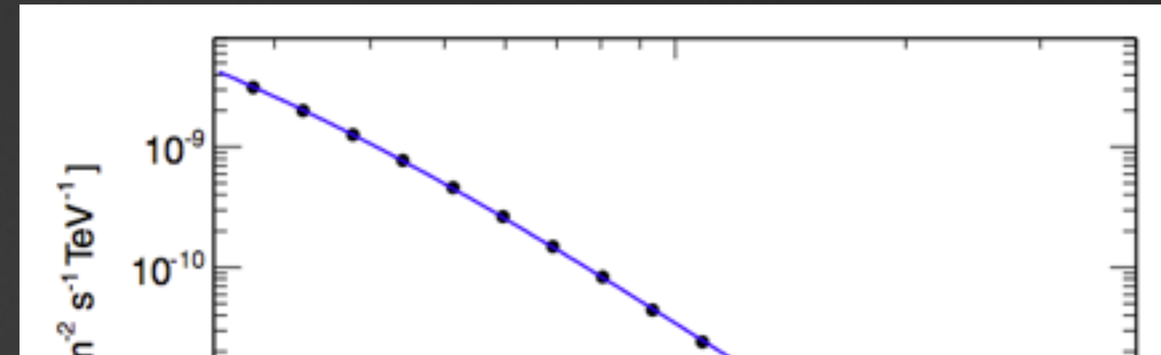
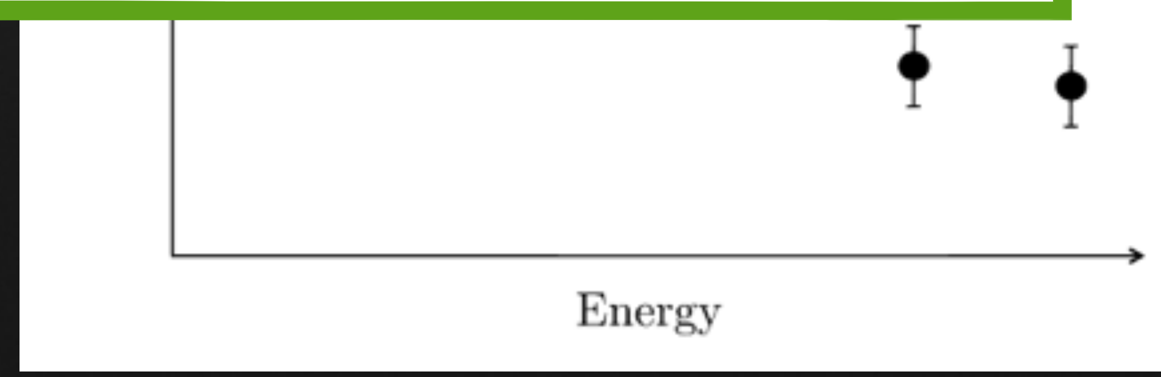
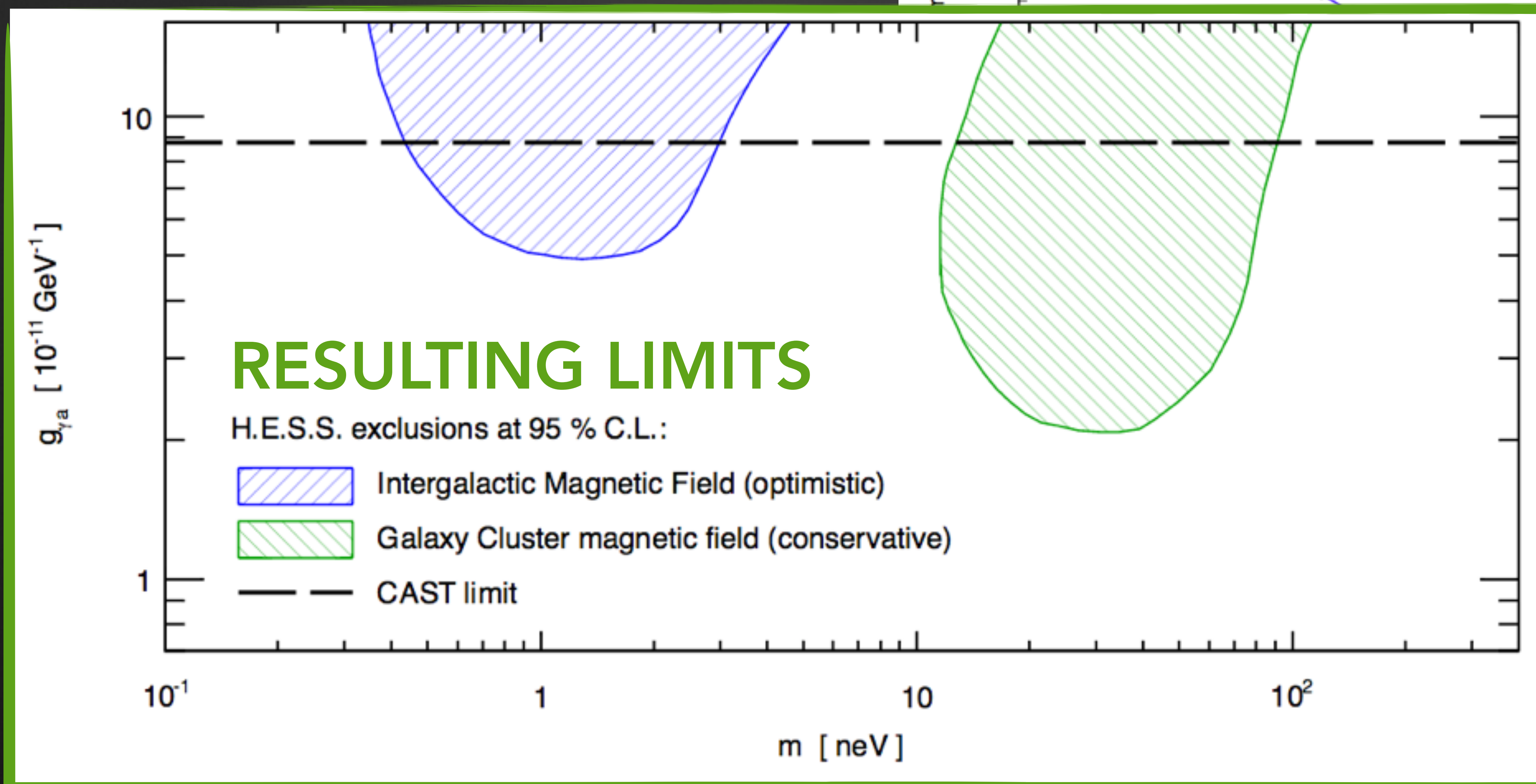






ALPs with certain mass and photon coupling existed

[Abramowski et al. 2013]

SEARCH FOR IRREGULARITIES WITH FERMI LAT FROM NGC 1275

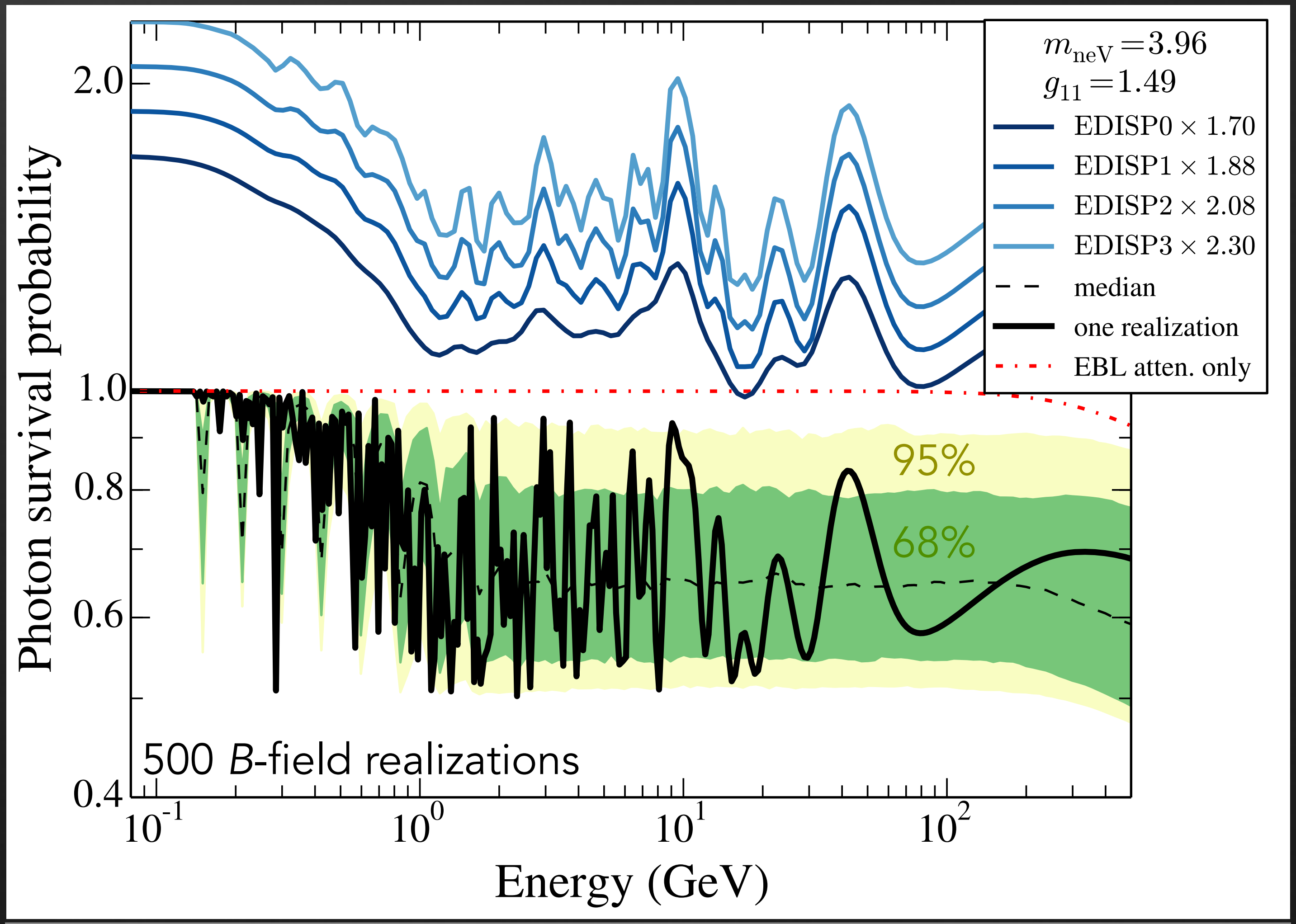
- **Radio galaxy NGC 1275**, **bright *Fermi* source** [e.g. Abdo et al. 2009]
- In the center of **cool-core** Perseus cluster
- Rotation measures: **central** B field ~**25μG** [Taylor+ 2006]
- **B ≳ 2 μG from non-observation of ɣ rays** [Aleksic et al. 2012]

[Ajello et al. 2016]

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

MODELING PHOTON-ALP CONVERSIONS IN PERSEUS CLUSTER

$$P_{\gamma\gamma}(E, m_a, g_{a\gamma}, \mathbf{B})$$



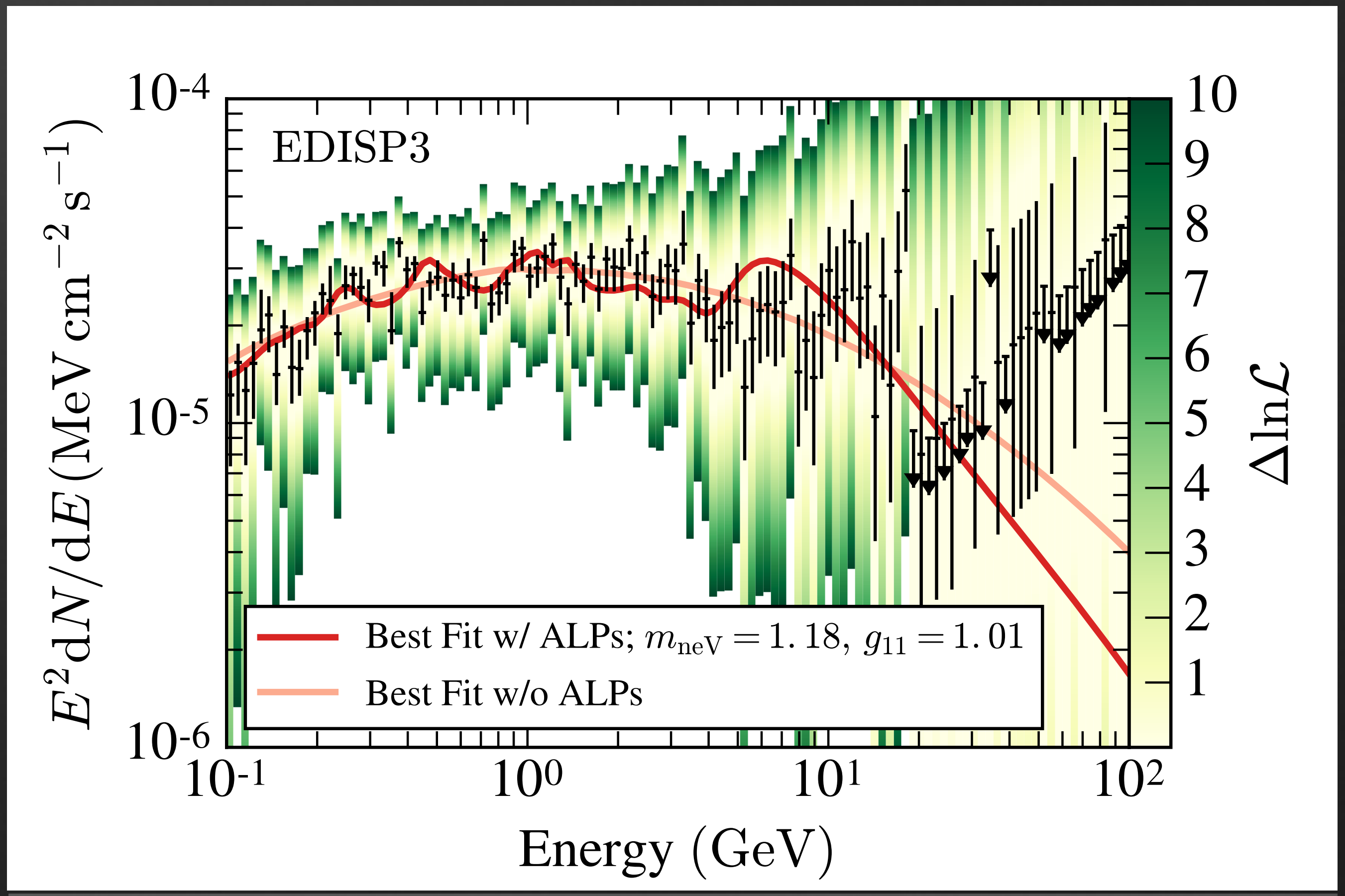
- Considered *B* fields: **Perseus cluster & Milky Way**
- **Conservative** estimate of central *B* field: **10 μG** [Aleksić et al. 2012]
- Includes **EBL absorption**

[Ajello et al. 2016]

FERMI-LAT DATA ANALYSIS

Fermi Gamma-ray Space Telescope

- **6 years** of **Pass 8** Source data
- Split into analysis **EDISP event types**
- Method: **log-likelihood ratio test** for no-ALP and ALP hypothesis
- Use **bin-by-bin likelihood curves**, similar to dSph analysis [Ackermann et al. 2014,2015]
- 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.; Intrinsic spectrum

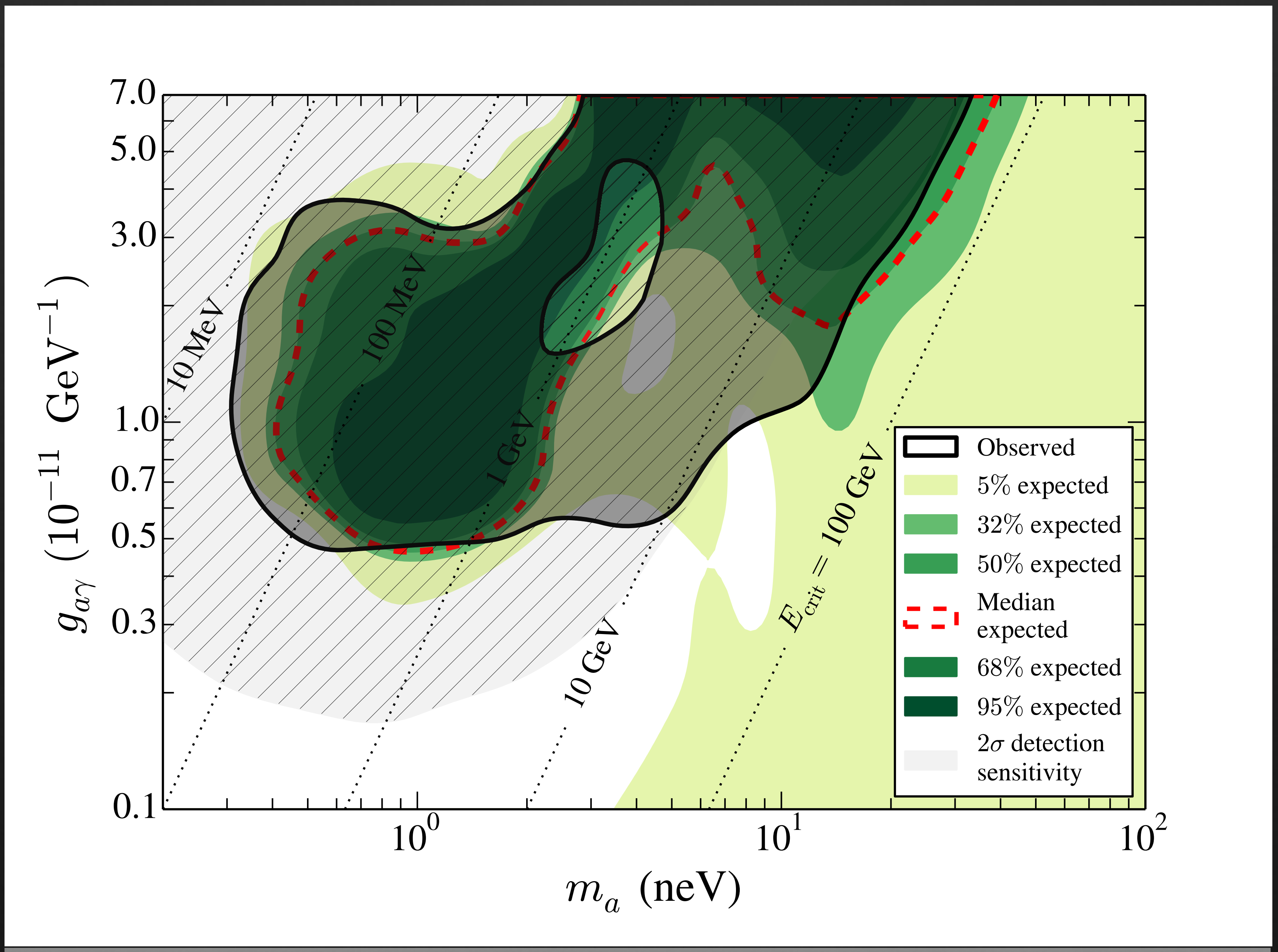
NO-ALP HYPOTHESIS: $\exp(-\tau) F(E)$

EBL attenuation only; Intrinsic spectrum

[Ajello et al. 2016]

NO ALP OBSERVED: CONSTRAINTS

FIT WITH ALPS NOT PREFERRED

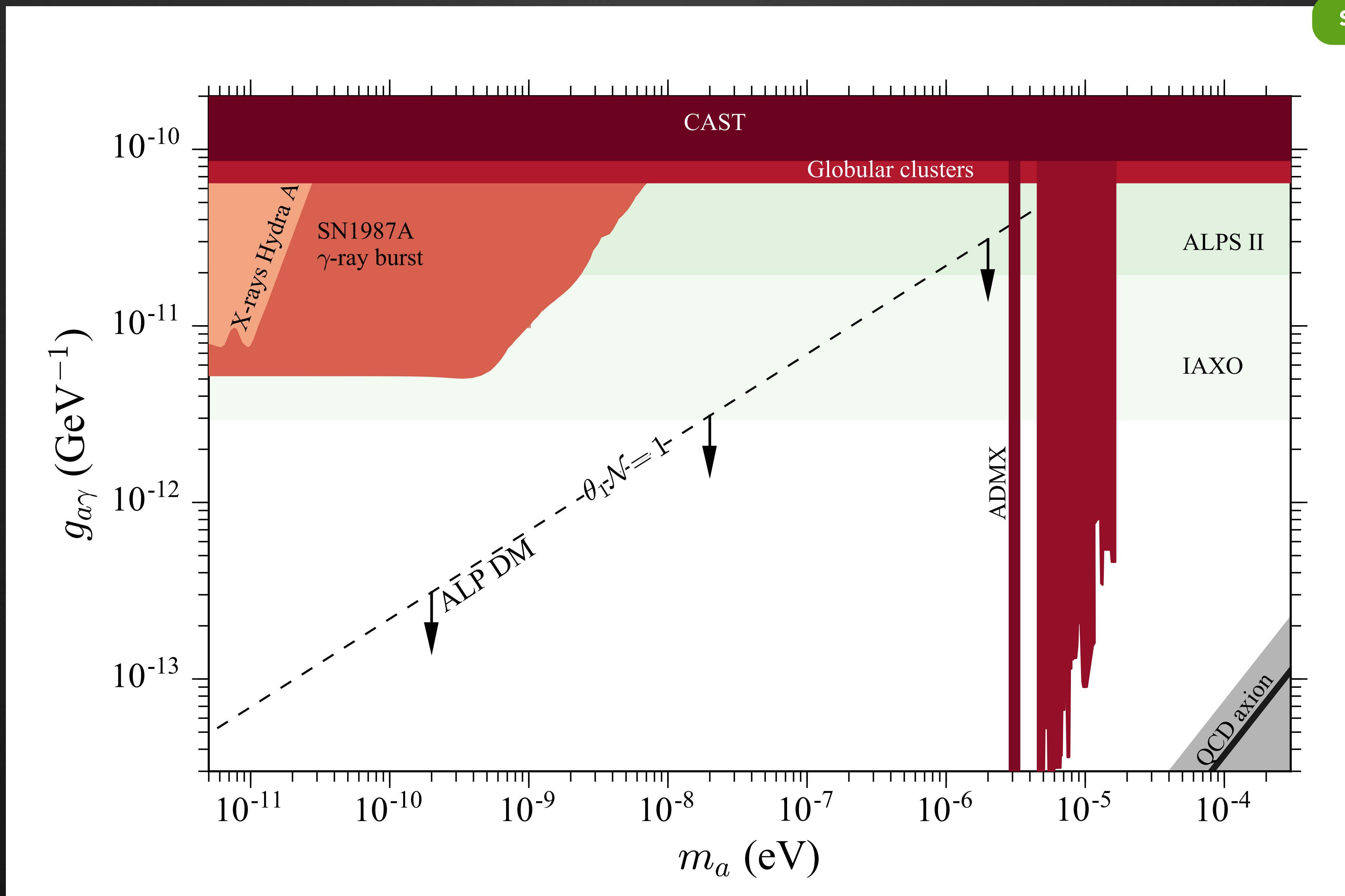


[Ajello et al. 2016]

CONSTRAINTS & SENSITIVITIES

LIMITS

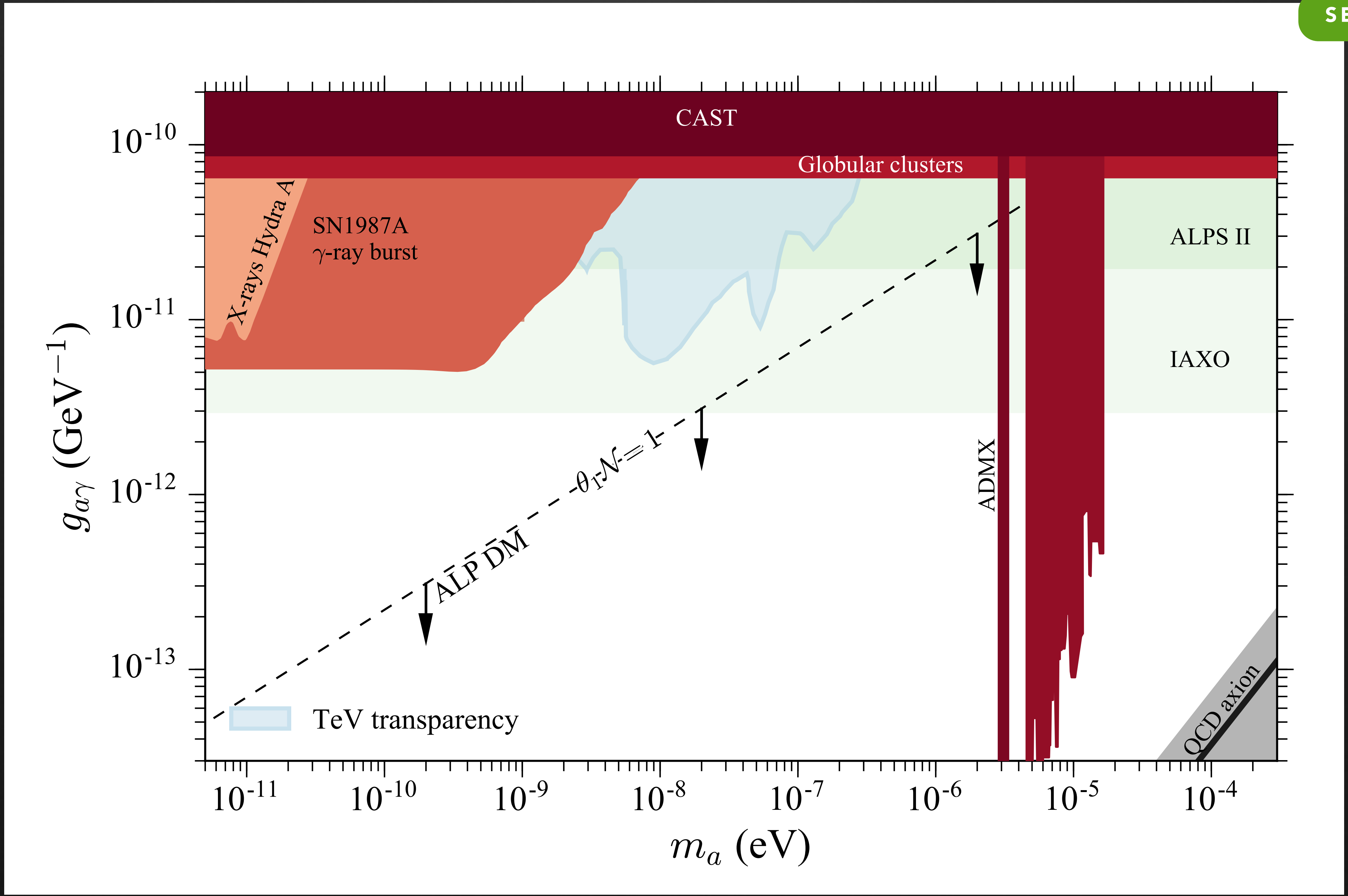
SENSITIVITIES



CONSTRAINTS & SENSITIVITIES

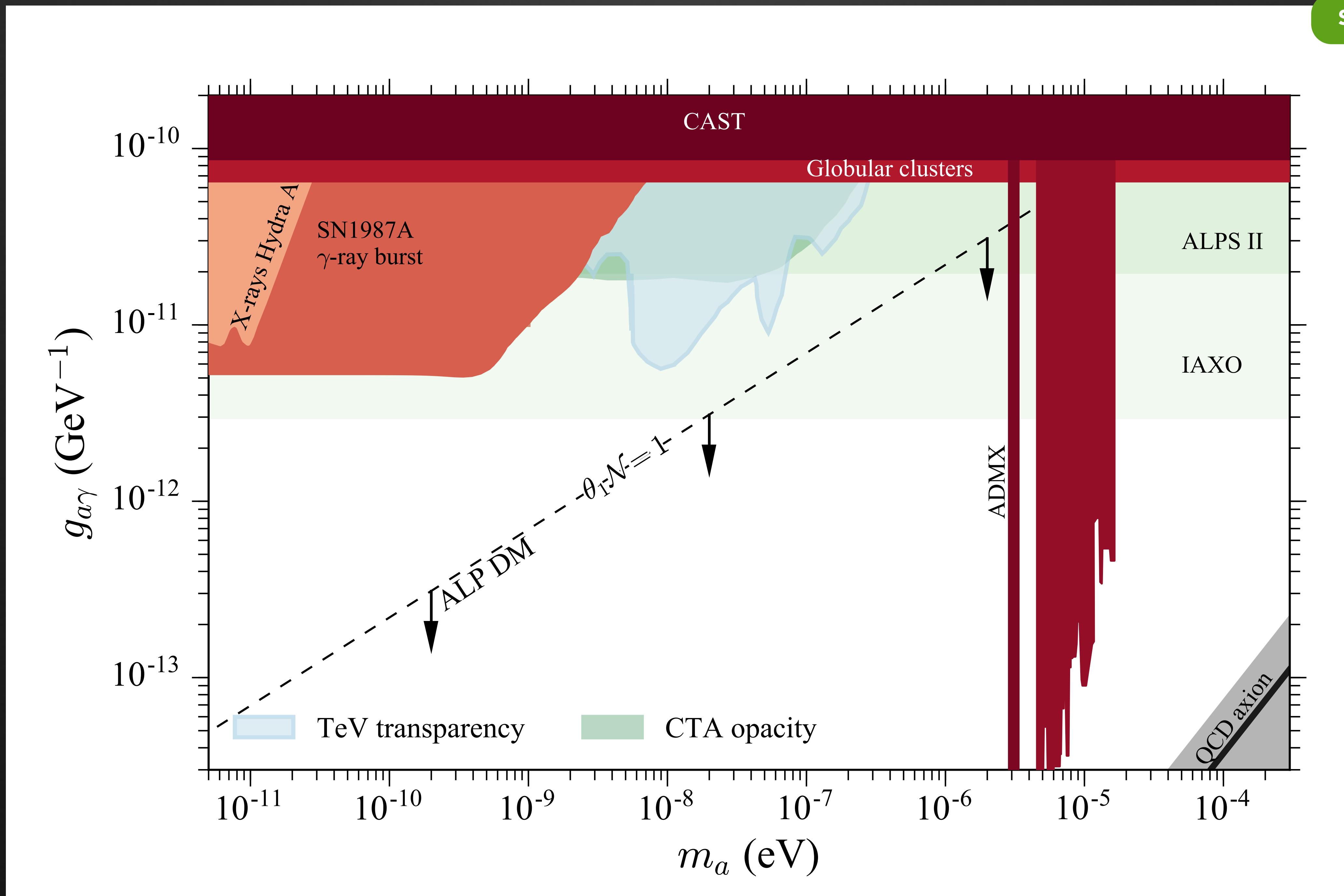
LIMITS

SENSITIVITIES



CONSTRAINTS & SENSITIVITIES

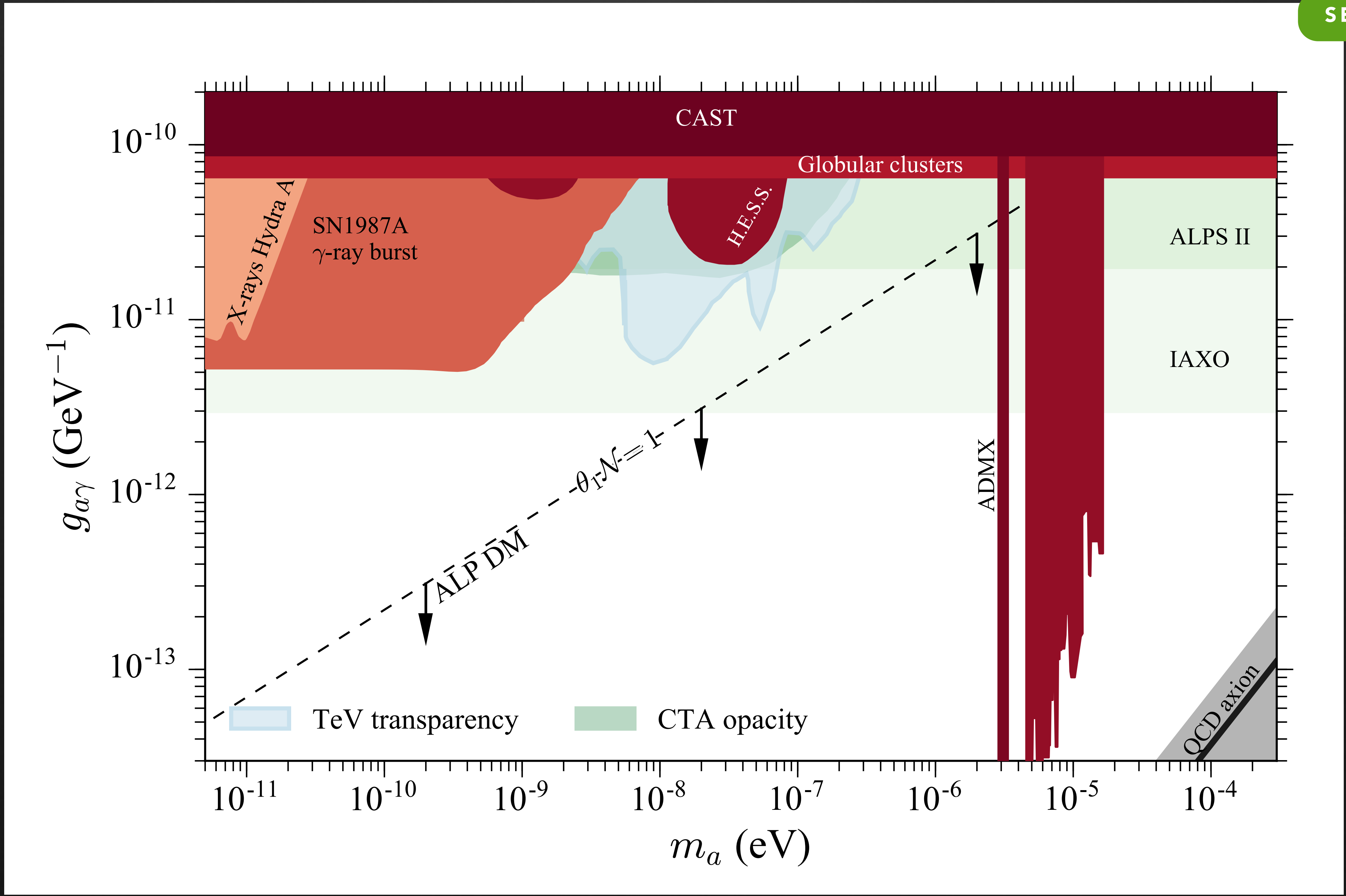
LIMITS
SENSITIVITIES



CONSTRAINTS & SENSITIVITIES

LIMITS

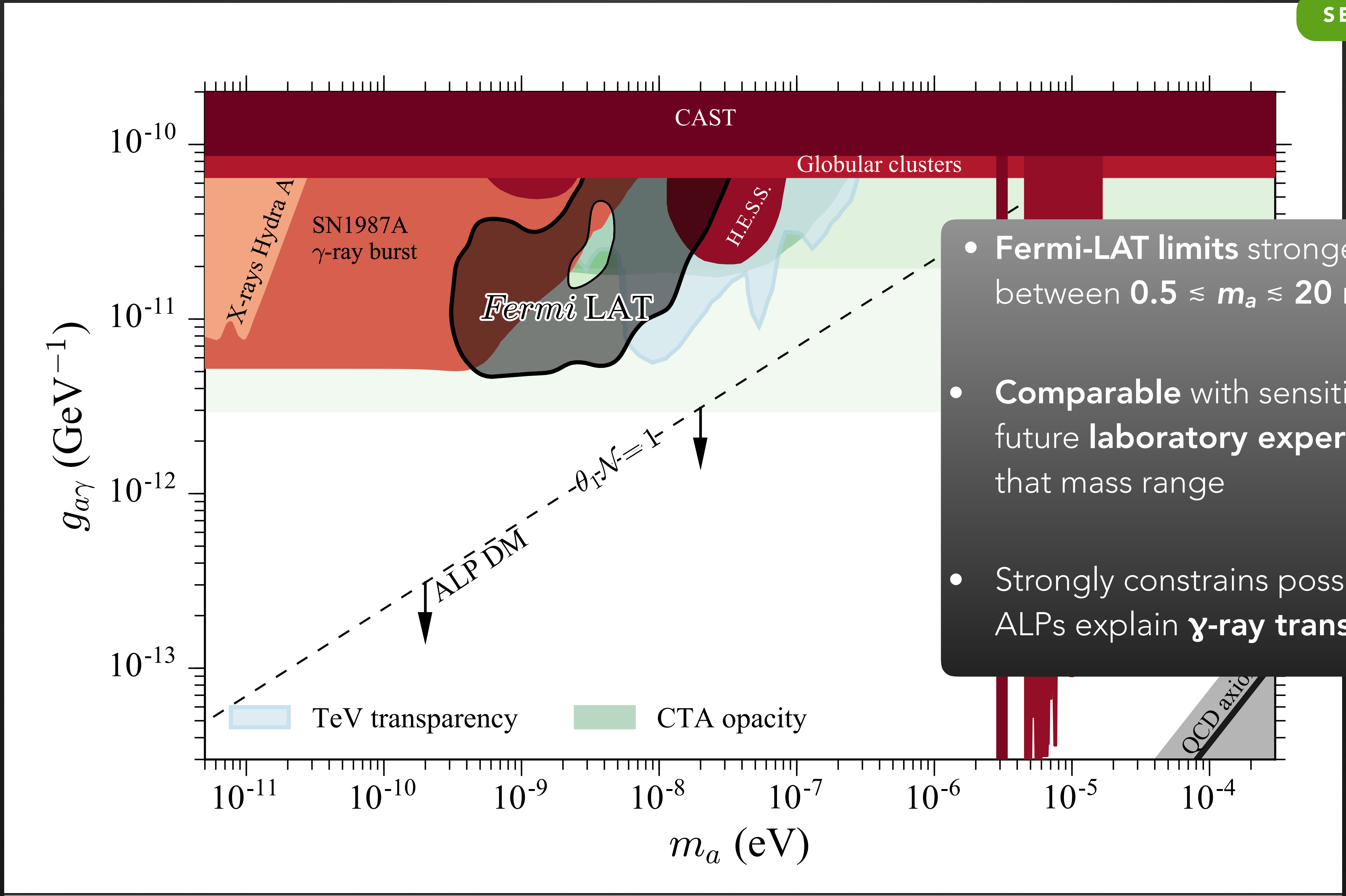
SENSITIVITIES



CONSTRAINTS & SENSITIVITIES

LIMITS

SENSITIVITIES

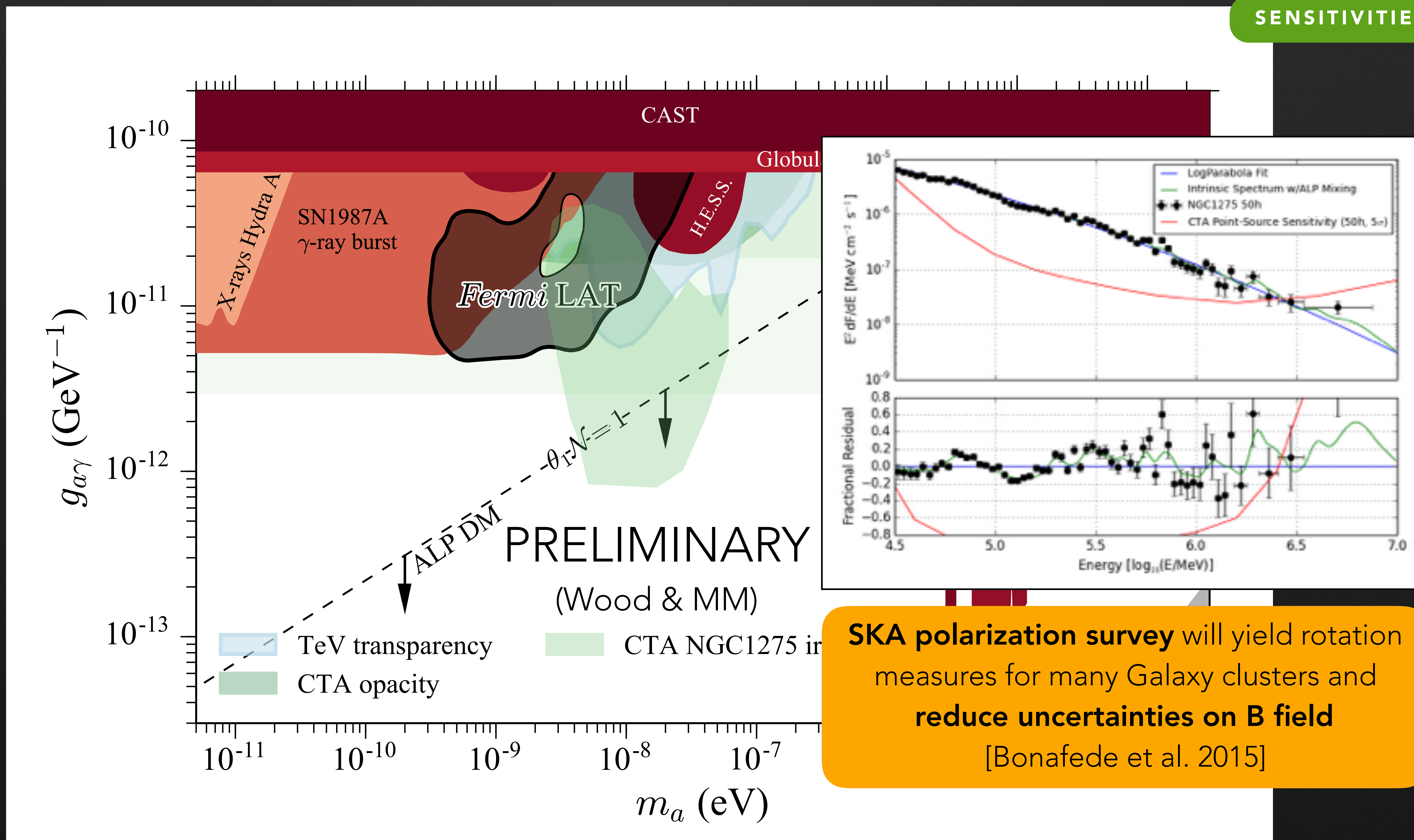


- **Fermi-LAT limits** strongest to date between **0.5 ≲ m_a ≲ 20 neV**
- **Comparable** with sensitivity of future **laboratory experiments** in that mass range
- Strongly constrains possibility that ALPs explain **γ-ray transparency**

CONSTRAINTS & SENSITIVITIES

LIMITS

SENSITIVITIES



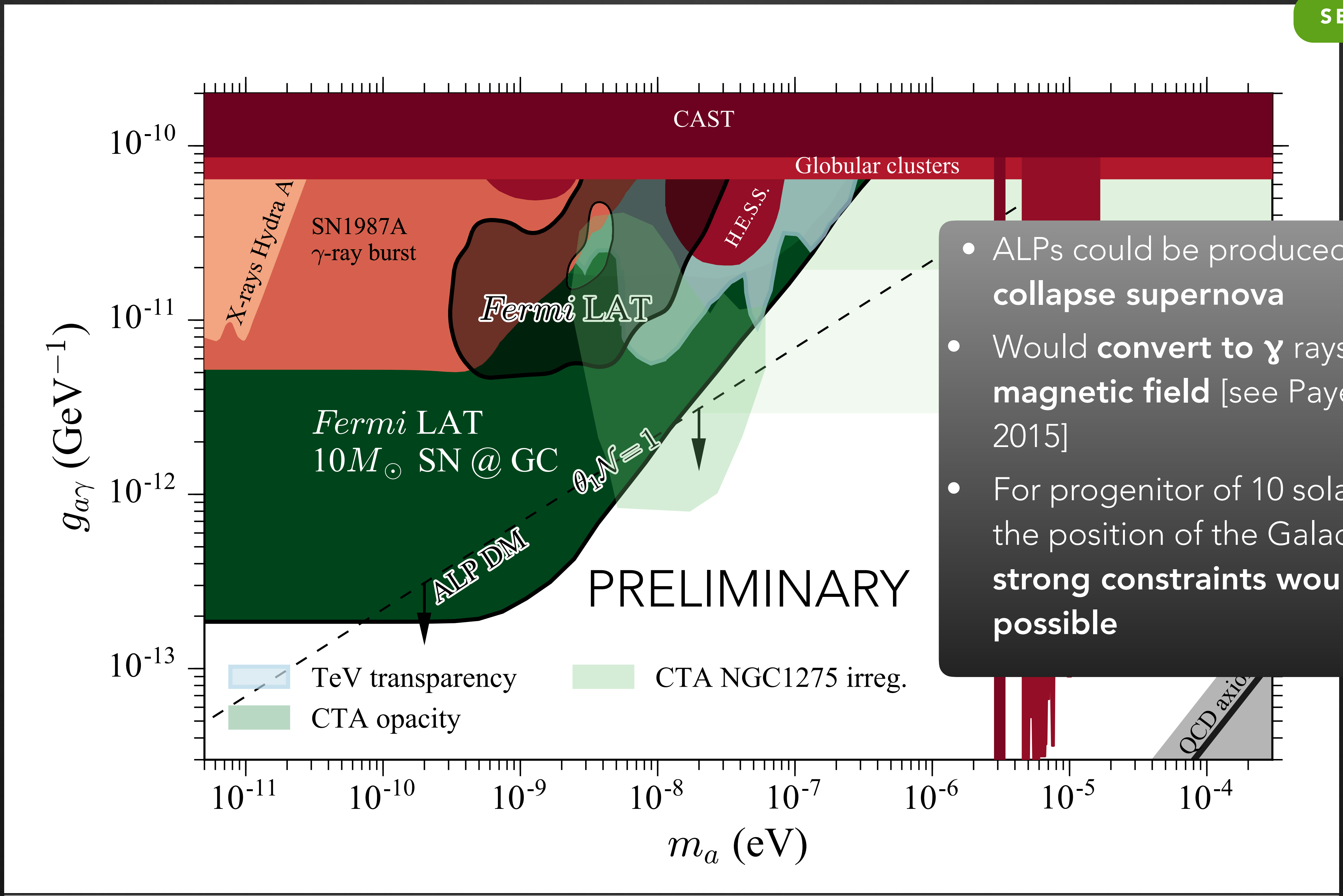
SKA polarization survey will yield rotation measures for many Galaxy clusters and **reduce uncertainties on B field** [Bonafede et al. 2015]

CONSTRAINTS & SENSITIVITIES

POSSIBLE CONSTRAINTS FROM NEXT GALACTIC SN

LIMITS

SENSITIVITIES



- ALPs could be produced in **core-collapse supernova**
- Would **convert to γ** rays in **Galactic magnetic field** [see Payez et al. 2015]
- For progenitor of 10 solar masses at the position of the Galactic center, **strong constraints would be possible**

[MM; M. Giannotti; A. Mirizzi; J. Conrad; M. Sanchez-Conde; in prep.]

SUMMARY AND CONCLUSIONS

- Axions and ALPs arise in various extensions of the Standard Model
- Well motivated **dark-matter candidates**
- Light ALPs could leave distinct **signatures in ɣ-ray spectra**
- **ALPs evade pair production**, could explain (debated) hints for reduced opacity
- Current and future observations with Fermi & CTA have potential to **probe** parameter space where **ALPs constitute entire dark matter**

BACKUP SLIDES

THE STRONG CP PROBLEM

- In electroweak interactions: Parity (P) and time-reversal (T) symmetries commonly broken
- However: not observed in QCD — But should be there!

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} G_{\mu\nu\,a} G_a^{\mu\nu} + \sum_q i\bar{q}\gamma^\mu D_\mu q - qm\bar{q} + \frac{\alpha_s}{8\pi}\theta G_{\mu\nu\,a}\tilde{G}_a^{\mu\nu}$$

P,T CONSERVING

P,T VIOLATING

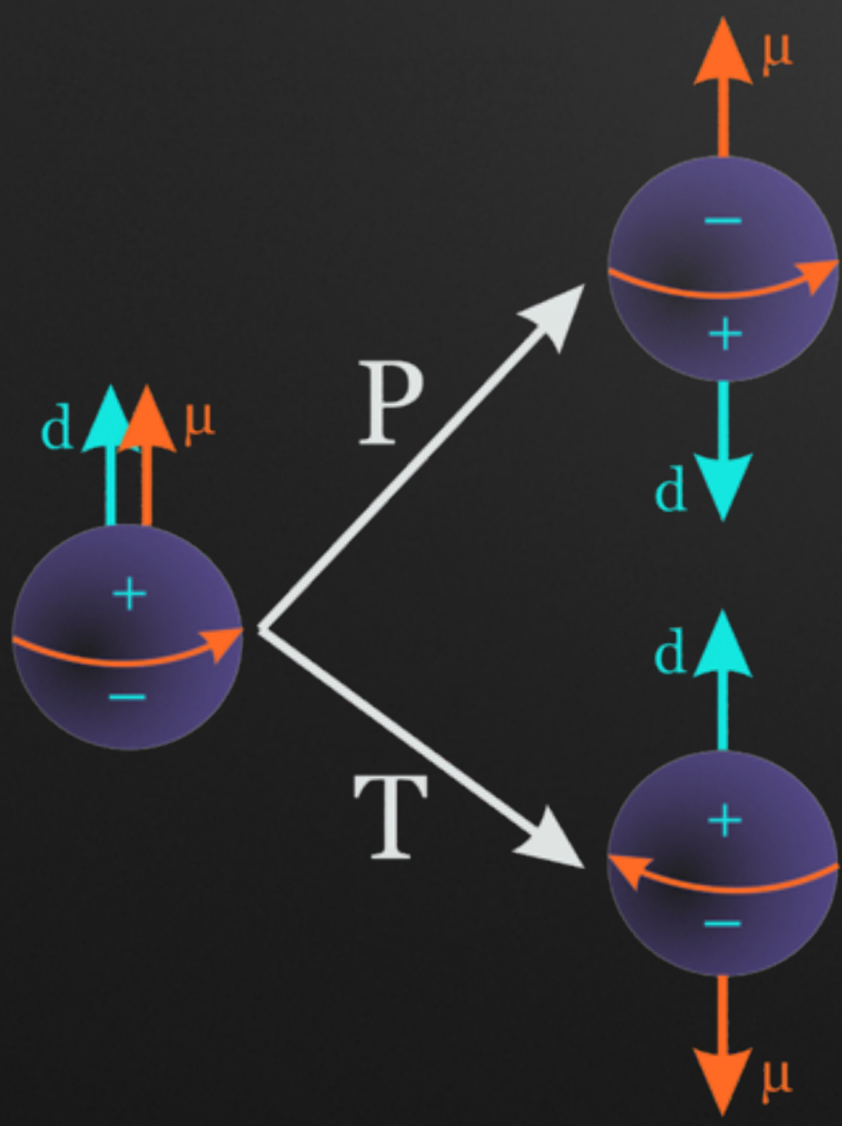
$\propto \theta$

$\theta \in (-\pi;\pi)$ Infinitely many versions of QCD — all violate P,T

[Slide adopted from J.Redondo]

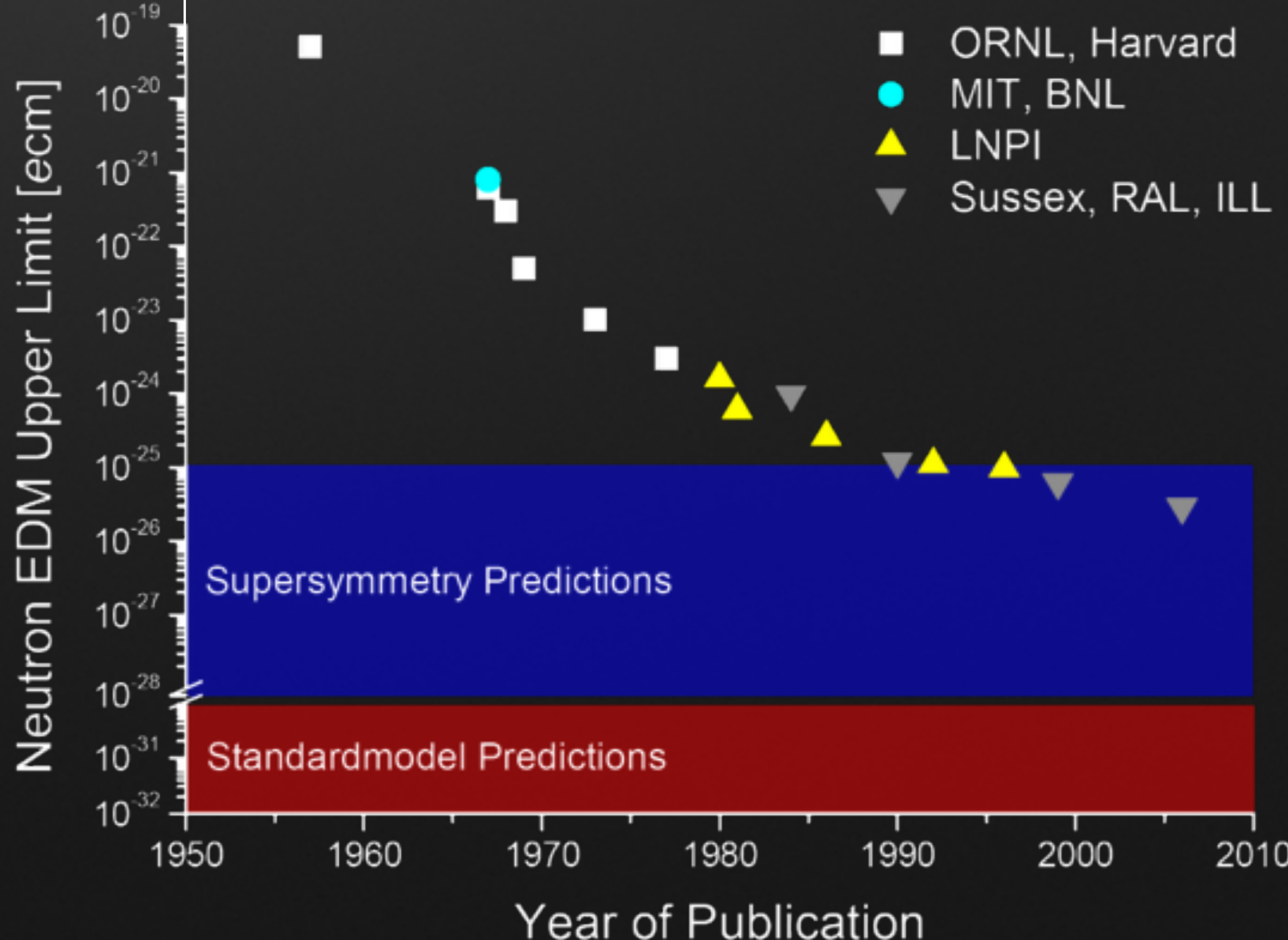
NEUTRON EDM

MOST IMPORTANT P,T VIOLATING OBSERVABLE



$$\theta \sim \mathcal{O}(1)$$

$$d_n \sim \theta \times \mathcal{O}(10^{-15})\mathrm{e\,cm}$$



[Slide adopted from J.Redondo]

NEUTRON EDM

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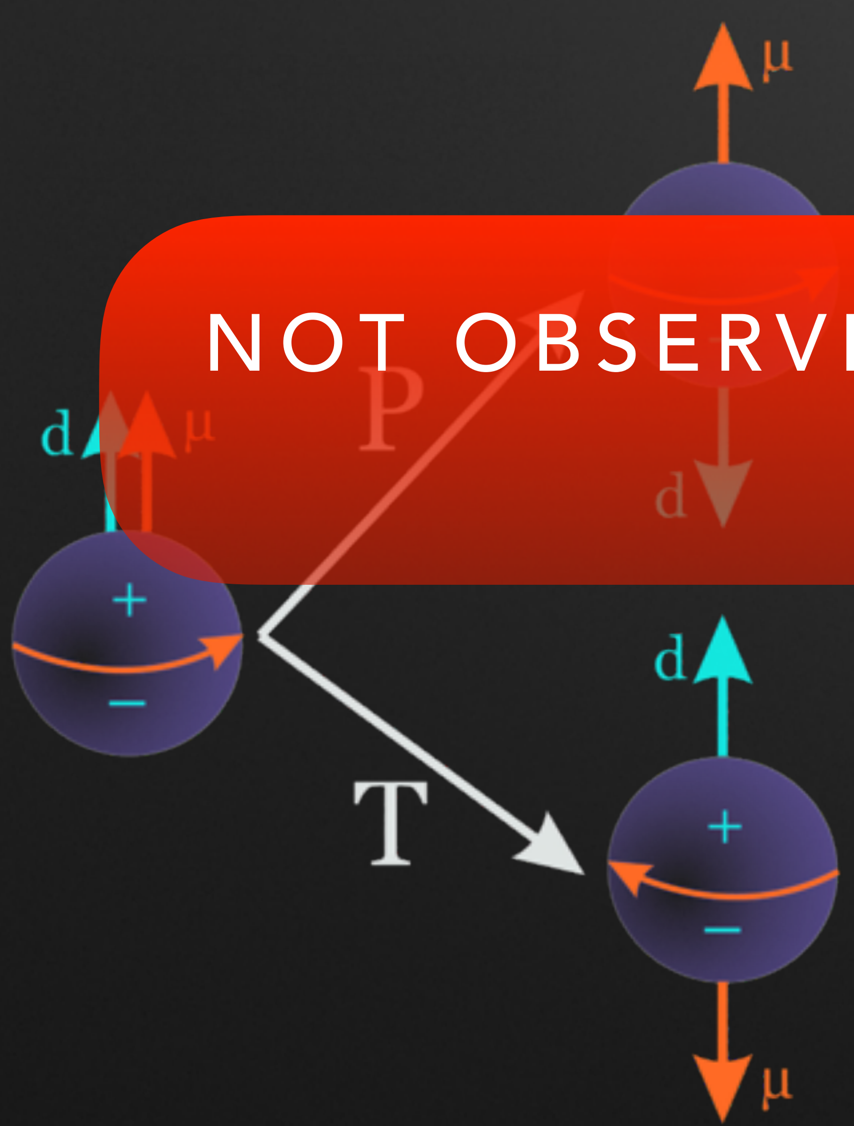

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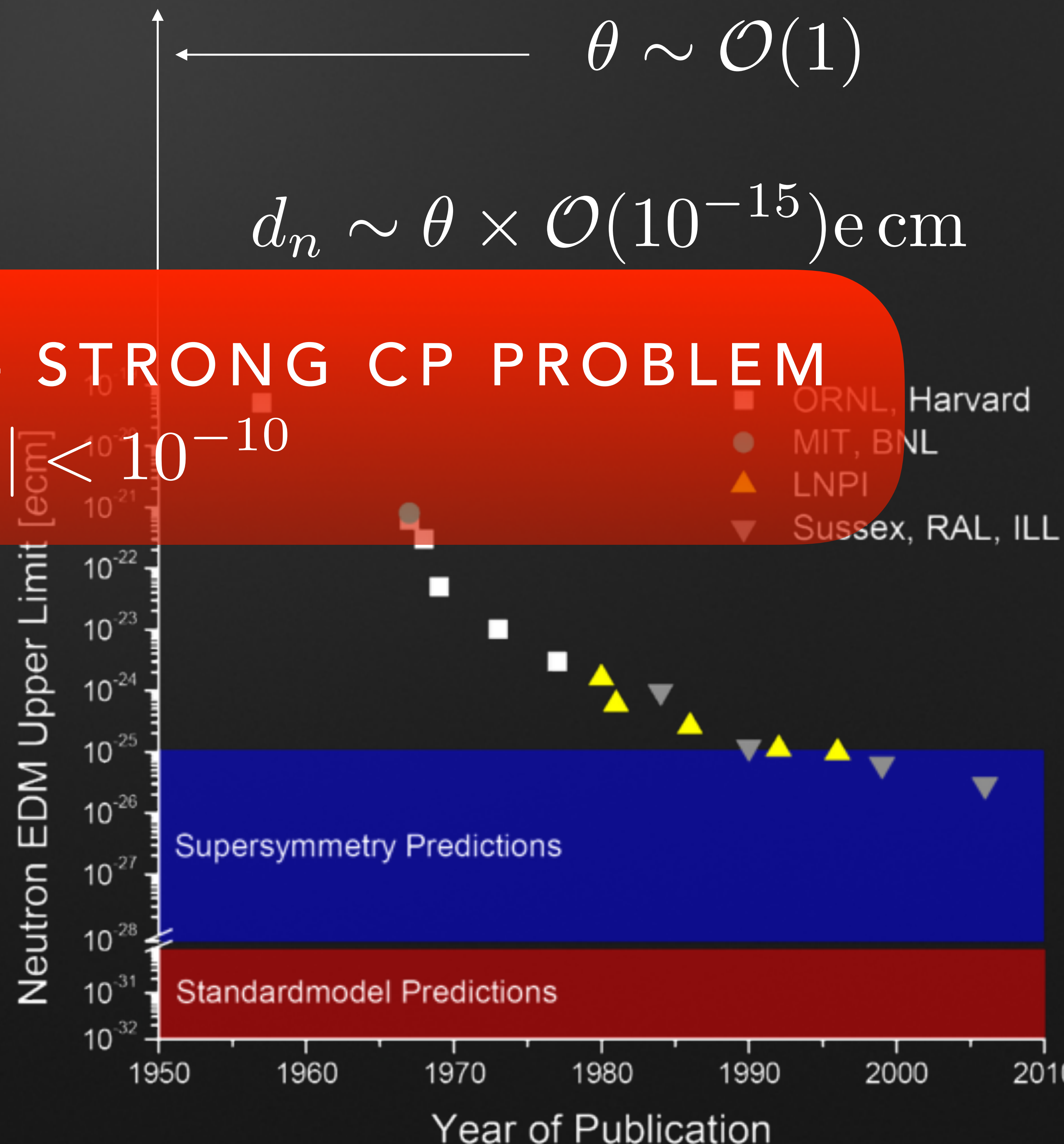
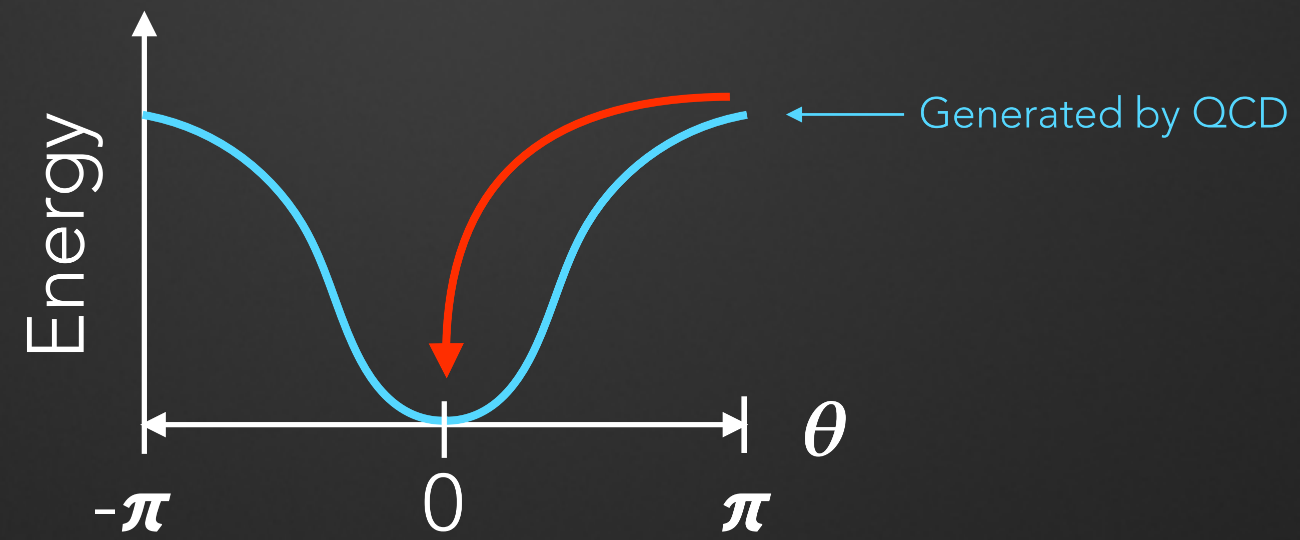


NOT OBSERVED — STRONG CP PROBLEM

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

[Slide adopted from J.Redondo]

SOLUTION: MAKE $\boldsymbol{\theta}(t, \boldsymbol{x})$ A DYNAMICAL FIELD



- If $\boldsymbol{\theta}(t,\boldsymbol{x})$ is dynamical field, relaxes to its minimum
- Solves strong CP problem [Peccei & Quinn 1977]

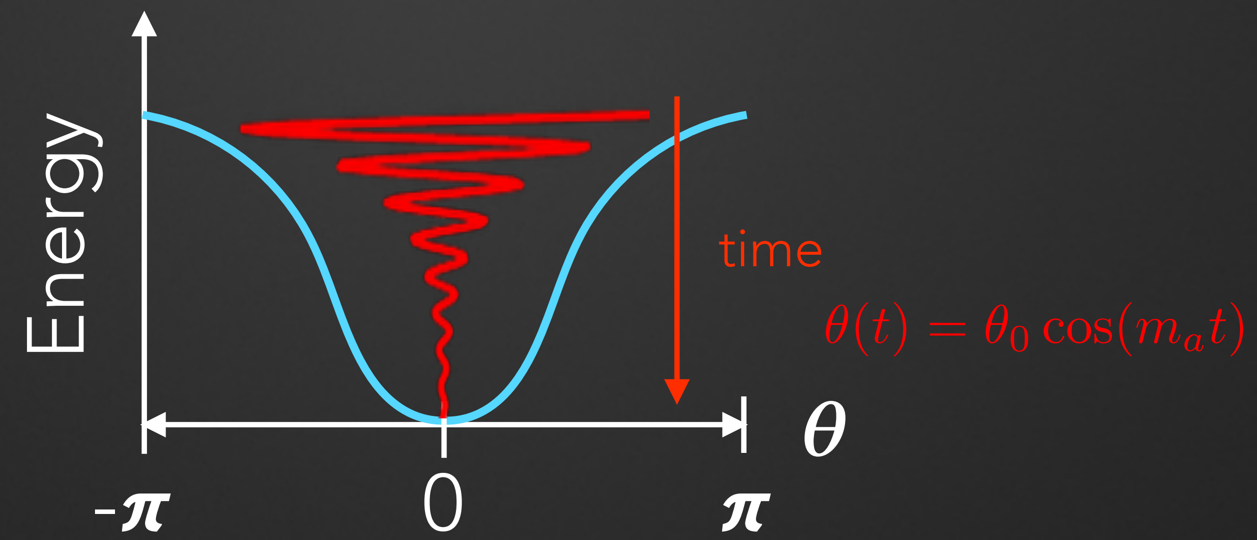
[Slide adopted from J.Redondo]

AXION-LIKE PARTICLES (ALPs)

- Phenomenology closely related to that of axions
- Predicted in several **extensions** of the standard model (Majoron, Familon, …)
  [Chikashige et al. 78; Langacker et al. 86; Wilczek 82]
- Occur whenever additional symmetries are explicitly broken
- Do **not solve** the **strong CP problem**
- For instance: occur as Kaluza-Klein zero modes in compactifications in **string theory** — whole **Axiverse** predicted!
  [Witten 84; Conlon 06; Arvanitaki et al. 09; Acharya et al. 10; Cicoli et al. 12]

AXIONS/ALPs AS DARK MATTER

MISALIGNMENT MECHANISM

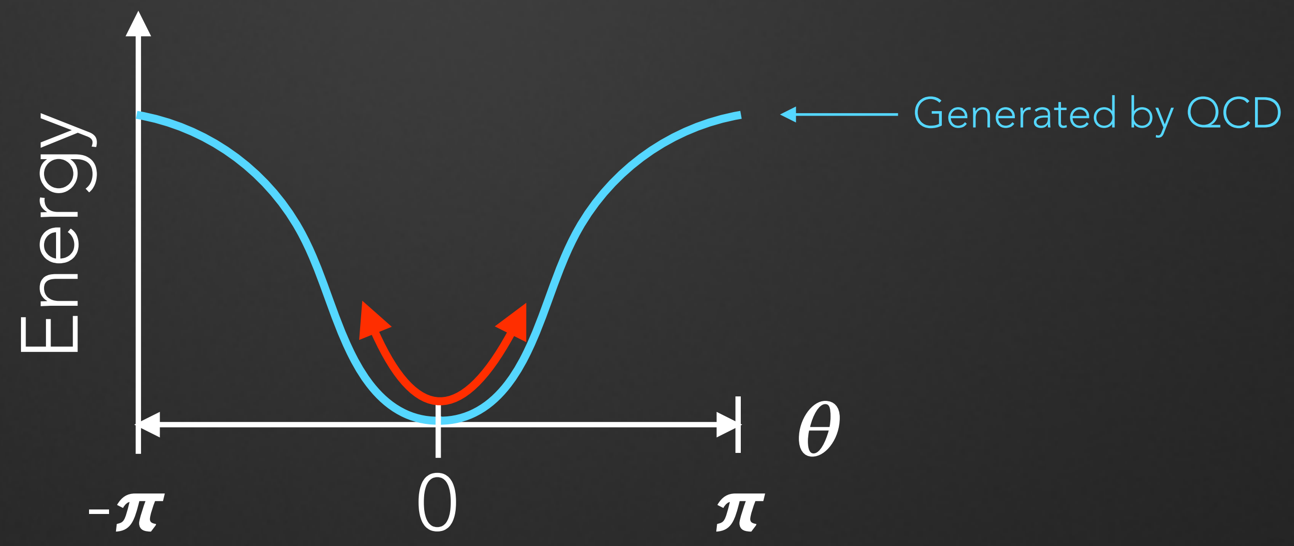


- **Coherent oscillations = dark matter axions**
- Oscillation frequency $\omega = m_a$
- Energy density: $\rho_{a\mathrm{DM}} \sim \frac{1}{2}(75\,\mathrm{MeV})^4\theta_0^2$

[e.g. Arias et al. 2012]

[Slide adopted from J.Redondo]

SOLUTION: MAKE $\theta(t, \mathbf{x})$ A DYNAMICAL FIELD — AND A NEW PARTICLE IS BORN!



- If $\theta(t,\mathbf{x})$ is dynamical field, relaxes to its minimum
- Solves strong CP problem [Peccei & Quinn 1977]
- Field excitations around the vacuum are particles [Weinberg 1978, Wilczek 1978]

[Slide adopted from J.Redondo]

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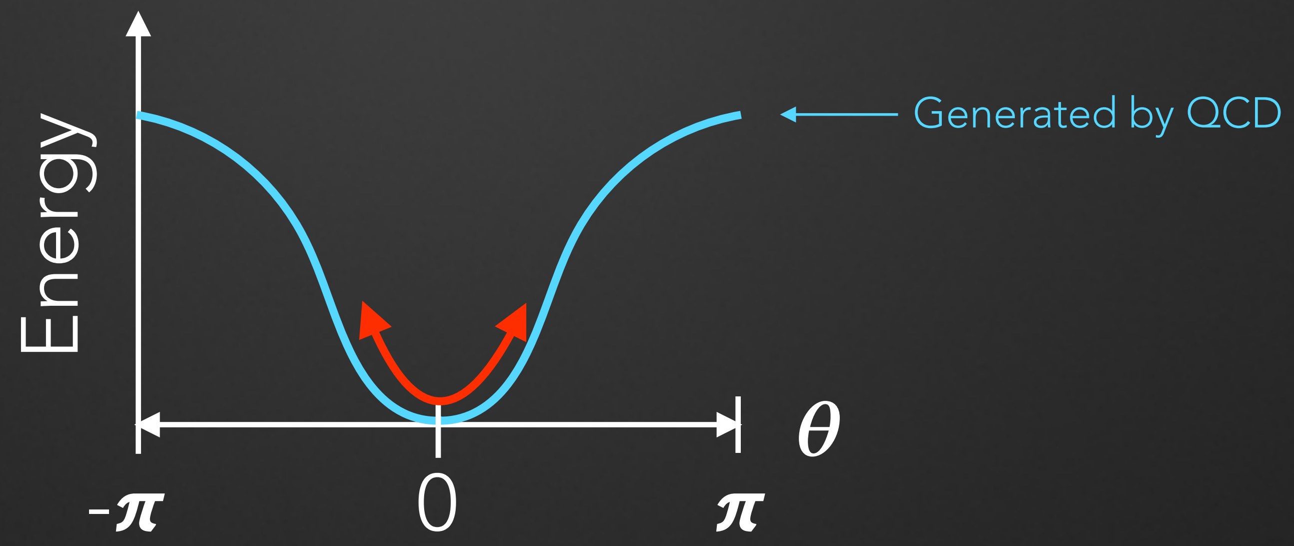

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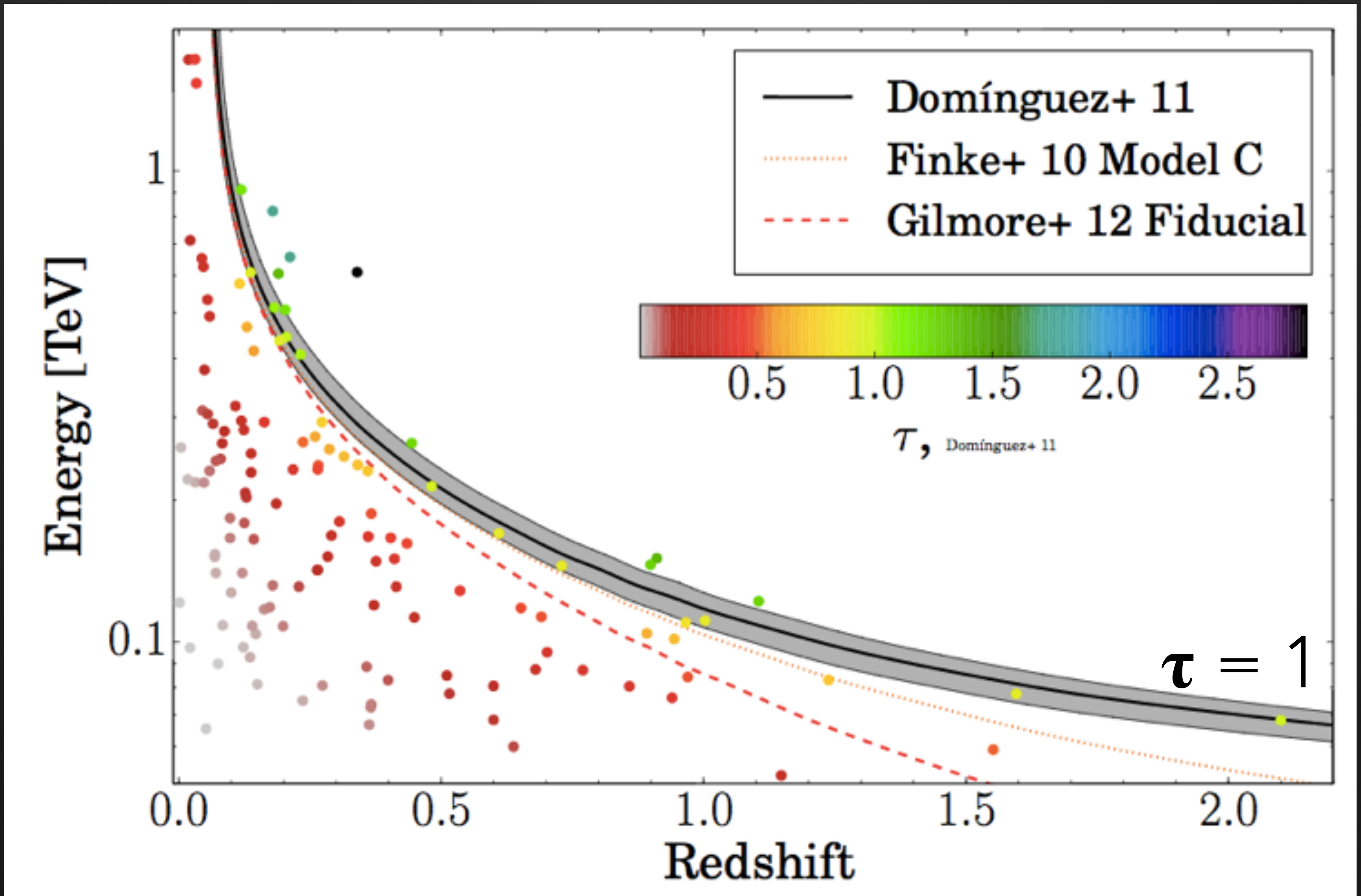
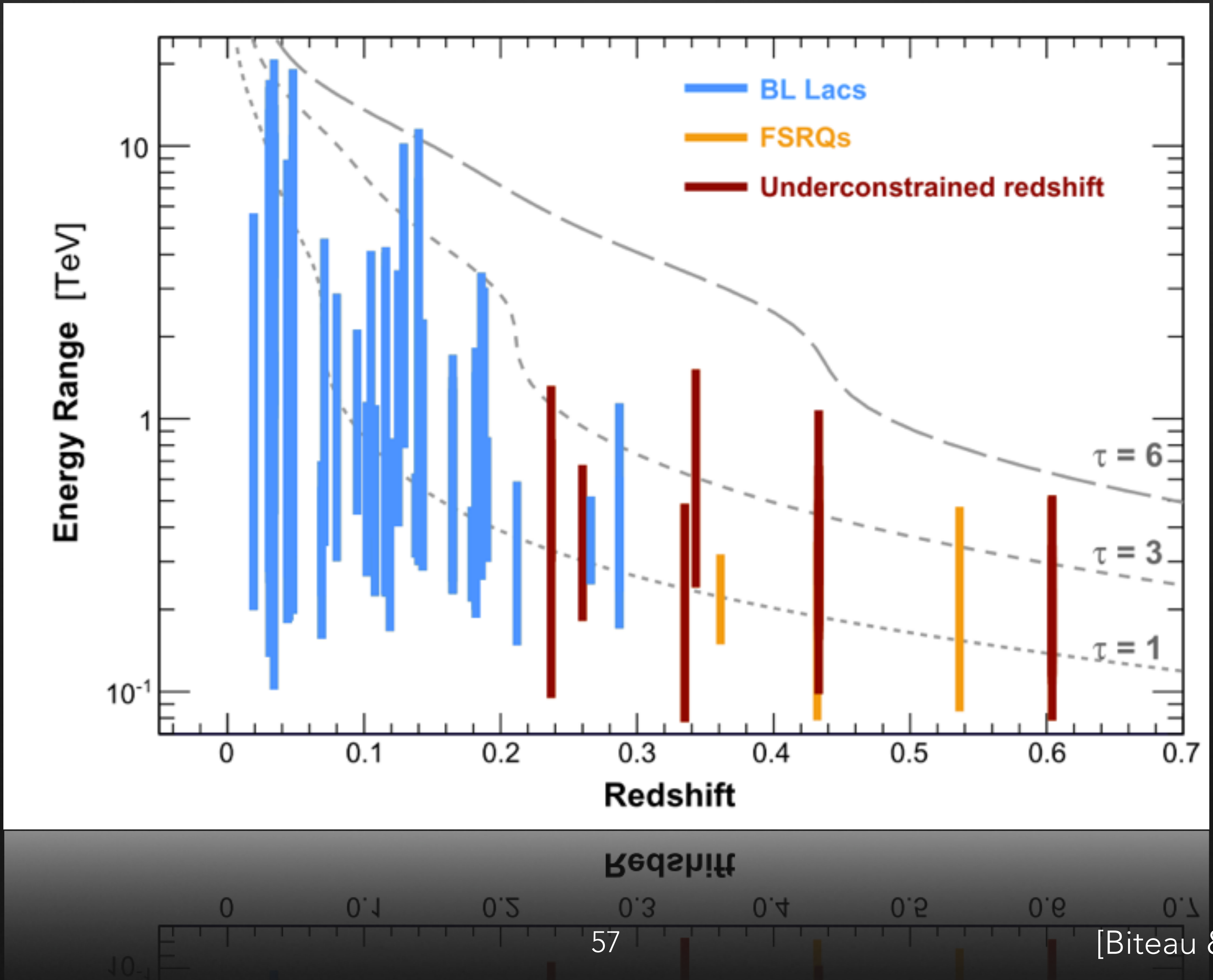
[Slide adopted from J.Redondo]

OPTICAL DEPTH PROBED WITH FERMI LAT



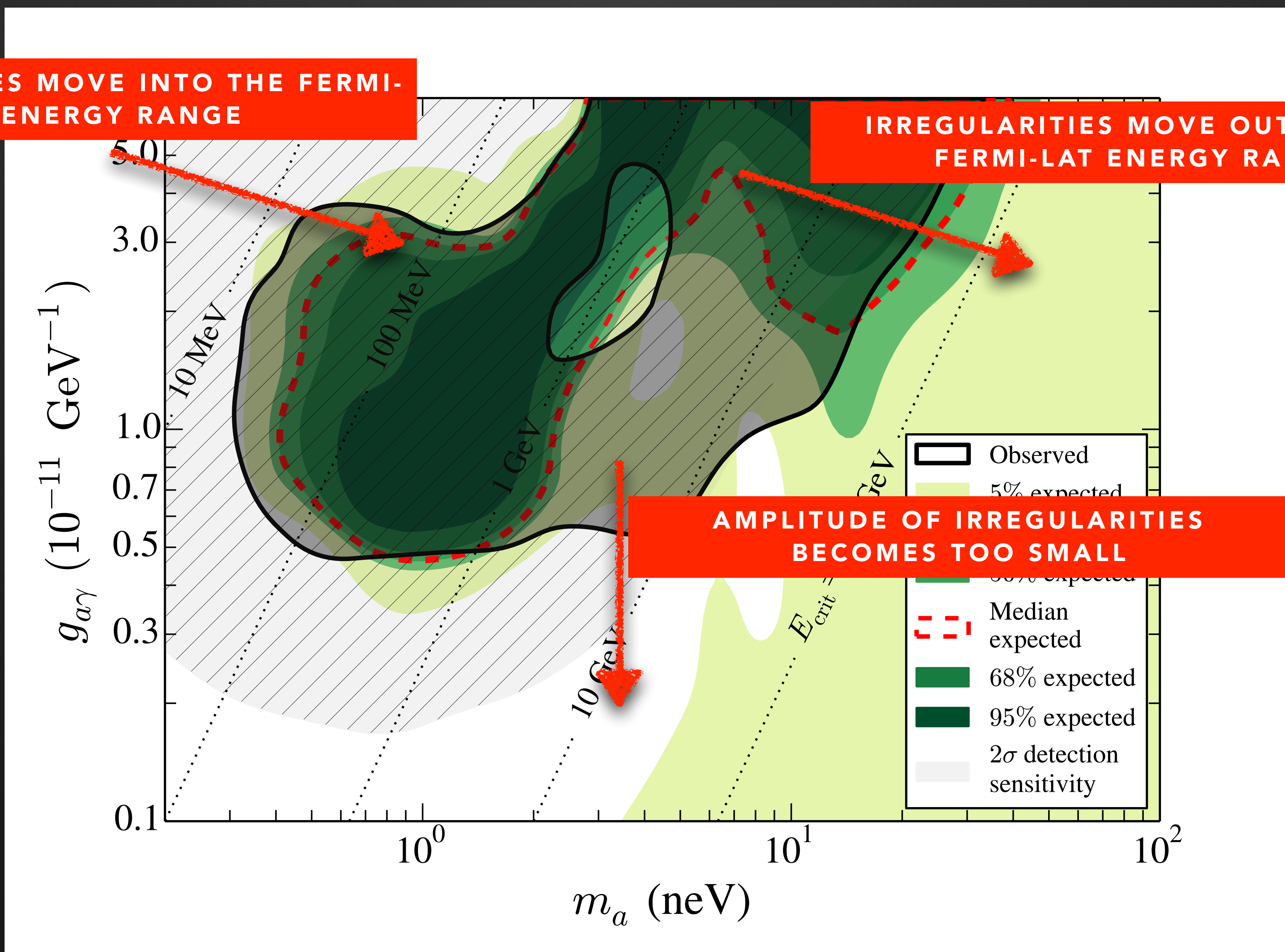
[Ackermann et al. 2015]

OPTICAL DEPTH PROBED WITH IACTs



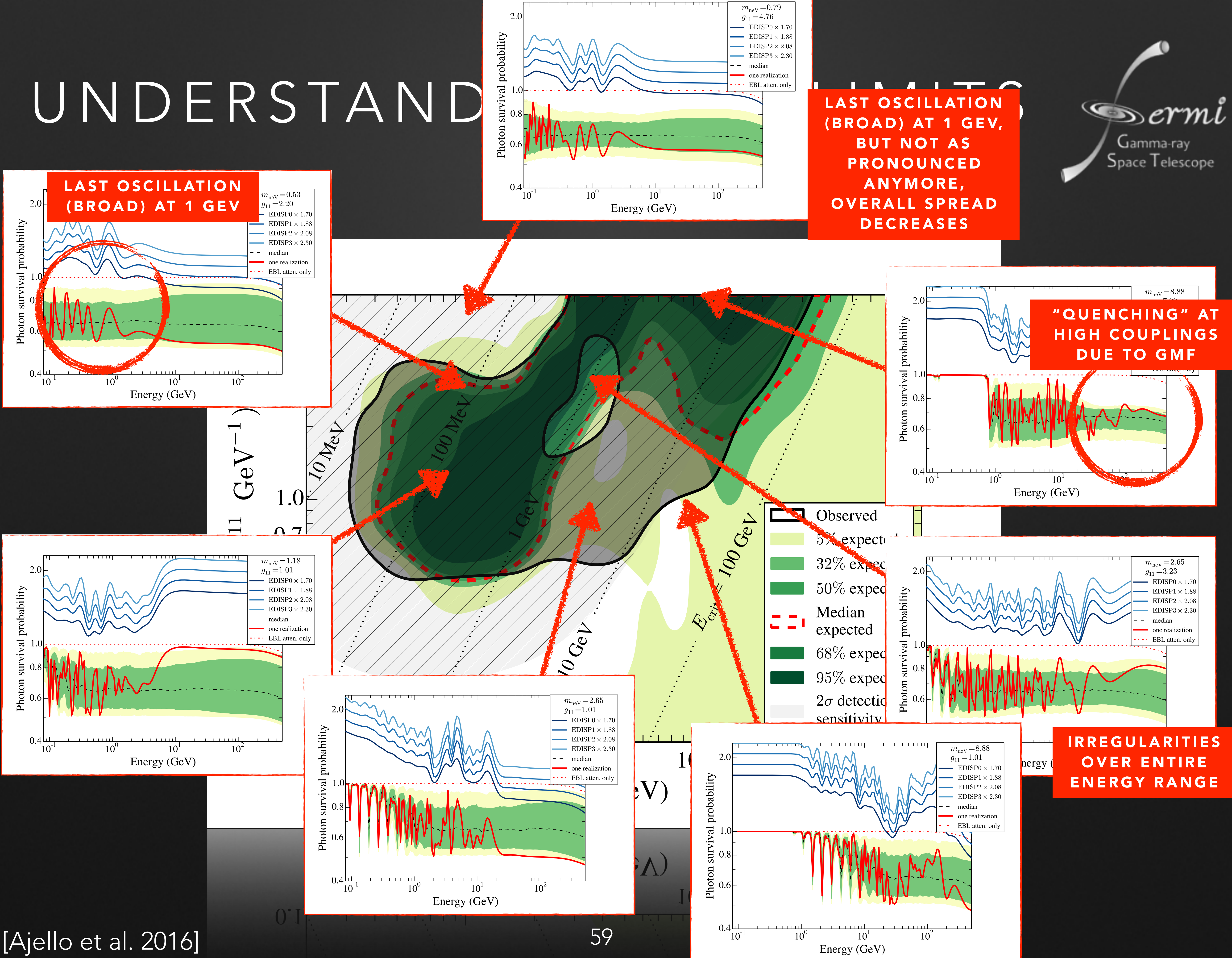
[Biteau & Williams 2015]

UNDERSTANDING THE LIMITS



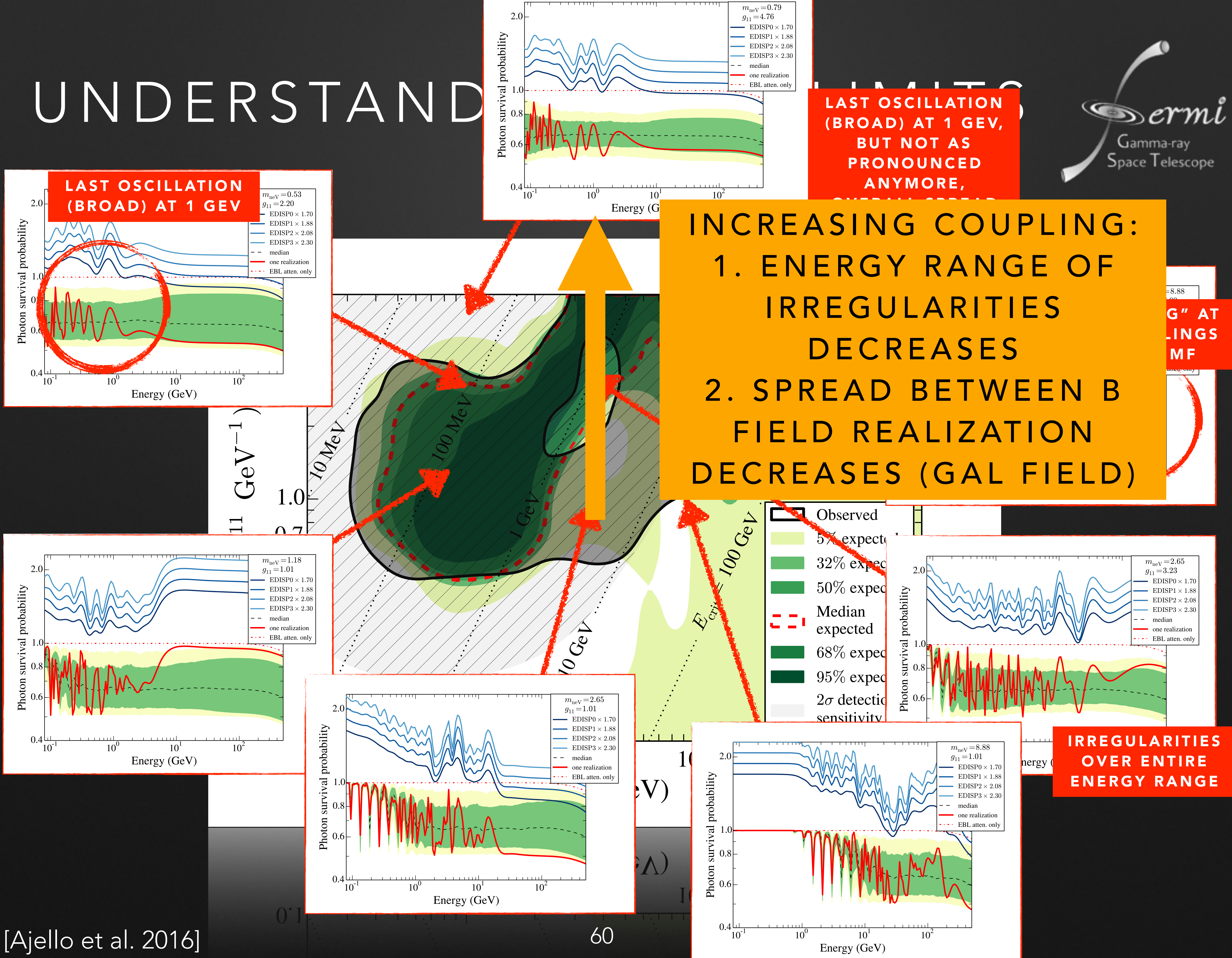
[Ajello et al. 2016]

UNDERSTAND… LIMITS



[Ajello et al. 2016]

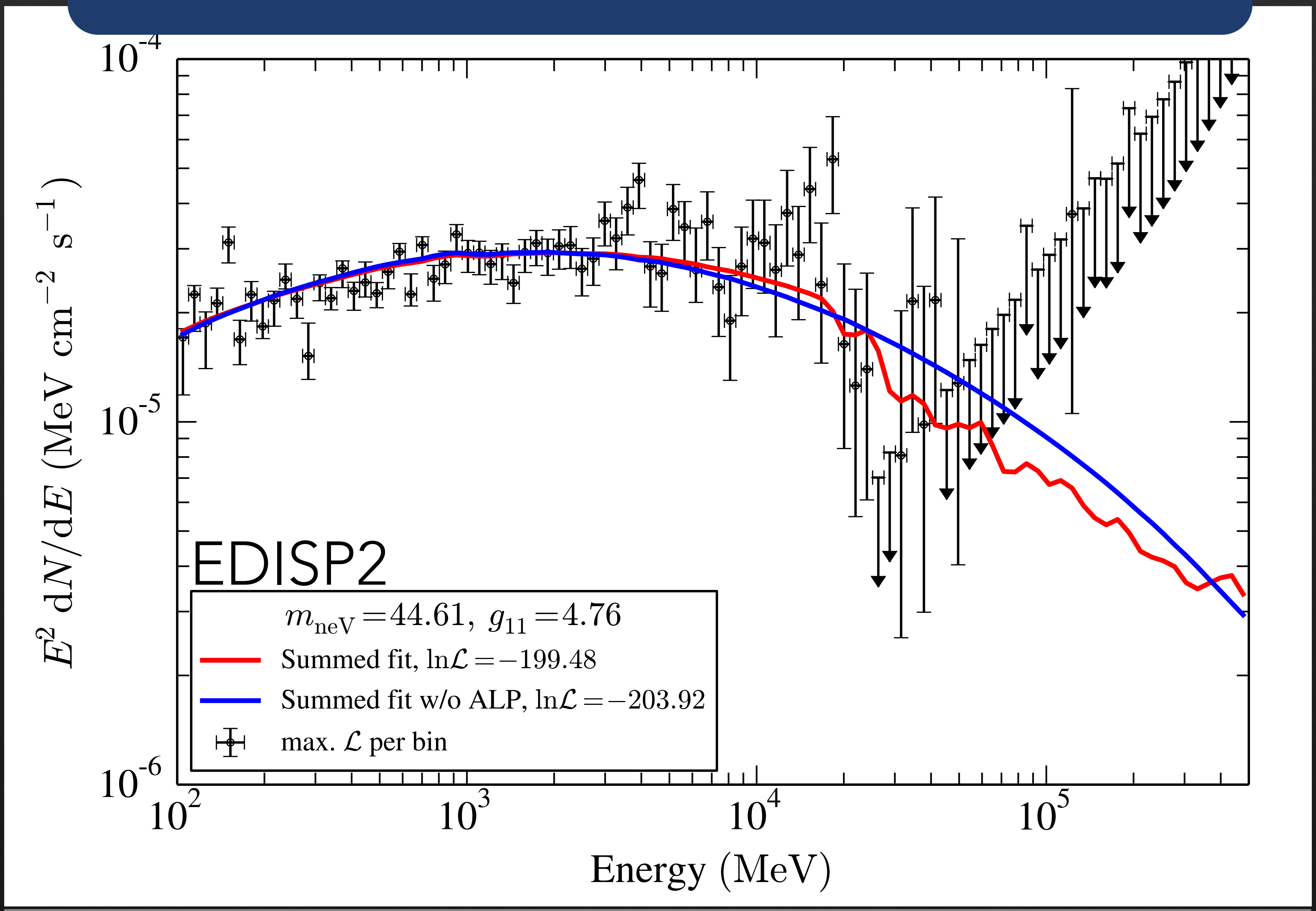
UNDERSTAND



[Ajello et al. 2016]

COMPARING EXCLUDED ALP PARAMETERS WITH BEST FIT

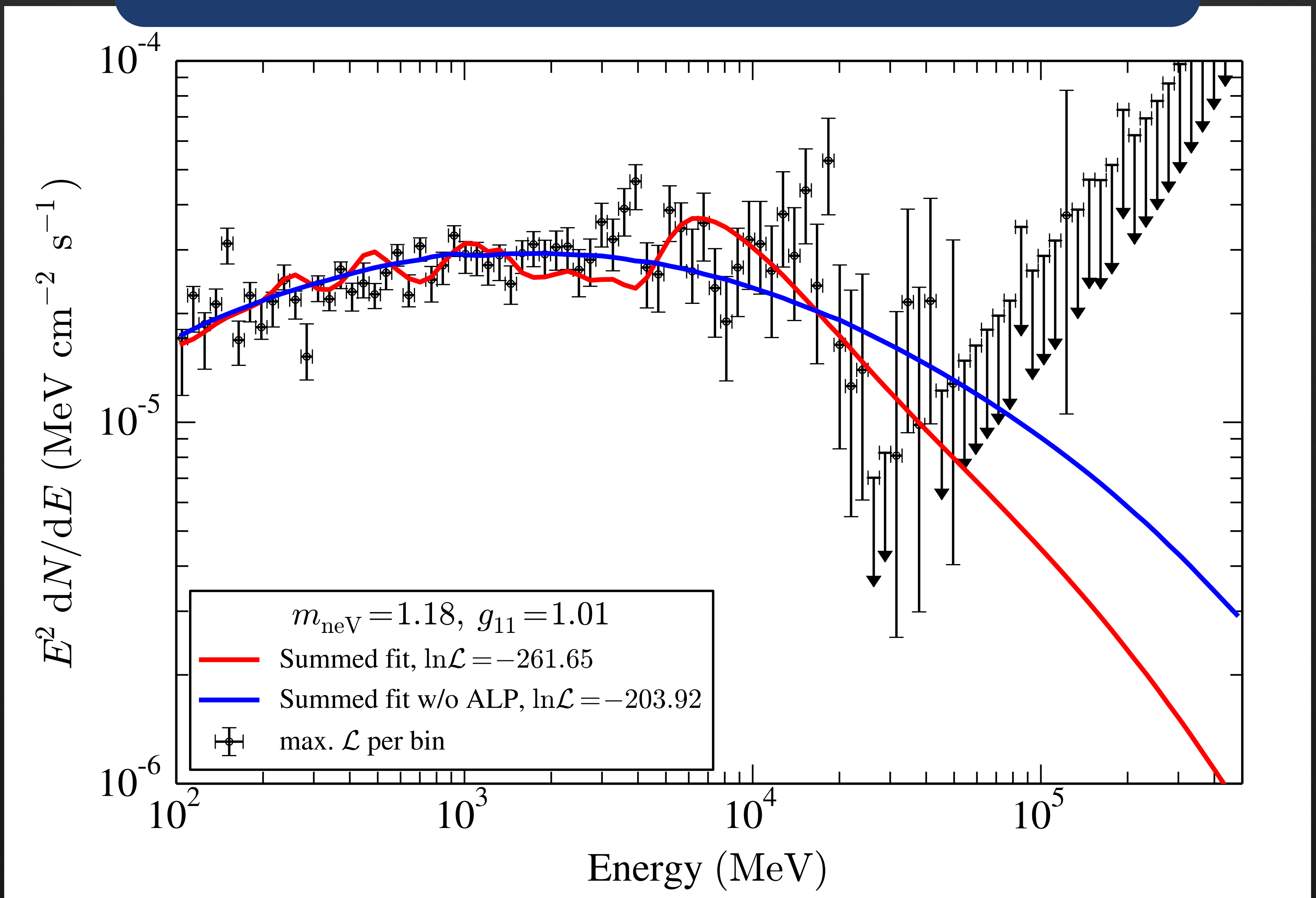
BEST FIT — NOT PREFERRED



[Ajello et al. 2016]

COMPARING EXCLUDED ALP PARAMETERS WITH BEST FIT

EXCLUDED AT > 95% C.L.



[Ajello et al. 2016]

COMPARING EXCLUDED ALP PARAMETERS WITH BEST FIT

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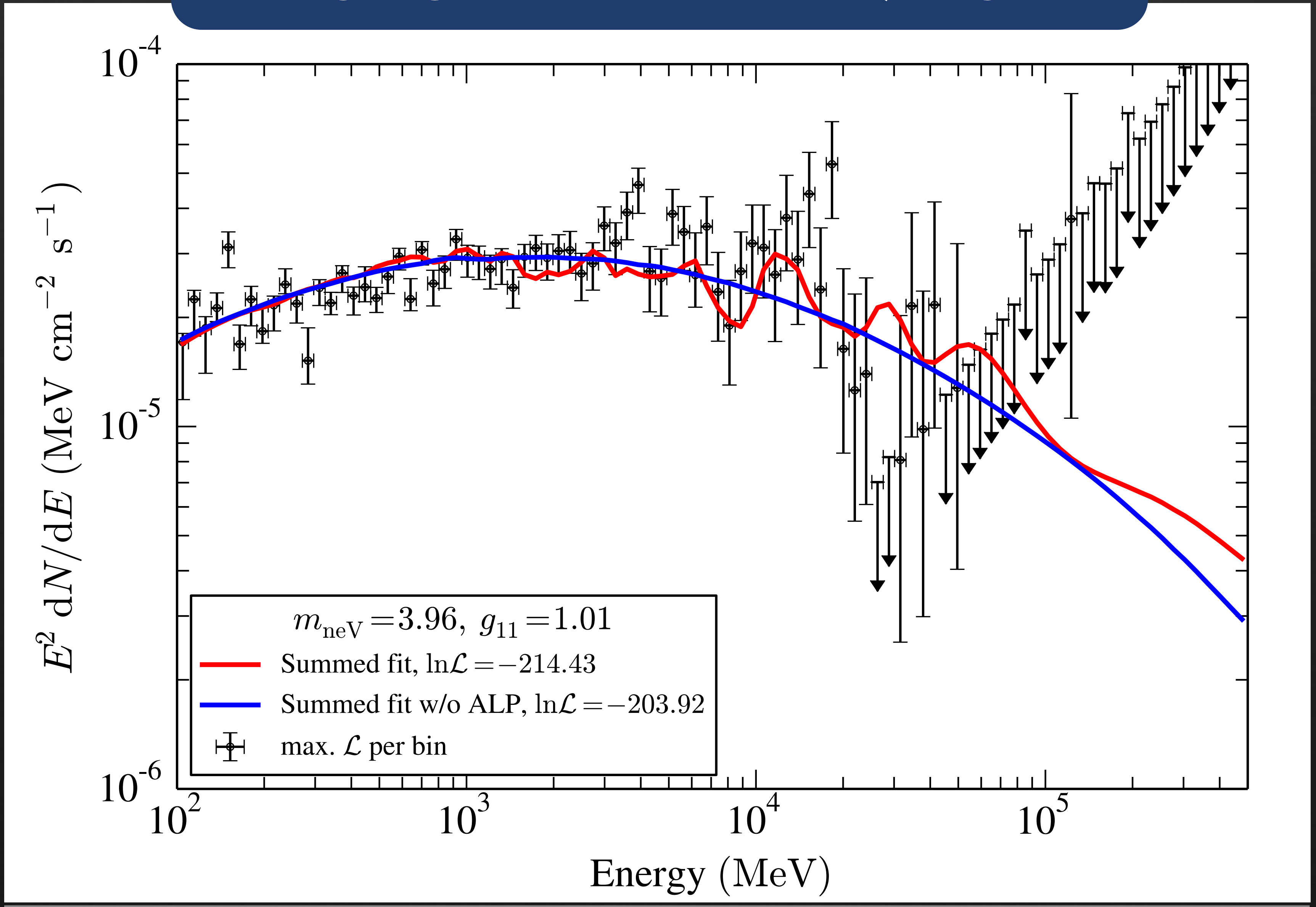
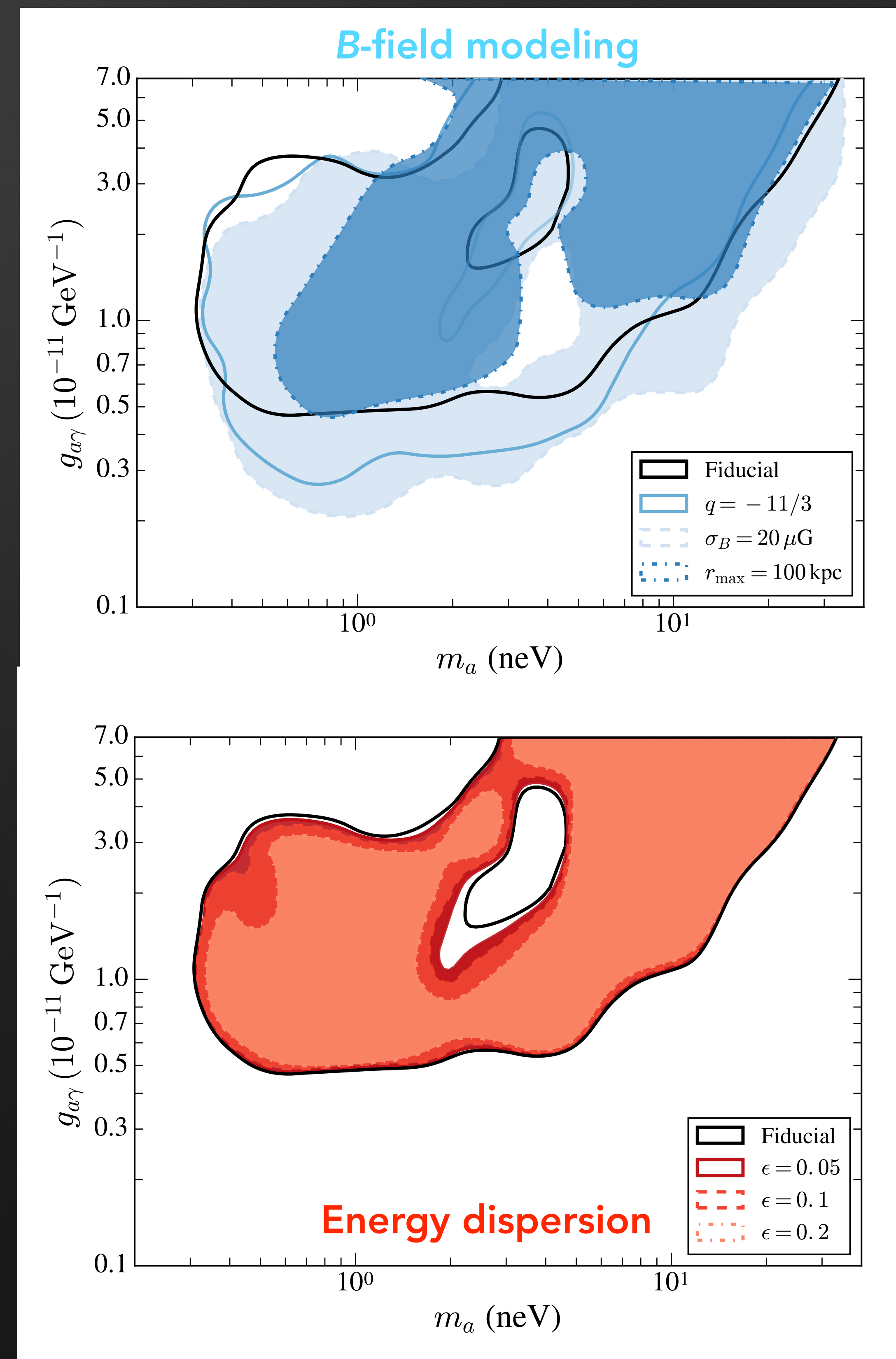


[Ajello et al. 2016]

SYSTEMATIC UNCERTAINTIES

- **B-field modeling:**
  - Kolmogorov turbulence: Power-law index of turbulence *q*
  - central magnetic field σ_B
  - Maximal spatial extent of *B* field $r_{\max}$
  - **Increasing σ_B increases** excluded area of parameter space **by 43%**

- **Energy dispersion:**
  - Artificially broadened with 5%,10%, 20%
  - **Reduces** excluded parameter space **up to 25%**



[Ajello et al. 2016]

NULL DISTRIBUTION FROM MC

WHAT IS THE TS VALUE FOR WHICH WE CAN CLAIM EVIDENCE FOR ALPS?

- **Non-linear behaviour of ALP effect,** scales with photon-ALP coupling, ALP mass, and magnetic field
- Testing 228 values of ALP mass and photon-ALP coupling introduces **trial factor**
- **⇒ Derive null distribution from simulations**
- For ***i*-th** B-field realization and ***j*-th** pseudo experiment the null distribution is formed by the test statistic

$$\mathrm{TS}_{ij} = -2\ln\left(\frac{\mathcal{L}(\boldsymbol{\mu}_0, \hat{\hat{\boldsymbol{\theta}}}|\mathbf{D}_j)}{\mathcal{L}(\hat{\boldsymbol{\mu}}_i, \hat{\boldsymbol{\theta}}|\mathbf{D}_j)}\right)$$

[Ajello et al. 2016]

NULL DISTRIBUTION FROM MC

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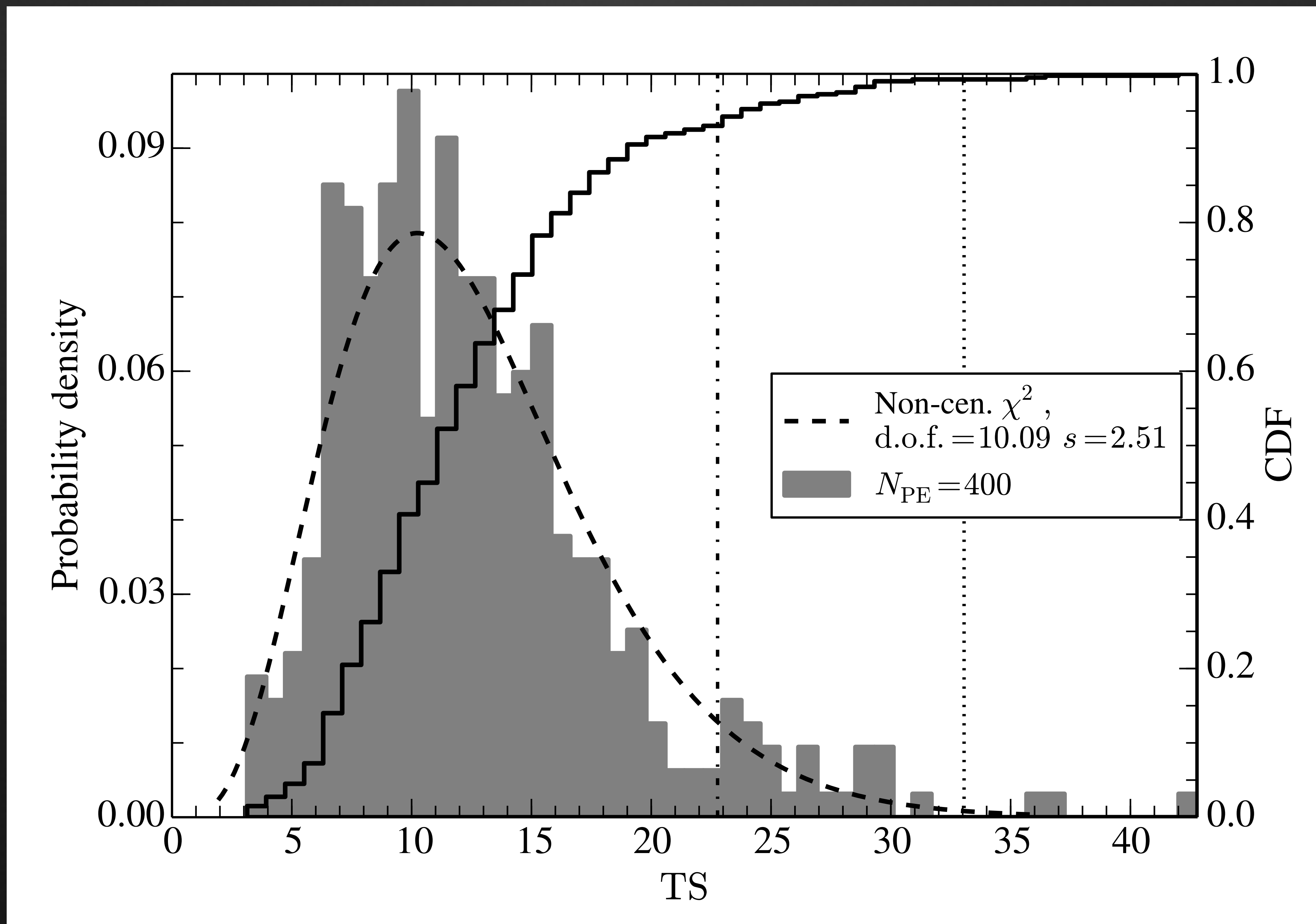


[Ajello et al. 2016]

SEARCHING FOR AN ALP SIGNAL WITH LOG LIKELIHOOD RATIO TEST

Joint likelihood ∀ event types *i* and reconstructed energy bins *k′*:

$$\mathcal{L}(\boldsymbol{\mu}, \boldsymbol{\theta} | \mathbf{D}) = \prod_{i,k'} \mathcal{L}(\mu_{ik'}(m_a, g_{a\gamma}, \mathbf{B}), \theta_i | D_{ik'})$$

expected number of counts ($\boldsymbol{\mu}$) — nuisance parameters ($\boldsymbol{\theta}$) — data ($\mathbf{D}$)

Test null hypothesis (no ALP, μ_0) with likelihood ratio test:

$$\mathrm{TS} = -2 \ln \left(\frac{\mathcal{L}(\boldsymbol{\mu}_0, \hat{\hat{\boldsymbol{\theta}}} | \mathbf{D})}{\mathcal{L}(\hat{\boldsymbol{\mu}}_{95}, \hat{\boldsymbol{\theta}} | \mathbf{D})} \right)$$

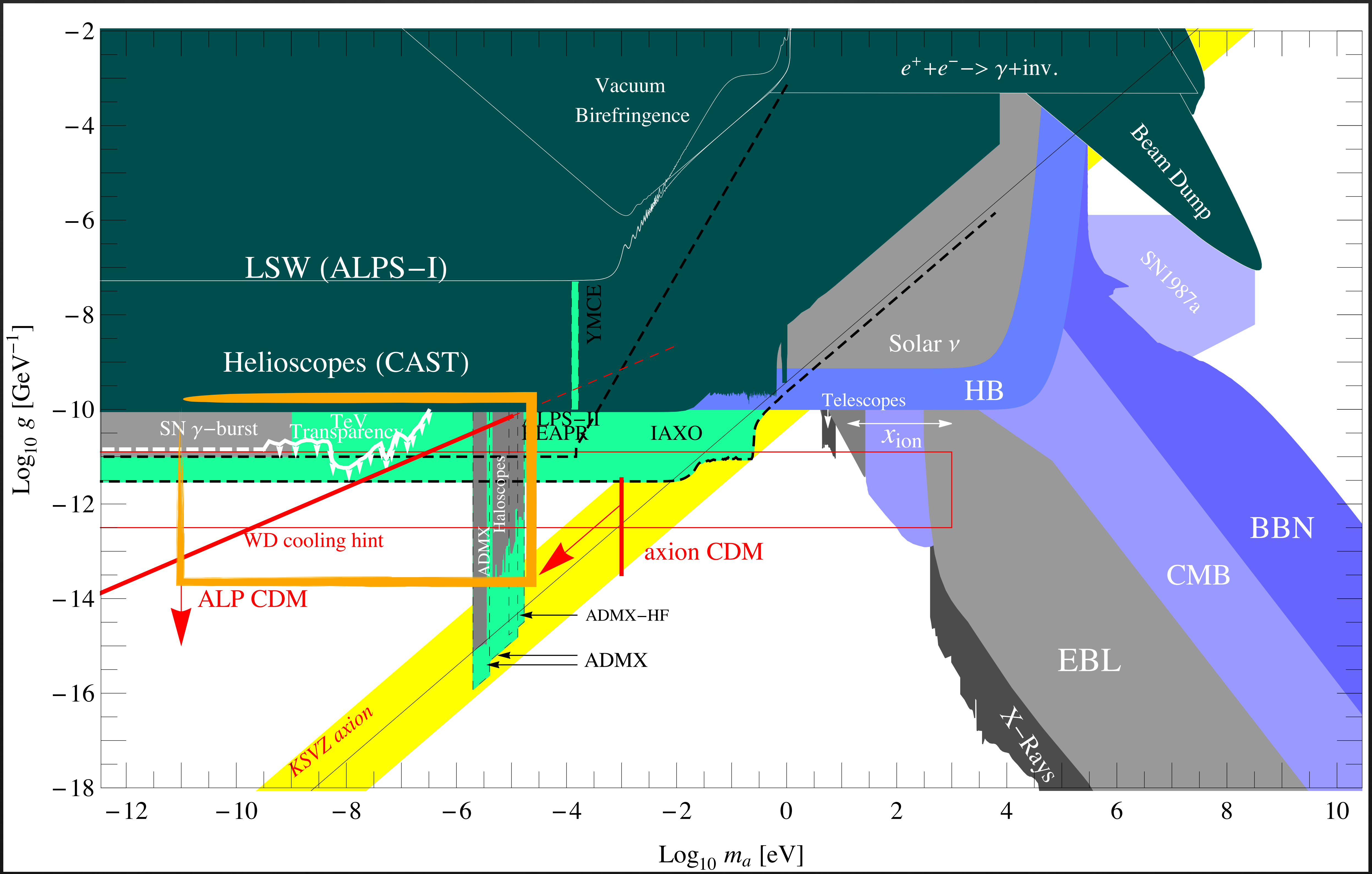
B FIELD RANDOM: SIMULATE MANY REALIZATIONS AND SELECT 95% QUANTILE OF LIKELIHOOD DISTRIBUTION

Threshold TS value for which we could claim ALP detection **derived from fit to Monte Carlo** simulations (Asymptotic theorems not applicable)

$\mathrm{TS}_{\mathrm{thr}}$ (3σ) = 33.1

[Ajello et al. 2016]

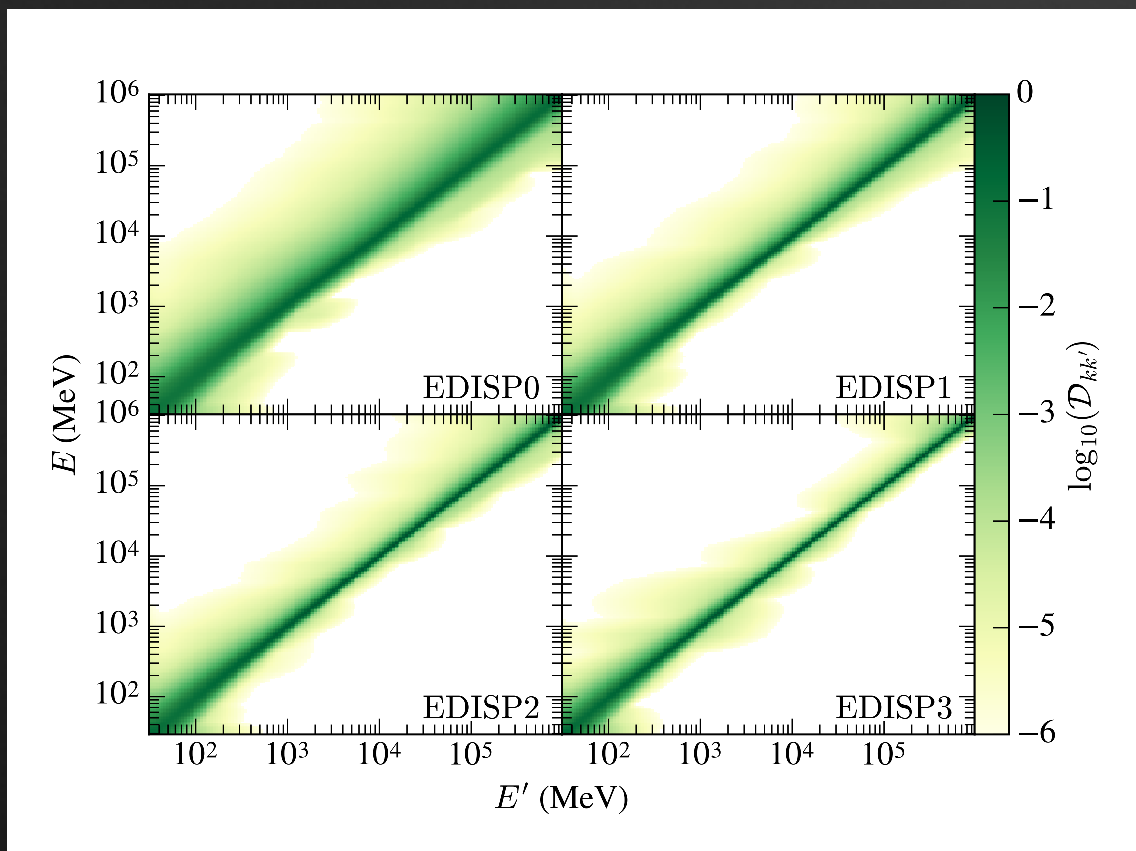
CONSTRAINTS & SENSITIVITIES



FERMI-LAT ENERGY RESOLUTION

FOR NGC1275 OBSERVATIONS

Energy Dispersion matrices



Energy resolution