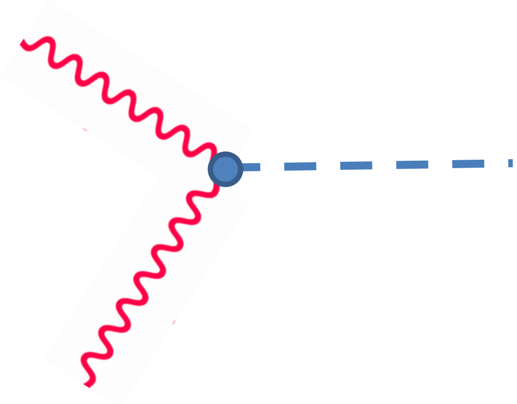
Axion-like particles motivated by astrophysics

Sergey Troitsky
(INR, Moscow)

Rencontres de Moriond, March 23, 2017

The axion and the ALP

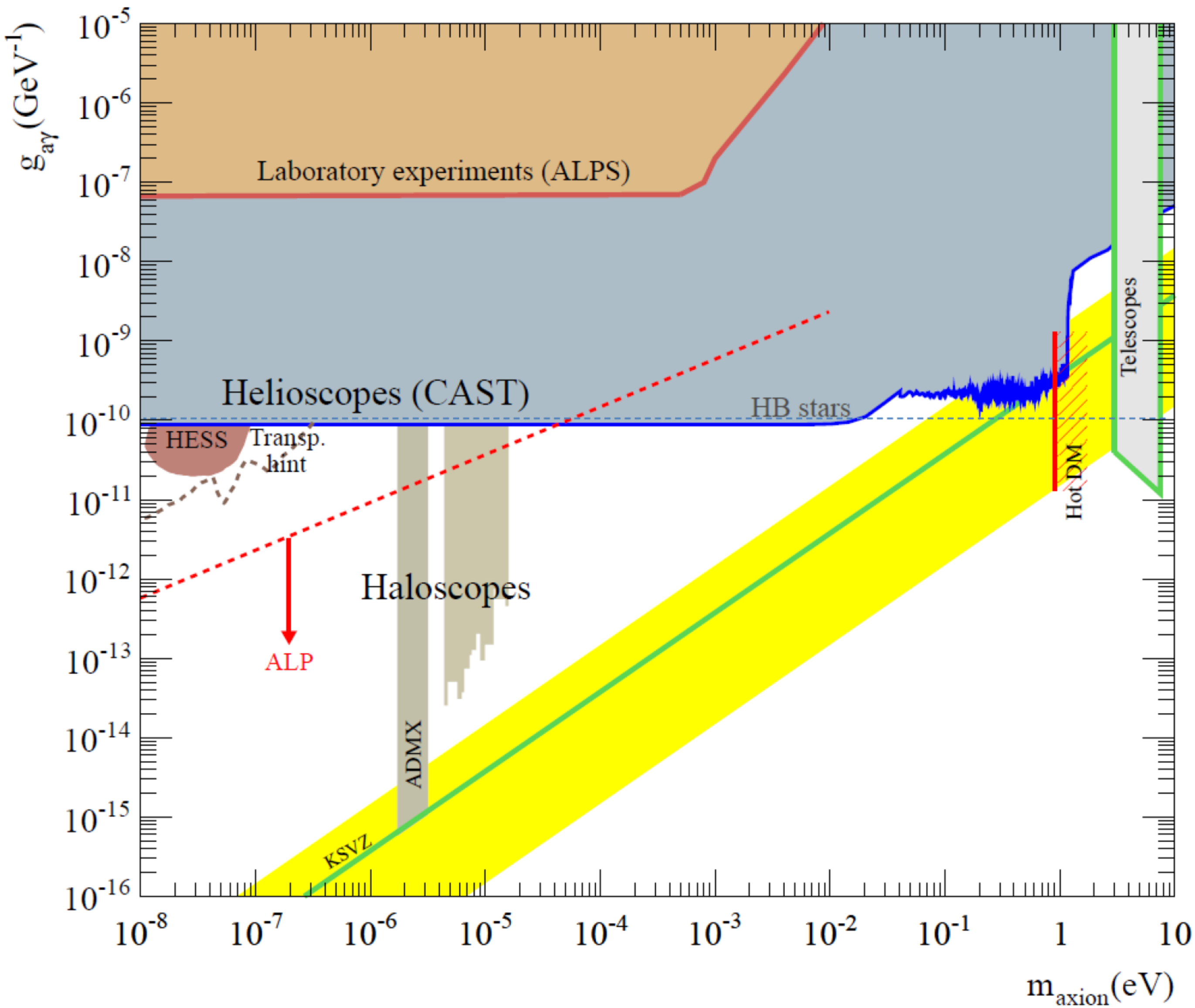
axion interactions



$$\frac{a}{M} F_{\mu\nu} \tilde{F}_{\mu\nu}, \quad M \sim f_A \sim \frac{\Lambda^2_{\mathrm{QCD}}}{m}$$

m, M independent ⇒ axion-like particle (ALP)

ALP parameters



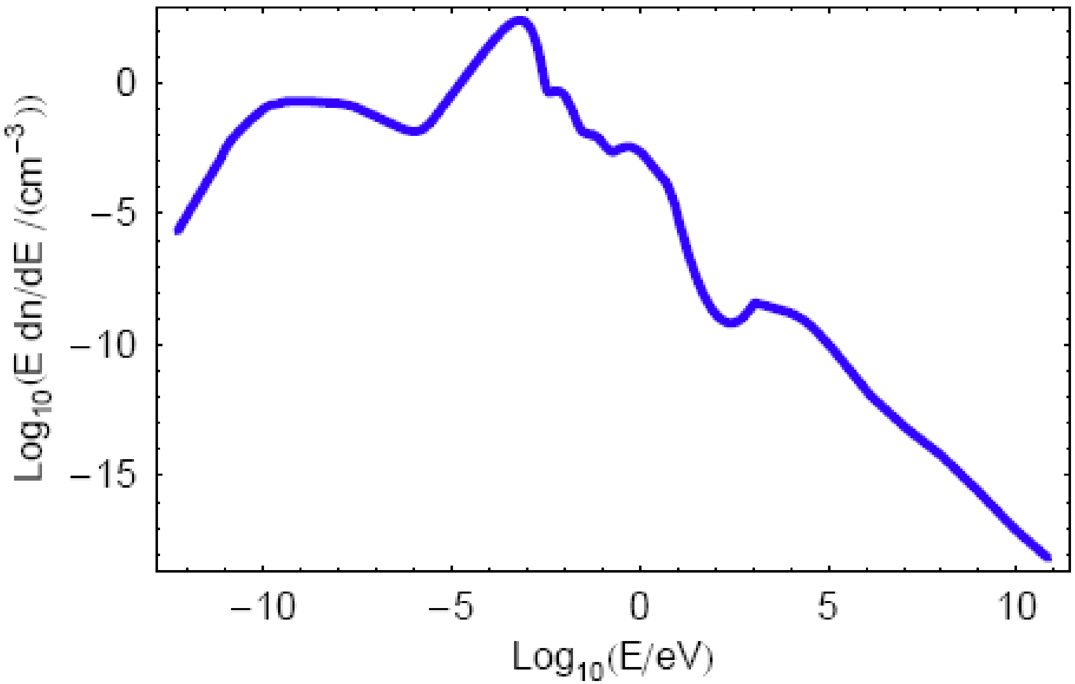
Gamma-ray propagation:
the Universe is opaque for gamma rays

Why opaque?

Pair production on background radiation

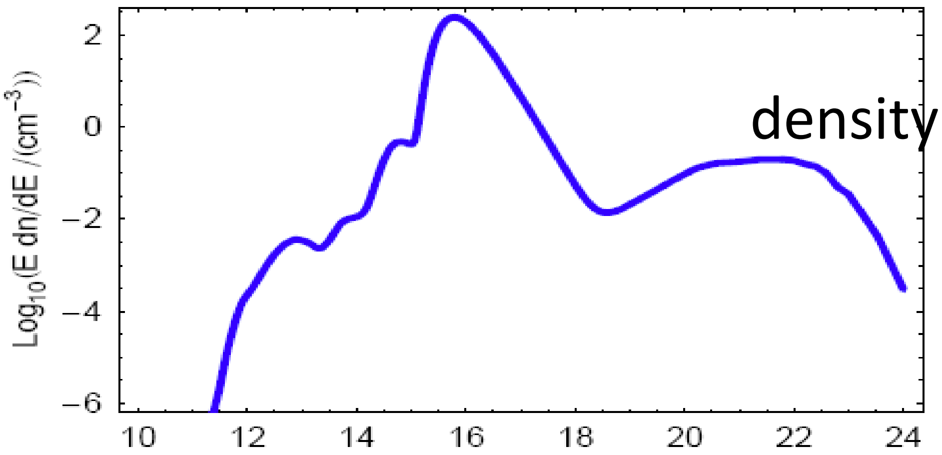
Nikishov 1962

The Universe is filled by radiation:

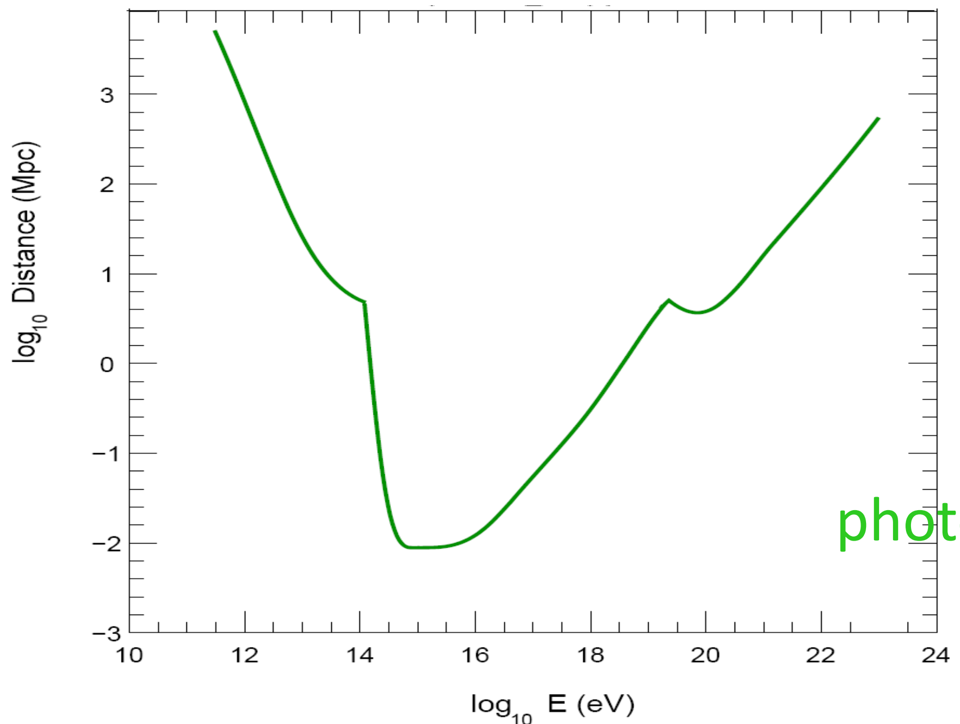


Why opaque?

Pair production on background radiation



density of background photons

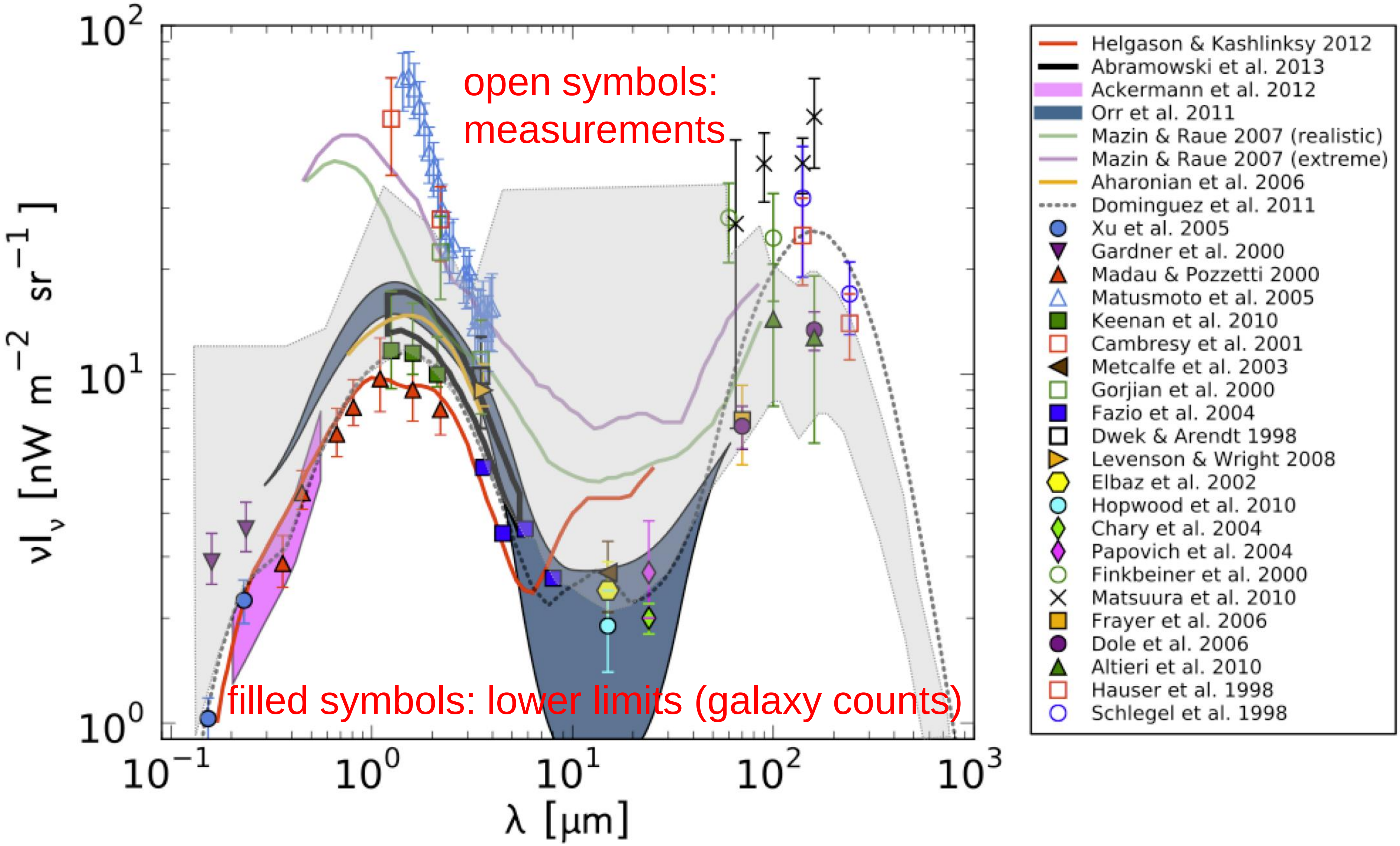


$\boxed{E_\gamma \sim 5\times10^{11}\ (\omega/eV)^{-1}\ eV}$

photon mean free path

Extragalactic background light density

Krennrich 2014



lines/areas: gamma-ray upper limits

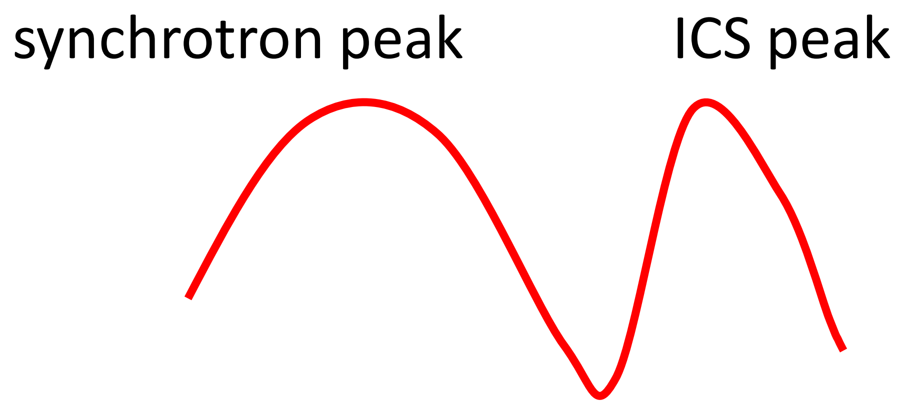
The IR/TeV crisis?

very distant gamma-ray sources observed (blazars)

optical depths >2

The IR/TeV crisis?

- very distant gamma-ray sources observed (blazars)
- blazar spectra are well studied:

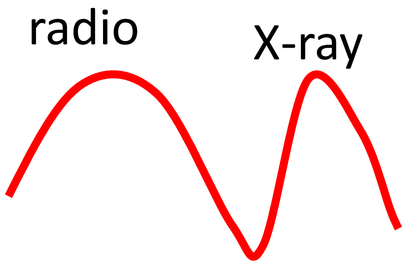


inverse Compton scattering
the same photons and electrons contribute to both peaks

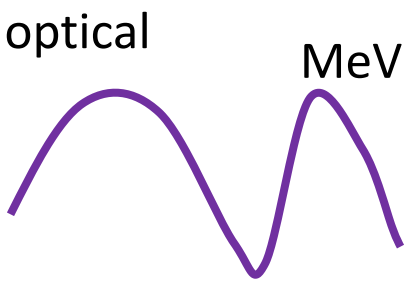
⇨ two peaks related

The IR/TeV crisis?

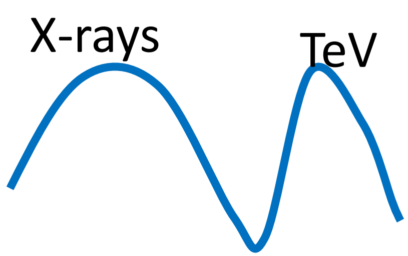
blazar spectra are well studied :
the blazar sequence…



FSRQ –
flat-spectrum radio quasars



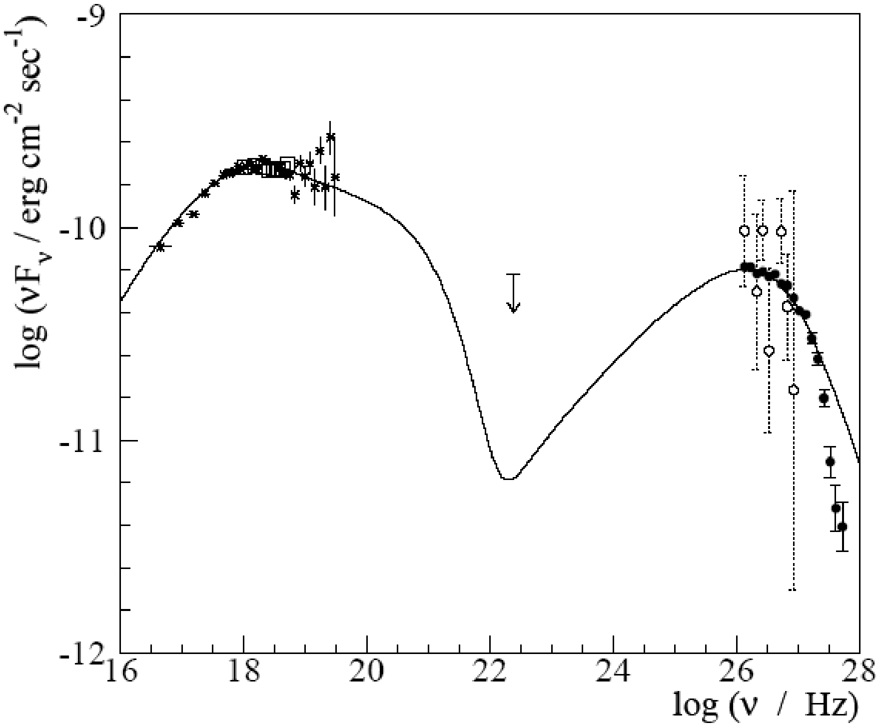
LBL – low-frequency-peaked BL Lacs

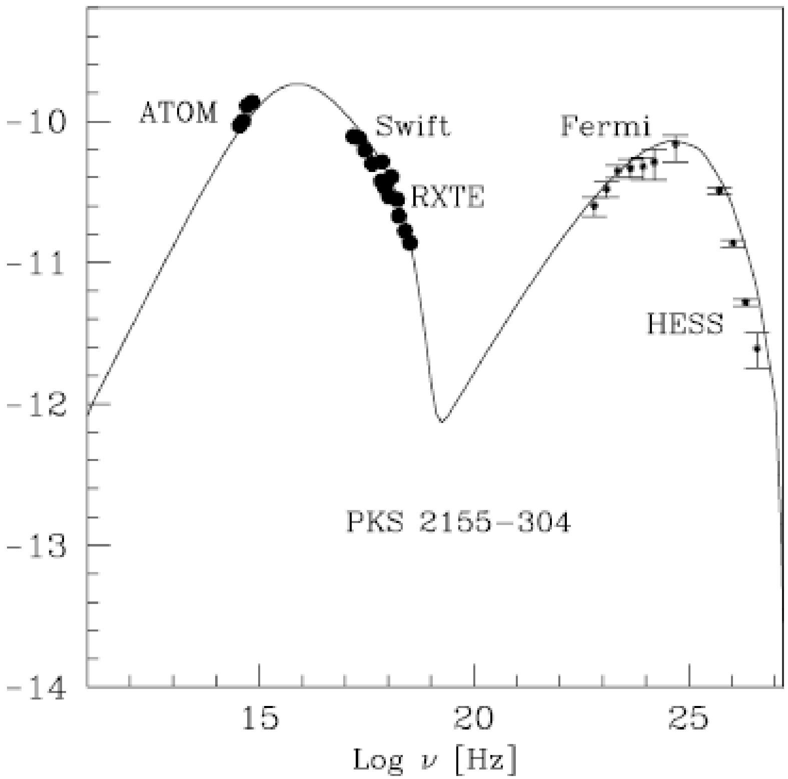


HBL – high-frequency-peaked BL Lacs

The IR/TeV crisis?

blazar spectra are well studied :
the blazar sequence…





The IR/TeV crisis?

- very distant gamma-ray sources observed (blazars) optical depths >2

- spectra corrected for absorption

- upward breaks at high energies in addition to 2 peaks (distant sources only)

The IR/TeV crisis?

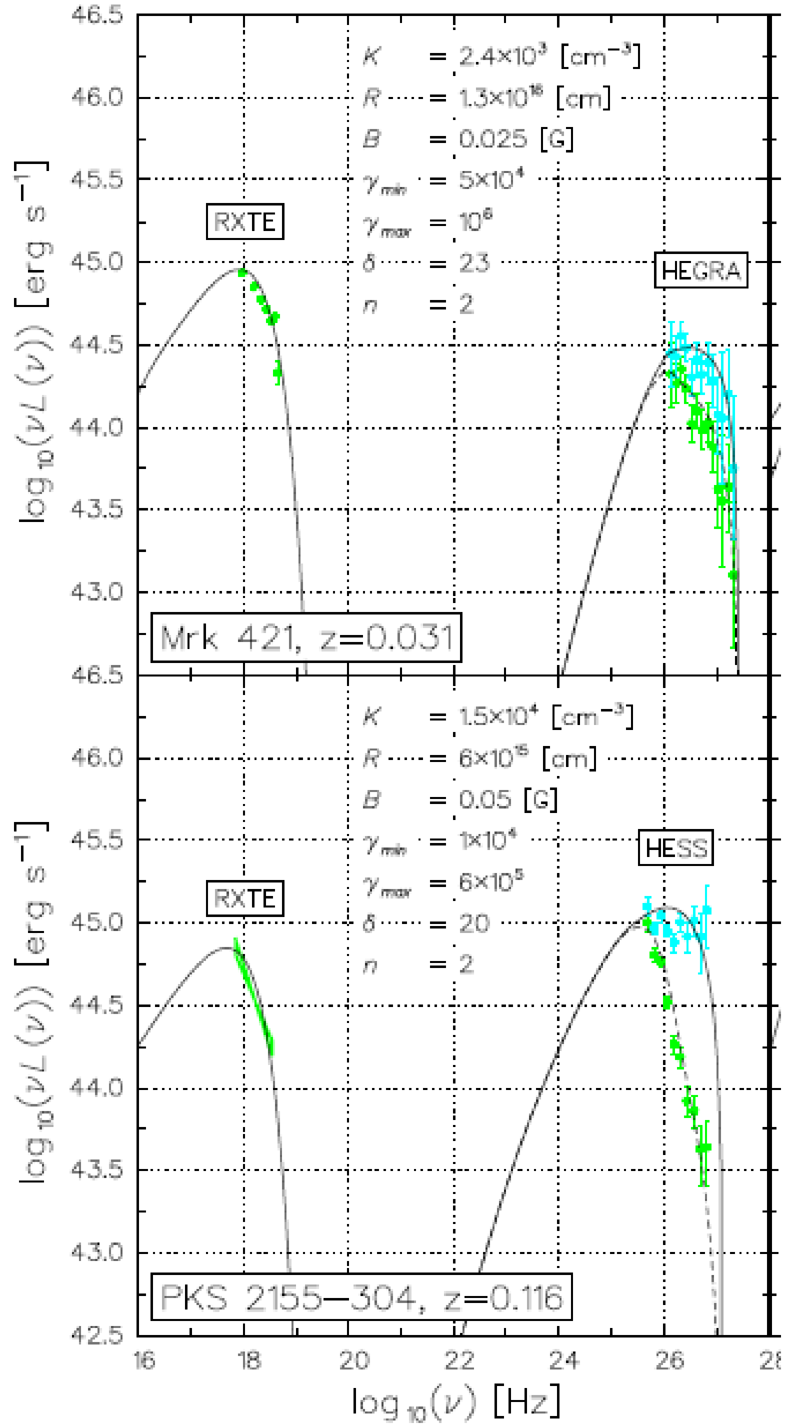
• need upward break to explain the data

• the break does not depend on the class (HBL, LBL, FSRQ)

• the break depends on the distance

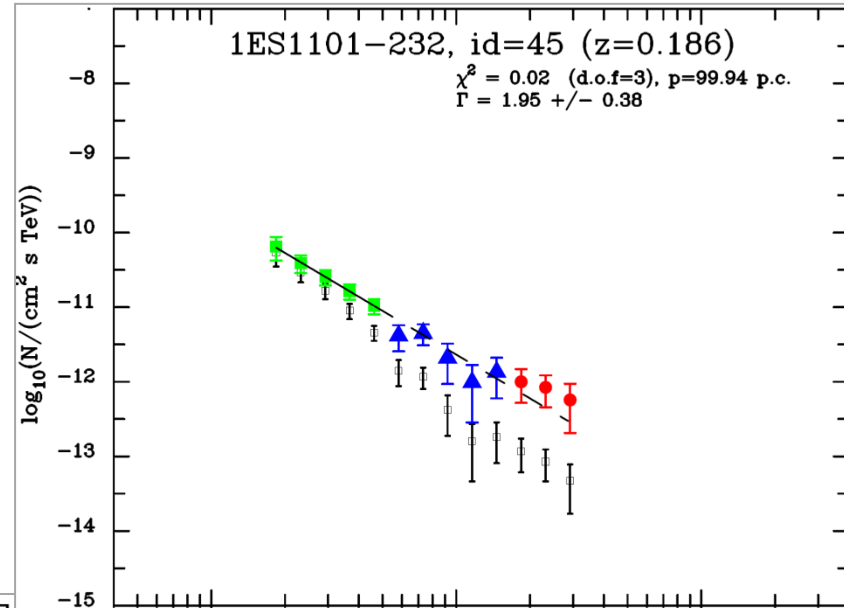
➡ **looks strange…**

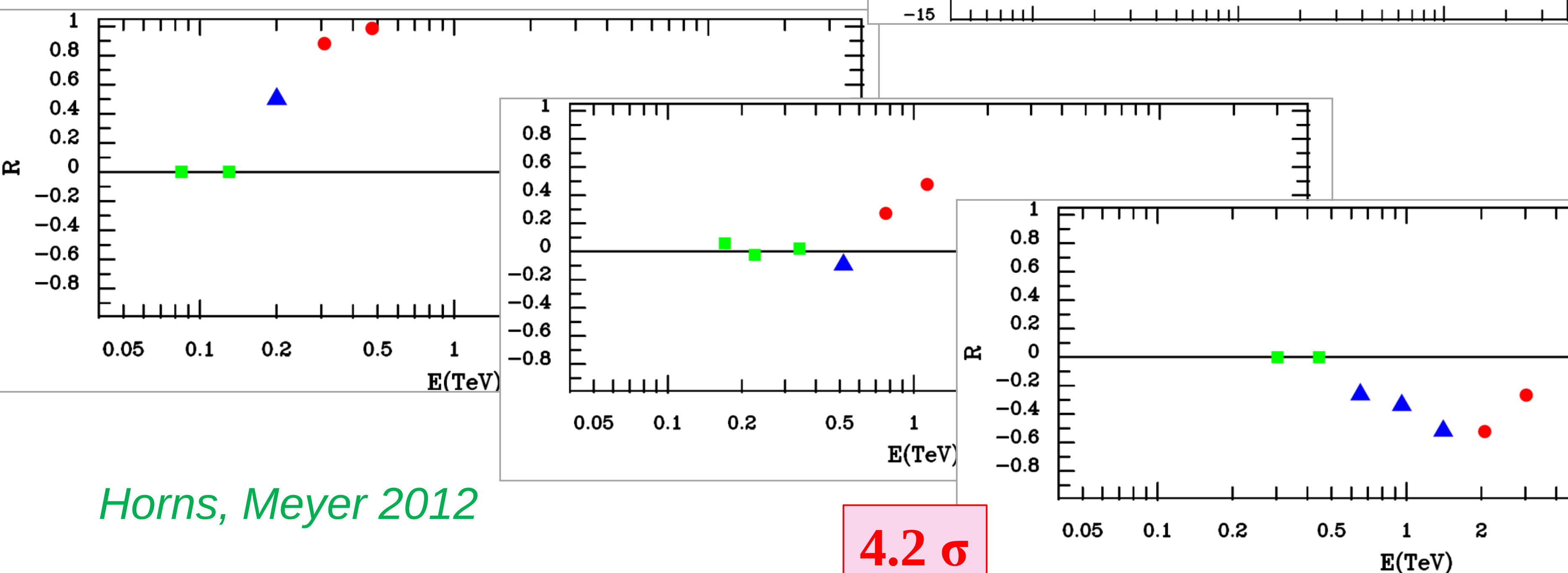
Kneiske ~2008



The IR/TeV crisis?

7 blazars, IACT
opacity >2, z≤0.536
redshift-dependent
break positions
in deabsorbed spectra





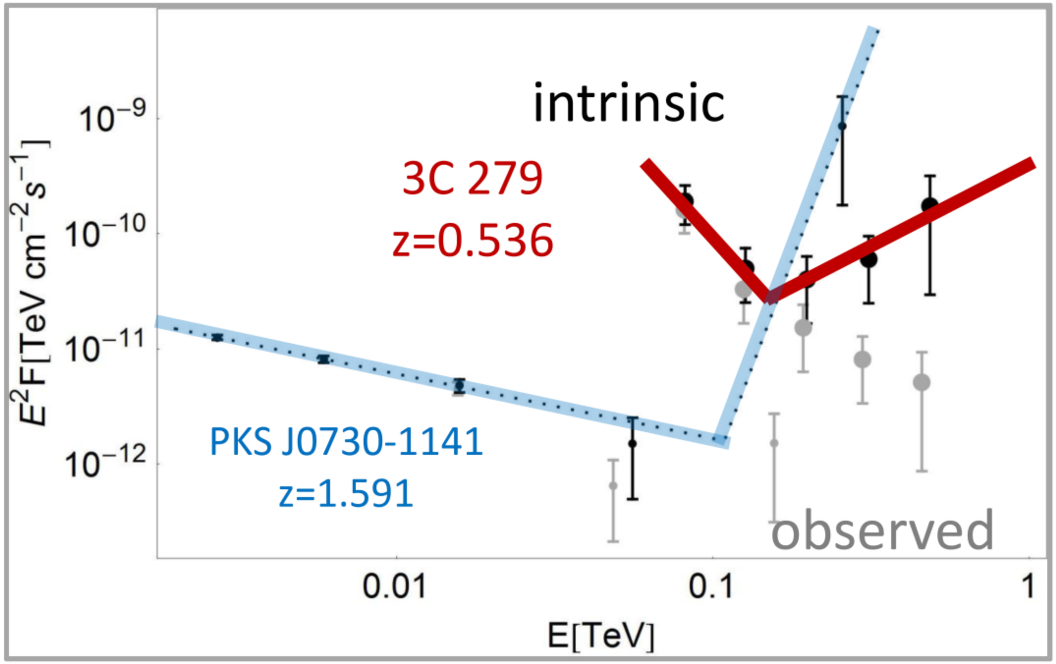
Horns, Meyer 2012

4.2 σ

20 blazars, 15 IACT + 5 FERMI LAT

opacity >1, z≤2.156

redshift-dependent break strength in deabsorbed spectra



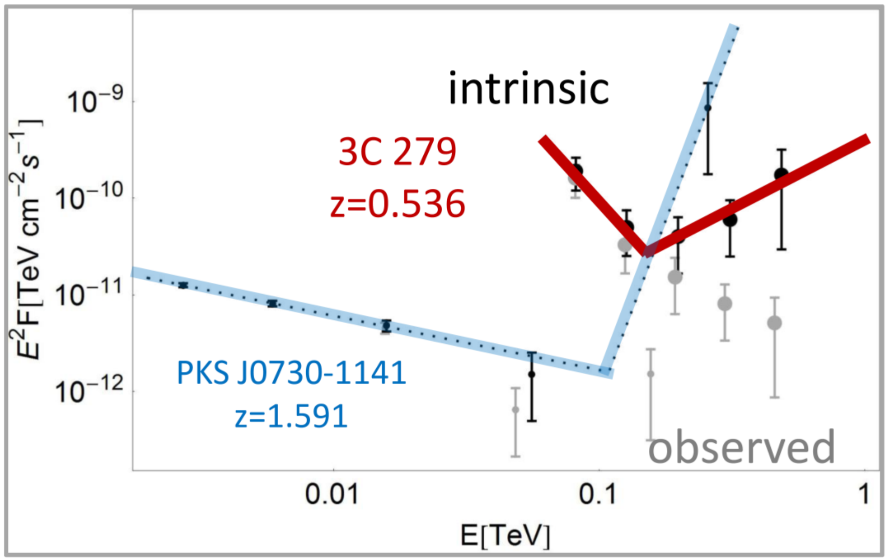
- **breaks are present**

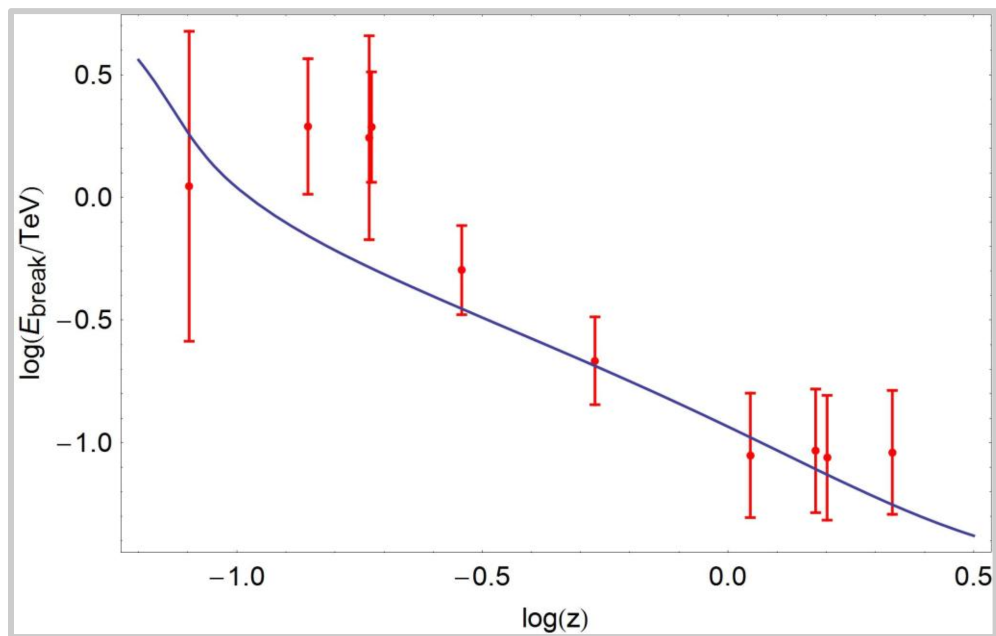
Rubtsov, ST 2014

20 blazars, 15 IACT + 5 FERMI LAT

opacity >1, z≤2.156

redshift-dependent break strength in deabsorbed spectra

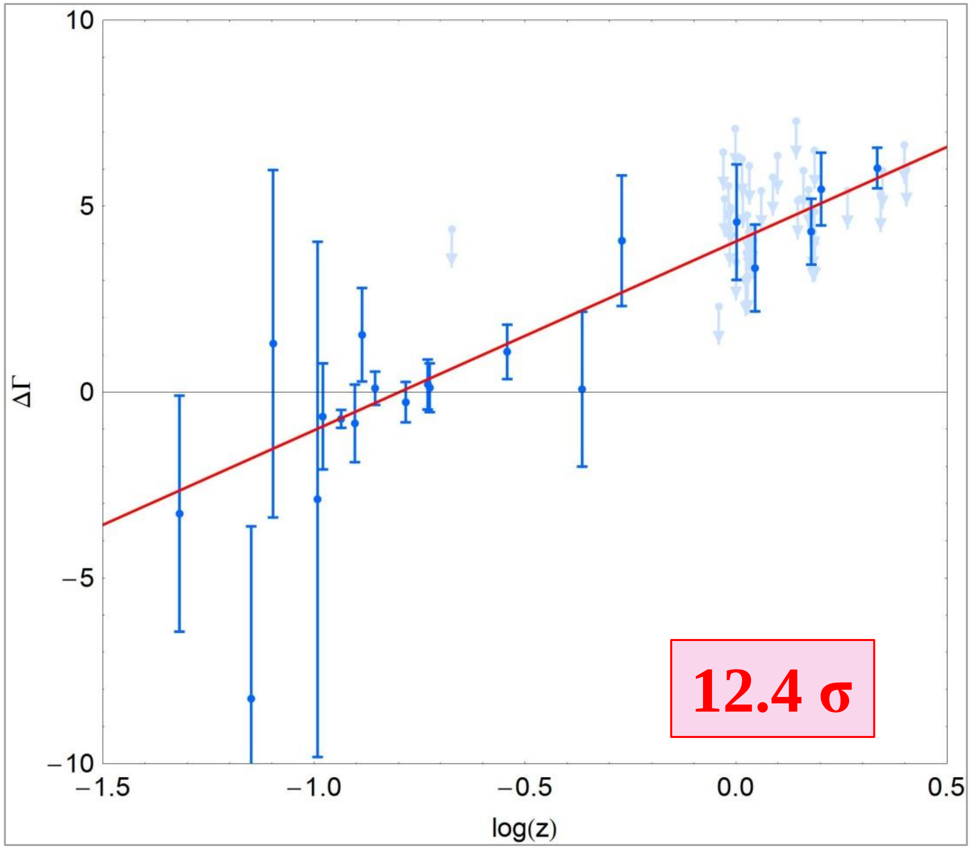




- **breaks are present**
- **break positions depend on distance**

20 blazars, 15 IACT + 5 FERMI LAT
opacity >1, $z \leq 2.156$
redshift-dependent break strength in deabsorbed spectra

- **BREAK STRENGTHS DEPEND ON DISTANCE (not on the source type)**



Rubtsov, ST 2014

The IR/TeV crisis! (the modern logic)

Individual source:

Observed spectrum → deabsorption (with the most conservative model) → Intrinsic spectrum with a break

Ensemble of sources:

Breaks at different energies for similar sources

Break position depends on distance

Break strength depends on distance

$\boxed{12\ \sigma}$

Breaks = artefacts.
Absorption model wrong.
New effects required.

Photon/ALP conversion

$$\boxed{\mathcal{L} = \frac{1}{2}(\partial^\mu \psi \partial_\mu \psi - m^2 \psi^2) - \frac{1}{4}\frac{\psi}{M} F_{\mu\nu} \widetilde{F}^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}}$$

ψ

pseudoscalar filed (ALP)

$F_{\mu\nu}$

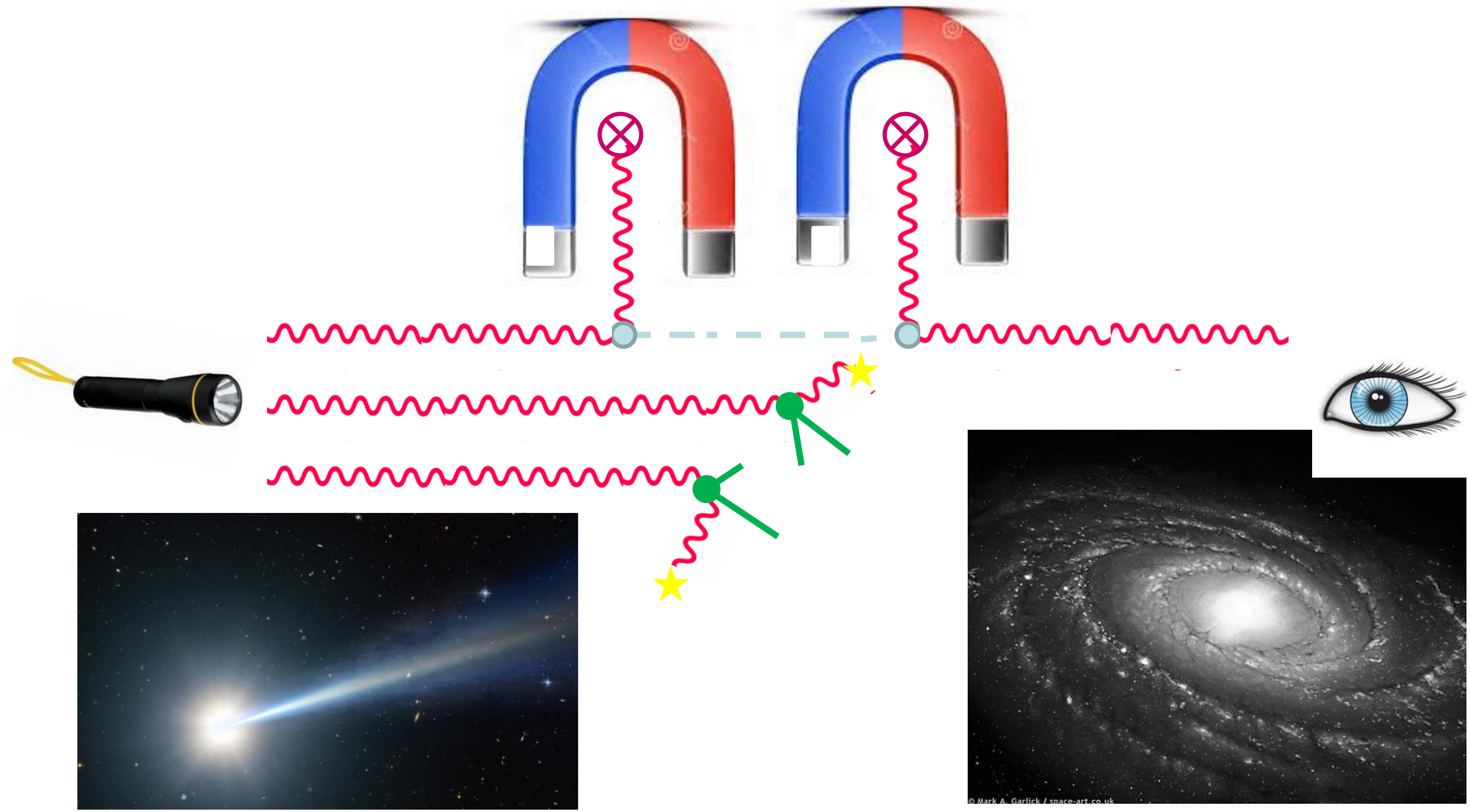
electromagnetic stress tensor

$\widetilde{F}_{\mu\nu} = \epsilon_{\mu\nu\rho\lambda} F_{\rho\lambda}$

dual tensor

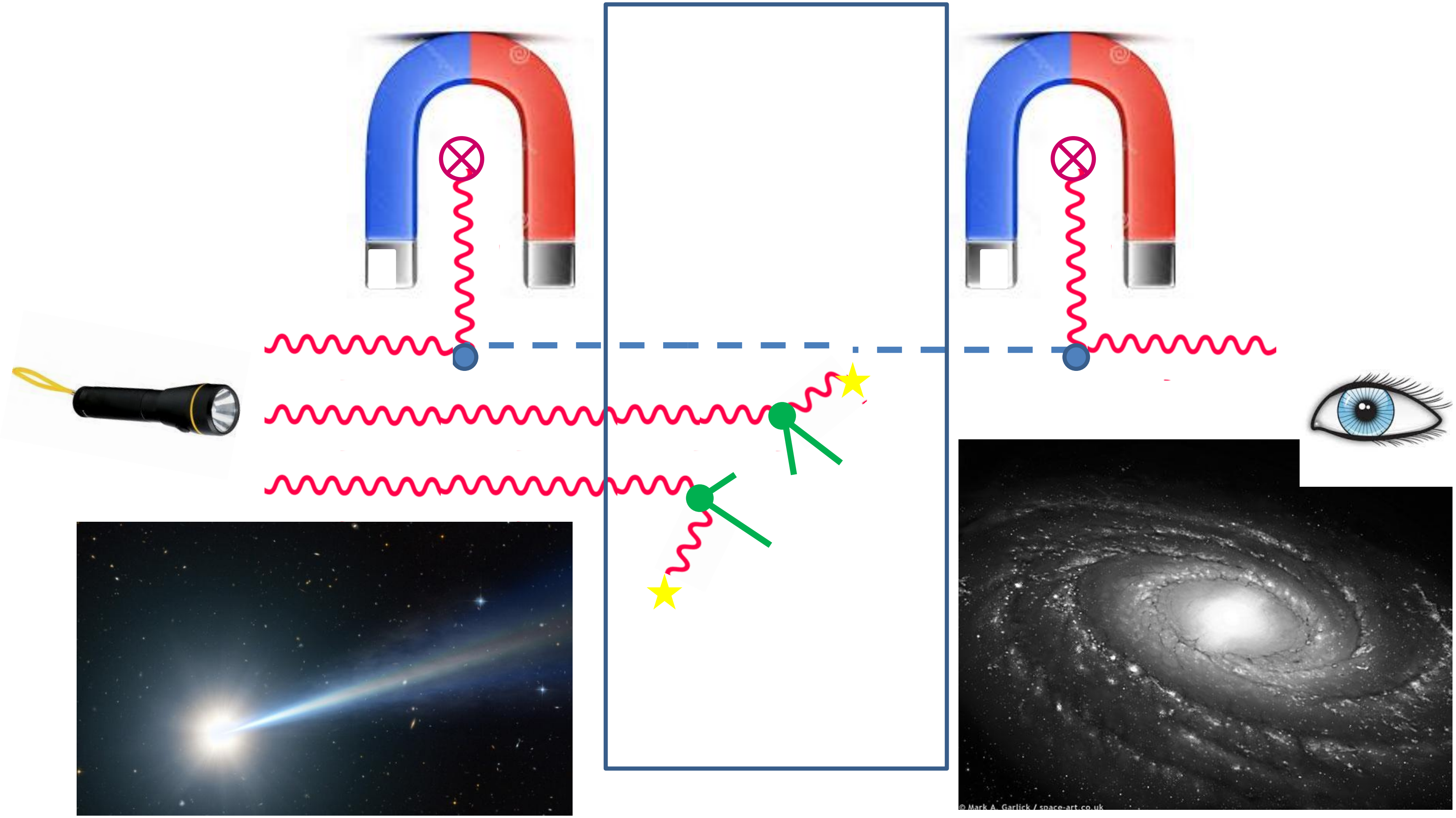
Shining light through the Universe: Extragalactic conversion

Csaki et al. 2003, De Angelis et al. 2007

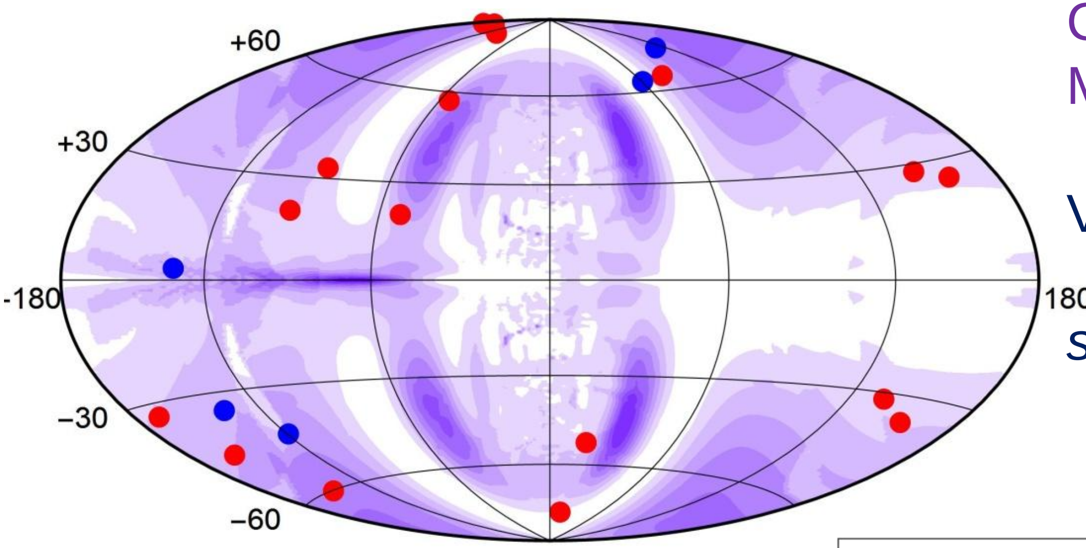


Shining light through the Universe: Galactic conversion

Simet et al. 2007, Fairbairn et al. 2009



Milky Way: anisotropy



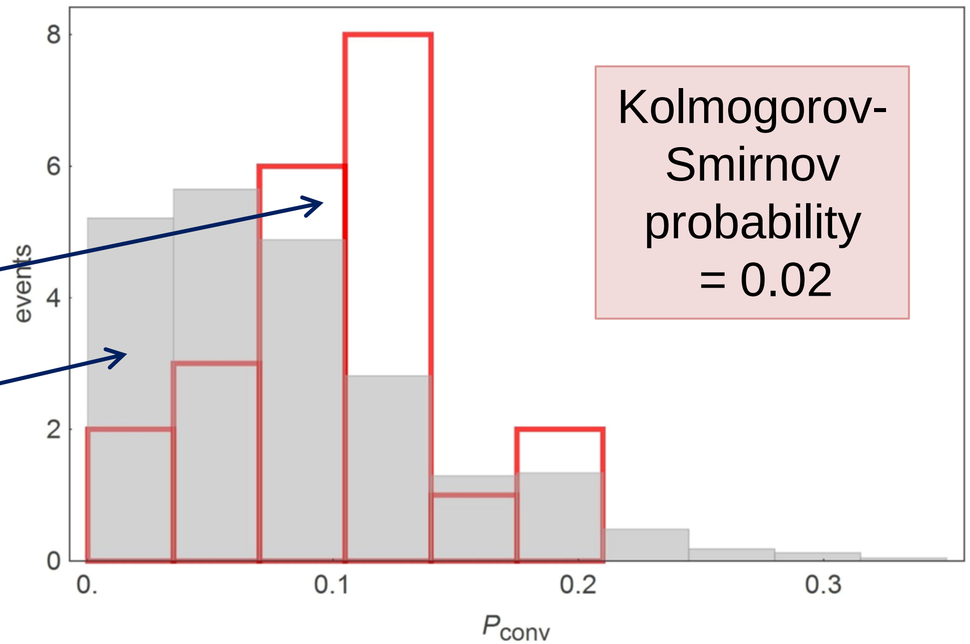
Conversion probability, Milky Way

VHE blazars, opacity>1, 2014
● $0.1<z<1$ ● $z>1$
sample of Rubtsov, ST 2014

Conversion probability distribution

VHE blazars, opacity>1

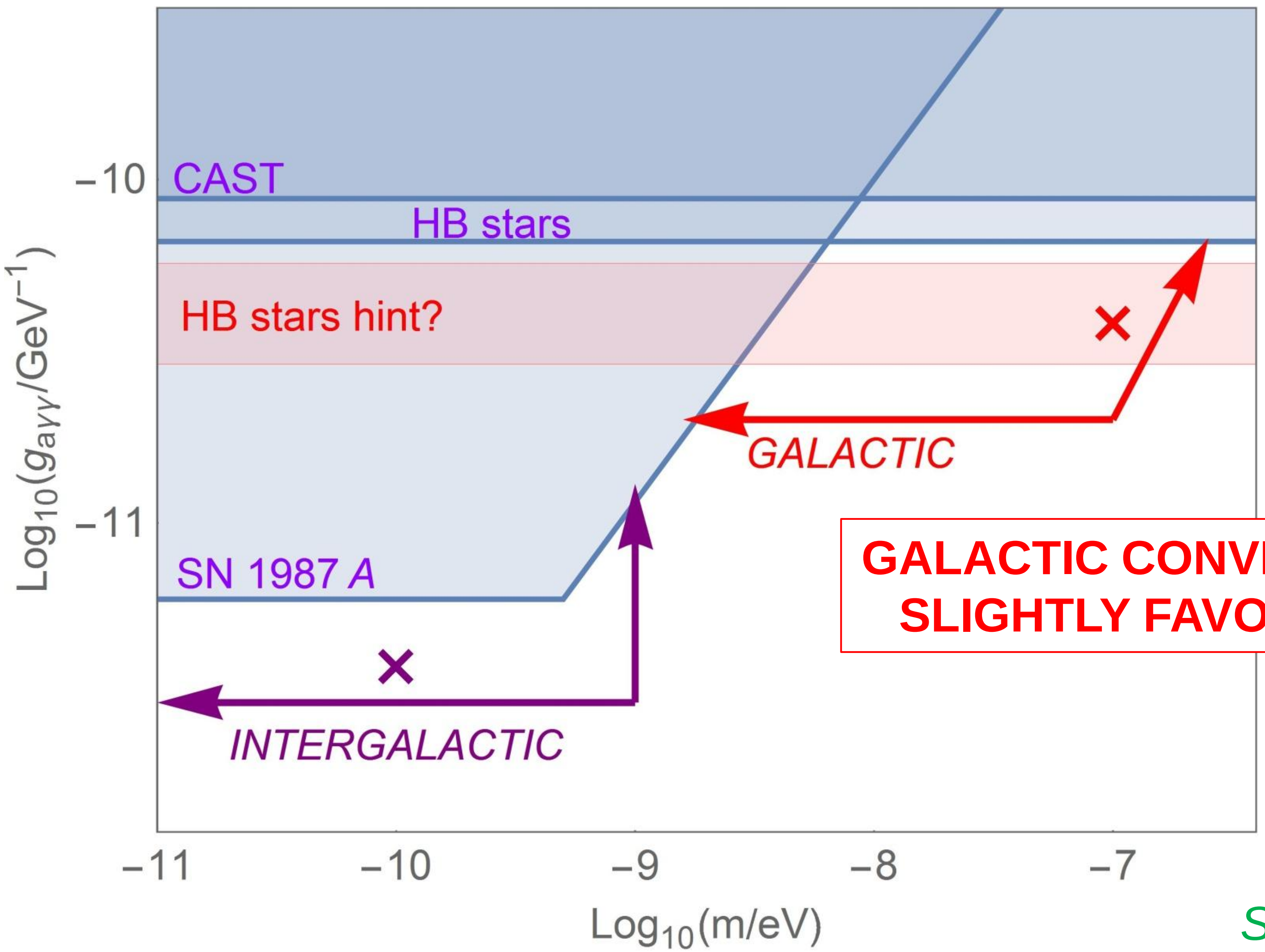
isotropic background



ST 2016

Required ALP parameters

for the two scenarios



GALACTIC CONVERSION SLIGHTLY FAVOURED

ST 2016

Required ALP parameters (benchmark)

$$\boxed{m \sim 10^{-8}\ \mathrm{eV}, \quad g_{a\gamma} \sim 5 \times 10^{-11}\ \mathrm{GeV}^{-1}}$$

(theoretical motivation wanted…)

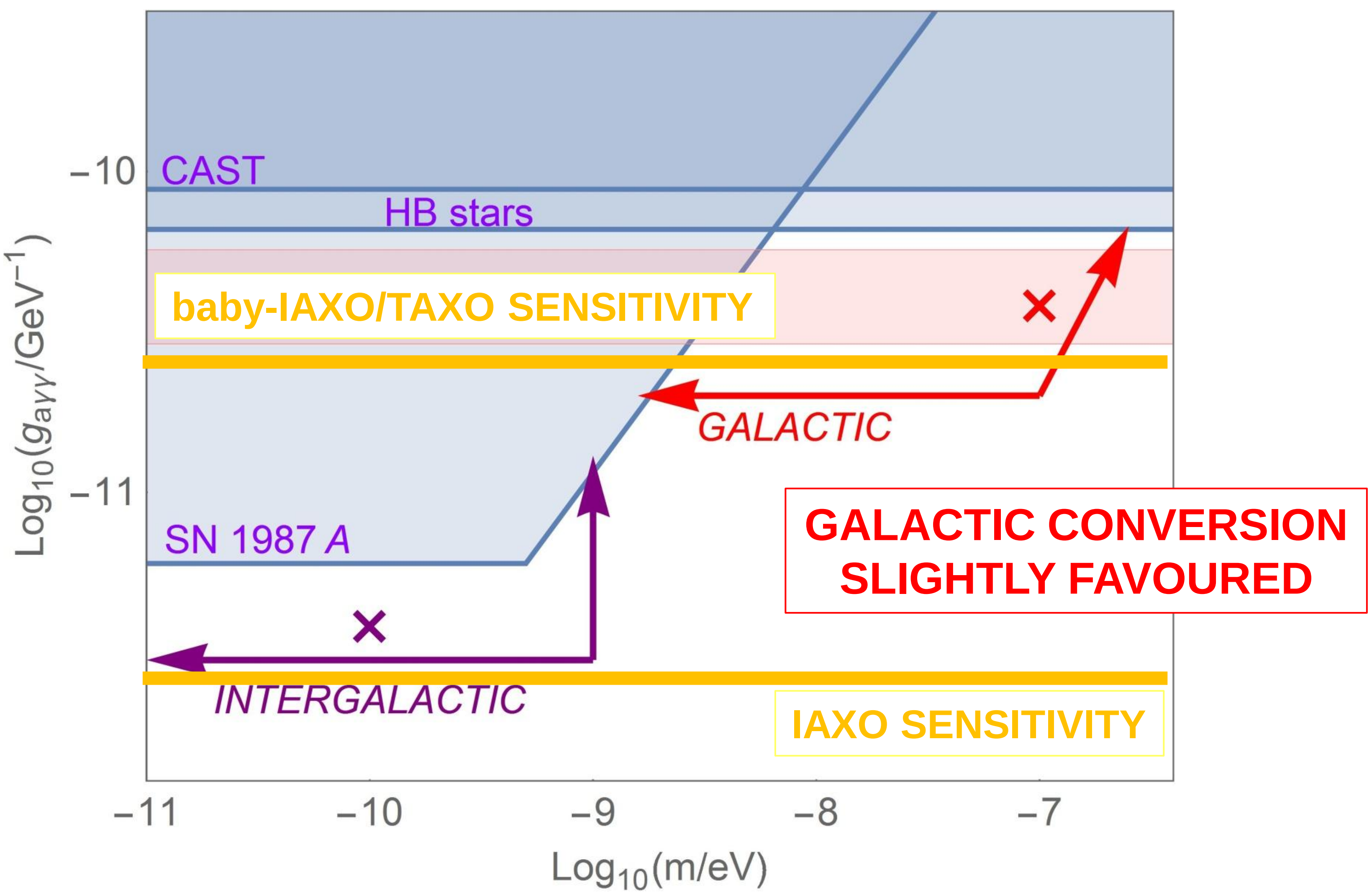
(experimental discovery wanted…)

FUTURE TESTS

- **Blazar gamma-ray astronomy**
  - more VHE sources FERMI, CTA
  - more distant sources, need (10-100) GeV
    ALEGRO (Atacama, Chile); EGO (Elbrus, Russia)
  - higher energies for “nearby” blazars
    EAS arrays: Carpet-2+ (Baksan, 2017), LHAASO, TAIGA
  - **detailed spectroscopy + anisotropy**
- **Intergalactic magnetic fields measurements/constraints**
- **Find an ALP and measure its coupling**
  IAXO, baby-IAXO, TAXO

Required ALP parameters

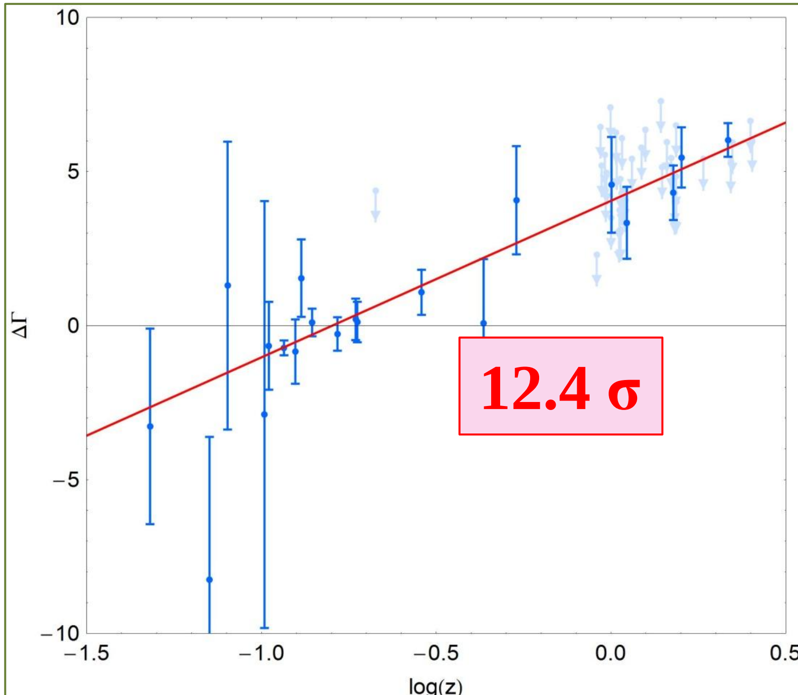
for the two scenarios



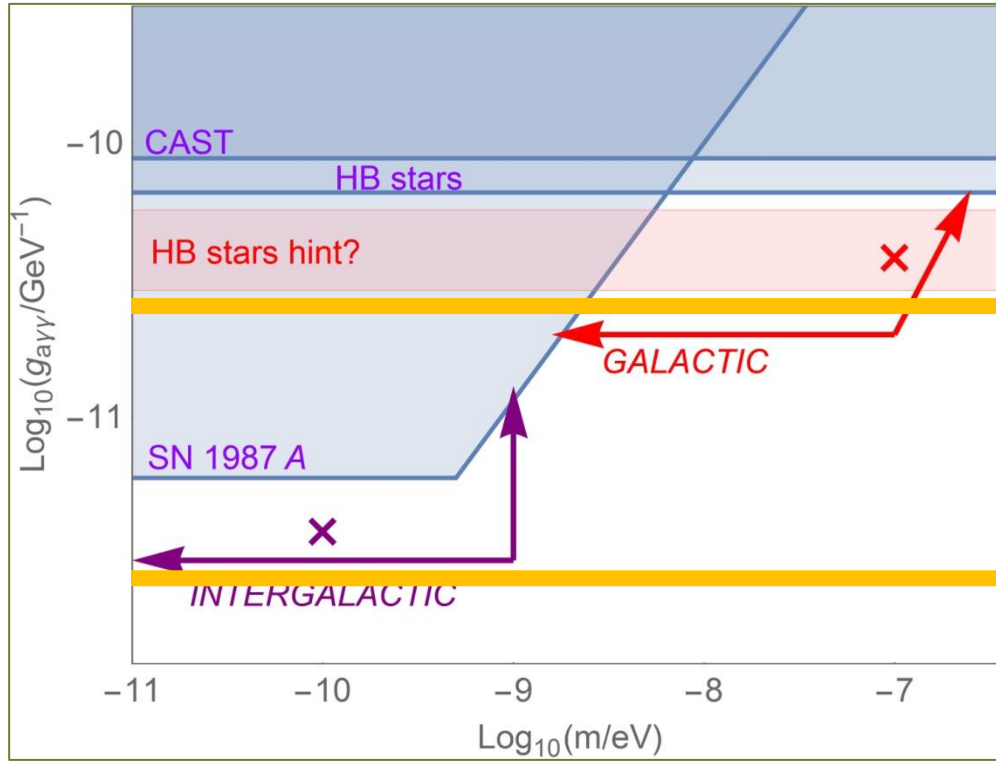
- ANOMALOUS TRANSPARENCY OF THE UNIVERSE
- ASTROPHYSICAL EXPLANATIONS DISFAVOURED
- CONVERSION OF PHOTONS TO AXION-LIKE PARTICLES HELPS
- GALACTIC AND EXTRAGALACTIC SCENARIOS MAY WORK
- WHY THESE PARAMETERS?
- FIND THE ALP!

GALACTIC: WITHIN THE baby-IAXO/TAXO SENSITIVITY

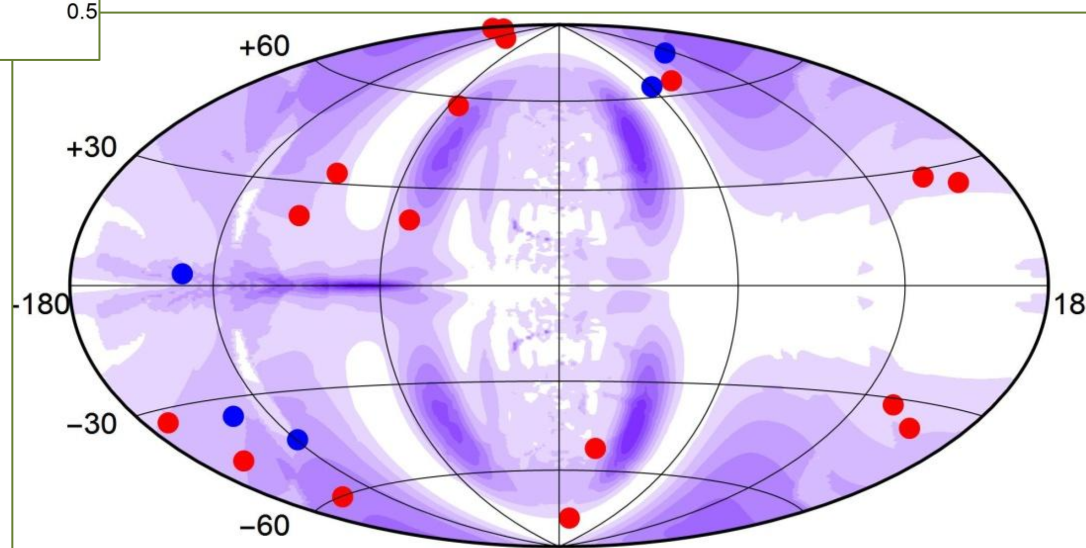
INTERGALACTIC: WITHIN THE full IAXO SENSITIVITY



10
5
0
−5
−10
ΔΓ
−1.5
−1.0
−0.5
0.0
0.5
log(z)
12.4 σ



−10
−11
$\mathrm{Log}_{10}(g_{a\gamma\gamma}/\mathrm{GeV}^{-1})$
CAST
HB stars
HB stars hint?
GALACTIC
SN 1987 A
INTERGALACTIC
−11
−10
−9
−8
−7
$\mathrm{Log}_{10}(\mathrm{m/eV})$

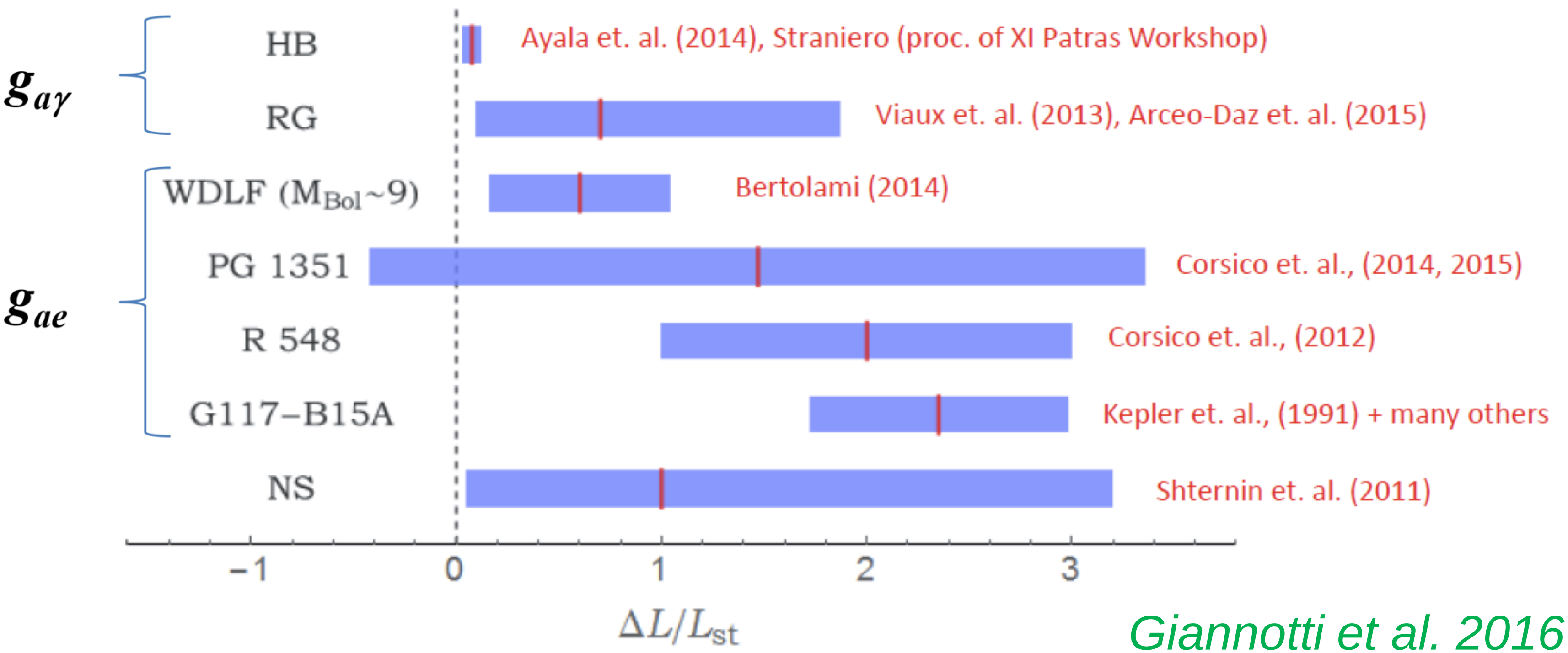


+60
+30
-180
180
−30
−60

THANK YOU!

BACKUP

Other astrophysical indications:
star cooling



Giannotti et al. 2016

horizontal-branch stars, red giants, white dwarfs, neutron stars – all cool faster than expected

(low significance, hard to combine)

Neutral UHE particles from BL Lacs?

- cosmic rays, $E>10^{18}$ eV
- HiRes stereo data (world-best angular resolution)
- 4% point to BL Lacs (1% expected background), $P\sim10^{-4}$-10^{-3}

Gorbunov, Tinyakov, Tkachev, ST 2004

HiRes collaboration 2005

- neutral particles from cosmological distances
- ALP/photon conversion = the only explanation

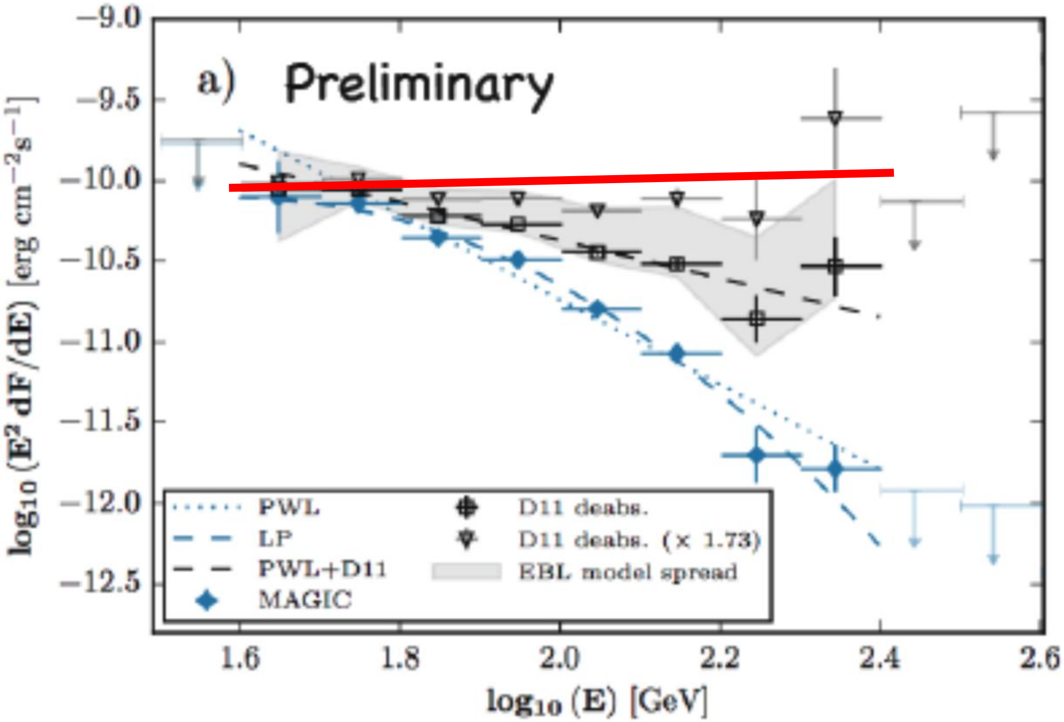
Fairbairn, Rashba, ST 2009

- the same ALP parameters

today's status:

- does not contradict to anything
- cannot be tested because of poor angular resolution of experiments (Auger, TA); Auger SD not sensitive to photons; TA too small.

The astronomical way of thinking:



MAGIC 2016

- ignore breaks, fit with power law ($\sim E^{-\alpha}$)

- intrinsic spectrum not very hard (α>1.5) ⇨ OK for the source

- can be done for every source ⇨ OK for the ensemble

Biteau, Williams 2015; Stecker, Scully, Malcan 2016

The astronomical way of thinking:

We don't see the anomaly with our observables. There is no anomaly.

- ignore breaks, fit with power law ($\sim E^{-\alpha}$)
- intrinsic spectrum not very hard (α>1.5) ⇨ OK for the source
- can be done for every source ⇨ OK for the ensemble

Biteau, Williams 2015; Stecker, Scully, Malcan 2016

The astronomical way of thinking:

We don’t see the anomaly with our observables. There is no anomaly.

A (maybe) better way of thinking:

Choose proper observables. Find the anomaly.

(example: H $\rightarrow \gamma\gamma$ vs. H $\rightarrow$ bb)

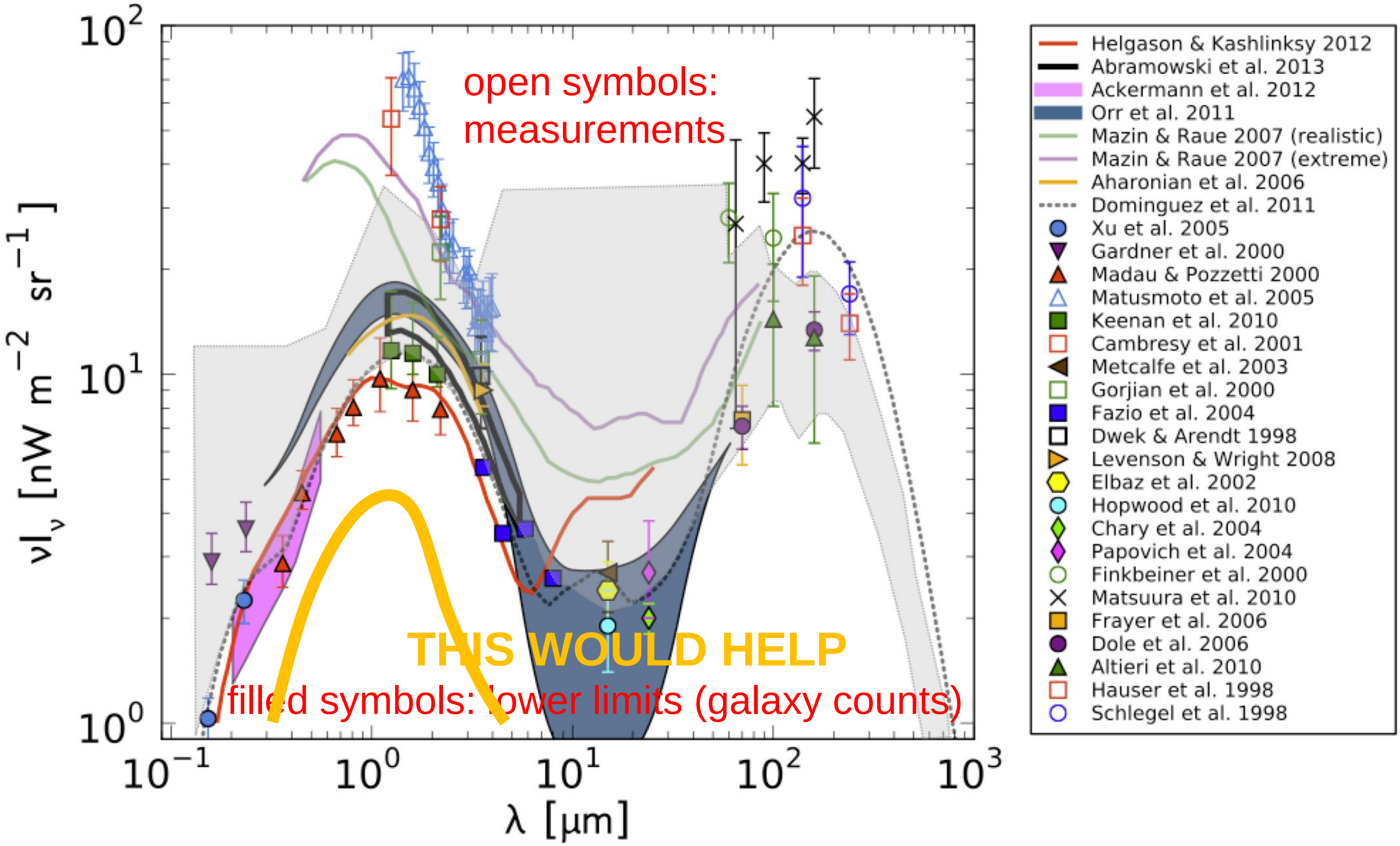
Non-axion explanations:

exotic astrophysics

I. Even lower extragalactic background light

Extragalactic background light density

Krennrich 2014



lines/areas: gamma-ray upper limits

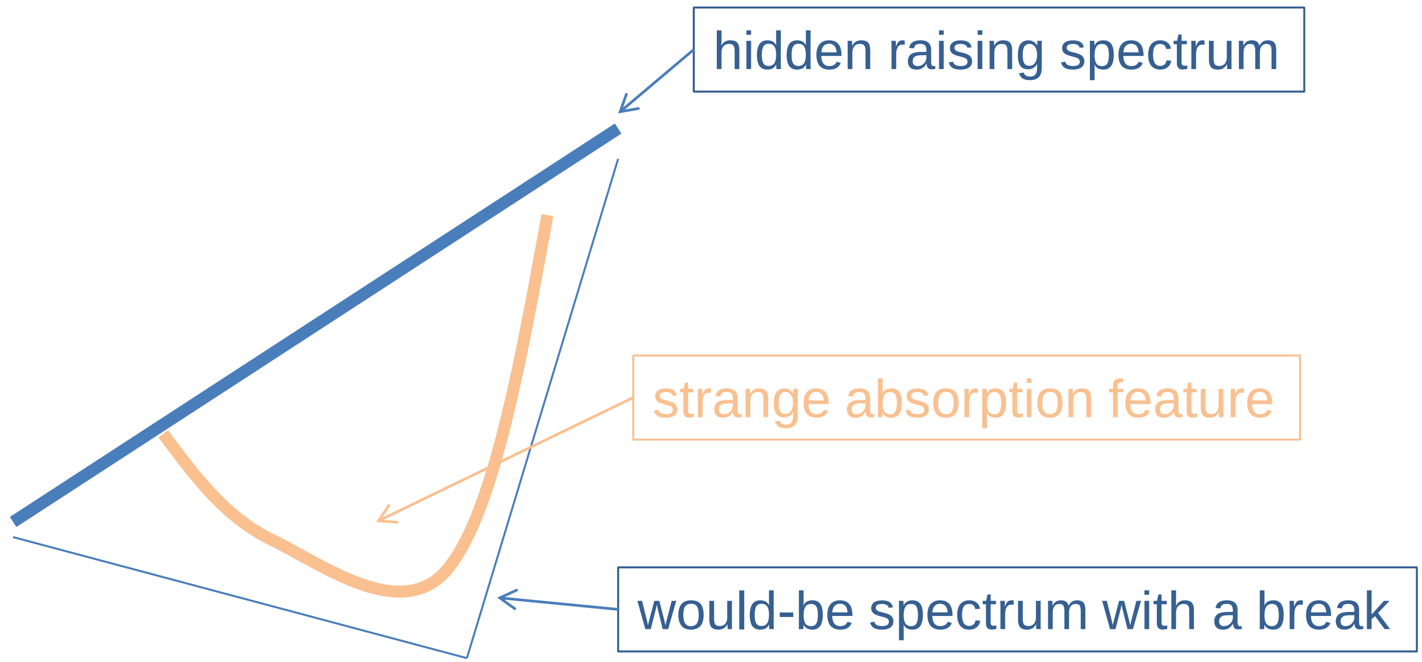
Non-axion explanations:

exotic astrophysics

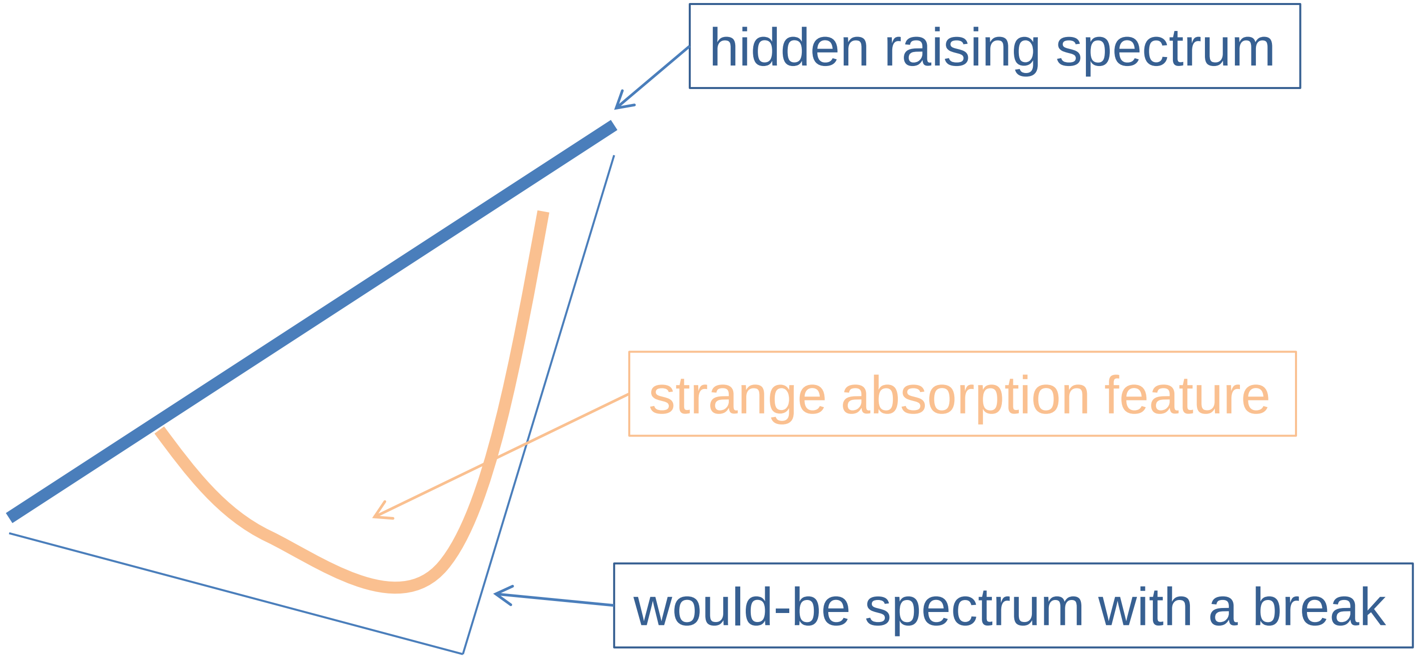
I. Even lower extragalactic background light

II. Redshift-dependent absorption features in sources

Absorption in the source:



Absorption in the source:



WORKING MODEL ABSENT EVEN WITHOUT REDSHIFT DEPENDENCE

Non-axion explanations:

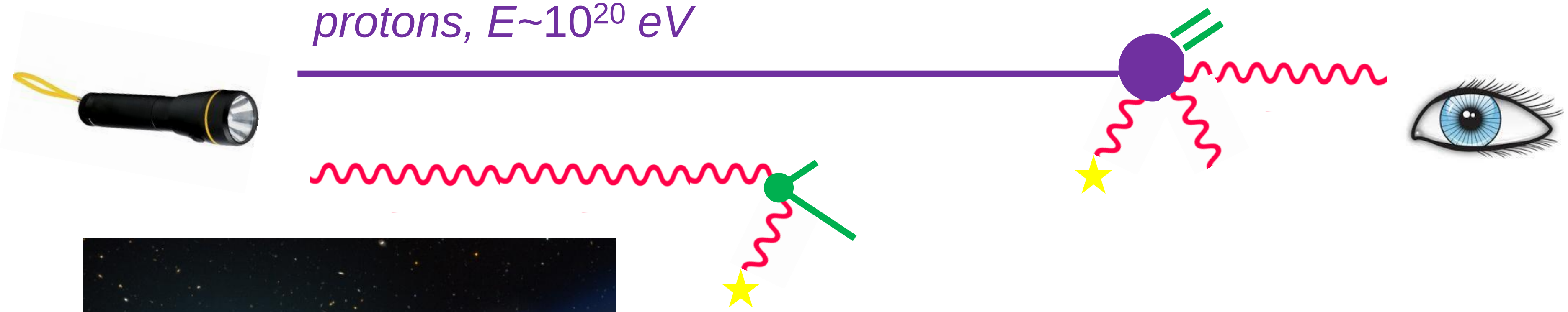
exotic astrophysics

I. *Even lower extragalactic background light*
II. *Redshift-dependent absorption features in sources*
III. *Photons not from the source*

Photons not from the source:

- the same sources fire ultra-high-energy cosmic rays
- the GZK process gives secondary photons (from π^0 decays)

Essay, Kusenko

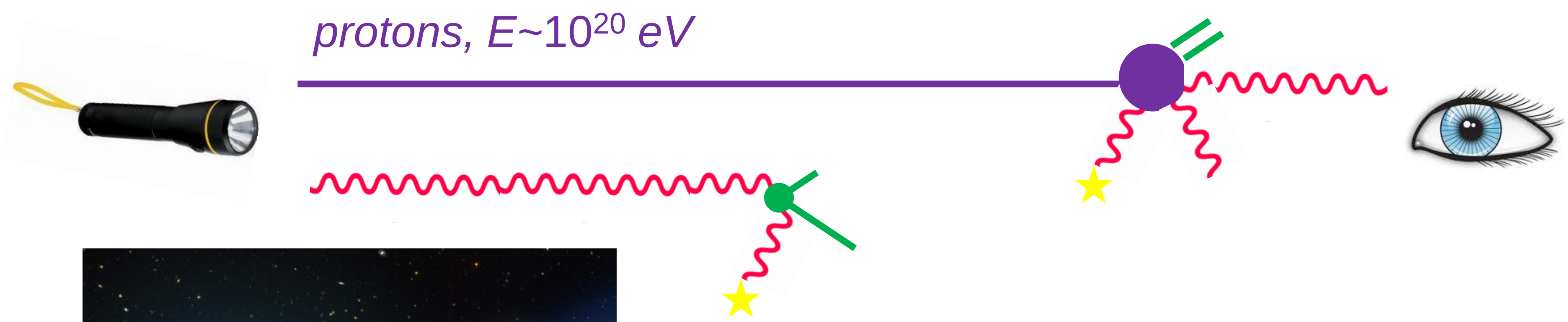


Photons not from the source:

- the same sources fire ultra-high-energy cosmic rays
- the GZK process gives secondary photons (from π^0 decays)

Essay, Kusenko

❑ unless extragalactic magnetic fields $<10^{-17}$ G ***everywhere***, unable to explain variability (e.g. of 4C+21.35)



Photon/ALP conversion

$$A(\mathbf{x},t) \quad \mapsto \quad A(\mathbf{x})\mathrm{e}^{-i\omega t}, \quad \omega^2 + \partial_z^2 \quad \mapsto \quad 2\omega\left(\omega - i\partial_z\right)$$

$$\Downarrow$$

$$(i\partial_z + \omega + \mathcal{M})\begin{pmatrix} A_x \\ A_y \\ a \end{pmatrix} = 0$$

where $\mathcal{M} \equiv \begin{pmatrix} \Delta_p + \Delta_{\mathrm{Q},\parallel} & 0 & \Delta_{Mx} \\ 0 & \Delta_p + \Delta_{\mathrm{Q},\perp} & \Delta_{My} \\ \Delta_{Mx} & \Delta_{My} & \Delta_m \end{pmatrix}$

Photon/ALP conversion

$$\Delta_p = \frac{\omega_p^2}{2\omega}$$

plasma frequency

$$\omega_p^2 = 4\pi\alpha\frac{n_e}{m_e}$$

QED contribution

$$\mathcal{M} \equiv \begin{pmatrix} \Delta_p + \Delta_{Q,\parallel} & 0 & \Delta_{Mx} \\ 0 & \Delta_p + \Delta_{Q,\perp} & \Delta_{My} \\ \Delta_{Mx} & \Delta_{My} & \Delta_m \end{pmatrix}$$

$$\Delta_M = \frac{B}{2M}$$

$$\Delta_m = \frac{m^2}{2\omega}$$

Photon/ALP conversion

conversion probability (constant B, n_e):

$$P = \frac{4\Delta_M^2}{(\Delta_p + \Delta_{Q,\perp} - \Delta_m)^2 + 4\Delta_M^2} \sin^2\left(\frac{1}{2} L \Delta_{\mathrm{osc}}\right)$$

where $$\Delta_{\mathrm{osc}}^2 = (\Delta_p + \Delta_{Q,\perp} - \Delta_m)^2 + 4\Delta_M^2$$

Photon/ALP conversion

Estimate required parameters

maximal mixing conditions:

$$\Delta_m \ll 2\Delta_M \quad \Rightarrow \quad \omega \gg 700 \text{ eV} \left(\frac{m}{10^{-9}\text{ eV}}\right)^2 \left(\frac{B}{\text{G}}\right)^{-1} \left(\frac{M}{10^{11}\text{ GeV}}\right)$$

$$\Delta_p \ll 2\Delta_M \quad \Rightarrow \quad n_e \ll 10^{13}\text{ cm}^{-3} \left(\frac{\omega}{\text{TeV}}\right) \left(\frac{B}{\text{G}}\right)$$

$$\Delta_{Q,\perp} \ll \Delta_M \quad \Rightarrow \quad \left(\frac{\omega}{\text{TeV}}\right) \left(\frac{B}{\text{G}}\right) \ll 7.52 \times 10^{-2}$$

$$L \gtrsim \frac{\pi}{\Delta_{\text{osc}}} \quad \Rightarrow \quad L \gtrsim 5.8 \times 10^{-2}\text{ pc} \left(\frac{B}{\text{G}}\right)^{-1} \left(\frac{M}{10^{11}\text{ GeV}}\right)$$

Photon/ALP conversion

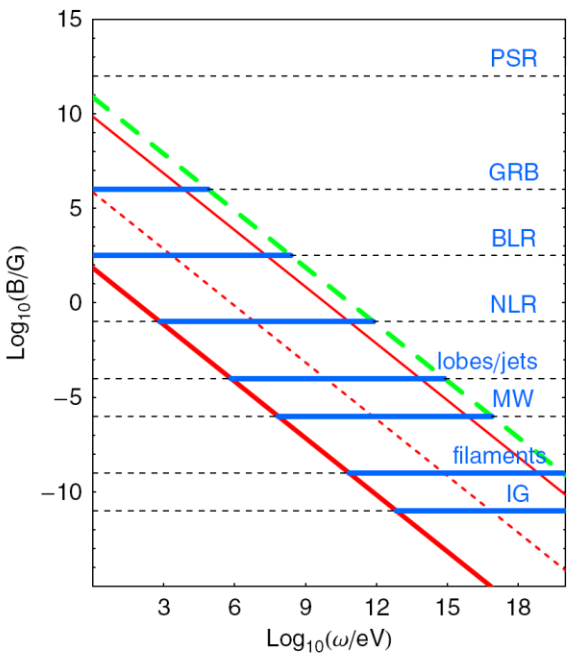
Estimate required parameters

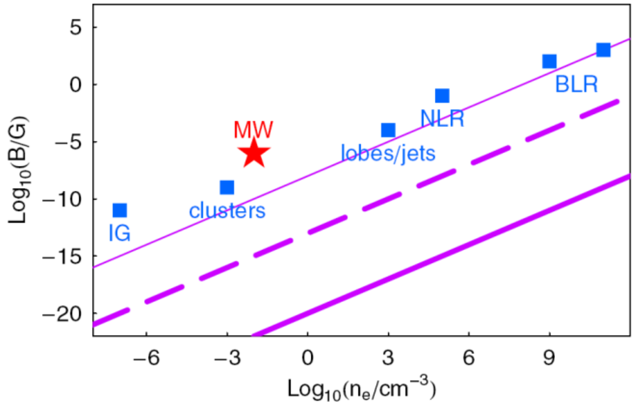
maximal mixing conditions:

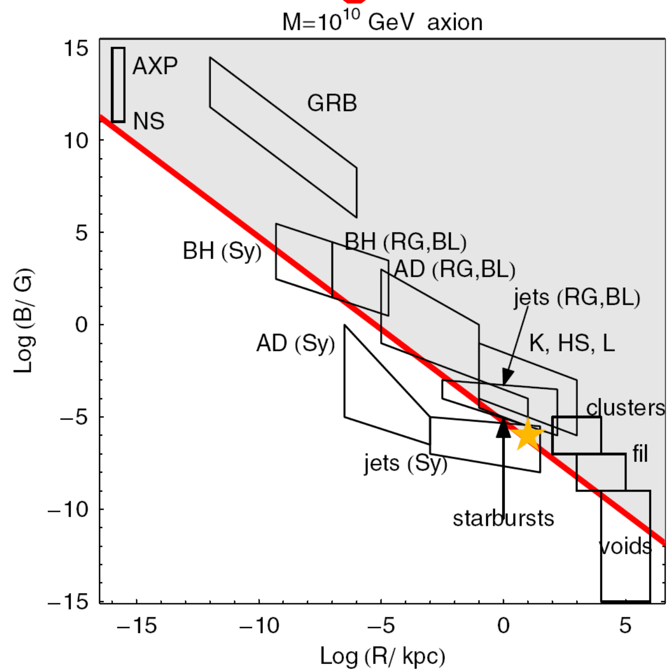
$$\Delta_m \ll 2\Delta_M$$
$$\Delta_{Q,\perp} \ll \Delta_M$$

$$\Delta_p \ll 2\Delta_M$$

$$L \gtrsim \frac{\pi}{\Delta_{\rm osc}}$$





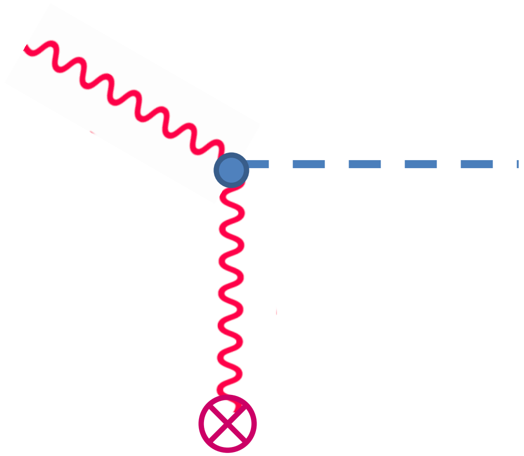


Fairbairn et al. 2009

Solar axions/ALPs:

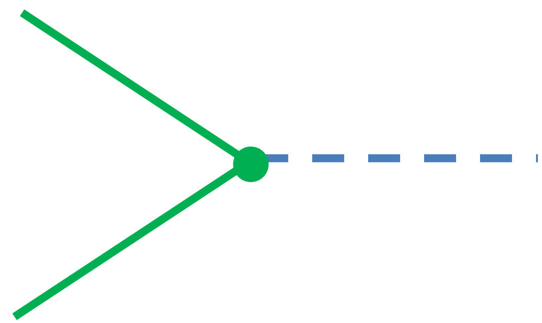
- **Sun = axion source:**

(1)



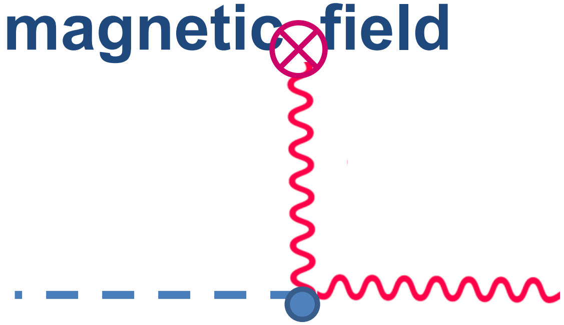
Primakoff effect

(2)



interaction with electrons

- **Reconversion in the telescope's magnetic field**



(other methods exist)

Solar axions/ALPs:

CAST = CERN axion solar telescope

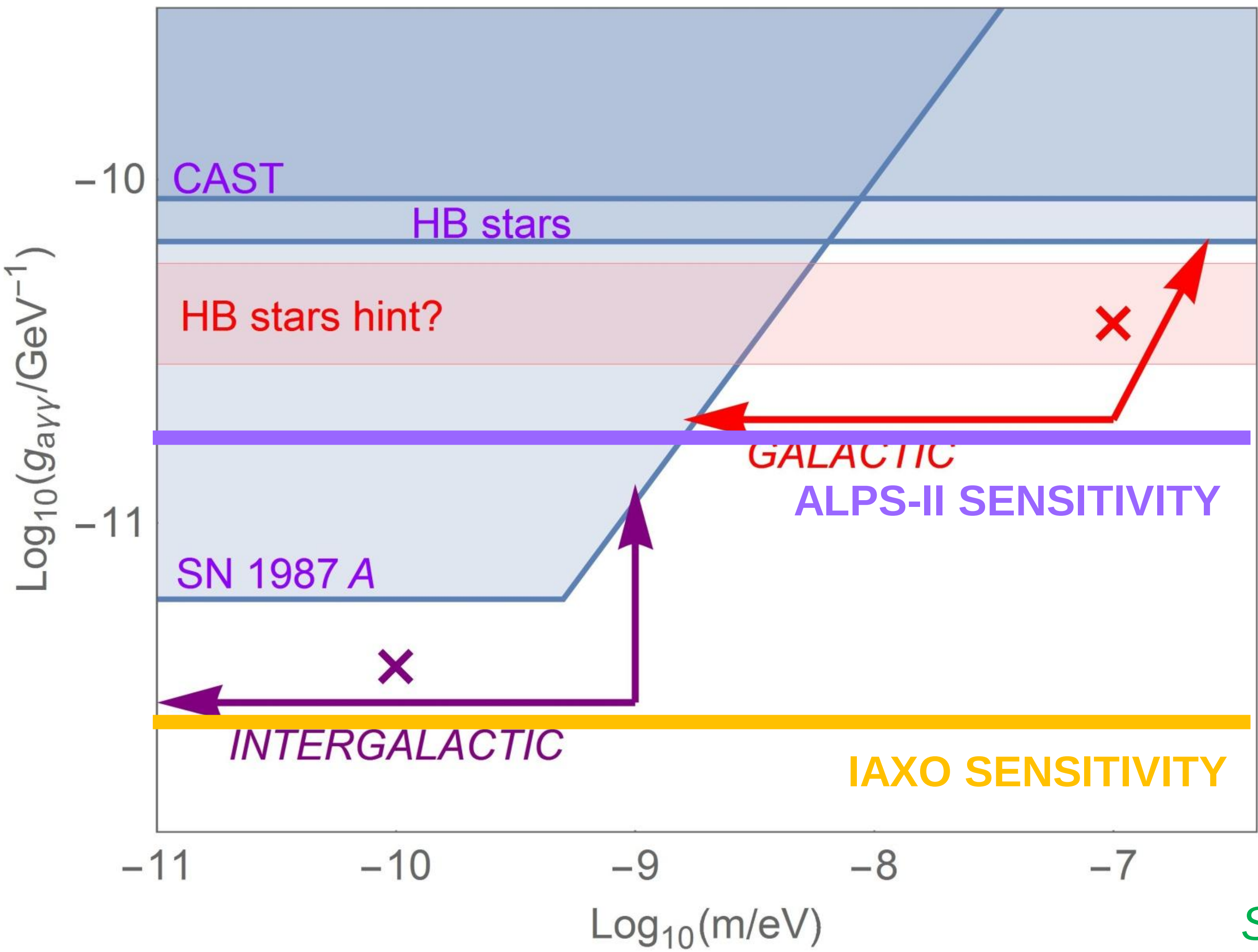
working

prospects

IAXO = International axion observatory

Required ALP parameters

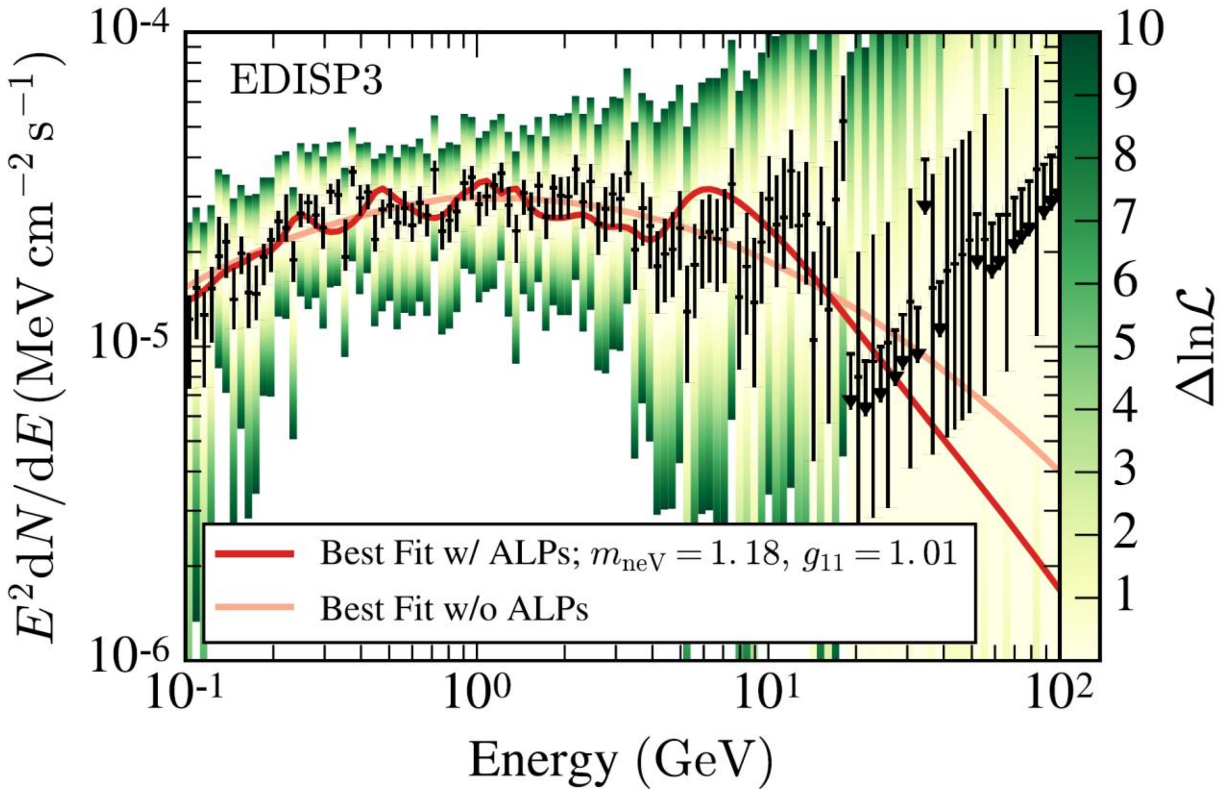
for the two scenarios



ST 2015

ALP spectra irregularities: constraints, hints…?

NGC 1275 in the Perseus cluster, FERMI-LAT data



Smooth fit better ➡ constraints on ALPs?

FERMI-LAT 2016

ALP spectra irregularities: constraints, hints…?

NGC 1275 in the Perseus cluster, FERMI-LAT data

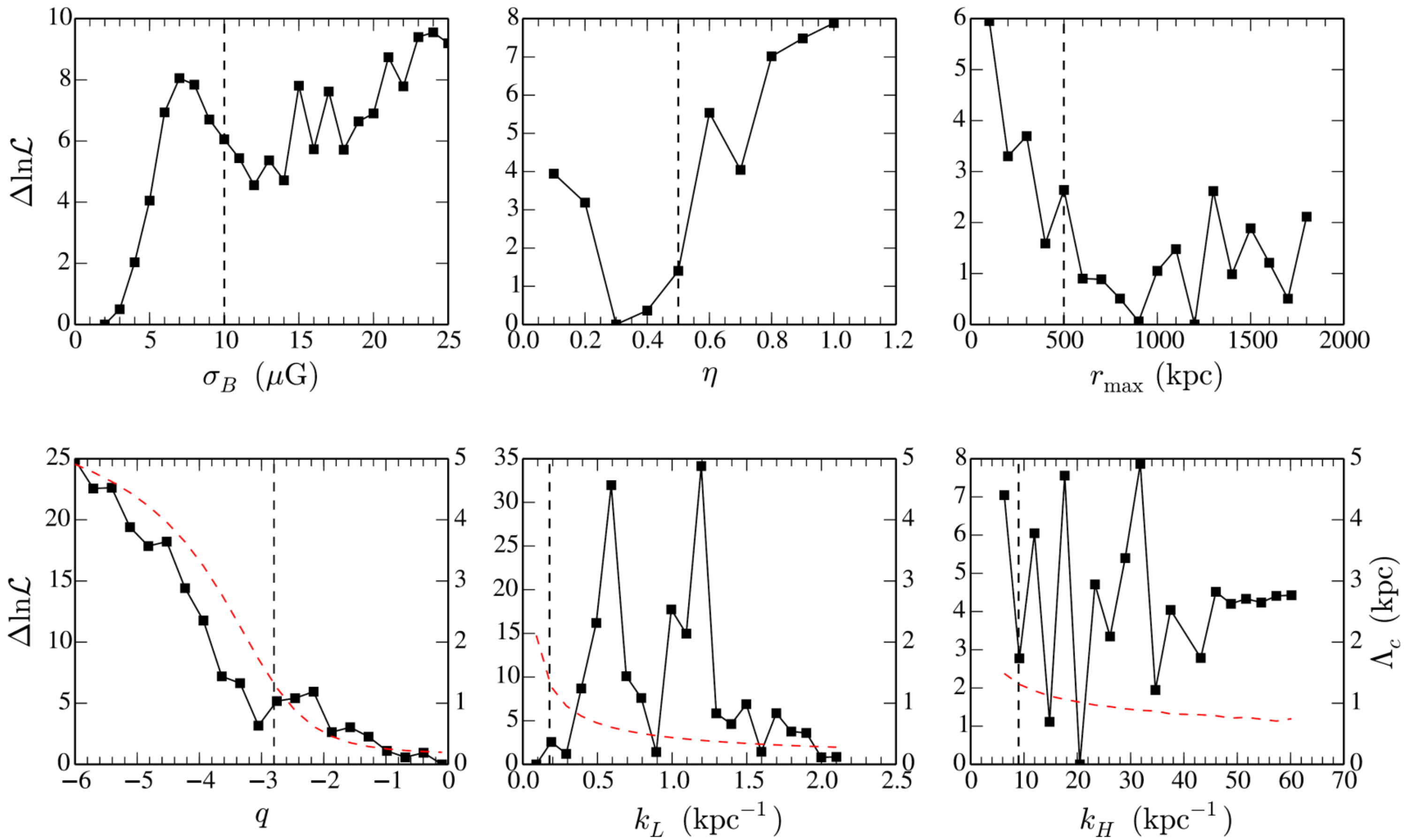
Magnetic field in the cluster not measured!

- a 6-parameter theoretical model used…
- no regular field, only turbulent
- no 6-parameter scan,
  only fiducial point + 1-parameter variations
- still perfect fits with ALPs in the “excluded” region…

FERMI-LAT 2016

ALP spectra irregularities: constraints, hints…?

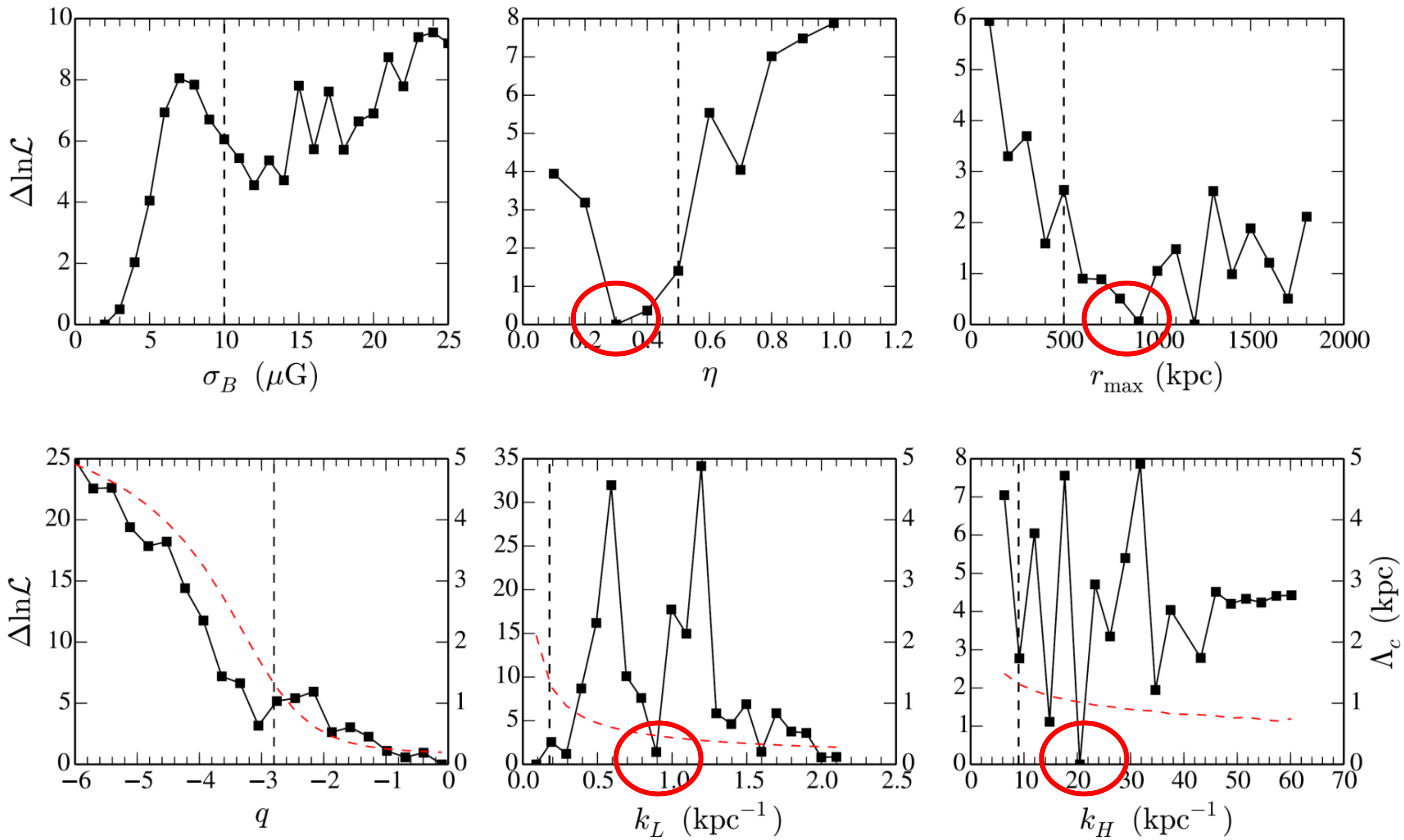
NGC 1275 in the Perseus cluster, FERMI-LAT data



FERMI-LAT 2016

ALP spectra irregularities: constraints, hints…?

NGC 1275 in the Perseus cluster, FERMI-LAT data



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ALP spectra irregularities: constraints, hints…?

Galactic sources, Galactic magnetic field – hints?

Searches for modulation of gamma-ray spectra in the Galactic magnetic field as a signature of photon-ALPs mixing

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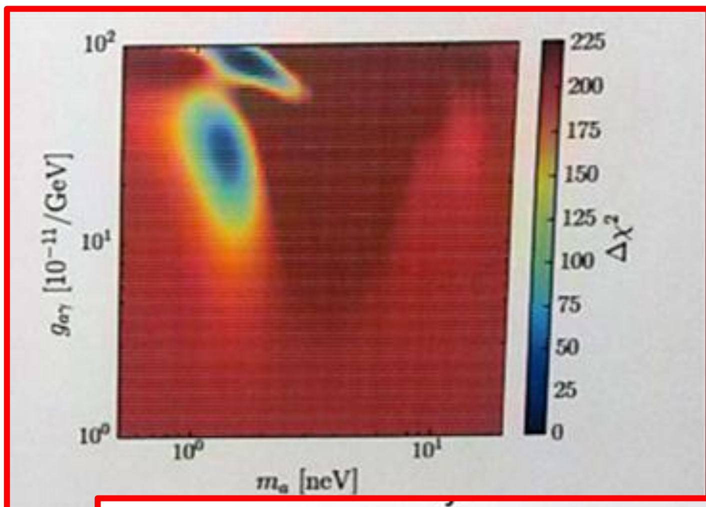
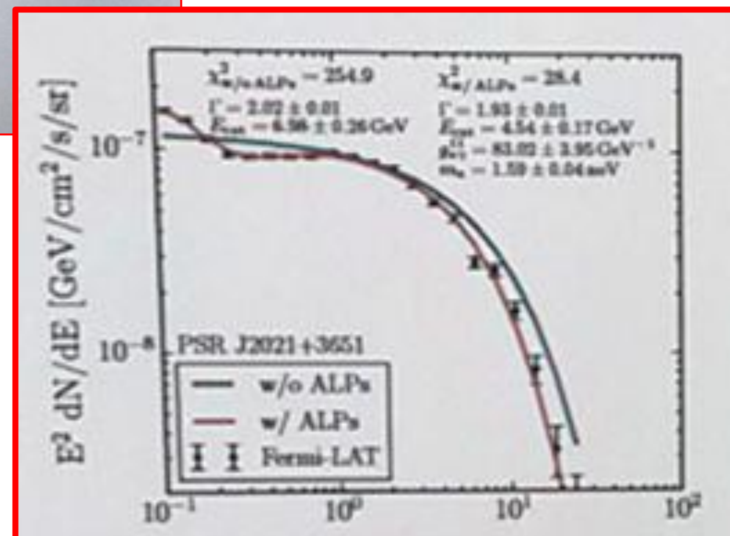
poster @ TeVPA 2016





- Allowing for a mixing of mass and coupling leads to a significant improvement of the resulting fit for two candidate spectra , i.e. PSR J2021+3651 and Fermi bubbles.