High-energy astrophysics & ALPs - 2

Photon-ALP conversion inside blazar jets

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IAXO The Search of Axions in the Universe
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Outline

Introduction

The strange case of PKS 1222+216

ALPs from VHE emitting BL Lac objects

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The strange case of PKS 1222+216

ALPs from VHE emitting BL Lac objects

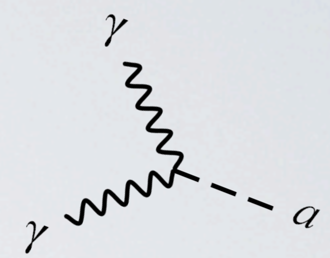
MOTIVATIONS

- Axion: pseudo-scalar boson expected in the PQ mechanism for solving the "strong CP problem"
- Axion-like particles (ALPs): light pseudo-scalar particles expected in several extensions of SM (e.g. string theory)
- Possible DM candidate

Beyond the SM at low energies

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

M>1.4x10^{10} GeV

or

$g_{a\gamma\gamma}$< 0.88x10^{-10} GeV^{-1}

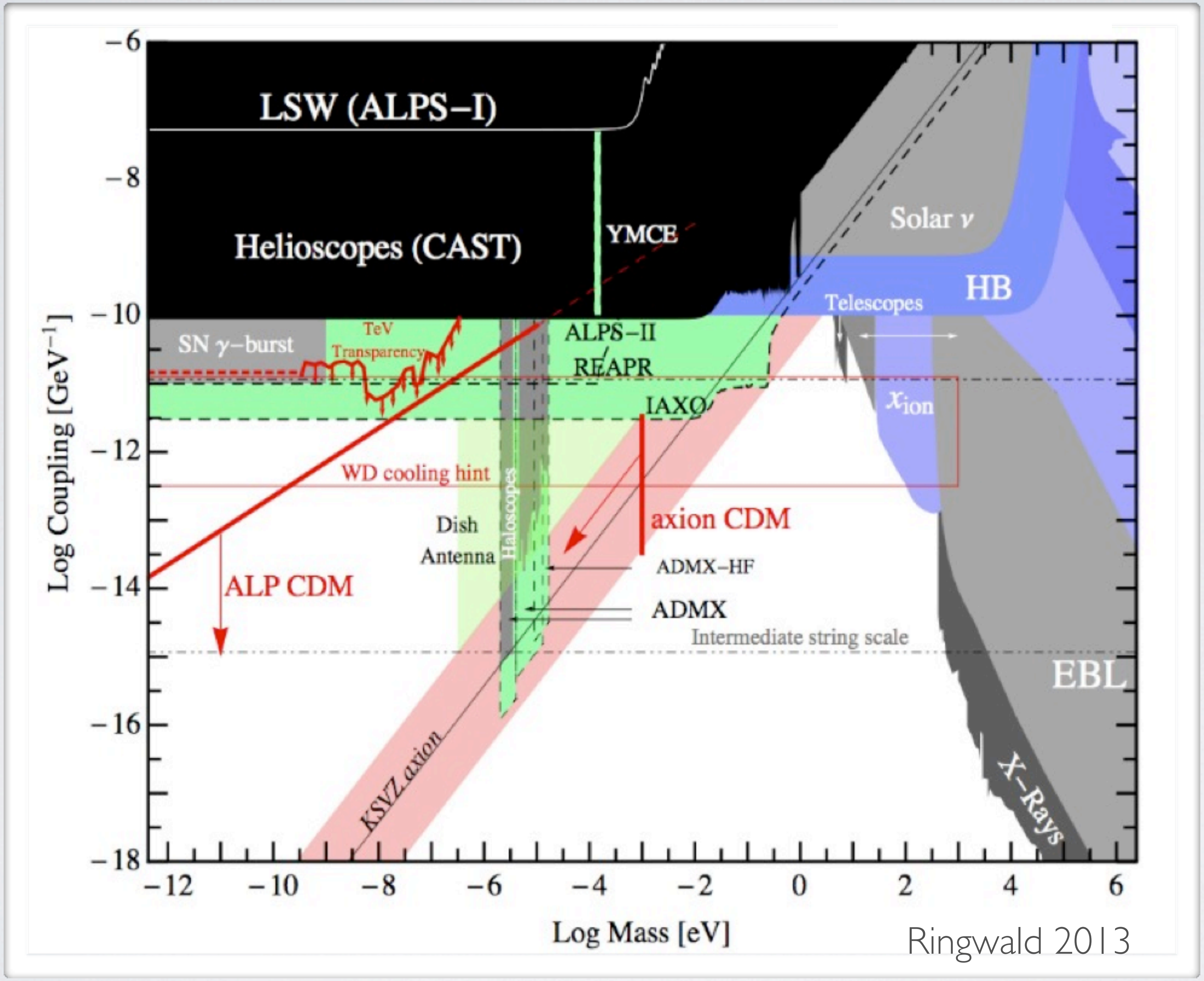
(CAST)

Only the "transverse" B-field relevant for conversion

Only 1/2 of unpolarized photons couple to ALPs

ALPs: phenomenology

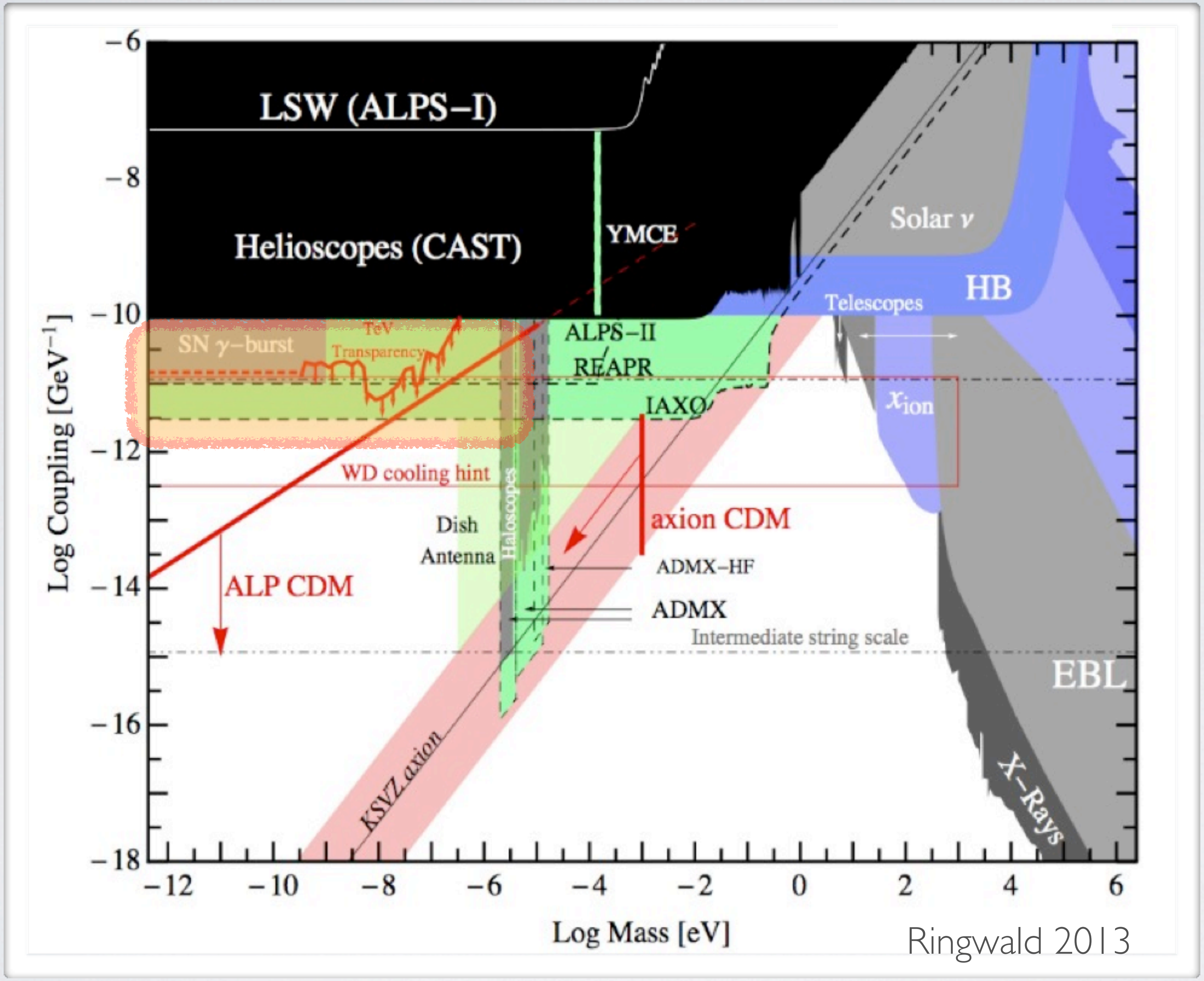
Coupling



Mass

ALPs: phenomenology

Coupling



Mass

ALPs: phenomenology

Photon-ALP conversion
in a uniform B-field

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

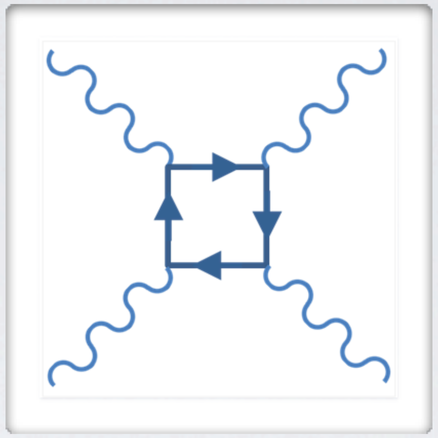
$$\Delta_{\rm osc}(E) \equiv \left[\left(\frac{m^2 - \omega_{\rm pl}^2}{2E}\right)^2 + g_{a\gamma\gamma}^2 B_T^2\right]^{1/2}$$

Strong mixing regime:
P maximal and E-independent

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

ALPs: phenomenology

Vacuum polarization (QED)



Effective lagrangian:

$$\mathcal{L}_{\mathrm{HEW}} = \frac{2\alpha^2}{45 m_e^4}\left[\left(\mathbf{E}^2 - \mathbf{B}^2\right)^2 + 7\left(\mathbf{E}\cdot\mathbf{B}\right)^2\right]$$

Dominating over photon-ALP conversion above:

$$E_H \simeq 2.1\left(\frac{G}{B_T}\right)\left(\frac{10^{11}\ \mathrm{GeV}}{M}\right)\ \mathrm{GeV}$$

Not relevant for small ($<10^{-6}$ G) B in clusters/ intergalactic space but not negligible in jets (B~1 G)

Model of the source

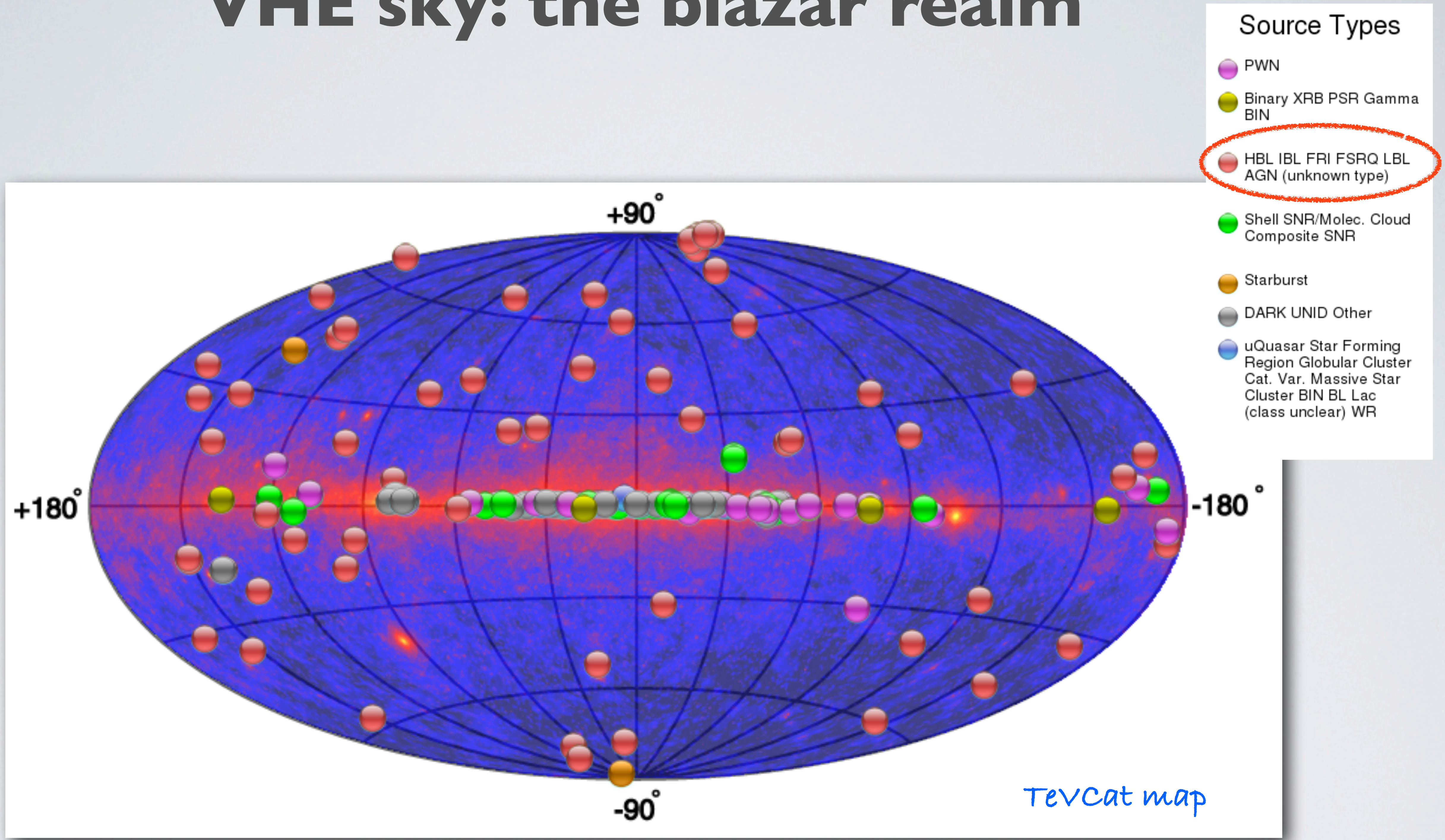
Conversion/reconversion in the intergalactic space and Milky Way rather well studied

(e.g., Hooper & Serpico 2007, De Angelis et al. 2008, 2011, Horns et al. 2013).

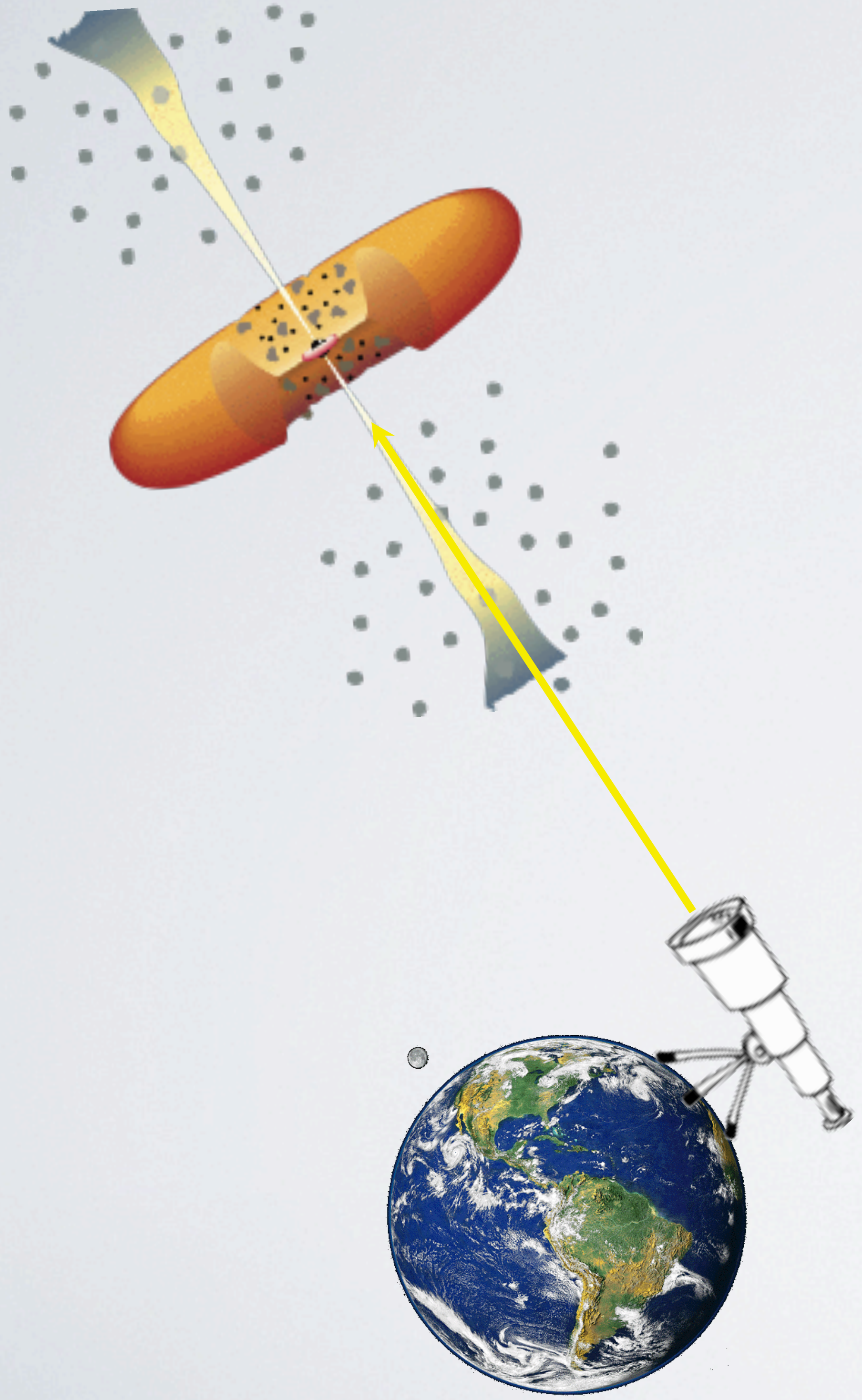
Calculations of conversion in the source still too simple.

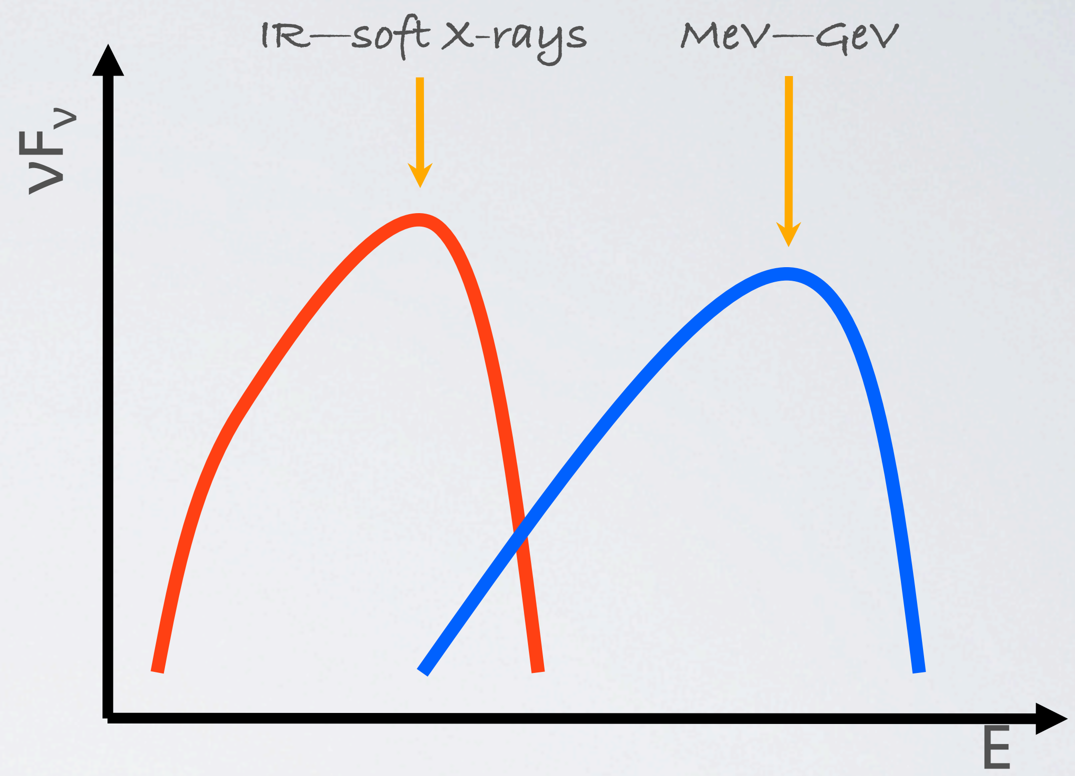
Often unrealistic assumptions (e.g., maximal conversion).

VHE sky: the blazar realm



Blazars: phenomenology



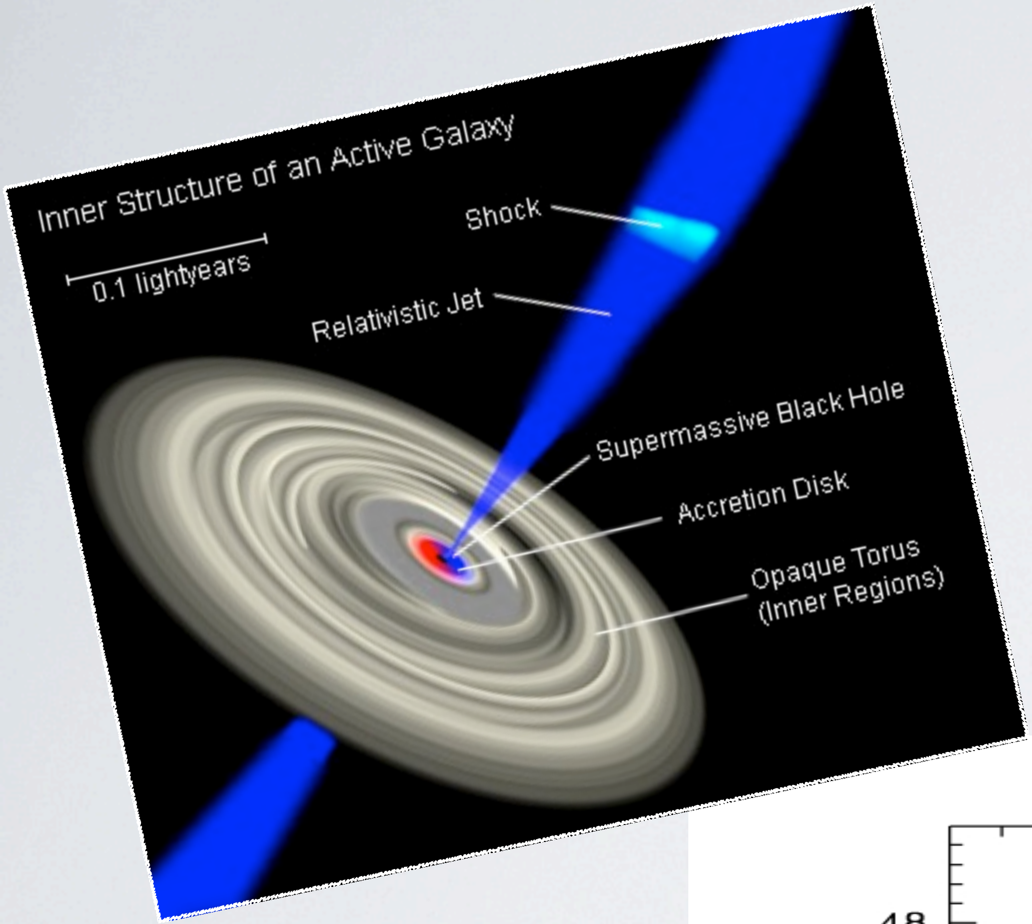


SED dominated by the <u>relativistically boosted</u> non-thermal continuum emission of the jet.

Synchrotron and IC in leptonic models

Also hadronic scenarios are considered

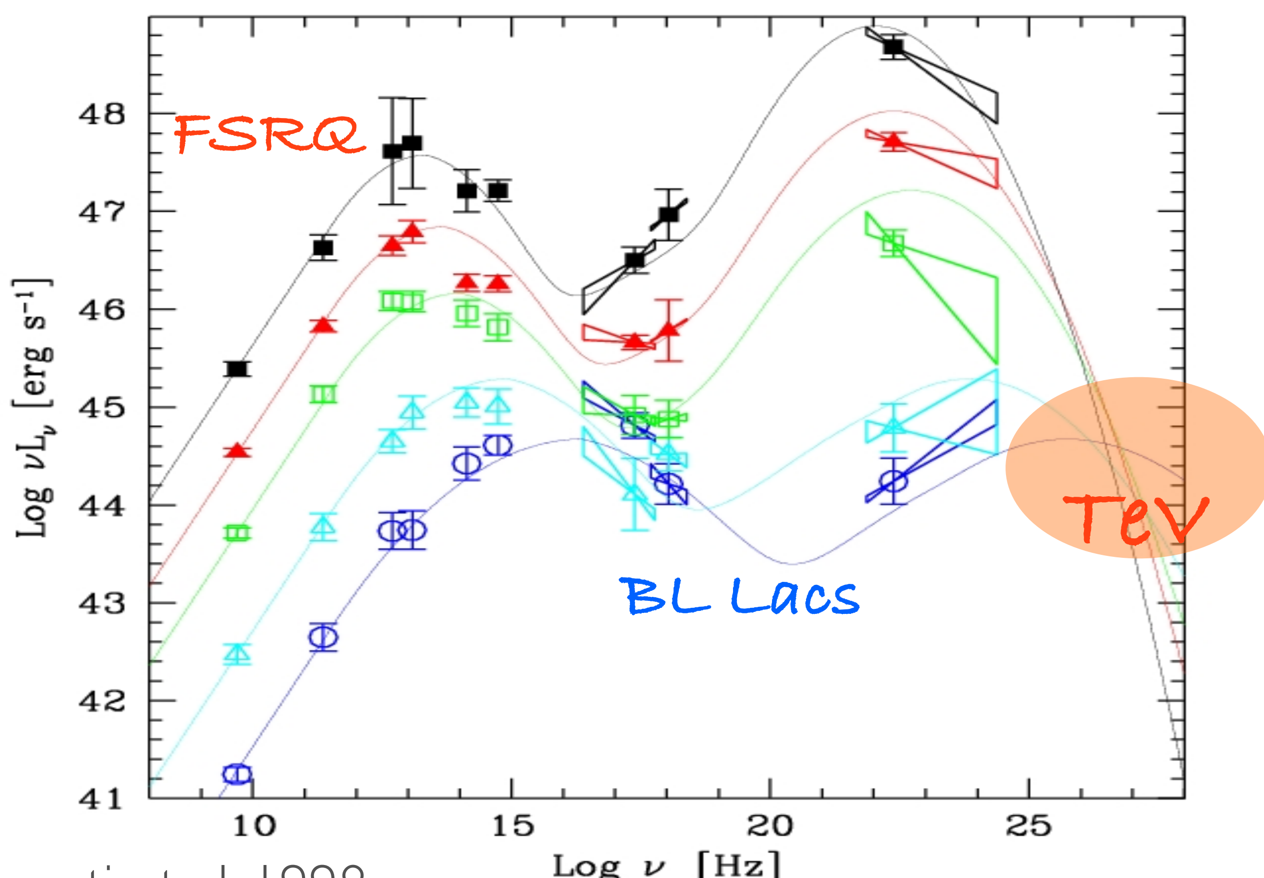
Blazars: phenomenology



Blazars occur in two flavors:

FSRQ: high power, thermal optical components

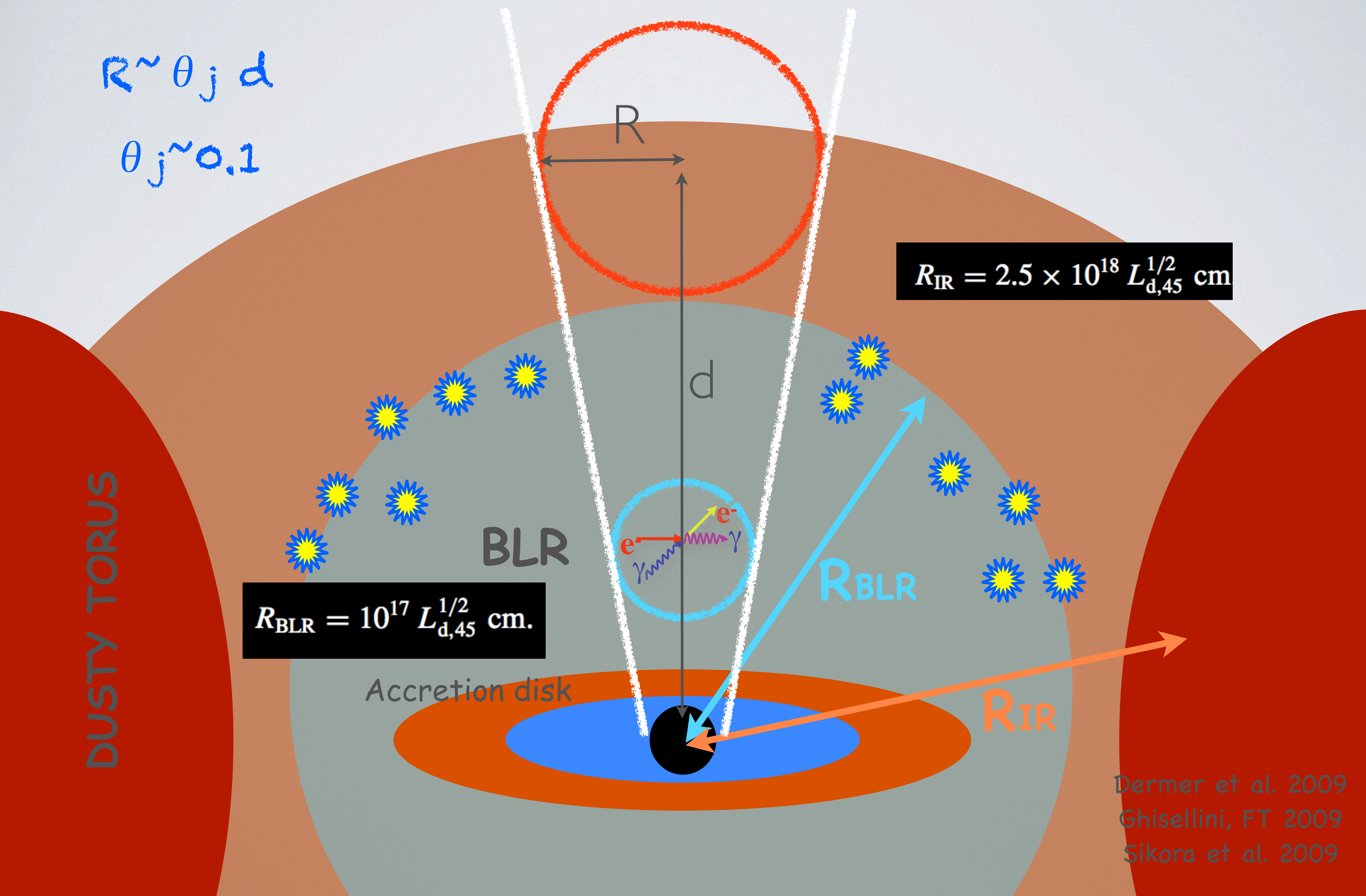
BL Lacs: low power, lack of important thermal comp.



Fossati et al. 1998

The blazar sequence

FSRQ: "dressed" jets



Dermer et al. 2009
Ghisellini, FT 2009
Sikora et al. 2009

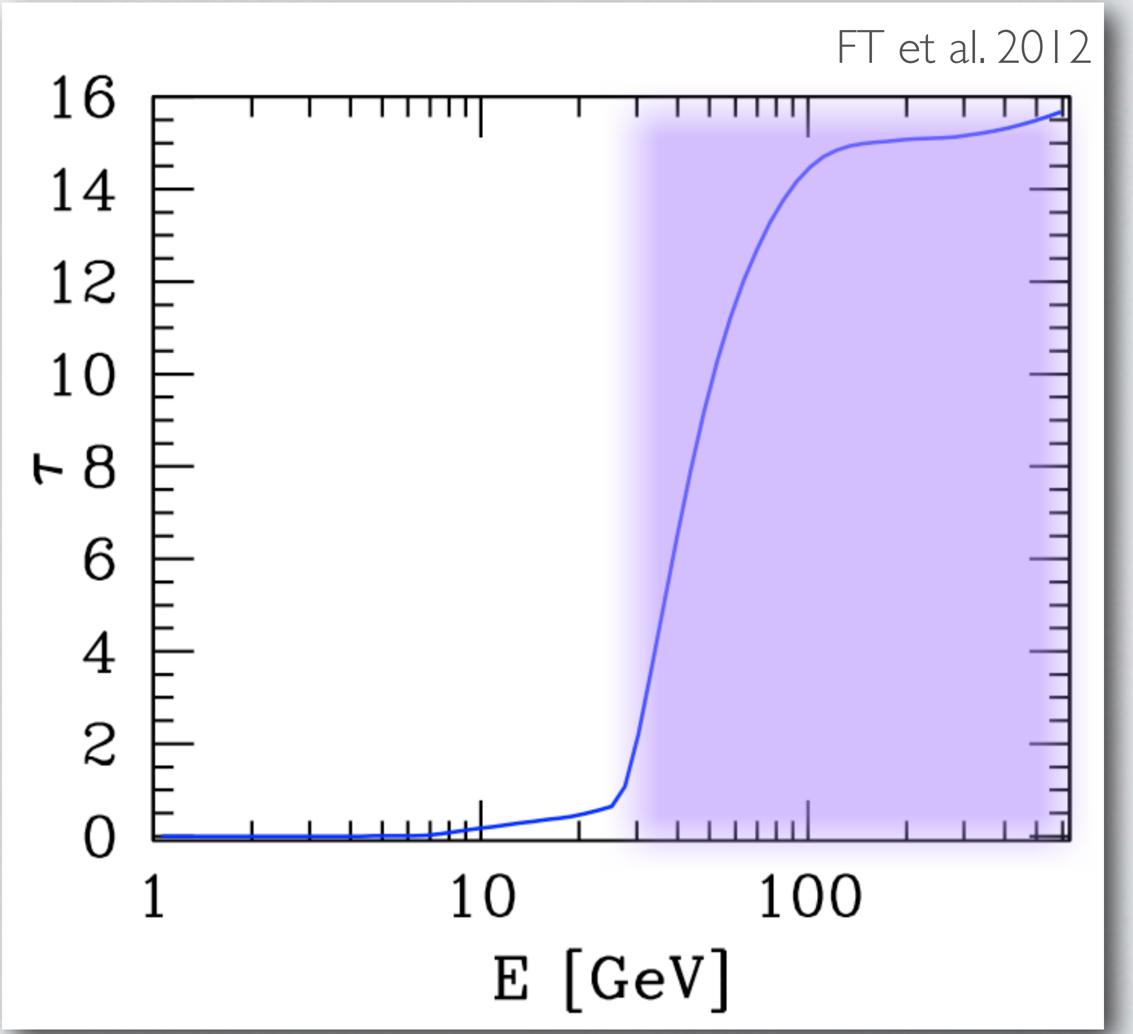
Absorption in FSRQ

$$\gamma + \gamma \to e^{\pm}$$

Threshold: $E\epsilon > m_e^2 c^4$ (head-on collision)

$$\epsilon(E) \simeq \left(\frac{500\ \mathrm{GeV}}{E}\right)\ \mathrm{eV}$$

$$F_{\rm obs}(E) = F_{\rm em}(E) e^{-\tau(E)}$$



Huge opacity above 30 GeV if emission occurs inside BLR (H Lyα photons)

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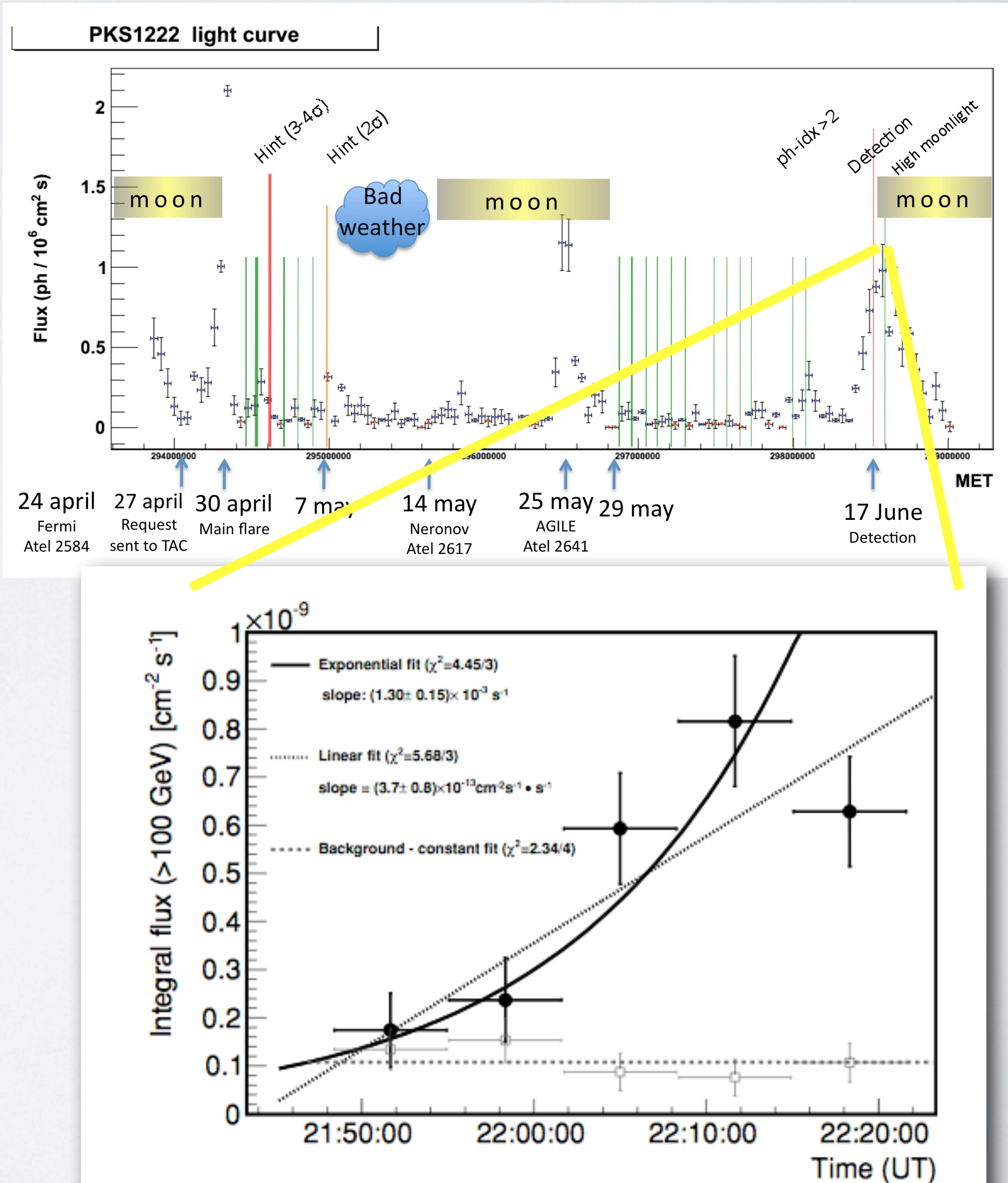
The strange case of PKS 1222+216

$t_{double} \sim 10$ min!

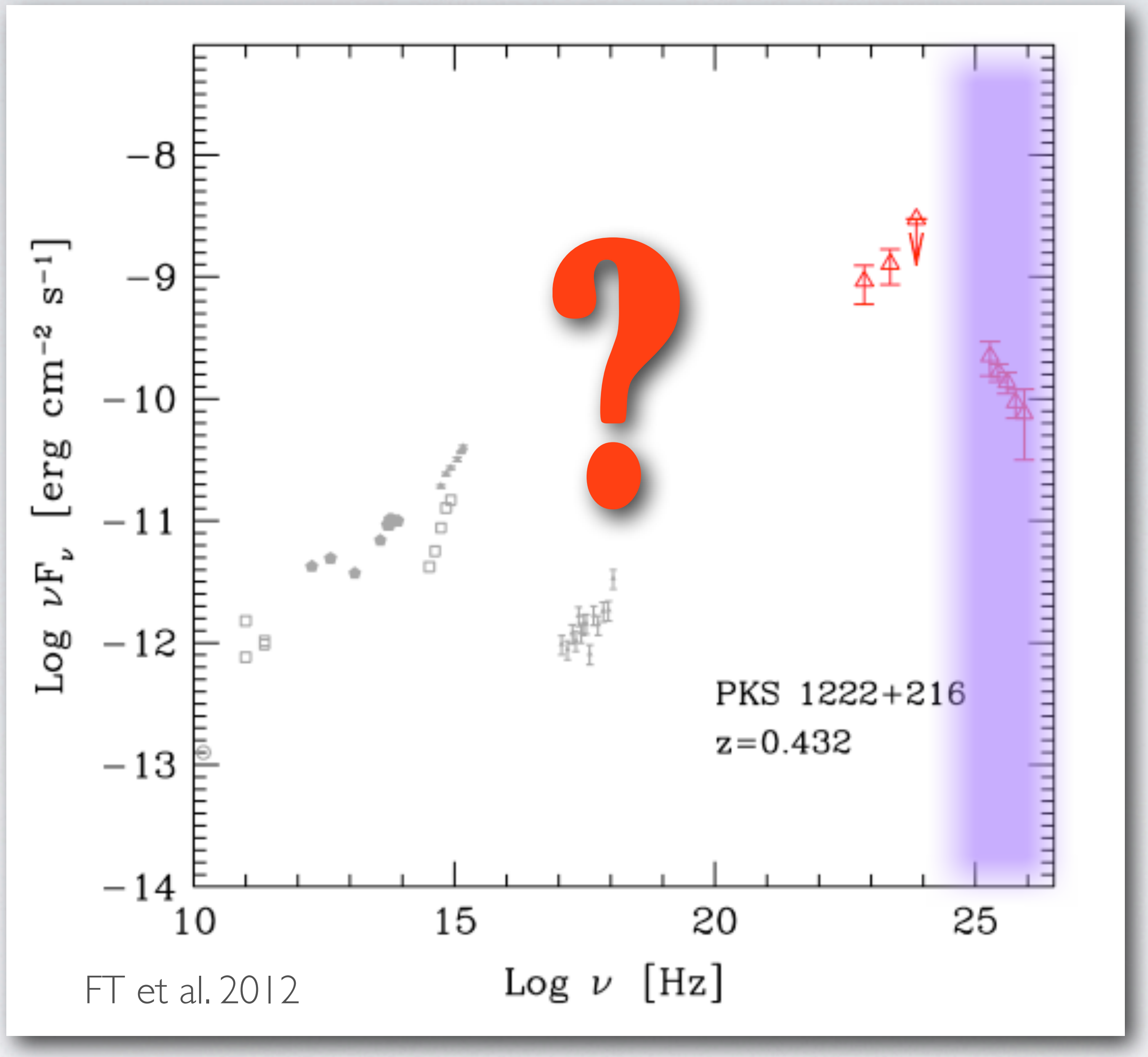
$$R < c t_{\rm var} \frac{\delta}{1+z} \simeq 1.2 \times 10^{14} \left(\frac{\delta}{10}\right) \text{ cm}$$

Deep inside BLR

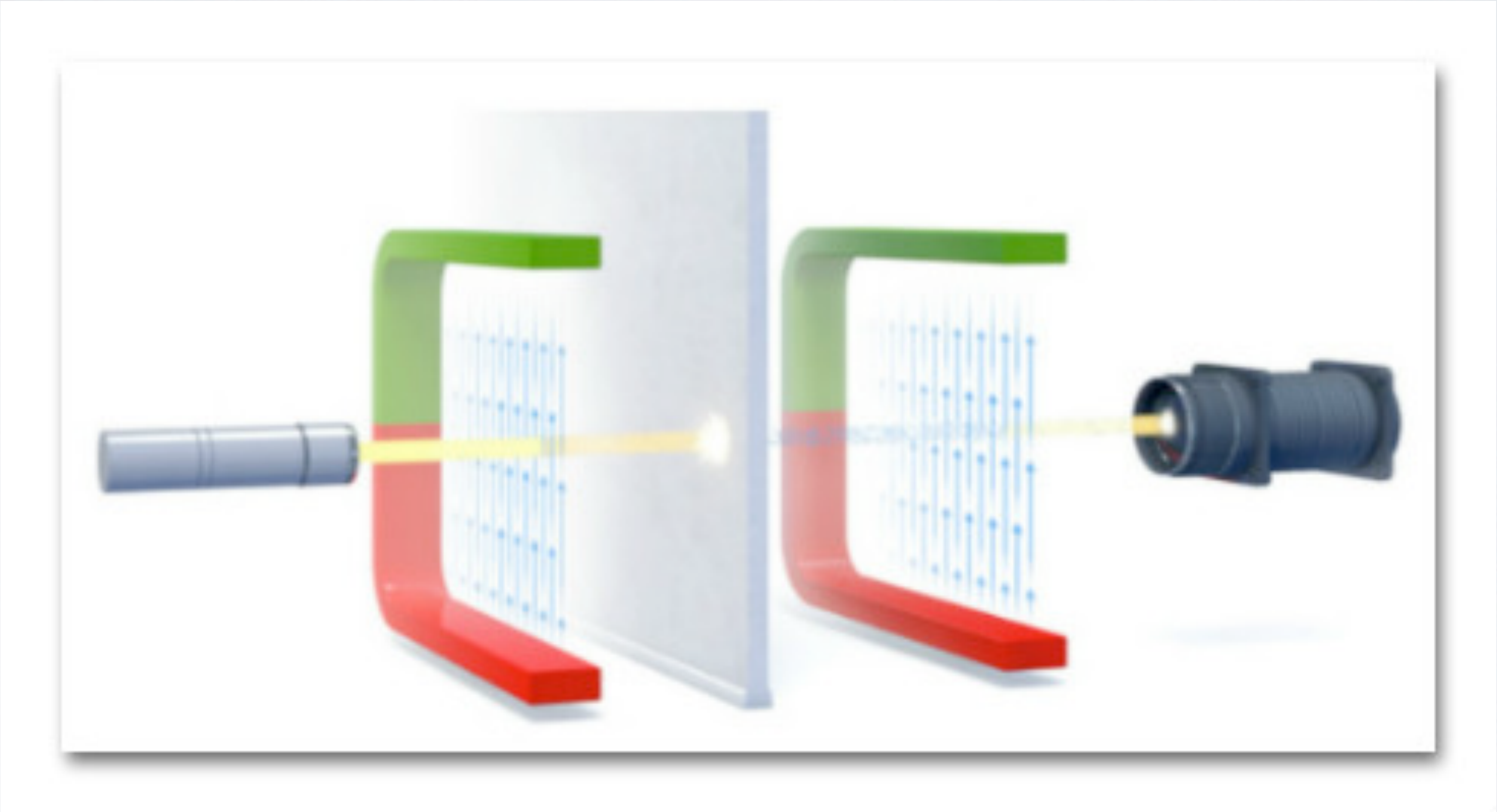
Huge absorption expected



The strange case of PKS 1222+216

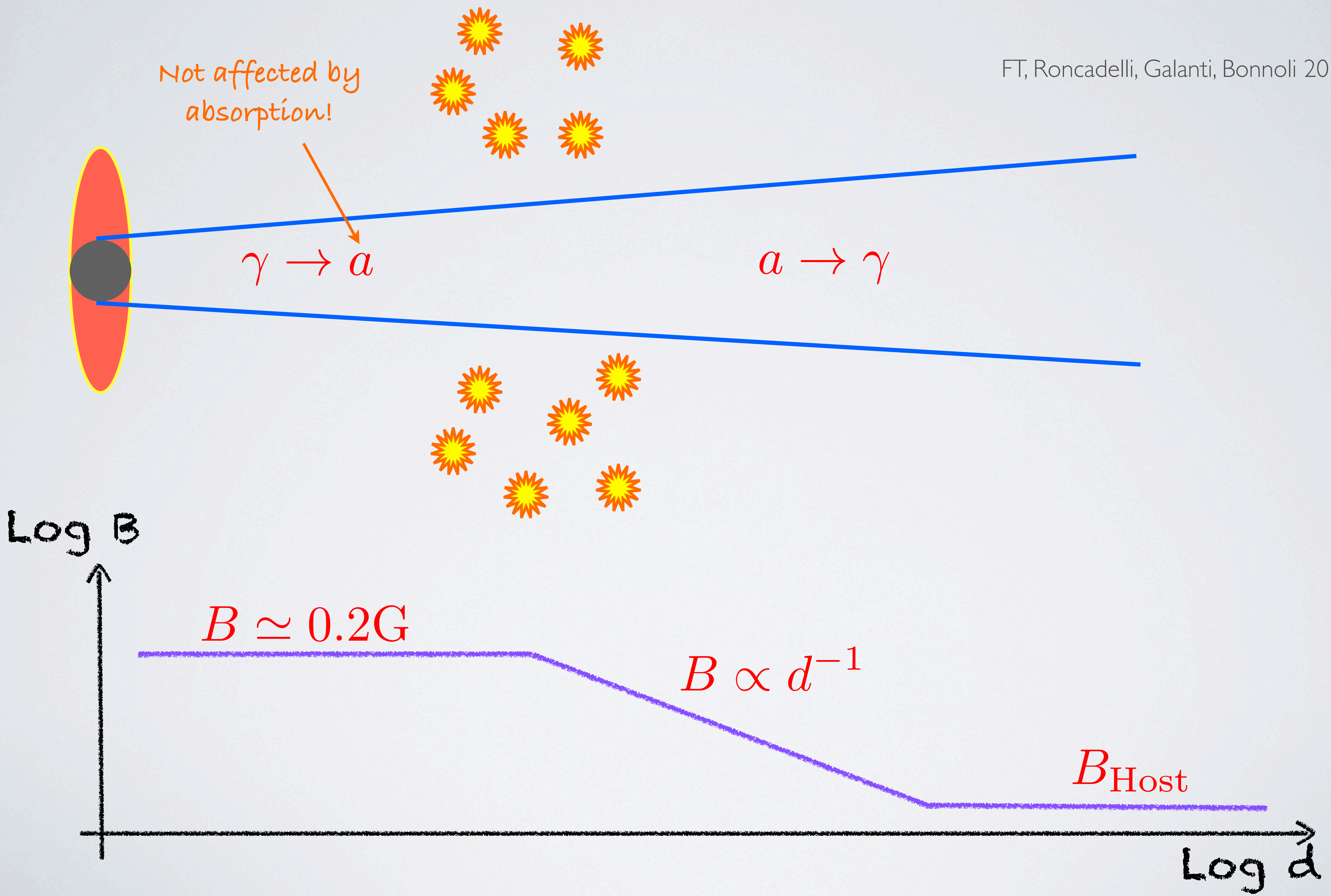


A cosmic “light shining through a wall” experiment?



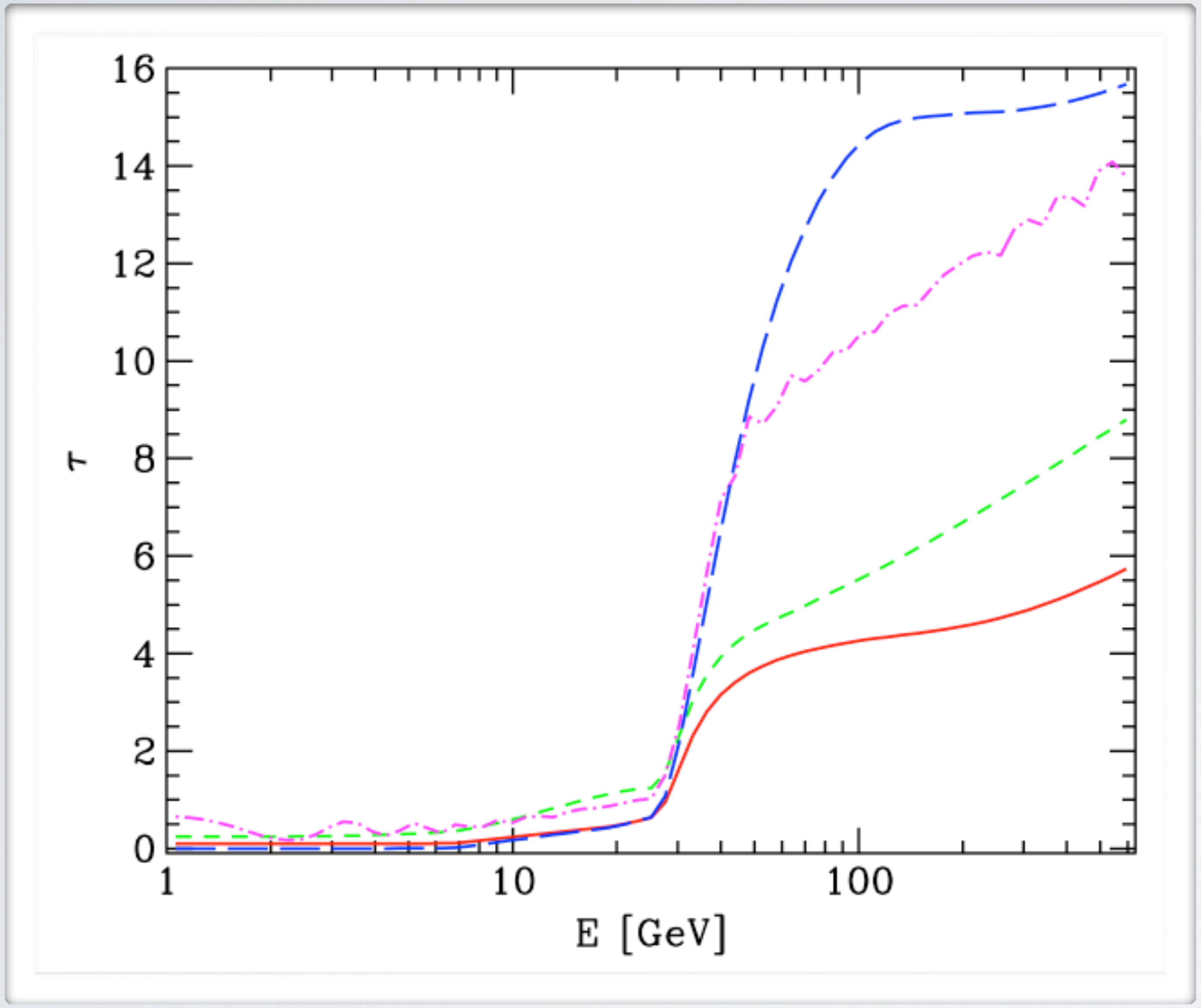
Model set-up

FT, Roncadelli, Galanti, Bonnoli 2012



Results

Optical depth:



$B = 2\ \text{G};\ M = 4 \times 10^{11}\ \text{GeV}$

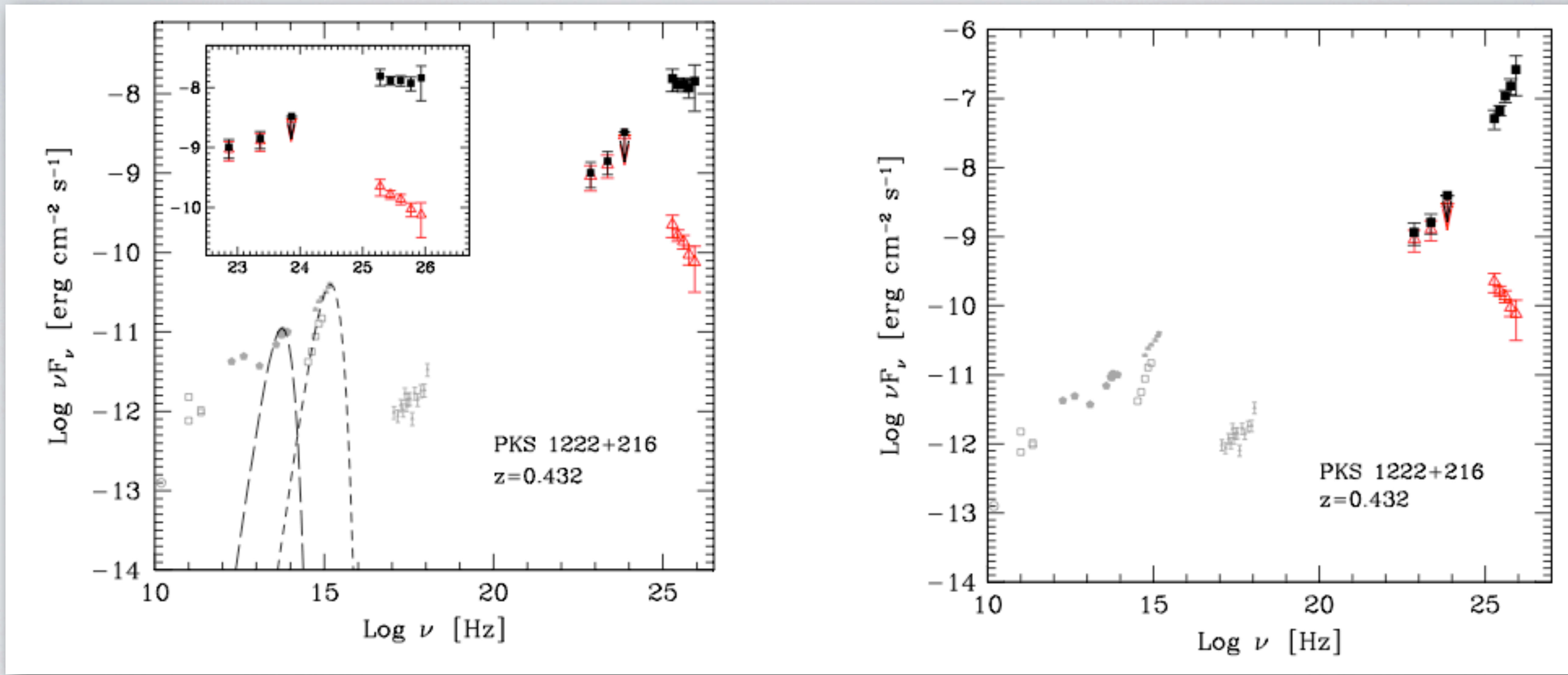
$B = 0.4\ \text{G};\ M = 1.5 \times 10^{11}\ \text{GeV}$

$B = 0.2\ \text{G};\ M = 7 \times 10^{10}\ \text{GeV}$

Results

Spectral Energy Distribution

Extragalactic conversions not included



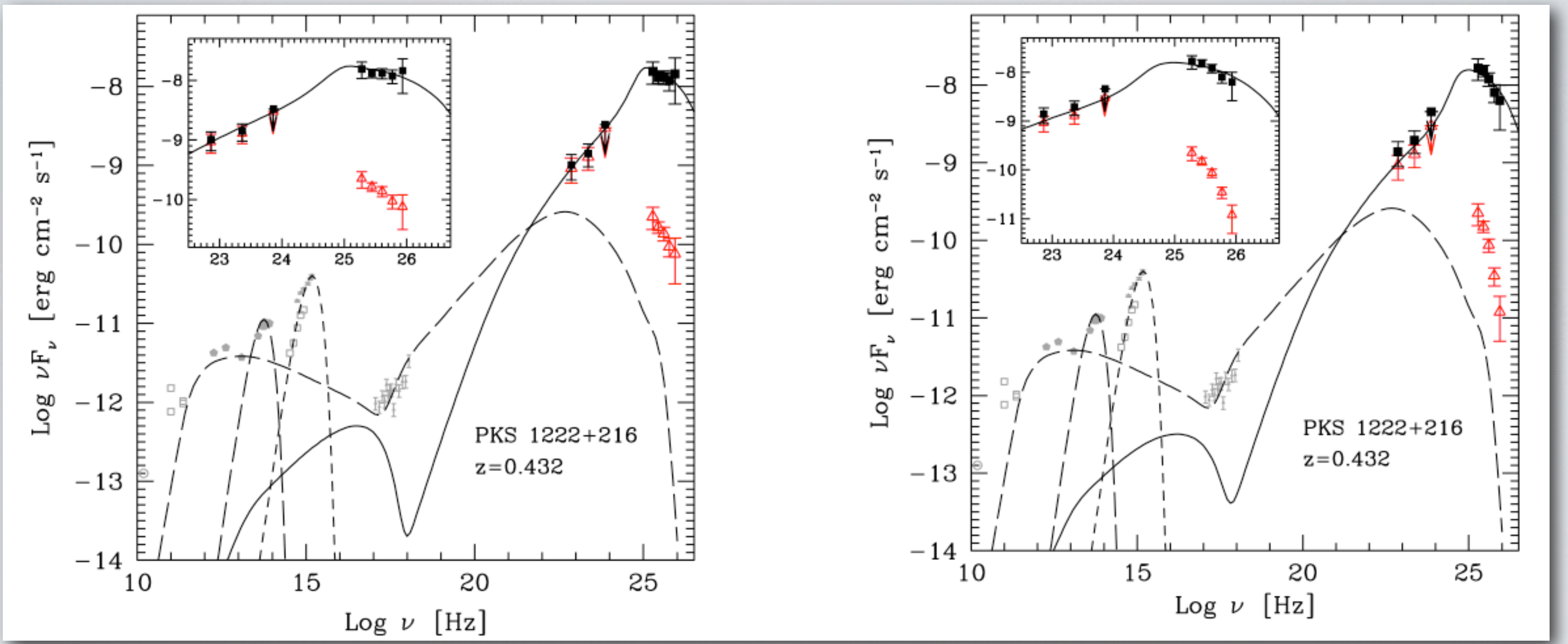
$B = 0.2$ G; $M = 7 \times 10^{10}$ GeV

$B = 0.4$ G; $M = 1.5 \times 10^{11}$ GeV

Results

No extragalactic conversions

Extragalactic conversions, B=0.7 nG



$$B = 0.2 \text{ G}; M = 7 \times 10^{10} \text{ GeV}$$

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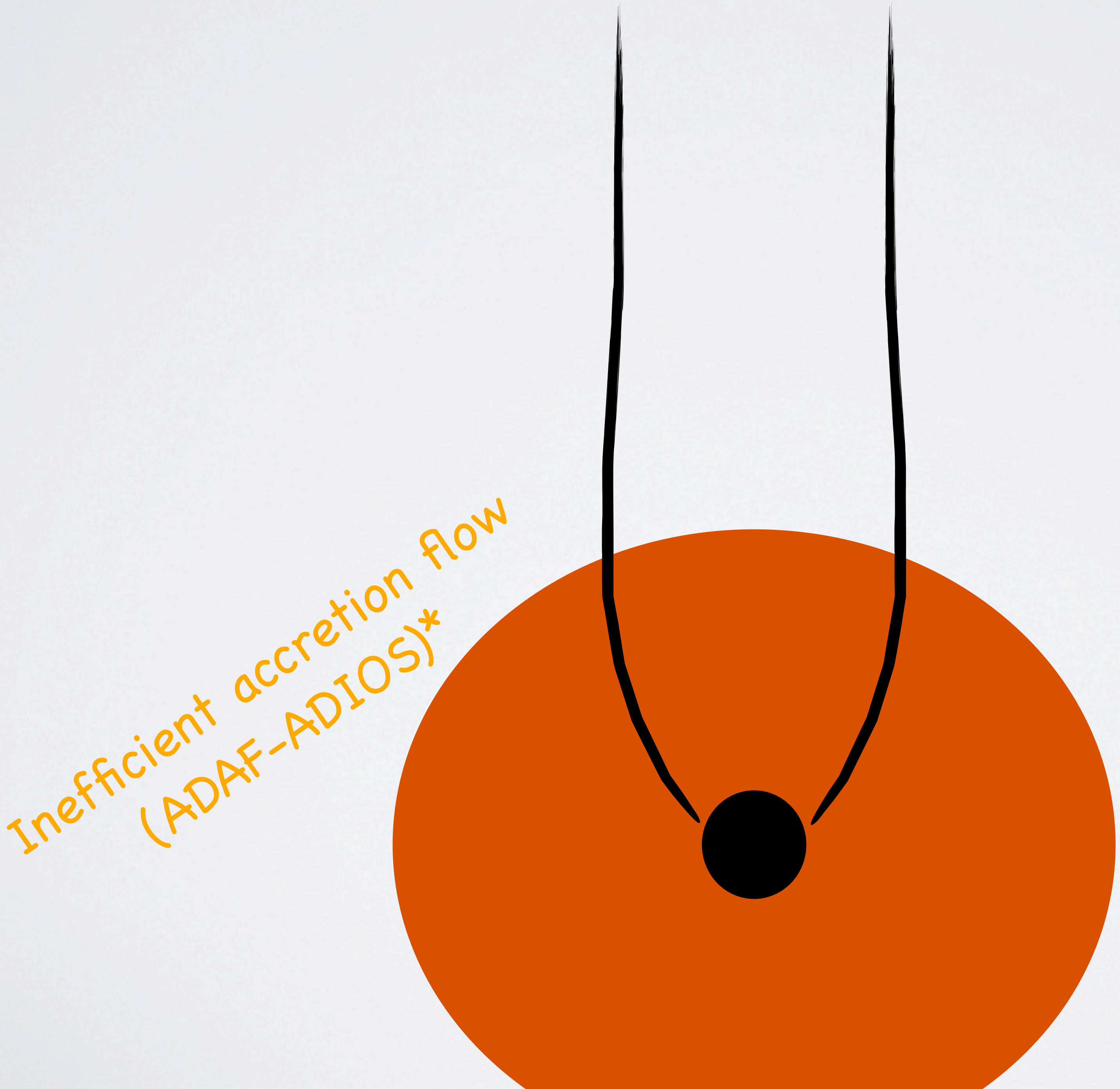
BL Lacs: “naked” jets



*but see Raiteri et al. 2009
Capetti et al. 2010 for BL Lac itself

Set-up: jet

BL Lacs: short jets
no hot spot/lobes

d~1 kpc
(e.g. Giroletti et al. 2004)

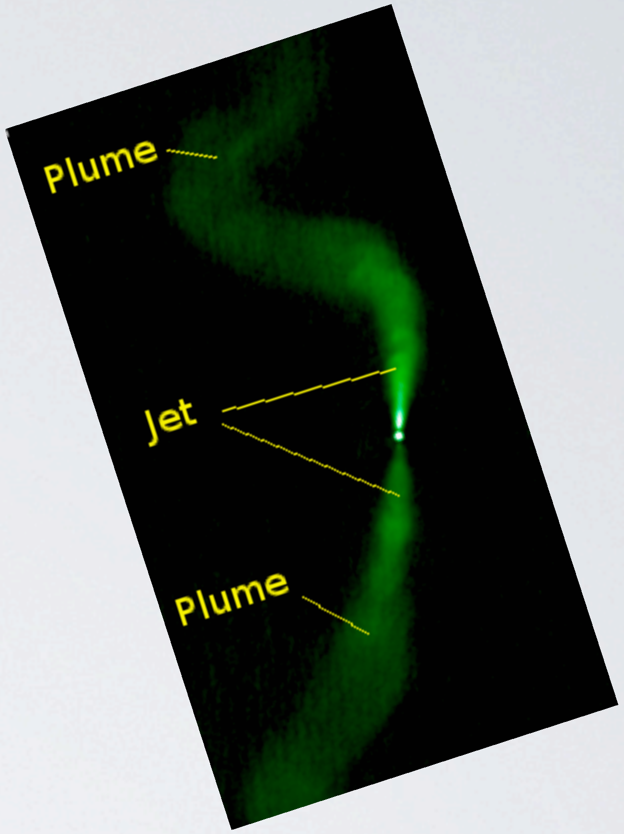
Magnetic field ordered,
predominantly tranverse

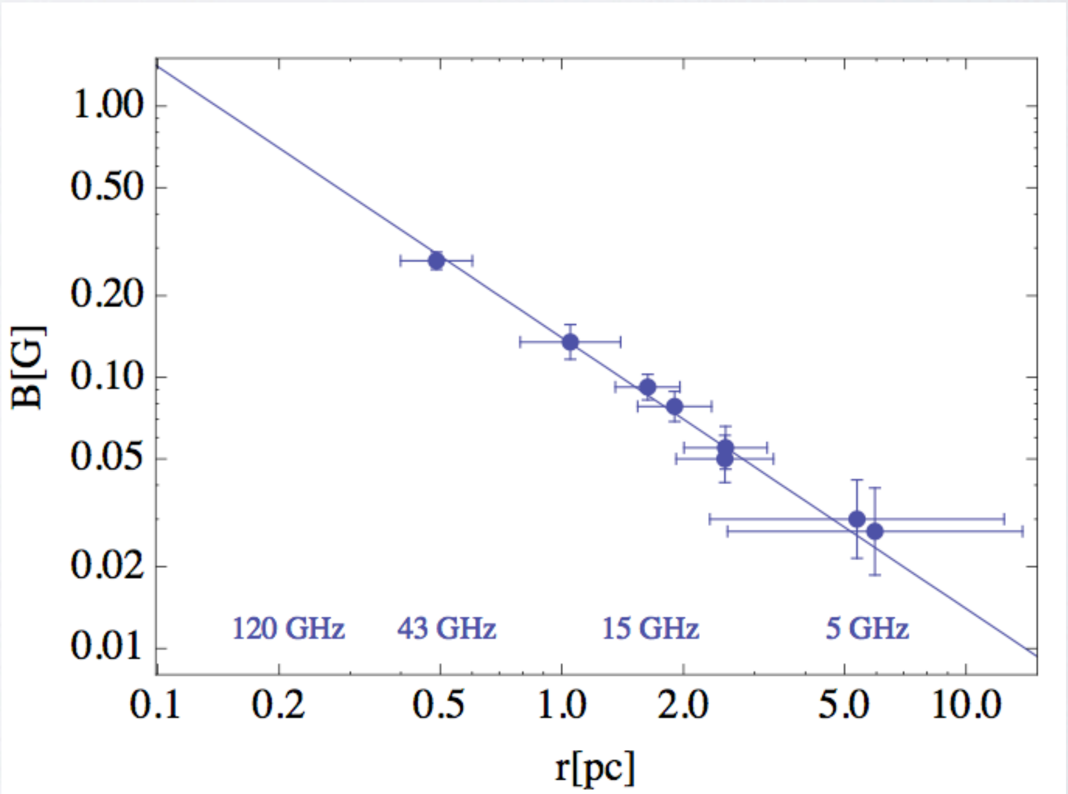
$$B_T(d) = B_T(d_o)\left(\frac{d}{d_o}\right)^{-1}$$

$$B_T(d_o) \simeq 0.1 - 1 \text{ G}$$

Jet comoving frame

Jet Lorentz factor 15

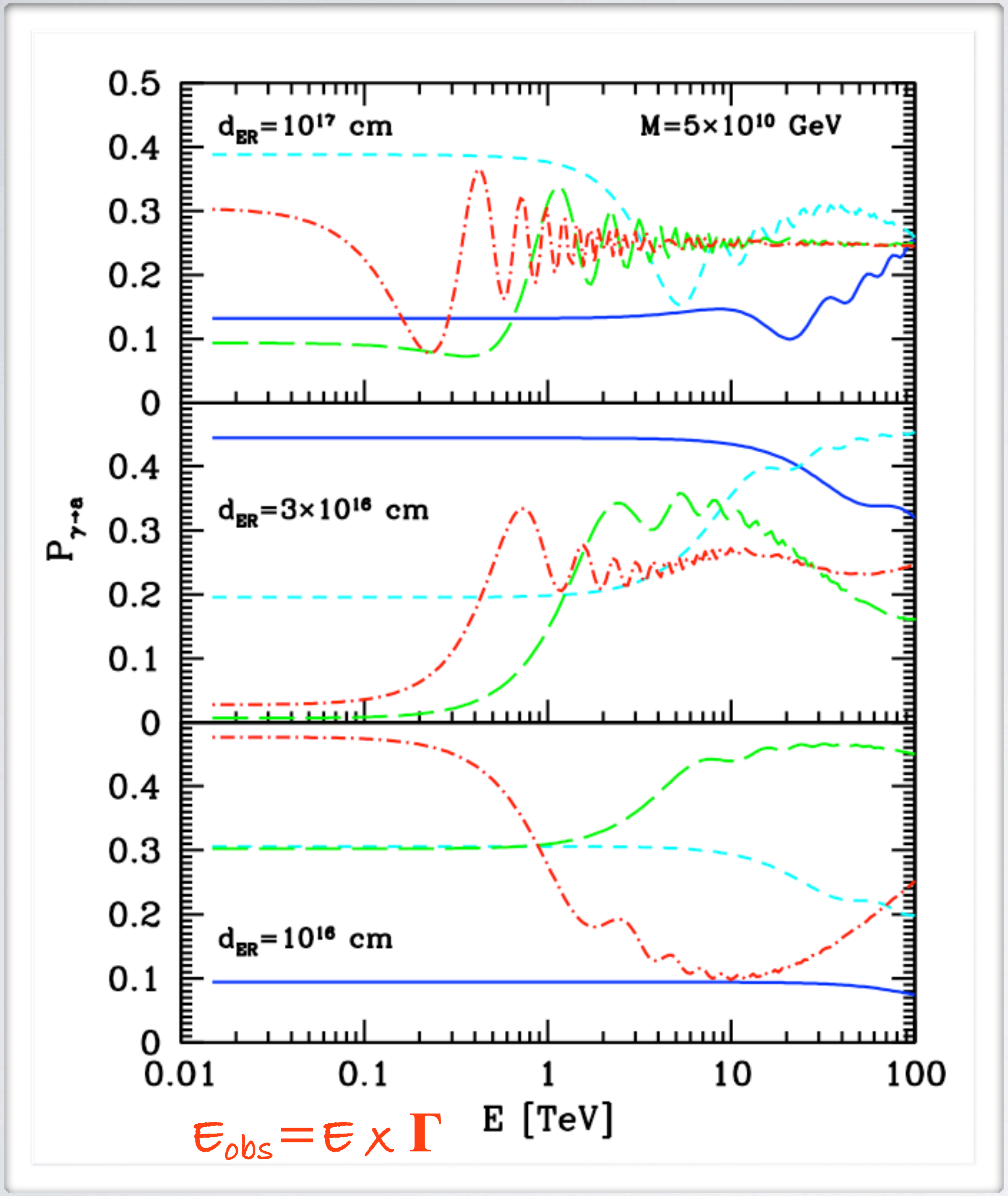




O'Sullivan & Gabuzda 2009

Results

$\gamma \rightarrow a$



QED term important!

$$E_H \simeq 2.1\left(\frac{G}{B_T}\right)\left(\frac{10^{11}\ \mathrm{GeV}}{M}\right)\ \mathrm{GeV}$$

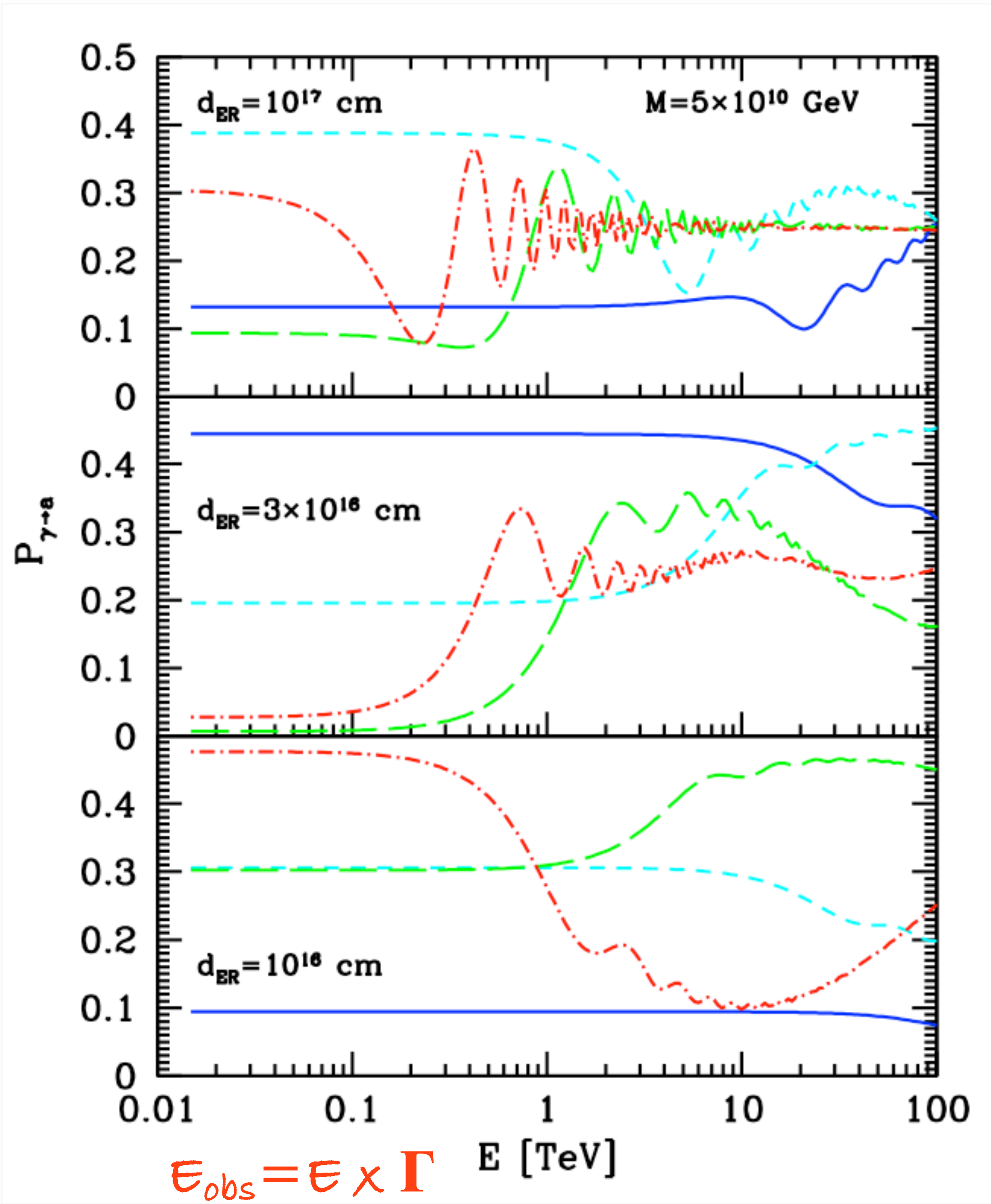
$$\Delta_{\rm osc}(E) \equiv \left\{\left[\frac{m^2-\omega_{\rm pl}^2}{2E} + \frac{3.5\alpha}{45\pi}\left(\frac{B_T}{B_{\rm cr}}\right)^2 E\right]^2 + \left(\frac{B_T}{M}\right)^2\right\}^{1/2}$$

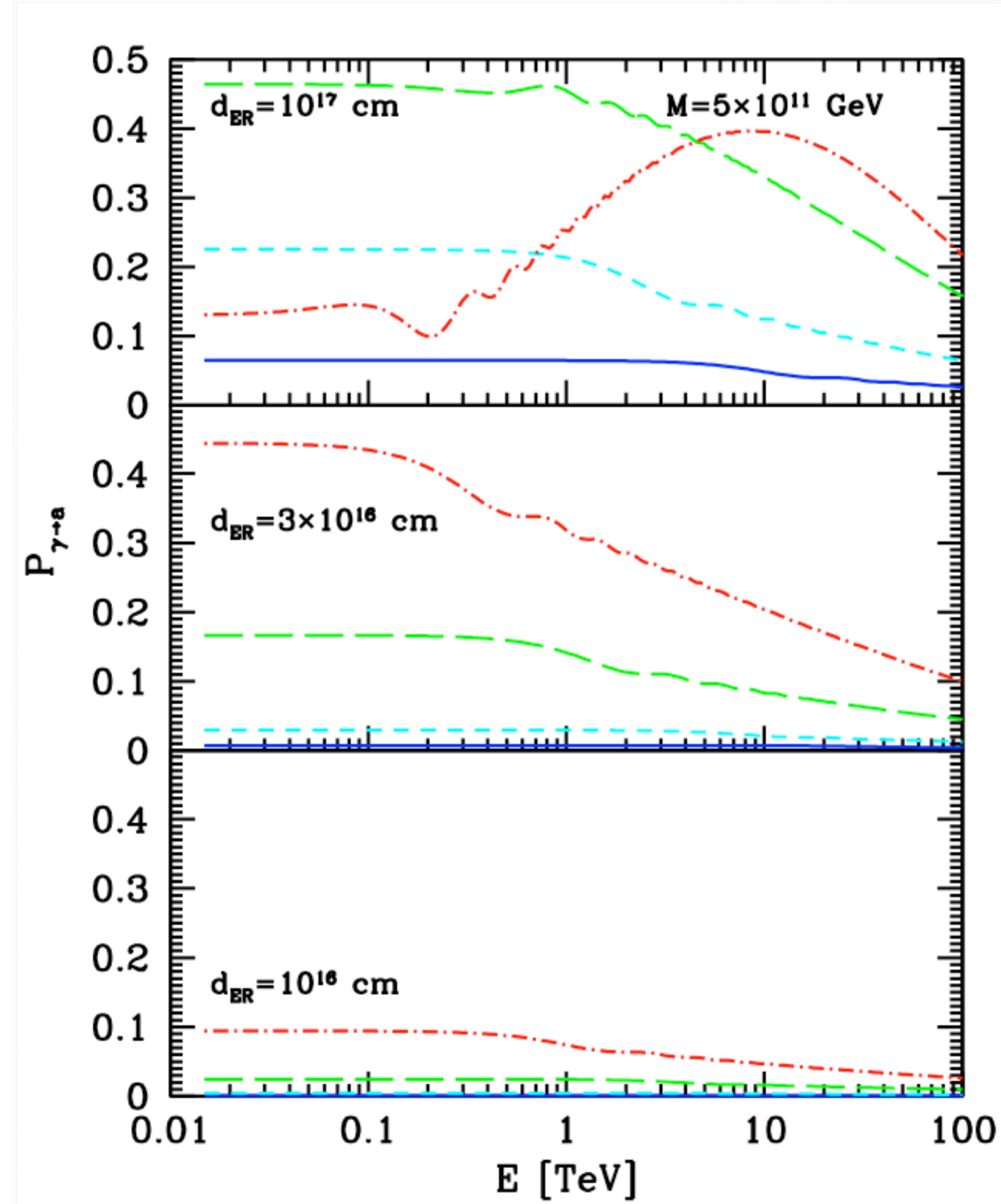
B_0=0.1,0.2,0.5,1 G   ljet=1 kpc

FT et al., 2015

Results

$\gamma \rightarrow a$



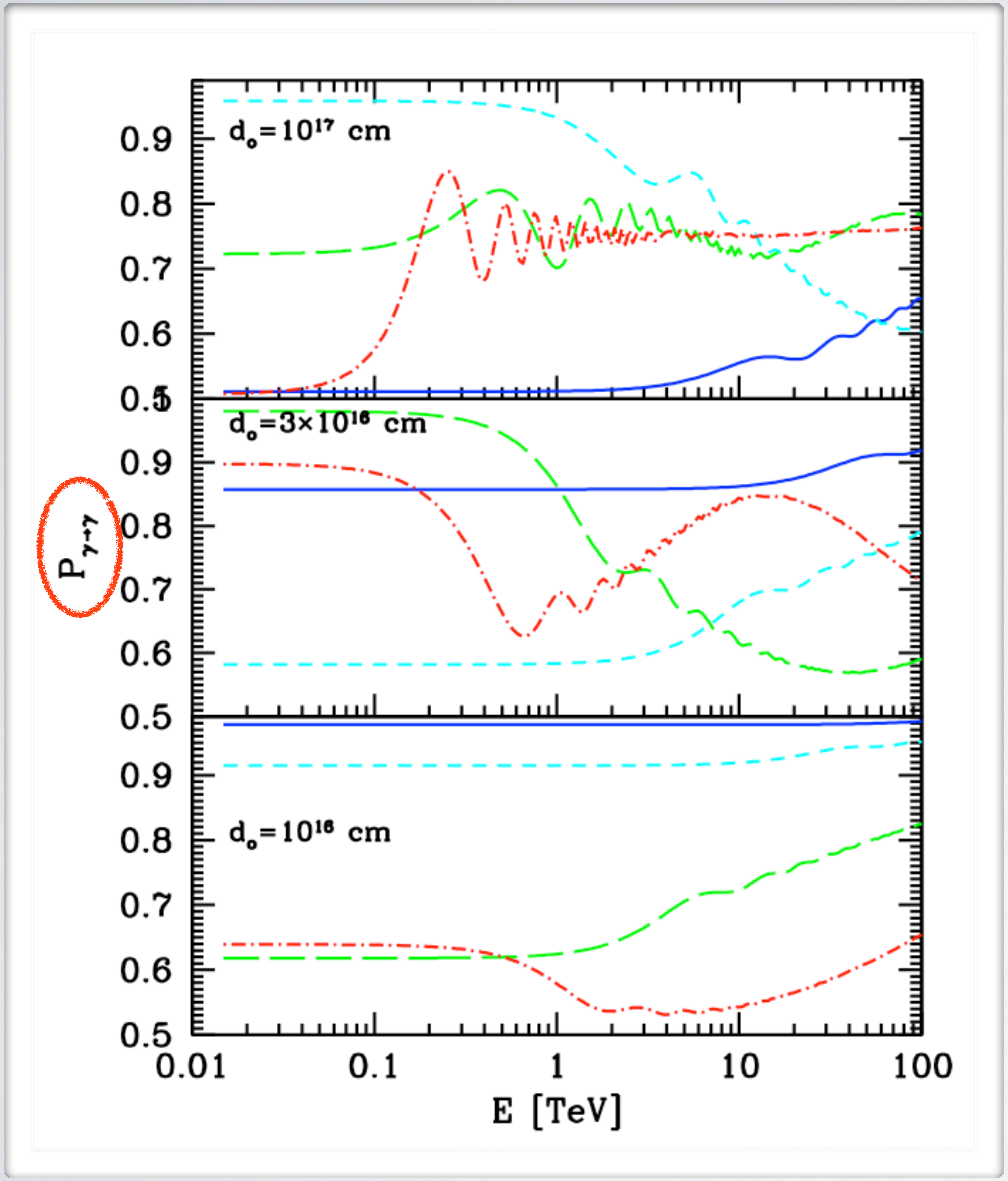


B_0=0.1,0.2,0.5,1 G   ljet=1 kpc

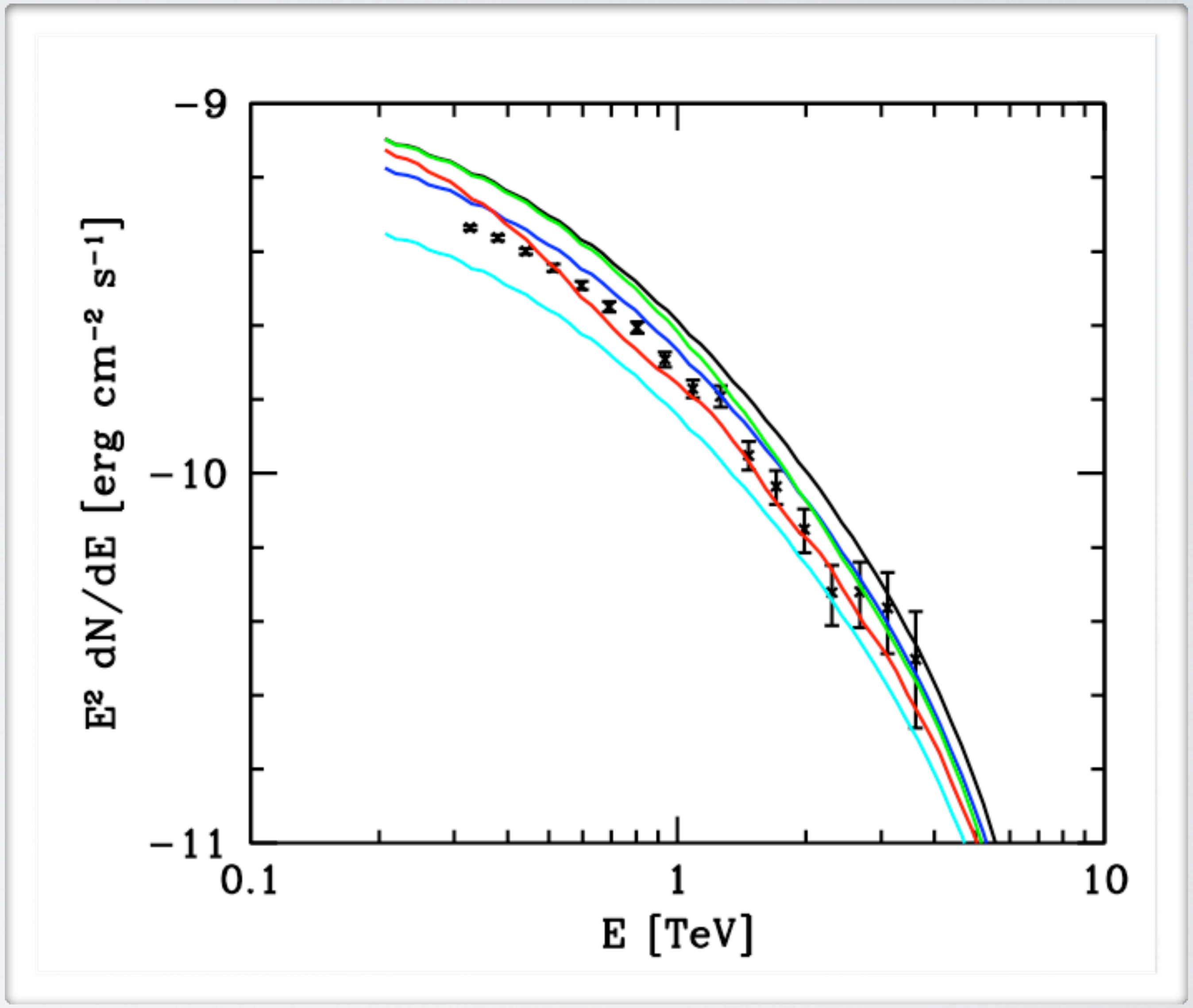
FT et al., 2015

Results

$\gamma \to \gamma$



Can we detect "wiggles" in the VHE spectrum of BL Lacs?



Summary

The strange case of PKS 1222+216: hint for ALPs?
Parameters testable with IAXO, ALPS-II

ALPs from VHE emitting BL Lac objects: complex and unpredictable behavior.
Consequences for proposed tests (e.g. correlation with galactic B-field etc...)

Thank you!

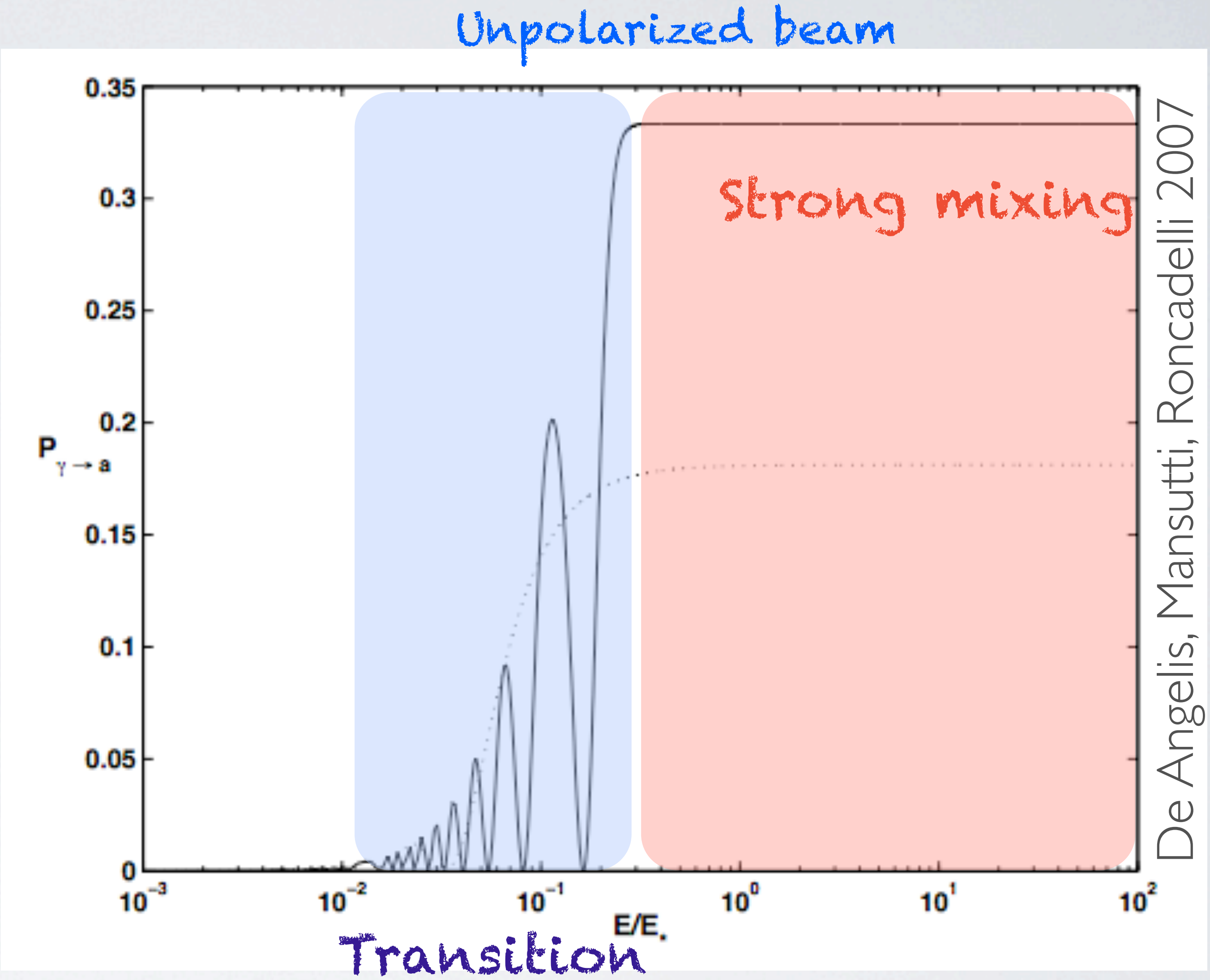
ALPs: phenomenology

Photon-ALP conversion
in a uniform B-field

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

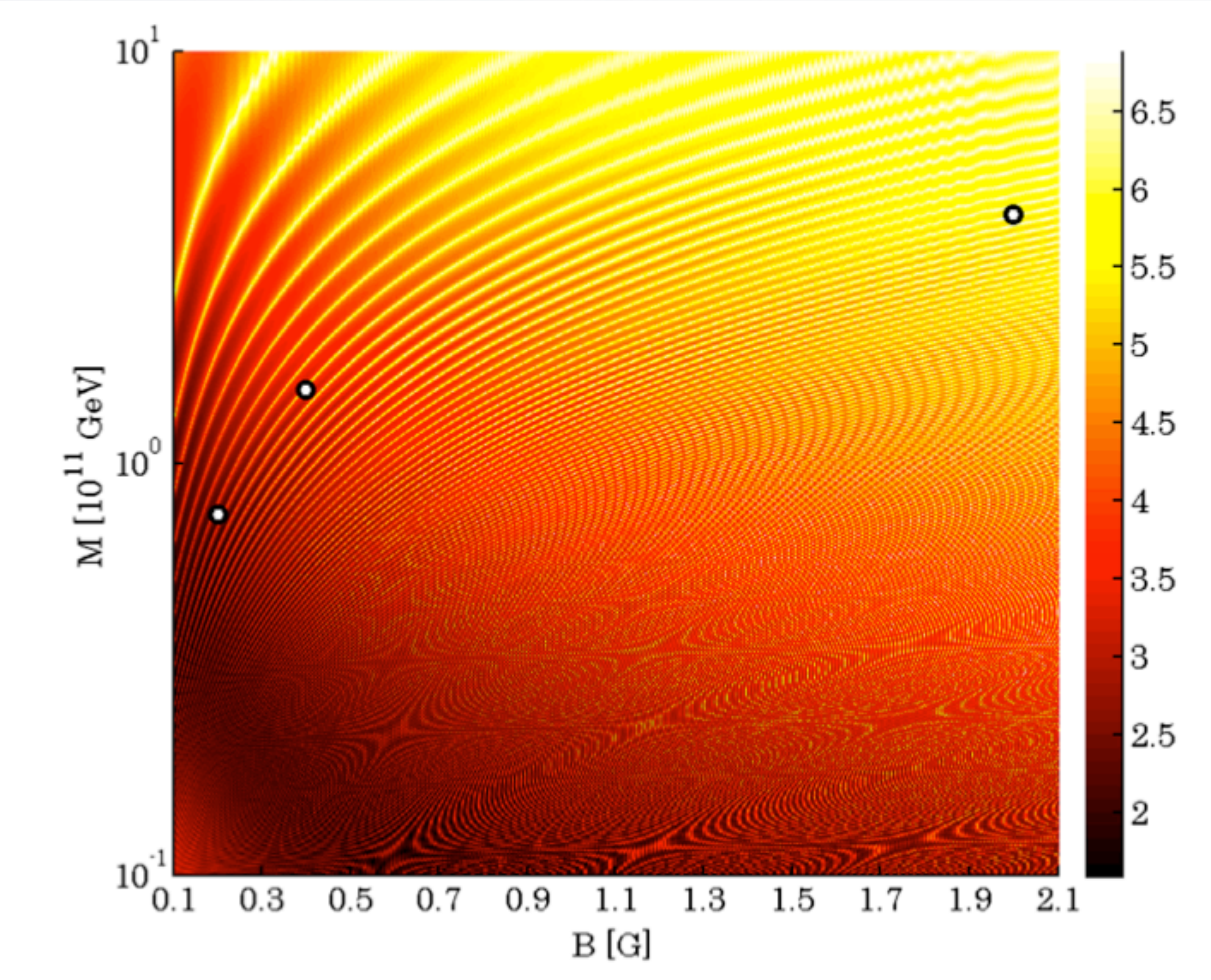
$$\Delta_{\rm osc}(E) \equiv \left[\left(\frac{m^2-\omega_{\rm pl}^2}{2E}\right)^2 + g_{a\gamma\gamma}^2 B_T^2\right]^{1/2}$$

Strong mixing regime:
P maximal and E-independent



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

Results



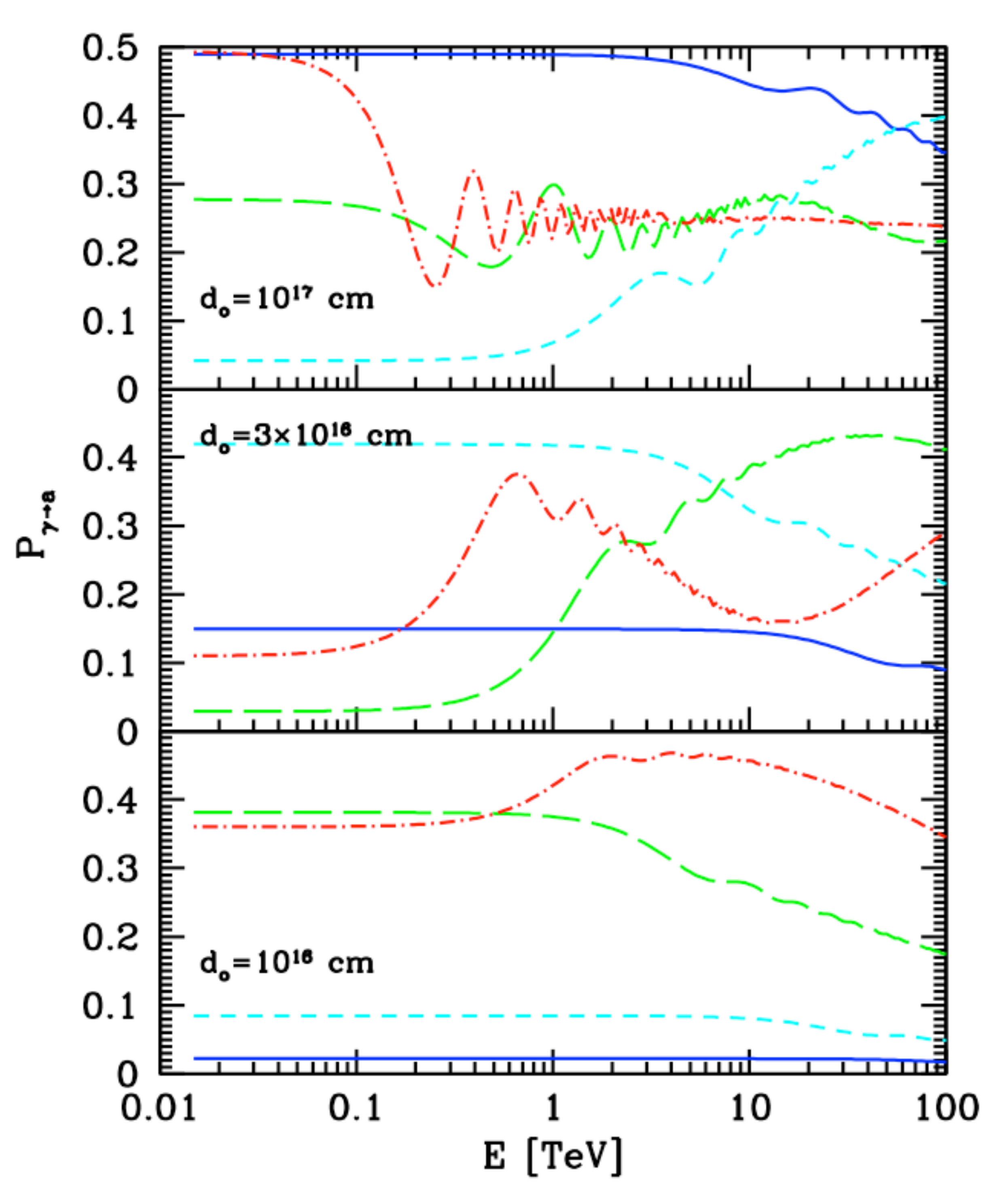
$$\Pi \equiv \log\left(\frac{P^{\mathrm{ALP}}_{\gamma\to\gamma}(R_{\mathrm{host}}, 0; 1\ \mathrm{GeV})}{P^{\mathrm{ALP}}_{\gamma\to\gamma}(R_{\mathrm{host}}, 0; 300\ \mathrm{GeV})}\right).$$

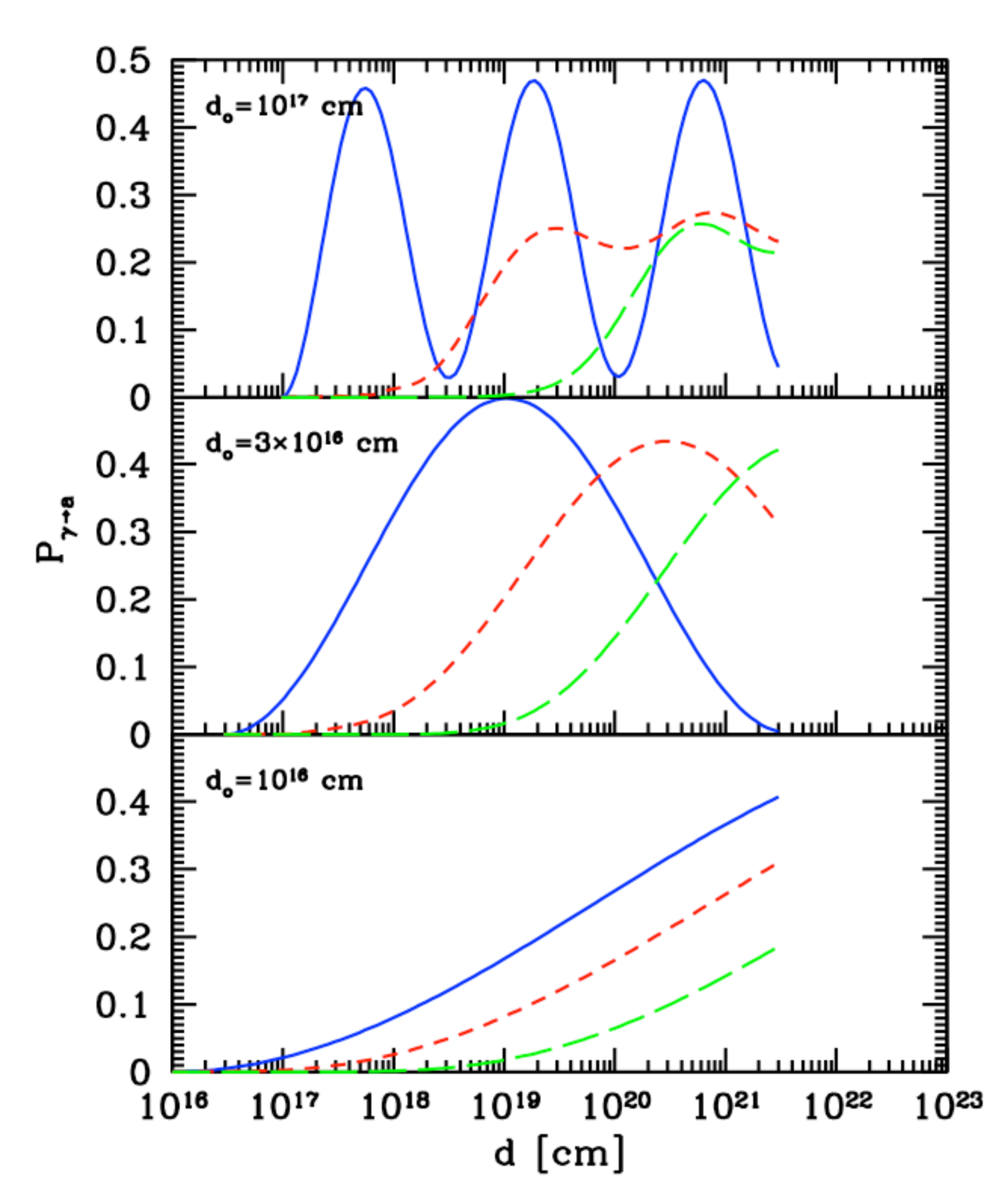
Results

B$_0$=0.1,0.2,0.5,1 G

BL Lacs: jet

E=0.15,7.5,150 TeV B=0.5 G





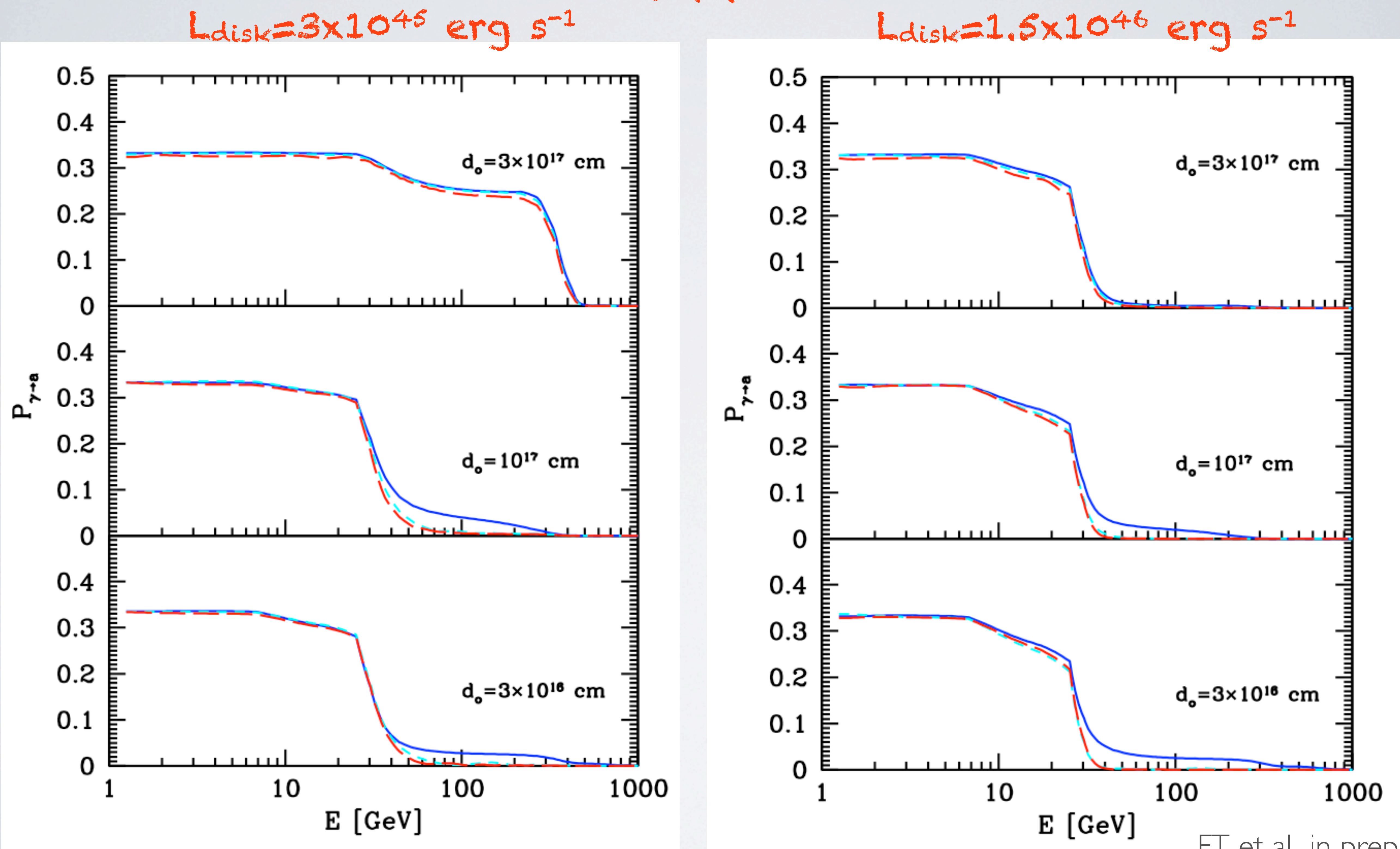
ljet=0.5 kpc

FT et al., 2015

Results

B_0=1,3,5 G

FSRQ



FT et al., in prep

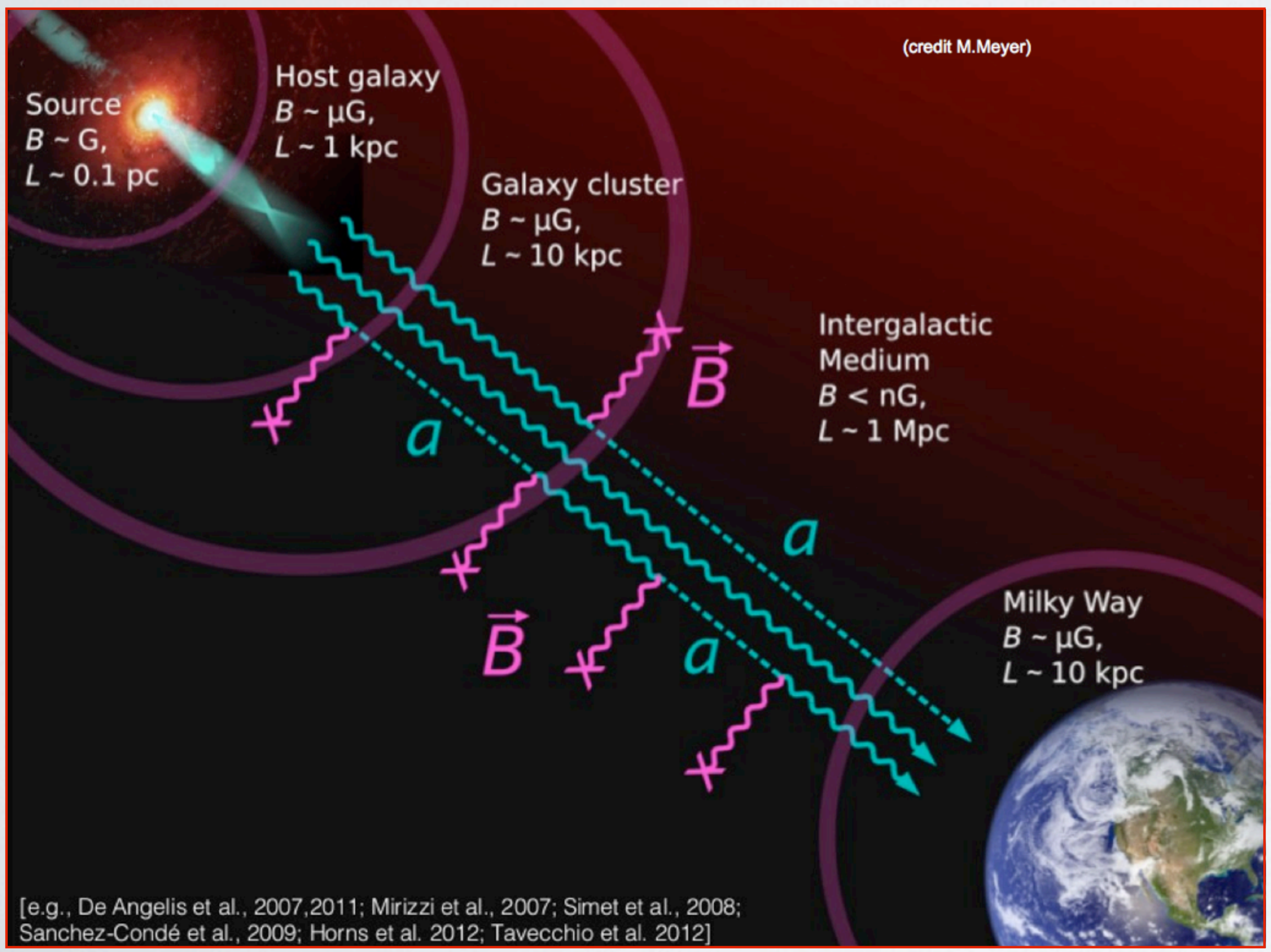
Relevance for VHE

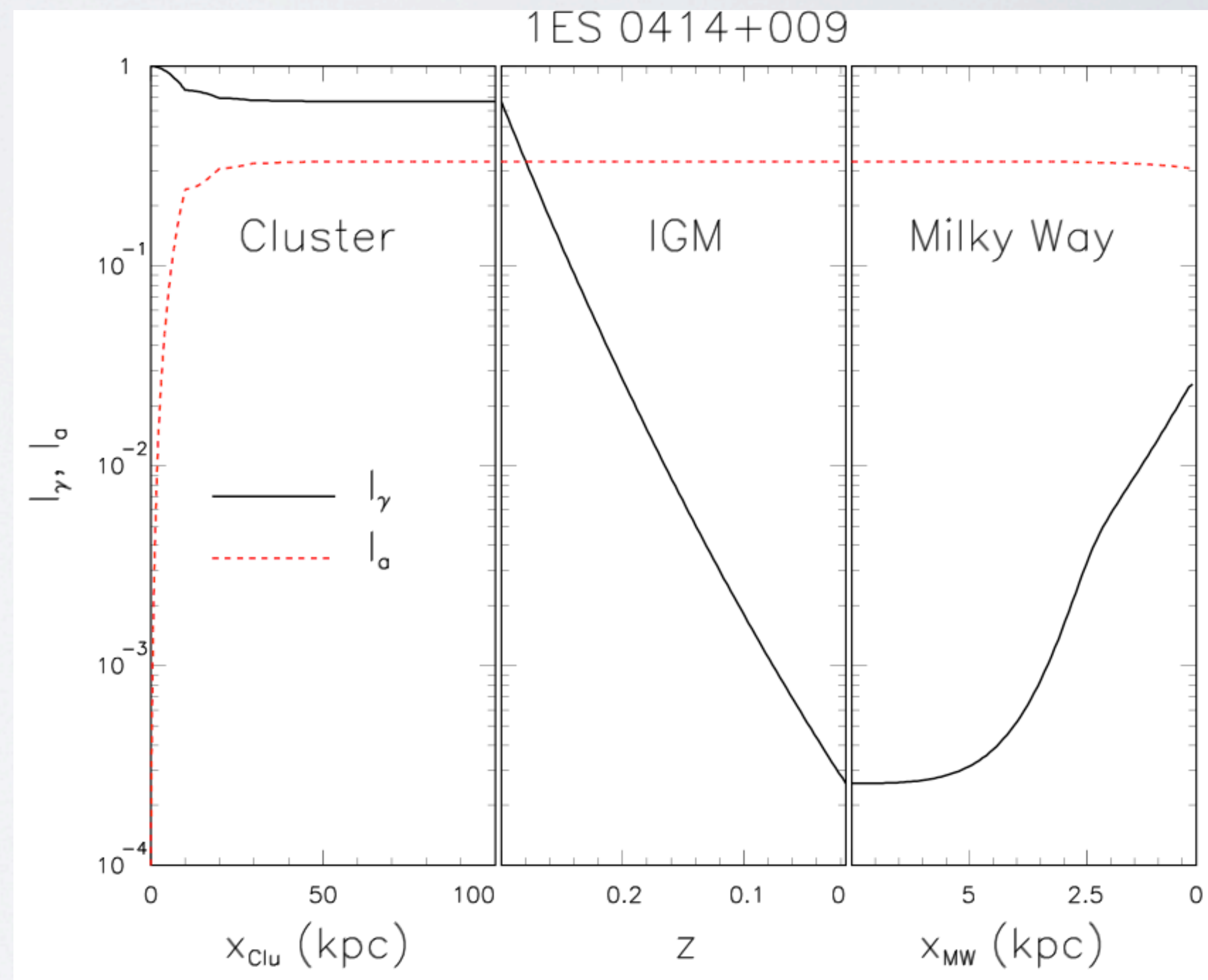
VHE gamma rays absorbed by intervening extragal. UV-IR background (EBL) or within the source

$$F_{\rm obs}(E) = F(E)e^{-\tau_{\gamma\gamma}(E)}$$

Photon-axion-photon conversion can modify the effective optical depth

More important for tau>1 (optically thick regime)





Horns et al. 2013