Oskar Klein centre

Stockholm University

Fermi Gamma-ray Space Telescope

SEARCH FOR AXION-LIKE PARTICLE SIGNATURES IN THE GAMMA-RAY SPECTRUM OF NGC 1275

Manuel Meyer, Jan Conrad, Miguel Sanchez-Conde,
on behalf of the Fermi-LAT Collaboration

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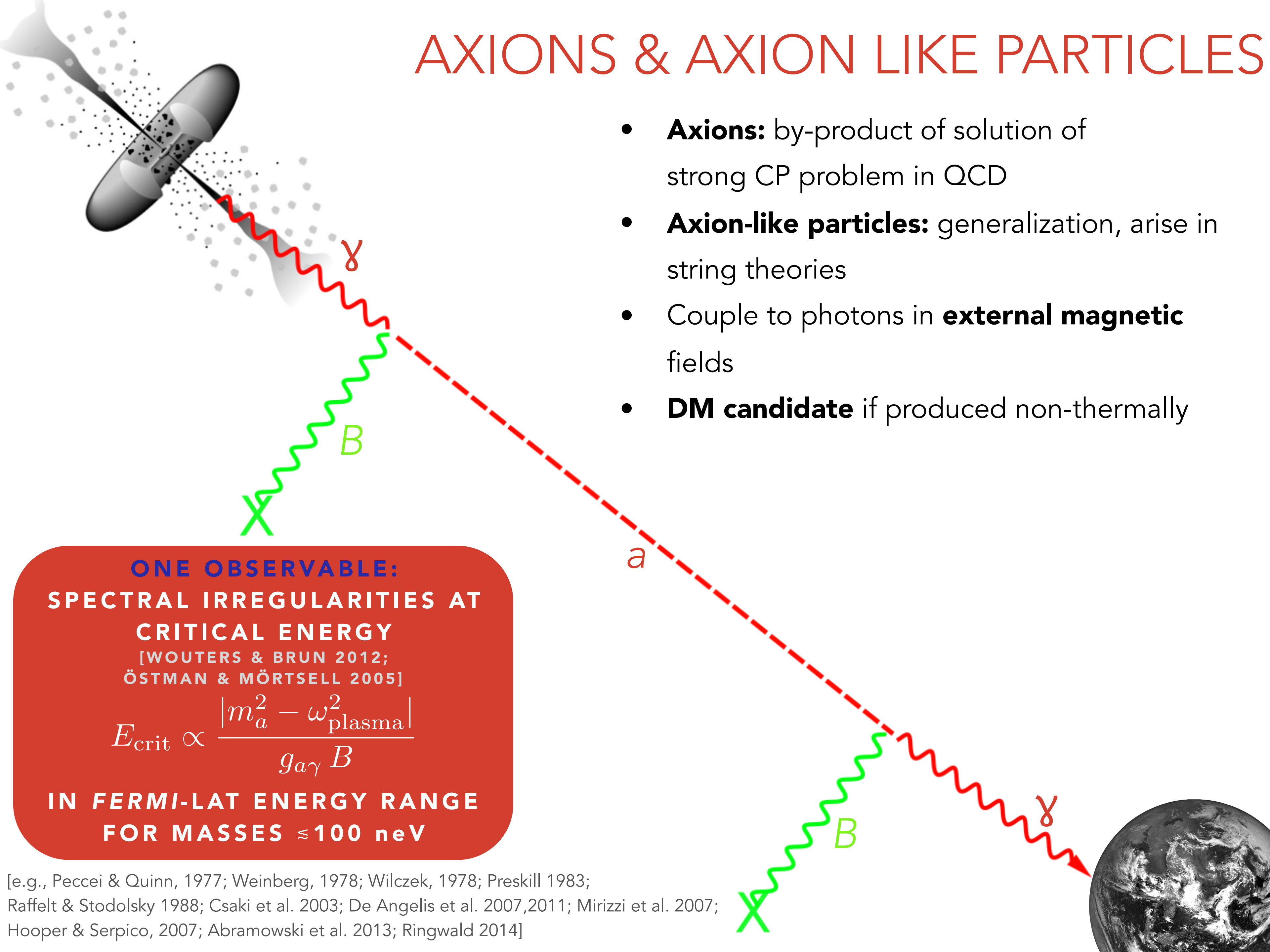
AXIONS & AXION LIKE PARTICLES

- **Axions:** by-product of solution of strong CP problem in QCD
- **Axion-like particles:** generalization, arise in string theories
- Couple to photons in **external magnetic** fields
- **DM candidate** if produced non-thermally



ONE OBSERVABLE:

SPECTRAL IRREGULARITIES AT CRITICAL ENERGY

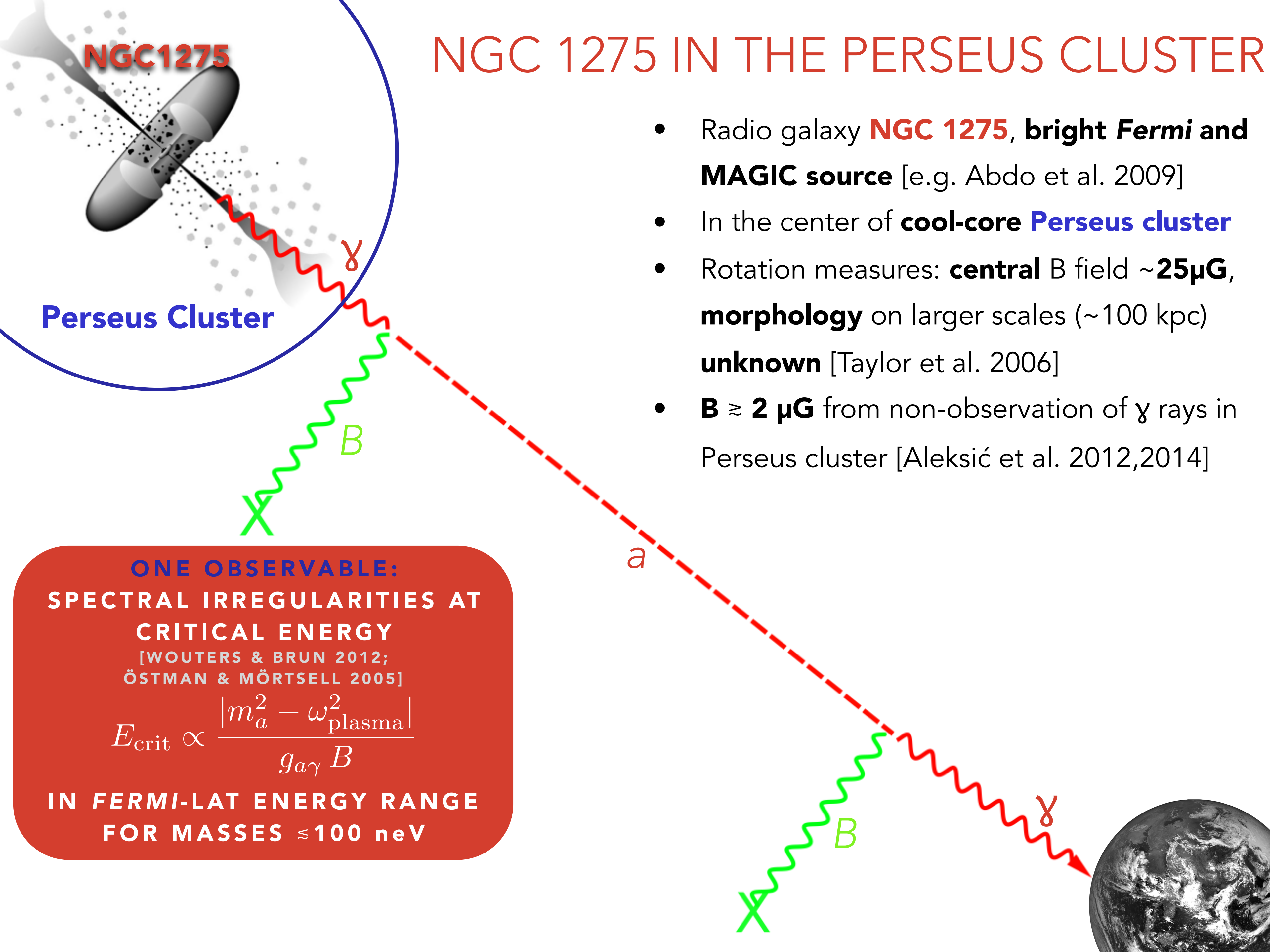
[WOUTERS & BRUN 2012; ÖSTMAN & MÖRTSELL 2005]

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

IN *FERMI*-LAT ENERGY RANGE FOR MASSES ≲100 neV

[e.g., Peccei & Quinn, 1977; Weinberg, 1978; Wilczek, 1978; Preskill 1983; Raffelt & Stodolsky 1988; Csaki et al. 2003; De Angelis et al. 2007,2011; Mirizzi et al. 2007; Hooper & Serpico, 2007; Abramowski et al. 2013; Ringwald 2014]

NGC 1275 IN THE PERSEUS CLUSTER



- Radio galaxy **NGC 1275**, **bright *Fermi* and MAGIC source** [e.g. Abdo et al. 2009]
- In the center of **cool-core Perseus cluster**
- Rotation measures: **central** B field ~**25μG**, **morphology** on larger scales (~100 kpc) **unknown** [Taylor et al. 2006]
- **B ≳ 2 μG** from non-observation of ɣ rays in Perseus cluster [Aleksić et al. 2012,2014]

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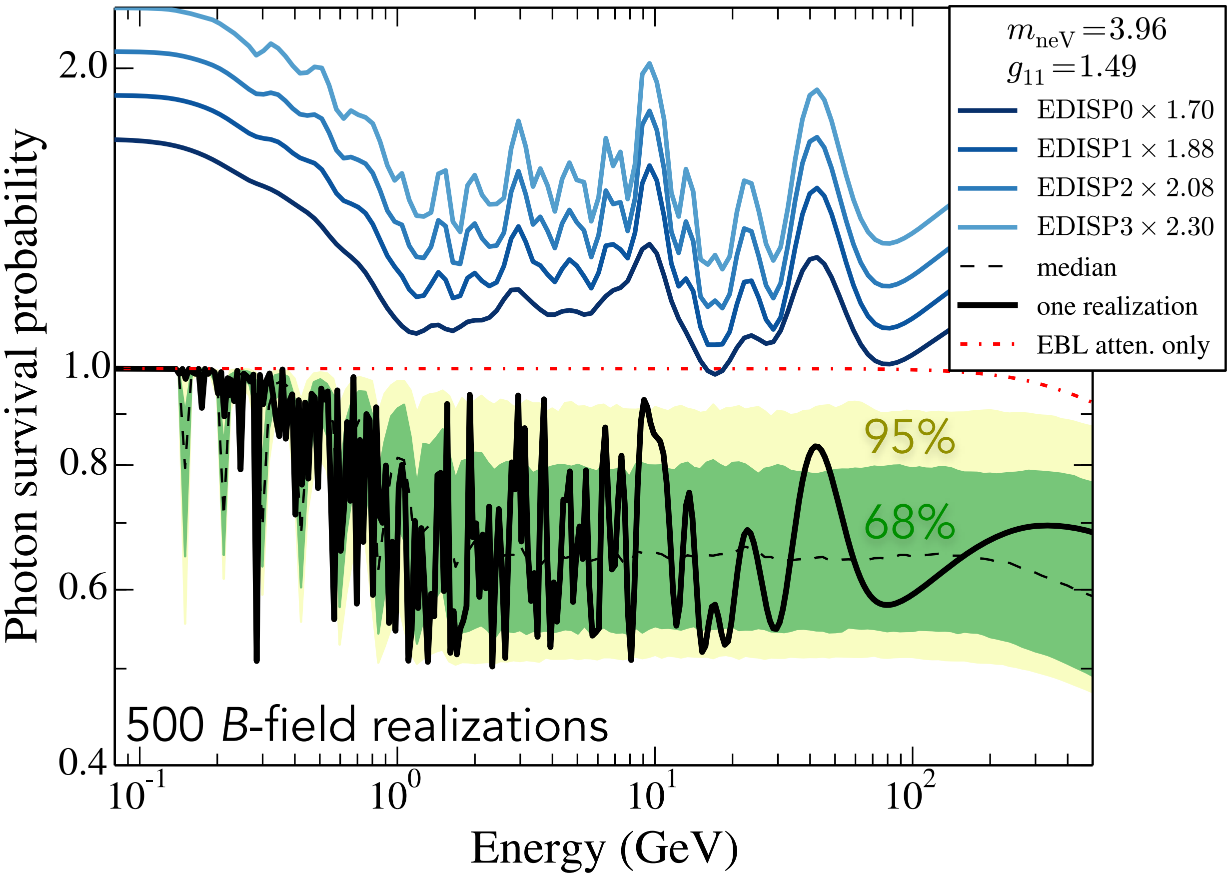
IN *FERMI*-LAT ENERGY RANGE FOR MASSES ≲100 neV

PHOTON-ALP CONVERSION MODEL

- Considered *B* fields: **Perseus cluster & Milky Way**
- Cluster field: gaussian **turbulence & follows electron density**
- Turbulence: **assumed the same as in A2199** [given in Vacca et al. 2012]
- **Conservative** estimate of central *B* field: **10 μG** [Aleksić et al. 2012]
- Includes **EBL absorption**

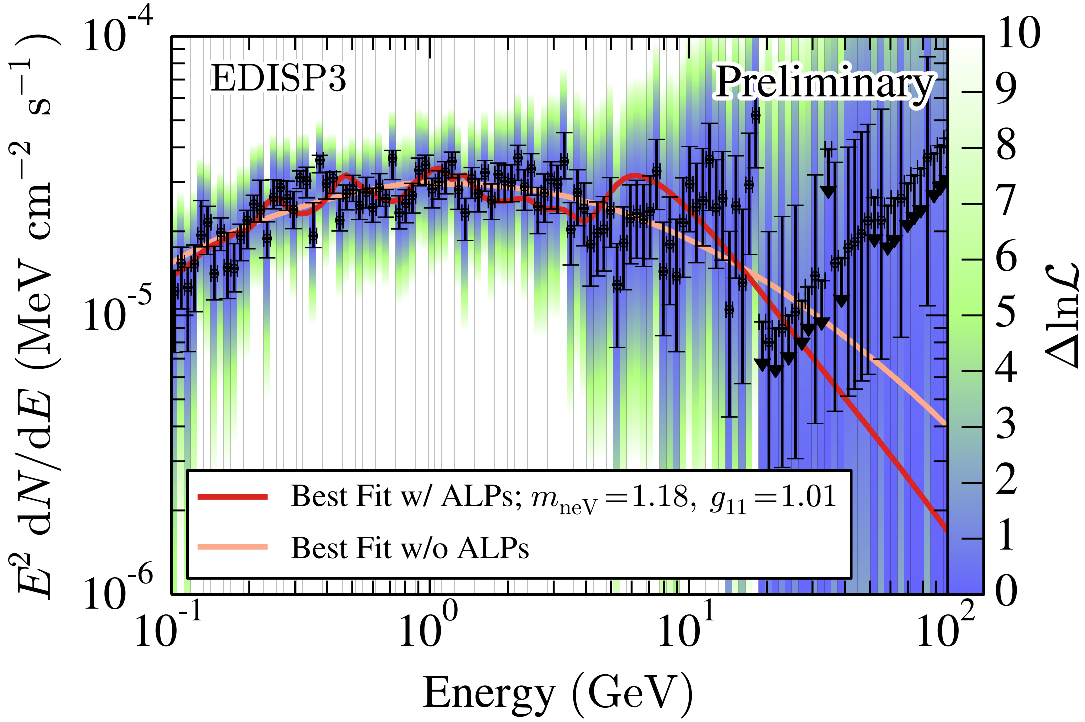
$$P_{\gamma\gamma}(E, m_a, g_{a\gamma}, \mathbf{B})$$



[Photon-ALP conversion calculation based on Csaki et al. 2003; De Angelis et al. 2007,2011; Horns et al. 2012; Meyer et al. 2014]

DATA ANALYSIS

- **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.

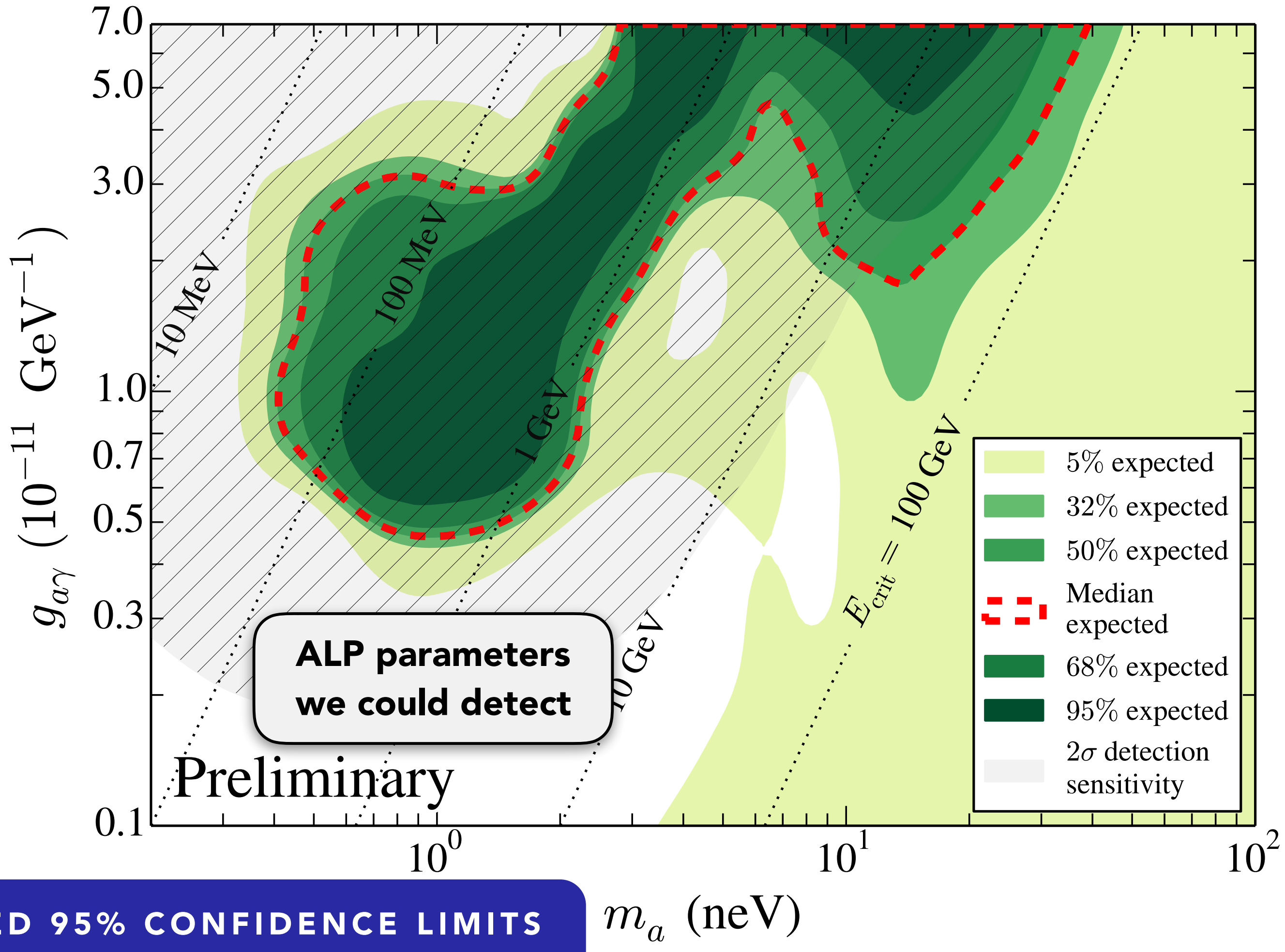
Intrinsic spectrum

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

EBL attenuation only

Intrinsic spectrum

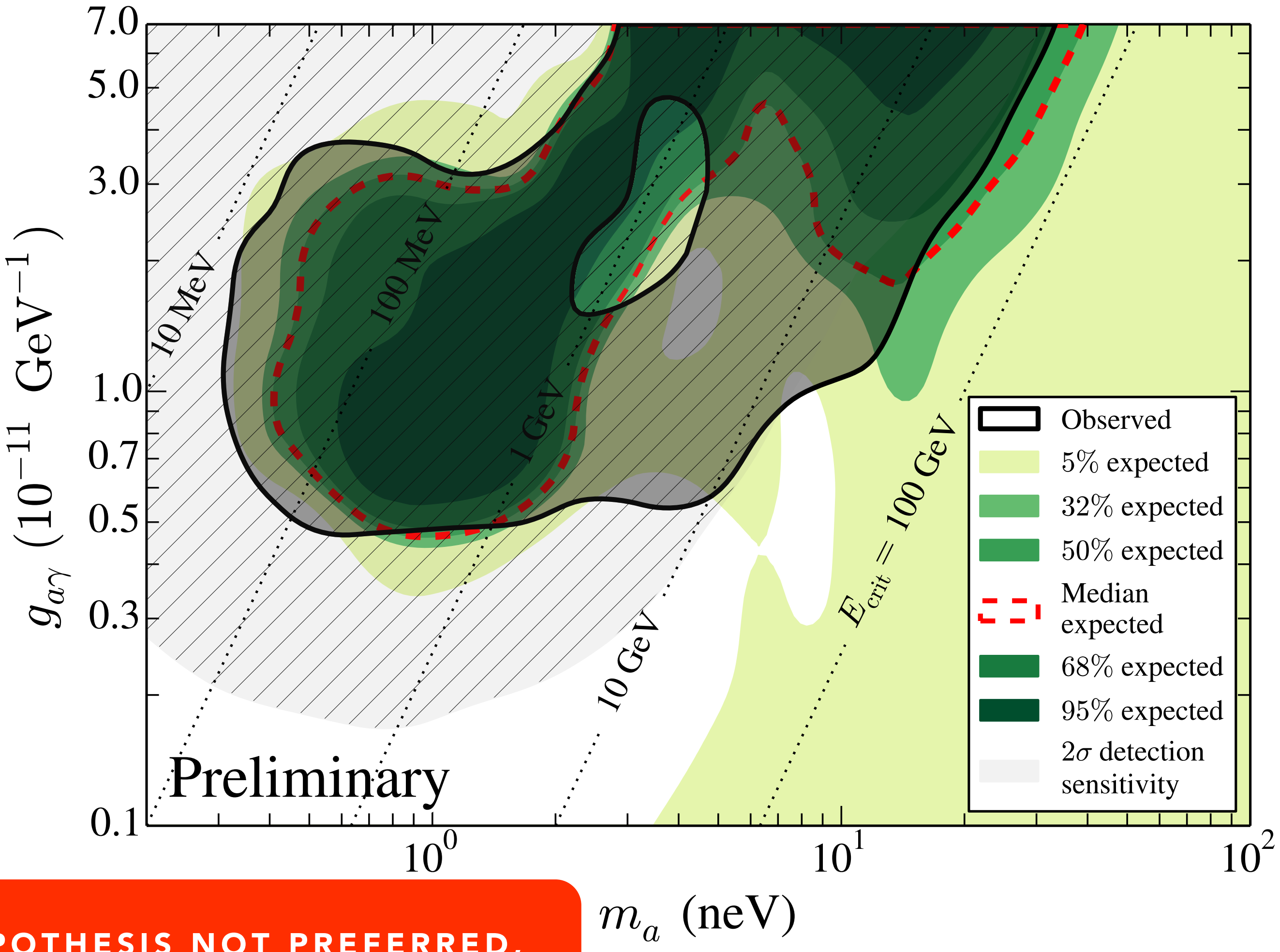
EXPECTED LIMITS AND DETECTION SENSITIVITY FROM SIMULATIONS



ALP parameters we could detect

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

NO ALP OBSERVED: SETTING LIMITS



ALP HYPOTHESIS NOT PREFERRED, DERIVE 95% CONFIDENCE LIMITS

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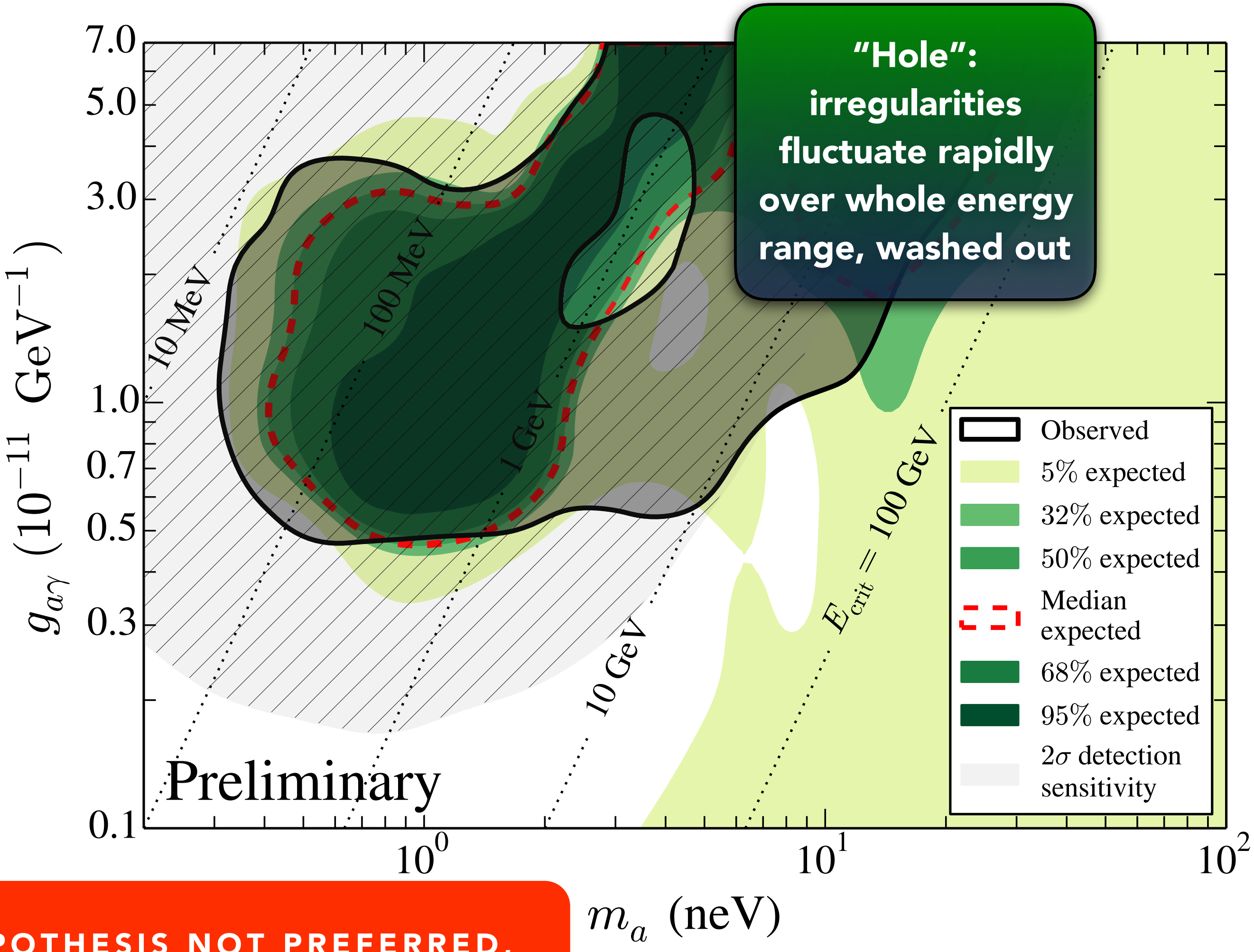


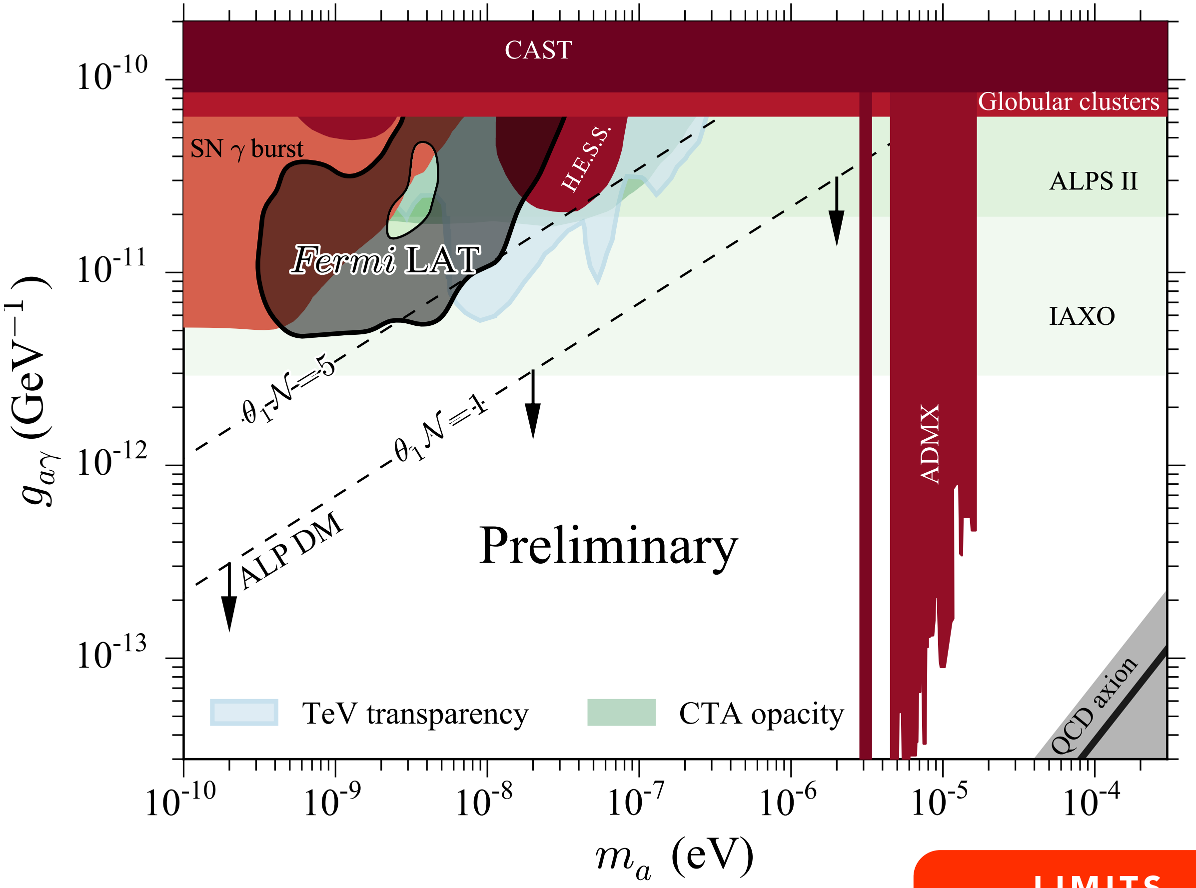
“Hole”: irregularities fluctuate rapidly over whole energy range, washed out

ALP HYPOTHESIS NOT PREFERRED, DERIVE 95% CONFIDENCE LIMITS

COMPARISON WITH OTHER LIMITS

- Strongest **limits** 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**

[e.g. Essig et al. 2013;
Meyer & Conrad 2014 and references therein]

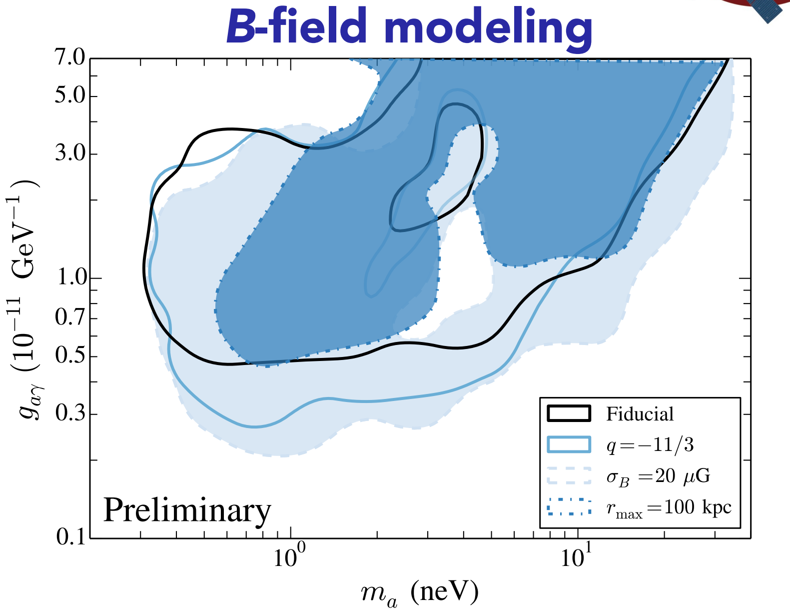


LIMITS

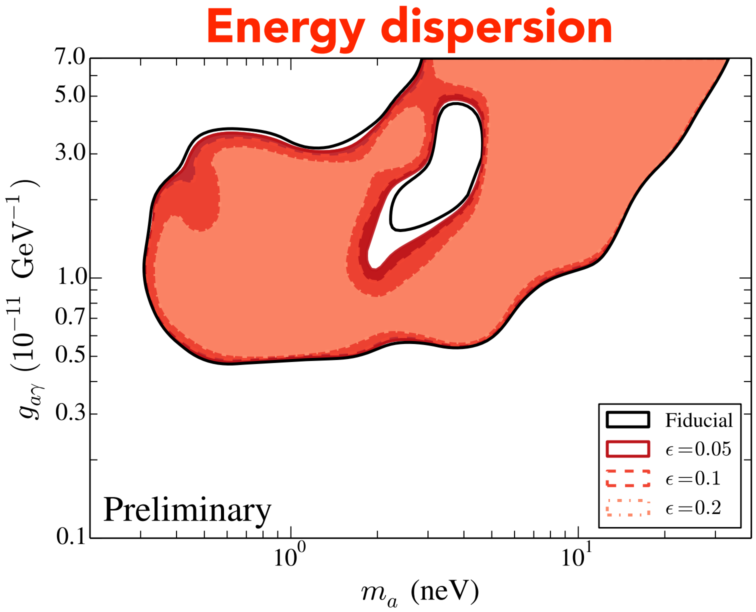
SENSITIVITIES

SYSTEMATIC CHECKS

- **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%**



B-field modeling



Energy dispersion

SUMMARY & CONCLUSIONS

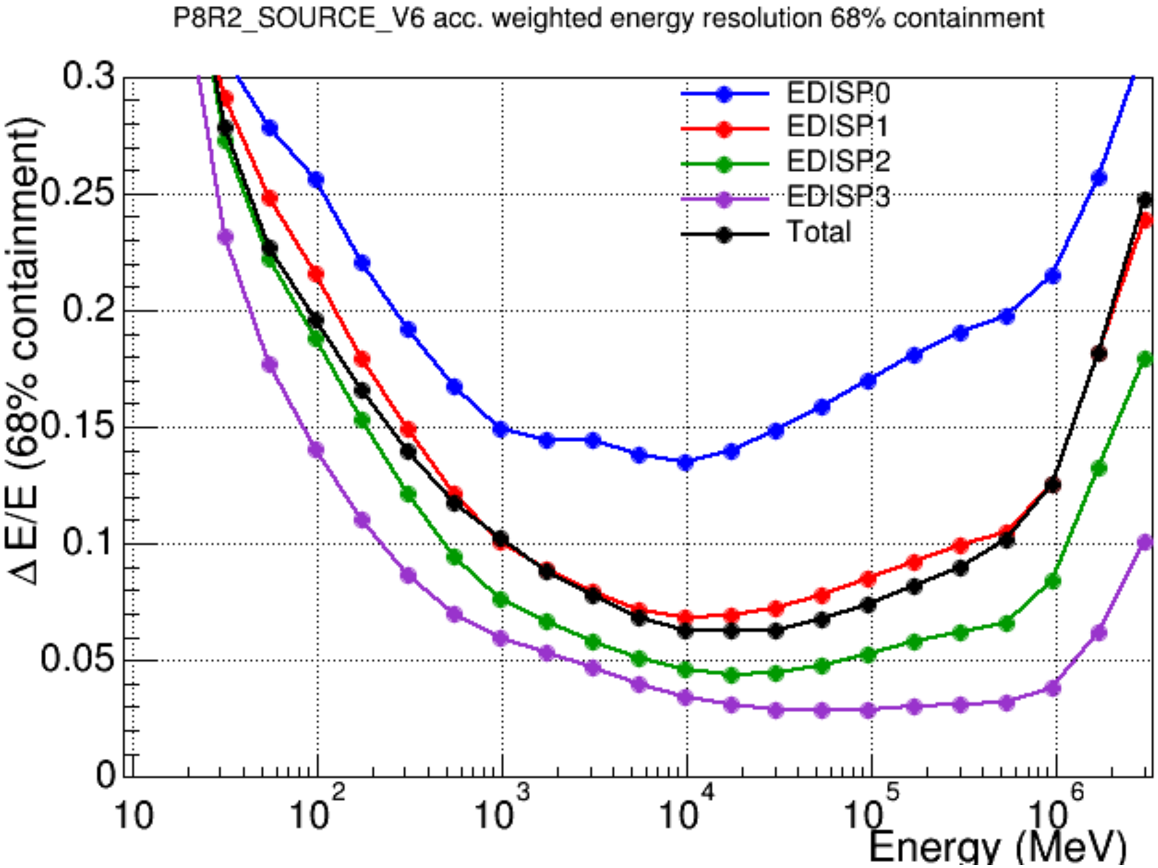
- We have **searched for spectral irregularities** induced by **photon-ALP oscillations** in the spectrum of **NGC 1275**
- We **do not find any indications** for ALPs and set the strongest **bounds** to date between **0.5** $\lesssim \boldsymbol{m_a} \lesssim$ **20 neV**
- In this mass range, the limits 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]

BACK UP

ENERGY DISPERSION EVENT TYPES

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

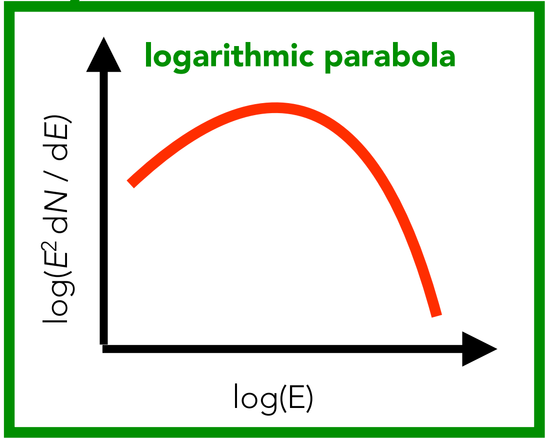
- Each event type has ~same number of events per bin



METHOD

- **Extract likelihood** for expected counts in every energy bin ➔ **independent of assumed spectrum** [similar to dSph 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*:

$$\mu_{ik'} = \sum_{k} \underbrace{\boxed{\mathcal{D}^{i}_{kk'}}}_{\text{Energy dispersion}} \int_{\Delta E_k} \mathrm{d}E \, \underbrace{\boxed{P_{\gamma\gamma}}}_{\text{photon survival prob.}} \underbrace{\boxed{F(E)}}_{\text{intrinsic spectrum}} \underbrace{\boxed{\mathcal{E}^{i}(E)}}_{\text{Exposure } (A_{\mathrm{eff}} \text{ x obs. time})}$$



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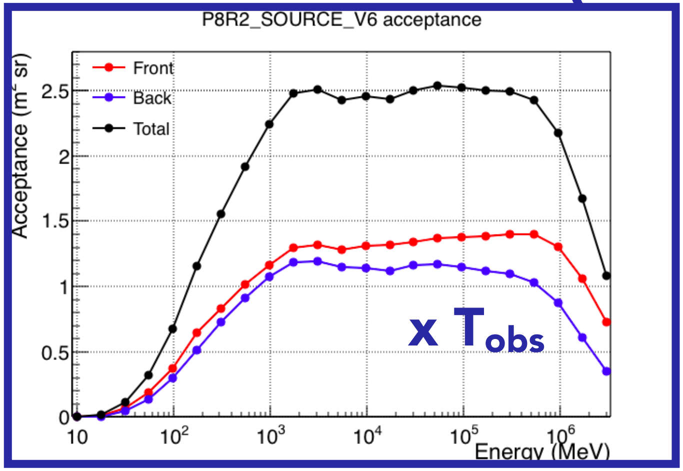

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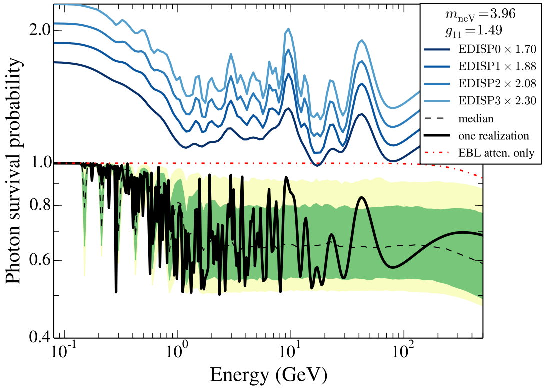
CONVERSION PROBABILITY



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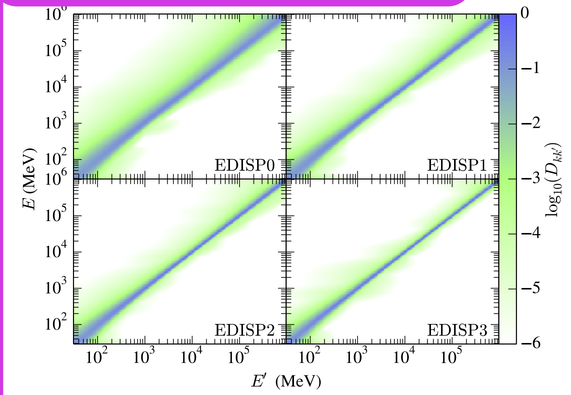
EXPOSURE AVERAGED ENERGY DISPERSION



SEARCHING FOR AN ALP SIGNAL WITH A LOG-LIKELIHOOD RATIO TEST

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

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

expected number of counts

nuisance parameters

data

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

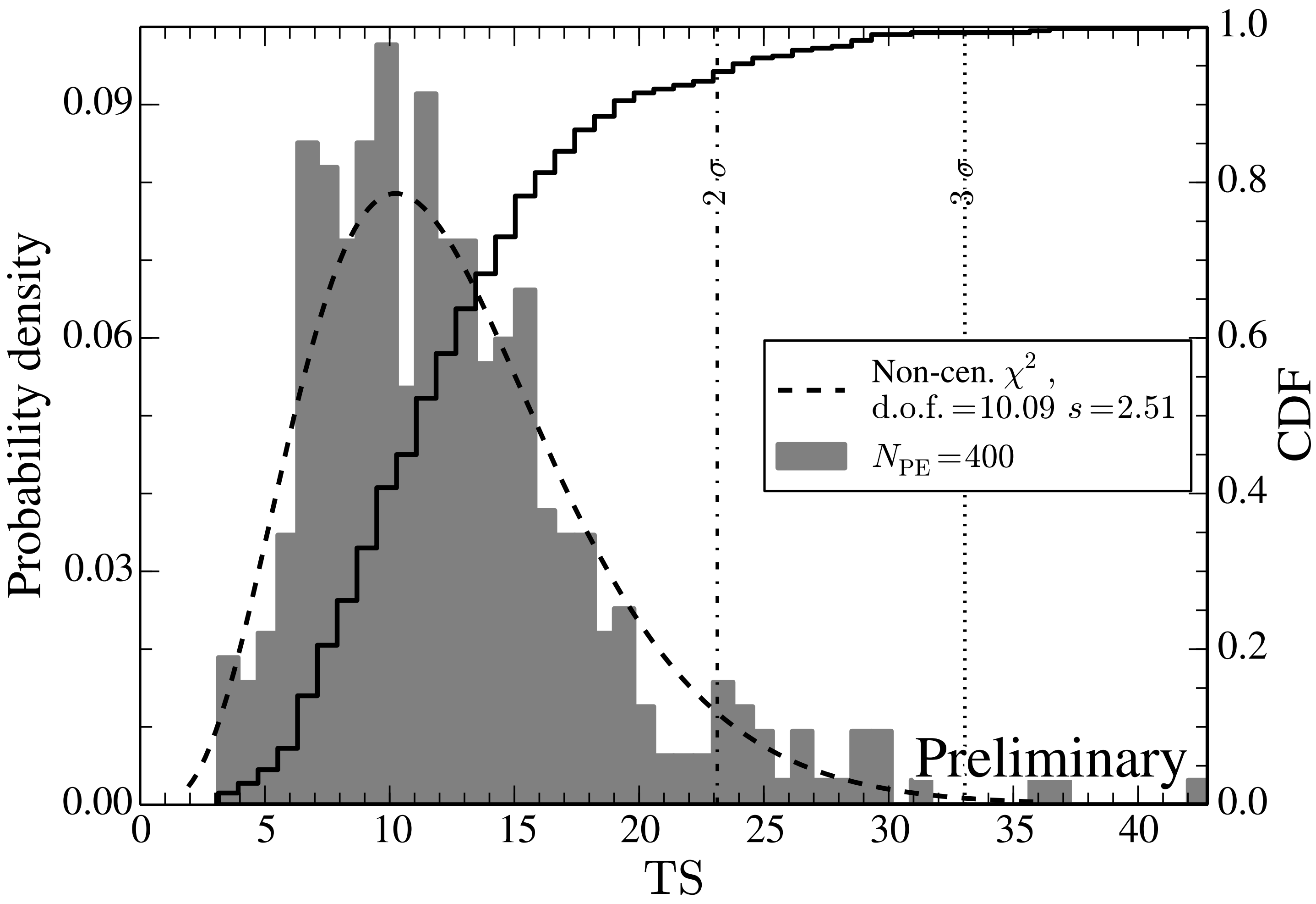
$$\mathrm{TS} = -2\ln\left(\frac{\mathcal{L}(\boldsymbol{\mu}_0,\hat{\hat{\boldsymbol{\theta}}}|\mathbf{D})}{\mathcal{L}(\hat{\boldsymbol{\mu}}_{95},\hat{\boldsymbol{\theta}}|\mathbf{D})}\right)$$

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

NULL DISTRIBUTION FROM MC



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

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**

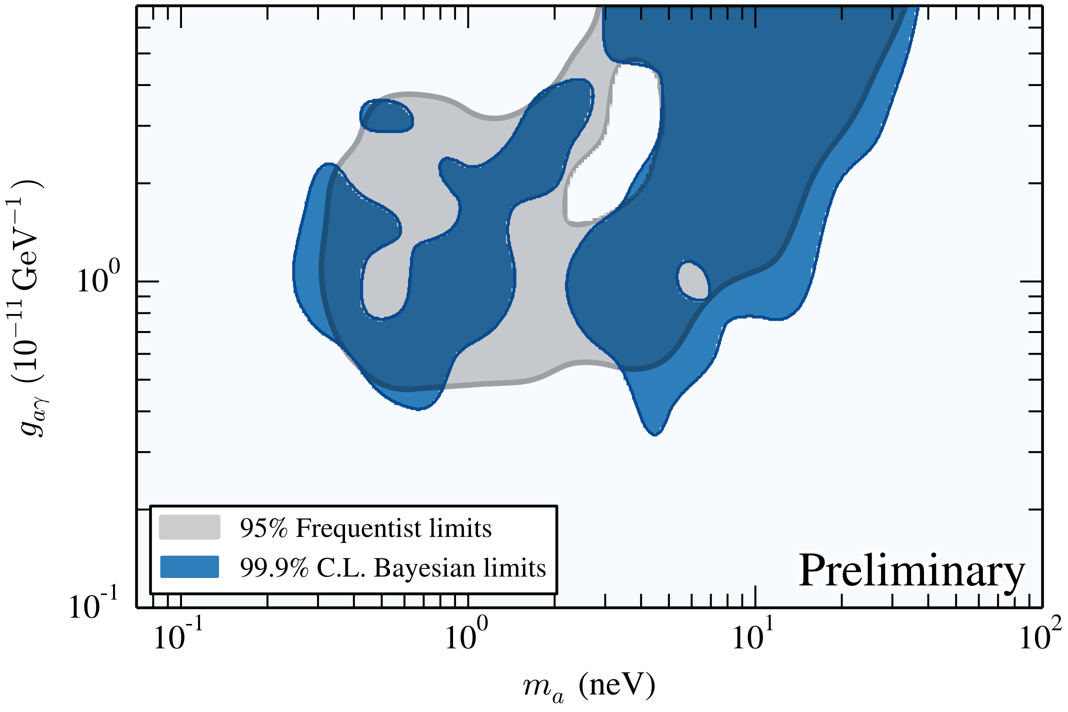
- Ansatz: derive λ_{thr} from null distribution and check coverage

- From null distribution: **$\lambda_{thr} = 22.8$ for 95% confidence**

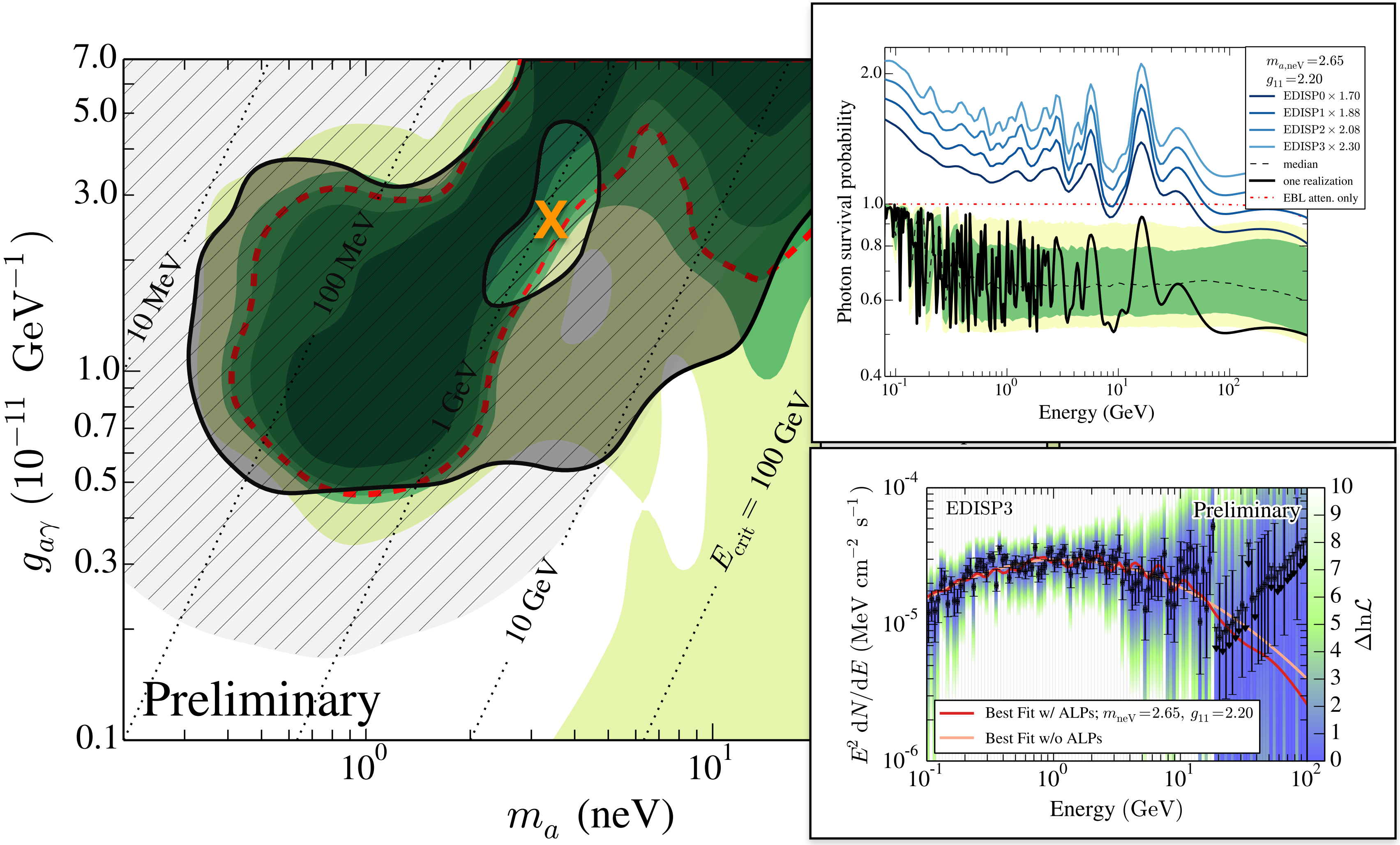
- Ansatz yields **over coverage** where irregularities are strongest ⇒ **conservative limits**

COMPARISON WITH BAYESIAN LIMITS

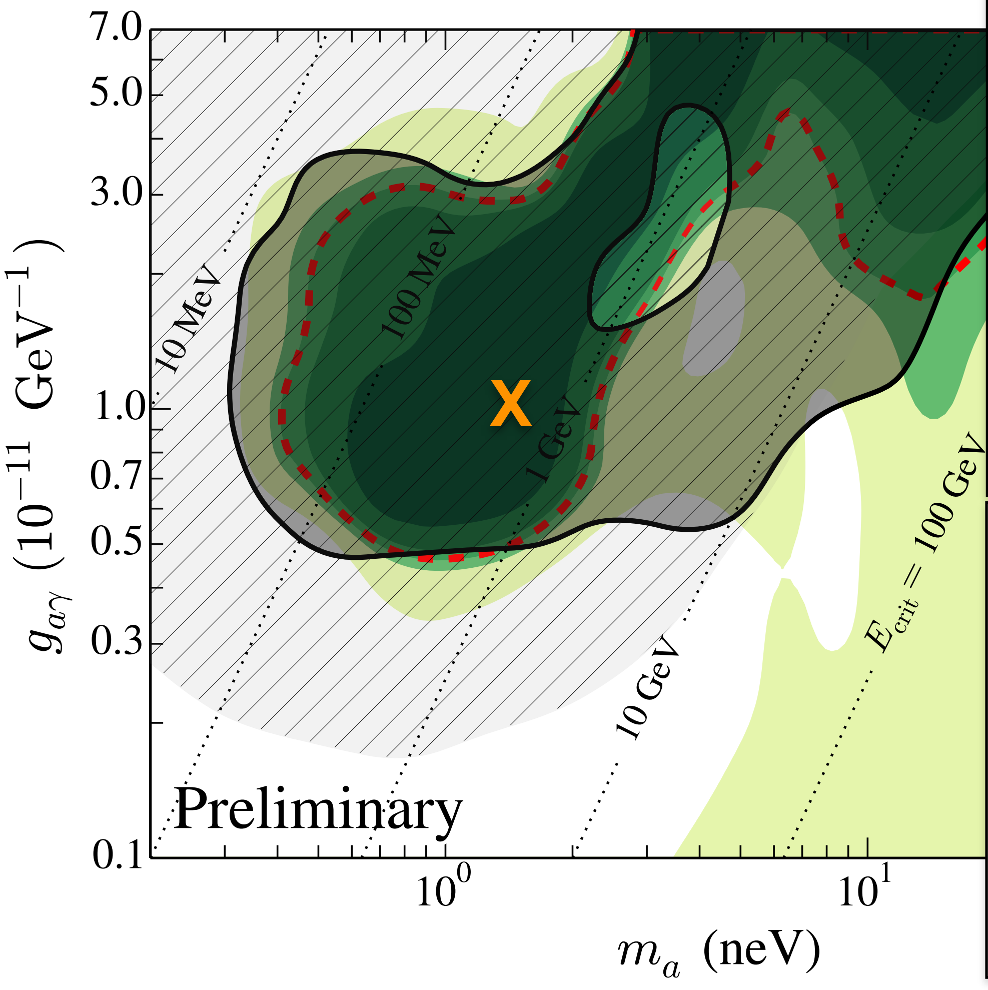
- Assuming **flat prior** for ***B*-field realizations**
- Assuming **logarithmic flat priors** on **ALP parameters**
- Posterior sorted by decreasing likelihood
- Bayesian limits give **under coverage**

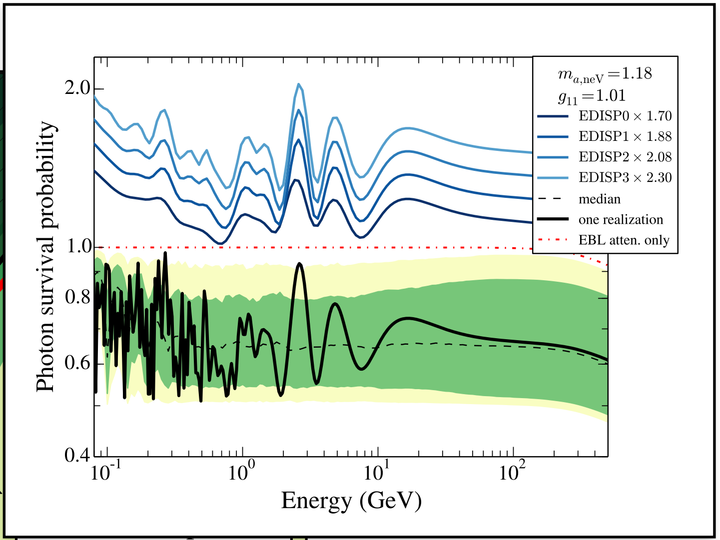


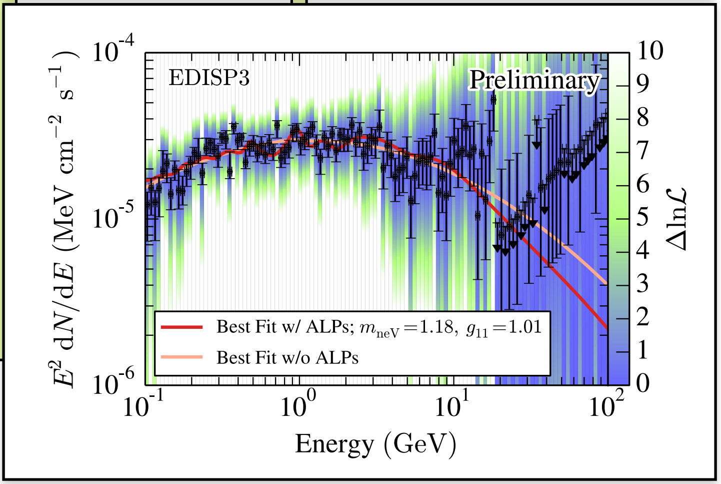
THE “HOLE” FEATURE



EXAMPLE FOR EXCLUDED ALP PARAMETERS







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