Massive Argon Space Telescope (MAST): concept and physical program

On the future of γ-ray astronomy
in the 100 MeV–1 TeV energy range

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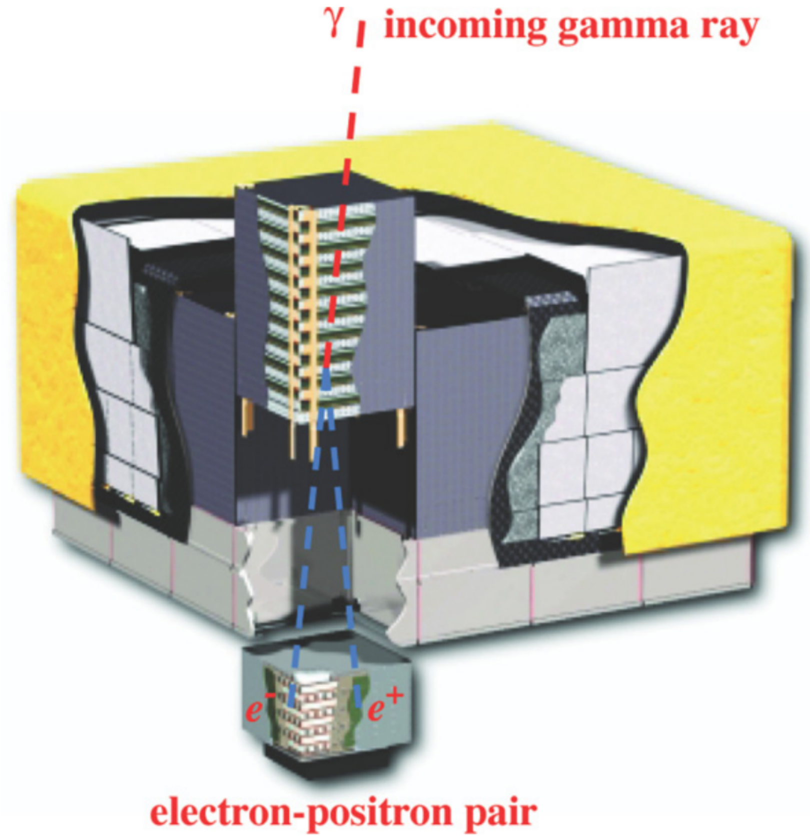
Dzhatdoev & Podlesnyi, APh, **112**, 1 (2019)
Dzhatdoev et al., Phys. Rev. D, **102**, 123017 (2020)
Khalikov & Dzhatdoev, MNRAS, 10.1093/mnras/stab1393 (2021) (astro-ph/1912.10570v2)
Podlesnyi & Dzhatdoev, Res. Phys., **19**, 103579 (2020)
Dzhatdoev et al., astro-ph/1810.06200

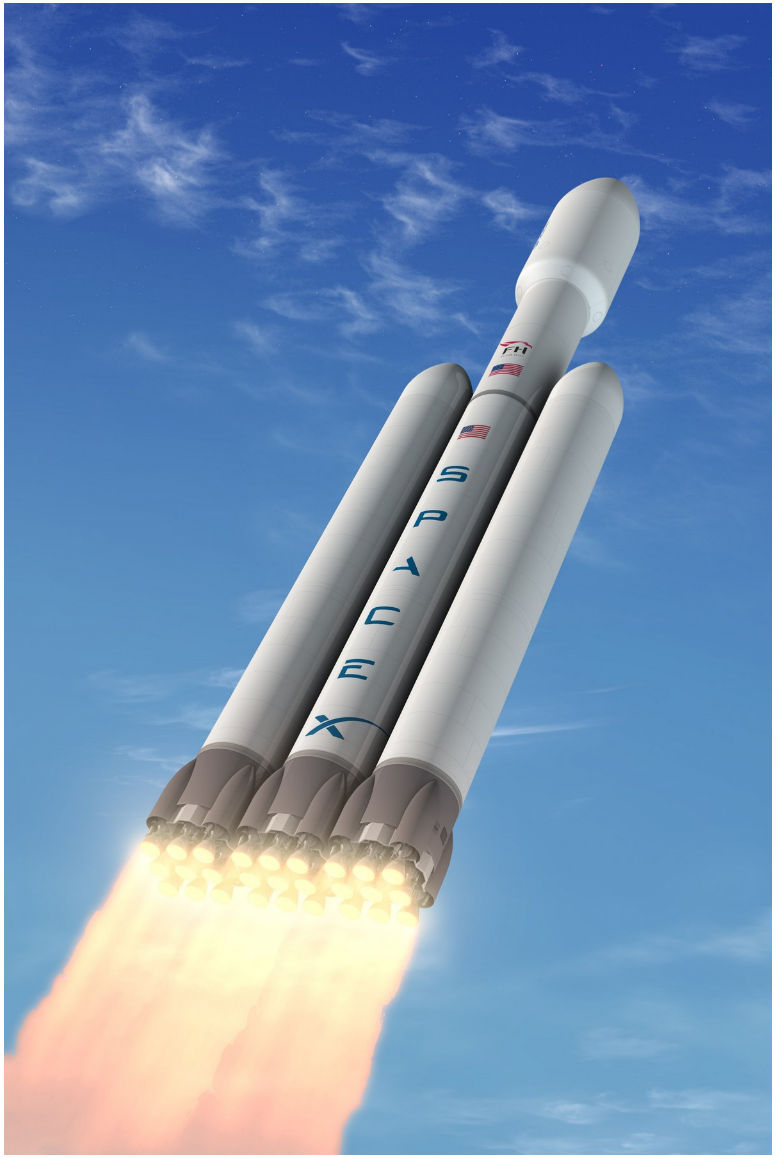
Fermi-LAT (Atwood et al., 2009): a great success of γ-ray astronomy!

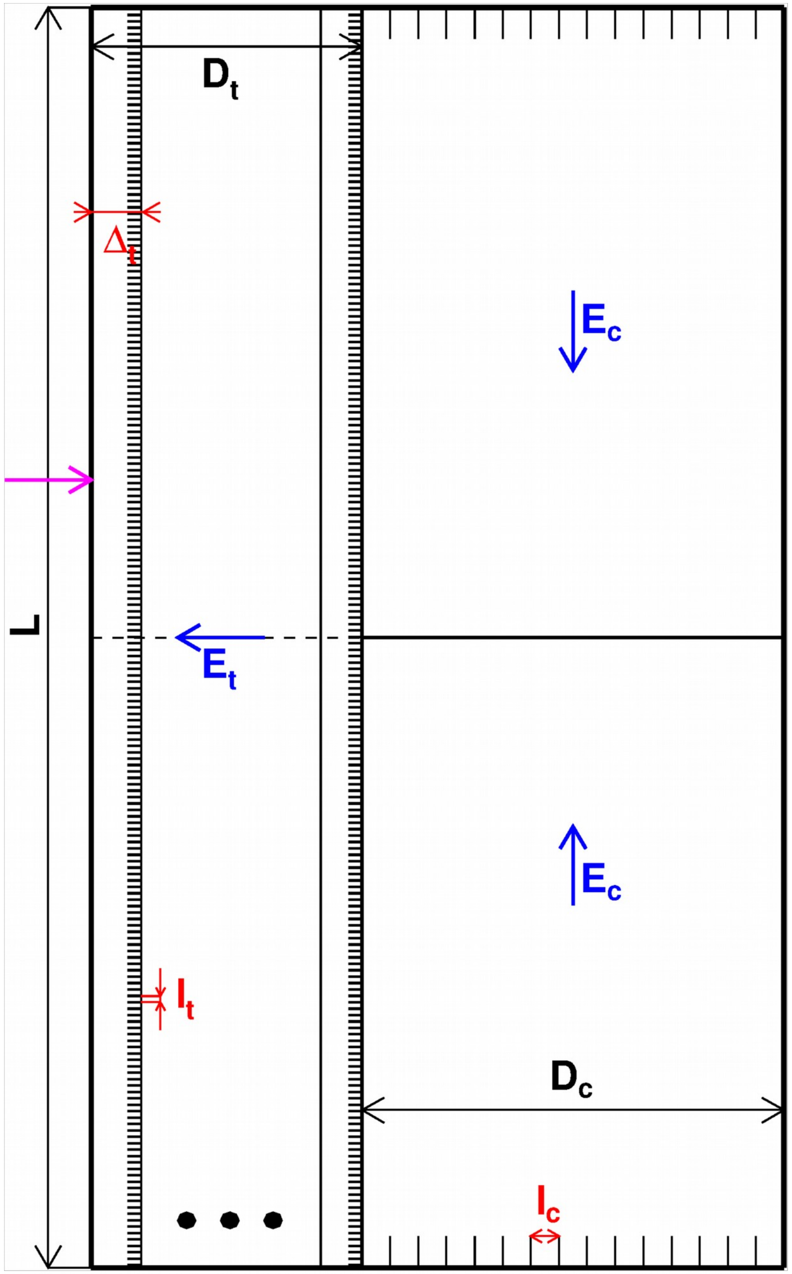


1) ~5 thousand sources (Abdollahi et al., 2020), mostly blazars
2) Measurement of extragalactic gamma-ray background (EGRB) up to 1 TeV (Ackermann et al., 2015)
3) Constraints on the extragalactic background light (EBL) (Ackermann et al., 2012; Fermi-LAT, 2018) and extragalactic magnetic field (EGMF) (Neronov & Vovk, 2010; Ackermann et al., 2018)
4) constraints on annihilating (Ackermann et al., 2015b) and decaying (Kalashev & Kuznetsov, 2016; Cohen et al., 2017) dark matter (DM)

1) Still no detection of DM decay/annihilation
2) Constraints on EGMF parameters are very shaky
3) Numerous problems in blazar models (including the models of neutrino-emitting blazars, IceCube 2018; IceCube et al., 2018)
4) No obvious counterpart of gravitational-wave (GW) events (in particular, GW 190521 was not detected, Podlesnyi & Dzhatdoev, 2020)

The Falcon Heavy launcher: 64 t for (R= 185 km); about 40 t for R= 565 km. We propose a new space instrument called Massive Argon Space Telescope (MAST) based on the time projection chamber concept





Liquid Argon (LAr) as a detector medium

I. Basic idea: electric field → drift on the third coordinate
Two-phase time projection chamber (TPC): Dolgoshein et al. (1970)
General discussion of the TPC concept: Nygren (1974)
Liquid Argon TPC: Rubbia (1977)

II. State-of-the-art for "large" (>100 t) LAr TPC: ICARUS T 600: Rubbia et al. (2011)
III. Future: DUNE 68 kt (!!) of LAr (Acciarri et al., 2015)

IV. A few tips on the technology:
1) The LAr technique allows to construct fully active, easily scalable, cost-effective detectors with reasonable spatial resolution
2) Boiling point @ 1 atm.: 87.3 K (nitrogen: 77.3 K)
3) Purification: extremely effective even with commercially available hardware (electronegative impurities $10^{-6} \rightarrow 10^{-12}$)

V. Many methodical studies in the recent years, in particular: recombination (R. Acciarri et al., ArgoNeuT collaboration (2013); Cataudella et al., 2017)
VI. Application in astroparticle physics: especially in the MeV energy range: Bernard et al. (2013); cf. gas TPC: Hunter et al. (2014) (AdEPT); Gros et al. (2018) (HARPO). Electronics: see e.g. Baudin et al., 2018

Liquid Argon as a detector medium: theory (Cataudella et al. (2017))

$$\frac{\partial N_+(\vec{r},t)}{\partial t} = D_+\nabla^2 N_+(\vec{r},t) - \alpha N_+ N_- + \mu_+\vec{E}\cdot\nabla N_+(\vec{r},t)$$

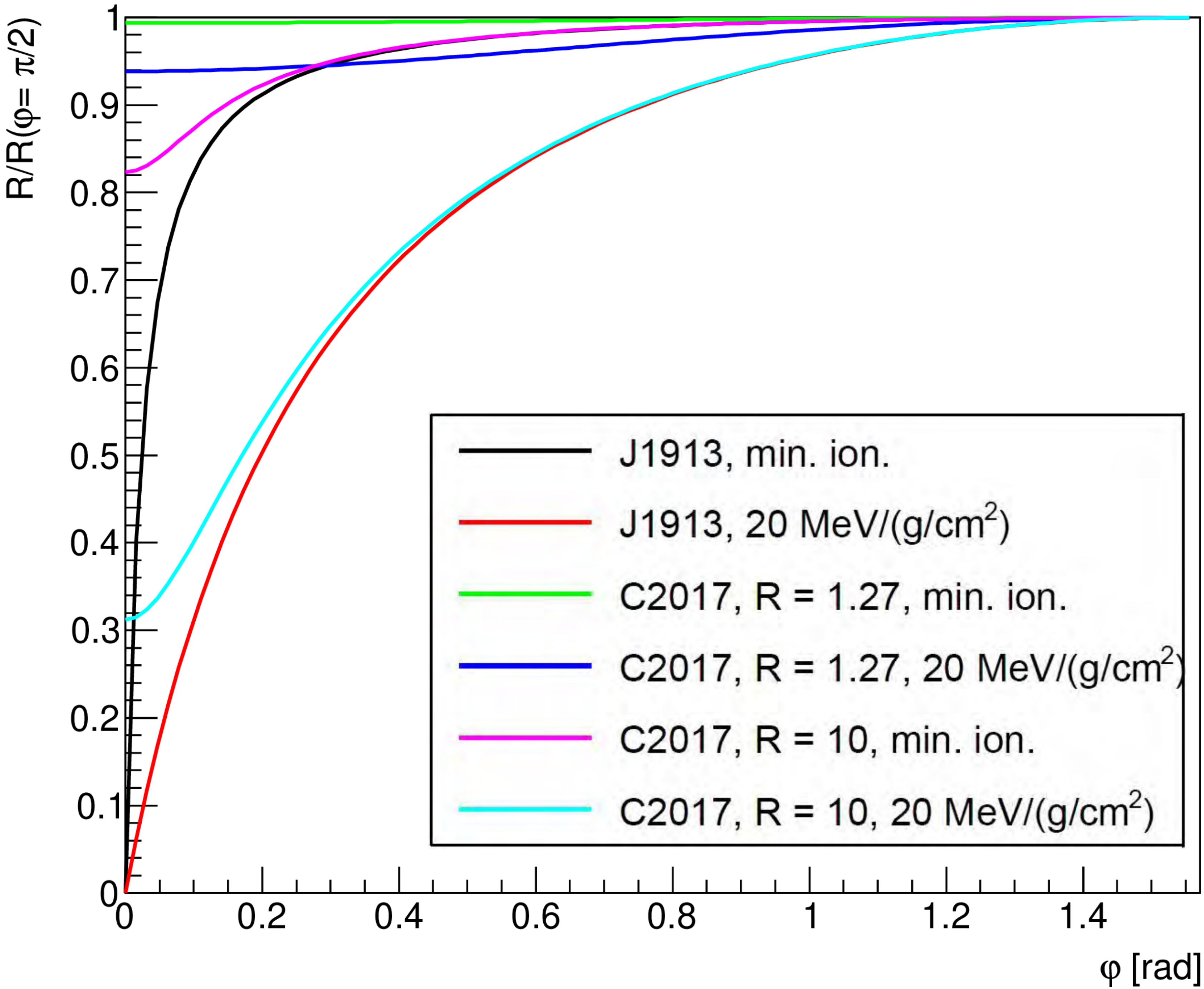
$$\frac{\partial N_-(\vec{r},t)}{\partial t} = D_-\nabla^2 N_-(\vec{r},t) - \alpha N_+ N_- - \mu_-\vec{E}\cdot\nabla N_-(\vec{r},t)$$

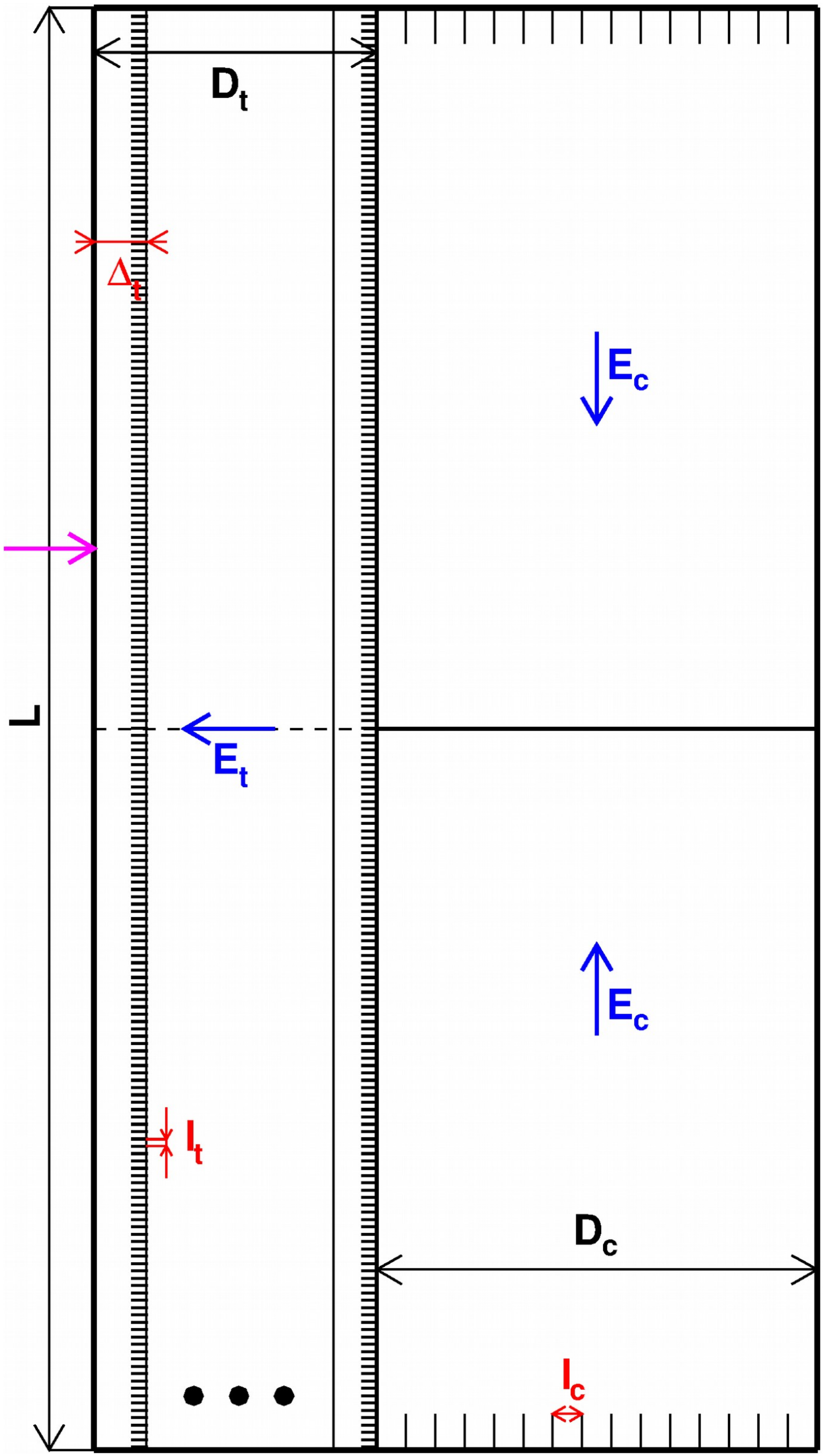
diffusion, recombination, and drift

$$N_0(\vec{r}) = N_-(\vec{r},0) = N_+(\vec{r},0) = \frac{Q_0}{(2\pi)^{3/2}R\sigma^3} e^{-\frac{1}{2\sigma^2}\left(x^2+y^2+\frac{z^2}{R^2}\right)}$$

the classical estimate for the charge carrier survival probability (~sin(φ), Jaffe) is far too pessimistic (1913) → (2017)

Charge carrier survival probability vs. the angle between the track and the electric field direction φ. Electric field E= 3 kV/cm





4m X 4m aperture; 11.4 rad. len.

M= 36 t (would need a Falcon Heavy!)

power: 4.4 kW (Fermi-LAT: 650 W)

Tracker

"parallel" TPC (E_t||axis); E_t = 3 kV/cm

Total thickness D_t= 50 cm, 50 layers, pitch l_t=100 mkm

~6 million channels (cf. Fermi-LAT: 0.88 million – Thompson (2015))

Calorimeter

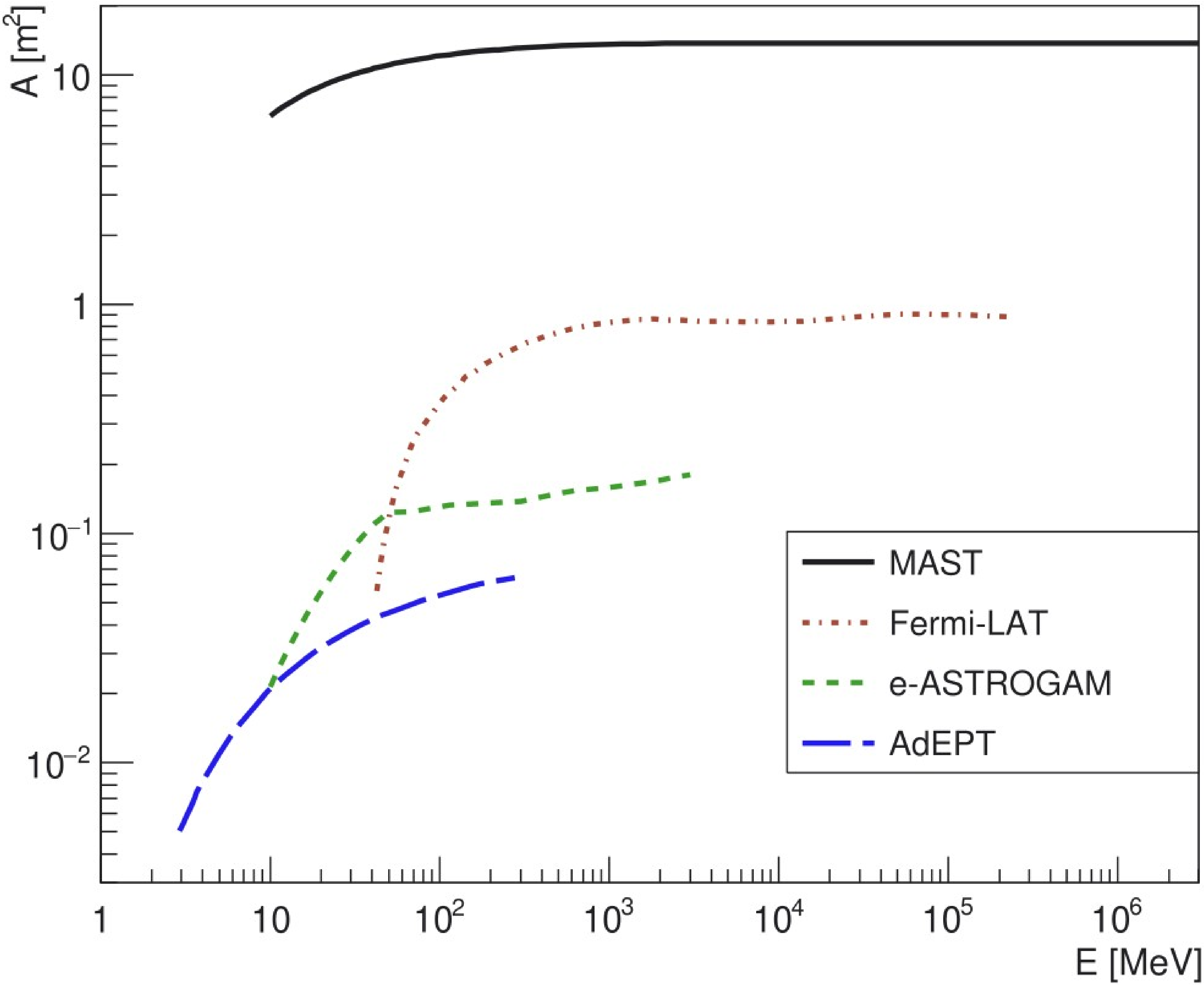
E_c = 0.5 kV/cm

Total thickness Dc= 110 cm, pitch l_c = 1 mm

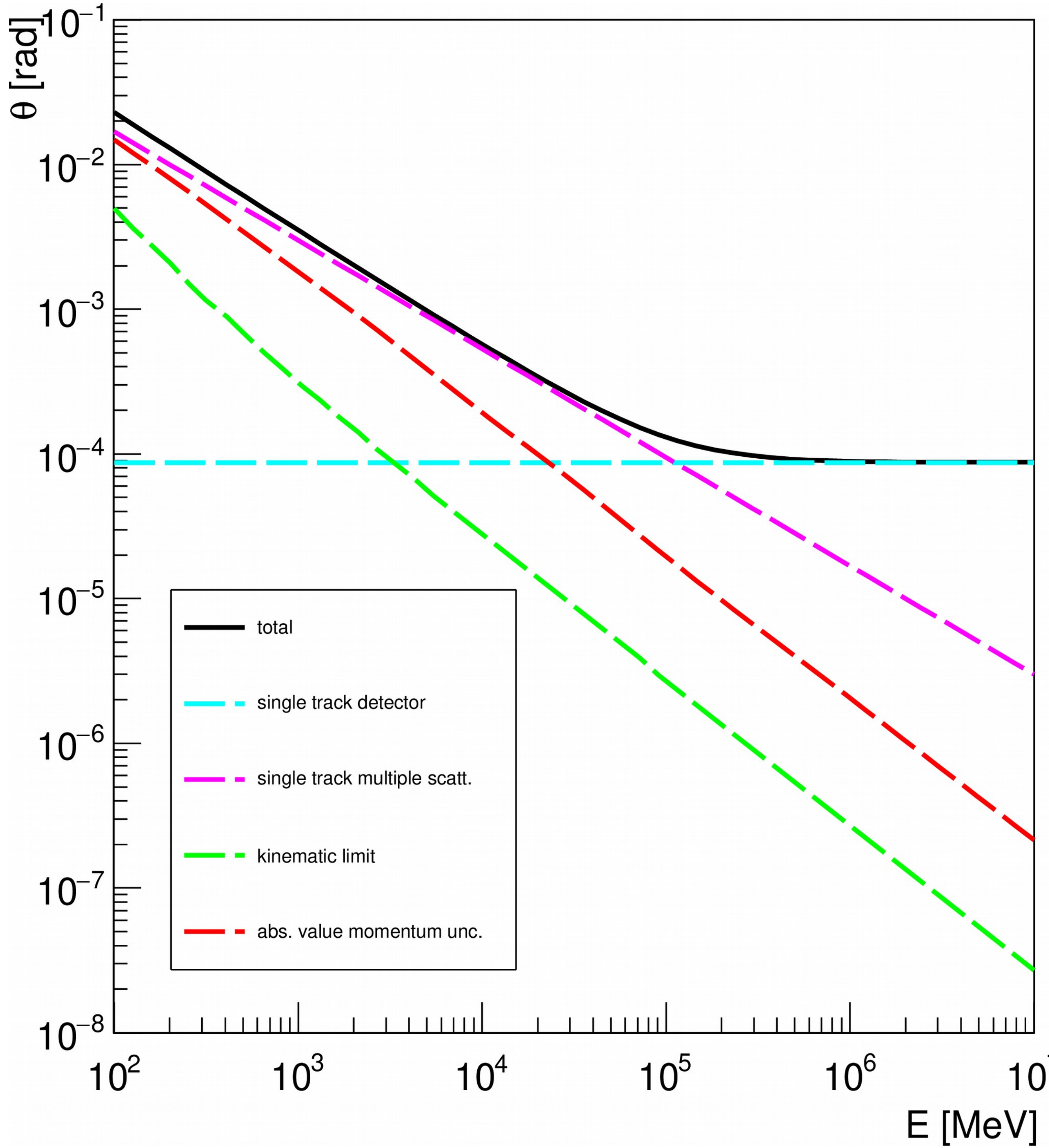
Anti-coincidence detector (not shown)

Could be similar to the Fermi-LAT one

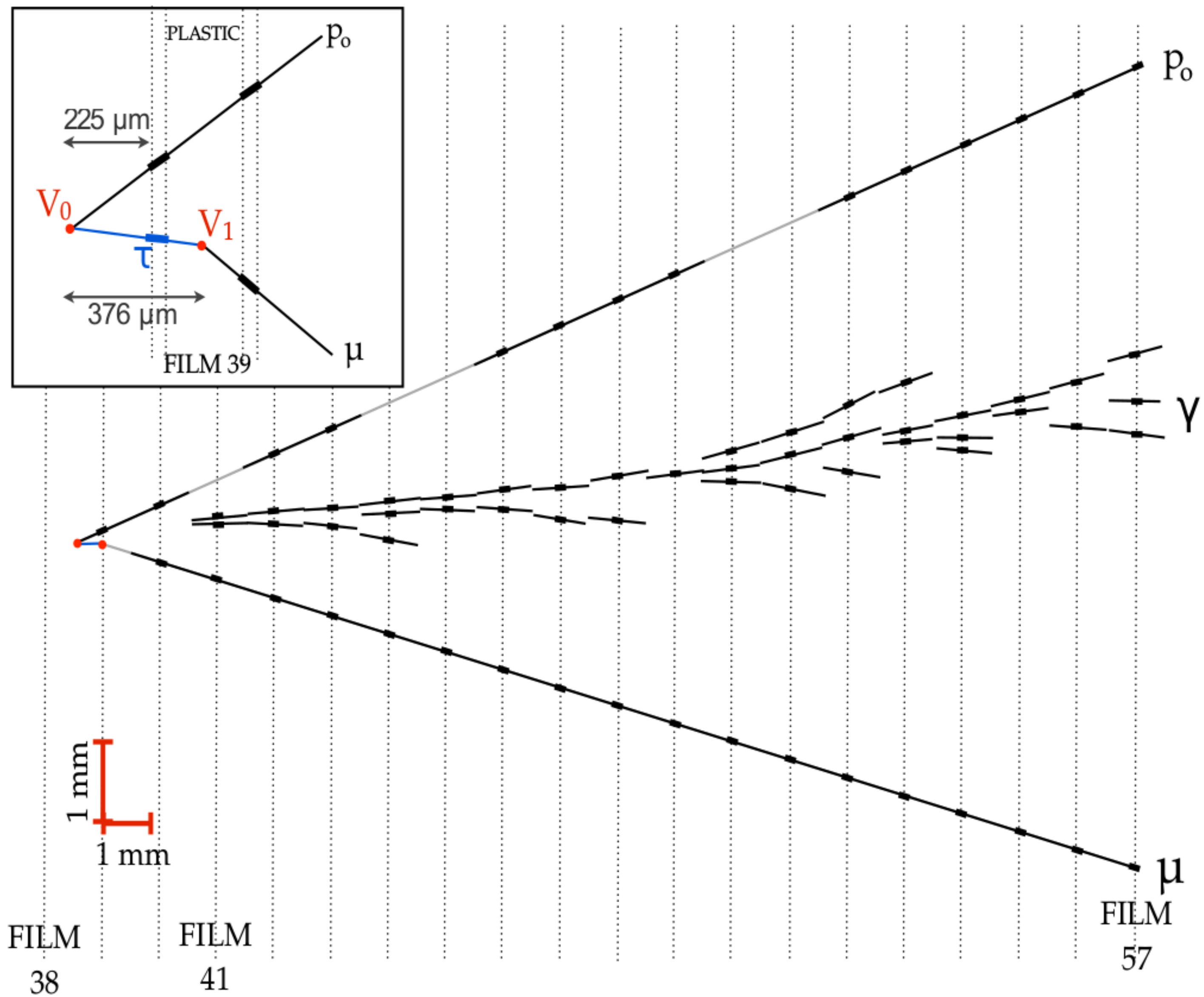
Effective area vs. energy



Angular resolution vs. energy: four main components



Can we measure p^+/p^-?

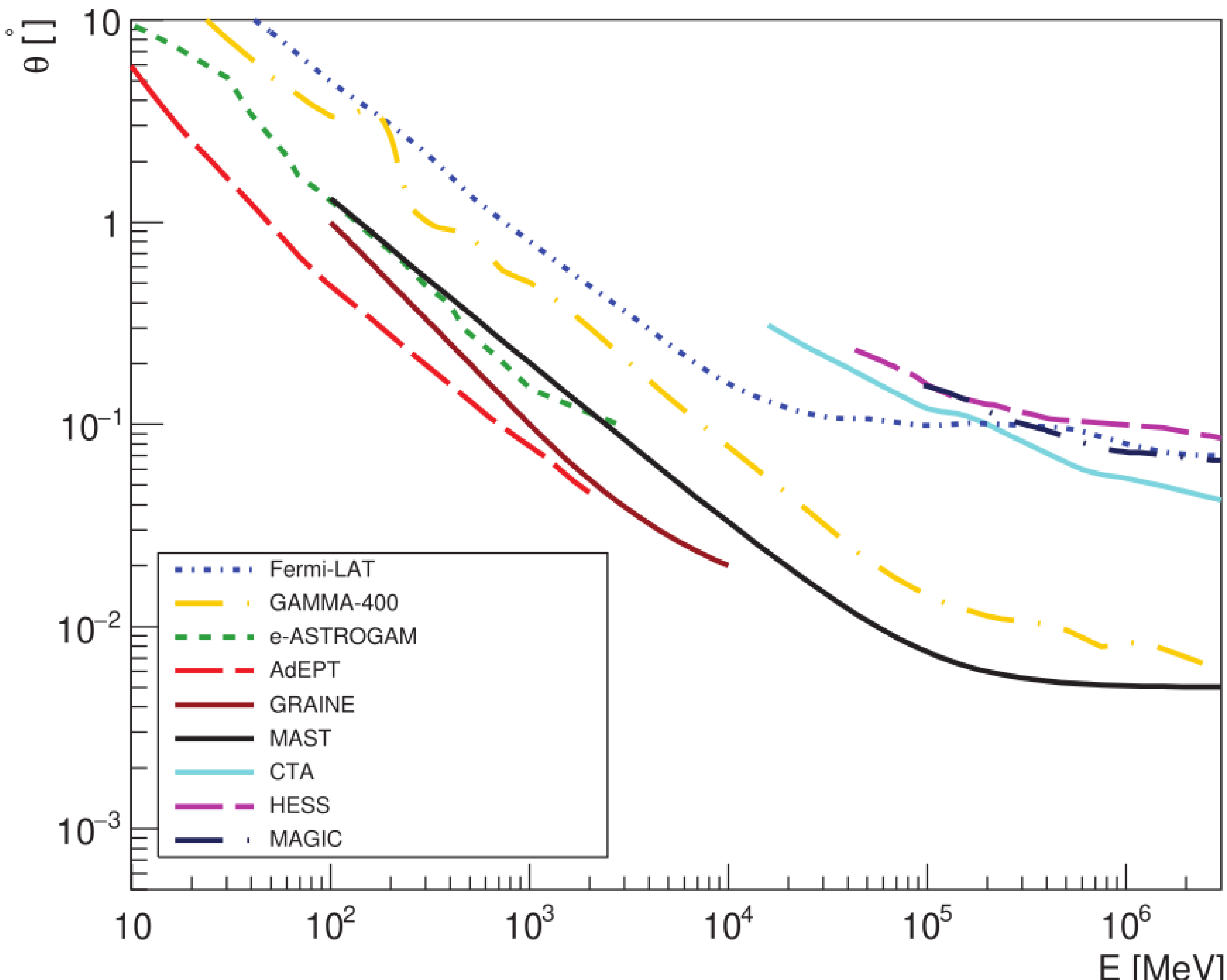


OPERA Experiment: an event display (Agafonova et al., 2014)

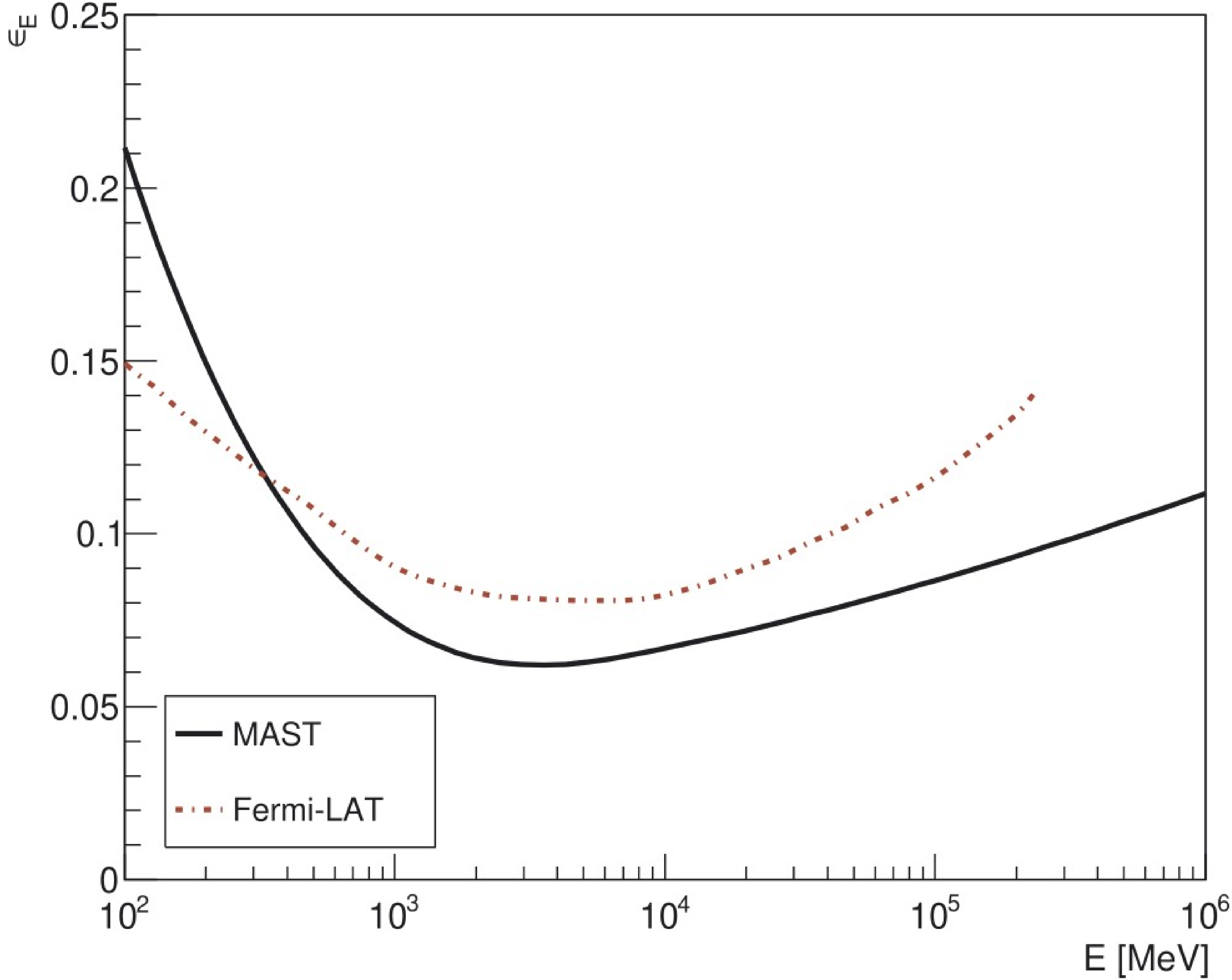
Electron and positron subshowers could overlap strongly! →

We assume $p^+/p^- = 1$, and then account for the corresponding methodical uncertainty

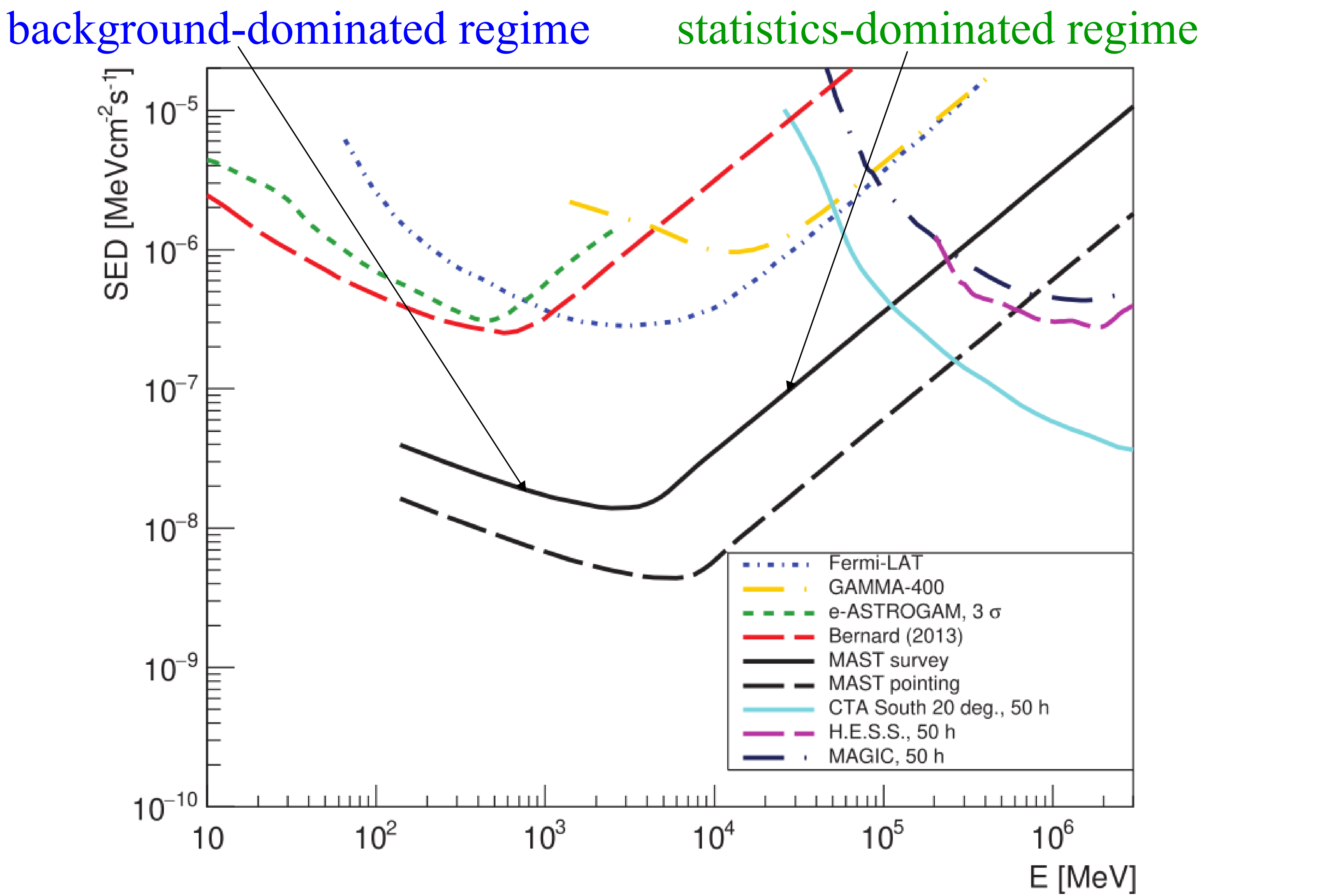
Angular resolution vs. energy: CTA, other IACT arrays (H.E.S.S., MAGIC); operating and projected space telescopes



Energy resolution vs. energy



Differential sensitivity for point-like sources: angular resolution is important at low energy (Dzhatdoev & Podlesnyi, APh, **112**, 1 (2019))



Anti-coincidence detector (ACD) and backgrounds

The ACD could be similar to the Fermi-LAT one
(plastic scintillator, inefficiency $\delta = 3\times10\text{-}4$ (Moiseev et al., 2007))

Trigger condition $(S_{ACD}=0)\&(E_{dep}>30\text{ MeV})$

Expected rates

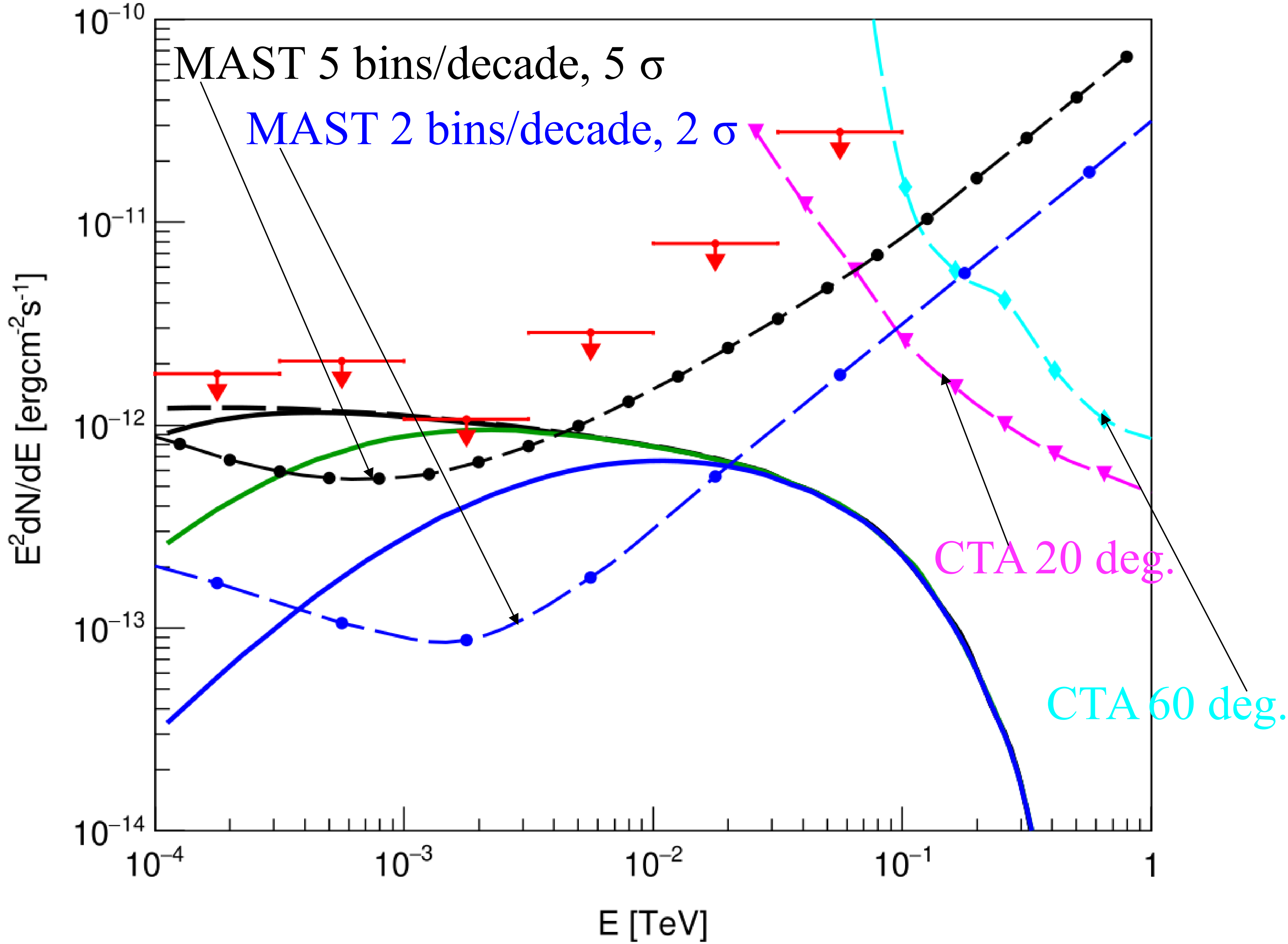
(background model according to Fermi-LAT from Atwood et al., 2009):

1) "Signal" γ-rays: ~20 Hz
2) Charged particles: ~30 Hz (after ACD suppression)
3) "Background" (terrestrial) γ-rays: ~500 Hz
4) "Background" (terrestrial) neutrons: ~500 Hz

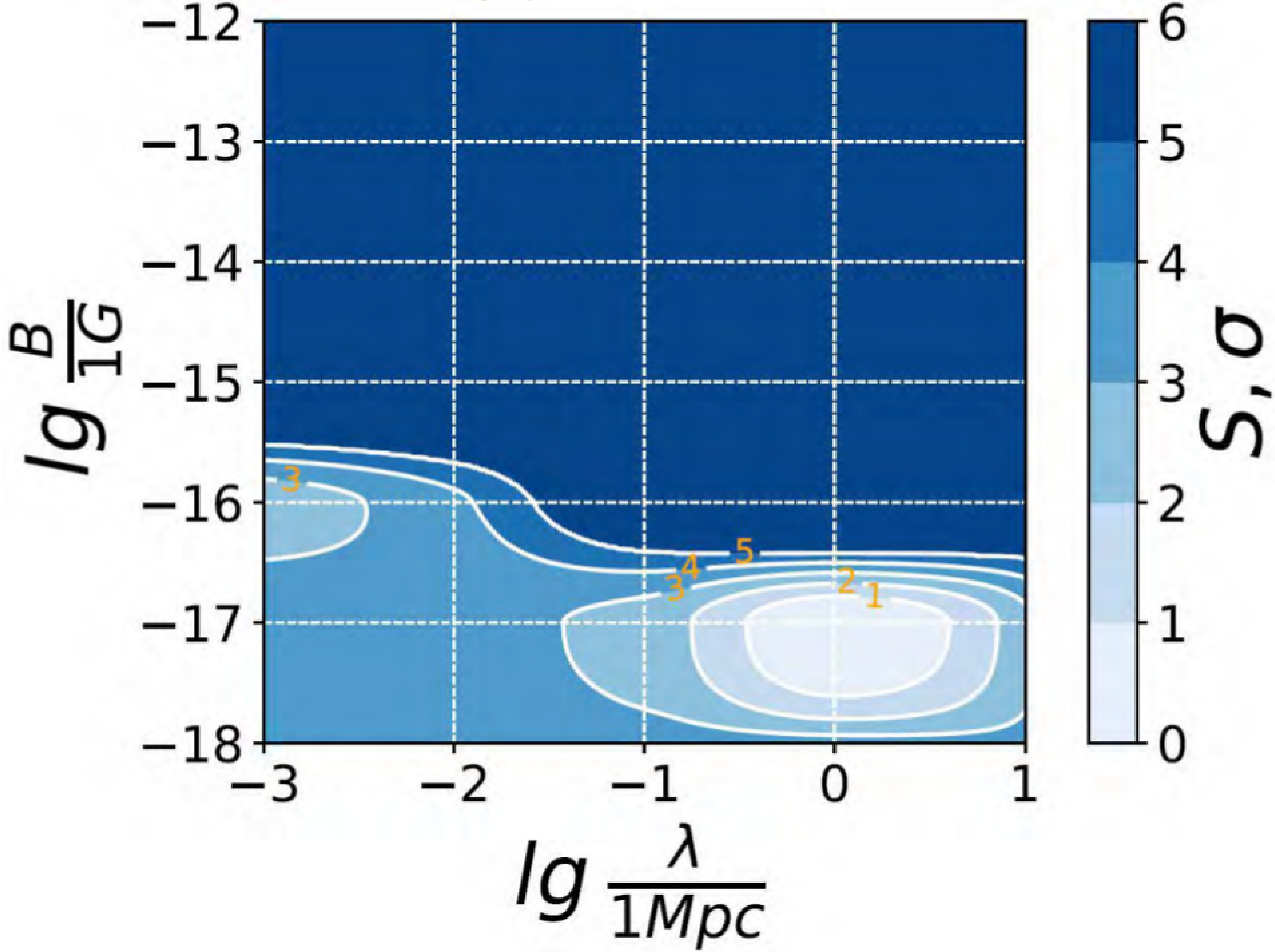
Cf.: Fermi-LAT max. downlink rate ~400 Hz
Neutral backgrounds are very dangerous!

To develop the physics case and advance astrophysical models together with experimental concepts (!?!)

Gamma-ray echo from GRB 190114C. B= 0.01 aG, 0.1 aG, 1 aG
(Dzhatdoev et al., Phys. Rev. D, **102**, 123017 (2020))



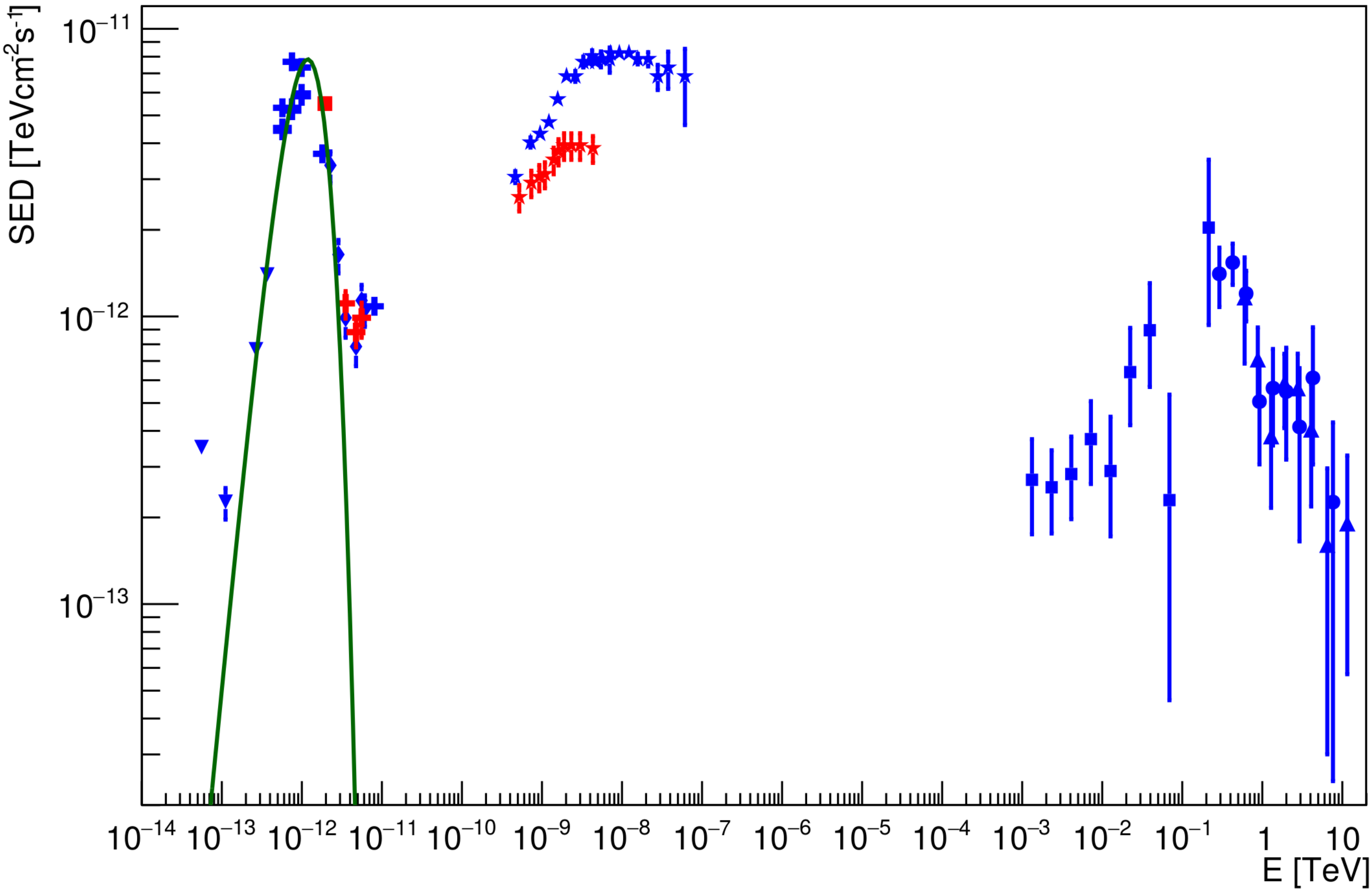
Constraints on the EGMF parameters with MAST, 3 year (survey mode), 1ES 0347-121 (spectrum+ang. distribution) (true MC: 10 aG, 1 Mpc)



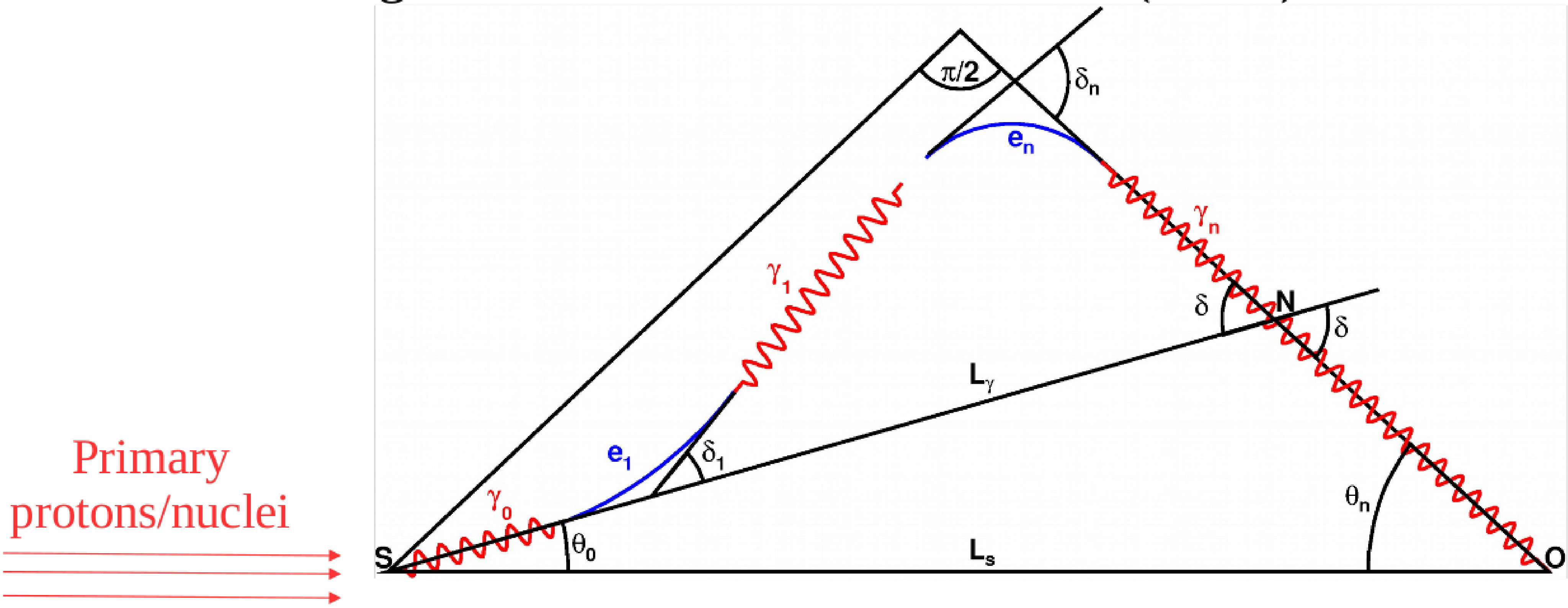
Together with CTA (Korochkin et al., 2021), MAST could cover the full range of B in voids from 0 to 10-11 G!!

Extreme TeV blazars (Biteau et al., 2020): intrinsic spectral energy distribution (SED) peaked at E>1 TeV, relatively weak and slow variability (compared to “classical” TeV blazars).

Here we show the observed SED of 1ES0229+200



Intergalactic hadronic cascade model (HCM)



Primary protons/nuclei

Waxman & Coppi, ApJ Lett., **464**, L75 (1996); Uryson, JETP, **86**, 213 (1998); Essey & Kusenko, APh, **33**, 81 (2010); Essey et al., Phys. Rev. Lett., **104**, 141102 (2010); Essey et al., ApJ, **731**, 51 (2011) (E11); Murase et al., ApJ, **749**, 63 (2012); Takami et al., ApJ Lett., **771**, L32 (2013); Essey & Kusenko, APh, **57**, 30 (2014); Yan et al. (2015); Zheng et al., A&A, **585**, A8 (2016); Cerruti et al., A&A, **606**, A68 (2017)

Let's assume the EGMF in clusters and filaments according to Dolag et al. (2005). Then the image of the object appears to be extended, even at the highest energies!
(Khalikov & Dzhatdoev, MNRAS, 10.1093/mnras/stab1393 (2021))

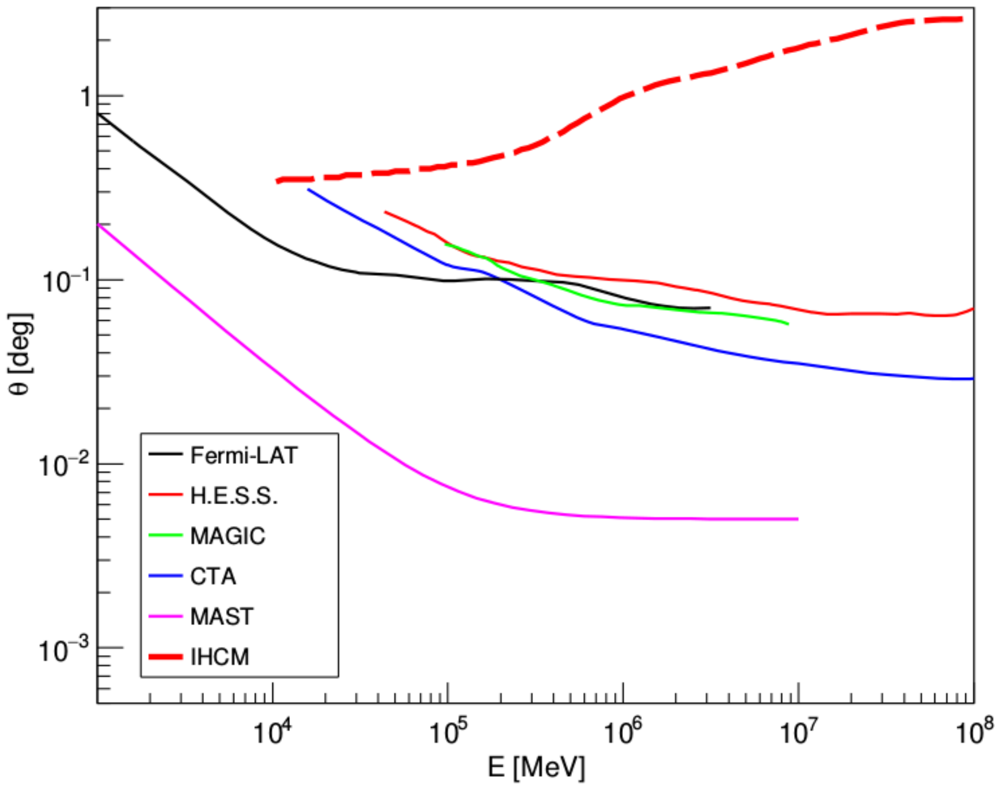


Figure 11. Angular resolution (68 % containment angle) of various gamma-ray instruments (solid curves: black curve denotes *Fermi-LAT*, red curve — *H.E.S.S.*, green curve — *MAGIC*, blue curve — *CTA*, magenta curve — *MAST*) vs. the 68 % containment angle of the observable emission assuming the MHCM with the KD10 EBL.

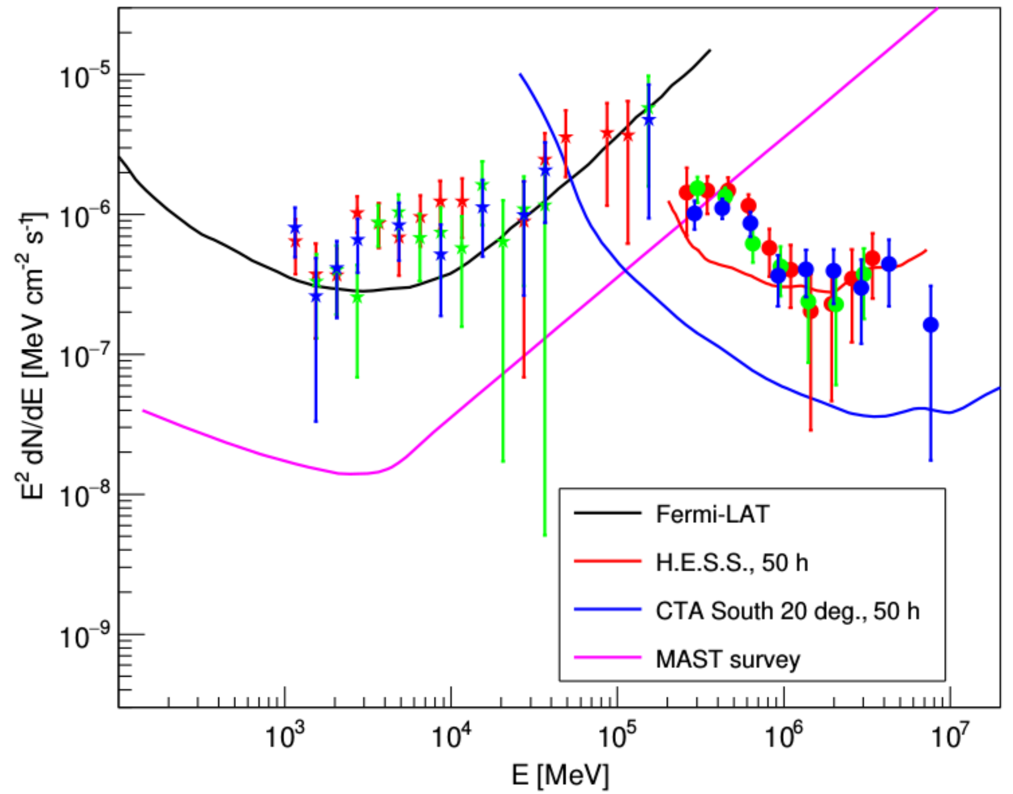


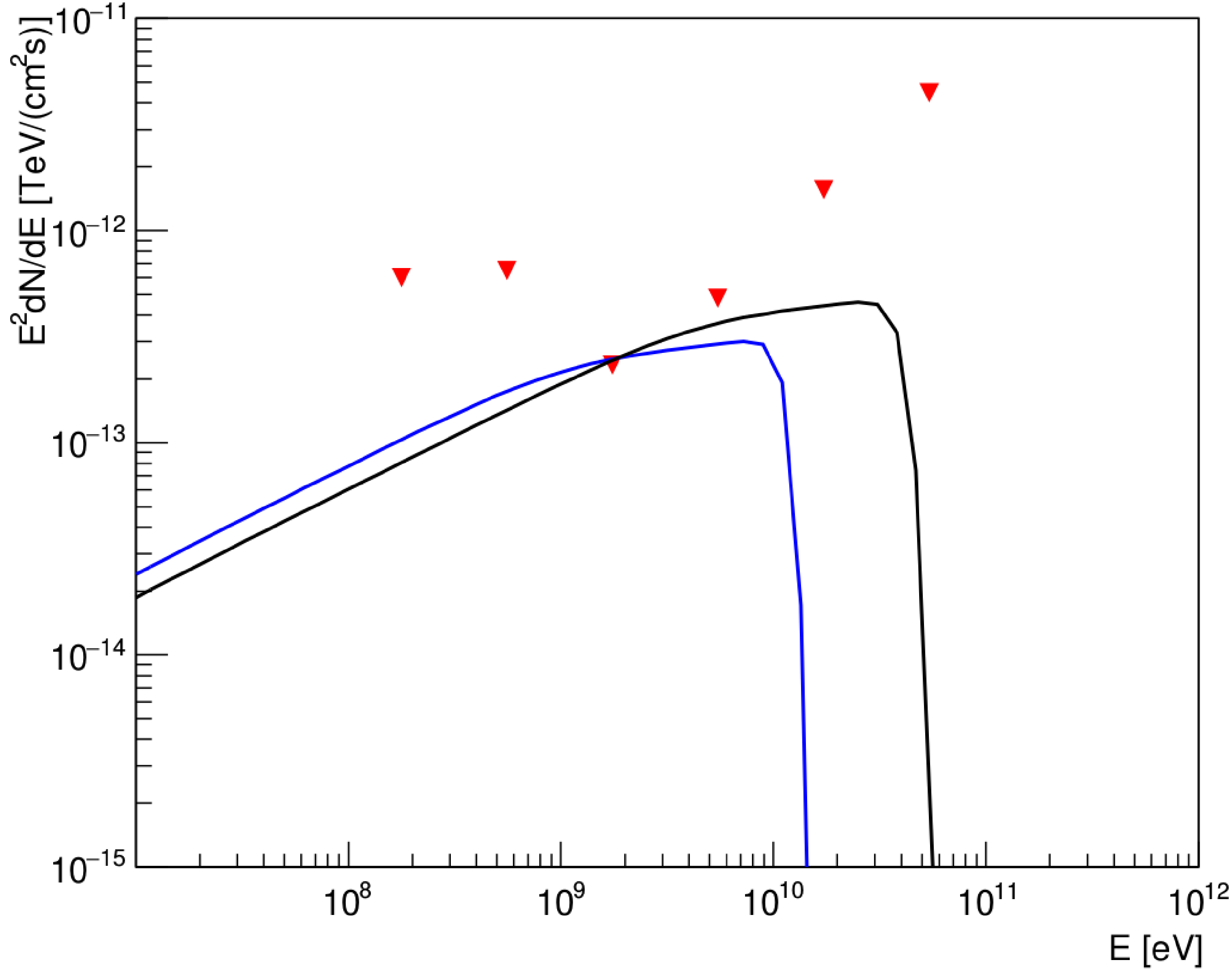
Figure 12. SEDs of some extreme TeV blazars measured with IACTs (circles) and *Fermi-LAT* (stars) together with sensitivities of several γ-ray telescopes. Red symbols denote 1ES 1101-232, green symbols — 1ES 0347-121, blue symbols — 1ES 0229+200; black curve denotes the sensitivity of *Fermi-LAT*, red curve — *H.E.S.S.*, blue curve — *CTA*, magenta curve — *MAST*.

GW 190521: associated optical signal was registered (Graham et al., 2020), L~ 10^{45} erg/s.

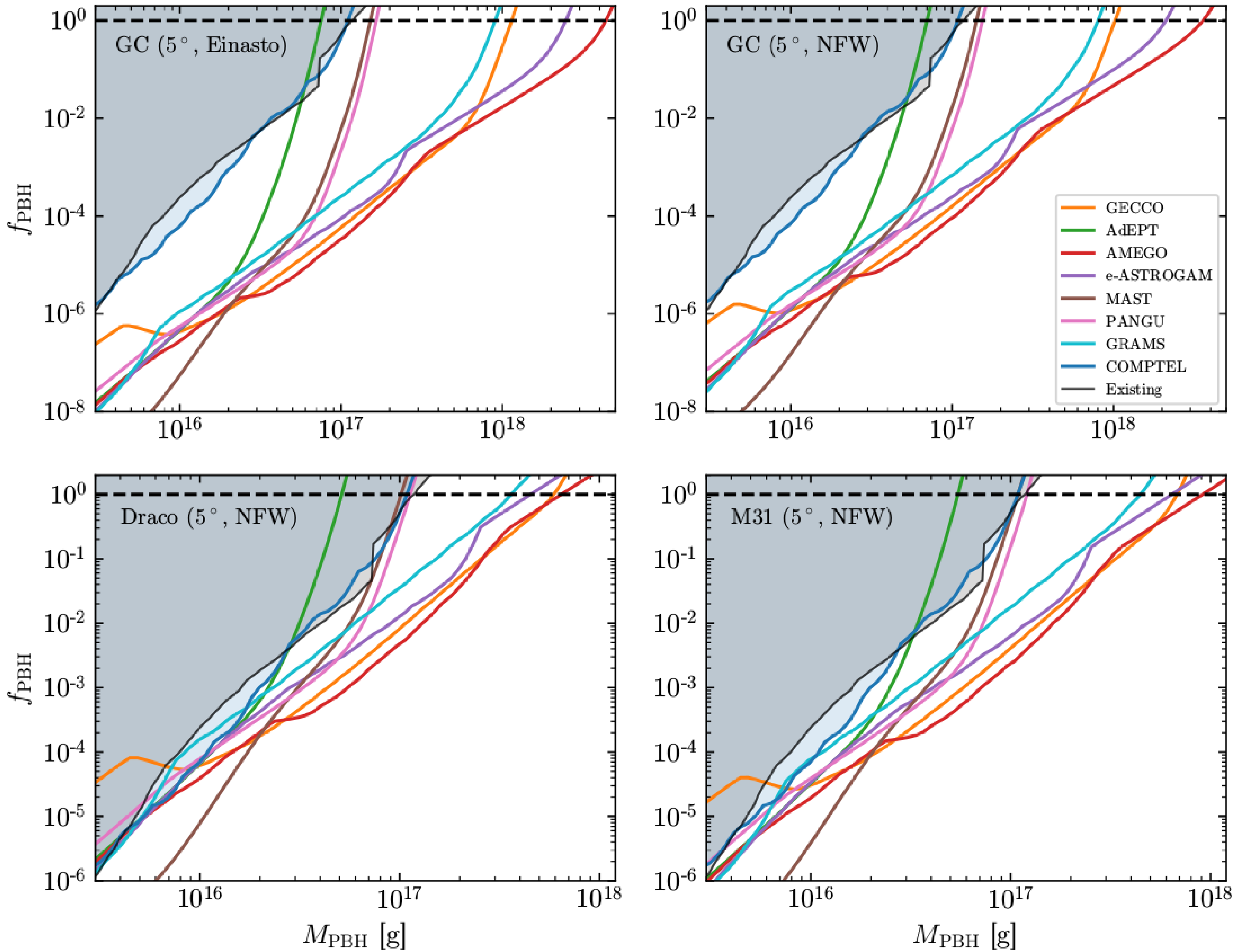
Fermi-LAT upper limits (Podlesnyi & Dzhatdoev, Res. Phys., **19**, 103579 (2020))

R= 10^{14} cm, L_{45}= L/(10^{45} erg/s)= 1.5

R= 10^{15} cm, L_{45}= 2.3



Hawking Radiation from Asteroid-Mass Primordial Black Holes
(Coogan et al., Phys. Rev. Lett., 126, 171101 (2021))
let's assume that black holes constitute a fraction f_{PBH} of the cosmological DM



Particle DM: Coogan et al., astro-ph/2101.10370; Coogan et al., astro-ph/2104.06168

Conclusions

The MAST concept allows for:
1) a very large (>10 m^2) effective area at E> 300 MeV
2) excellent angular resolution, 3–10 times better than the Fermi-LAT one depending on the energy
3) very good sensitivity
4) reasonable energy resolution (≈20% at 100 MeV and 6–10% for the 10 GeV –1 TeV energy range)

5) Such a telescope would be instrumental in a broad range of long-standing astrophysical problems, including blazar studies, GW transient counterpart search, EBL and EGMF measurement, dark matter searches, etc.
6) Probably it is possible to reduce the mass of the instrument significantly by replacing the LAr calorimeter with a high-Z (e.g. Tungsten) calorimeter.

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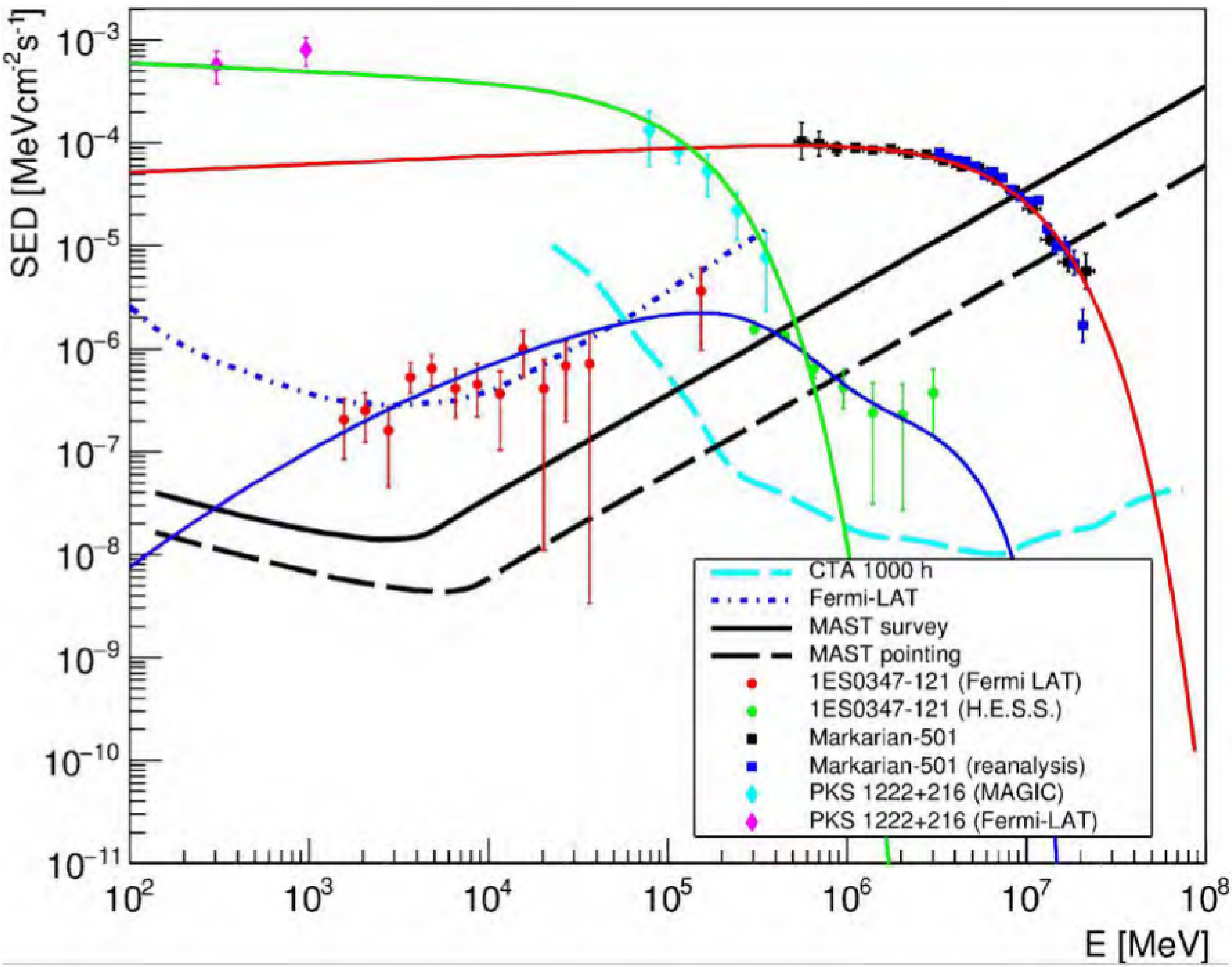
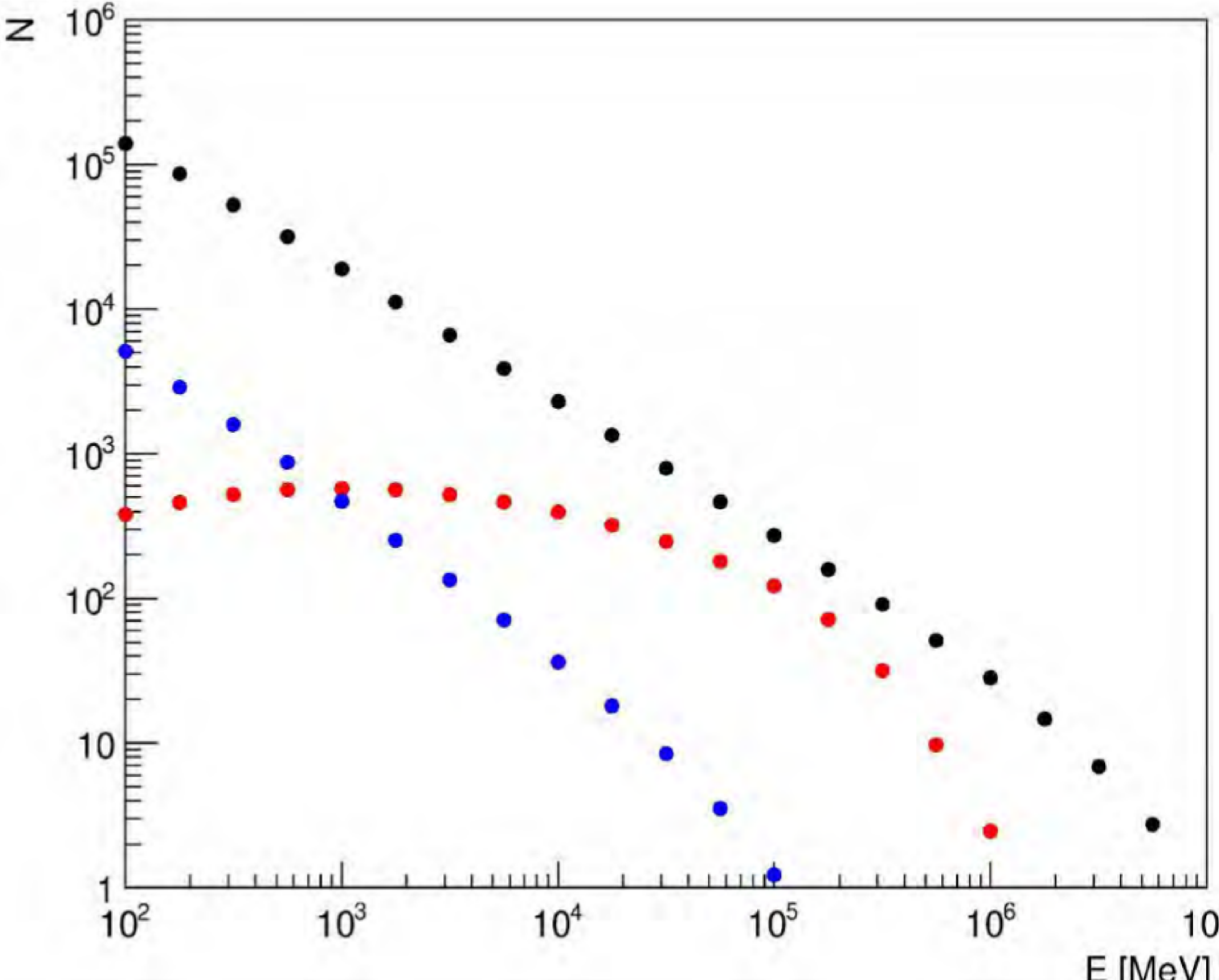
Additional slides

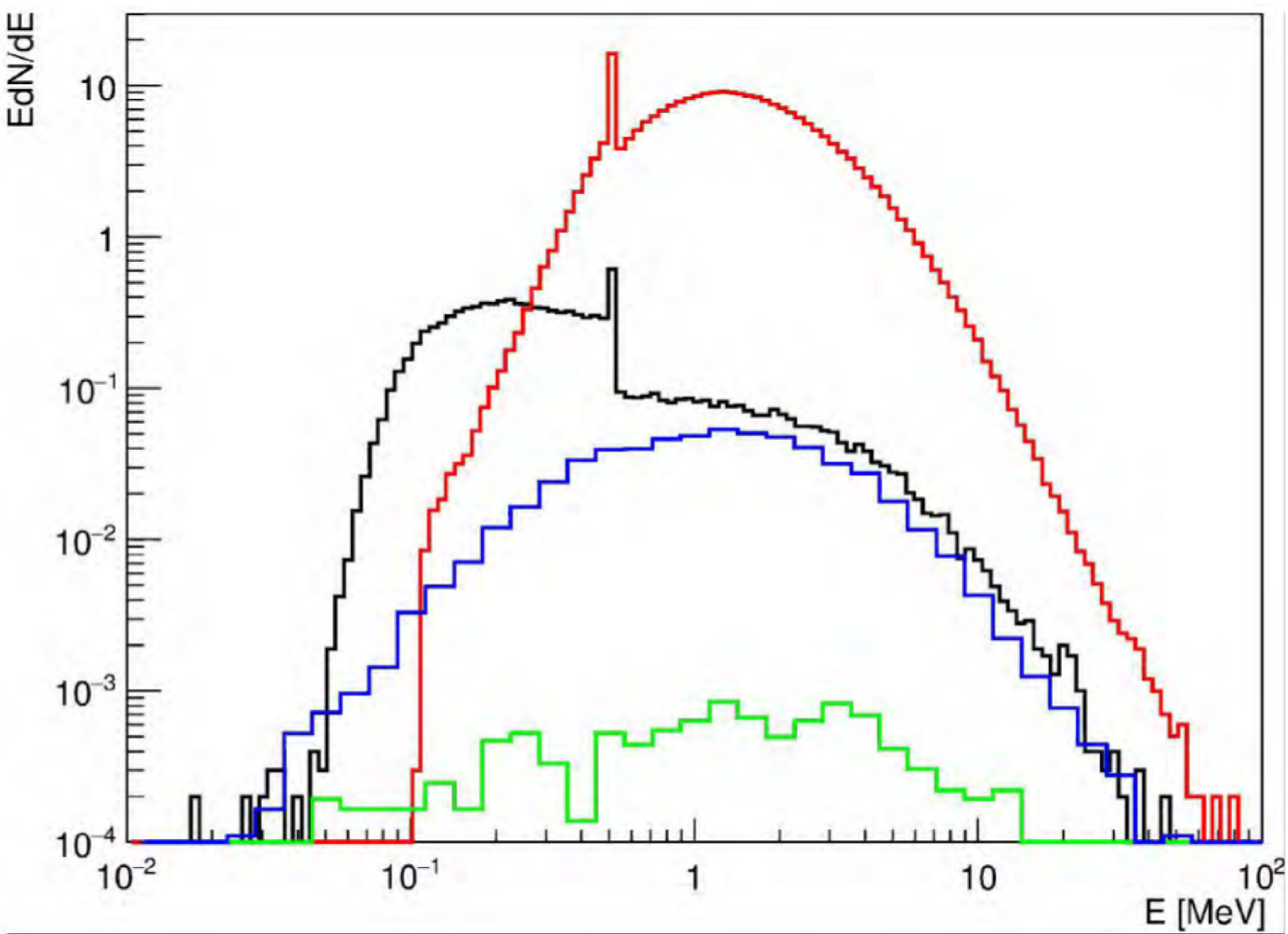
Prospects for AGN observation: 1ES 0347-121 (10 years, survey mode), Mkn 501 (6.5 month flare, survey mode), PKS 1222+216 (2.5 h flare, pointing mode)

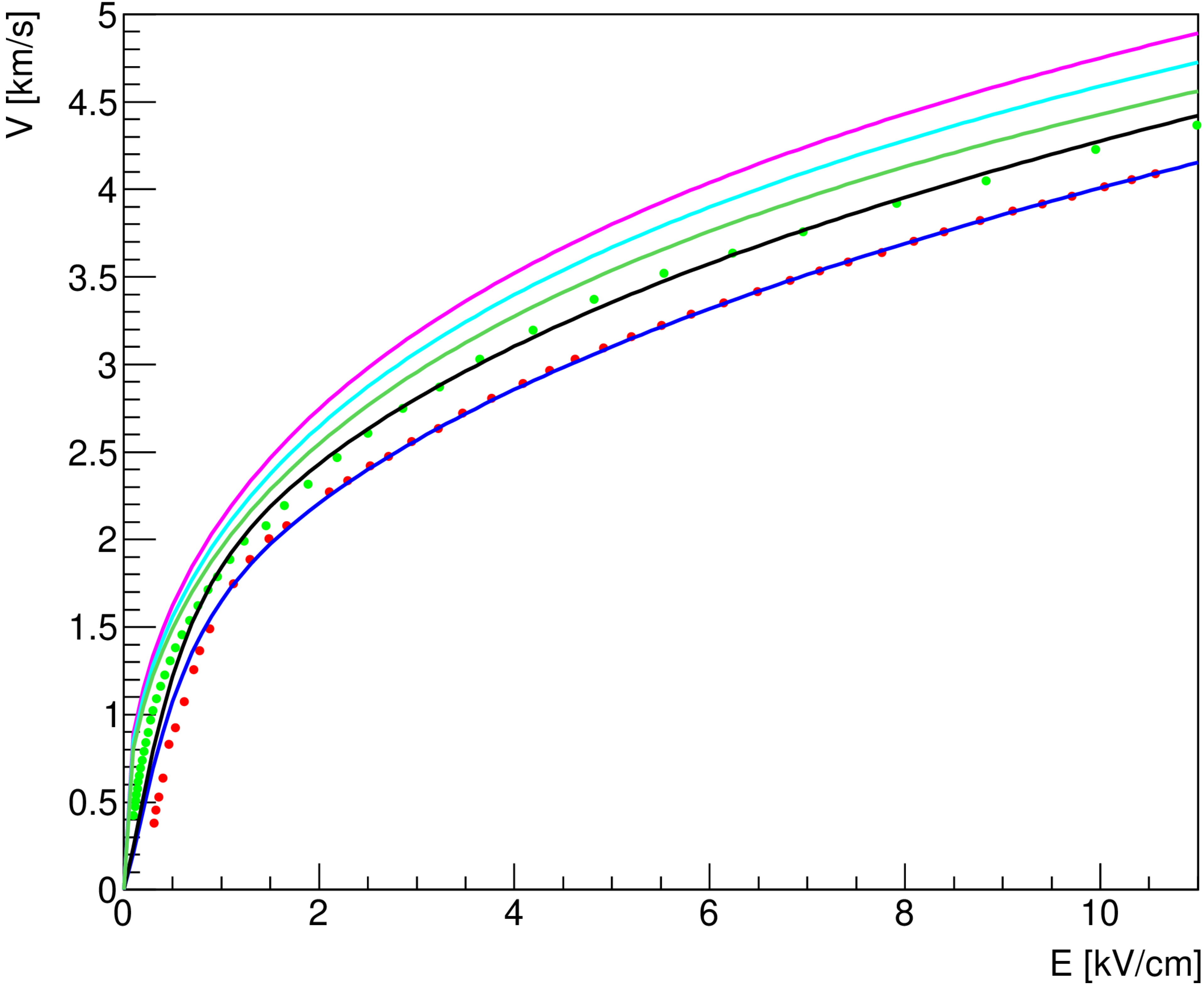


Event number histograms: Mkn 501 (black), 1ES 0347-121 (red), PKS 1222+216 (blue)



The flux of “backsplash” (“reverse current”) for Argon (γ-rays: black; $e^{+}+e^{-}$: green) and Tungsten (γ-rays: red; $e^{+}+e^{-}$: blue)




V [km/s]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
E [kV/cm]

$$\sigma_{\theta 1} = \frac{2\sigma_d}{x}\sqrt{\frac{3}{N+3}}$$

Finite detector resolution→ angular uncertainty

$$\sigma_{\theta 2} = \frac{(2\sigma_d)^{1/4} l_t^{1/8}}{X_0^{3/8}} \left(\frac{p_0}{p}\right)^{3/4}$$

Multiple scattering→ angular uncertainty

$$\sigma_d = \sqrt{\frac{l_t^2}{12} + \frac{K_D \Delta_t}{v_d}}$$

Effective spatial resolution of the detector