New hints for ALPs from GRB 221009A and prospects for COSI

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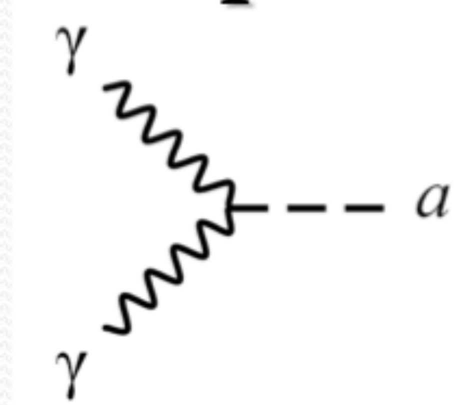
Axion-like particles (ALPs)

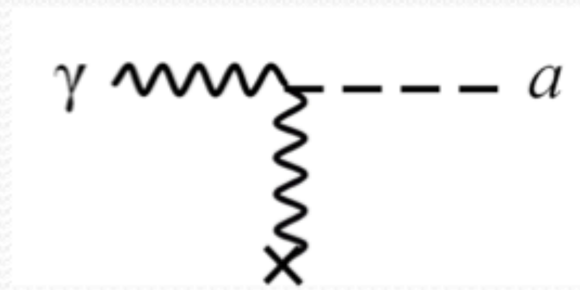
- Predicted by String Theory
- Very light particles *a* ($m_a < 10^{-8}$ eV)
- Spin 0
- **Interaction with** two **photons** (coupling $g_{a\gamma\gamma}$)
- Interactions with other particles discarded
- Possible candidate for dark matter
- Induce the **change of the polarization state** of photons

Two photons

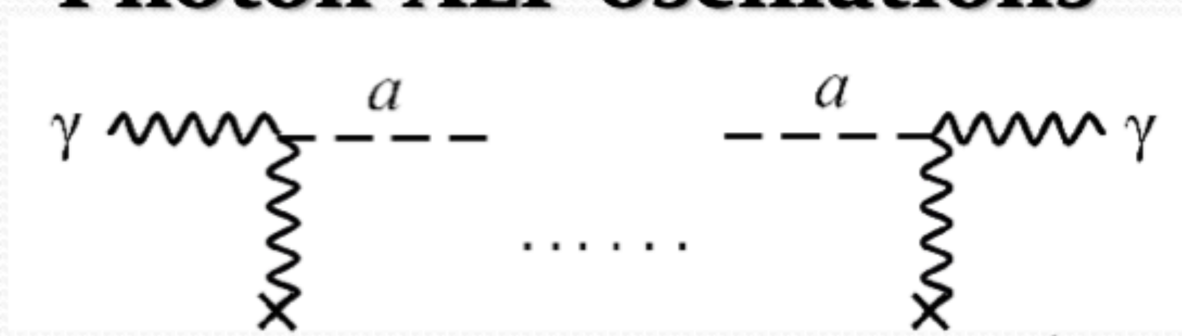


$$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$$

In an external B field

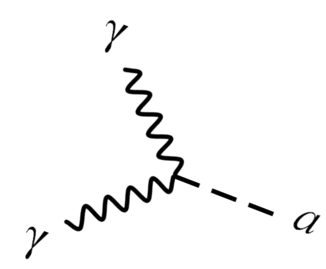


Photon-ALP oscillations



ALPs: phenomenology

The ALP Lagrangian:



mass — $\equiv g_{a\gamma\gamma}$

$$\mathcal{L}^0_{\mathrm{ALP}} = \frac{1}{2}\,\partial^\mu a\,\partial_\mu a - \frac{1}{2}\,m^2 a^2 + \frac{1}{M}\mathbf{E}\cdot\mathbf{B}\,a\;,$$

coupling term

$g_{a\gamma\gamma} < 0.88\text{x}10^{-10}\ \mathrm{GeV}^{-1}$
(CAST)

$g_{a\gamma\gamma} < 5.4\text{x}10^{-12}\ \mathrm{GeV}^{-1}$
UL on polarization of WD
Dessert et al. 2022

Only the "transverse" B-field relevant for conversion

Only 1/2 of unpolarized photons couple to ALPs

ALPs: phenomenology

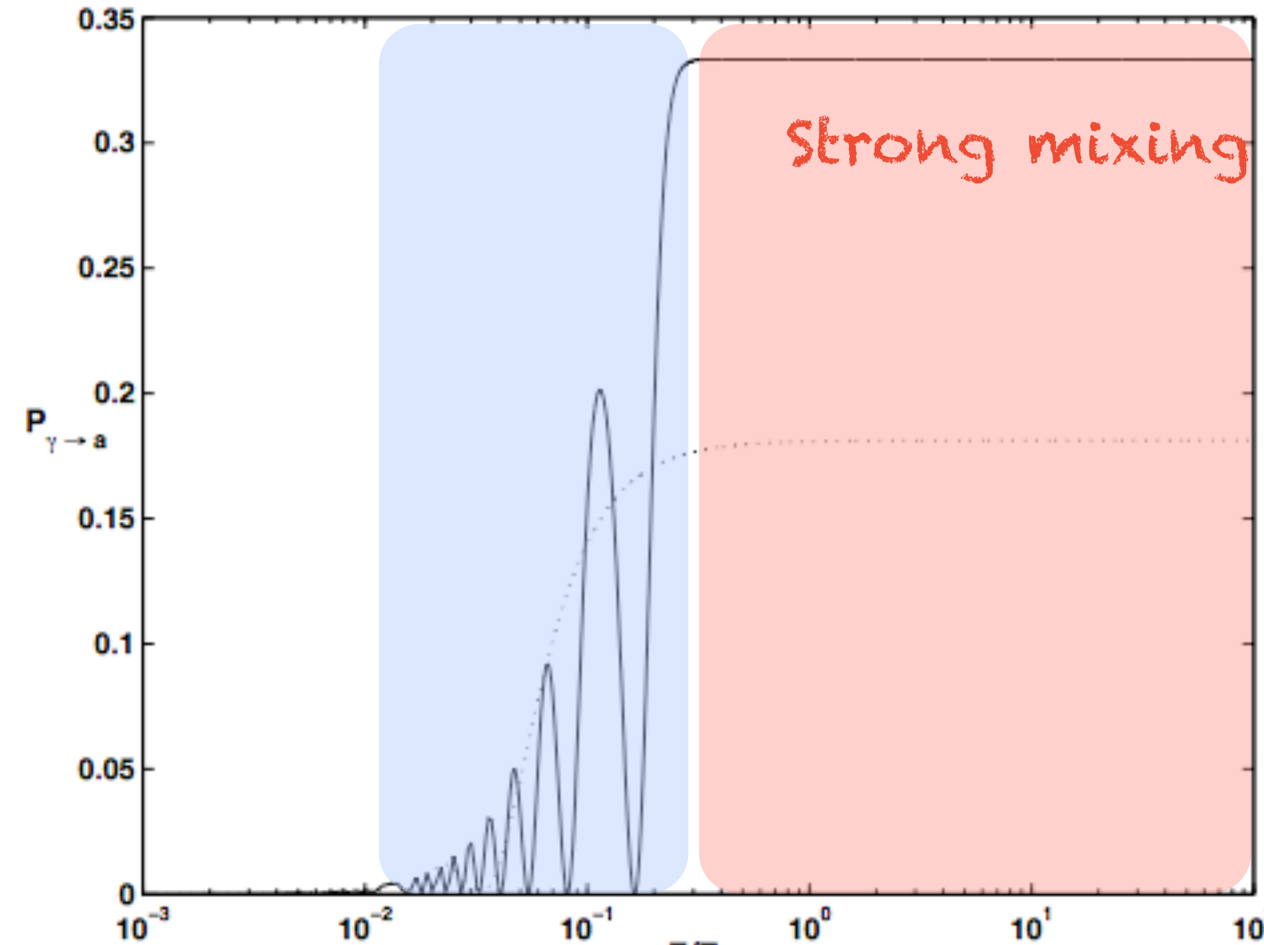
Photon-ALP conversion in a uniform B-field

$$P_{\gamma\to a}(E) = \left(\frac{g_{a\gamma\gamma} B_T}{\Delta_{\rm osc}(E)}\right)^2 \sin^2\left(\frac{\Delta_{\rm osc}(E)\, y}{2}\right)$$

$$\Delta_{\rm osc}(E) \equiv \left[\left(\frac{m^2-\omega_{\rm pl}^2}{2E}\right)^2 + g_{a\gamma\gamma}^2 B_T^2\right]^{1/2}$$

Strong mixing regime:
P maximal and E-independent

Unpolarized beam



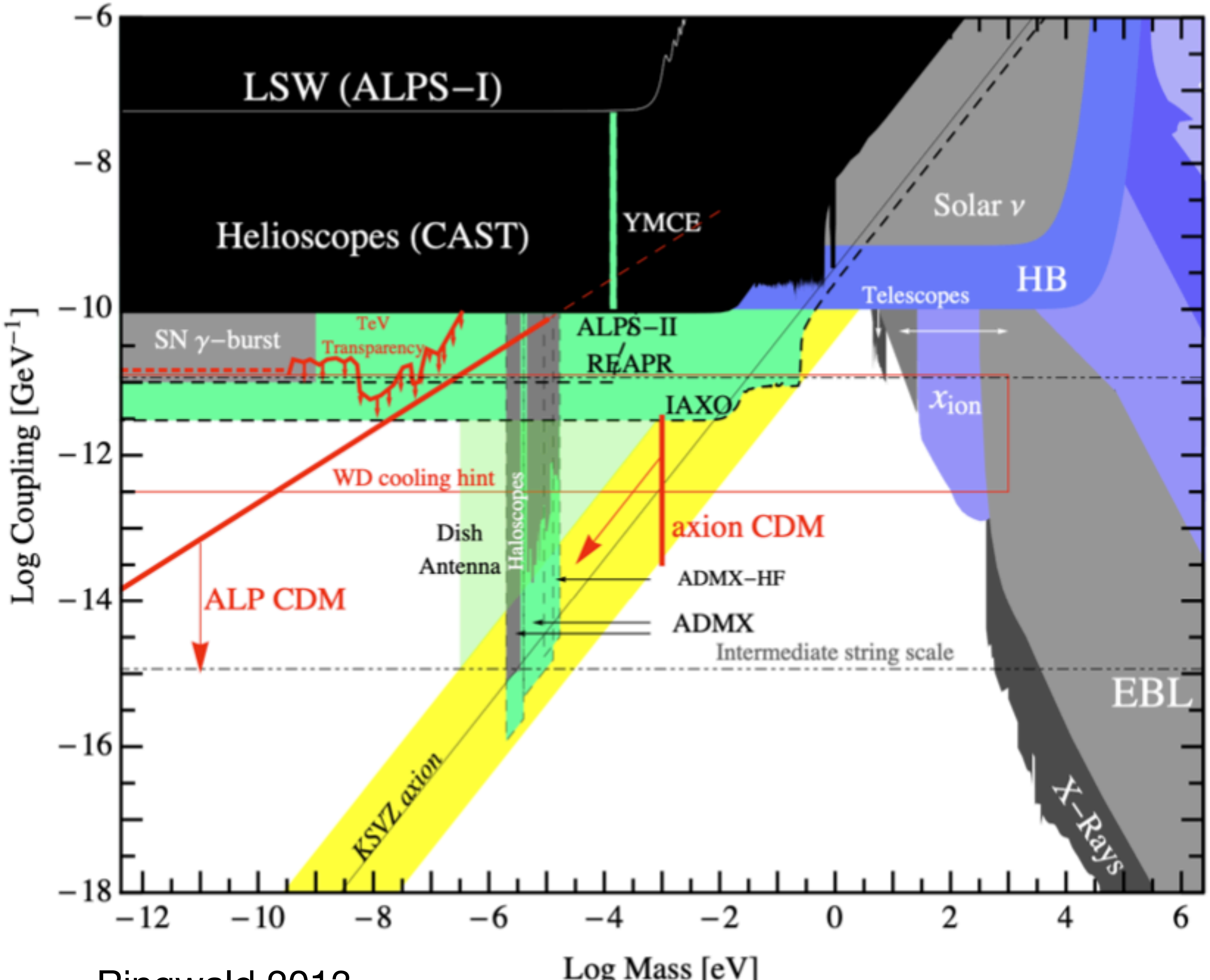
Transition

De Angelis, Mansutti, Roncadelli 2007

$$E_L \simeq 25 \left|\left(\frac{m}{10^{-10}\,{\rm eV}}\right)^2 - 0.13\left(\frac{n_e}{{\rm cm}^{-3}}\right)\right| \left(\frac{G}{B_T}\right)\left(\frac{M}{10^{11}\,{\rm GeV}}\right){\rm eV}$$

ALPs as cold DM

ALPs as cold DM



Ringwald 2013

Because of the low mass, a potential ALPs component suitable to play the role of cold DM cannot be produced by thermal processes but by other mechanisms, in particular the so-called vacuum-realignment mechanism, through which they are produced as a coherent state of many, extremely non-relativistic particles in the form of a classical, spatially coherent oscillating field.

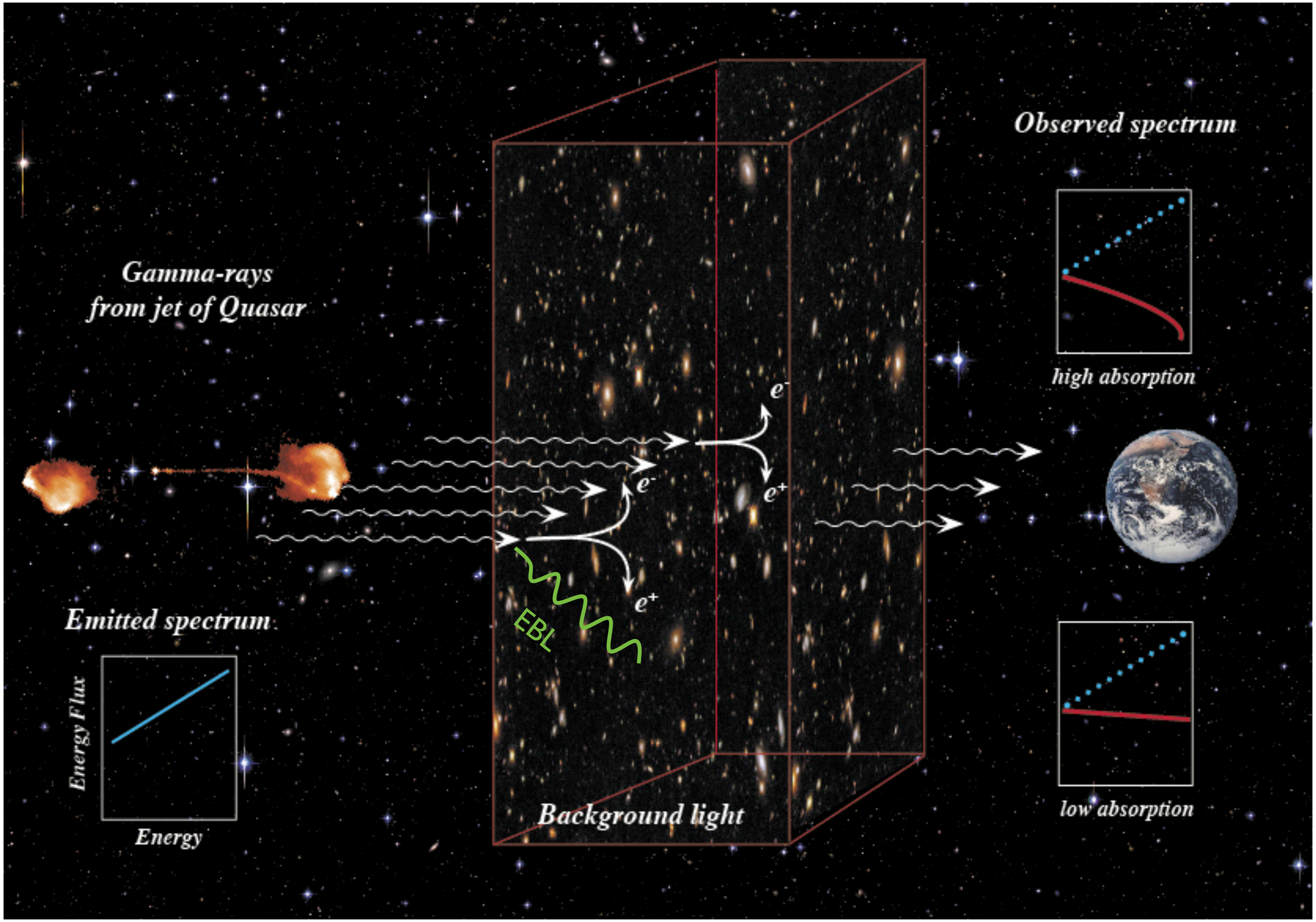
For suitable values of unconstrained and free parameters of ALPs (see Arias et al. 2012), the DM region fully includes the area where the effects that we intend to study are relevant.

ALPs in VHE astrophysics

- ALPs very **elusive** in laboratory experiments (low coupling) → **astrophysical environment** is the **best opportunity** to study ALPs and ALP effects (*for free*)
- Photon/ALP beam in the VHE band $E >> m_a$
- For E < 10 GeV → negligible photon absorption due to EBL
  - **Photon-ALP interaction** produces effective **photon absorption**
- For E > 10 GeV → photons absorbed by EBL ($\gamma\gamma \rightarrow e^+e^-$), **ALPs** are **not absorbed**
  - **Photon-ALP oscillations increase medium transparency**

See Galanti & Roncadelli 2022

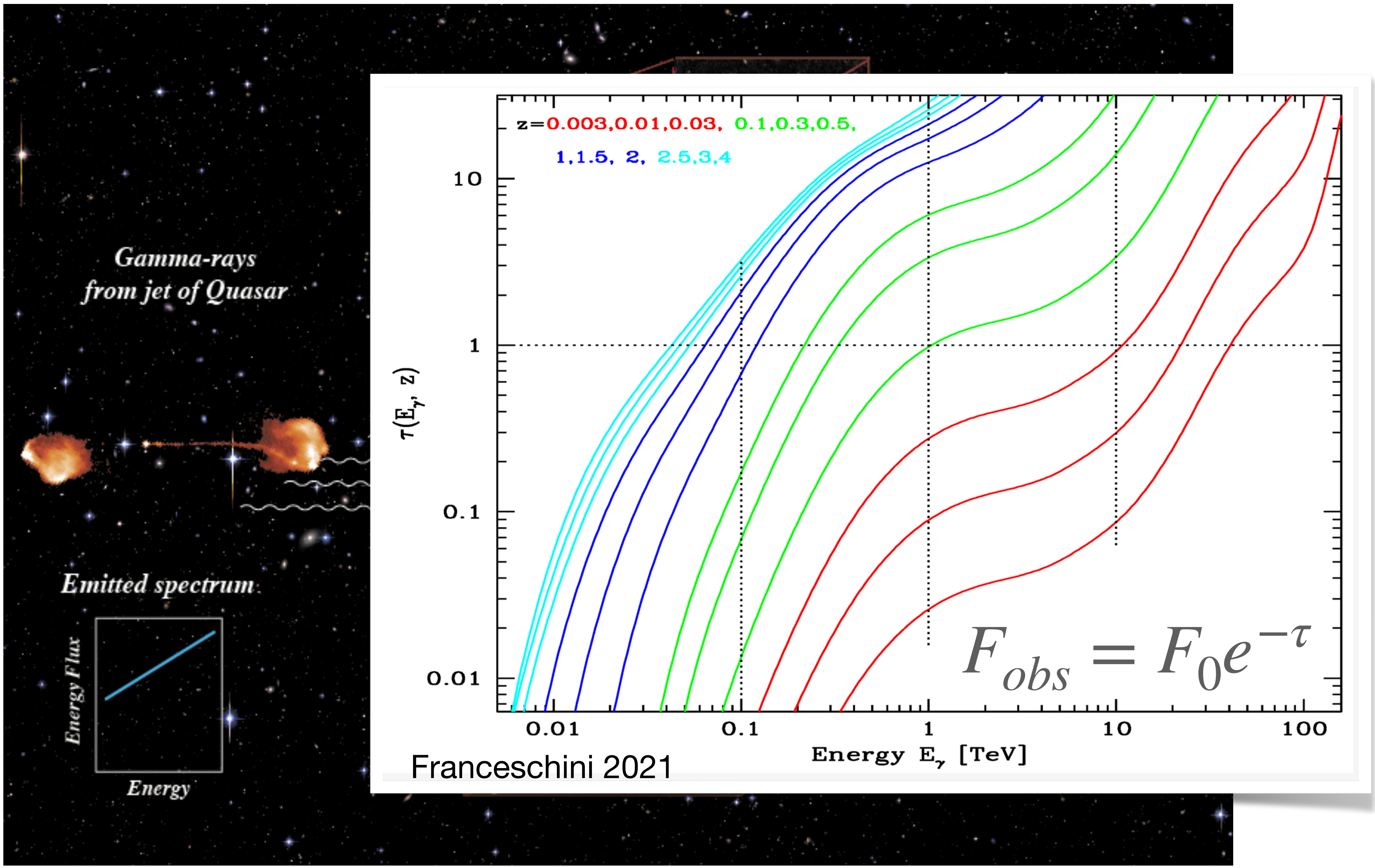
Propagation effects: EBL



The extragalactic background light consists of all photons emitted by stars (and reprocessed by dust) during the Universe history

e.g. Dwek & Krennrich 2013

Propagation effects: EBL



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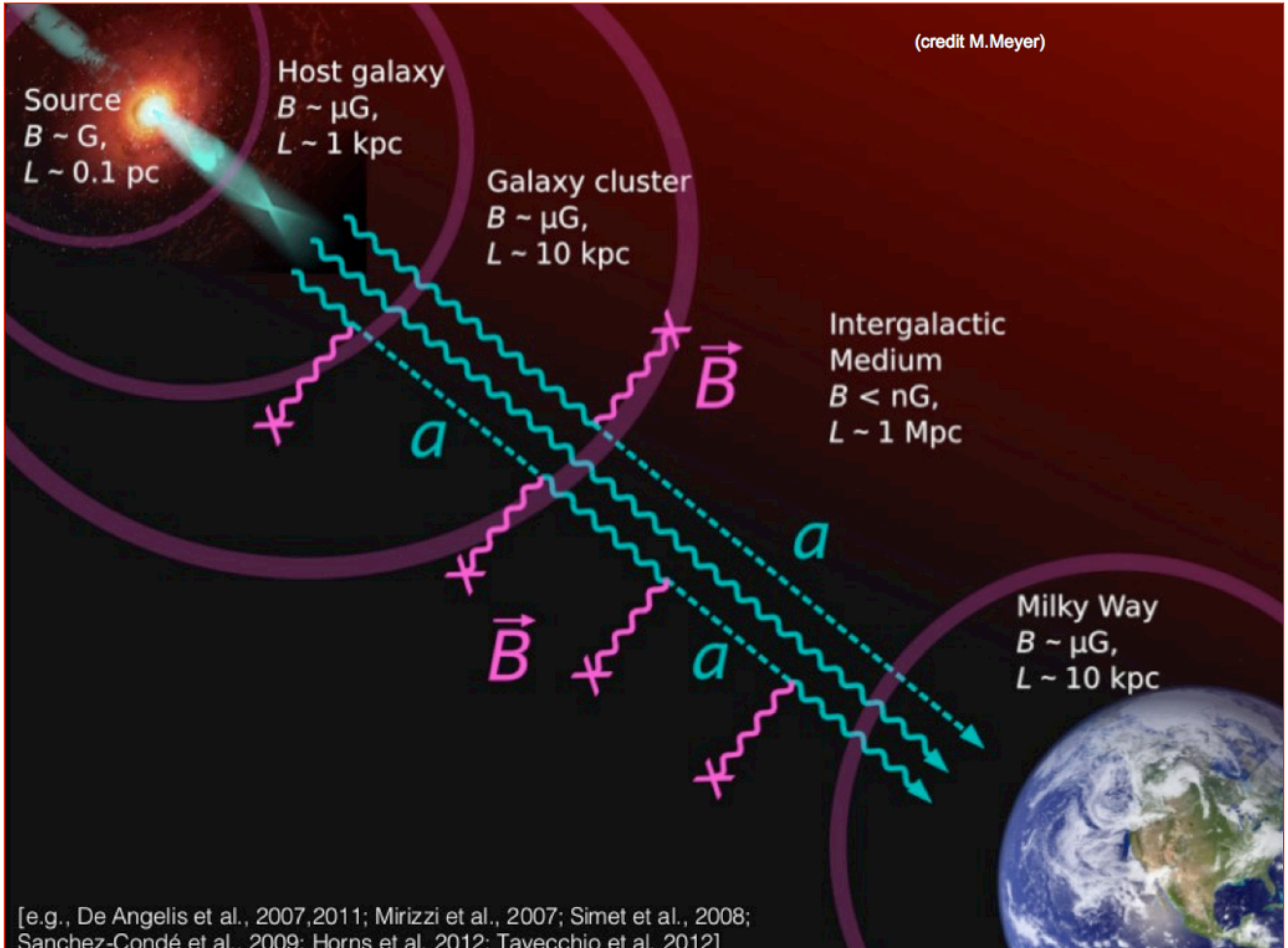
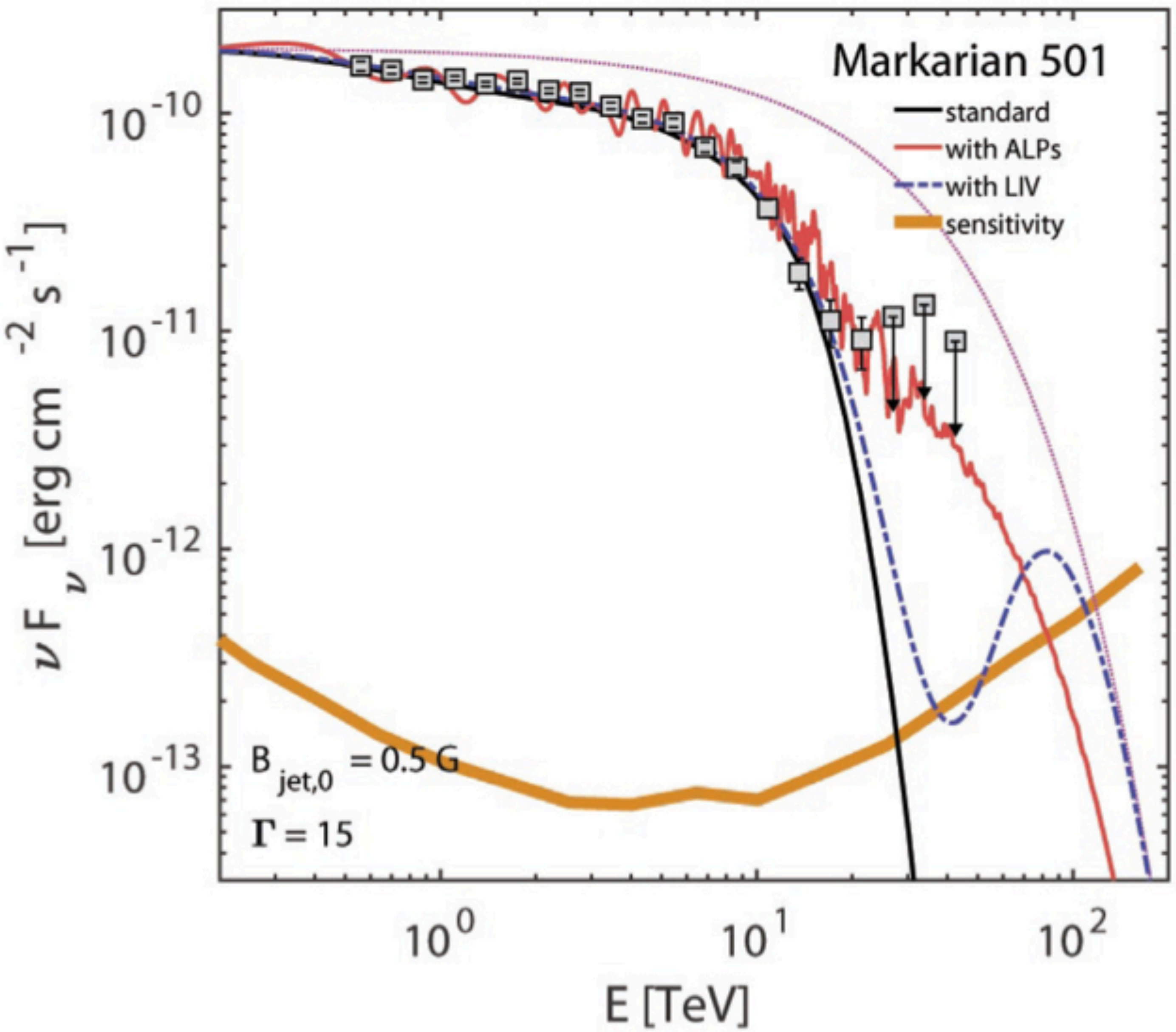
Propagation effects: EBL & ALPs



Proper modeling of B fields is crucial

Propagation effects: EBL

Galanti et al. 2020



Searches for spectral anomalies of blazars is one of the key observational challenges of the Cherenkov Telescope Array

CTA consortium 2021

Polarization effects

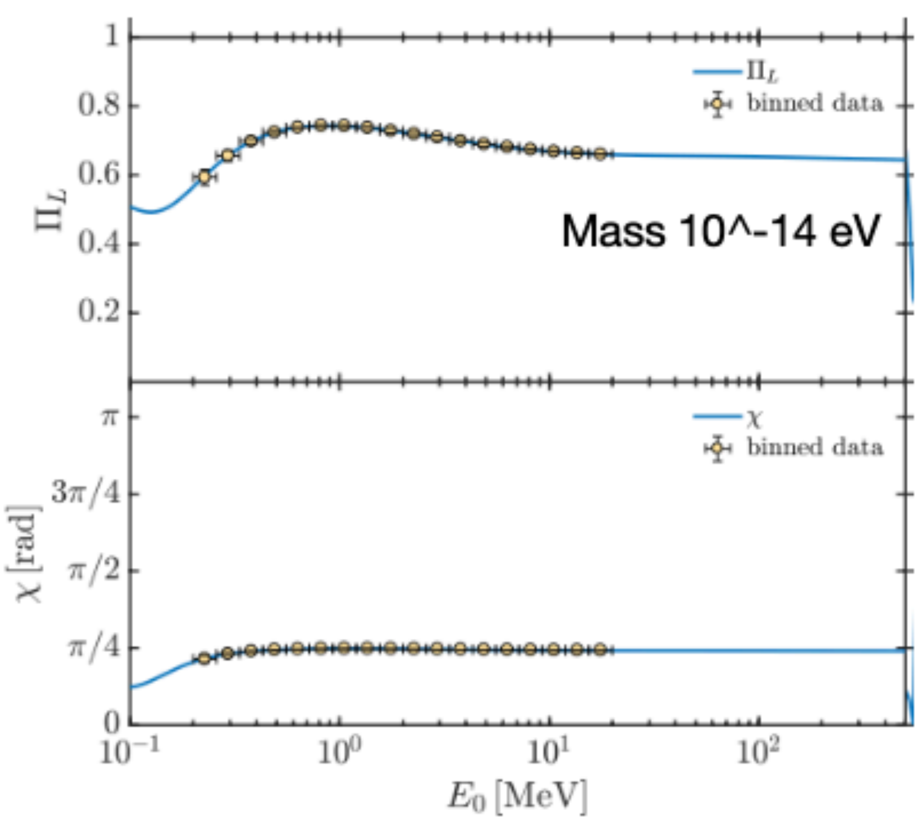
e.g. Raffelt & Stodolsky 1988

Blazars as a case study

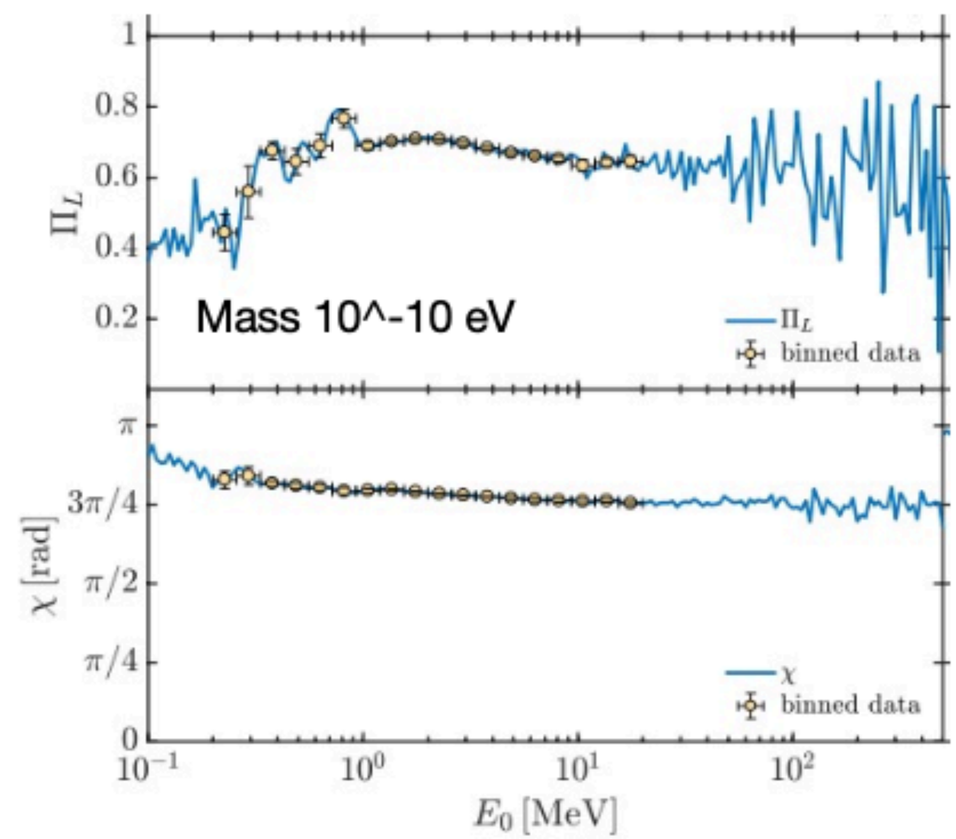
Galanti, Roncadelli & Tavecchio 2023

$g_{a\gamma\gamma} = 5 \times 10^{-12}\,\mathrm{GeV}^{-1}$

Polarization as a function of energy



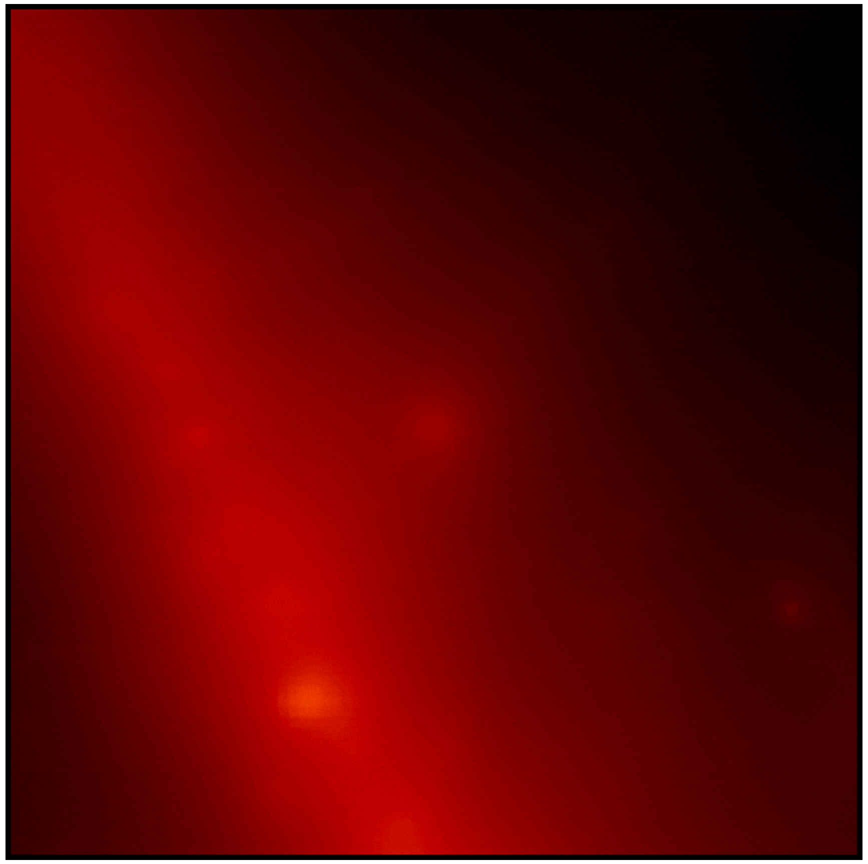
Blazar OJ 287



Initial polarization 20% Large >60% polarization observed (leptonic model). Hadronic model predicts even higher, (difficult to explain by astrophysics)

Only slightly dependent on mass

GRB 221009A

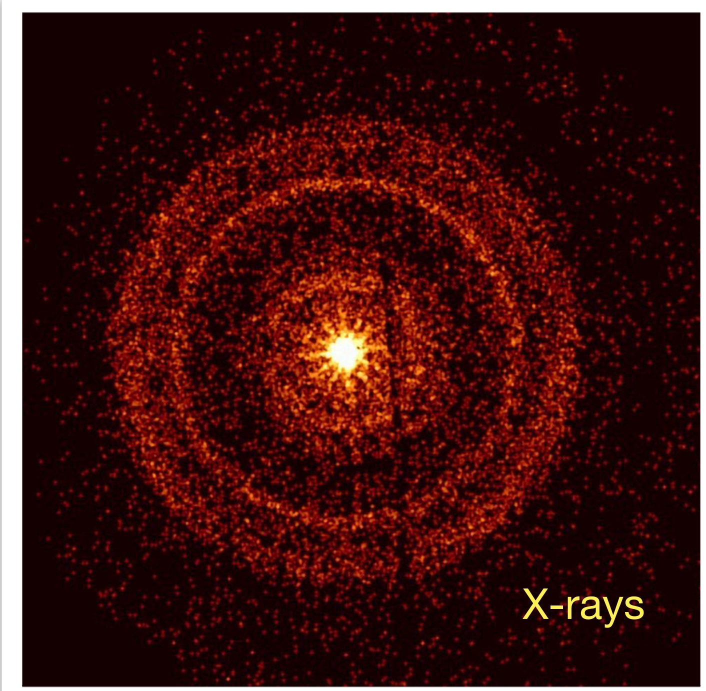


Fermi-LAT

An unusually bright and long-lasting GRB. **Fluence 0.2 erg cm-2**

One of the closest gamma-ray bursts (z=0.151) and among the most energetic and luminous bursts

e.g. Burns et al. 2023



LHAASO detected VHE photons in correspondence with the burst. One photon energy reaching 18 TeV (details still unknown) (LHAASO Coll. 2022)

EBL absorption

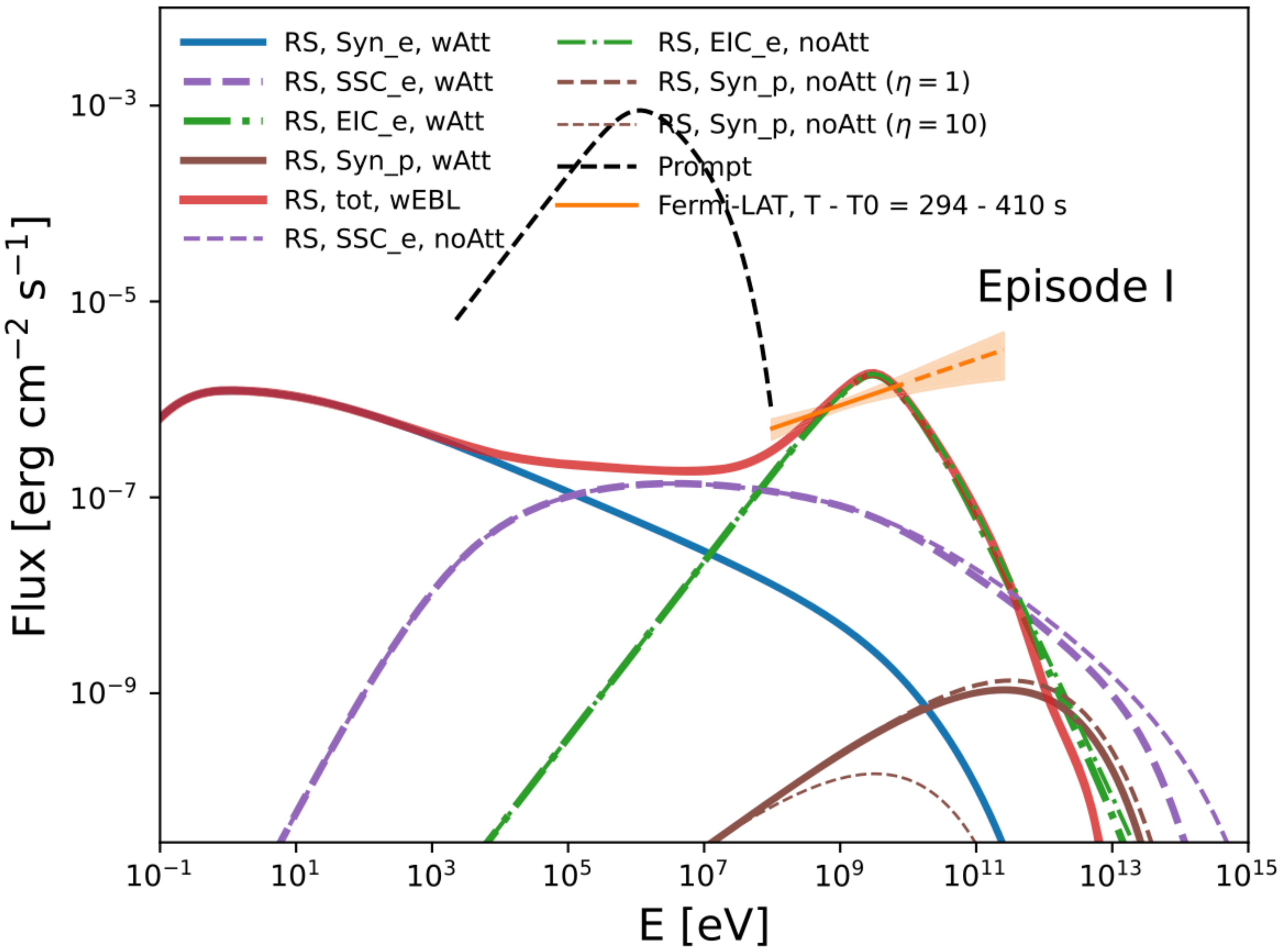
EBL	15 TeV		18 TeV		100 TeV		251 TeV	
	τ_{CP}	P_{CP}	τ_{CP}	P_{CP}	τ_{CP}	P_{CP}	τ_{CP}	P_{CP}
FR	10.1	4×10^{-5}	14.1	7×10^{-7}	333	2×10^{-145}	15411	~0
G	9.4	8×10^{-5}	13.1	2×10^{-6}	246	2×10^{-107}	9502	~0
SL	12.8	3×10^{-6}	18.3	10^{-8}	220	3×10^{-96}	>9251	~0

τ_{CP} -> optical depth; P_{CP} -> photon survival probability
FR -> EBL model by Franceschini & Rodighiero 2017
G -> EBL model by Gilmore et al. 2012
SL -> EBL model by Saldana-Lopez et al. 2021

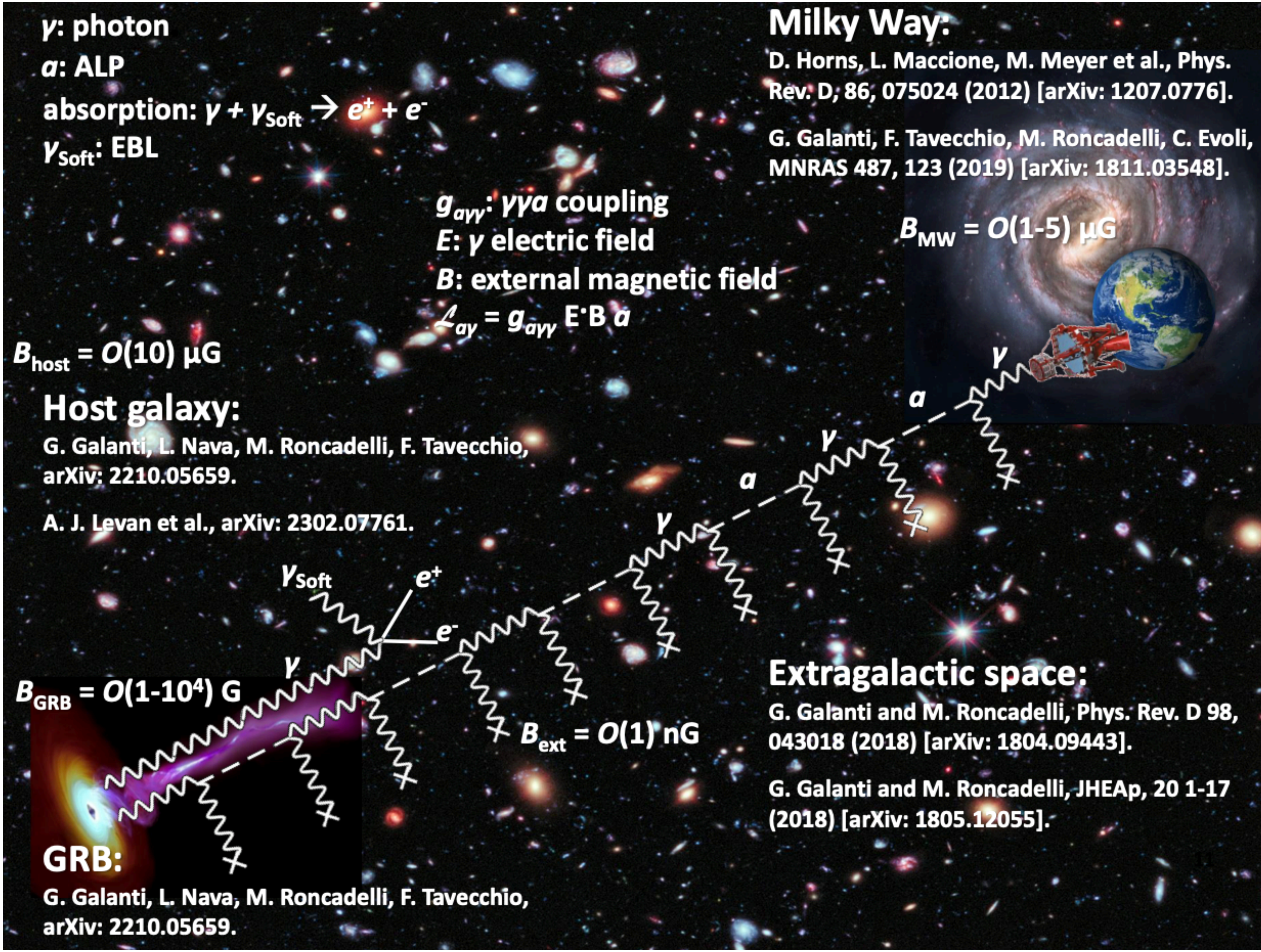
Observed flux: $$F_{obs} = F_0 e^{-\tau}$$

Excessive Fo for all (non-exotic) radiative scenarios

EBL absorption



Zhang et al. 2023



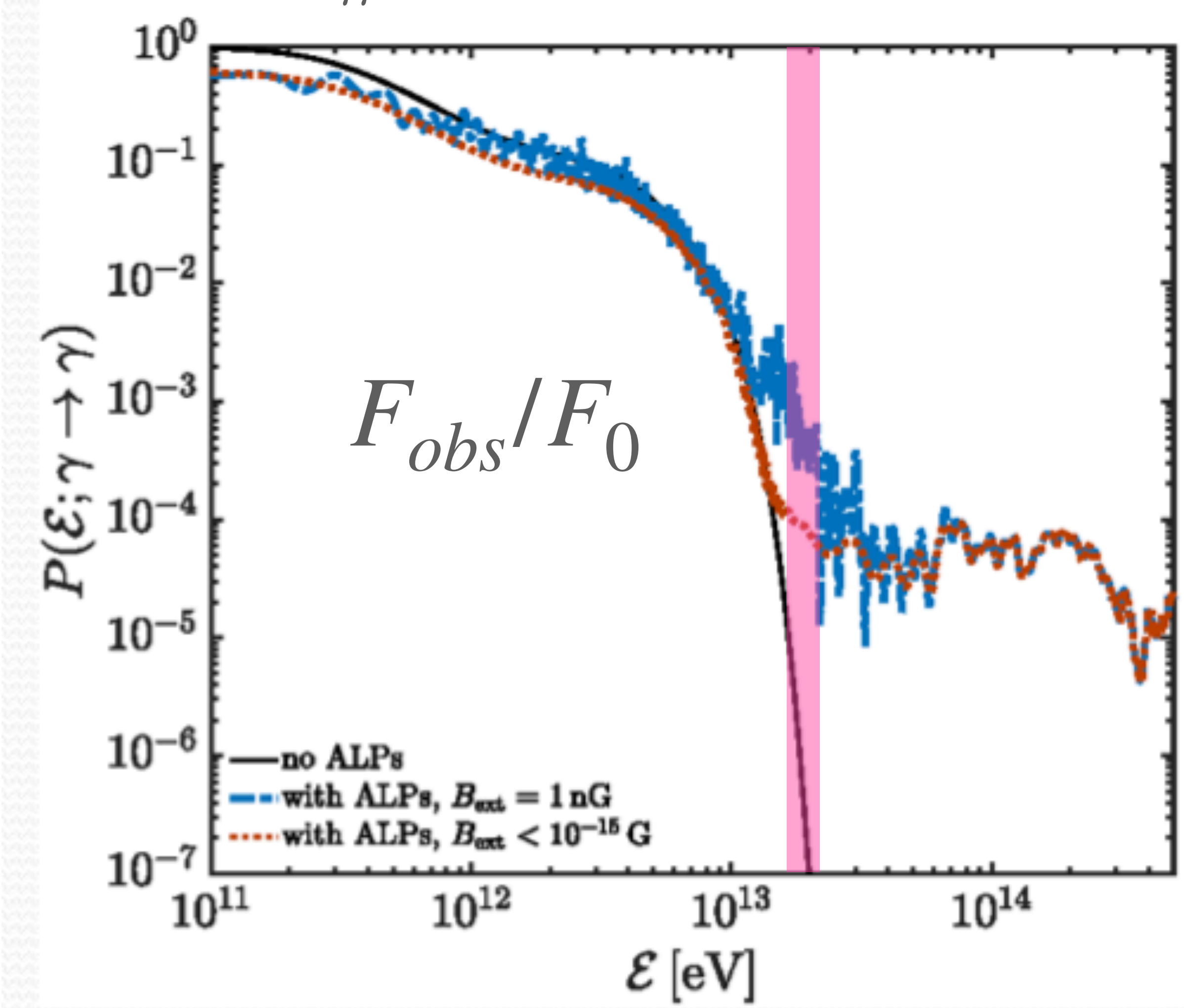
γ: photon
a: ALP
absorption: $\gamma + \gamma_{Soft} \rightarrow e^+ + e^-$
γ_{Soft}: EBL
$g_{a\gamma\gamma}$: $\gamma\gamma a$ coupling
E: γ electric field
B: external magnetic field
$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}\, E \cdot B\, a$
Milky Way:
D. Horns, L. Maccione, M. Meyer et al., Phys. Rev. D, 86, 075024 (2012) [arXiv: 1207.0776].
G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, MNRAS 487, 123 (2019) [arXiv: 1811.03548].
$B_{MW} = O(1\text{-}5)\ \mu G$
$B_{host} = O(10)\ \mu G$
Host galaxy:
G. Galanti, L. Nava, M. Roncadelli, F. Tavecchio, arXiv: 2210.05659.
A. J. Levan et al., arXiv: 2302.07761.
γ
a
γ_{Soft}
e^+
e^-
$B_{GRB} = O(1\text{-}10^4)\ G$
$B_{ext} = O(1)\ nG$
Extragalactic space:
G. Galanti and M. Roncadelli, Phys. Rev. D 98, 043018 (2018) [arXiv: 1804.09443].
G. Galanti and M. Roncadelli, JHEAp, 20 1-17 (2018) [arXiv: 1805.12055].
GRB:
G. Galanti, L. Nava, M. Roncadelli, F. Tavecchio, arXiv: 2210.05659.

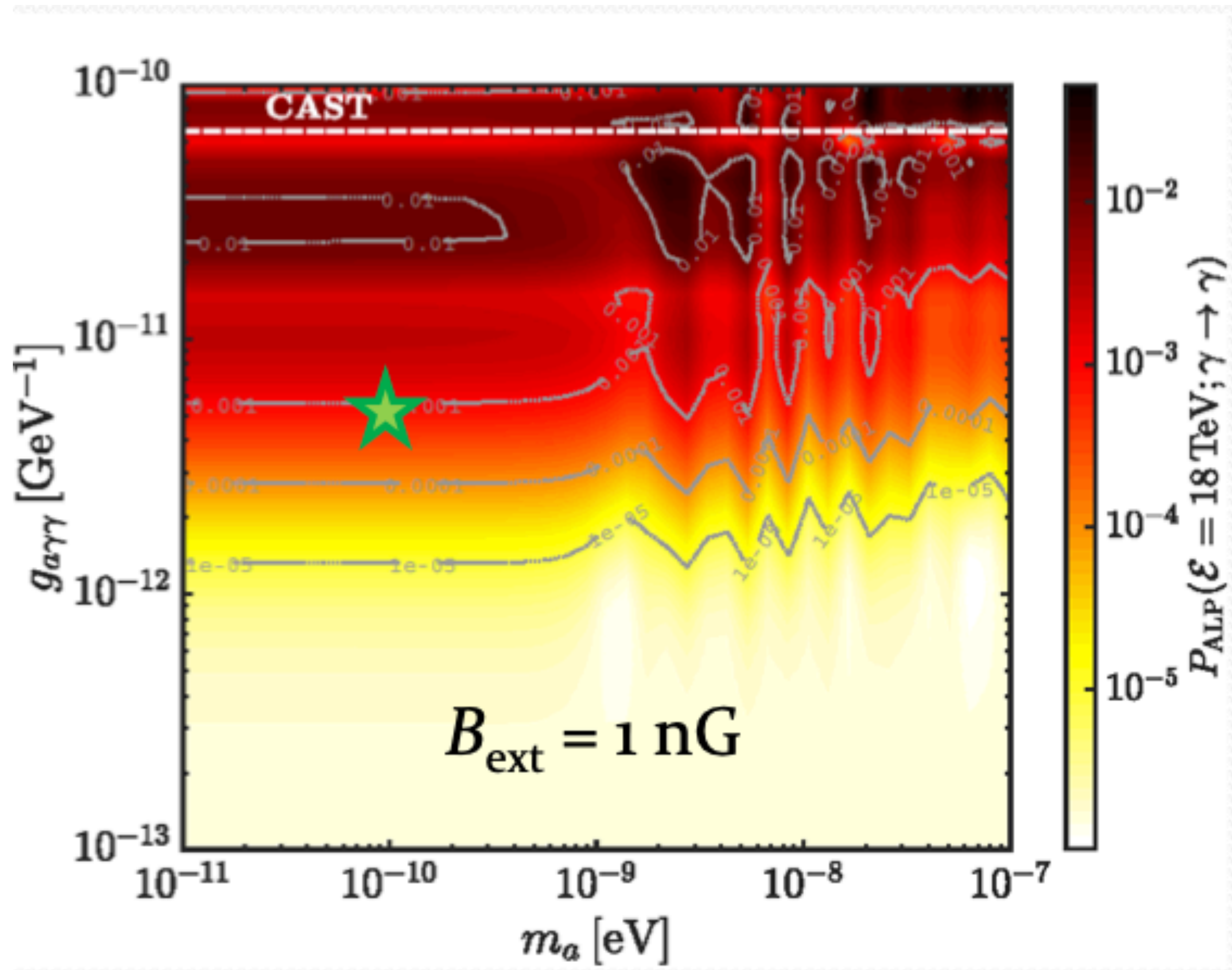
EBL absorption with ALPs

Galanti, Nava, Roncadelli & Tavecchio 2023

$m_a = 10^{-10}\,\mathrm{eV}$

$g_{a\gamma\gamma} = 5 \times 10^{-12}\,\mathrm{GeV}^{-1}$

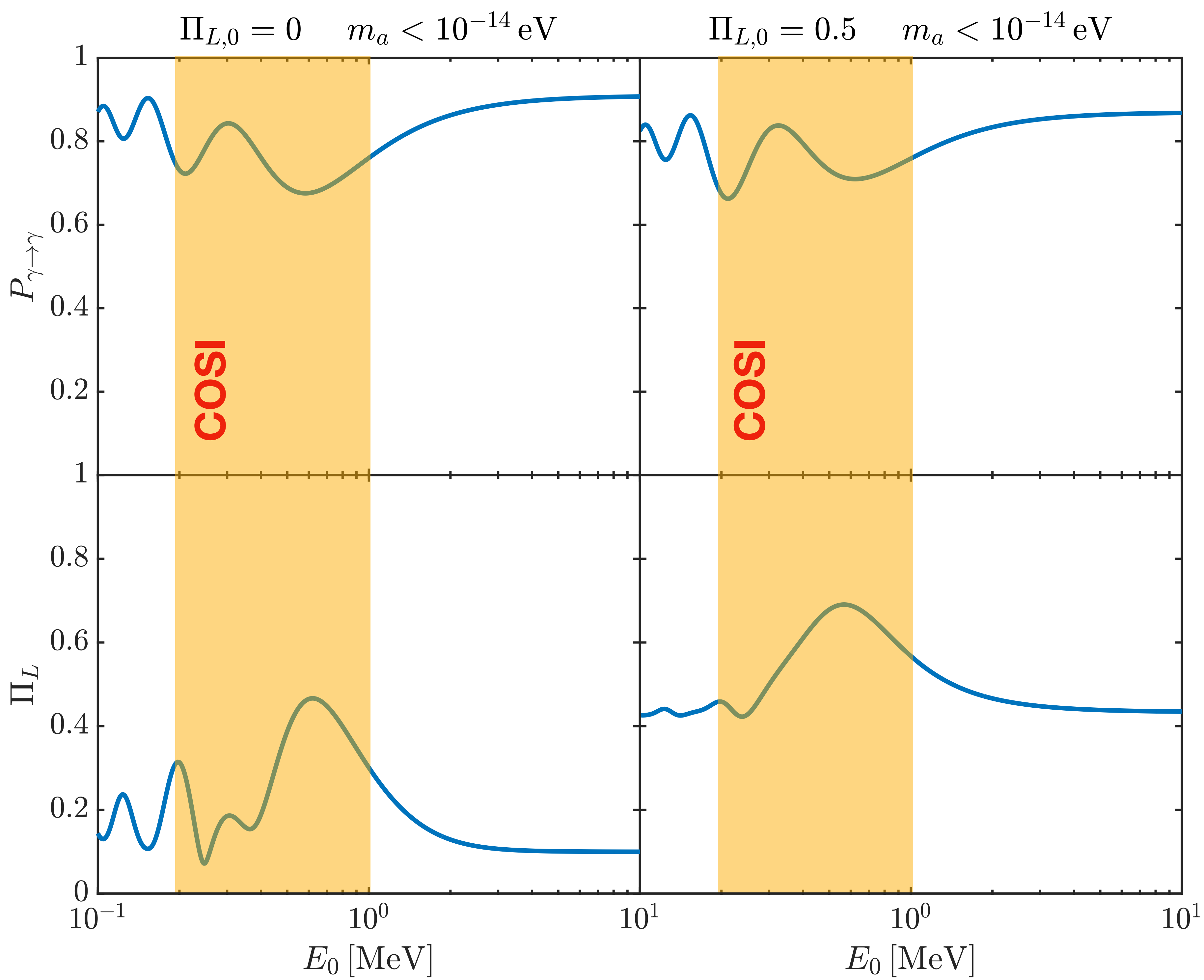




Assuming a starburst-like host galaxy.
Similar results for a spiral host

Absorption can be safely reduced to values manageable by emission models

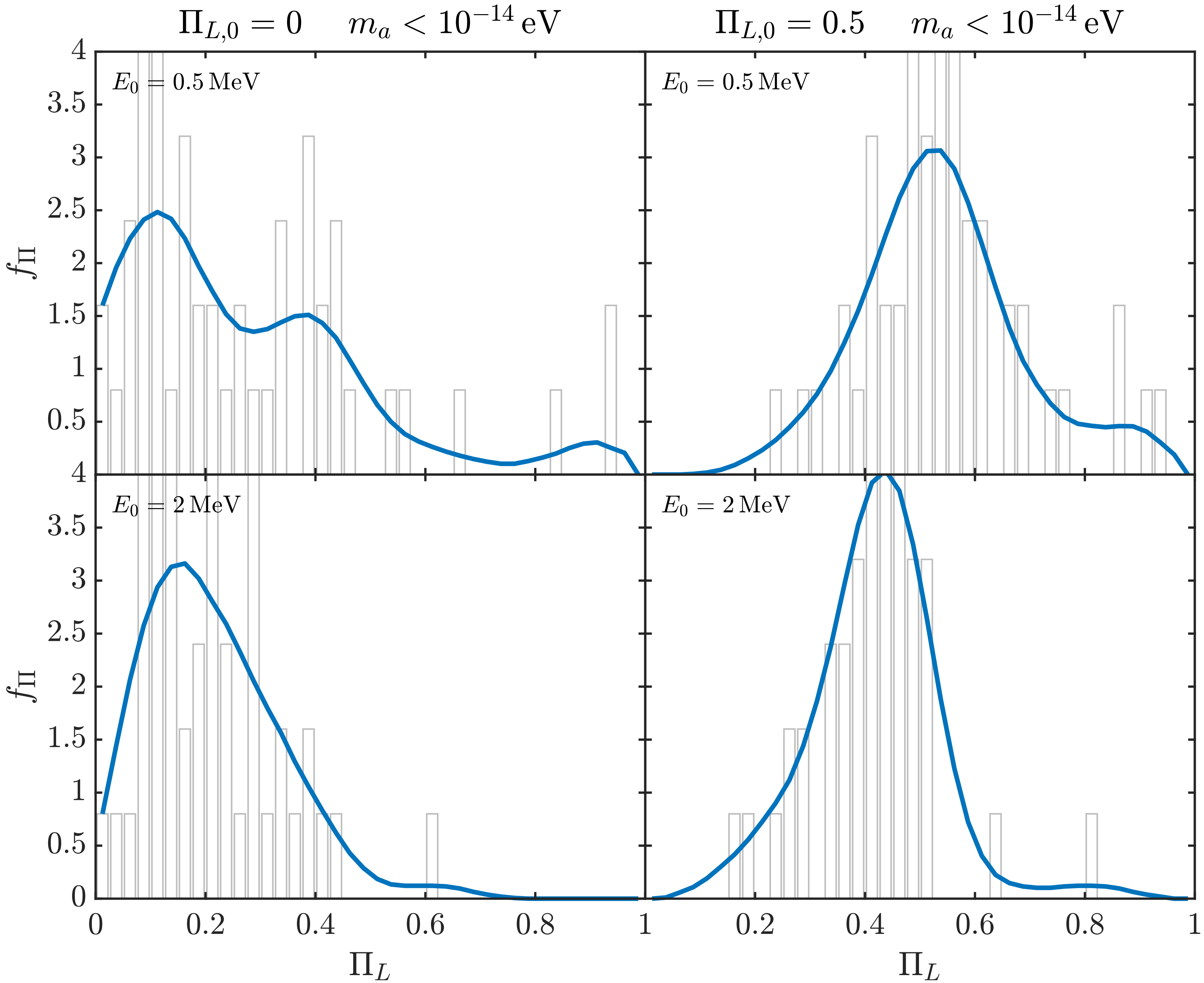
Polarization signal



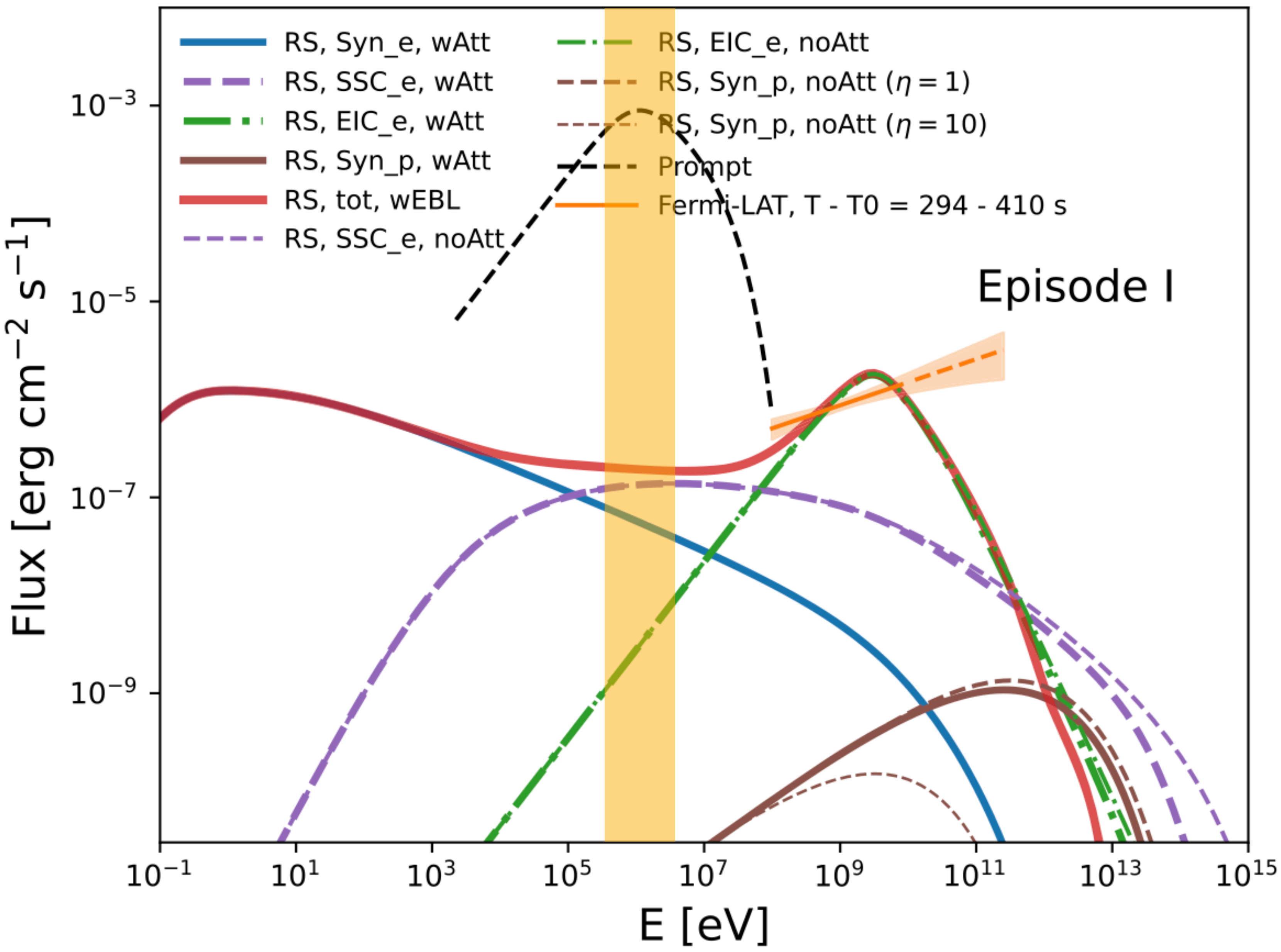
Large, highly modulated polarization

Very preliminary!

(Very) preliminary results



Prospects for COSI



Zhang et al. 2023

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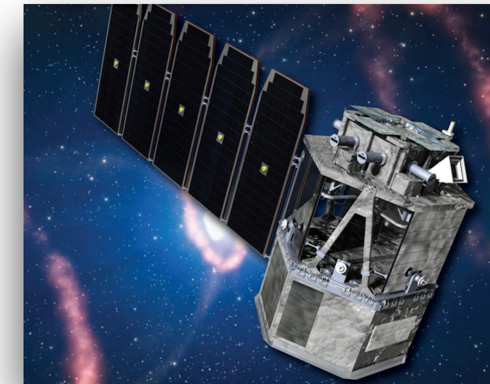

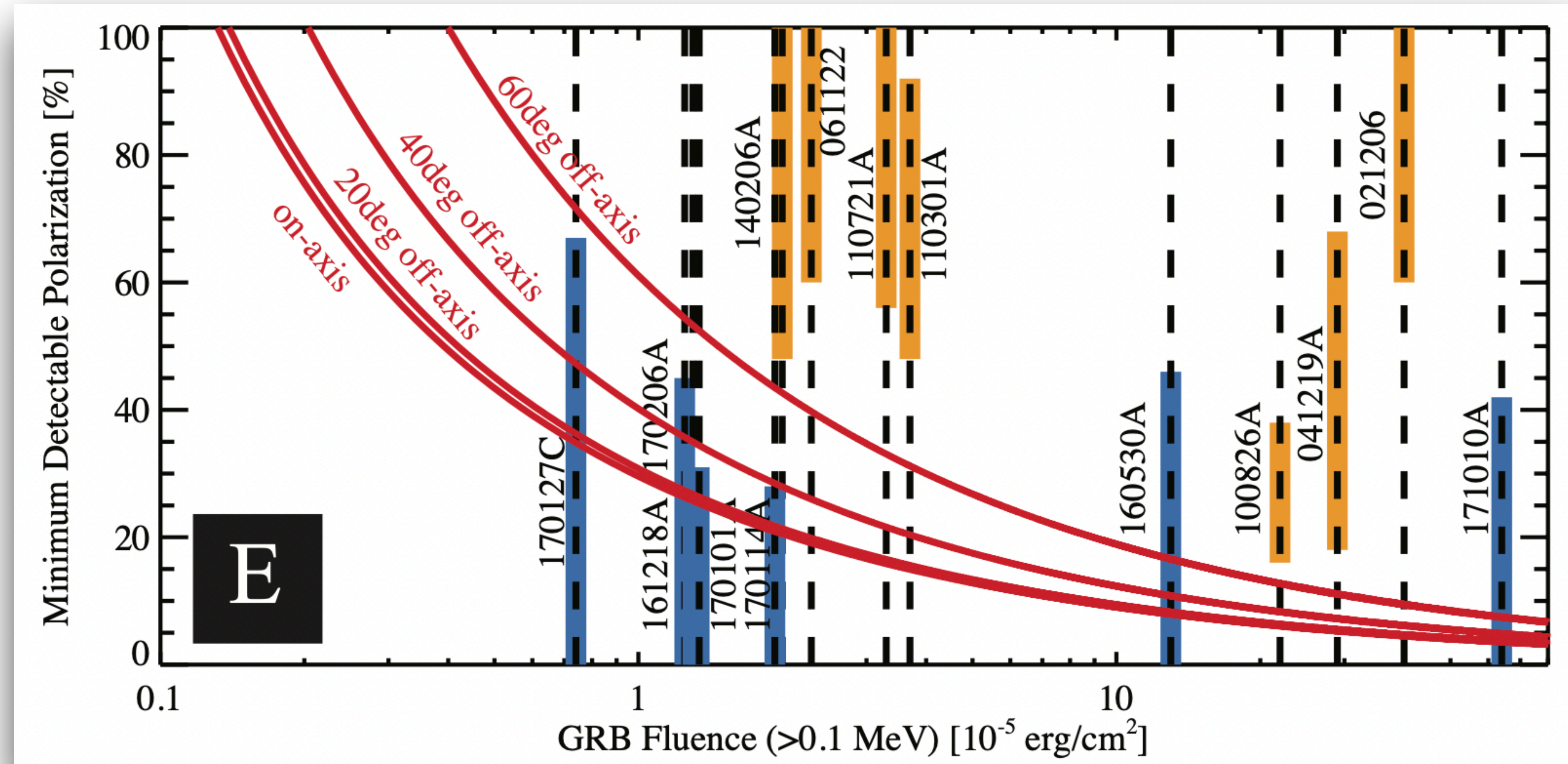

Expectations

About 40 GRBs with MDP < 50%

About 10 with MDP < 5-10%

To be refined by using state-of-the-art population models…

Thank you!