Oskar Klein centre

Stockholm University

Fermi Gamma-ray Space Telescope

SEARCHES FOR AXIONLIKE PARTICLES WITH THE FERMI LARGE AREA TELESCOPE

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FOR THE FERMI-LAT COLLABORATION
TeVPA 2016
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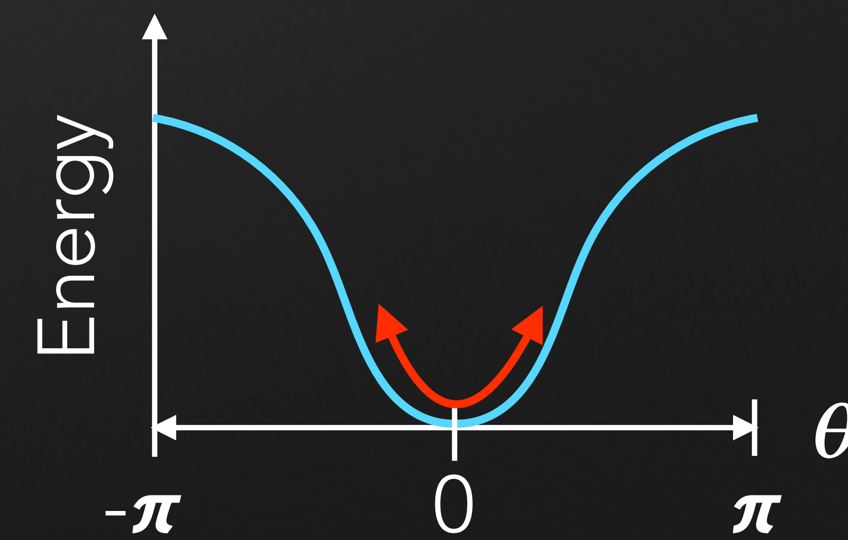
AXIONS AND AXION-LIKE PARTICLES

- QCD: has CP violating term with strength θ, measurement: $|\theta| < 10^{-10}$
- Introduce symmetry, θ is a dynamical field, relaxes to zero in potential
- Symmetry broken at scale f_a ⇒ **new particle: the axion!** (similar to Higgs mechanism)
- Axion mass $m_a \sim f_a^{-1}$
- 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**

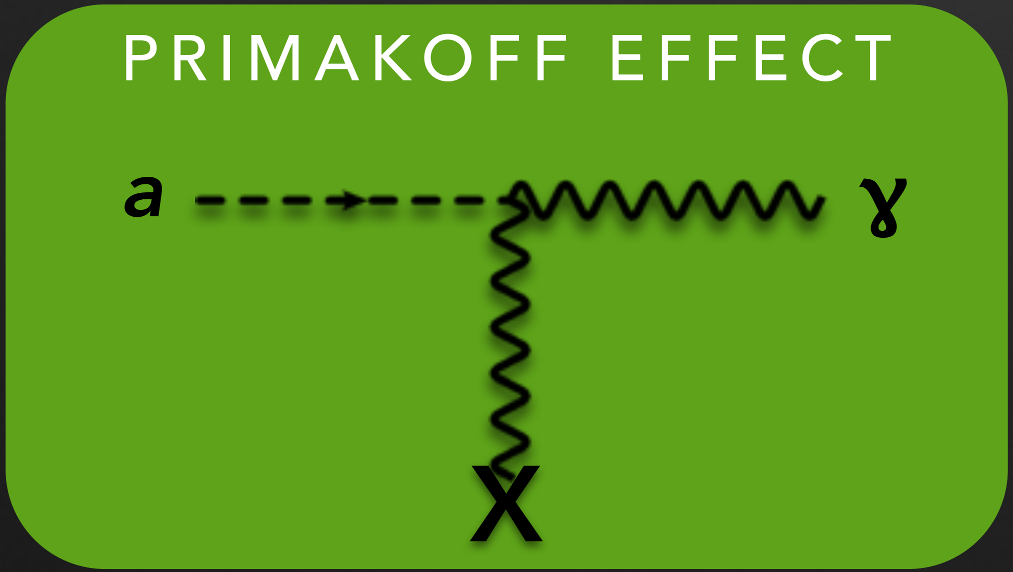


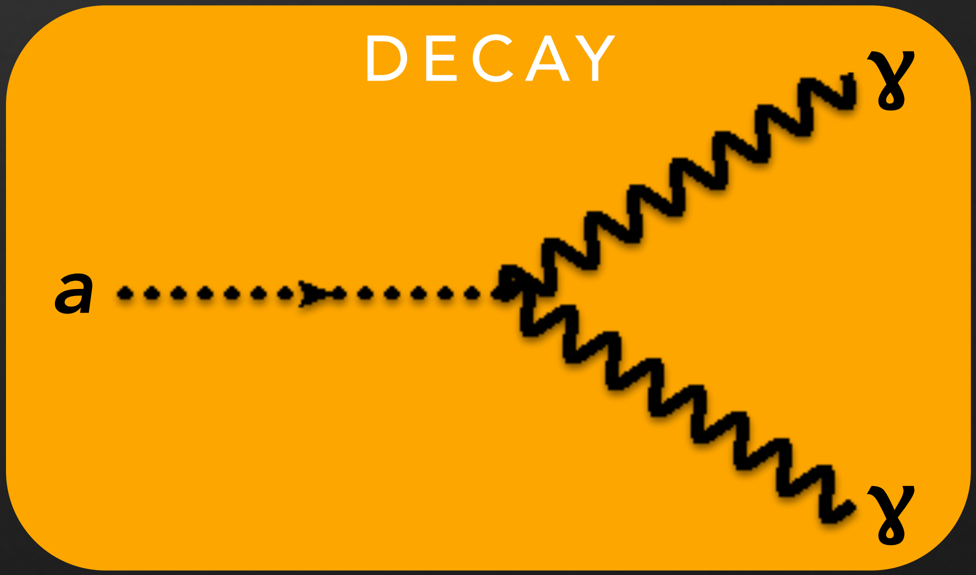
[Peccei & Quinn 77; Wilczek 78; Weinberg 78; Preskill et al. 83; Abbott & Sikivie 83; Witten 84; e.g. Arvanitaki et al. 09; Cicoli et al. 12; Arias et al. 2012]

DETECTING AXIONS/ALPs WITH GAMMA RAYS

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

$$g_{a\gamma} = \frac{\alpha}{2\pi} \frac{1}{f_a} \mathcal{N}$$





See, e.g., Fermi-LAT constraints for decaying relativistic axions produced in neutron stars [Berenji, Gaskins, MM 2016]

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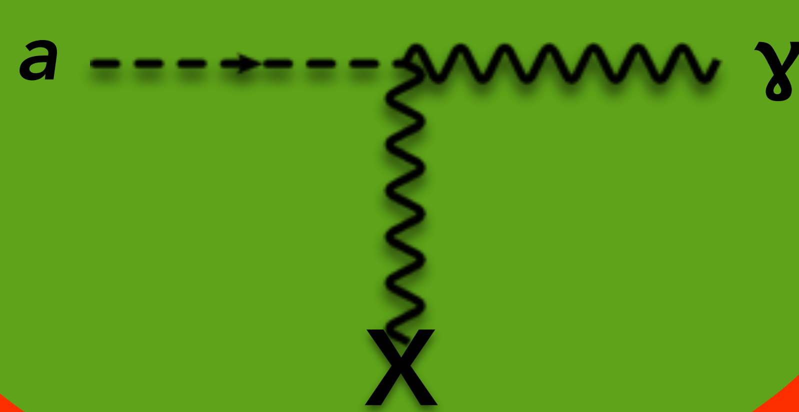
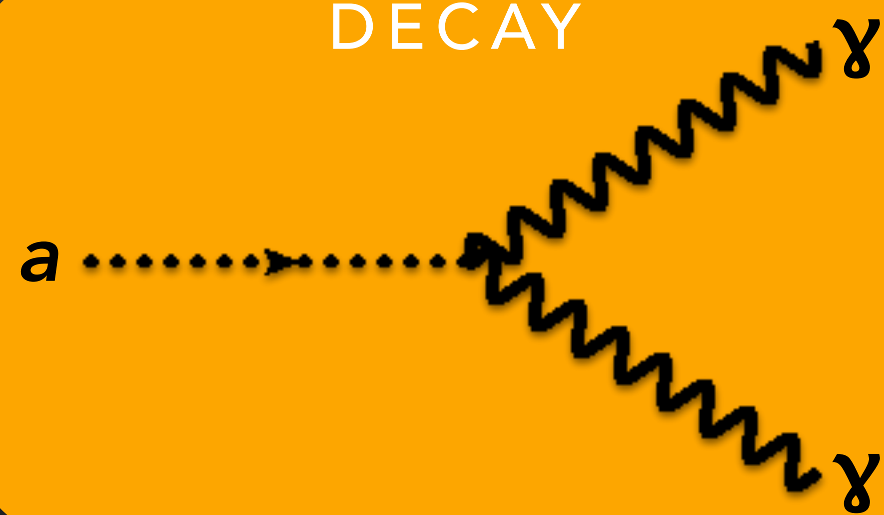
PRIMAKOFF EFFECT



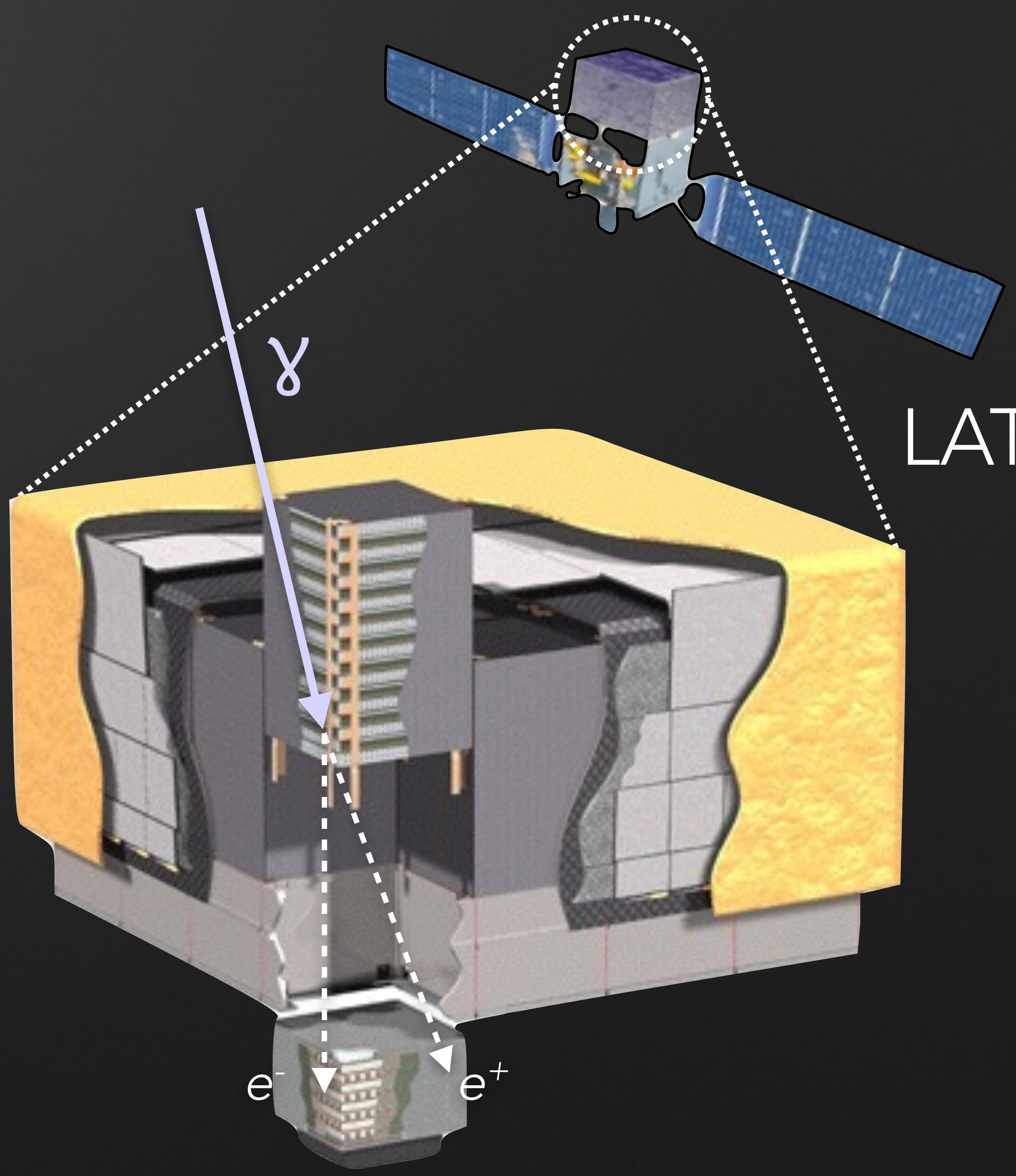
DECAY



See, e.g., Fermi-LAT constraints for decaying relativistic
axions produced in neutron stars
[Berenji, Gaskins, MM 2016]

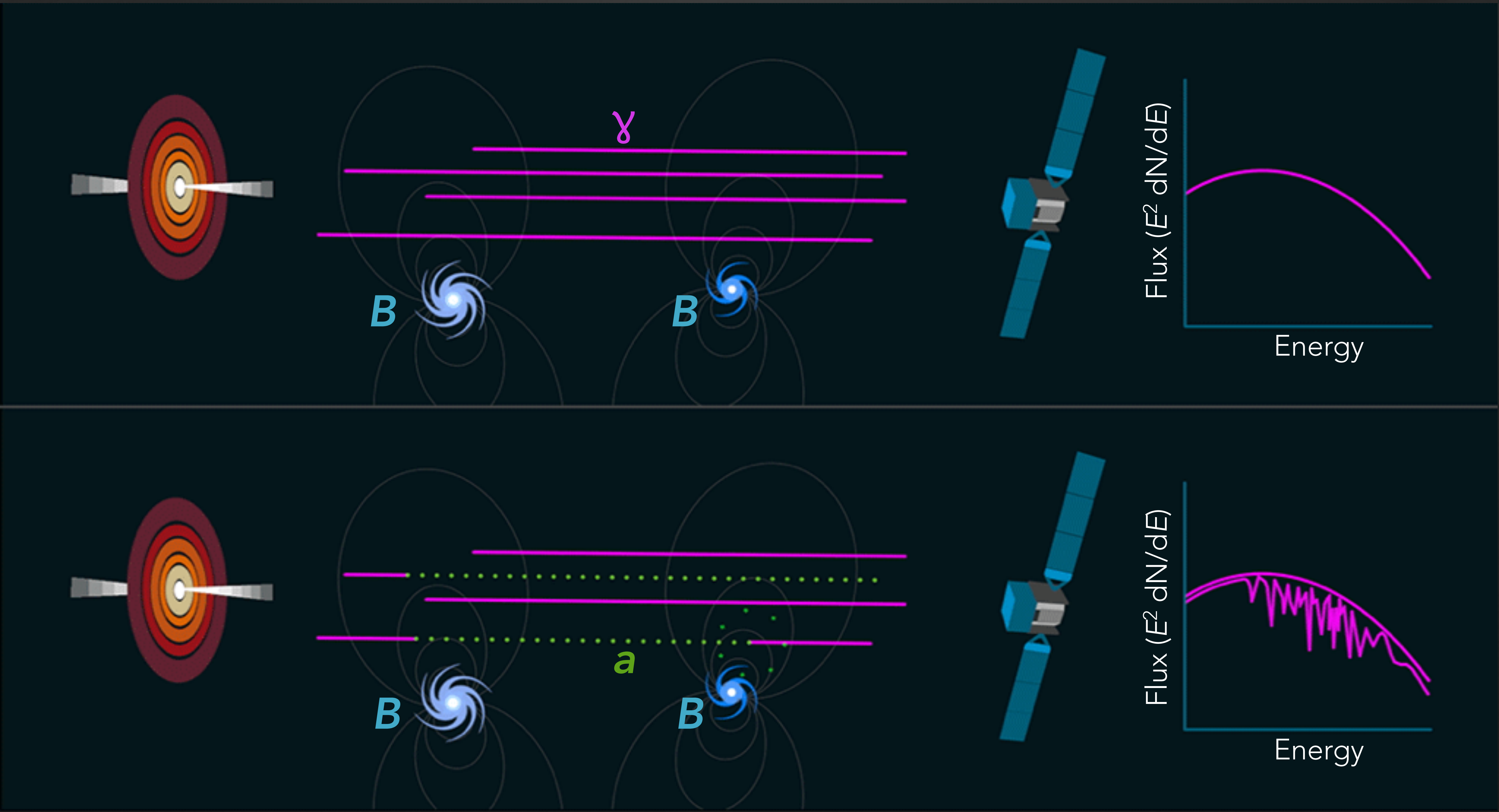
DETECTING GAMMA RAYS WITH THE FERMI LAT

Energy range	20 MeV - over 300 GeV
Effective Area (E > 1 GeV)	~ 1 m^2
Point spread function (PSF)	~ 0.8° @ 1 GeV
Energy resolution ΔE/E	5% - 15% @ 10 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

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]

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 $\gtrsim$ 2 μG** from non-observation of ɣ rays [Aleksic et al. 2012]

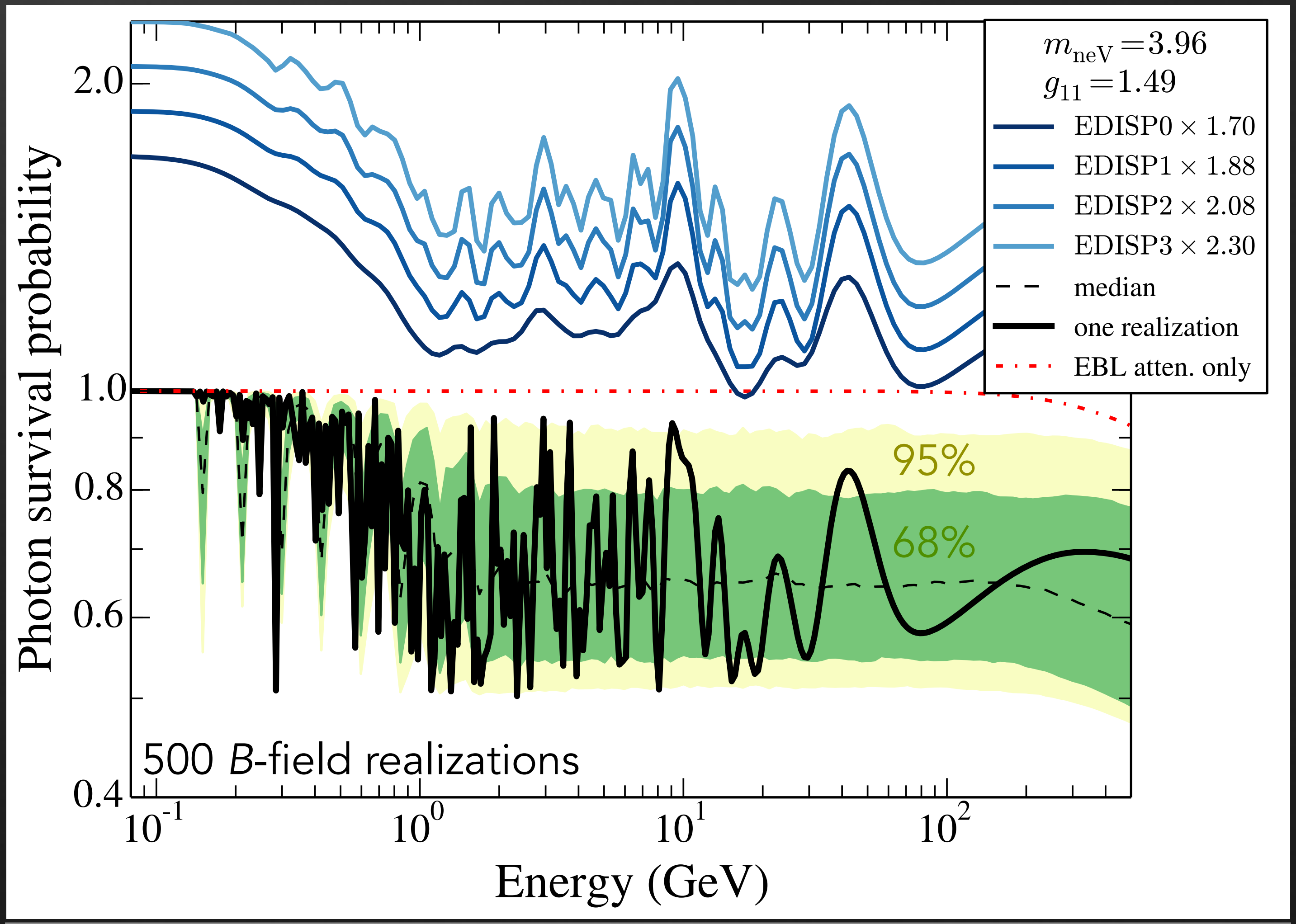
[Ajello et al. 2016]

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

MODELING PHOTON-ALP CONVERSIONS IN PERSEUS CLUSTER

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

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

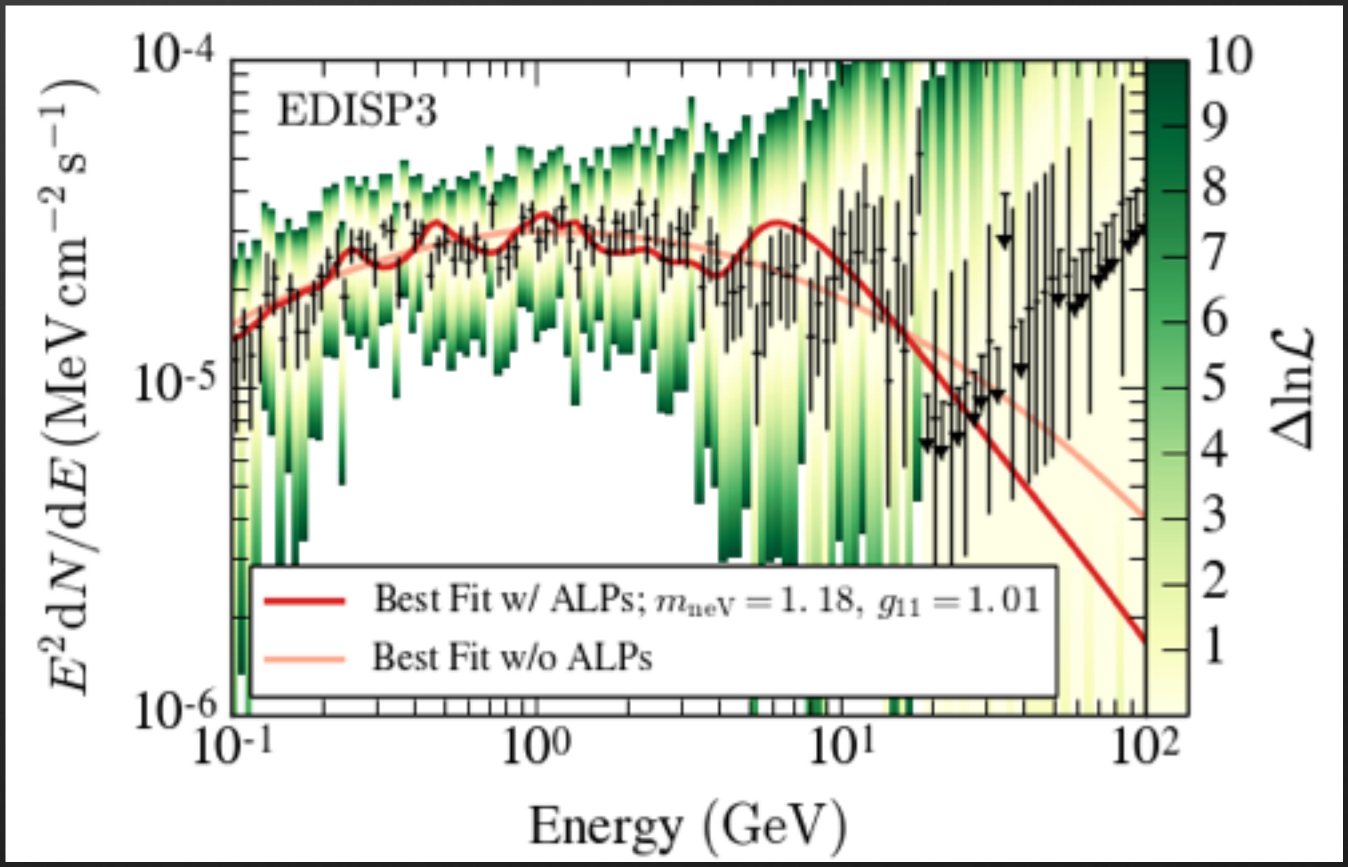


[Ajello et al. 2016]

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
- 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. with EBL attenuation — Intrinsic spectrum

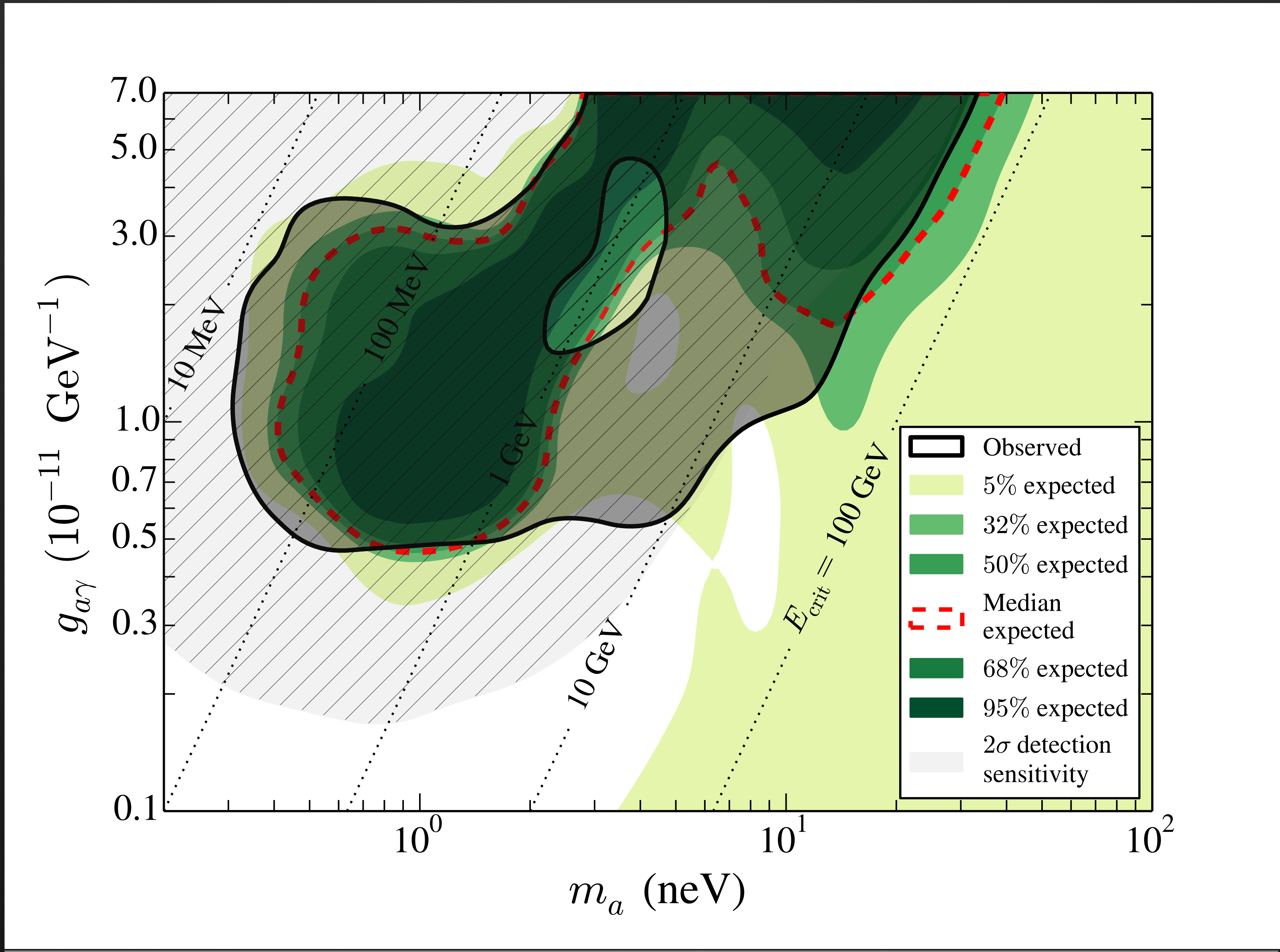
NO-ALP HYPOTHESIS: $\exp(-\tau) F(E)$

EBL attenuation only — Intrinsic spectrum

[Ajello et al. 2016]

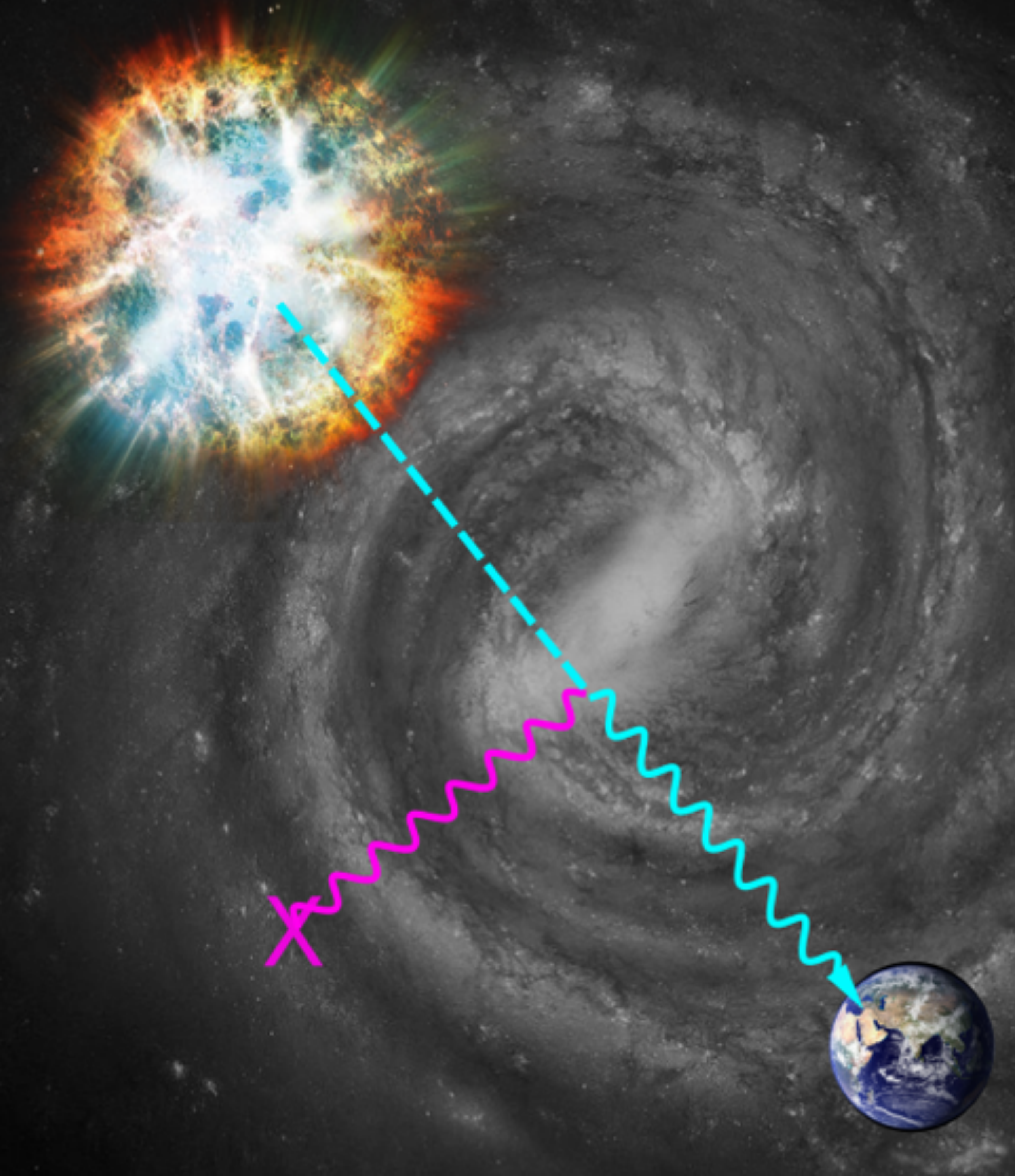
NO ALP OBSERVED: CONSTRAINTS

FIT WITH ALPs NOT PREFERRED



[Ajello et al. 2016]

AXIONLIKE PARTICLES FROM CORE COLLAPSE SUPERNOVAE

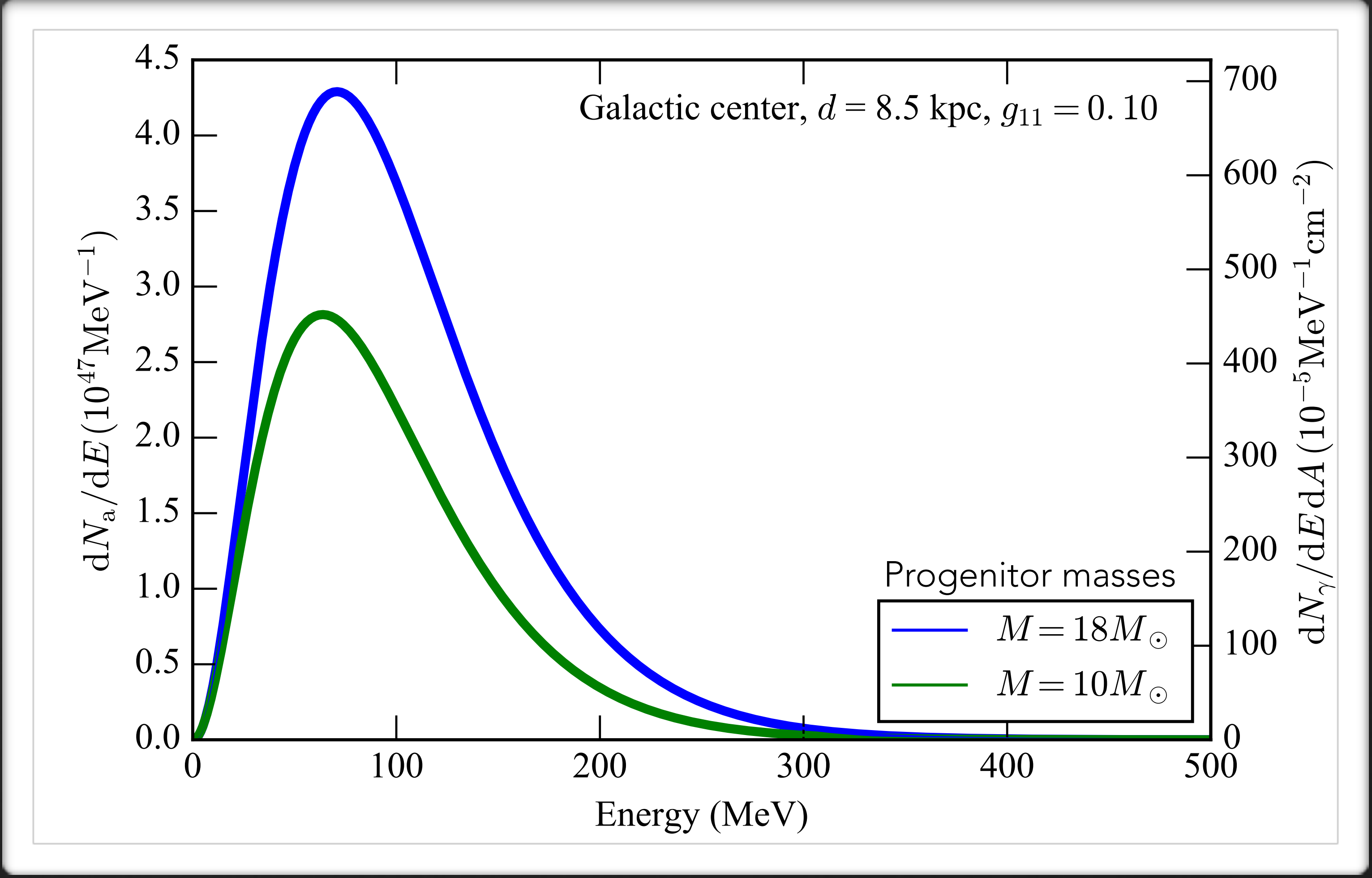


- ALPs would be **produced in a core-collapse SN** explosion via Primakoff process
- Could **convert into gamma-rays in Galactic magnetic field**
- Non-observation of signal from **SN1987A** with Gamma-Ray Spectrometer on Solar Maximum Mission satellite still **strongest bounds for ALPs with masses $m_a \lesssim$ 1neV** [Payez et al. 2015]

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

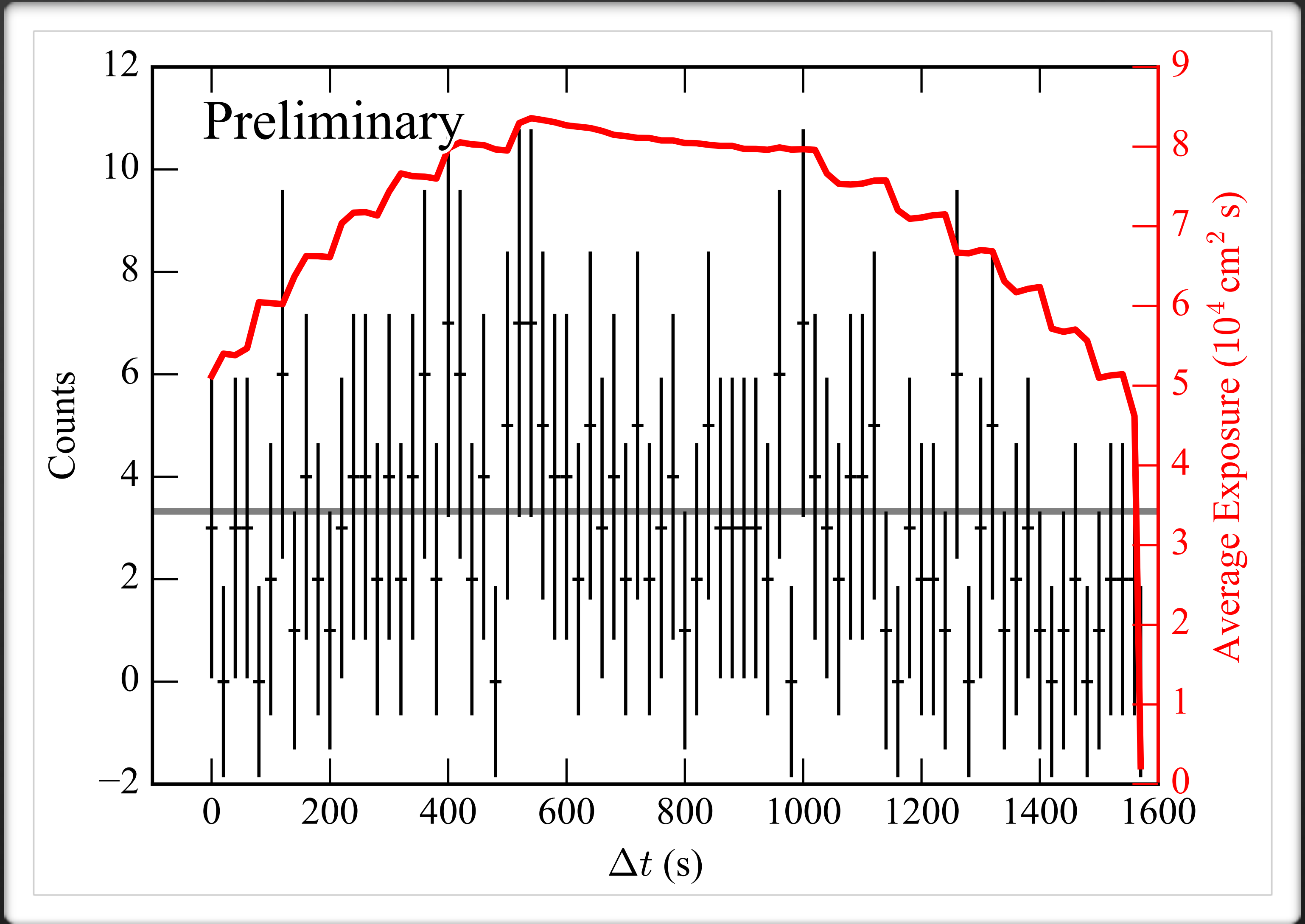


Better **gamma-ray sensitivity and large FoV** of *Fermi* LAT promise **unparalleled sensitivity** for ALPs in case of a Galactic core-collapse SN within *Fermi*-LAT lifetime and FoV

[Payez et al. 2015]

GC LIGHT CURVE OF ONE GTI WITHIN 68% PSF CONTAINMENT

- Use **Galactic Center** as target
- Estimate number of background counts from **data**:
  - From one exposure of the Galactic Center (~1500s)
  - Energy Range: **50-500 MeV**
  - Within **68% PSF (~ 11 degrees @ 50 MeV)**
  - Use **20s time bins** (full explosion time)
- **Expected number of background counts: ~3.3**
- Compare against number of **expected counts from SN explosion**
- Use **statistical test for low-count regime** [Feldman & Cousins 1998]

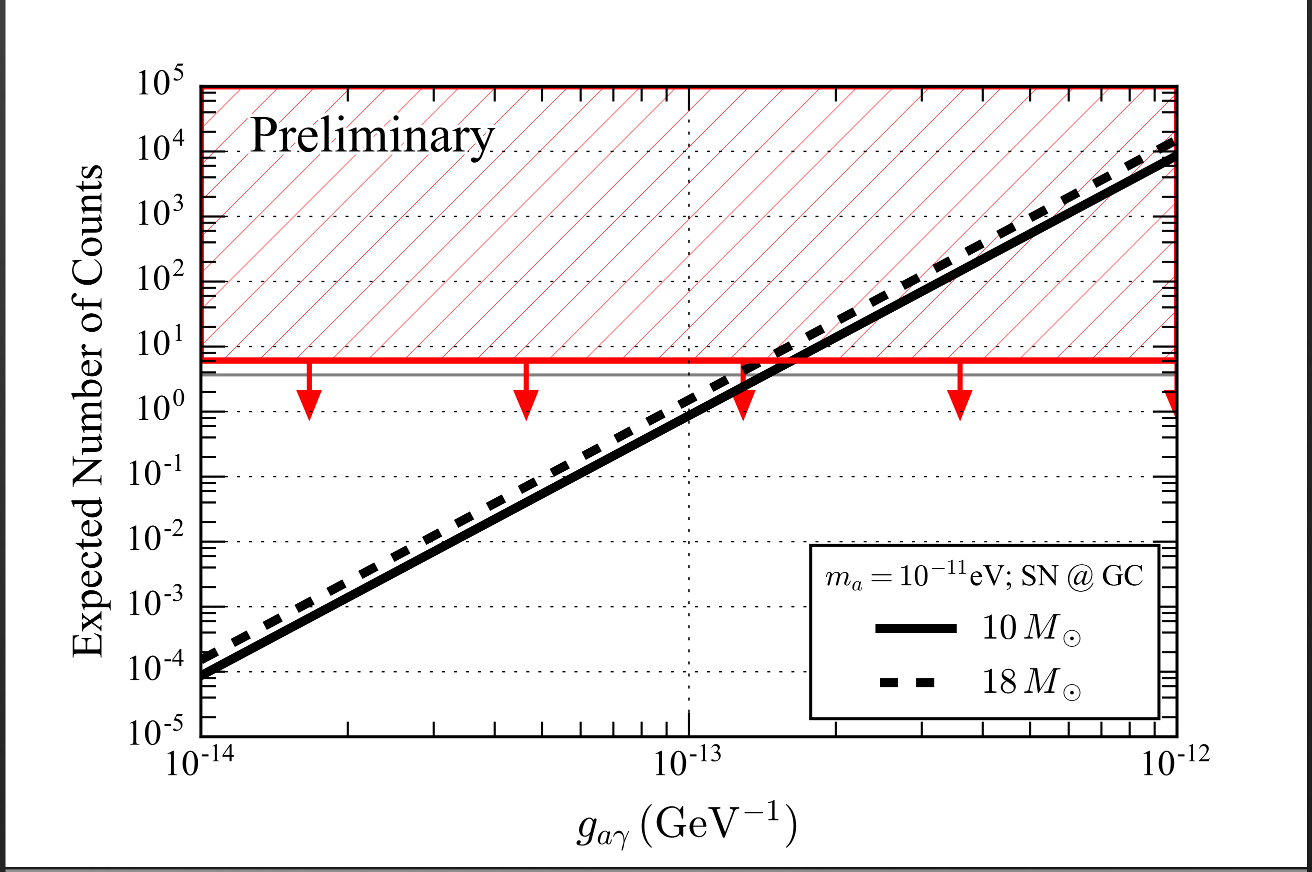


Energy range	50-500 MeV
Event Class / IRF	P8R2_TRANSIENT020_V6
Zenith Angle	< 80°

[MM; M. Giannotti; A. Mirizzi; J. Conrad; M. Sanchez-Conde; submitted; arXiv:1609:02350]

EXPECTED COUNTS FROM ALP MODEL

- Integrated over explosion **time** (~20s)
- Integrated over **energy**, 50-500 MeV
- Folded with Fermi-LAT **instrumental response function**
- Expected number of counts ~ $g_{a\gamma}^4$
- **Little dependence** on progenitor mass



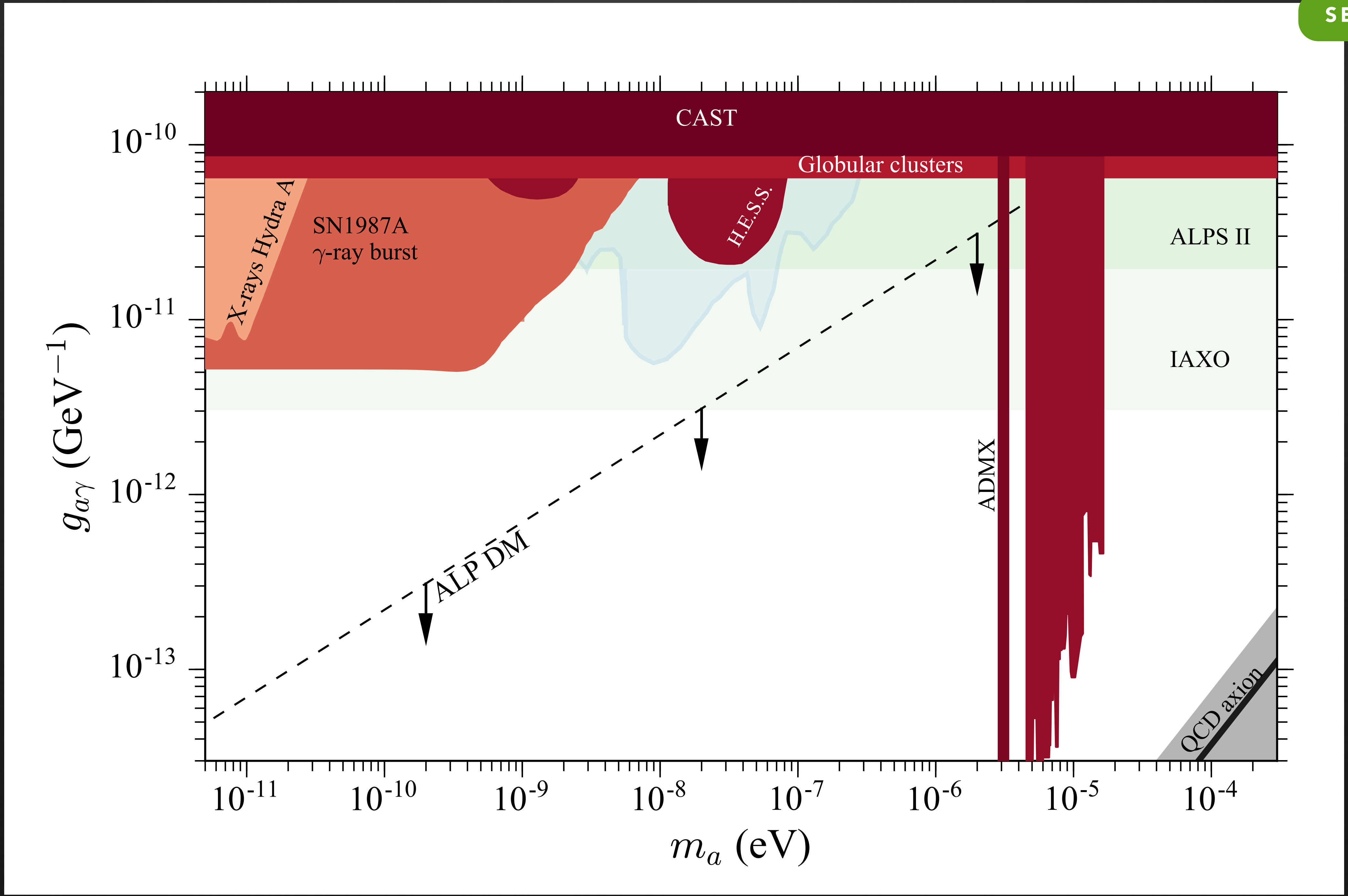
Assuming 4 background counts in one 20s time bin:
Exclude ALP models predicting more than 6.4 counts at 95% confidence

[MM; M. Giannotti; A. Mirizzi; J. Conrad; M. Sanchez-Conde; submitted; arXiv:1609:02350]

CONSTRAINTS & SENSITIVITIES

LIMITS

SENSITIVITIES



CONSTRAINTS & SENSITIVITIES

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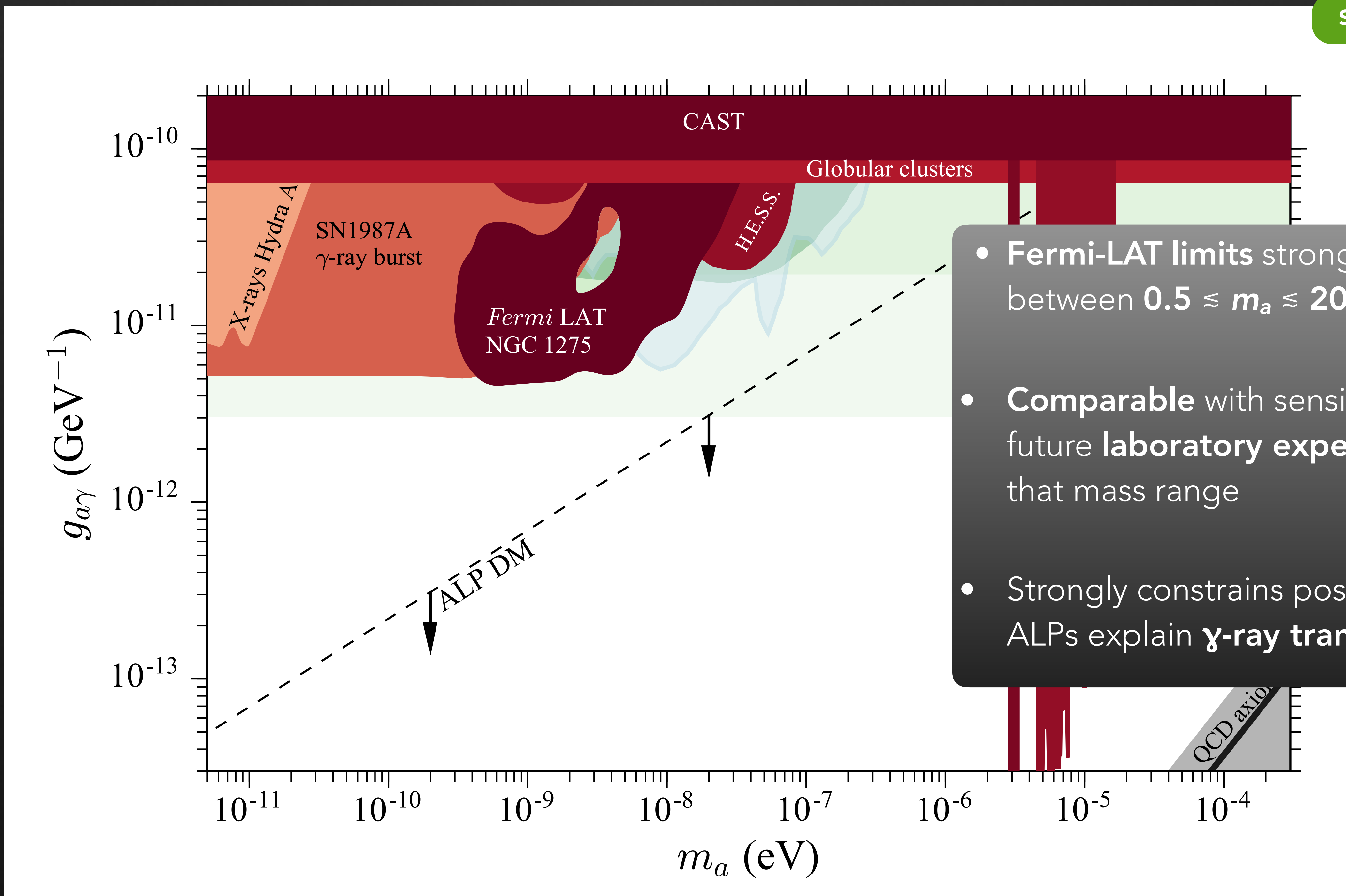
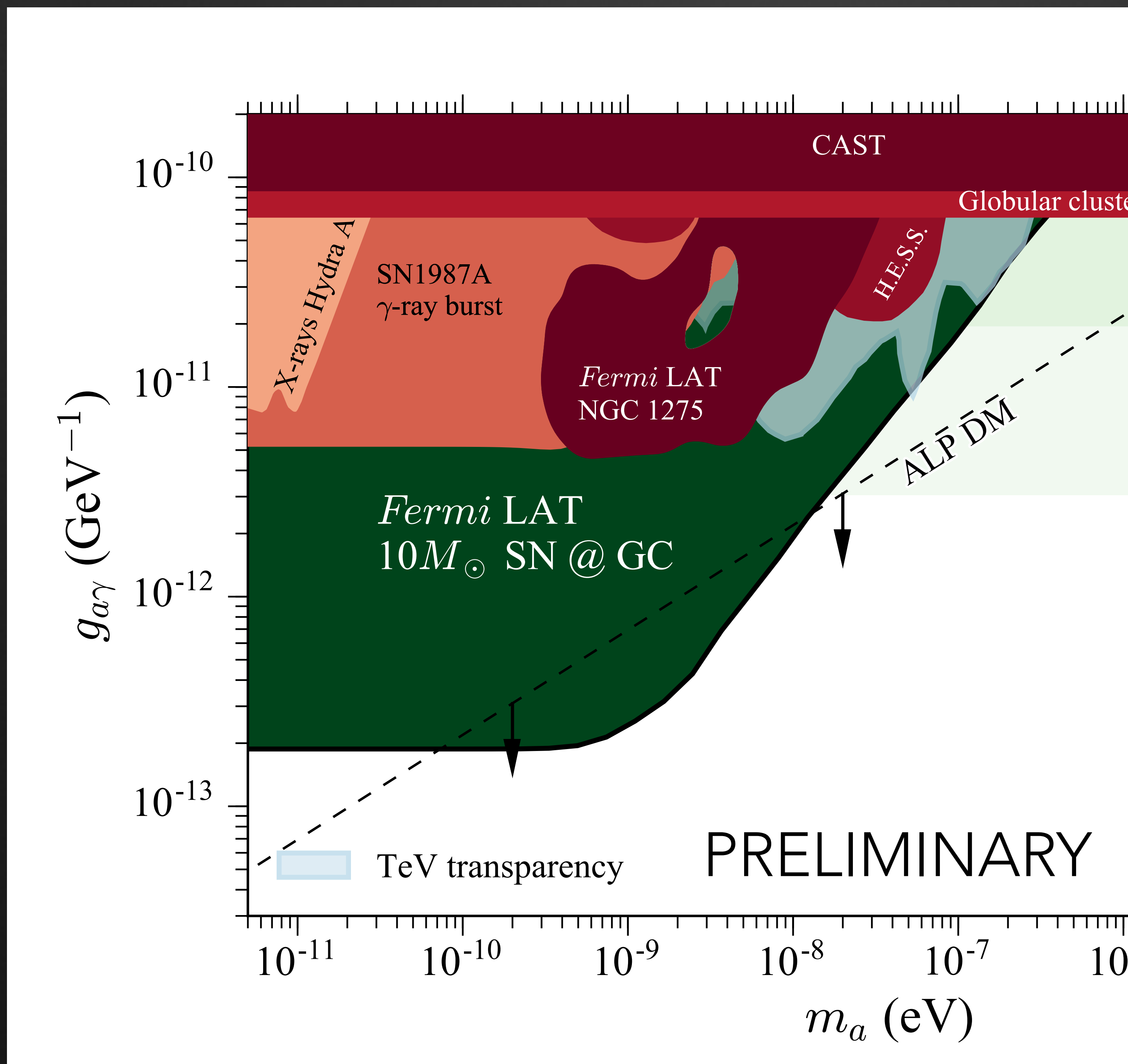


- **Fermi-LAT limits** strongest to date between **0.5 ≲ m_a ≲ 20 neV**
- **Comparable** with sensitivity of future **laboratory experiments** in that mass range
- Strongly constrains possibility that ALPs explain **γ-ray transparency**

CONSTRAINTS & SENSITIVITIES

LIMITS
SENSITIVITIES



- 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; submitted; arXiv:1609:02350]

SUMMARY & CONCLUSIONS

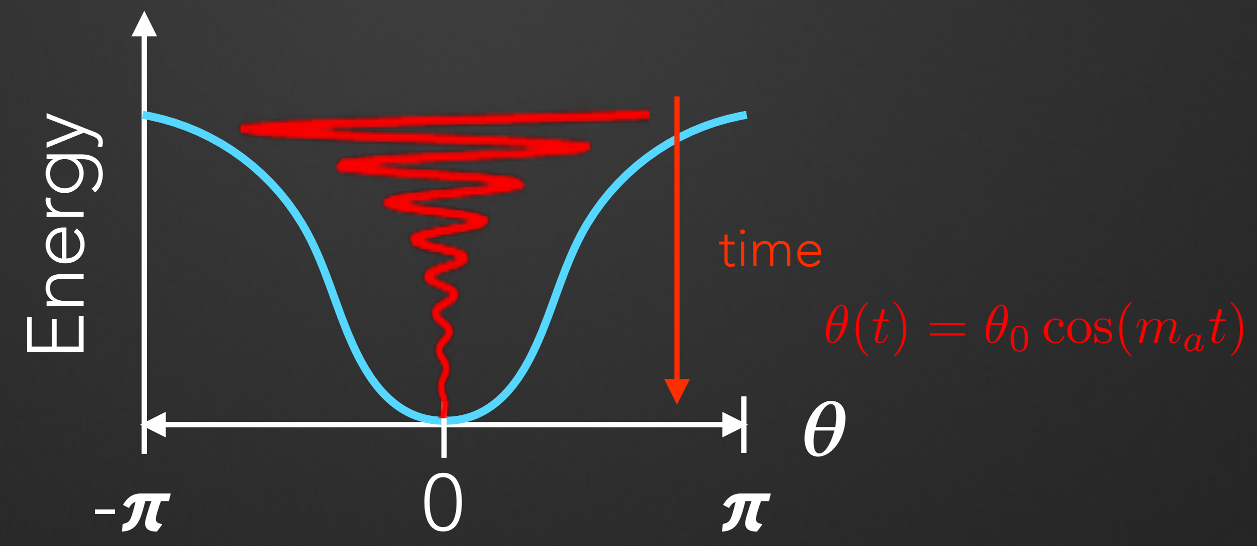
- Axions and ALPs arise in various extensions of the Standard Model
- Well motivated **dark-matter candidates**
- We have **searched for spectral irregularities** induced by **photon-ALP oscillations** in the spectrum of **NGC 1275**
- We **do not find any indications** for ALPs and set the strongest **bounds** to date between **$0.5 \lesssim m_a \lesssim 20$ 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**
- *Fermi*-LAT observation of galactic core collapse SN would yield **strong bounds on ALP parameters, would probe dark-matter parameter space**

BACK-UP SLIDES

AXIONS/ALPs AS DARK MATTER

MISALIGNMENT MECHANISM

$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(t)\theta = 0$$



- **Coherent oscillations = dark matter axions**
- Oscillations should start at latest by matter-radiation equality, so that ALP mass is stable
- Oscillation frequency $\omega = m_a$
- Energy density: $\rho_{a\mathrm{DM}} \sim \frac{1}{2}(75\,\mathrm{MeV})^4\theta_0^2$

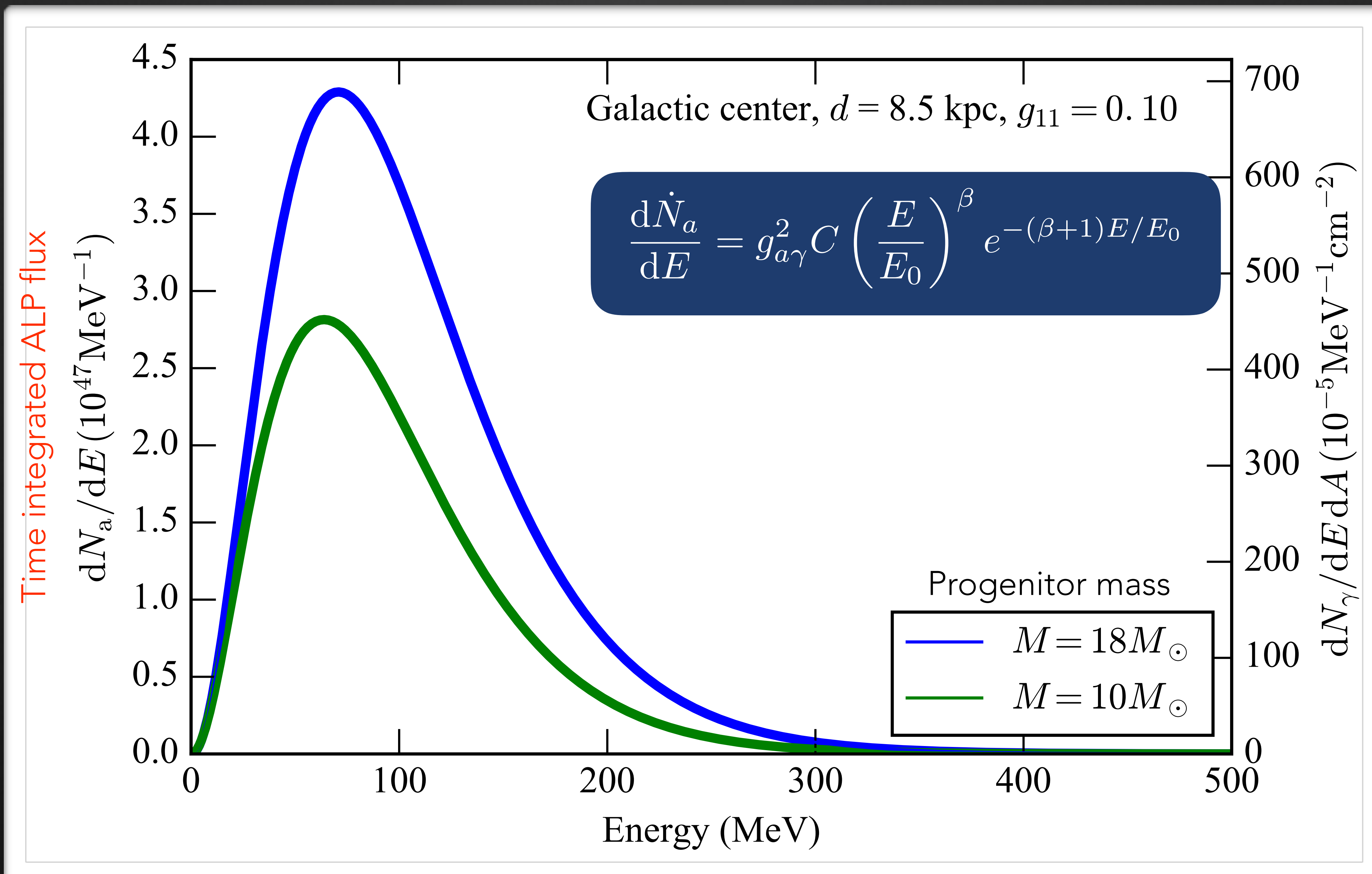
$$\frac{g_{a\gamma}}{\mathrm{GeV}^{-1}} \lesssim 2.2 \times 10^{-12} \frac{\alpha}{2\pi}\theta_1 \mathcal{N} \sqrt{\frac{m_a}{\mathrm{eV}} \frac{\Omega_{\mathrm{DM}}}{\Omega_a}}$$

[e.g. Arias et al. 2012]

[Slide adopted from J.Redondo]

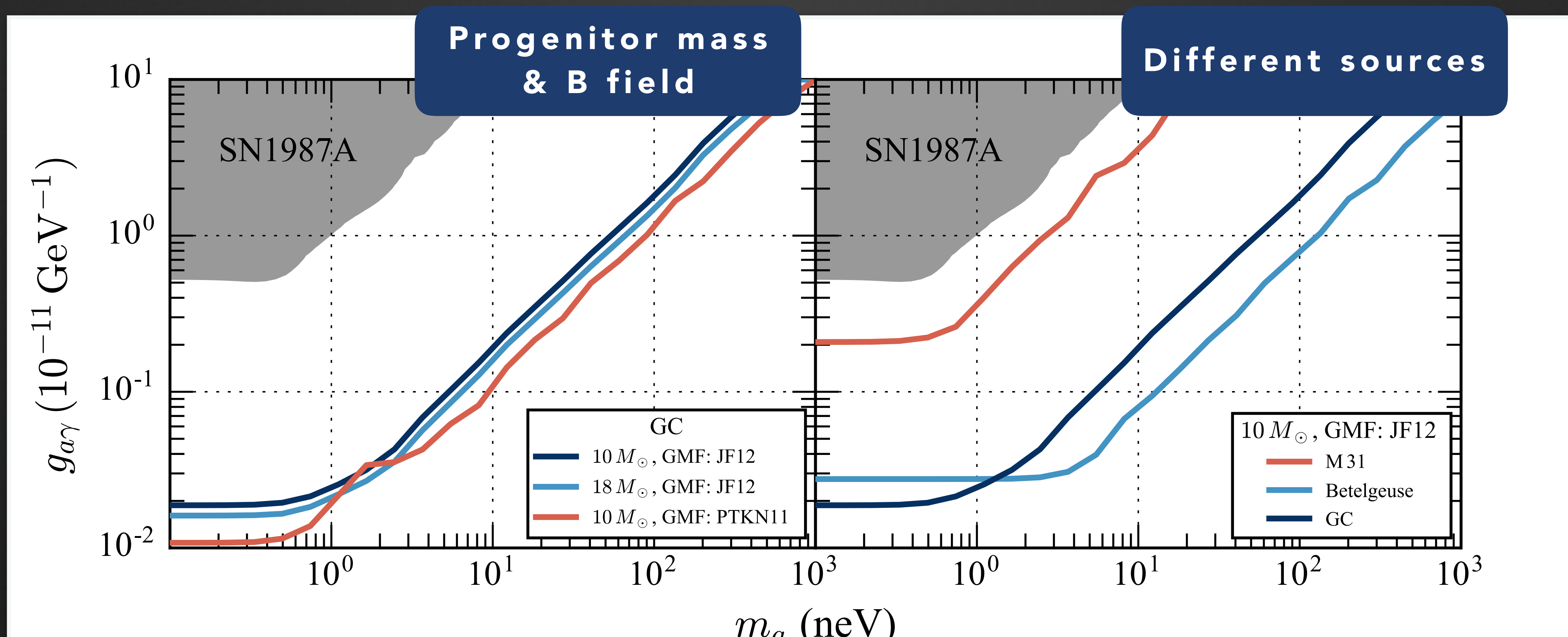
TIME INTEGRATED EXPECTED ALP / γ-RAY FLUX

- Integrated over SN explosion time (20s for 18 solar masses, 10s for 10 solar mass progenitor)



[Collaboration with Giannotti & Mirizzi, see also Payez et al. 2015]

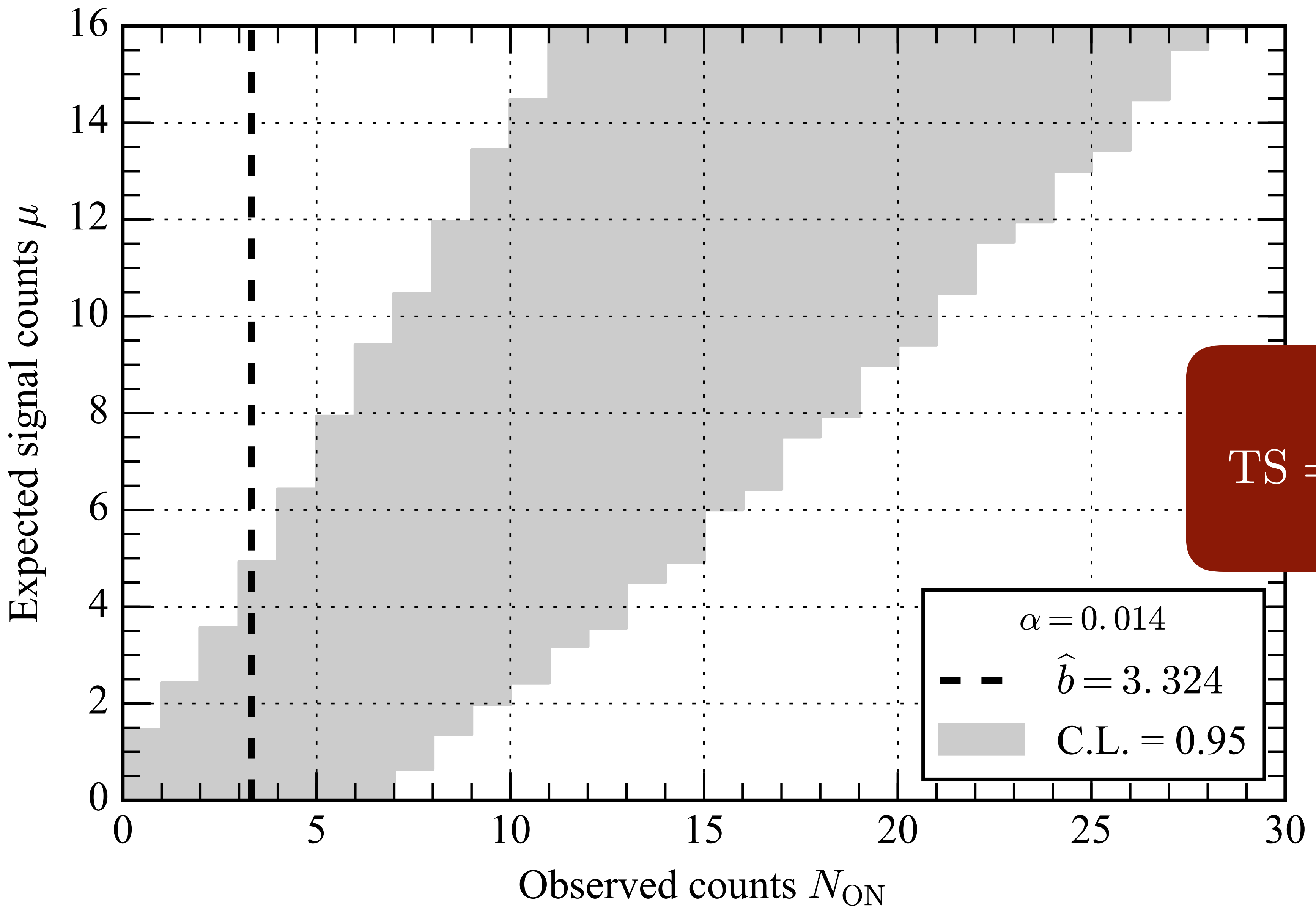
SYSTEMATIC CHECKS



- ✓ Different progenitor masses
- ✓ **Different Galactic magnetic field models (largest effect)**
- ✓ Different sources (less background compared to GC)
- ✓ Different time intervals
- ✓ Analysis repeated with different time binning of 30 and 60s

	GC	Betelgeuse	M 31
R.A. (°)	266.42	88.79	10.63
Dec. (°)	−28.99	7.41	41.30
Distance (kpc)	8.5	0.197	778
t_0 (MJD)	57, 231.582	57, 231.284	57, 231.144
Δt (s)	1581	1519	1079
$\langle r_{68} \rangle$(°)	10.92	9.73	10.37
$\hat{b}$	3.32	1.11	0.94
α	0.014	0.014	0.030
μ_{UL}	6.43	5.61	4.19

CONSTRUCTING F&C CONFIDENCE INTERVAL



1. **Step through expected counts μ**
2. For each value **μ**: calculate **log likelihood ratio** (LLR) for a range of observed counts N_{ON}
3. Sum up **poisson likelihoods** for N_{ON} **sorted by LLR** until you reach desired confidence level

LOG LIKELIHOOD RATIO

$$\mathrm{TS} = -2\ln\left(\frac{\mathcal{L}(\mu, \hat{b}(\mu); \alpha | N_{\mathrm{ON}}, n)}{\mathcal{L}(\hat{\mu}, \hat{b}; \alpha | N_{\mathrm{ON}}, n)}\right)$$

Off counts: $n = \sum_i n_i$

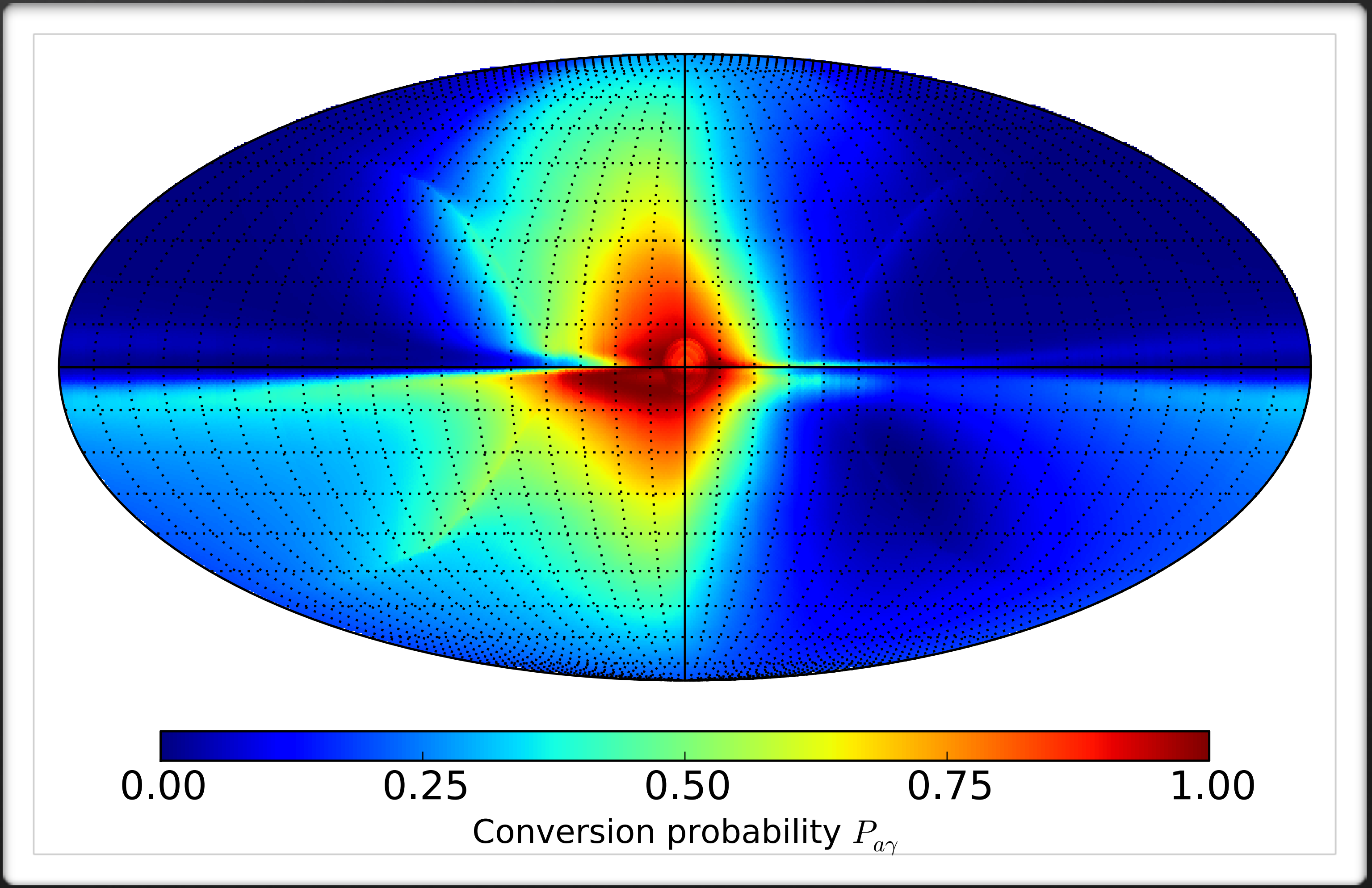
Exposure ratios $\alpha = \left(\sum_i \epsilon_i\right)^{-1}$

Maximum likelihood estimators $\hat{b} = \alpha n$, $\hat{\mu} = N_{\mathrm{ON}} - \alpha n$

[Feldman & Cousins 1998; Rolke et al. 2005]

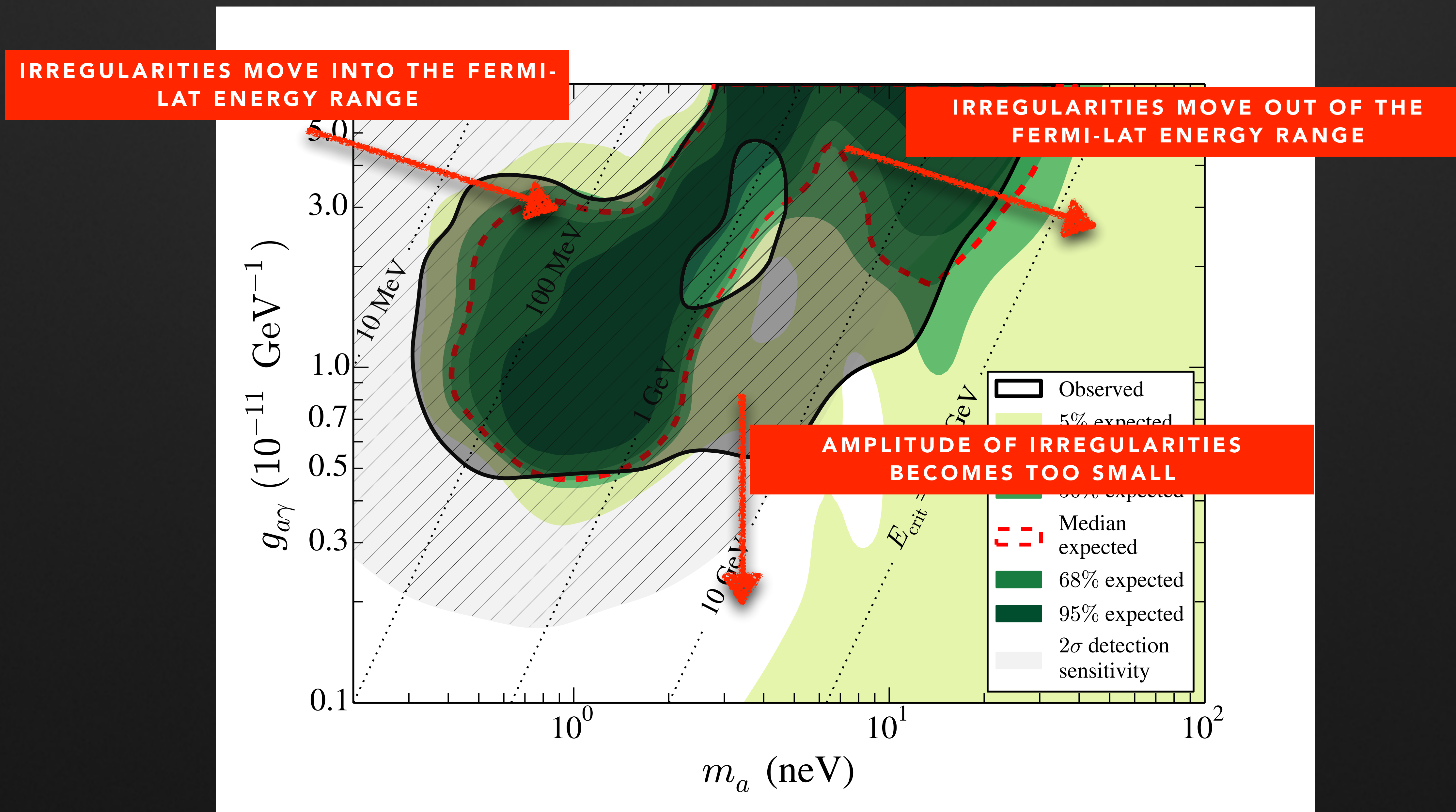
PHOTON-ALP CONVERSION IN GALACTIC MAGNETIC FIELD

- Mixing in **coherent component of B field**
- **Position of SN** will determine ɣ-ray yield
- Two state-of-the-art models implemented



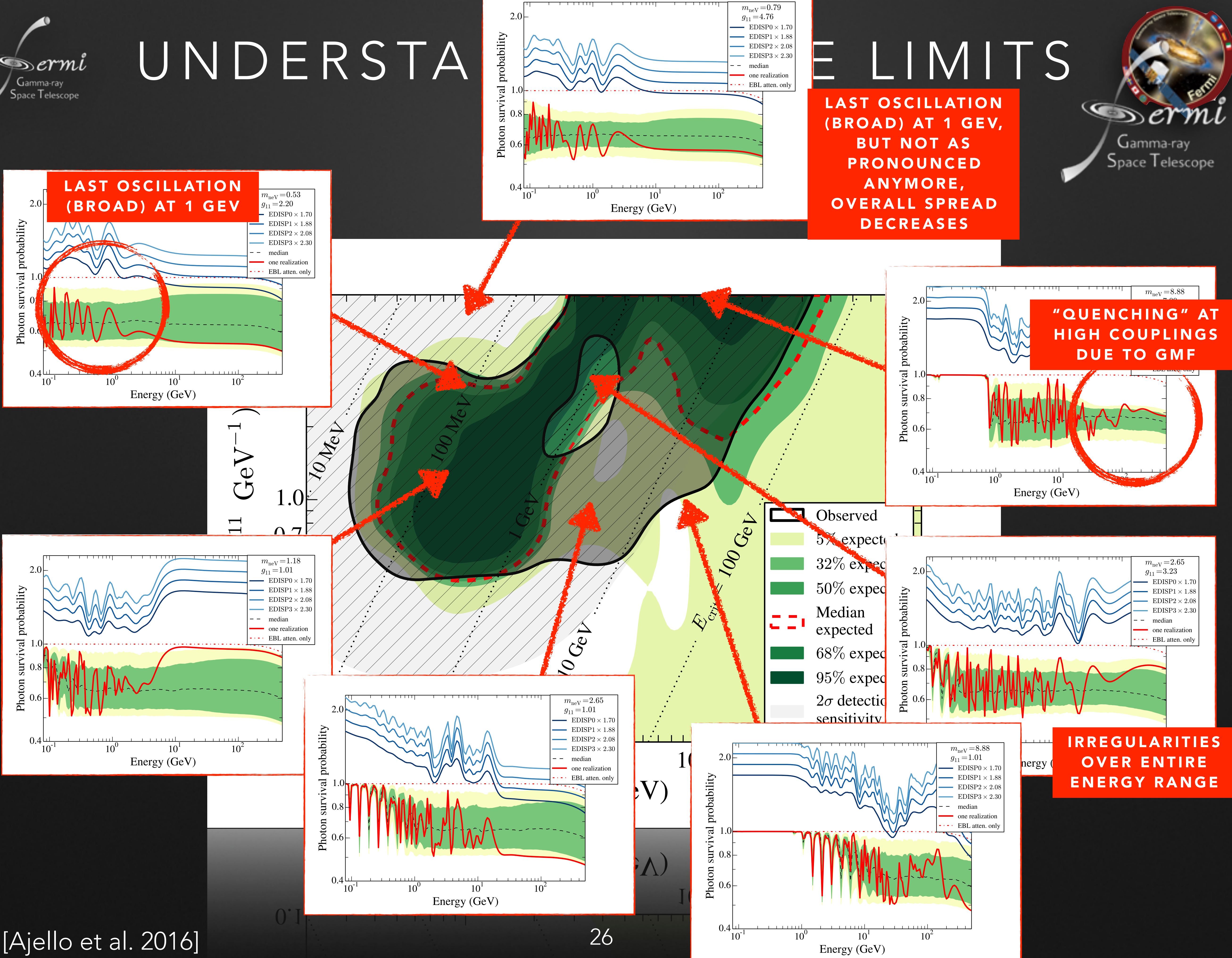
$g_{a\gamma}$ = 5 x 10^{-11} GeV^{-1}
pure ALP beam
propagating through entire Milky Way
[Jansson & Farrar 2012 model]

UNDERSTANDING THE LIMITS



[Ajello et al. 2016]

UNDERSTA E LIMITS



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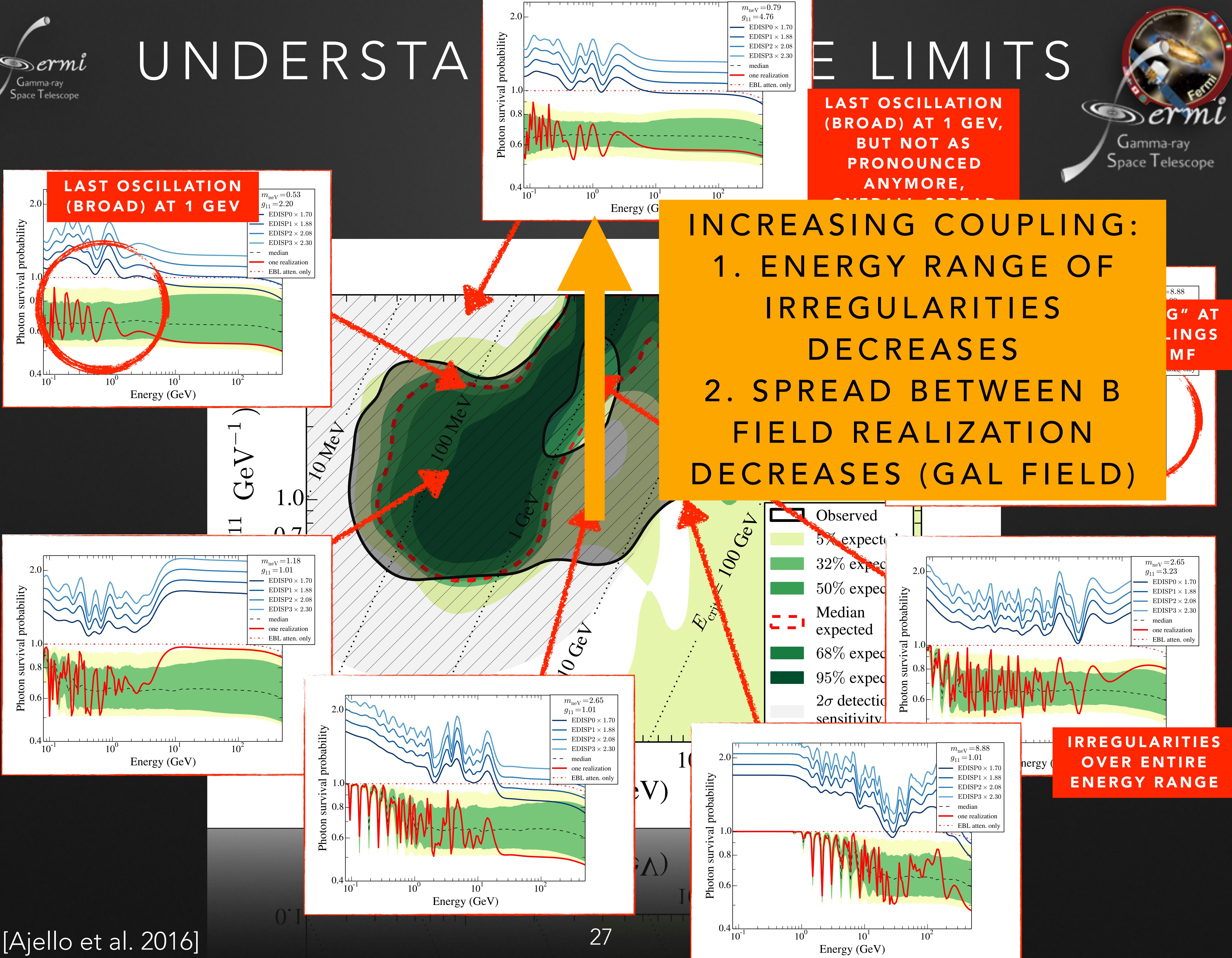
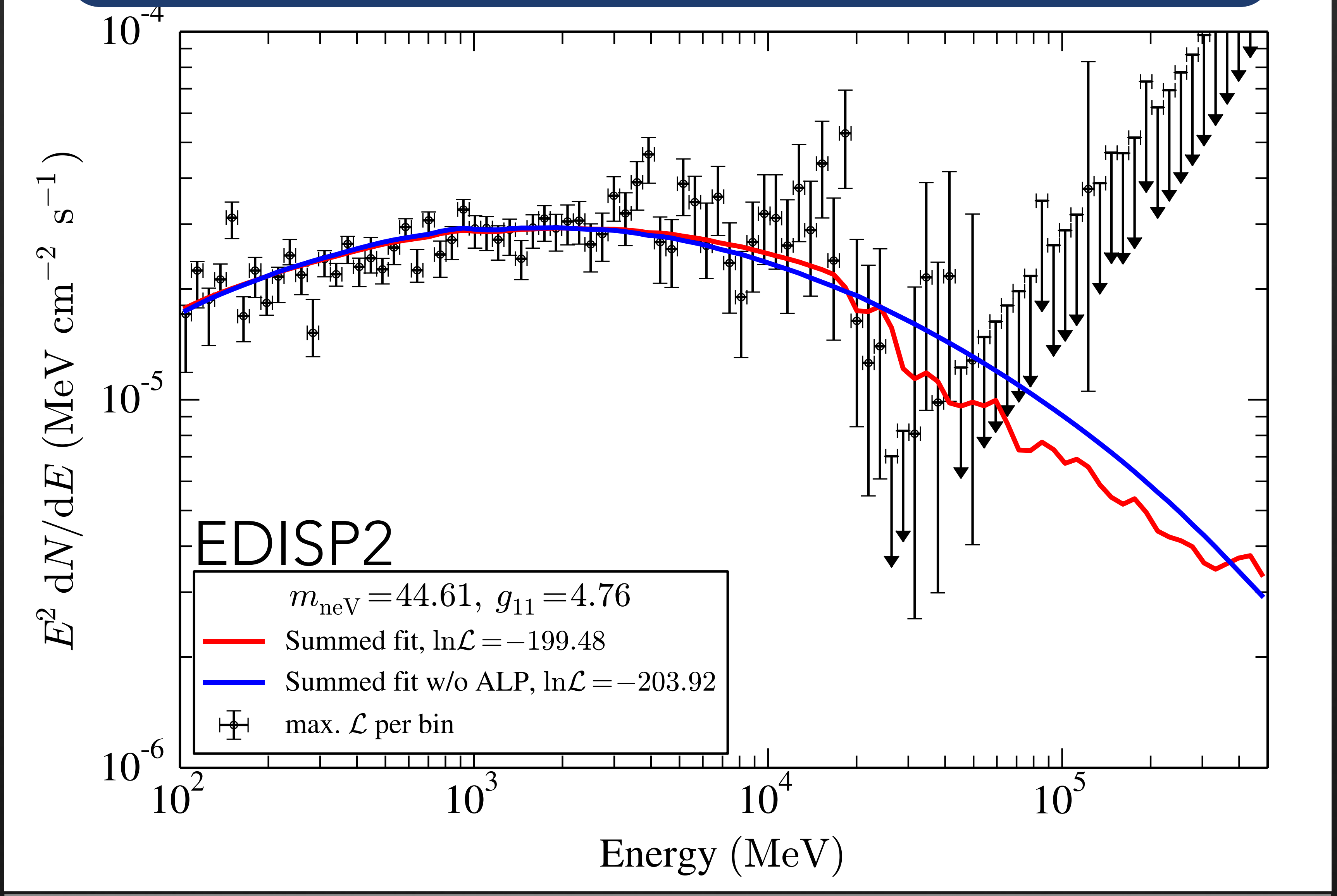
UNDERSTA… E LIMITS



[Ajello et al. 2016]

COMPARING EXCLUDED ALP PARAMETERS WITH BEST FIT

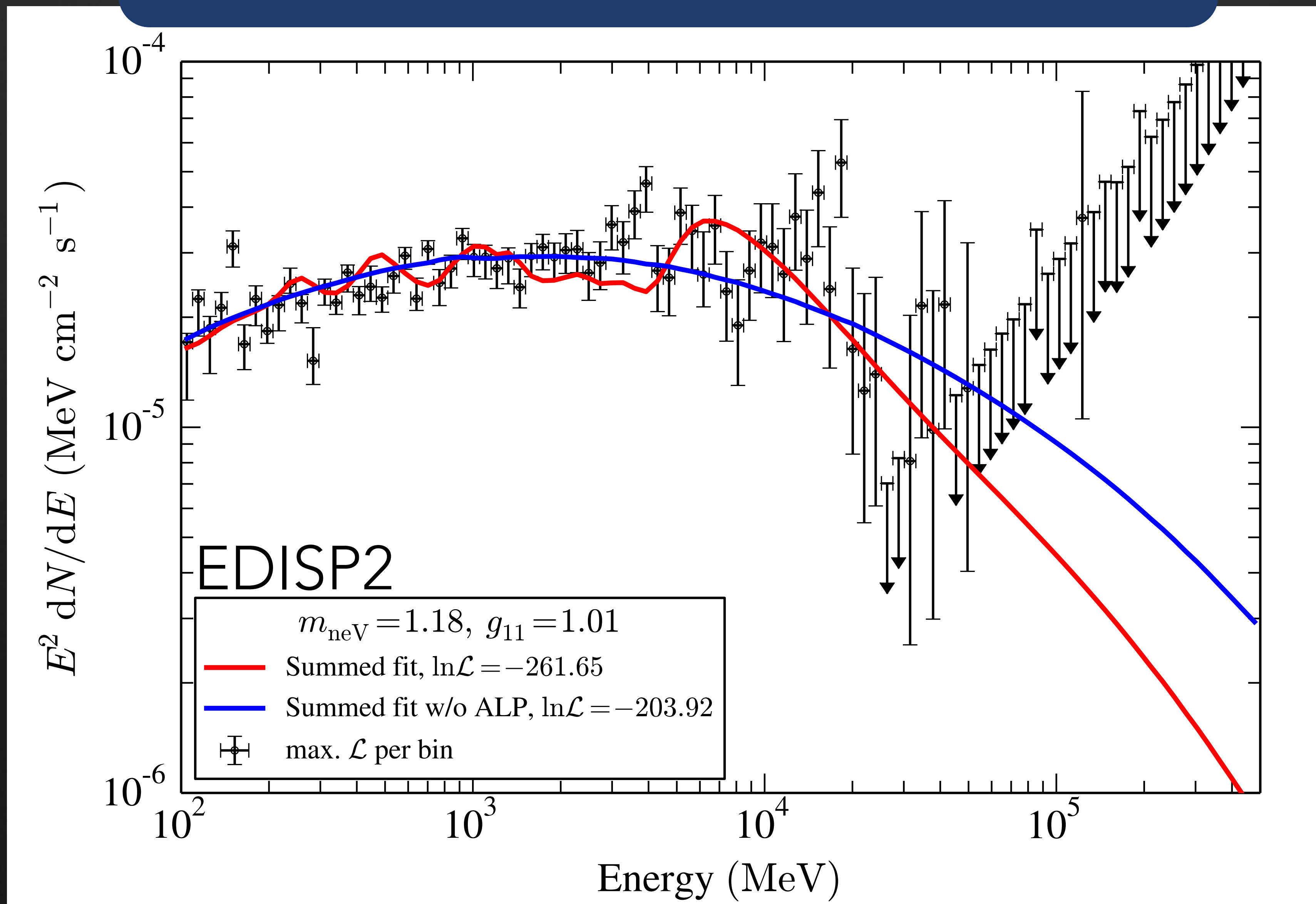
BEST FIT — NOT PREFERRED



[Ajello et al. 2016]

COMPARING EXCLUDED ALP PARAMETERS WITH BEST FIT

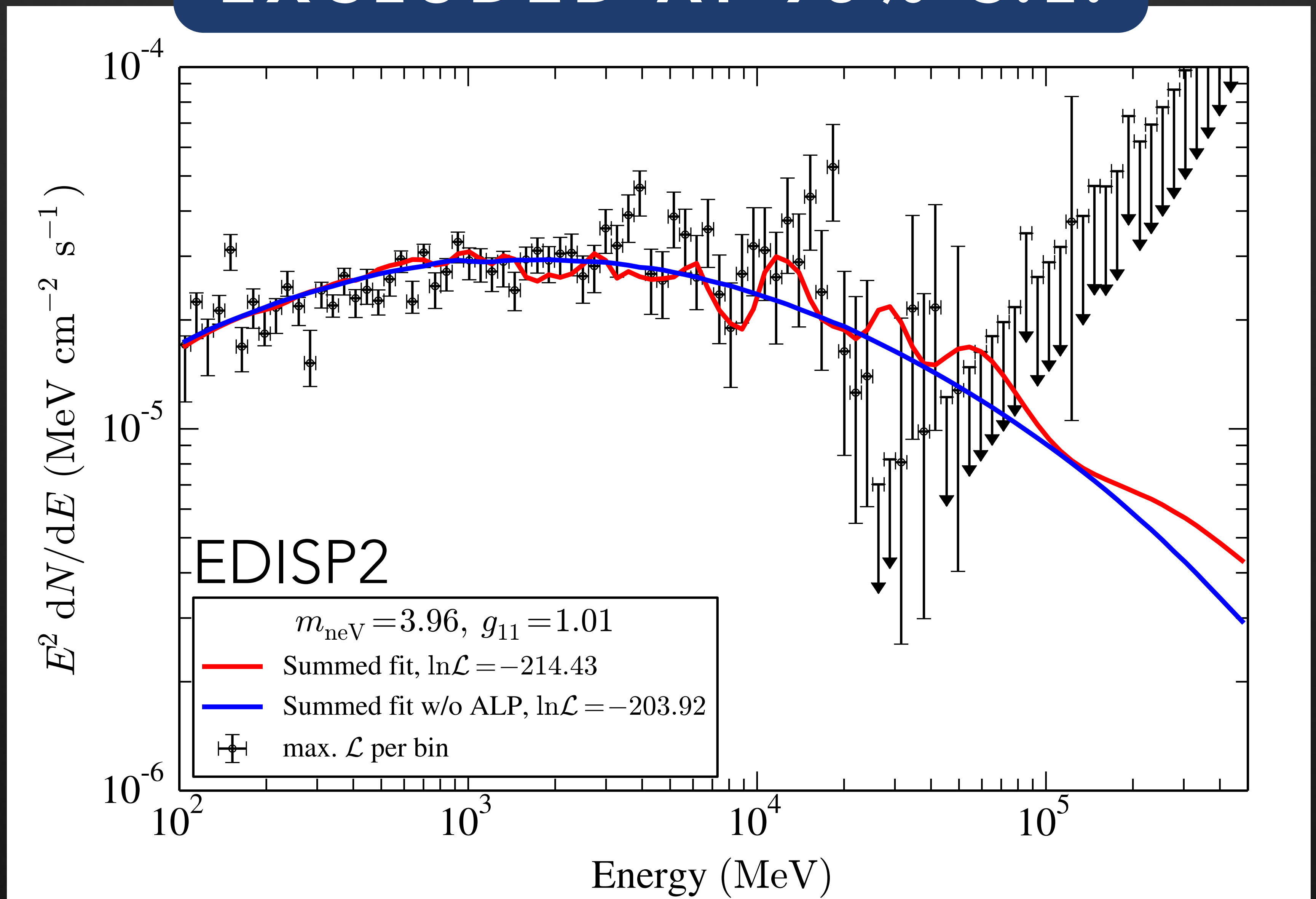
EXCLUDED AT > 95% C.L.



[Ajello et al. 2016]

COMPARING EXCLUDED ALP PARAMETERS WITH BEST FIT

EXCLUDED AT 95% C.L.

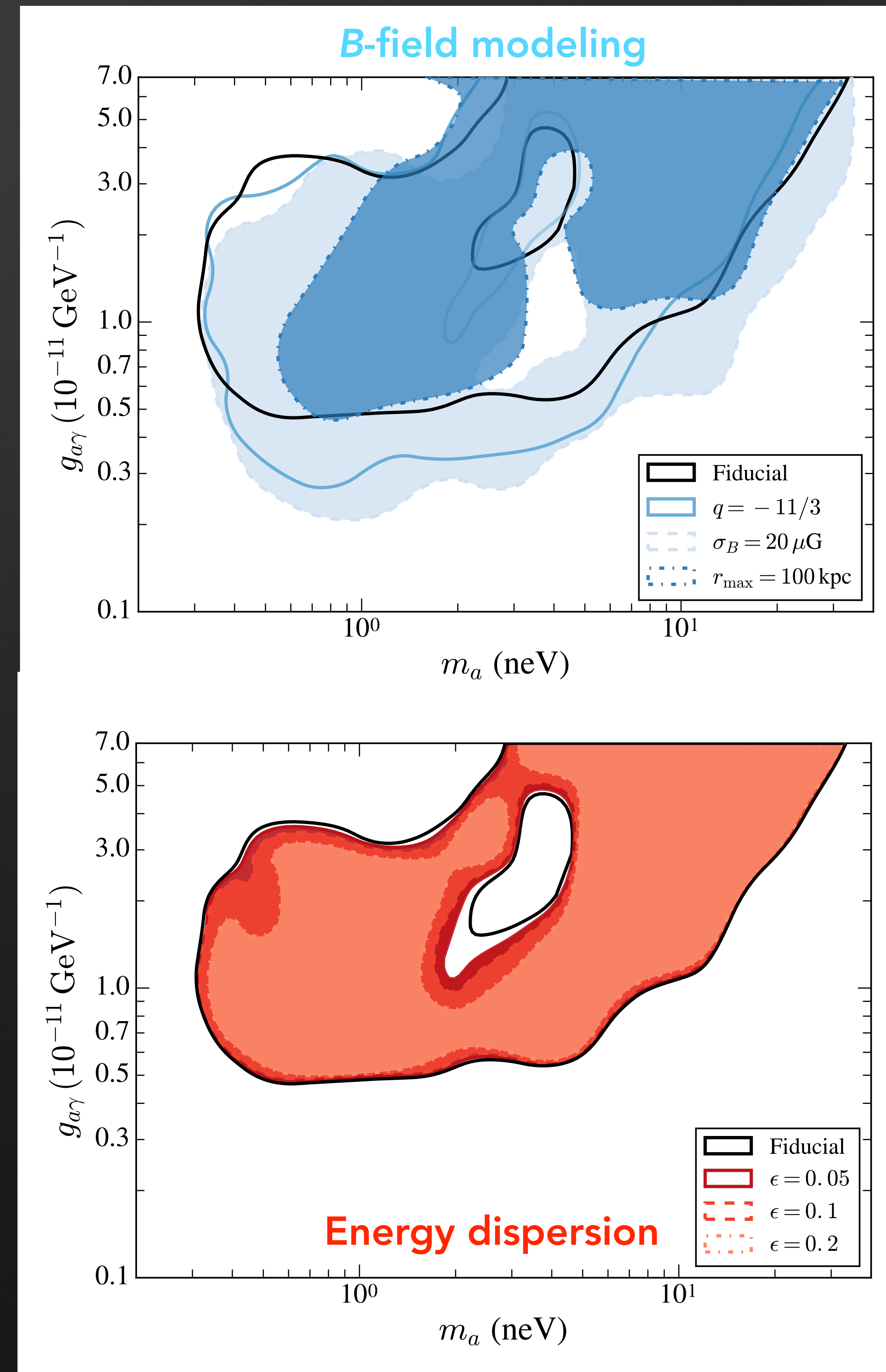


[Ajello et al. 2016]

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

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

[Ajello et al. 2016]

NULL DISTRIBUTION FROM MC

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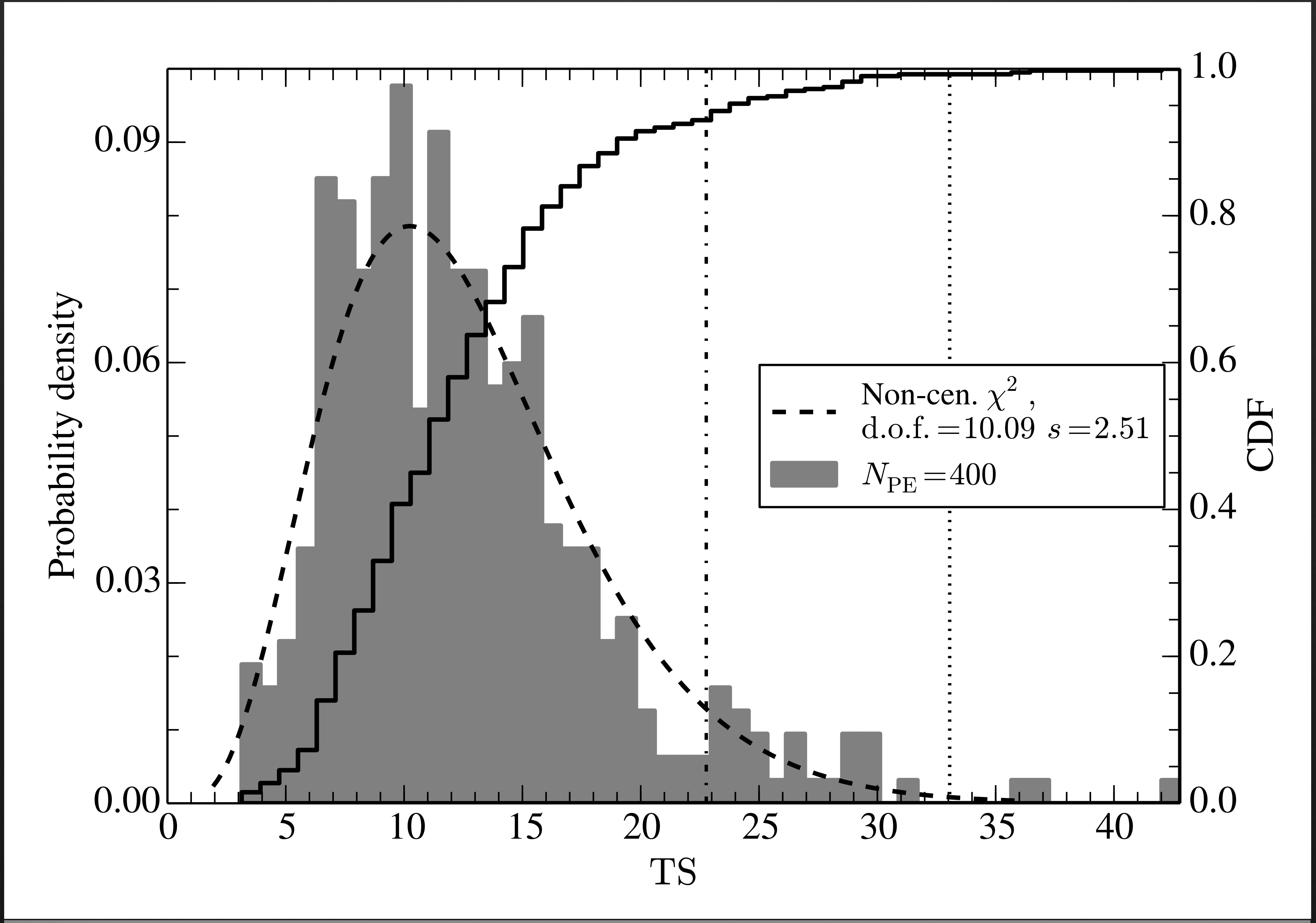

[Ajello et al. 2016]

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

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)

$$\mathbf{TS_{thr}\ (3\sigma) = 33.1}$$

[Ajello et al. 2016]