Heavy liquid Argon time projection chamber as a new-generation space γ-ray telescope

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

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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. The state-of-art: ICARUS T 600 (600 t of LAr) --- 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 cartriges (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))
VI. Application in astroparticle physics: mainly MeV energy range --- Bernard et al. (2013); cf. gas TPC: Hunter et al. (2014) (AdEPT); Gros et al. (2018) (HARPO)

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

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

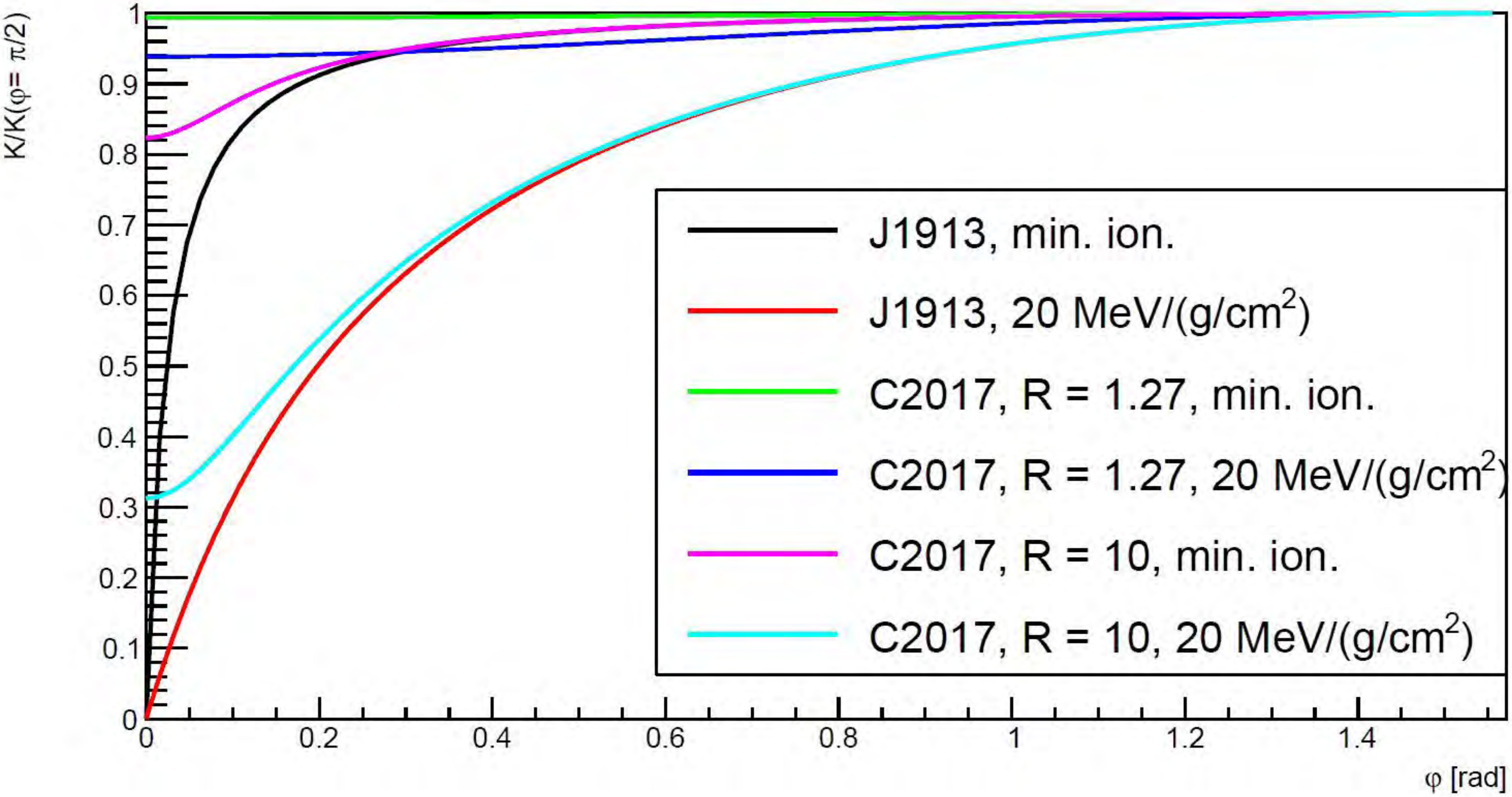
$$\frac{\partial N_-(\vec{r},t)}{\partial t} = D_-\nabla^2 N_-(\vec{r},t) - \alpha N_+ N_- - \mu_- \vec{E}\cdot\nabla N_-(\vec{r},t)$$

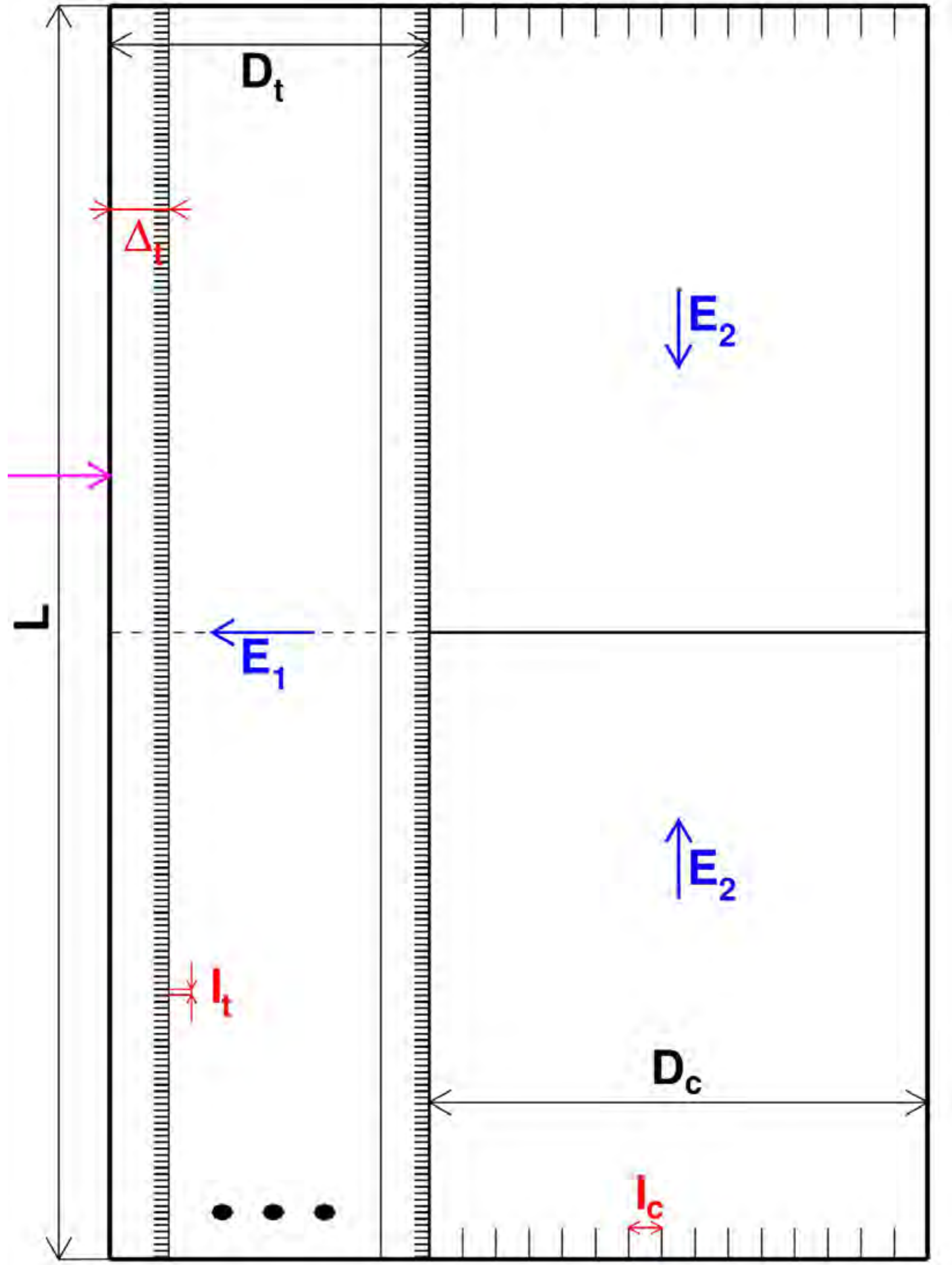
diffusion, recombination, and drift

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

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

Charge carrier survival probability vs. φ



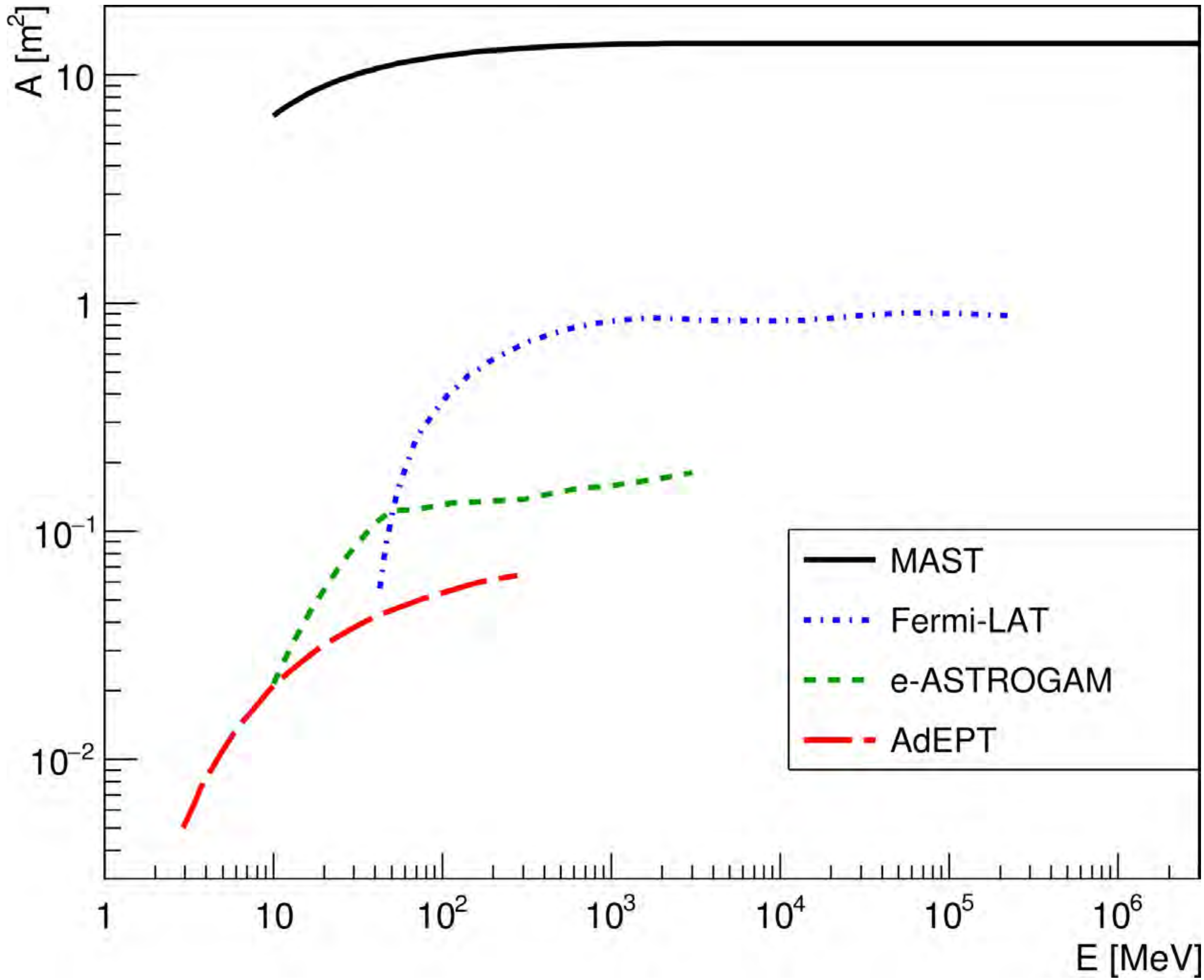


“parallel” TPC (E_1||axis)
~6 million channels
(cf. Fermi-LAT: 0.88 million
--- Thompson (2015))

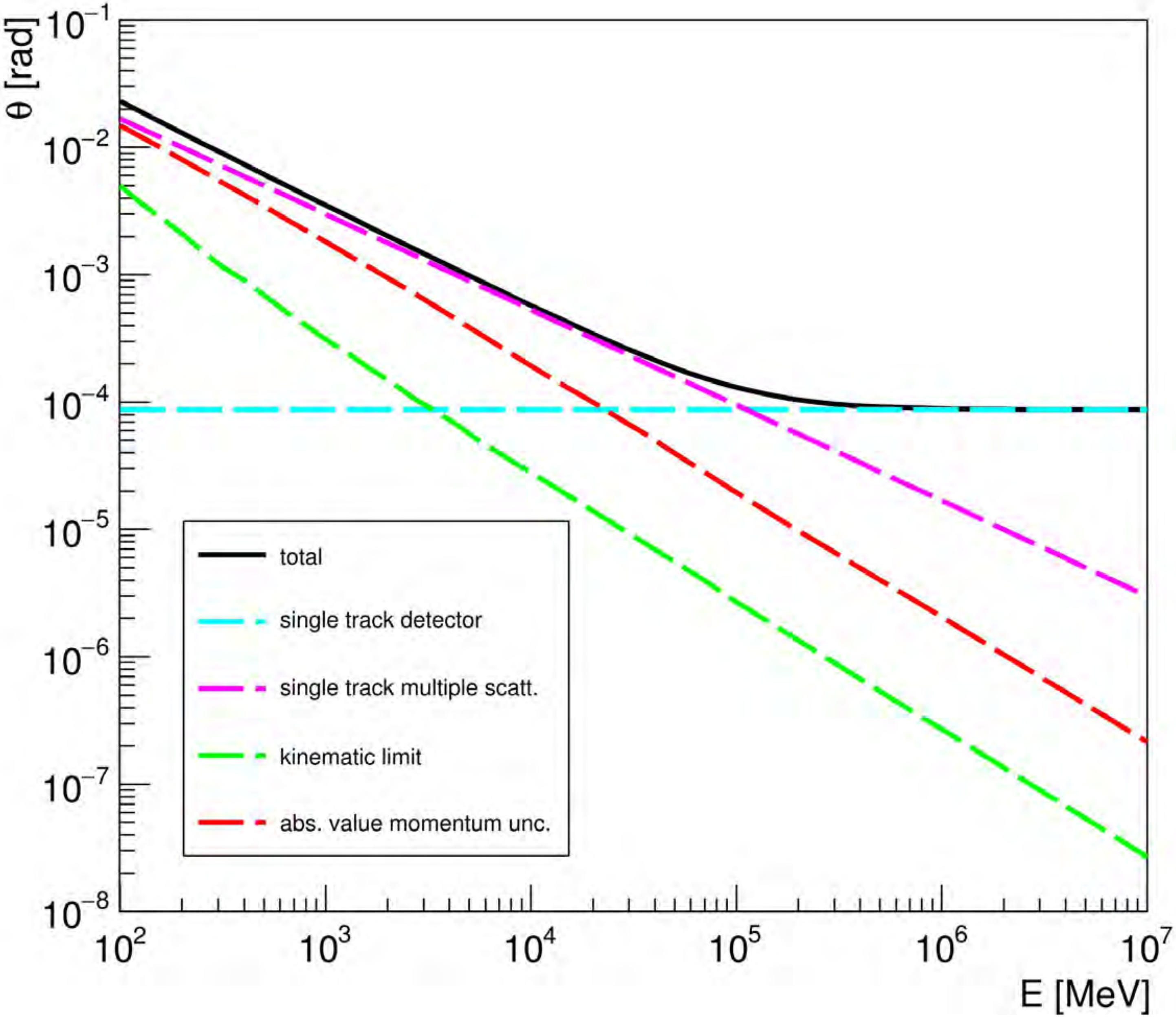
M= 36 t (would need a Falcon Heavy!); power: 4.4 kW (Fermi-LAT: 650 W)
4m X 4m aperture
11.4 radiation units

Tracker pitch: 100 mkm
Tracker consists of 50 layers (total thickness of the tracker= 50 cm), E_1= 3 kV/cm
Calorimeter pitch: 1 mm (total thickness of the calorimeter= 110 cm), E_2= 0.5 kV/cm

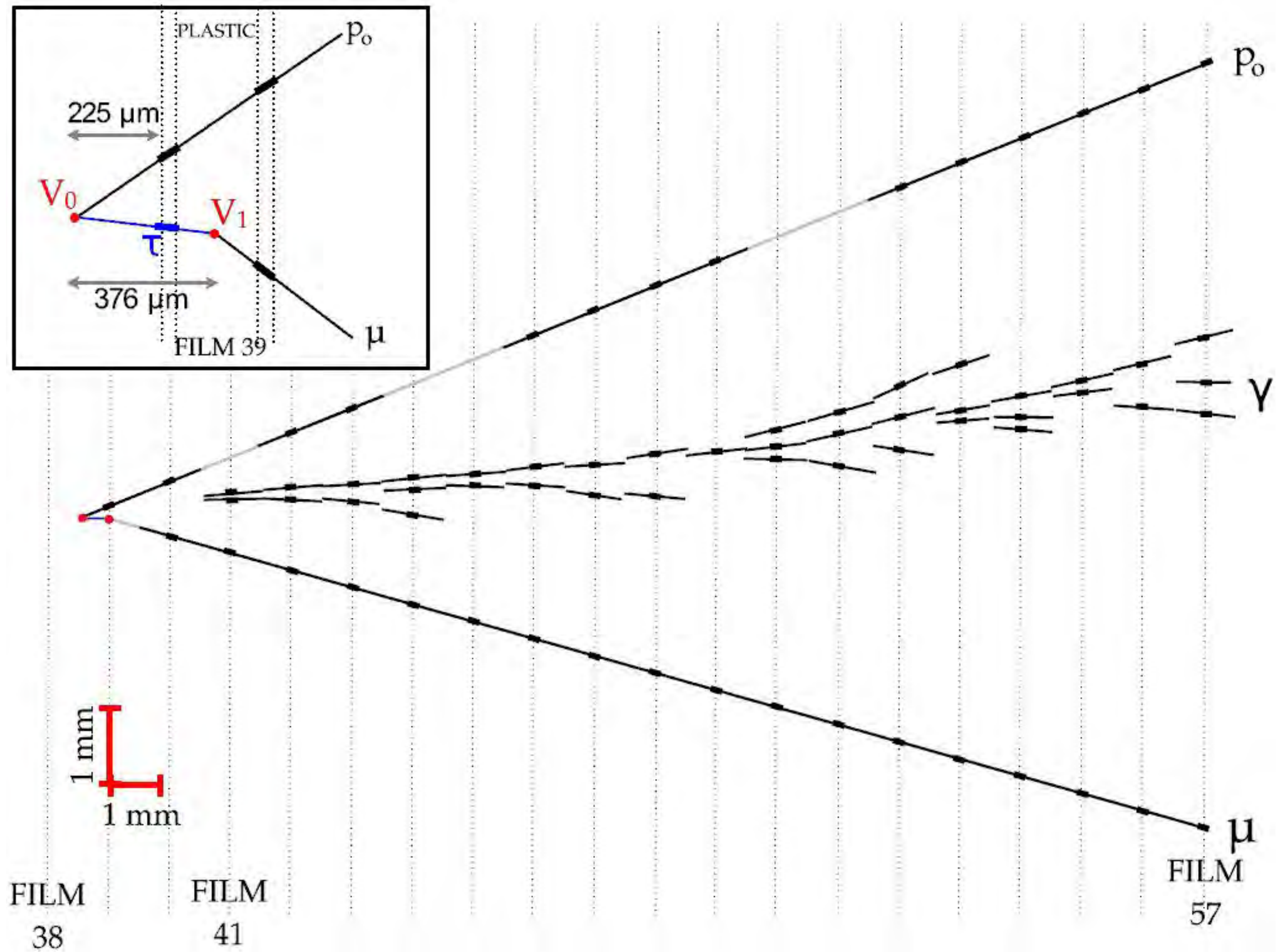
Effective area vs. energy



Angular resolution vs. energy: four main components



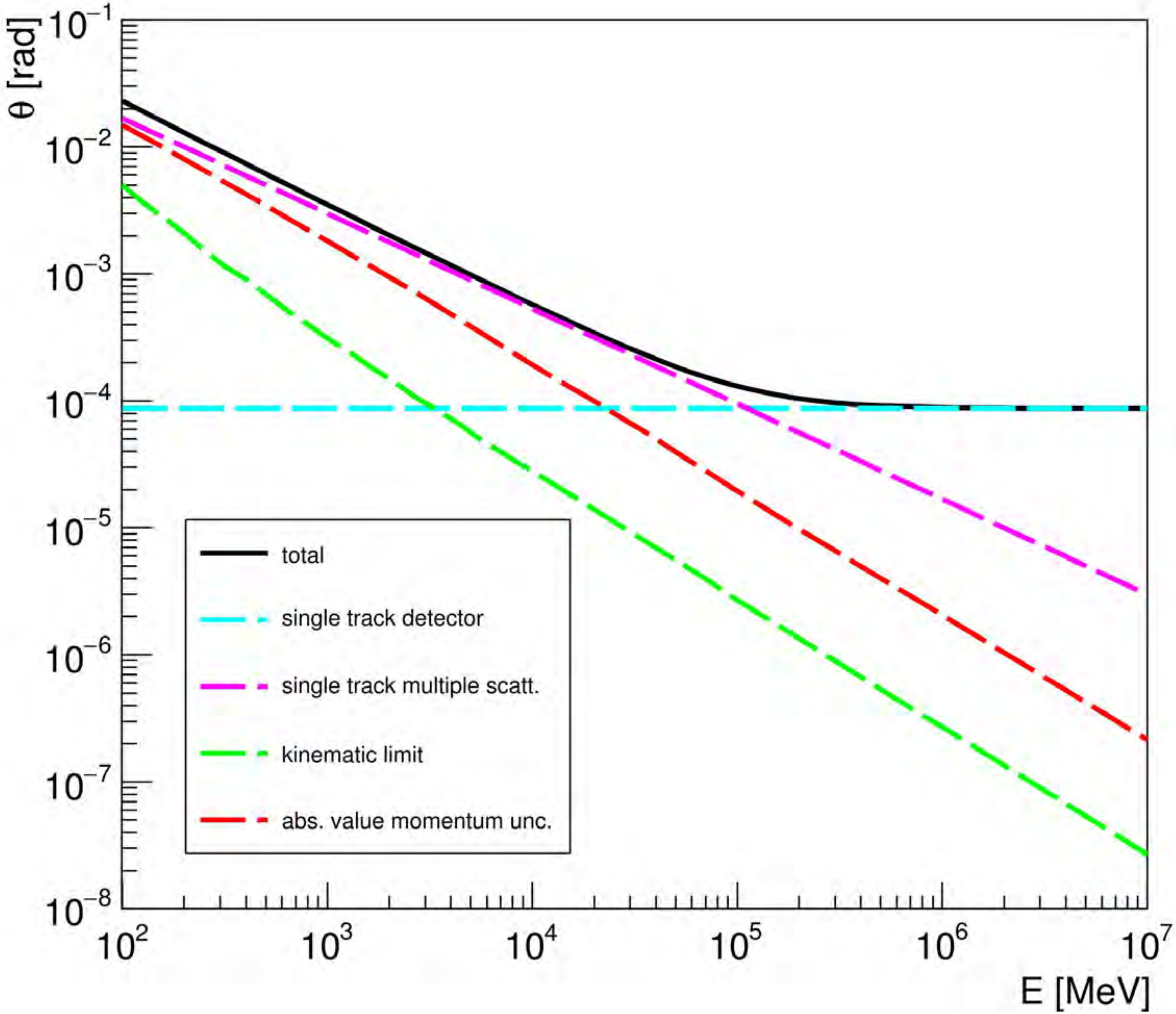
Can we measure p+/p-?



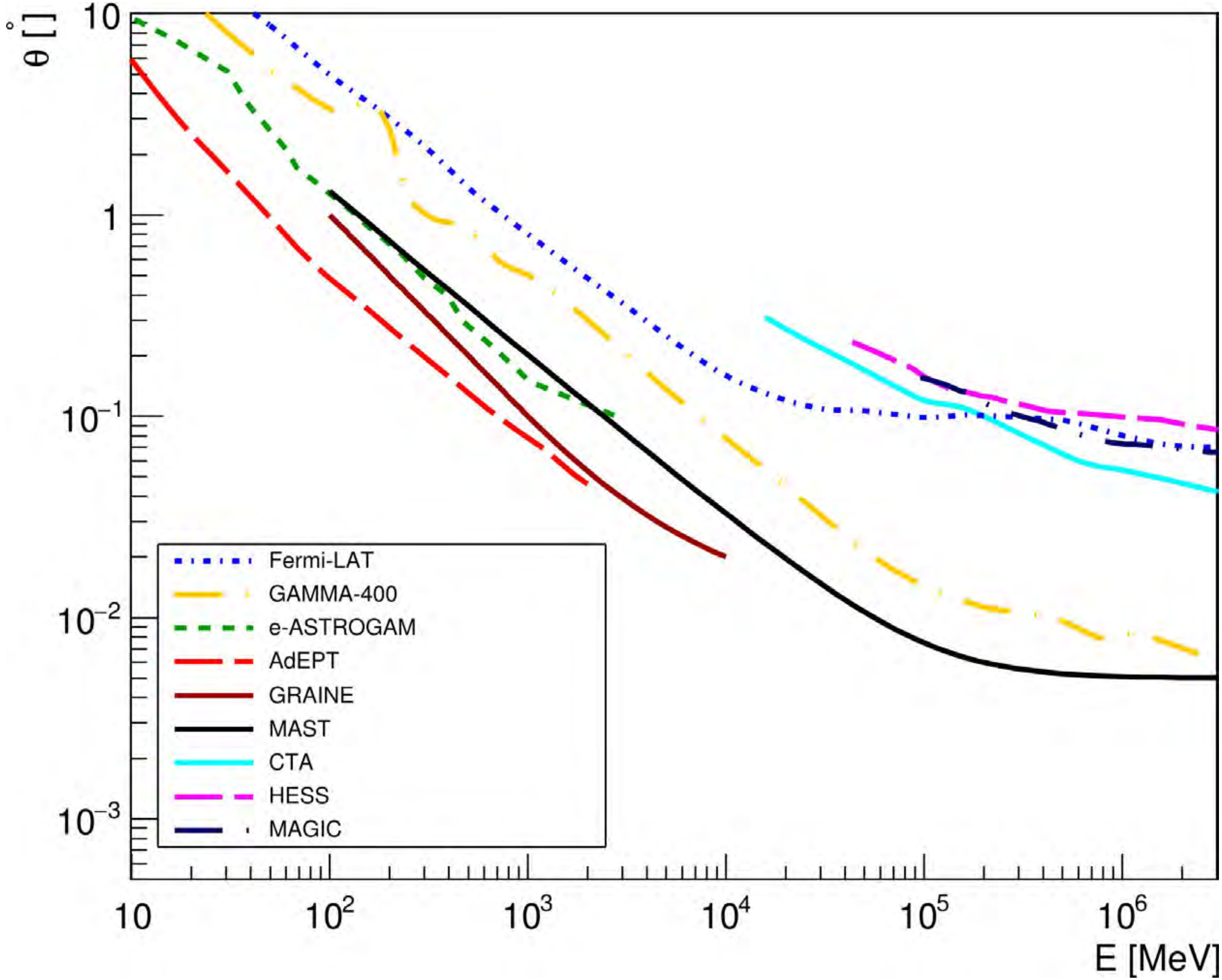
We have had some experience with GeV showers in the OPERA experiment (Agafonova et al. (2014))

Electron and positron subshowers could overlap strongly! → We assume $p^+/p^-= 1$, and then account for the associated methodical uncertainty

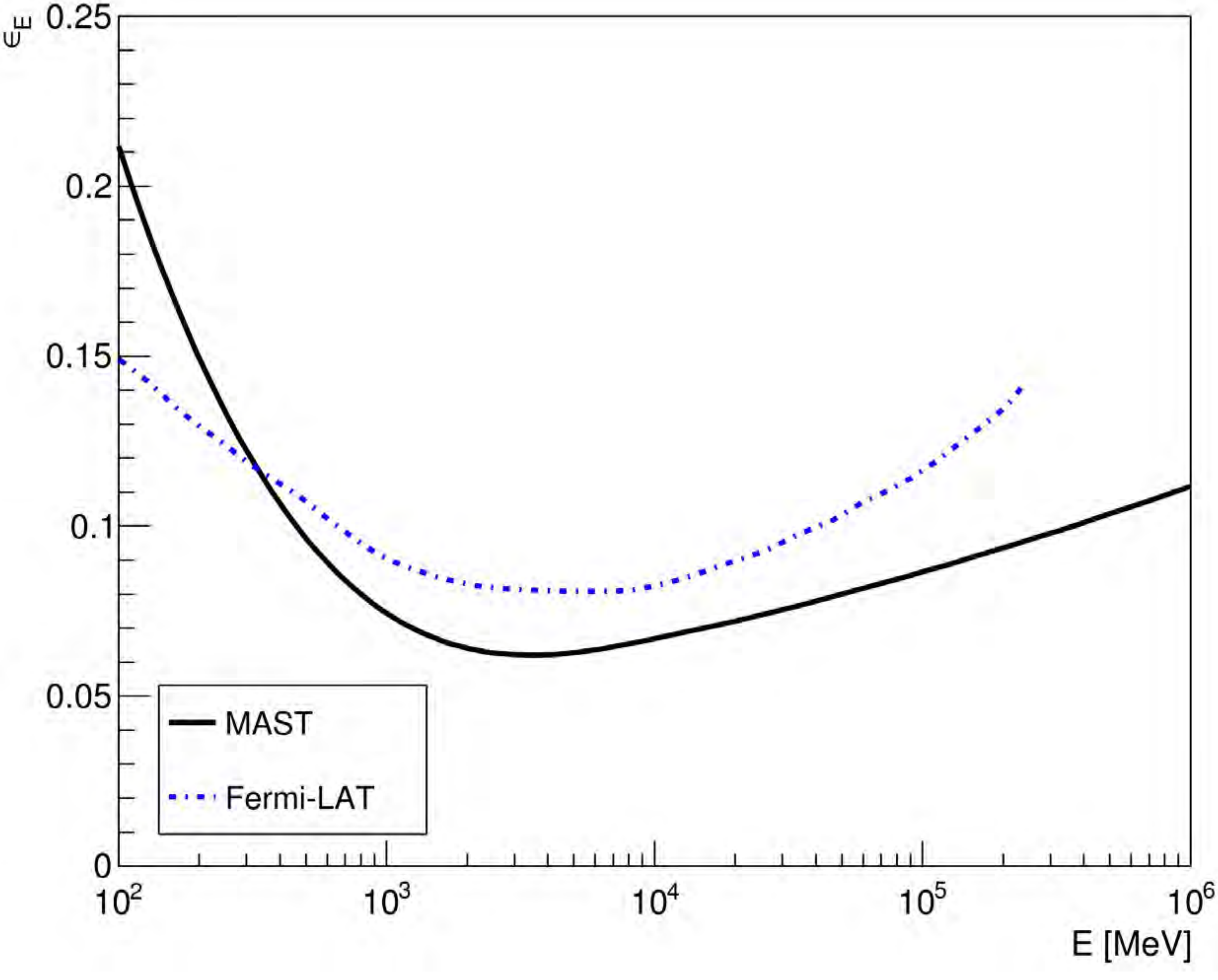
Angular resolution vs. energy: the contribution associated with the p^+/p^- uncertainty can be significant!



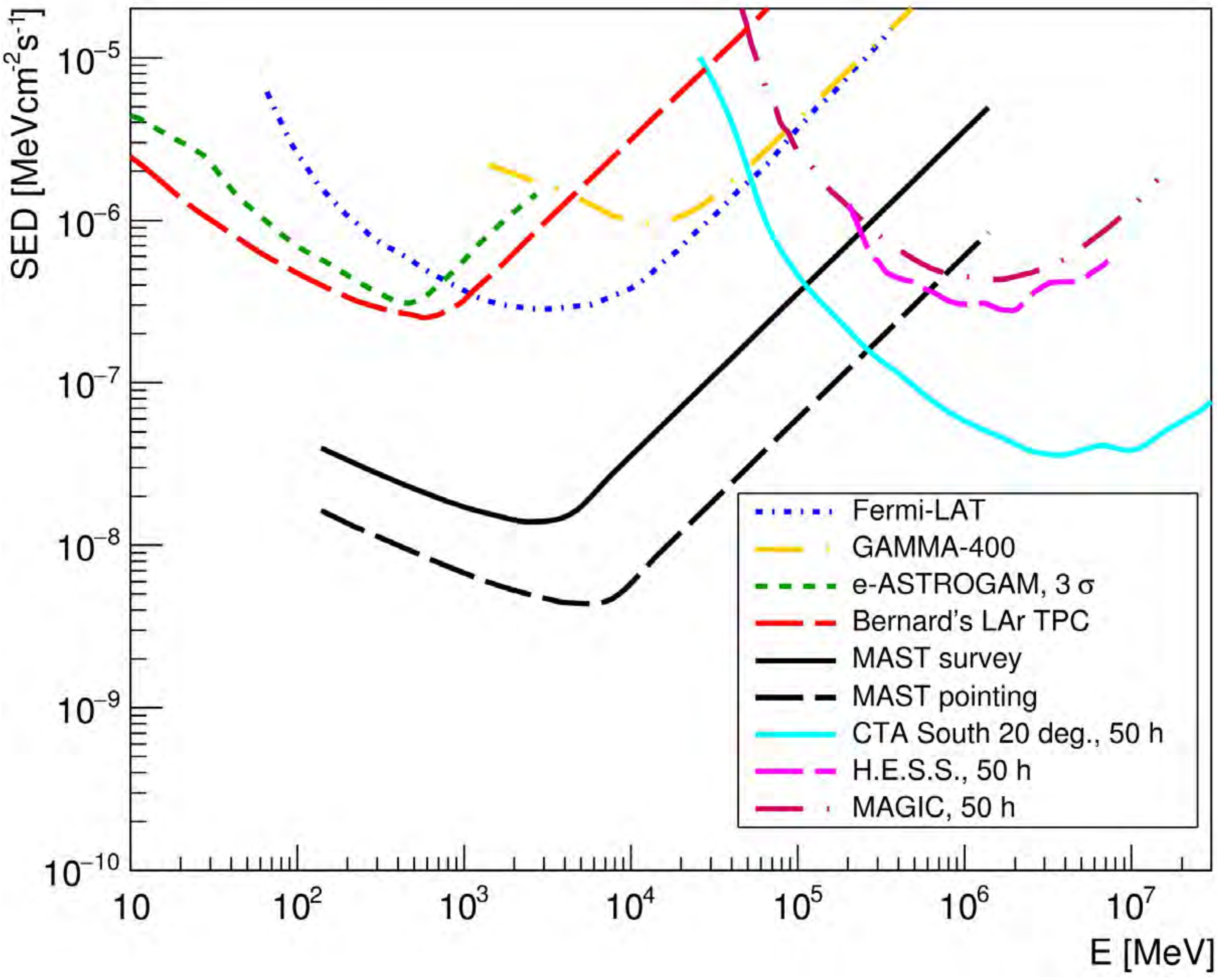
Angular resolution vs. energy



Energy resolution vs. energy



Differential sensitivity for point-like sources



Anti-coincidence detector (ACD) and backgrounds

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

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

Expected rates

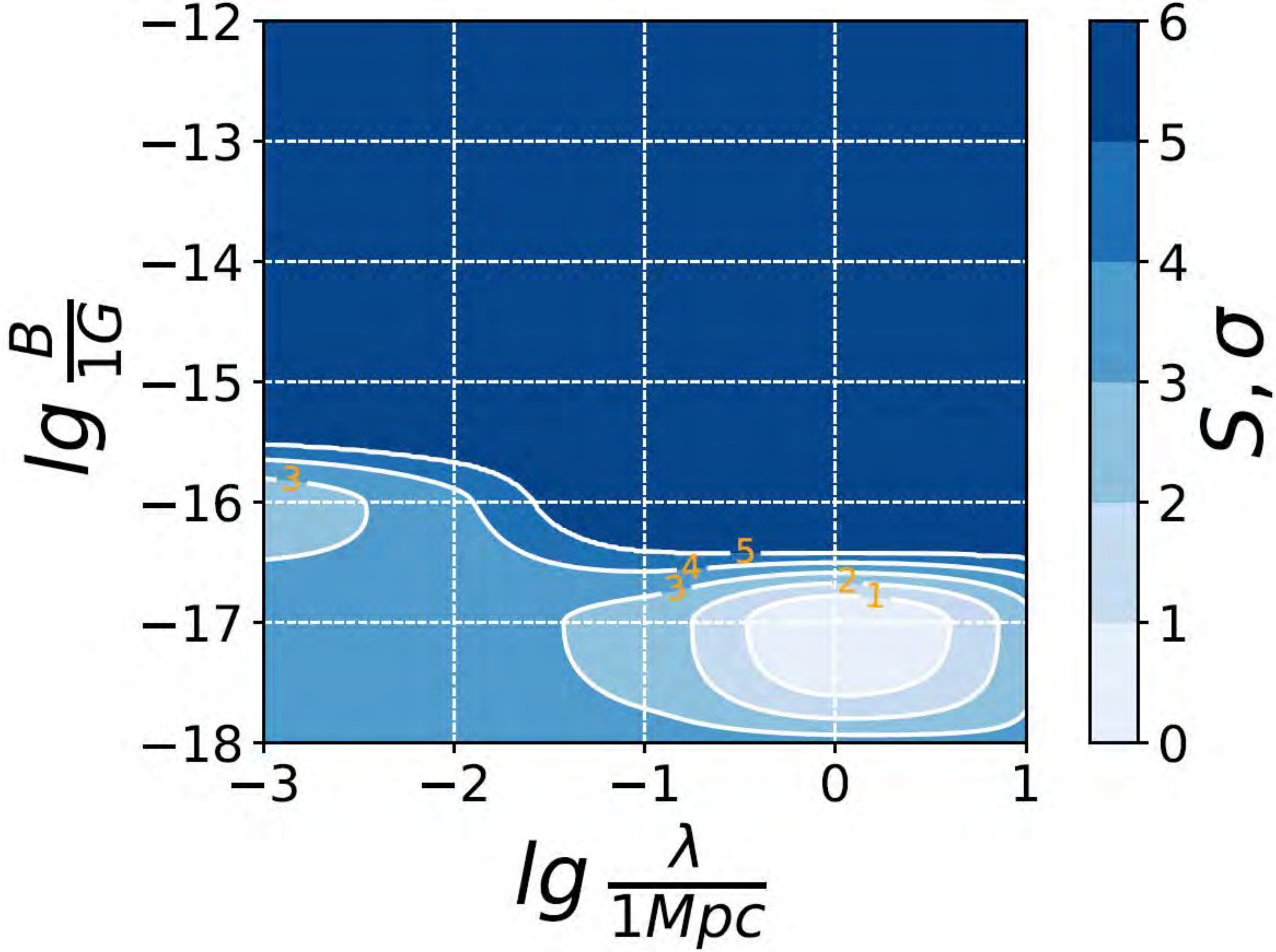
(background model according to Fermi-LAT --- Atwood et al., 2009):

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

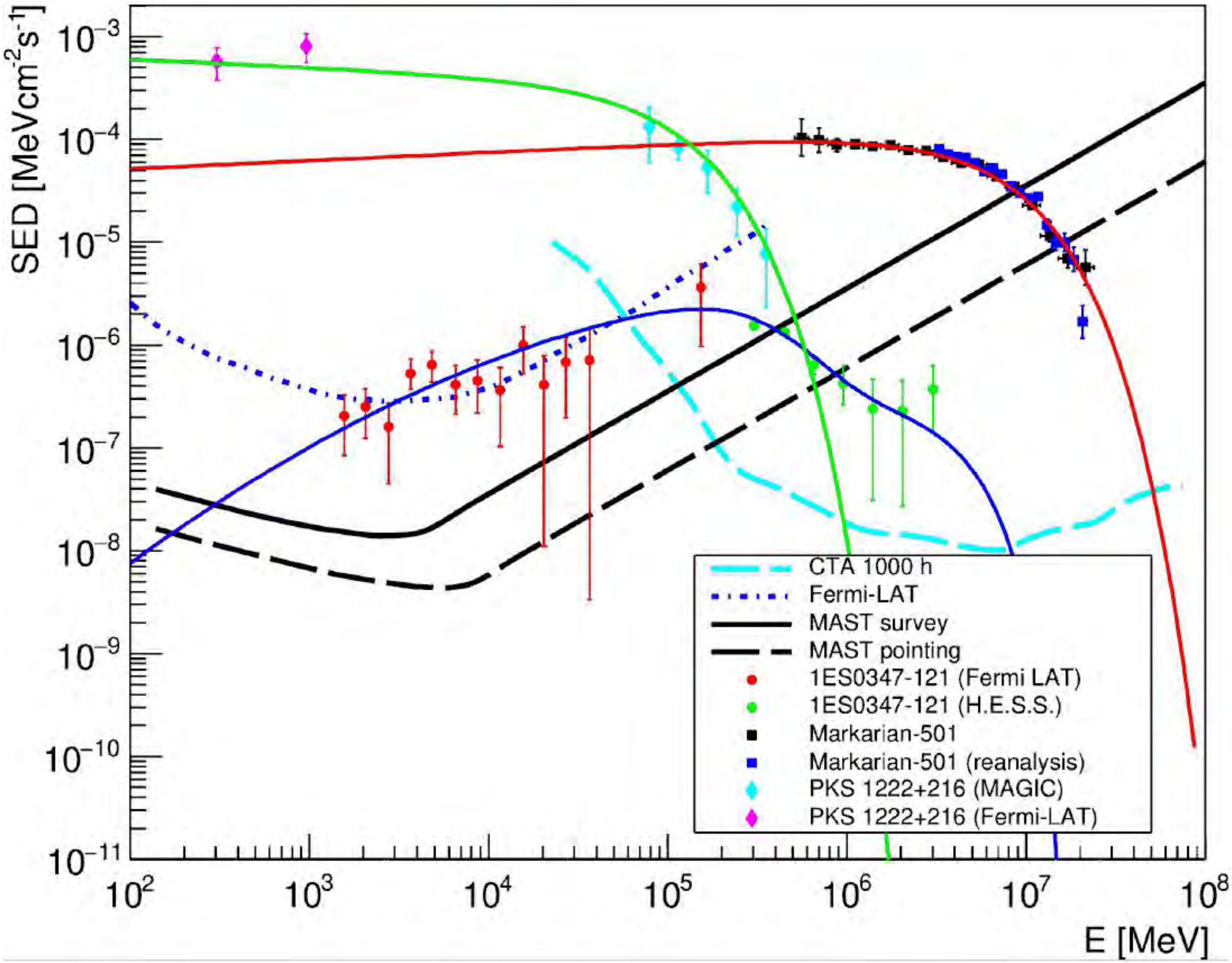
Cf.: Fermi-LAT max. downlink rate ~400 Hz

Neutral backgrounds are very dangerous!

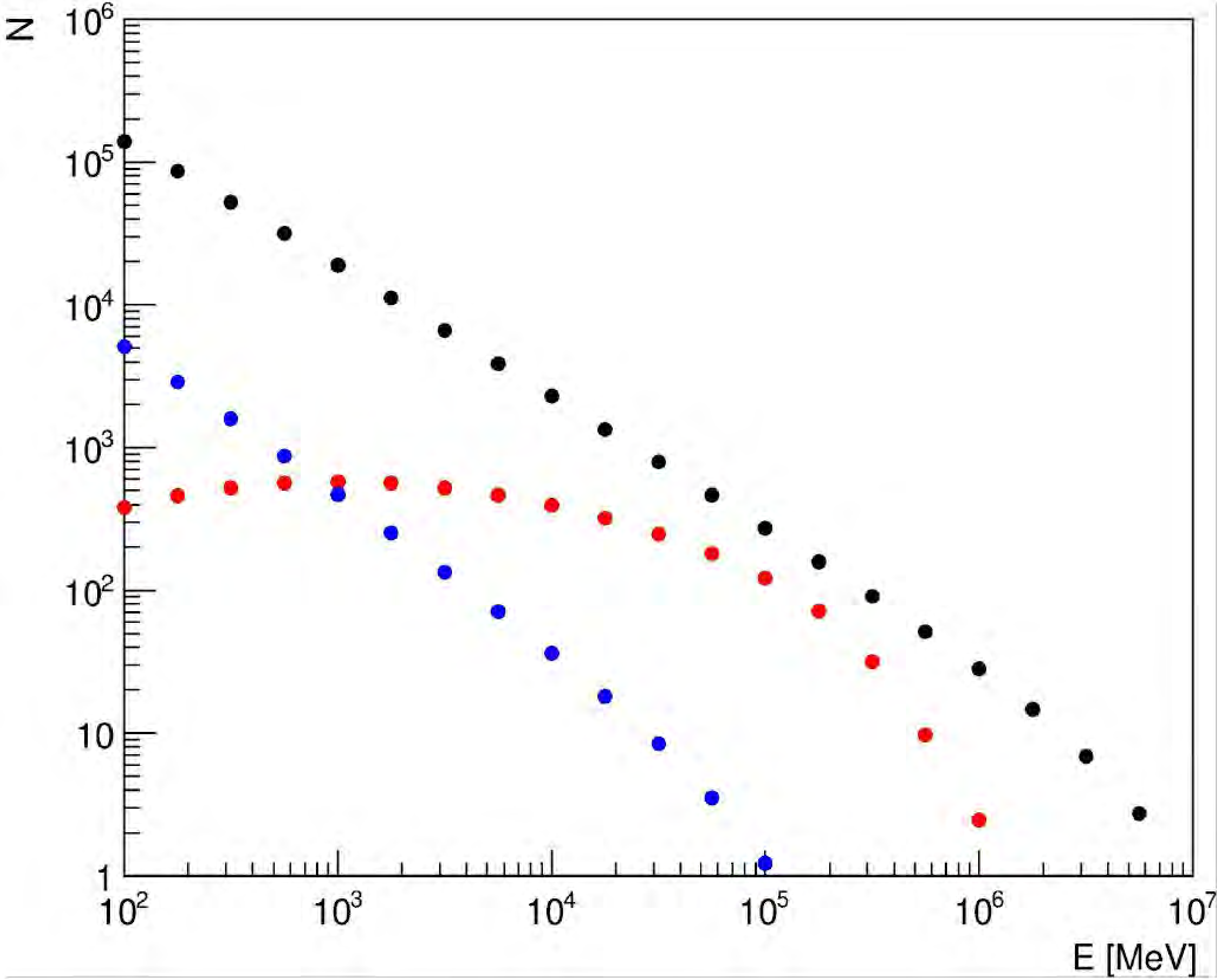
Constraints on the EGMF parameters with MAST, 3 year (survey mode), 1ES 0347-121 (spectrum+ang. distribution) (true MC: 10 aG, 1 Mpc) (preliminary)



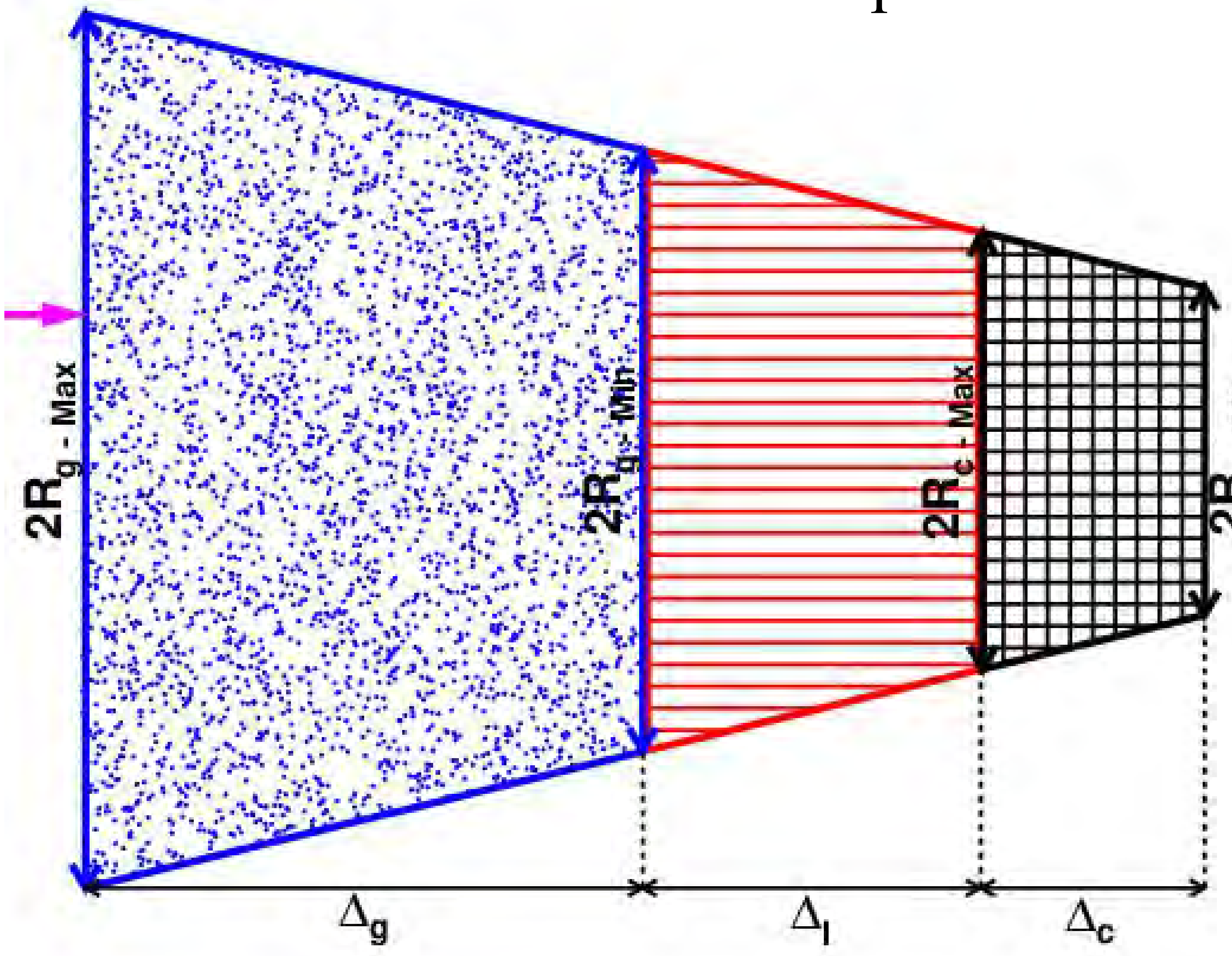
Prospects for AGN observation: 1ES 0347-121 (10 years, survey mode), Mkn 501 (6.5 month flare, survey mode), PKS 1222+216 (2.5 h flare, pointing mode)



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

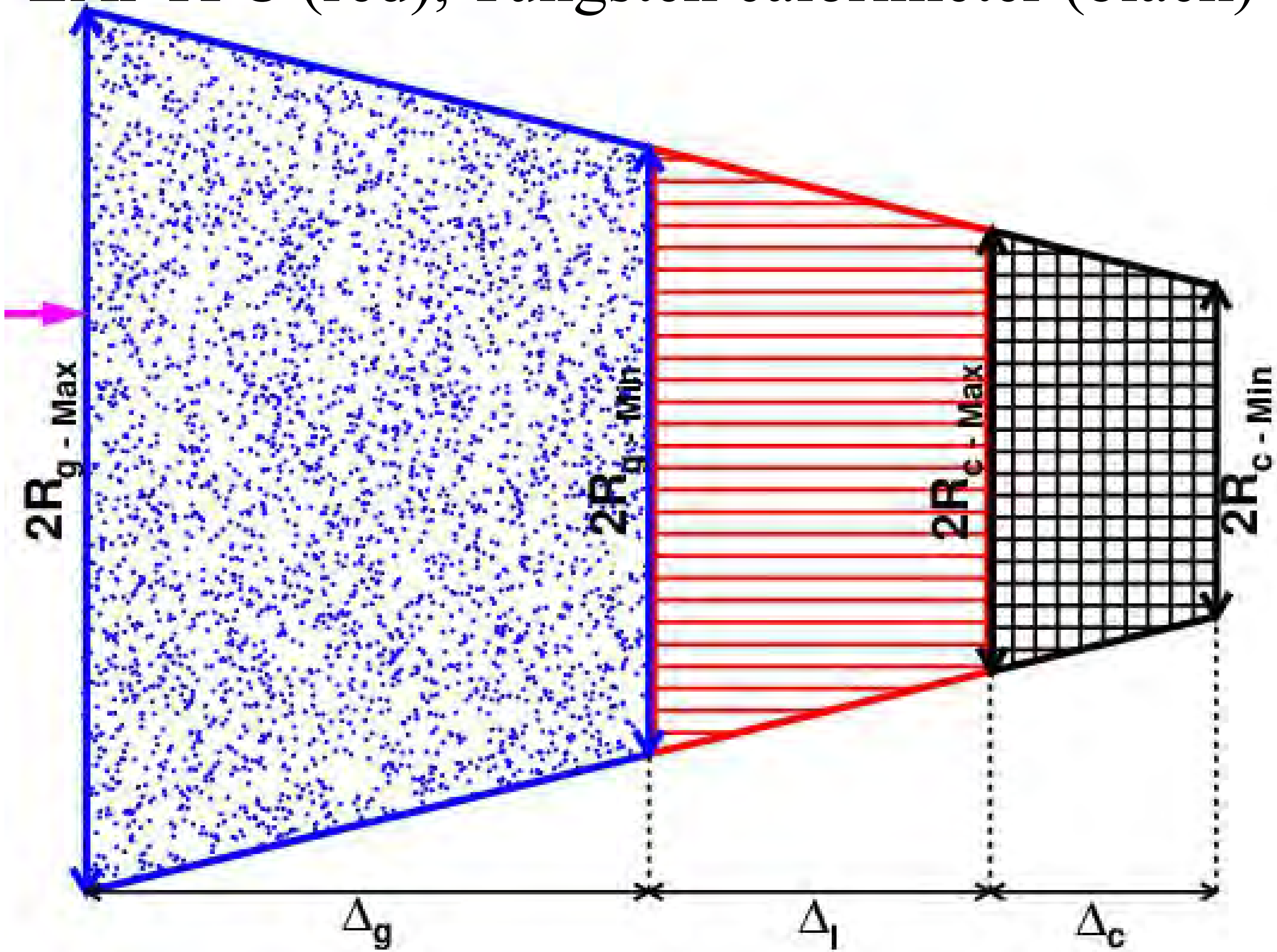


Optimize the detector mass (!?) → The Non La detector concept

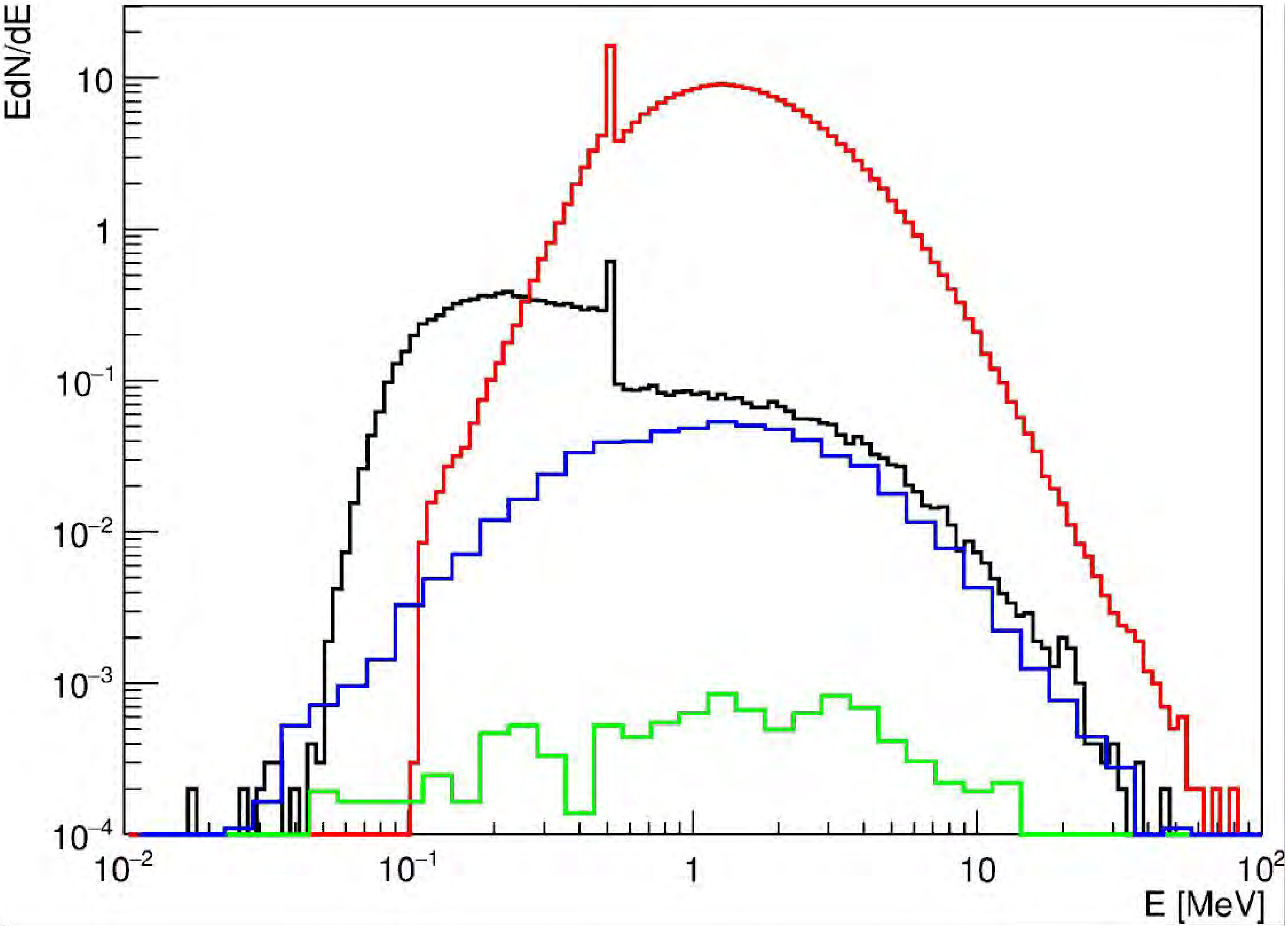


The Non La detector concept
(https://www.alibaba.com)

The Non La detector concept: gas TPC (blue), LAr TPC (red), Tungsten calorimeter (black)



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



Conclusions

The MAST concept allows for:
1) a very large effective area (~10 m^2)
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
6) Probably it is possible to reduce the mass of the instrument significantly by replacing the LAr calorimeter with a heavy-Z (e.g. Tungsten) calorimeter.

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Additional slides

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

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

The TACT detector concept