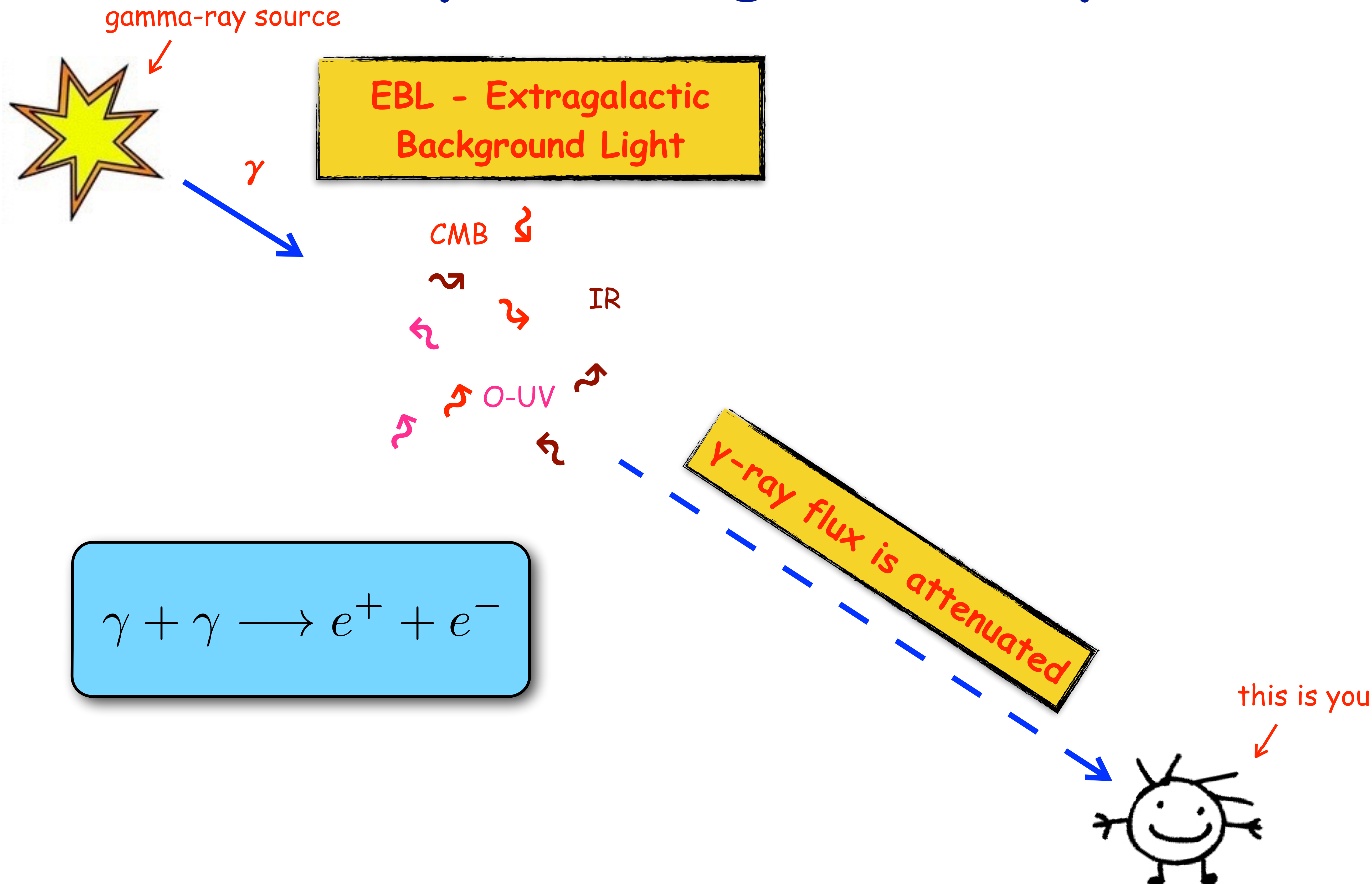
Intergalactic magnetic fields: constraints from gamma-ray observations

Stefano Gabici
APC, Paris

Absorption of gamma-rays



$$\gamma + \gamma \longrightarrow e^+ + e^-$$

Nikishov 1962, Gould & Shrèder 1967 … … … Felix Aharonian's book

Photon-photon pair production

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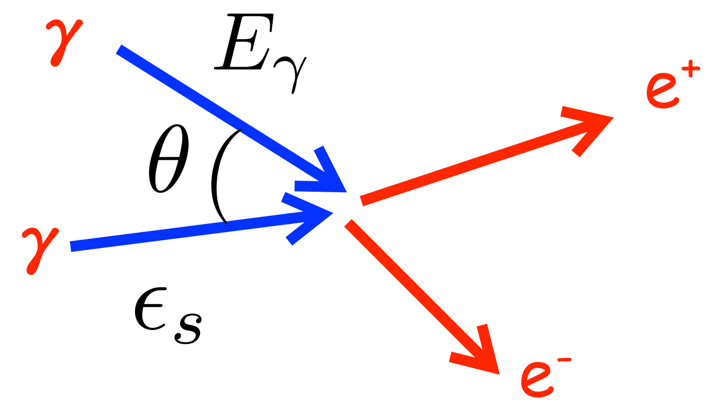

$$s_0 = \frac{E_\gamma \epsilon_s}{(m_e c^2)^2}$$

kinematic threshold -> $s_0\,(1 - \cos\theta) > 2$

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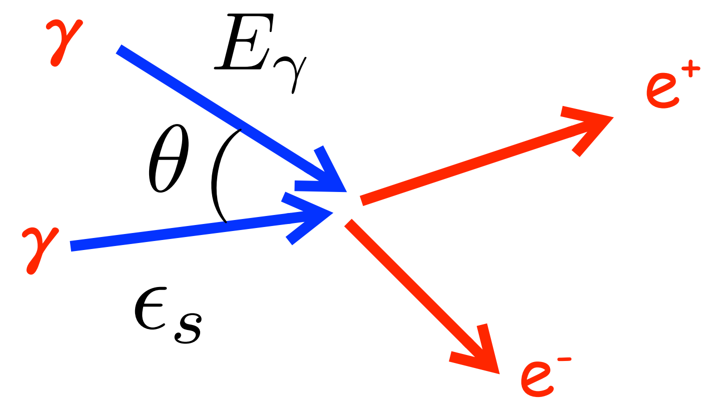

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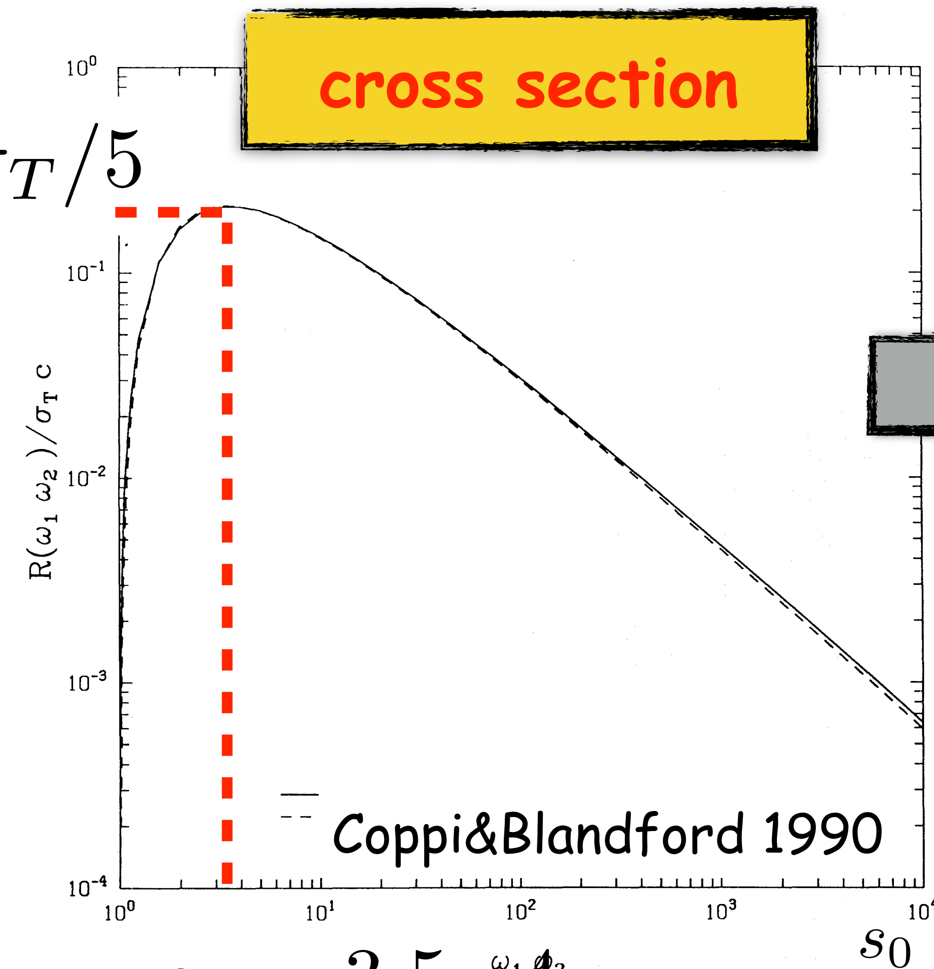
$\sigma_{\gamma\gamma} \sim \sigma_T/5$



$s_0 \sim 3.5...4$

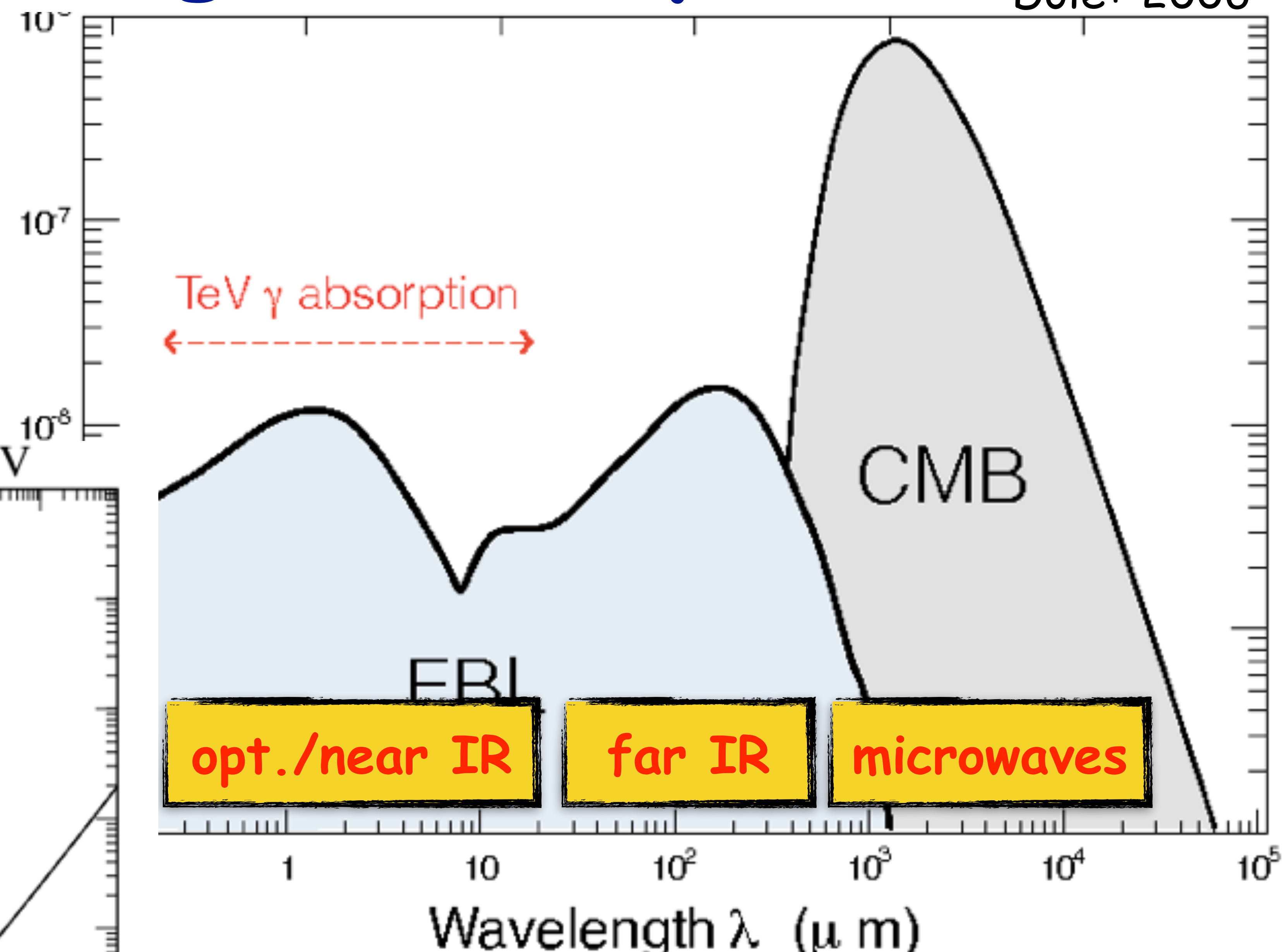
$$\lambda_s \sim 1.5 \left(\frac{E_\gamma}{1\ \mathrm{TeV}}\right) \mu m$$

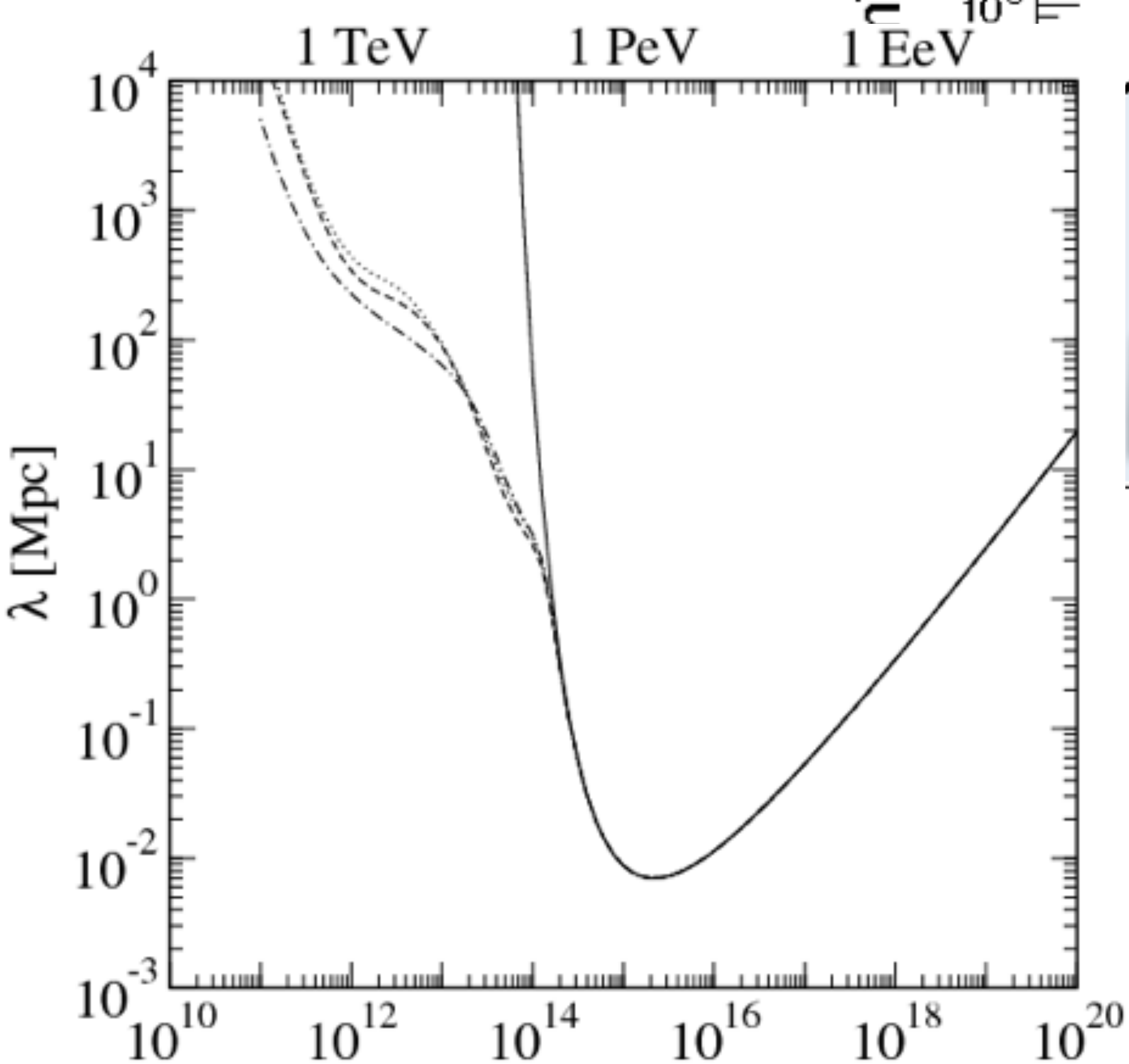
IR band ⟷ TeV domain

Nikishov 1962, Gould & Shrèder 1967 ... ... Felix Aharonian's book

EBL and gamma rays

Dole+ 2006





Venters 2010

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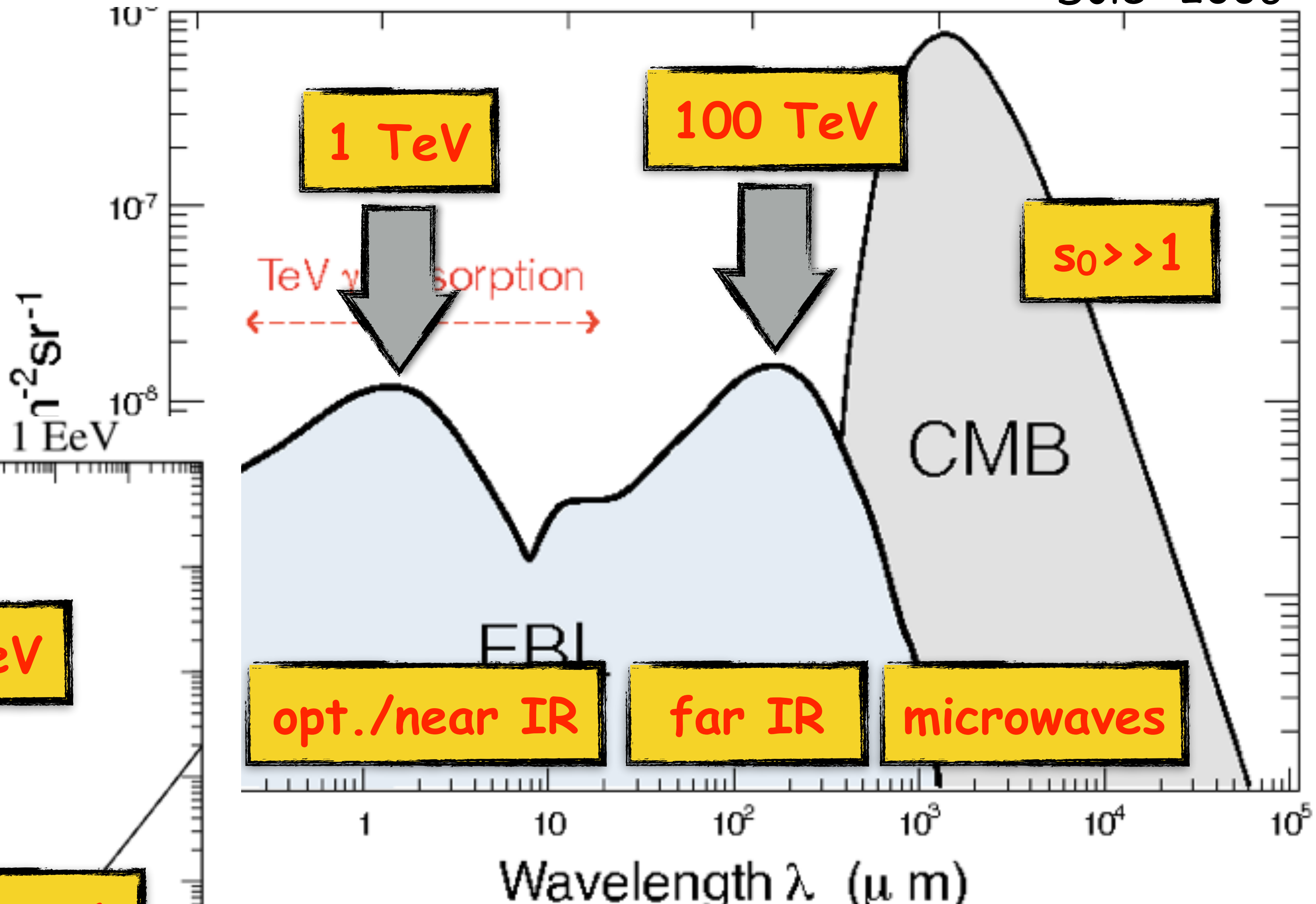
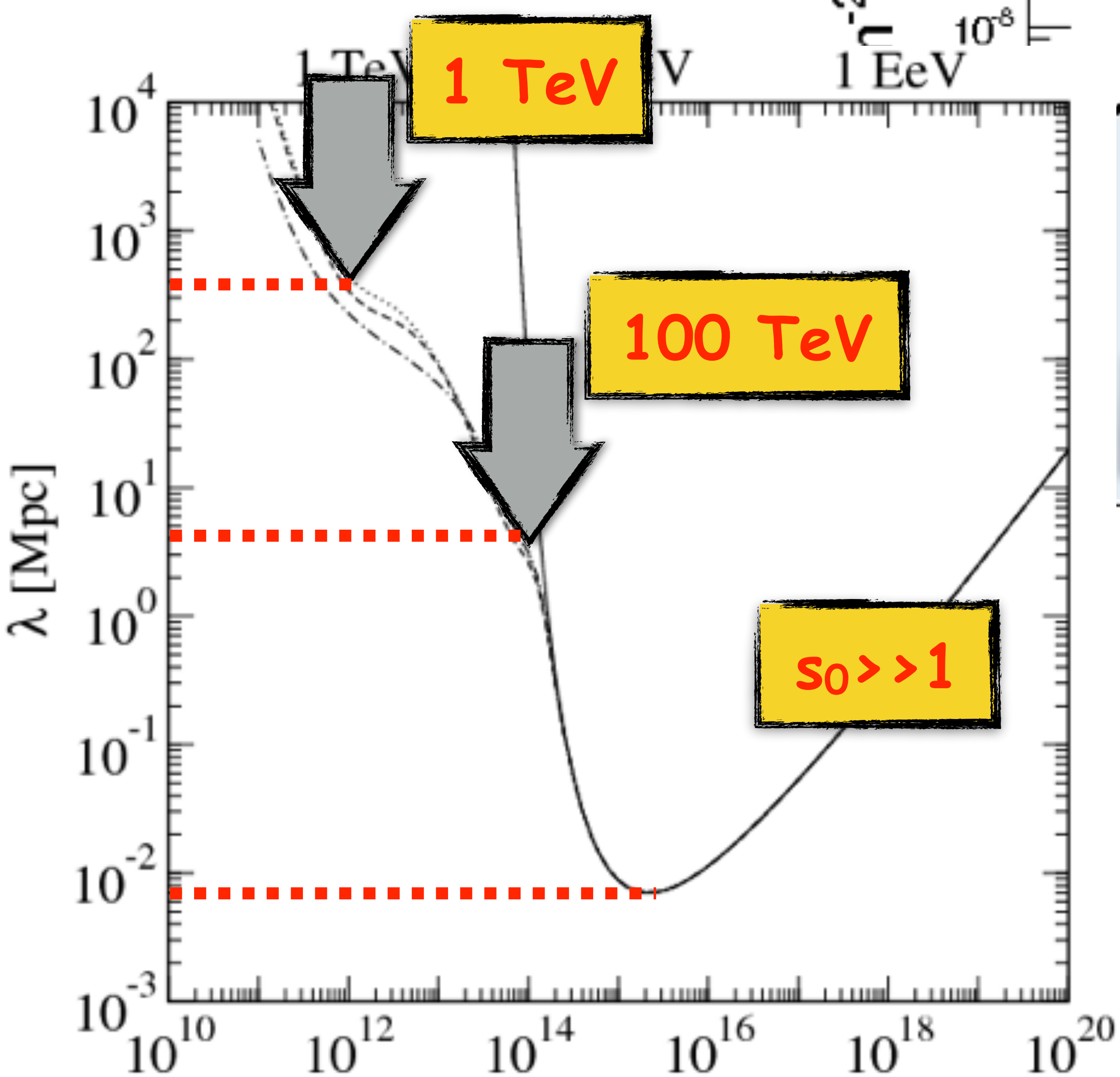
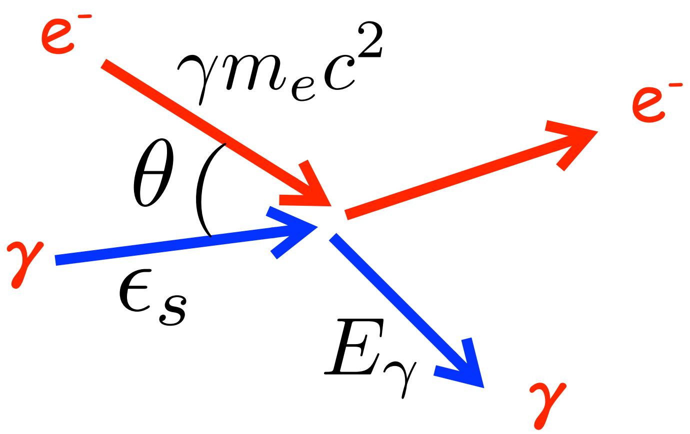




Venters 2010

Inverse Compton scattering



$$E_\gamma = \frac{4}{3}\gamma^2\epsilon_s \longrightarrow E_e \sim 10\left(\frac{E_\gamma}{0.4\ \mathrm{TeV}}\right)^{1/2} \mathrm{TeV}$$

Eungwanichayapant&Aharonian 2009

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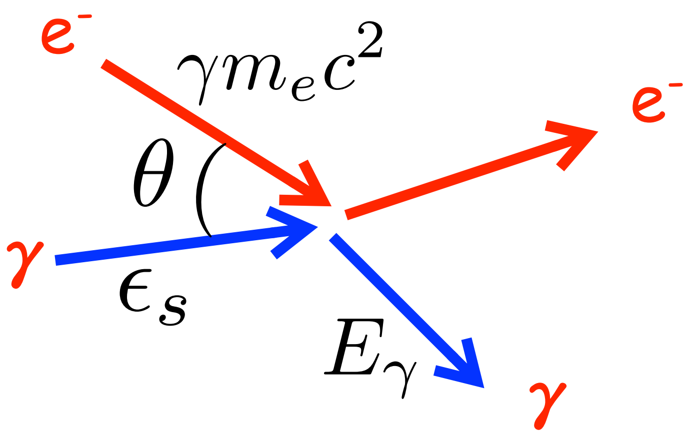

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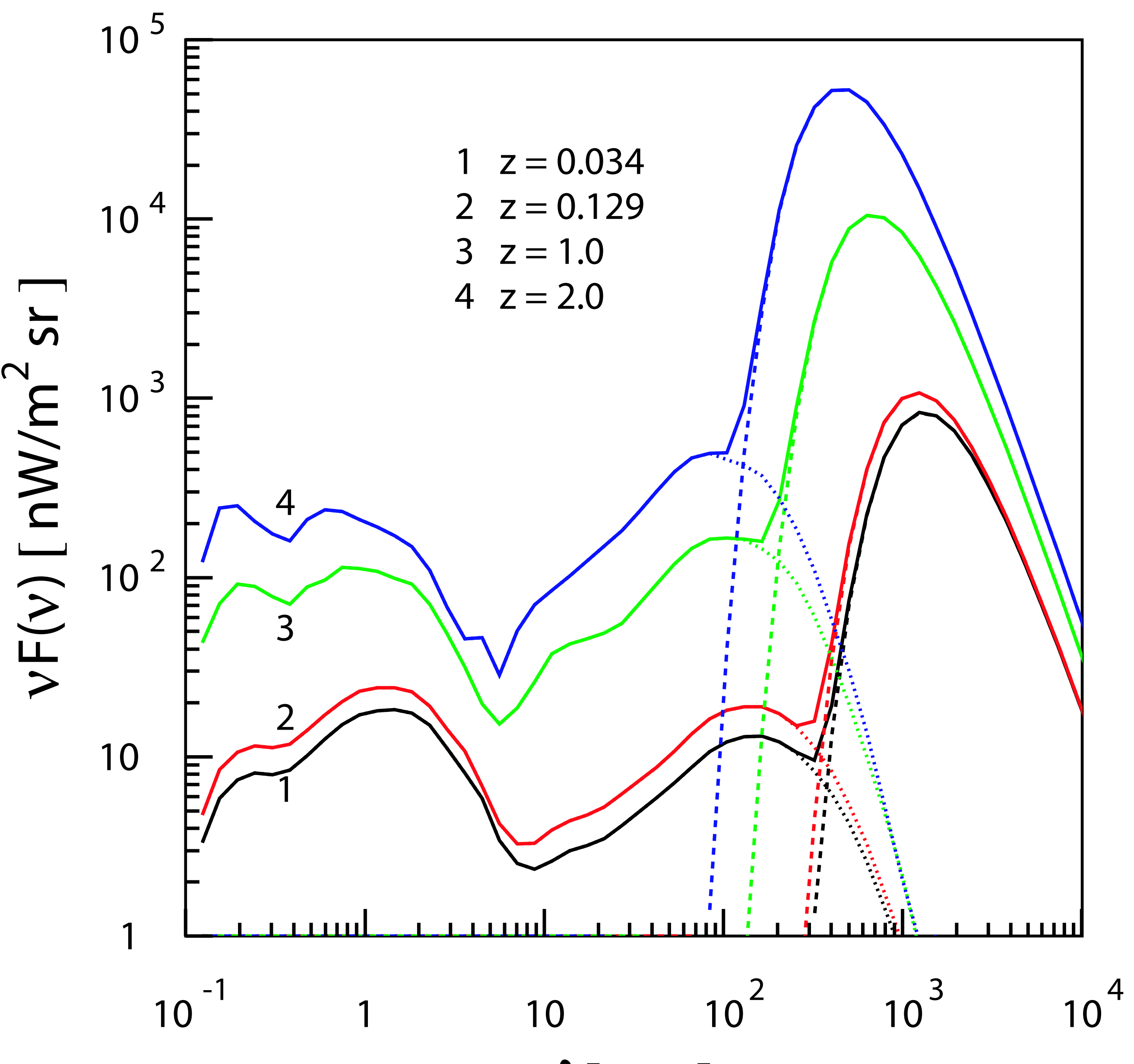

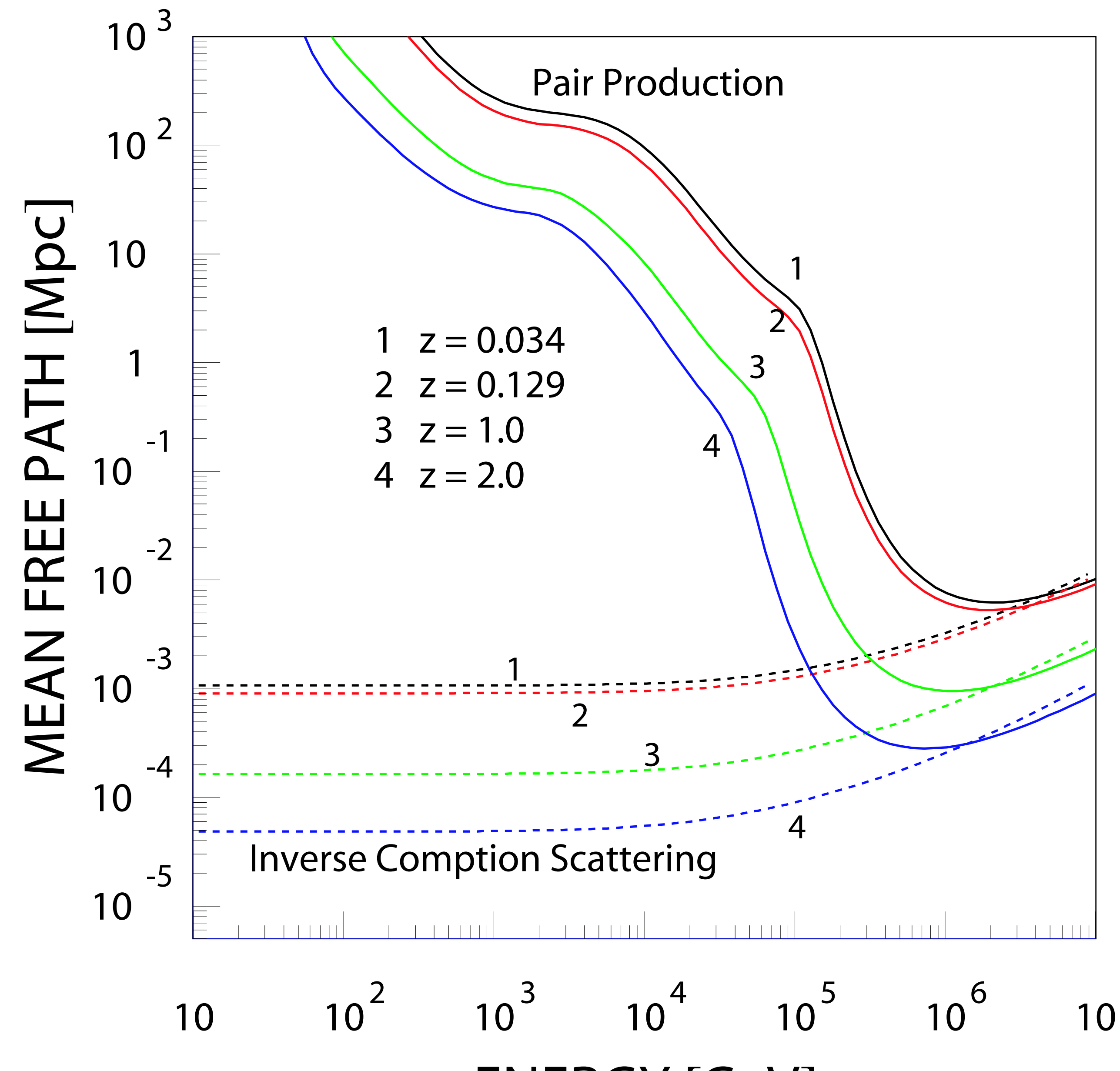

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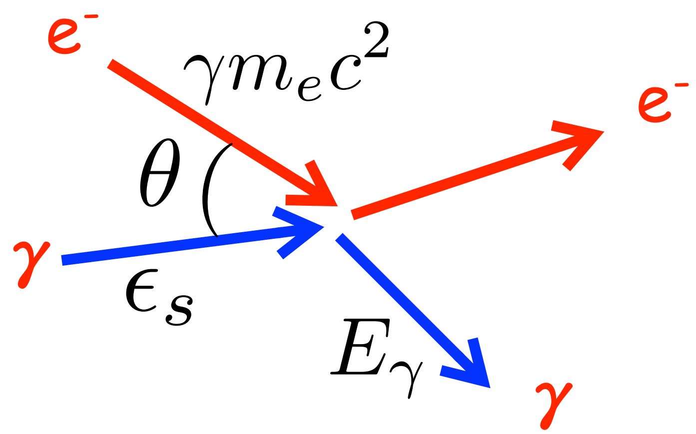

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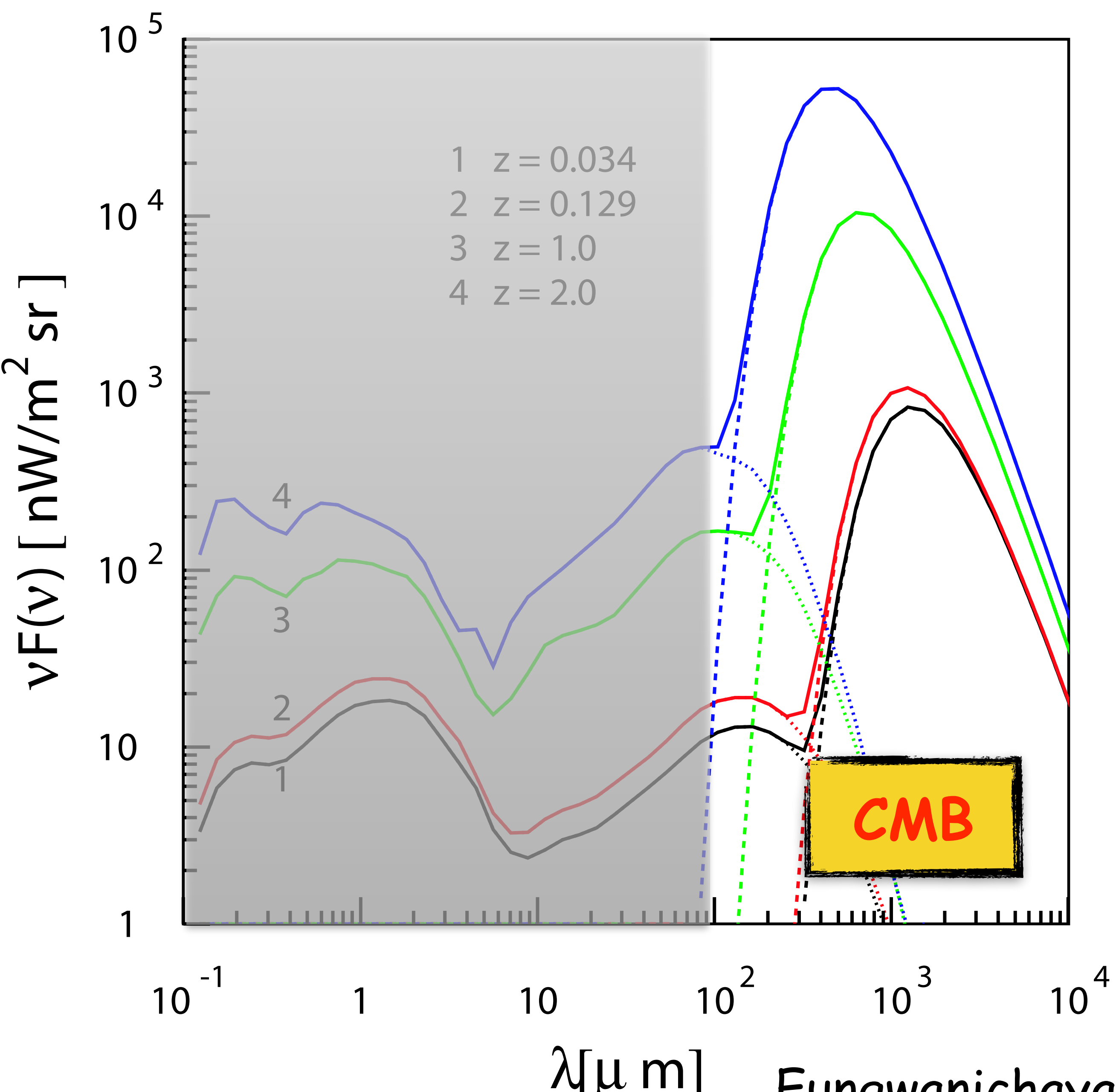

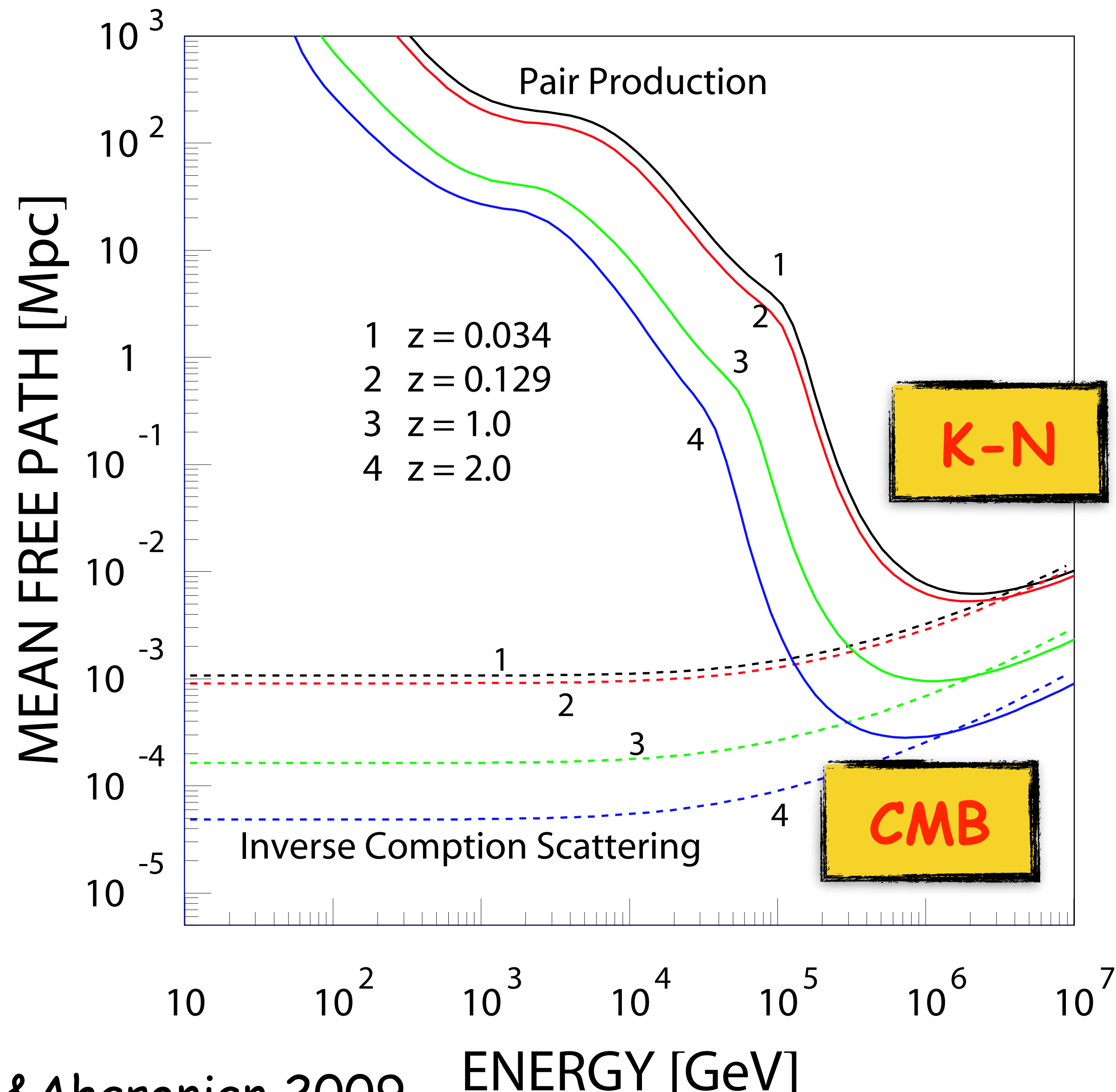

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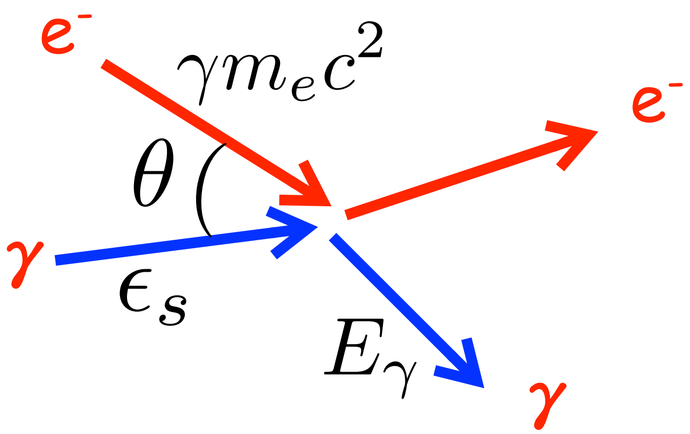

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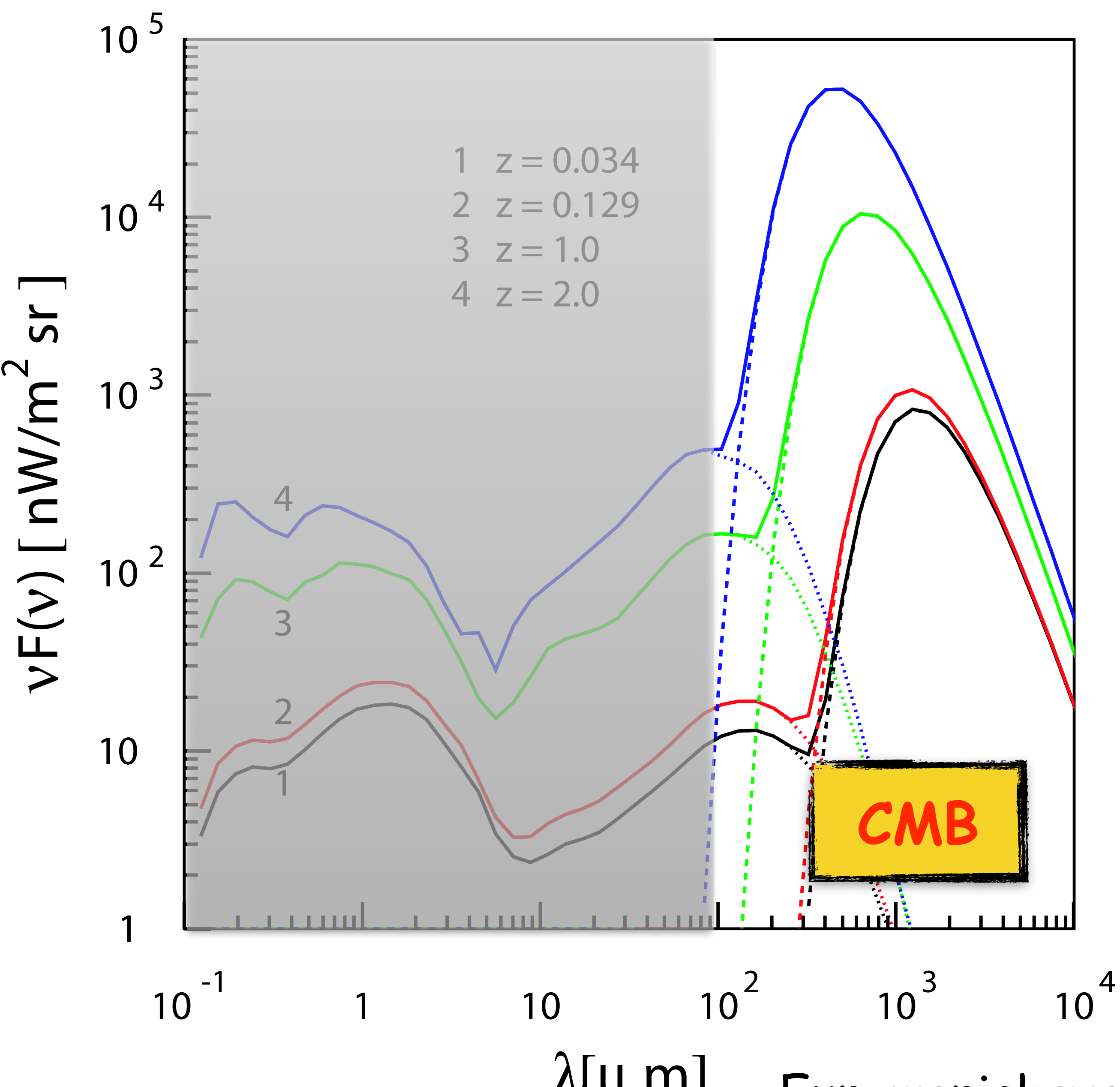

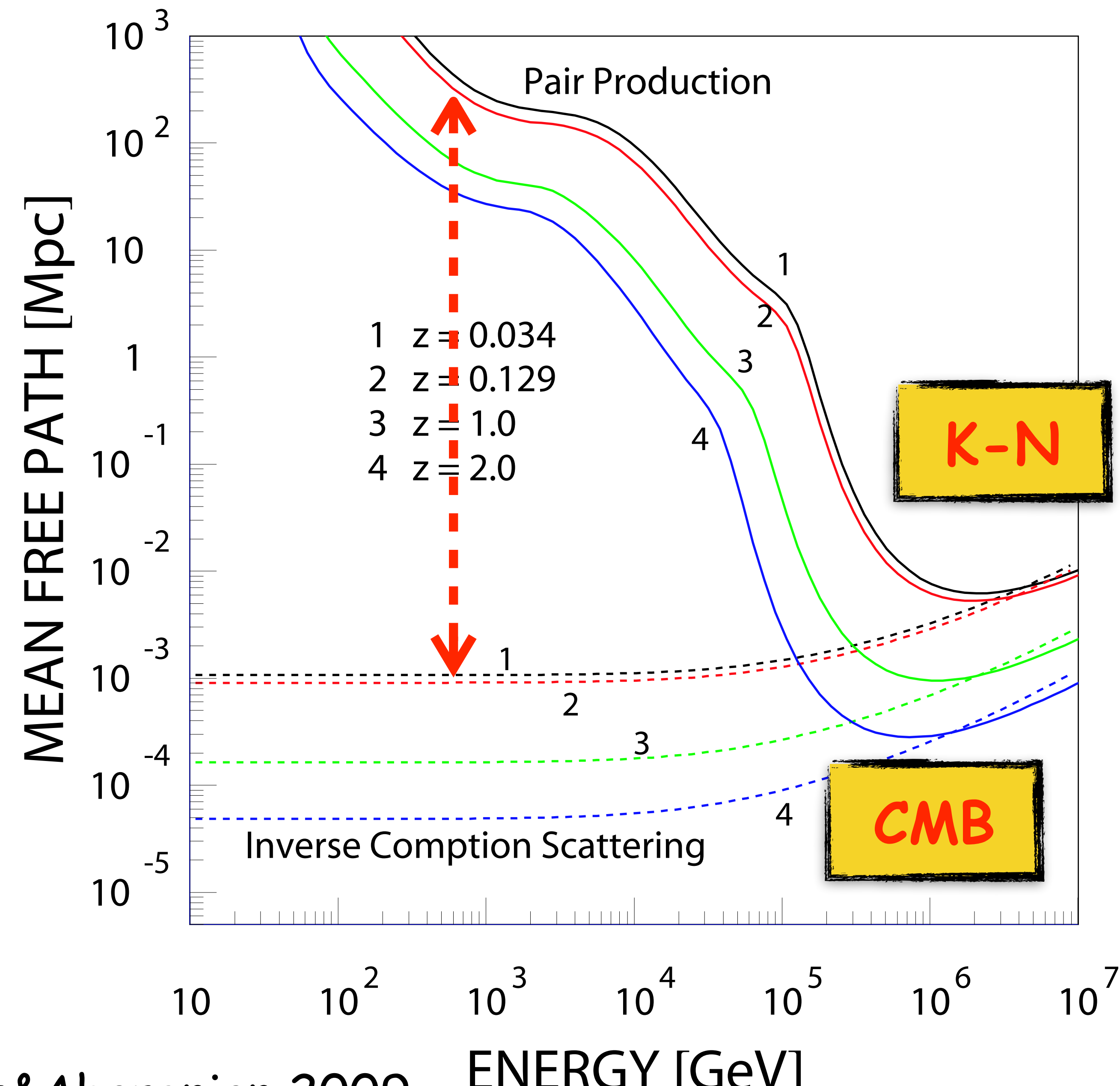

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Electromagnetic cascade: development

$$s_0 = \frac{E_\gamma \epsilon_s}{(m_e c^2)^2}$$

Electromagnetic cascade: development

"Klein-Nishina"

$s_0 >> 1$

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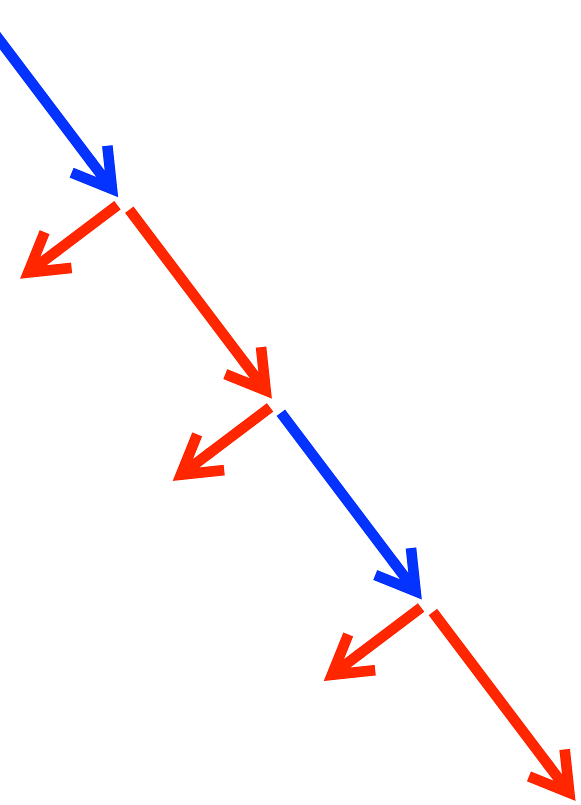

1 leading particle

Electromagnetic cascade: development

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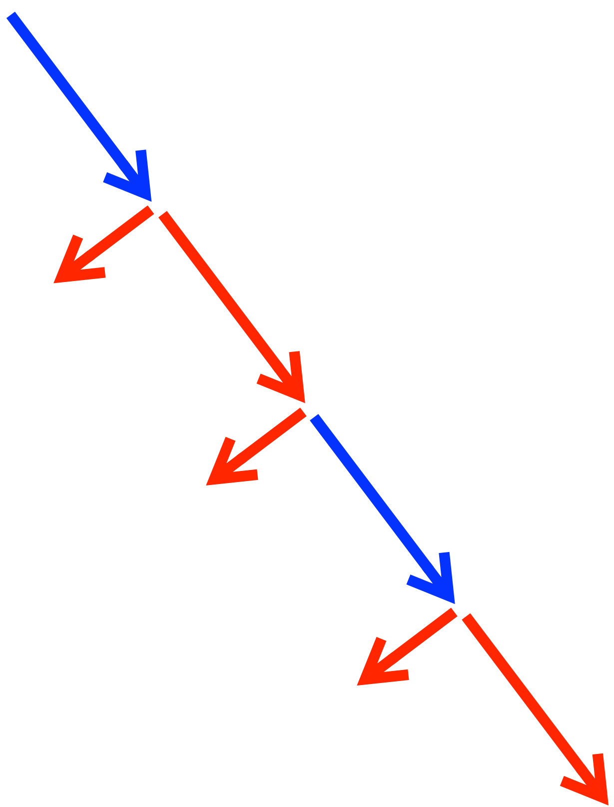
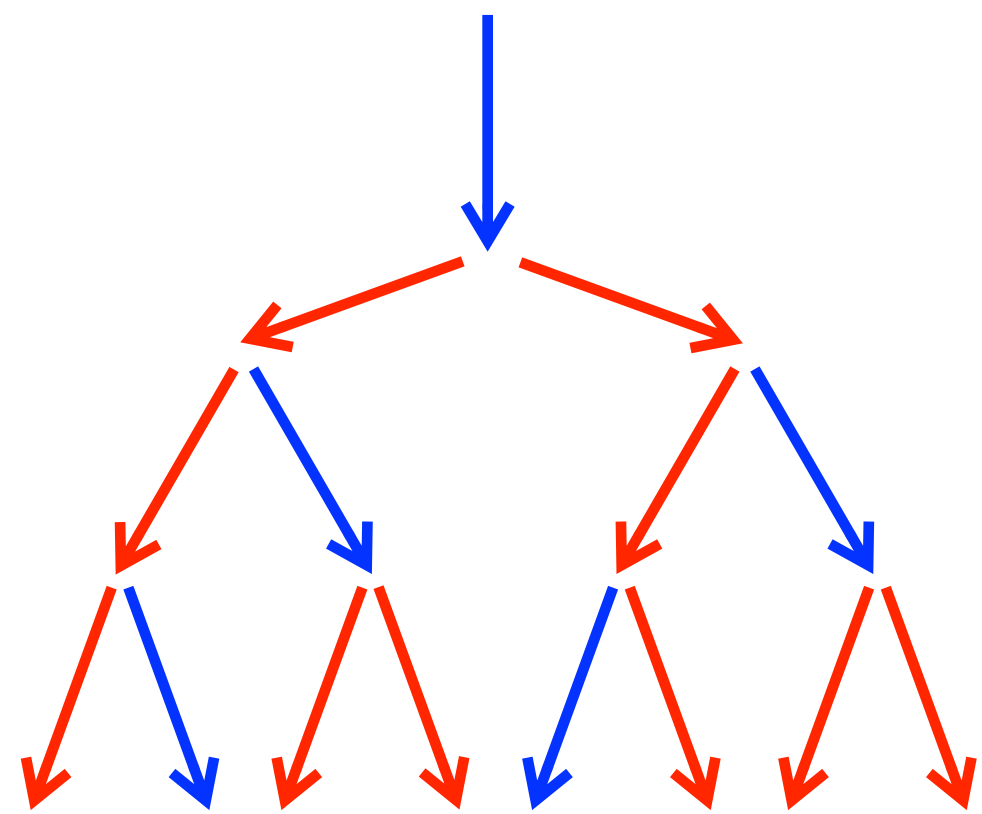
"Thomson"

$s_0 \sim 1$

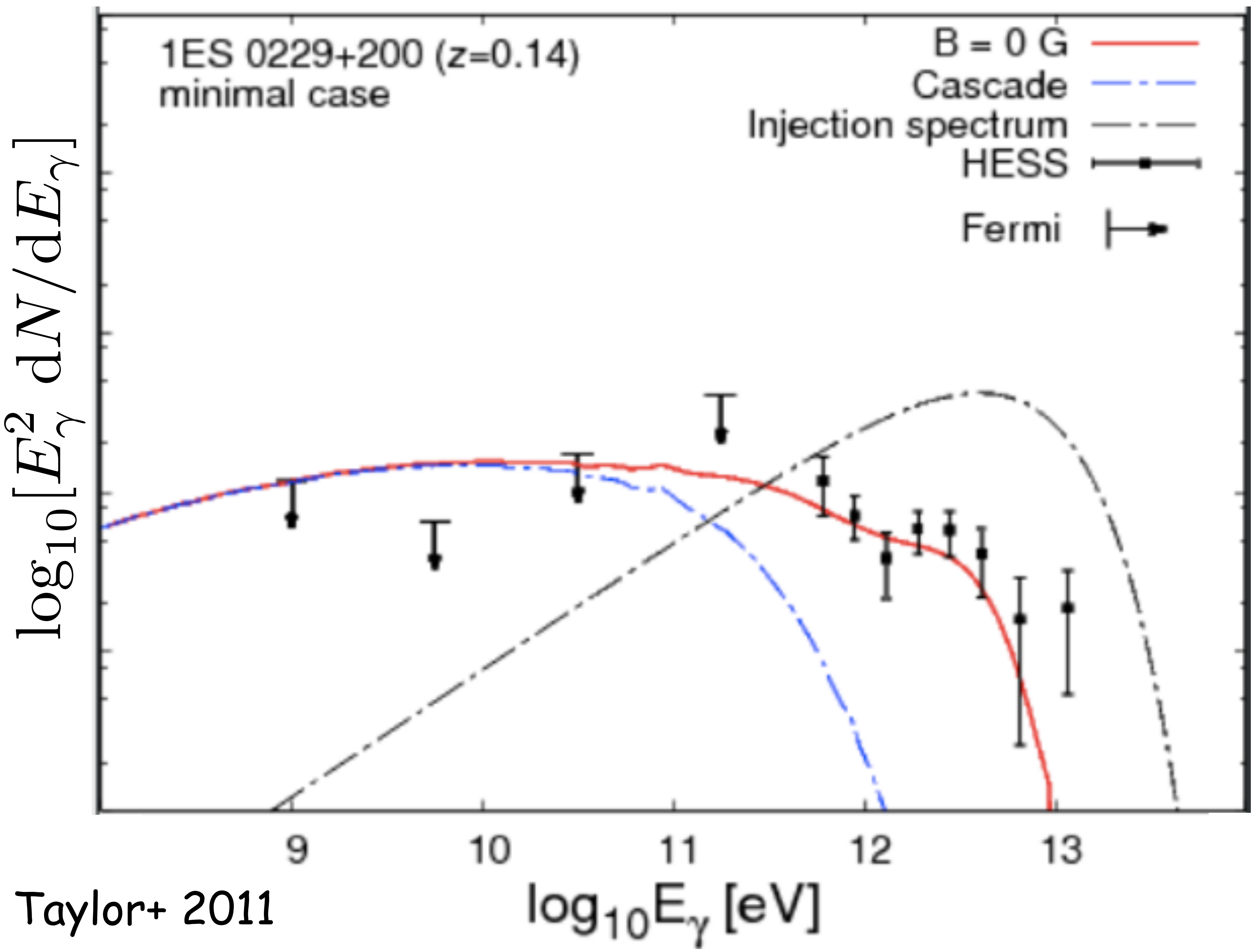




1 leading particle

many particles

Electromagnetic cascade: spectrum



Taylor+ 2011

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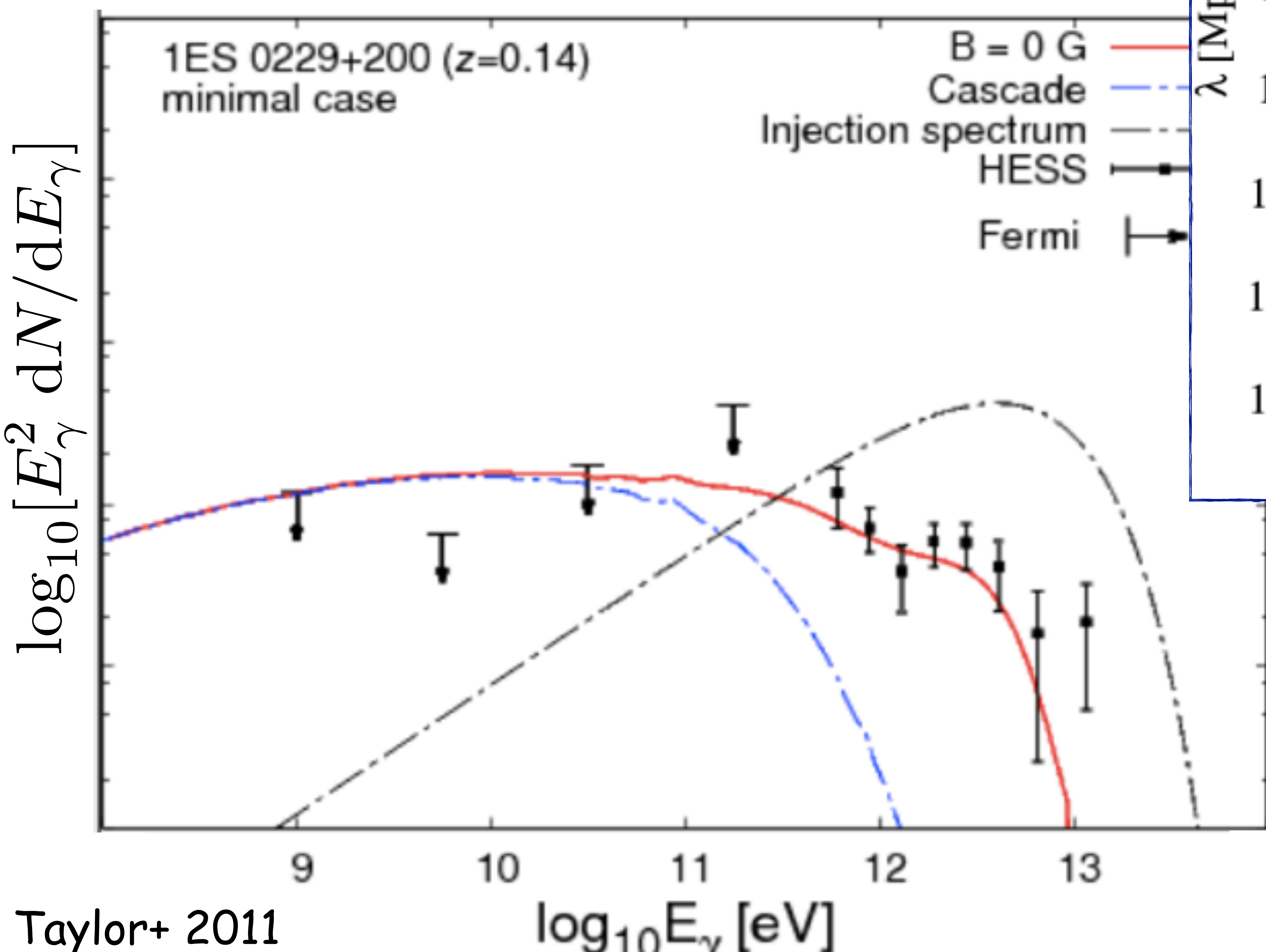
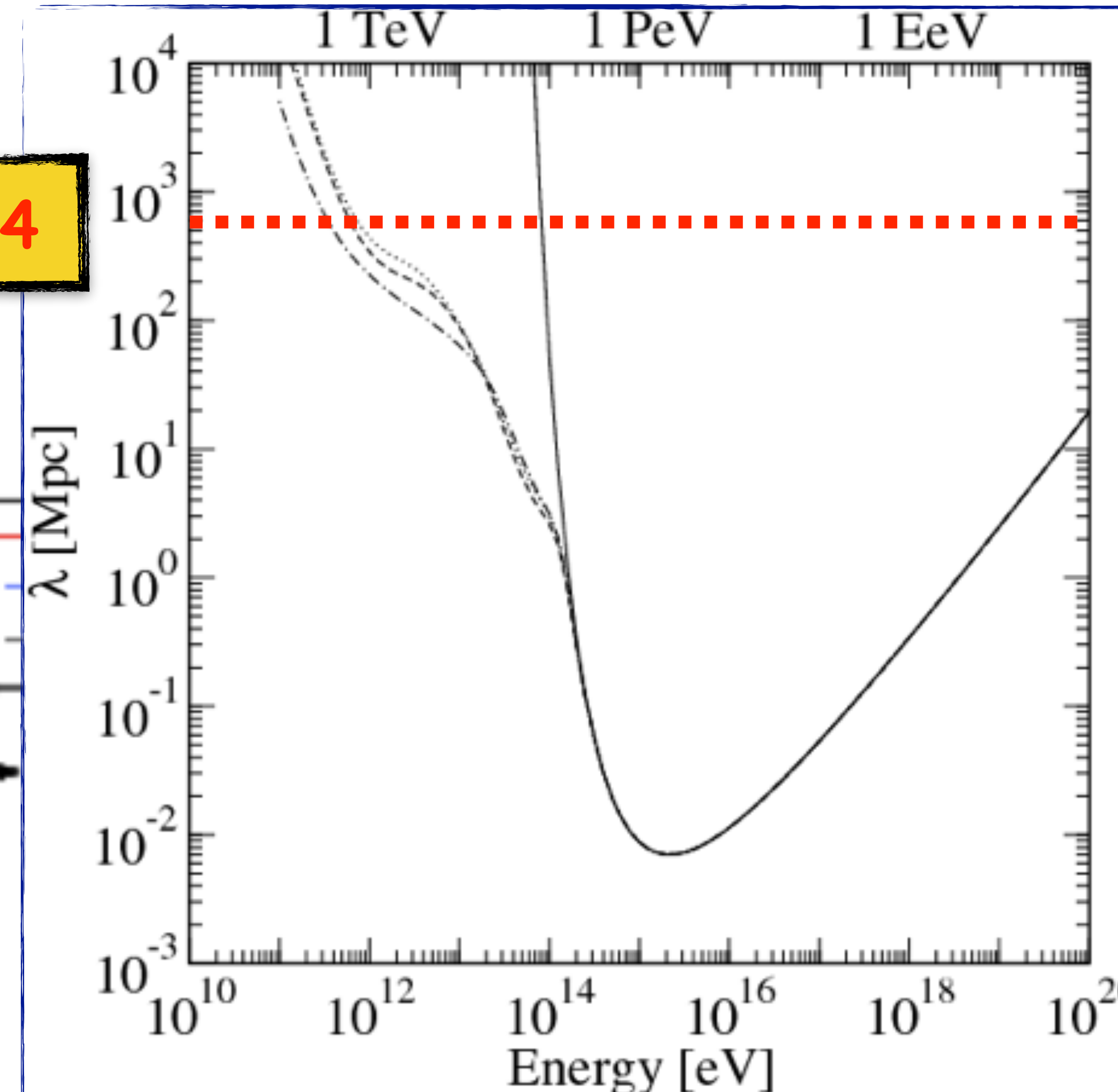
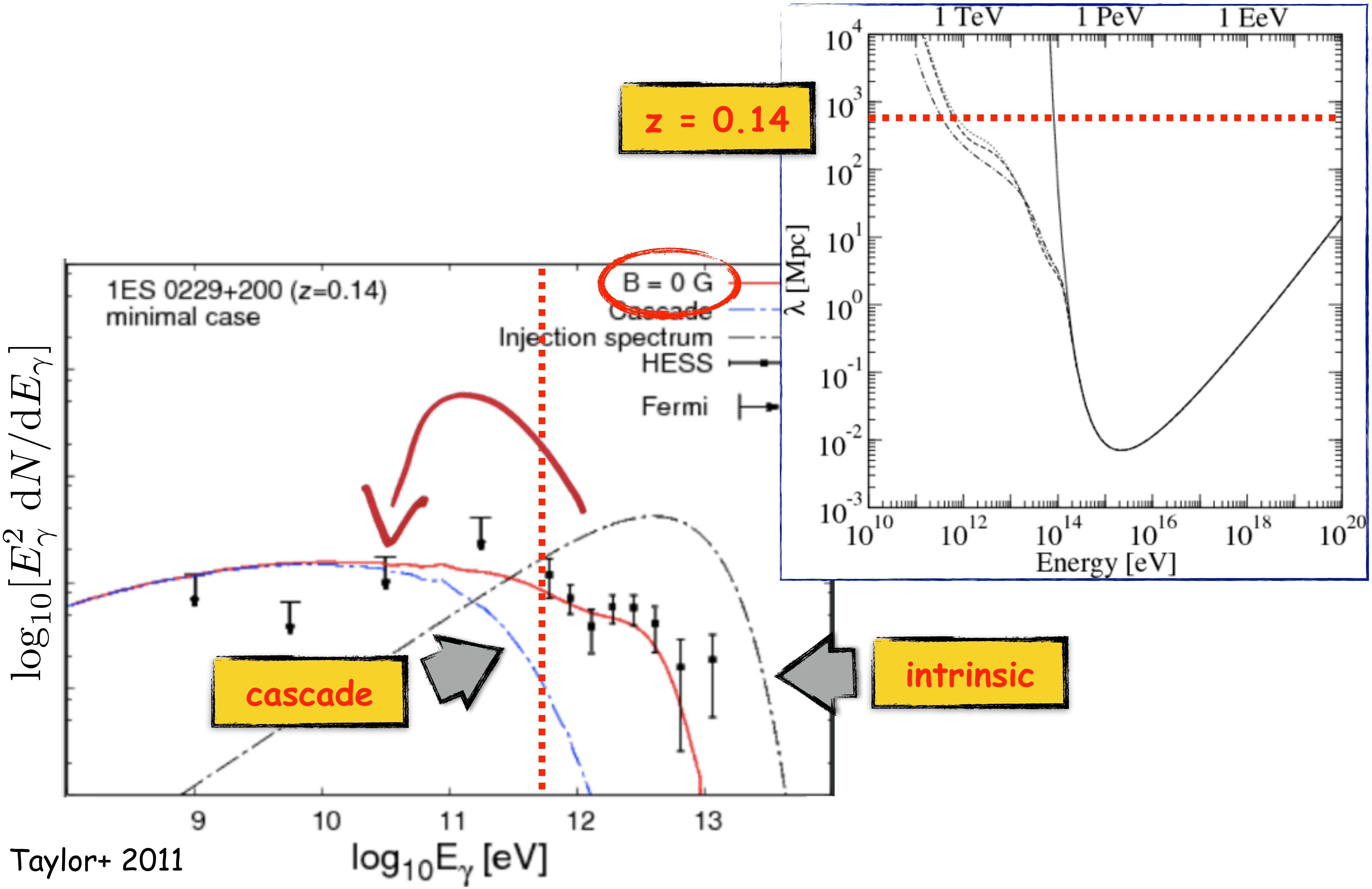




z = 0.14

Taylor+ 2011

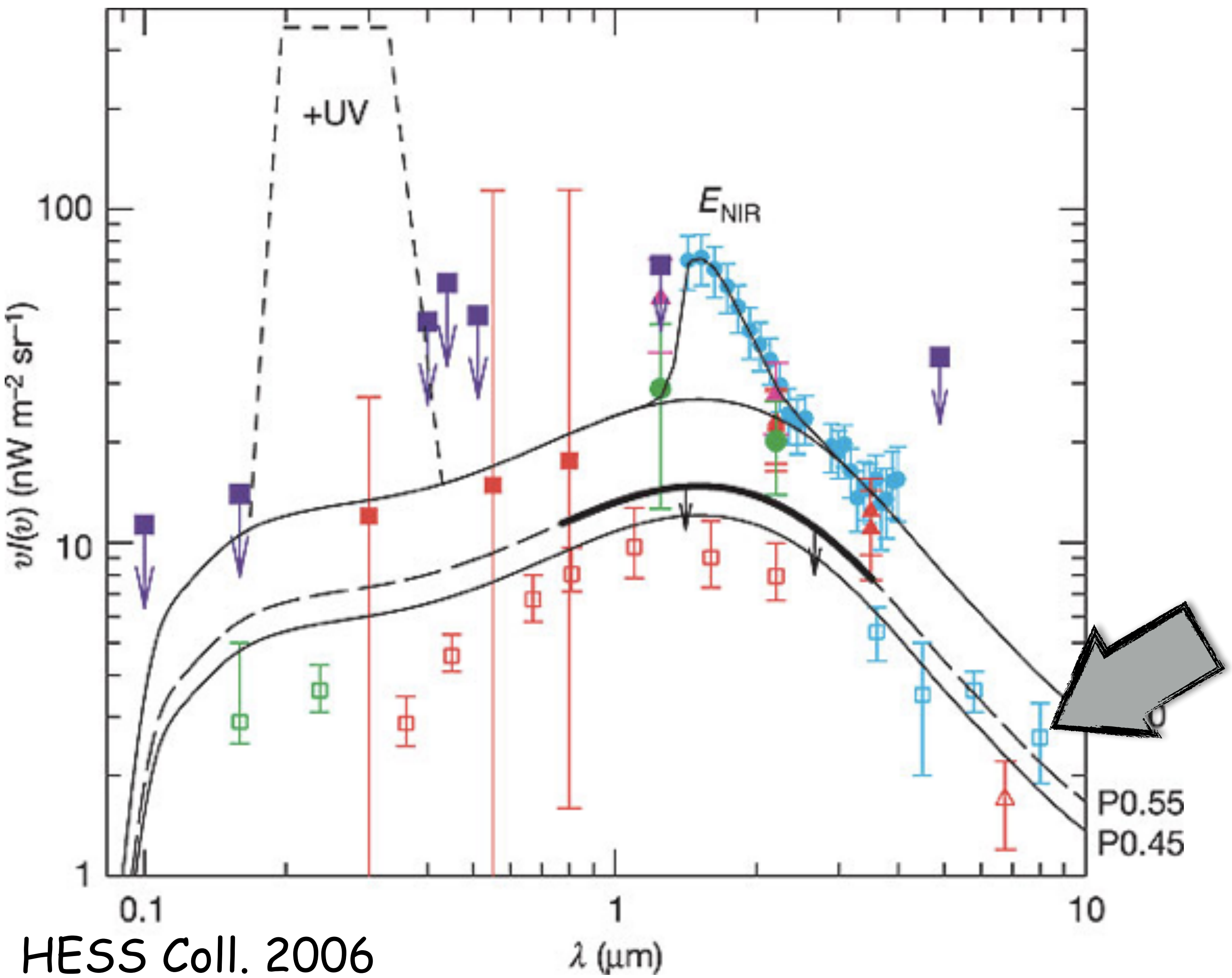
Electromagnetic cascade: spectrum



Taylor+ 2011

How well do we know the EBL?

for a review see
Costamante 2013



HESS Coll. 2006

galaxy counts
-> lower limit

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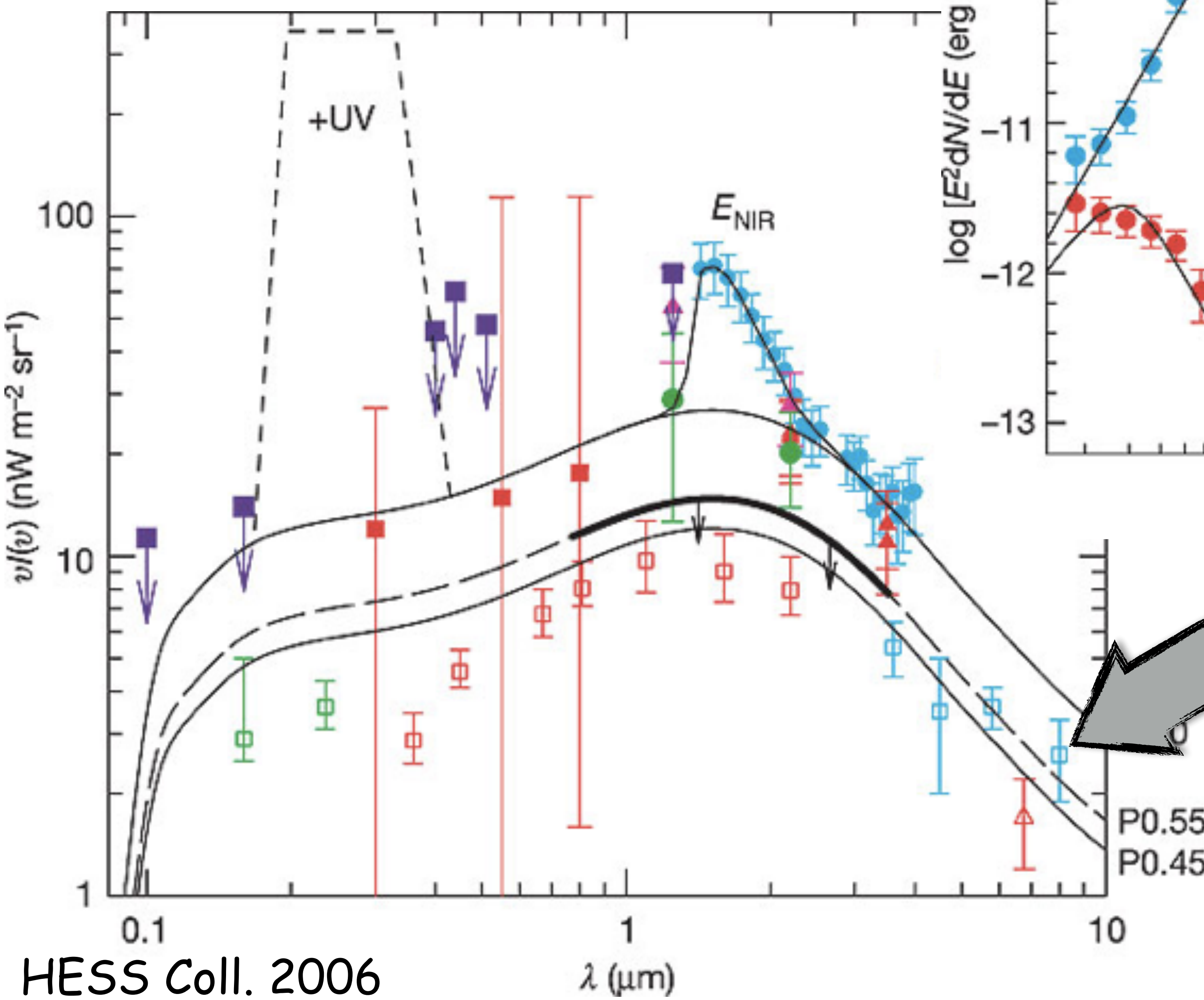

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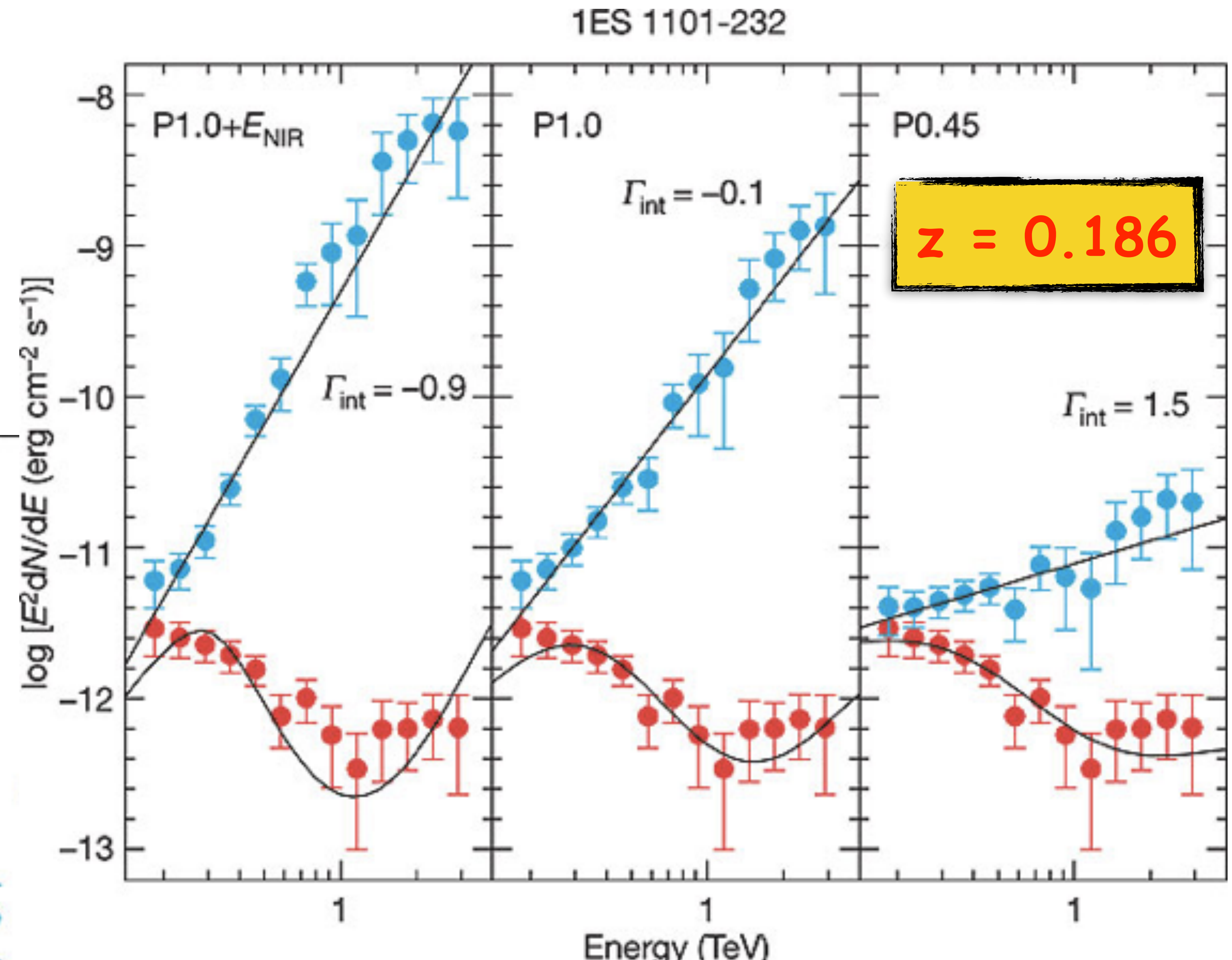

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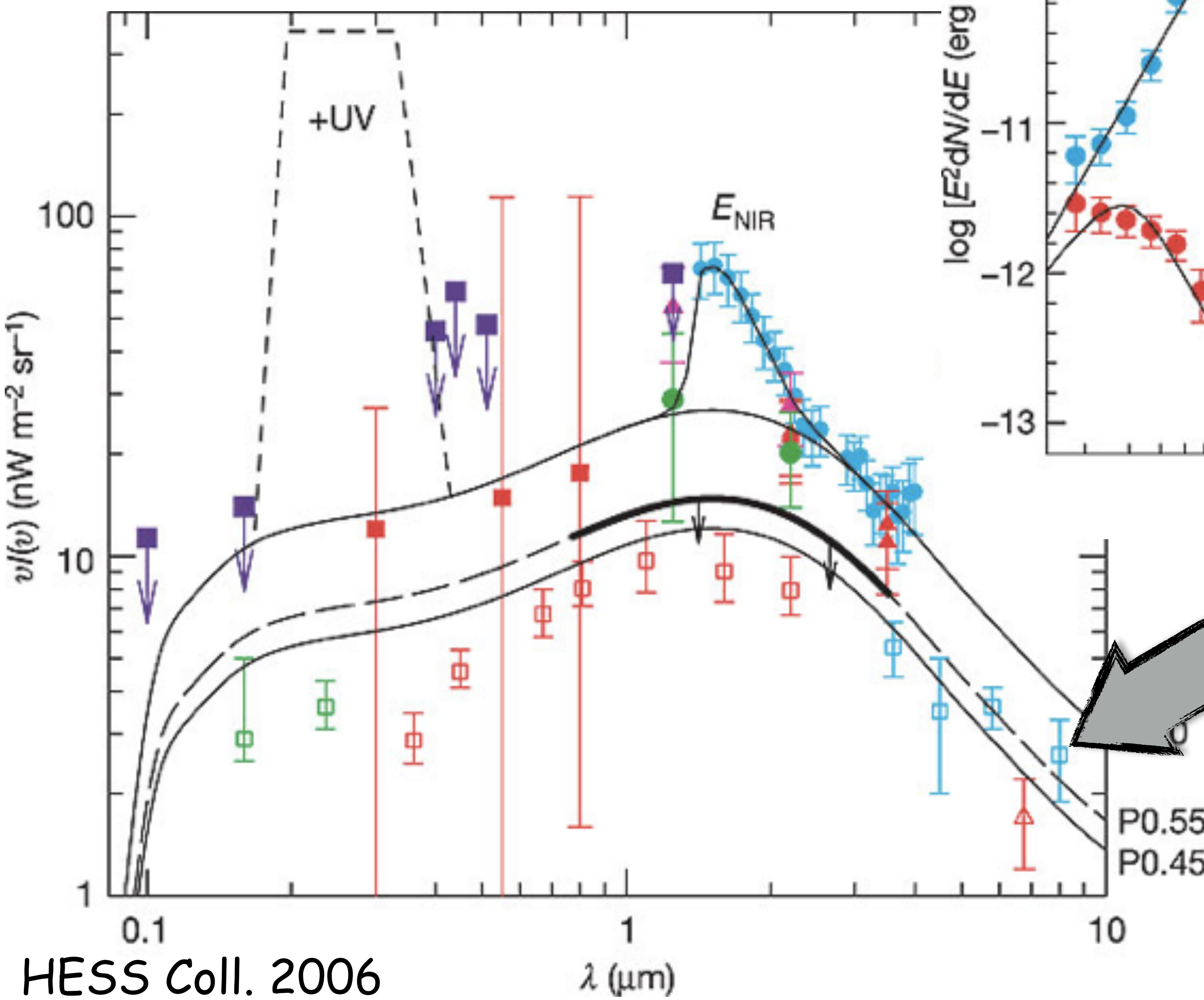

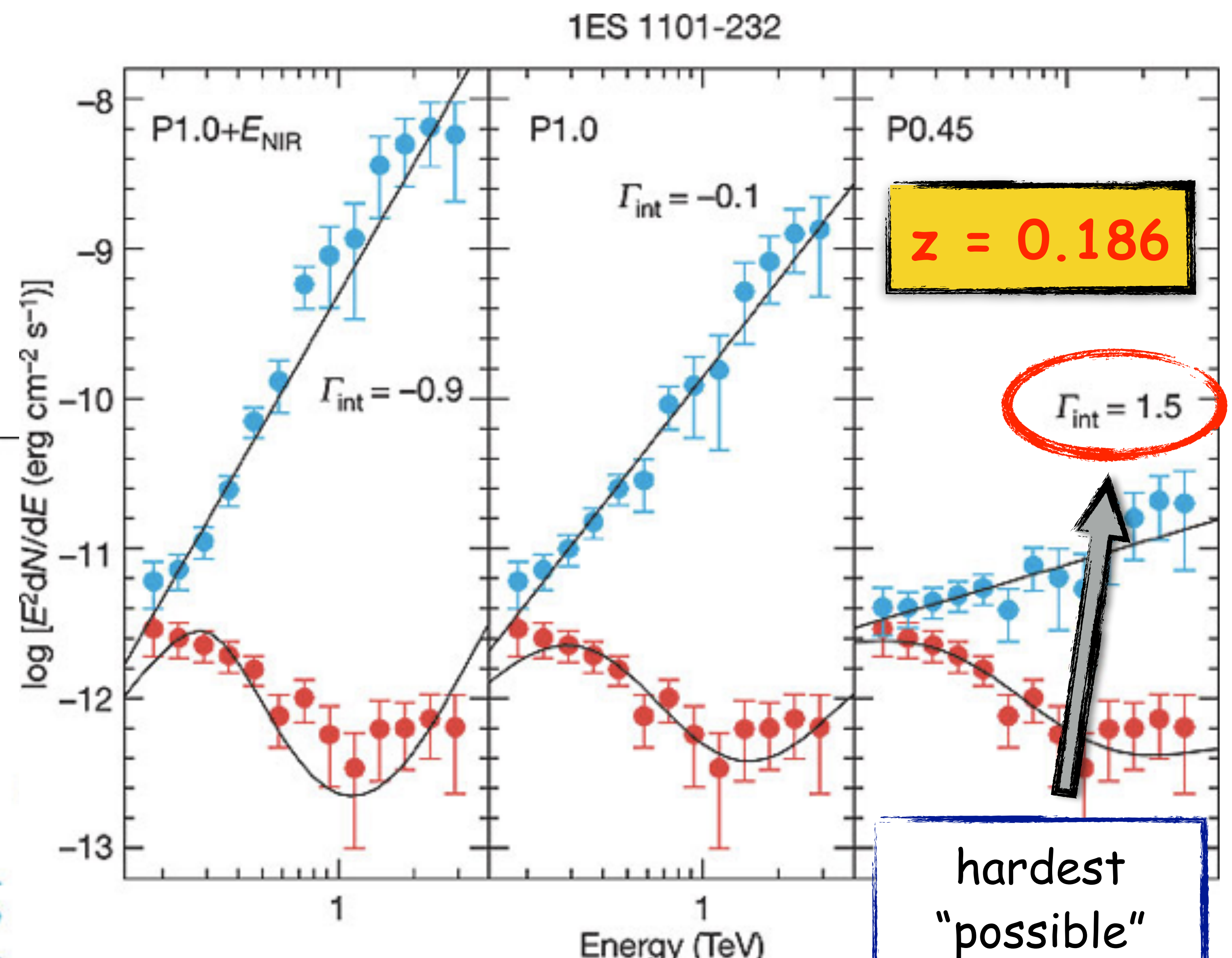

galaxy counts -> lower limit

hardest "possible" spectrum

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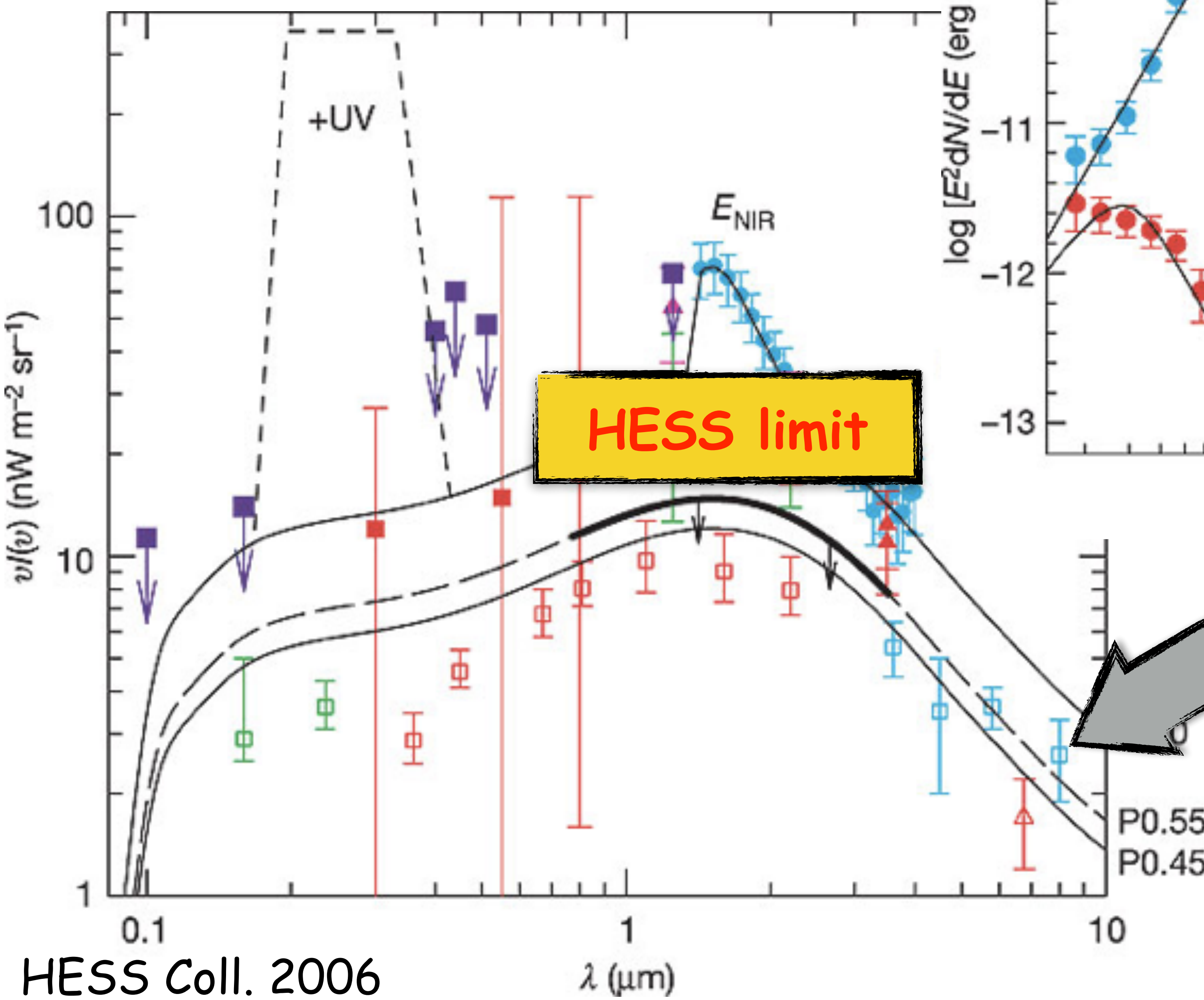
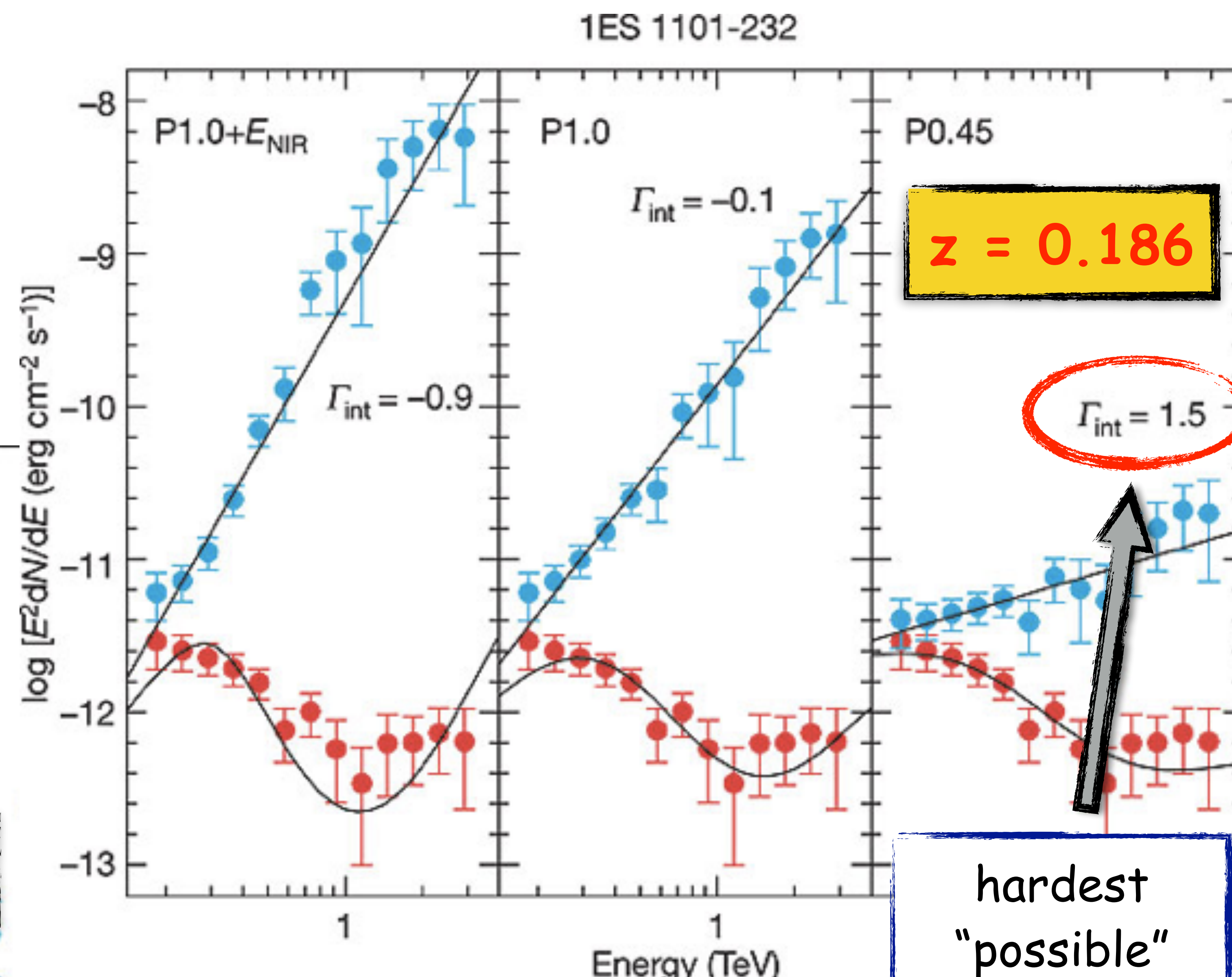


HESS limit

HESS Coll. 2006



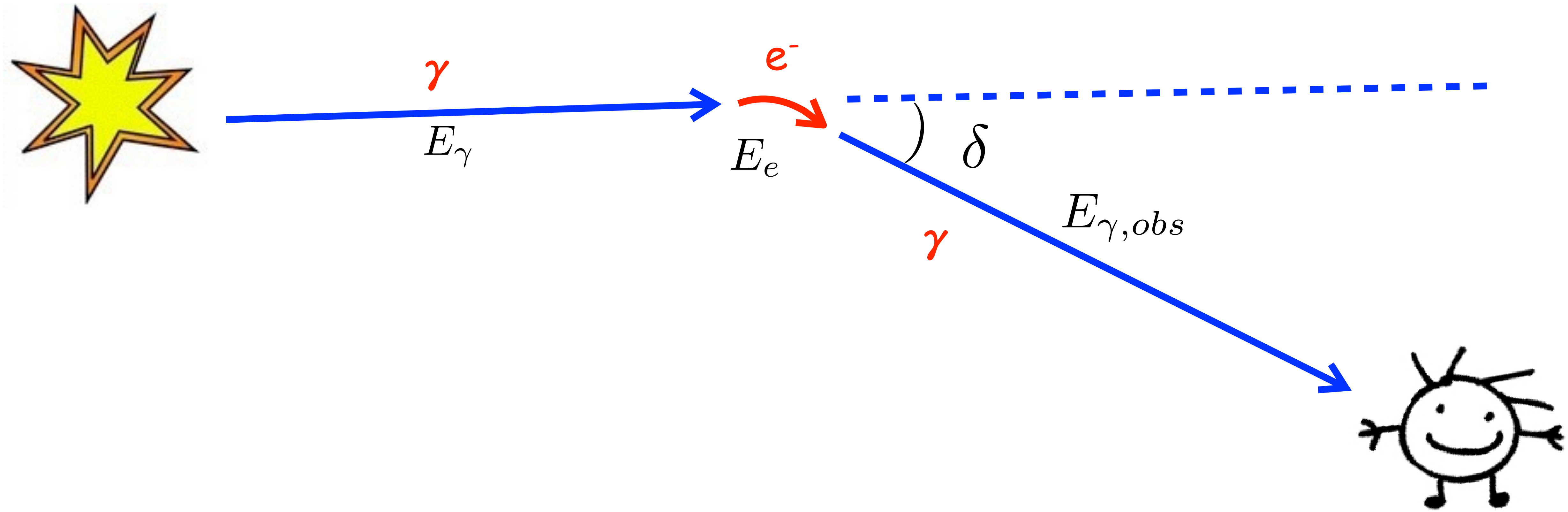
z = 0.186

hardest "possible" spectrum

galaxy counts -> lower limit

the Universe is more transparent to γ-rays than expected

Magnetic fields: why should we care?



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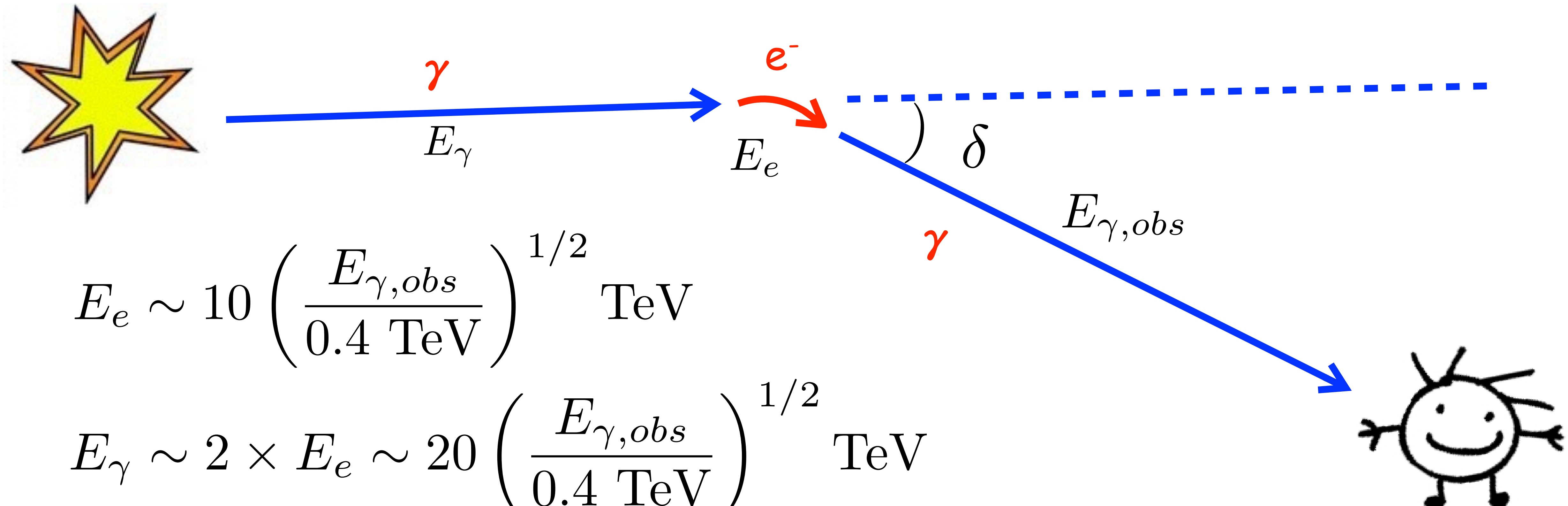

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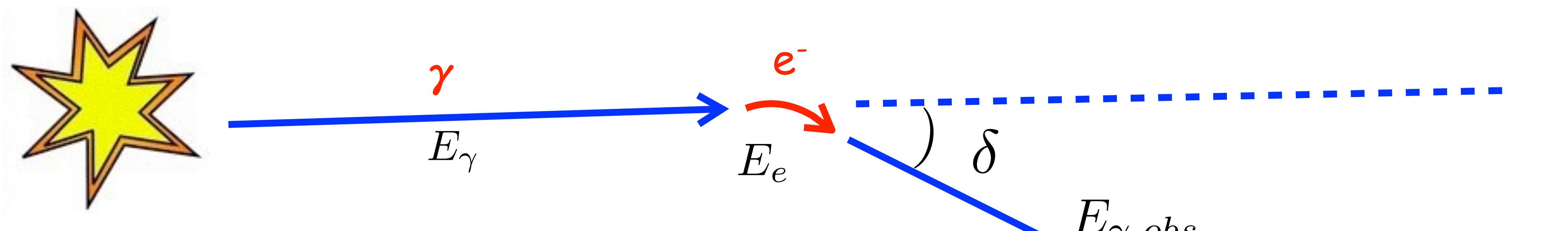

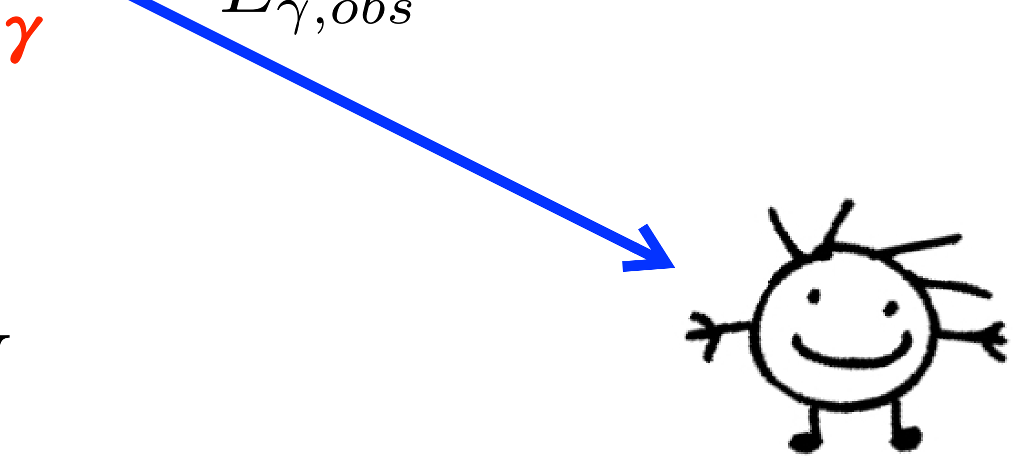

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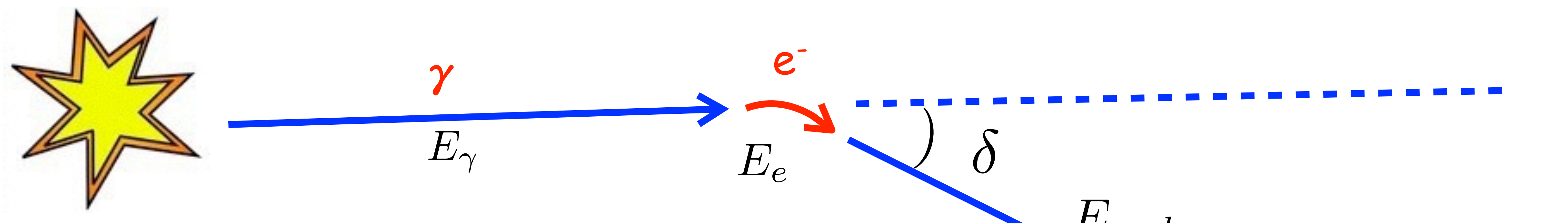
Compton cooling length -> $$\lambda_e \sim 40 \left(\frac{E_{\gamma,obs}}{0.4\ \mathrm{TeV}} \right)^{-1/2} \mathrm{kpc}$$

Deflection-> $$\delta = \frac{\lambda_e}{R_L} \sim 0.2^\circ \left(\frac{E_{\gamma,obs}}{0.4\ \mathrm{TeV}} \right)^{-1} \left(\frac{B}{10^{-15}\ \mathrm{G}} \right)$$

Magnetic fields: why should we care?



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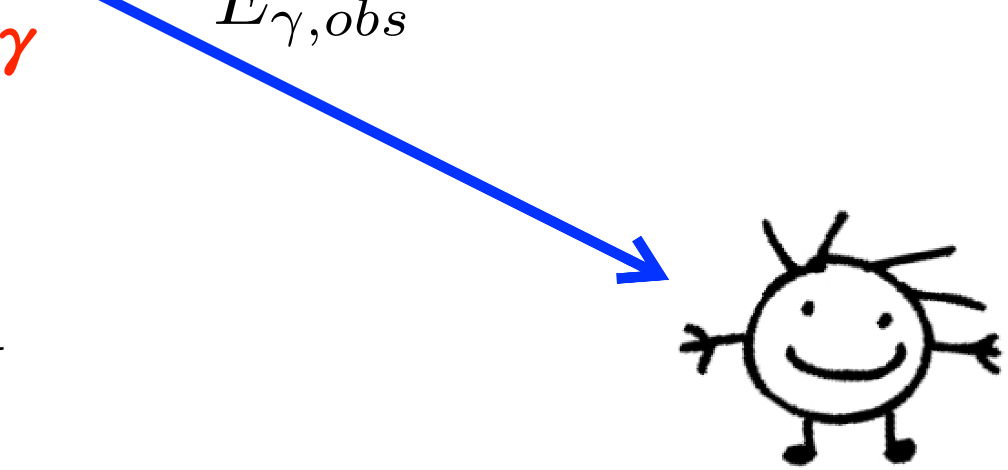

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reduced by a random walk factor $\left(\frac{\lambda_B}{\lambda_e}\right)^{1/2}$ — if $\lambda_B << \lambda_e$

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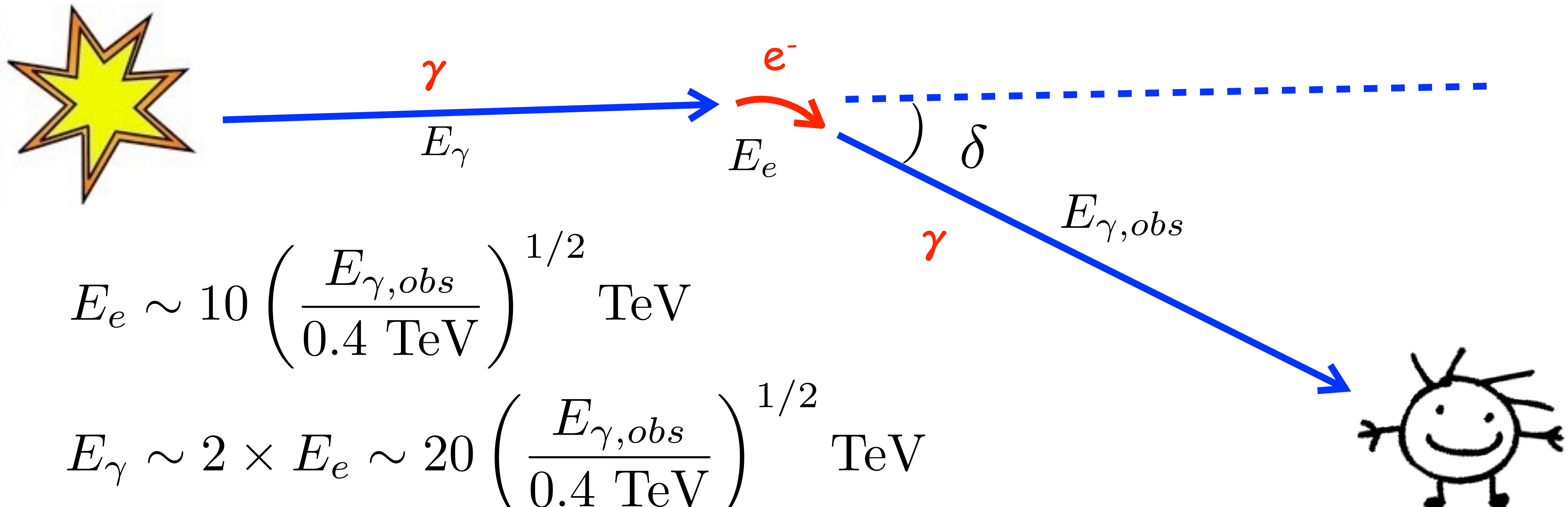

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upper limits from Faraday rotation of distant quasars and CMB fluctuations are at the nanoGauss level -> gamma-rays can be used to measure or constrain B!

Deflection->

$$\delta = \frac{\lambda_e}{R_L} \sim 0.2^\circ \left(\frac{E_{\gamma,obs}}{0.4\ \mathrm{TeV}}\right)^{-1} \left(\frac{B}{10^{-15}\ \mathrm{G}}\right)$$

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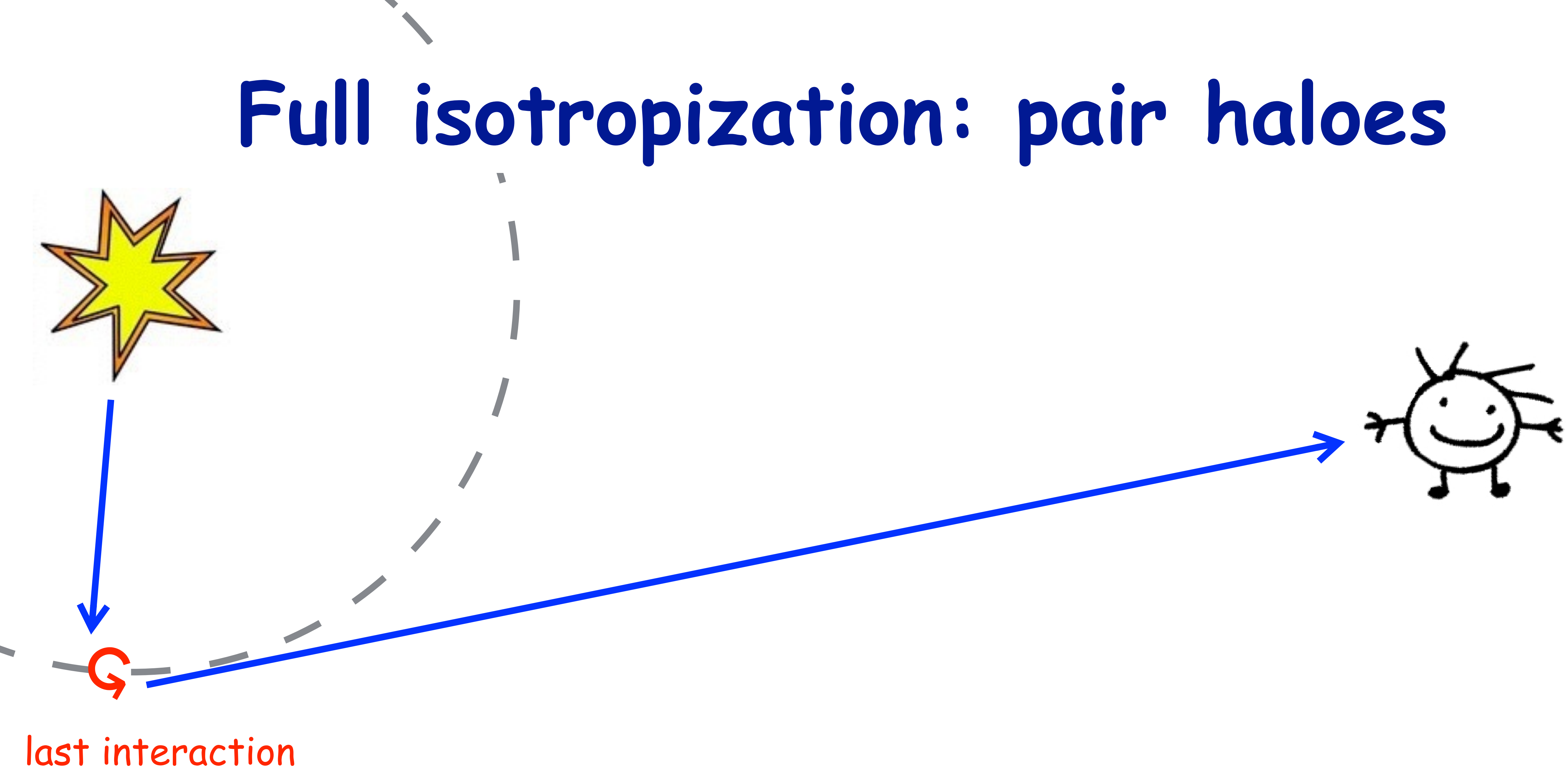
Full isotropization: pair haloes



Aharonian, Coppi & Voelk 1994

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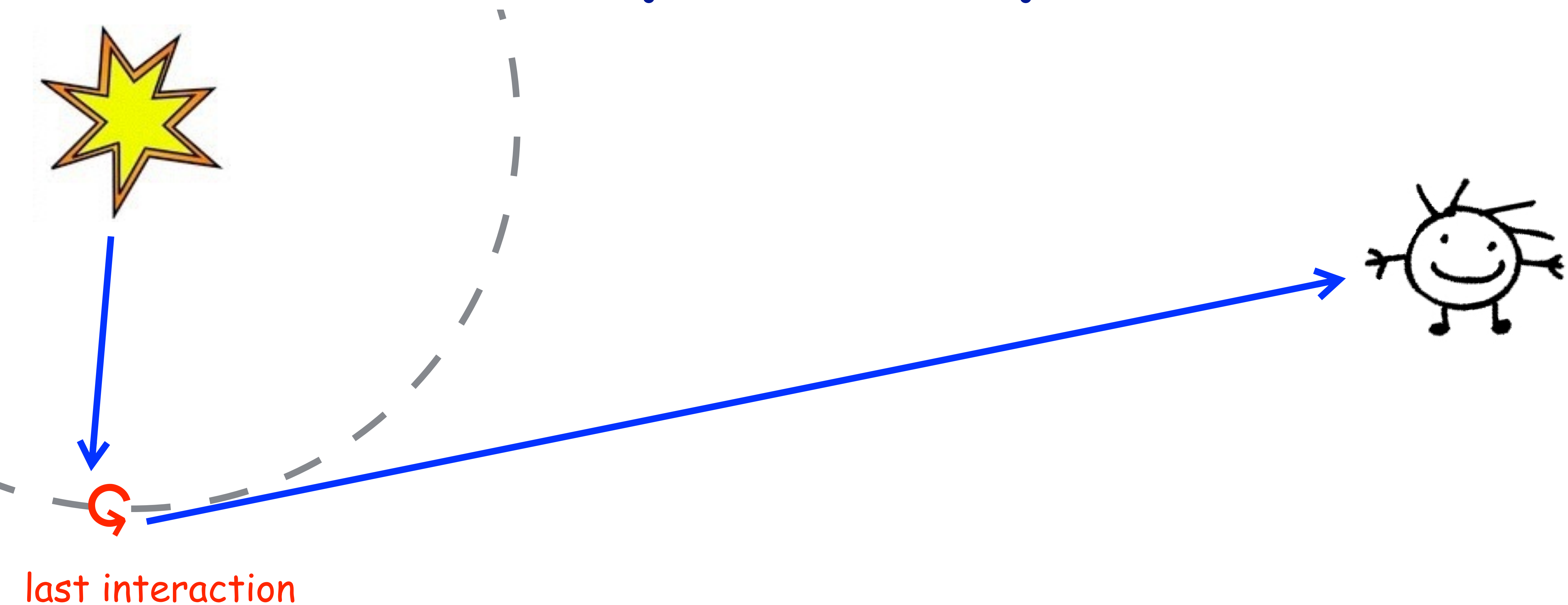

pairs are isotropised when

$$B \gtrsim 2 \times 10^{-12} \left(\frac{E_{\gamma,obs}}{0.4\ \mathrm{TeV}} \right) \mathrm{G}$$

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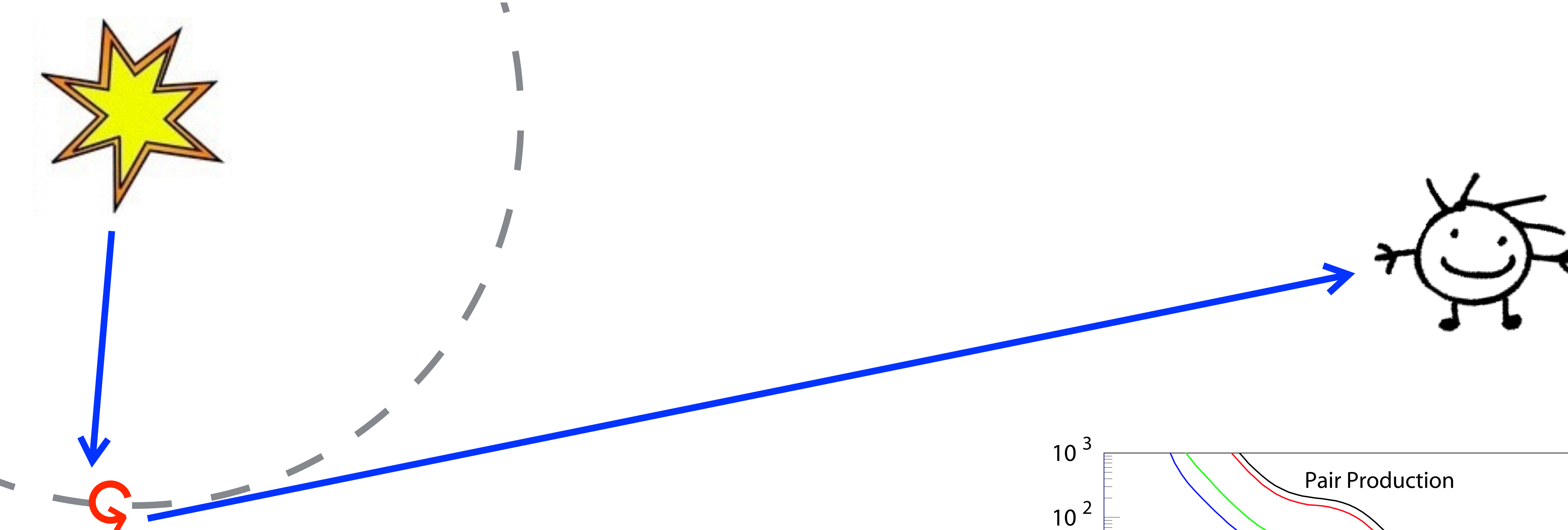


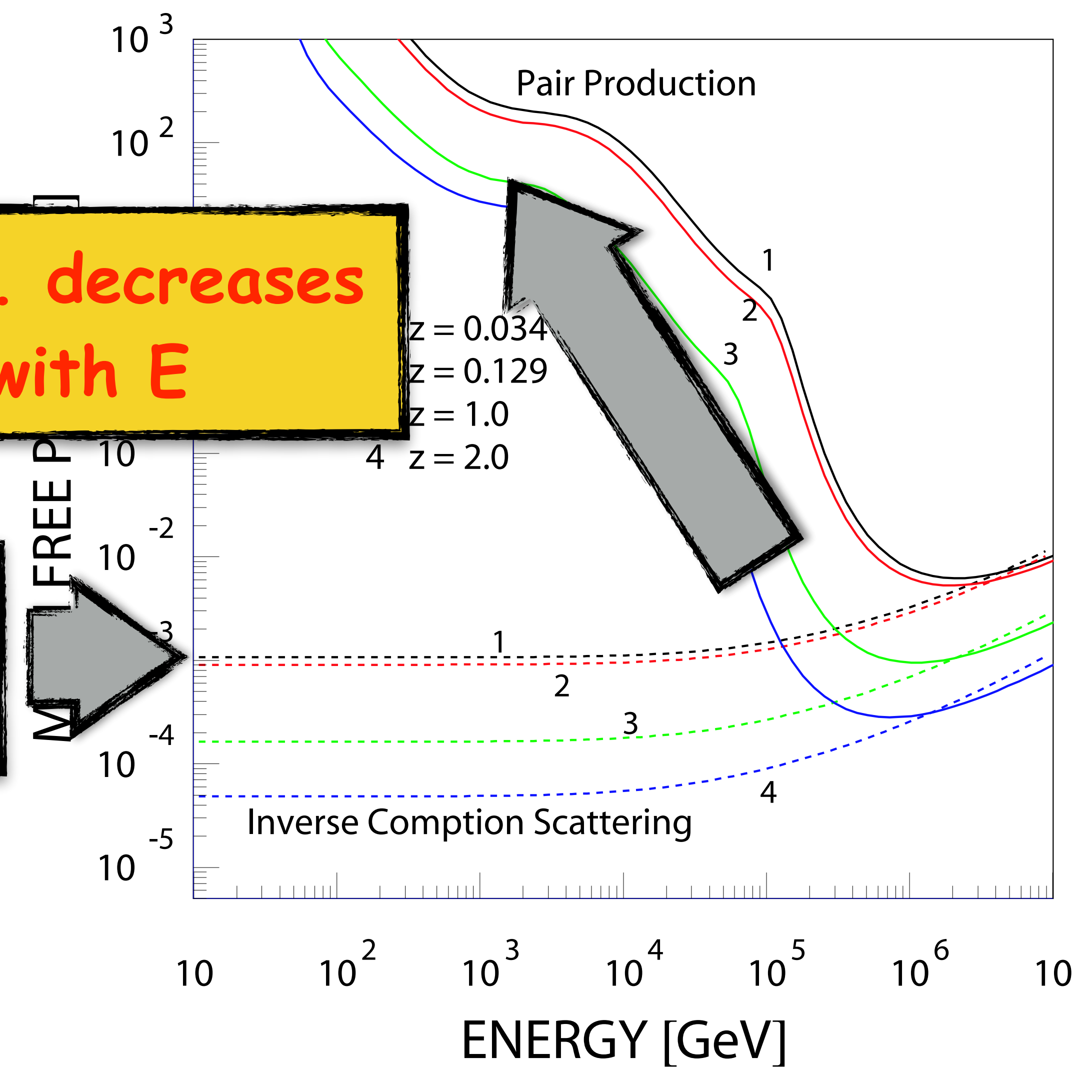
last interaction

pairs are isotropised when

$$B \gtrsim 2 \times 10^{-12} \left(\frac{E_{\gamma,obs}}{0.4\ \mathrm{TeV}} \right) \mathrm{G}$$

pairs do not move

m.f.p. decreases with E



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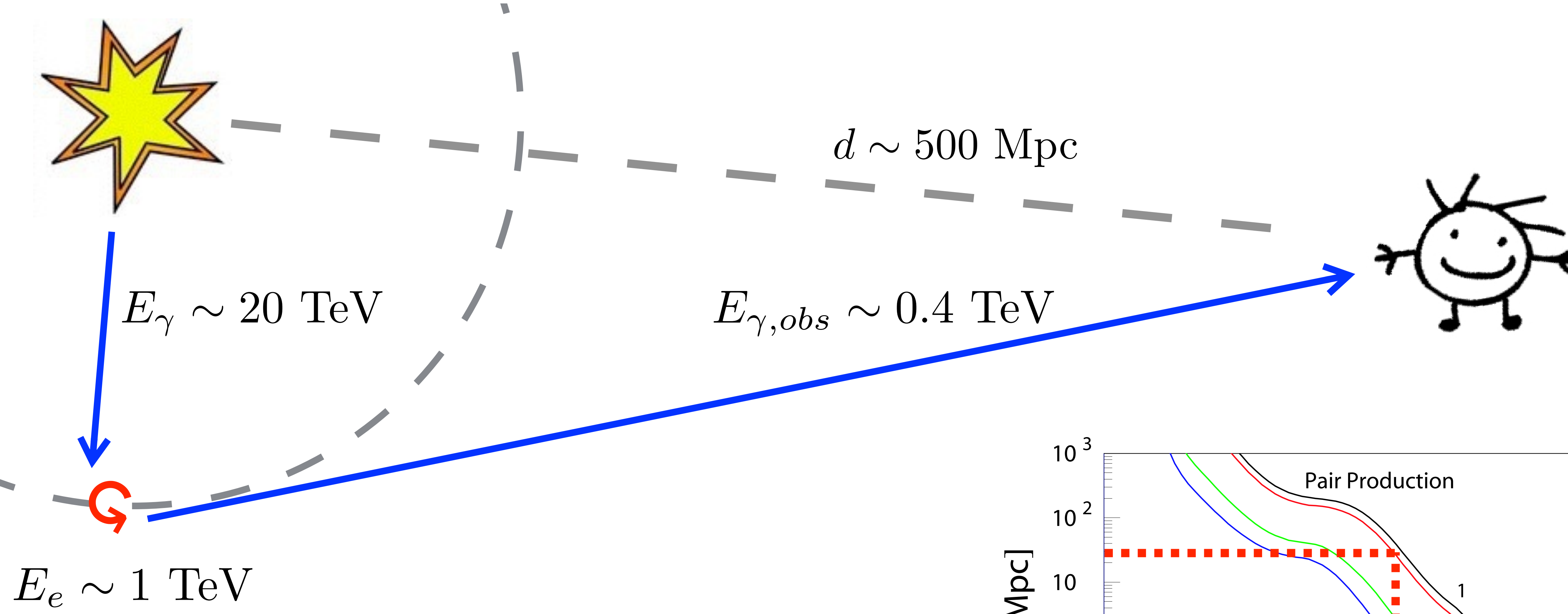
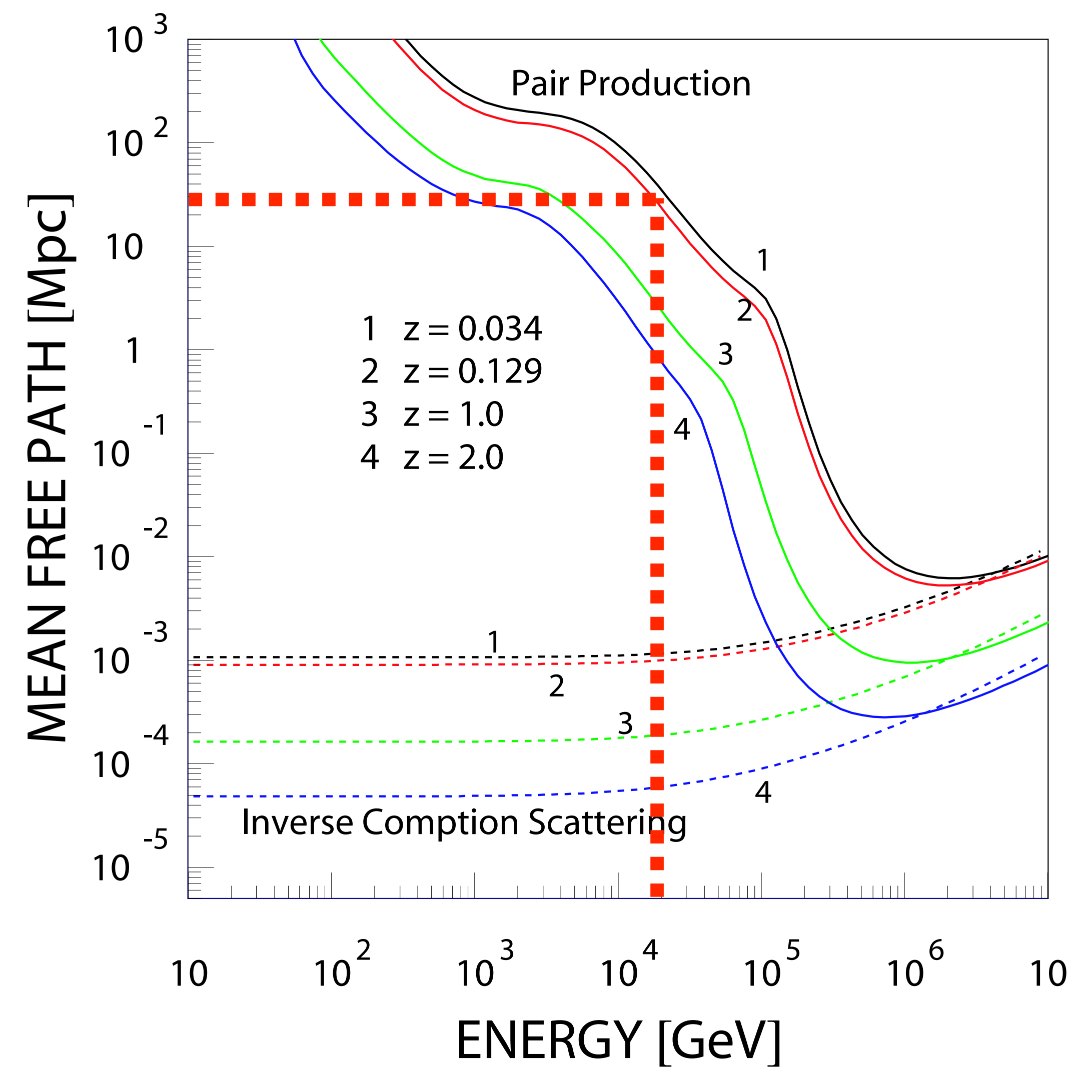
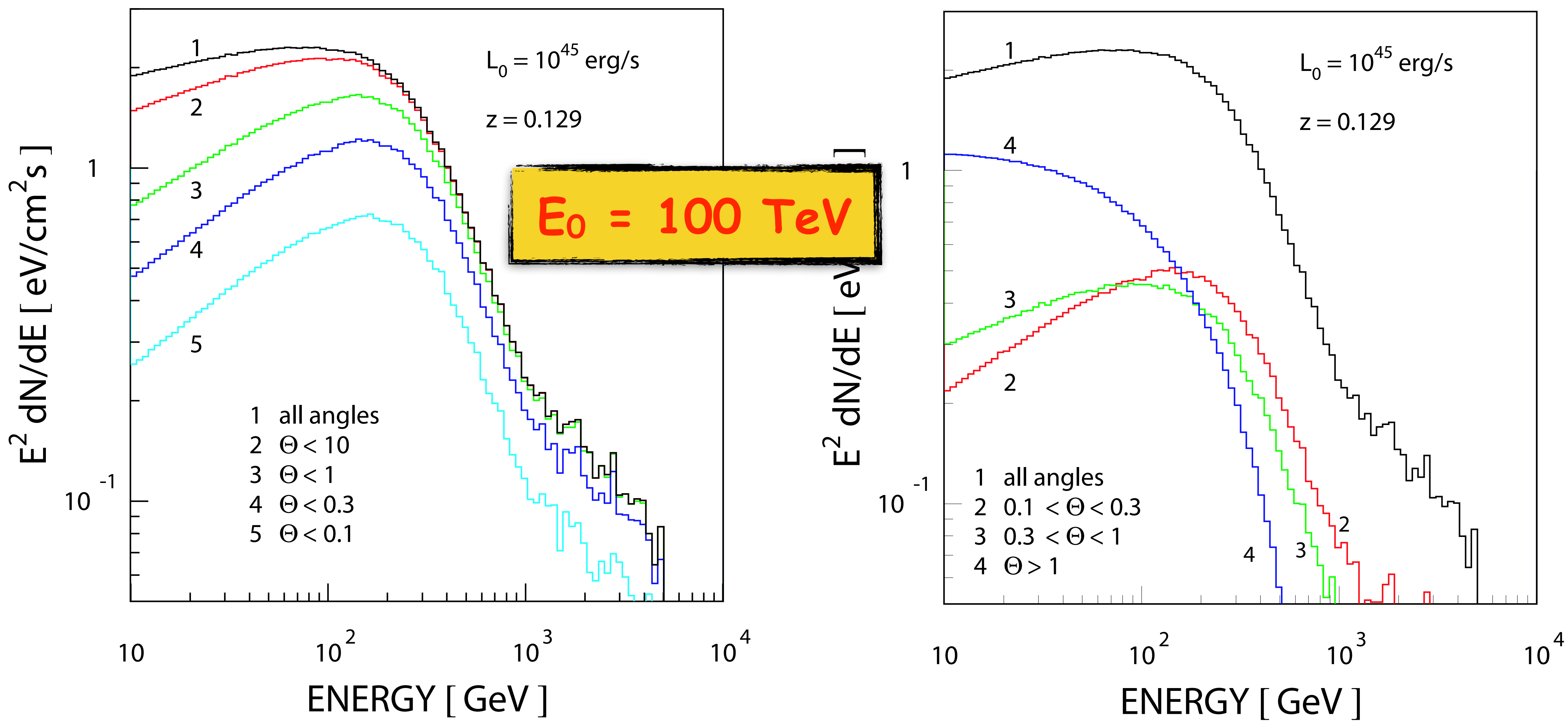


$$\vartheta_{halo} \sim \frac{\lambda_{\gamma\gamma}(E_\gamma)}{d} \approx 3^\circ$$



Pair haloes: spectra and morphology

Eungwanichayapant&Aharonian 09



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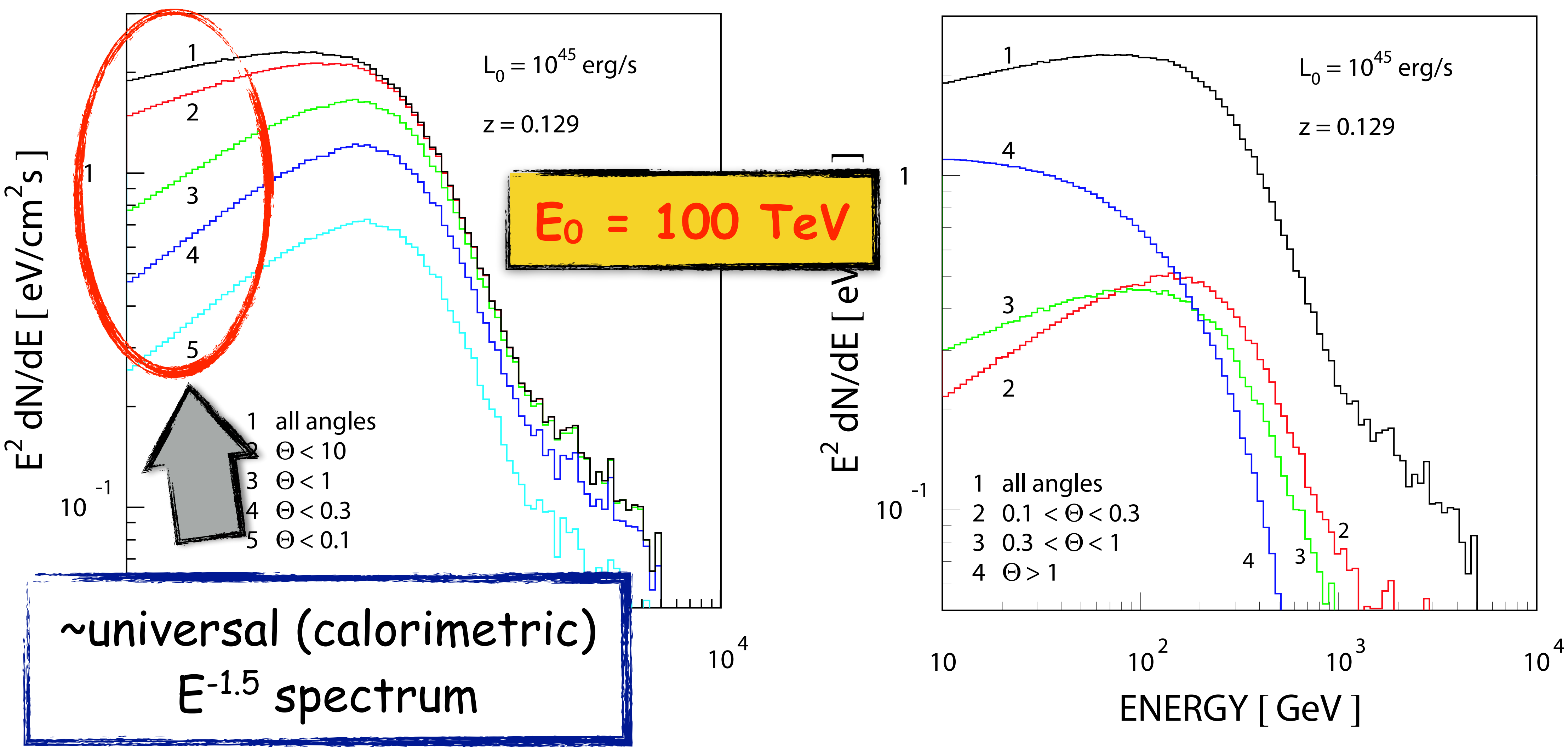

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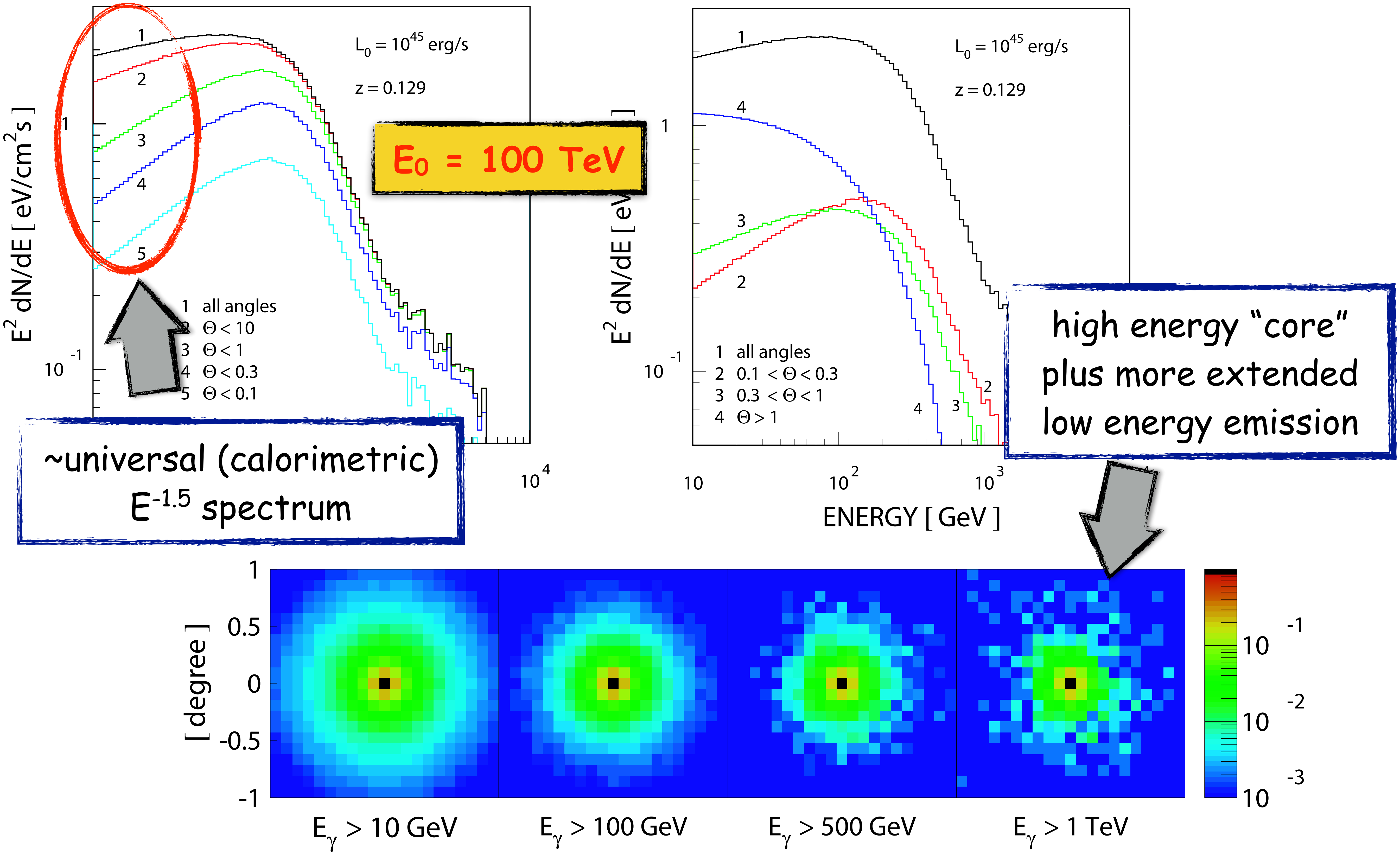

Pair haloes: cosmological probes

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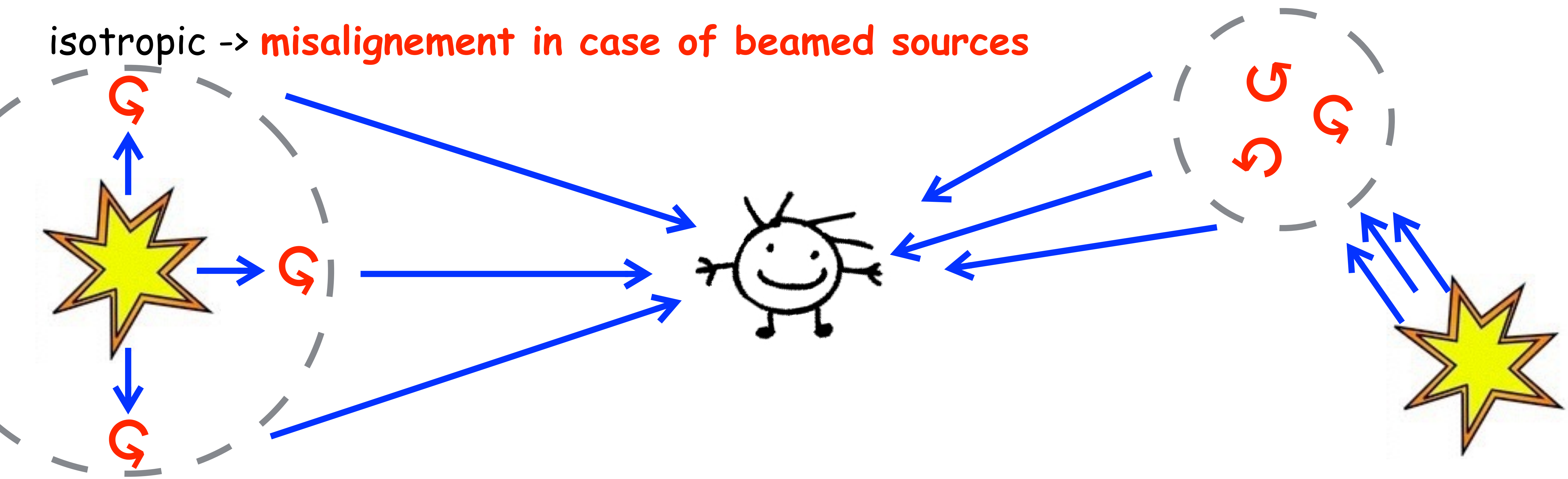
- pair haloes -> **time integrated power in very high energy gamma rays** of the central source (Compton cooling time of electrons <1 Myr)
- the halo emission is centered onto the central source if the primary emission is isotropic -> **misalignement in case of beamed sources**



Detection of pair halos/γ-ray halos?

some confusion in the literature
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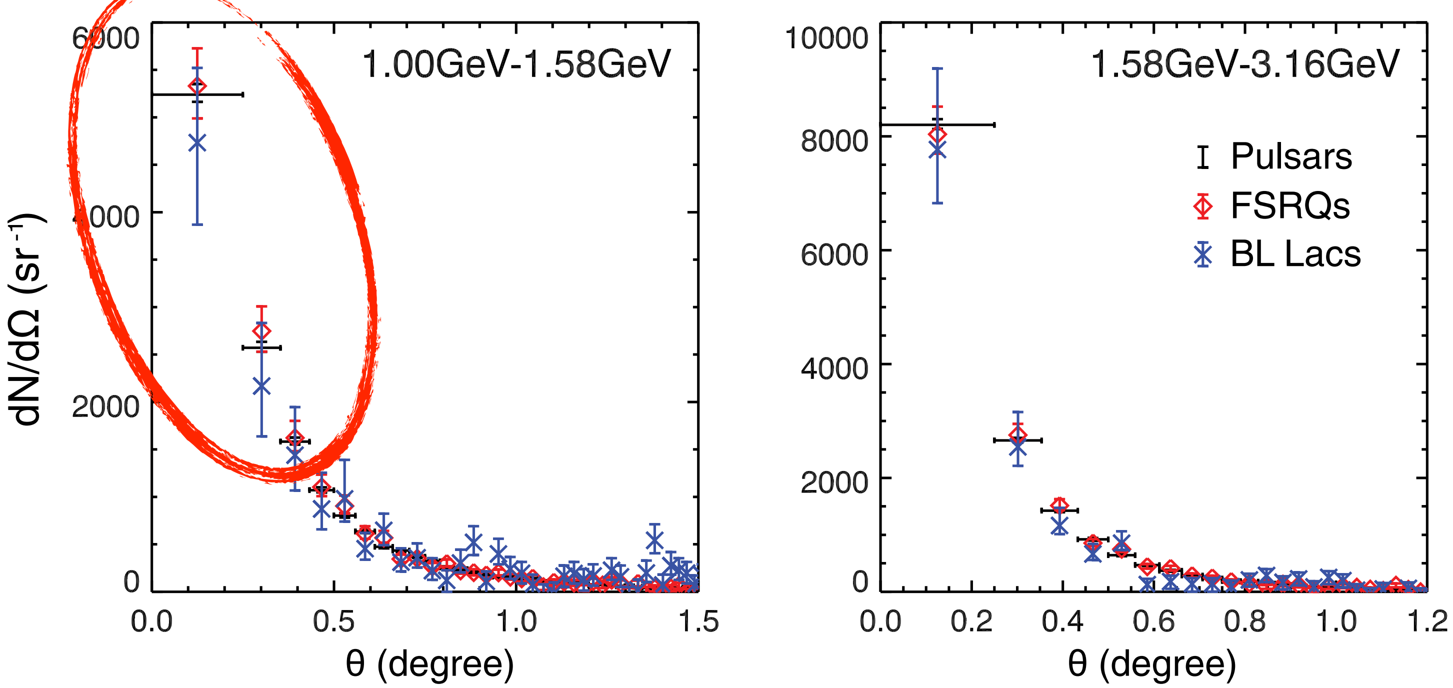
stacking of 24 BL Lac objects

Chen+ 2015



evidence for pair halos

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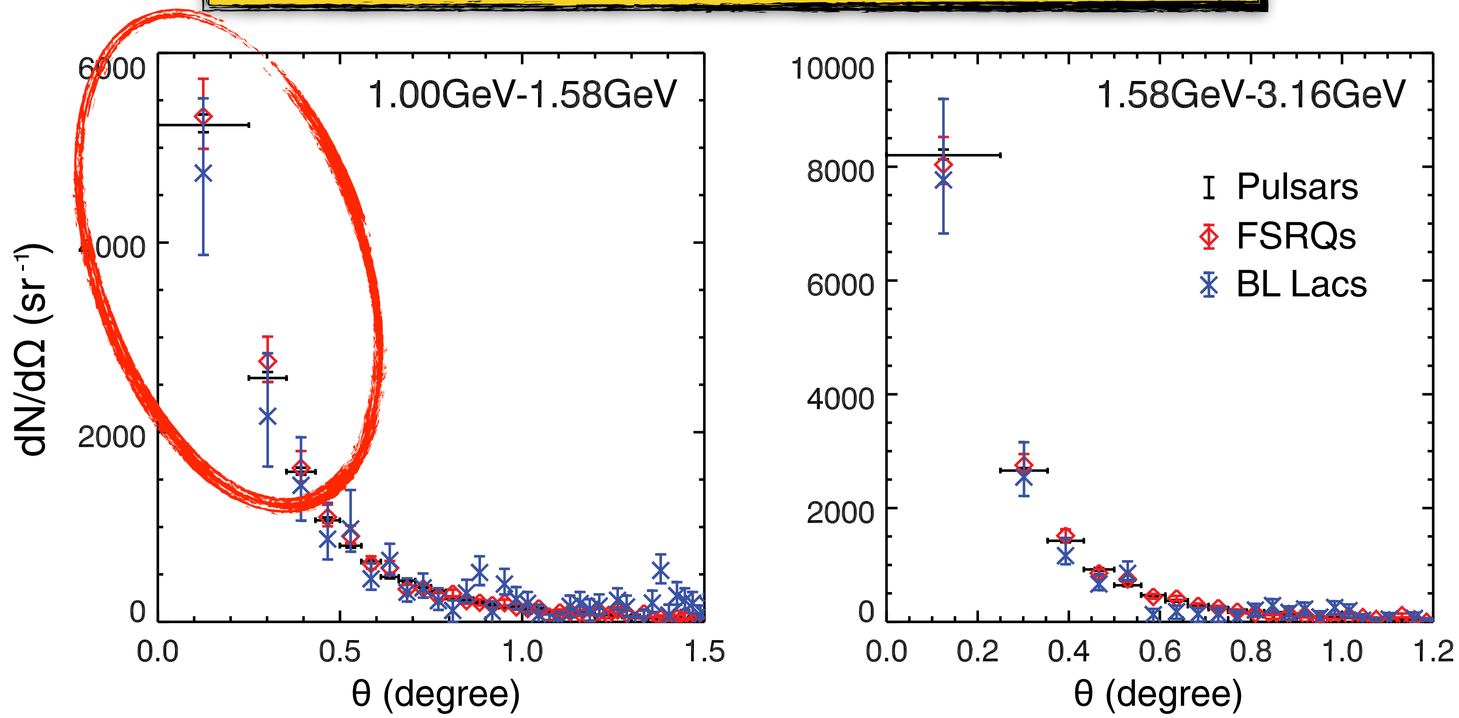

evidence for pair halos

Prokhorov&Moraghan 2016

comparison of angular distribution of photons for quiescent and flaring (no halo contribution) blazars

no evidence for pair halos

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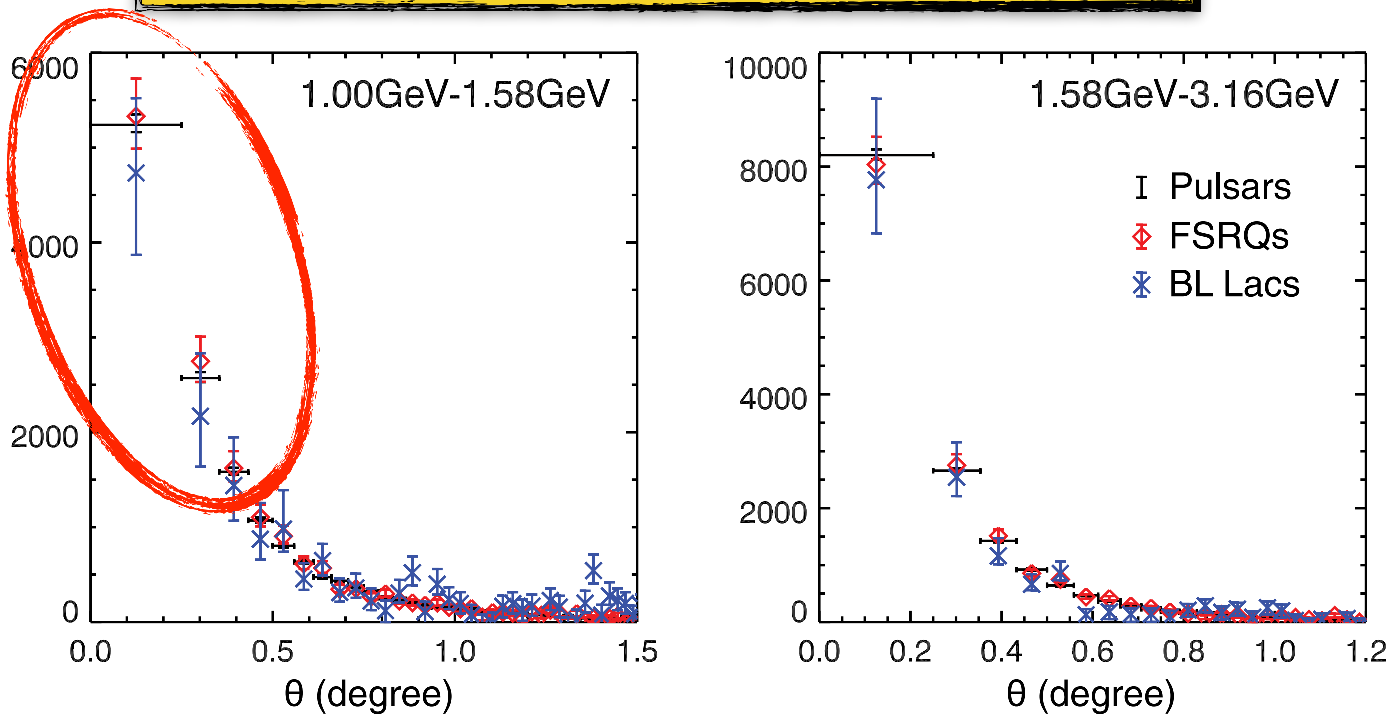
stacking of 24 BL Lac objects

Chen+ 2015



evidence for pair halos

Prokhorov&Moraghan 2016

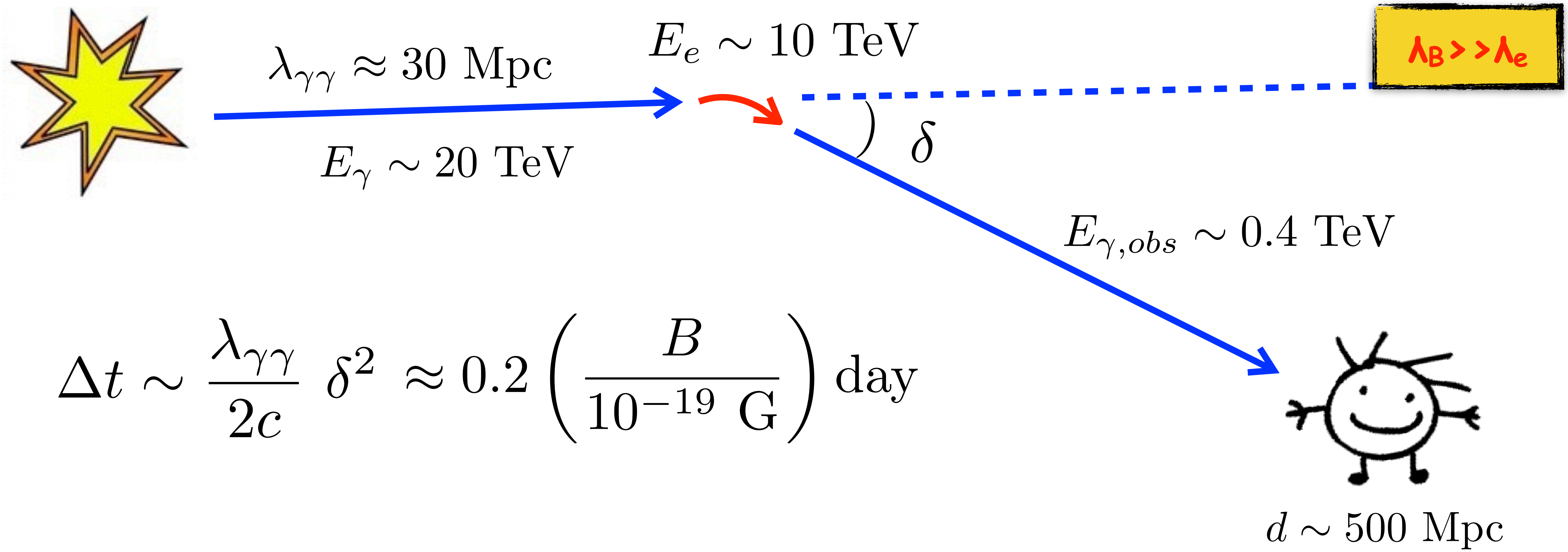
comparison of angular distribution of photons for quiescent and flaring (no halo contribution) blazars

no evidence for pair halos

no evidence for pair halos from HESS observations

HESS Coll. 2014

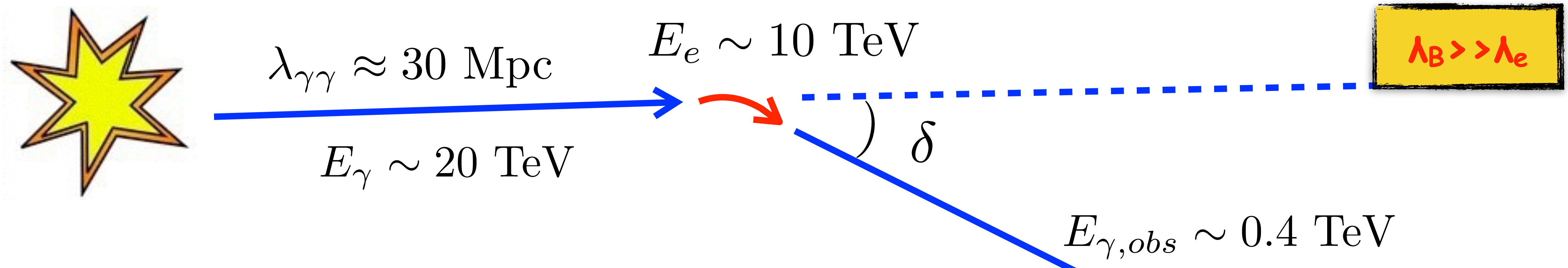
Deflection: time delays in γ-ray pulses



$$\Delta t \sim \frac{\lambda_{\gamma\gamma}}{2c}\,\delta^2 \approx 0.2\left(\frac{B}{10^{-19}\ \mathrm{G}}\right)\mathrm{day}$$

Plaga 1995, Cheng&Cheng 1996

Deflection: time delays in γ-ray pulses



$$\Delta t \sim \frac{\lambda_{\gamma\gamma}}{2c}\,\delta^2 \;\approx 0.2 \left(\frac{B}{10^{-19}\ \mathrm{G}}\right) \mathrm{day}$$

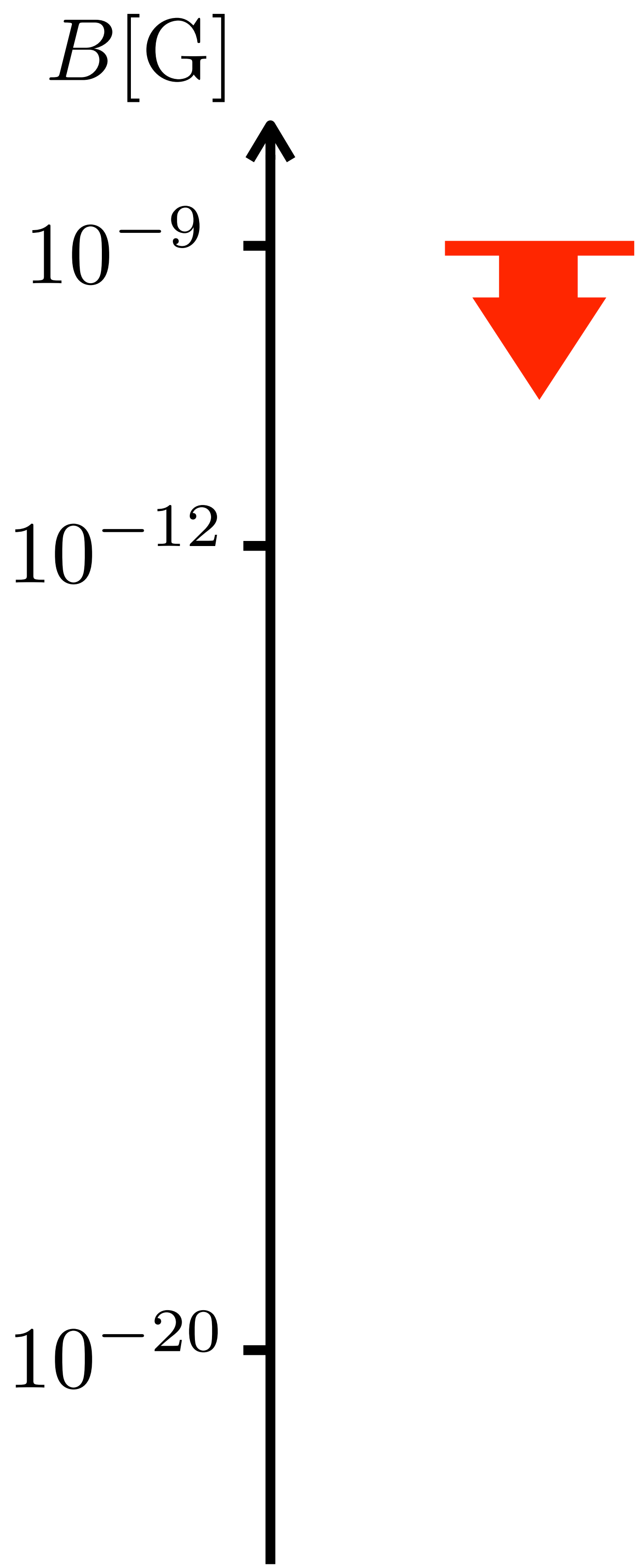
intrinsic deflection (interaction) -> $1/\gamma$

$$\delta \sim 2/\gamma \longrightarrow B_{min} \sim 3 \times 10^{-20}\mathrm{G}$$

minimum field that can be constrained with time delays

Plaga 1995, Cheng&Cheng 1996

Brief (and very rough) summary

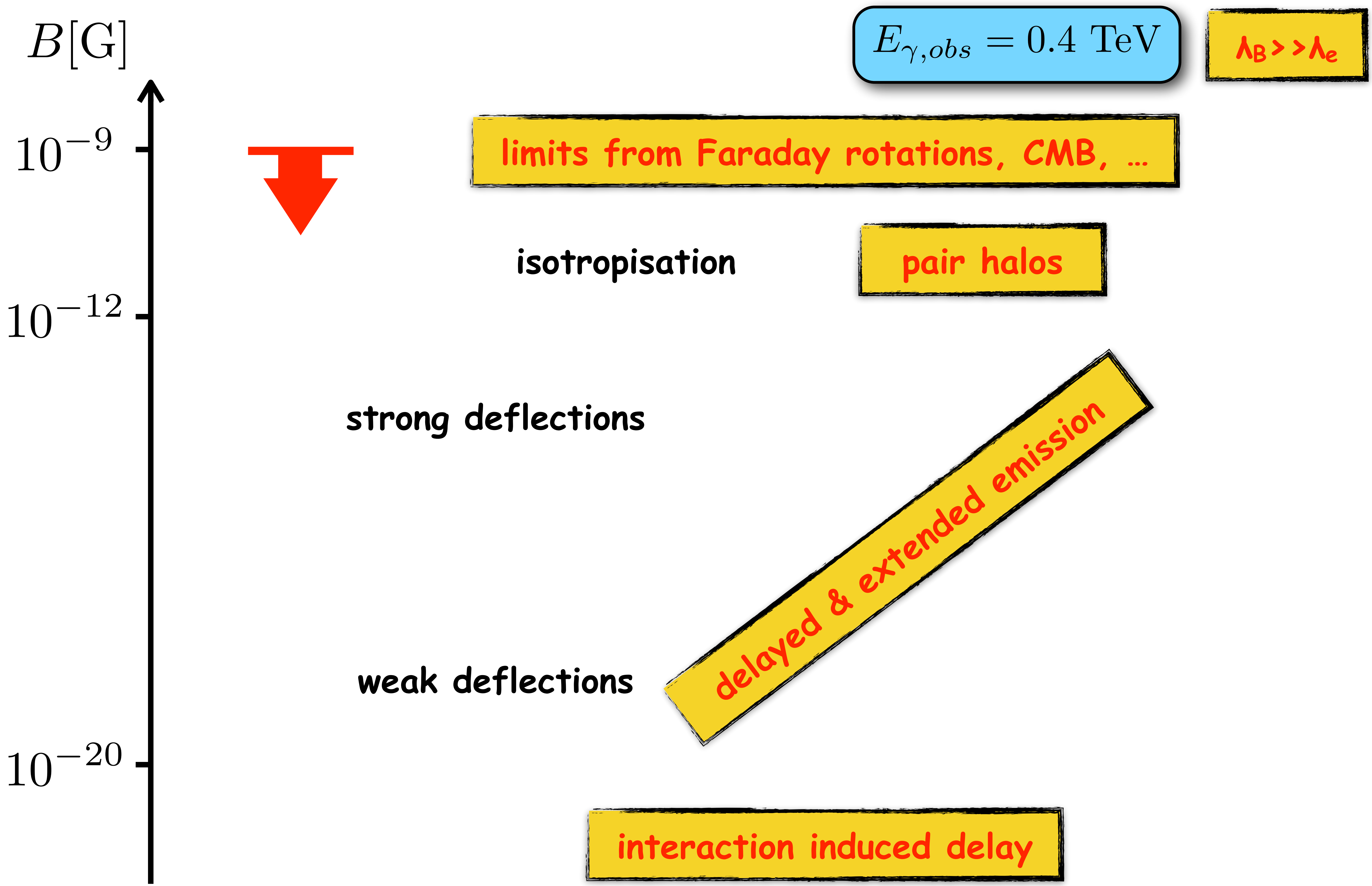


$E_{\gamma,obs} = 0.4$ TeV

$\lambda_B >> \lambda_e$

limits from Faraday rotations, CMB, ...

Brief (and very rough) summary



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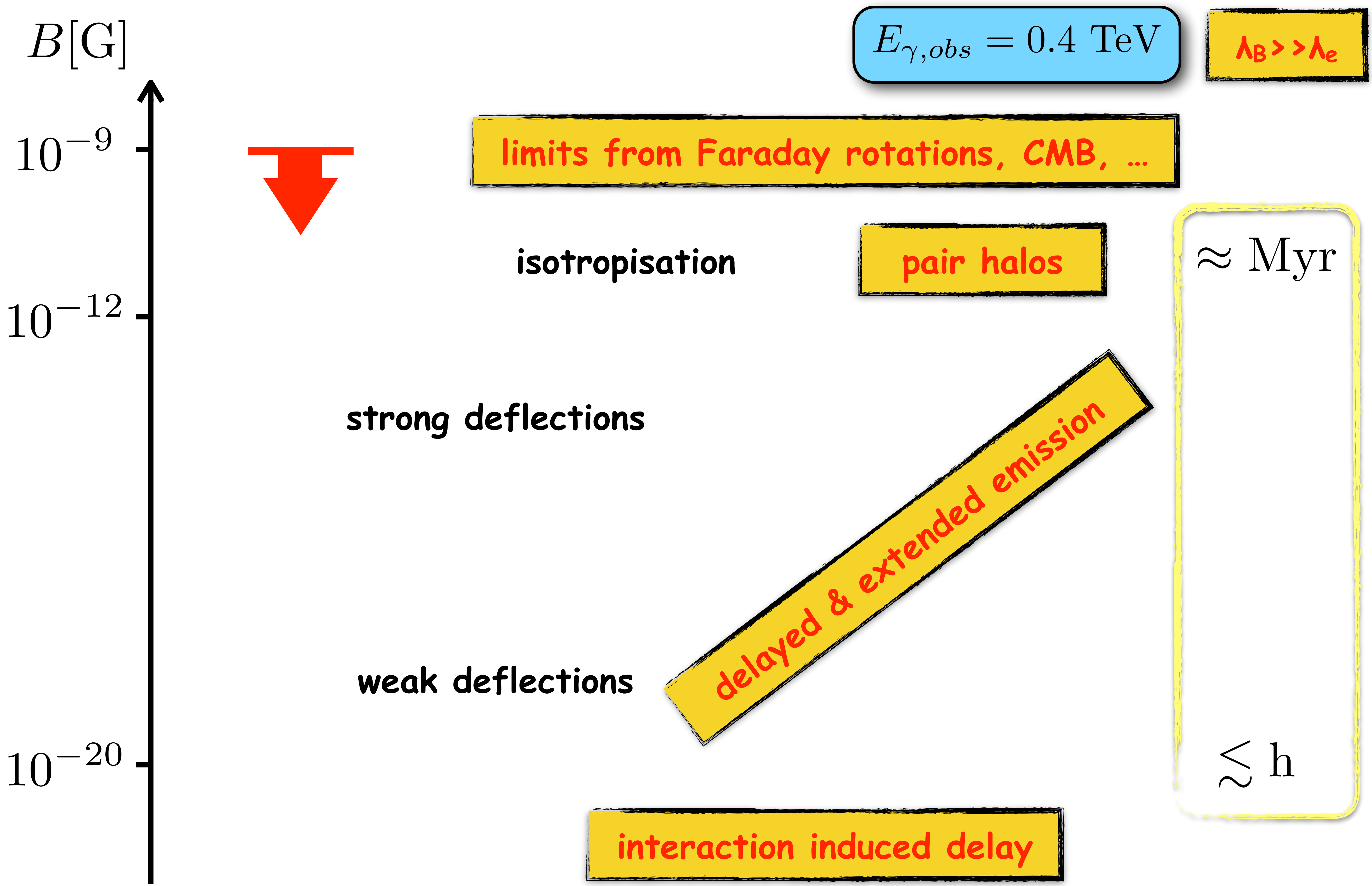

Delayed emission from blazars

t_{var} -> typical time for blazar variability (days?)

time broadening of the signal:often assumed to be of the order of the delay time Δt

$$F_{delay} \approx \frac{t_{var}}{t_{var} + \Delta t} F_0$$

cascade emission is suppressed

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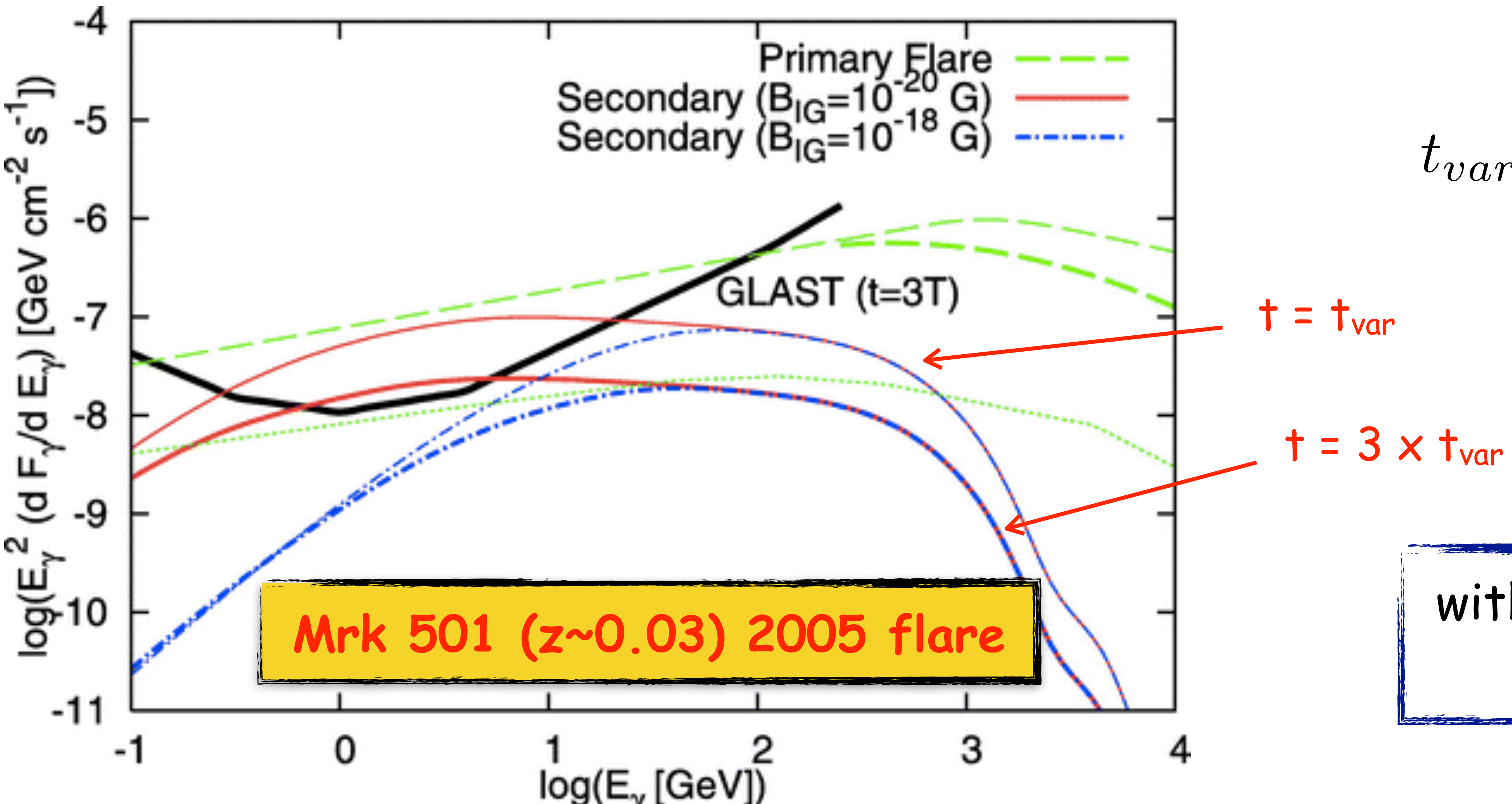
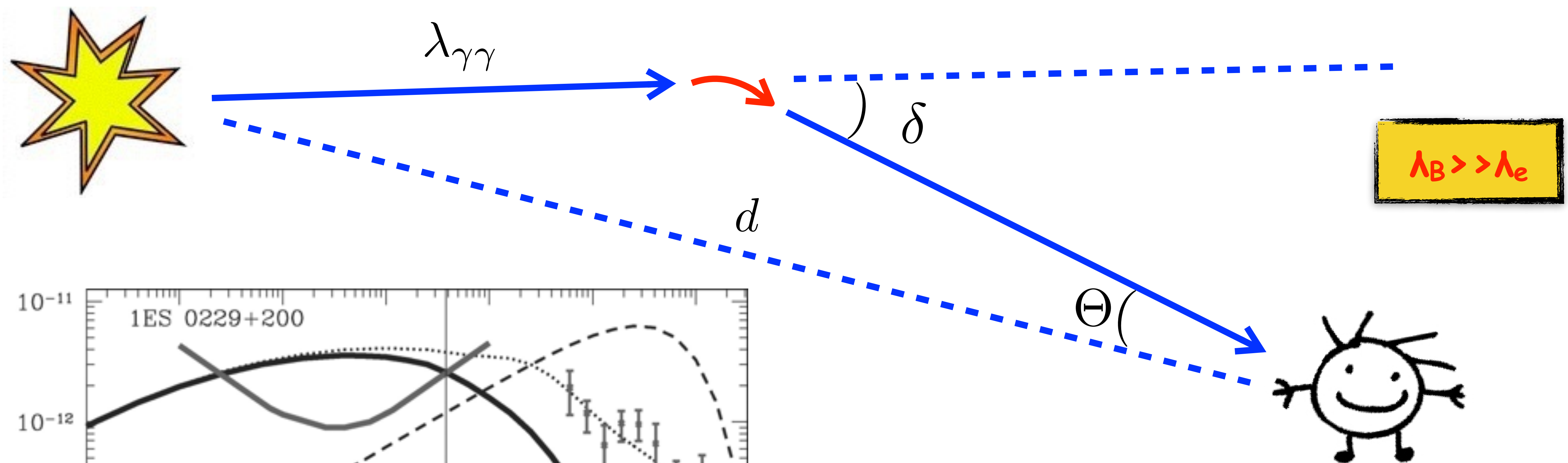


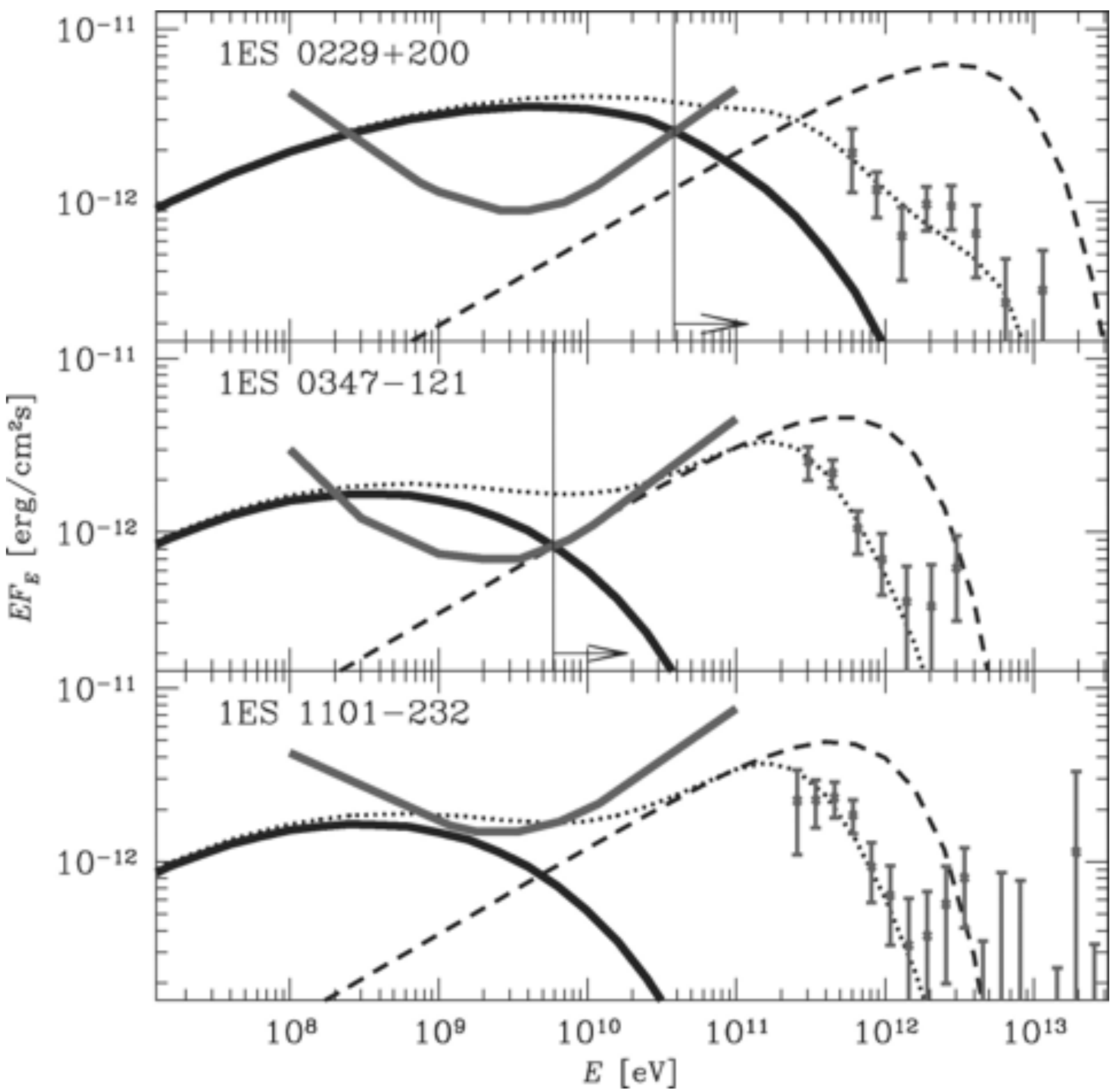
$t_{var} \approx 0.5\text{day}$

within the reach of FERMI

Dai+ 2002, Murase+ 2008, Neronov&Semikoz 2009

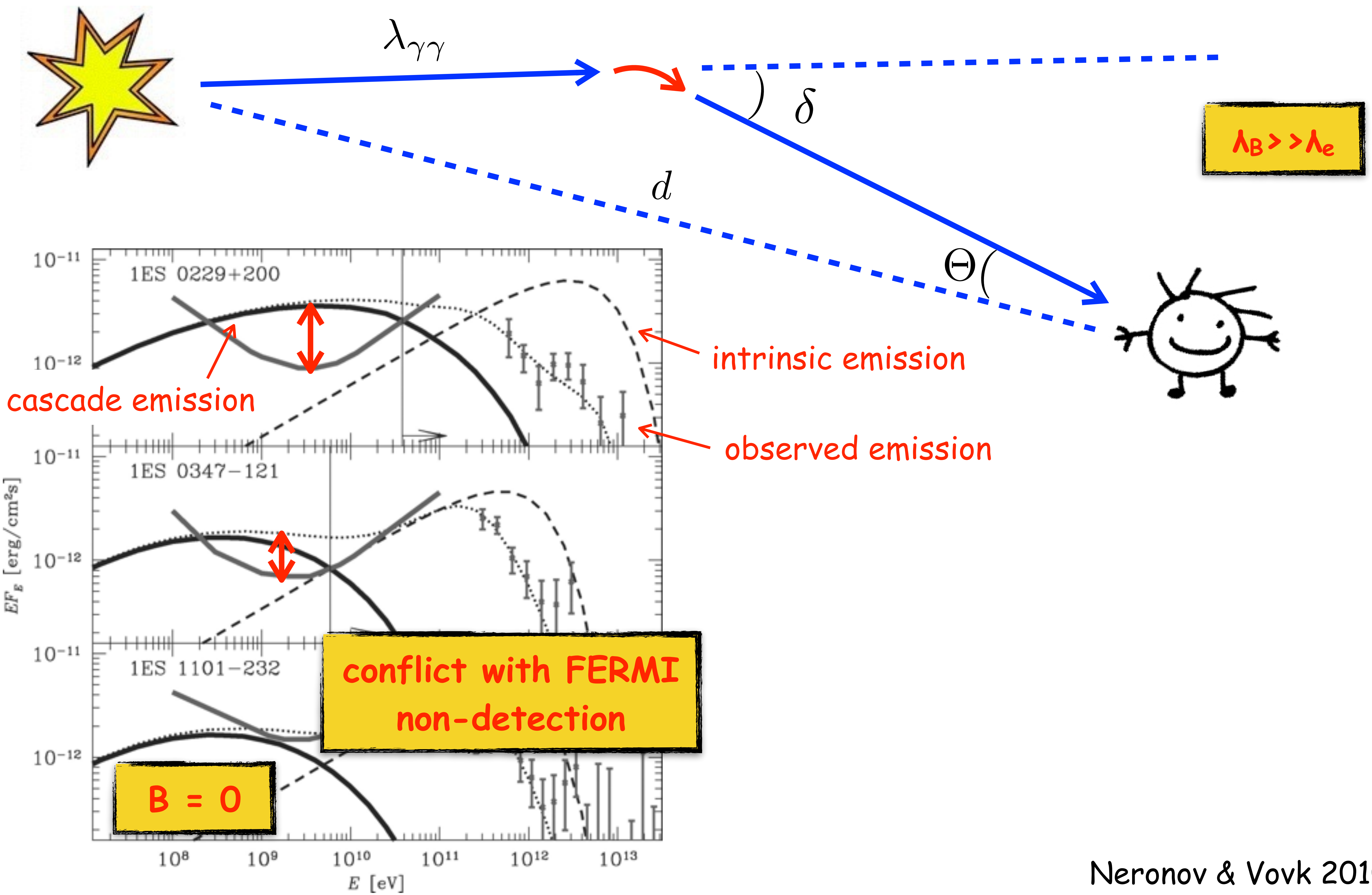
Constraints from GeV-TeV observations





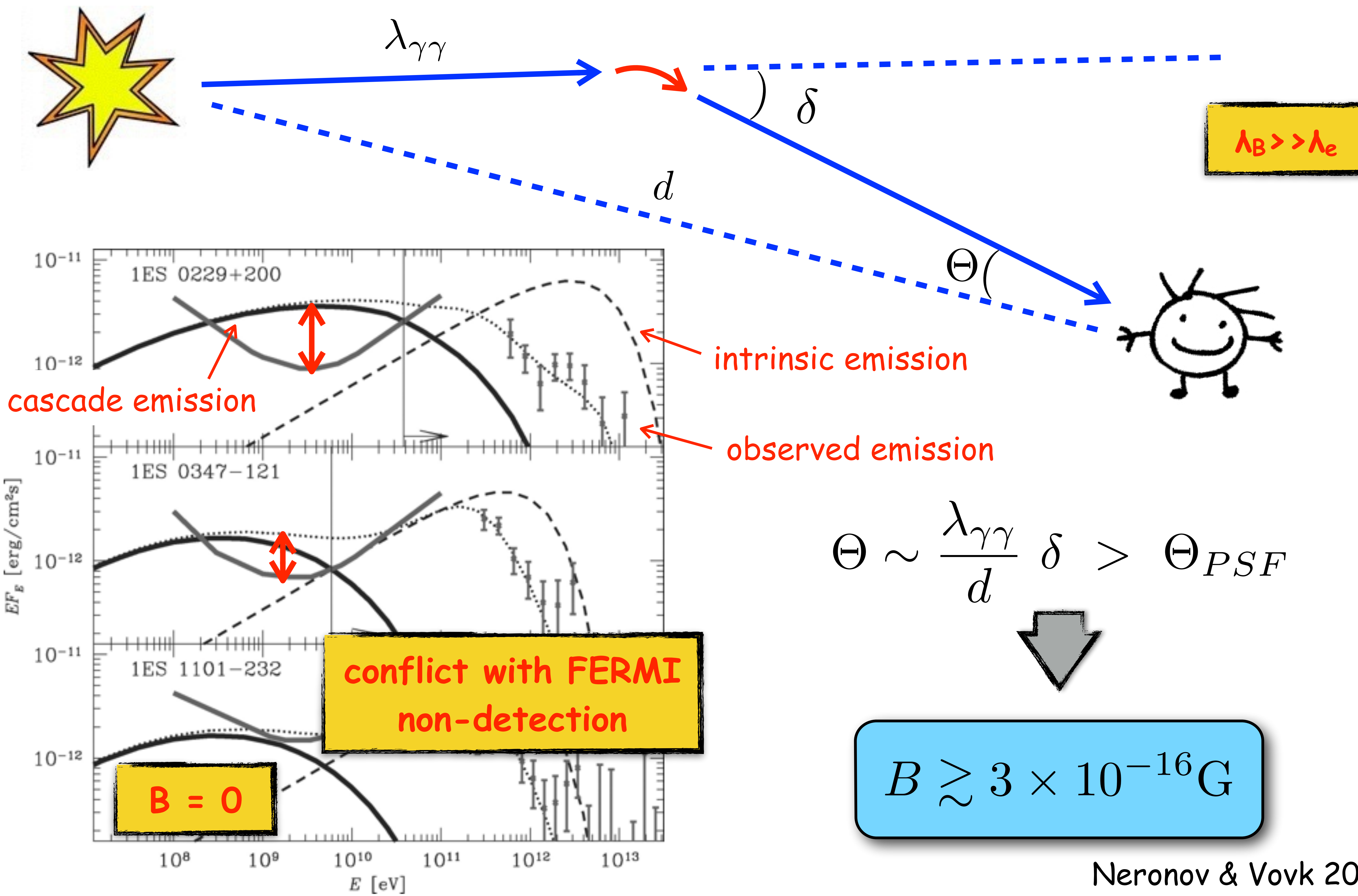
Neronov & Vovk 2010

Constraints from GeV-TeV observations



Neronov & Vovk 2010

Constraints from GeV-TeV observations



$$\Theta \sim \frac{\lambda_{\gamma\gamma}}{d}\,\delta \;>\; \Theta_{PSF}$$

$$B \gtrsim 3 \times 10^{-16}\mathrm{G}$$

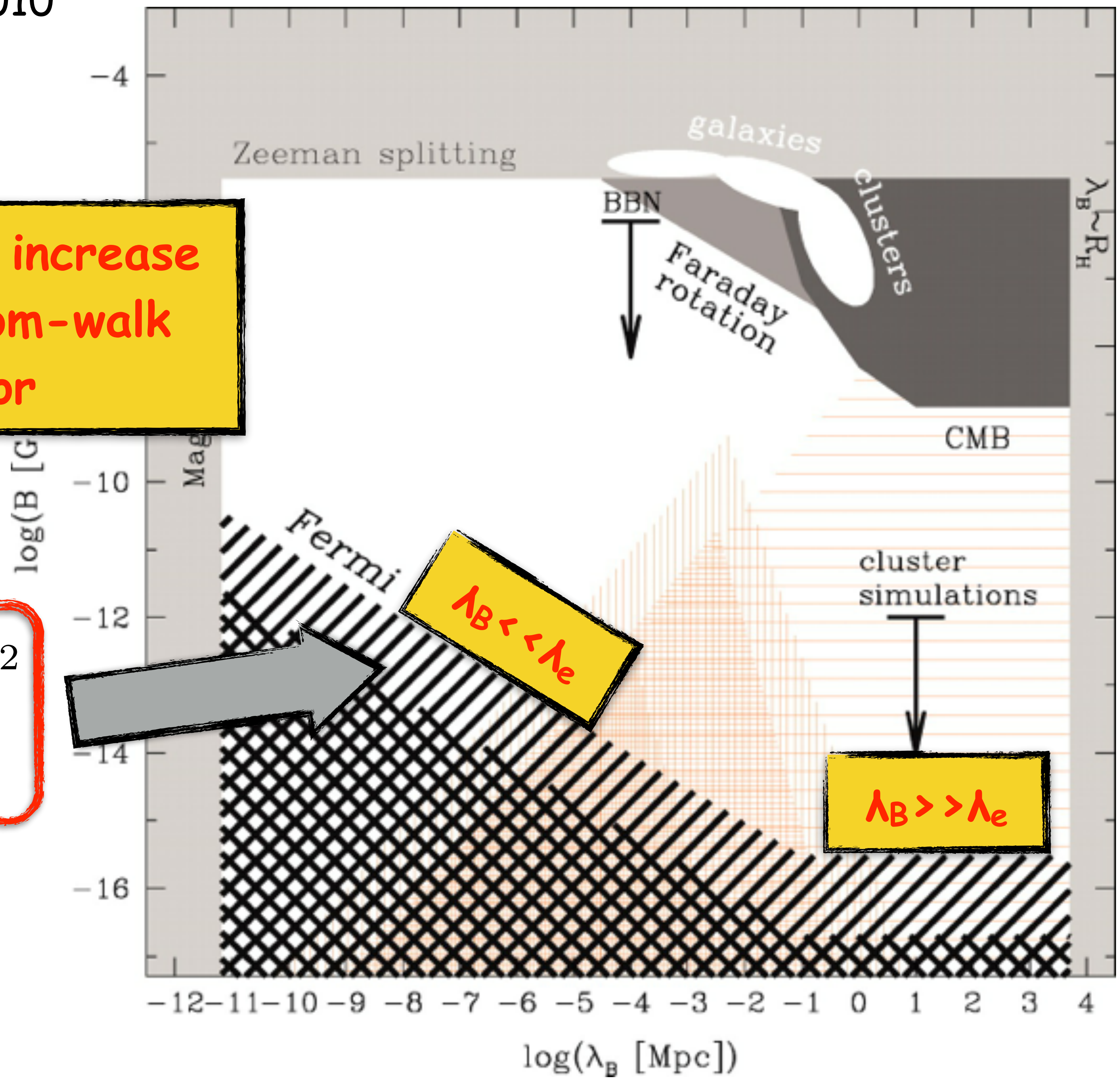
Neronov & Vovk 2010

Constraints from GeV-TeV observations

Neronov & Vovk 2010

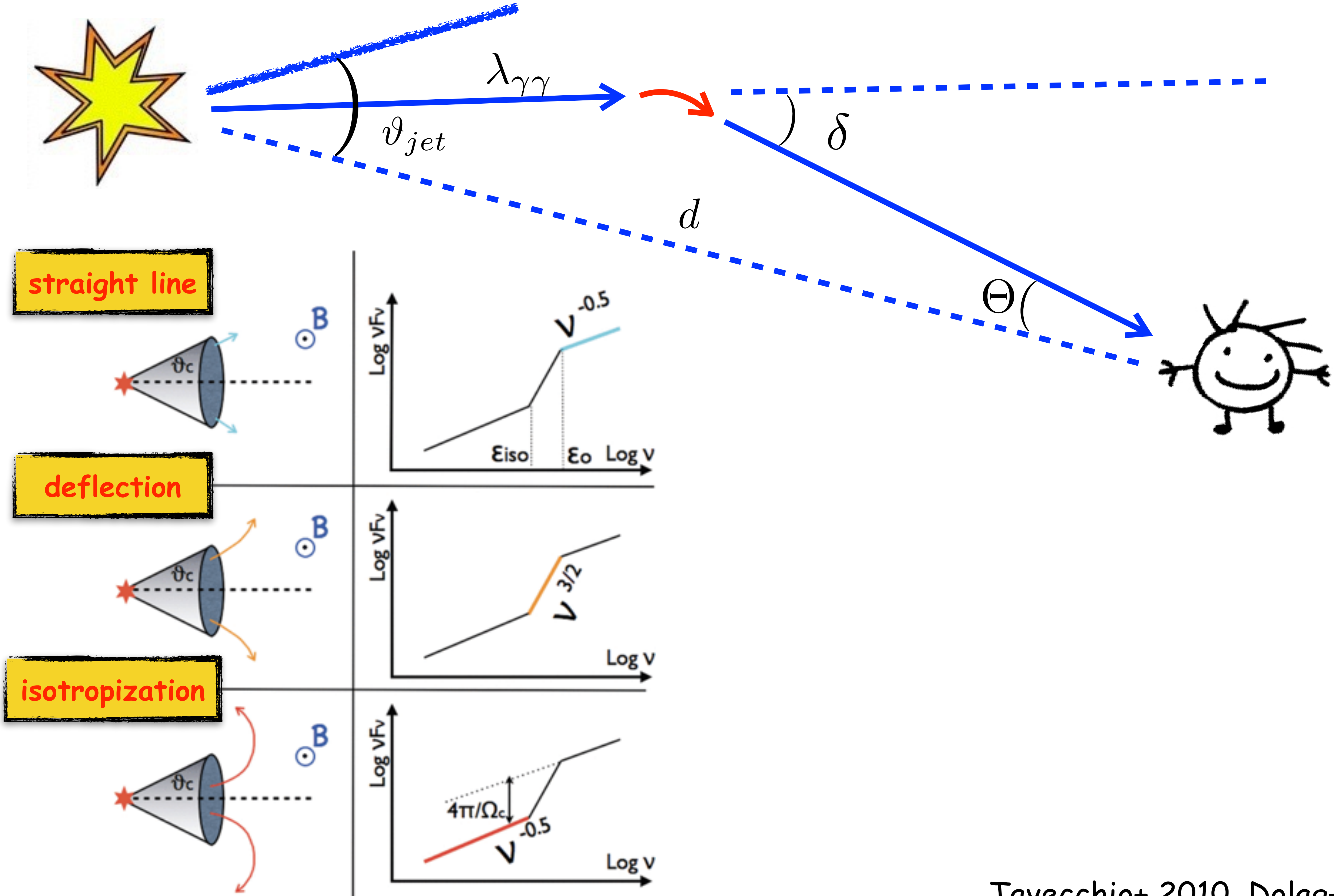
lower limits increase by a random-walk factor

$$\left(\frac{\lambda_B}{\lambda_e}\right)^{1/2}$$



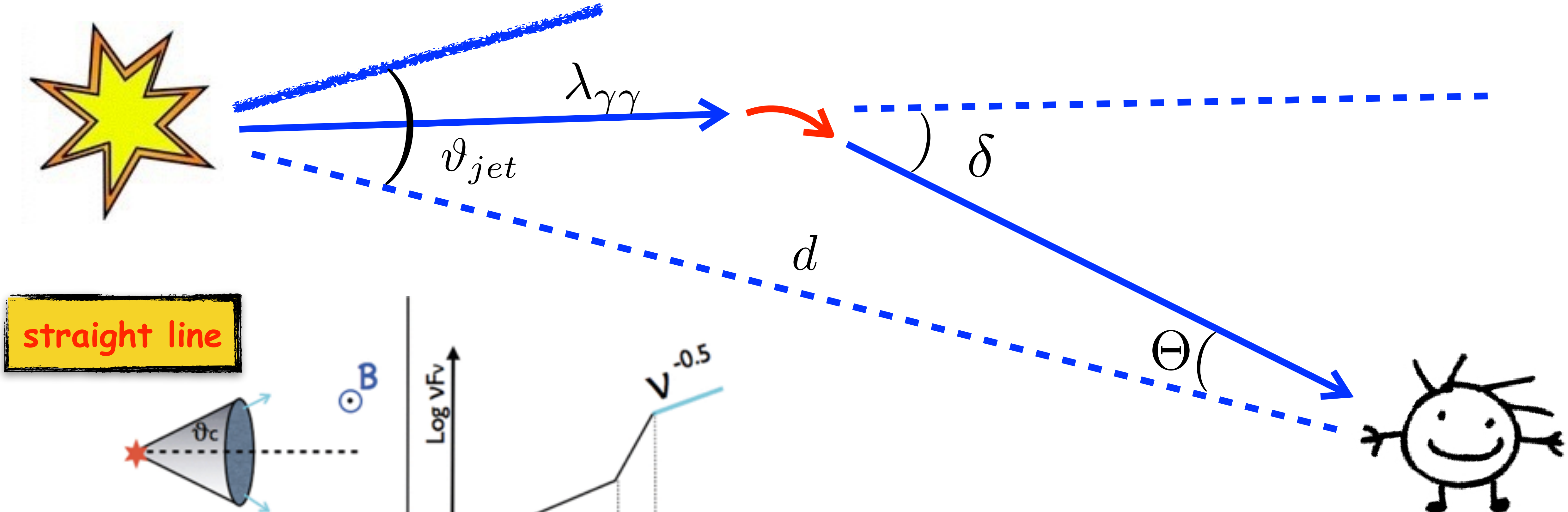
implicit assumption: steady and isotropic emission from the blazars

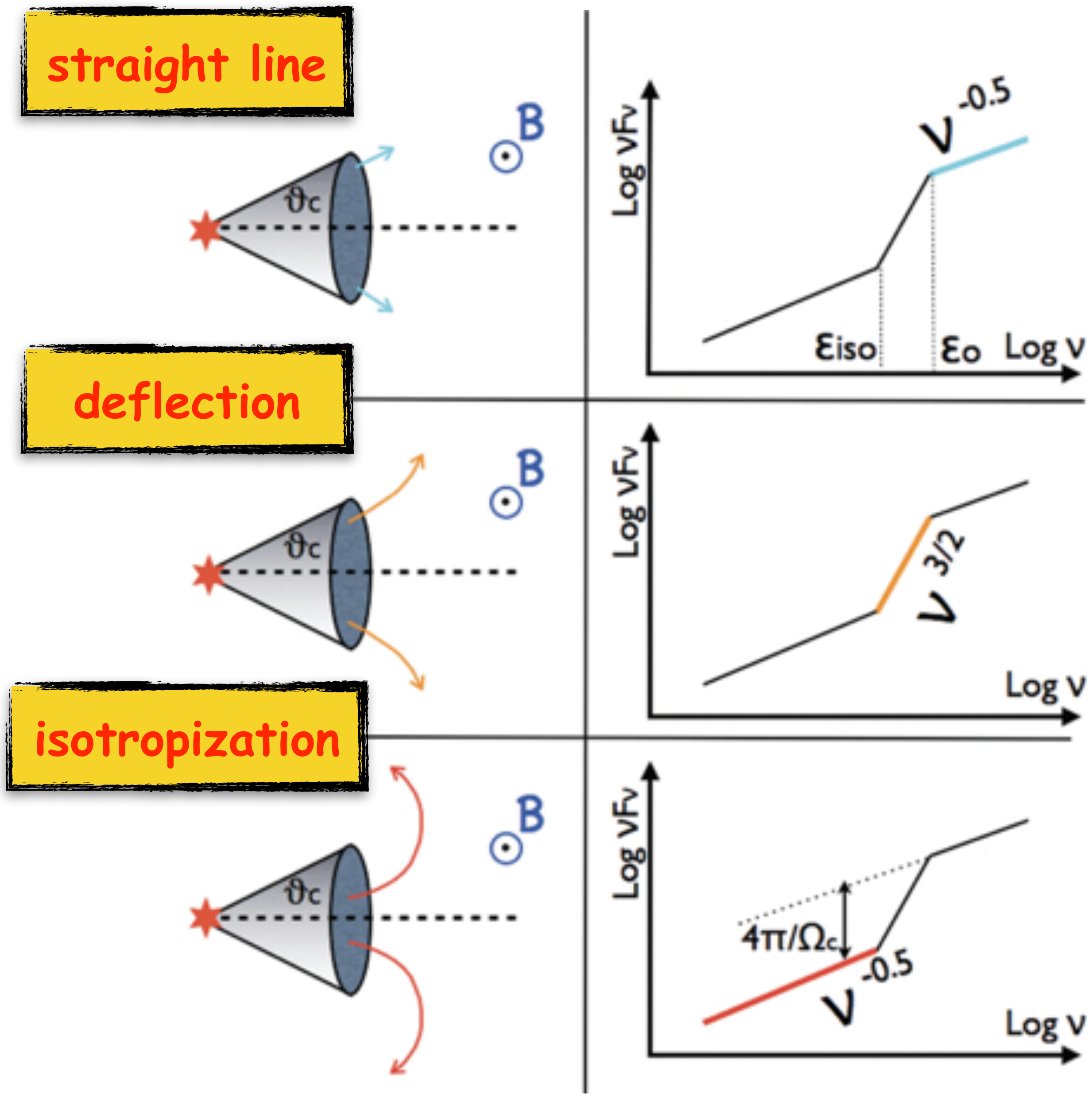
On the isotropy assumption



Tavecchio+ 2010, Dolag+ 2011

On the isotropy assumption





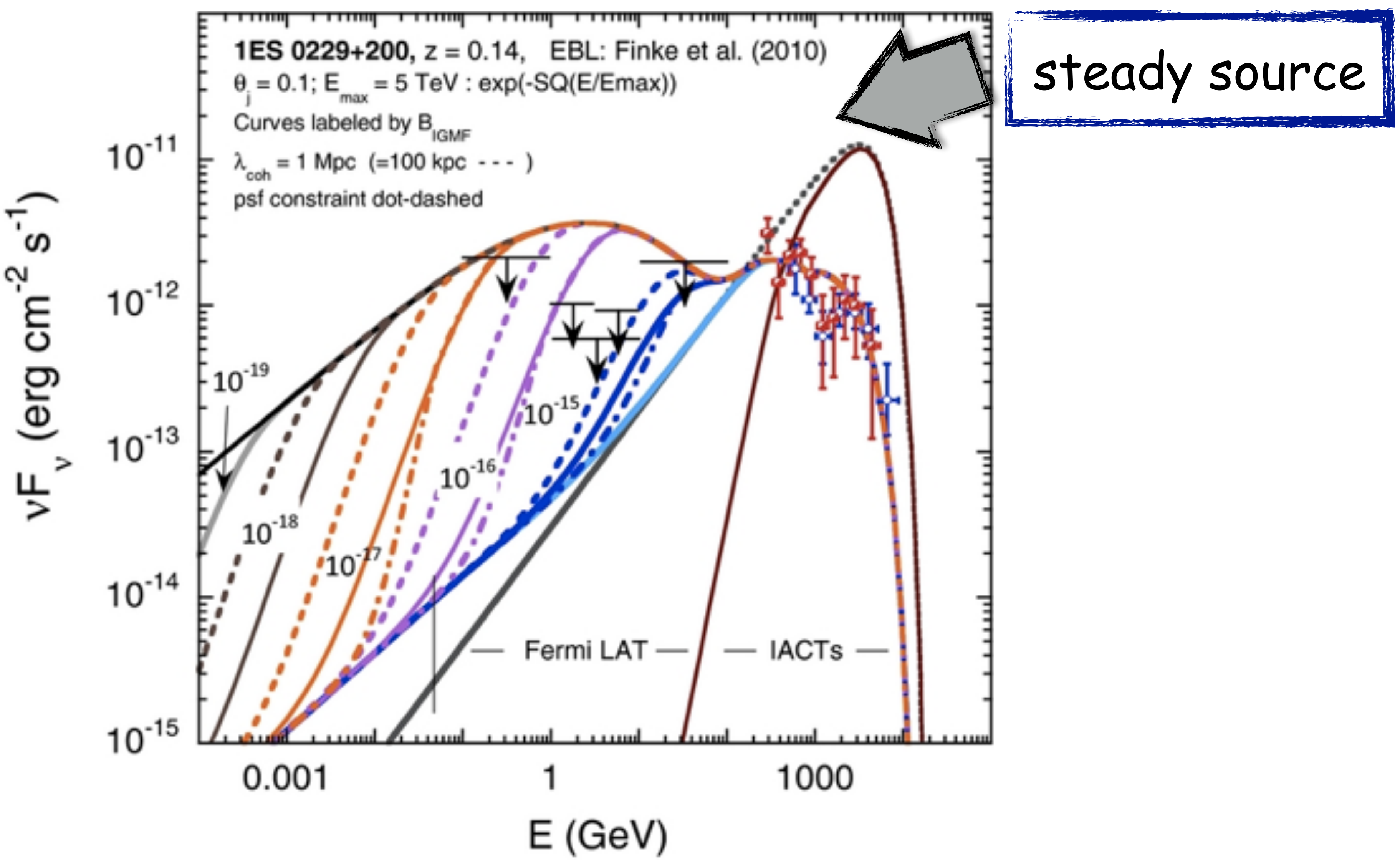
isotropic source $\Theta \sim \frac{\lambda_{\gamma\gamma}}{d}\,\delta$

beamed source $\Theta \leq \frac{\lambda_{\gamma\gamma}}{d}\,\vartheta_{jet}$

Tavecchio+ 2010, Dolag+ 2011

On the steady state assumption

how do we know whether the emission from a blazar is steady or not?



$$B \gtrsim 3 \times 10^{-16} \mathrm{G}$$

Dermer+ 2011

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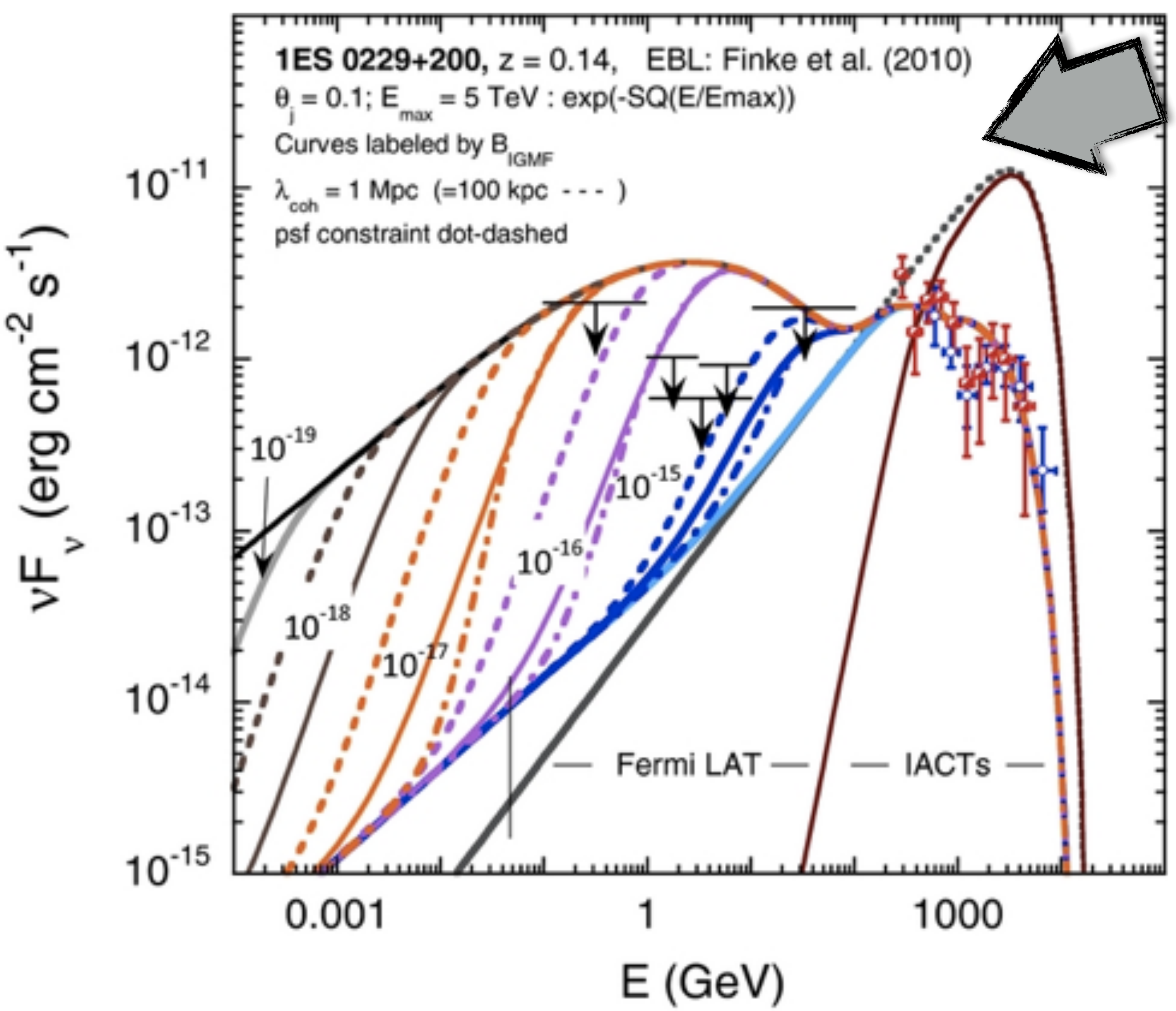

steady source

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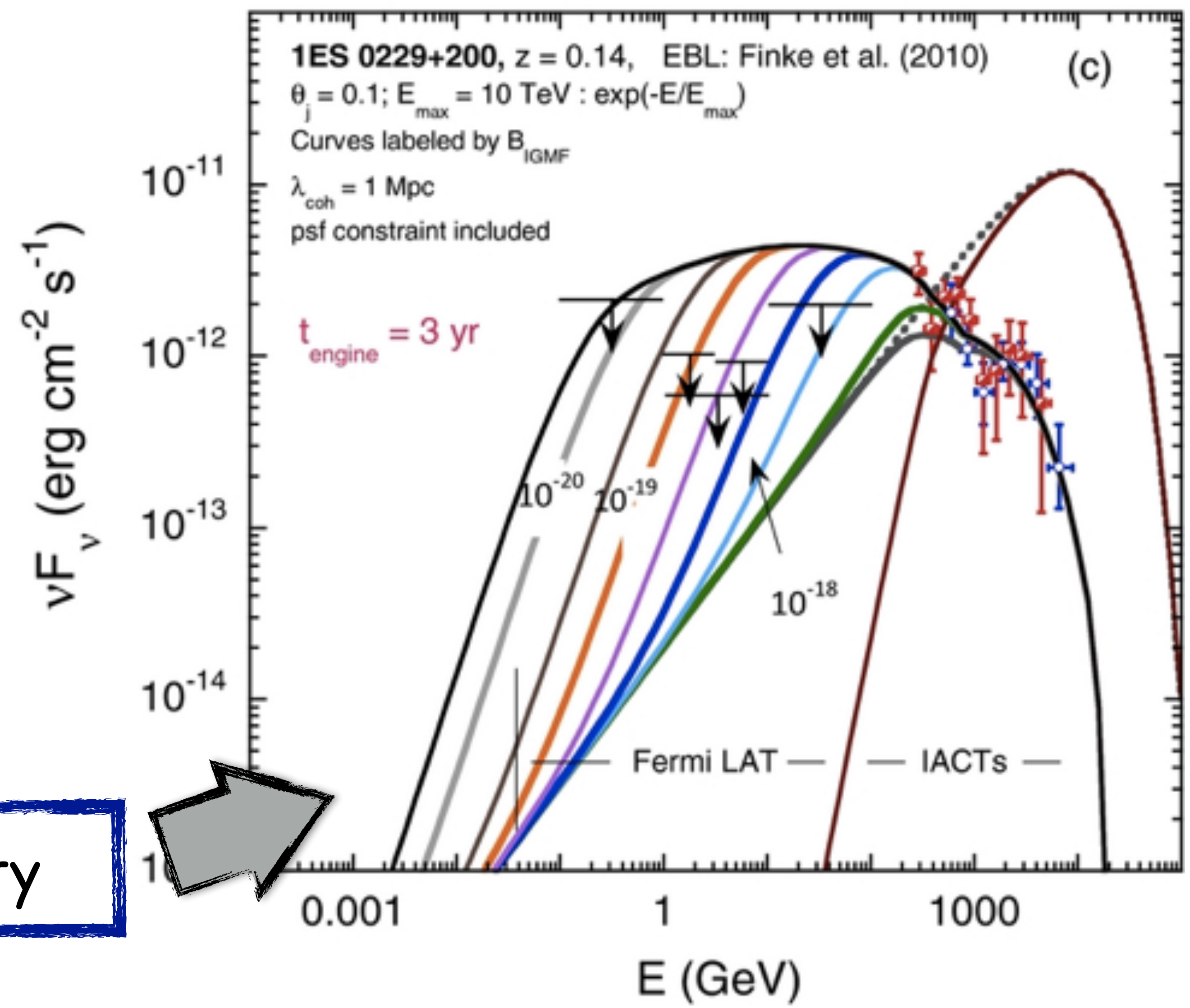
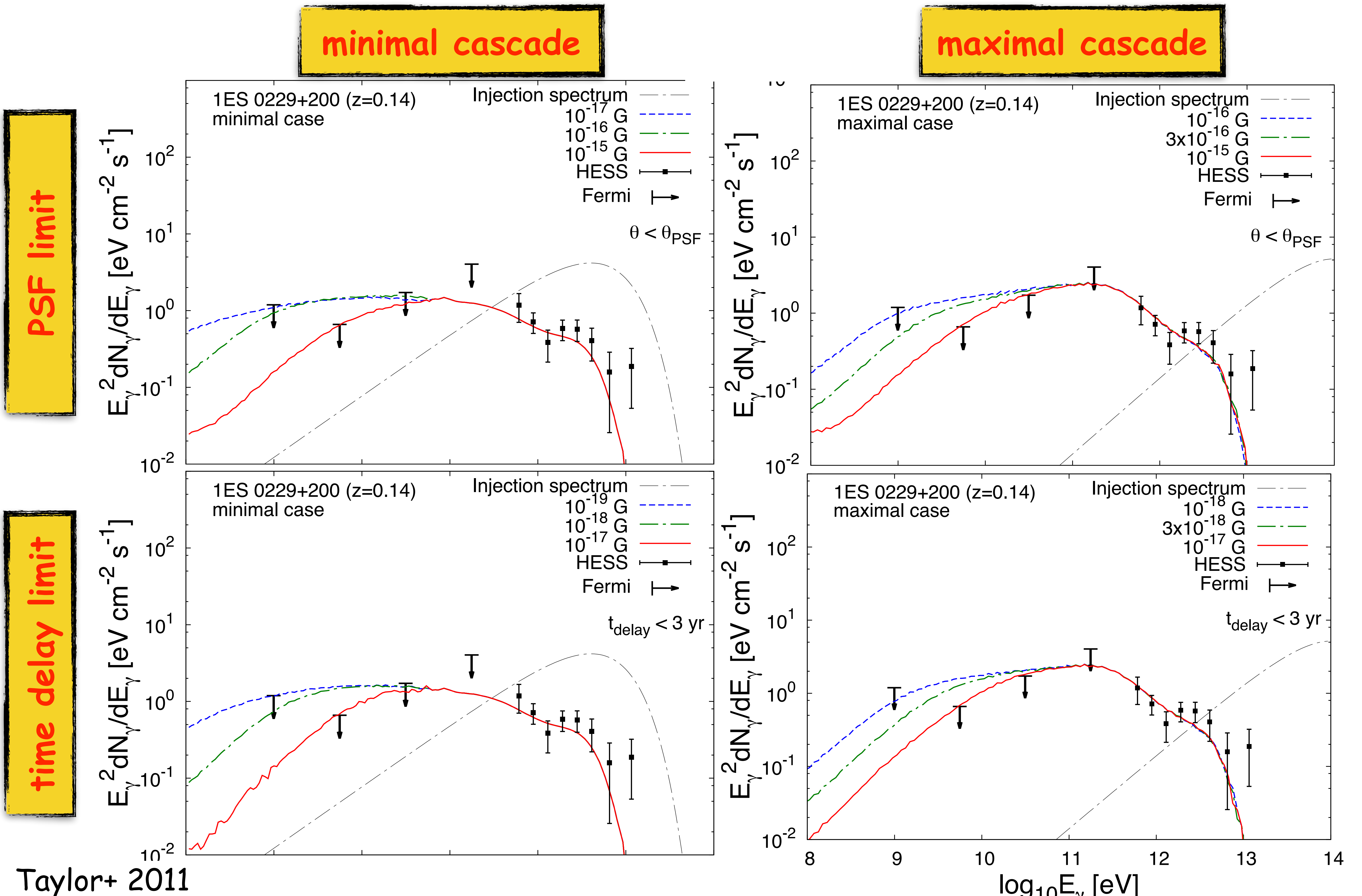


$B \gtrsim 10^{-18}\mathrm{G}$

3 yr activity

Dermer+ 2011

Monte Carlo simulations

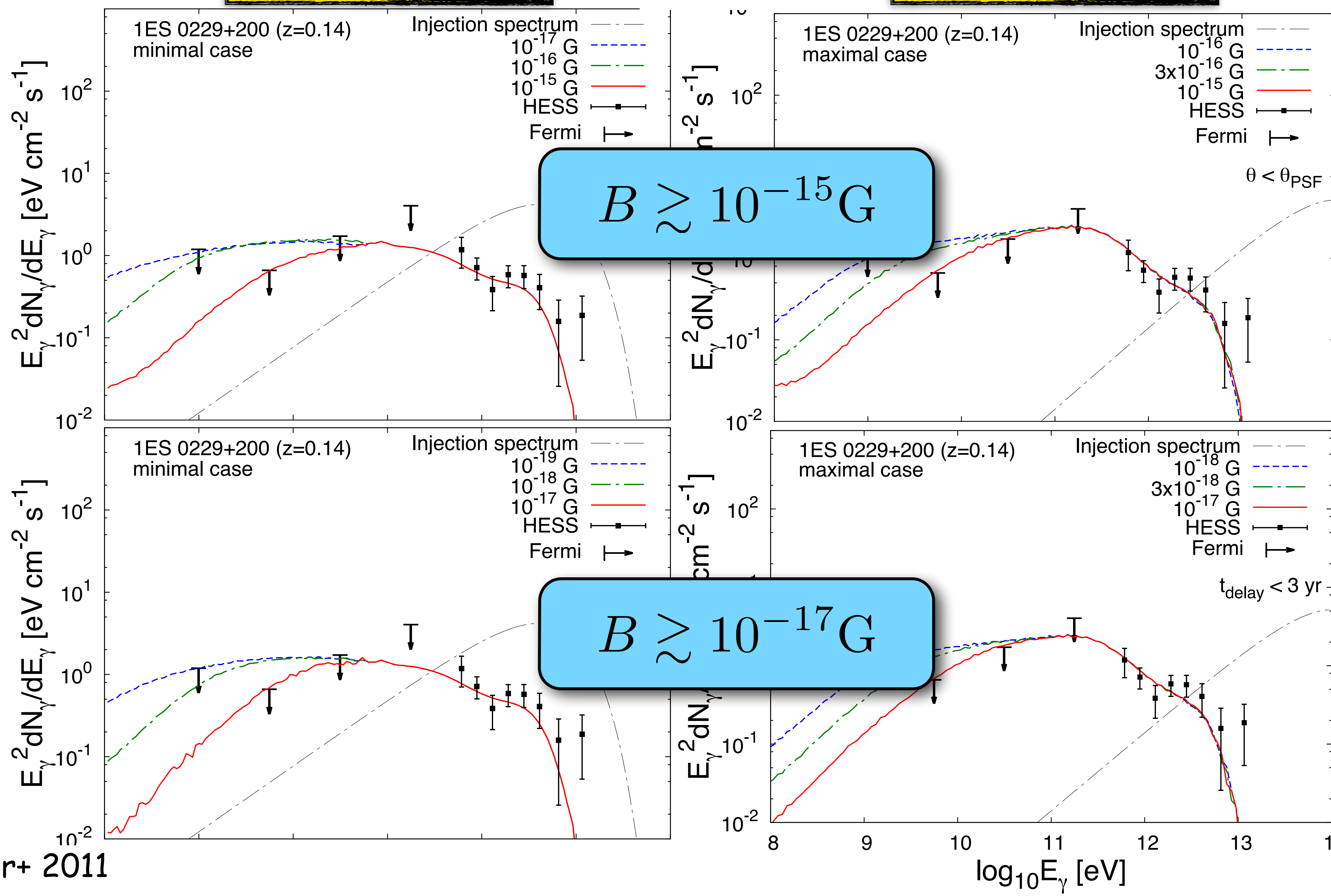


Taylor+ 2011

Monte Carlo simulations

minimal cascade | maximal cascade

PSF limit



$$B \gtrsim 10^{-15} \mathrm{G}$$

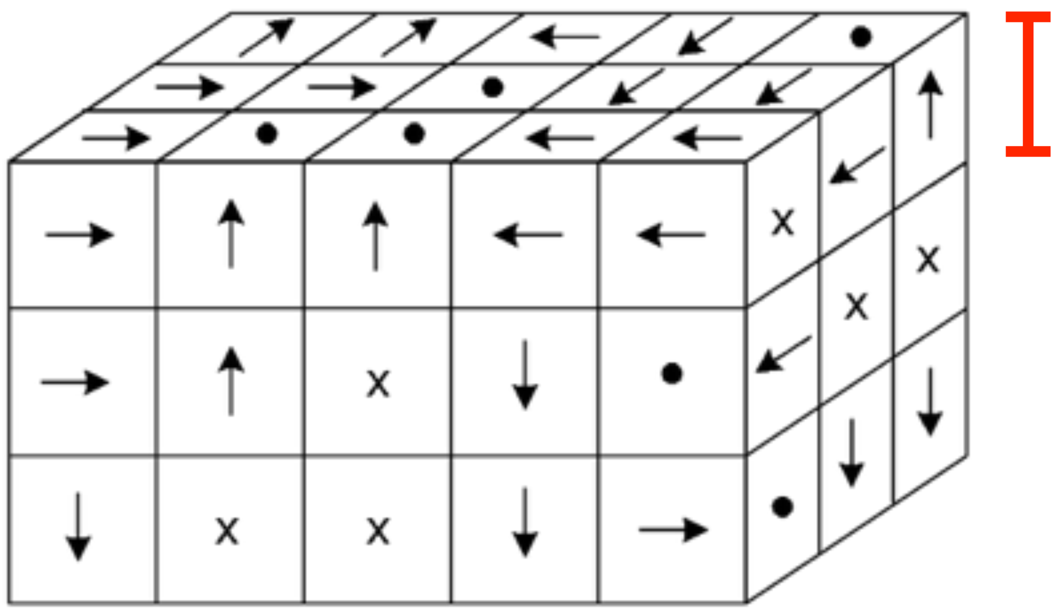
time delay limit

$$B \gtrsim 10^{-17} \mathrm{G}$$

Taylor+ 2011

The role of the power spectrum

many works assumed cells with uniform B randomly oriented



λ_B

$\nabla B \neq 0$

random walk

Caprini&Gabici 2015

The role of the power spectrum

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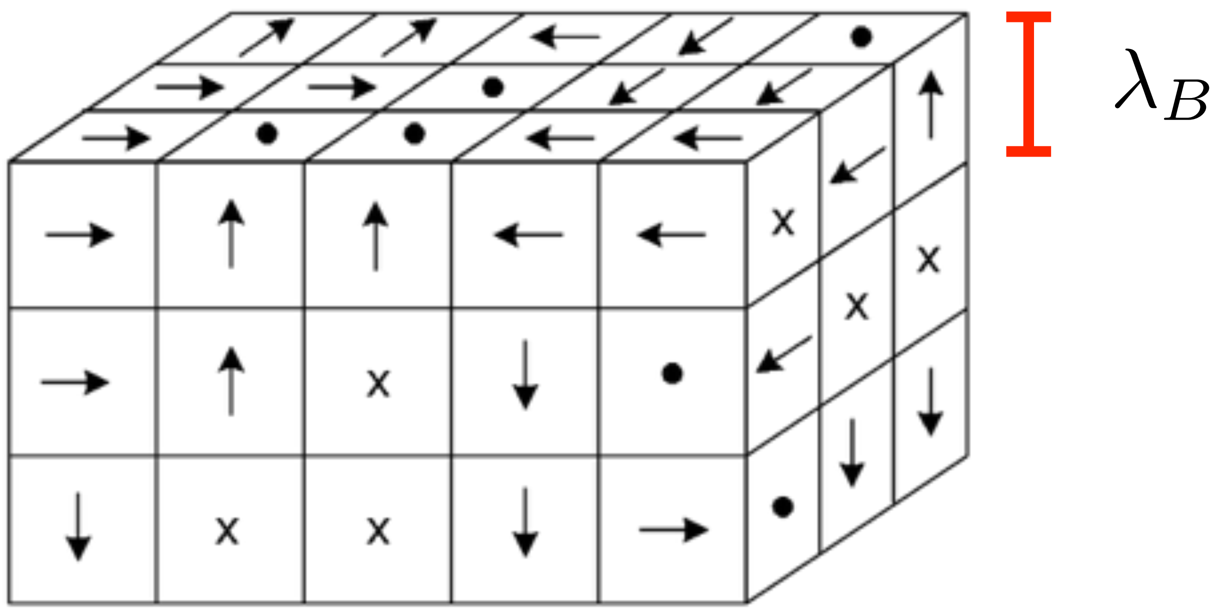

$\Rightarrow$ $\nabla B \neq 0$

random walk

more realistically...

$\nabla B = 0$ and $P_B(k) = A \begin{cases} \left(\frac{k}{k_0}\right)^{n_B} & \text{if} \quad k < k_0 \\ \left(\frac{k_0}{k}\right)^{m_B} & \text{if} \quad k > k_0 \end{cases}$

$n_B > -3 \quad \text{and} \quad m_B > 3$ to avoid divergencies

Caprini&Gabici 2015

Coherence length and deflections

$$P_B(k) = A \begin{cases} \left(\frac{k}{k_0}\right)^{n_B} & \text{if} \quad k < k_0 \\ \left(\frac{k_0}{k}\right)^{m_B} & \text{if} \quad k > k_0 \end{cases}$$

11/3 (Kolmogorov)

operative definition

$$\lambda_B \equiv \frac{2\pi}{k_0}$$

Caprini&Gabici 2015

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11/3 (Kolmogorov)

operative definition

$$\lambda_B \equiv \frac{2\pi}{k_0}$$

coherence length -> $\lambda_B \sim \int \mathrm{d}k P_B(k) k$

not well defined for $n_B > -2$

$-3 < n_B < -2$ -> red spectrum -> no causal origin -> might be generated during inflation

Caprini&Gabici 2015

Coherence length and deflections

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11/3 (Kolmogorov)

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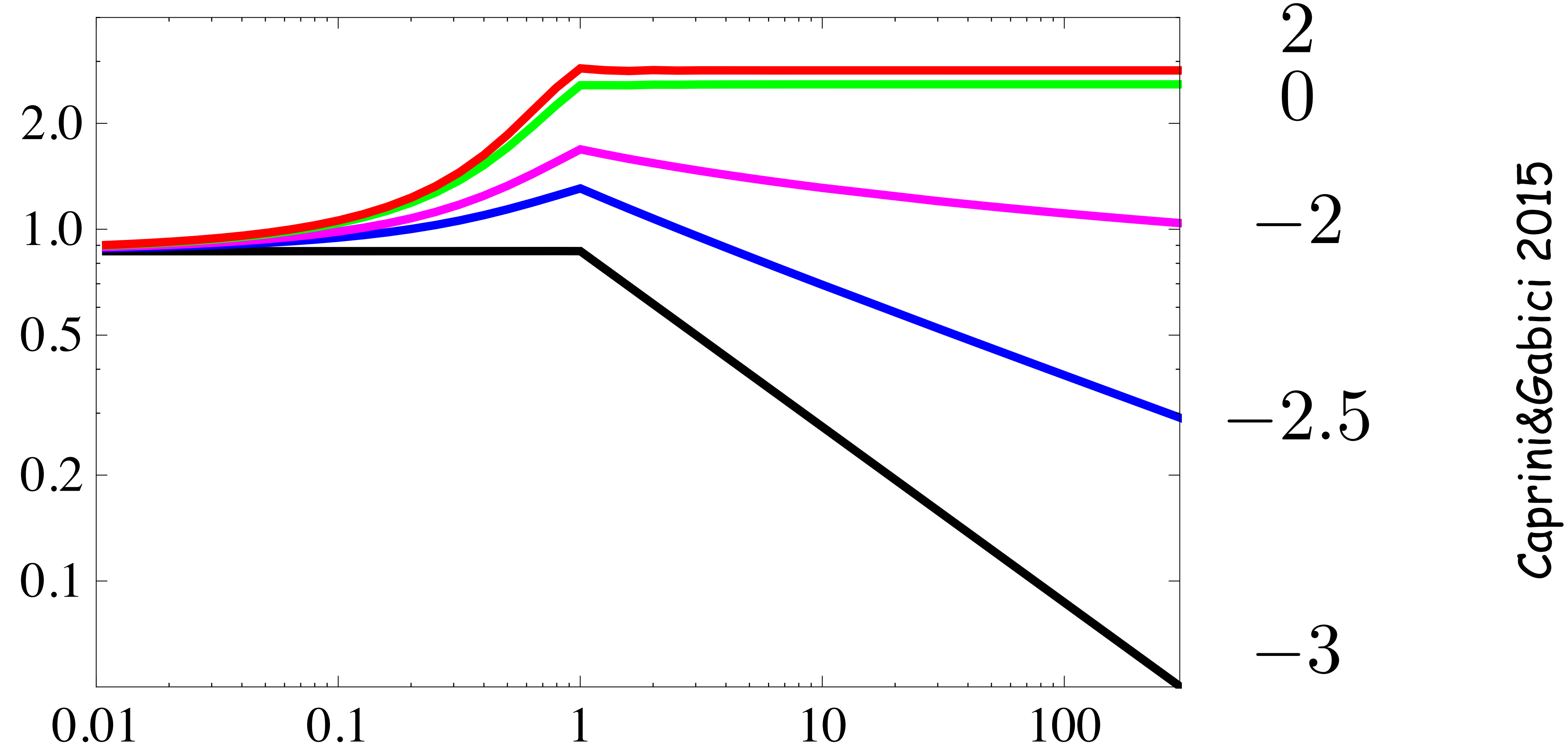
$$\lambda_B \equiv \frac{2\pi}{k_0}$$

"this work" deflection

"random walk" deflection



Compton cooling length ⟶ D_e/λ_B

Coherence length and deflections

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m_B = 11/3 (Kolmogorov)

operative definition

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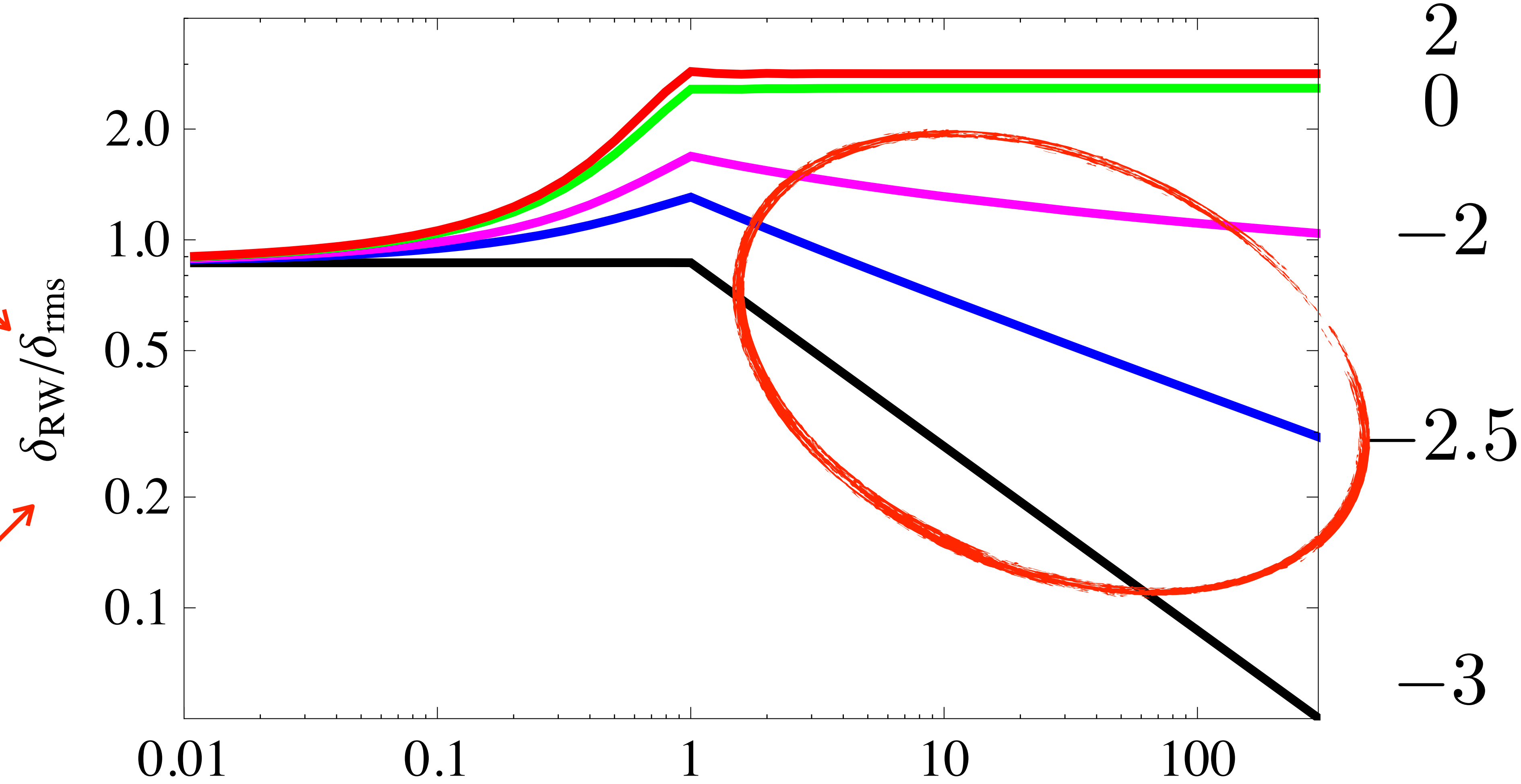
"this work" deflection

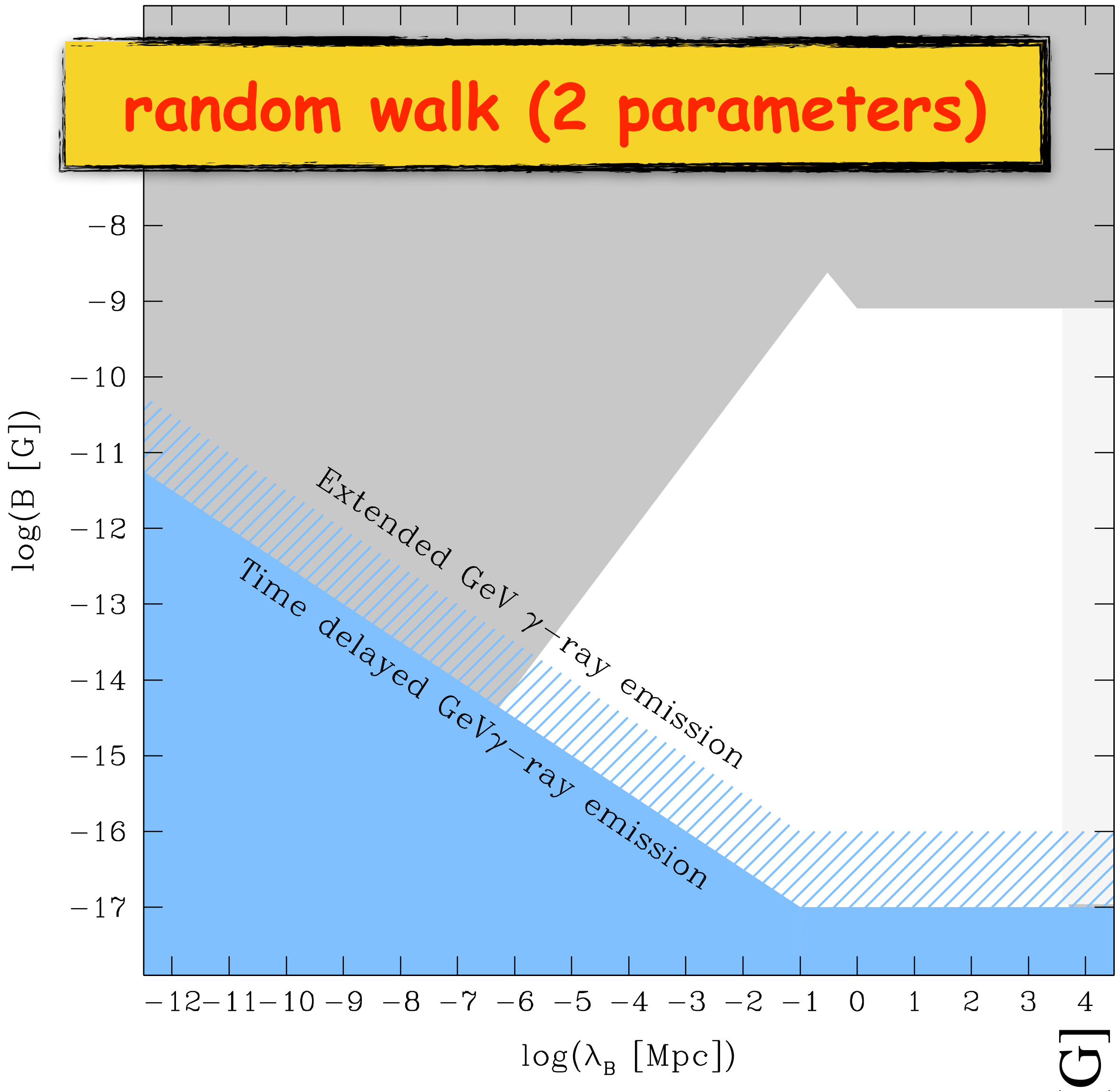
"random walk" deflection



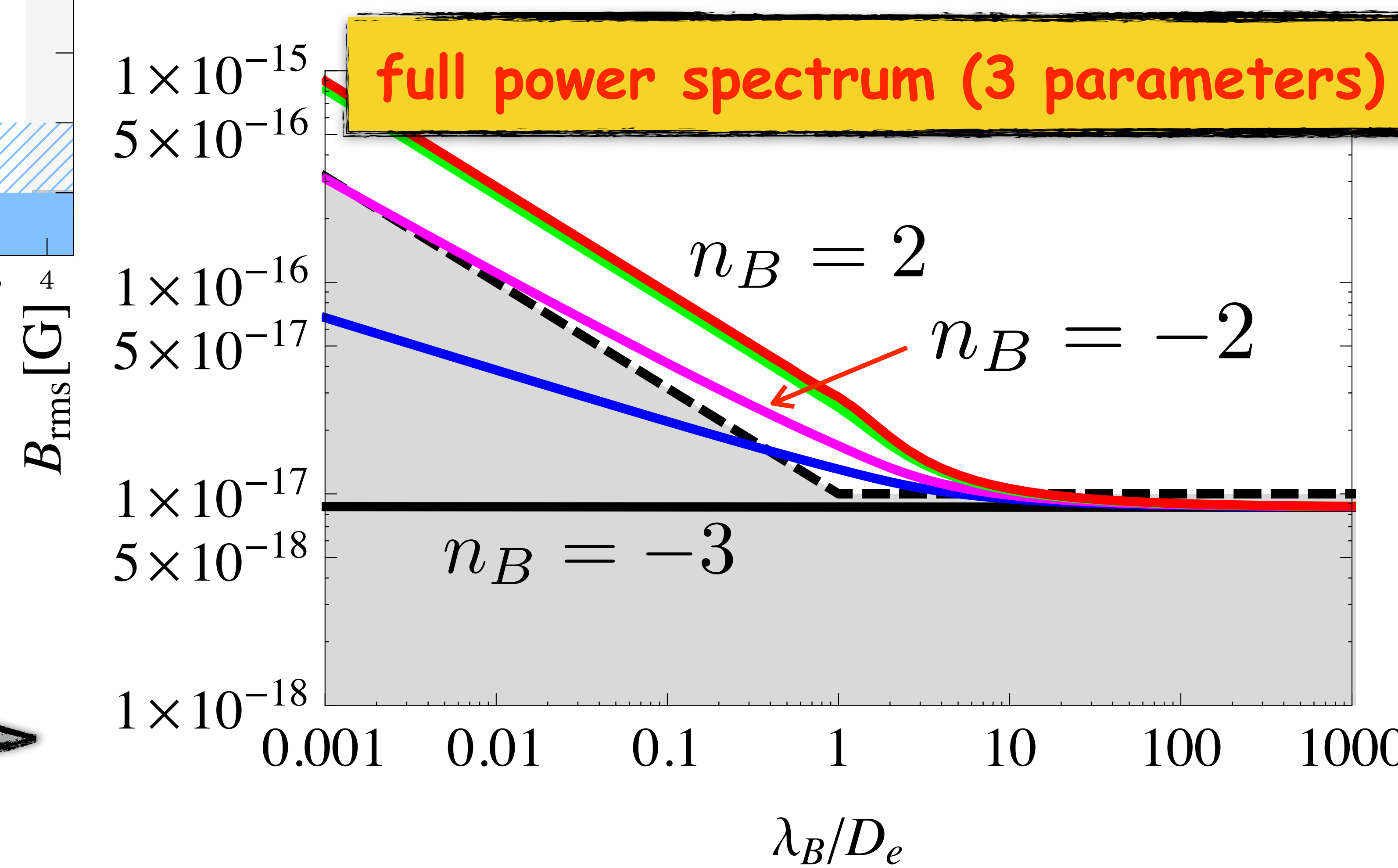
Compton cooling length → D_e/λ_B

Caprini&Gabici 2015

The role of the power spectrum



Neronov&Durrer 2013



Caprini&Gabici 2015

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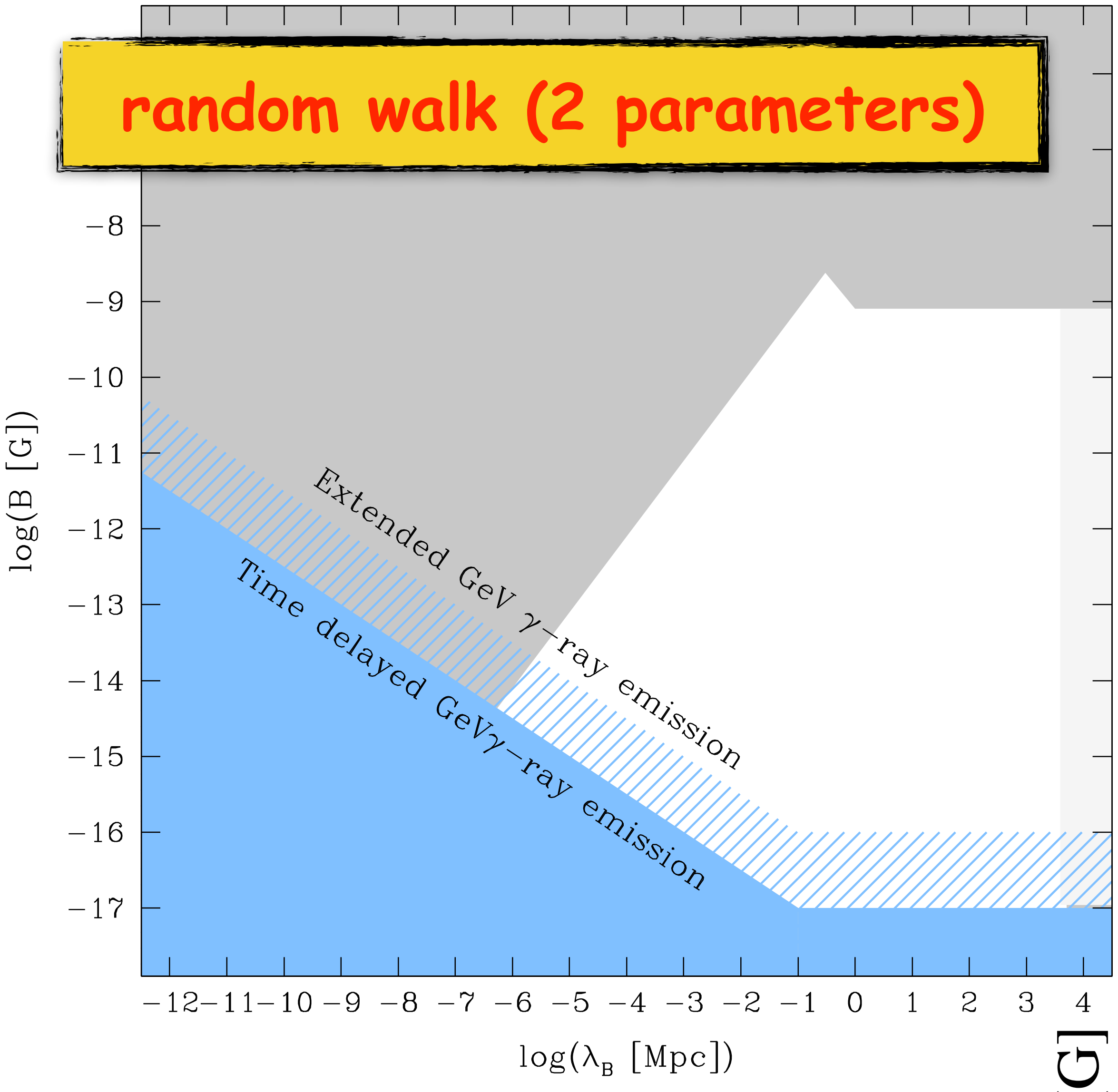

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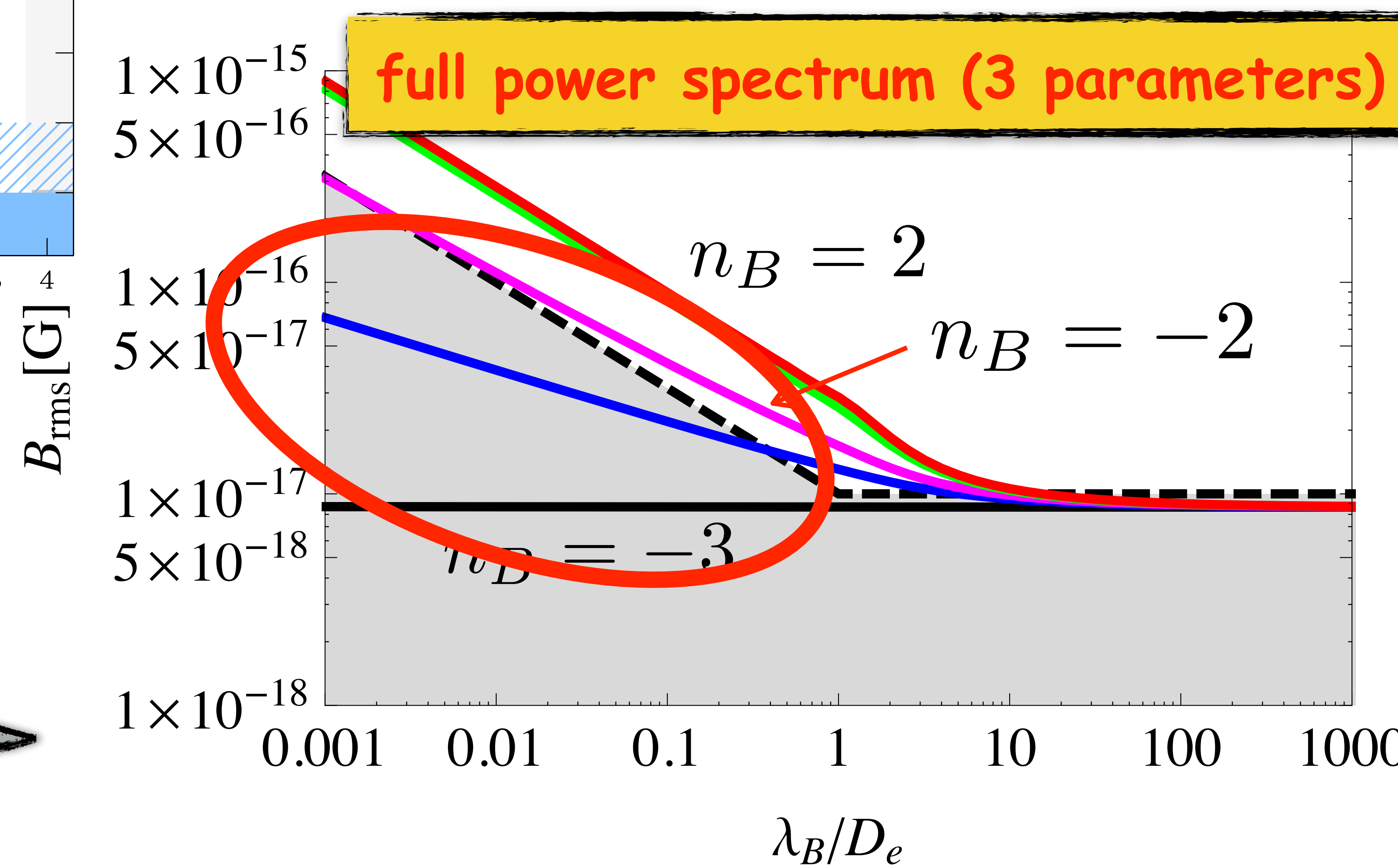
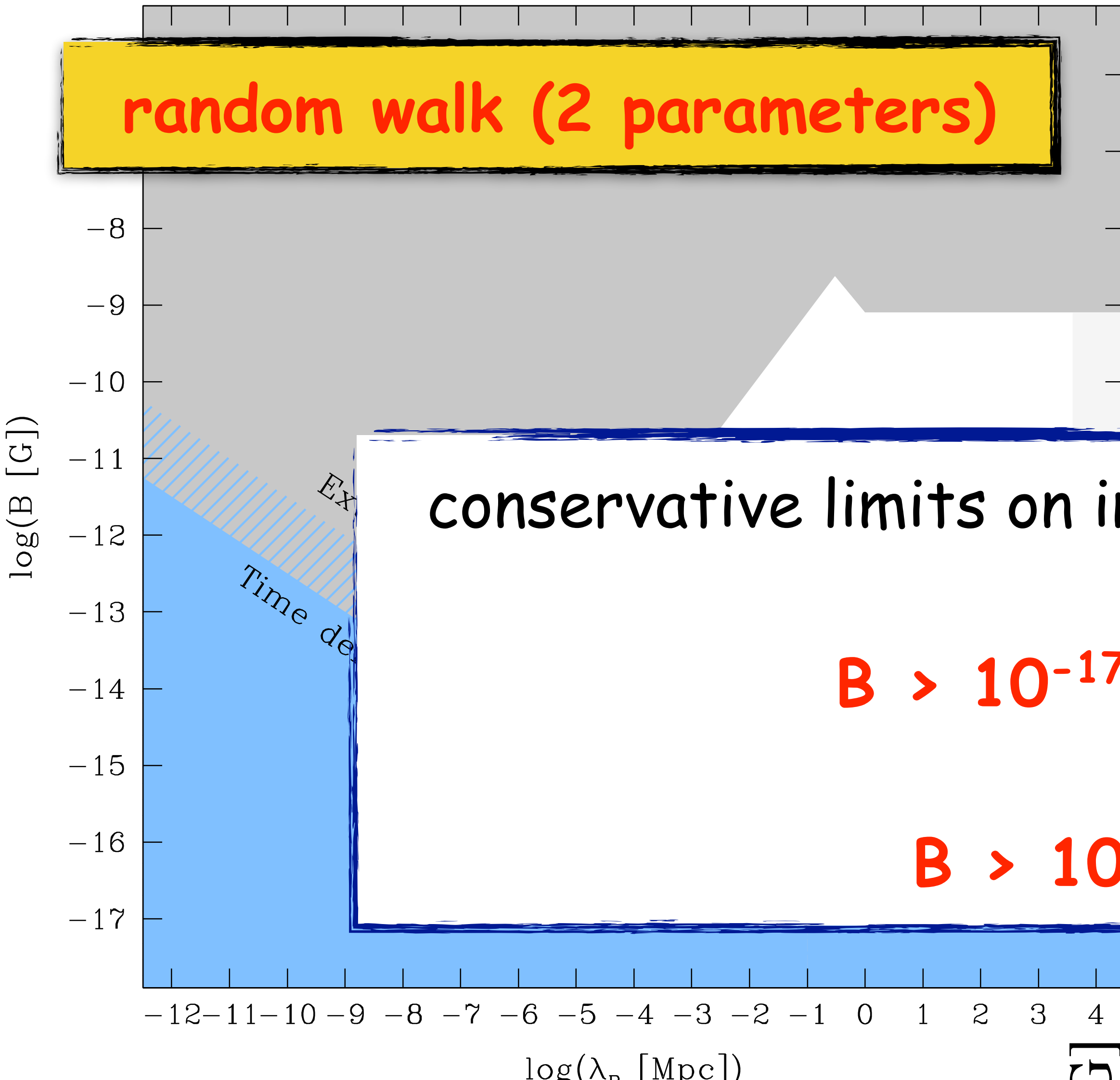


Caprini&Gabici 2015

The role of the power spectrum

random walk (2 parameters)



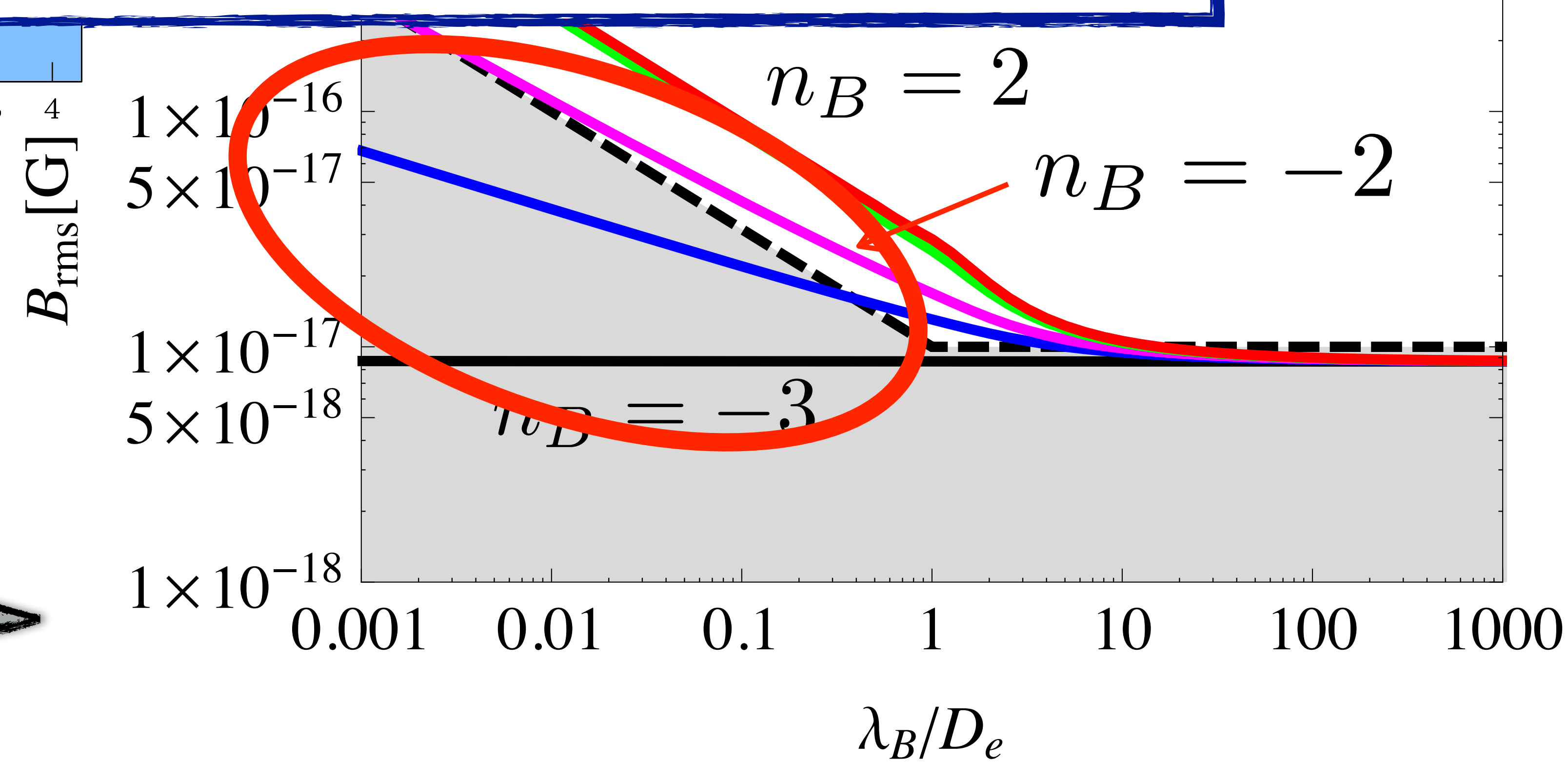
Neronov&Durrer 2013

conservative limits on intergalactic B fields at **ALL scales**:

$B > 10^{-17}$ G (time delay limit)

$B > 10^{-15}$ G (PSF limit)

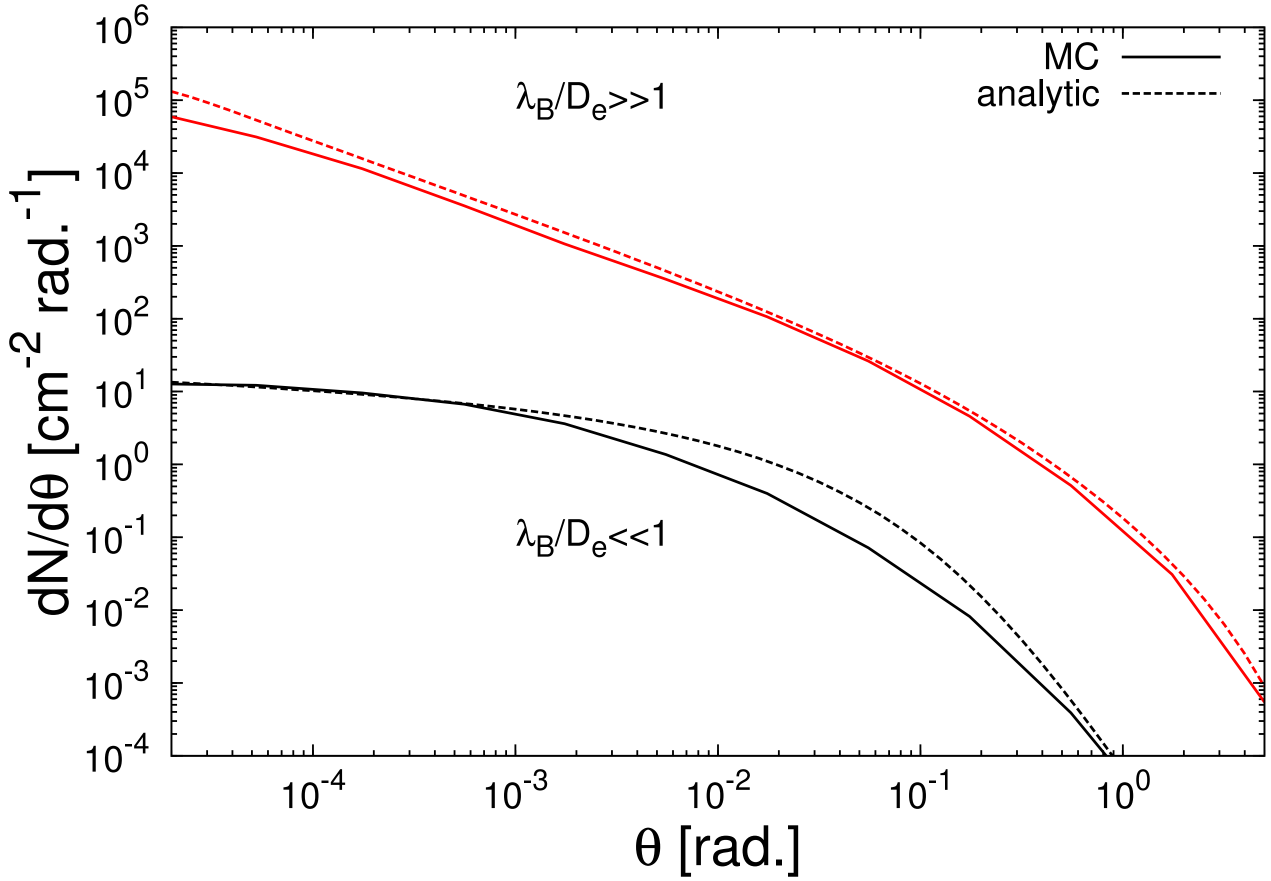
...rameters)



Caprini&Gabici 2015

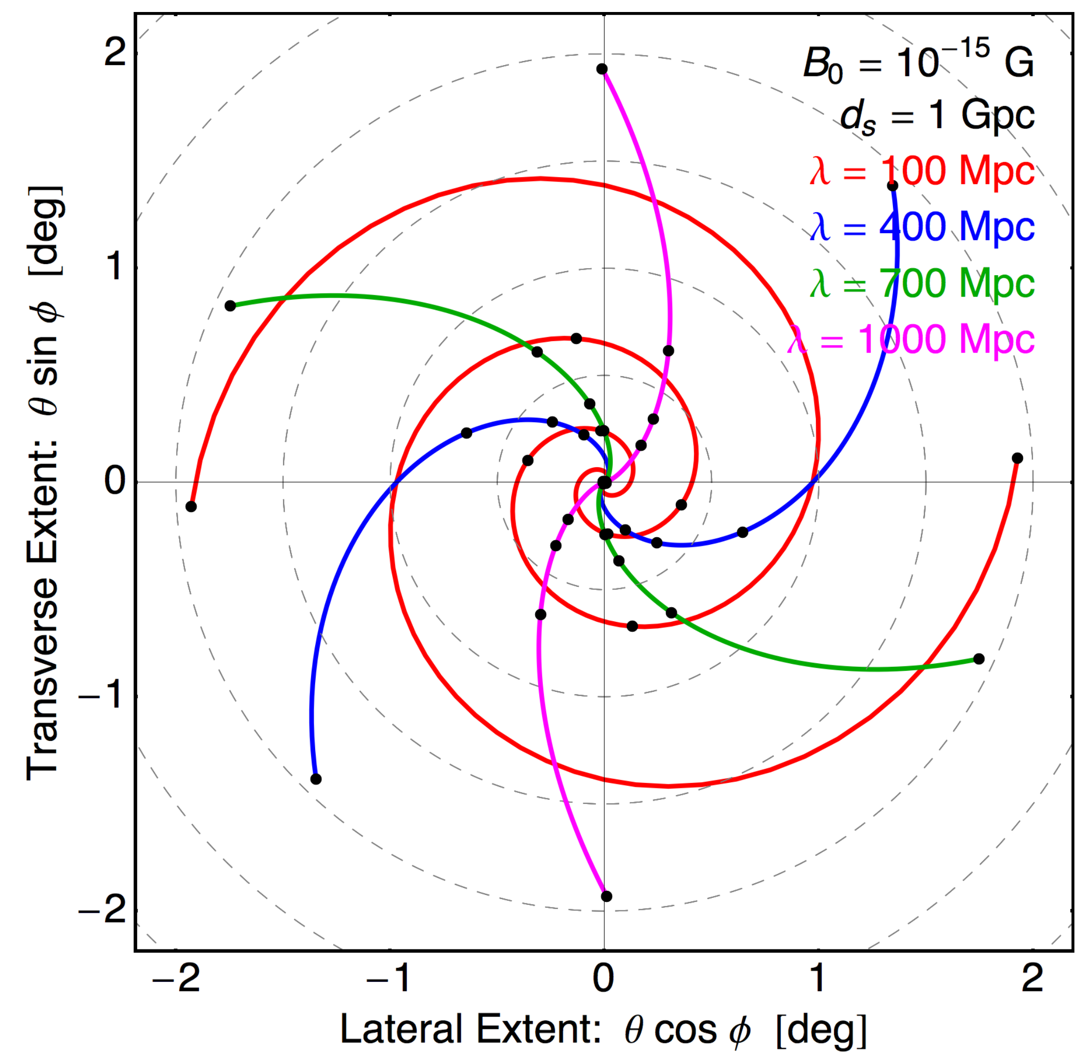
Helicity, coherence length…

Neronov+ 2013



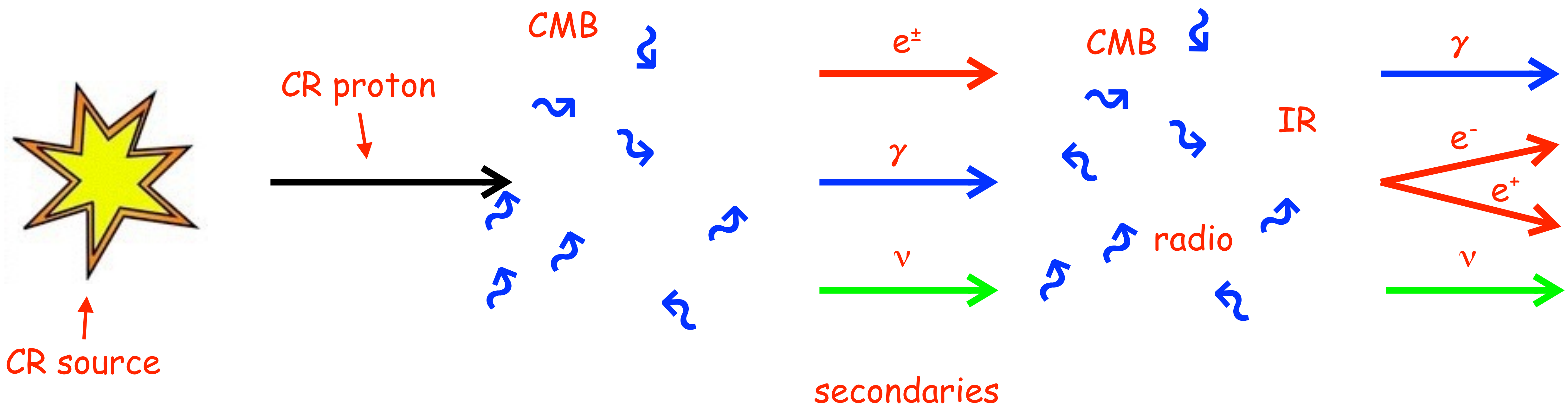
brightness profile of cascade emission for different coherence lengths

signatures of magnetic helicity in the morphology of the cascade emission



e.g. Long & Vachaspati 2015

Cascade initiated by Ultra High Energy Cosmic Rays



$$p + \gamma \longrightarrow n + \pi^+$$

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

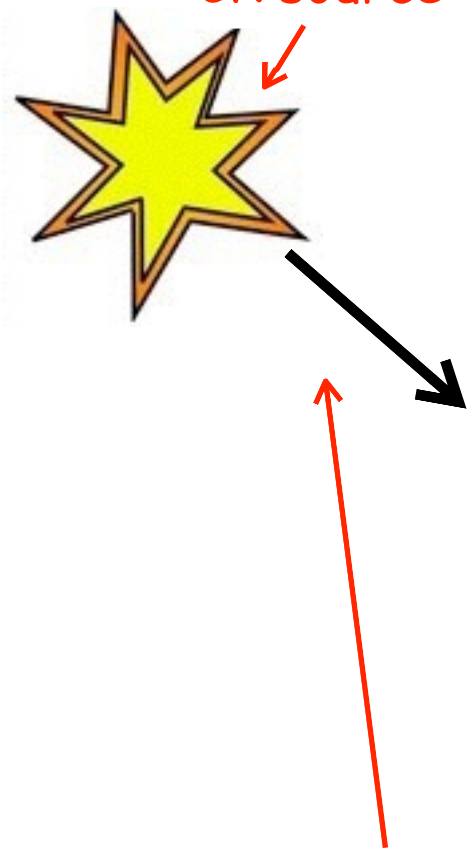
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$p + \gamma \longrightarrow p + \pi^0$$

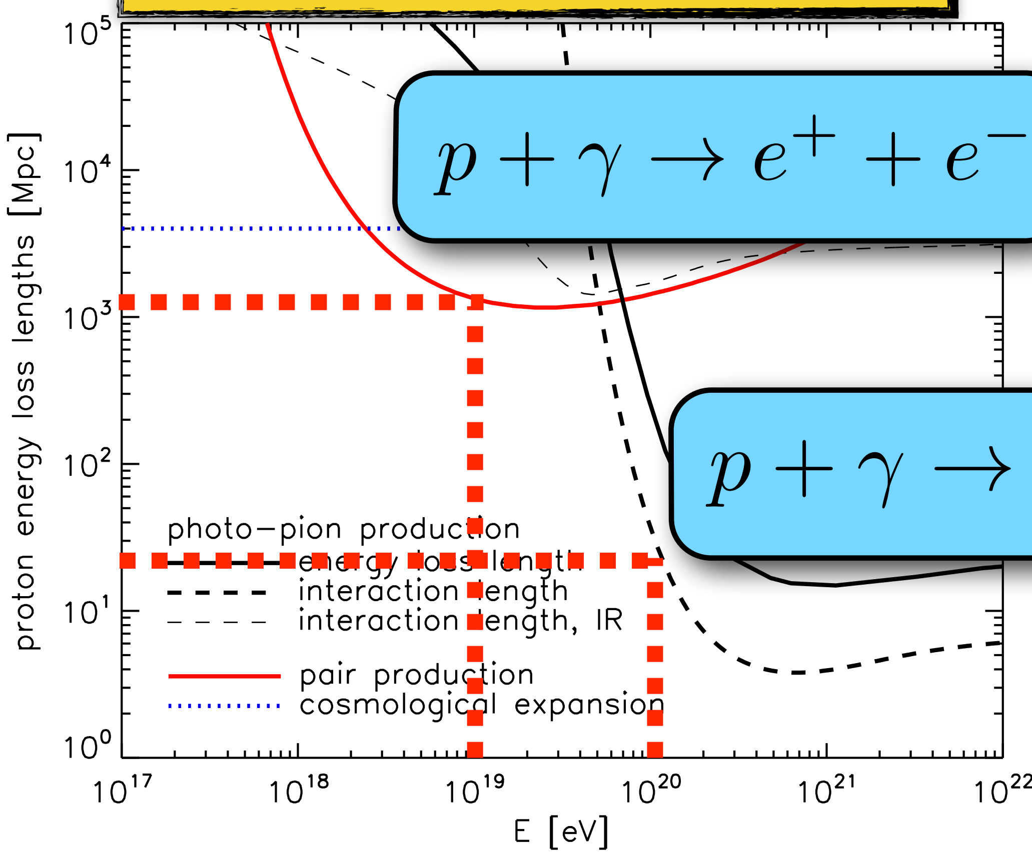
$$\pi^0 \longrightarrow \gamma + \gamma$$

$$p + \gamma \longrightarrow p + e^+ + e^-$$

EM cascade
neutrinos



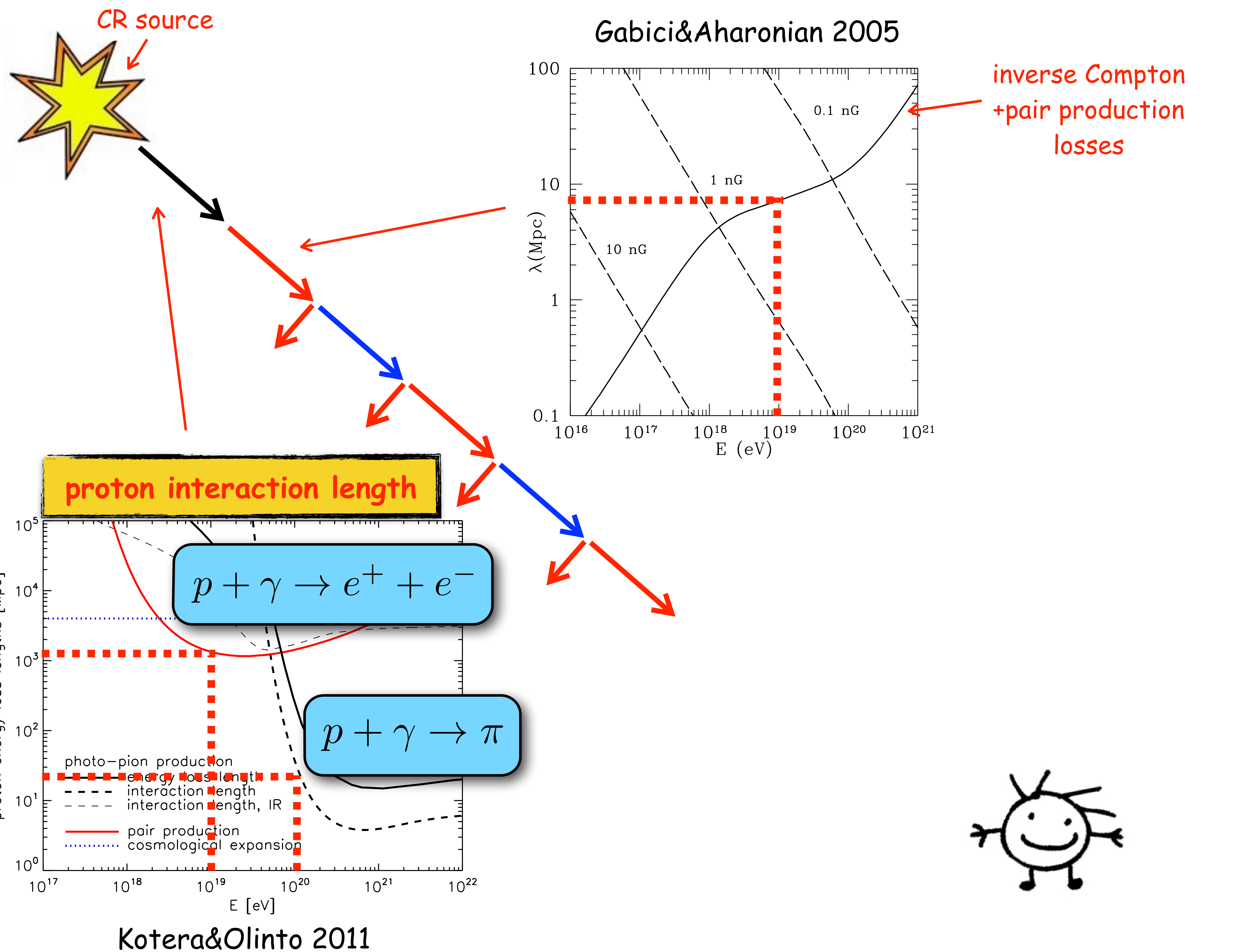
proton interaction length

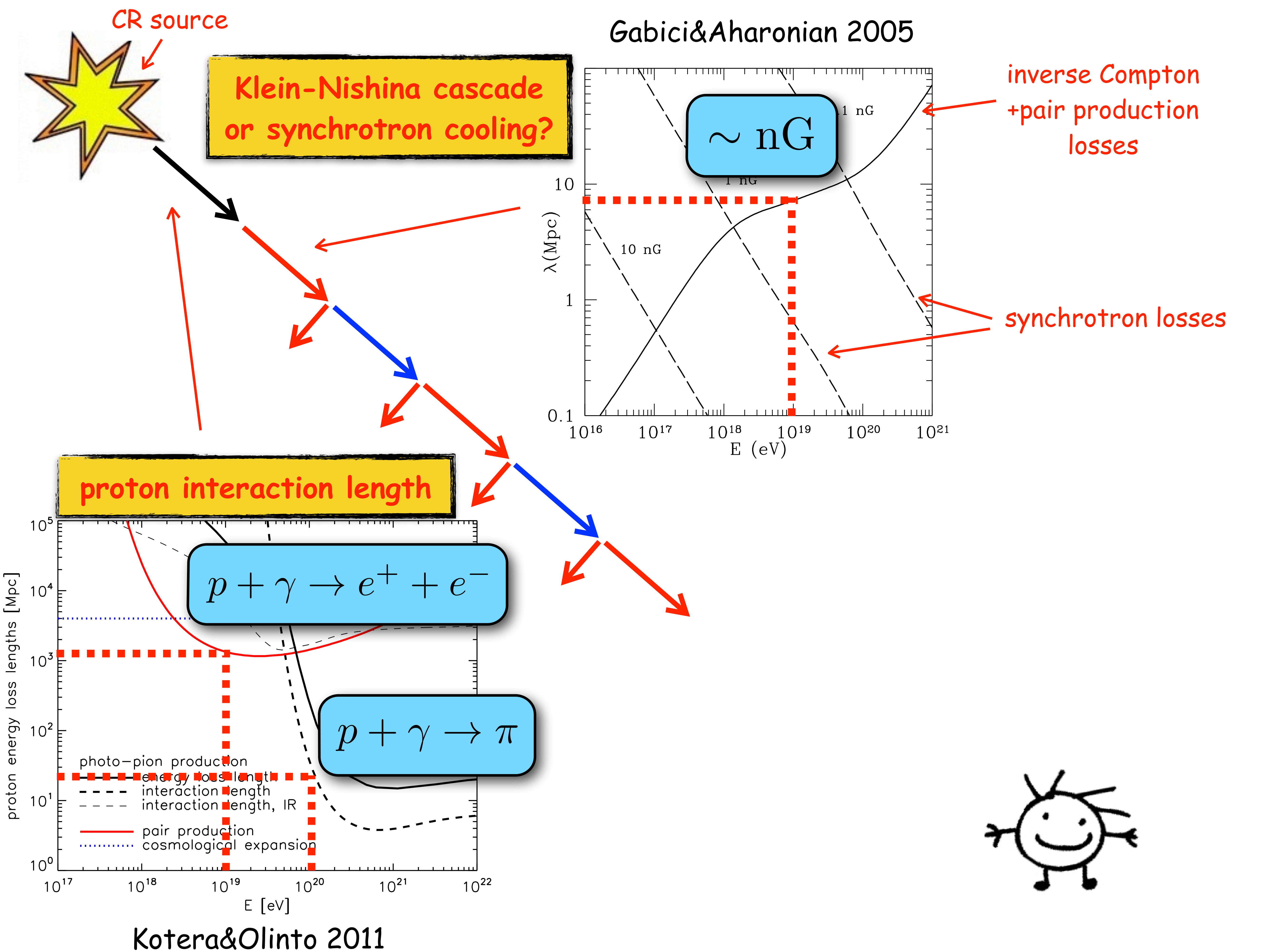


$$p + \gamma \rightarrow e^{+} + e^{-}$$

$$p + \gamma \rightarrow \pi$$

Kotera&Olinto 2011


CR source
Gabici&Aharonian 2005
inverse Compton
+pair production
losses
0.1 nG
1 nG
10 nG
λ(Mpc)
E (eV)
proton interaction length
$p + \gamma \rightarrow e^+ + e^-$
$p + \gamma \rightarrow \pi$
proton energy loss lengths [Mpc]
photo−pion production
energy loss length
interaction length
interaction length, IR
pair production
cosmological expansion
E [eV]
Kotera&Olinto 2011



CR source
Klein-Nishina cascade or synchrotron cooling?
Gabici&Aharonian 2005
$\sim$ nG
inverse Compton +pair production losses
synchrotron losses
1 nG
10 nG
λ (Mpc)
E (eV)
proton interaction length
$p + \gamma \rightarrow e^+ + e^-$
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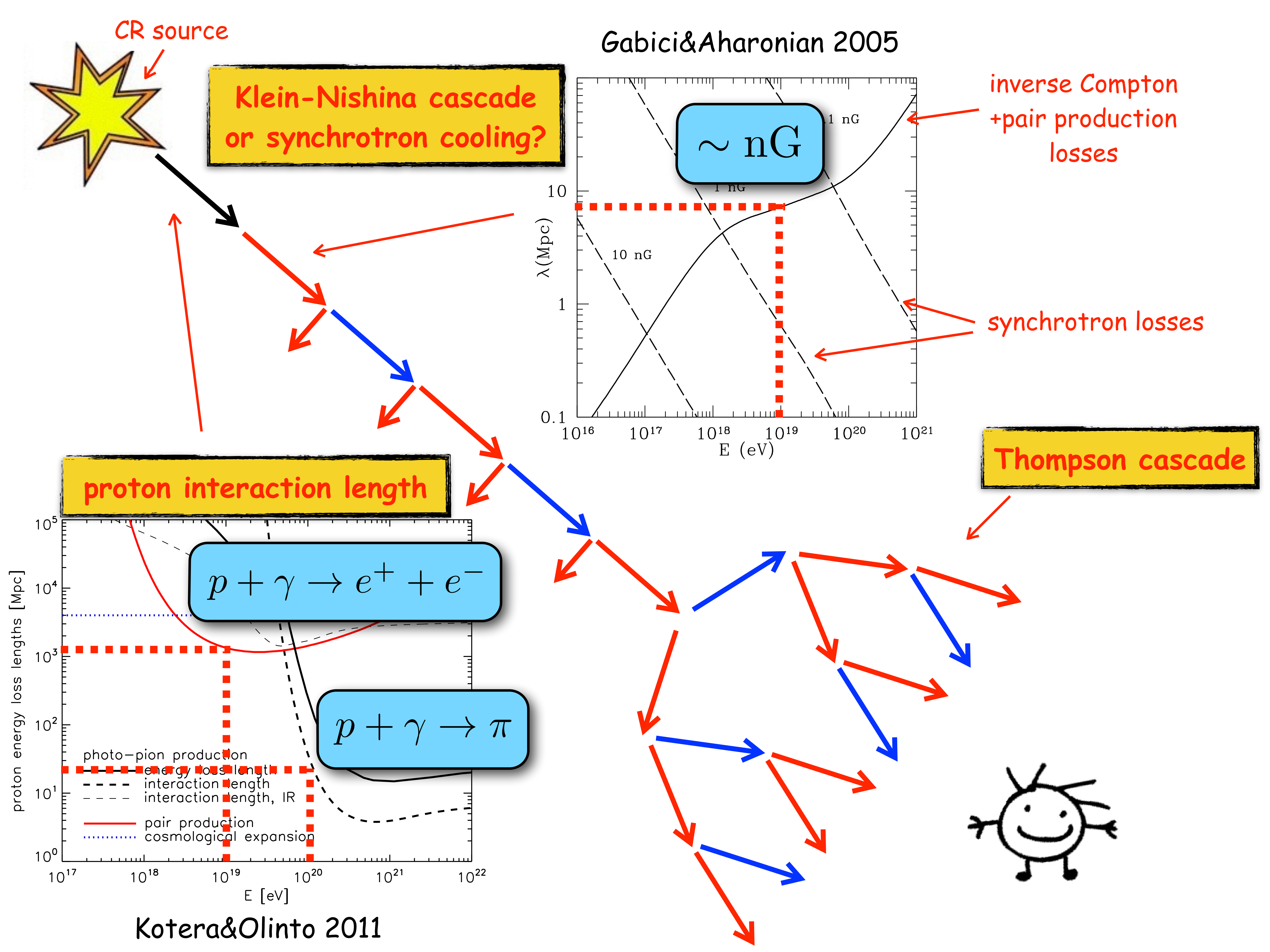
Kotera&Olinto 2011



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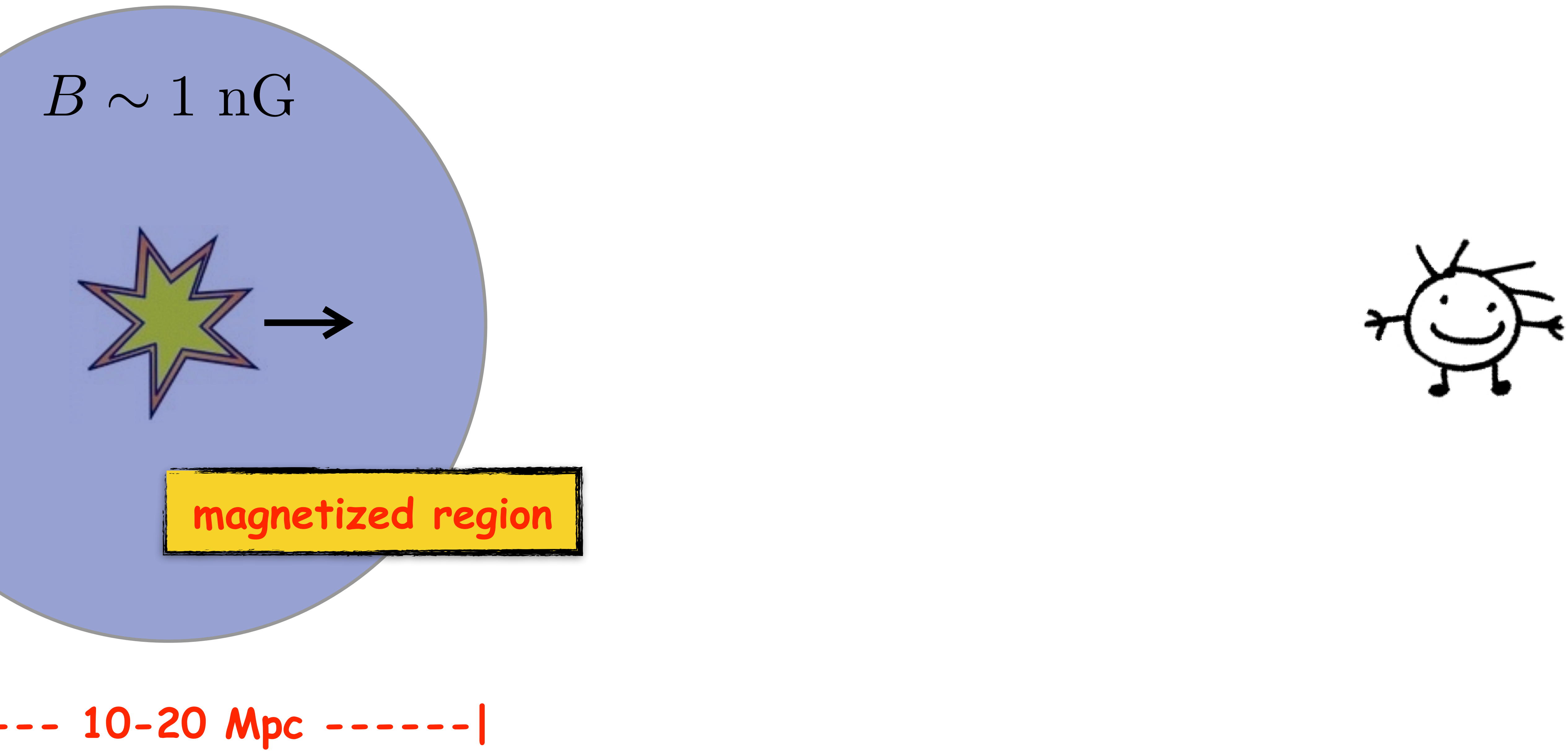
Kotera&Olinto 2011

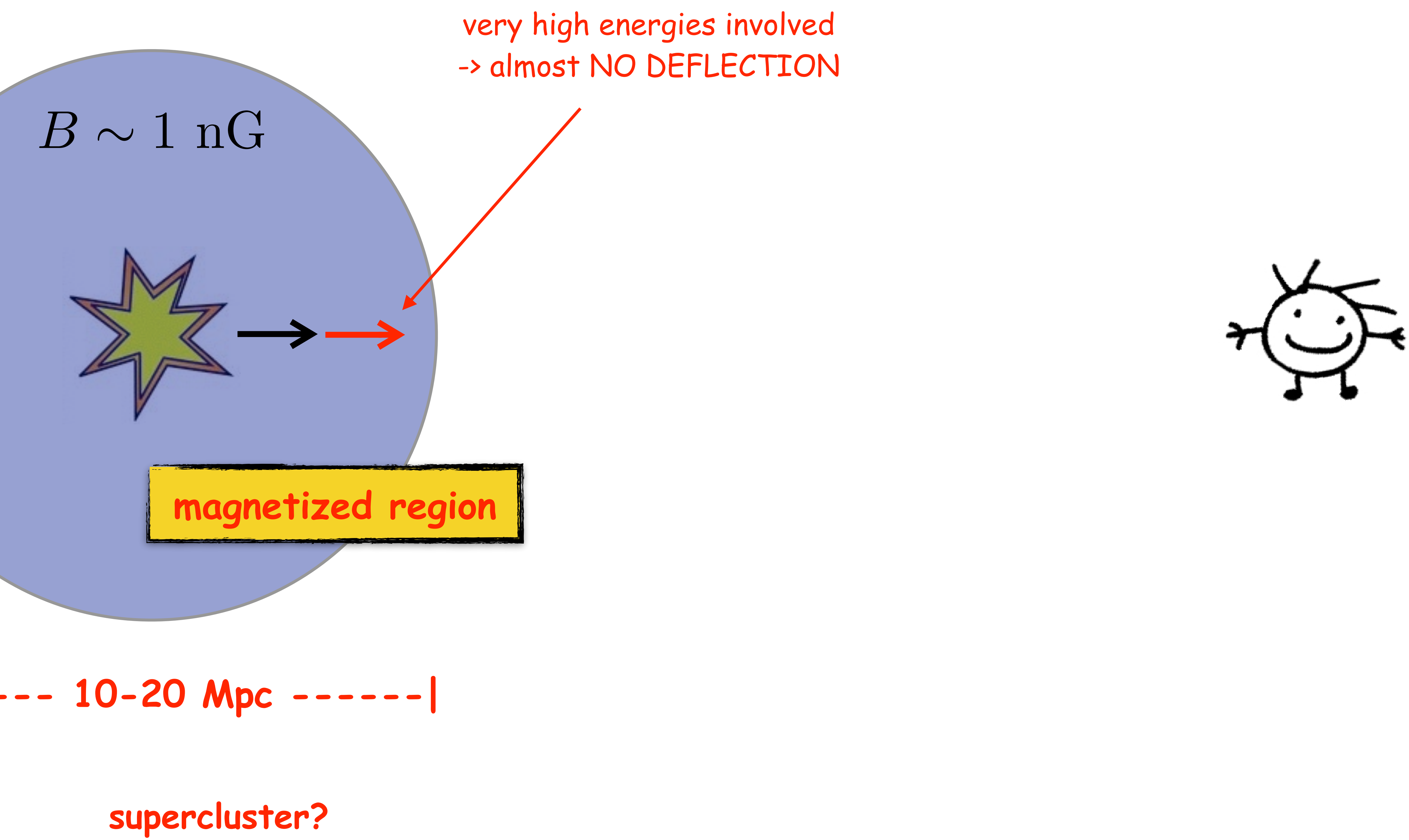
A new channel: synchrotron gamma rays



supercluster?

Gabici&Aharonian 2005, 2007

A new channel: synchrotron gamma rays



Gabici&Aharonian 2005, 2007

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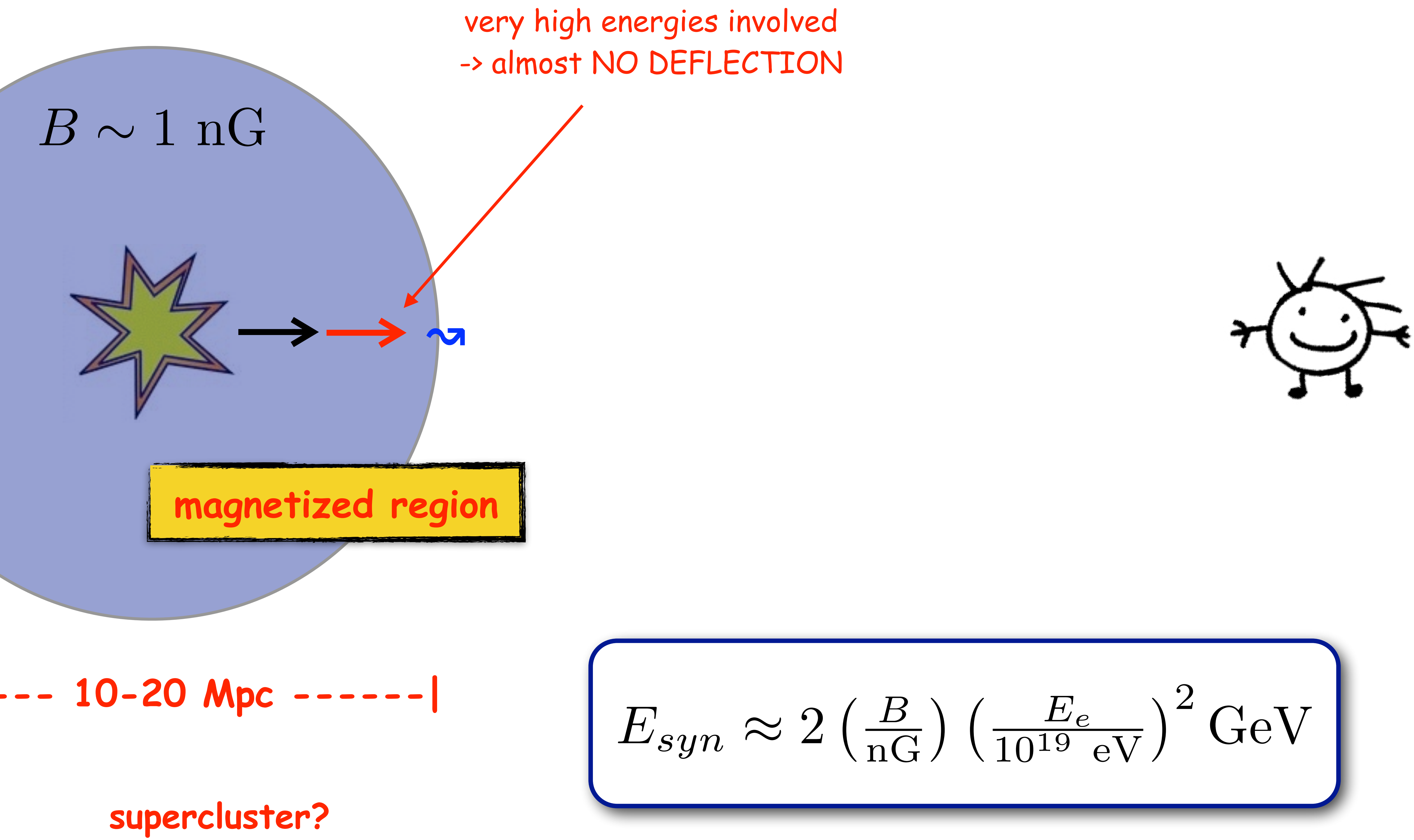
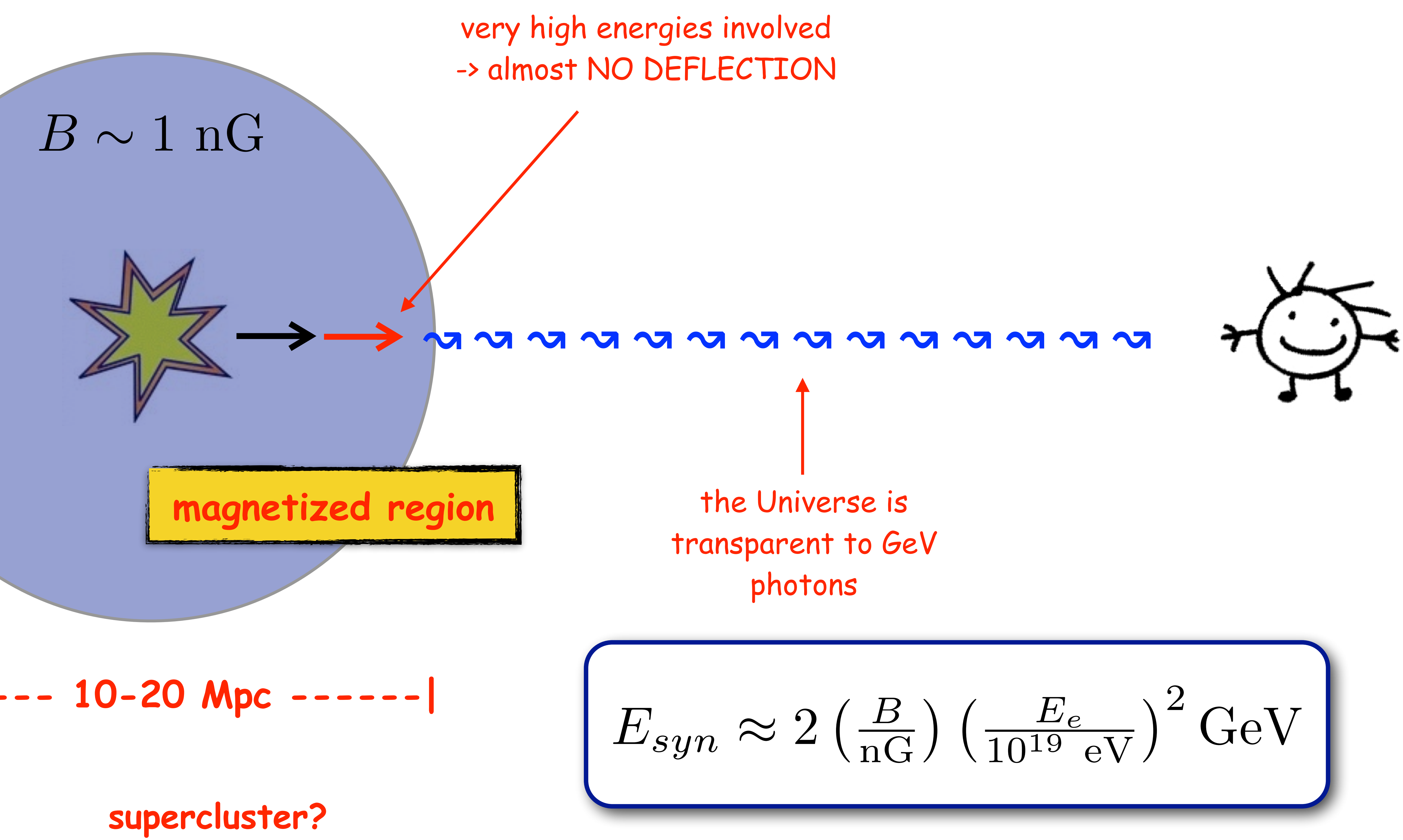


$$E_{syn} \approx 2 \left(\frac{B}{\mathrm{nG}}\right) \left(\frac{E_e}{10^{19}\ \mathrm{eV}}\right)^2 \mathrm{GeV}$$

Gabici&Aharonian 2005, 2007

A new channel: synchrotron gamma rays



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Gabici&Aharonian 2005, 2007

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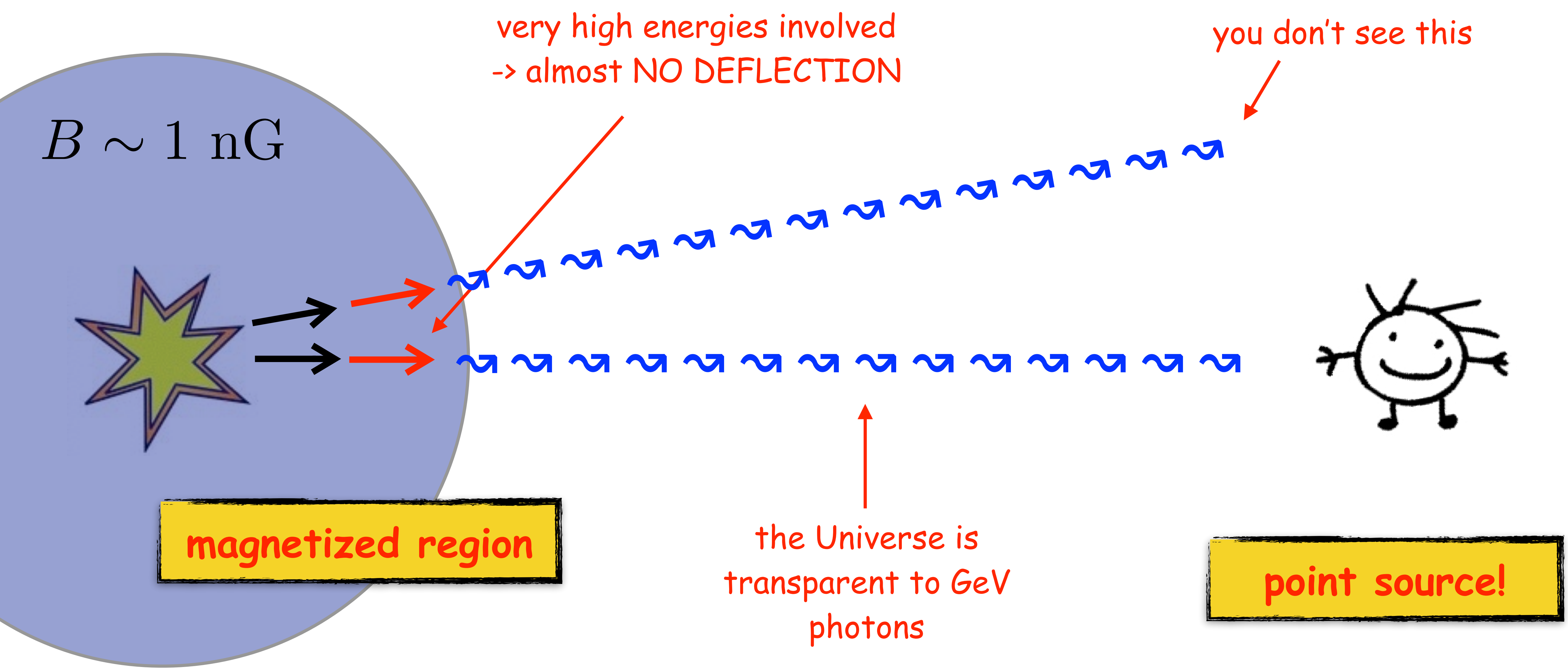

--- 10-20 Mpc ------|

supercluster?

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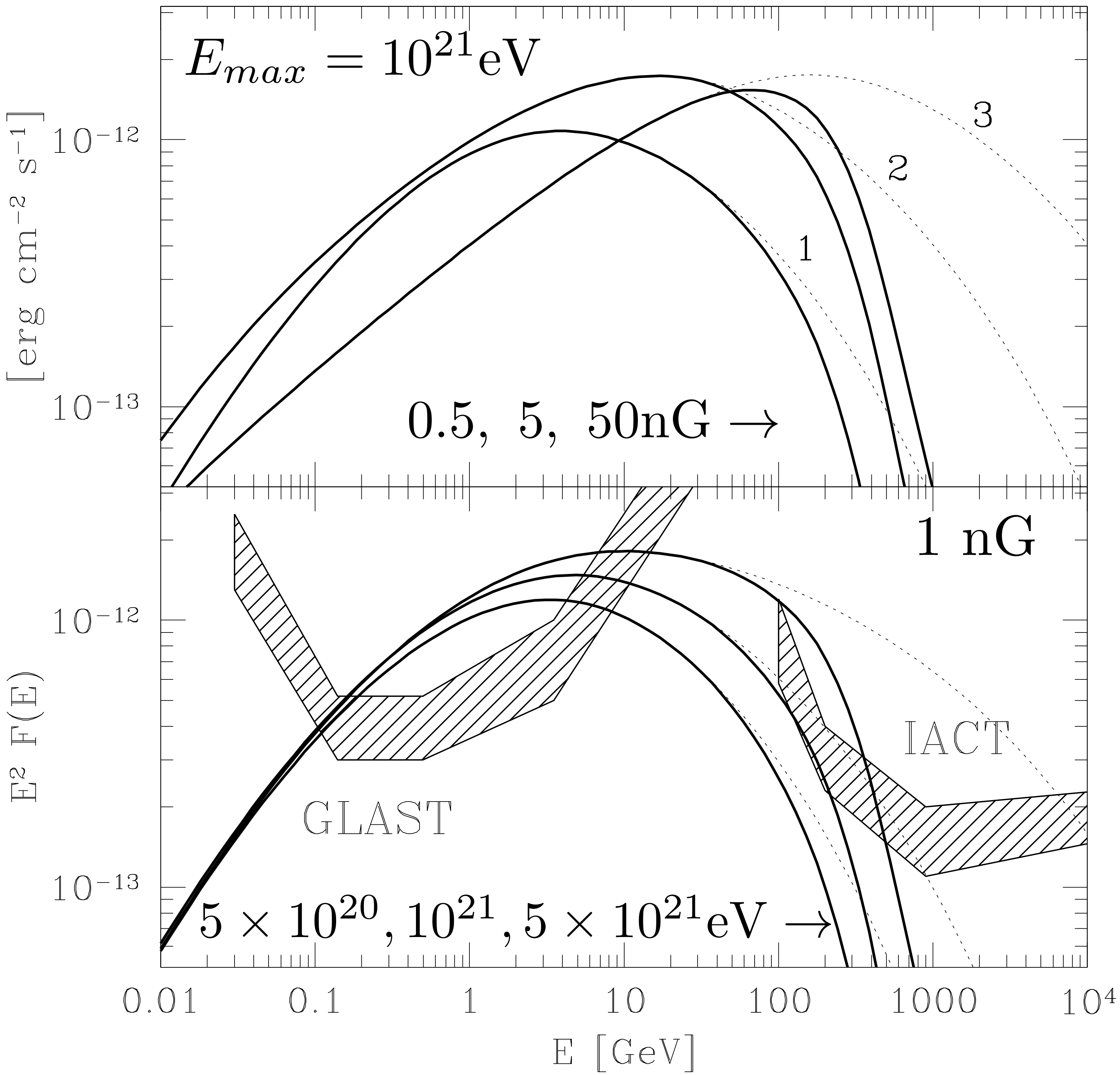
Gabici&Aharonian 2005, 2007

Detectability condition

L_{UHECR} = 10^{46} erg/s, d = 1 Gpc

Gabici&Aharonian 2005, 2007



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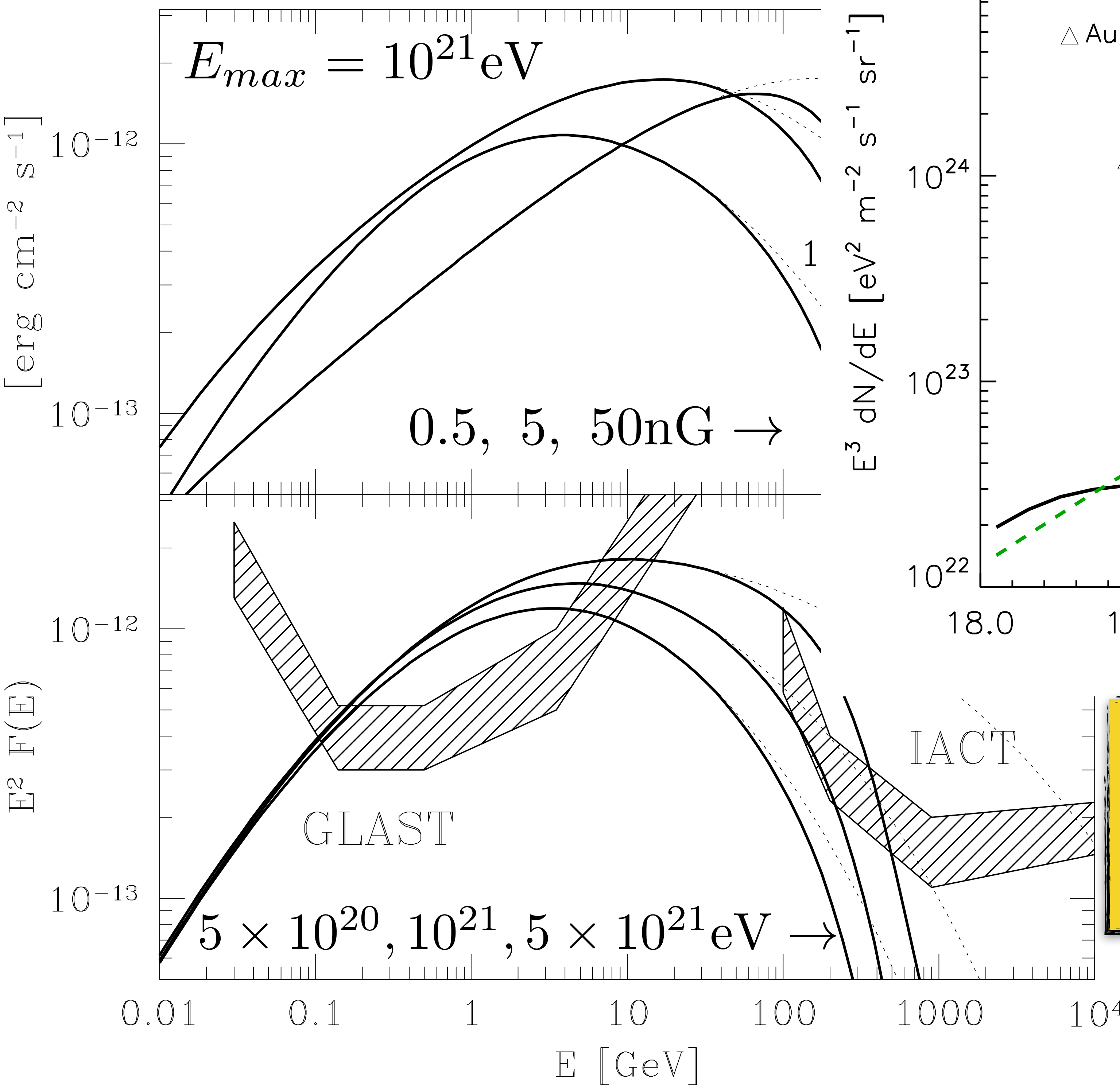
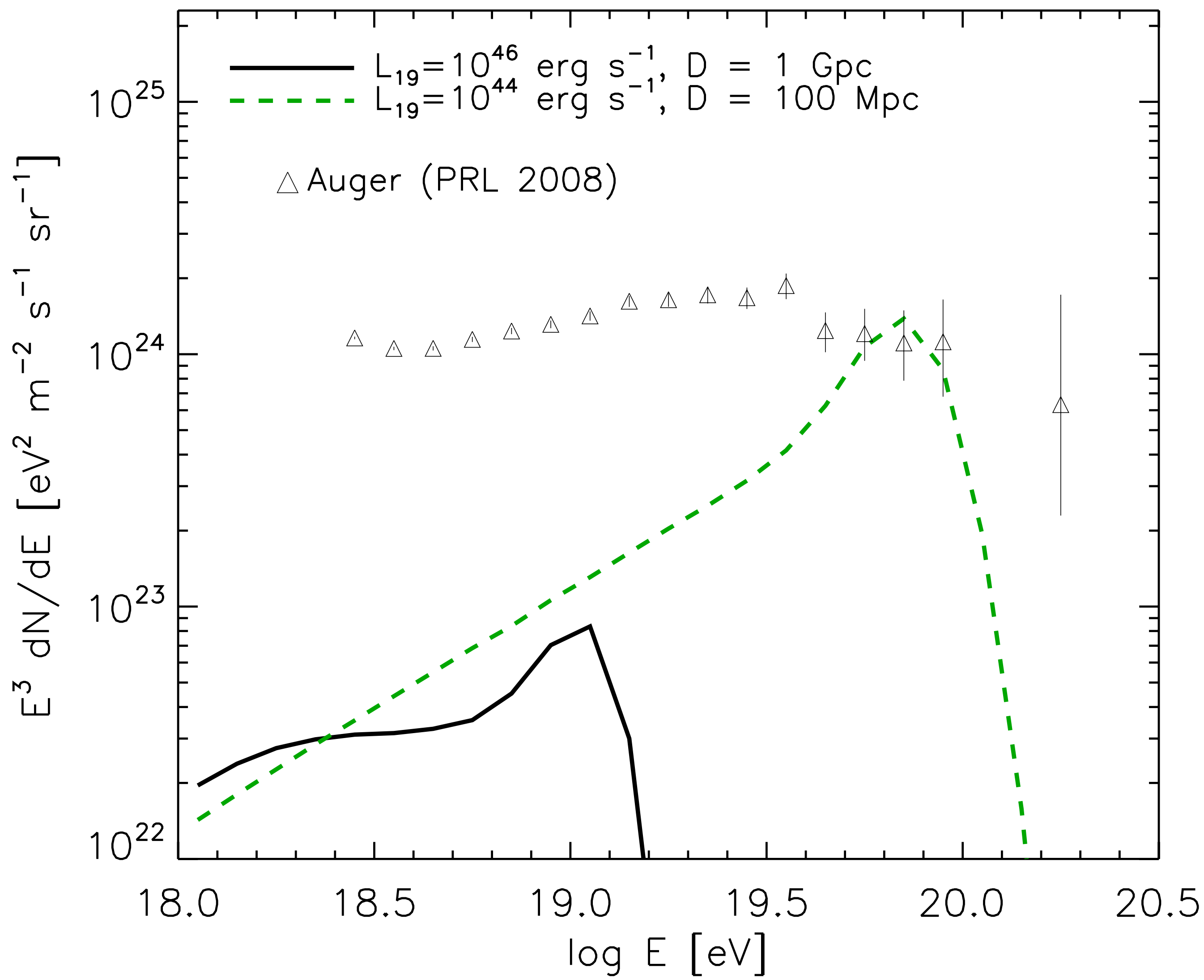
Gabici&Aharonian 2005, 2007



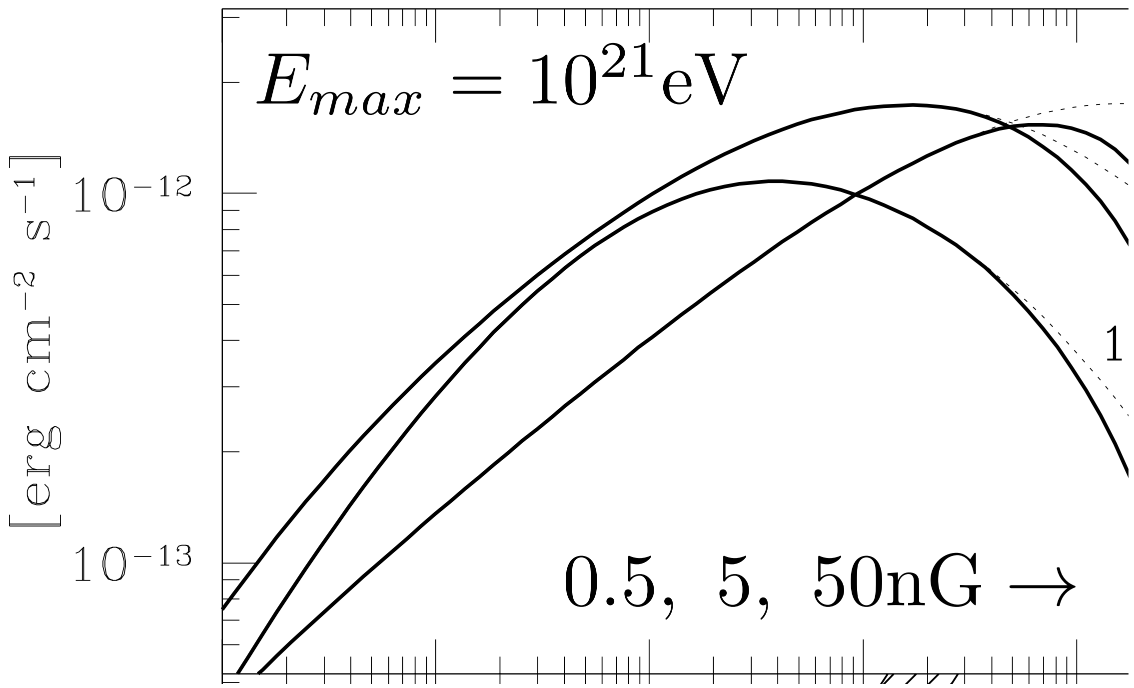


Kotera+ 2011

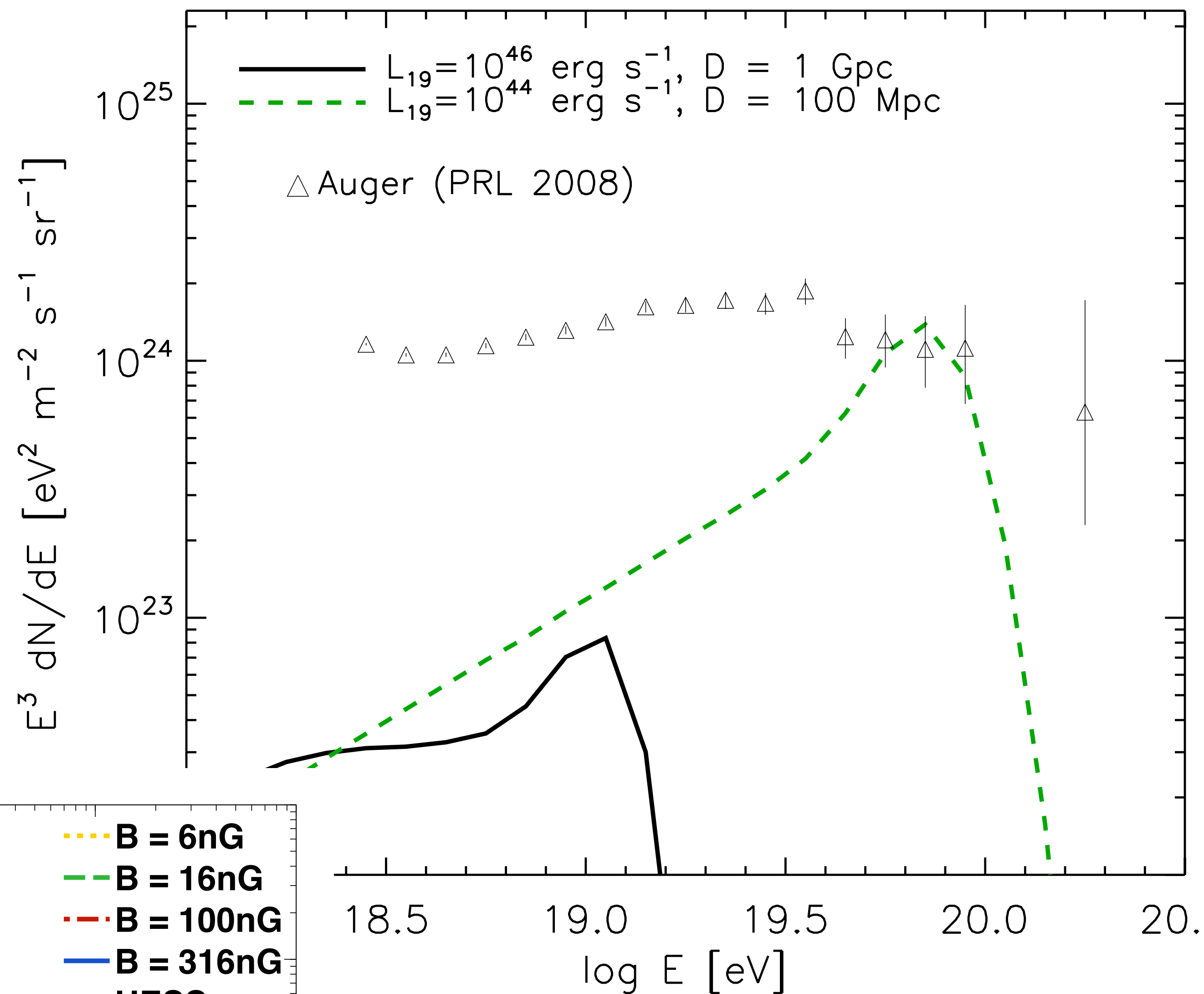
caveats: must be protons and must not overshoot UHECR diffuse spectrum

Detectability condition

$L_{UHECR} = 10^{46}$ erg/s, d = 1 Gpc

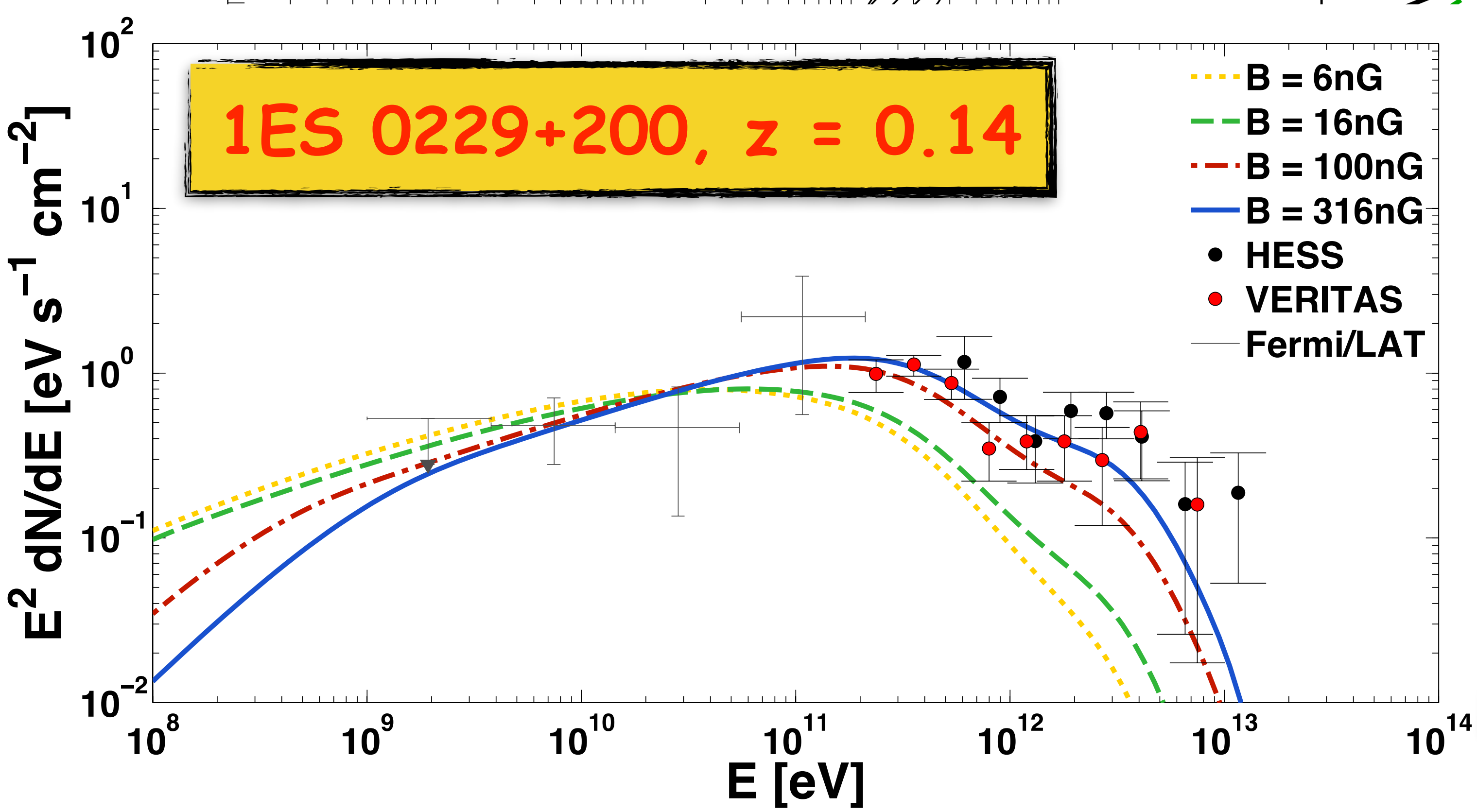


Gabici&Aharonian 2005, 2007



Kotera+ 2011

1ES 0229+200, z = 0.14



Oikonomou+ 2014

caveats: must be protons and must not overshoot UHECR diffuse spectrum

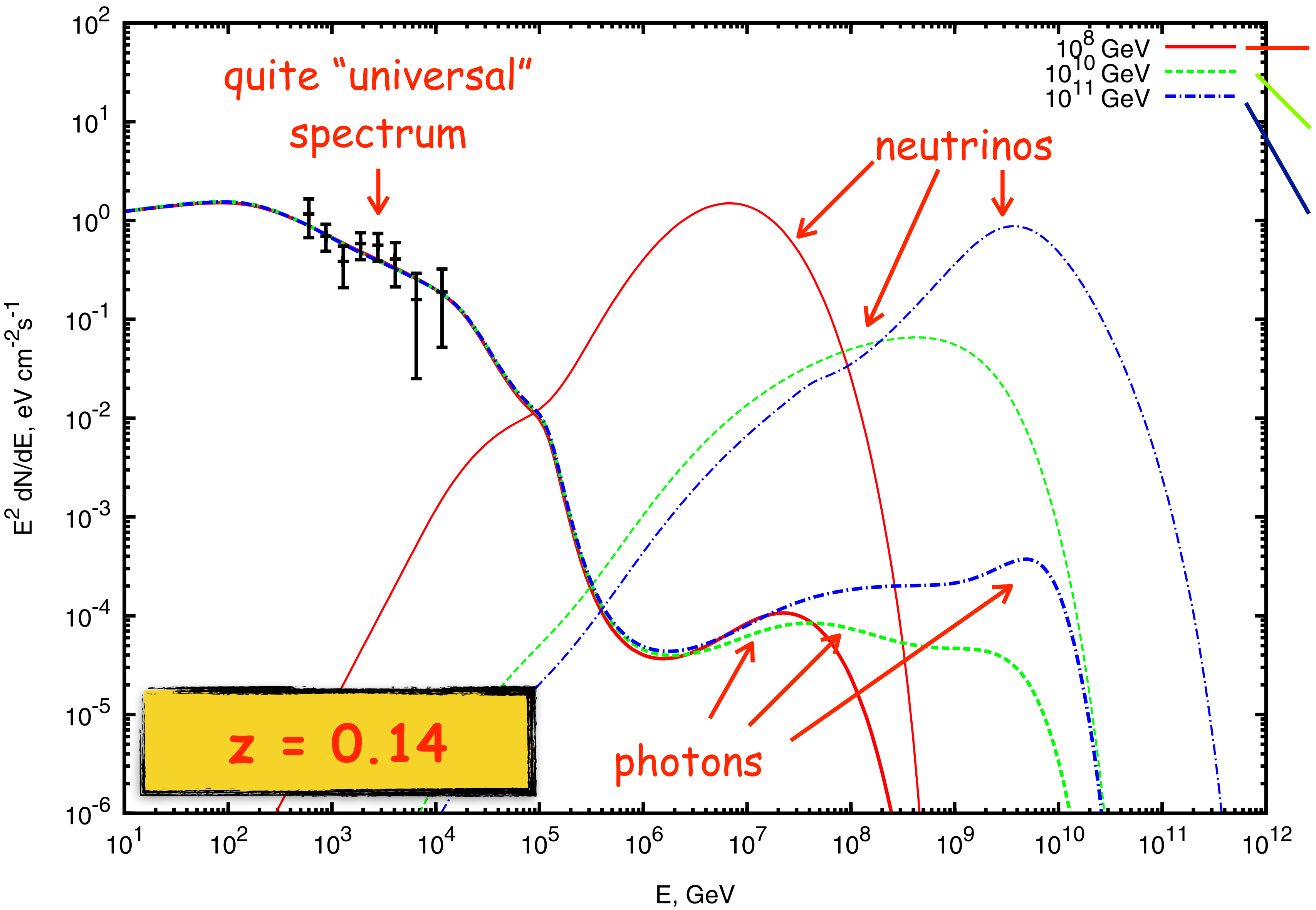
caveat: steady emission

see also Aharonian+2010 Prosekin+ 2011

γ-ray blazar: an alternative scenario

Essey & Kusenko 2010, Essey+ 2010, 2011

all the γ-ray emission comes from the cascade initiated by UHECR interactions



$L_{eff}(> 10^7 \text{ GeV}) = 6 \times 10^{48}$ erg/s

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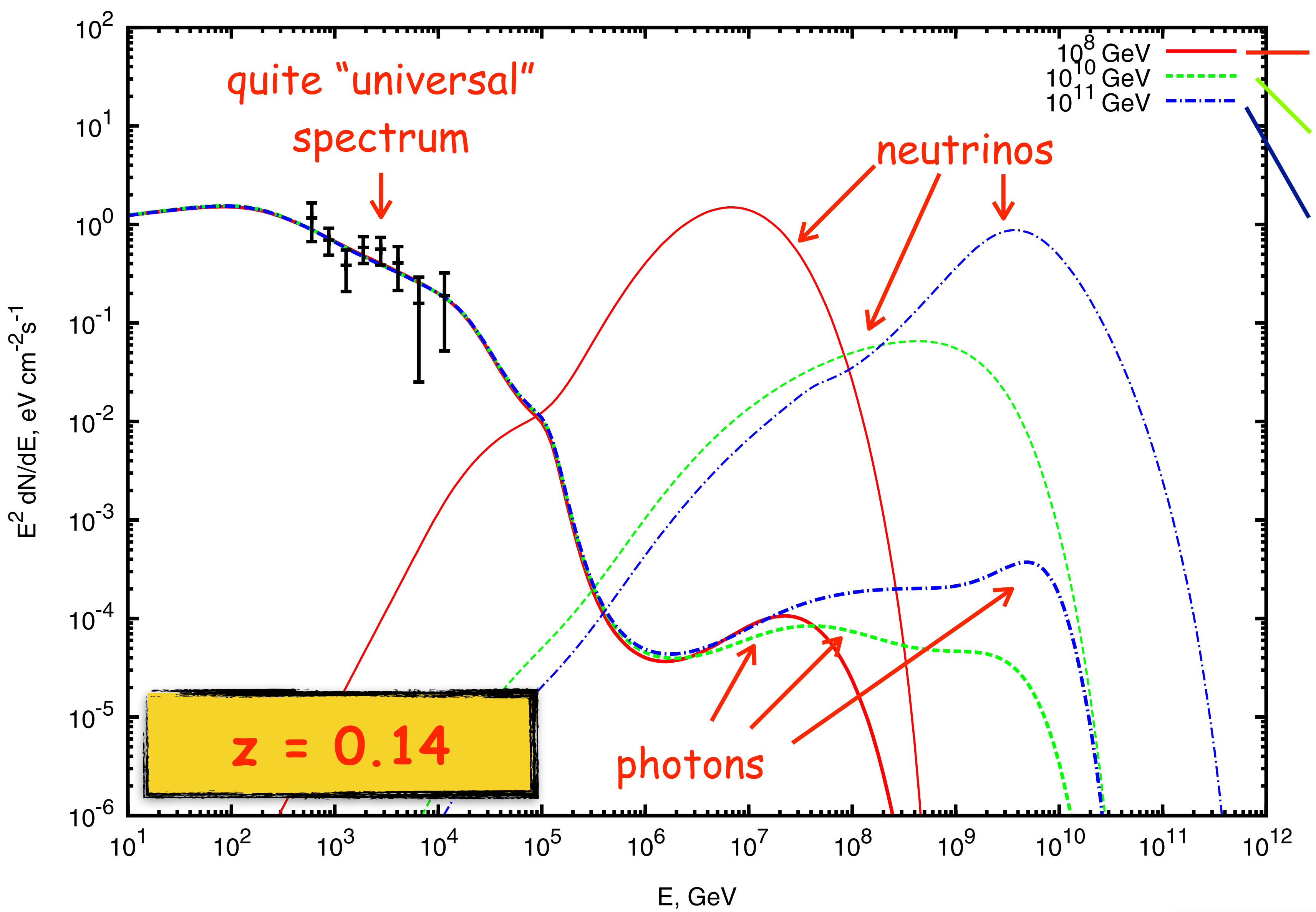

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variability? -> low B

Fermi non detection + HESS detection ->

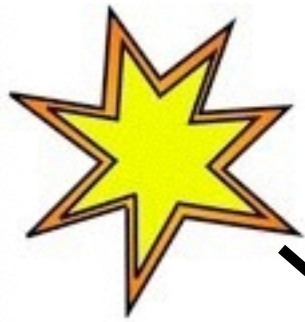
$$10^{-17}\mathrm{G} < B < 3 \times 10^{-14}\mathrm{G}$$

γ-rays from high z blazar

rationale: blazars at z~0.2 -> EBL close to minimum possible level
-> we shouldn't see gamma rays from blazars at z>0.2

Aharonian+ 2013

γ-rays from high z blazar



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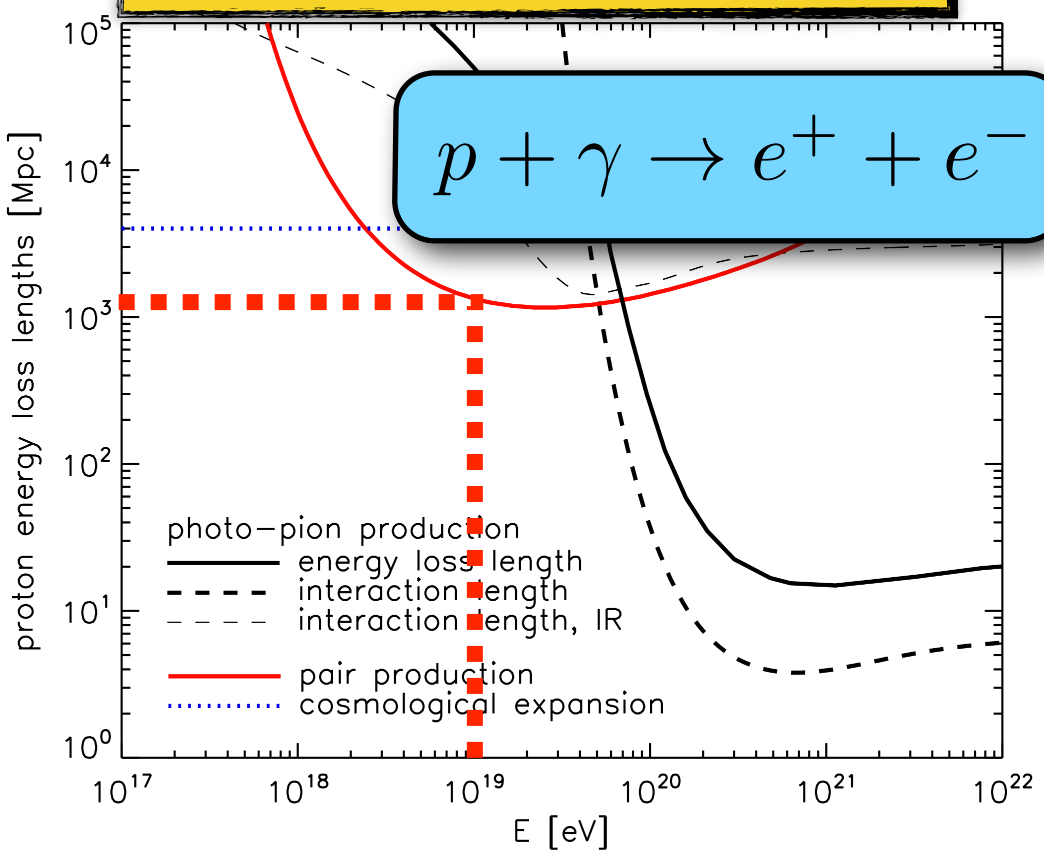
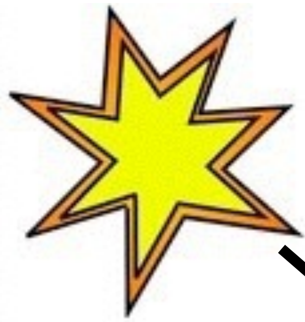
proton interaction length



$$p + \gamma \rightarrow e^+ + e^-$$

Aharonian+ 2013

γ-rays from high z blazar



rationale: blazars at z~0.2 -> EBL close to minimum possible level
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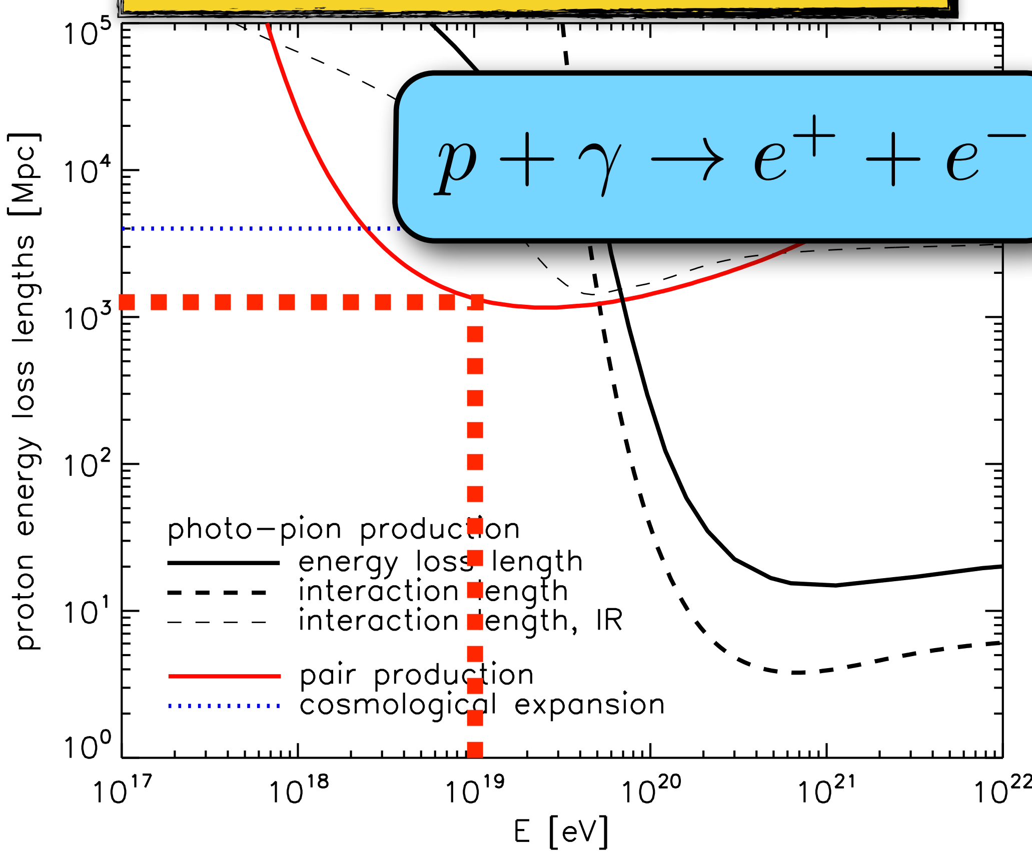
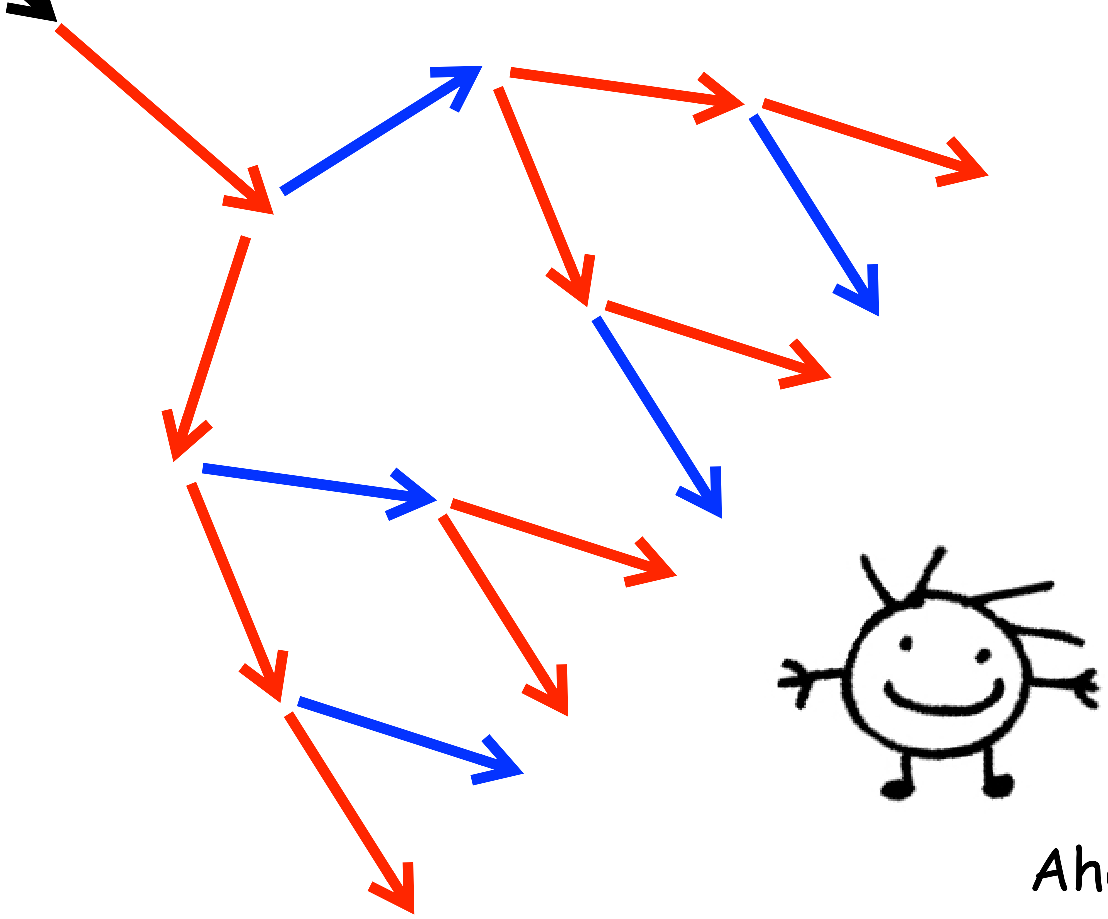
$$E_e \sim \left(\frac{m_e}{m_p}\right) E_p = 10^{15} \left(\frac{E_p}{2\times10^{18}\ \mathrm{eV}}\right) \mathrm{eV}$$

proton interaction length

$$p + \gamma \to e^+ + e^-$$





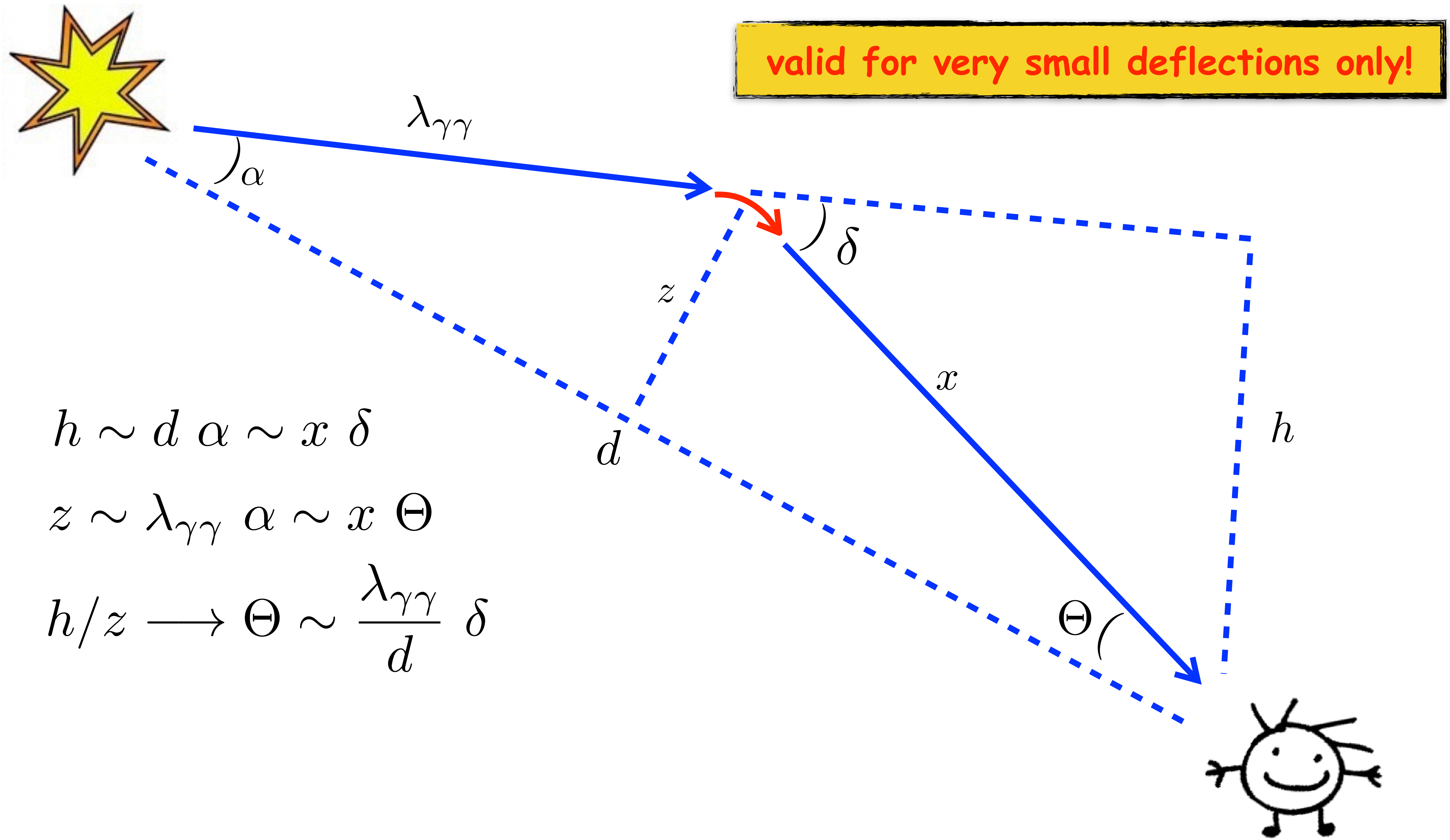
Aharonian+ 2013

Conclusions

- **gamma ray observations of blazars** -> EM cascade in EBL -> **constrain the extragalactic magnetic fields** (especially in voids)
- PSF constrain: **B > 10^{-15} G**
- time delay constrain: **B > 10^{-17} G**
- **alternative scenarios** to the pure electromagnetic cascade exist: cascades initiated by **UHECR** interactions. this typically works well for distant and very powerful sources (remember that powerful sources are indeed expected to be distant!)
- extreme synchrotron scenario -> accelerator immersed in a nG field (steady emission)
- UHECR scenario -> gamma rays from very distant blazars without axions and/or violation of Lorentz invariance

Simple sketch

valid for very small deflections only!



$$h \sim d\,\alpha \sim x\,\delta$$

$$z \sim \lambda_{\gamma\gamma}\,\alpha \sim x\,\Theta$$

$$h/z \longrightarrow \Theta \sim \frac{\lambda_{\gamma\gamma}}{d}\,\delta$$