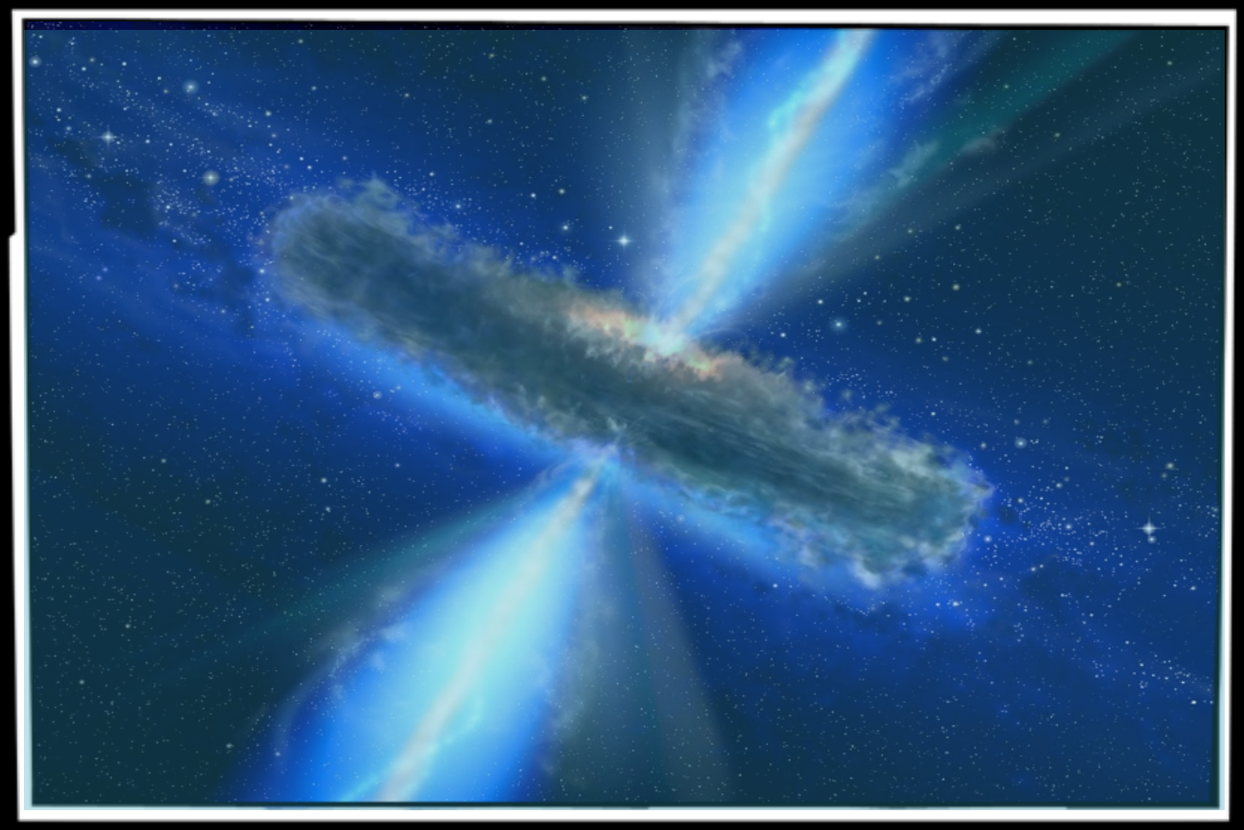
Time dependence of AGN pair echo, and halo emission as a probe of extragalactic magnetic fields



FO, Murase & Kotera, 2017, in prep
FO, Murase & Kotera, PoS(ICRC2017)869
FO, Murase & Kotera, A&A 568, A110 (2014)

Introduction/Motivation

TeV emitting blazar

B in structured region

B in voids

Introduction/Motivation

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Emission scenarios:

- leptonic
- hadronic

Introduction/Motivation

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Inverse Compton

Synchrotron

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Introduction/Motivation

TeV emitting blazar

Emission scenarios:

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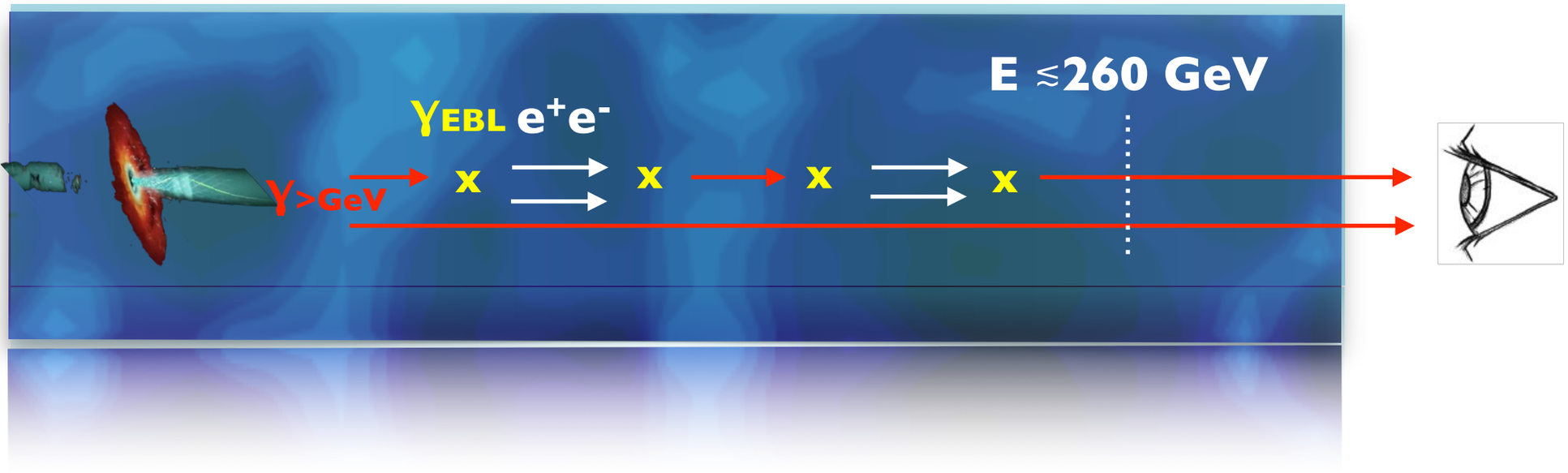
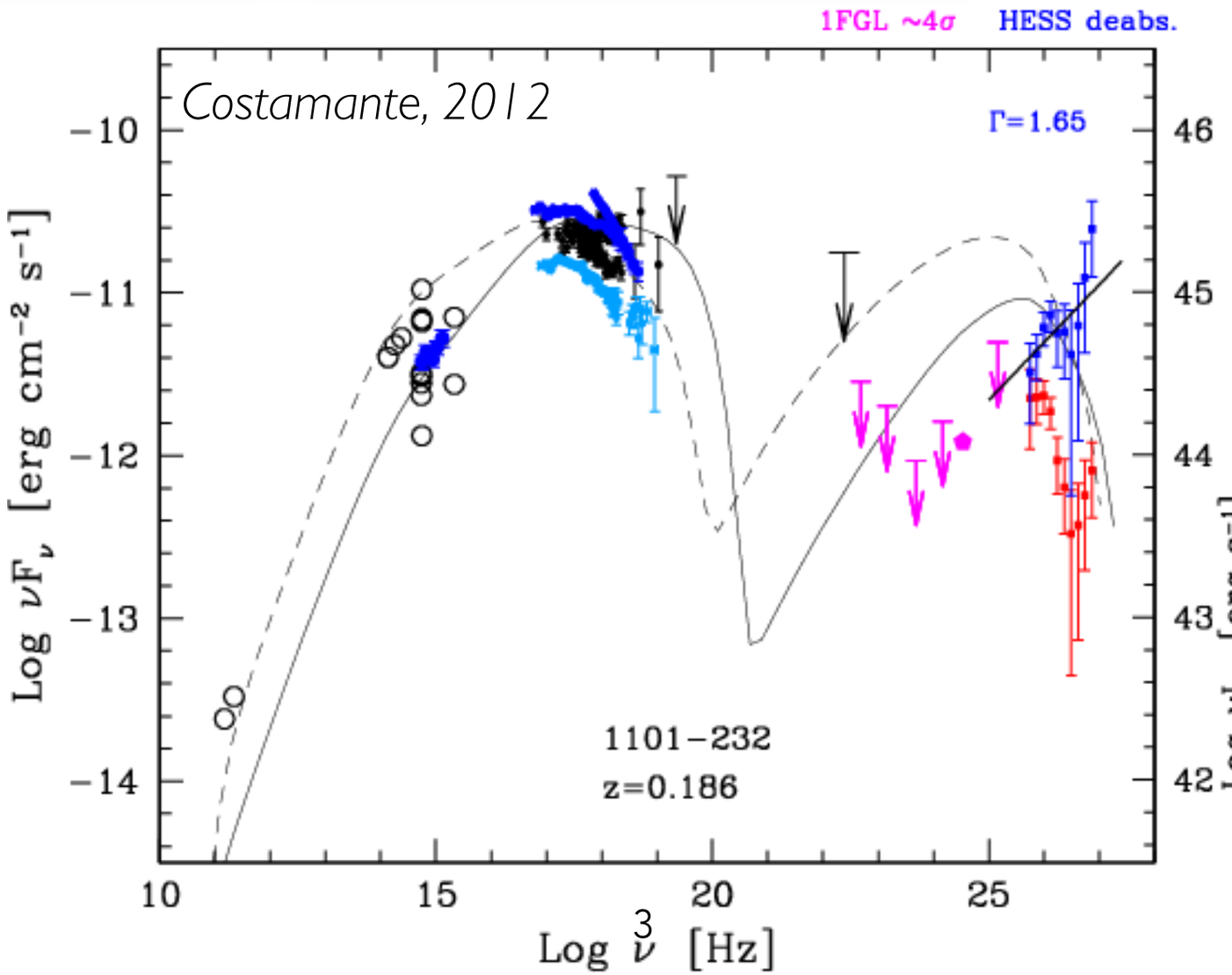
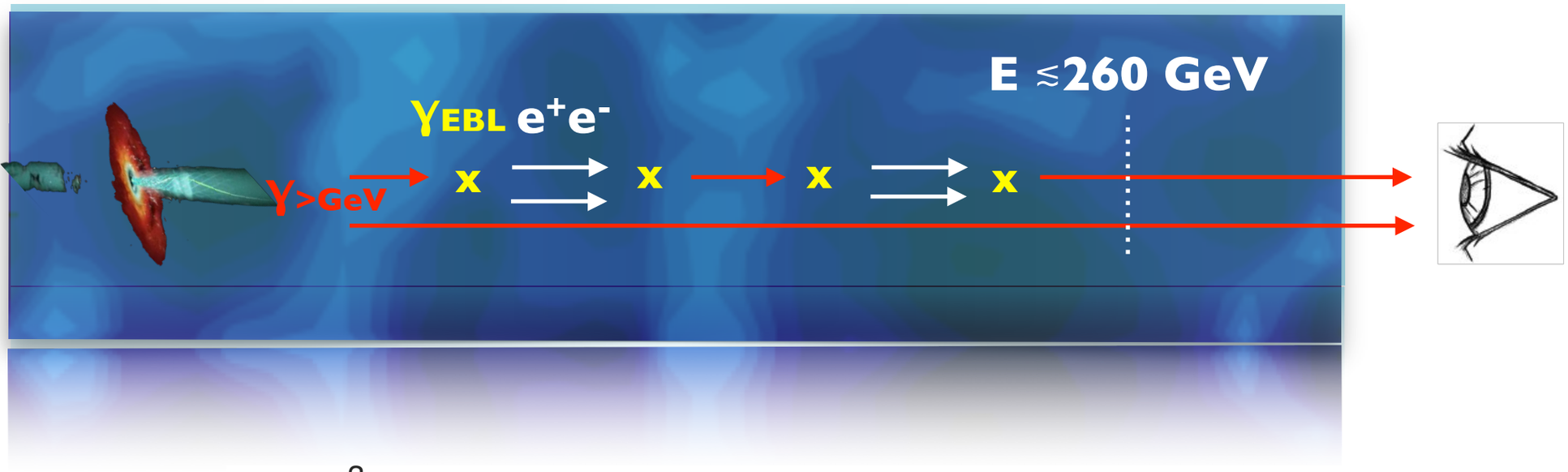
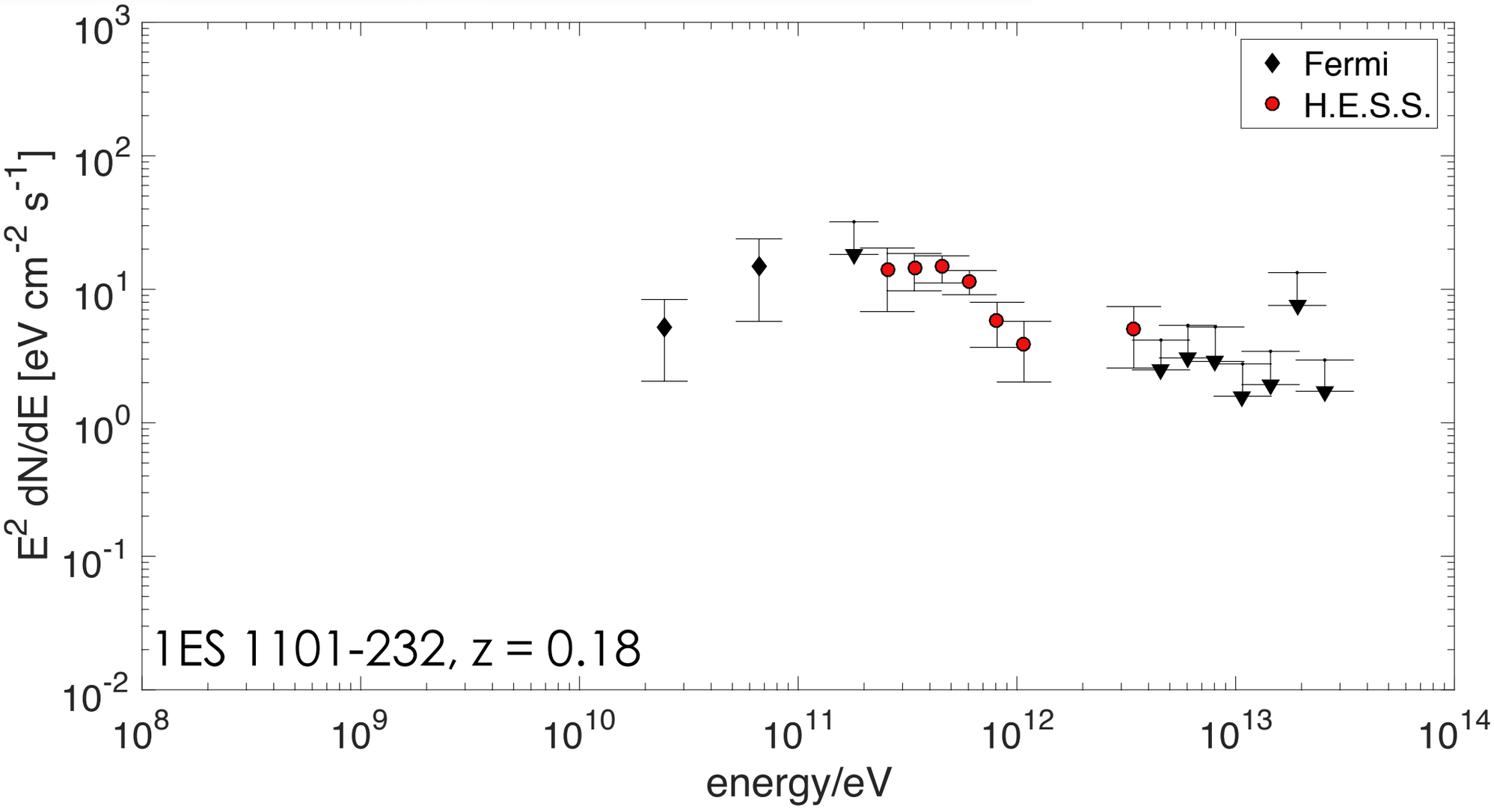
Blazar gamma-ray emission



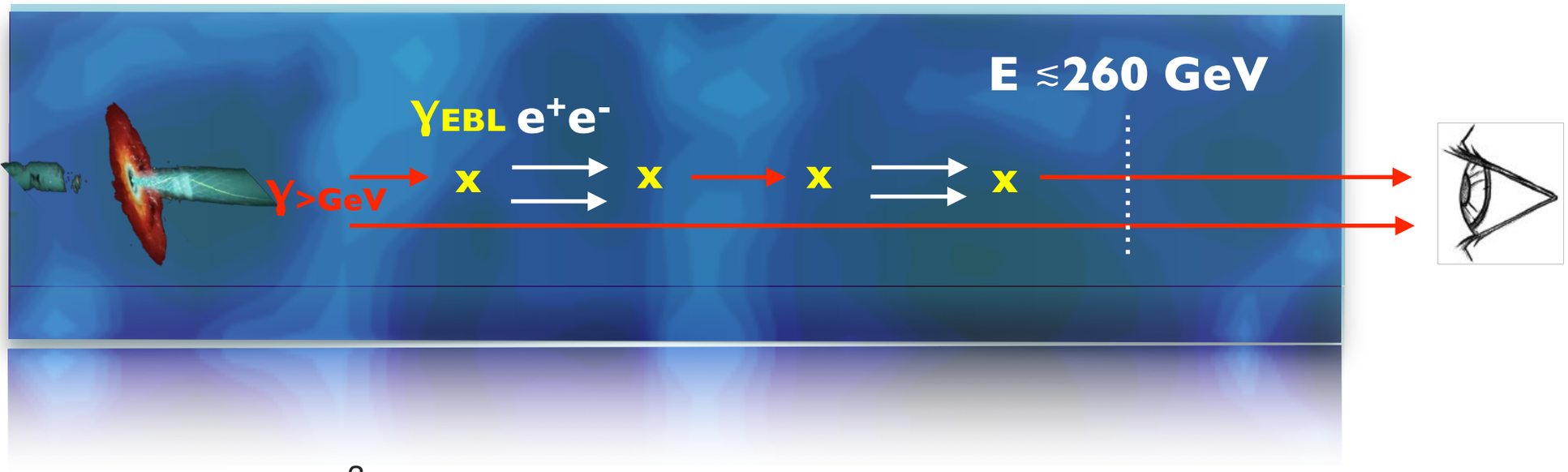


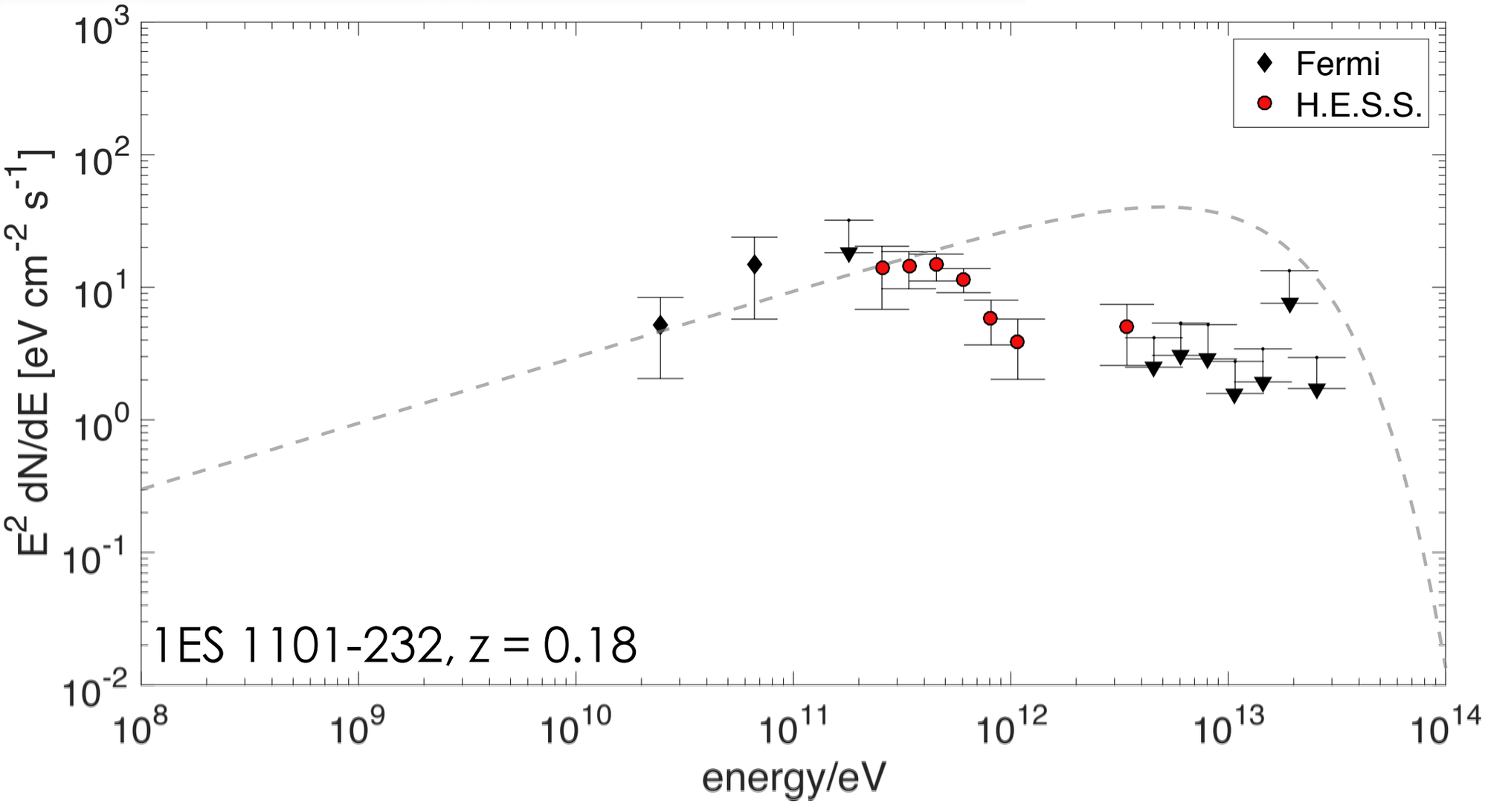
Inverse-Compton echo



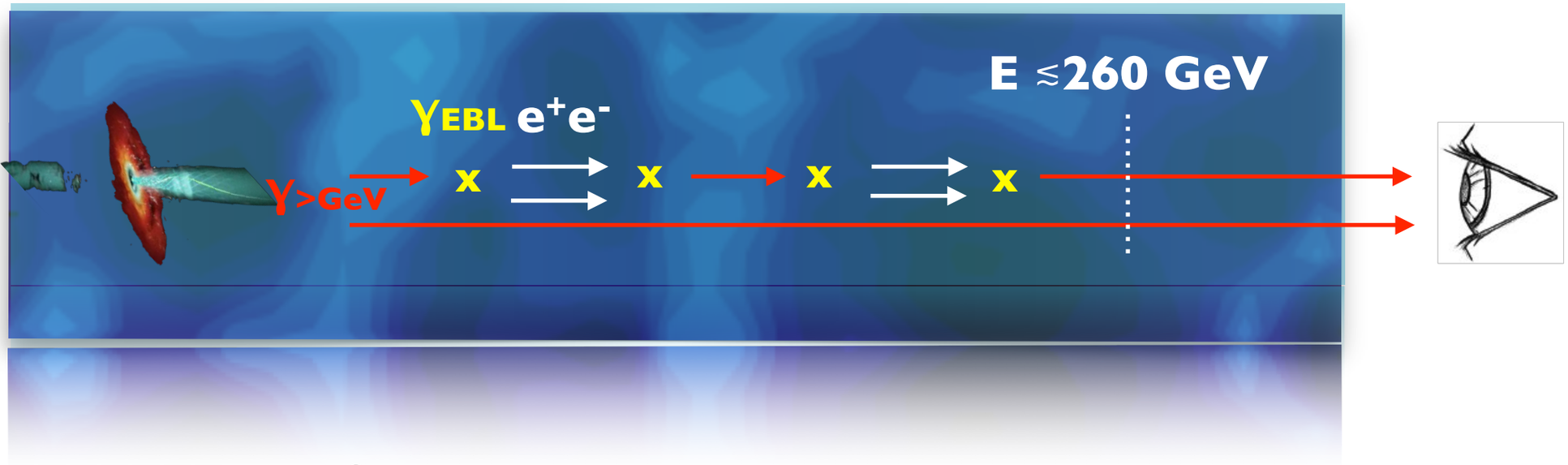


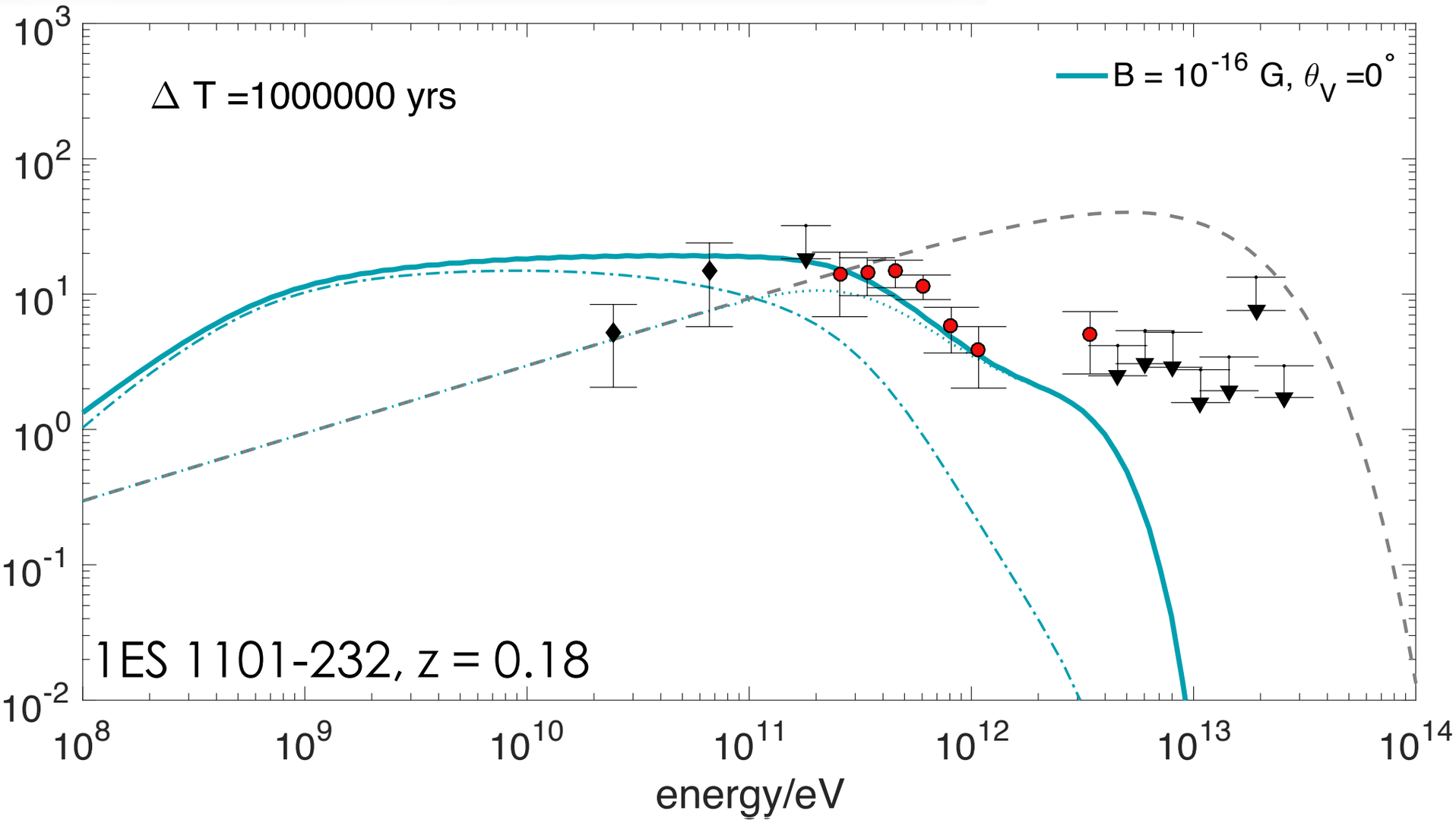
Inverse-Compton echo



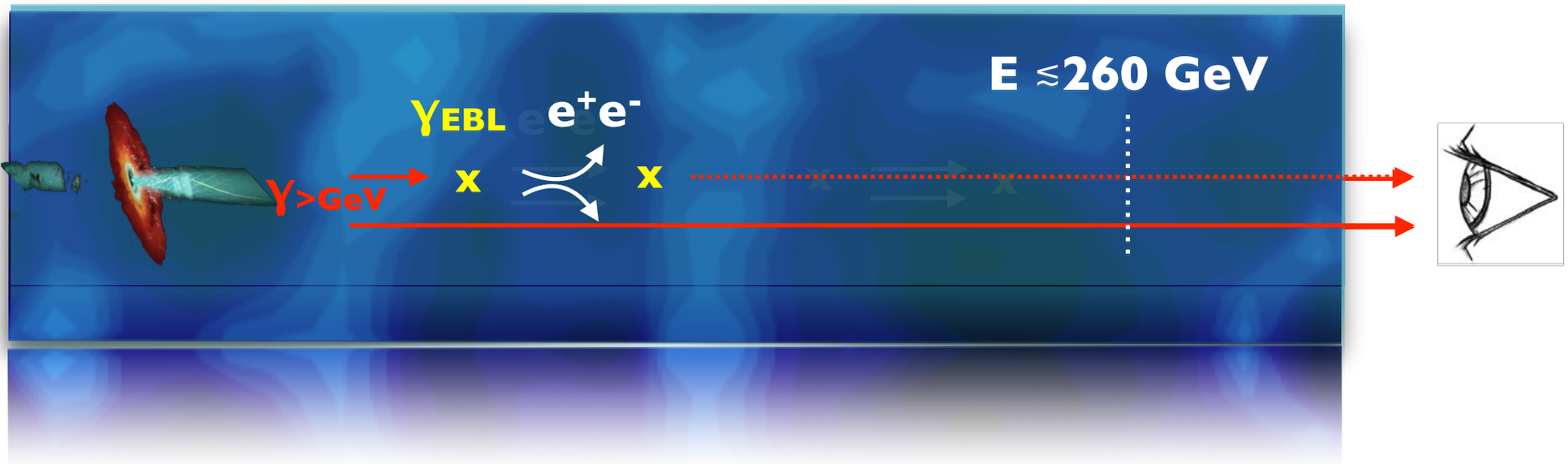


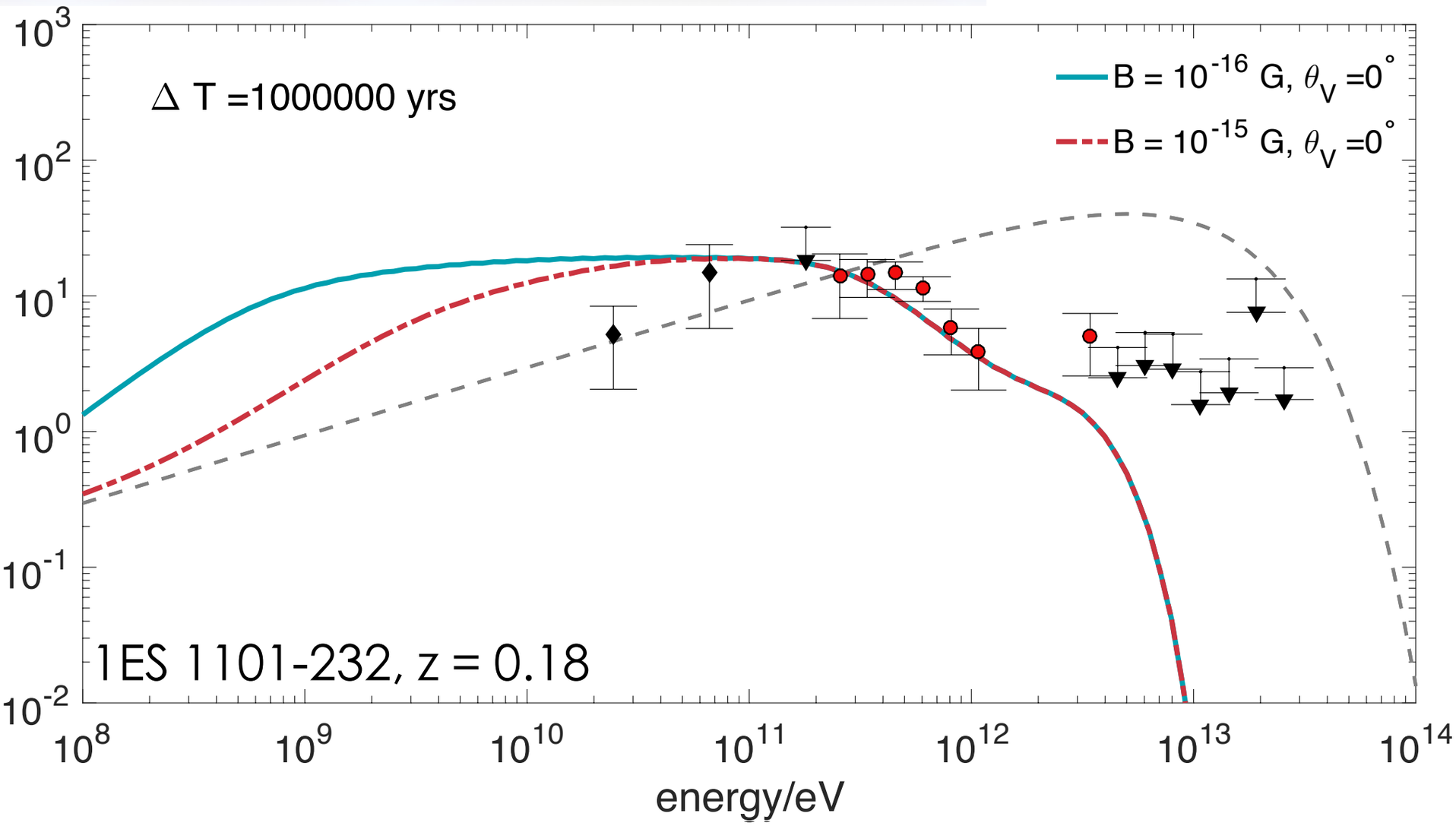
Inverse-Compton echo



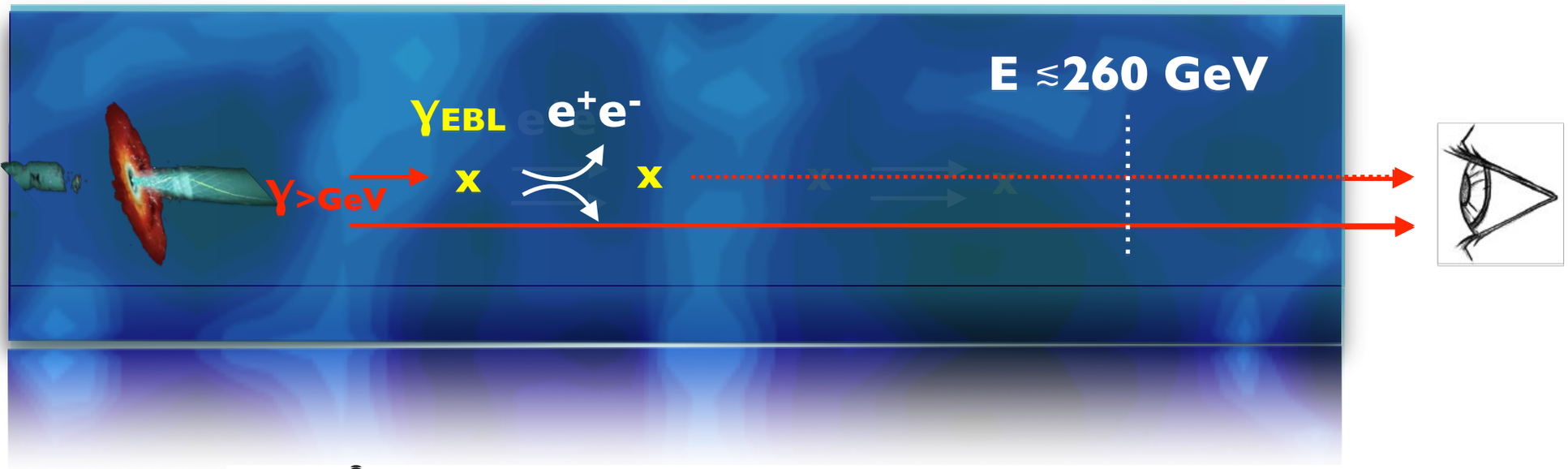


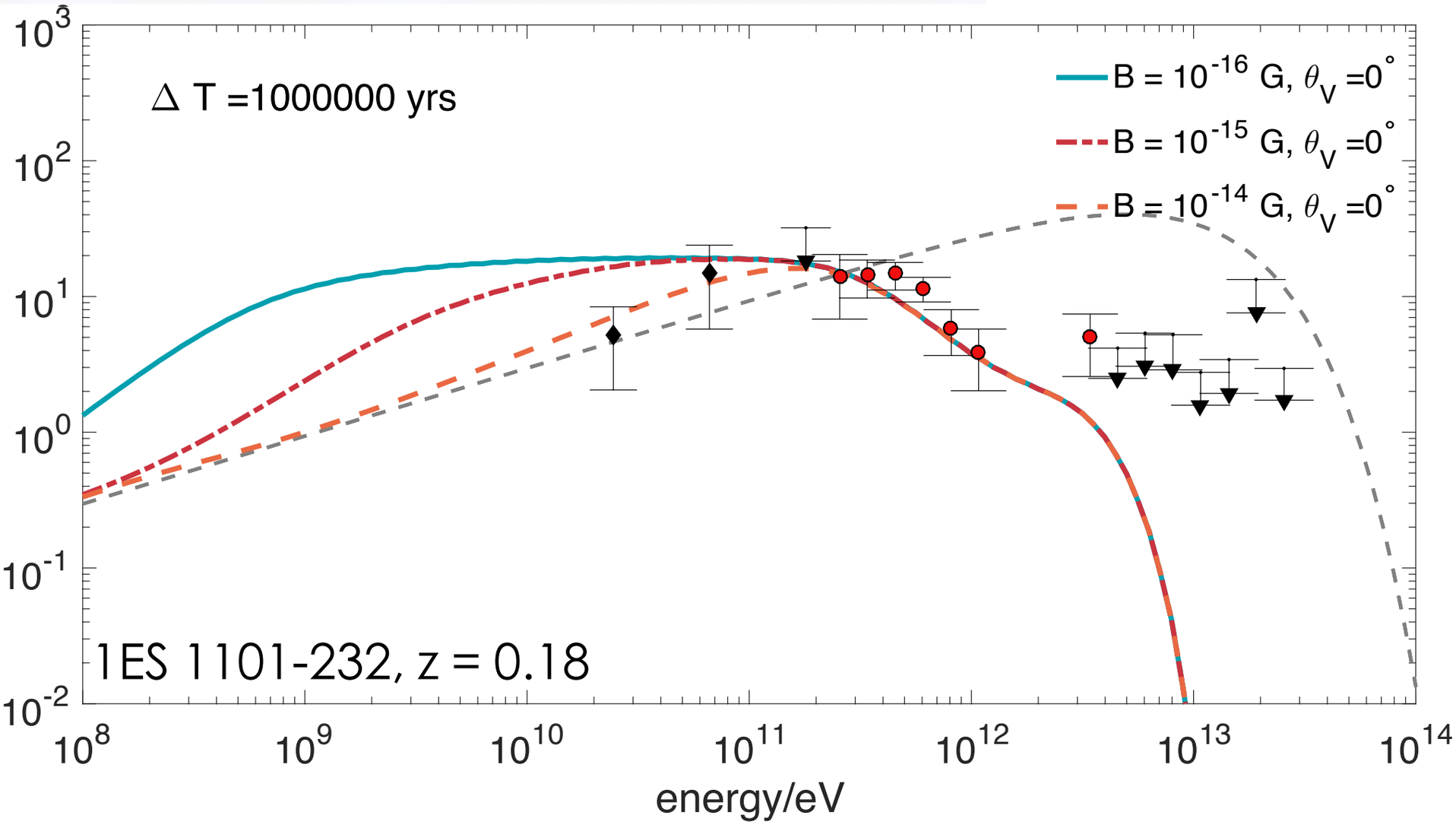
Inverse-Compton echo





Inverse-Compton echo





Formalism

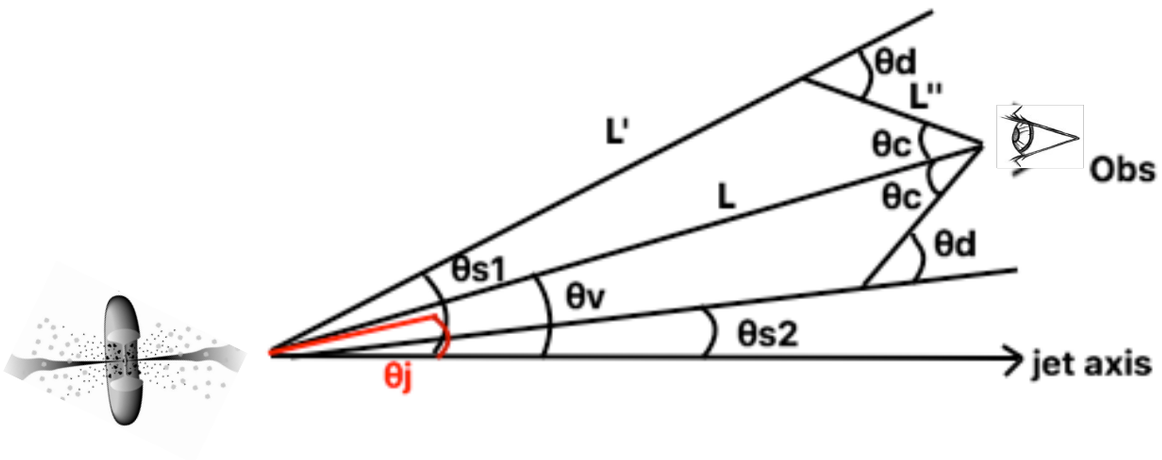
FO, Murase, Kotera, in prep. / PoS(ICRC2017)869

$$\frac{\mathrm{d}N}{\mathrm{d}E\mathrm{d}t} = \int \mathrm{d}\gamma_E \, 2m_e c^2 \; f(\epsilon = 2E_e, \theta_s) \int \mathrm{d}\varepsilon \left(\frac{8\pi\varepsilon^2}{h^3c^3} \frac{1}{e^{\varepsilon/kT(1+z)} - 1} + \frac{\mathrm{d}n_{\mathrm{CIB}}(z)}{\mathrm{d}\varepsilon} \right)$$

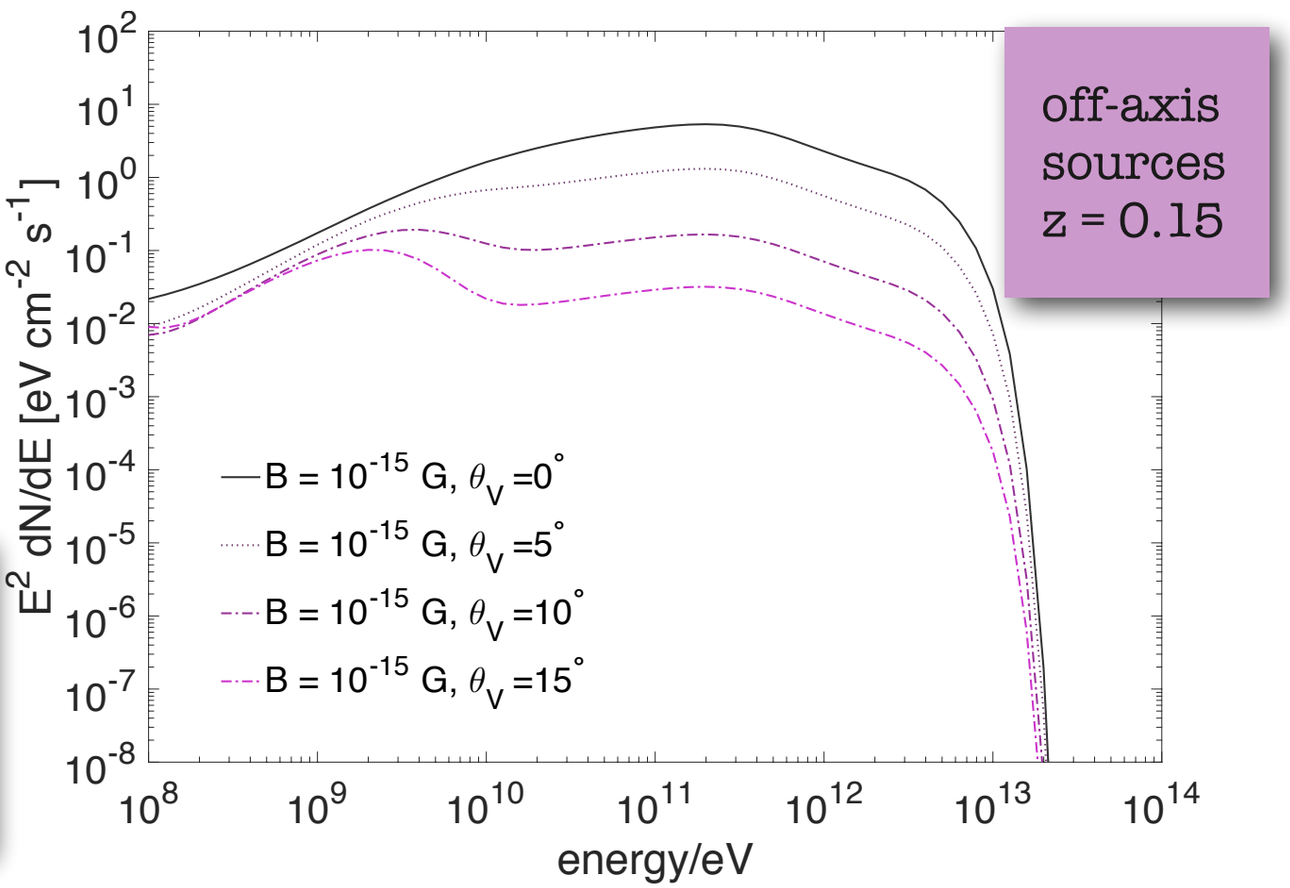
$$\left\langle \frac{\mathrm{d}\sigma_{\mathrm{IC}}}{\mathrm{d}E} c(1-\mu) \right\rangle \int \mathrm{d}\theta_f \sin\theta_f \cdot \int \mathrm{d}L' \frac{e^{-L'/\lambda(\epsilon)}}{\lambda(\epsilon)} \cdot \exp\left(-\sqrt{L^2 + L'^2 - 2LL'\cos(\theta_d - \theta_c - \theta_v)}/\lambda(E)\right)$$

full KN cross-section

on or off-axis jet

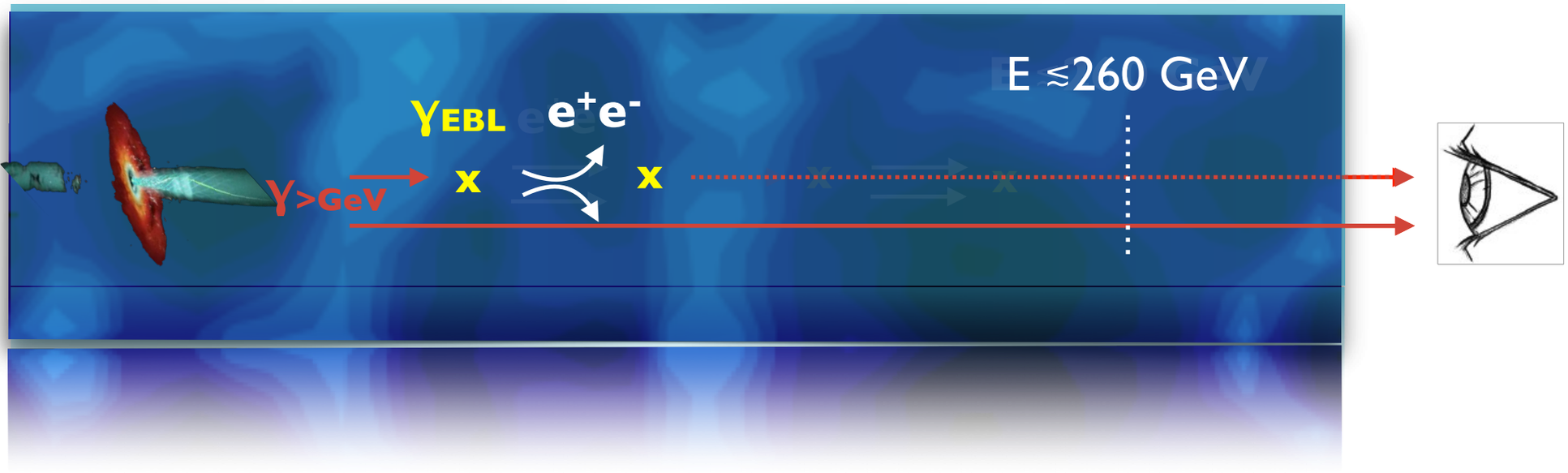


- Fast implementation for Fermi Analysis/ parameter surveys
- Time dependent/exact geometry
- Benchmark with Monte Carlo (ELMAG)

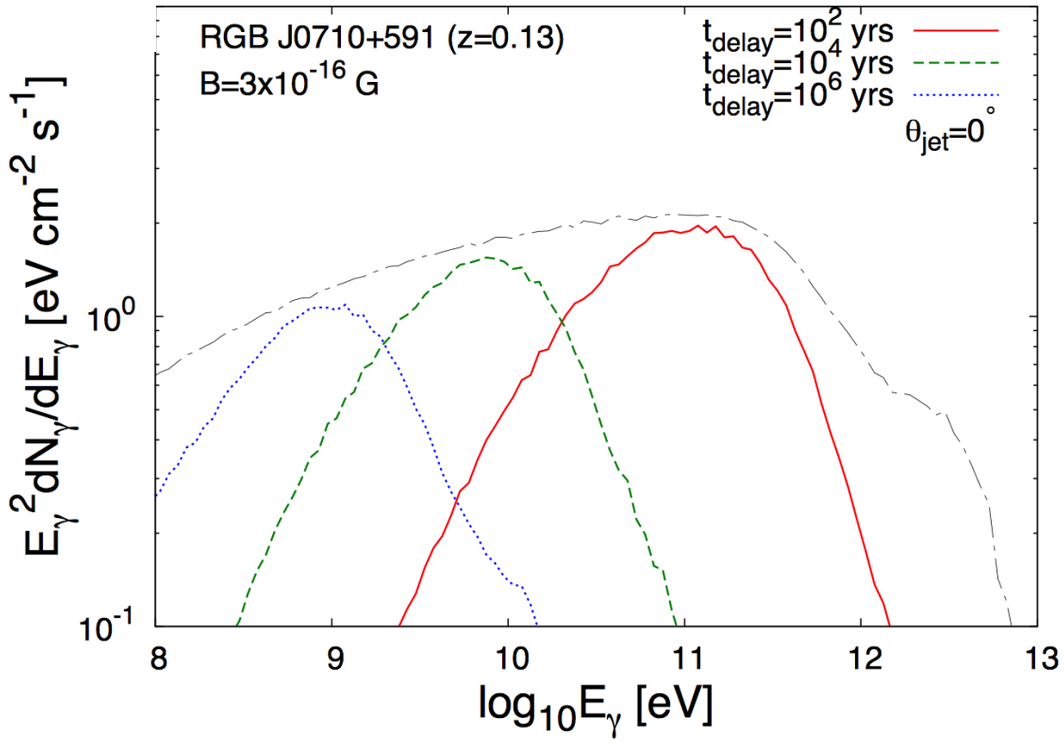


*see also *Neronov & Vovk 2010, Taylor et al 2011, Dermer et al. 2011, Murase et al. 2008, Ichiki et al. 2008, Dolag et al. 2011, Huan et al. 2011*

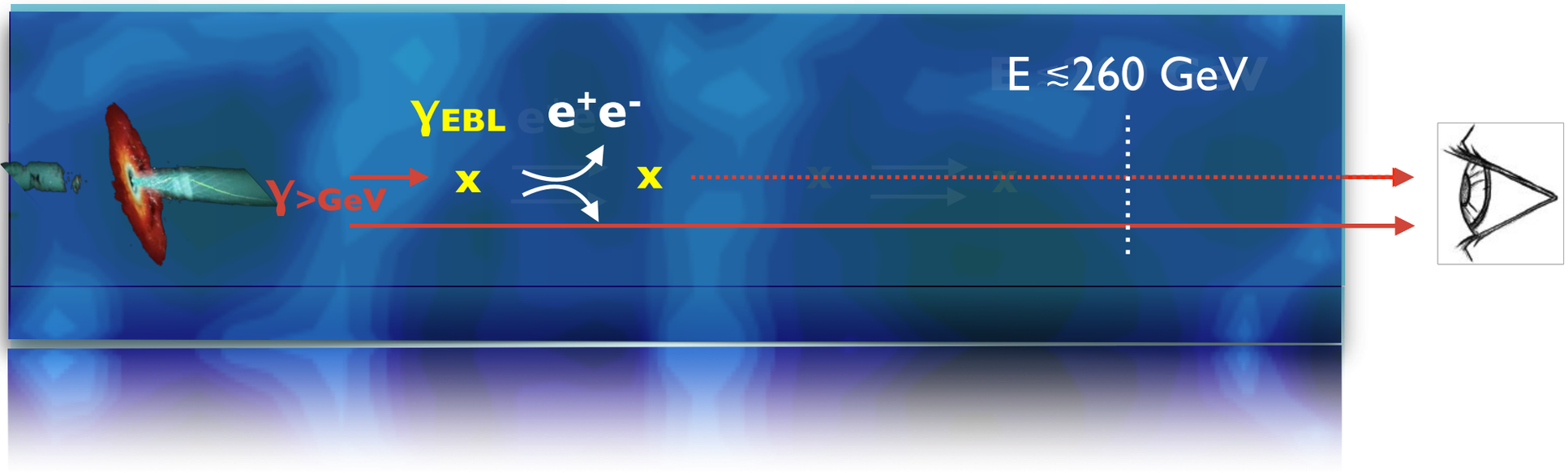
Inverse-Compton Echo-Transient

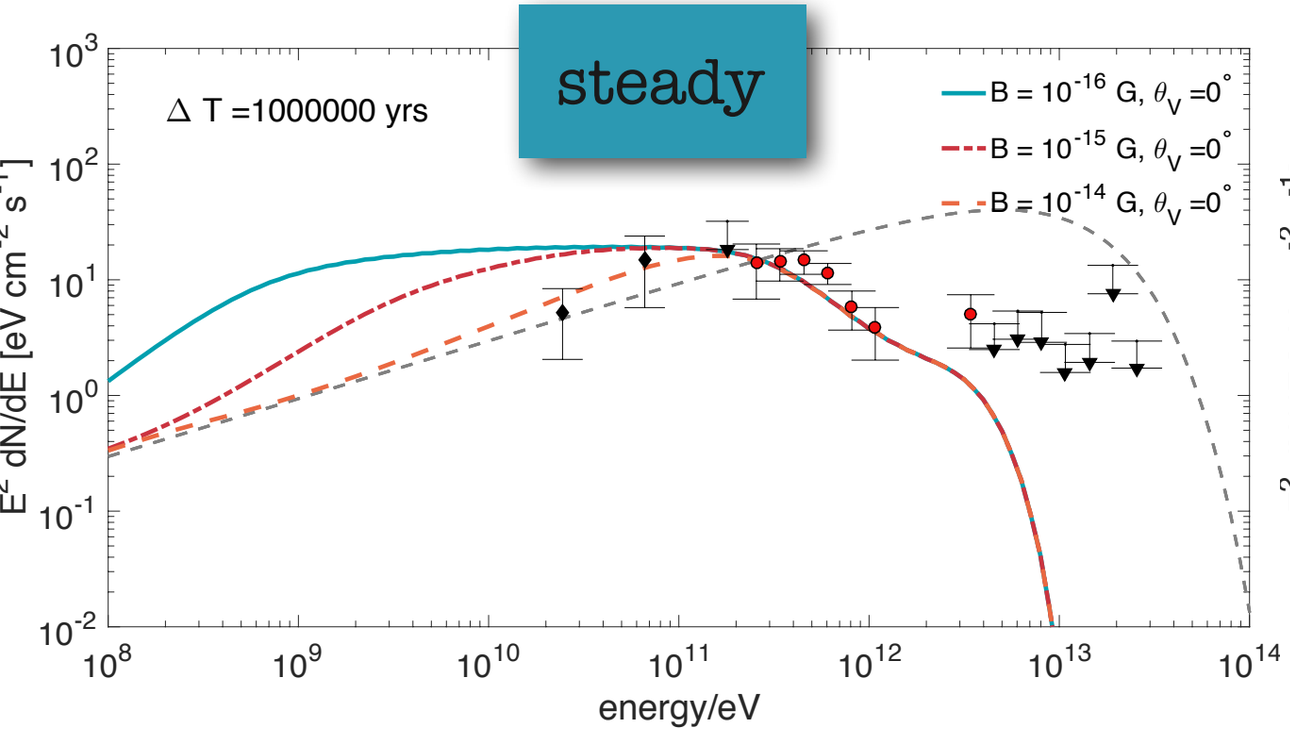


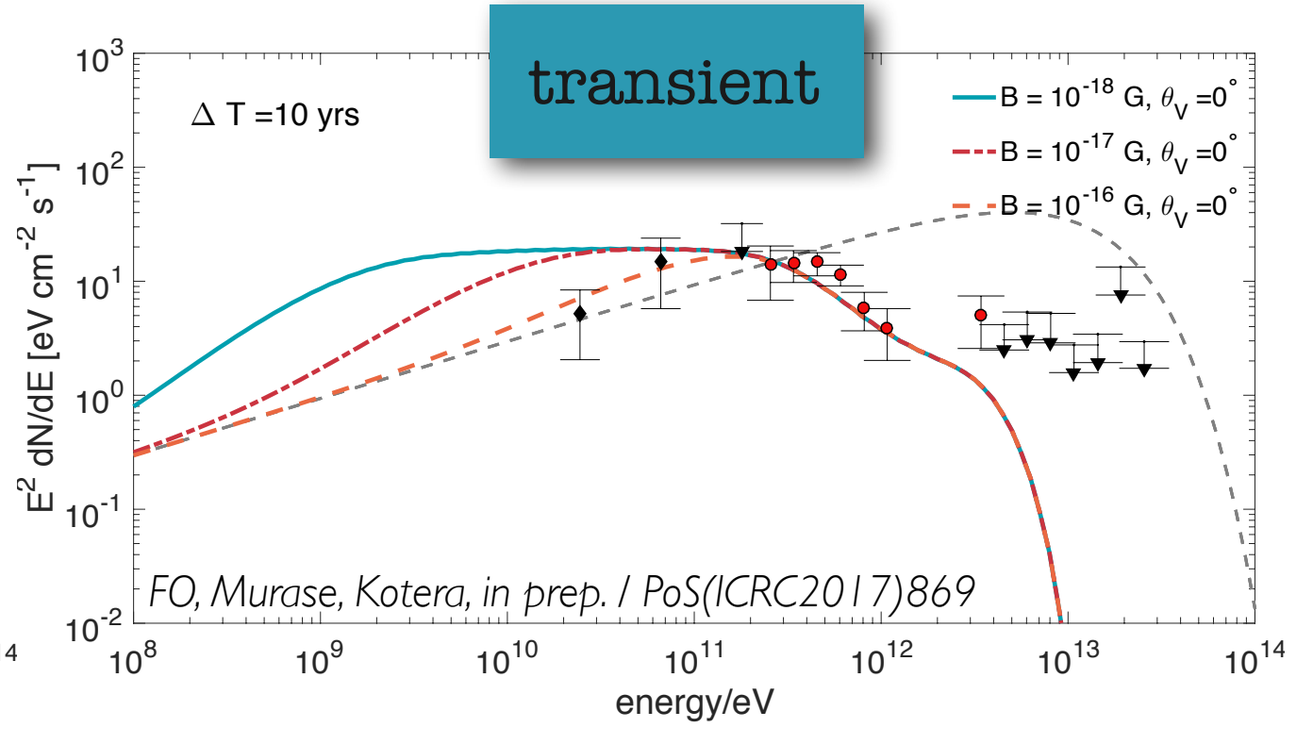
Taylor et al. A&A 529, A144 (2011)



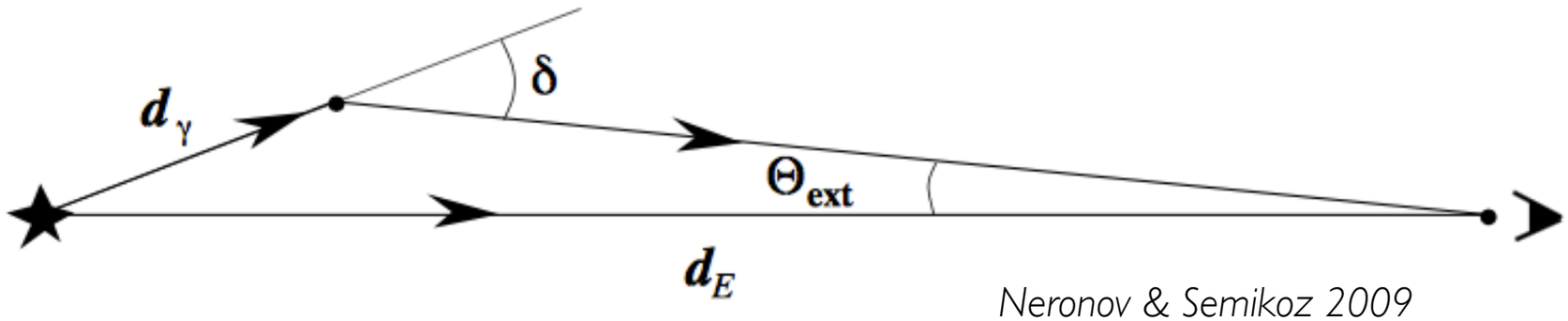
Inverse-Compton Echo-Transient





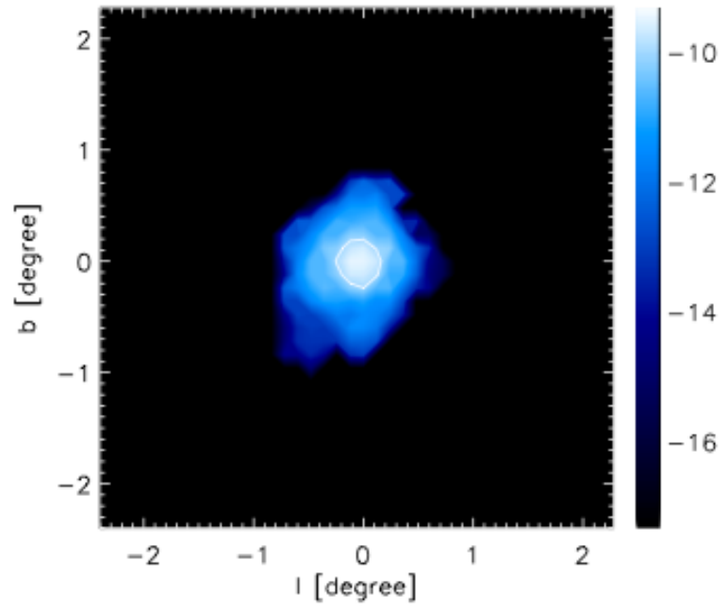


Inverse-Compton pair halo emission

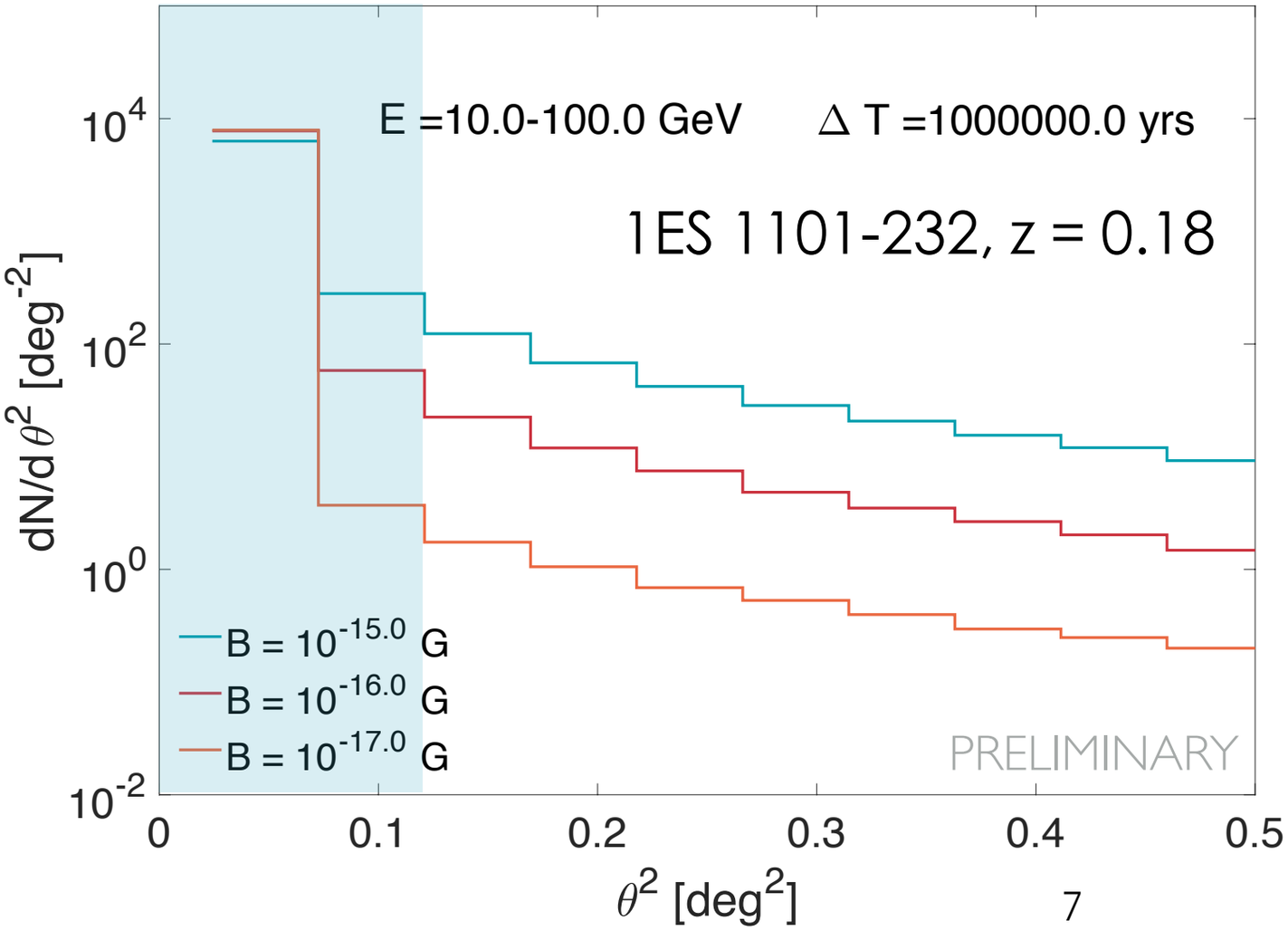


Neronov & Semikoz 2009

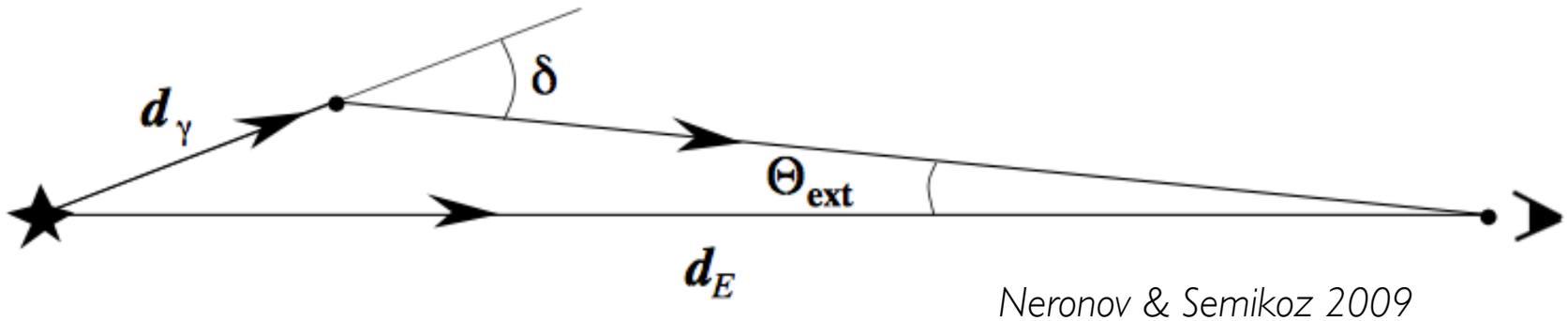
$$\Theta_{\rm ext} \approx 0.5^\circ (1+z)^{-2} \left[\frac{10 \cdot d_\gamma}{d_E}\right] \left[\frac{E_\gamma}{0.1\ {\rm TeV}}\right]^{-1} \left[\frac{B}{10^{-14}\ {\rm G}}\right]$$



Fermi PSF



Inverse-Compton pair halo emission



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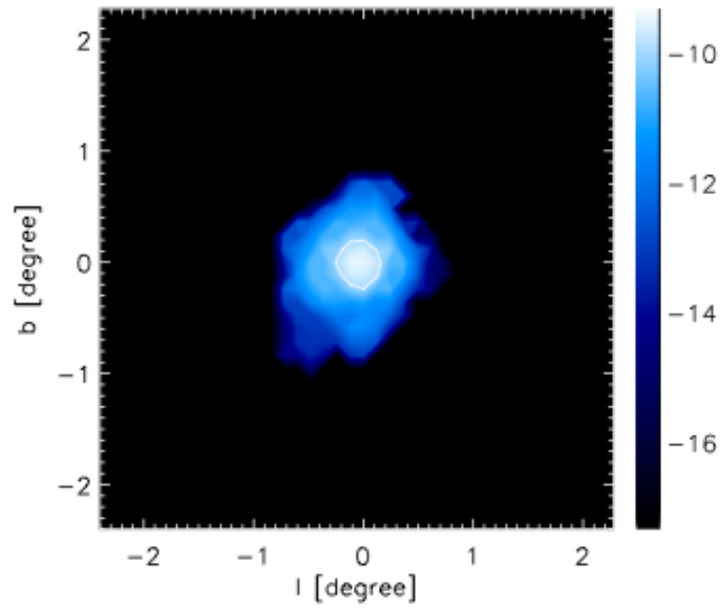

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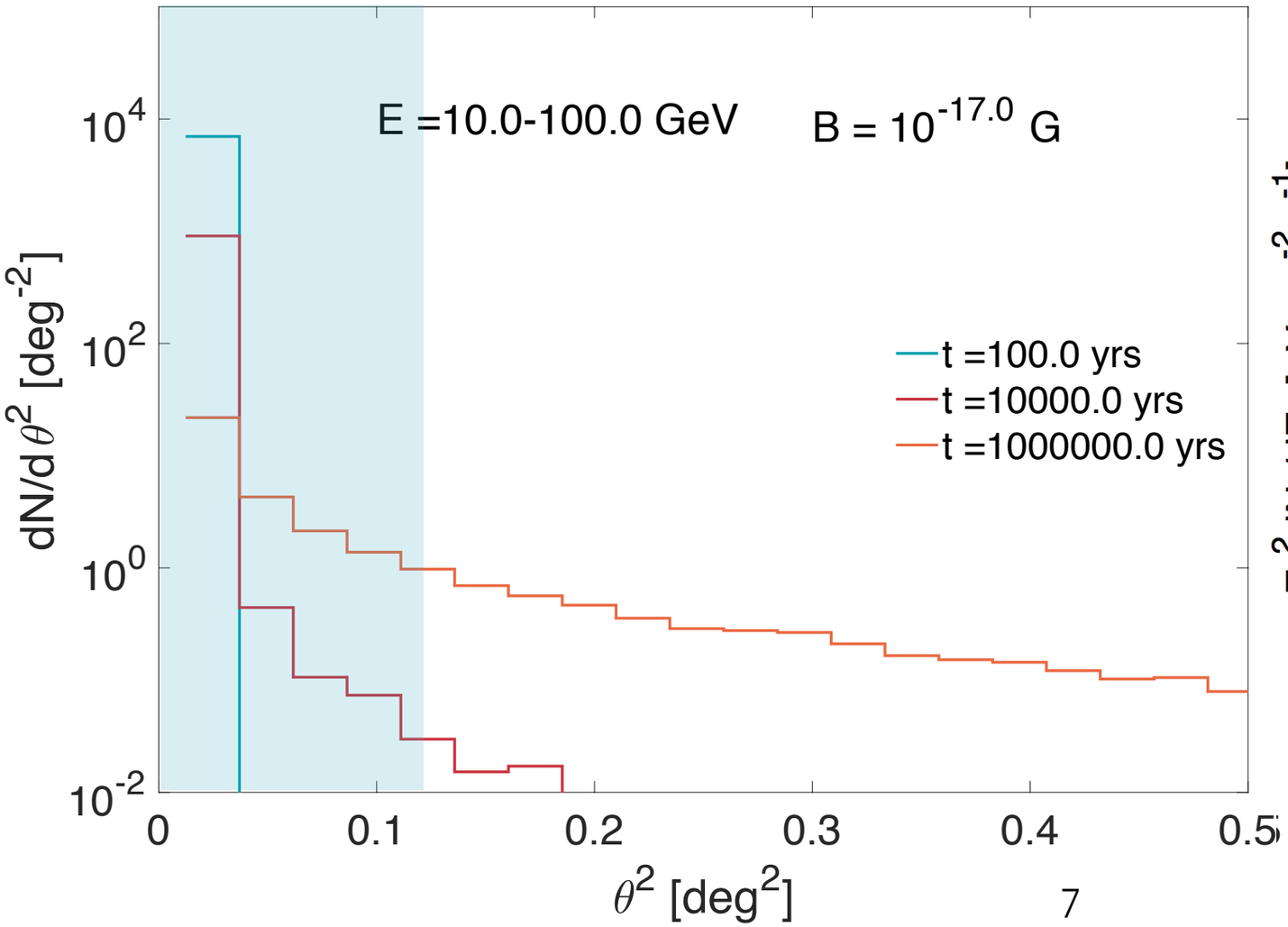
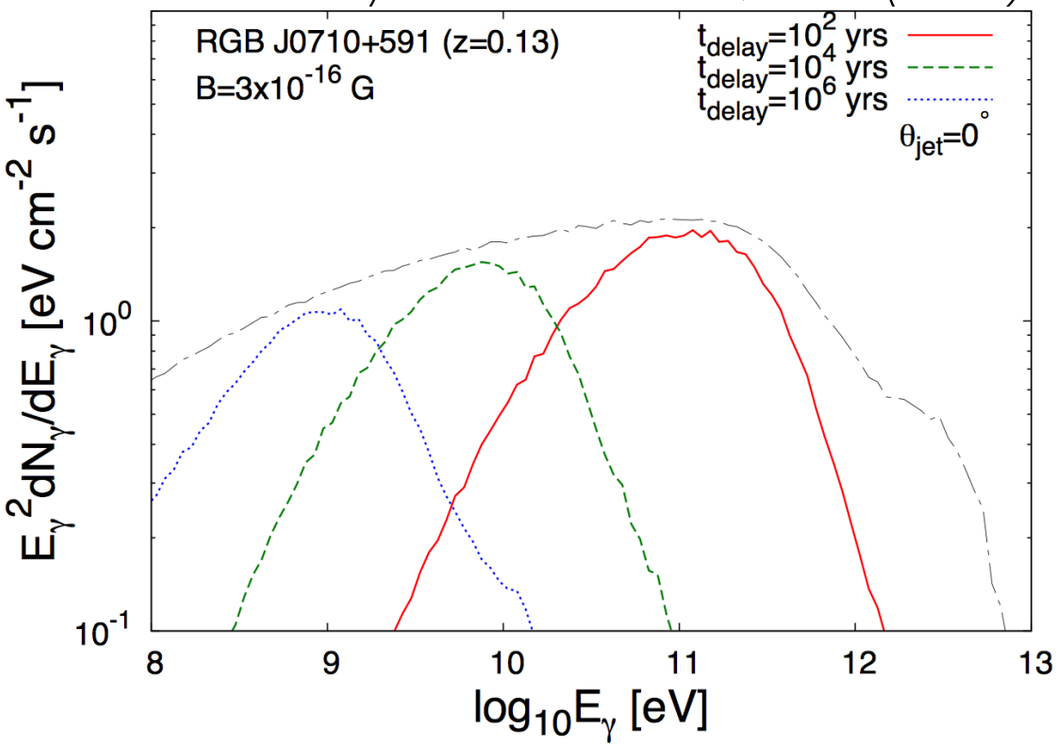
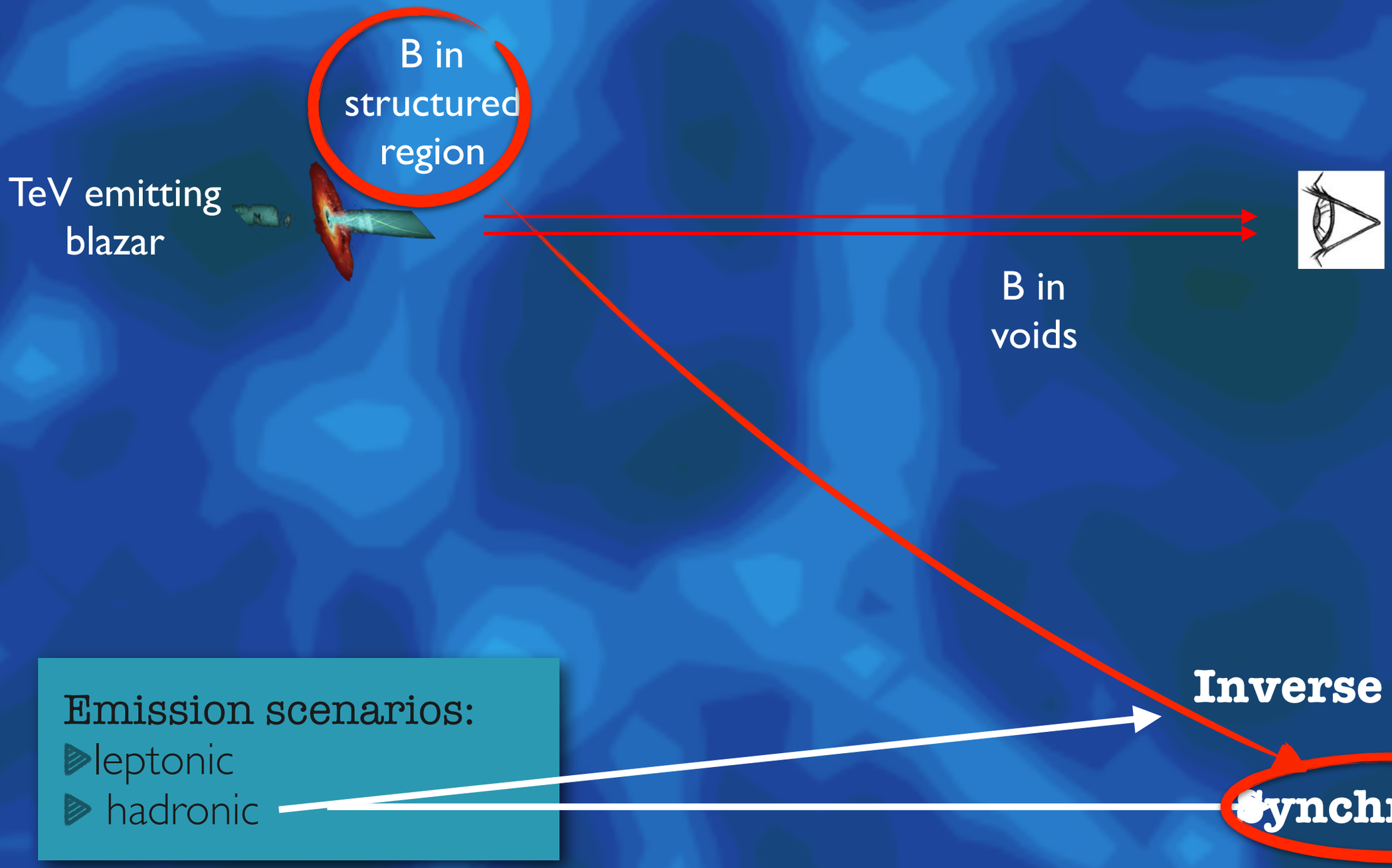


Taylor et al. A&A 529, A144 (2011)

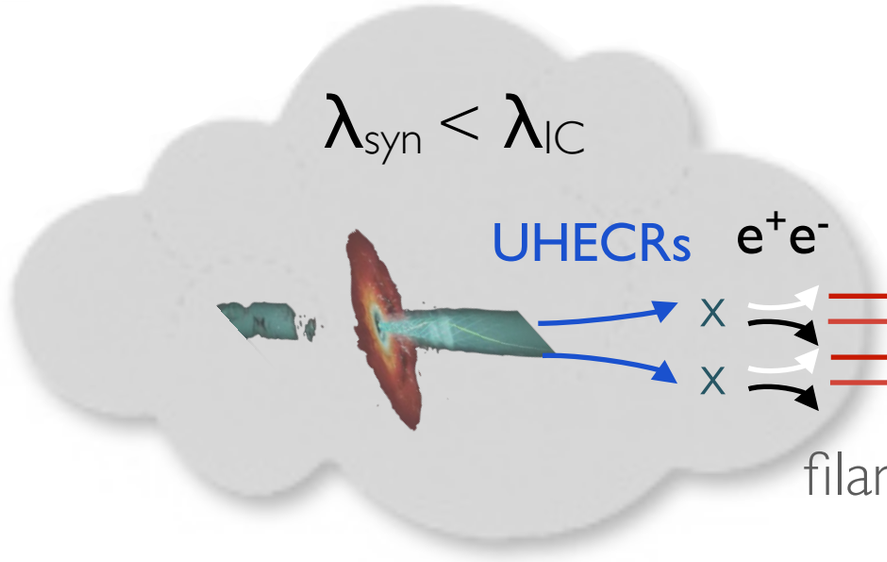




Emission scenarios:

- leptonic
- hadronic

UHECR induced synchrotron pair echo/halo

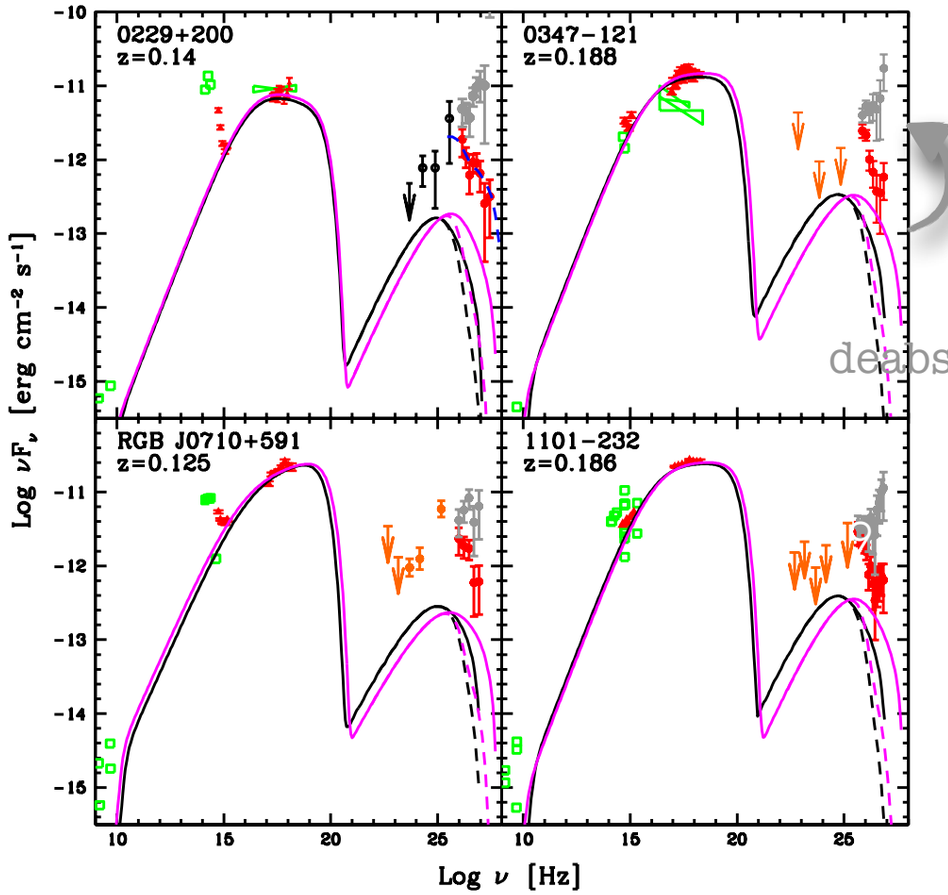


Gabici, Aharonian 2005,7
Kotera, Allard, Lemoine 2011
FO, Murase, Kotera 2014

prompt synchrotron γ-rays

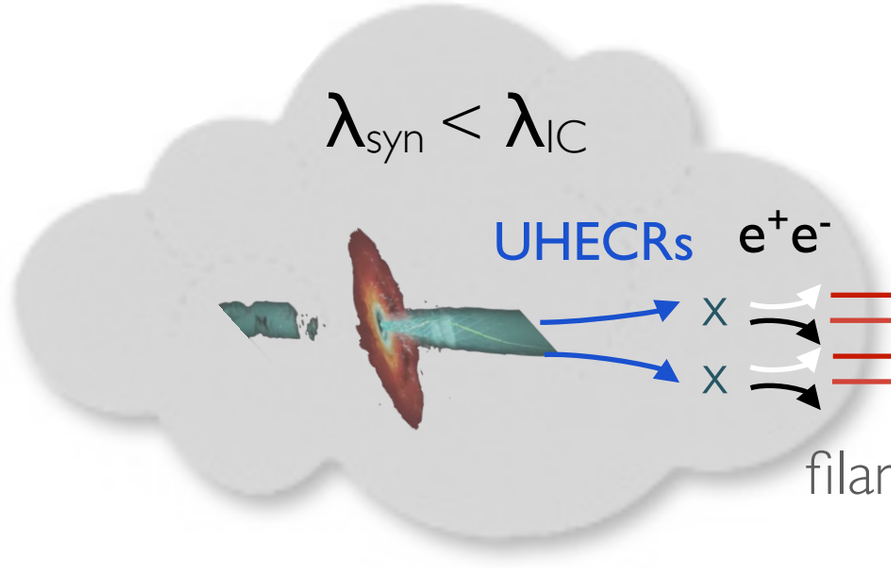
filament/galaxy cluster
B > nG
typically ~few Mpc

Tavecchio 2014

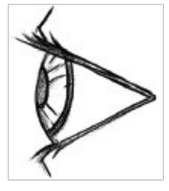


deabsorbed

UHECR induced synchrotron pair echo/halo



prompt synchrotron γ-rays



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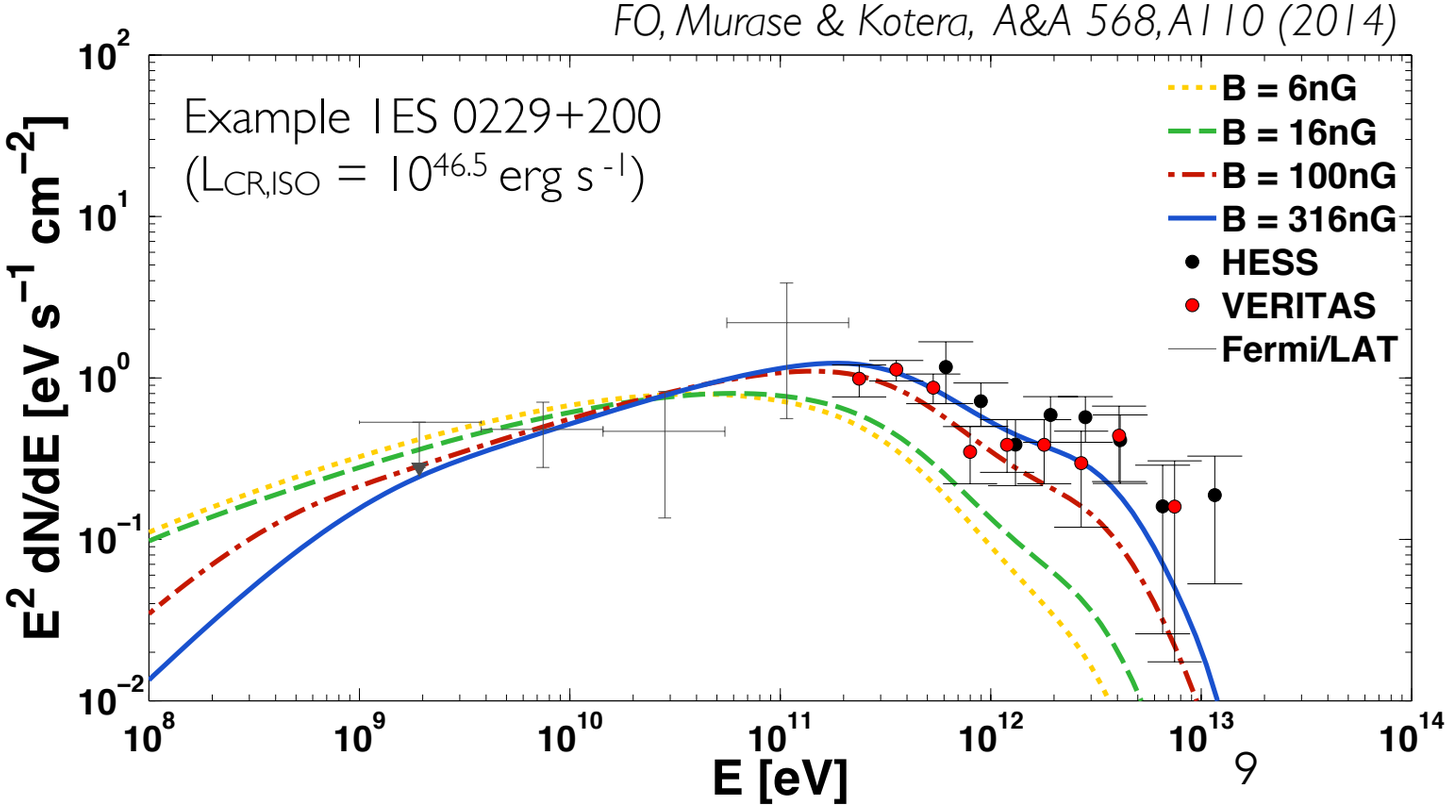
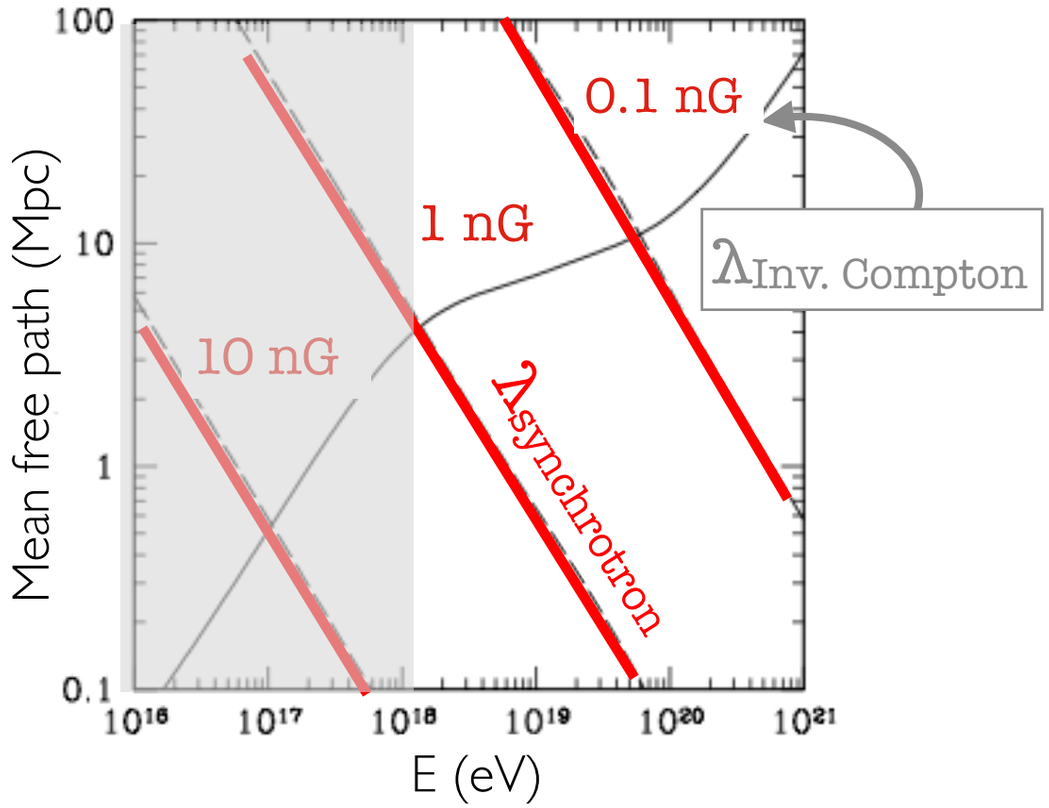
filament/galaxy cluster
B > nG
typically ~few Mpc

$$E_{\gamma,\mathrm{syn}} \sim 68\ \mathrm{GeV} \left(\frac{\mathrm{B}}{10\ \mathrm{nG}}\right) \left(\frac{\mathrm{E_e}}{10^{19}\ \mathrm{eV}}\right)^2$$

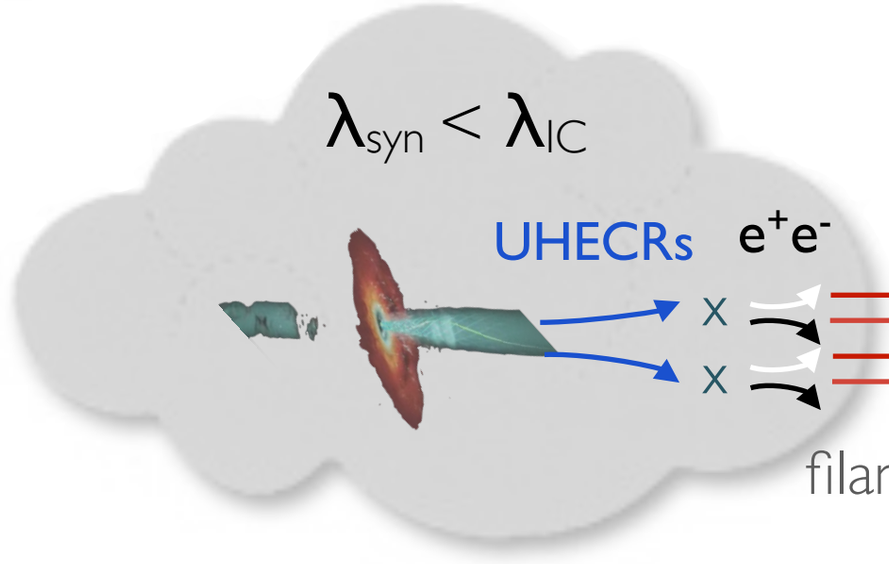
FO, Murase & Kotera, A&A 568, A110 (2014)



Guaranteed when $\lambda_{syn} < \lambda_{IC}$



UHECR induced synchrotron pair echo/halo



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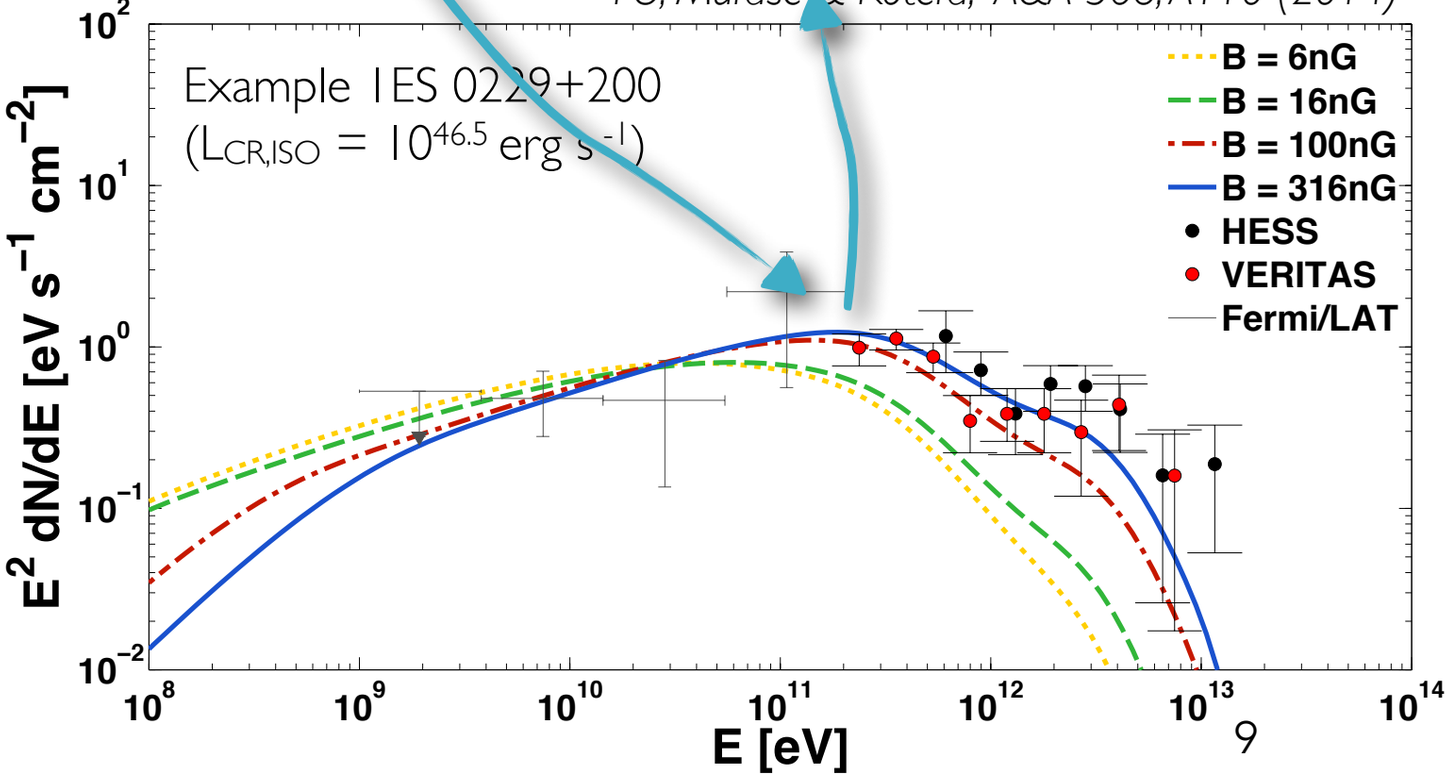

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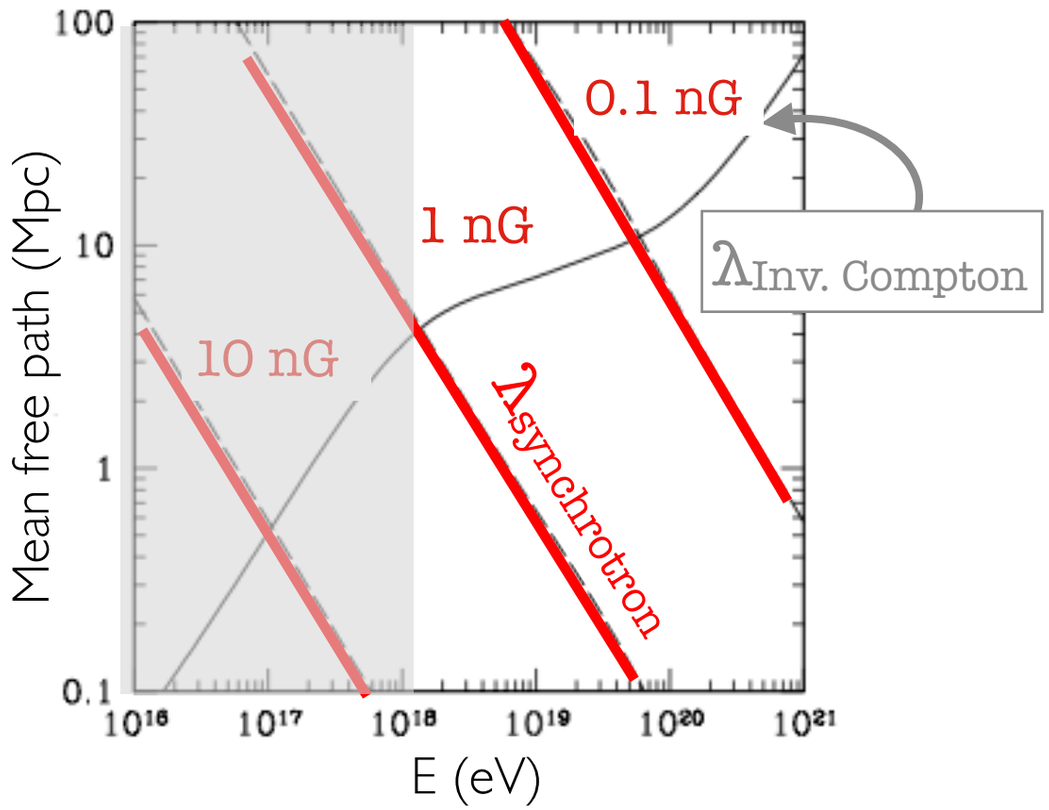


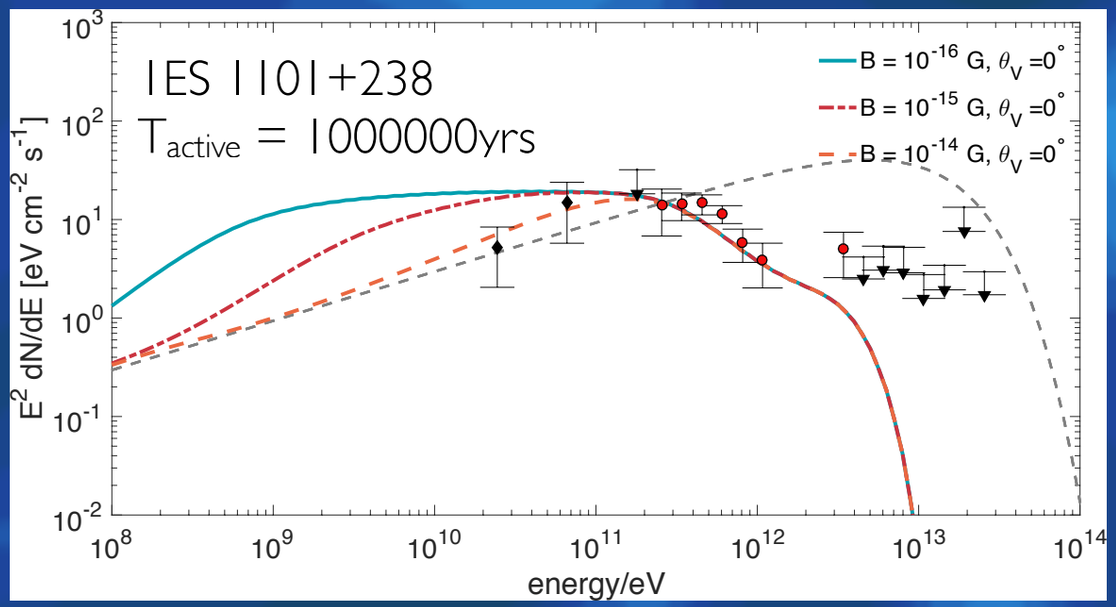
Summary

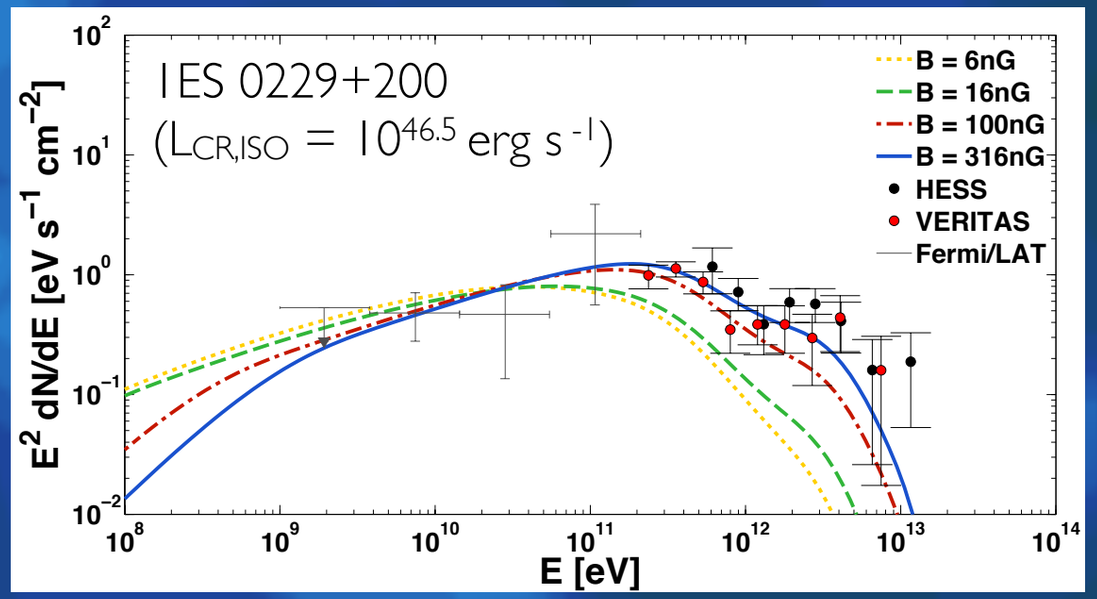
New analytical formalism to constrain EGMF strength with blazar pair-echoes/halos

Treatment of **time-dependent** pair-echo and pair-halo emission (transient sources) and **off-axis emission** (radio galaxies)

Fast implementation/Fermi-LAT parameter surveys

Synchrotron emission by UHECRs can explain hard-spectrum ultra-high energy peaked blazars (UHBLs) and probes MF strength in structured regions

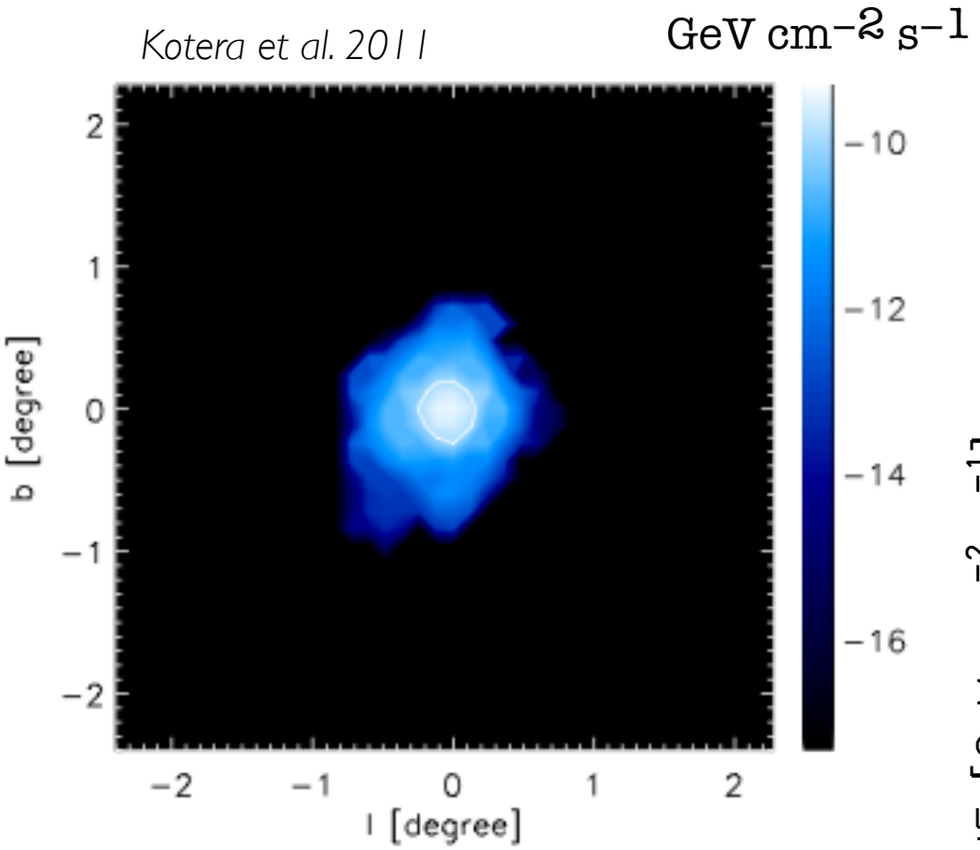




UHECR induced synchrotron pair echo/halo

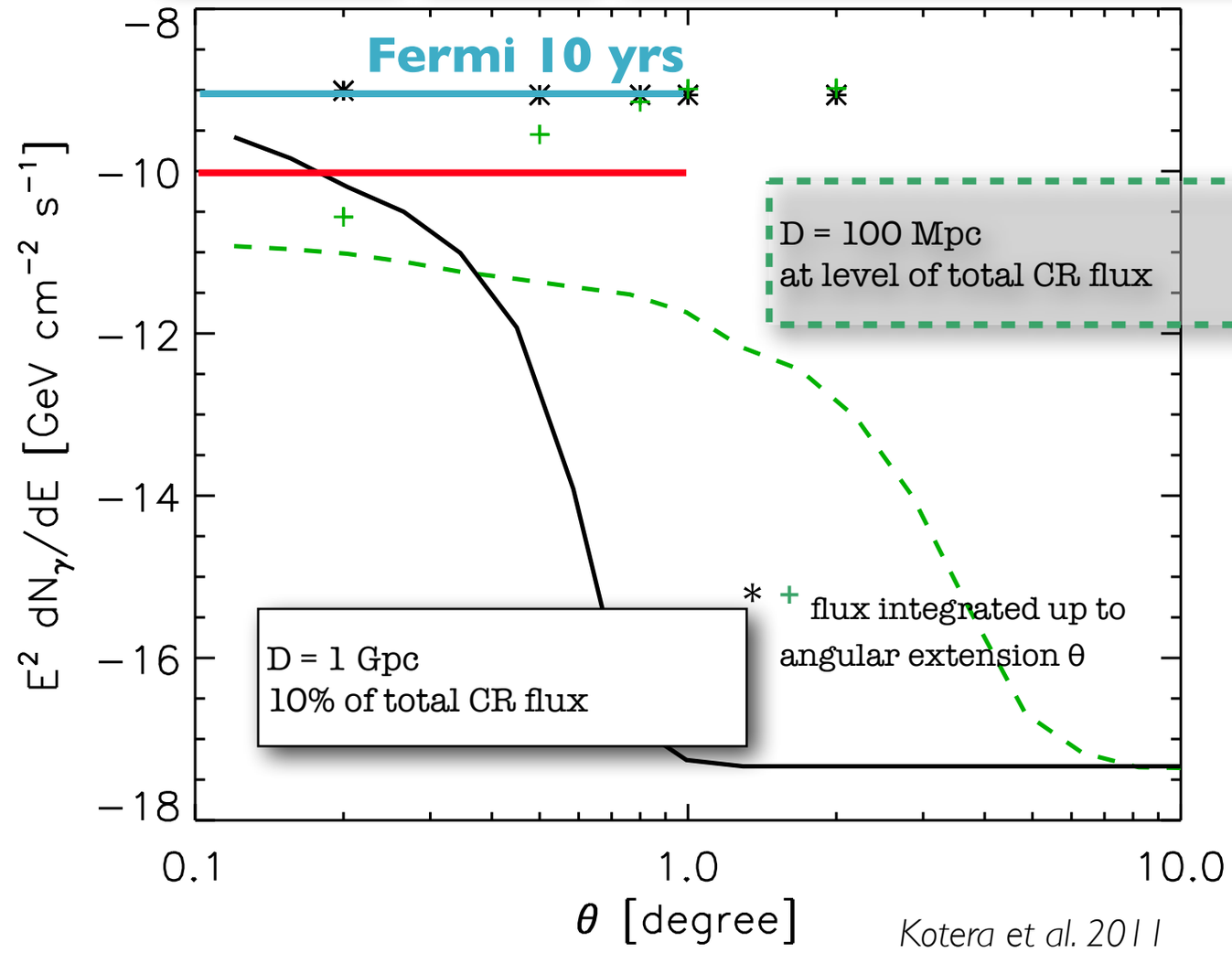
*sensitive to EGMFs in structured regions

Kotera et al. 2011



D = 1 Gpc
B = 1 nG
Eγ = 1–100 GeV
$L_{CR,19} = 10^{46}$ erg s−1

assuming CTA at 10 GeV:
~ 10^{-10} GeV cm^{-2} s^{-1} (θ_{source} /1°)



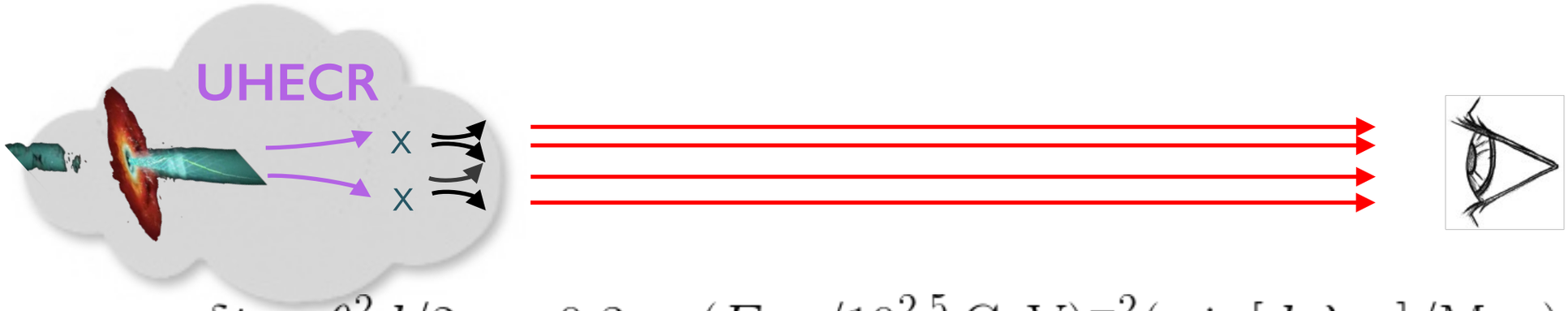
Kotera et al. 2011

Back-up: UHECRs vs. UHE neutrals

FO, Murase & Kotera, 2017 [PoS(ICRC2017)869]

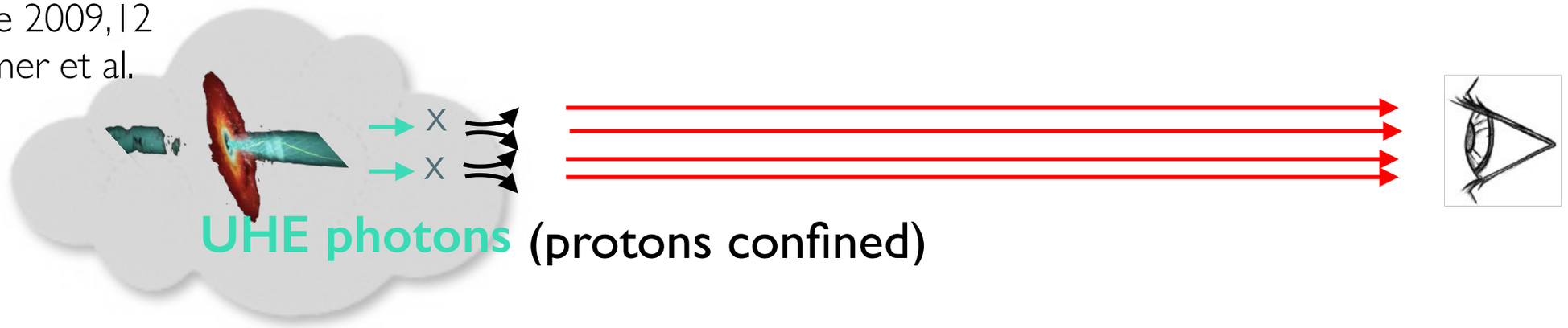
*sensitive to EGMFs in structured regions

$$\delta t \sim \theta_p^2 d/2c \sim 1.6 \times 10^3 \text{ yr } (B/10 \text{ nG})(\lambda_{\rm coh}/d)(d/\text{Mpc})^3(E/10^{20} \text{ eV})^{-2}$$



$$\delta t \sim \theta_e^2 d/2c \sim 0.3 \text{ yr } (E_{\rm syn}/10^{2.5} \text{ GeV})^{-2}(\min[d, \lambda_{\gamma\gamma}]/\text{Mpc})$$

Murase 2009,12
Dermer et al.



UHE photons (protons confined)

Back-up: UHECRs vs. UHE neutrals

FO, Murase & Kotera, 2017 [PoS(ICRC2017)869]

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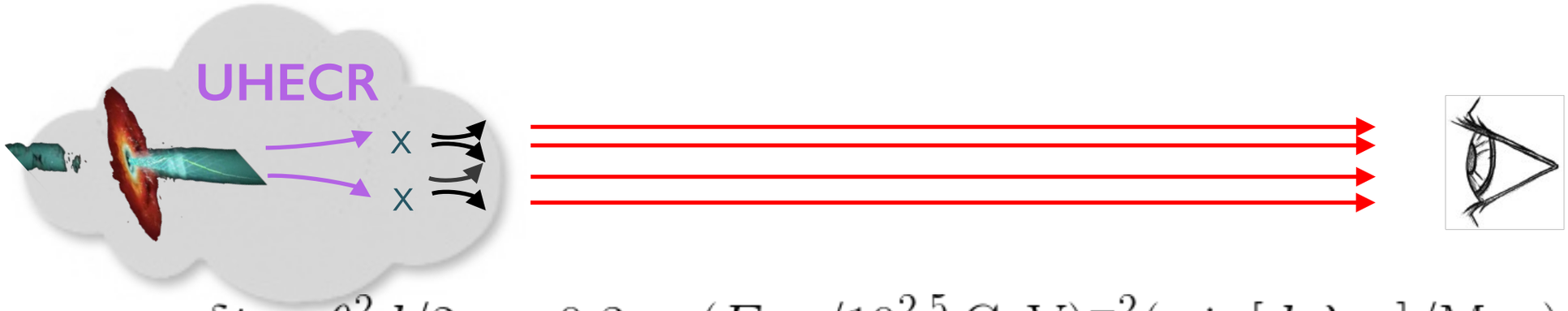
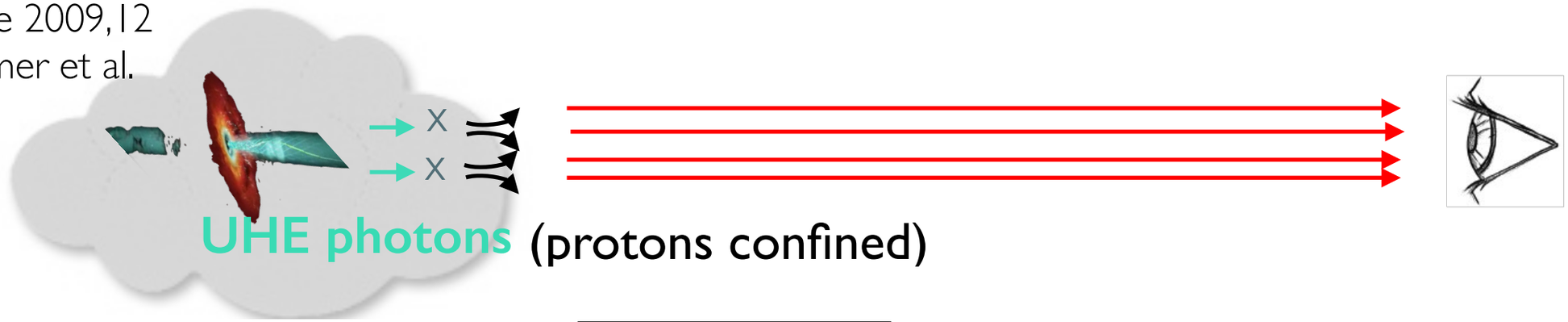
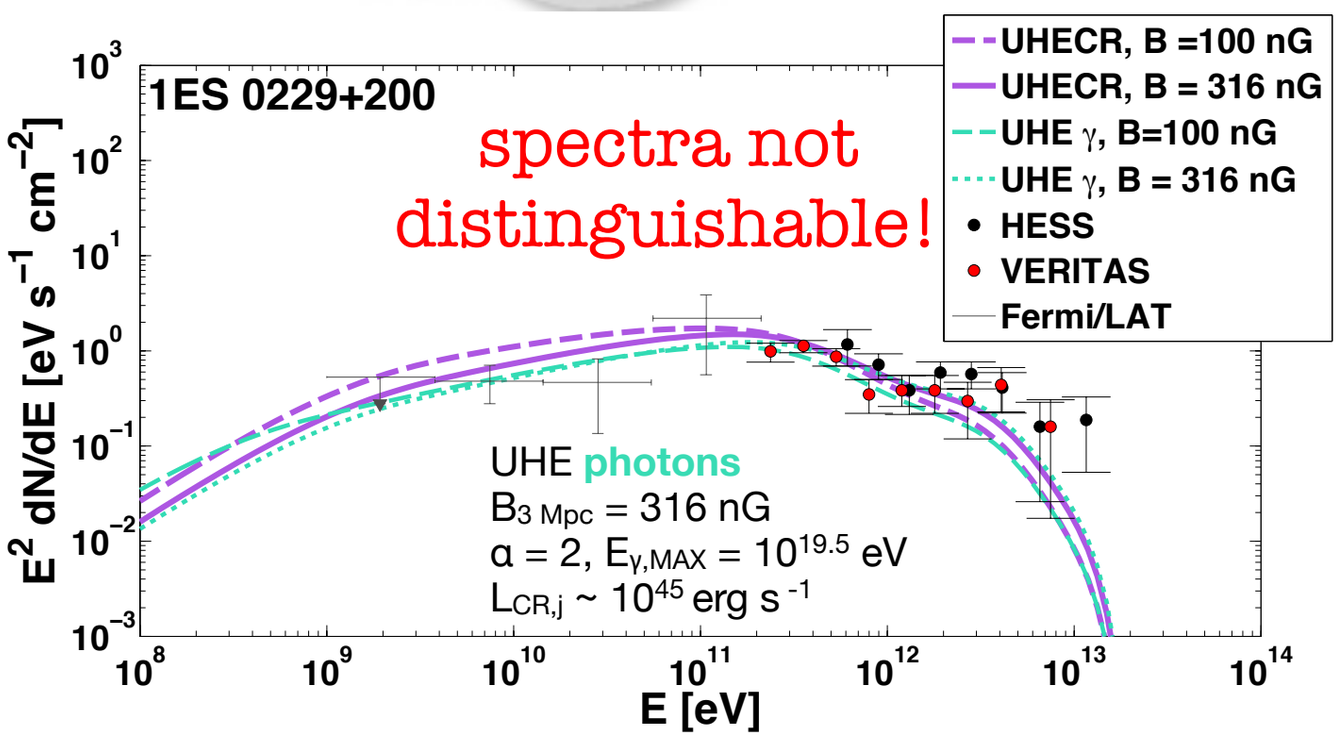


$$\delta t \sim \theta_e^2 d/2c \sim 0.3 \text{ yr } (E_{\rm syn}/10^{2.5} \text{ GeV})^{-2}(\min[d, \lambda_{\gamma\gamma}]/\text{Mpc})$$

Murase 2009,12
Dermer et al.





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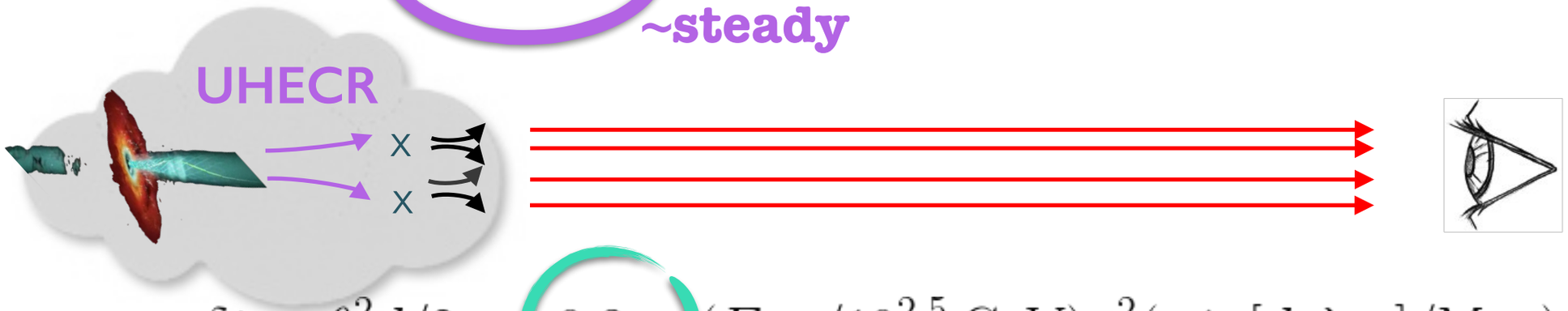
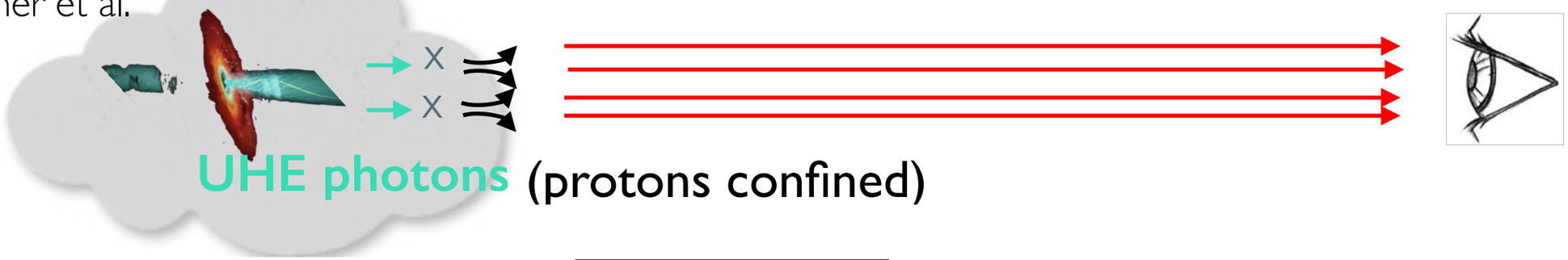
$$\delta t \sim \theta_p^2 d/2c \sim 1.6\times10^3\ \mathrm{yr}\,(B/10\ \mathrm{nG})(\lambda_{\rm coh}/d)(d/\mathrm{Mpc})^3(E/10^{20}\ \mathrm{eV})^{-2}$$

~steady

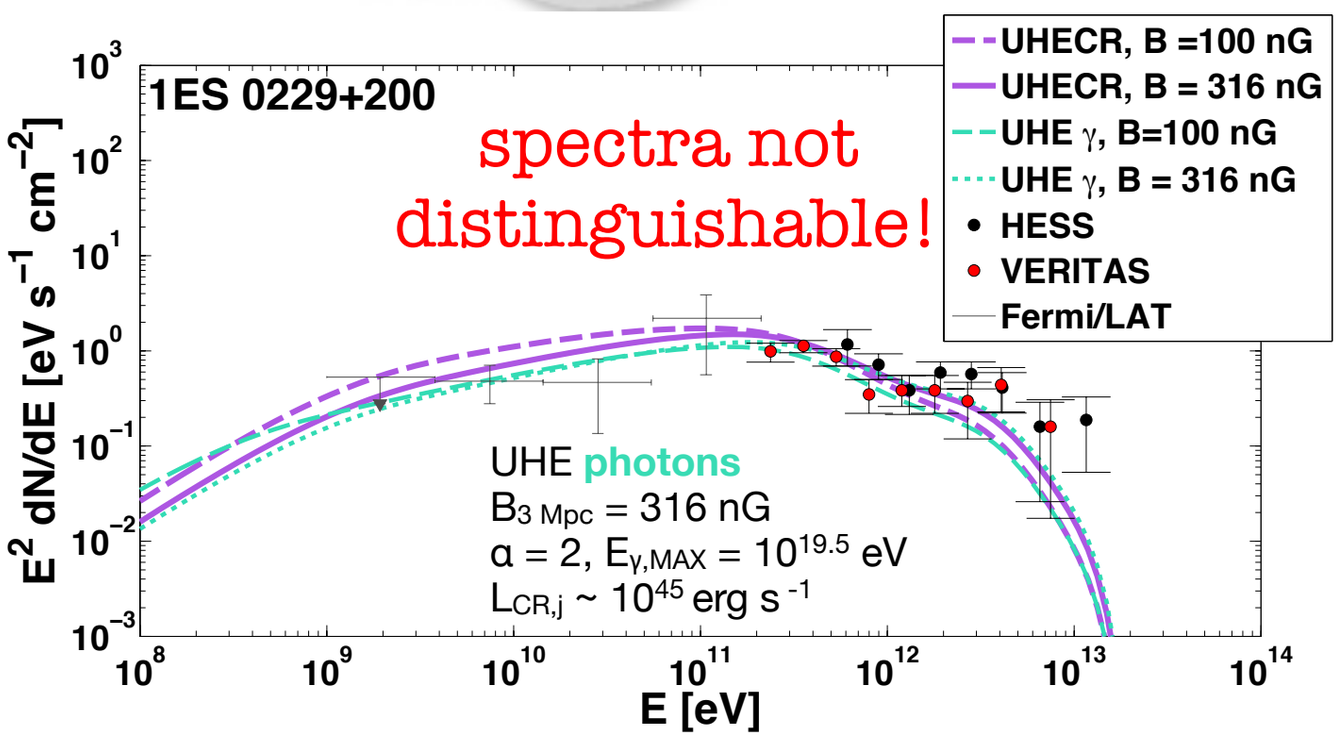


$$\delta t \sim \theta_e^2 d/2c \sim 0.3\,\mathrm{yr}\,(E_{\rm syn}/10^{2.5}\ \mathrm{GeV})^{-2}(\min[d,\lambda_{\gamma\gamma}]/\mathrm{Mpc})$$

Murase 2009,12
Dermer et al.



UHE photons (protons confined)



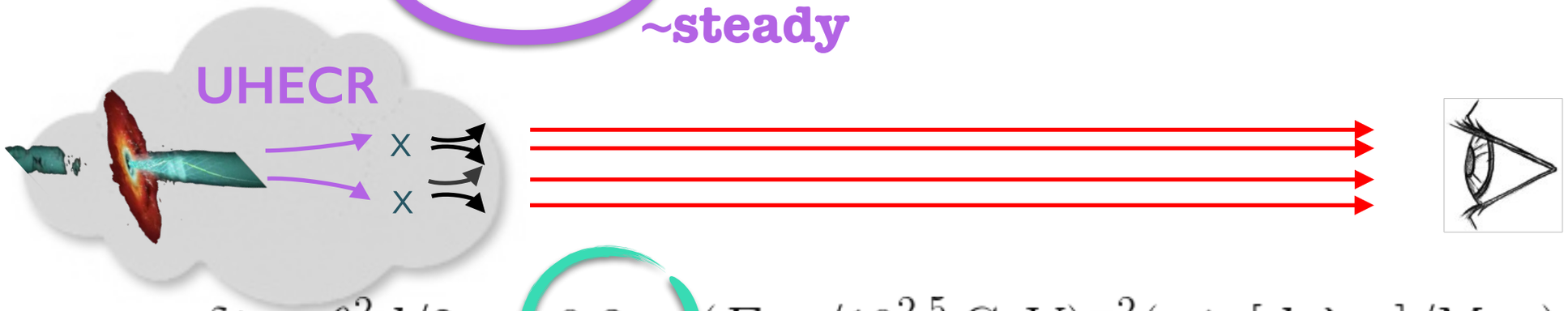
Back-up: UHECRs vs. UHE neutrals

FO, Murase & Kotera, 2017 [PoS(ICRC2017)869]

*sensitive to EGMFs in structured regions

$$\delta t \sim \theta_p^2 d/2c \sim 1.6\times10^3\ \mathrm{yr}\,(B/10\ \mathrm{nG})(\lambda_{\rm coh}/d)(d/\mathrm{Mpc})^3(E/10^{20}\ \mathrm{eV})^{-2}$$

~steady



$$\delta t \sim \theta_e^2 d/2c \sim 0.3\,\mathrm{yr}\,(E_{\rm syn}/10^{2.5}\ \mathrm{GeV})^{-2}(\min[d,\lambda_{\gamma\gamma}]/\mathrm{Mpc})$$

Murase 2009,12
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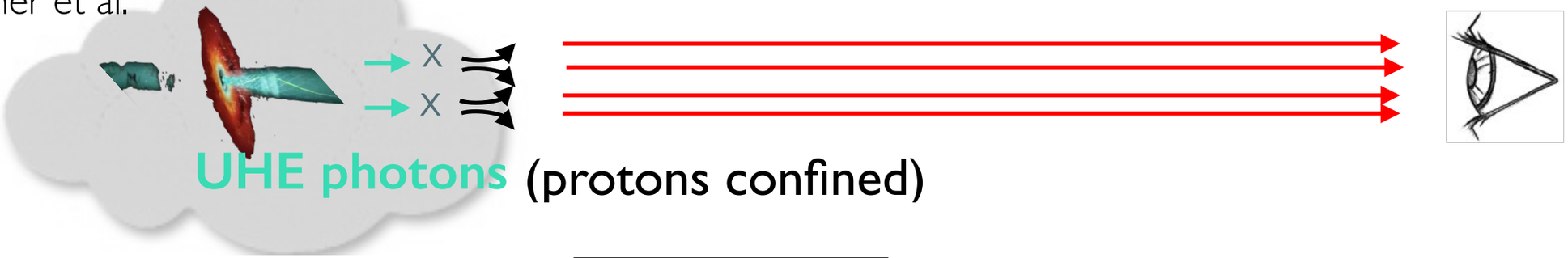
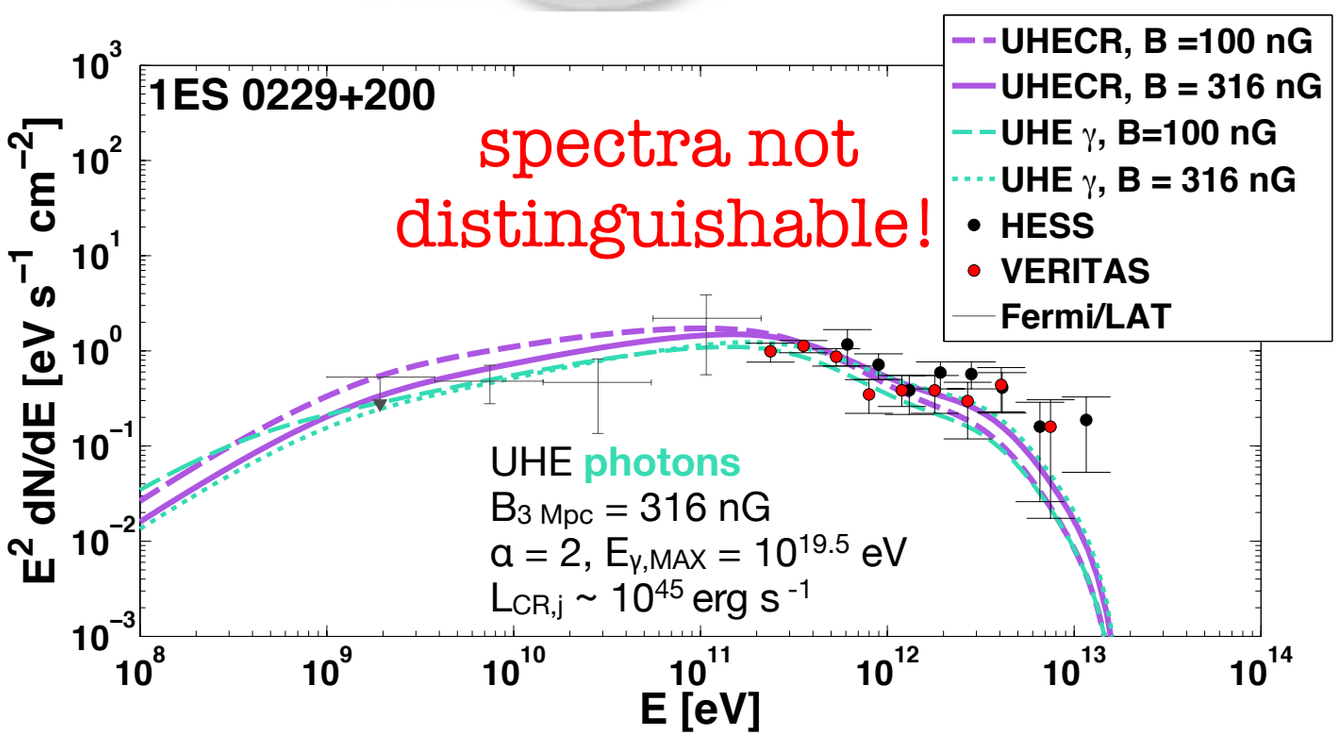


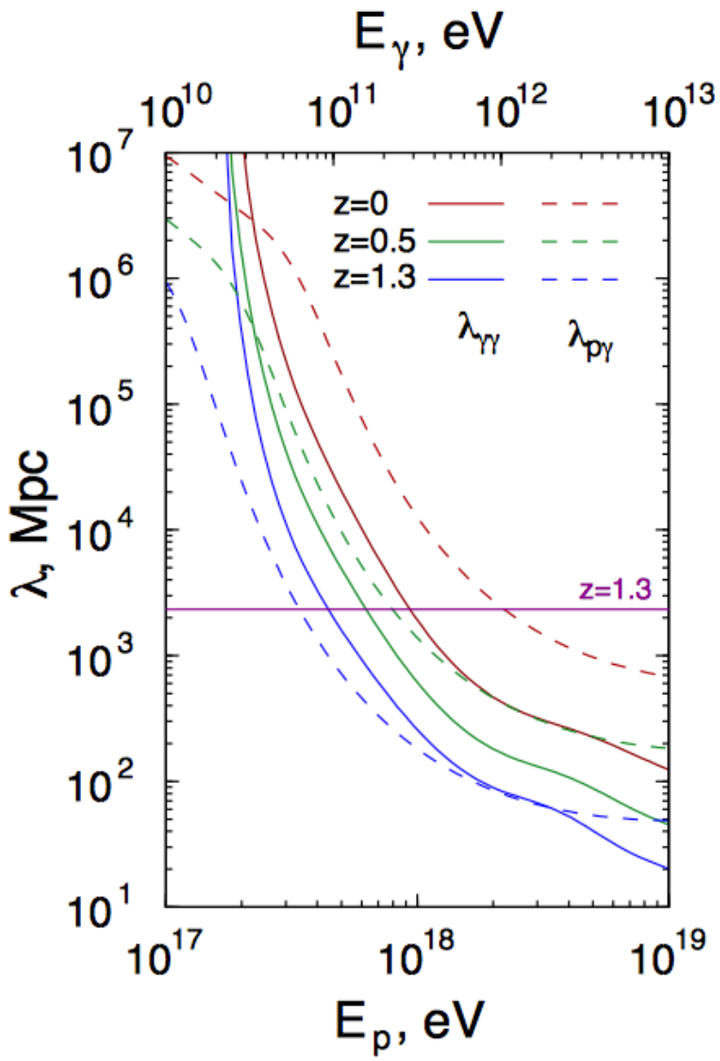
UHE photons (protons confined)



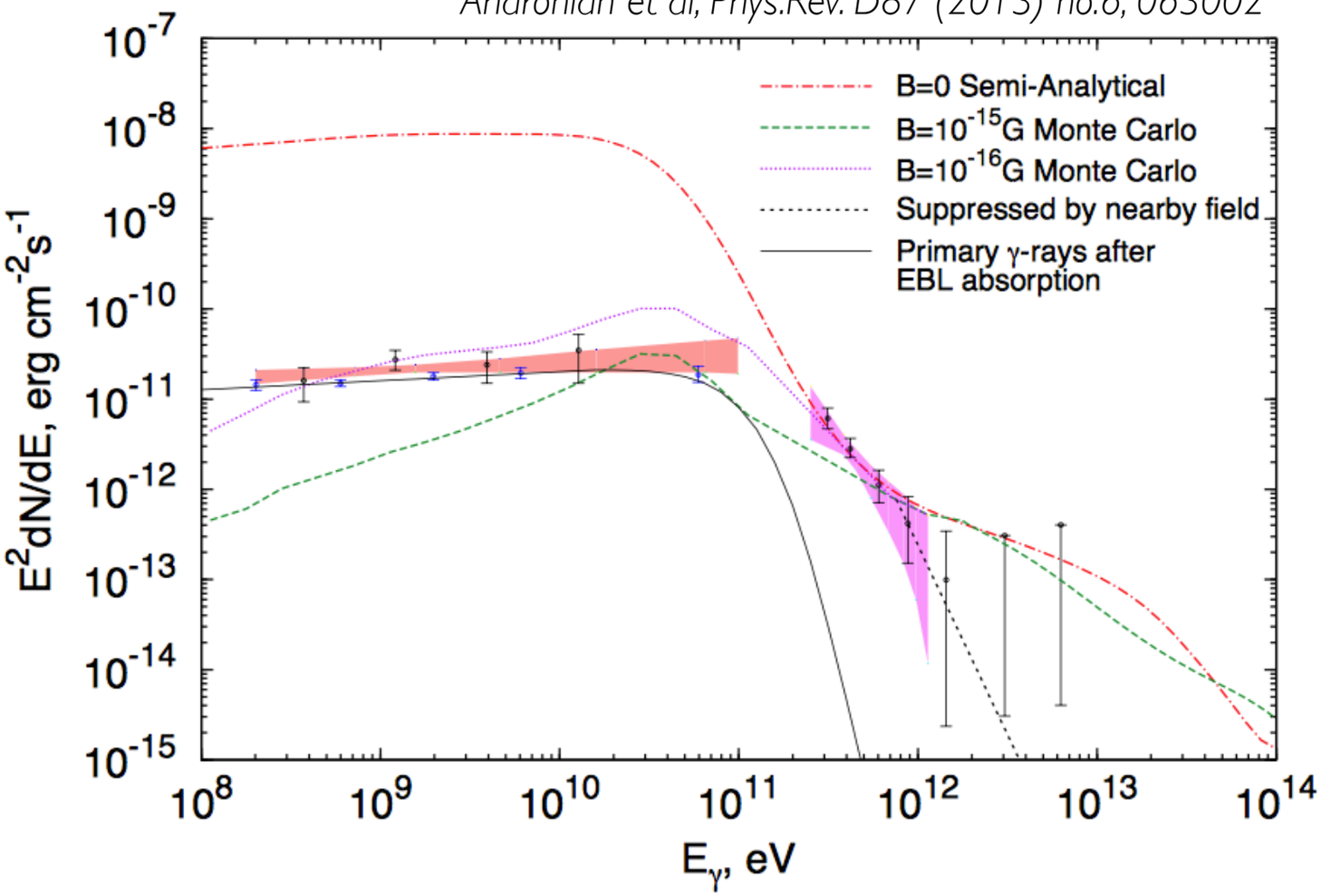
~ year TeV variability? Aliu et al 2014

UHECR IC cascade/
UHECR seeded synchrotron
strongly disfavoured

Back-up: Source at z>1

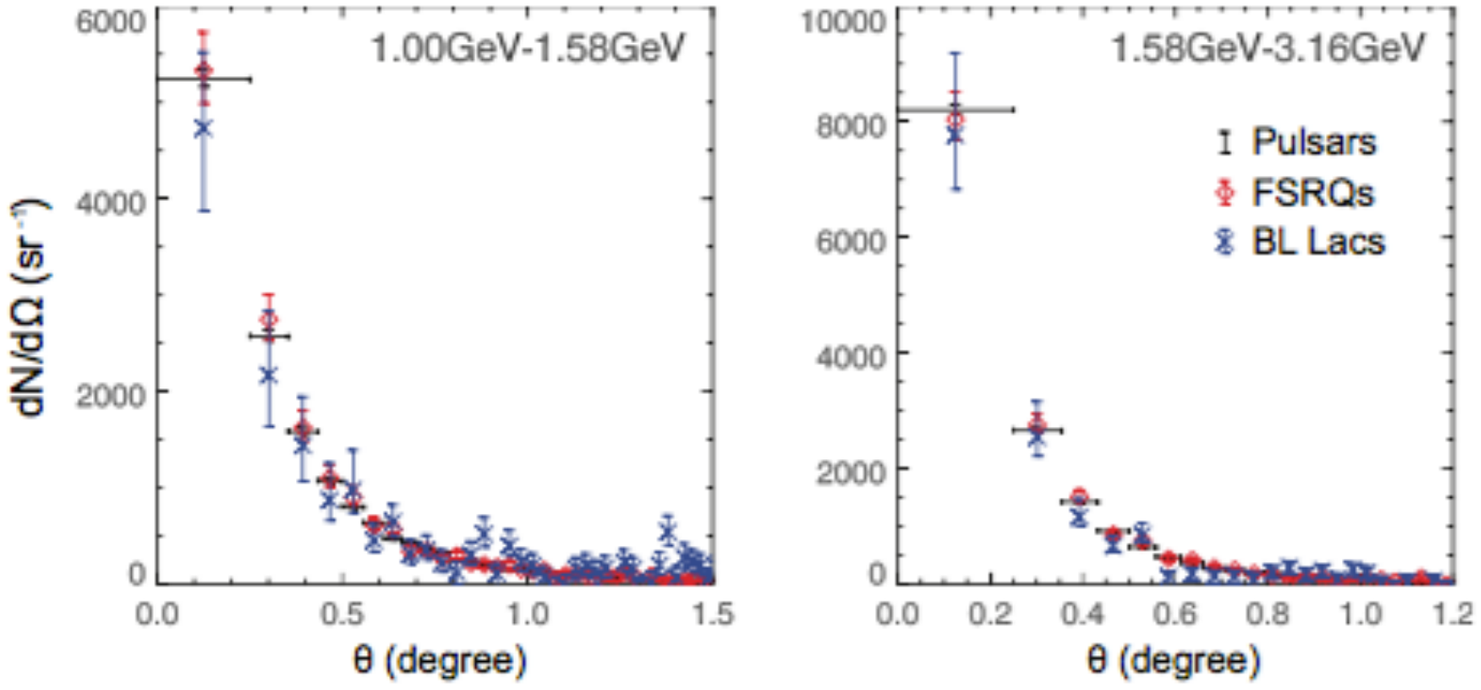


Aharonian et al, Phys.Rev. D87 (2013) no.6, 063002

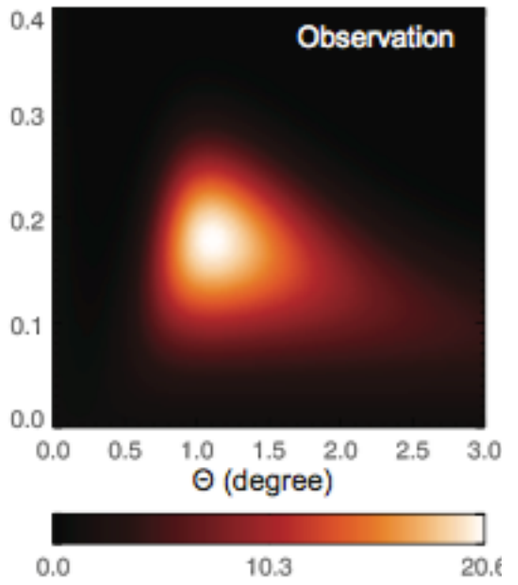


Hint of halo emission by Chen et al. 2015 analysis

Chen et al. Phys.Rev.Lett. 115 (2015)



Chen et al. 2015

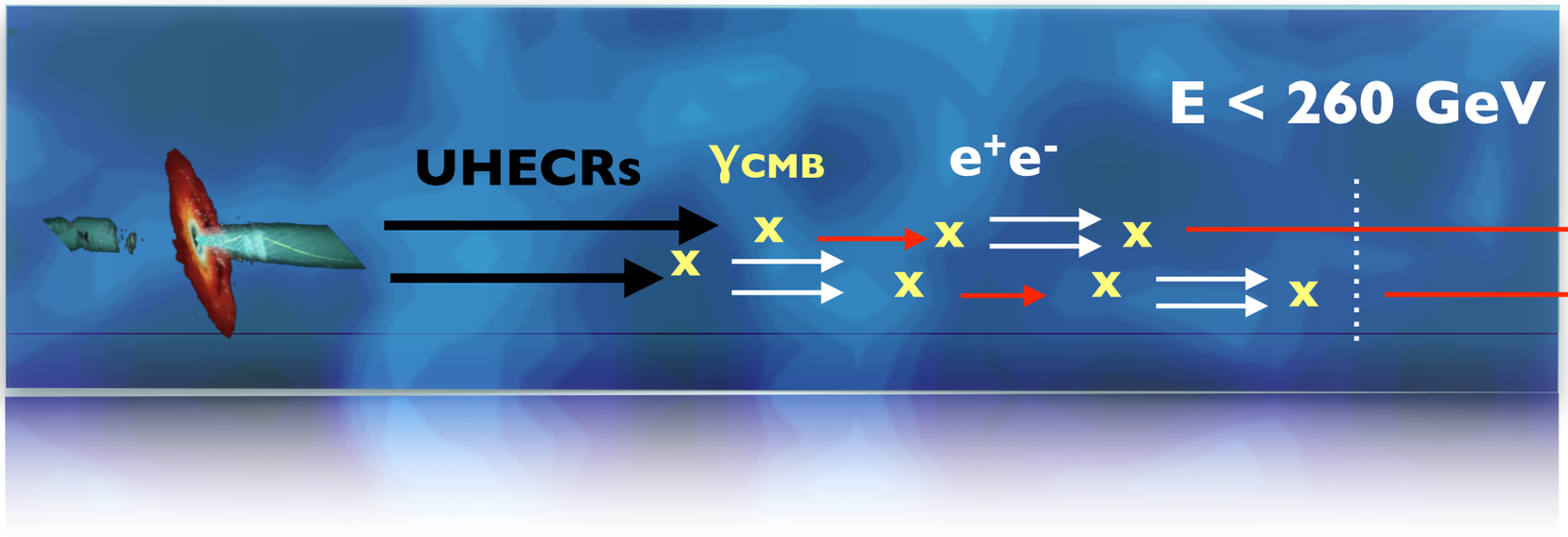


24 ***Fermi*** stacked BL Lacs $0.069 < z < 0.5$

$\Theta = 0.5°$

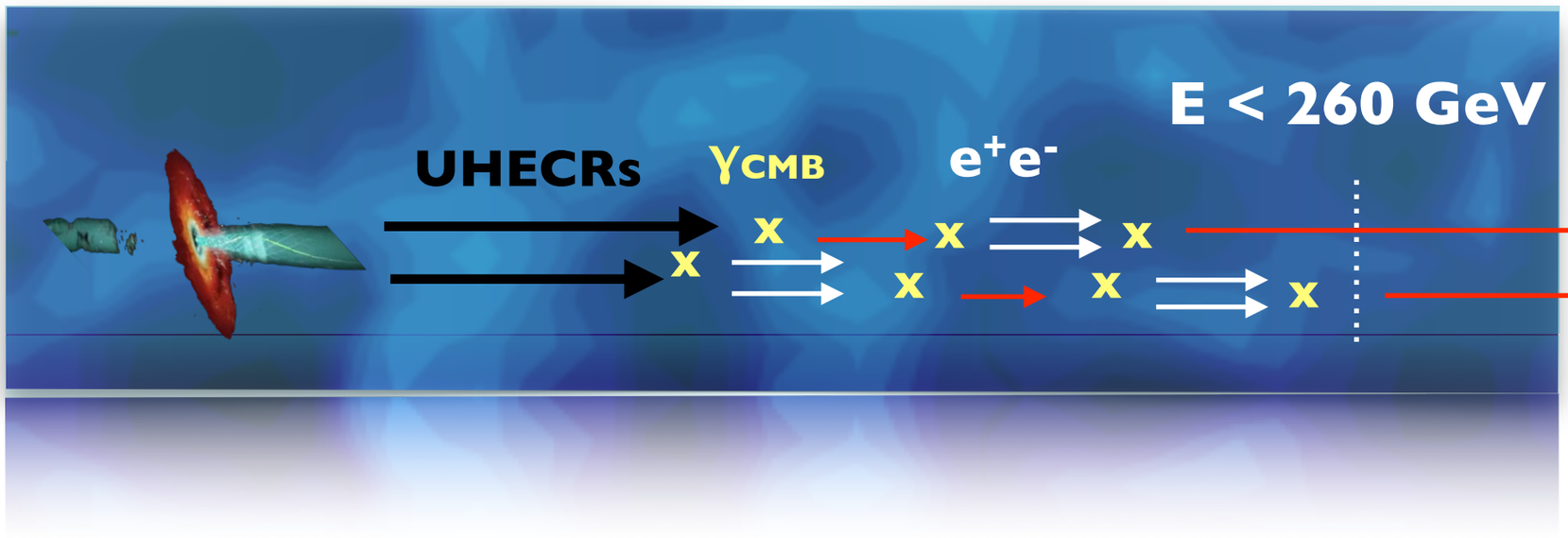
Consistent with $B = 10^{-17}$-10^{-15} G (if sources steady)

UHECR Inverse-Compton cascade



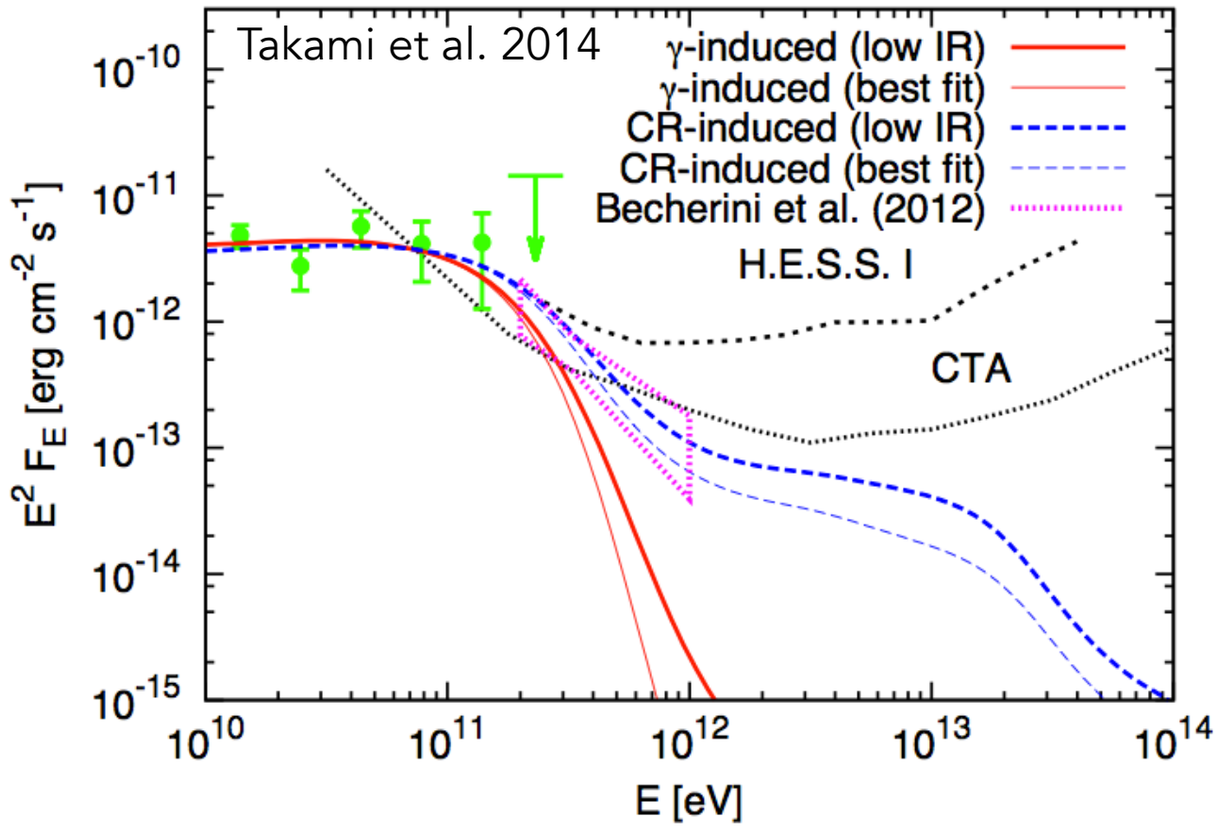
e.g., Essey et al 2010a,b, Murase et al 2012, Tavecchio 2014

UHECR Inverse-Compton cascade

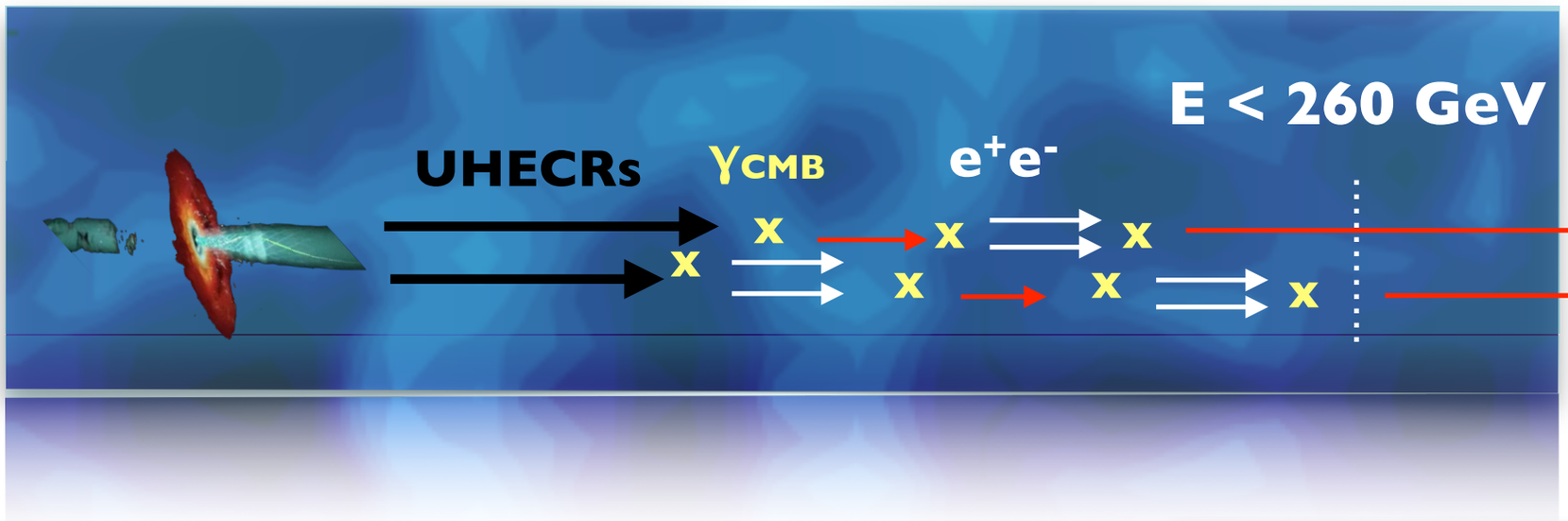


e.g., Essey et al 2010a,b, Murase et al 2012, Tavecchio 2014

Example: KUV 00311−1938 (z = 0.61)



UHECR Inverse-Compton cascade

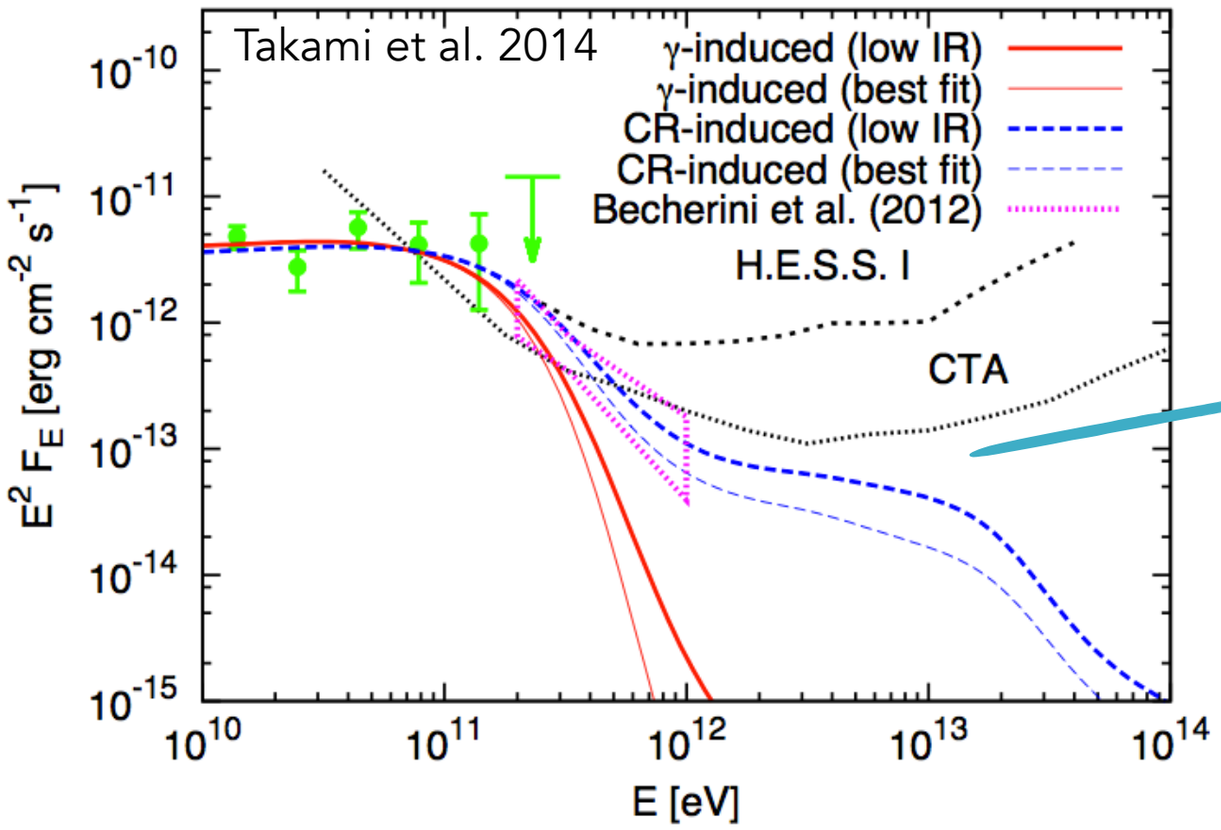


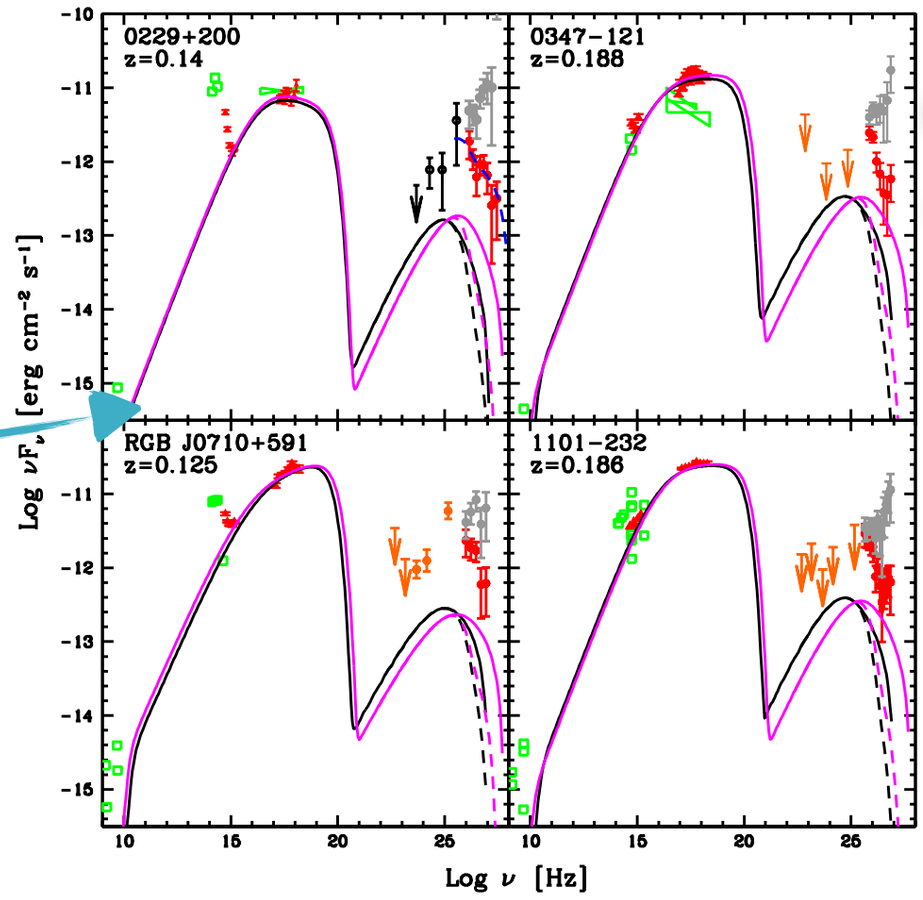
e.g., Essey et al 2010a,b, Murase et al 2012, Tavecchio 2014

Can explain hard spectrum TeV blazars

Tavecchio 2014

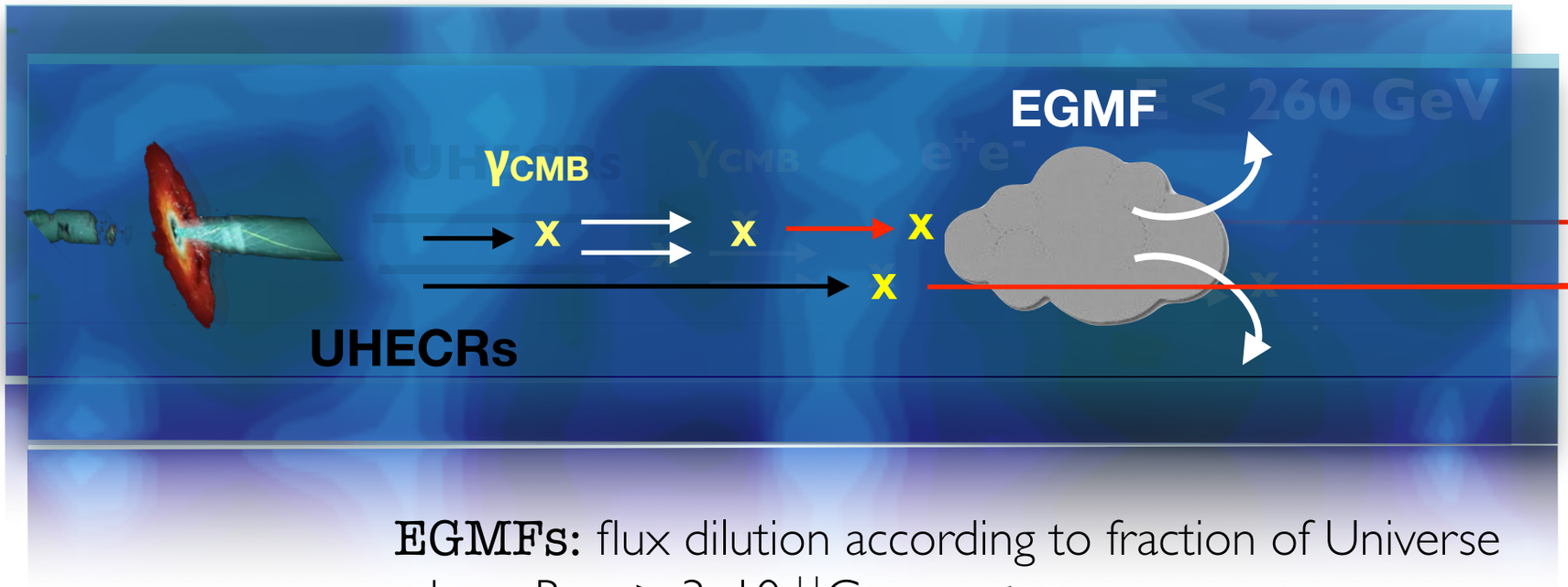
Example: KUV 00311−1938 (z = 0.61)





deabsorbed

UHECR Inverse-Compton cascade

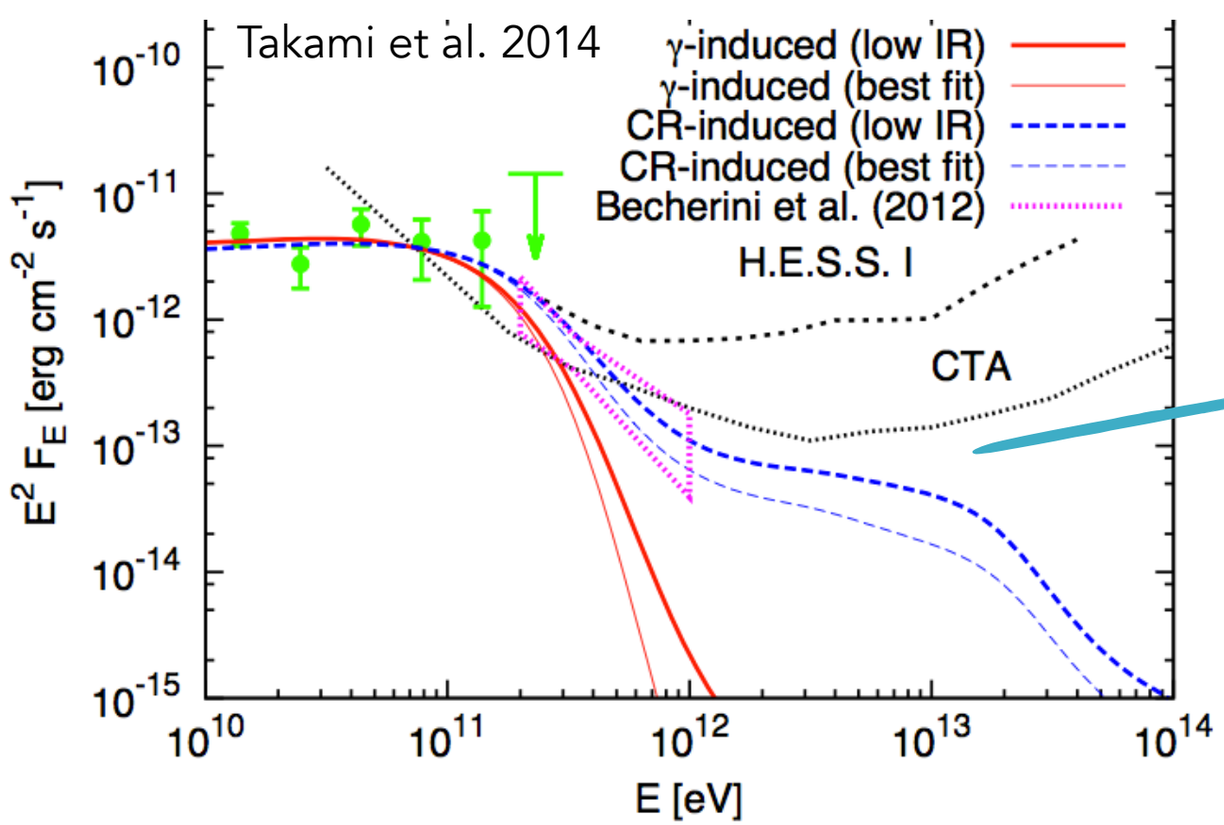


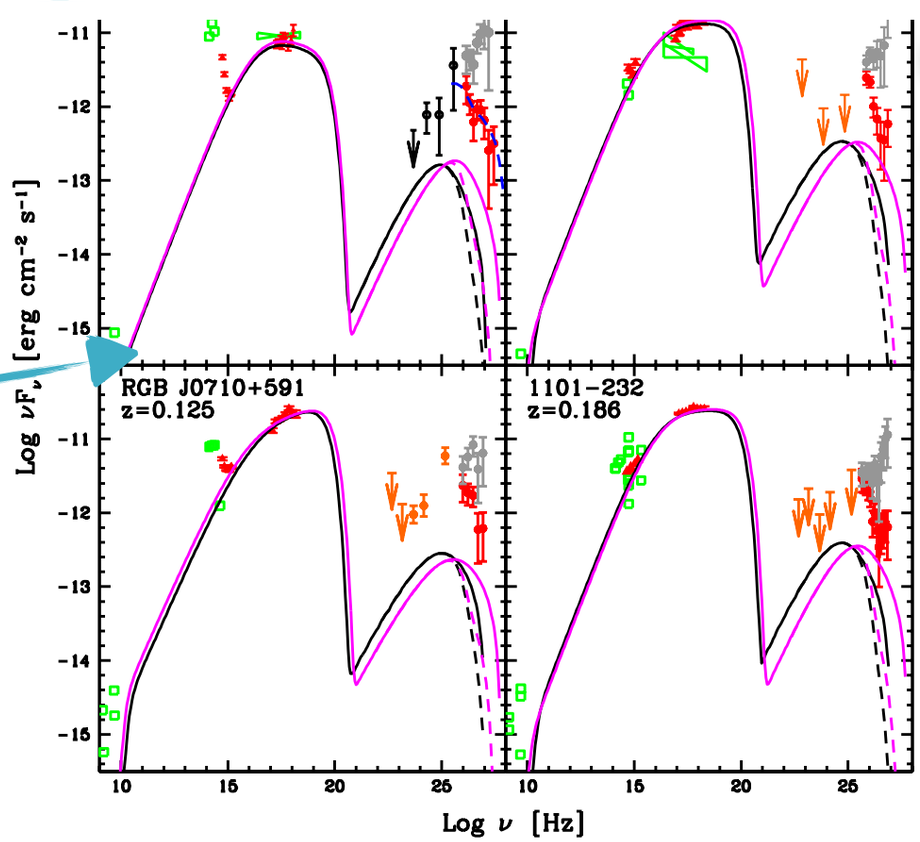
e.g., Essey et al 2010a,b, Murase et al 2012, Tavecchio 2014

EGMFs: flux dilution according to fraction of Universe where $B_{IGM} > 3\times10^{-11}$G

Kotera et al, 2011

$$E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} \approx f_{1d}(< B_\theta)\, \chi_e \frac{L_{cr}}{8\pi d^2} \left(\frac{E_\gamma}{E_{\gamma,max}}\right)^{1/2}$$





deabsorbed