Oskar Klein centre

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Fermi Gamma-ray Space Telescope

SEARCH FOR AXION-LIKE PARTICLE SIGNATURES IN GAMMA-RAY DATA

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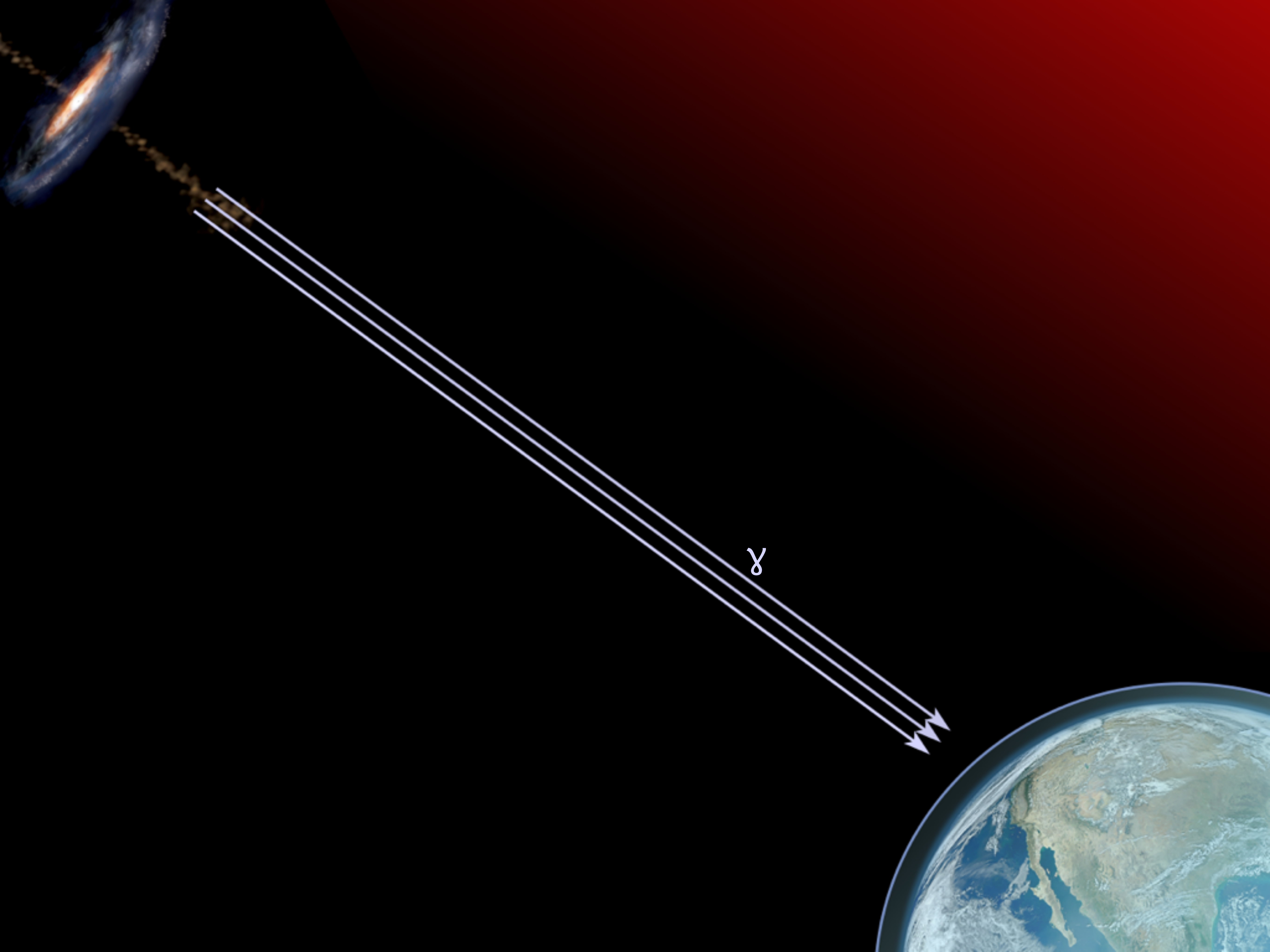
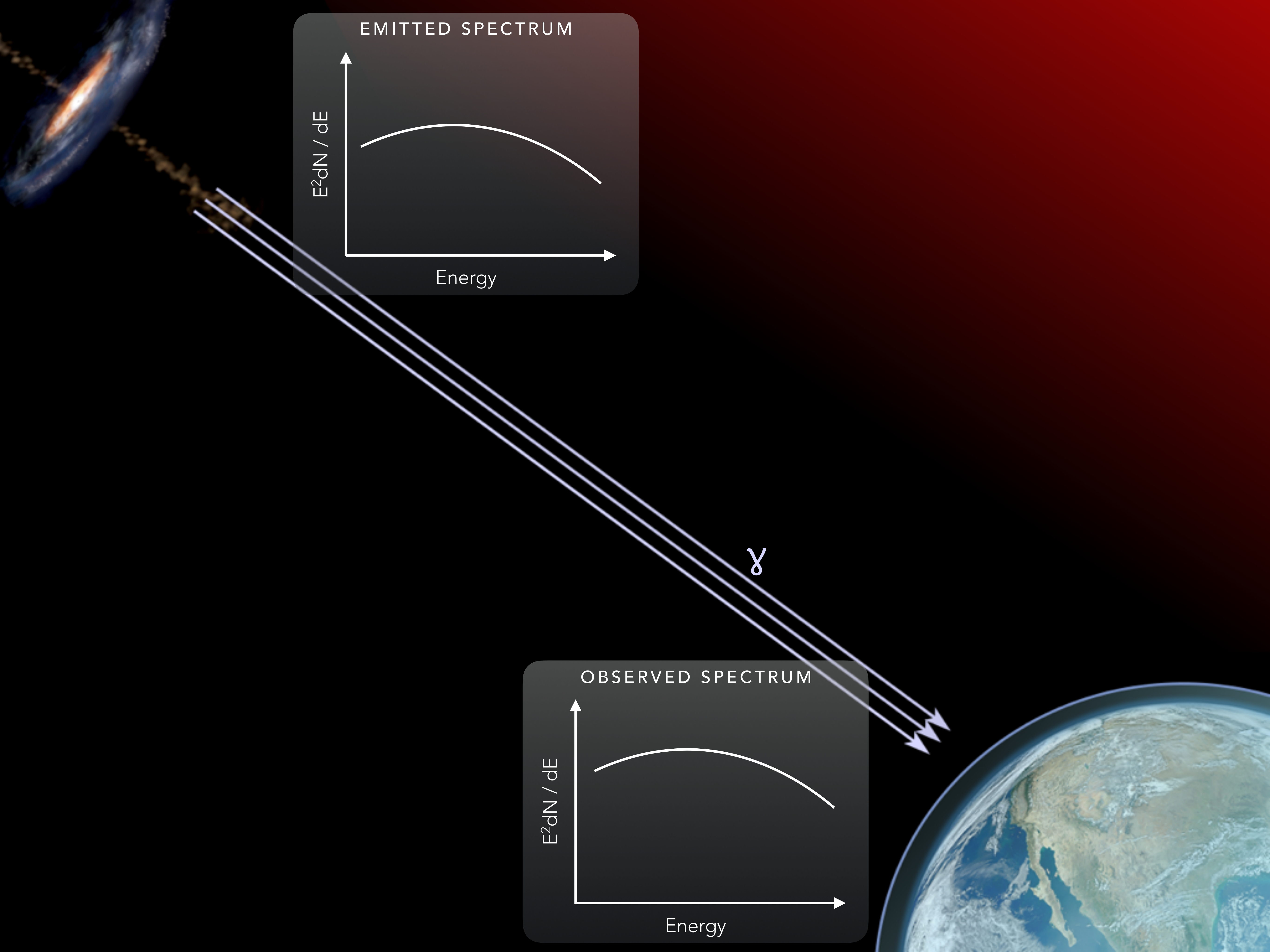
AXIONS AND AXION-LIKE PARTICLES

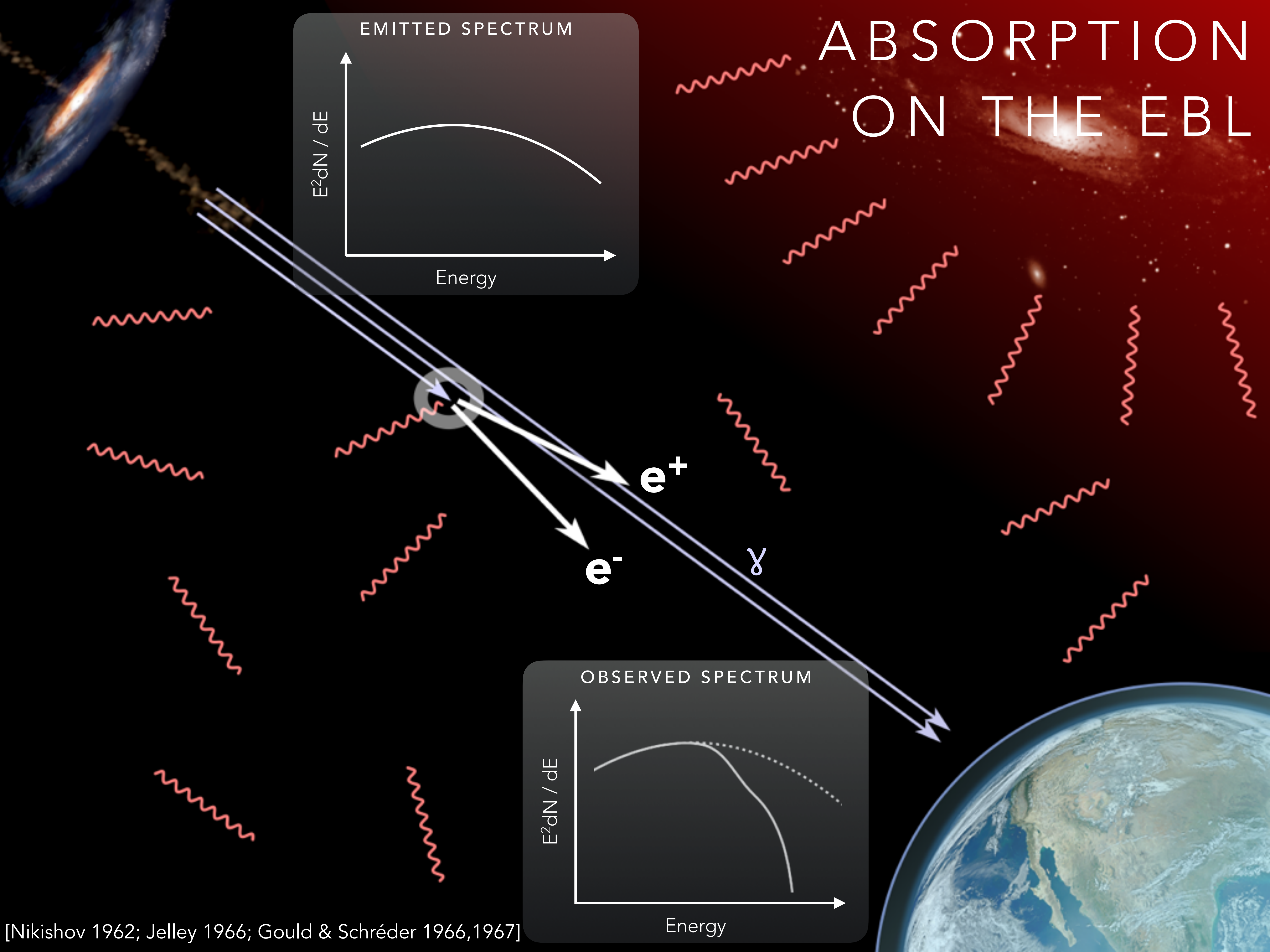
- **Axions:** by-product of solution of strong CP problem in QCD
- Couple to photons in **external magnetic** fields
- **Axion-like particles (ALPs):** generalization, arise in Standard Model extensions, e.g. **string theories**
- **ALPs:** mass and photon coupling independent parameters
- **DM candidate** if produced non-thermally
- For coupling to ɣ rays in astrophysical B fields: **light ALPs $m_a \lesssim$ μeV**

[Peccei & Quinn, 1977; Weinberg, 1978; Wilczek, 1978; Raffelt & Stodolsky 1988; Csaki et al. 2003; Hooper & Serpico, 2007; Ringwald 2014]


γ

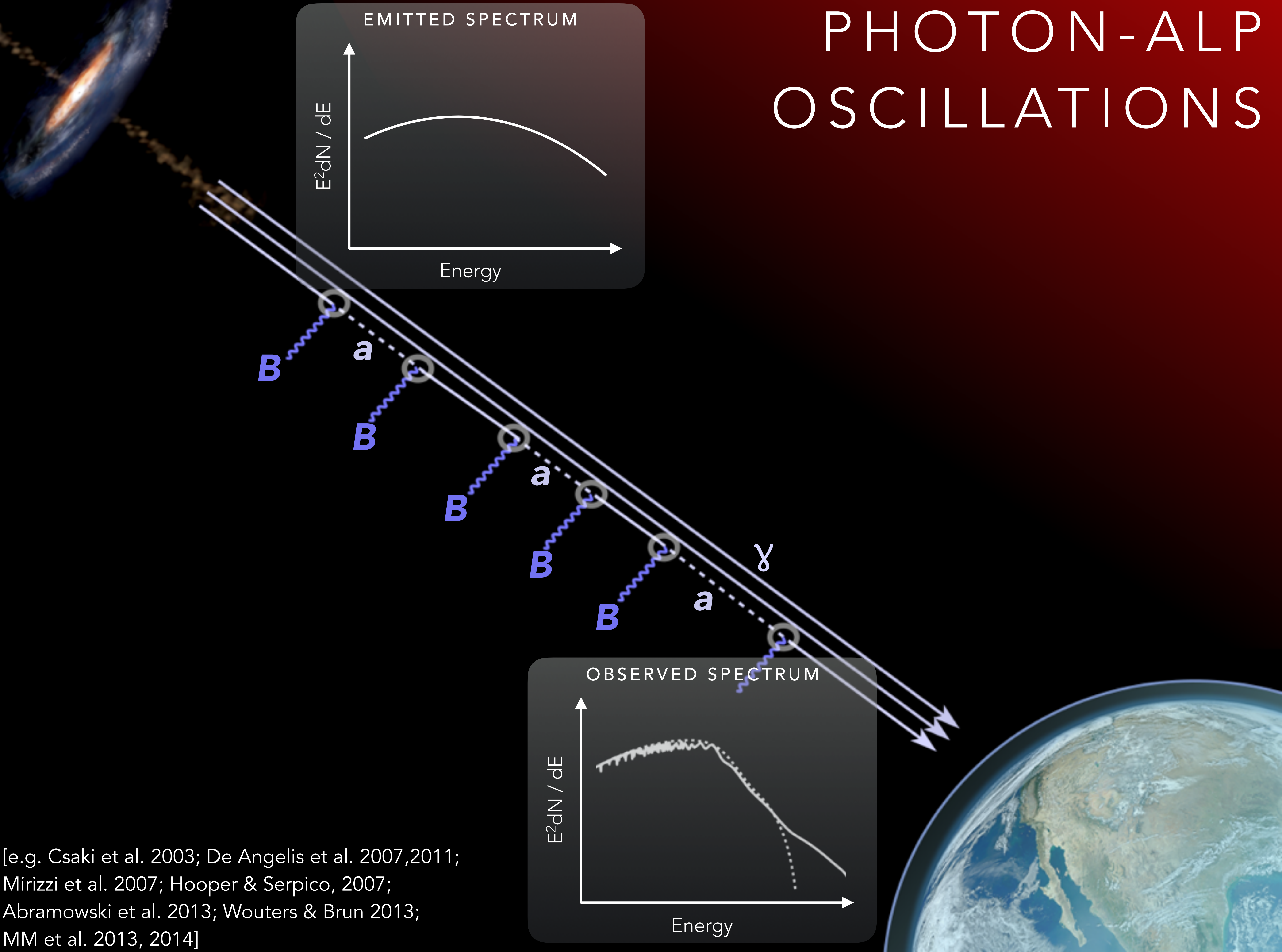

EMITTED SPECTRUM
E²dN / dE
Energy
γ
OBSERVED SPECTRUM
E²dN / dE
Energy

ABSORPTION ON THE EBL



[Nikishov 1962; Jelley 1966; Gould & Schréder 1966,1967]

PHOTON-ALP OSCILLATIONS



[e.g. Csaki et al. 2003; De Angelis et al. 2007,2011;
Mirizzi et al. 2007; Hooper & Serpico, 2007;
Abramowski et al. 2013; Wouters & Brun 2013;
MM et al. 2013, 2014]

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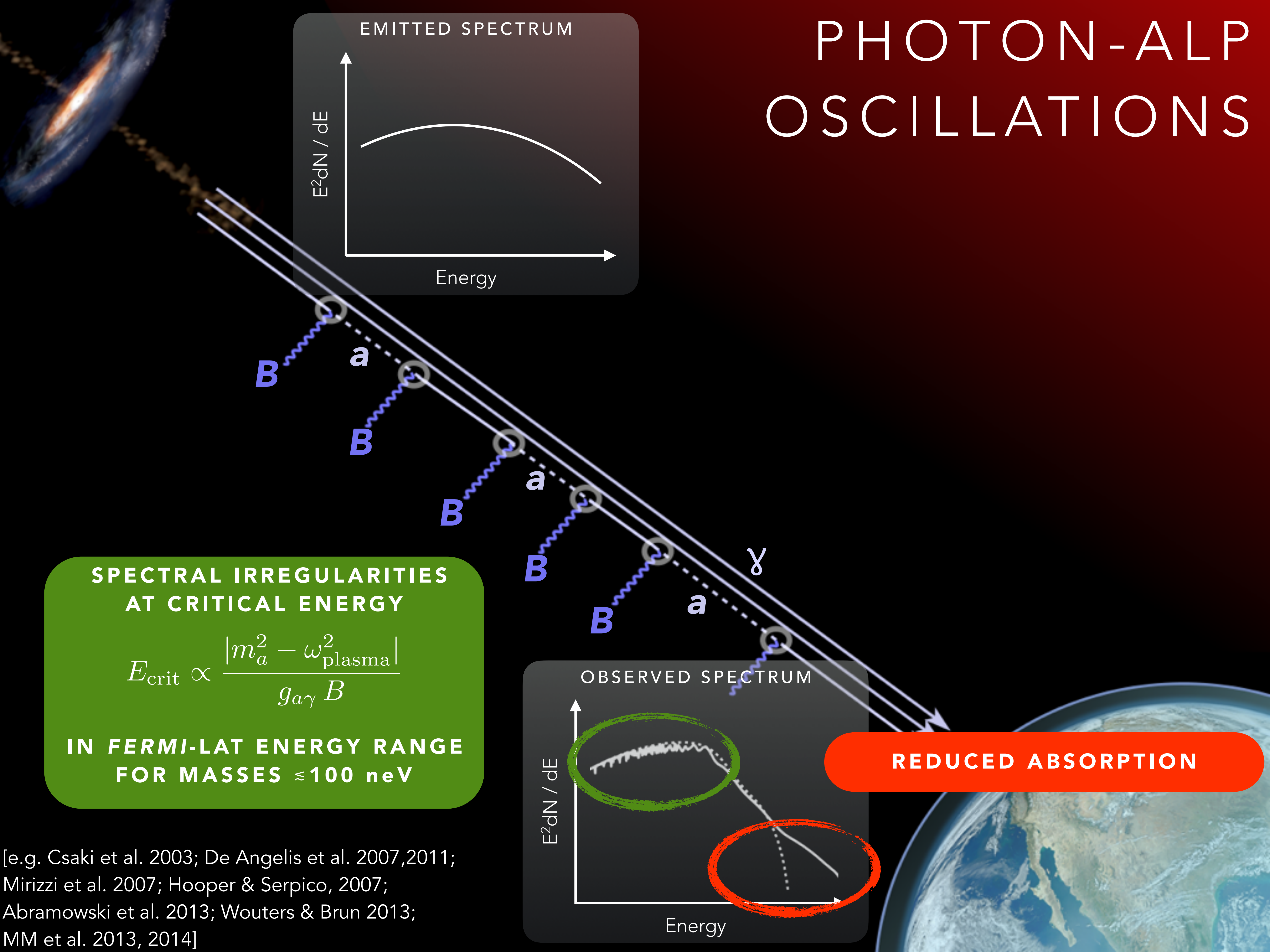


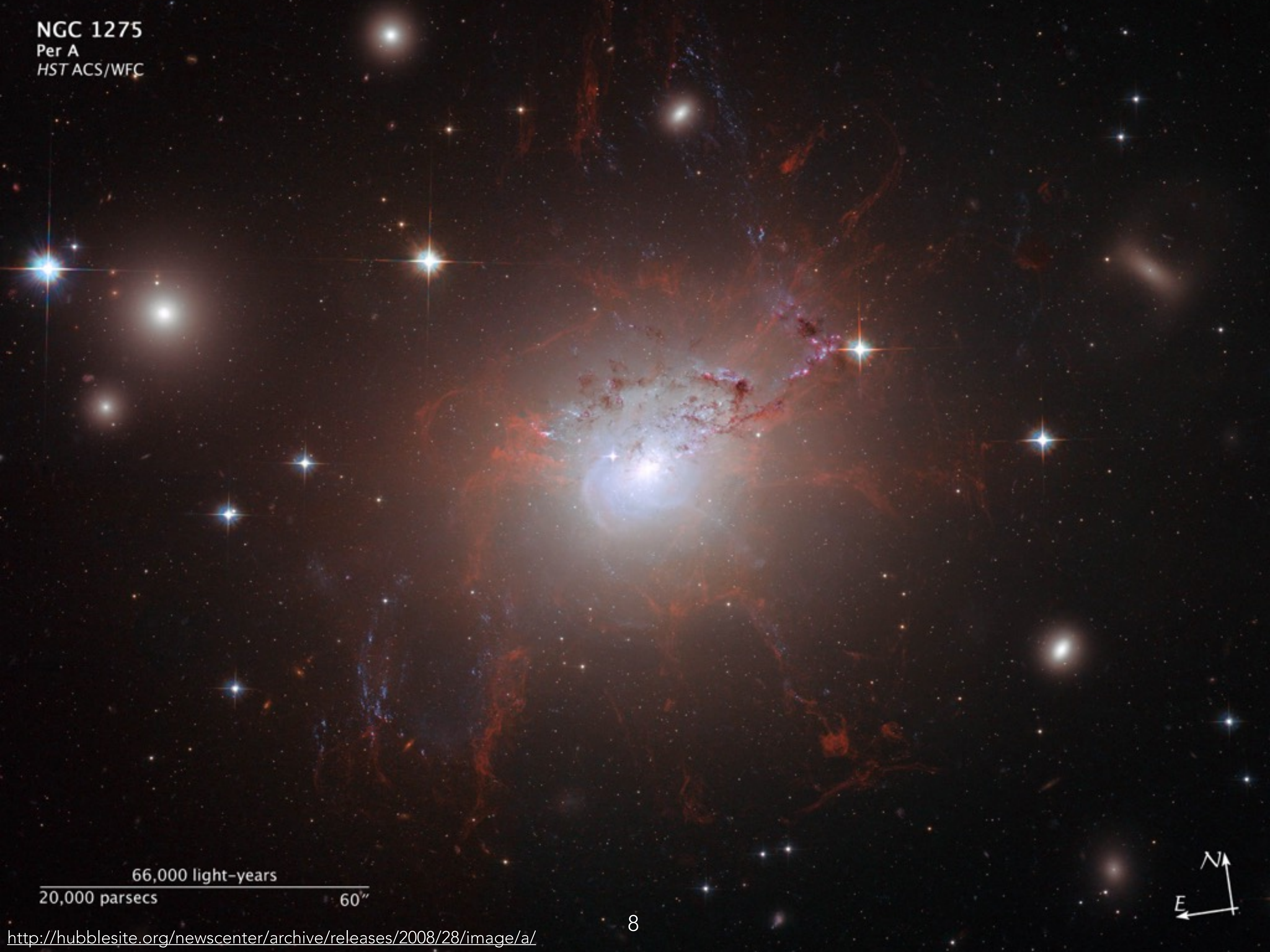
REDUCED ABSORPTION

SPECTRAL IRREGULARITIES AT CRITICAL ENERGY

$$E_{\text{crit}} \propto \frac{|m_a^2 - \omega_{\text{plasma}}^2|}{g_{a\gamma}\, B}$$

IN *FERMI*-LAT ENERGY RANGE FOR MASSES $\lesssim$100 neV

[e.g. Csaki et al. 2003; De Angelis et al. 2007,2011; Mirizzi et al. 2007; Hooper & Serpico, 2007; Abramowski et al. 2013; Wouters & Brun 2013; MM et al. 2013, 2014]



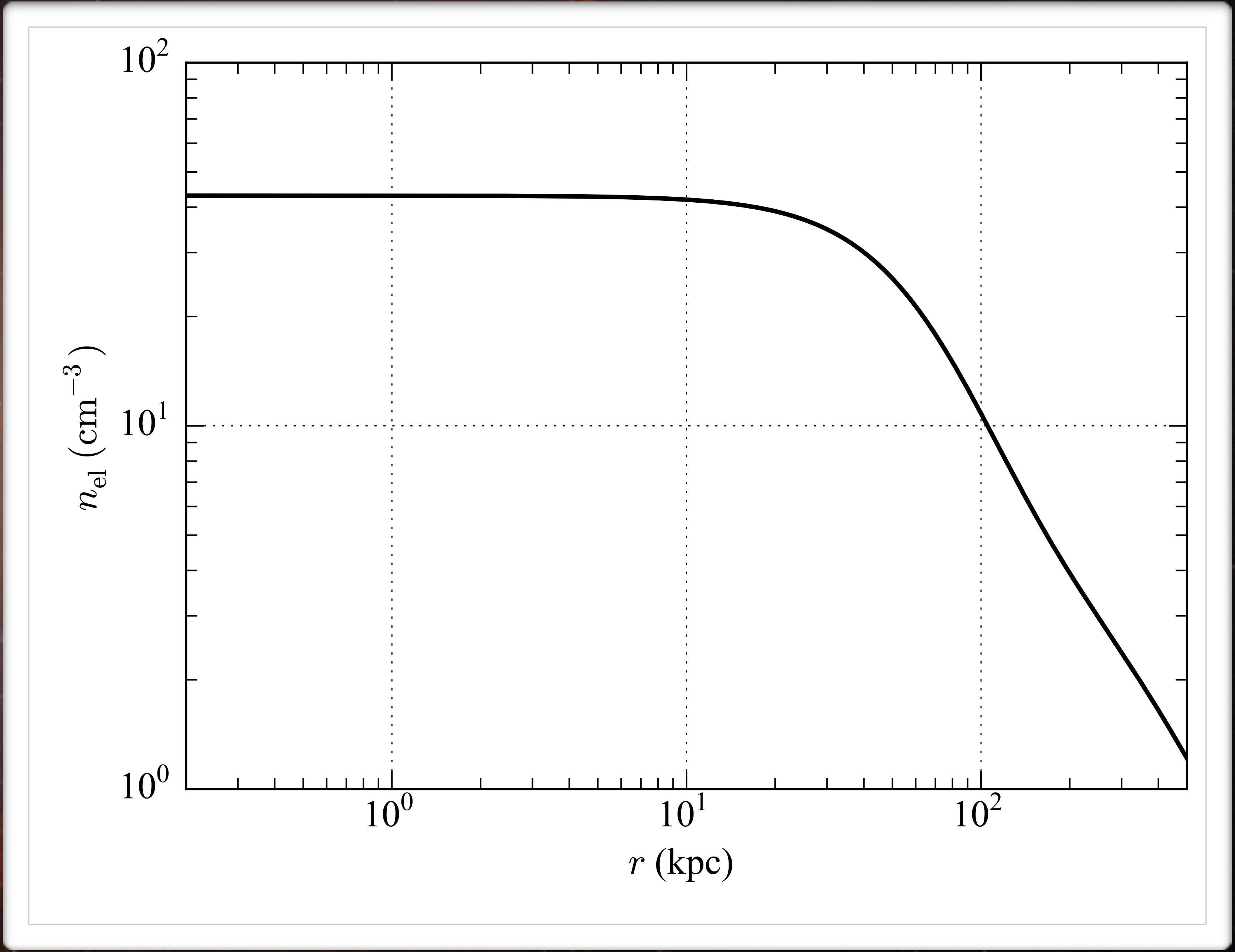
http://hubblesite.org/newscenter/archive/releases/2008/28/image/a/

- Radio galaxy **NGC 1275**, **bright *Fermi* and MAGIC source** [e.g. Abdo et al. 2009]
- In the center of **cool-core Perseus cluster**
- Redshift **z = 0.017559**

NGC 1275
Per A
HST ACS/WFC

CLUSTER ELECTRON DENSITY

- Electron density derived from X-ray observations [Churazov et al. 2003]



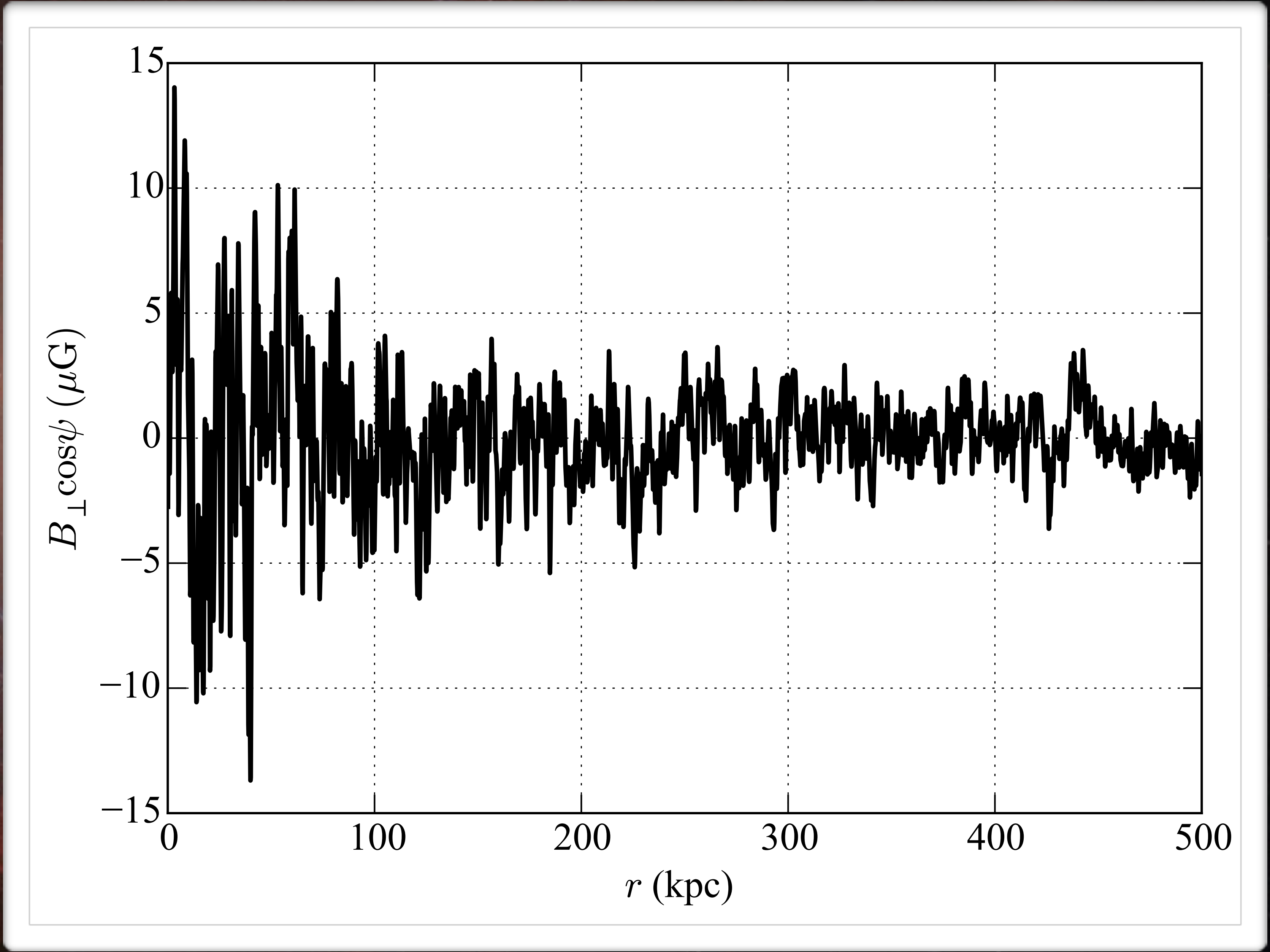
66,000 light-years
20,000 parsecs
60″

N
E

NGC 1275
Per A
HST ACS/WFC

CLUSTER MAGNETIC FIELD

- Cluster *B* field modelled as **gaussian turbulent field** [MM et al. 2014]
- Follows electron density
- Rotation measures: central B field ~ **25 µG** [Taylor et al. 2006]
- **Conservative** estimate of central B field: **10 µG** [Aleksic et al. 2012]
- **Turbulence**: assumed the same as in cluster A2199 [Vacca et al. 2012]



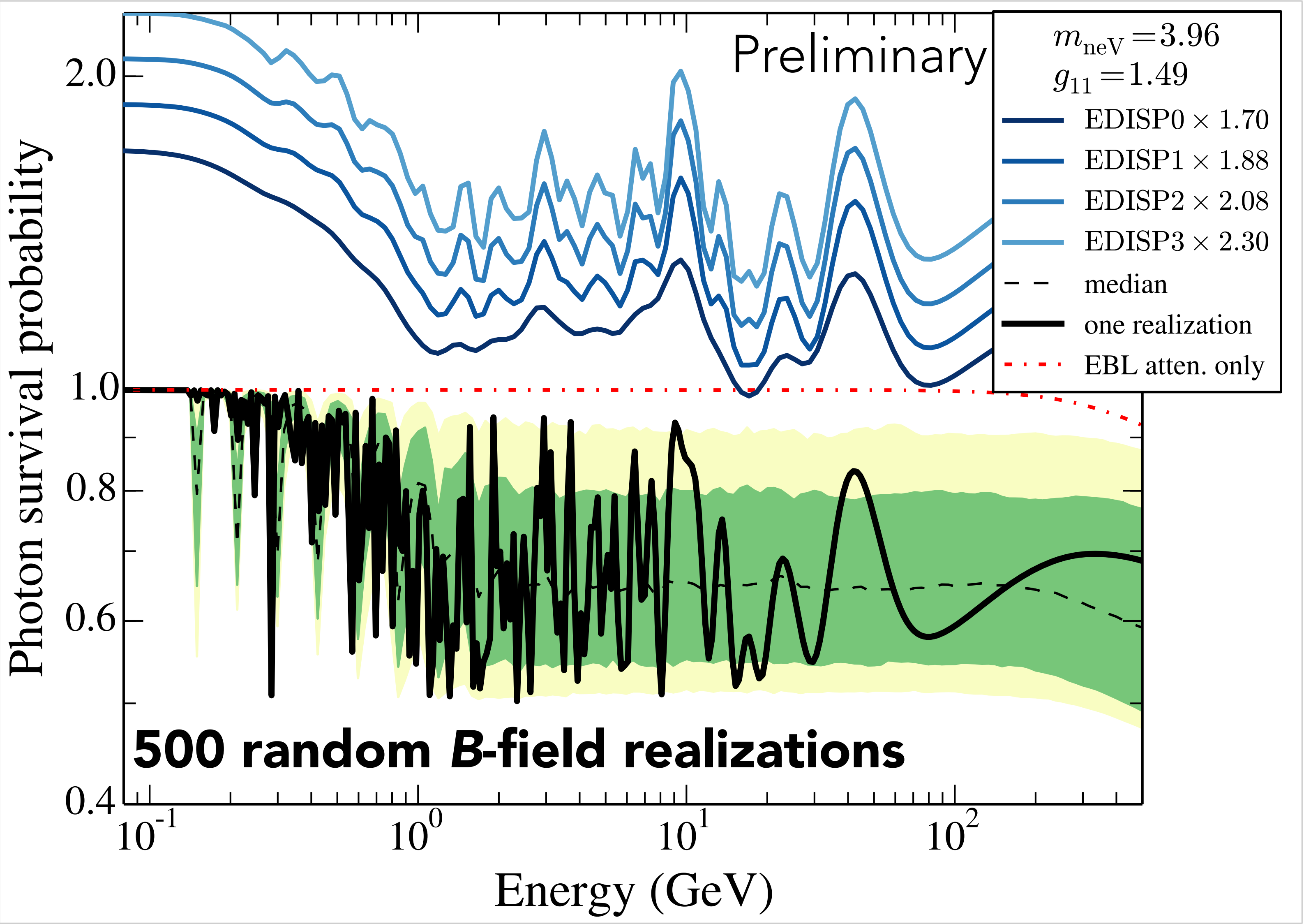
66,000 light-years
20,000 parsecs
60″
N
E

NGC 1275
Per A
HST ACS/WFC

PHOTON SURVIVAL PROBABILITY

- Considered *B* fields: **Perseus cluster & Milky Way**
- EBL absorption included
- Irregularities smeared with **energy dispersion**

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



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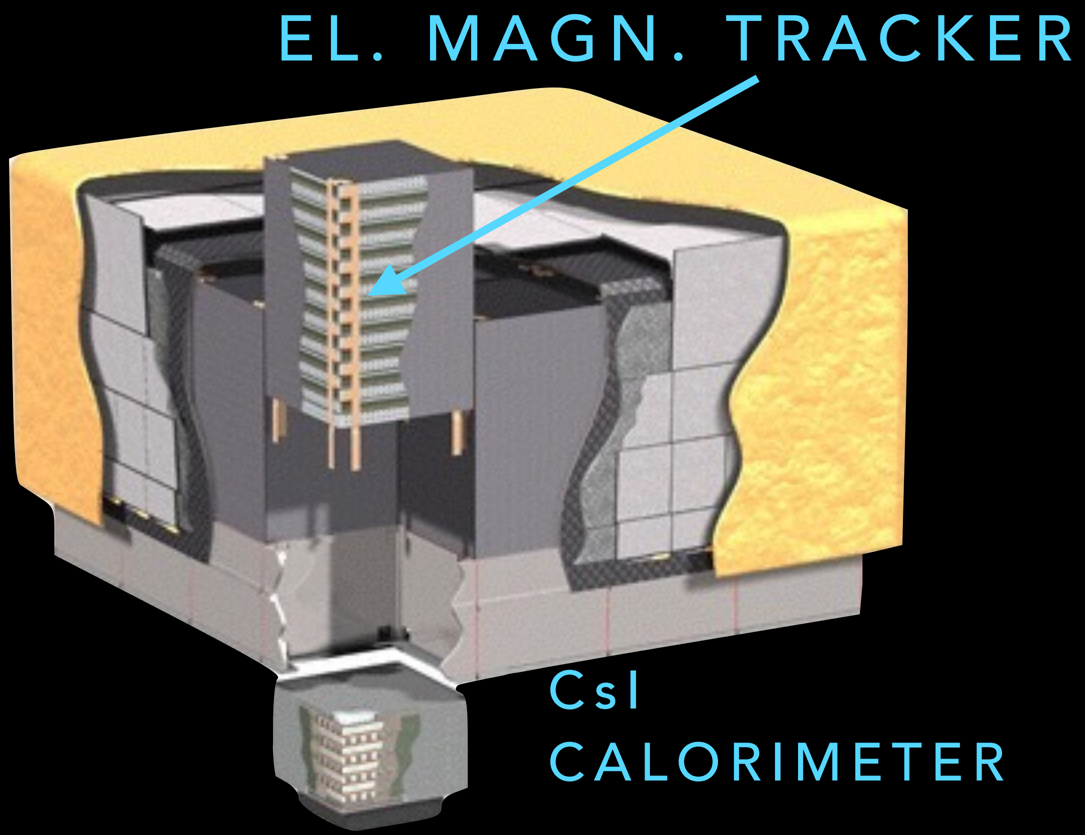
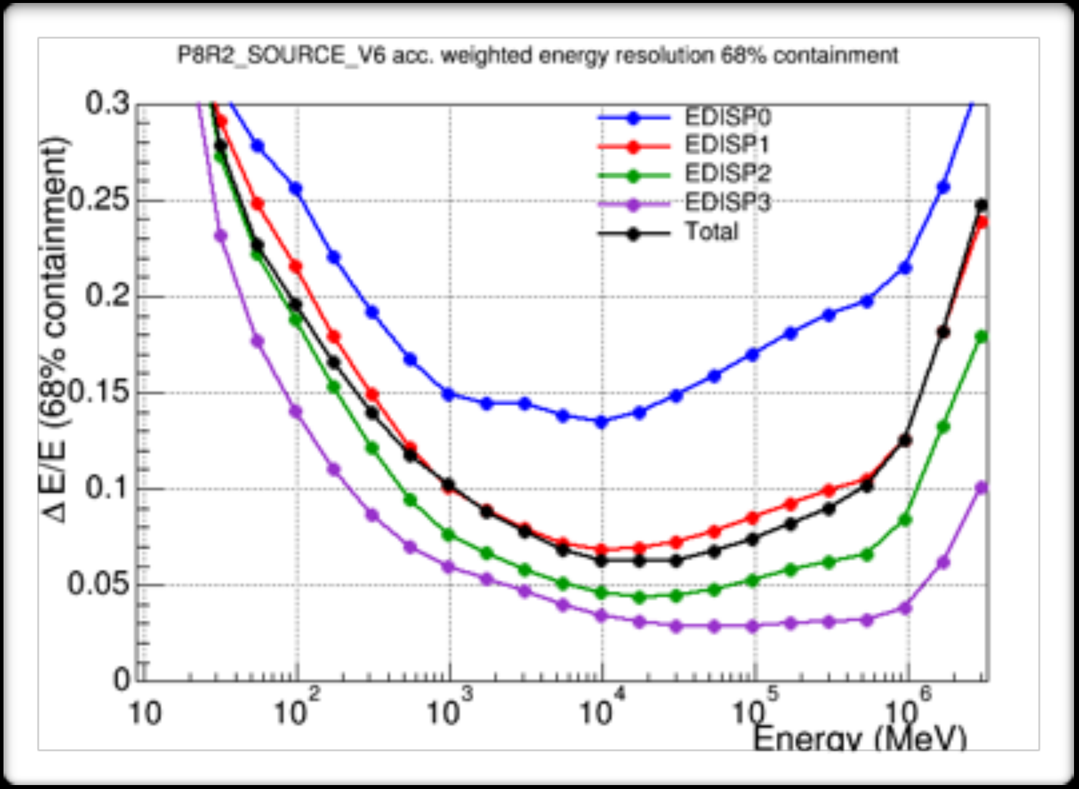
E

THE FERMI LARGE AREA TELESCOPE (LAT)

Energy range	30 MeV - over 300 GeV
Effective Area ($E > 1$ GeV)	~ 1 m^2
Point spread function (PSF)	~ 0.8° at 1 GeV
Field of view	2.4 sr
Orbital period	91 minutes
Altitude	565 km



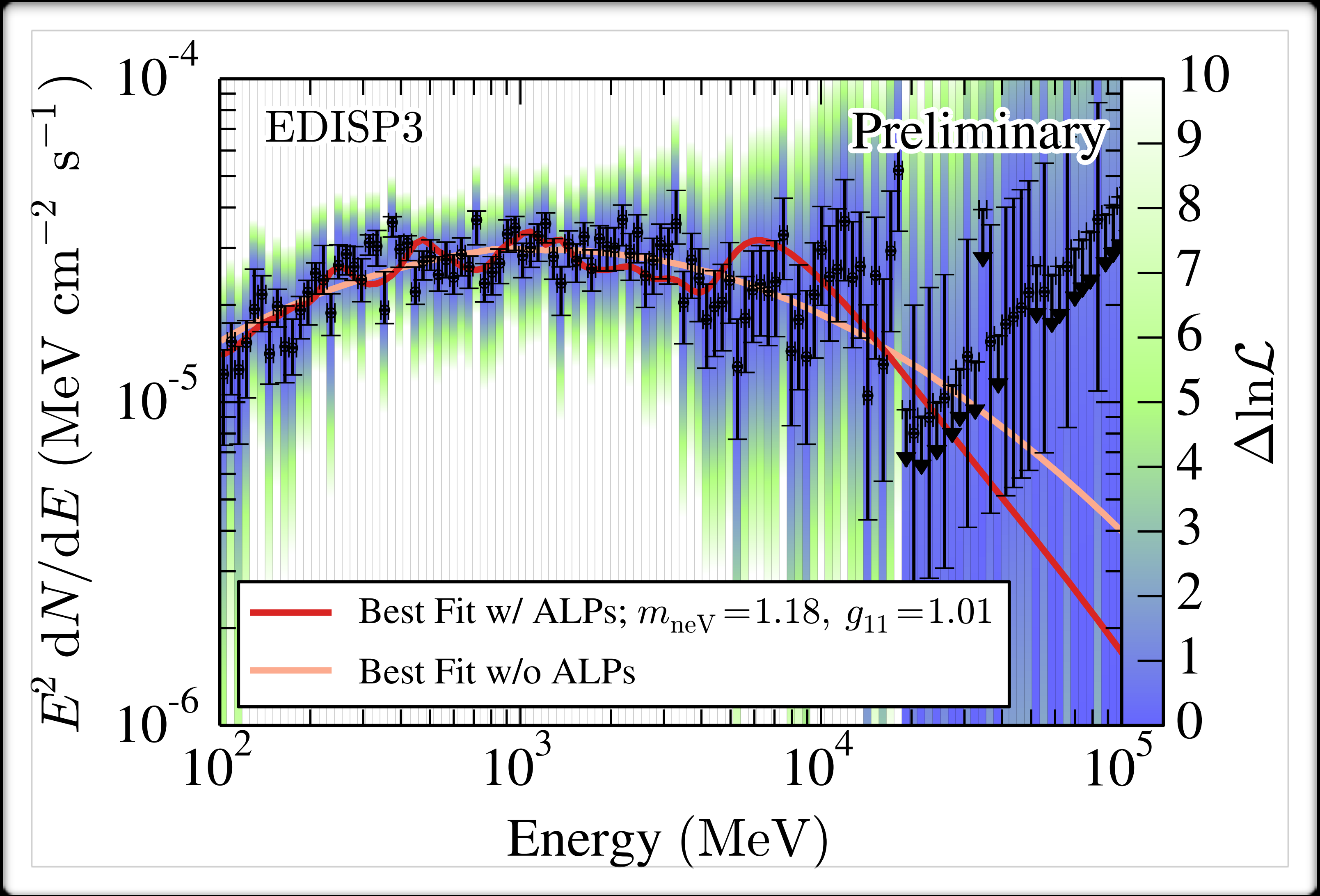
- **New Pass 8** released for the public this year
- Improves effective area, PSF, …
- Now possible to **split data** corresponding to **quality of energy reconstruction**



DATA ANALYSIS

[Ajello et al. 2015, for the LAT Collaboration, submitted]

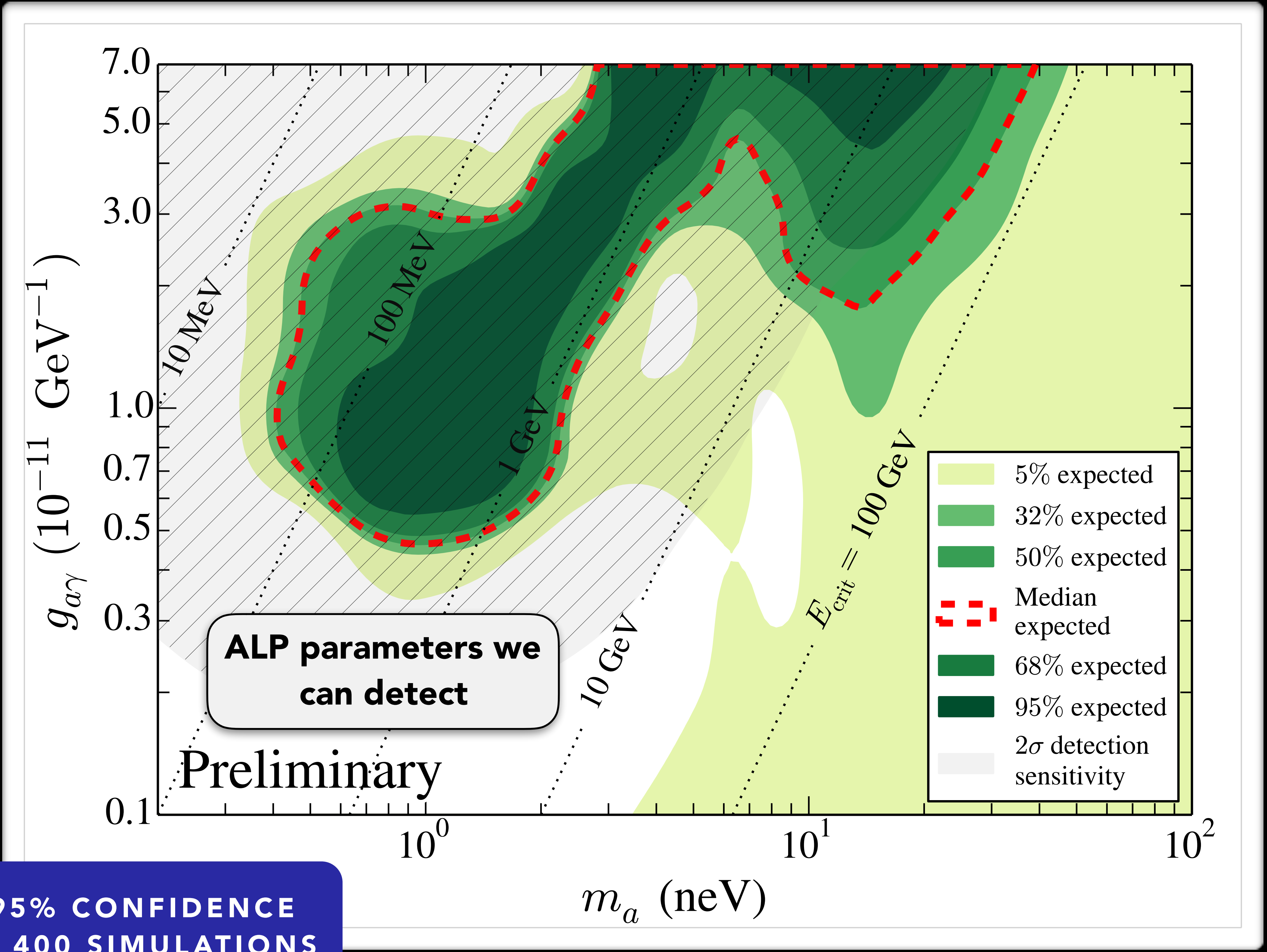
- **6 years** of **Pass 8** Source data
- Split into analysis **EDISP event types**
- Method: **log-likelihood ratio test** for no-ALP and ALP hypothesis
- Use **bin-by-bin likelihood curves**, similar to dwarf galaxy analysis [Ackermann et al. 2014,2015]
- Hypothesis test **calibrated with Monte-Carlo simulations**



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

NO-ALP HYPOTHESIS: $\exp(-\tau_{\gamma\gamma})\, F(E)$

EXPECTED LIMITS AND DETECTION SENSITIVITY FROM SIMULATIONS

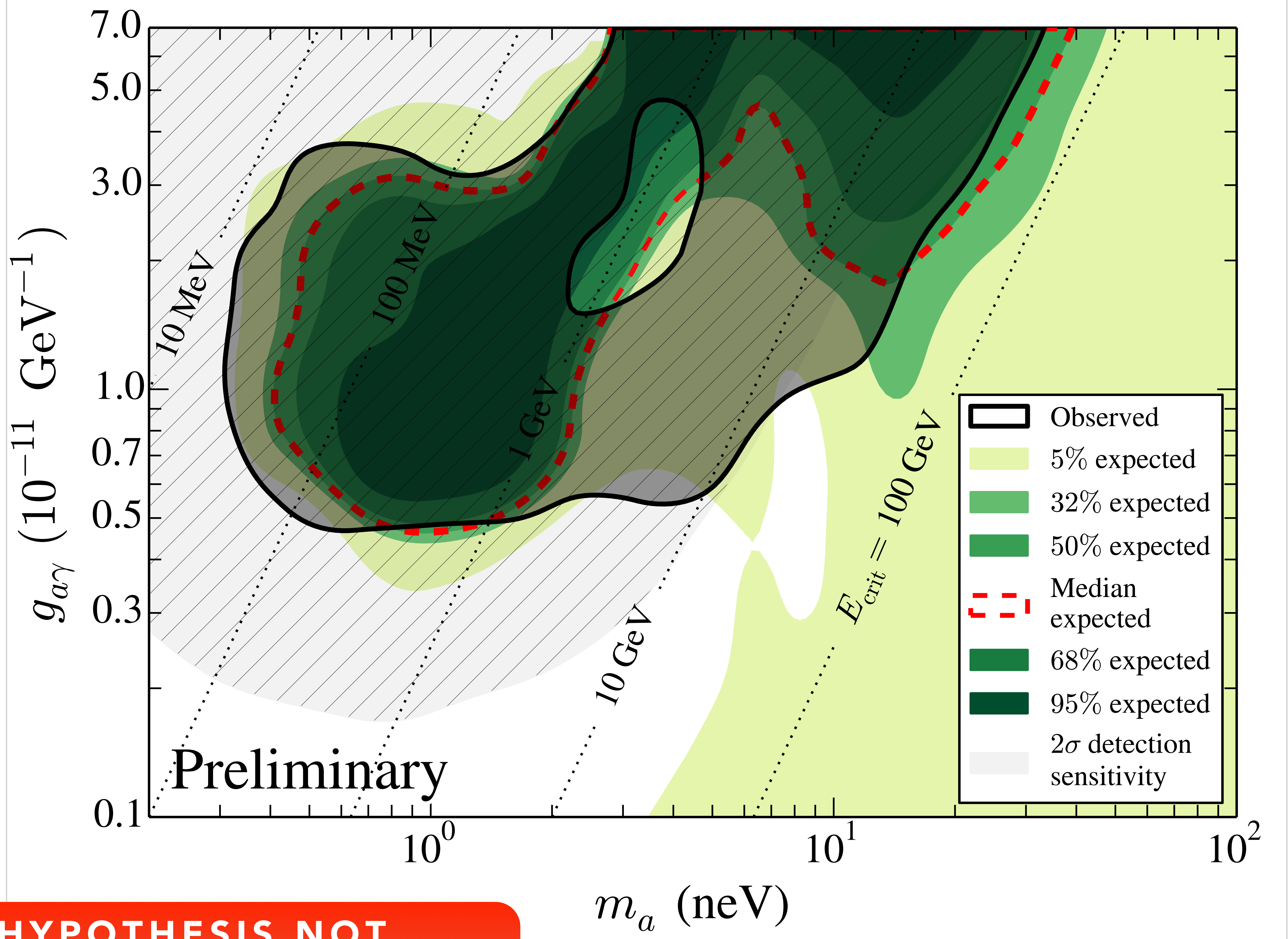


ALP parameters we can detect

EXPECTED 95% CONFIDENCE LIMITS FROM 400 SIMULATIONS W/O AN ALP SIGNAL

[Ajello et al. 2015, for the LAT Collaboration, submitted]

NO ALP OBSERVED: SETTING LIMITS



ALP HYPOTHESIS NOT PREFERRED, DERIVE 95% CONFIDENCE LIMITS

[Ajello et al. 2015, for the LAT Collaboration, submitted]

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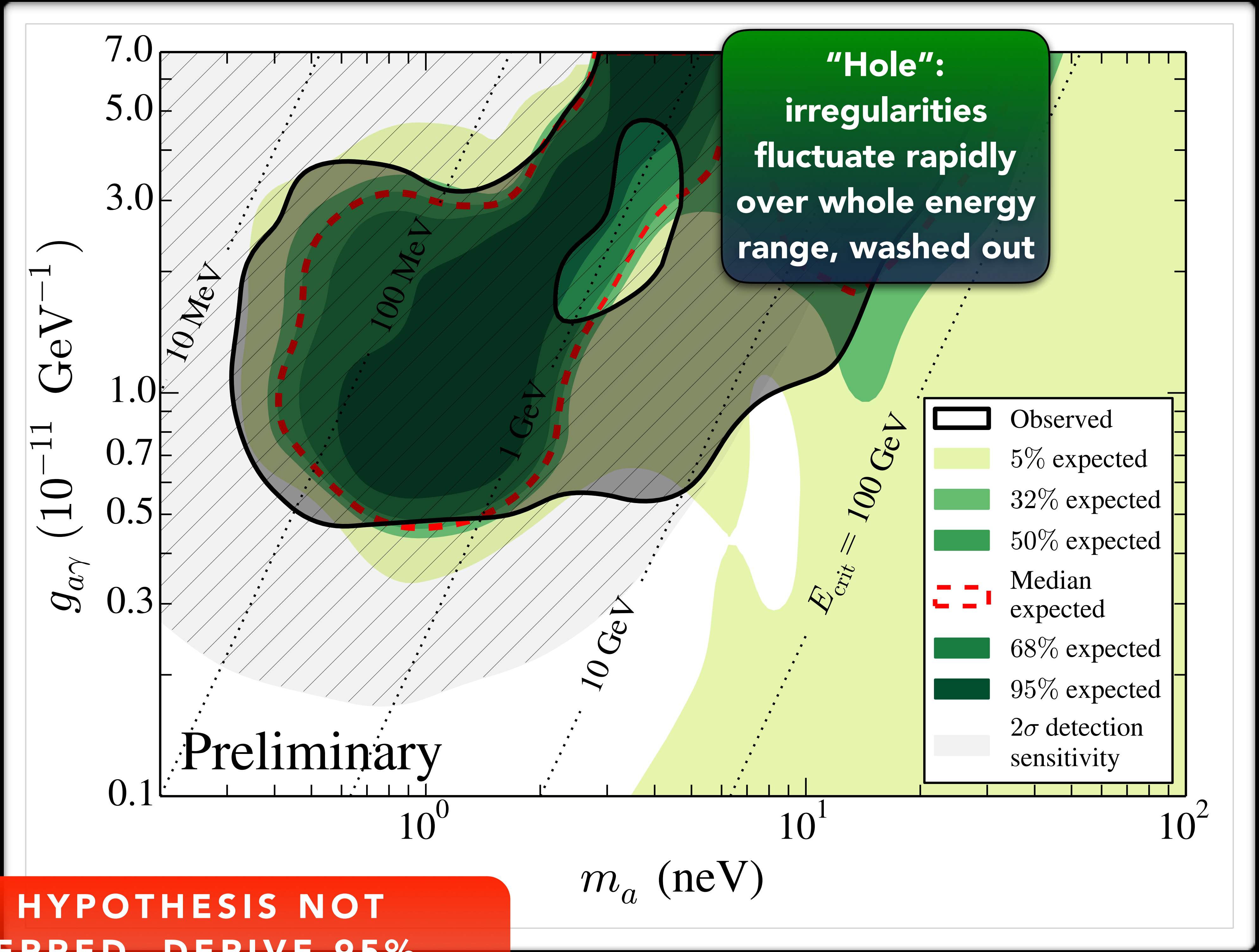


"Hole": irregularities fluctuate rapidly over whole energy range, washed out

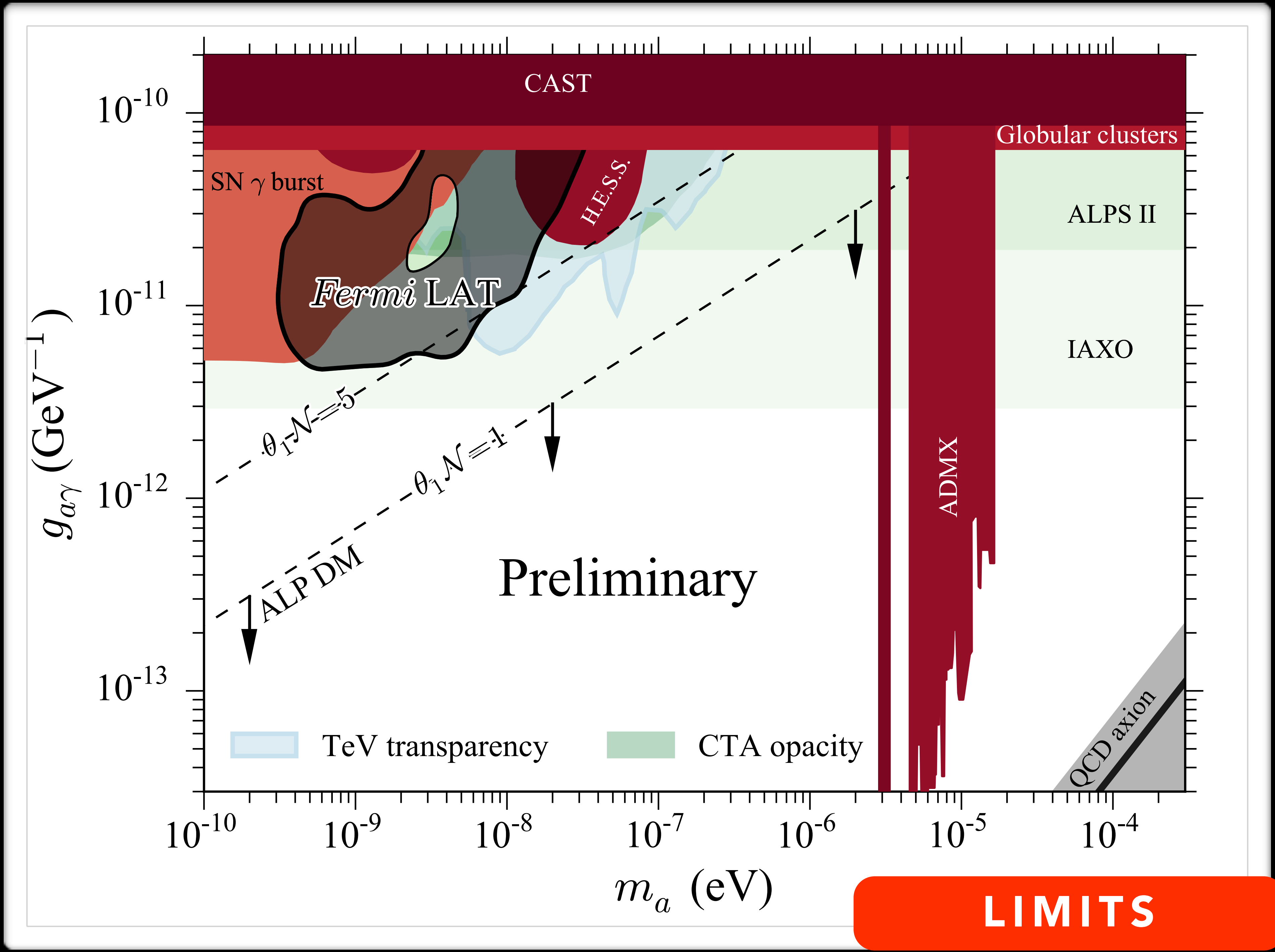
ALP HYPOTHESIS NOT PREFERRED, DERIVE 95% CONFIDENCE LIMITS

[Ajello et al. 2015, for the LAT Collaboration, submitted]

COMPARISON WITH OTHER LIMITS

[Ajello et al. 2015, for the LAT Collaboration, submitted]

- **Strongest limits** to date between **0.5 < m$_a$ < 20 neV**
- **Competitive** with sensitivities of **future laboratory experiments**
- Strongly **constrains possibility that ALPs explain TeV transparency hint** [MM et al. 2013]



LIMITS

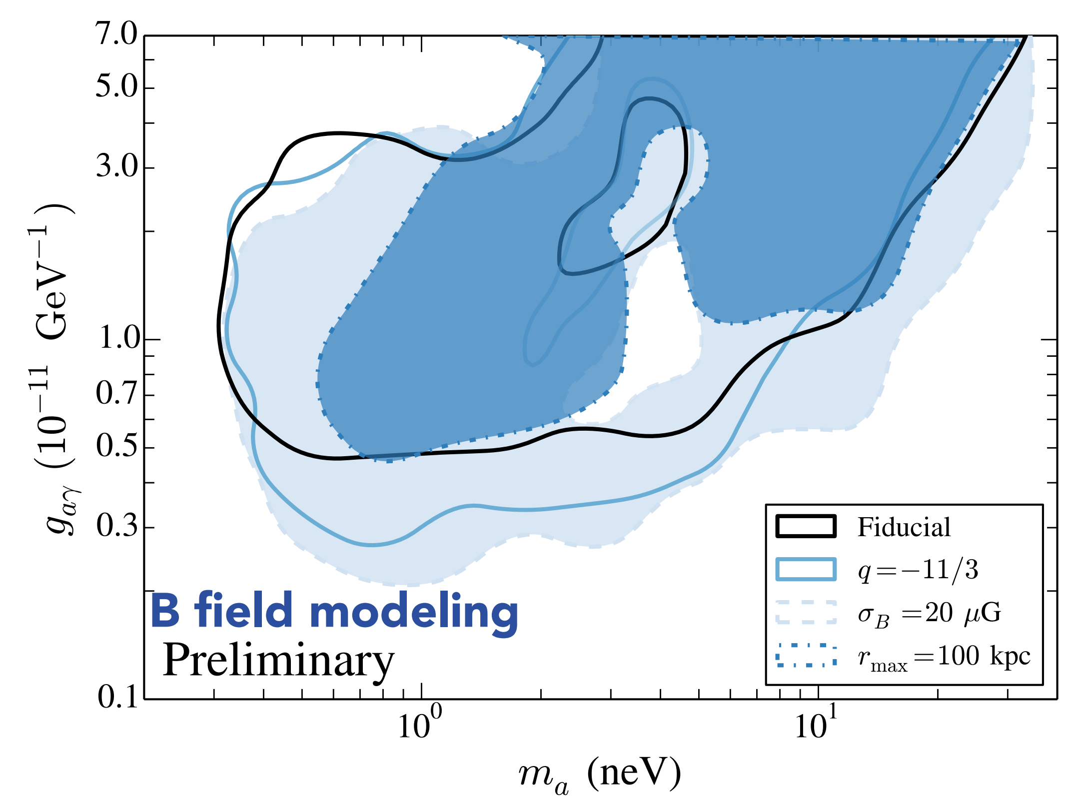
SENSITIVITIES

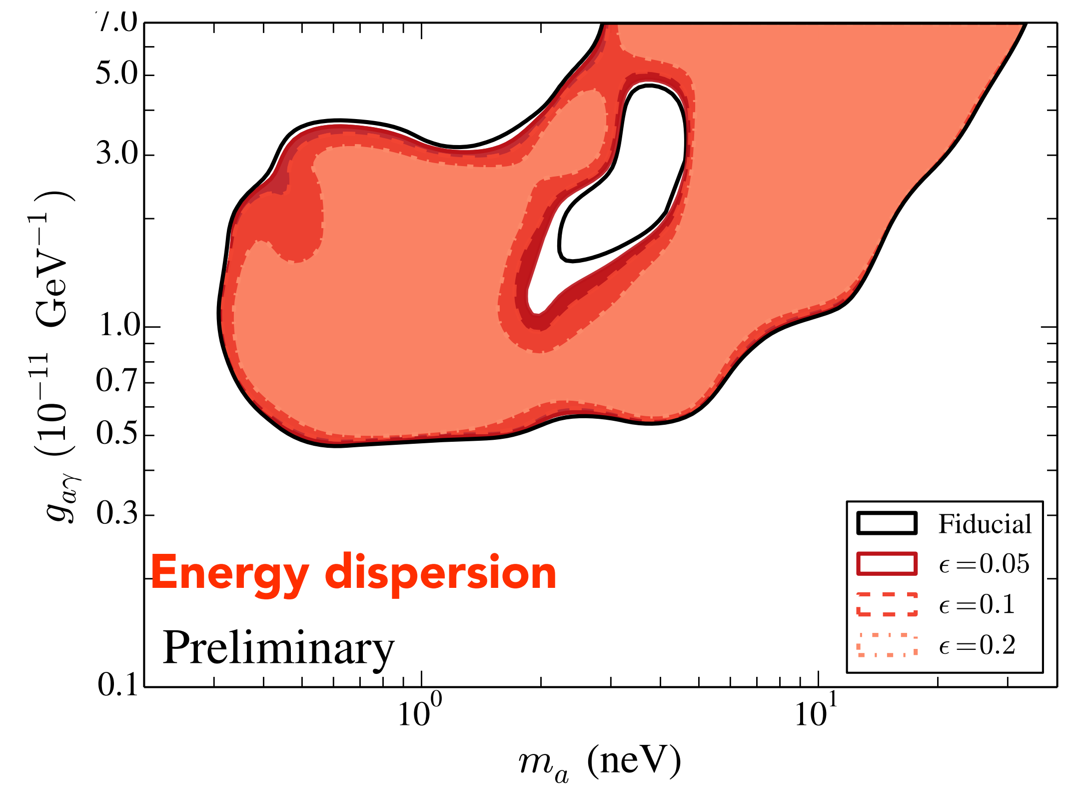
SYSTEMATIC UNCERTAINTIES

[Ajello et al. 2015, for the LAT Collaboration, submitted]

- **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%**





SUMMARY & CONCLUSIONS

- We have **searched for spectral irregularities** induced by **photon-ALP oscillations** in the spectrum of **NGC 1275**
- We **do not find any indications** for ALPs and set the strongest **bounds** to date between **0.5** ≲ m_a ≲ **20 neV**
- In this mass range, the limits are **comparable to the sensitivity of future laboratory experiments**
- Together with other limits, the possibility that **ALPs could explain a reduced ɣ-ray opacity** of the Universe is now **strongly constrained**
- Systematic effects with strongest impact on limits: Modeling the **magnetic field and the energy dispersion**
- Better handle on magnetic field with future **SKA all-sky rotation measure survey** [Gaensler et al. 2004; Bonafede et al. 2015]
- Analysis can be extended to other sources, e.g. M87 in Virgo

Me looking for ALPs

BACK UP SLIDES

METHOD

- **Extract likelihood** for expected counts in every energy bin ➔ **independent of assumed spectrum** [similar to dwarf spheroidal dark matter analysis, e.g. Ackermann et al. 2014, 2015]
- **Joint likelihood fit** over EDISP event types *i* using bin-by-bin likelihood
- **Number of expected counts** in reconstructed energy bin *k′* and event type *i*:

$$\mu_{ik'} = \sum_k \mathcal{D}^i_{kk'} \int\limits_{\Delta E_k} \mathrm{d}E\, P_{\gamma\gamma} F(E) \mathcal{E}^i(E),$$

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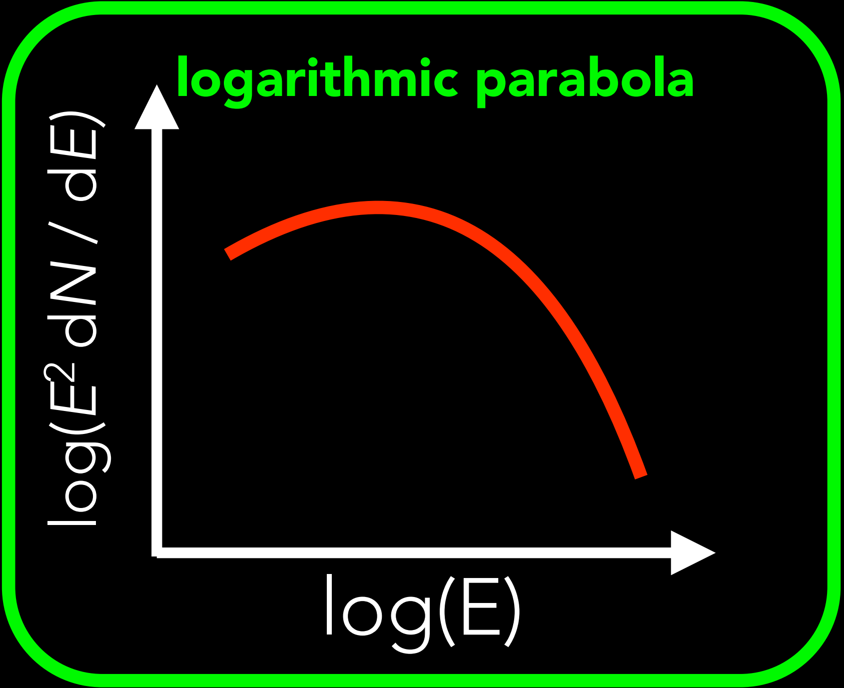
intrinsic spectrum


logarithmic parabola

[Aleksic et al. 2012;
Ackermann et al. 2015 (3FGL)]

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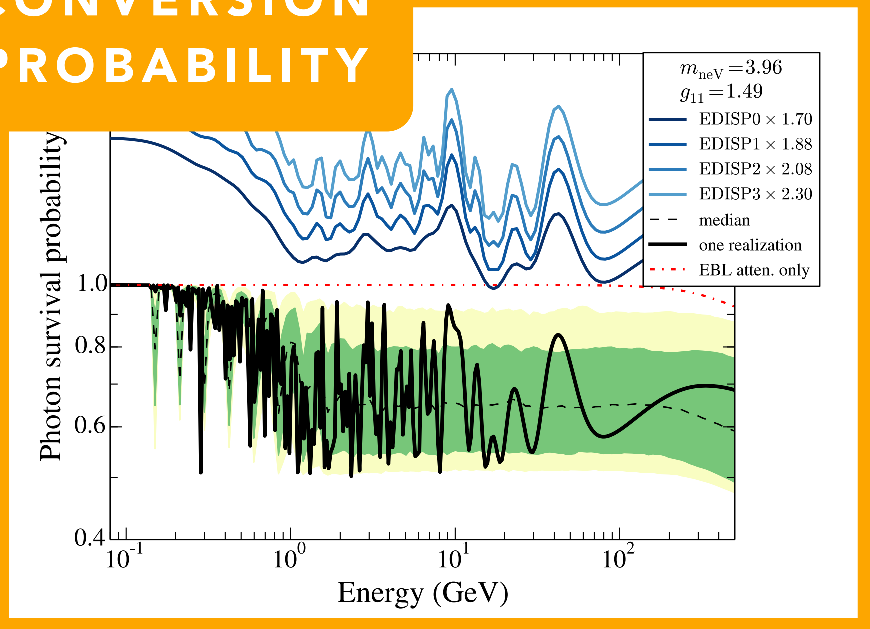
CONVERSION PROBABILITY



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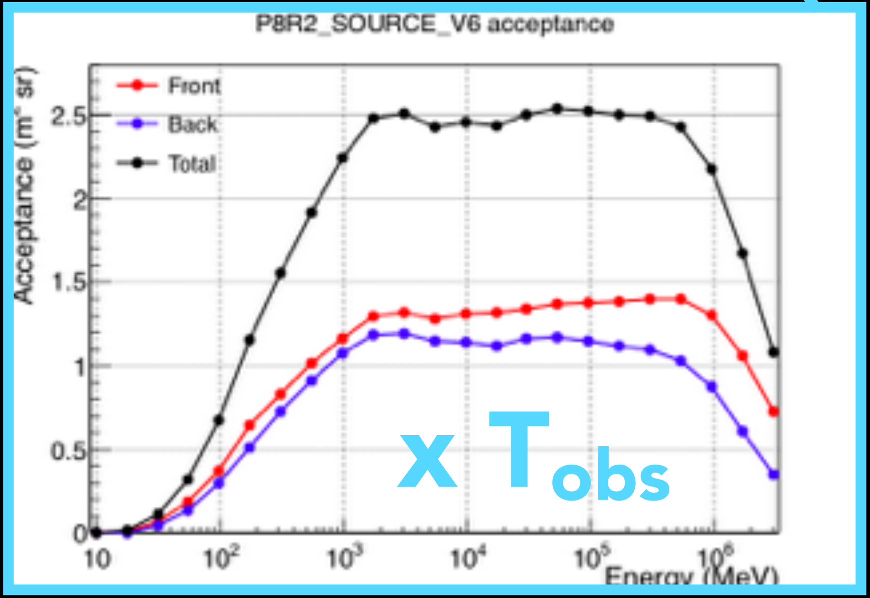
photon survival prob.

intrinsic spectrum

Exposure (A_{eff} x obs. time)



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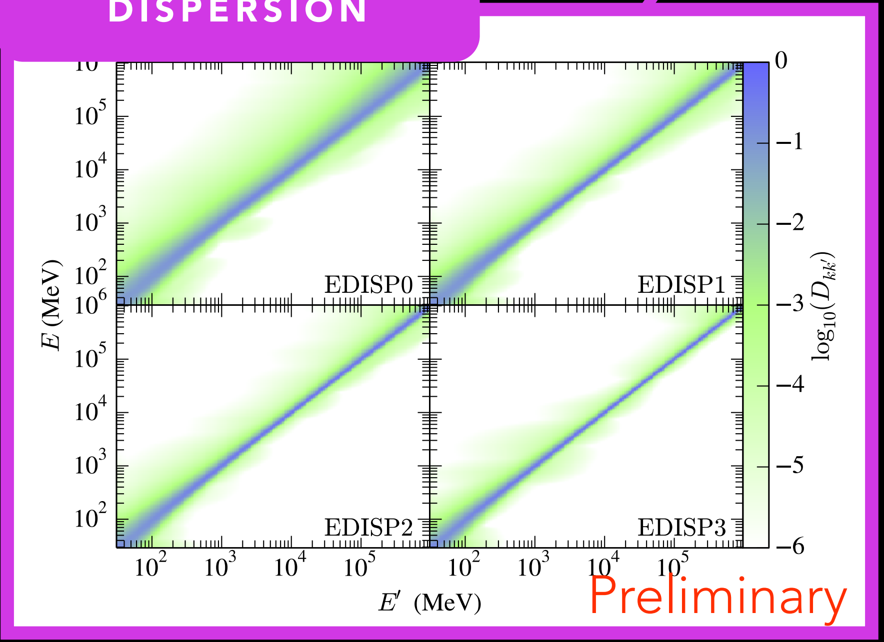
EXPOSURE AVERAGED ENERGY DISPERSION

METHOD

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COMPARE NO-ALP AND ALP HYPOTHESES WITH
LOG-LIKELIHOOD RATIO TEST
FOR EACH TESTED MAGNETIC FIELD REALIZATION

CALIBRATE SENSITIVITY USING MONTE-CARLO SIMULATIONS

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

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

NULL DISTRIBUTION FROM MC

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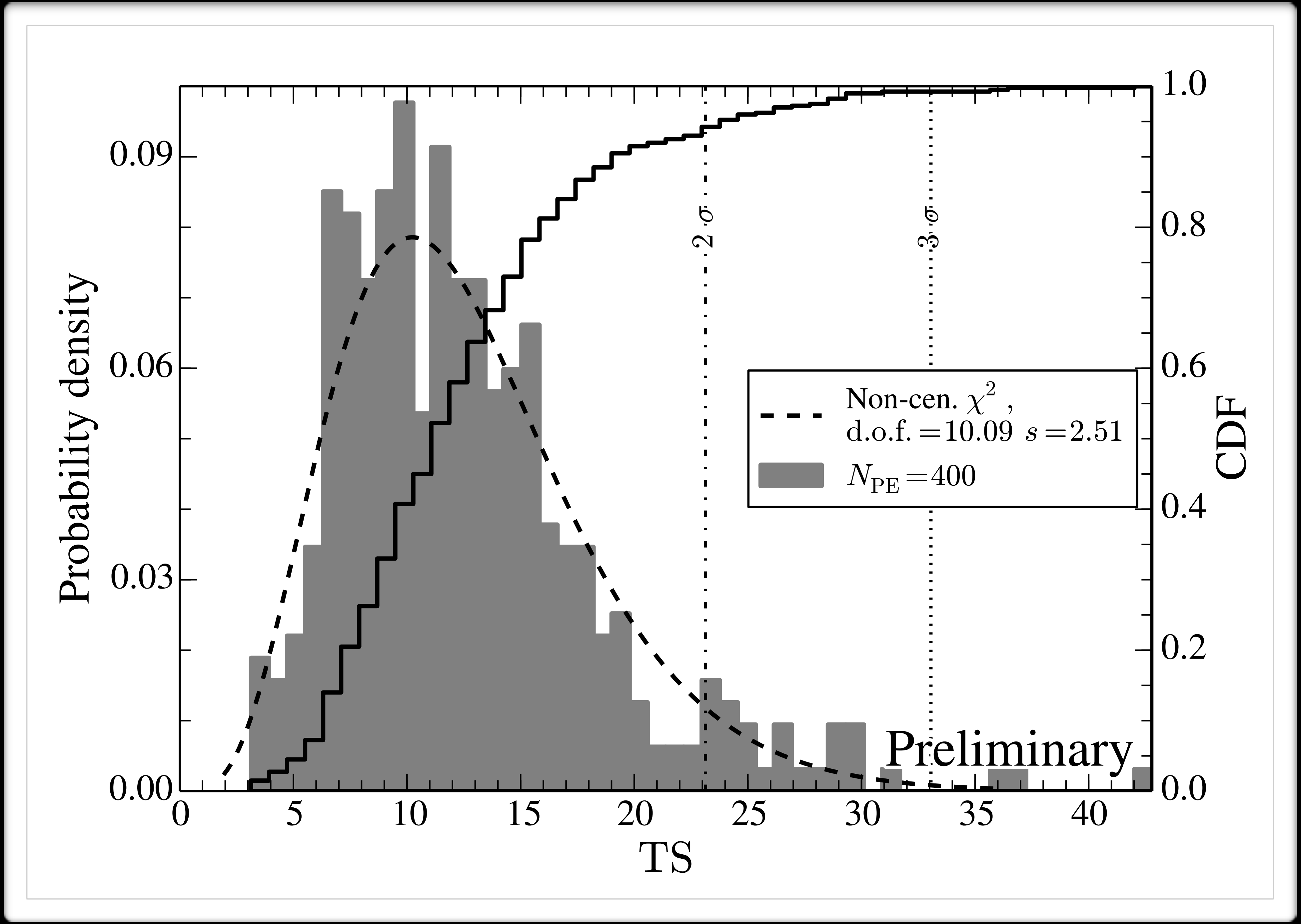


SEARCHING FOR AN ALP SIGNAL WITH LOG LIKELIHOOD RATIO TEST

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

nuisance parameters

data

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

DERIVING LIMITS ON ALP PARAMETERS

Calculate likelihood ratio between best fit and ALP parameter:

$$\lambda(m_a, g_{a\gamma}) = -2\ln\left(\frac{\mathcal{L}(\boldsymbol{\mu}_{95}(m_a, g_{a\gamma}), \hat{\hat{\boldsymbol{\theta}}}|\mathbf{D})}{\mathcal{L}(\hat{\boldsymbol{\mu}}_{95}, \hat{\boldsymbol{\theta}}|\mathbf{D})}\right)$$

If **$\lambda > \lambda_{thr}$: ALP parameter excluded.**

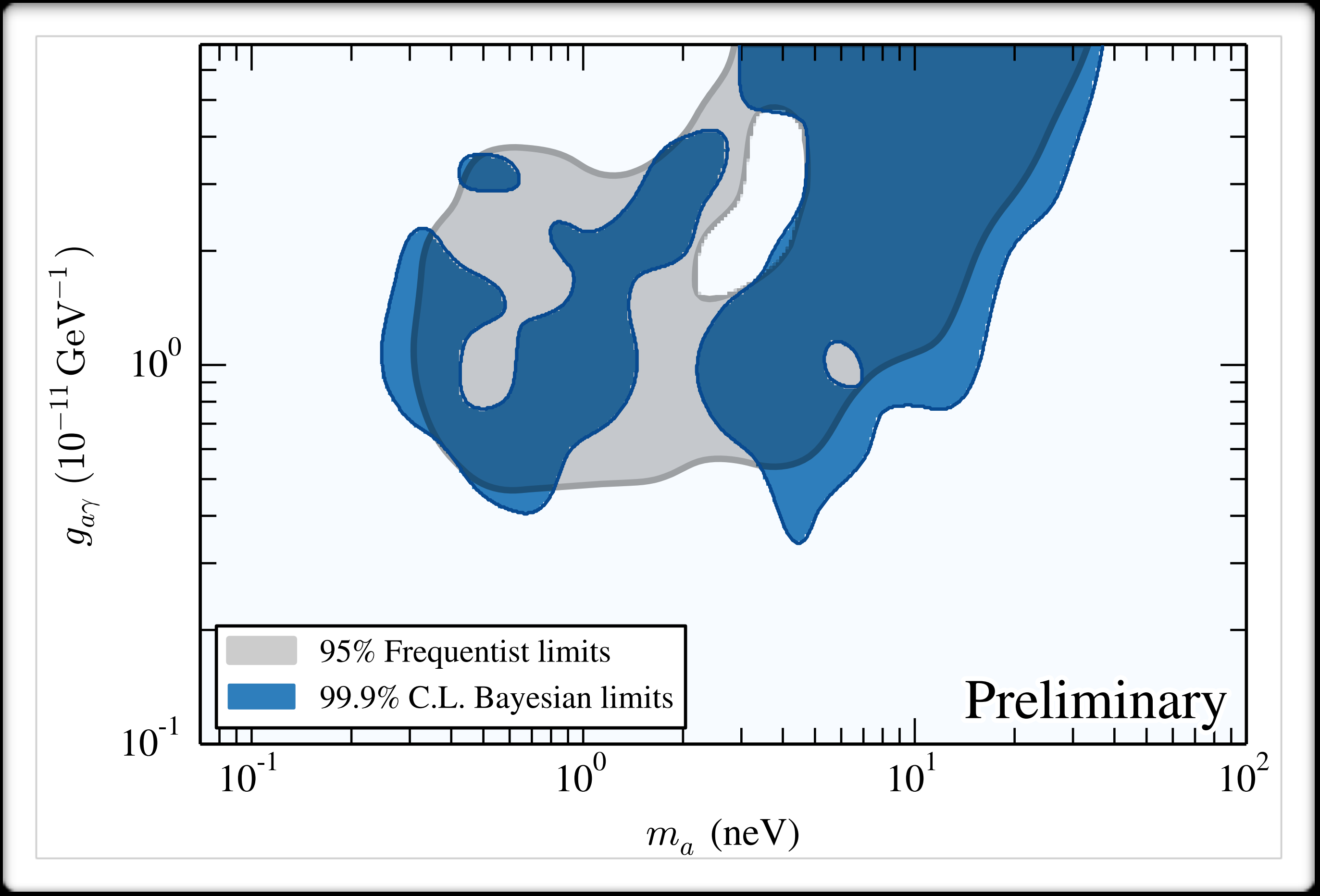
Ansatz: derive λ_{thr} from null distribution and check **coverage**

- Assuming **flat prior** for ***B*-field realizations**

- Assuming **logarithmic flat priors** on **ALP parameters**

- Posterior sorted by decreasing likelihood

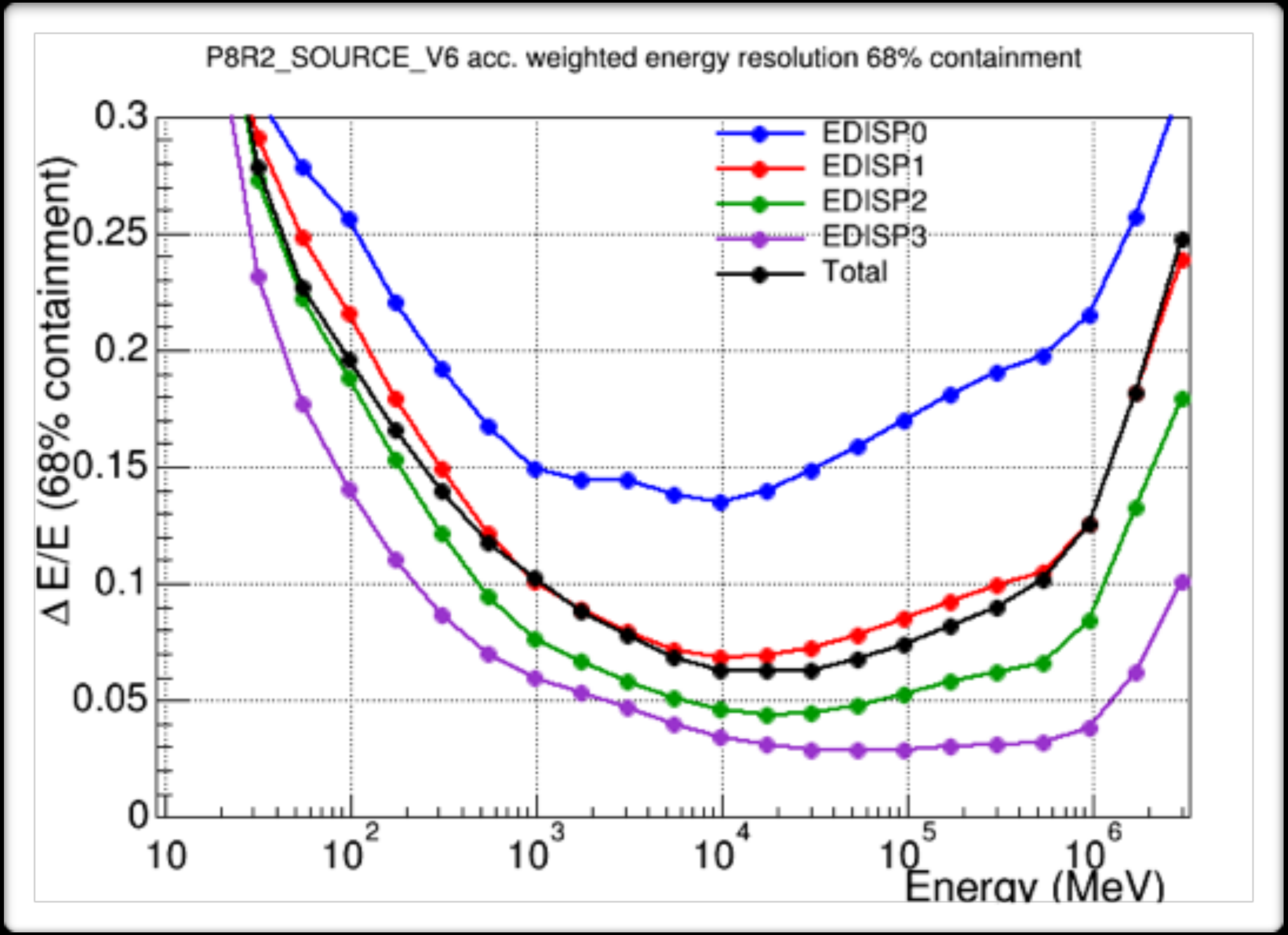
- Bayesian limits give **under coverage**



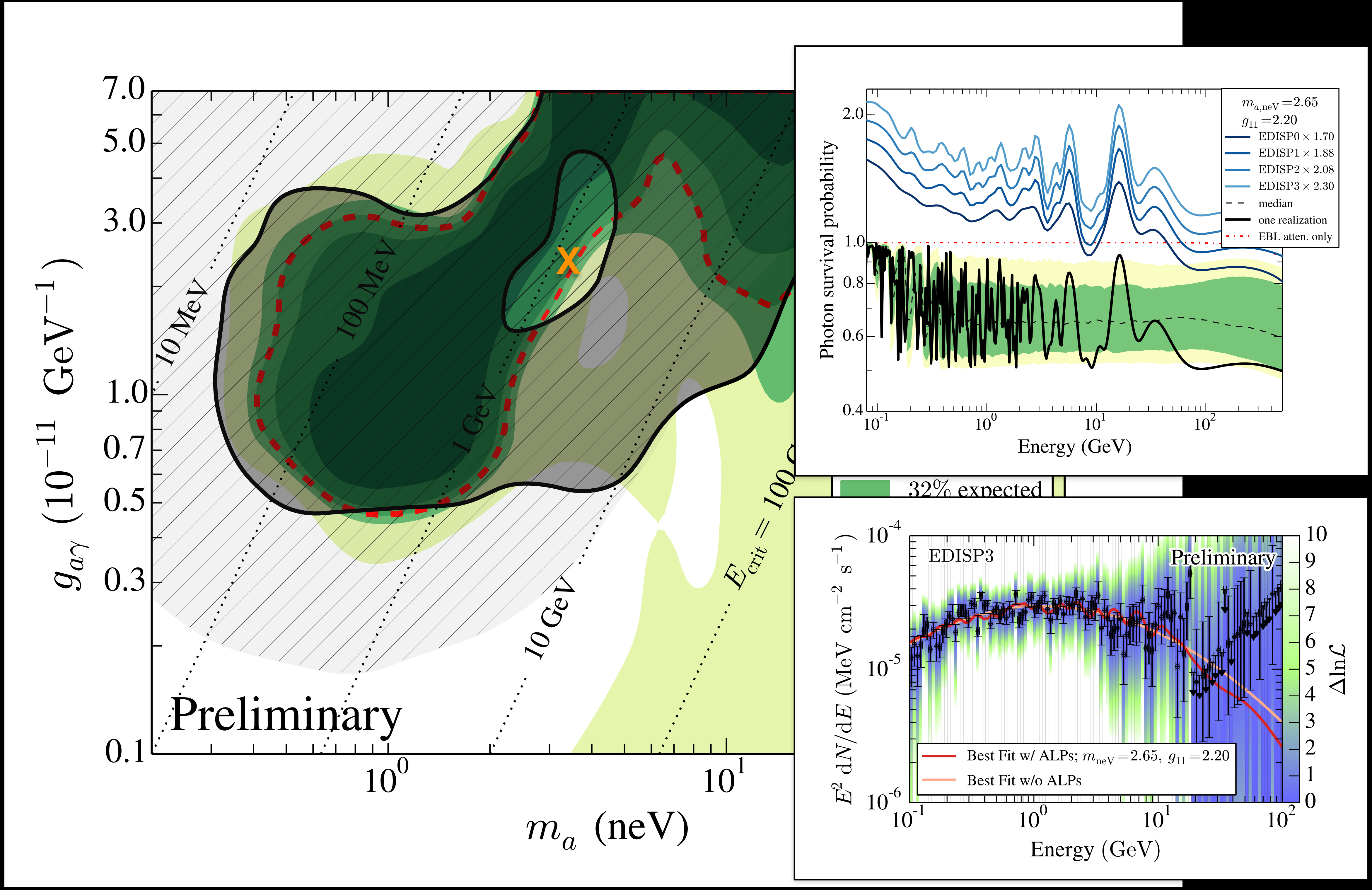
ENERGY DISPERSION EVENT TYPES

- **Events** in **PASS 8** can be **split** into sub classes (event types) according to **quality of energy reconstruction**

- Each event type has ~same number of events per bin



UNDERSTANDING THE SHAPE OF THE LIMITS



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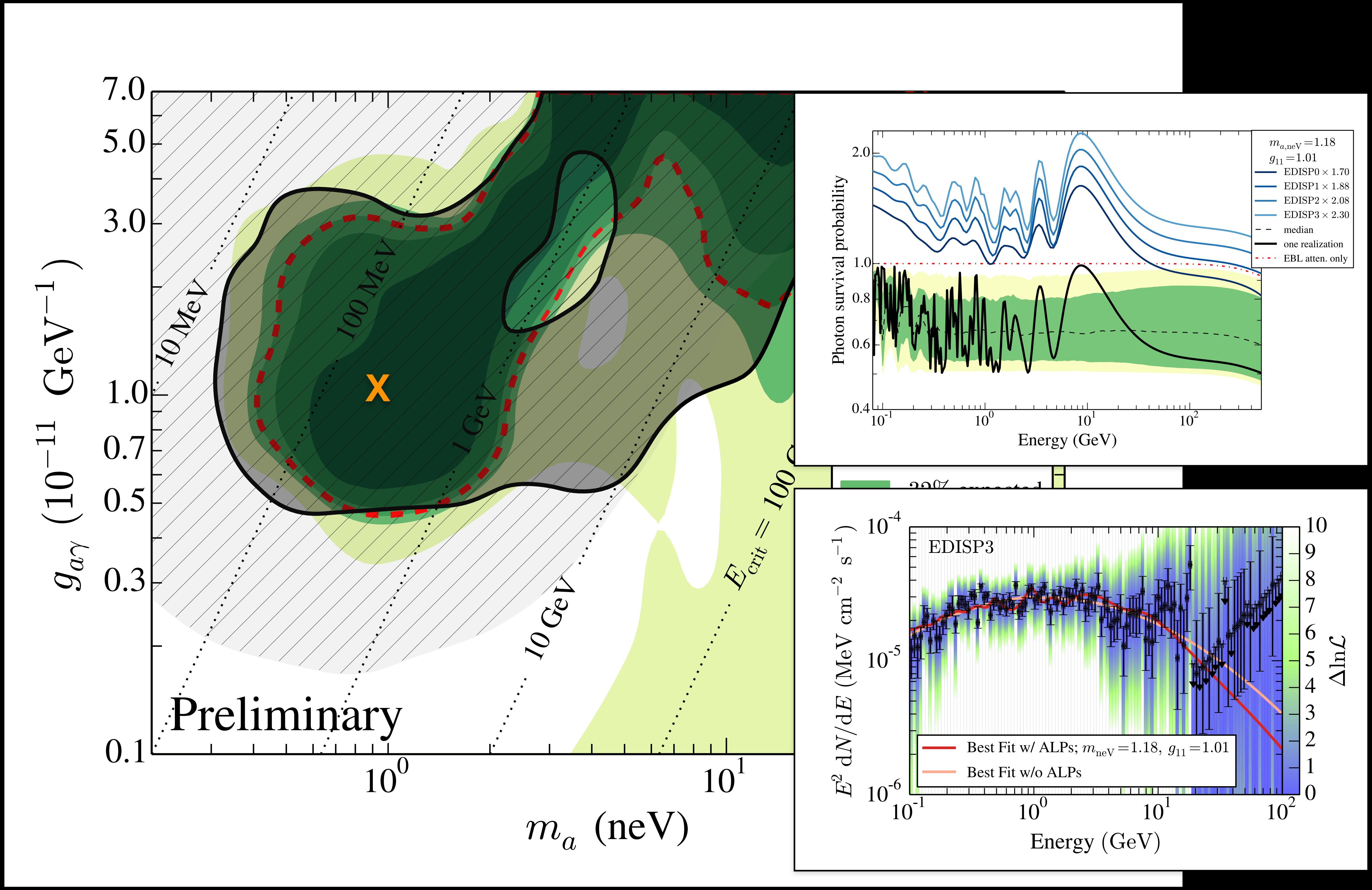

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