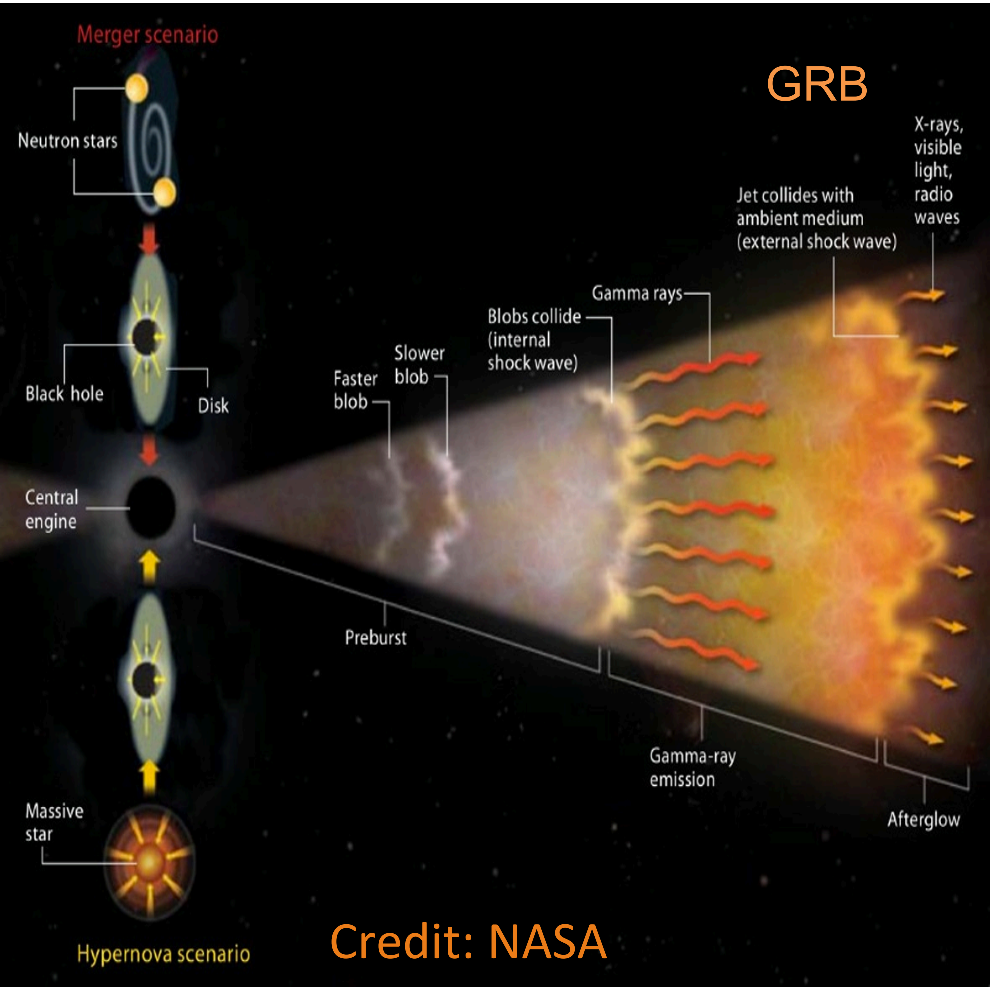
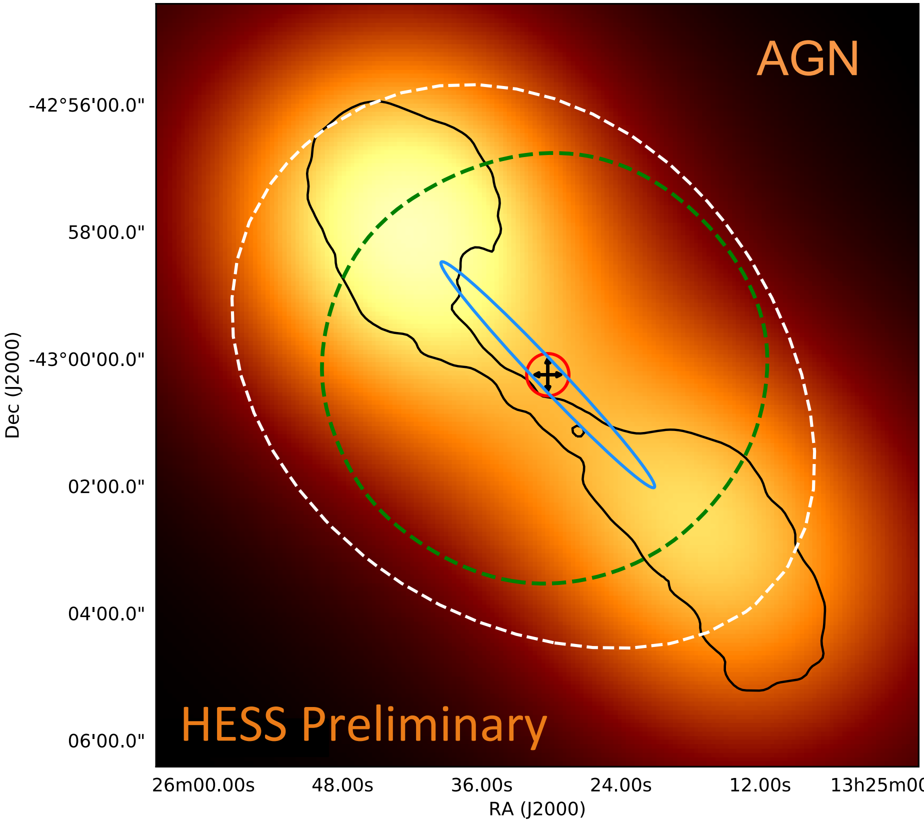
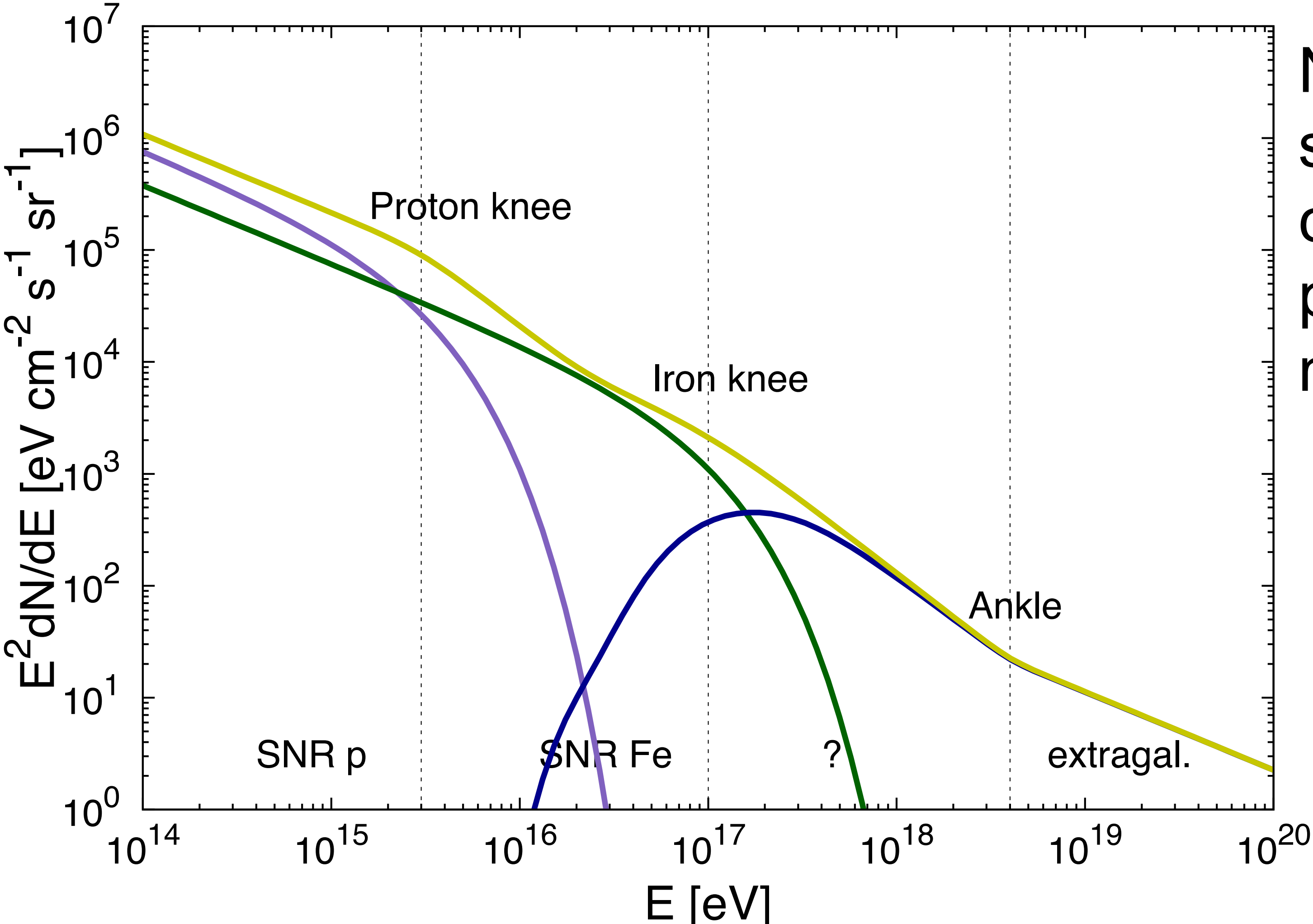
The Search for Efficient Particle Accelerators in the Universe





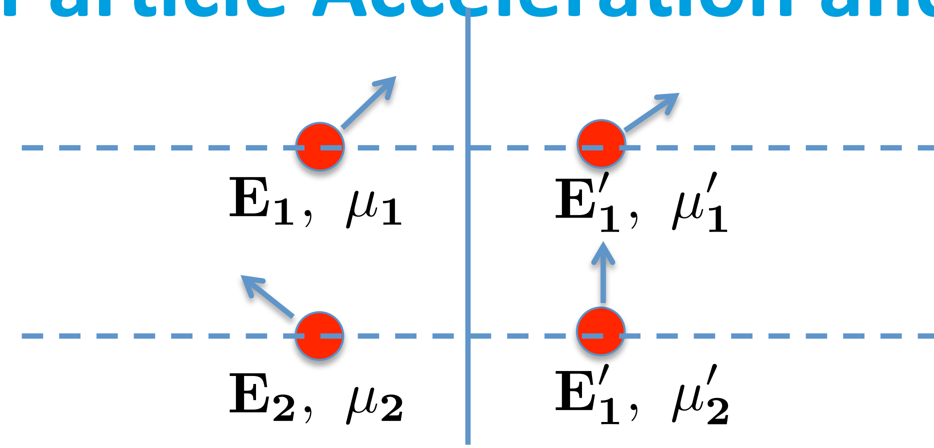
The Challenge of the Existence of Ultra High Energy Cosmic Rays



[A. Taylor, Nature 2016]

Note- spectrum composted on protons and nuclei

Particle Acceleration and Magnetic Turbulence

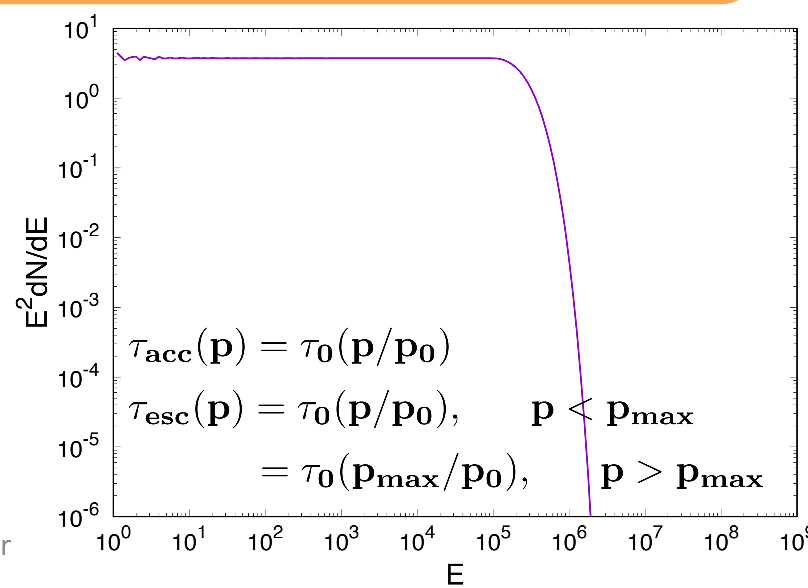


- Shifting of μ_1‘ to μ_2‘ is caused by magnetic turbulence, rate described by scattering time, which in Larmor time units is described by **η**

- Scattering agent velocity **β** dictates energy gain each crossing cycle

$$\cancel{\frac{\partial \mathbf{n}}{\partial \mathbf{t}}} = -\nabla_{\mathbf{p}} \cdot \left[\frac{\mathbf{p}}{\tau_{\mathbf{acc}}(\mathbf{p})}\mathbf{n} - \cancel{\frac{\mathbf{p}}{\tau_{\mathbf{loss}}(\mathbf{p})}}\mathbf{n}\right] - \frac{\mathbf{n}}{\tau_{\mathbf{esc}}(\mathbf{p})} + \mathbf{Q}$$

Note- shock acceleration isn’t the only acceleration mechanism on the block!

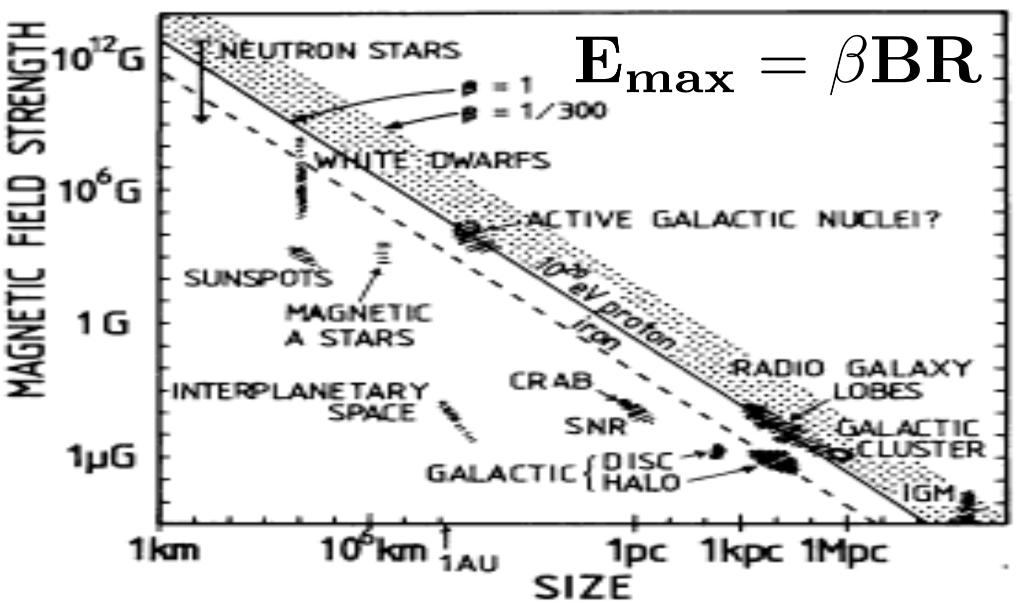


Cosmic Ray Source Requirements

$$\mathbf{t_{acc}} = \eta \frac{\mathbf{R_{lar}}}{\mathbf{c}\beta^{\mathbf{2}}}$$

$$\mathbf{t_{esc.}} = \frac{\mathbf{R}}{\mathbf{c}\beta}$$

[AM Hillas (1984)]



$$\mathbf{E_{max}} = \beta \mathbf{BR}$$

[Norman et al. (1995)]

$$\mathbf{L_B} = \mathbf{U_B 4}\pi\mathbf{R^2 c}$$

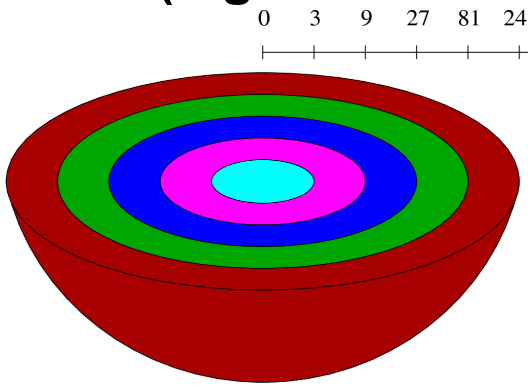
Under the assumption of equipartition of energy between kinetic energy and magnetic field:

$$\mathbf{L_0} > \mathbf{3} \times \mathbf{10^{42}} \frac{\mathbf{1}}{\beta^{\mathbf{2}}} \left(\frac{\mathbf{E_p}}{\mathbf{3} \times \mathbf{10^{18}}\ \mathrm{eV}} \right)^{\mathbf{2}} \mathrm{erg\ s^{-1}}$$

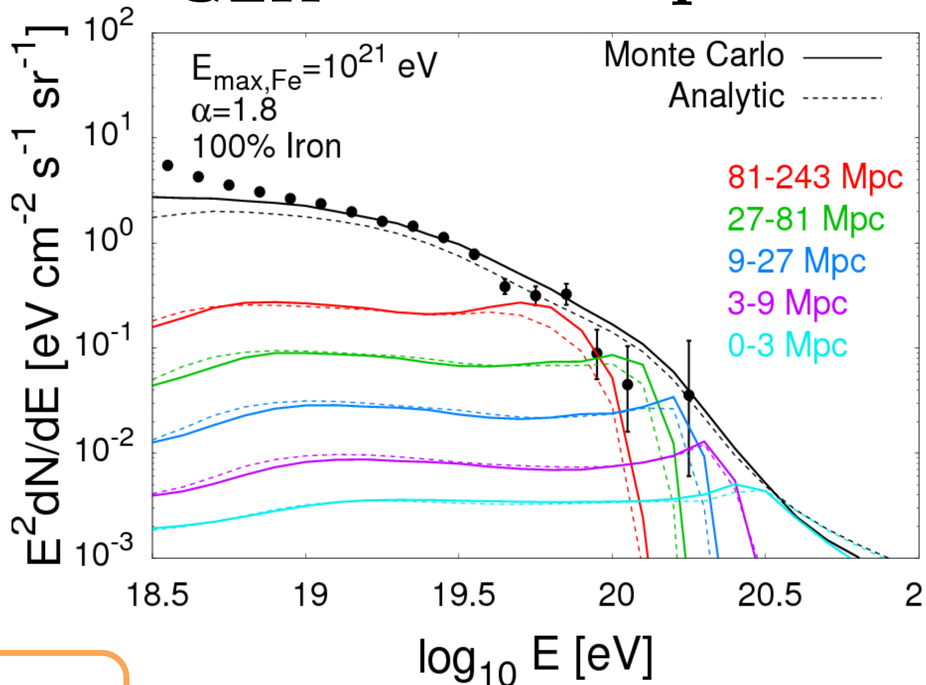
DESY.

Local Scales Effect Highest Energies

(logarithmic scale)



$$\mathrm{d_{GZK}} \sim 100\ \mathrm{Mpc}$$



[A. Taylor et al., Phys Rev D (2011)]

[R. Lang and A. Taylor in prep.]

$$\mathcal{L}_0 \approx 4 \times 10^{44}\ \mathrm{erg\ Mpc^{-3}\ yr^{-1}}$$

[E. Waxman, Astrophys. J. 452 (1995)]

$$\mathcal{L}_0 \approx \mathrm{L_0 n_0} \approx \mathrm{E_0 \dot{n}_0} \Rightarrow \mathrm{n_0} \sim 10^{-5}\ \mathrm{Mpc^{-3}}, \quad \mathrm{\dot{n}_0} \sim 10^{-6}\ \mathrm{Mpc^{-3}\ yr^{-1}}$$

Only AGN and GRB appears to satisfy these requirements as the sources of extragalactic cosmic rays

Electron Acceleration with Cooling

$$\mathbf{t_{acc}} = \eta \frac{\mathbf{R_{lar}}}{\mathbf{c}\beta^{\mathbf{2}}}$$

$$\mathbf{t_{cool}} = \frac{\mathbf{9}}{\mathbf{8}\pi\alpha}\left(\frac{\mathbf{U_{Bcrit}}}{\mathbf{U_B}}\right)\left(\frac{\mathbf{h}}{\mathbf{E_e}}\right)$$

$$\mathbf{B_{crit}} = \mathbf{4} \times \mathbf{10^{13}G}$$

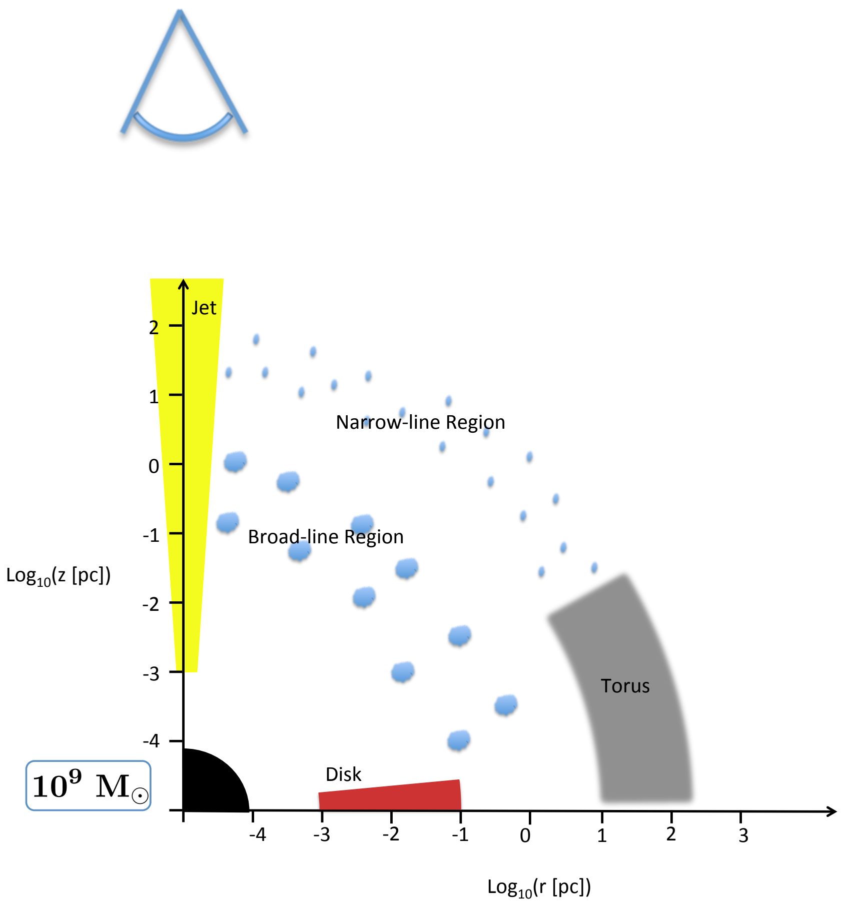
$$\mathbf{E_e^{max}} = \left(\frac{\eta^{\mathbf{-1/2}}}{\alpha^{\mathbf{1/2}}(\mathbf{B}/\mathbf{B}_{\mathrm{crit}})^{\mathbf{1/2}}}\right)\mathbf{m_e c^2}$$

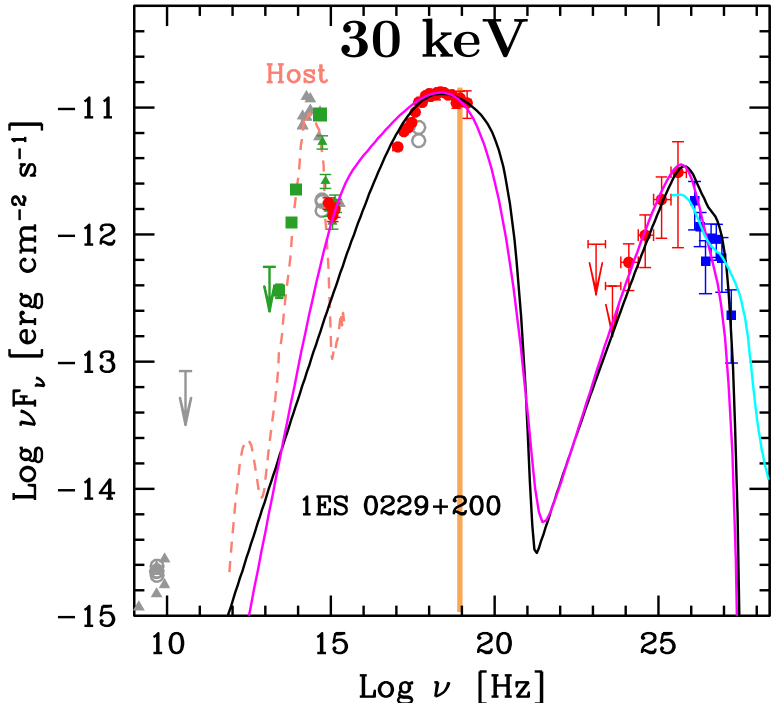
Maximum synchrotron energy tells us how efficient accelerator is!

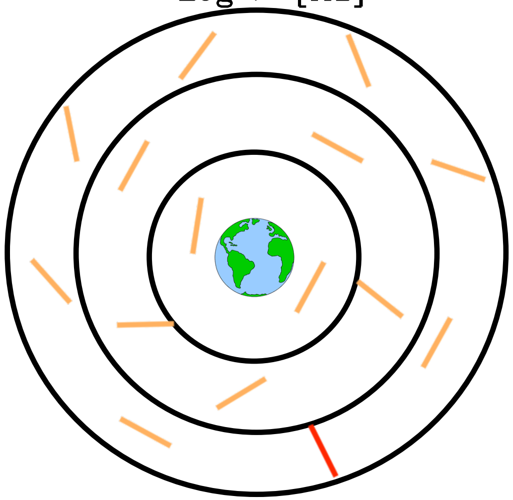
$$\mathbf{E_\gamma^{sync}} \approx \frac{\mathbf{9}}{\mathbf{4}}\eta^{\mathbf{-1}}\beta^{\mathbf{2}}\frac{\mathbf{m_e}}{\alpha}$$

Where do synchrotron cutoffs for AGN and GRB sit in energy?

Most Promising AGN (Blazars)
Extragalactic Cosmic Ray Source Candidates

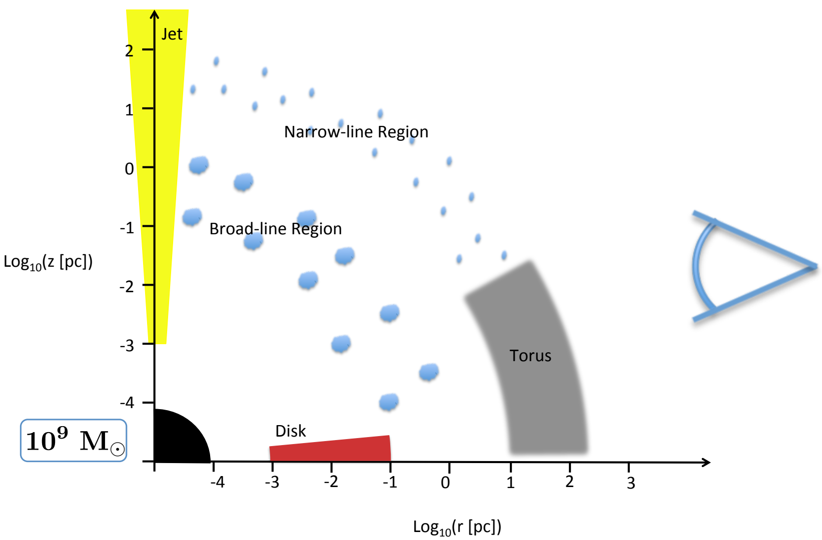




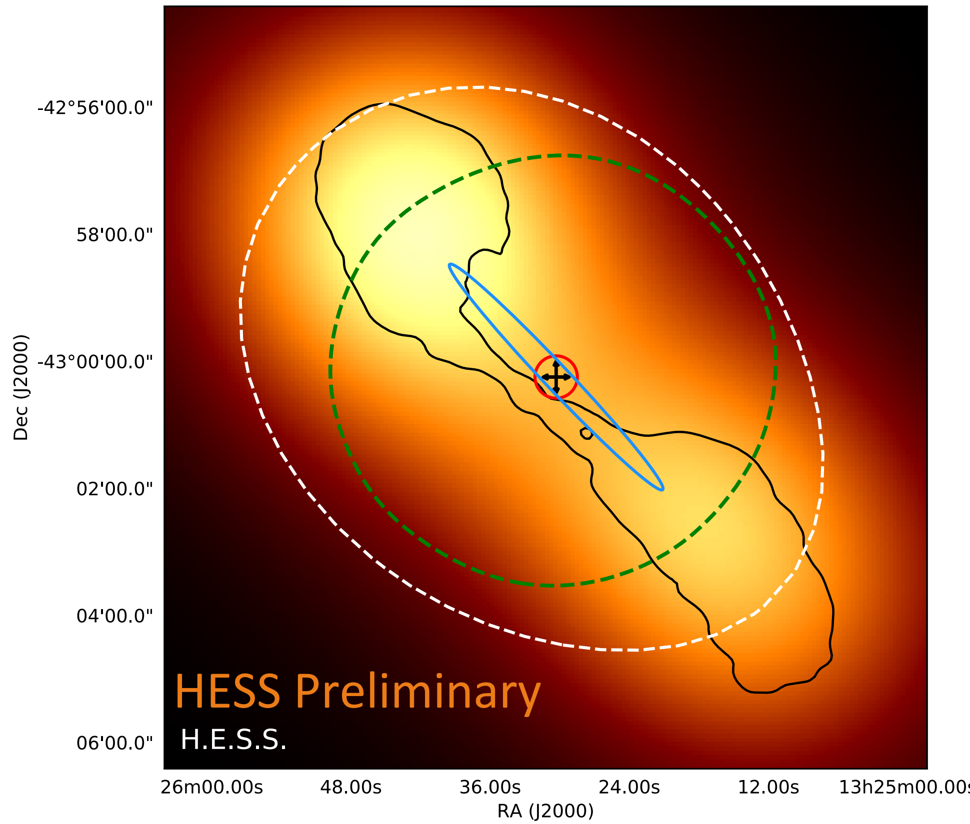


[J. Biteau, E. Pueschel, A. Taylor, et al., Nature Astronomy 2020]

Centaurus A - VHE Extension



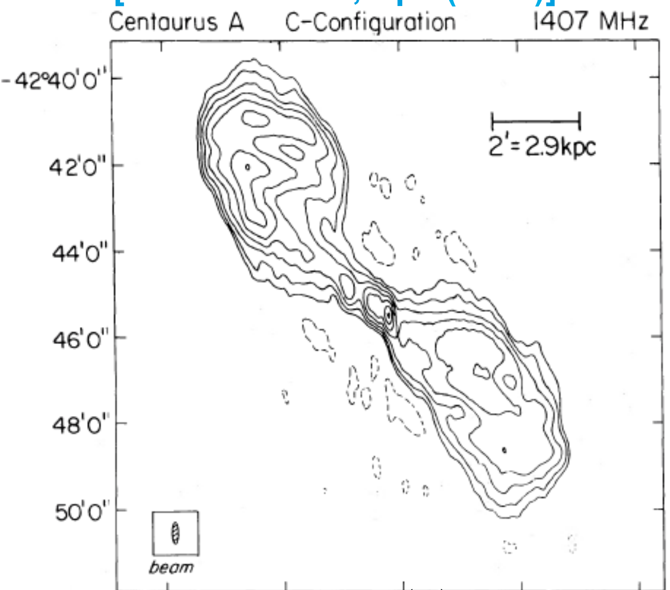
HESS Detected Extension on ~2kpc scale



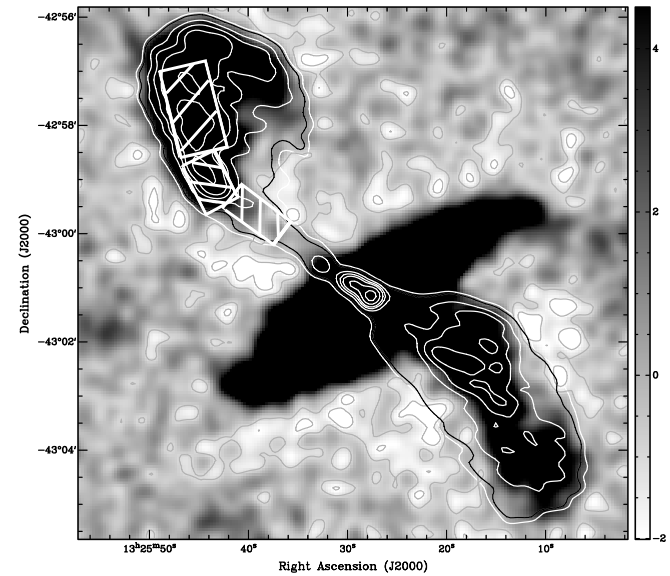
[HESS- F. Rieger, A. Taylor, et al., Nature- accepted today!]

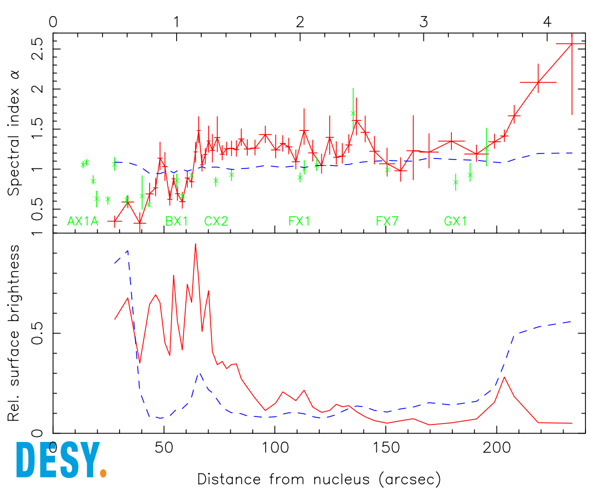
Centaurus A's Inner Jet- A Cosmic Lab

[J. Burns et al., ApJ (1983)]



[A. Weiss et al., A&A (2008)]

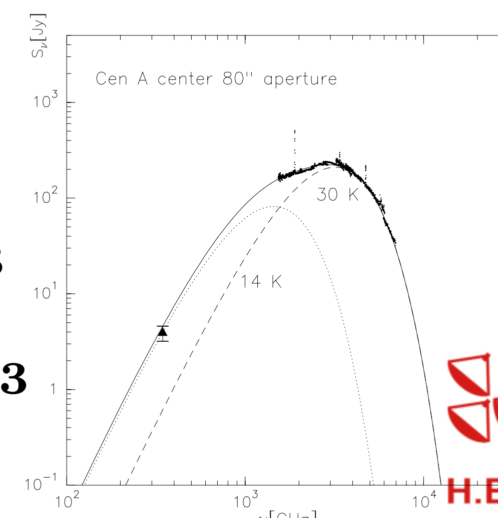




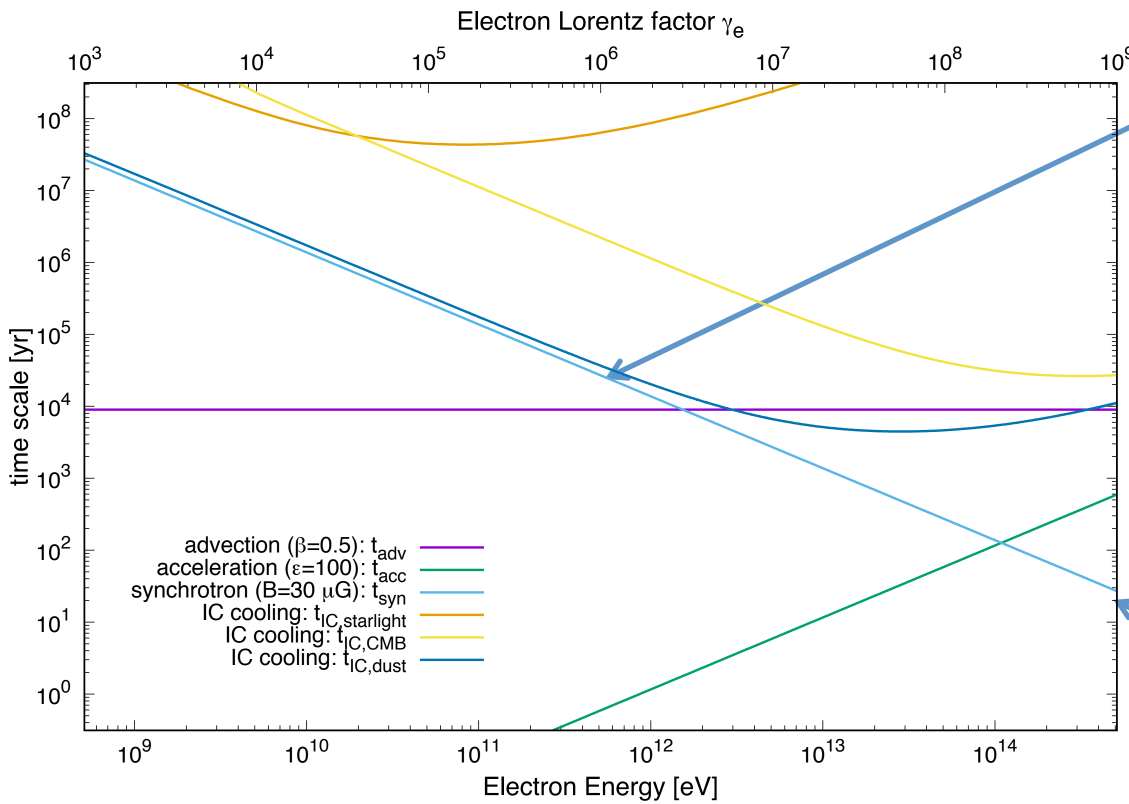
$$\mathrm{B_{eq}} = 60\ \mu\mathrm{G}$$

$$\mathrm{U_B} \approx 10\ \mathrm{eV\ cm^{-3}}$$

$$\mathrm{U_{IR}} \approx 10\ \mathrm{eV\ cm^{-3}}$$



Transport & Cooling Times of Electrons in Cen A's Jets



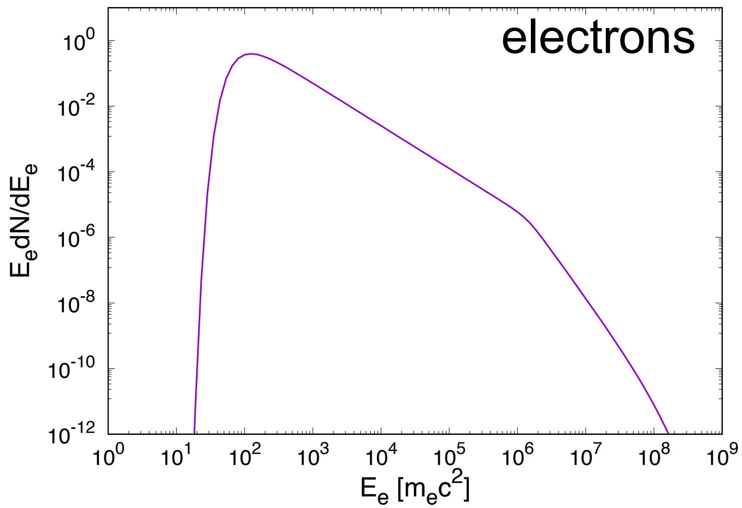
Synchrotron cooling dominates

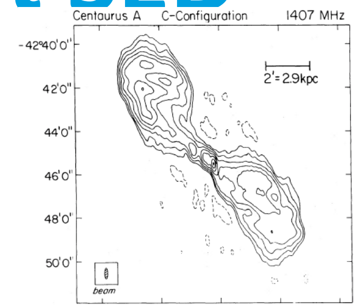
Cooling time becomes shorter than advection time

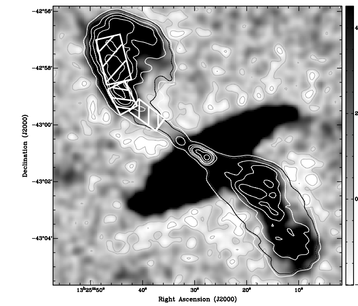
Electrons accelerated to 0.1 PeV energies

$$\cancel{\frac{\partial \mathbf{n}}{\partial \mathbf{t}}} = -\nabla_{\mathbf{p}} \cdot \left[\frac{\mathbf{p}}{\tau_{\mathbf{acc}}(\mathbf{p})}\mathbf{n} - \frac{\mathbf{p}}{\tau_{\mathbf{loss}}(\mathbf{p})}\mathbf{n} \right] - \frac{\mathbf{n}}{\tau_{\mathbf{esc}}(\mathbf{p})} + \mathbf{Q}$$

Distinguishing Cen A's Nucleus and Inner Jet SED

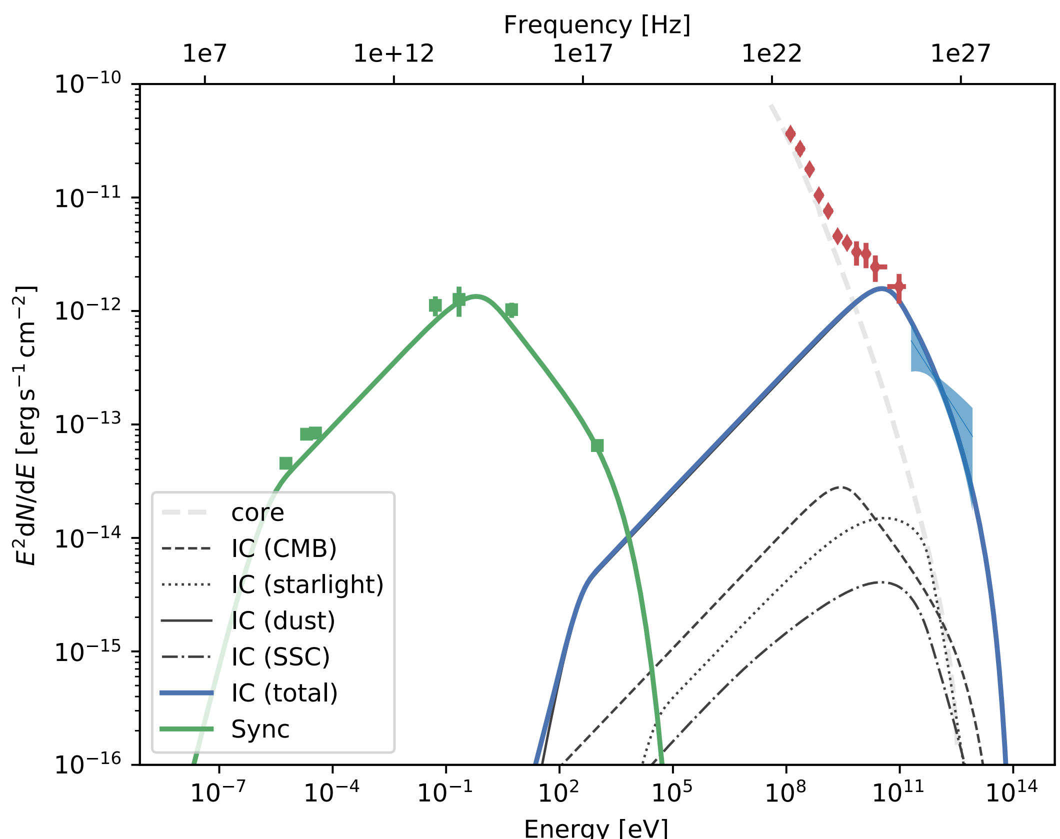






$$\eta = \frac{1}{{\Gamma_e^{max}}^2 (B/B_{crit})\alpha}$$

$$\approx 10^4 \left(\frac{10^8}{\Gamma_e^{max}}\right)^2 \left(\frac{20\mu G}{B}\right)$$



[HESS- F. Rieger, A. Taylor, et al., Nature-accepted today!]

DESY.

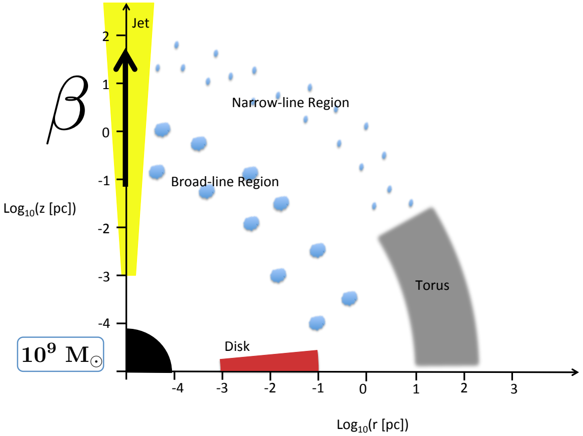
Dissecting Cen A's Acceleration Sites

Acceleration on kpc scales:

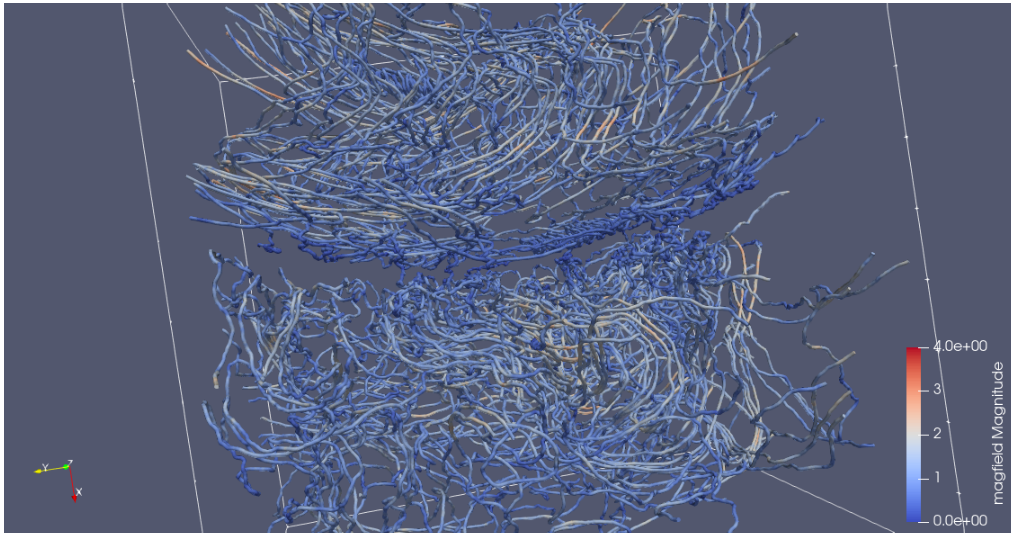
$$\boxed{\mathbf{E_{max}} = \beta \mathbf{B} \mathbf{R}/\eta}$$

$$\beta_{\mathbf{scat.}} \approx \mathbf{0.5}, \quad \eta \approx \mathbf{10^4}$$

$$\boxed{\mathbf{E}_{\mathrm{max}} \approx \mathbf{10^{15} eV}}$$



Acceleration on larger scales:

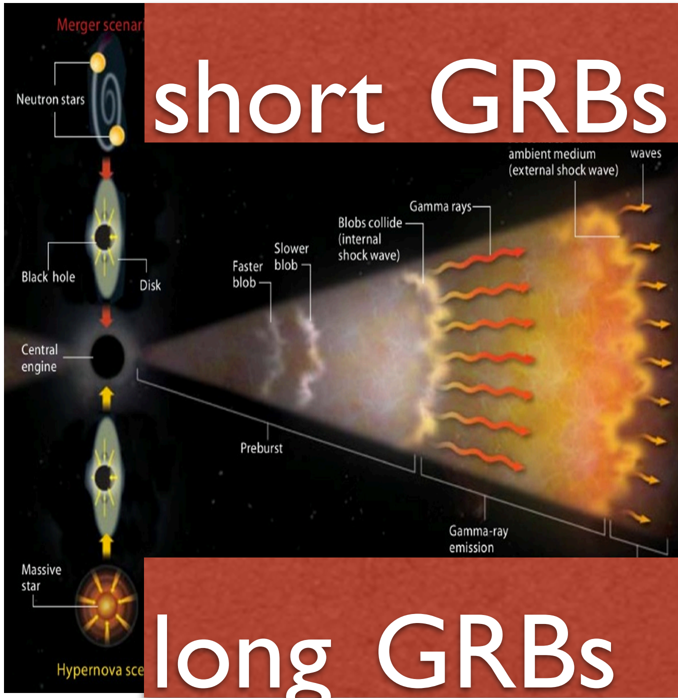


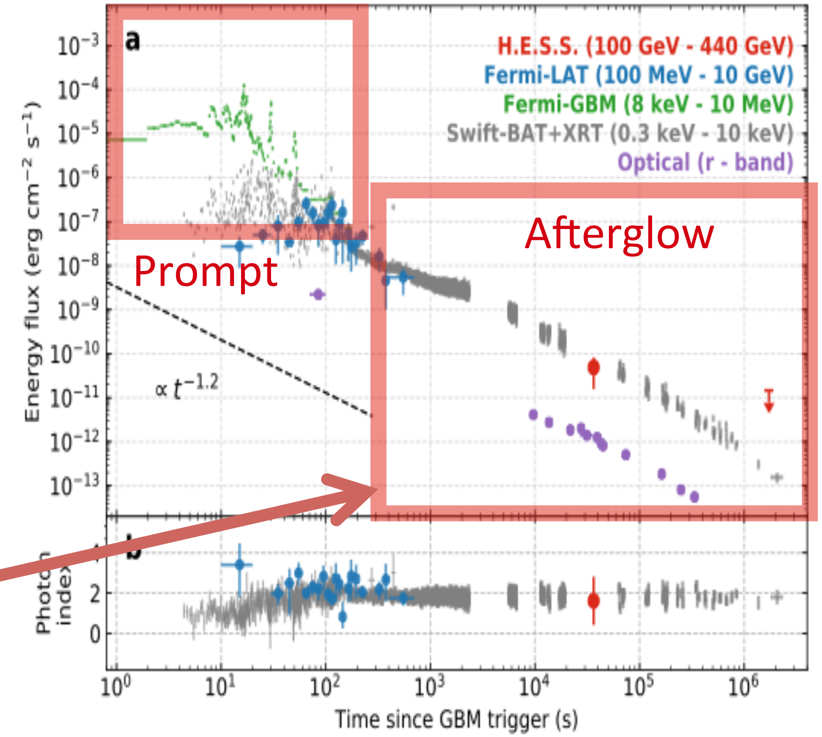
[S. O'Sullivan, A. Taylor, B. Reville in prep.]

Energy dependence of acceleration time only approaches the Bohm level (η~1) at the highest energies

$$\mathbf{E}_{\mathrm{max}} \approx \mathbf{10^{18} eV}$$
$$\mathbf{t}_{\mathrm{acc}} \approx \mathbf{0.1\ Myr}$$

…..the Synchrotron Cutoff of (Long) GRBs?





[HESS- C. Hoishen, A. Taylor, et al., Nature 2019]

- E_{iso}~10^{54} erg is close to Gravitational binding energy limit
- Not actually isotropic outflows, but can be considered as "quasi-isotropic" since $\theta_{jet} > 1/\Gamma$

13

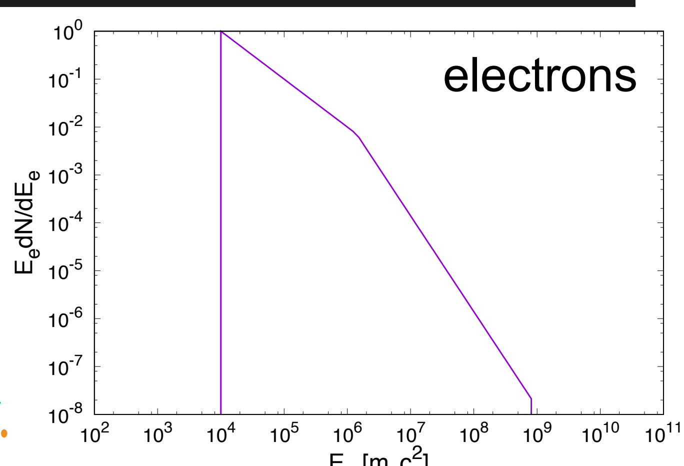
- Extremely efficient emitters in terms of converting kinetic energy flux to radiation

No Synchrotron Cutoff of the Brightest GRB Seen by Fermi-LAT

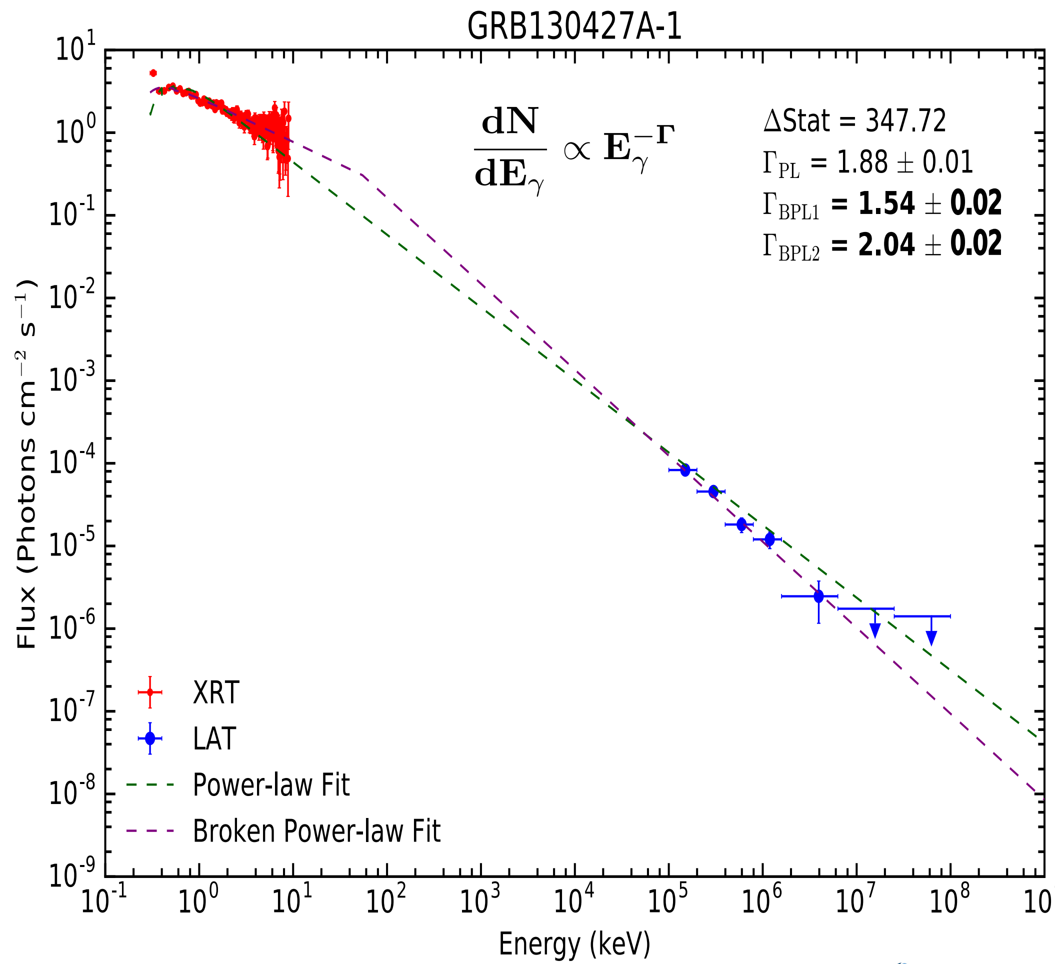
- GRBs at HE and VHE:
  ~12 GRBs per year Fermi-LAT

- However, most science learnt from brightest event- GRB130427A: 94 GeV max energy photon.

VHE emission has been a decades-long mystery

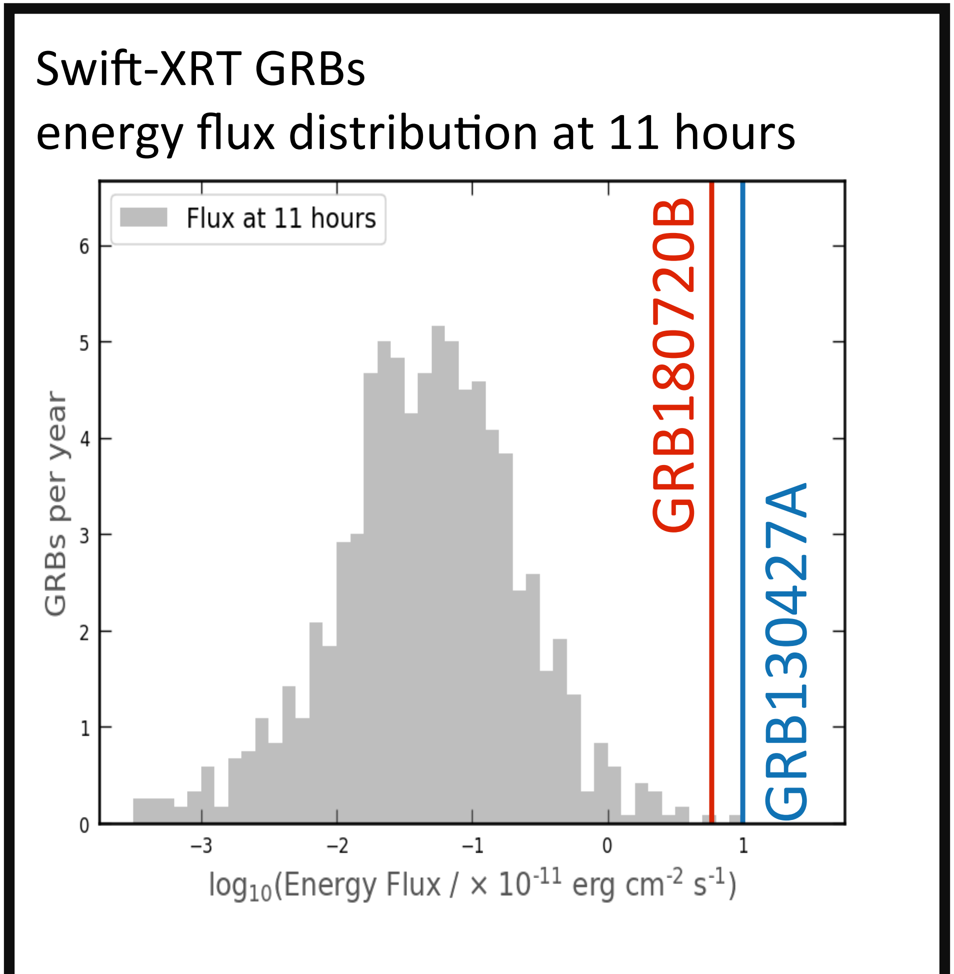


[Ajello et al., ApJ 863 138 (2018)]



t^{GBM}_{90} ~ 140 s, t^{BAT}_{90} ~ 160 s
z = 0.34

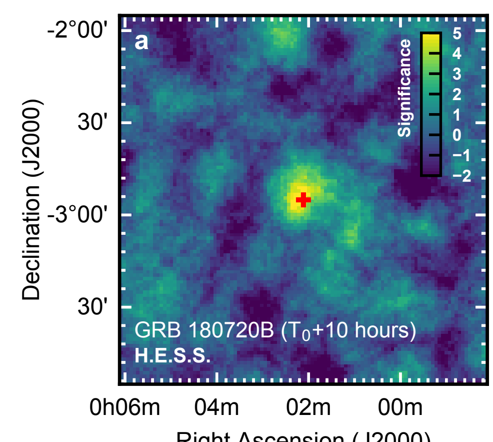
GRB 180720B X-ray 11 hr Energy Flux in Comparison to Other Bright Bursts



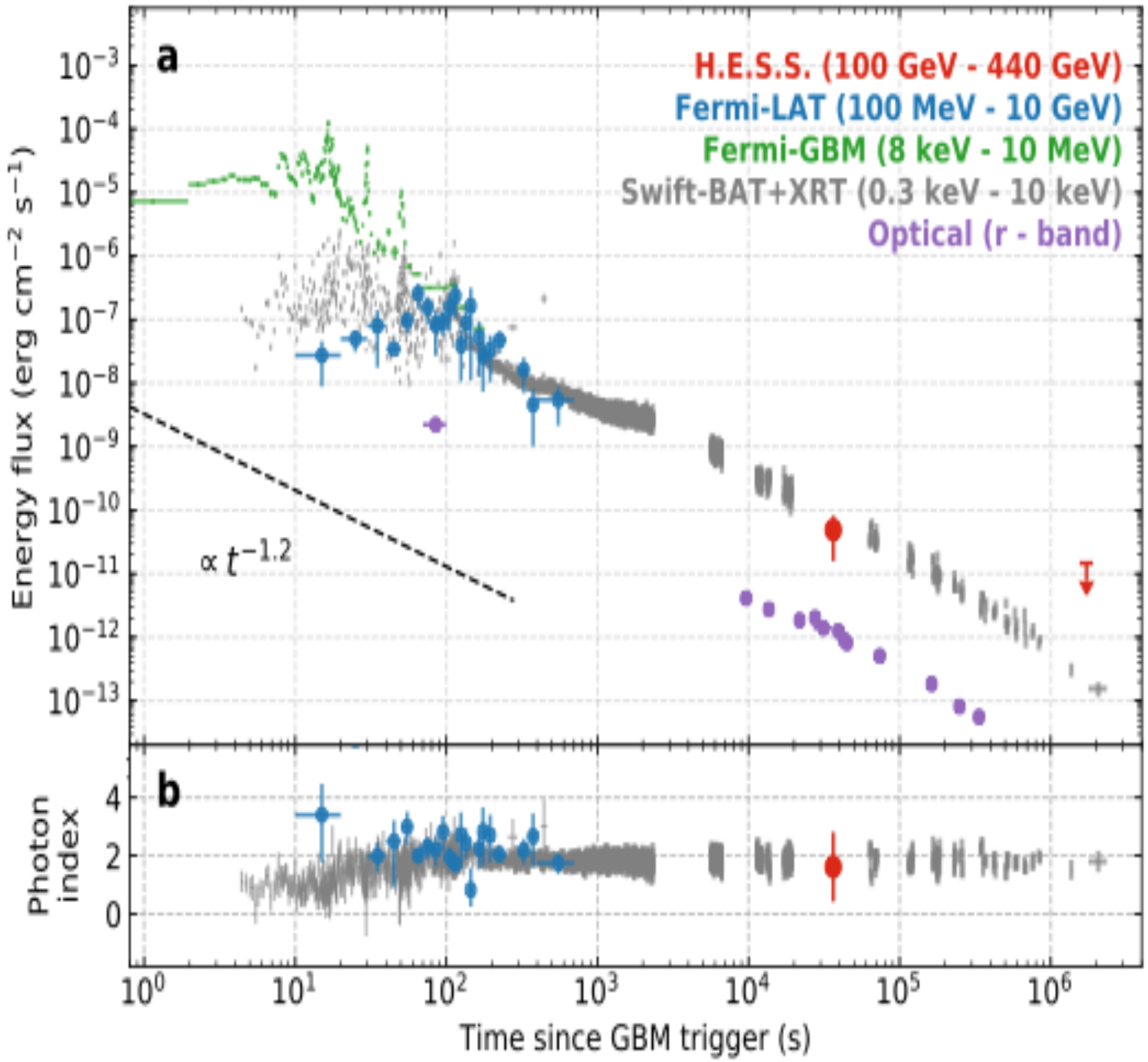
t^{GBM}_{90} ~ 50 s, t^{BAT}_{90} ~ 100 s
z = 0.653

- Fermi-LAT detection from T_0 to T_0+700 s (max. energy photon 5 GeV).
- Extremely bright burst:
  - 2nd brightest afterglow measured by Swift-XRT.
- Very similar x-ray light curve to GRB130427A and GRB190114C.

$$100\ \mathrm{GeV} < \mathrm{E}_\gamma < 440\ \mathrm{GeV}$$



GRB 180720B Multi-Wavelength Light Curve

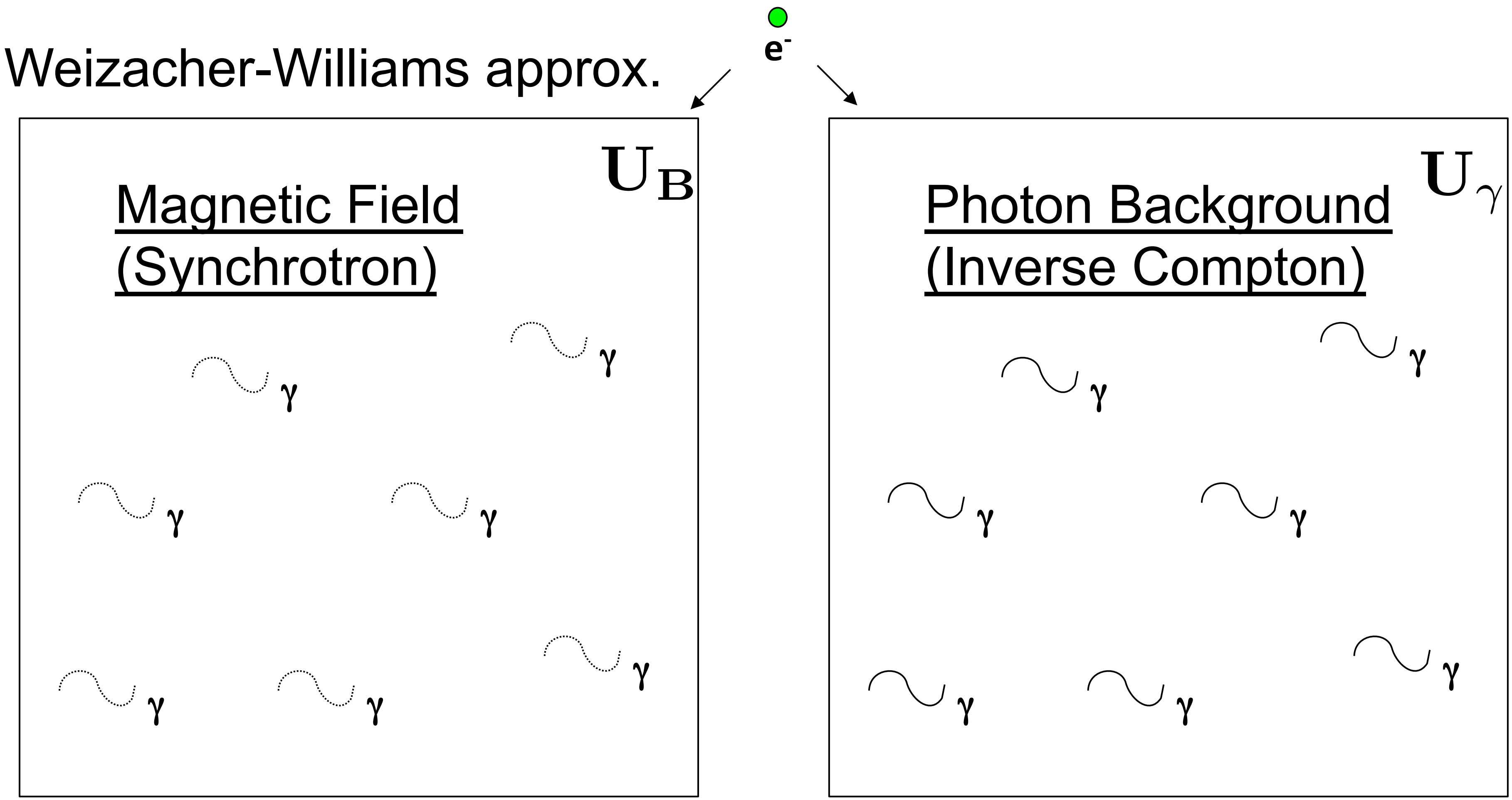


[HESS- C. Hoishen, A. Taylor, et al., Nature 2019]

$$\frac{dN}{dE_\gamma} \propto E_\gamma^{-\Gamma}$$

- H.E.S.S. flux (100 - 440 GeV). Photon index consistent with -2.0.
- Fermi-LAT (detection < 700 s). Photon index -2.0.
- XRT Photon index is -2.0.
- X-ray, HE + VHE Gamma-ray energy fluxes all sit at a consistent level.
- Afterglow falling at same rate in all high energy wavelengths.

Possible VHE Emission Processes



Virtual Photons

$$E_\gamma^{target} = \left(\frac{B}{B_{crit}}\right) m_e c^2$$

Real Photons

$$E_\gamma^{target}$$

Efficiency of Synchrotron Emission

$$\boxed{\mathbf{E}_\gamma^{\mathbf{sync}} \approx \frac{\mathbf{b}}{\mathbf{3}}\mathbf{E_e}}$$

$$\mathbf{b} = \frac{\mathbf{4E_e E_\gamma^{\mathrm{target}}}}{\left(\mathbf{m_e c^2}\right)^{\mathbf{2}}}$$

$$\mathbf{E}_\gamma^{\mathbf{target}} = \left(\frac{\mathbf{B}}{\mathbf{B_{crit}}}\right)\mathbf{m_e c^2}$$

$$(\mathbf{B}_{\mathrm{crit}} = \mathbf{4} \times \mathbf{10^{13}}\ \mathrm{G})$$

$$\boxed{\mathbf{E}_\gamma^{\mathrm{sync}} = \frac{\mathbf{400}\ \mathrm{GeV}}{\mathbf{\Gamma}} \qquad \mathbf{B} = \mathbf{1}\ \mathrm{G} \qquad \mathbf{\Gamma} = \mathbf{20}}$$

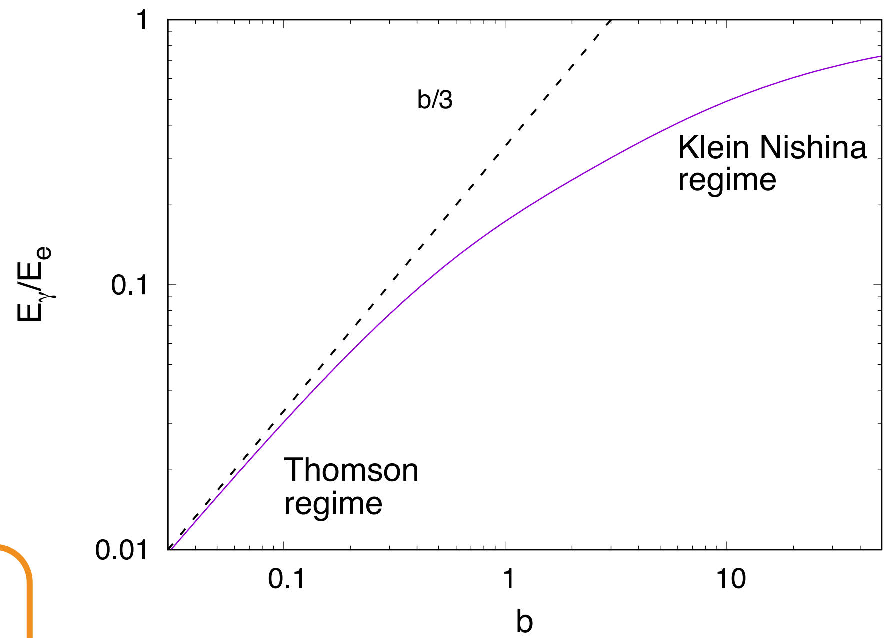
Requires: $\mathbf{E_e} > \mathbf{PeV}$

Efficiency of Inverse Compton Emission

$$\boxed{\mathbf{E_\gamma^{IC} \approx \left(\frac{b}{1+b}\right) E_e}}$$

$$\mathbf{b = \frac{4E_e E_\gamma^{target}}{(m_e c^2)^2}}$$

$$\boxed{\mathbf{E_\gamma^{target} = \frac{1\ \mathrm{keV}}{\Gamma} \qquad \Gamma = 20}}$$



$$\mathbf{\left(\frac{b}{1+b}\right) \approx 1}$$

Requires: $\mathbf{E_e > 400\ \mathrm{GeV}}$

Electron Acceleration to PeV Energies Taking into Account Cooling?

$$\mathbf{t_{acc}} = \eta \frac{\mathbf{R_{lar}}}{\mathbf{c}\beta^{\mathbf{2}}}$$

$$\mathbf{t_{cool}} = \frac{\mathbf{9}}{\mathbf{8}\pi\alpha}\left(\frac{\mathbf{U_{Bcrit}}}{\mathbf{U_B}}\right)\left(\frac{\mathbf{h}}{\mathbf{E_e}}\right)$$

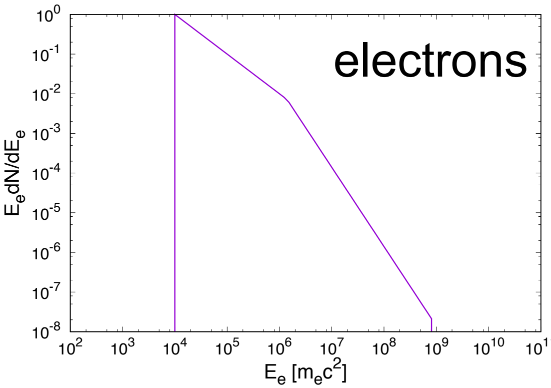
$$\mathbf{E_e^{max}} = \left(\frac{\eta^{-\mathbf{1/2}}}{\alpha^{\mathbf{1/2}}(\mathbf{B/B_{\mathrm{crit}}})^{\mathbf{1/2}}}\right)\mathbf{m_e c^2}$$

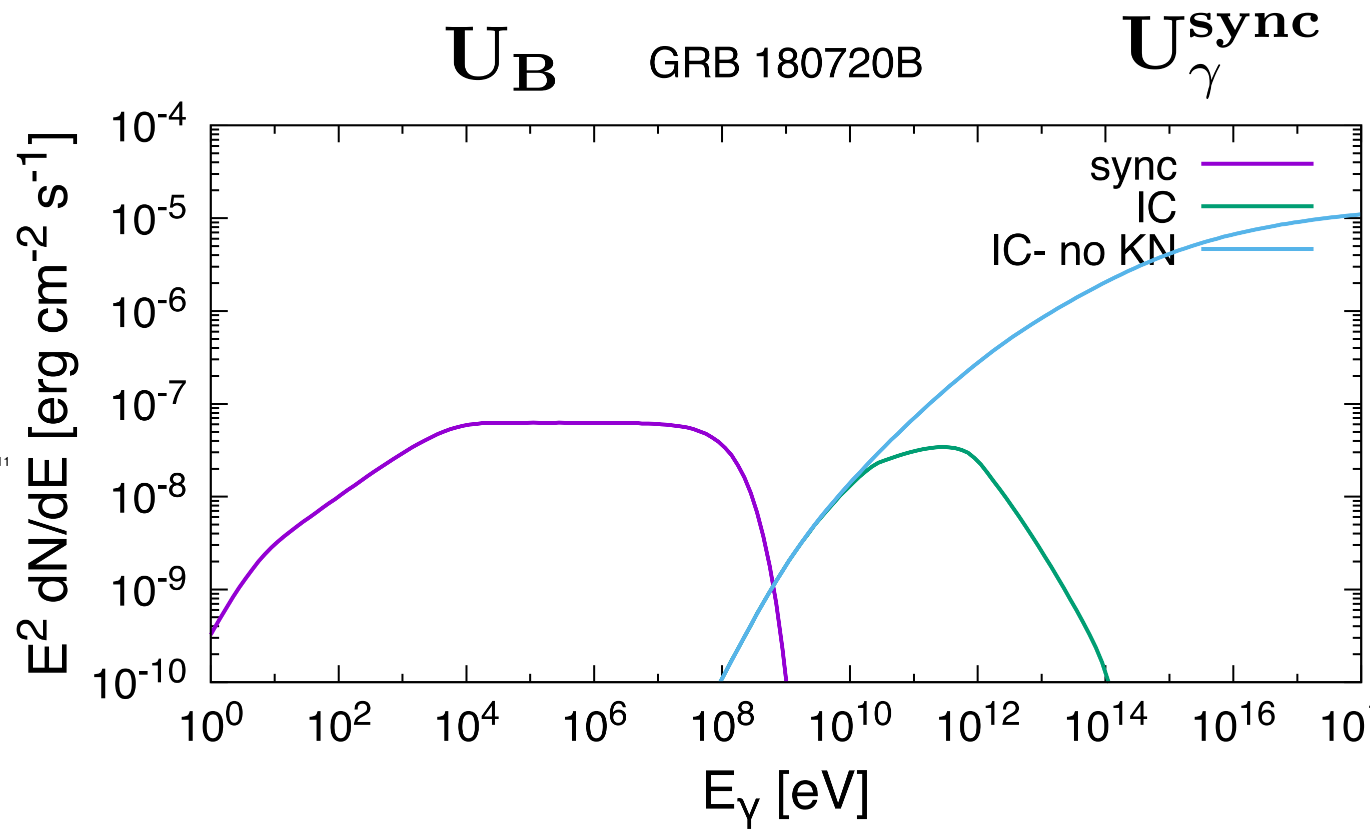
$$= \mathbf{3}\ \eta^{-\mathbf{1/2}}\left(\frac{\mathbf{B}}{\mathbf{100\mu G}}\right)^{-\mathbf{1/2}}\ \mathbf{PeV}$$

ie. would require weak B-fields in acceleration region

DESY.

GRB 180720B SED- SSC Model Fit

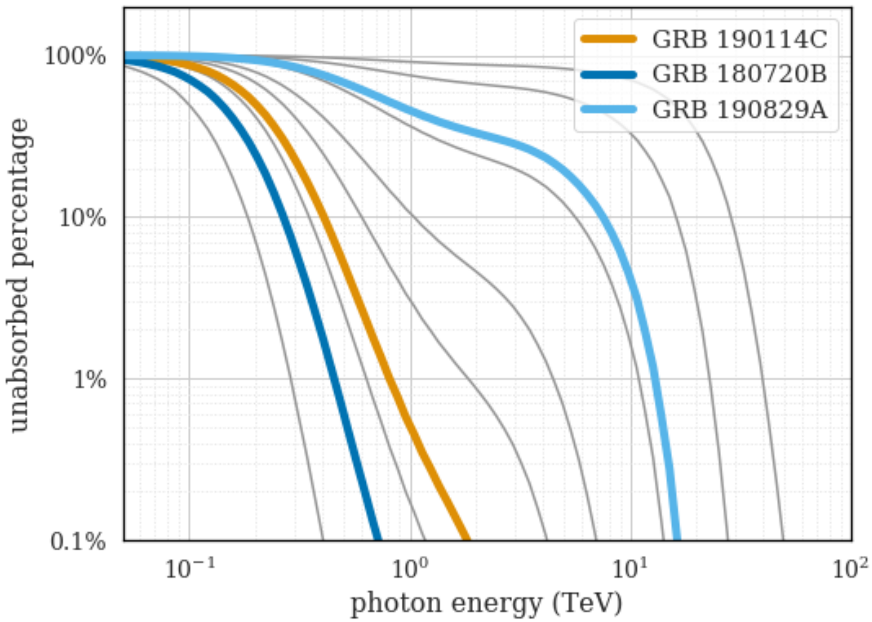




Without KN effects, the ratio of the heights of the IC to Synchrotron bumps would scale with U_e/U_B

However, an SSC Origin of the Emission was that adopted by others to describe early time emission **[Nature 575, 459-463 (2019)]**

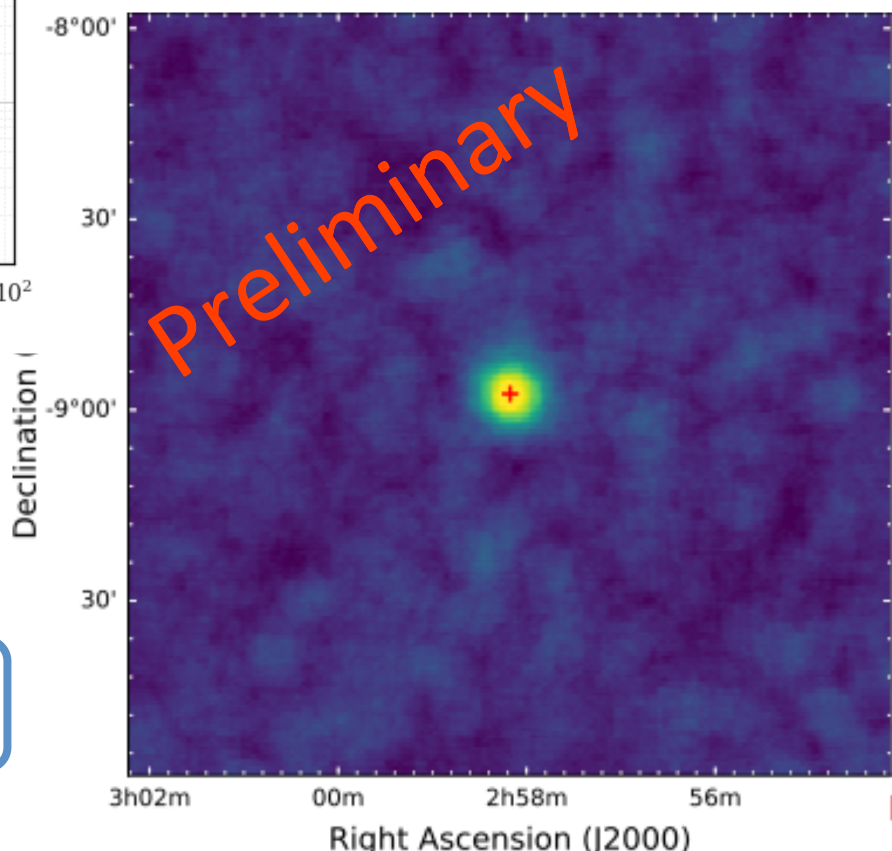
HESS Detection of GRB 190829A



[Previous | Next | ADS]

GRB190829A: Detection of VHE gamma-ray emission with H.E.S.S.

ATel #13052; *M. de Naurois (H. E. S. S. Collaboration)*
on 30 Aug 2019; 07:12 UT
Credential Certification: Fabian SchÃ Â¼ssler (fabian.schussler@cea.fr)



t^{GBM}_{90} ~ 60 s, t^{BAT}_{90} ~ 60 s
z = 0.078

H.E.S.S.

DESY.

Ways to Bypass the Synchrotron Maximum Energy Limit

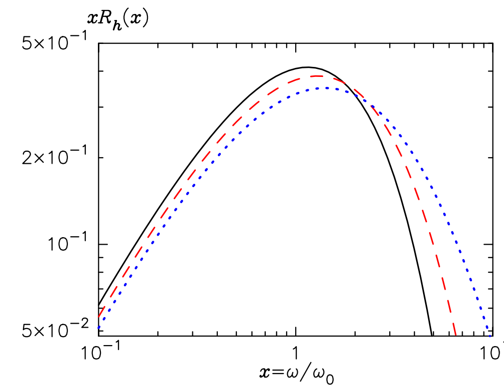
$$\mathbf{E_e^{max}} = \left(\frac{\eta^{-1/2}}{\alpha^{1/2}(\mathbf{B}/\mathbf{B}_{\mathrm{crit}})^{1/2}} \right) \mathbf{m_e c^2} \quad \Rightarrow \quad \mathbf{E_\gamma^{sync}} \approx \frac{9}{4}\eta^{-1}\beta^2 \frac{\mathbf{m_e}}{\alpha}$$

$$\boxed{\mathbf{t_{acc}} = \eta \frac{\mathbf{R_{lar}}}{\mathbf{c}\beta^2}} \qquad \boxed{\mathbf{t_{cool}}}$$

- Faster than Bohm acceleration
- Electrons as secondary particles
- Multiple magnetic field strengths in system

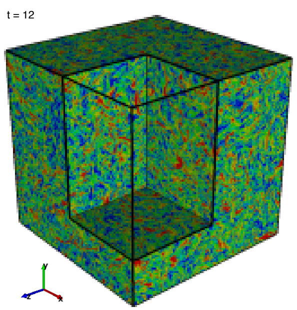
Synchrotron Emission with Multiple Magnetic Field Strengths

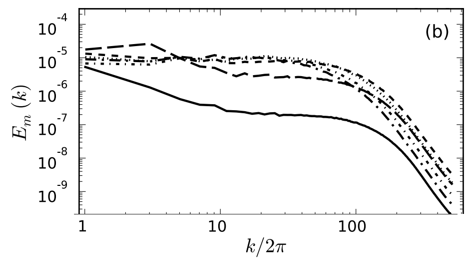
[S. Kelner et al. ApJ (2013)]



Existence of a broad range of magnetic field strengths (mG-multi G) **uniformly distributed in space** has a rather minor effect on synchrotron emission spectrum

[MacFadyen et al. ApJ (2009)]

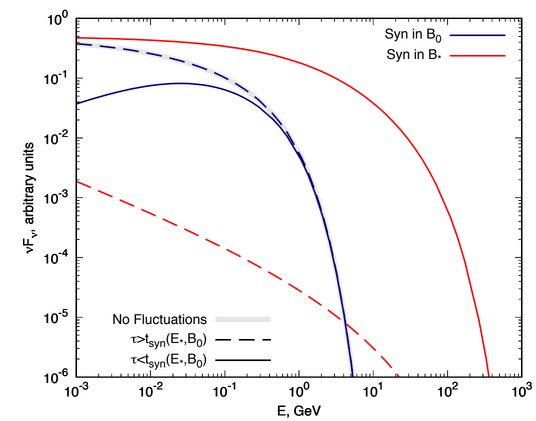




[D. Khangulyan, A. Taylor, F. Aharonian in prep.]

energy losses (large scale, low B-field regions) source

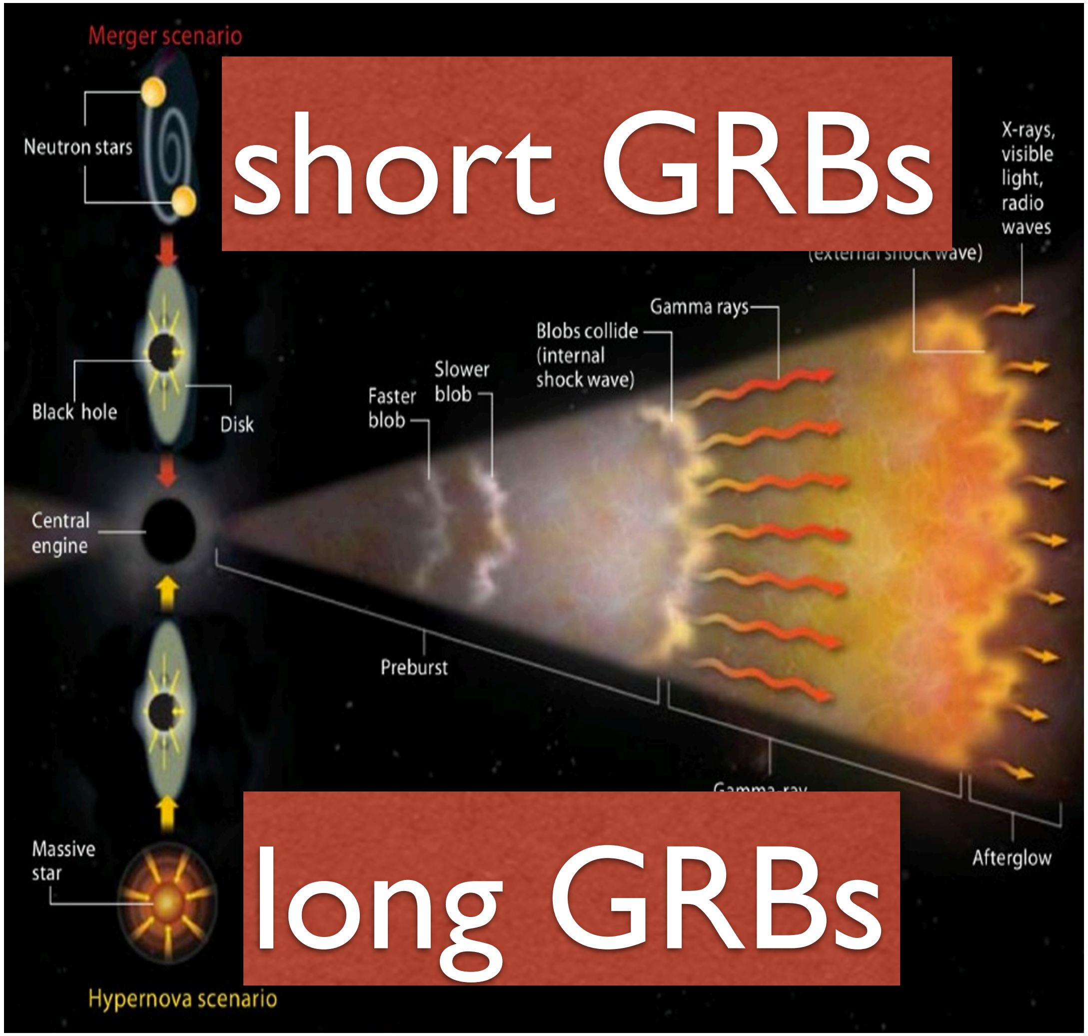
$$\frac{\partial \mathbf{n}}{\partial \mathbf{t}} + \frac{\partial}{\partial \mathbf{p}}\left[\frac{\mathbf{pn}}{\tau_{\mathbf{loss}}(\mathbf{p})}\right] + \frac{\mathbf{n}\theta(\mathbf{p}-\mathbf{p}_*)}{\tau} = \mathbf{Q}$$



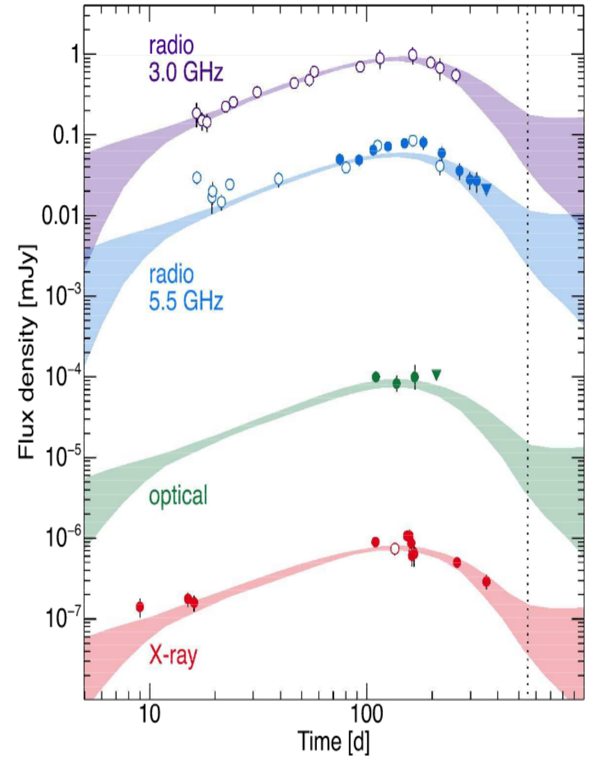
catastrophic losses (small scale, large B-field regions)

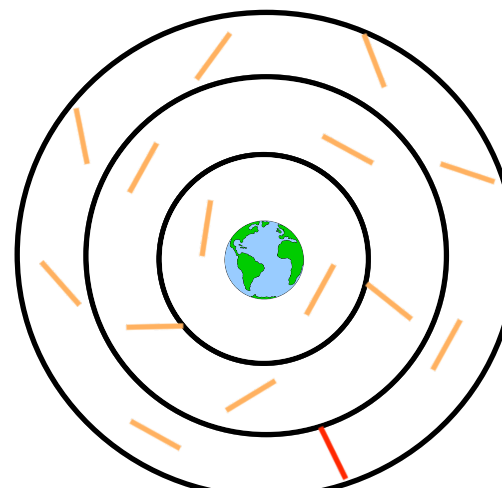
DESY.

Local (Short) GRBs



Afterglow





Credit: NASA

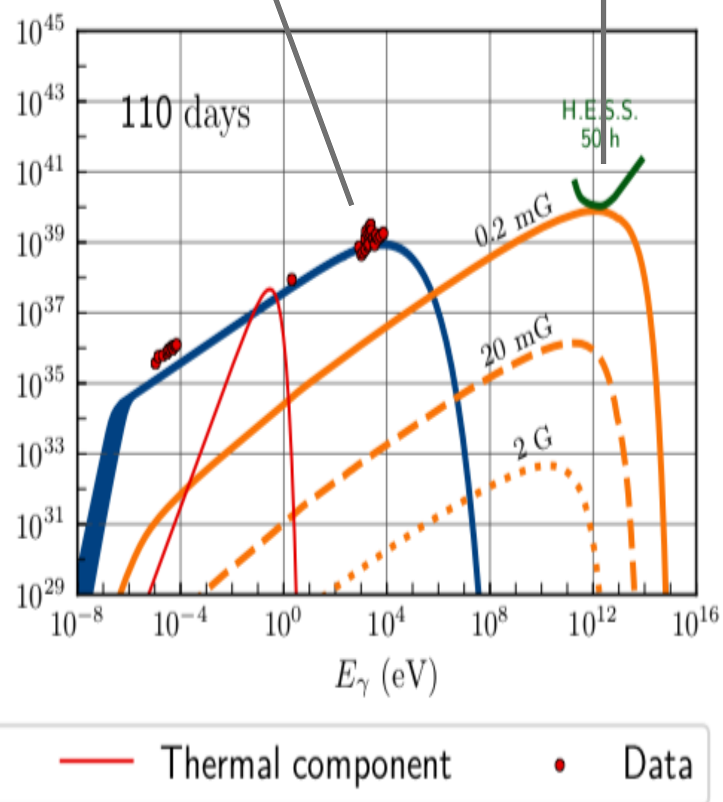
Gamma rays from GRB/GW 170817

- **Synchrotron emission** depends on the product $u_e * u_B$
- An inverse Compton **(SSC)** origin of **gamma-rays** assumed
- HESS long-term monitoring constrains the minimum B-field to >0.2 mG

synchrotron

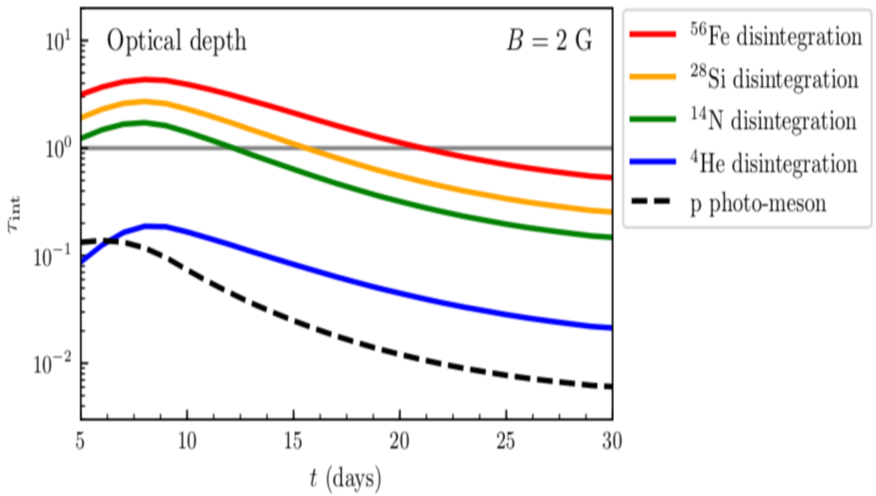
inverse Compton

$$F_{\rm Xray} \sim u_e u_B \qquad F_\gamma \sim u_e^2 u_B$$



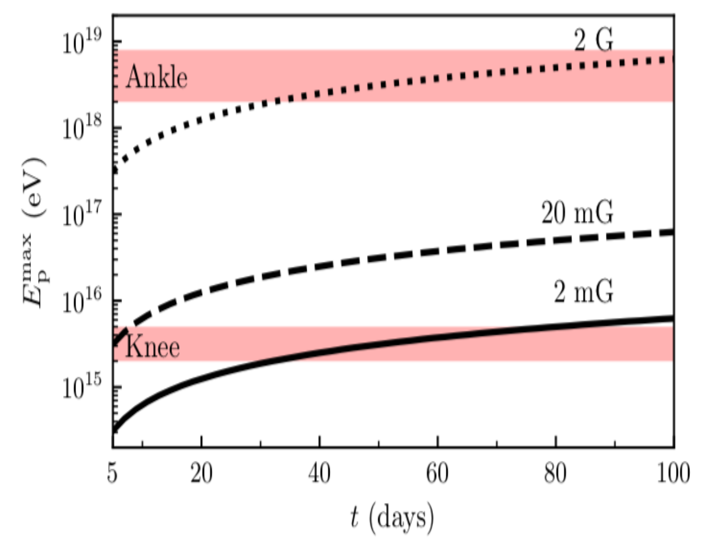
[X. Rodrigues, A. Taylor, et al., ApJ 2019]

GRB Outflow as a Cosmic Ray Source

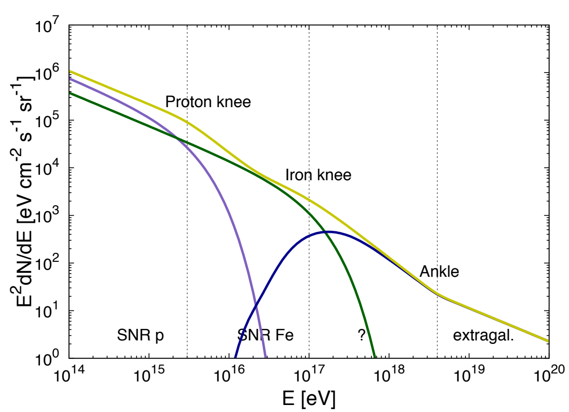


- Early on, the optical thickness to gamma-gamma annihilation implies some level of nuclear photo-disintegration
- **Nuclei** heavier than carbon may not escape the source, but cascade down to lighter elements

- As the source expands, **CRs** can be accelerated to energies between the **knee and the ankle**
- If the SED is emitted by fresh electrons, the *B*-field can be as large as 10 G -> possibility of **UHECRs**



[X. Rodrigues, A. Taylor, et al., ApJ 2019]

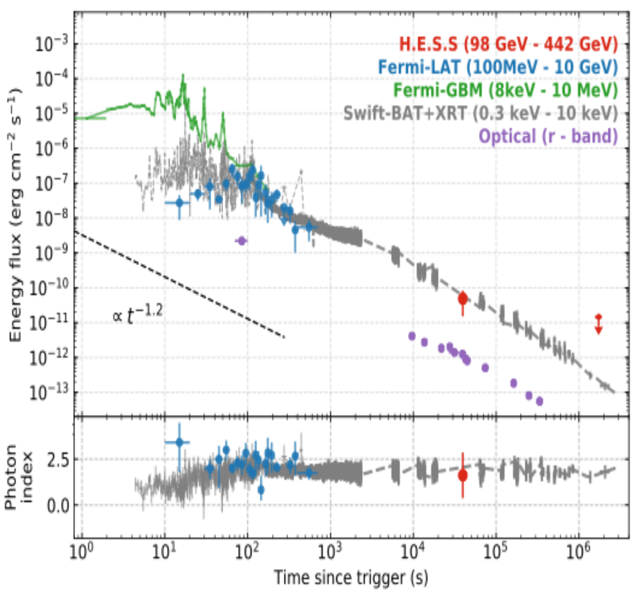


Conclusions

- AGN and GRB appear to be the most viable sources of extragalactic cosmic rays
- Synchrotron emission from AGN and Long GRB tell us directly how efficient these sources operate as cosmic ray accelerators
- The nearest AGN candidate doesn't appear to operating as a very efficient accelerator (at least on small ~kpc scales)
- Long GRB outflows appear to operate as extremely efficient particle accelerators, with their synchrotron emission going beyond the expected supposed theoretical limit
- What we've learnt about long GRB VHE emission can be applied to BNS (short GRB) emission, and can provide important insight into maximum energy achievable within the source

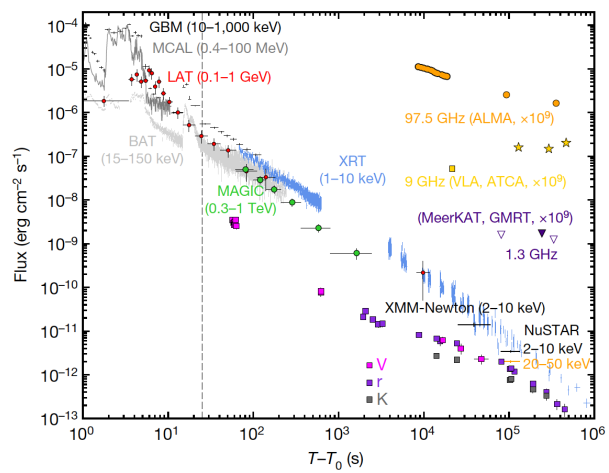
Based on GRB180720B*, GRB190114C** and GRB130427A***

*HESS (100 to 440 GeV) @ $10^{4.6}$–$10^{4.7}$ s



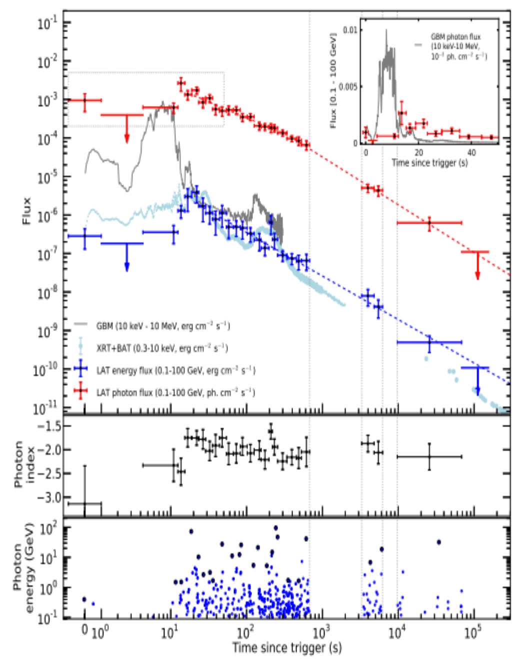
[HESS- C. Hoishen, A. Taylor, et al., Nature 2019]

**MAGIC (>300 GeV) @ $10^{1.7}$–$10^{3.1}$ s



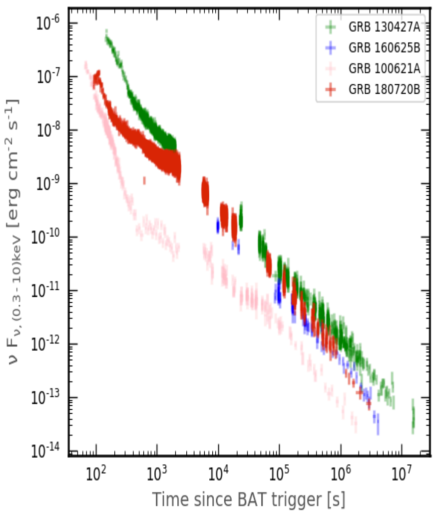
[MAGIC- Nature 575, 459-463 (2019)]

***Fermi-LAT (<98 GeV) < $10^{4.5}$ s



[Fermi- Science 343 (2014)]

Evidence for a canonical GRB afterglow light curve in the Swift-XRT data



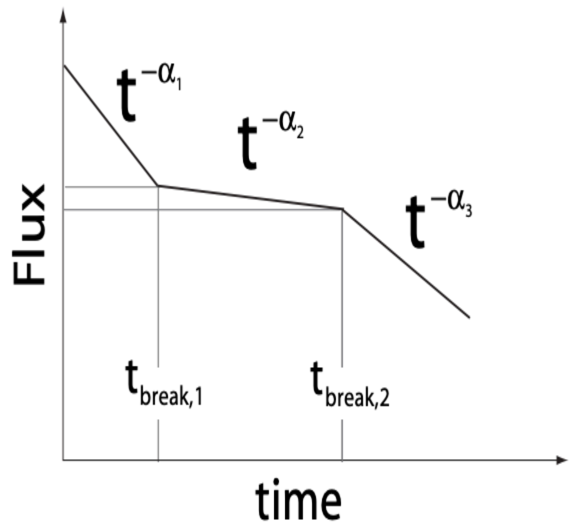


Fig. 3.— A schematic diagram of the canonical behavior of the early X-ray light curve for GRBs observed with *Swift* XRT. It consists of three power law segments where $F_\nu \propto \nu^{-\beta} t^{-\alpha}$: (i) a fast initial decay with $3 \lesssim \alpha_1 \lesssim 5$, (ii) a very shallow decay with $0.5 \lesssim \alpha_2 \lesssim 1.0$, (iii) a somewhat steeper decay with $1 \lesssim \alpha_3 \lesssim 1.5$. The transition between these power law segments occurs at two break times, $t_{\rm break,1}$ and $t_{\rm break,2}$.

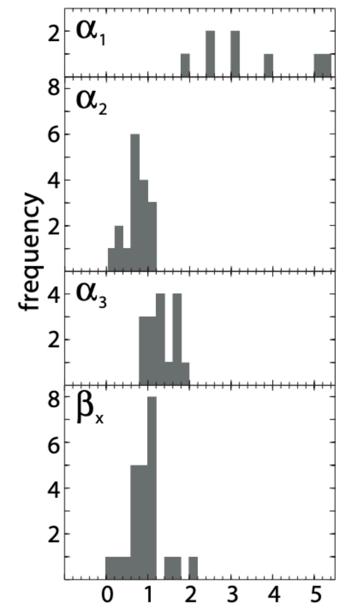
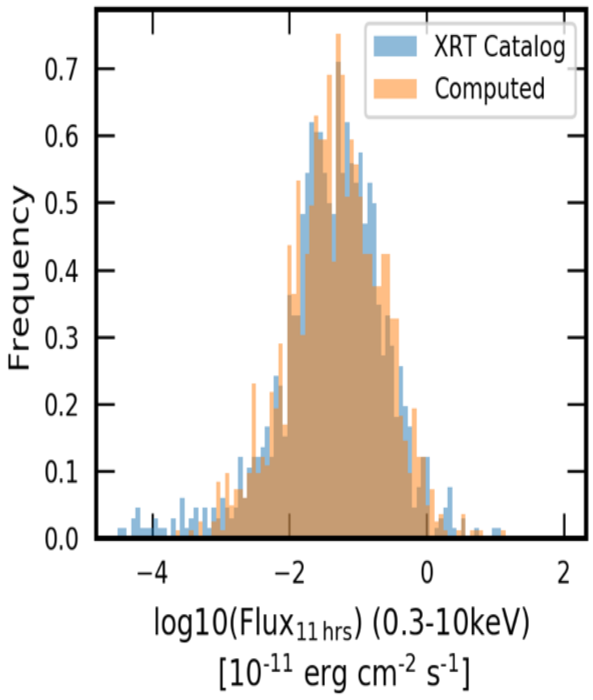
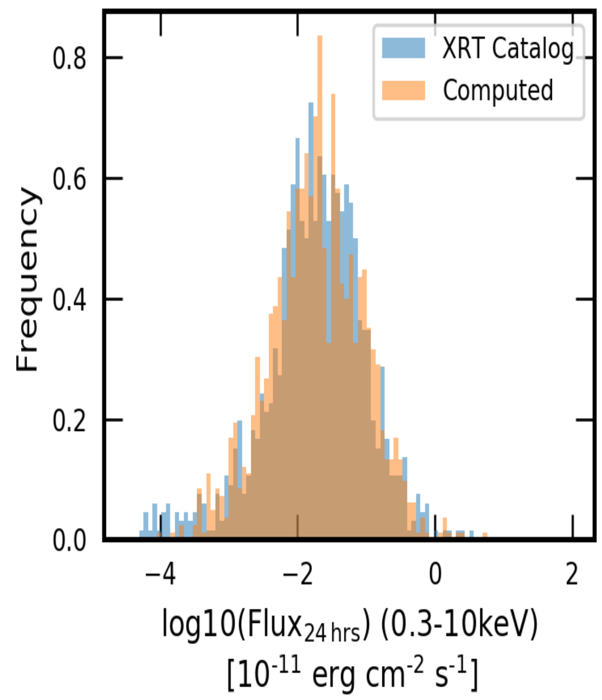


Fig. 4.— Histogram of the spectral index β_x and the temporal indices α_1, α_2 and α_3, for the GRBs in Table 1. Note that only $\beta_{1,x}$ is plotted here for the events with evolving spectral properties. The x-scale range is the same for all indices.

https://arxiv.org/abs/astro-ph/0508332

From Swift-XRT Catalog GRB Flux Distribution





DESY.

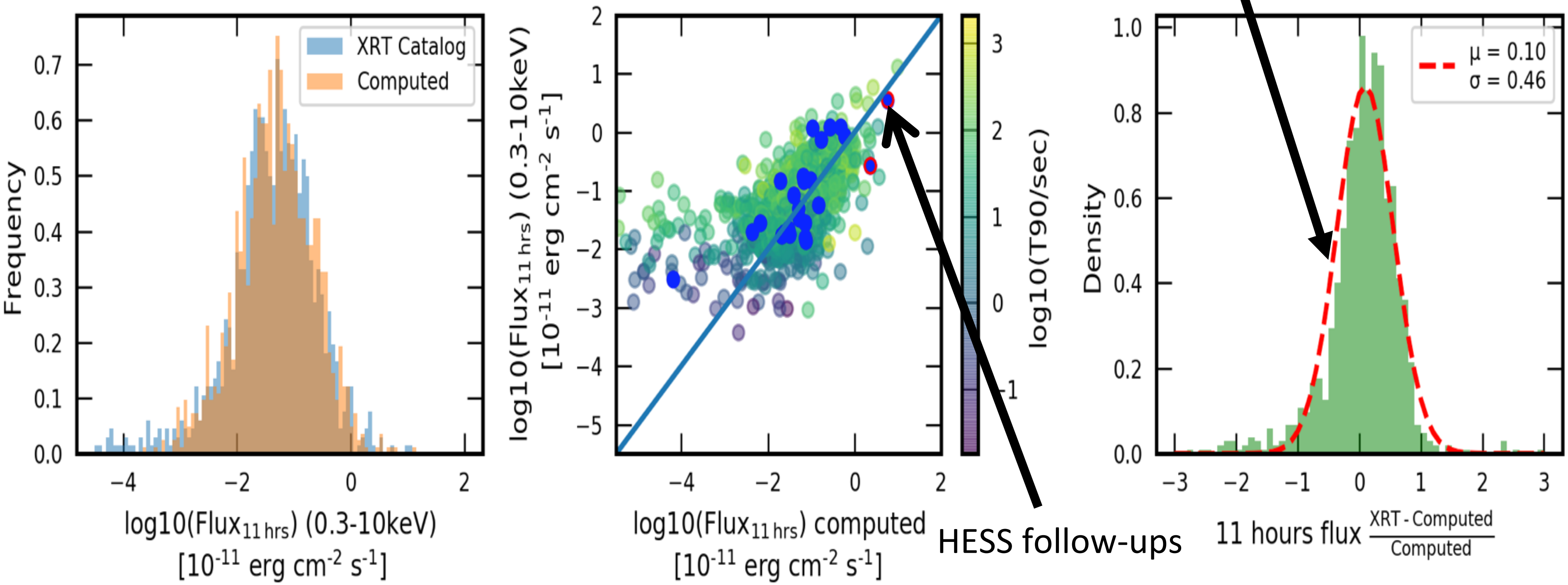
Andrew Taylor

H.E.S.S.

XRT flux (@11 hours)

Tolerance in prediction (0.46 sigma spread)

$$\mathrm{Flux_{11hrs}} \approx \frac{1}{\tau_{800}} \mathrm{Fluence_{BAT}} \cdot \left(\frac{\mathrm{t}}{\tau_{50}}\right)^{-1.2}$$



(this also works for the 24 hours flux)

Based on the these previous slides:

- The afterglow of GRBs at XRT energies is very canonical.
- The VHE emission is highly connected with the X-Ray one and falls at a similar level (maybe this is also something canonical)

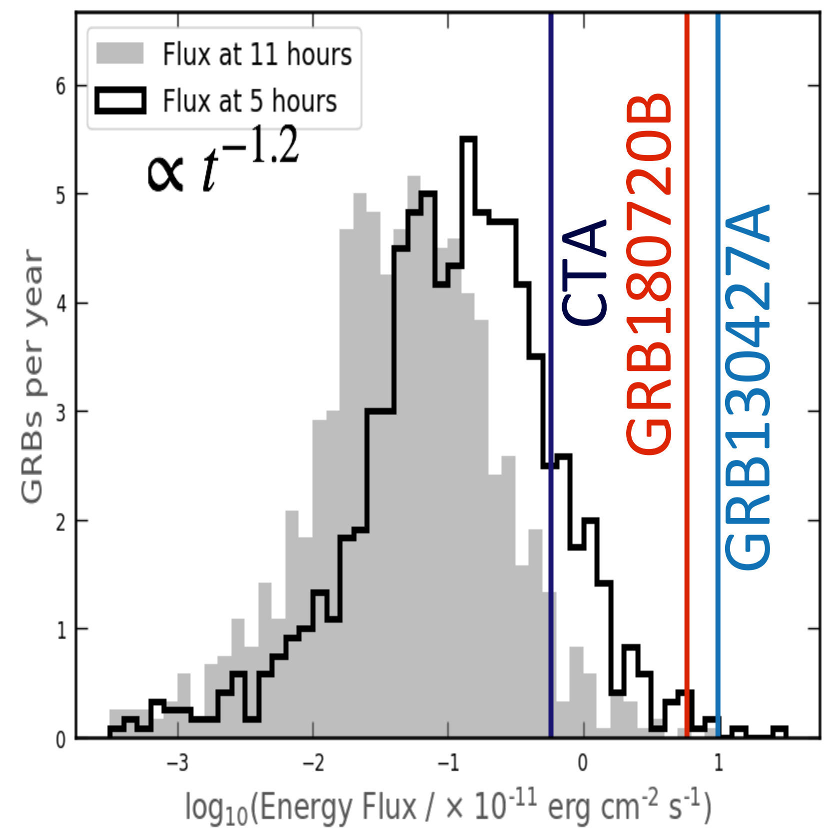
Consequences:

- We can easily predict (with some accuracy) the afterglow emission of Swift-XRT.
- Also we can easily predict the level of the VHE emission.

Prospects for Future Observatories

- CTA to have ~10 times better sensitivity than H.E.S.S.
- Will be able to detect flux over many decades in time with detailed spectra information.
- Boost the detection of GRBs at VHE.
  – ~ 3 GRBs per year at 11 hours after burst.
  – ~ 11 GRBs per year at 5 hours after burst

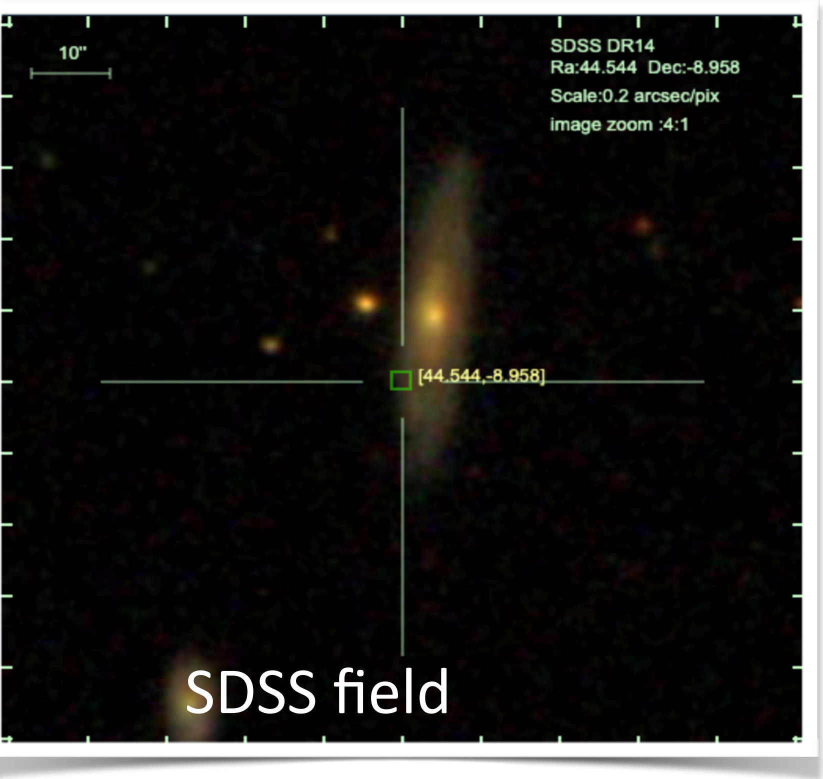
Swift-XRT GRBs energy flux distribution



[HESS- C. Hoishen, A. Taylor, et al., Nature 2019]

HESS Detection of GRB 190829A

T90 ~ 60 seconds
z = 0.078



[Previous | Next | ADS]

GRB190829A: Detection of VHE gamma-ray emission with H.E.S.S.

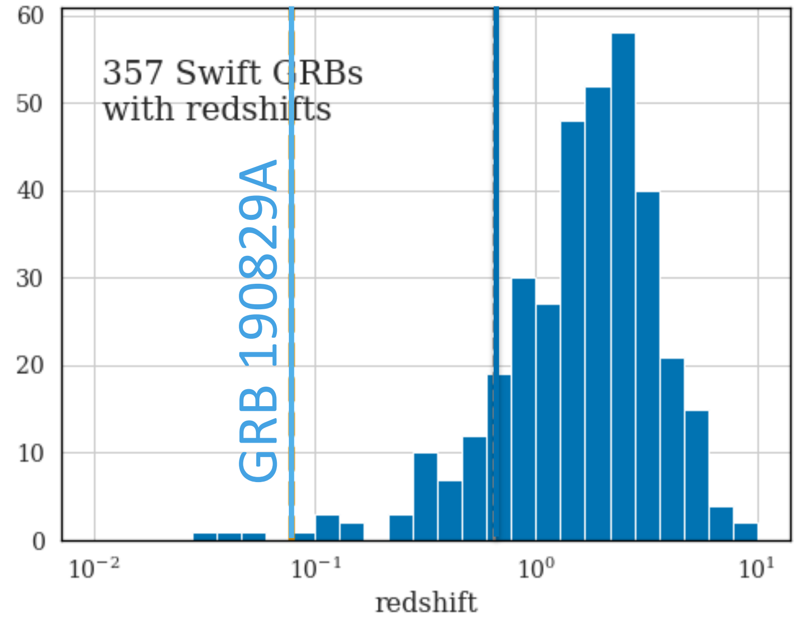
ATel #13052; *M. de Naurois (H. E.S. S. Collaboration)*
on 30 Aug 2019; 07:12 UT
Credential Certification: Fabian SchÃ Â¼ssler (fabian.schussler@cea.fr)

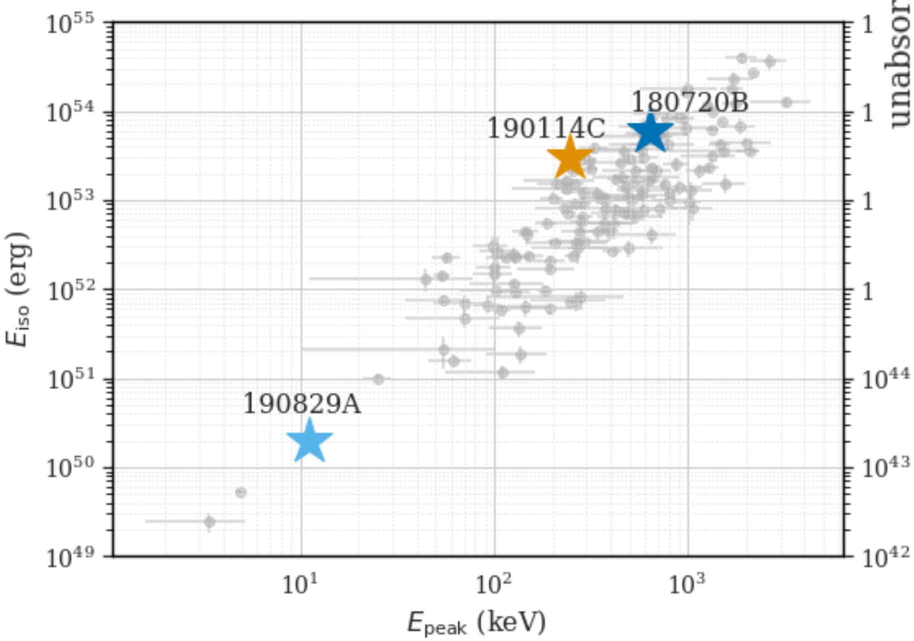
Subjects: Gamma Ray, >GeV, TeV, VHE, Gamma-Ray Burst

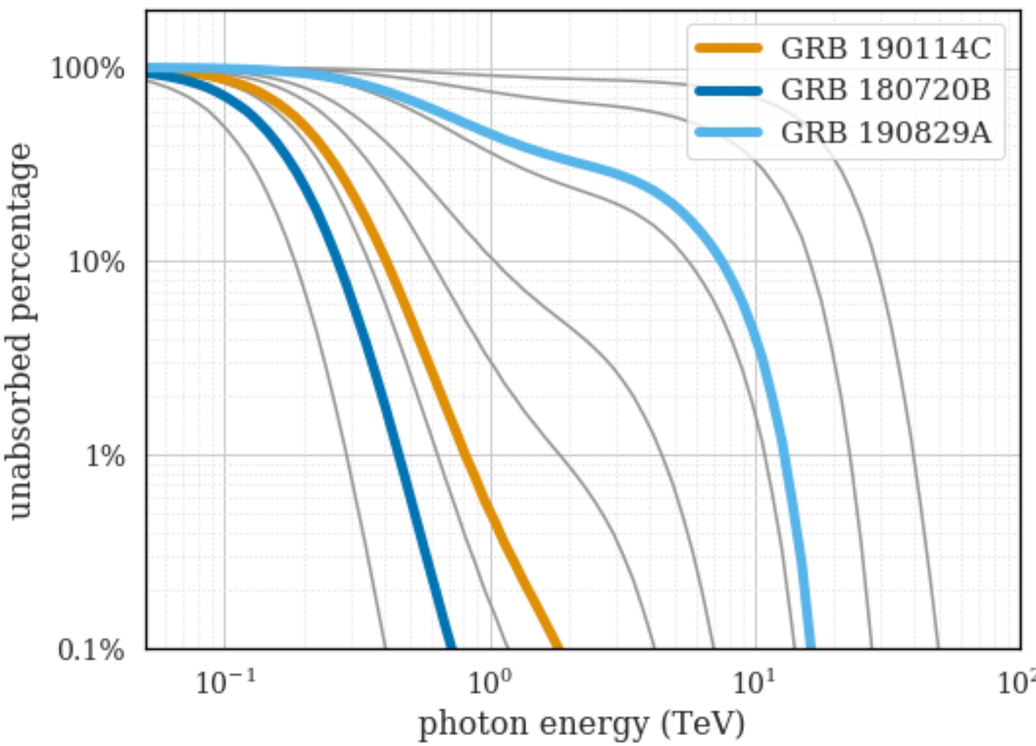
Tweet The detection of VHE emission in the deep afterglow of GRB 180720B

The H.E.S.S. array of imaging atmospheric Cherenkov telescopes was used to carry out follow-up observations of the afterglow of GRB 190829A (Dichiara et al., GCN 25552). At a redshift of z = 0.0785 +/- 0.005 (A.F. Valeev et al., GCN 25565) this is one of the nearest GRBs detected to date. H.E.S.S. Observations started July 30 at 00:16 UTC (i.e. T0 + 4h20), lasted until 3h50 UTC and were taken under good conditions. A preliminary onsite analysis of the obtained data shows a >5sigma gamma-ray excess compatible with the direction of GRB190829A. Further analyses of the data are on-going and further H.E.S.S. observations are planned. We strongly encourage follow-up at all wavelengths. H.E.S.S. is an array of five imaging atmospheric Cherenkov telescopes for the detection of very-high-energy gamma-ray sources and is located in the Khomas Highlands in Namibia. It was constructed and is operated by researchers from Armenia, Australia, Austria, France, Germany, Ireland, Japan, the Netherlands, Poland, South Africa, Sweden, UK, and the host country, Namibia. For more details see https://www.mpi-hd.mpg.de/hfm/HESS/

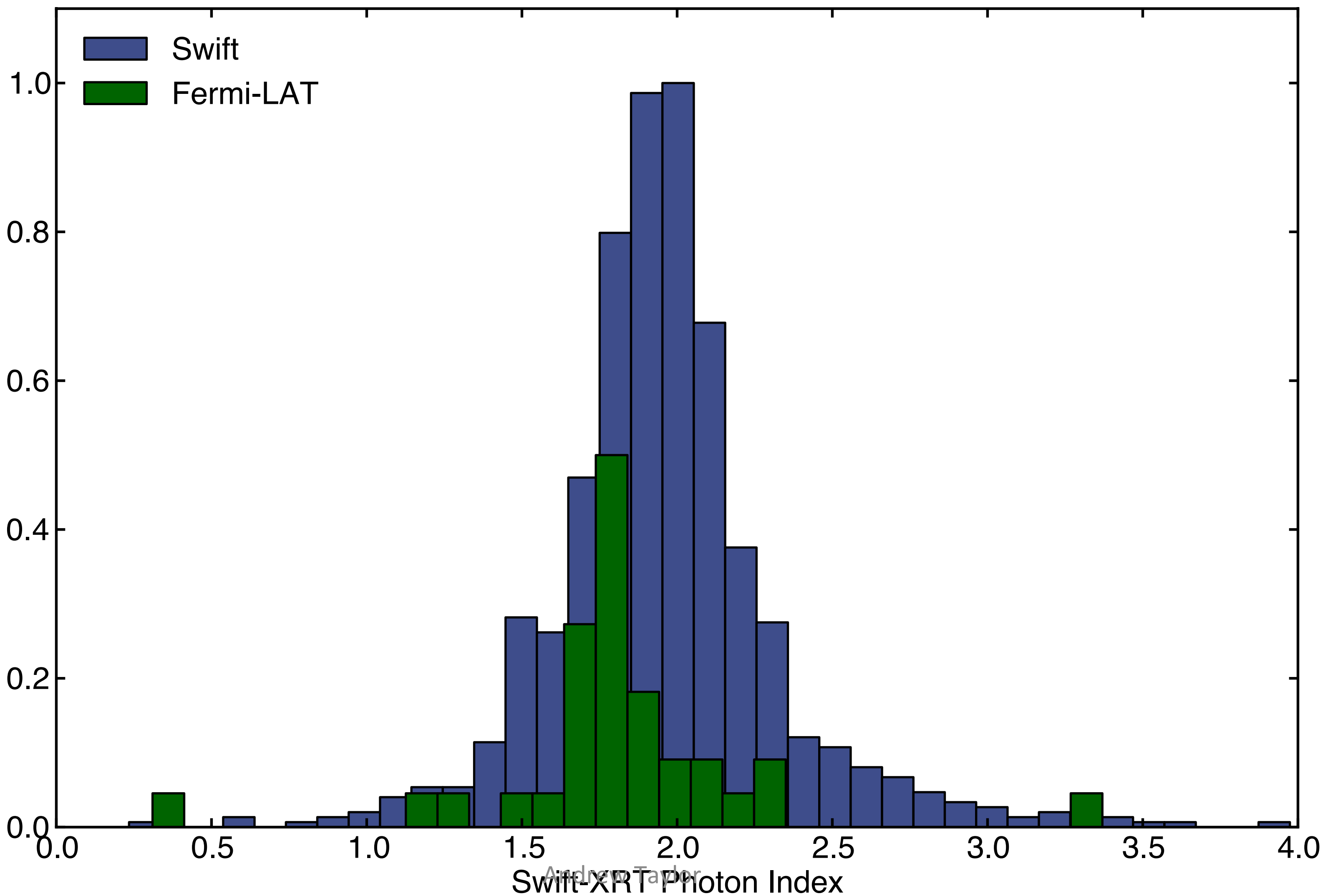
HESS Detection of GRB 190829A



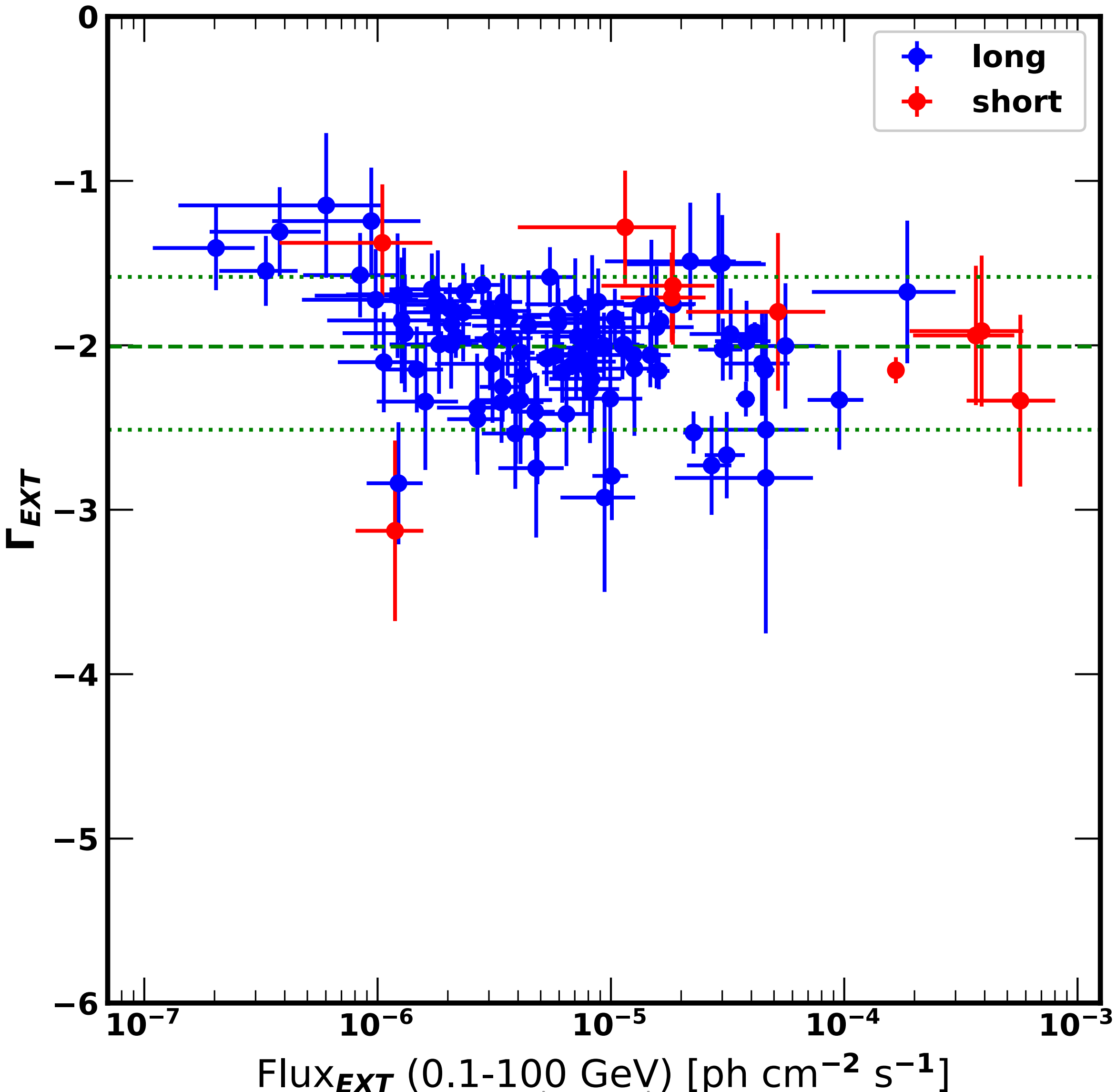




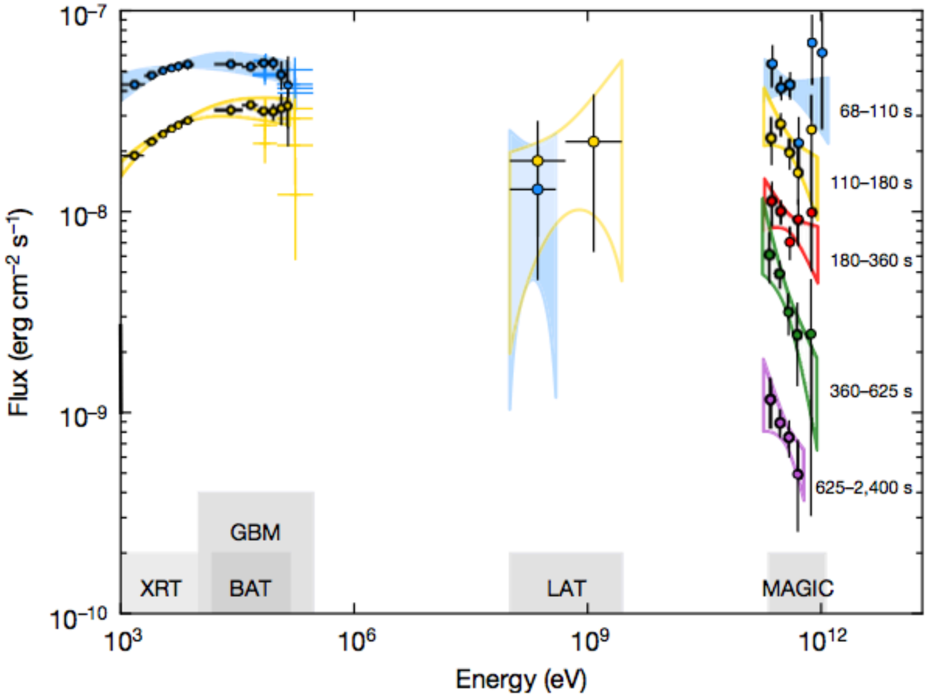
Swift XRT Photon Index Distribution

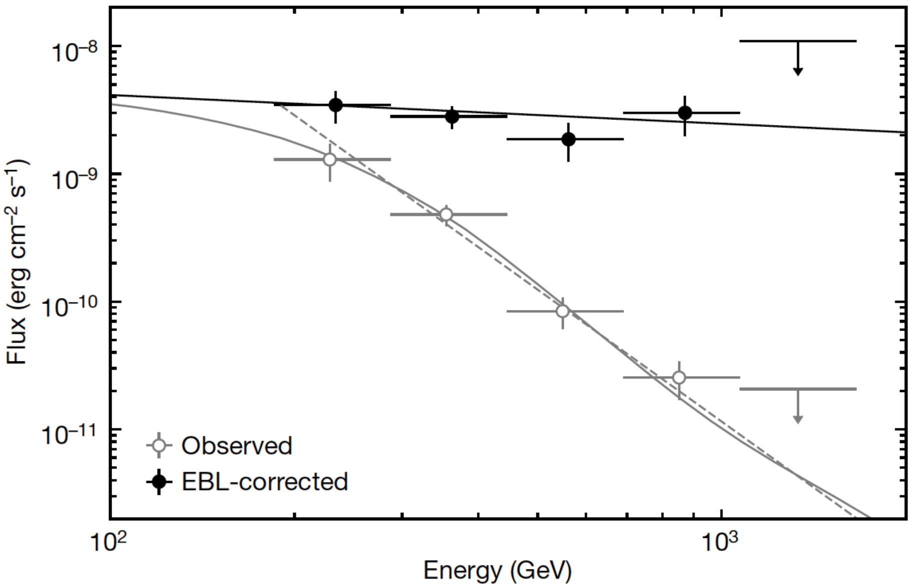


Fermi-LAT Photon Index Distribution



GRB 190114C SED





[Nature 575, 459-463 (2019)]

Follow-up observations of GW170817

The source was at a distance of ~40 Mpc

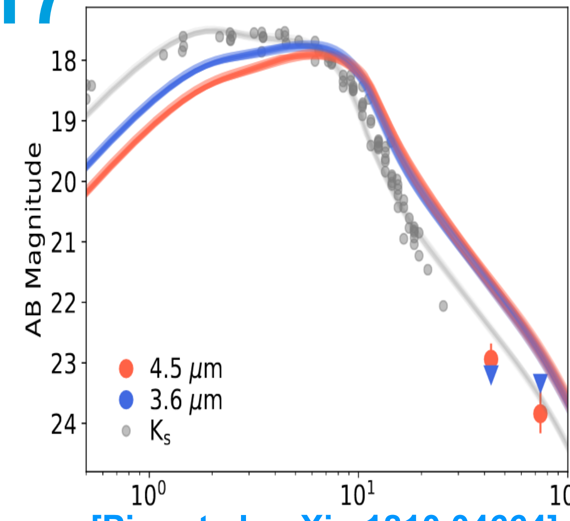
Optical (Thermal)

- Bright thermal emission in the first ~10 days
- Radioactively-powered kilonova

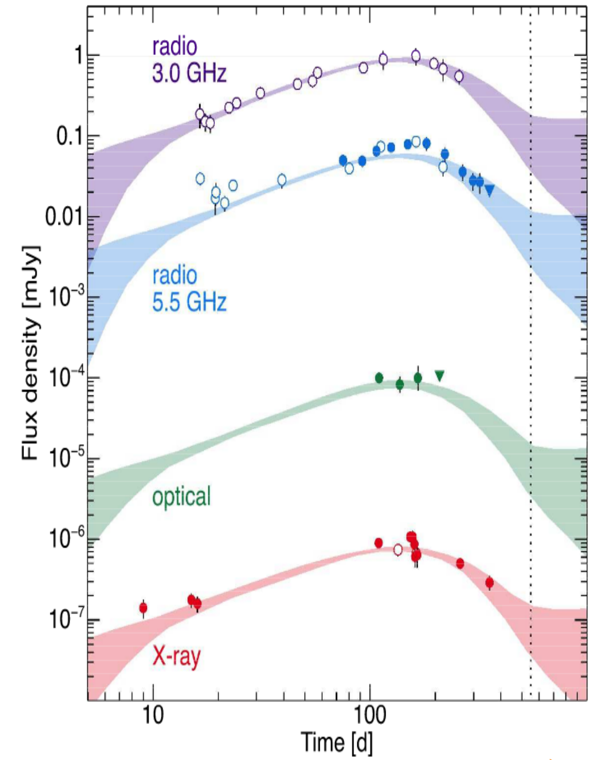
Radio + X-rays (Non-Thermal)

- Delayed onset
- Brightening (L ~ t^0.6) up to ~160 days
- Rapid decline after ~160 days

[Vilar et al, ApJ 862 (2018)]



[Piro et al, arXiv:1810.04664]



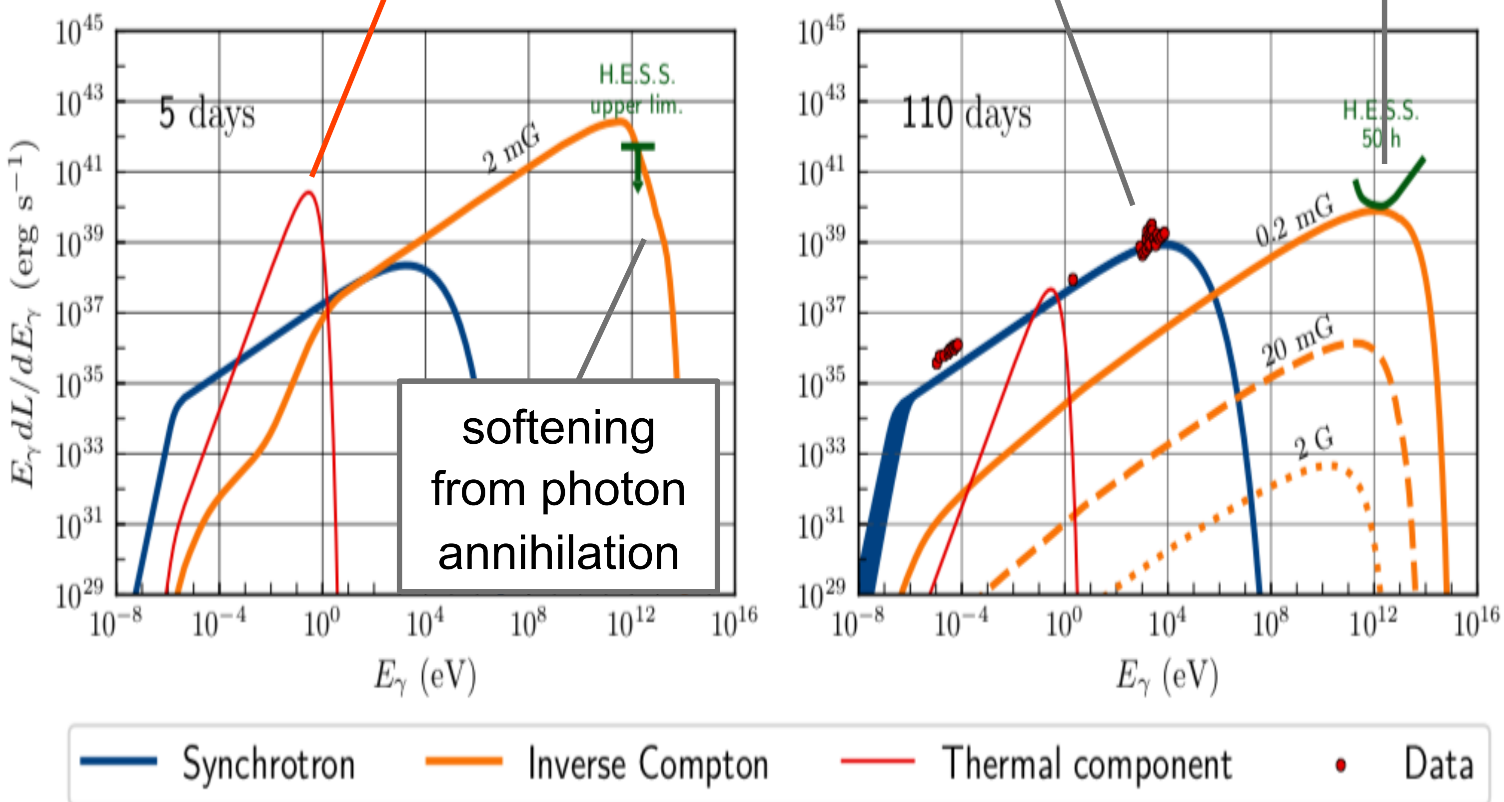
time since merger

Gamma rays from GW170817

Early times:
inverse Compton of kilonova photons can constrain u_e

synchrotron $F_{\mathrm{Xray}} \sim u_e u_B$

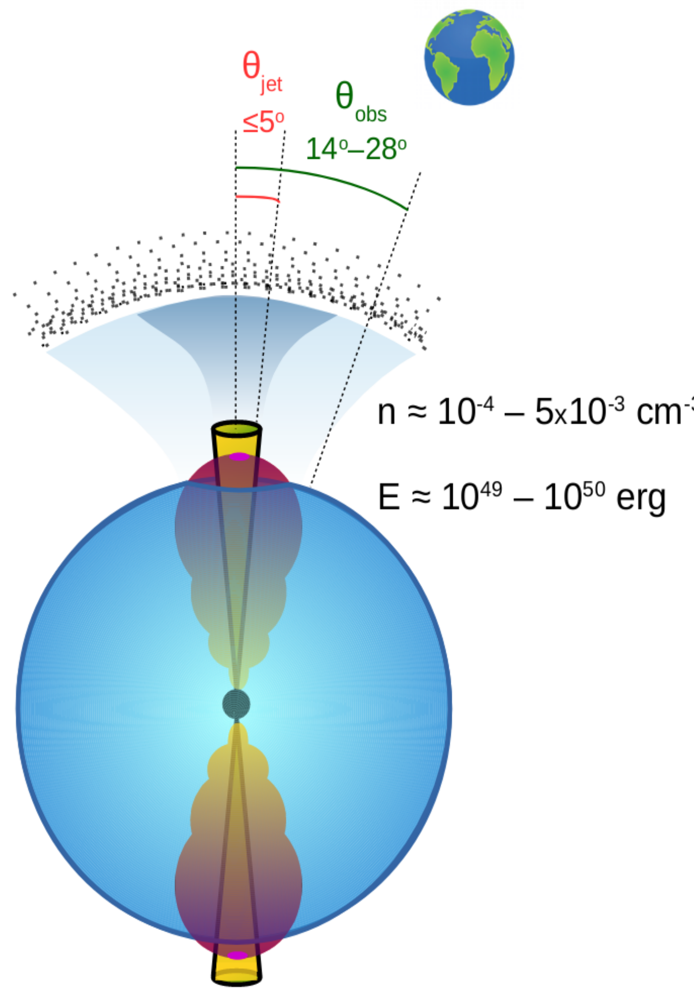
inverse Compton $F_\gamma \sim u_e^2 u_B$



[XR, D Biehl, D Boncioli, A Taylor, Astropart. Phys. 106 (2019)]

Source model

- Weak prompt non-thermal emission and long-term brightening not expected in GRB models
- An off-axis observation can explain the delayed onset
- Radio observations seem to favour a wide-angle outflow, such as a cocoon
- Superluminal motion [Mooley+ 2018] suggests early emission from cocoon, late-time emission from an off-axis relativistic jet



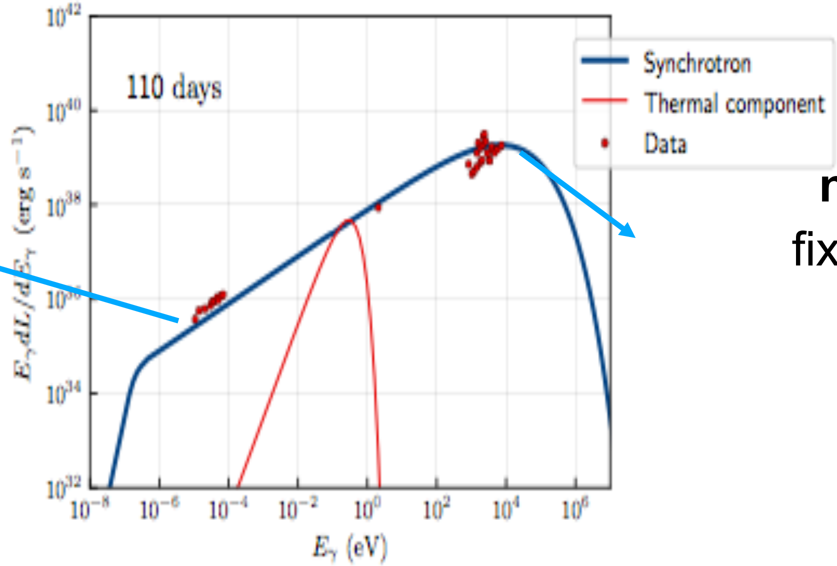
[Mooley et al, Nature 561 (2018)]

SED modeling

- We assume acceleration to occur in a spherical volume expanding isotropically with *V/c = 0.2*
- Non-thermal SED consistent with synchrotron emission from an E^{-2} electron spectrum $\mathbf{E_\gamma \frac{dN}{dE_\gamma} \propto E_\gamma^{-0.5}}$

Lack of self-absorption cutoff

$$\mathbf{B < 10\ G}$$



Maximum electron energy and **number of electrons** fixed for a given *B*-field value

- Additional *B*-field constraints from synchrotron emission:

Observed Emission at hard X-rays

$$\mathbf{t_{acc} < 110\ days}$$

No cooling break below 10 keV

$$\mathbf{t_{syn}(10\ keV) > 110\ days}$$

$$\mathbf{0.03\ mG < B < 2mG}$$

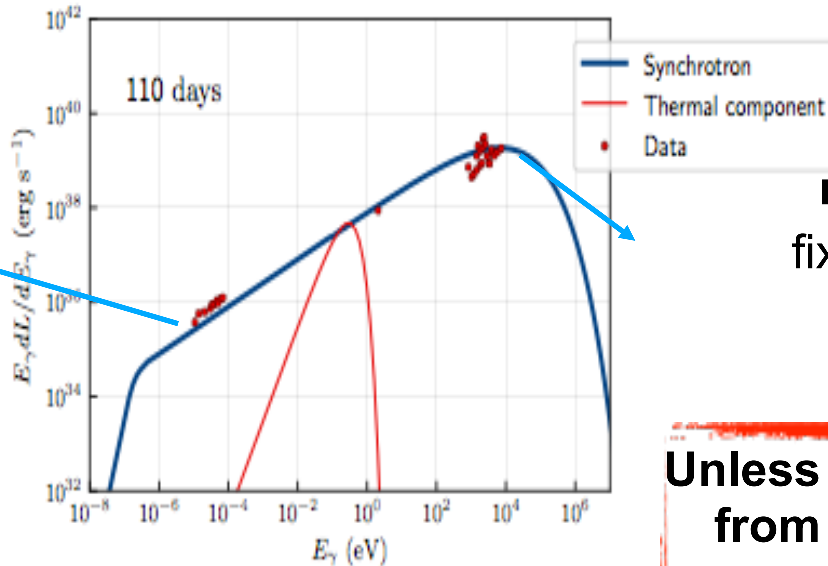
SED modeling

- We assume acceleration to occur in a spherical volume expanding isotropically with *V/c = 0.2*

- Non-thermal SED consistent with synchrotron emission from an E^{-2} electron spectrum

Lack of self-absorption cutoff

$$\mathrm{B} < 10\ \mathrm{G}$$



Maximum electron energy and **number of electrons** fixed for a given *B*-field value

Unless synchrotron comes from freshly picked up electrons in the surrounding medium

- Additional *B*-field constraints from synchrotron emission:

Observed Emission at hard X-rays

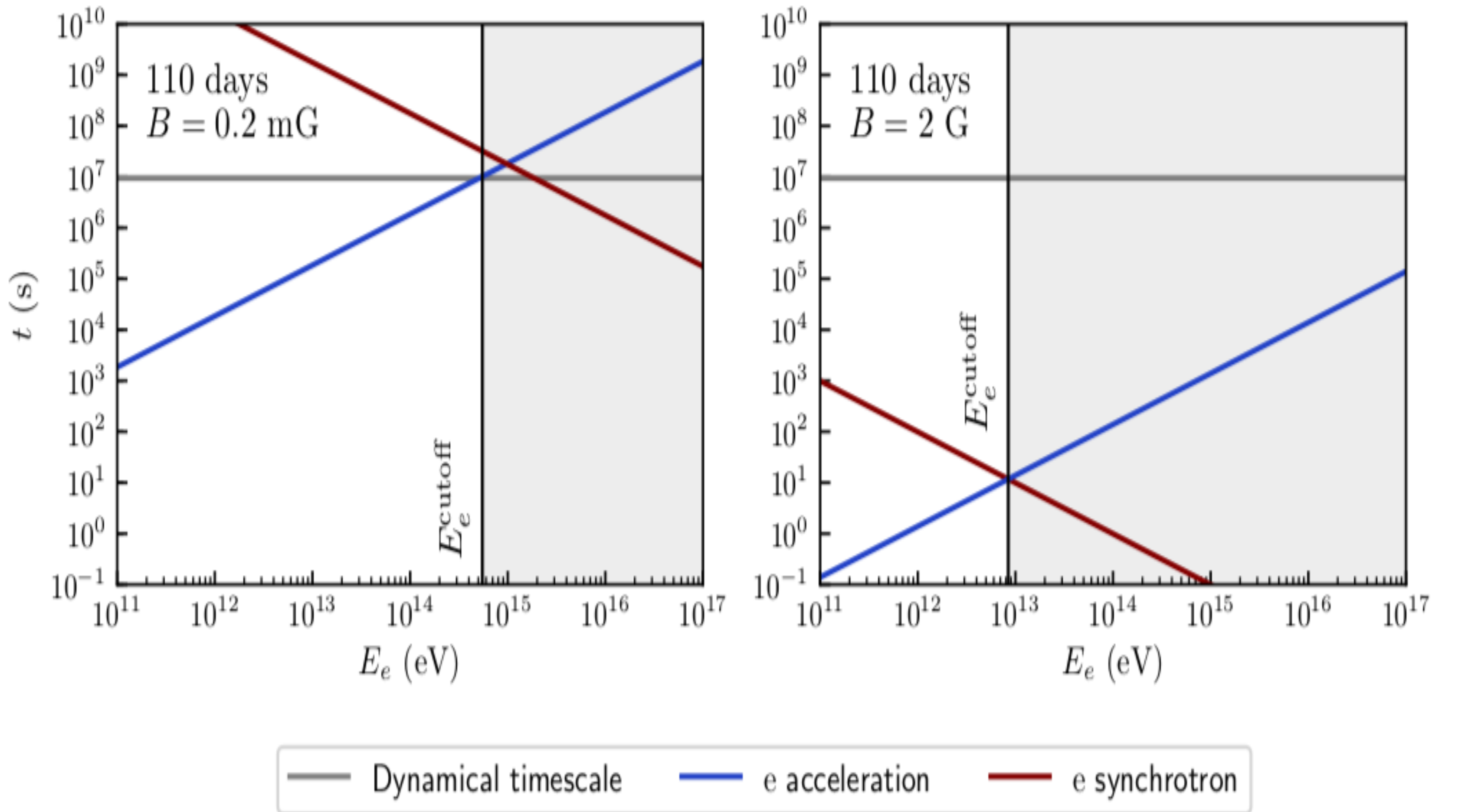
$$\mathrm{t_{acc}} < 110\ \mathrm{days}$$

No cooling break below 10 keV

$$\mathrm{t_{syn}}(10\ \mathrm{keV}) > 110\ \mathrm{days}$$

$$0.03\ \mathrm{mG} < \mathrm{B} < 2\mathrm{mG}$$

Acceleration in the GRB Outflow



[XR, D Biehl, D Boncioli, A Taylor, Astropart. Phys. 106 (2019)]

Particle Acceleration in Sources

$$\cancel{\frac{\partial n}{\partial t}} = -\nabla_p \cdot \left[\frac{p}{\tau_{acc}(p)}n - \cancel{\frac{p}{\tau_{loss}(p)}}n\right] - \frac{n}{\tau_{esc}(p)} + Q$$

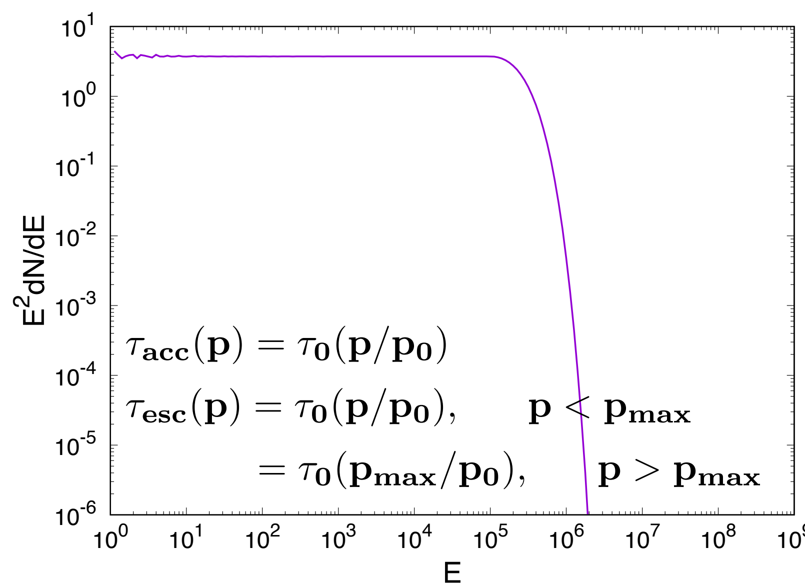
Steady state

No losses

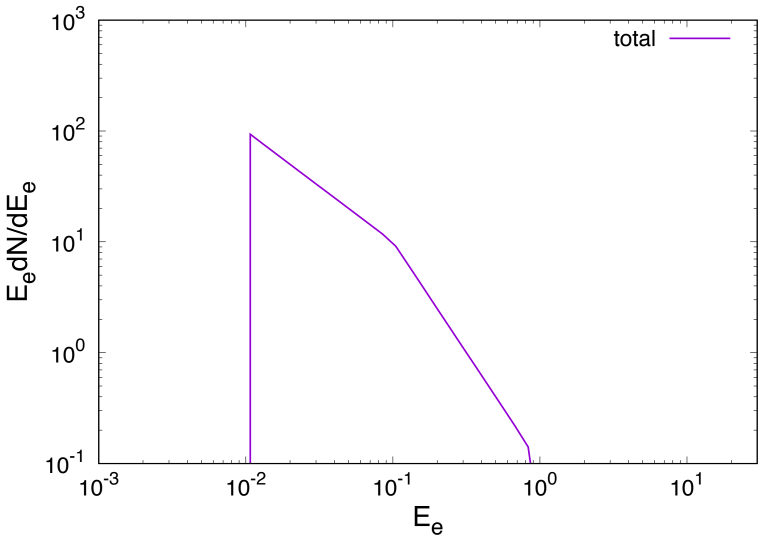
Delta injection

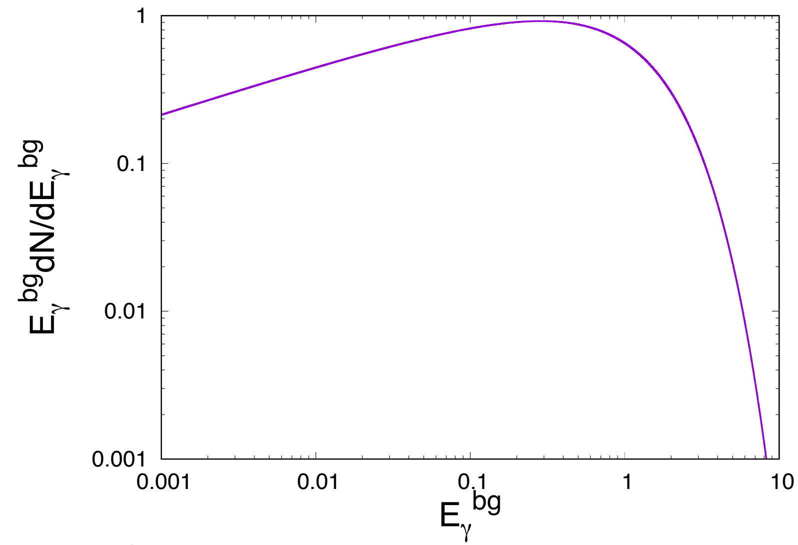
$$\frac{dn}{dp} = Q\left(\frac{p}{p_0}\right)^{-\left(1+\frac{\tau_{acc}}{\tau_{esc}}\right)}$$

Note- shock acceleration is not the only acceleration process on the block

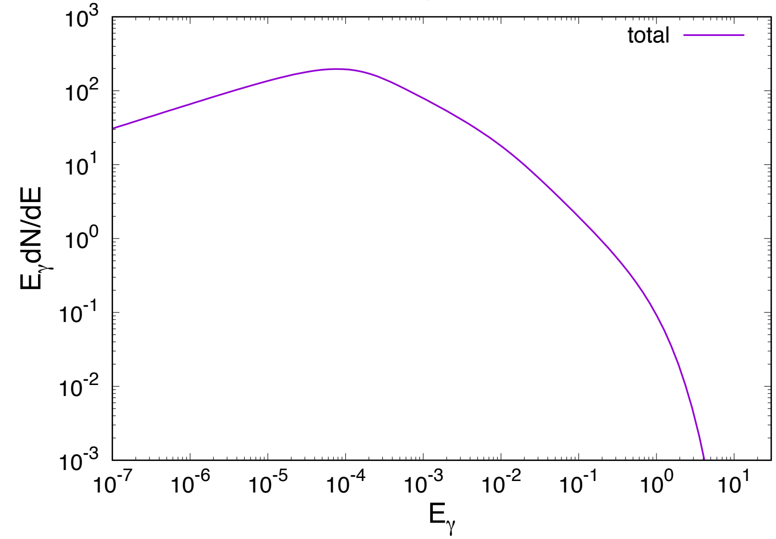


Generalities on Non-Thermal Emission from Accelerators



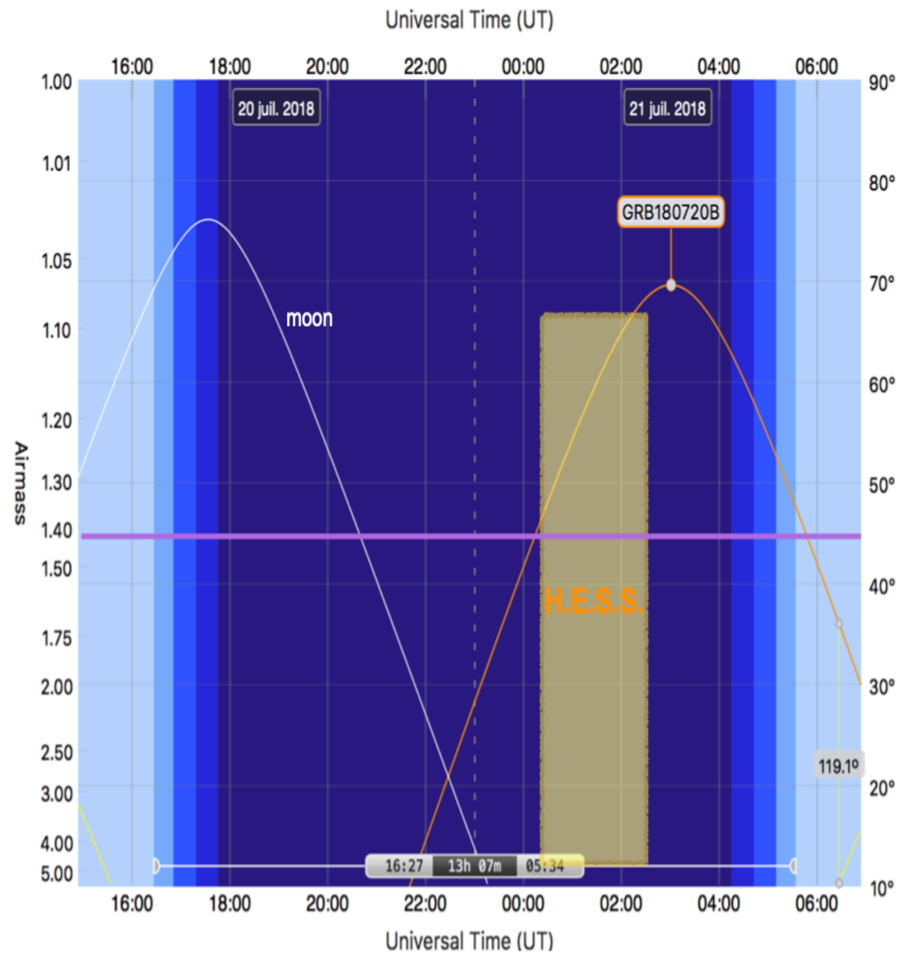


$$\mathbf{E_\gamma = \gamma_e^2 \left(\frac{B}{B_{crit}}\right) m_e}$$



H.E.S.S. Observations of GRB 180720B

- Observation started ~10 hours after the burst.
- Such GRB observations were exceptionally late time for HESS to carry out (motivated by late-time brightness of afterglow in X-ray)
- Follow-up performed for ~2 consecutive hours (zenith 40º to 25º)
- Moderate presence of clouds at the beginning not affecting the observations.

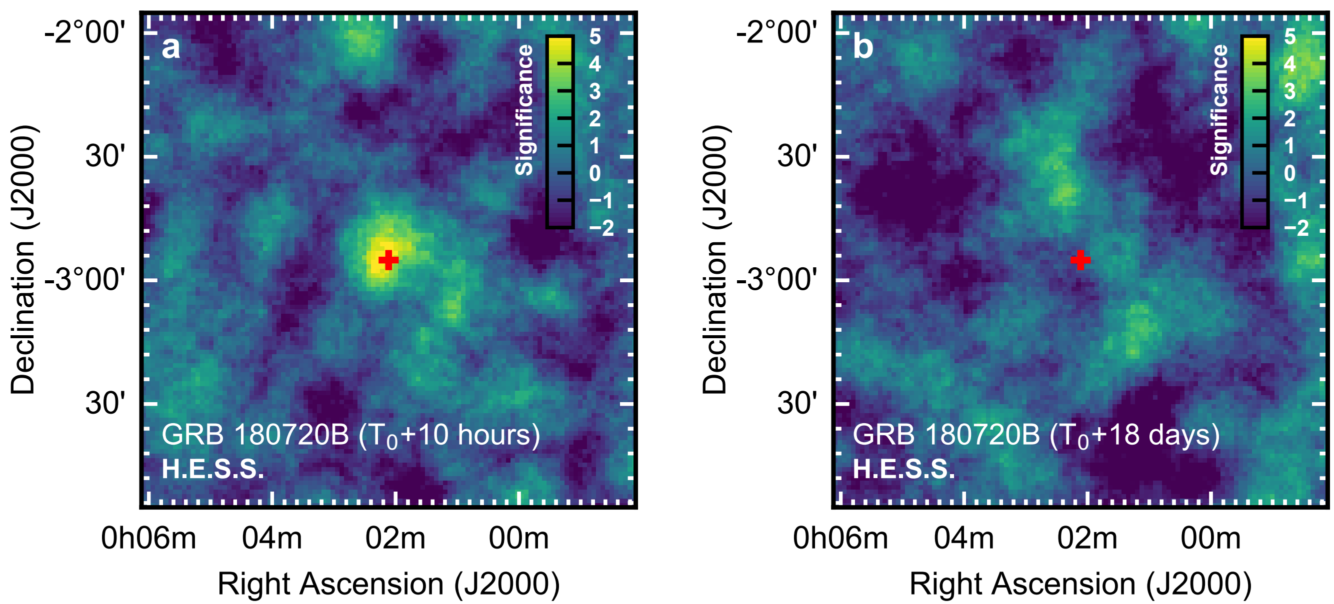


GRB 180720B H.E.S.S. Detection

- Observation started ~10 hours after the burst.
- Follow-up performed for ~2 consecutive hours (zenith 40º to 25º)

H.E.S.S. detection: ~5.3σ pre-trial, 5.0σ post-trial (5 similar searches).

- Gone in re-observation 18 days after T_0.
- Cross-check analysis (totally independent calibration and analysis chain), influence weather conditions and other systematics

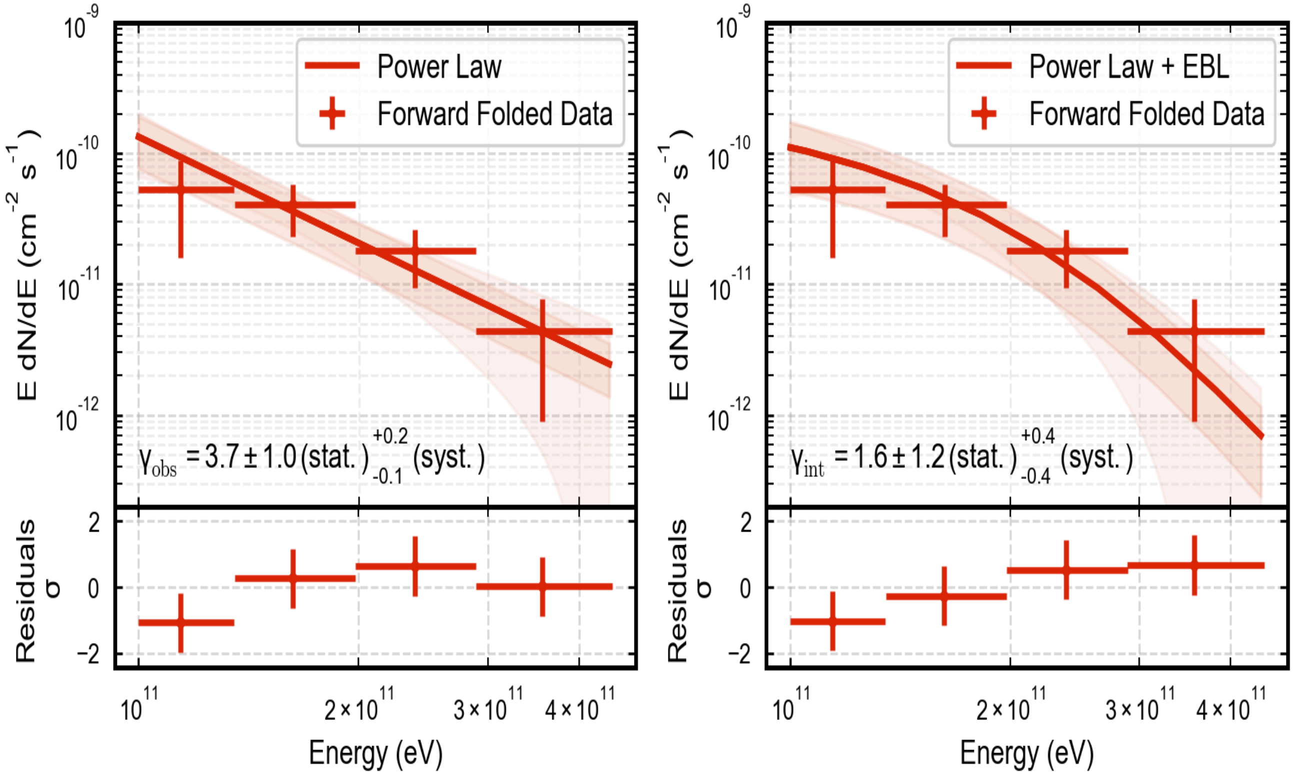


HESS Collaboration *Nature* **575**, 464–467 (2019)

GRB 180720B H.E.S.S. Detection

$$\frac{dN}{dE} = \Phi_0 \left(\frac{E}{E_0}\right)^{-\gamma_{int}} \times exp(-\tau(E,z))$$

Steep spectrum from 100 GeV to 440 GeV

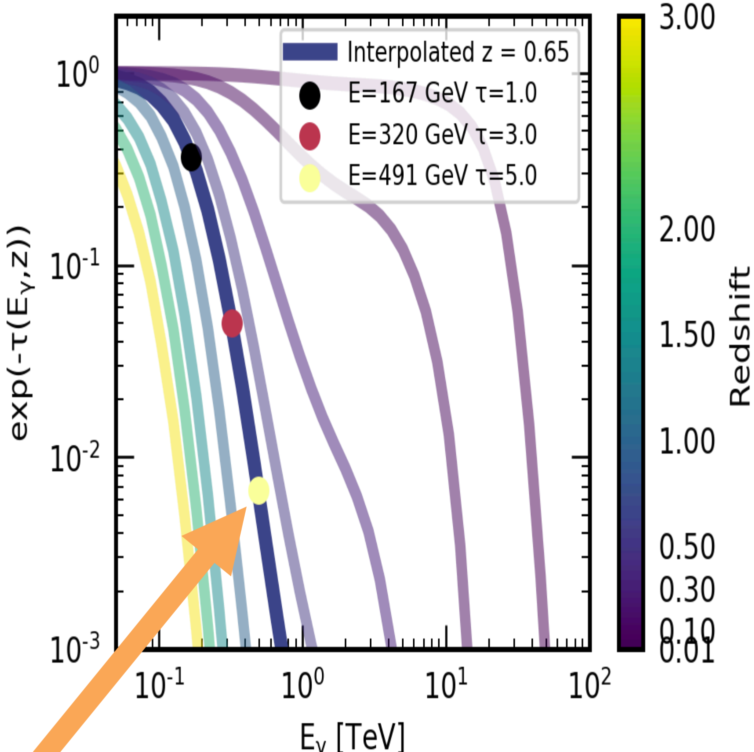


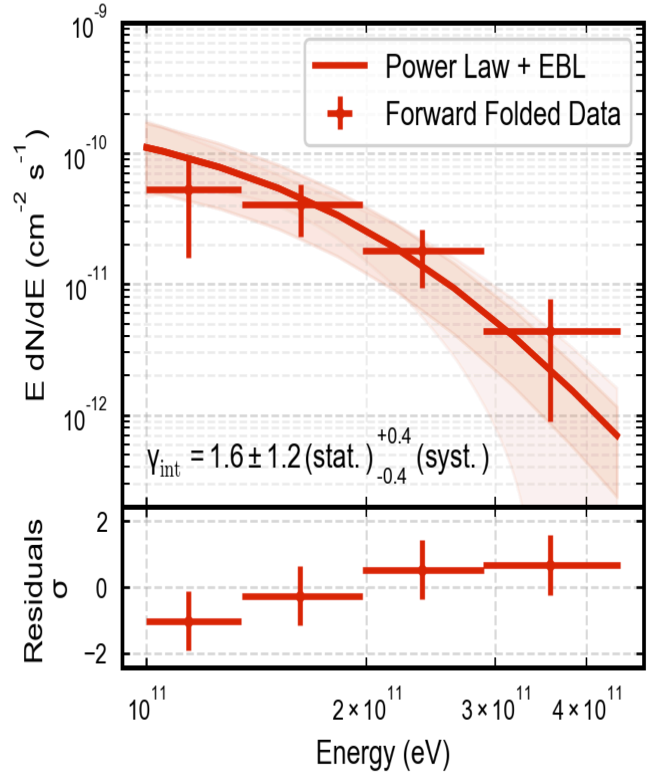
HESS Collaboration *Nature* **575,** 464–467 (2019)

GRB 180720B H.E.S.S. Detection

Very hard intrinsic spectrum (EBL de-absorbed), $\frac{dN}{dE} = \Phi_0 \left(\frac{E}{E_0}\right)^{-\gamma_{int}} \times exp(-\tau(E,z))$

redshift 0.65 (most distant GRB from the 3 detected at VHE)





98% absorption at ~500 GeV due to EBL

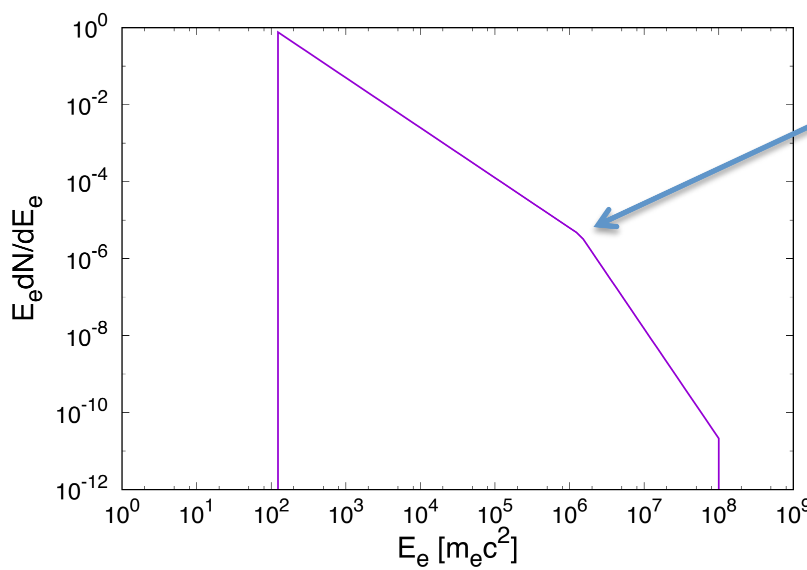
HESS Collaboration *Nature* **575,** 464–467 (2019)

Particle Spectrum Production in Cen A

$$\cancel{\frac{\partial \mathbf{n}}{\partial \mathbf{t}}} = \nabla_{\mathbf{p}} \cdot \left[\frac{\mathbf{p}}{\tau_{\mathbf{loss}}(\mathbf{p})} \mathbf{n} \right] - \frac{\mathbf{n}}{\tau_{\mathbf{esc}}(\mathbf{p})} + \mathbf{Q}$$

Steady state

Power-law injection



transition between two different transport mechanisms

Particle Transport Equation

- Cut-offs arise naturally in the general solution of the transport equation for particles

$$\frac{\partial \mathbf{f}}{\partial \mathbf{t}} = \nabla_{\mathbf{p}} \cdot \left[\left(\mathbf{D_{pp}} \nabla_{\mathbf{p}} \mathbf{f} \right) - \frac{\mathbf{p}}{\tau_{\mathbf{loss}}(\mathbf{p})} \mathbf{f} \right] - \frac{\mathbf{f}}{\tau_{\mathbf{esc}}(\mathbf{p})} + \frac{\mathbf{Q}}{\mathbf{p}^2}$$

Acceleration

Radiative Losses

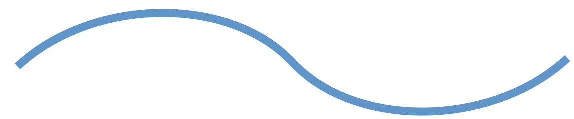
Escape

Source term

Diffusion Coefficient

- From resonant scattering between particles and magnetic field perturbations

With Larmor radius $\mathbf{R_L}$



$\mathbf{B_0 + \delta B(k)}$ resonance for $\boldsymbol{k \sim R_L^{-1}}$

$$\mathbf{P(k) \propto k^{-q}}$$

$$\frac{\mathbf{D_{xx}}}{\beta} = \left\langle \frac{\mathbf{B_0^2}}{(\delta \mathbf{B(k)})^2} \right\rangle \mathbf{R_L} = \frac{\mathbf{R_L}}{\mathbf{kP(k)}}$$

Probability to scatter off resonant mode within Larmor period

$$\propto \mathbf{p^{2-q}}$$

- Bohm -> q=1
- Kolmogorov -> q=5/3
- Kraichnan -> q=3/2
- Hard-sphere -> q=2

Since $$\frac{\mathbf{p^2}}{\mathbf{D_{pp}}} \sim \frac{\mathbf{D_{xx}}}{\beta^2_{\mathbf{scat}}}$$

$$\mathbf{D_{pp} \propto p^q}$$

Radiative Loss Timescale

- Relativistic particle will loose its energy on a timescale that depends of the different processes

$$\tau_{\mathrm{cool}}(\mathbf{E}) \propto \mathbf{E}^{\mathbf{r}}$$

Synchrotron:
r = -1

Inverse Compton *(Thomson)*:
r = -1

Inverse Compton (K.N):
r = 1

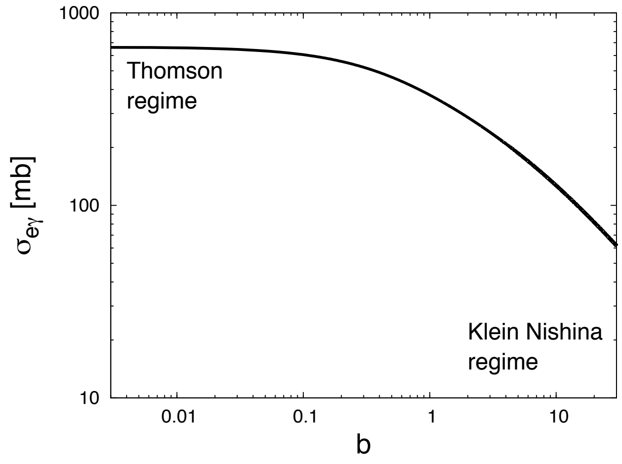
Radiative Loss Timescale

$$\tau_{\mathrm{cool}}(\mathbf{E}) \propto \mathbf{E}^{\mathbf{r}}$$

Synchrotron:
r = -1

Inverse Compton *(Thomson)*:
r = -1

Inverse Compton (K.N):
r = 1



$$\mathbf{E}_\gamma \approx \gamma_{\mathbf{e}}^{\mathbf{2}} \left(\frac{\mathbf{B}}{\mathbf{B}_{\mathrm{crit}}}\right) \mathbf{m}_{\mathbf{e}} = \mathbf{b}\mathbf{E}_{\mathbf{e}}$$

$$\mathbf{E}_\gamma = \left(\frac{\mathbf{b}}{\mathbf{1}+\mathbf{b}}\right) \mathbf{E}_{\mathbf{e}}$$

Cut-off Shape

- Interplay of acceleration and cooling defines the value of the cut-off of the primary particles: $\beta_{\mathbf{e}} = \mathbf{2} - \mathbf{q} - \mathbf{r}$

$$\frac{\mathbf{dN}}{\mathbf{dE_e}} \propto \mathbf{E_e^{-\Gamma} e^{-(E_e/E_{max})^{\beta_e}}}$$

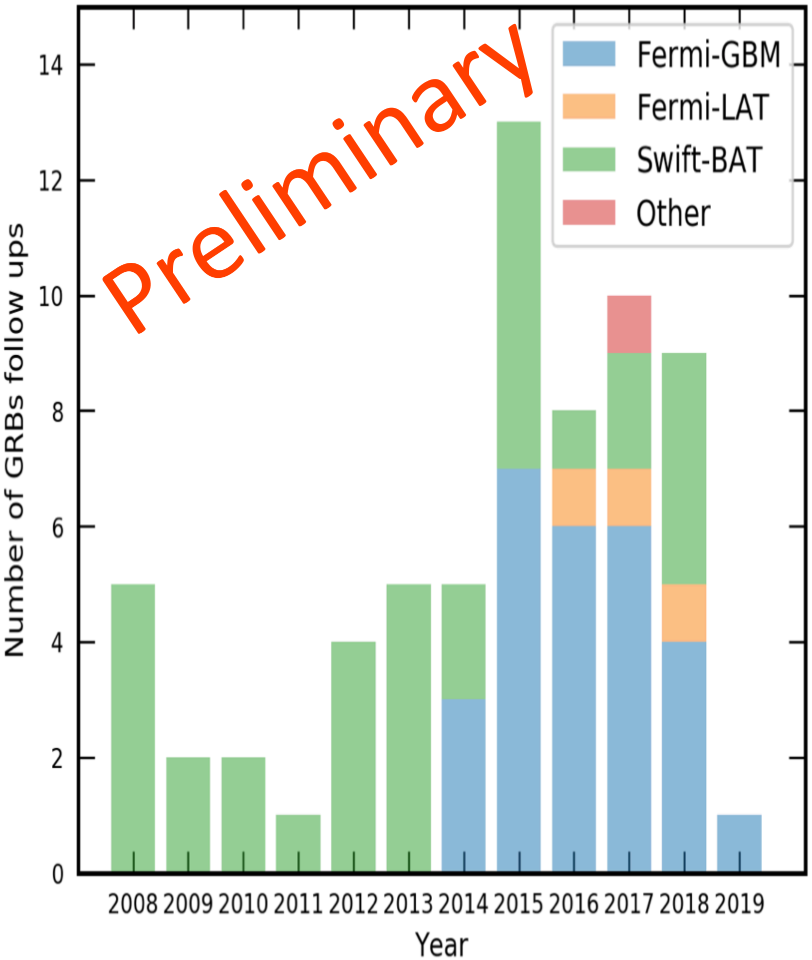
- In the following, demonstrations for this result will be shown for the case of stochastic acceleration scenarios. However, in reality, this result is more general, holding also for shock acceleration scenarios.

[see Schlickeisser et al. 1985, Zirakashvili et al. 2007, Stawarz et al. 2008]

Research Focus Since 2017

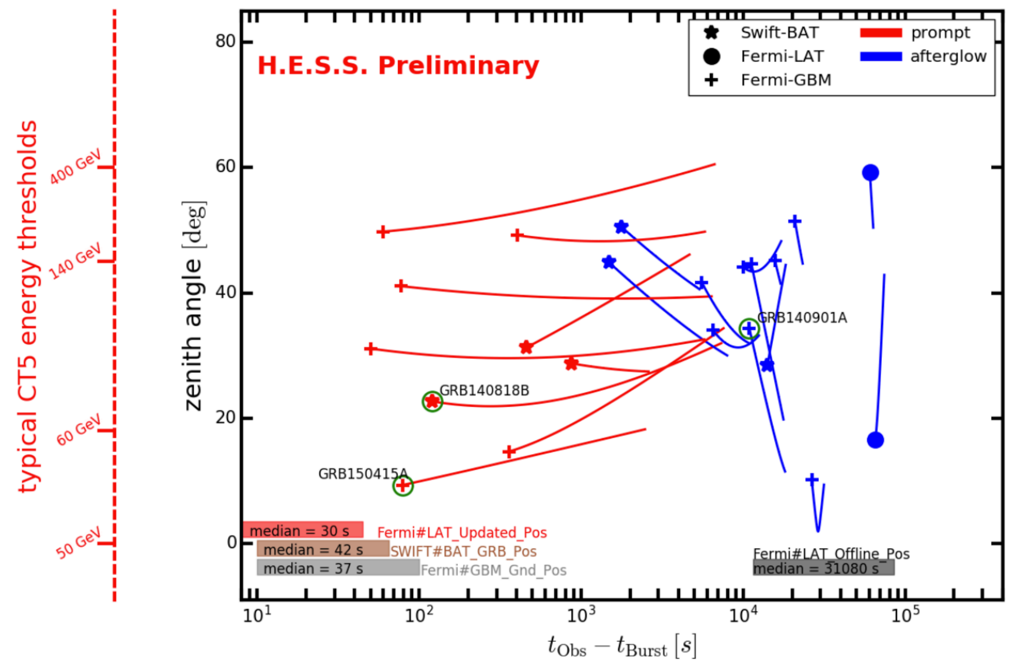
- Starburst galaxies- inferring their intrinsic proton spectra and its implication for neutrino emission
- Galactic outflow and halo emission- modeling a Galactocentric wind and its non-thermal radiation signatures
- Cen A VHE Extension- interpretation of the discovery of extended very high emission
- Solar Flares- inferring the intrinsic proton spectra from solar flares
- Cosmic Rays and Young Stellar Objects- the role that cosmic rays can play in their accretion
- TXS 0506+056- a hadronic (pp) model for the flare/neutrino emission from this AGN
- GW 170817 (neutron star merger event)- constraining the magnetic field in the outflow environment
- HESS GRB Detections- the first discovery of very high energy emission from a GRB 180720B, and the question of the emission process which can be well probed with GRB 190829A

H.E.S.S. GRB follow-up observations: 2012 to 2017



(note- plot made early 2019)

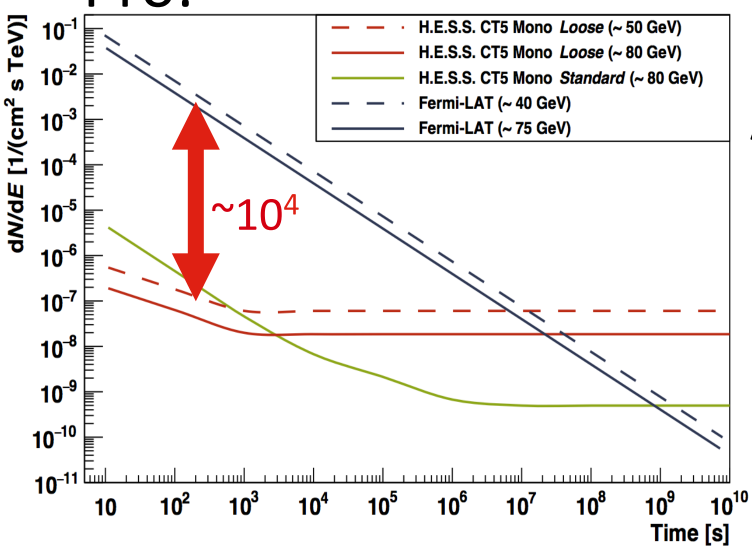
- ~10 Fermi-GBM GRBs/yr
- ~1 Fermi-LAT GRB/yr



HESS Collaboration (ICRC 2017)

H.E.S.S. GRB follow-up observations: 2012 to 2017

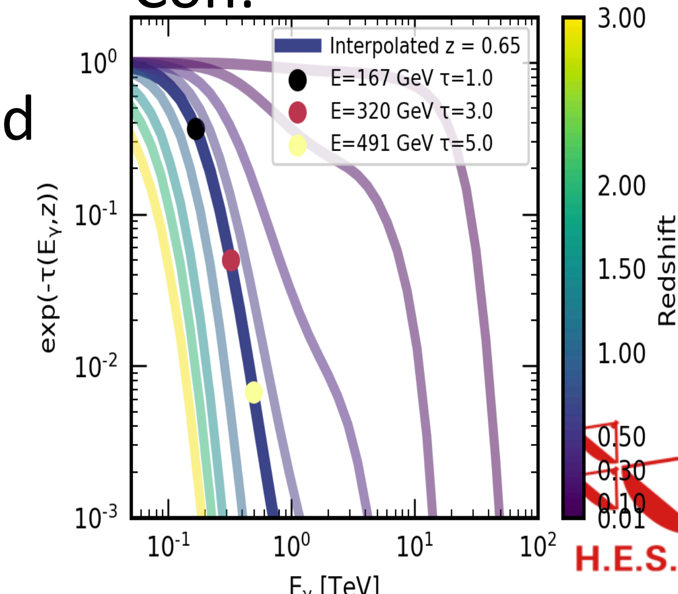
Pro:



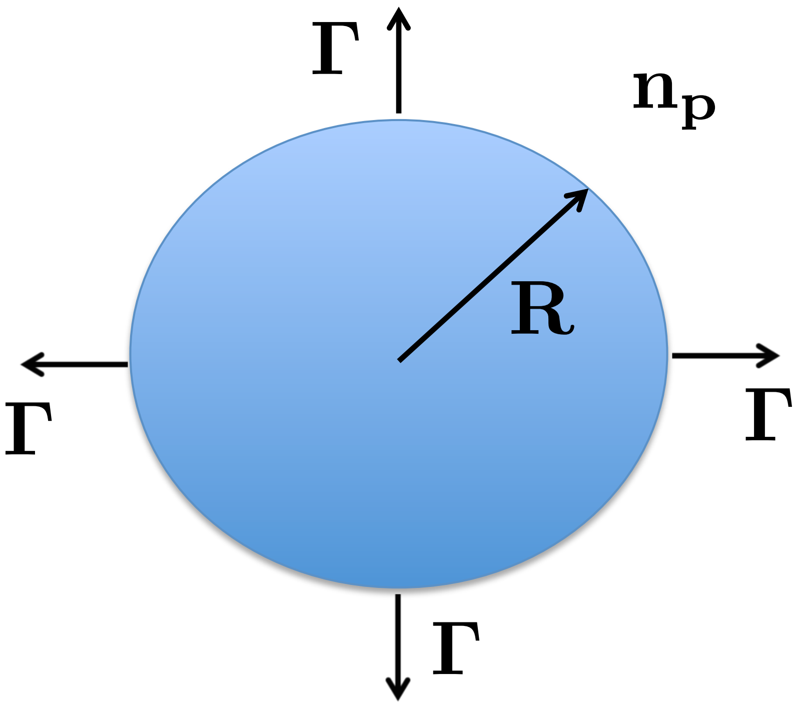
HESS Collaboration(ICRC 2015)

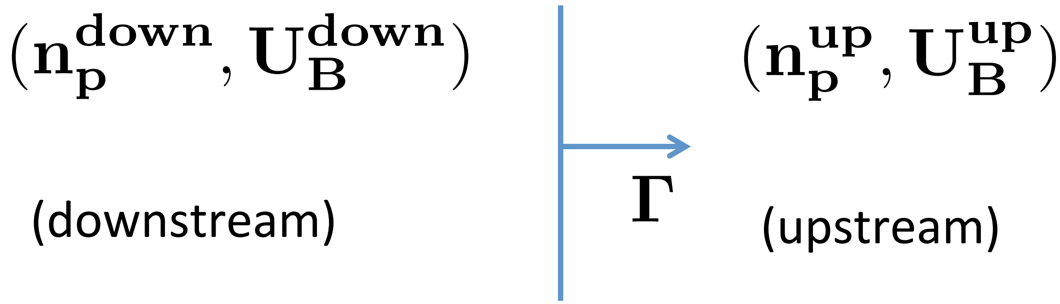
A low threshold energy is everything!

Con:



Origin of Synchrotron Temporal Decay





$$\frac{\mathbf{L^{iso}_{sync}}}{4\pi\Gamma^2\mathbf{R}^2\mathbf{c}} = \eta\Gamma^2\mathbf{n_p}\mathbf{m_p}\mathbf{c}^2$$

$$\Gamma \propto \mathbf{t}^{-3/8} \qquad \mathbf{R} \propto \mathbf{t}^{1/4}$$

$$\mathbf{L^{iso}_{sync}} \propto \mathbf{t}^{-1}$$