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
FOR THE *FERMI*-LAT COLLABORATION

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11TH PATRAS WORKSHOP 2015
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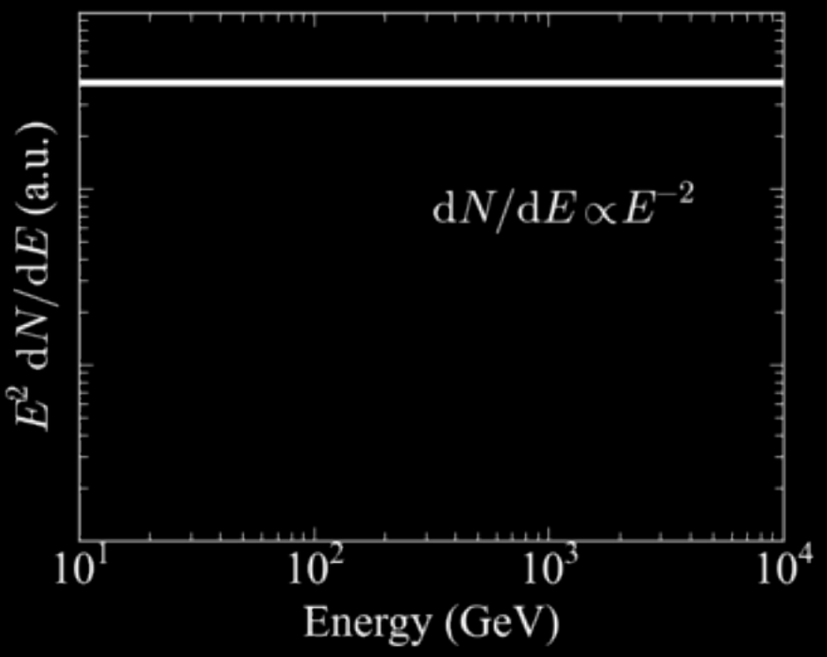
WHY SHOULD WE CARE ABOUT γ RAYS AND ALPS?

γ

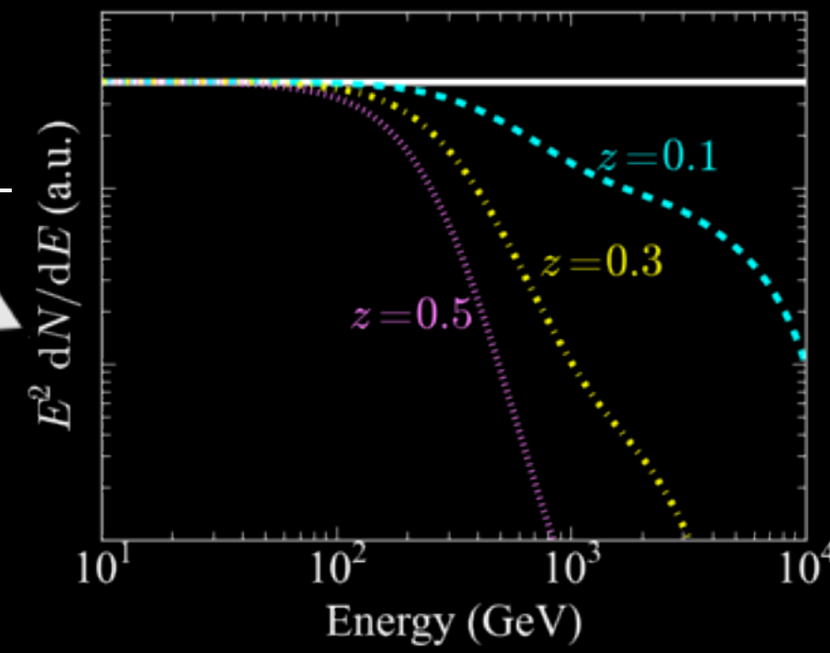
Emitted spectrum



e⁻

e⁺

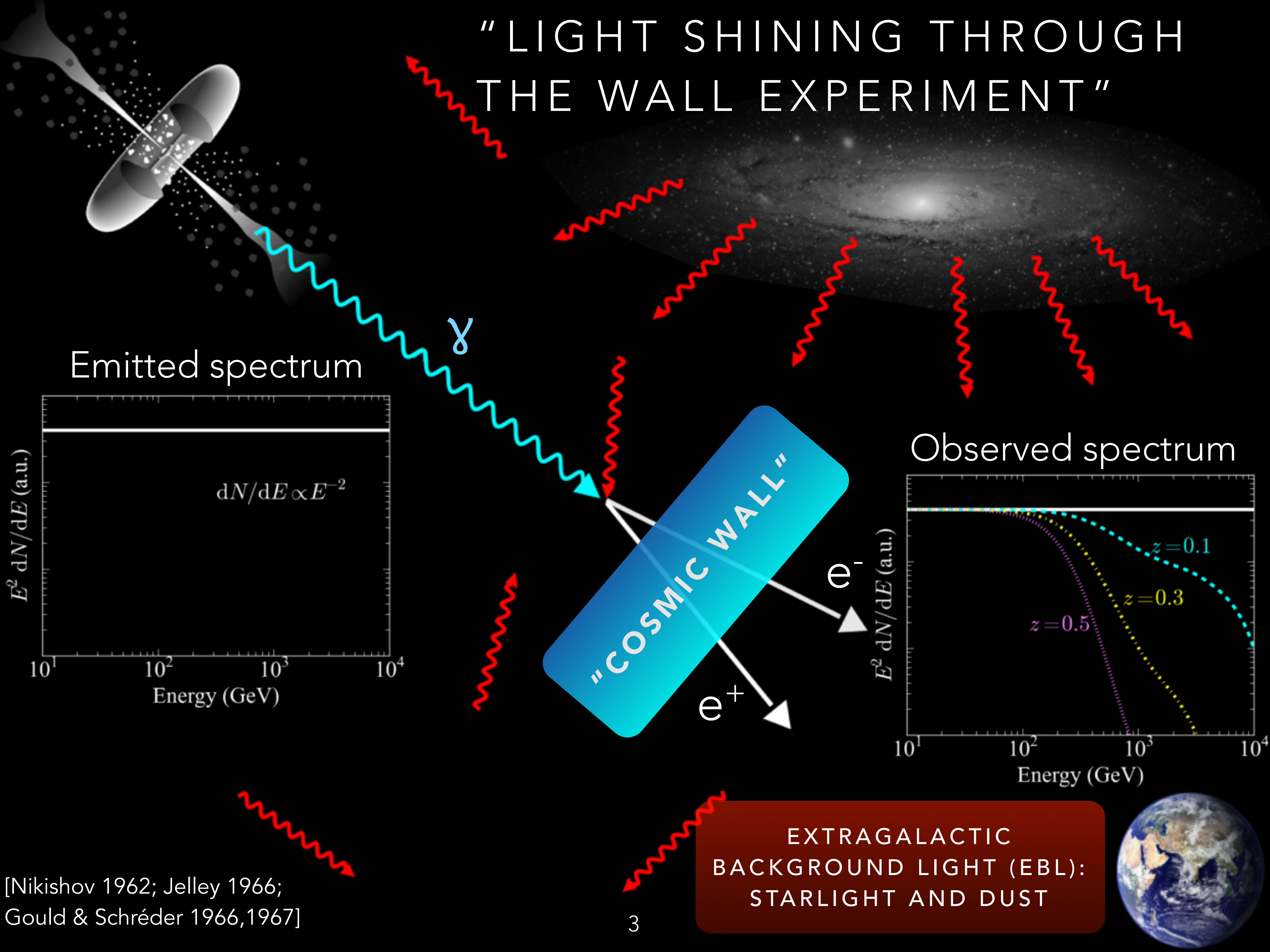
Observed spectrum



EXTRAGALACTIC BACKGROUND LIGHT (EBL): STARLIGHT AND DUST

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

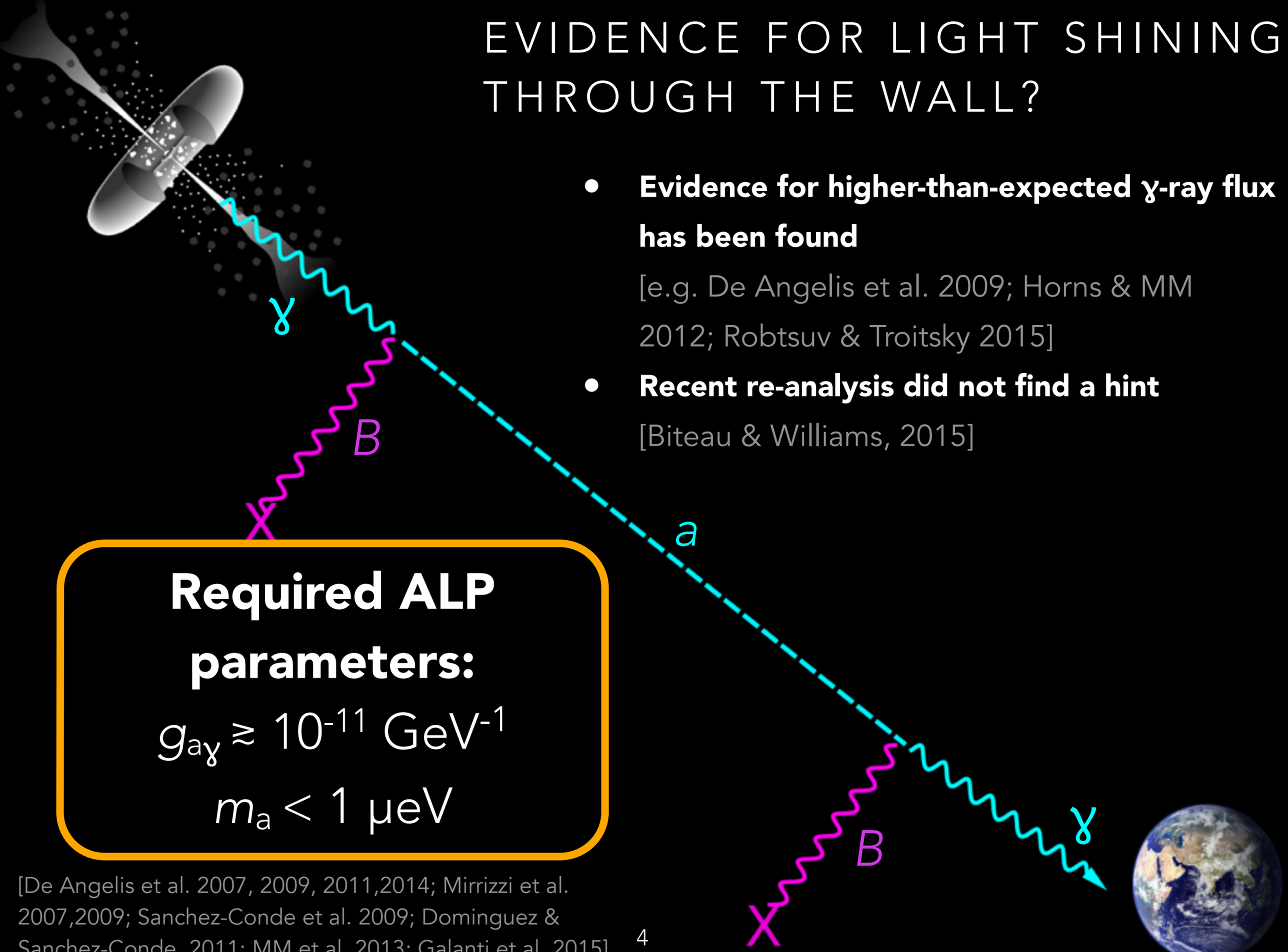
"LIGHT SHINING THROUGH THE WALL EXPERIMENT"



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

EVIDENCE FOR LIGHT SHINING THROUGH THE WALL?

- **Evidence for higher-than-expected γ-ray flux has been found**
  [e.g. De Angelis et al. 2009; Horns & MM 2012; Robtsuv & Troitsky 2015]
- **Recent re-analysis did not find a hint**
  [Biteau & Williams, 2015]



Required ALP parameters:

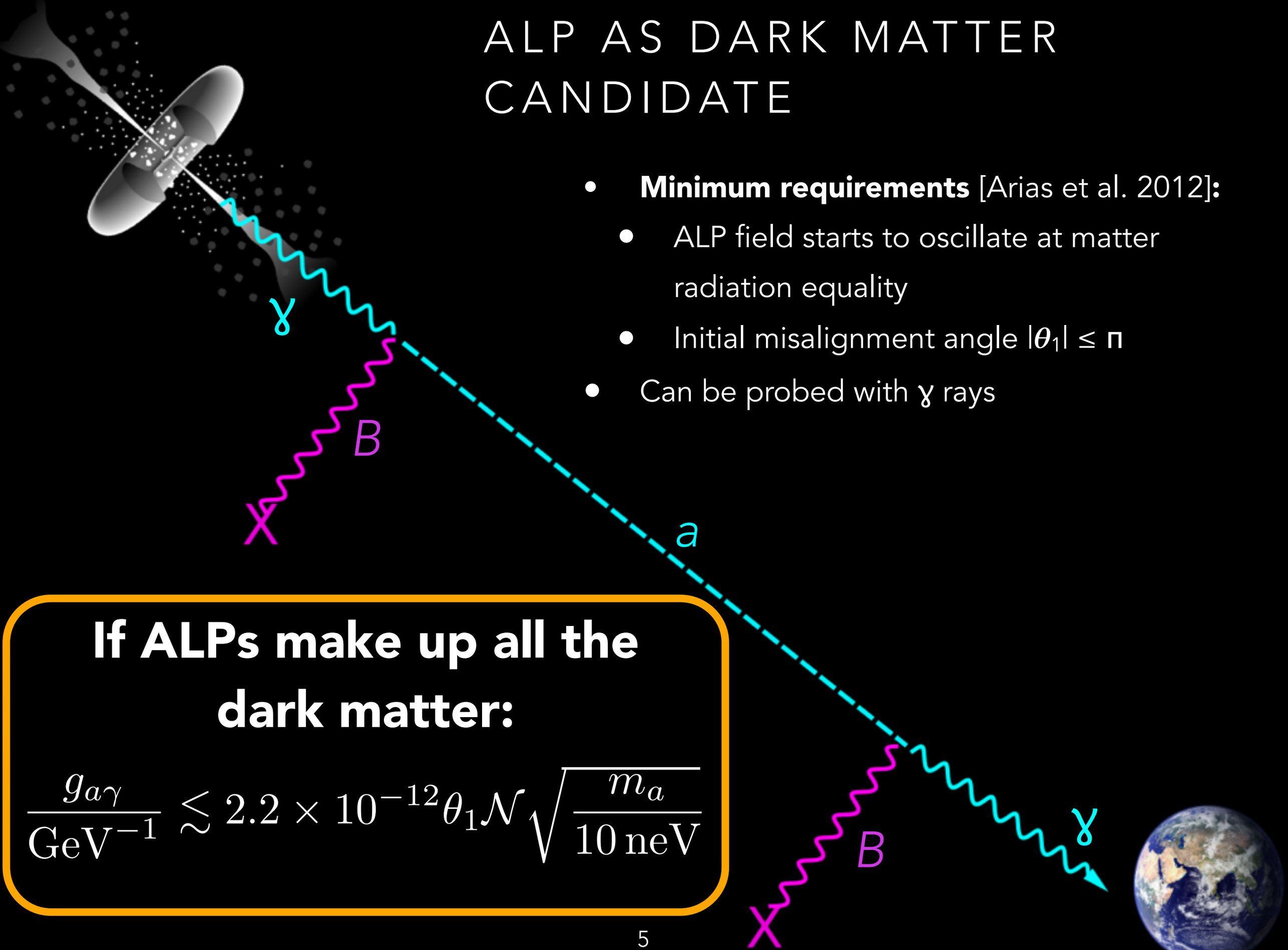
$g_{a\gamma} \gtrsim 10^{-11}$ GeV^{-1}

$m_a < 1$ μeV

[De Angelis et al. 2007, 2009, 2011,2014; Mirrizzi et al. 2007,2009; Sanchez-Conde et al. 2009; Dominguez & Sanchez-Conde, 2011; MM et al. 2013; Galanti et al. 2015]

ALP AS DARK MATTER CANDIDATE

- **Minimum requirements** [Arias et al. 2012]**:**
  - ALP field starts to oscillate at matter radiation equality
  - Initial misalignment angle $|\theta_1| \leq \pi$
- Can be probed with γ rays

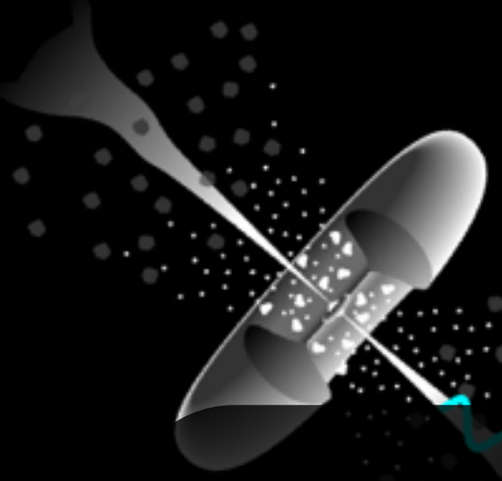


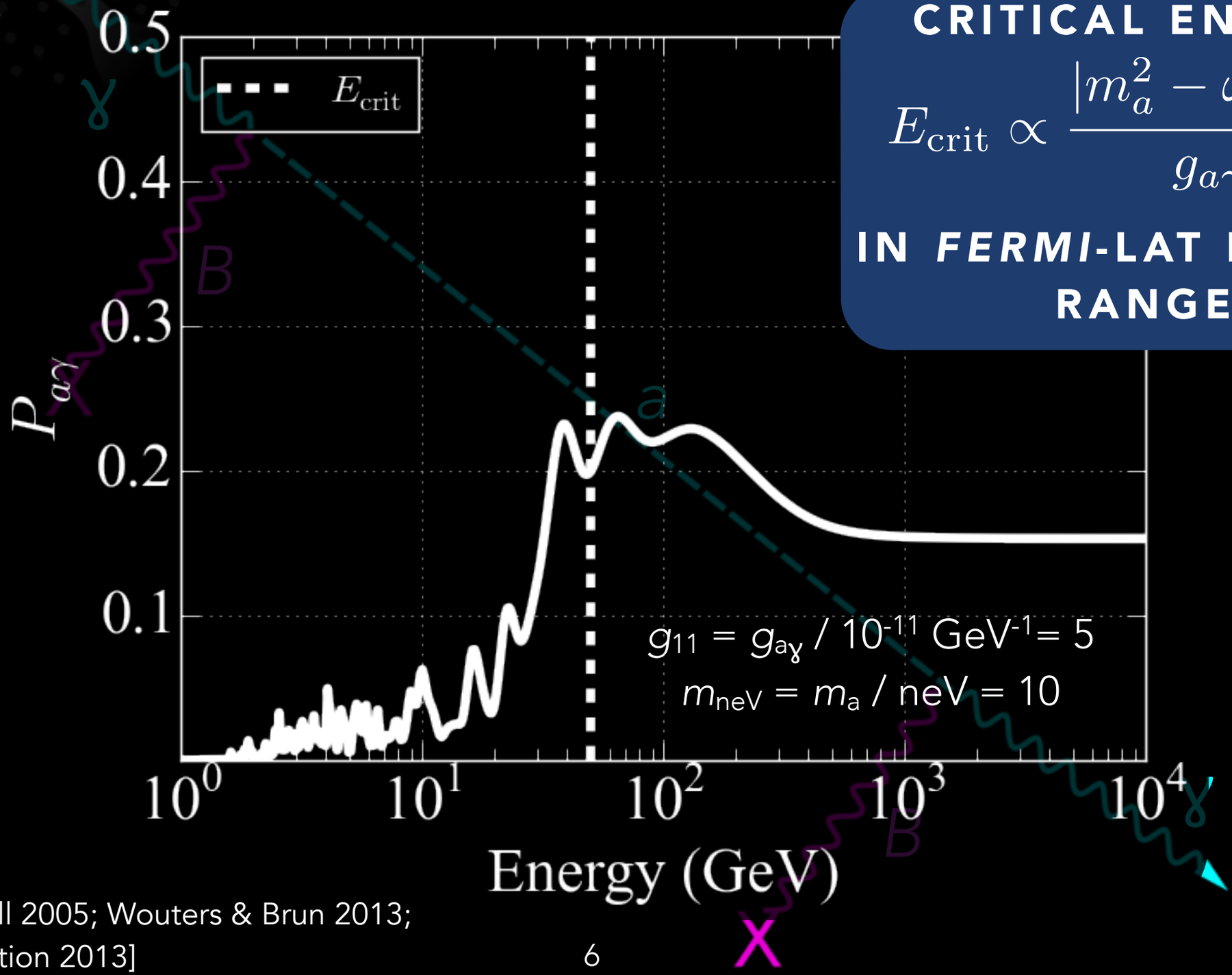
If ALPs make up all the dark matter:

$$\frac{g_{a\gamma}}{\mathrm{GeV}^{-1}} \lesssim 2.2 \times 10^{-12} \theta_1 \mathcal{N} \sqrt{\frac{m_a}{10\,\mathrm{neV}}}$$

ADDITIONAL PREDICTION:
SPECTRAL IRREGULARITIES

E.G. MIXING IN GALAXY CLUSTER AND THE MILKY WAY





CRITICAL ENERGY

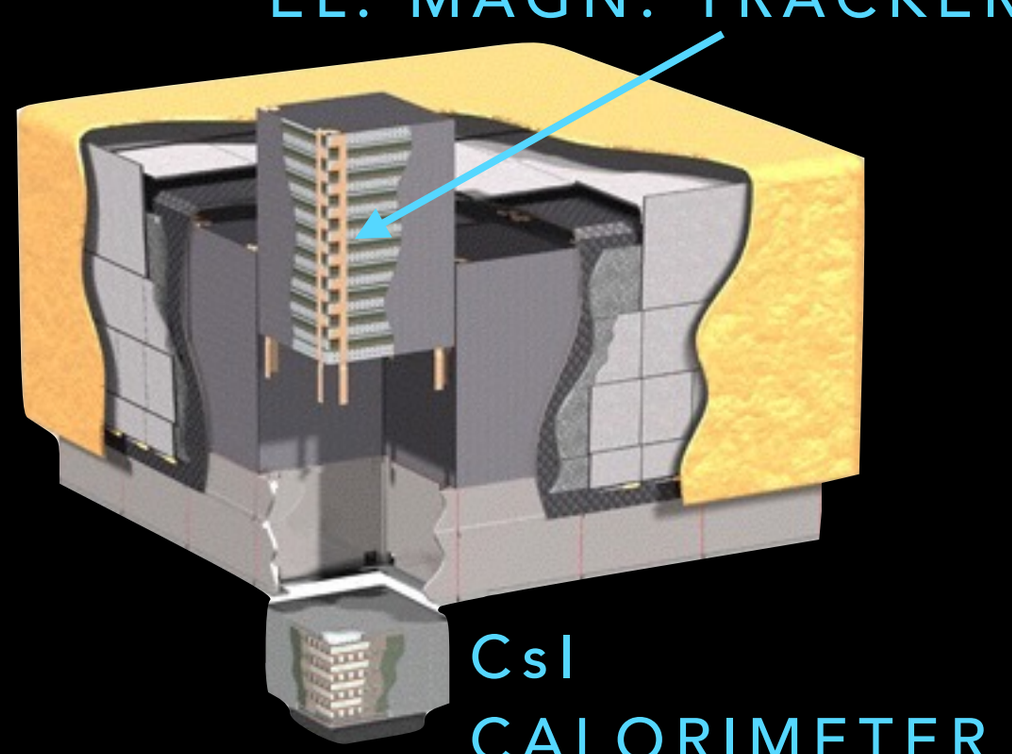
$$E_{\rm crit} \propto \frac{|m_a^2 - \omega_{\rm plasma}^2|}{g_{a\gamma}\, B}$$

IN *FERMI*-LAT ENERGY RANGE

[Östman & Mörtsell 2005; Wouters & Brun 2013; H.E.S.S. Collaboration 2013]

THE FERMI LARGE AREA TELESCOPE (LAT)

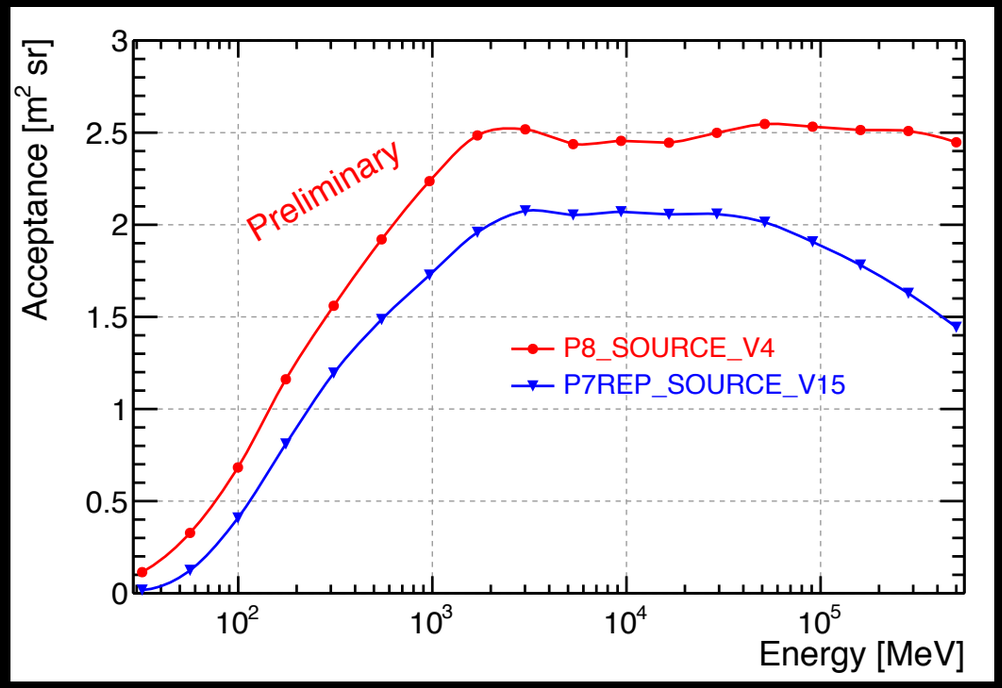
Energy range	30 MeV - over 300 GeV
Effective Area (E > 1 GeV)	~ 1 m^2
Point spread function (PSF)	~ 0.8˚ at 1 GeV
Field of view	2.4 sr
Orbital period	91 minutes
Altitude	565 km

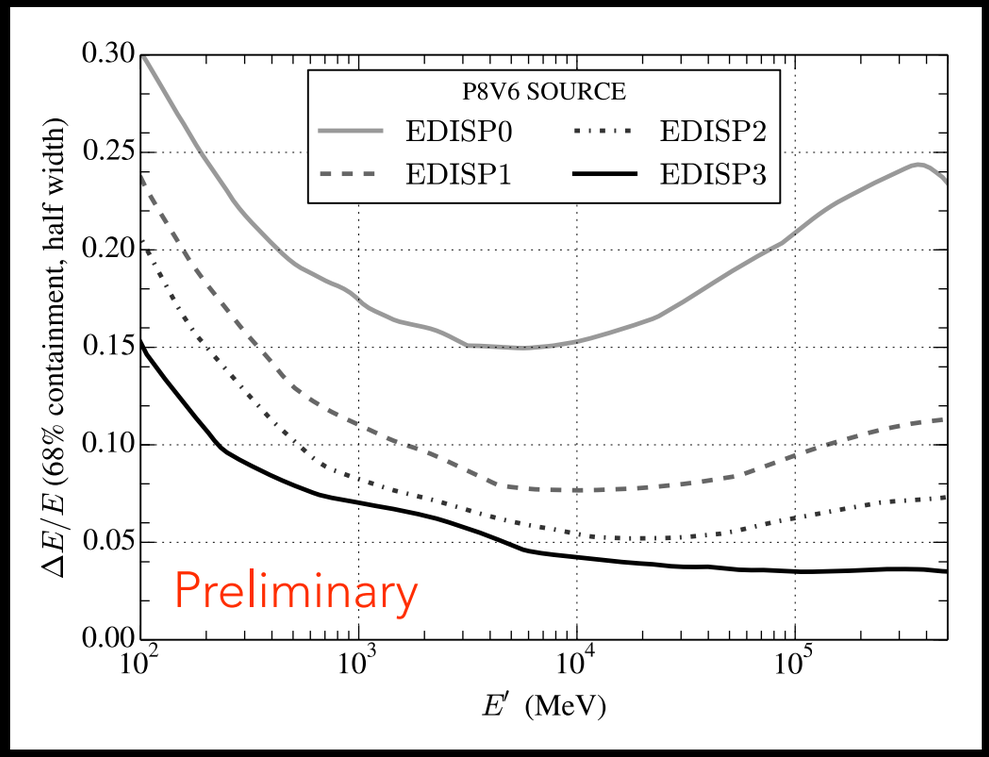


- **Survey** mode: observes **full sky every 3 hours**
- **Public data**, available within 12 hours
- Just celebrated **7 years** in orbit

PASS 8

- **Pass := corresponds to version of LAT data:**
  - Instrument simulation
  - Reconstruction code
  - Event selection
  - Instrument Response Functions (IRFs)
  - Systematic uncertainties
  - …
- **New Pass 8** just released for the public
- Improves effective area, PSF, …
- Now possible to **split data corresponding to quality of energy reconstruction**
- Joint analysis for these 4 ***EDISP* event types**





[Atwood et al. 2013]

NGC 1275 AND THE PERSEUS CLUSTER

- **Radio galaxy NGC 1275**, **bright *Fermi* source**
  [e.g. Abdo et al. 2009]

- In the center of **cool-core** cluster, **redshift *z* = 0.01759**

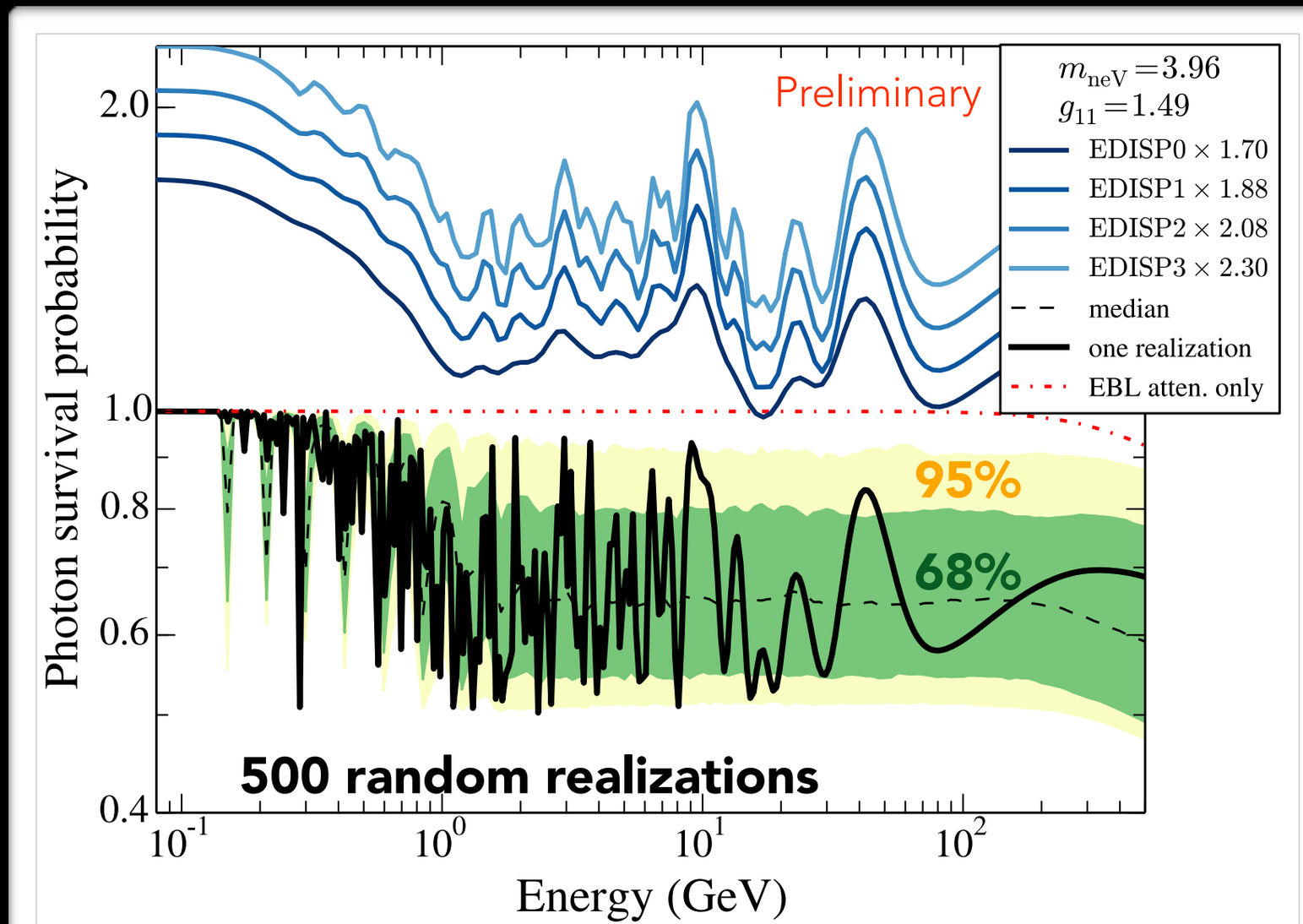
- Rotation measures: **central** B field ~**25μG**, **morphology on larger scales** (~100 kpc) **unknown**
  [Taylor+ 2006]

- **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/

PHOTON SURVIVAL PROBABILITY FROM NGC 1275

- B-field modelled as **gaussian turbulent field** [MM et al. 2014]
- Turbulence spectrum taken from **galaxy cluster A2199** [Vacca et al. 2012]
- **Central B field: 10 μG** [Aleksic et al. 2012]
- B field **decreases with electron density**
- **Irregularities washed out with energy dispersion**



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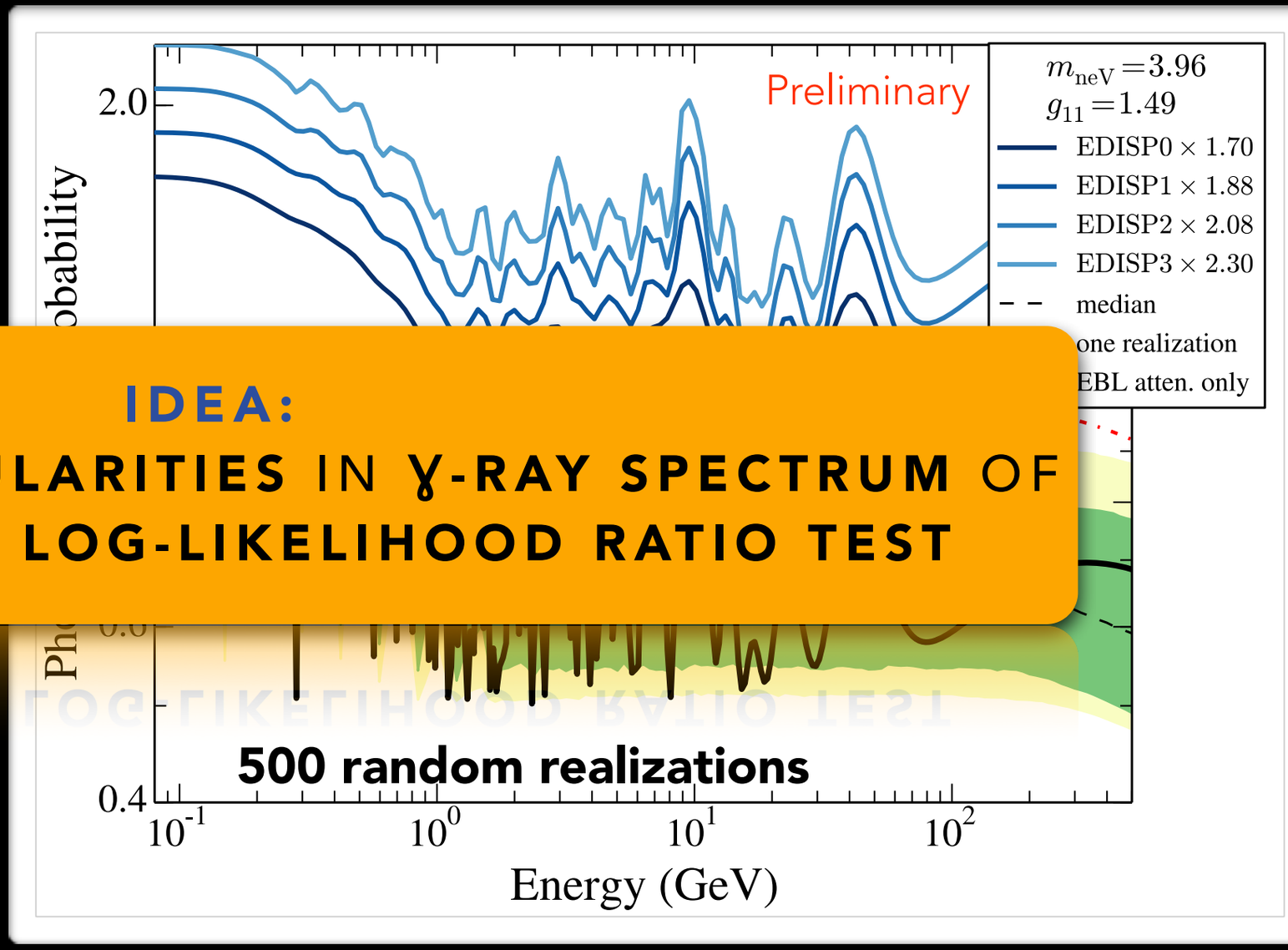

IDEA:

SEARCH FOR **IRREGULARITIES** IN **γ-RAY SPECTRUM** OF **NGC 1275** USING **LOG-LIKELIHOOD RATIO TEST**

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*:

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

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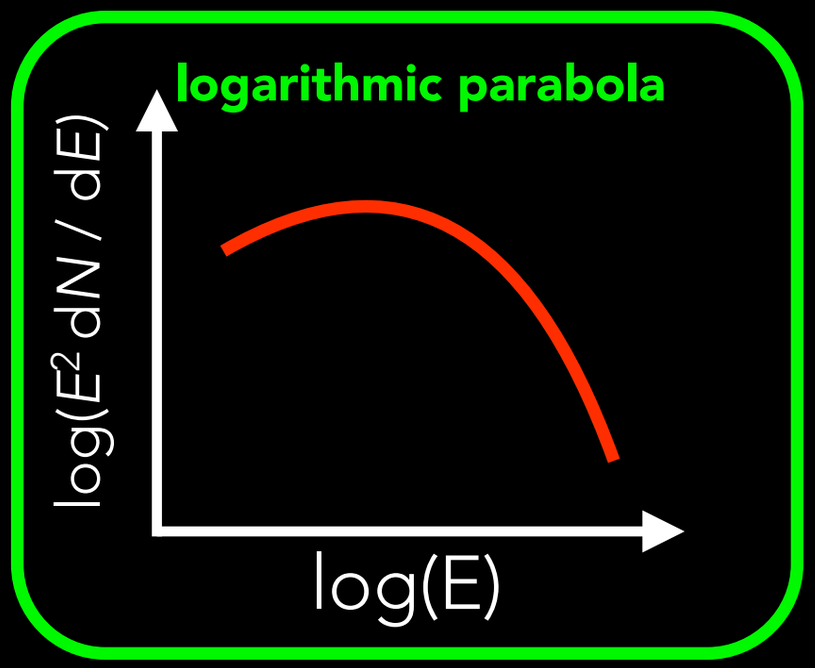
intrinsic spectrum



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

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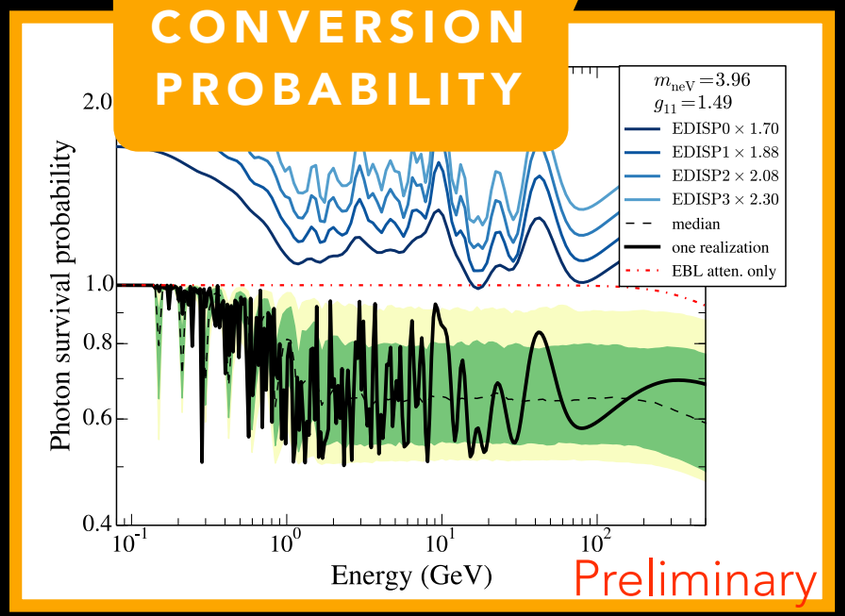
photon survival prob.

intrinsic spectrum

CONVERSION PROBABILITY



j-th B-field realization

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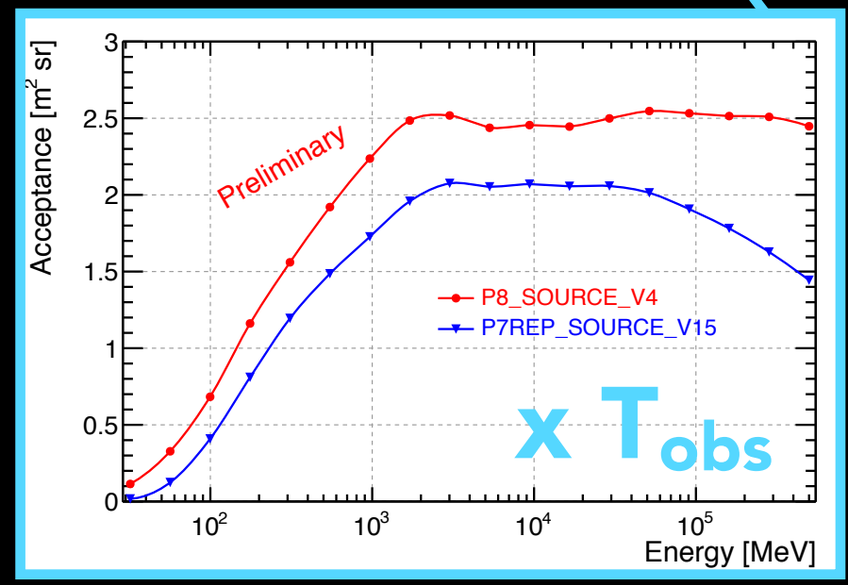
photon survival prob. | **intrinsic spectrum** | **Exposure (A_{eff} x obs. time)**



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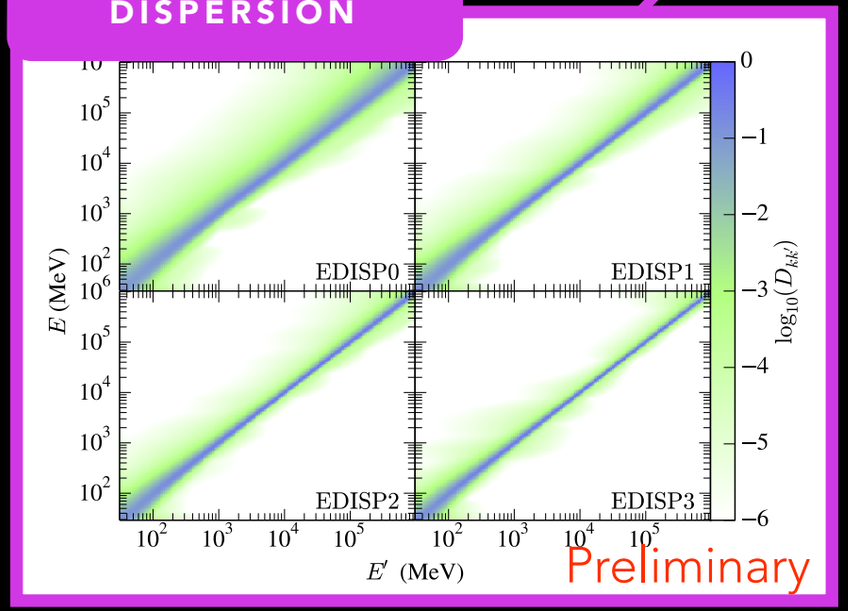
- $D^i_{kk'}$: Energy dispersion
- $P_{\gamma\gamma}$: photon survival prob.
- $F(E)$: intrinsic spectrum
- $\mathcal{E}^i(E)$: Exposure (A_{eff} x obs. time)

EXPOSURE AVERAGED ENERGY DISPERSION



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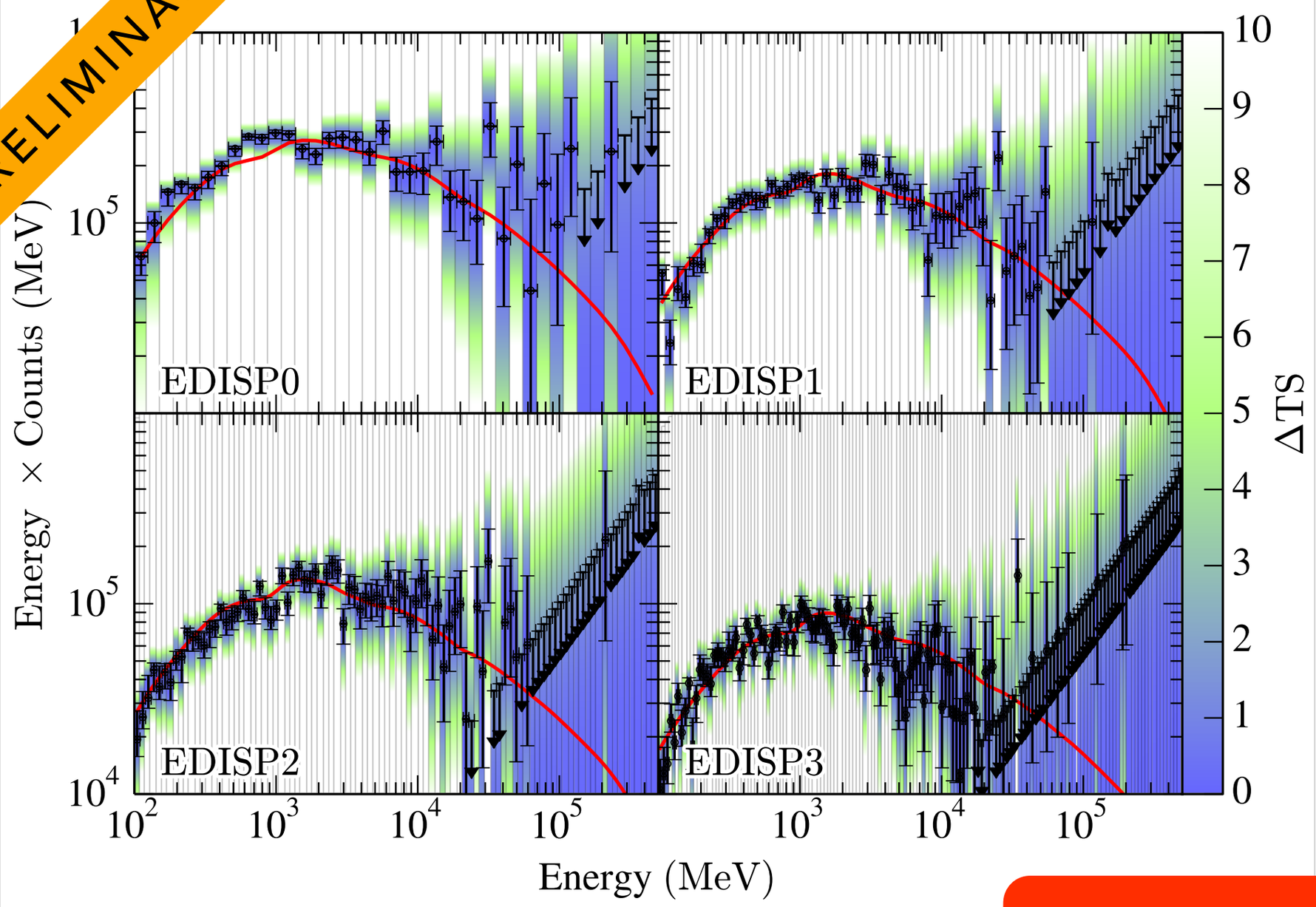
Energy dispersion | photon survival prob. | intrinsic spectrum | Exposure (A_{eff} x obs. time)

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

SIMULATED OBSERVATIONS (NO ALP) FOR NGC 1275

PRELIMINARY



fit w/o ALP

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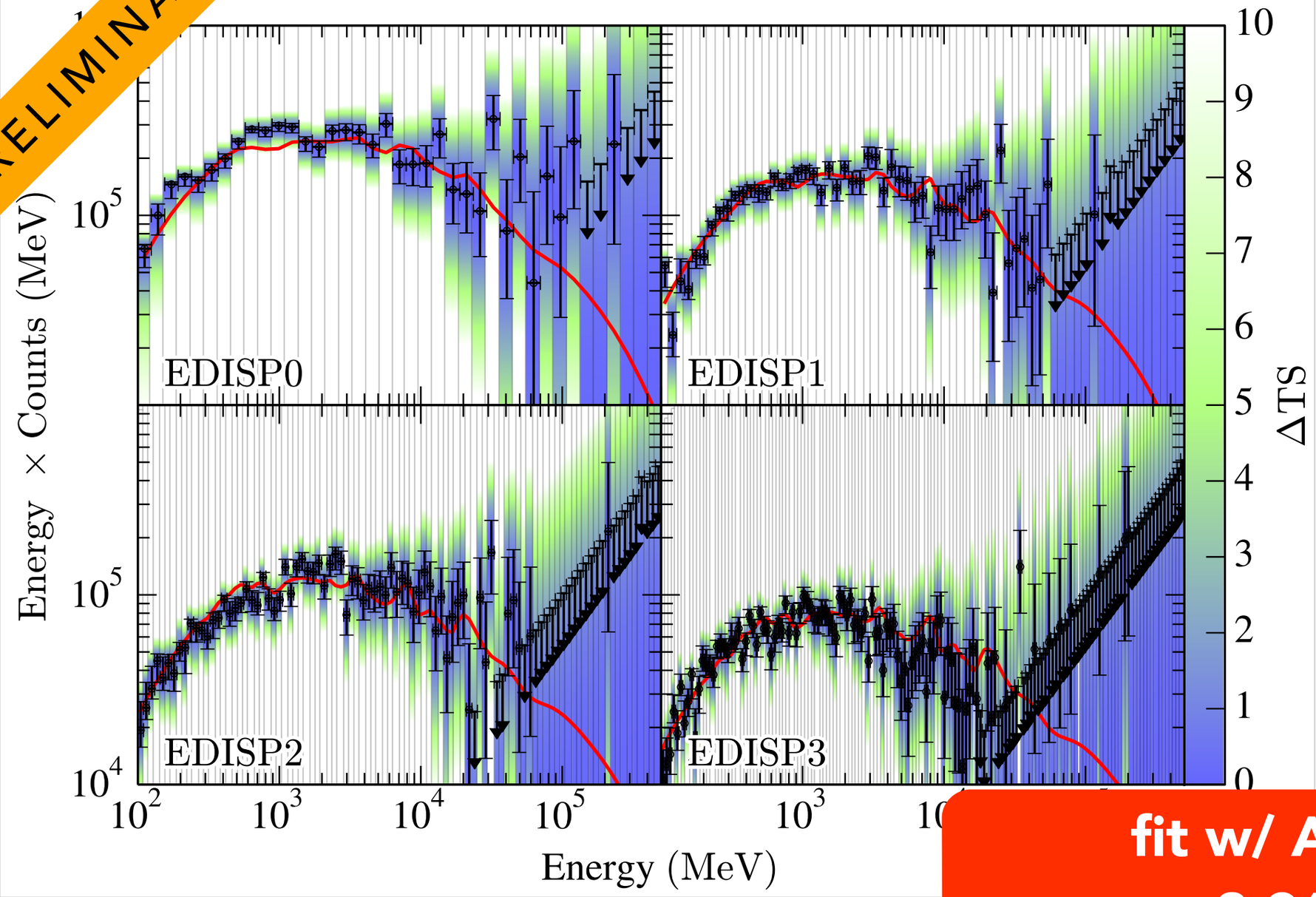


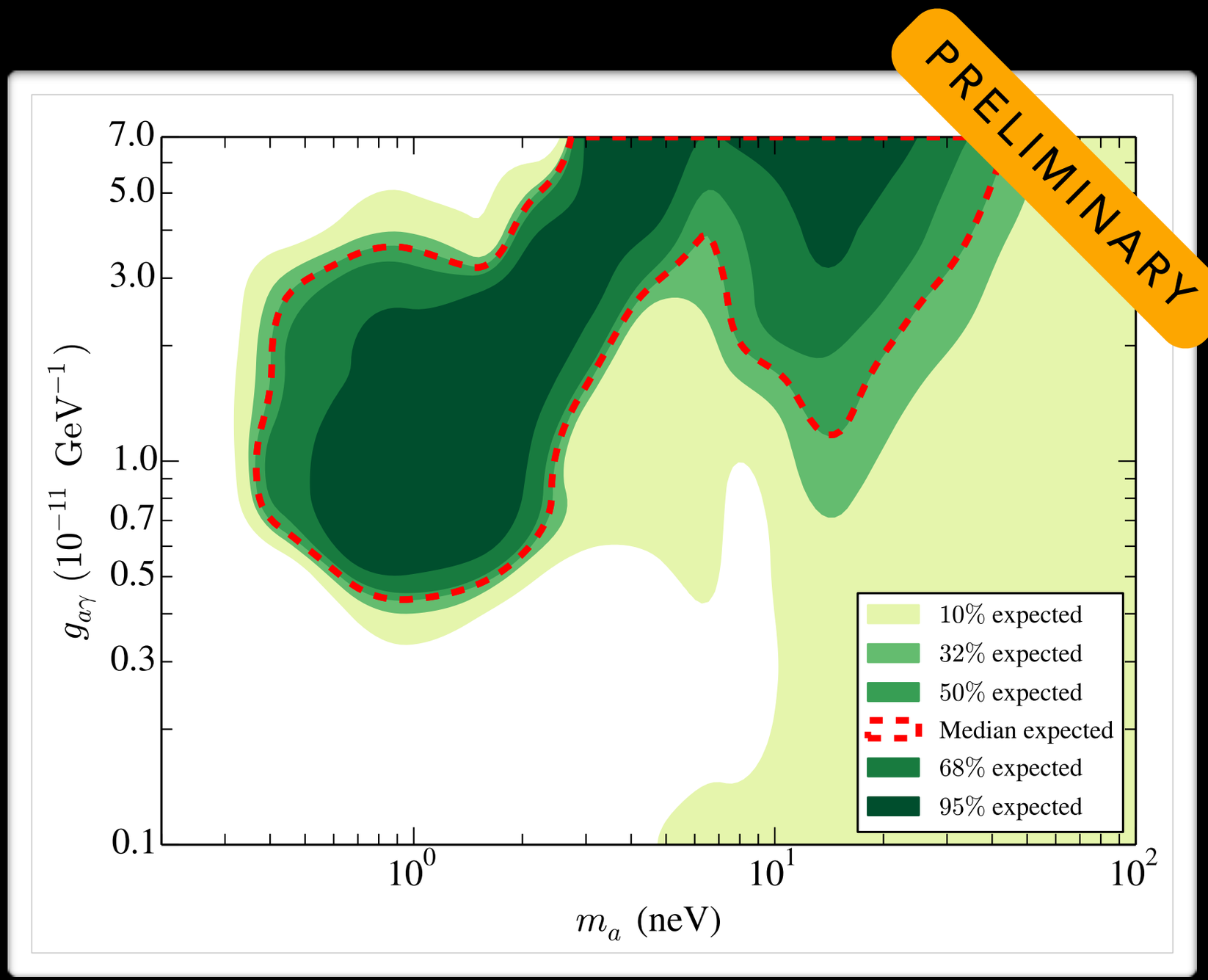
fit w/ ALP

m_a = 3.96 neV

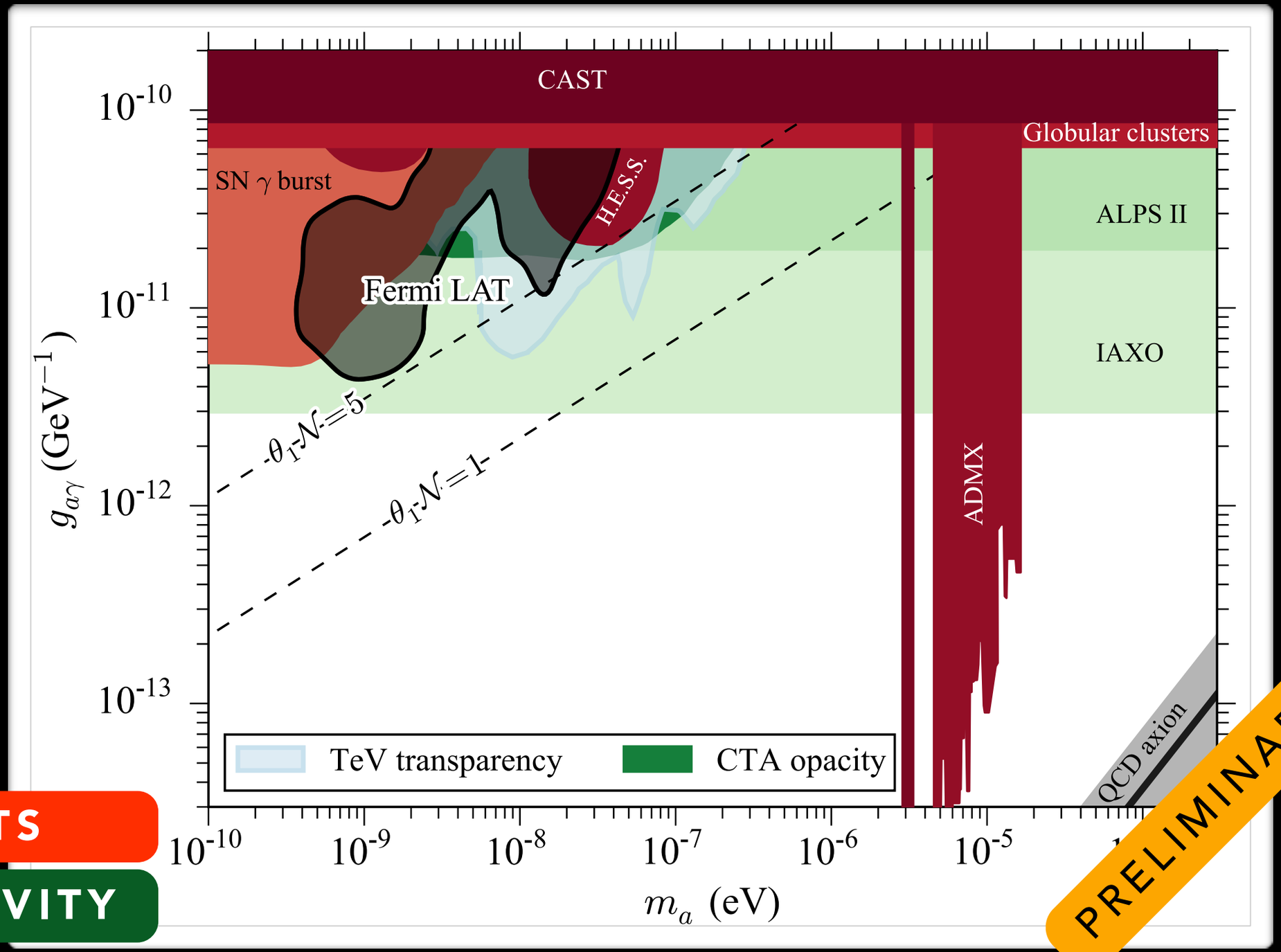
$g_{a\gamma}$ = 1.49 x 10^{-11} GeV^{-1}

EXPECTED LIMITS FOR 200 SIMULATED OBSERVATIONS

- For limits: select *B*-field realization that maximizes (95% quantile) likelihood
- Shape loosely follows expectation from critical energy



COMPARING THE EXPECTED LIMITS



LIMITS

SENSITIVITY

PRELIMINARY

CONCLUSION & OUTLOOK

- ALP have been proposed to explain potential evidences for larger-than-expected ɣ-ray fluxes from extragalactic sources

- Further general prediction: **spectral irregularities around critical energy**

- For ALP masses **0.5 neV < m_a < 50 neV**: critical energy within **Fermi-LAT energy range**

- **Expected sensitivity in un-probed parameter space**, similar to sensitivity of future laboratory experiments

- Probably we will not be able to probe ALP dark matter scenarios in which ALPs make up all the dark matter

- Data analysis almost complete, **stay tuned!**

BACK UP SLIDES

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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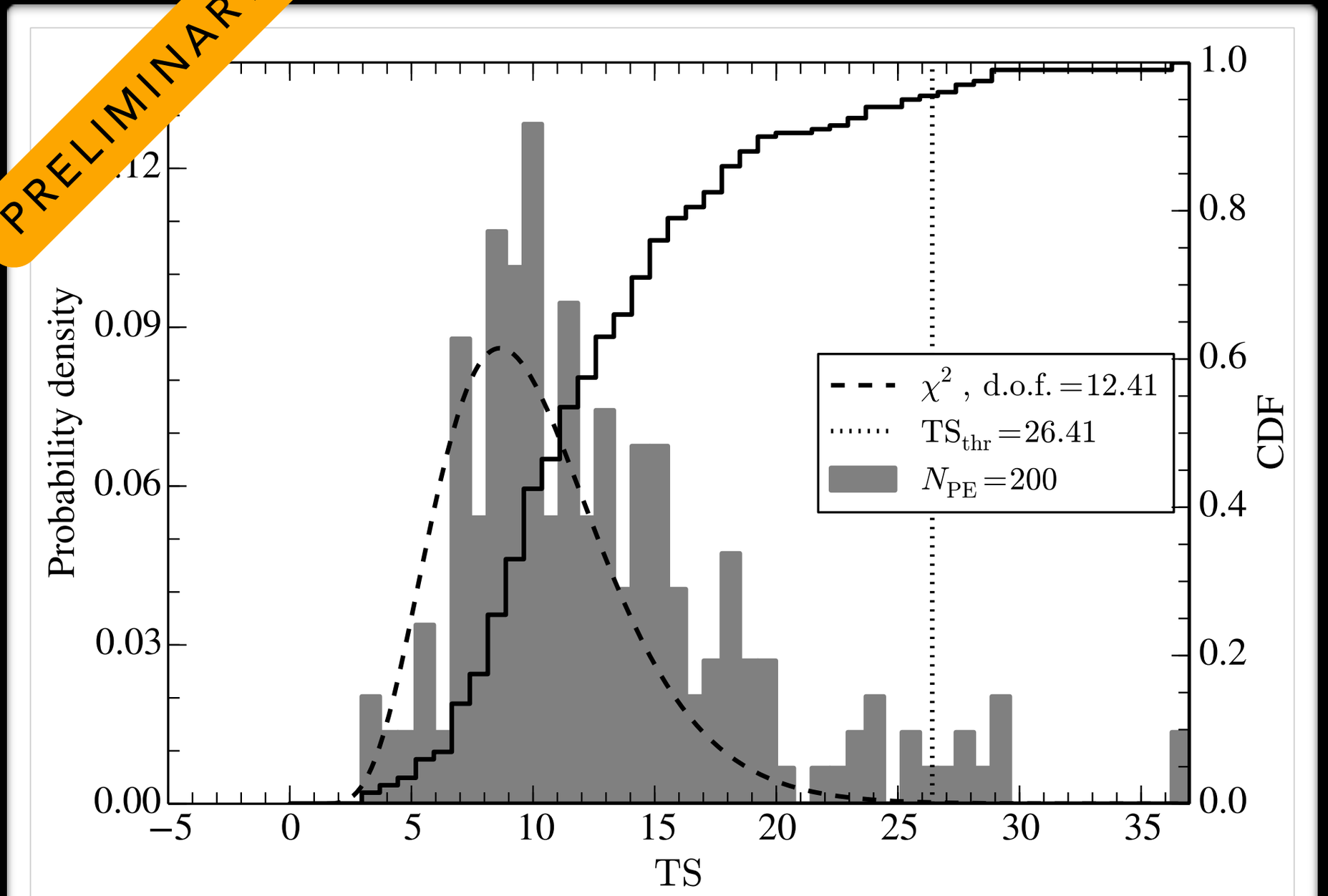
PRELIMINARY



EXTRACTING THE BIN-BY-BIN LIKELIHOOD

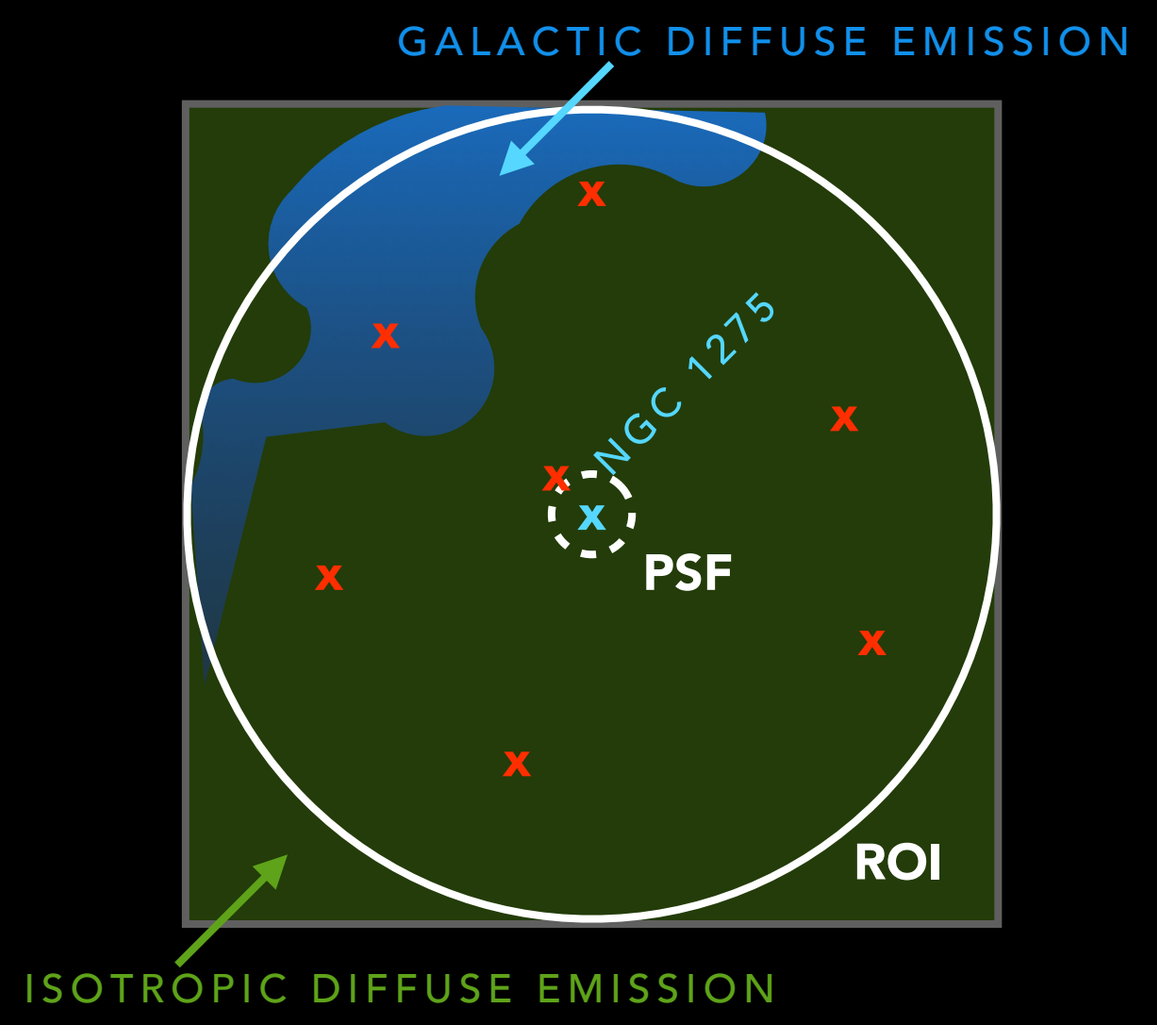
1. **Fit entire Region Of Interest** (ROI) **over full energy range** (100 MeV - 500 GeV)

2. **Fix spectral parameters of background sources** to best-fit values

3. **Re-fit central source** (NGC 1275) in narrow energy bins

4. Step over expected number of counts, **extract likelihood** in each step

- **Background sources**:
  - **Point sources**
  - **Galactic diffuse emission**
  - **Isotropic diffuse emission** (includes residual cosmic-ray contamination)



x = background point source

JOINT LIKELIHOOD FIT AND SETTING LIMITS

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

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

expected number of counts — **nuisance parameters** — **data**

Maximize likelihood for ALP parameters: profile over nuisance parameters:

$$\lambda(m_a, g_{a\gamma}, \tilde{\mathbf{B}}) = \prod_i \mathcal{L}(m_a, g_{a\gamma}, \tilde{\mathbf{B}}, \hat{\hat{\boldsymbol{\theta}}}(m_a, g_{a\gamma}, \tilde{\mathbf{B}}) | \mathbf{D}_i)$$

Setting limits: steps away from best fit parameters ➔ increase TS value until above a certain threshold (depends on confidence level):

$$\Delta\mathrm{TS} = -2 \ln \left(\frac{\lambda(m_a, g_{a\gamma}, \tilde{\mathbf{B}})}{\lambda(\hat{m}_a, \hat{g}_{a\gamma}, \tilde{\mathbf{B}})} \right)$$

B-Field that corresponds to 95% quantile (instead of maximizing)

[Rolke et al. 2005; Mattox et al. 1996]