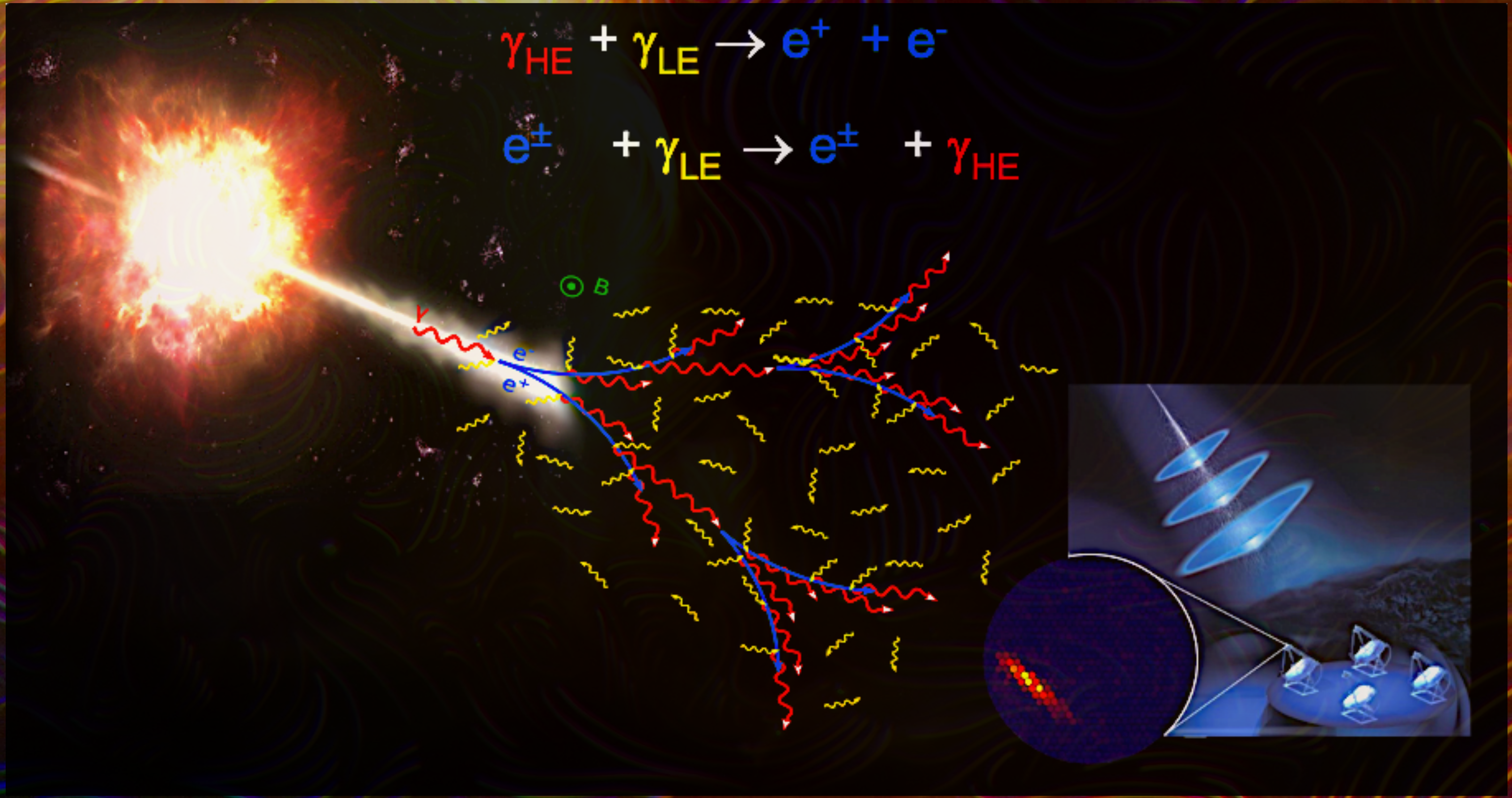
InterGalactic Magnetic Field and Gamma-Ray Bursts with CTAO

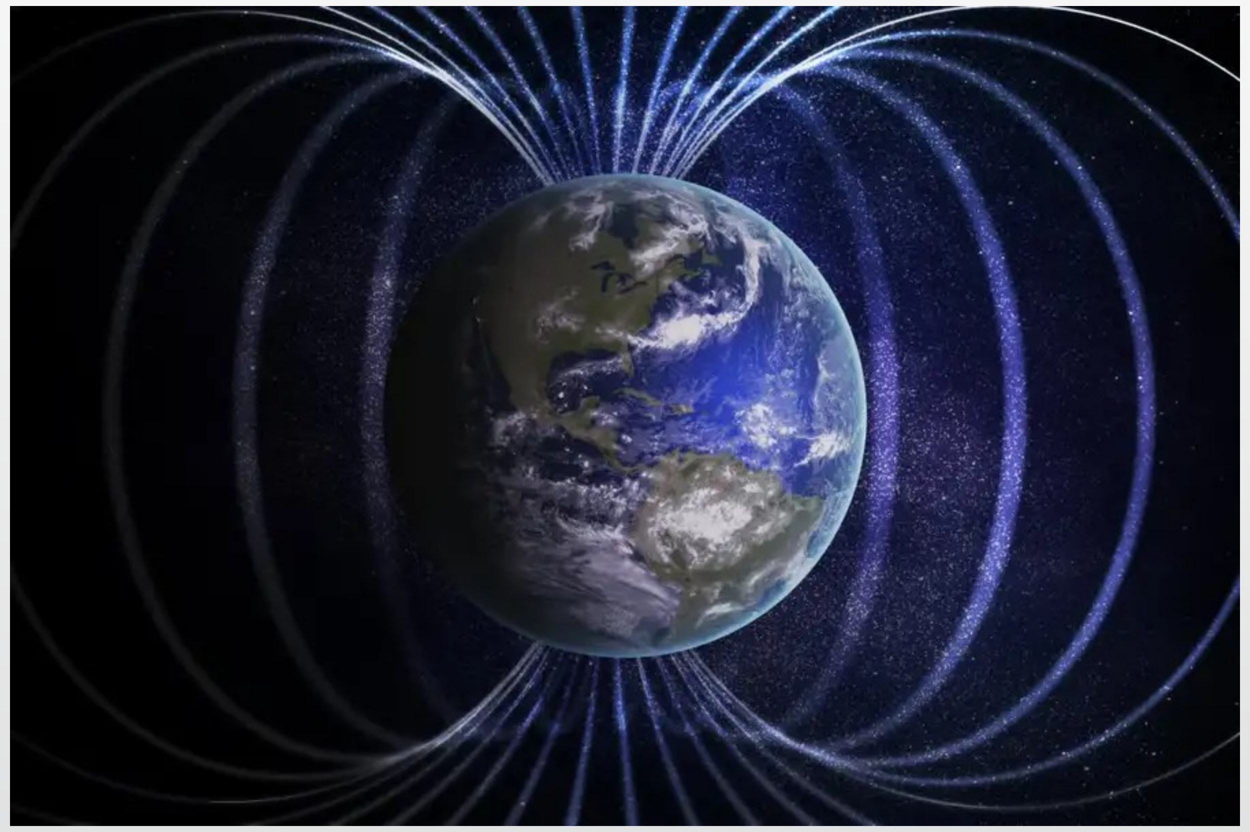


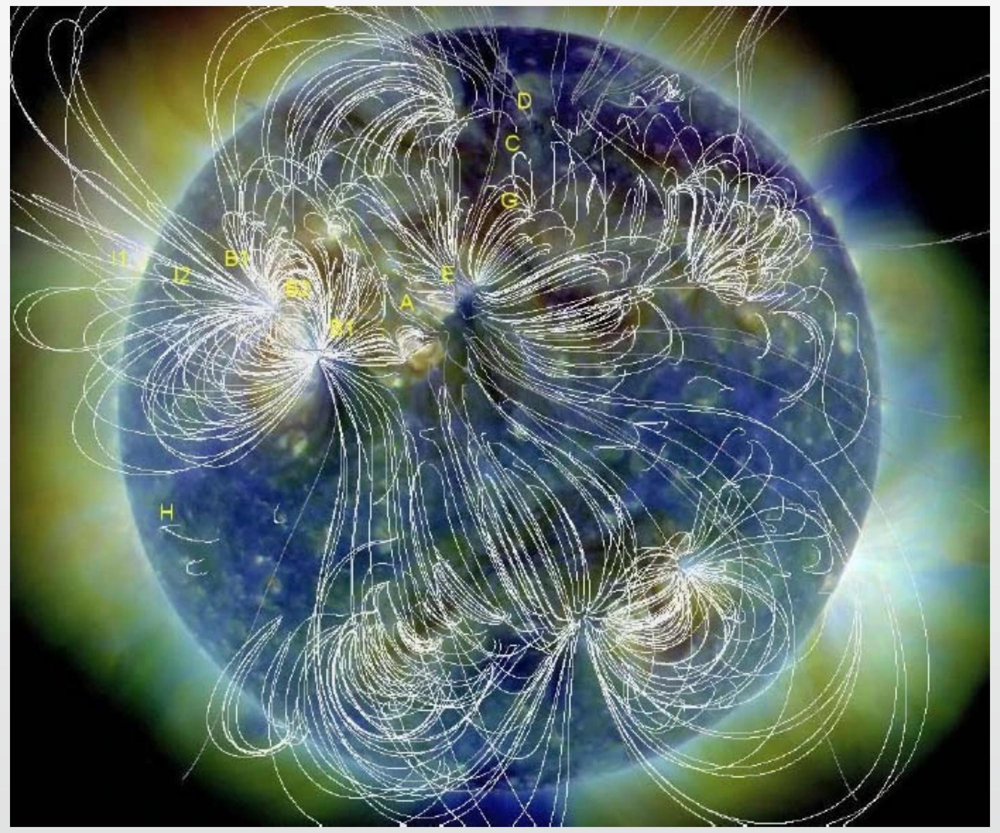
Téneméan Keita

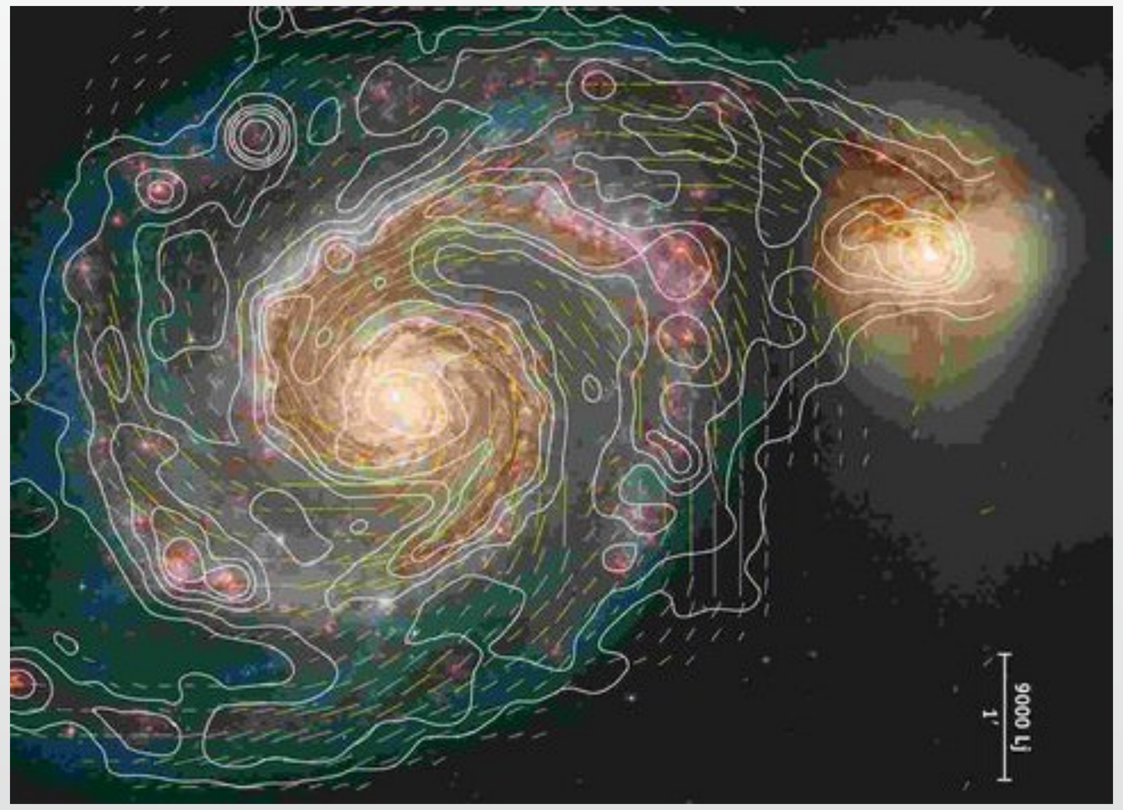
CTAO summer school: 16/06/24 - 29/06/24

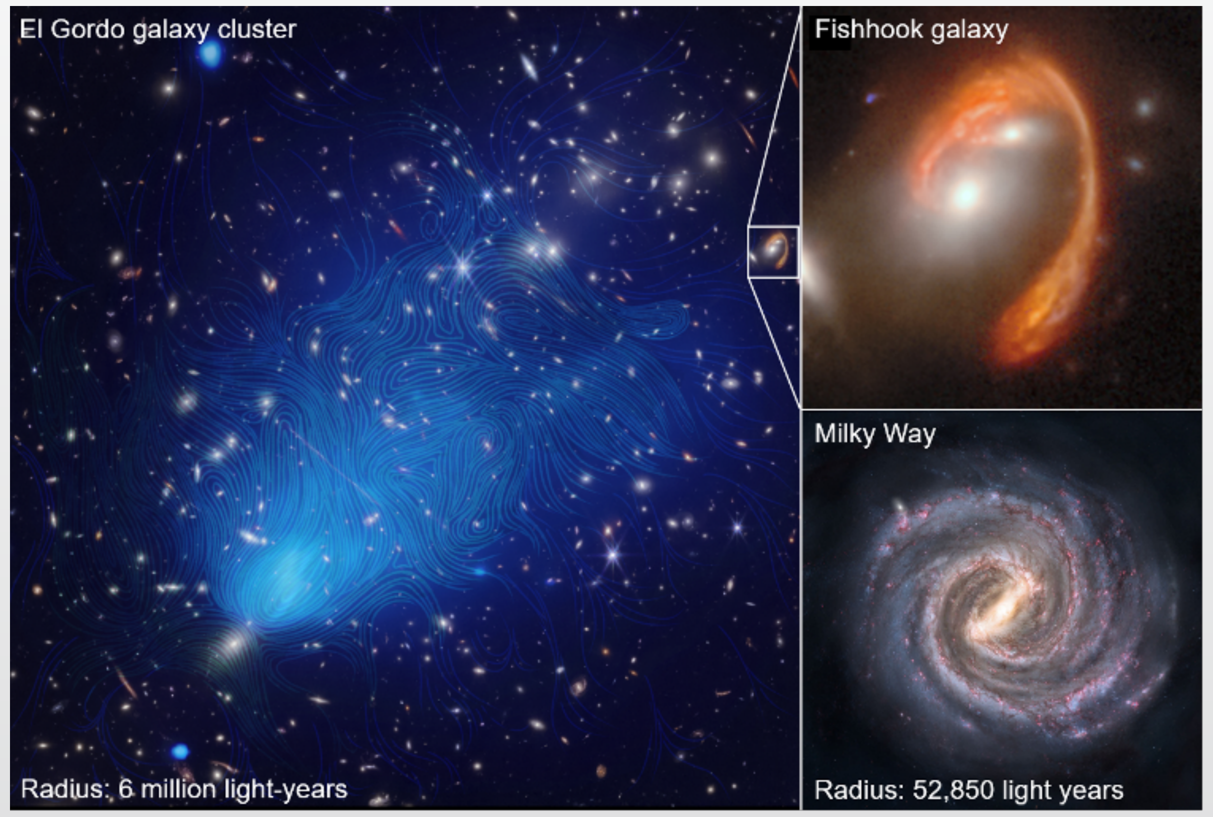
Pauline Voß for Quanta Magazine

Magnetic fields universality









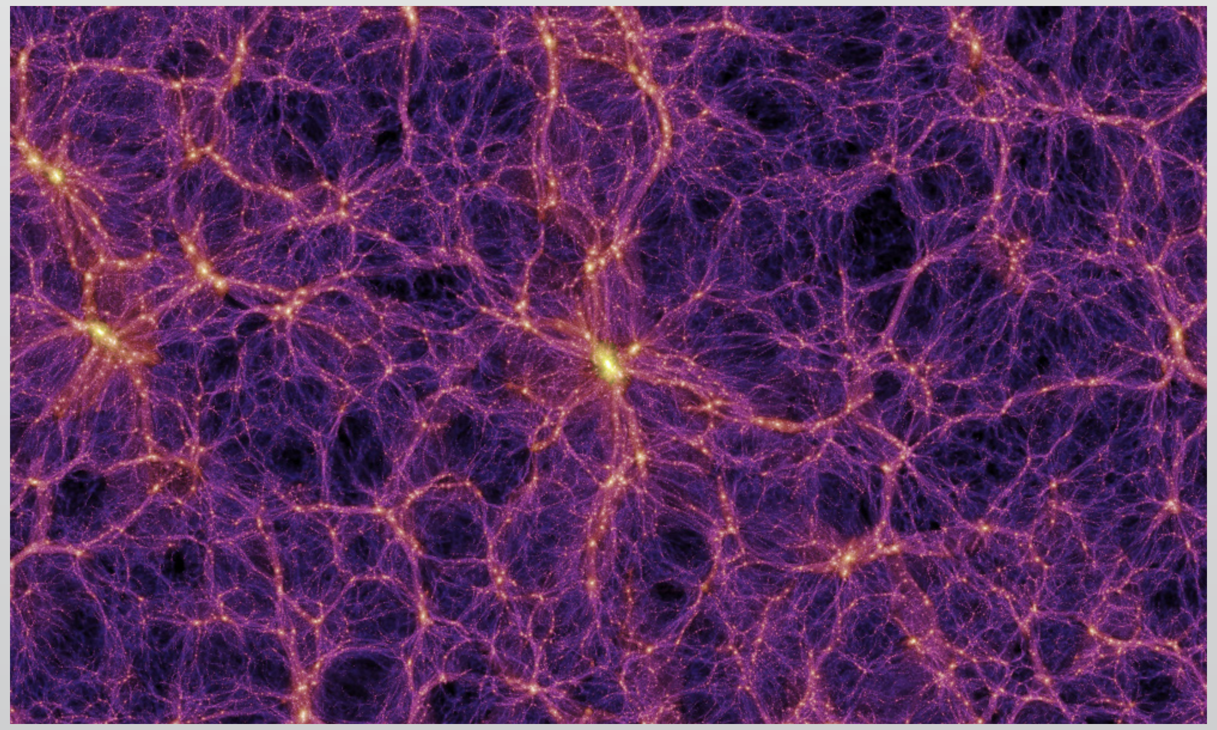
50 G
1 G
10 μG
30 nG
?? fG

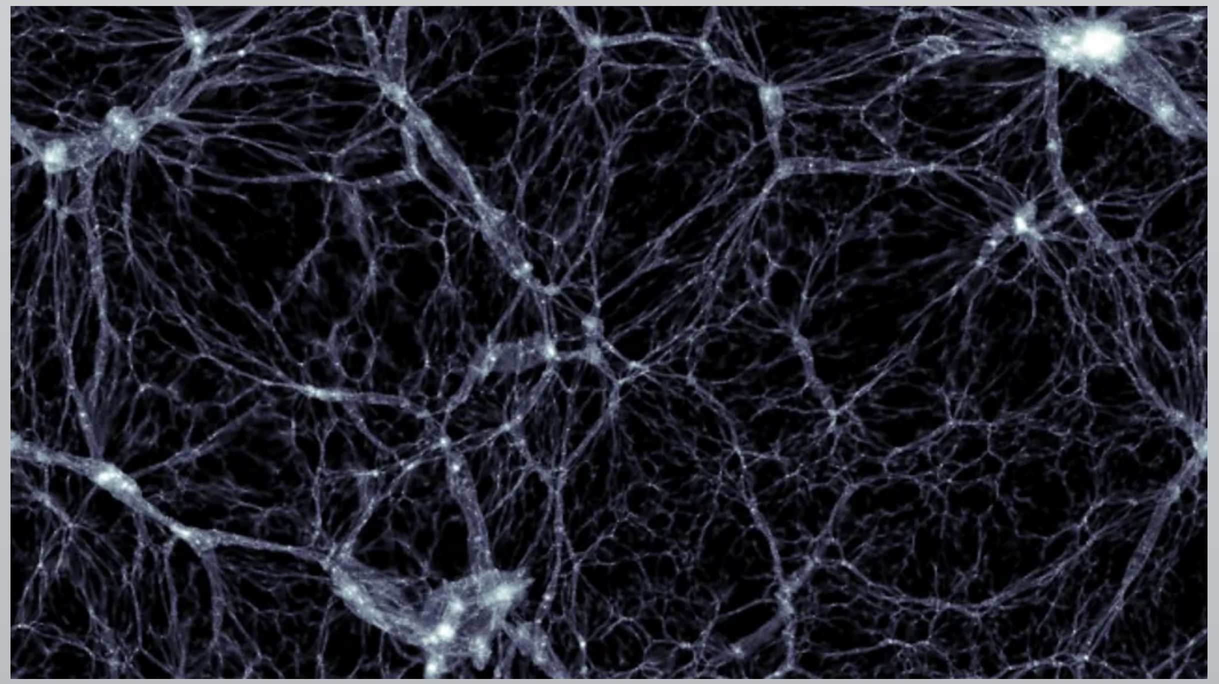
Planets
Stars
Galaxies
Clusters
Filaments
Voids

Cosmological size

Magnetic intensity

Refs in appendix

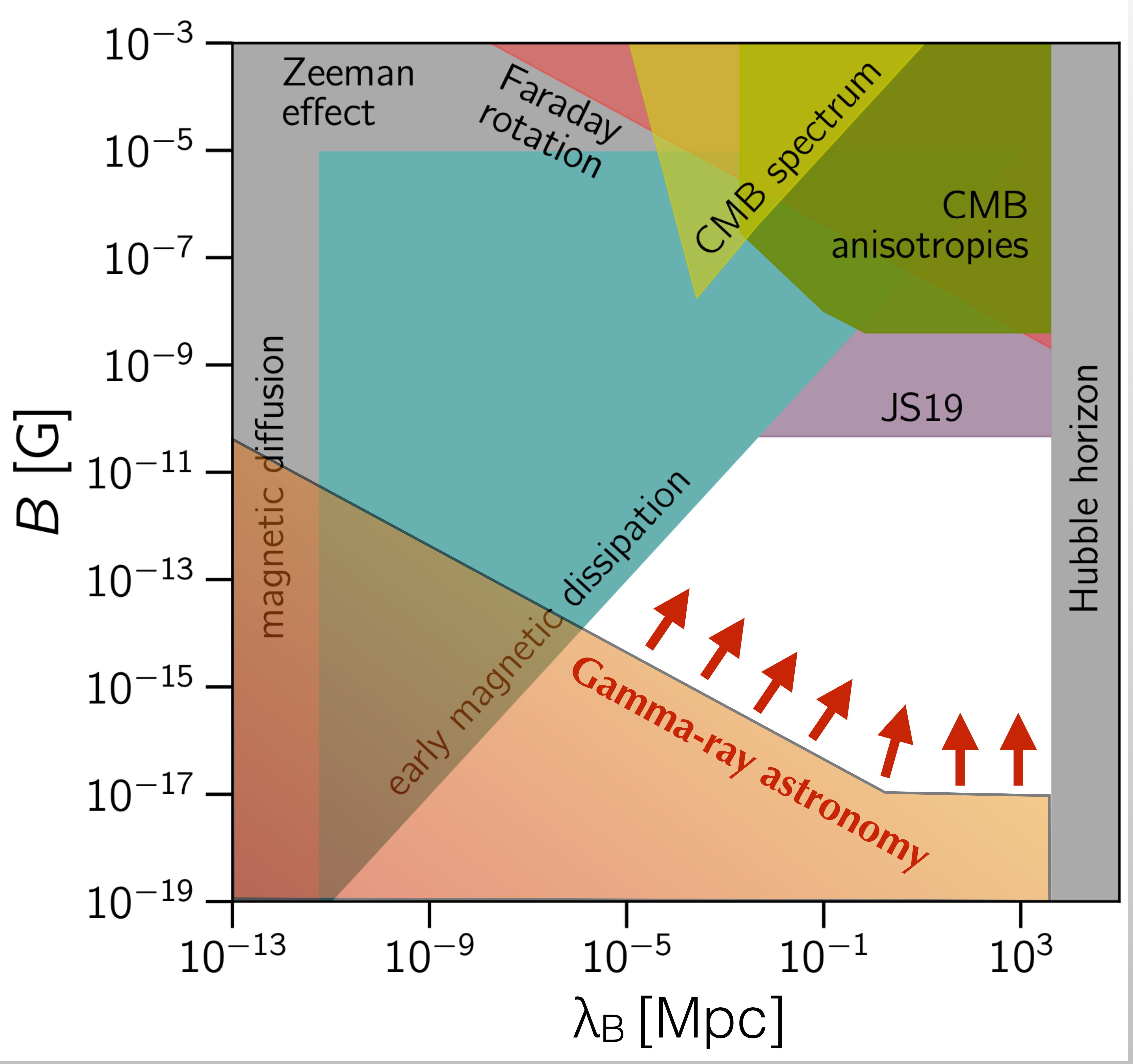




- **Magnetic fields exist at every scale**
- **What is the origin of cosmological magnetic fields ?**
  - ➡ **The InterGalactic Magnetic Field (IGMF)**

The InterGalactic Magnetic Field (IGMF)

- **A turbulent field: mean intensity B, correlation length λ_B**
- **Too weak for a direct detection**
- **Altered in galaxy clusters and filaments**
- **Constraining the IGMF in the voids may help understanding its origin**



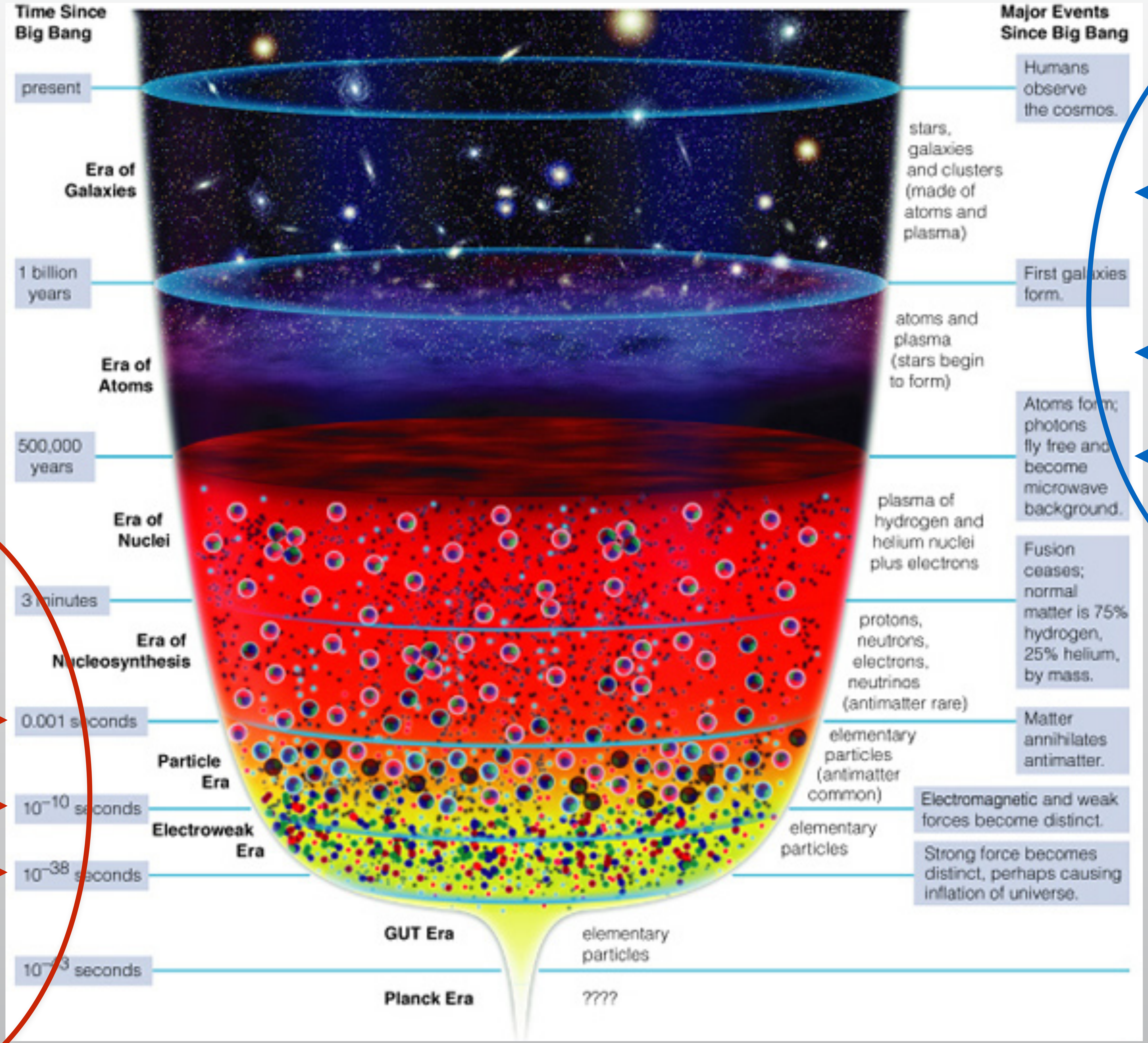
Observational constraints

Primordial magnetogenesis

Primordial

- QCD phase transition
- EW phase transition
- Inflaton coupling

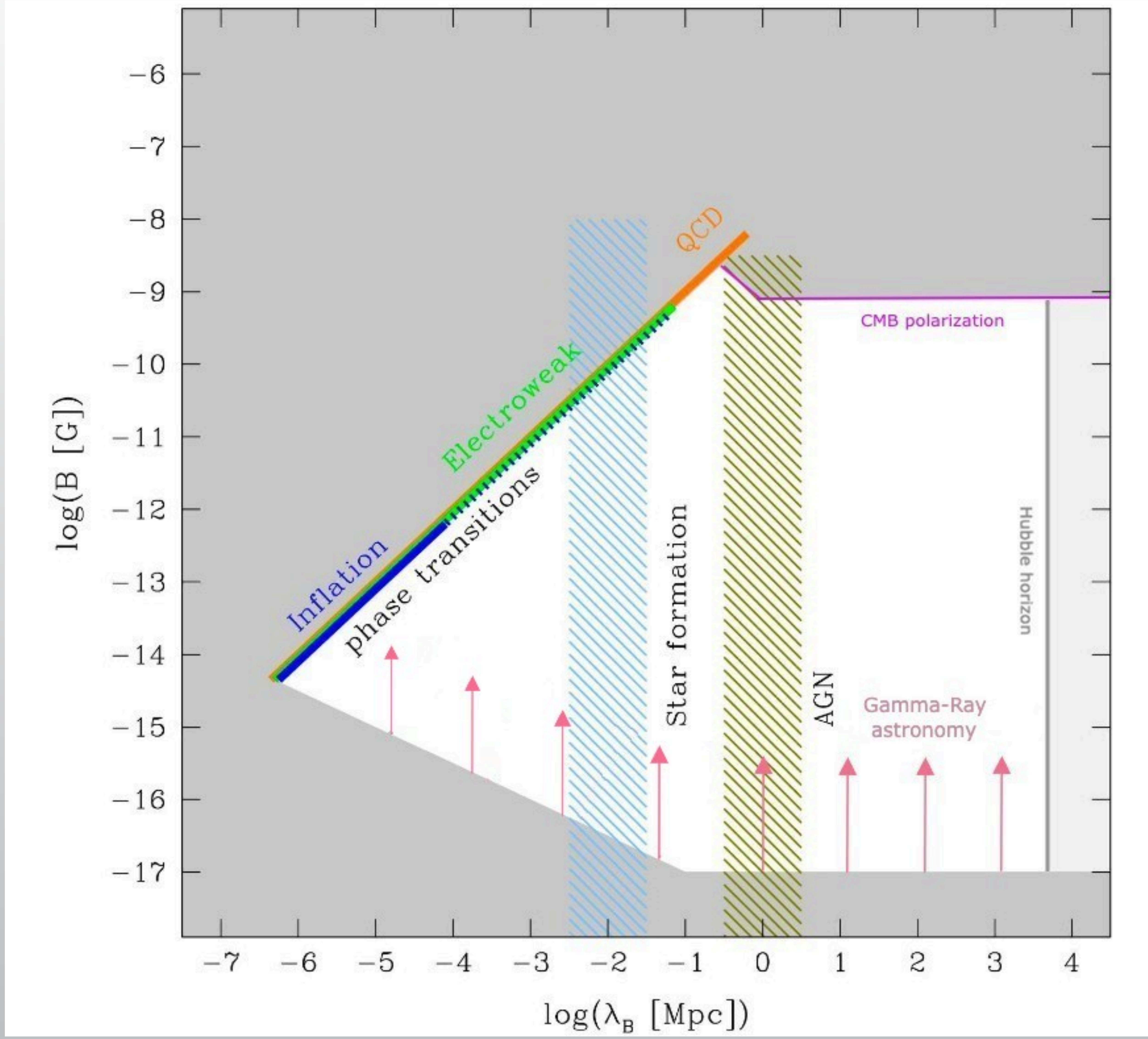
Could be linked to…



- AGN magnetised jets
- Reionization epoch
- Photon decoupling

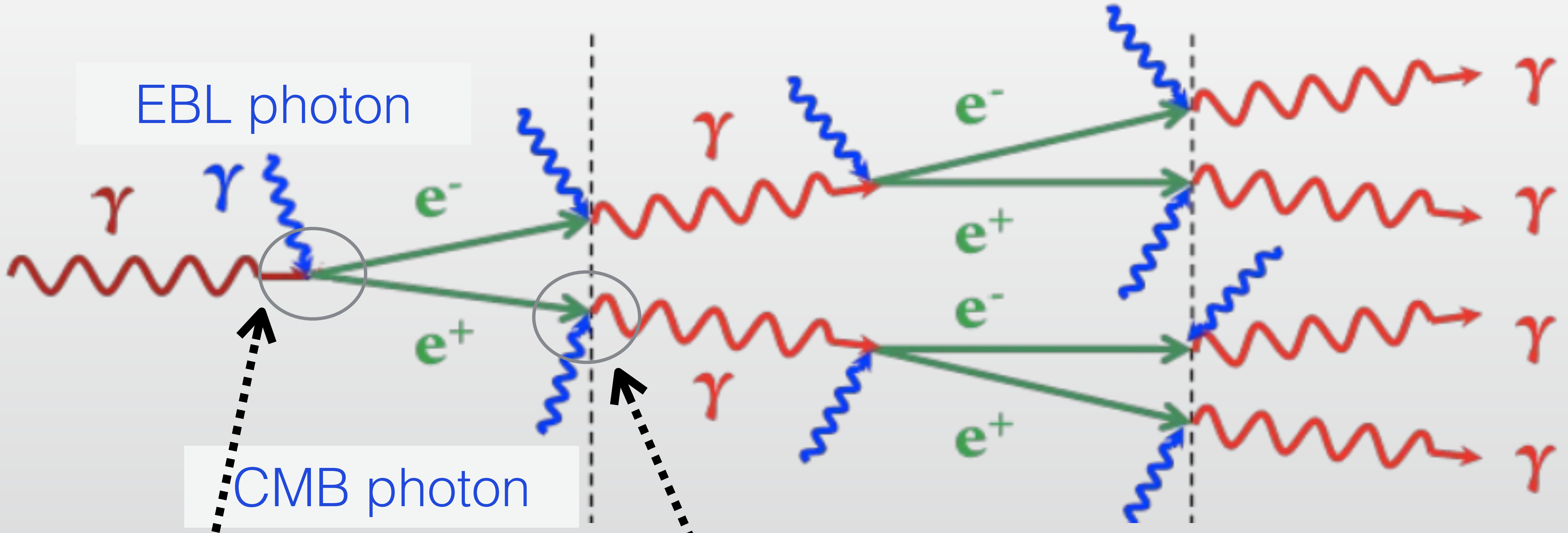
Astrophysical

Theoretical constraints

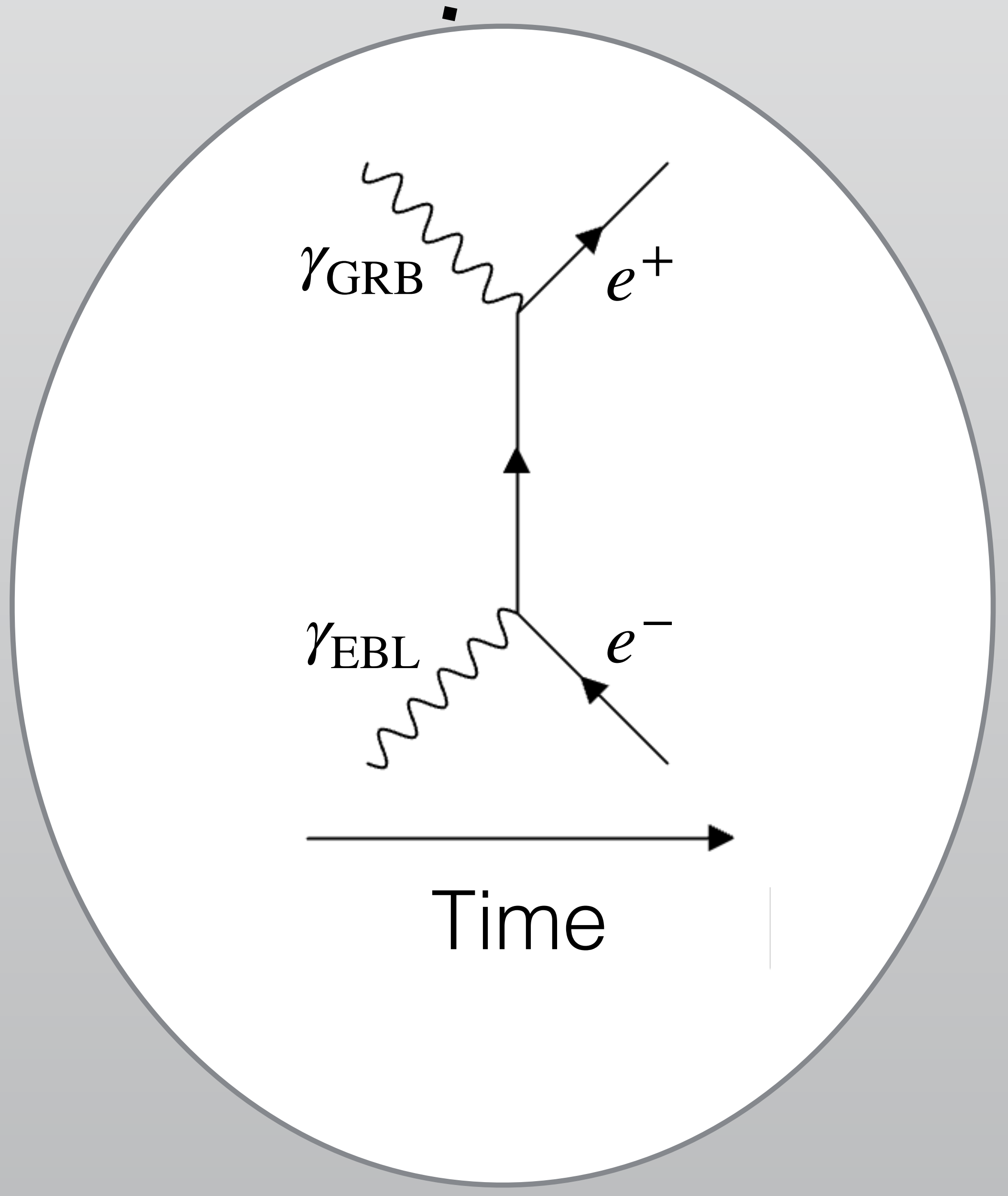


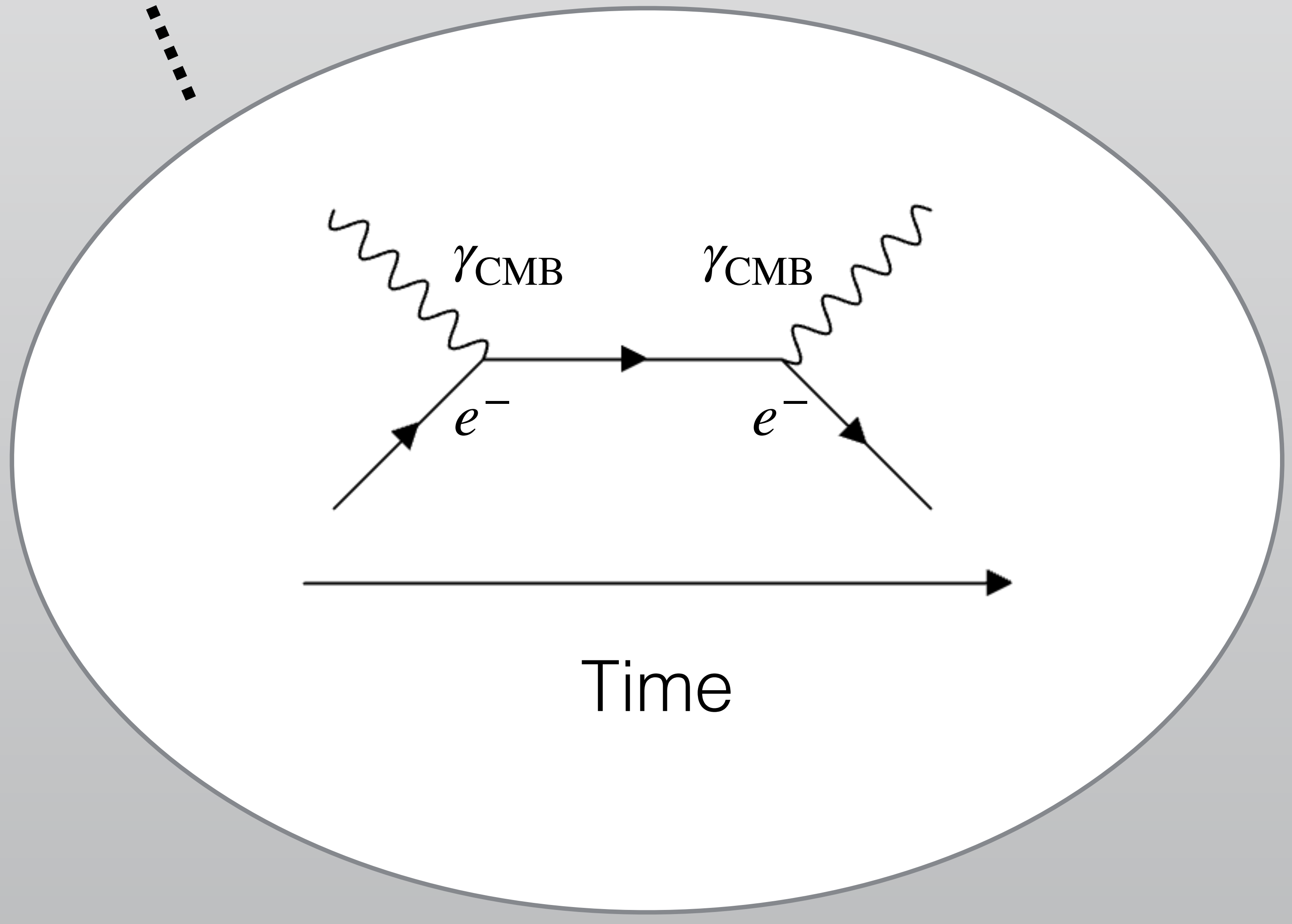
Gamma-Ray Burst

Cosmological electromagnetic cascades

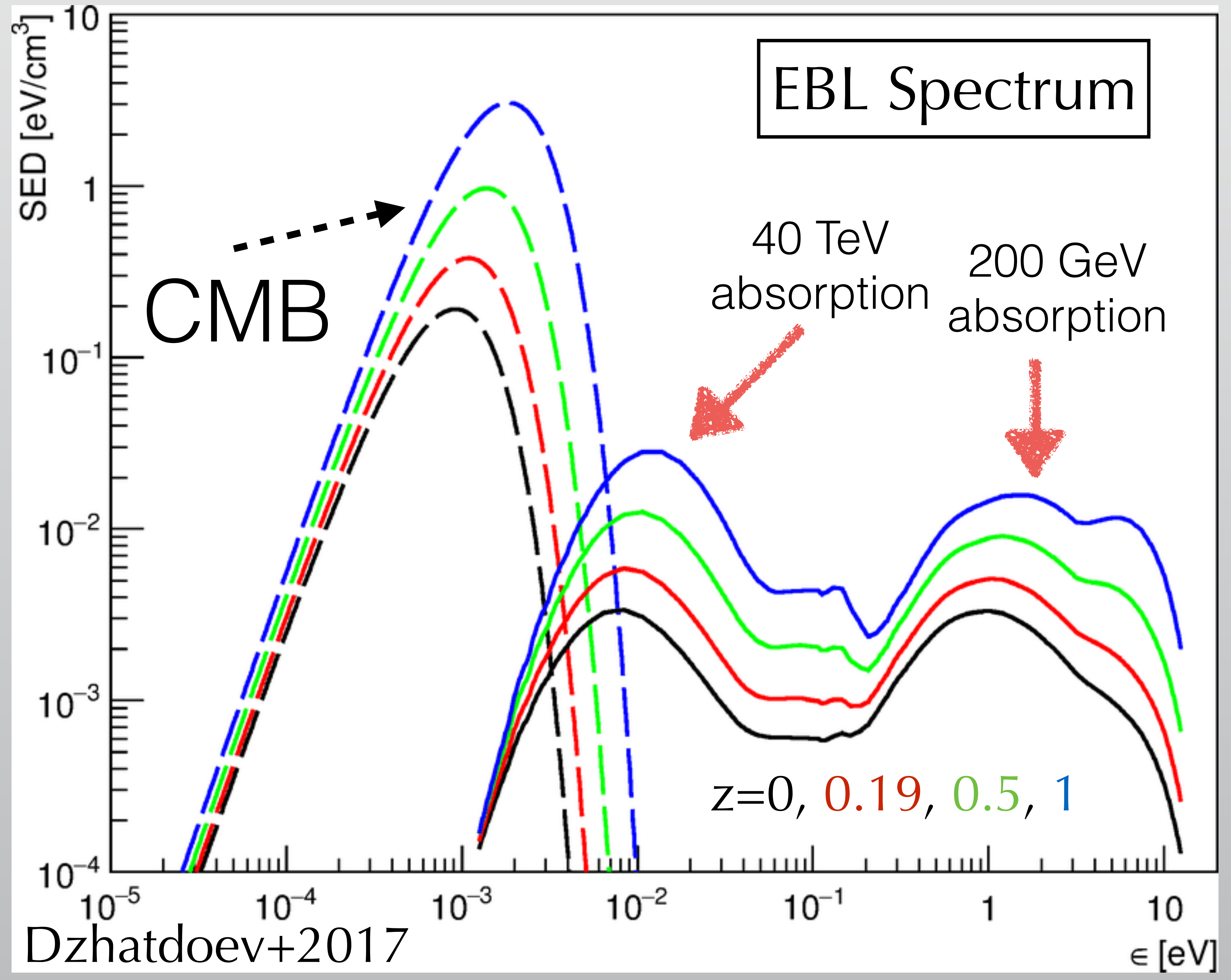


Courtesy: T. Fitoussi



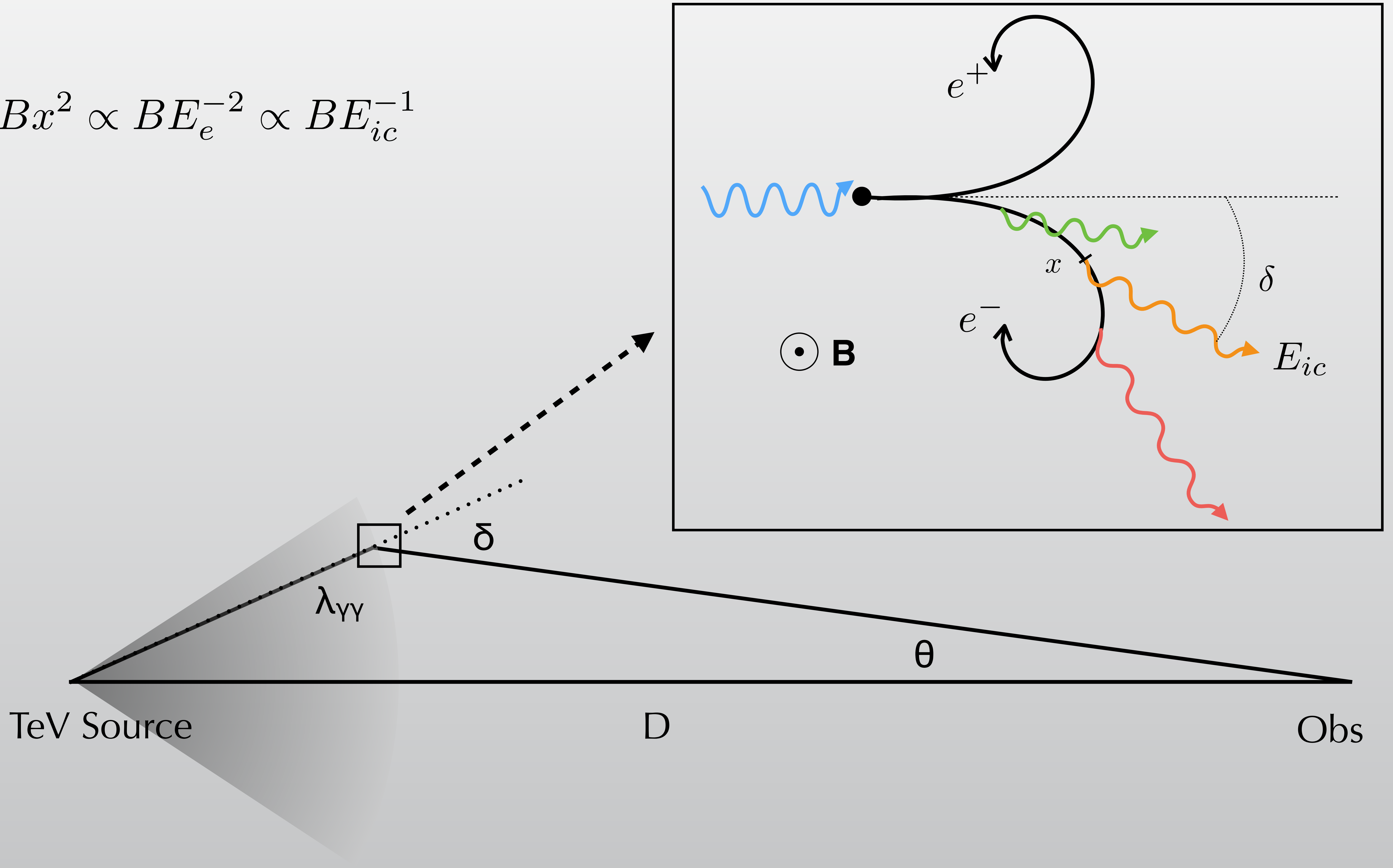


- **Secondary emission expected in the GeV-TeV band**
  - No unambiguous detection so far…
  - => **lower limits on the IGMF**



Expected IGMF signatures

- **The Intergalactic Magnetic Field deflects pairs in the cascade**
  - For large correlation length (uniform field): $\delta \propto Bx^2 \propto BE_e^{-2} \propto BE_{ic}^{-1}$
- **Angular effect:**
  - Require stable, long living sources: **AGN**
- **Temporal effect:**
  - Need for transient sources: **GRBs**
- **Time and angular effects are well separated and complementary**

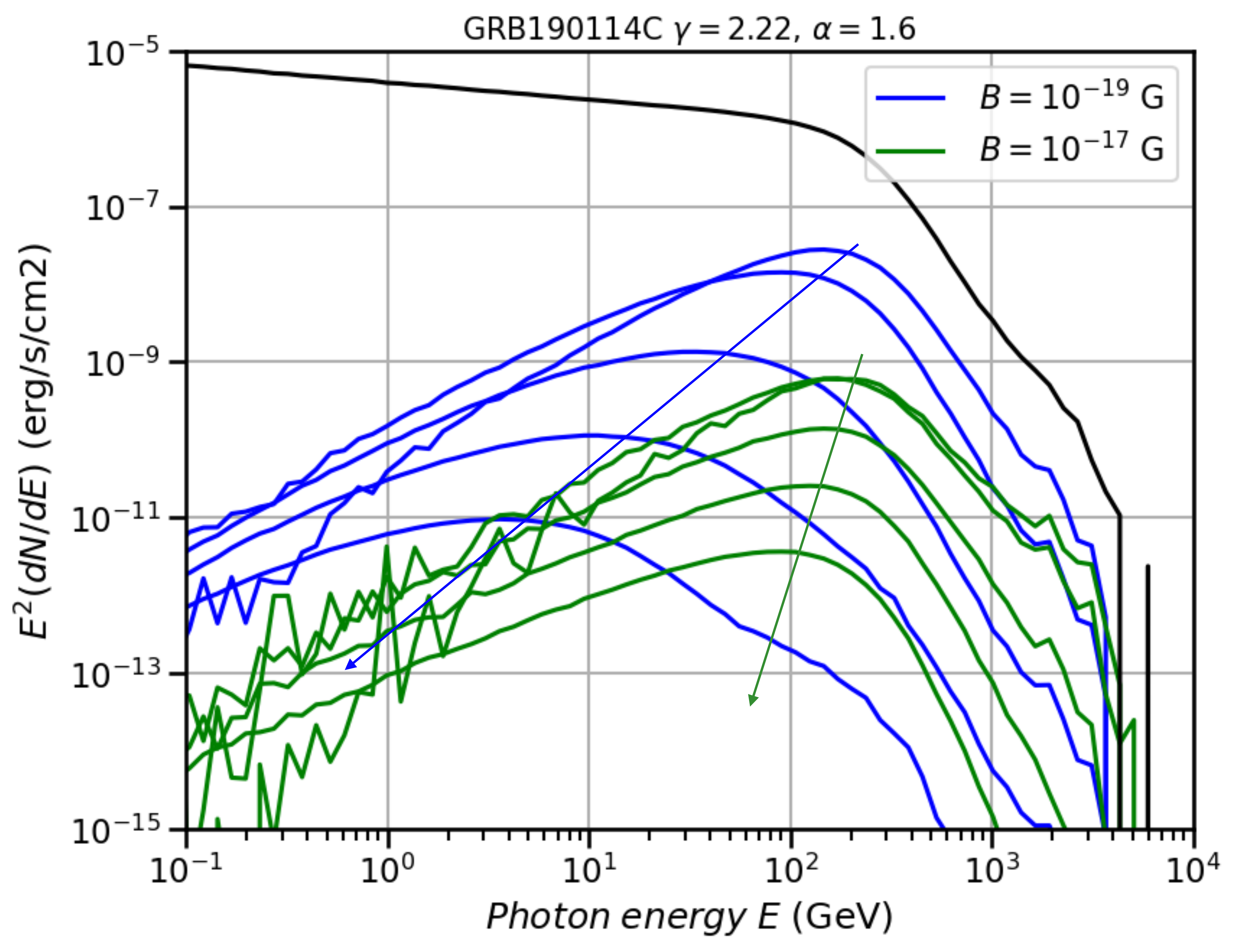


$$\Delta t \approx 5 \times 10^4 \left(\frac{D}{1\mathrm{Gpc}}\right)^2 \left(\frac{\lambda_{\gamma\gamma}}{100\mathrm{Mpc}}\right)^{-1} \left(\frac{\theta}{0.1^o}\right)^2 \mathrm{yr}$$

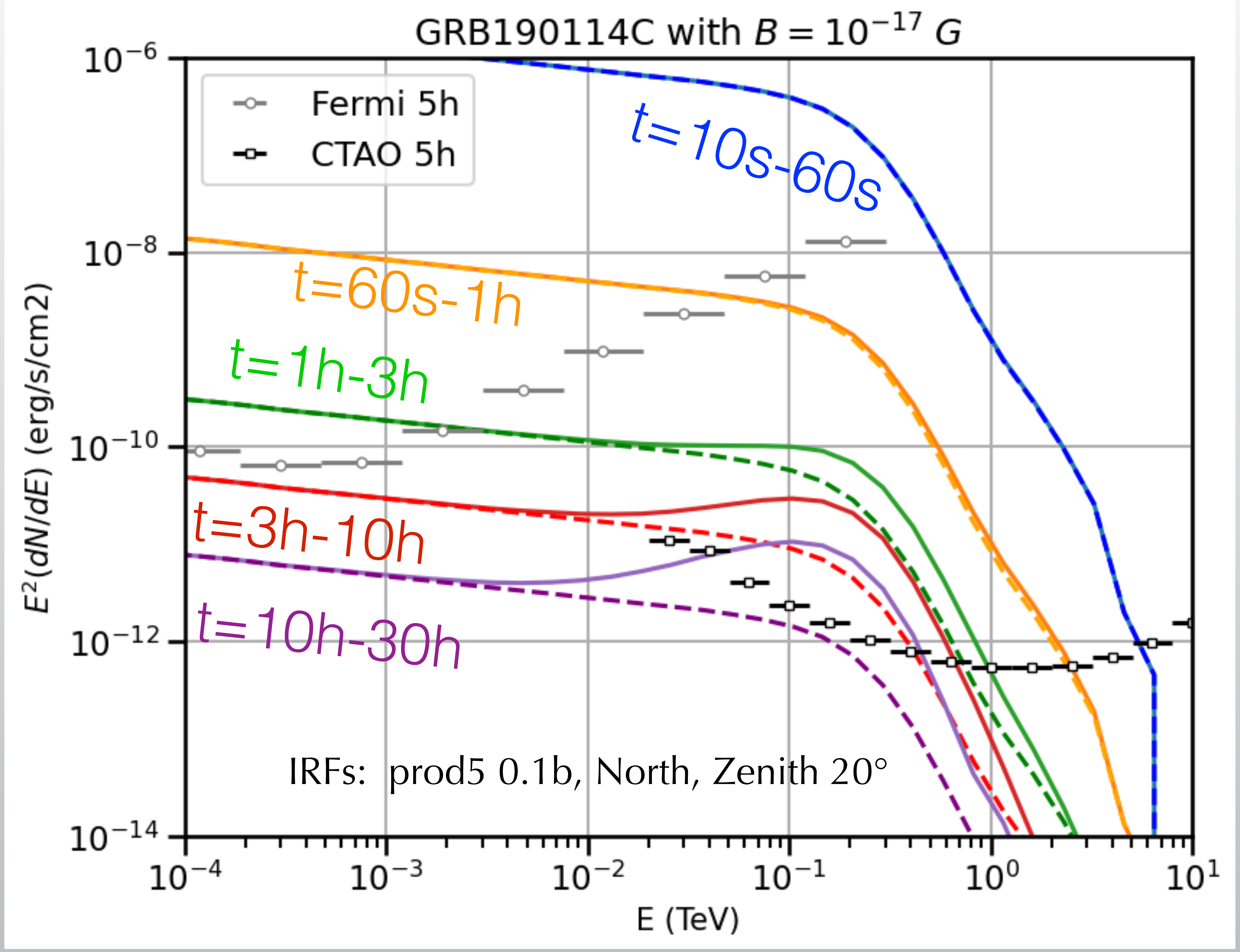
$\Delta t \sim 1$ hour $\Rightarrow \theta \sim 0.00002^\circ$

$\theta \sim 0.1^\circ \Rightarrow \Delta t \sim 50000$ years

IGMF effect on cascade emission

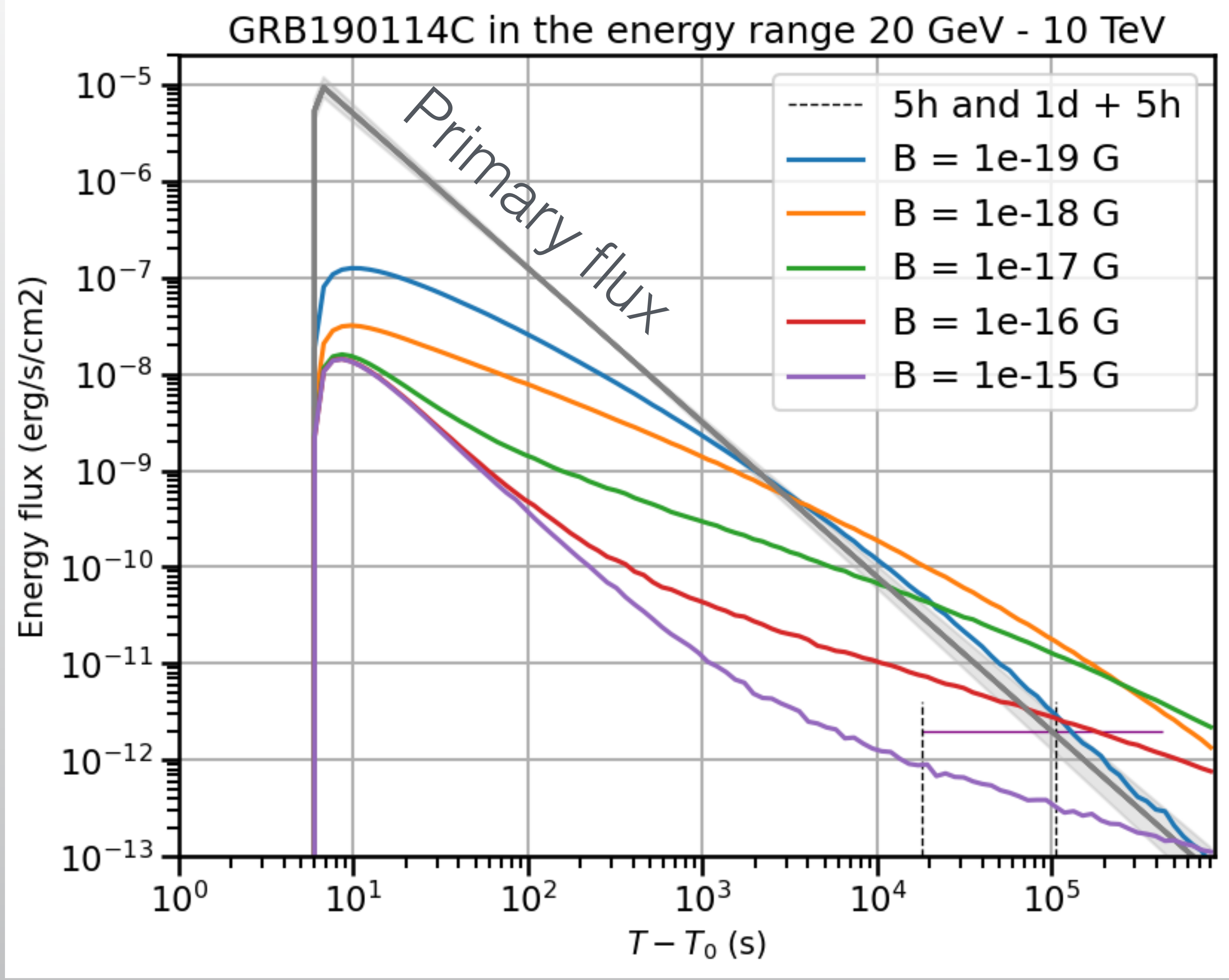


Energy spectra through time



- **A case study: GRB190114C**
  - Power law: spectral index (Γ=2.2), and temporal index (α=1.6) behaviour
  - Primary (dashed line) versus Total (solid line)
  - Same plot for various B
- **Results:**
  - Secondary emission dominates at late times (~days)
  - Fermi-LAT constraints for B in [10^{-20} -10^{-18}]G
  - CTAO constraints for B in [10^{-18} -10^{-16}]G

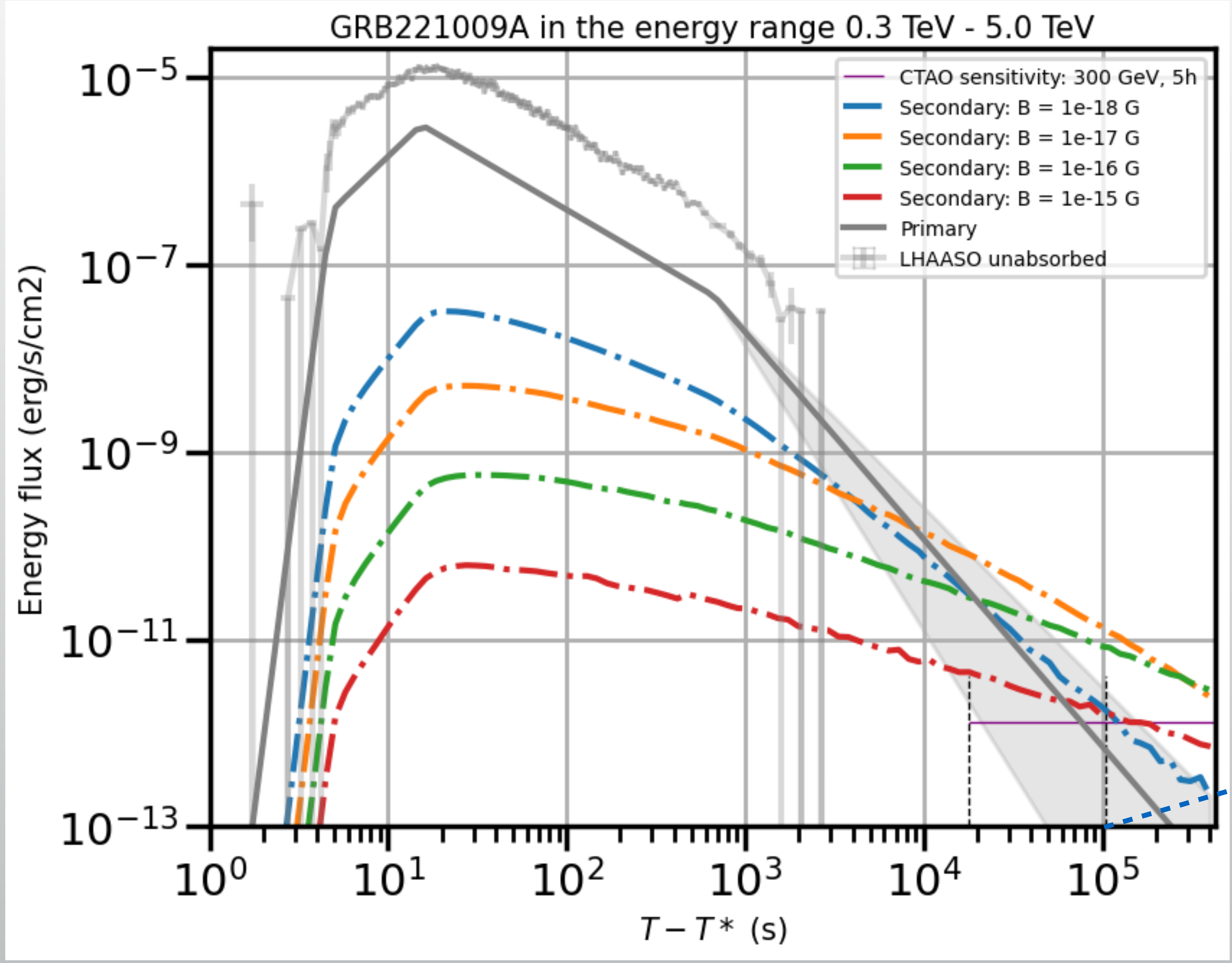
Light curve



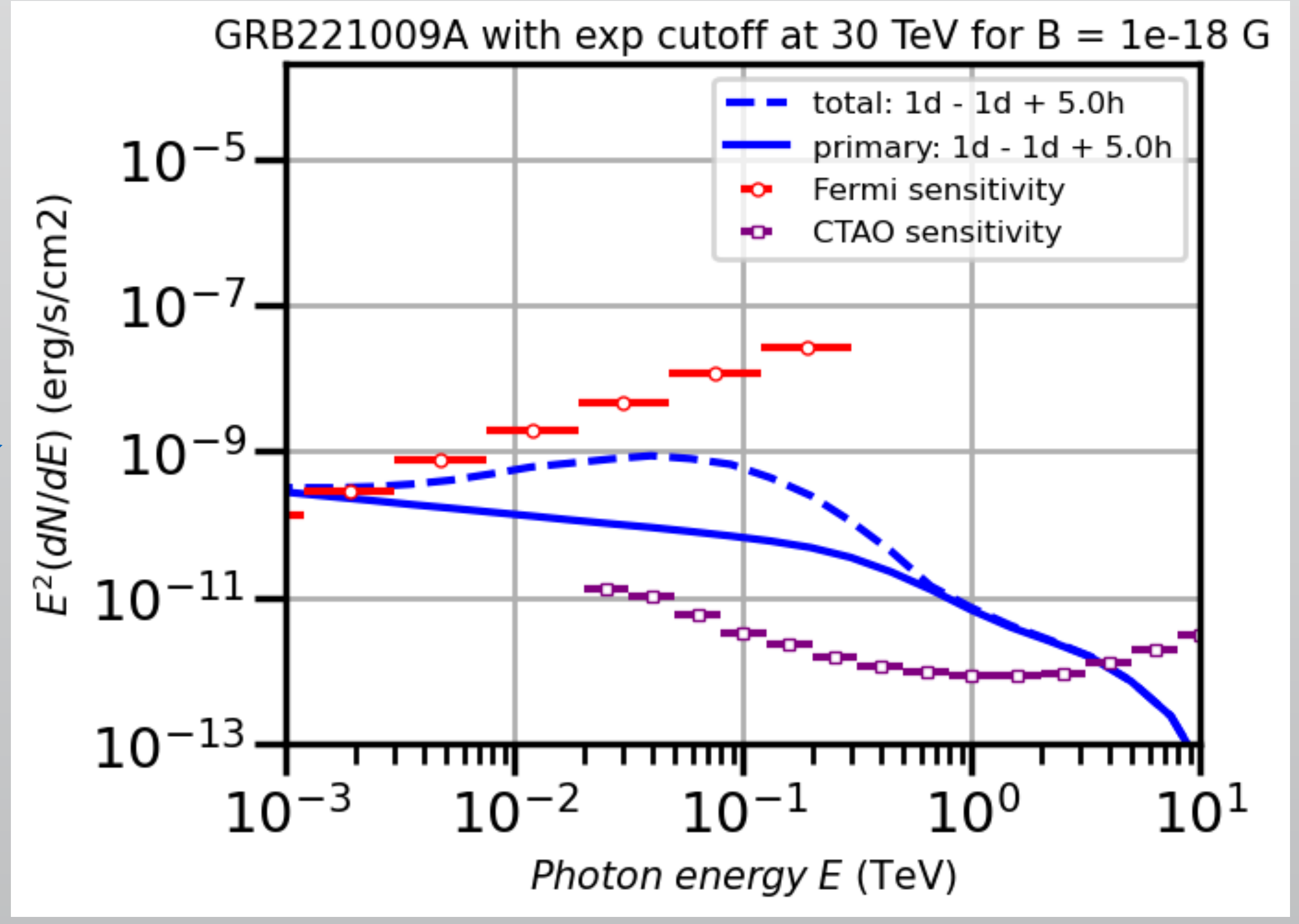
Light curve:

- Secondary emission dominates at late time (from hours to days)
- Possible to observe the GRB with CTAO during several days depending on B
- CTAO would have constrained B in the [10^{-18} -10^{-16}]G range with GRB190114C in ideal conditions
- Complementary with energy spectra analysis at multiple time periods

GRB221009A case



5 hours, 2nd night



Light curve:

- The BOAT
- Larger constraints up to 10^{-15} G
- Unlikely to be seen during CTAO's activity

Conclusions

- **On a bright GRB (GRB190114C), our preliminary results show that with CTAO it will be possible to**
  - Detect GRB emissions for several days
  - Measure any B in the 10^{-18}-10^{-16} G range
  - Put lower limits at $B=10^{-16}$ G for any larger field

- **This result will be extended:**
  - Various λ_B
  - Complex spectral shapes
  - Time dependent spectral fitting

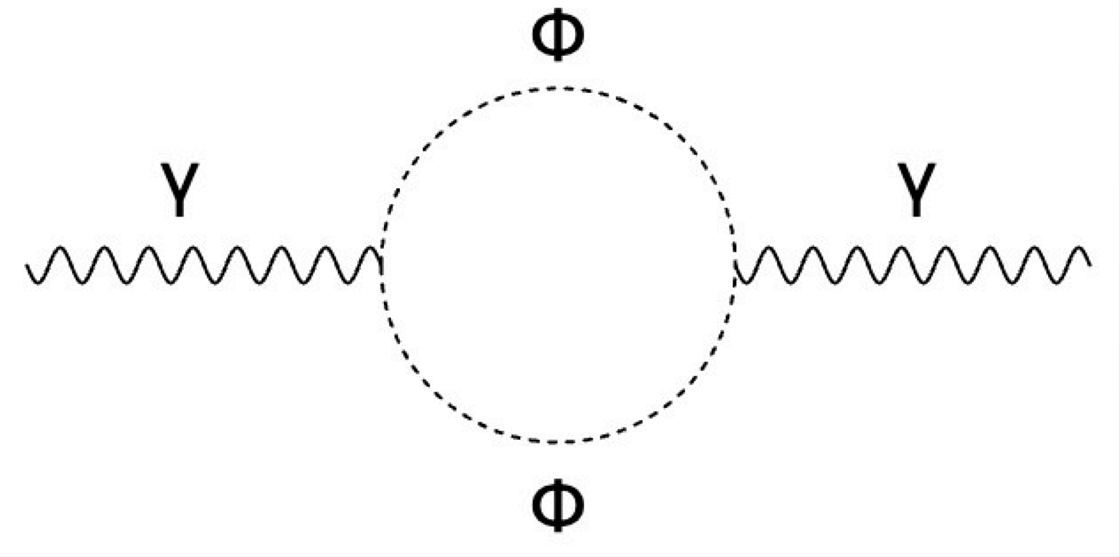
Appendix

References for slide 2 (left to right, up to down)

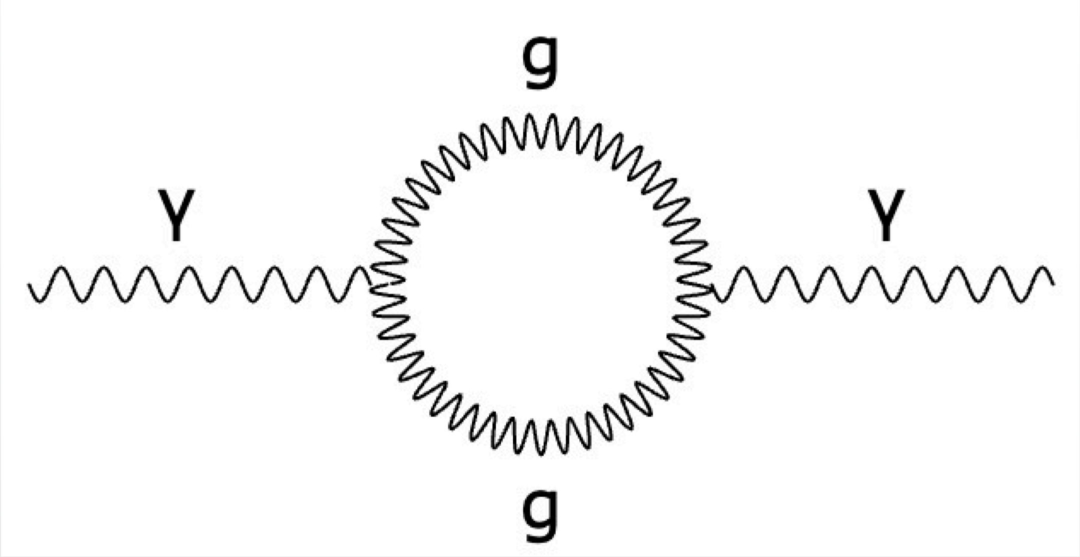
- Earth magnetosphere, **Murugesu, *New Scientist*, April 12, 2022.**
- Sun magnetosphere, **Schriver and Title, 2011.**
- M51 (Hubble telescope) intensity contours, **Effelsberg and VLA, MPIfR Bonn**
- Left: El Gordo cluster (Chandra X-ray observatory & Ground-based telescopes), Right: Fishhook galaxy and Milky-Way galaxy, **NASA/ESA/CSA**
- An image from the millenium simulation, **Springel+2005**
- Dark matter distribution, **Markus Haider/Illustris collaboration**

Two main methods

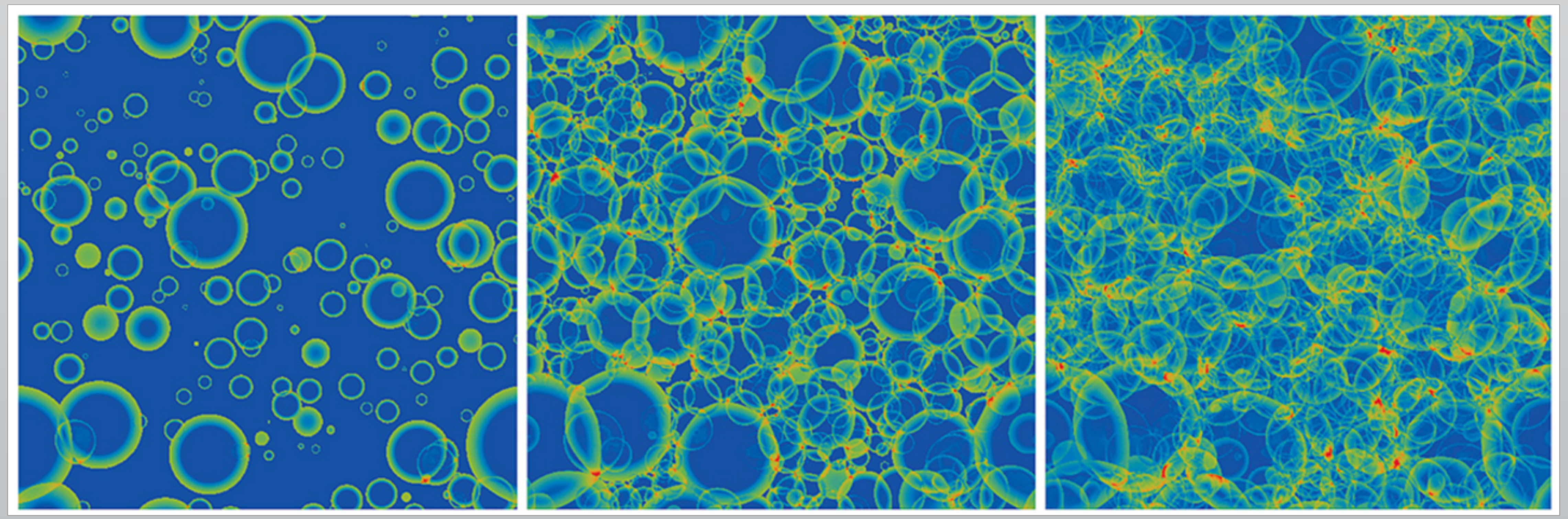
- **Inflationary coupling** $\mathcal{L} \Rightarrow A_\mu \Rightarrow P_B \Rightarrow \rho_B \Rightarrow (B,\lambda_B)$
  - **Simple inflation coupling**
  - **Helical inflation coupling**
  - **Curvature coupling**
- **1st order phase transitions** *Leptogenesis sector*
  - **Electroweak phase transition**
  - **Quantum chromodynamics phase transition**



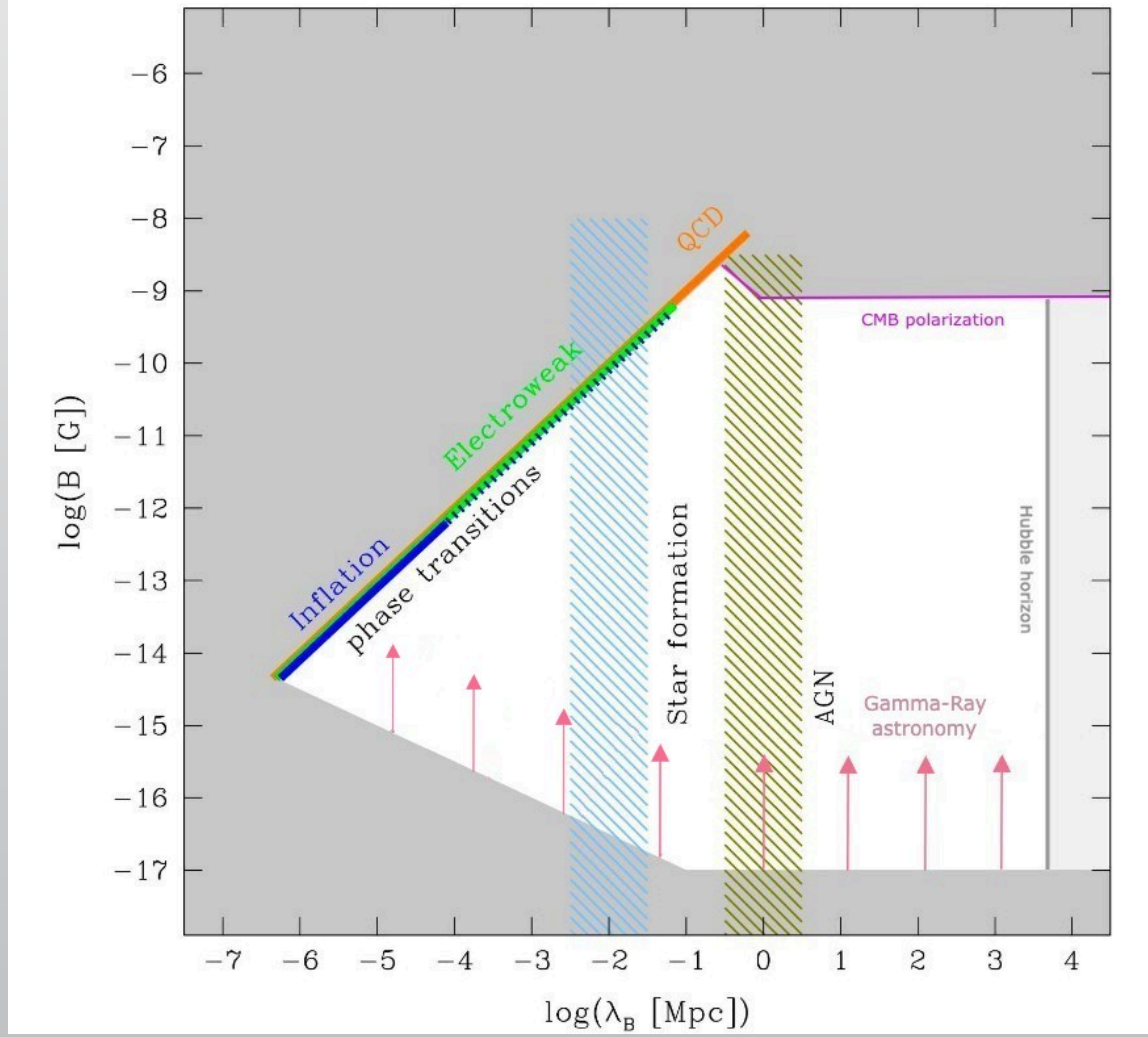
Inflationary interacting photons



Gravitationally interacting photons



Bubble nucleation



Complete map of constraints for the IGMF

Inflationary magnetogenesis

Recipe

$$\partial_\nu\left(\frac{\partial\mathcal{L}}{\partial(\partial_\mu A_\nu)}\right)=\frac{\partial\mathcal{L}}{\partial A^\mu}$$

$$Equations\ of\ motion\ (A^\mu)=0$$

$$\hookrightarrow \quad P_B=4\pi\frac{k^2}{f^2}\,|\tilde{\mathcal{A}}(k,t)|^2$$

↙ ↘

$$\rho_B=\frac{1}{2\pi^2 a^4}\int\frac{\mathrm{d}k}{k}k^3P_B(k)$$

↓

$$B=\sqrt{2\rho_B}$$

$$\frac{\mathrm{d}\rho_B}{\mathrm{d}\log k}=\frac{k^3P_B(k)}{2\pi^2}$$

$$\lambda_B=\frac{2\pi}{\rho_B}\int\rho_B(k)\frac{\mathrm{d}k}{k}$$

P_B: Magnetic power spectrum
ρ_B: Magnetic energy density
A^μ: 4-potential
a: scale factor

Lagrangian

$$\mathcal{L}=\sqrt{-g}\left[\frac{R}{2\kappa^2}+\mathcal{L}_\phi+\frac{1}{4}f(\phi)F_{\mu\nu}F^{\mu\nu}\right]$$

Simple coupling

$$\mathcal{L}=\sqrt{-g}\left[\frac{R}{2\kappa^2}+\mathcal{L}_\phi+\frac{1}{4}f(\phi)F_{\mu\nu}\widetilde{F^{\mu\nu}}\right]$$

Helical coupling

$$\mathcal{L}=\sqrt{-g}\left[\frac{R}{2\kappa^2}+\mathcal{L}_\phi+\frac{1}{4}F_{\mu\nu}F^{\mu\nu}+\frac{\alpha}{4m^2}R^{\mu\nu\alpha\beta}F_{\mu\nu}\widetilde{F_{\alpha\beta}}\right]$$

Curvature coupling

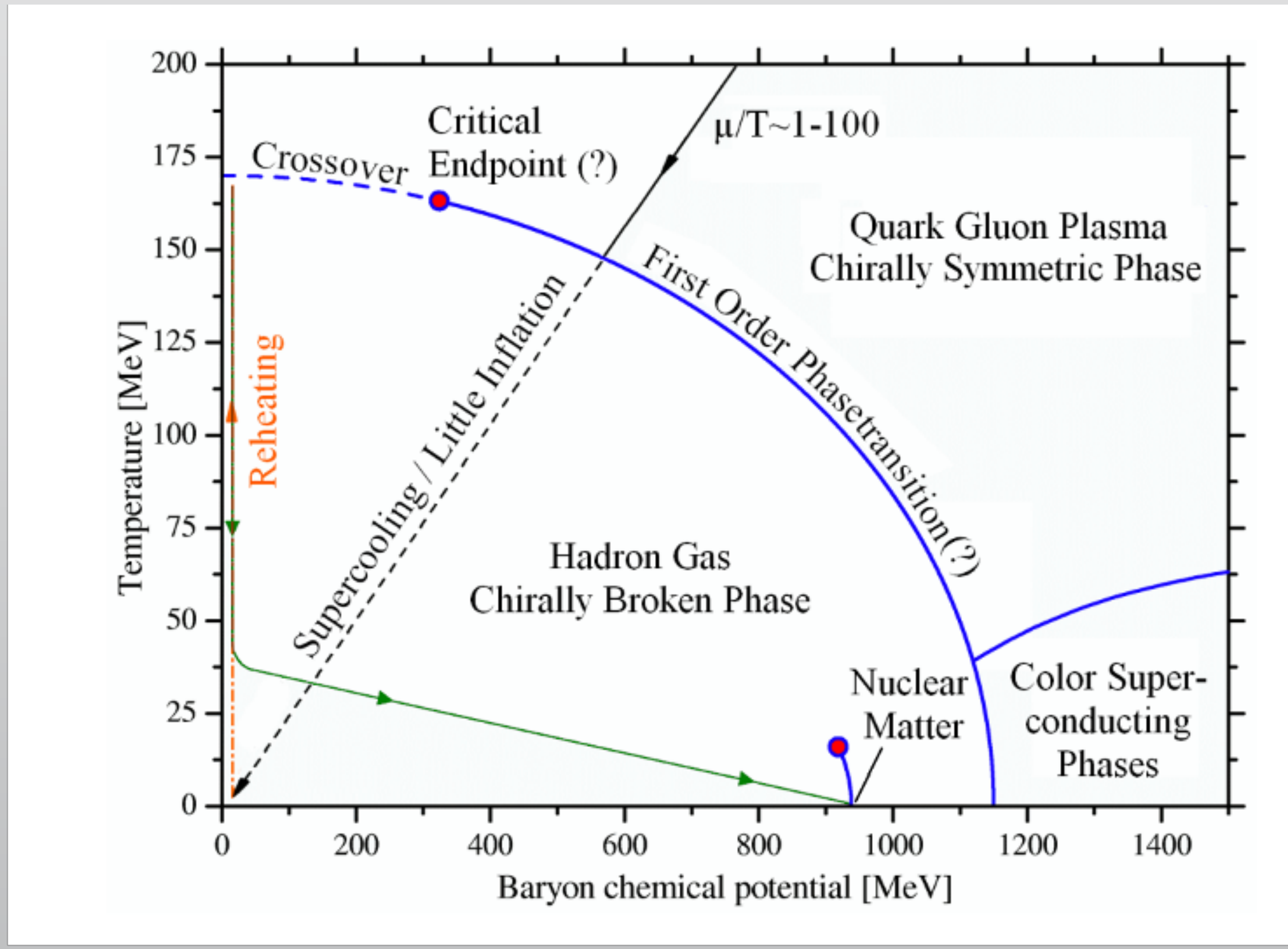
Phase transitions

Electroweak scenarios: Lepton asymmetry

↗ Axial current $\rightarrow \partial_\mu j_R^\mu = -\frac{g'^2 Y_R^2}{64\pi^2} F^{\mu\nu} F_{\mu\nu} \rightarrow \Delta N_R = \frac{1}{2} Y_R^2 \Delta N_{CS} \rightarrow N_{CS} = -\frac{g'^2}{32\pi^2} \int d^3 x \epsilon_{ijk} F_{ij} A_k$

↘ Top quark current $\rightarrow \nabla^2 A^0 = -e\rho_{EM}(x) \rightarrow B_{Bubble} \sim \frac{M_{Bubble}}{R_{Bubble}^3}$

Chromodynamics scenarios:



QCD phase diagram

$\Delta(B-L) = 0, \quad \Delta B \sim 10^{-10}$ BUT $\frac{\Delta L}{\Delta B} \leq 2.10^{-8} \rightarrow$ Weakly constraint lepton asymmetry

↪ Large baryon asymmetry → Little inflation → Observationally consistent endpoint

Cosmic evolution

1. Initial conditions

$$P_B(k,t_*) = P_{*B}k^{n_s} \qquad P_K(k,t_*) = P_{*K}k^{n_k}$$

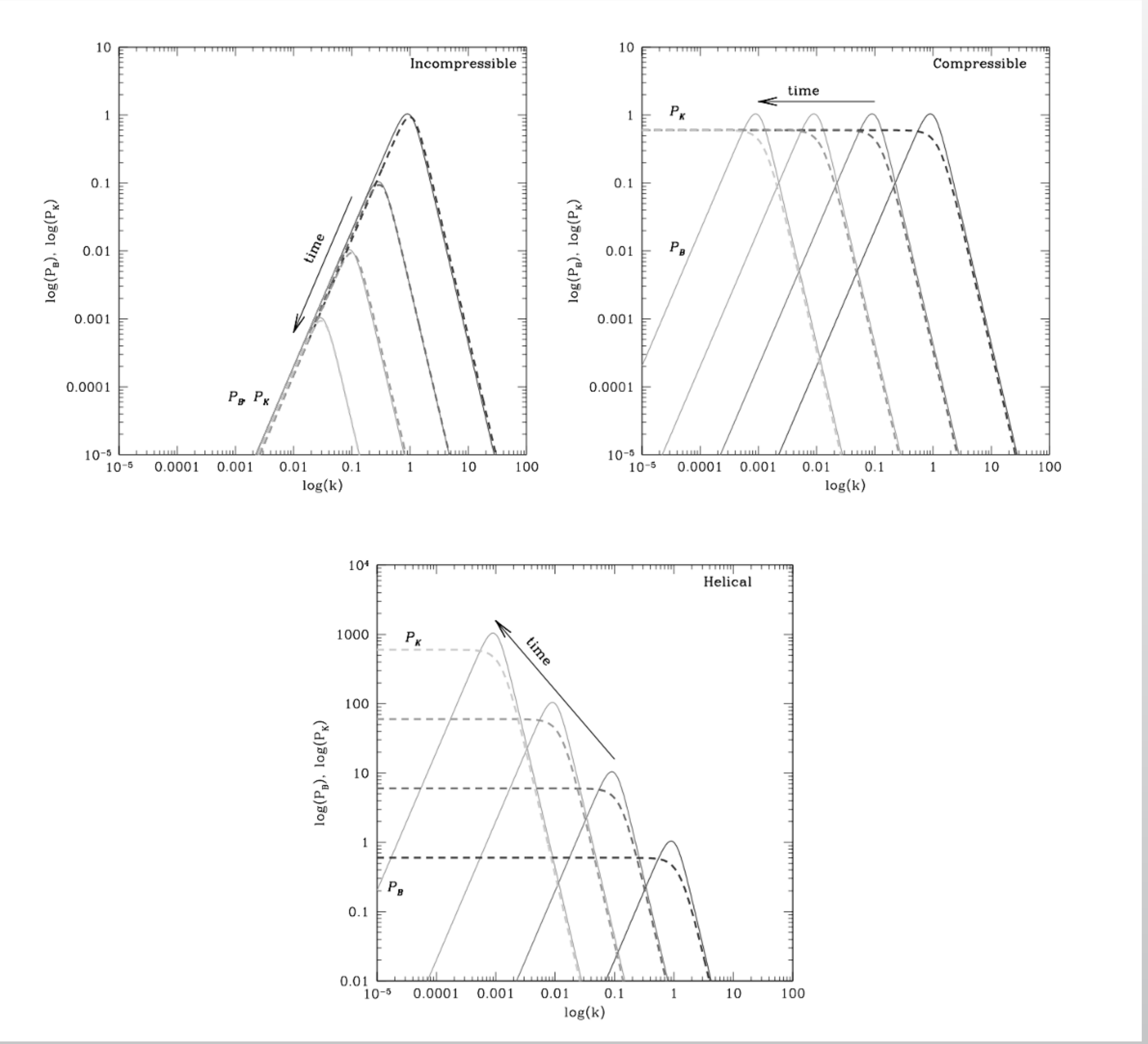
2. MHD turbulence

$$\frac{\partial\tilde{\rho}}{\partial t} + \nabla\big((\tilde{p}+\tilde{\rho})\vec{v}\big) = 0$$

$$\frac{\partial\vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\vec{v} + \frac{\vec{v}}{\tilde{\rho}+\tilde{p}}\frac{\partial\tilde{p}}{\partial t} + \frac{\nabla\tilde{p}}{\tilde{\rho}+\tilde{p}} + \frac{\vec{\tilde{B}}\times\left(\nabla\times\vec{\tilde{B}}\right)}{\tilde{\rho}+\tilde{p}} = \tilde{\nu}\left(\Delta\vec{v} + \frac{1}{3}\nabla(\nabla\cdot\vec{v})\right)$$

$$\frac{\partial\vec{\tilde{B}}}{\partial t} - \nabla\times\left(\vec{v}\times\vec{\tilde{B}}\right) = \frac{1}{\tilde{\sigma}}\Delta\vec{\tilde{B}}$$

3. Cosmological decoupling regimes

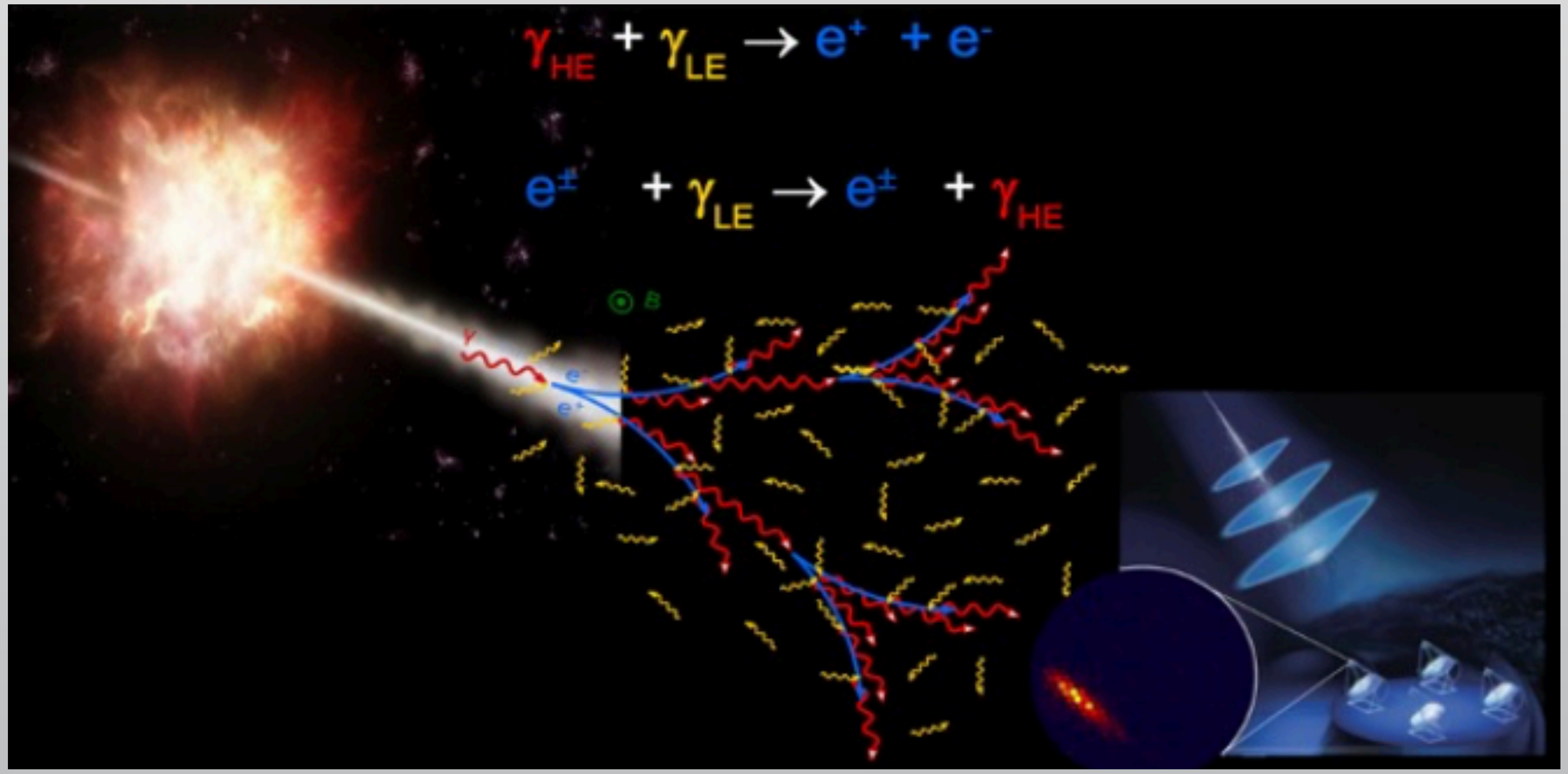


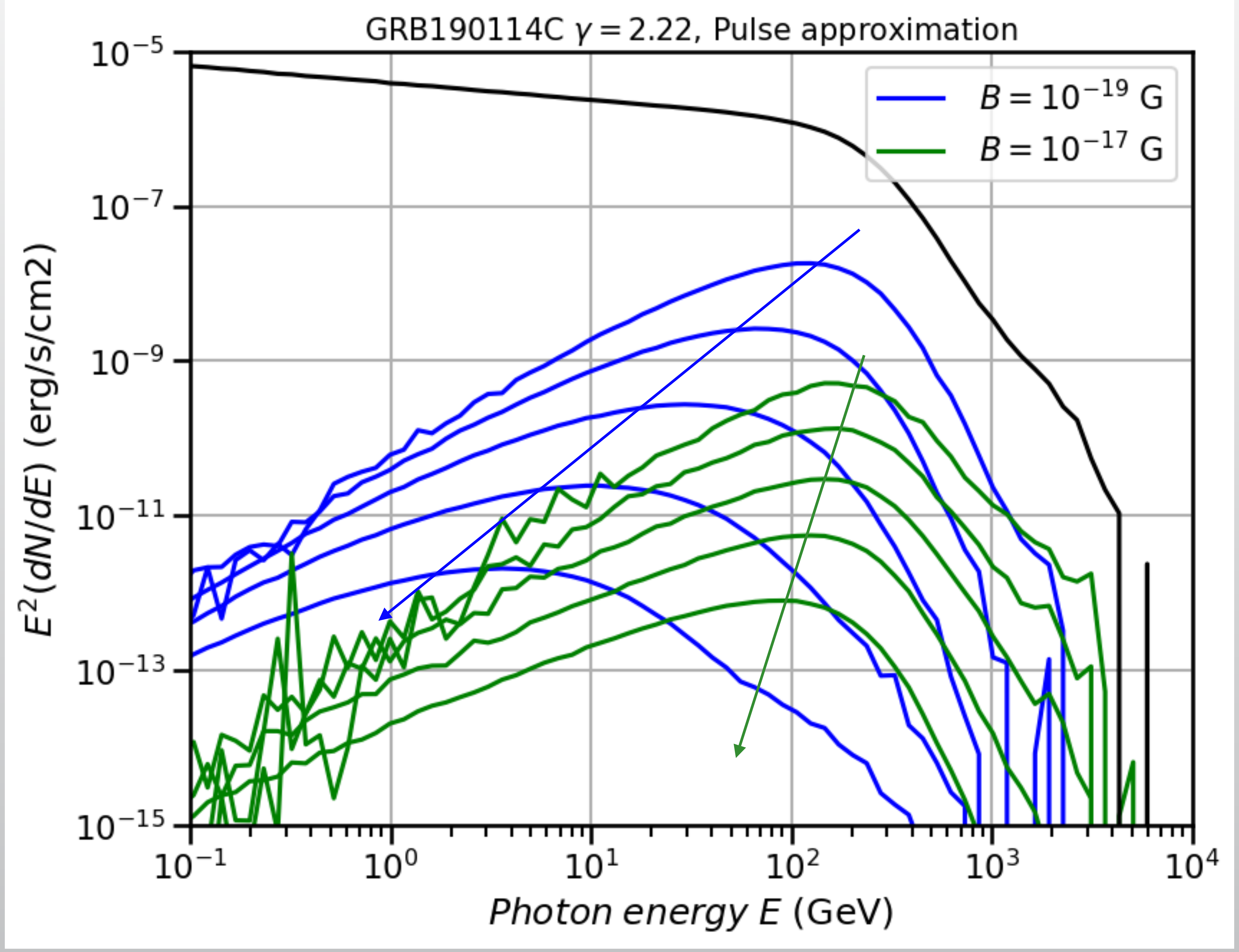
Magnetic power spectrum behaviours

Time delays with GRBs: current status

- **Most studies assume an instantaneous primary emission:**
  - Good approximation for late time
  - Not so much at early times
- **Peak energy of the secondary emission:**

$$E_{ic} \approx 60 \left(\frac{\lambda_{\gamma\gamma}}{100\mathrm{Mpc}}\right)^{1/2} \left(\frac{\Delta t}{1\mathrm{hour}}\right)^{-1/2} \left(\frac{B}{10^{-19}\mathrm{G}}\right) \mathrm{GeV}$$

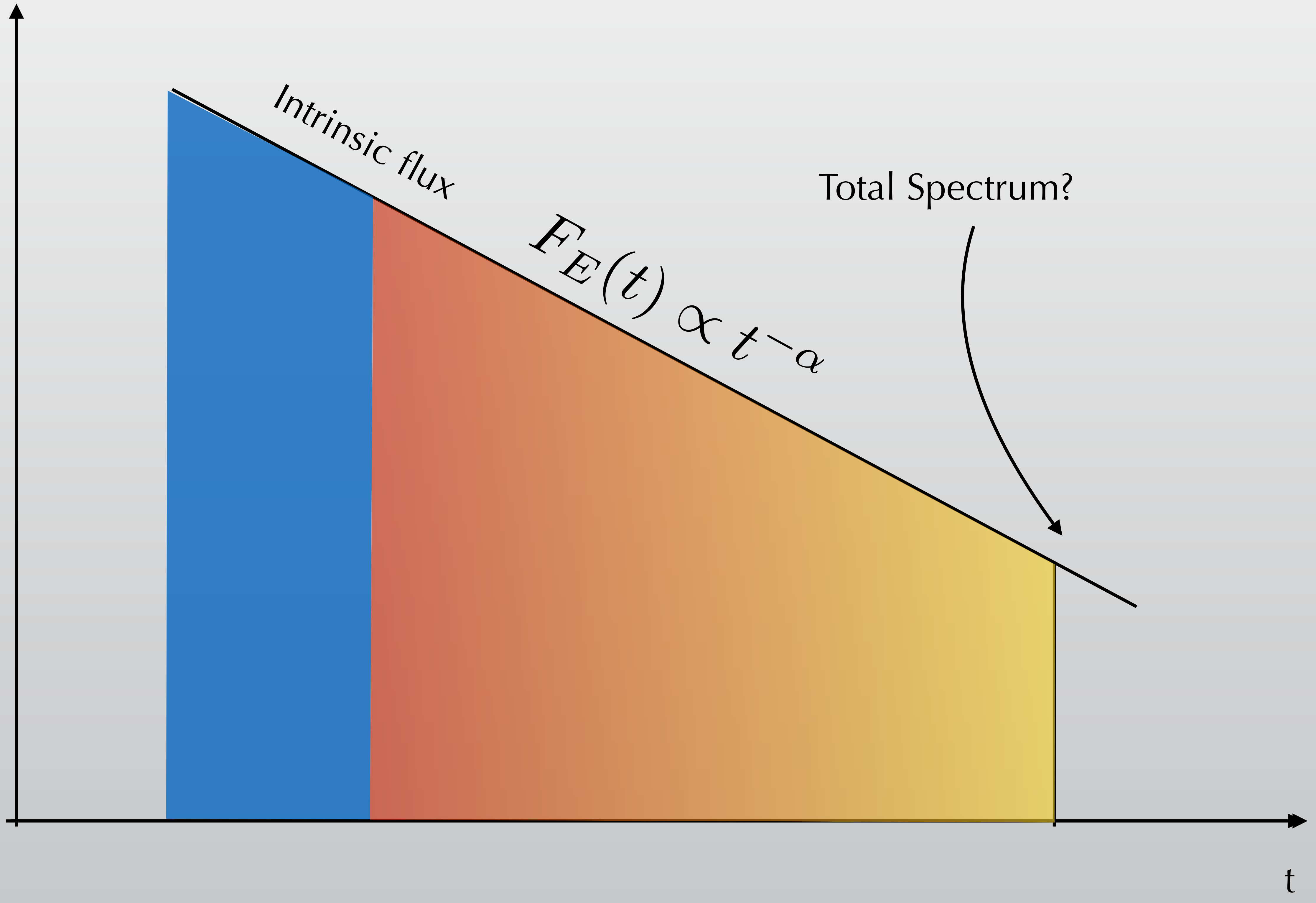




Cascade numerical simulation

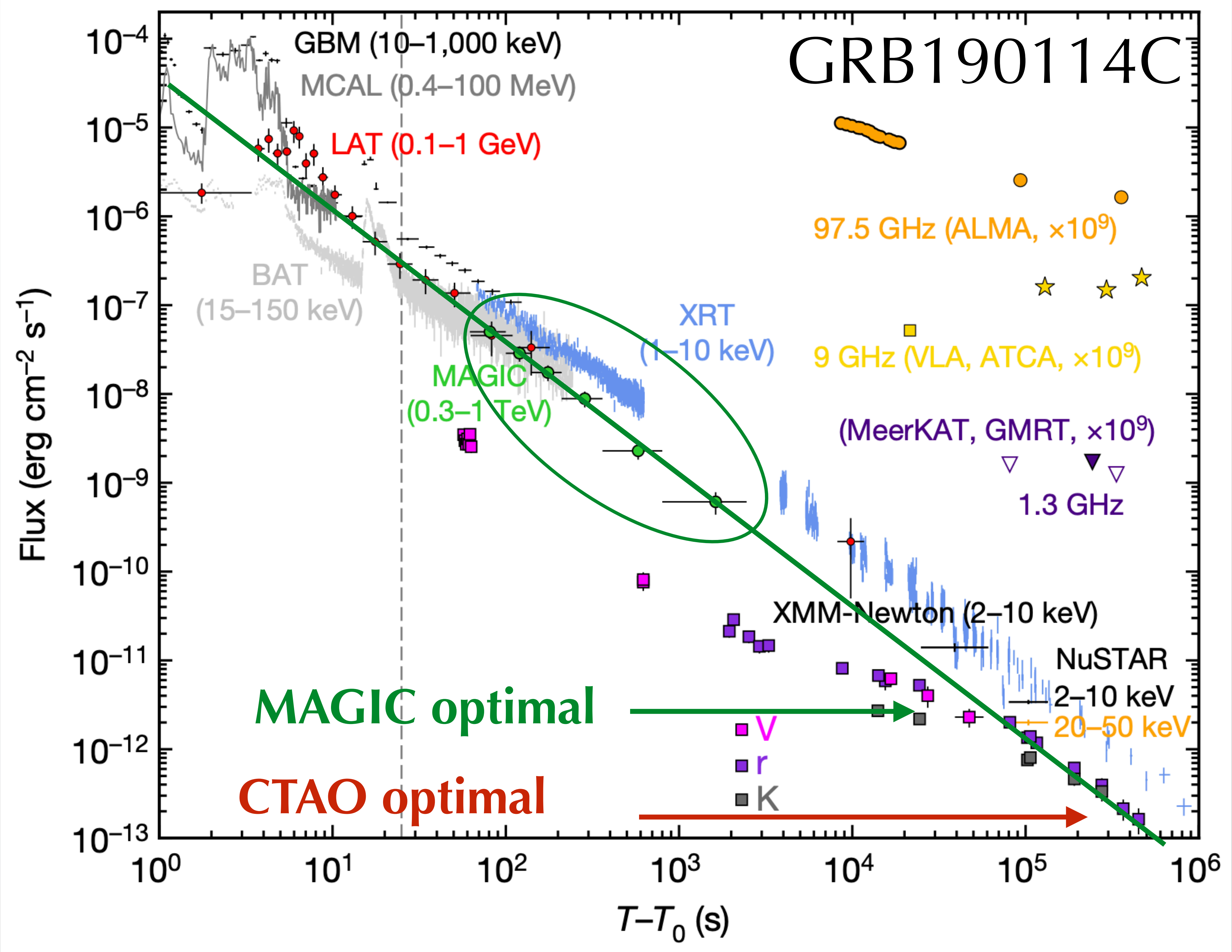
- **Full 3D Monte Carlo simulations of the cascade with non-instantaneous intrinsic flux**
- **One approximation: cubes of uniform magnetic field (here 1 Mpc) and random orientations —> reproduces magnetic turbulence**
- **Monte Carlo simulation for the pair creation and inverse Compton scattering**
- **Particles characteristics (E_0,E,Δt,θ,z,B,λ_B) stored when reaching the Earth**
- **Post-treatment: source intrinsic properties recovered by reweighing the detected events:**

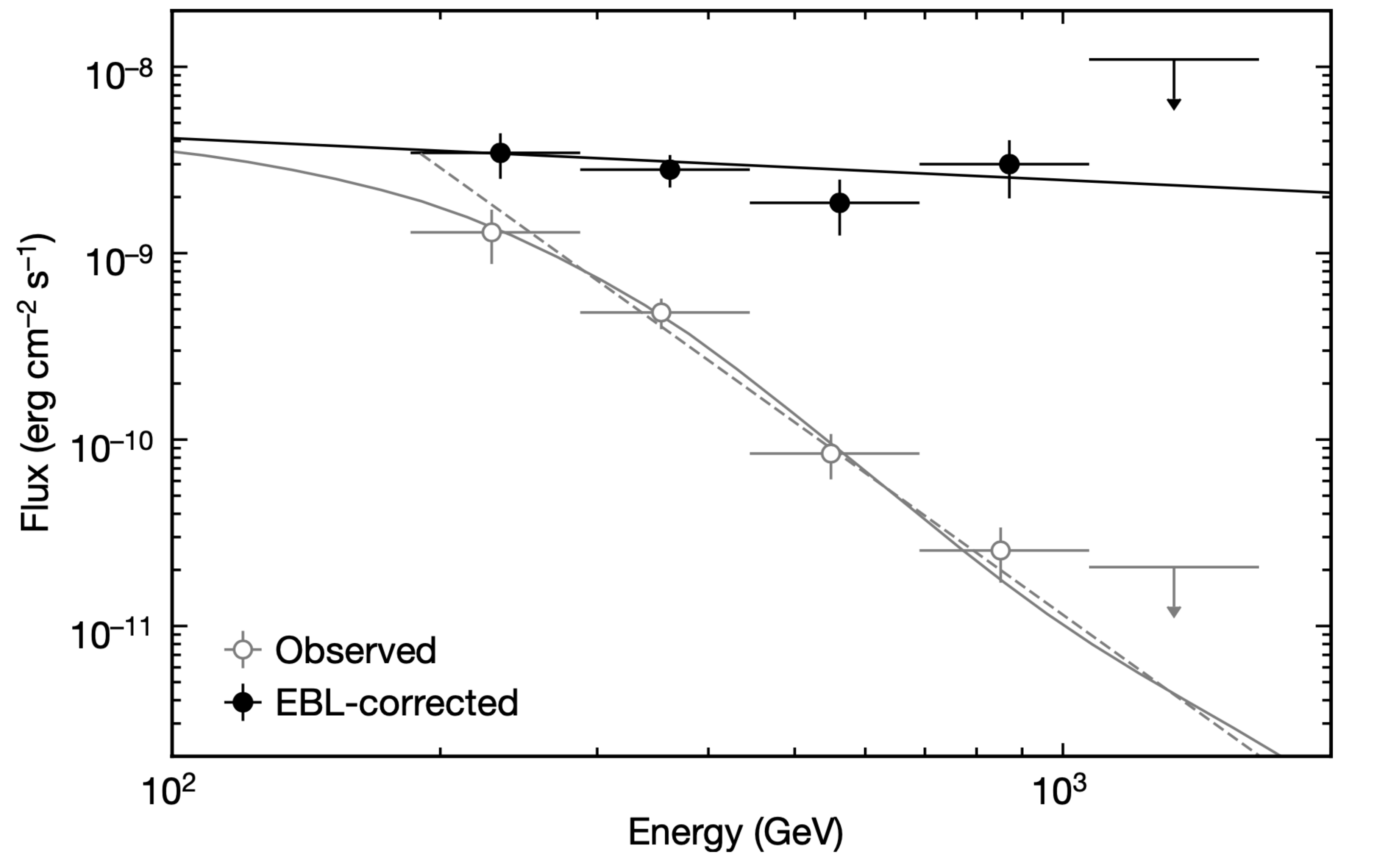
$$N_{E_0}(t) \propto t^{-\alpha} E_0^{-\Gamma}$$



Intrinsic flux evolution

GRBs in the VHE band





MAGIC coll. 2020a,b

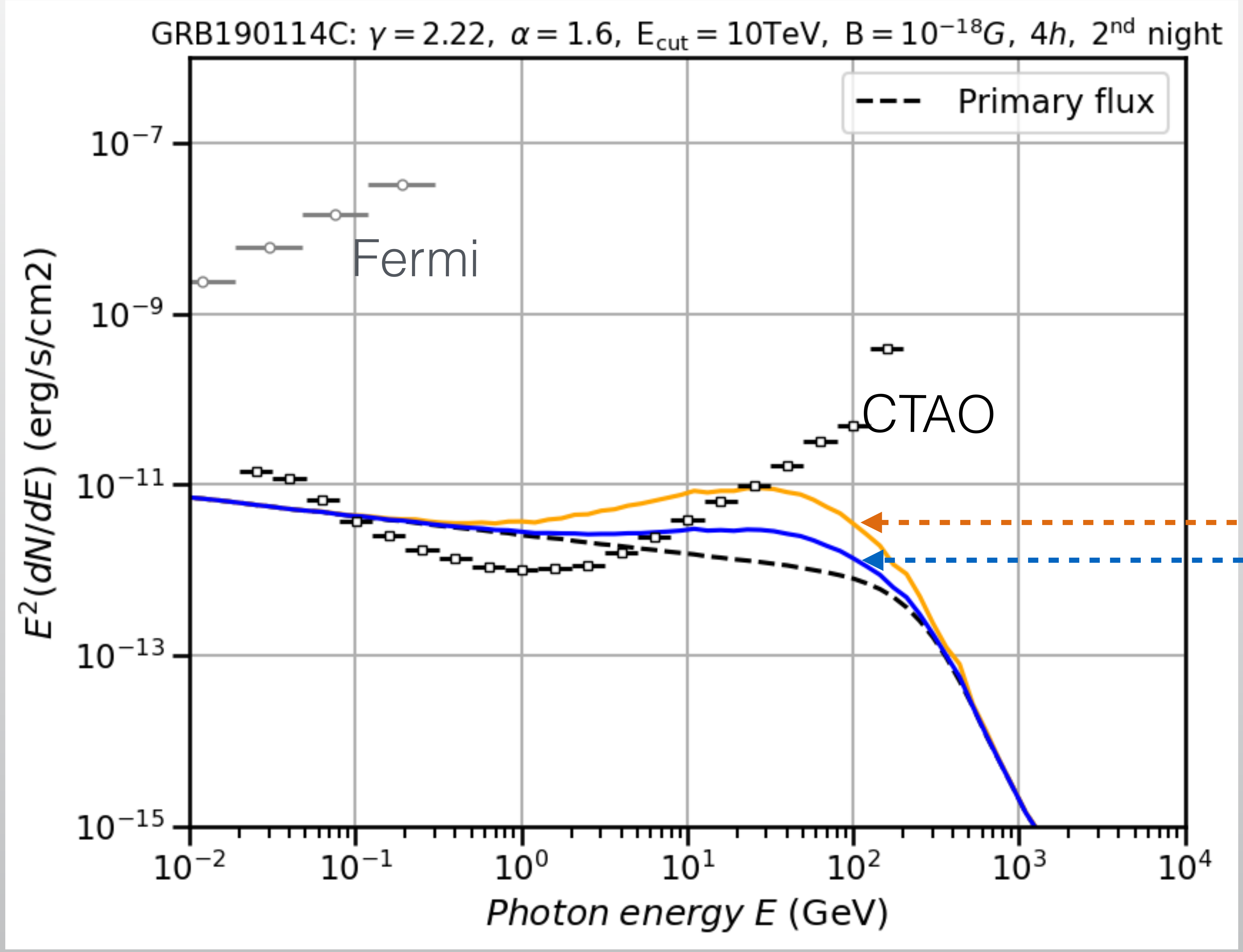
- **Observed up to a couple of days**
- **Consistent with power-laws:**

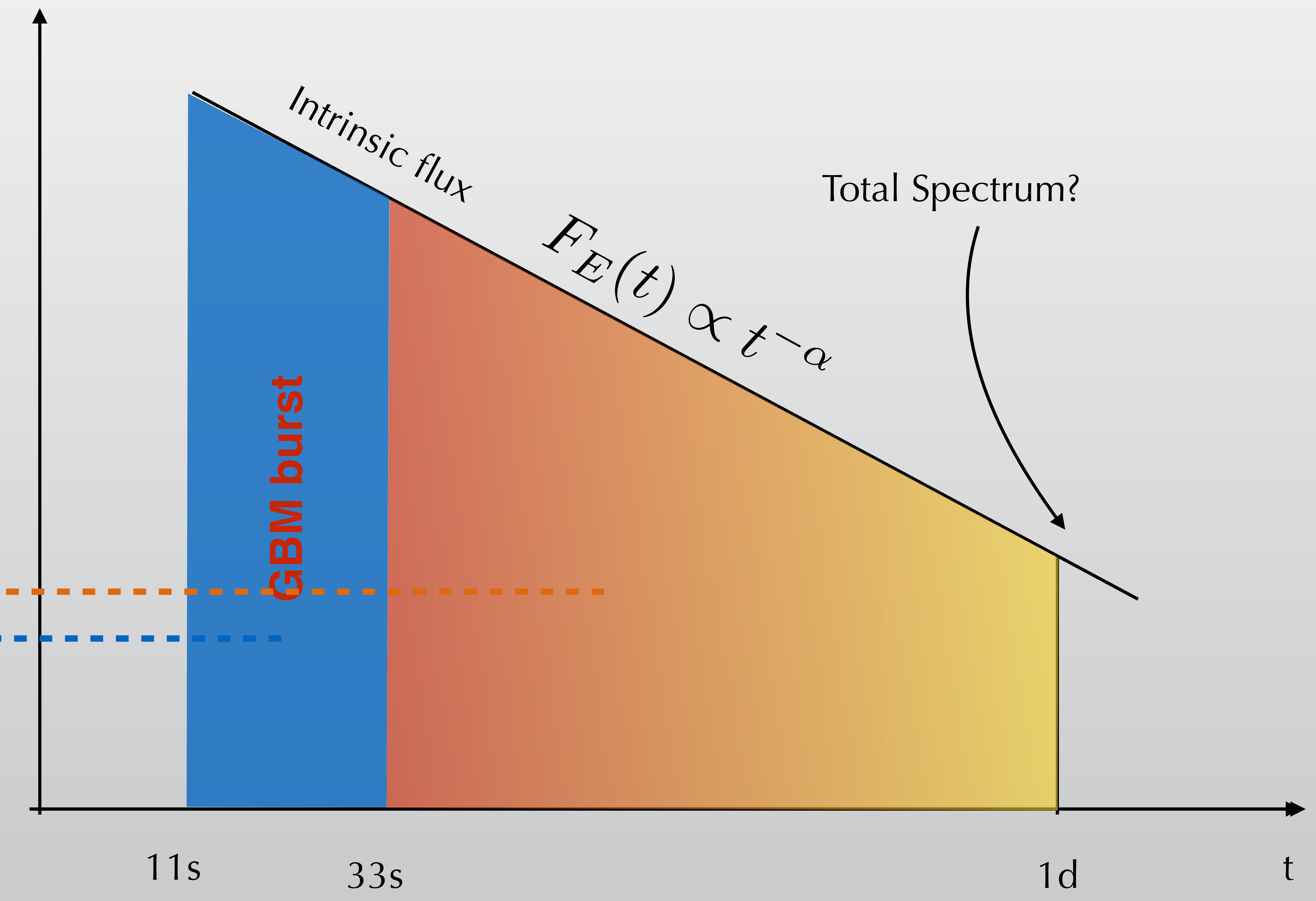
$$N_E(t) \propto t^{-\alpha} E^{-\Gamma}$$

- **Unknown cutoff energy: E_{cut}**

	IACT	z	t_{max}	$\Gamma_{(EBL\ corr)}$	α	Highest E
GRB130427C	*(LAT)*	*0.34*	*20h*	*1.66*	*1.17*	----
GRB160921B	MAGIC	0.16				0.5 TeV
GRB180720B	HESS	0.65	12h	**1.6**	?	0.4 TeV
GRB190114C	MAGIC	0.42	40min	2.22	1.6	1 TeV
GRB190829A	HESS	0.08	**56h**	2.07	1.09	4 TeV
GRB201216C	MAGIC	1.1	2h			----
GRB221009A	Lhaaso	0.15	1h	2.3	1.1/2.2	**7 TeV**

Pulse versus Power law





Fresh secondaries:

- stronger emission + plateau => Stronger constraints
- e.g. GRB221009A, Pulse: $B>10^{-19}$ G, PL: $B>10^{-17}$ G)

IGMF effect at fixed time