DP, K. Bondarenko, M. Doro, T. Kobayashi
***Phys. Dark Univ.* 46 (2024), 101704**

DP, M. Doro, T. Kobayashi
arXiv:2505.xxxxx

UNIVERSITÀ DEGLI STUDI DI PADOVA

MAGNETIC MONOPOLES IN COSMIC MAGNETIC FIELDS: ACCELERATION AND CONSTRAINTS

Michele Doro (University of Padova)
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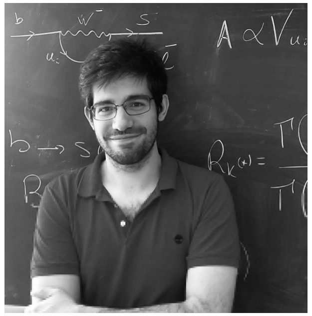


QUESTION?

- Are cosmic magnetic fields relevant for terrestrial experimental bounds on MMs?

#1 MM INTRO AND EXPERIMENTS

QUICK INTRO: DIRAC'S CLASSIC MONOPOLE

Dirac himself said of MM *"One would be surprised if Nature had made no use of it"*

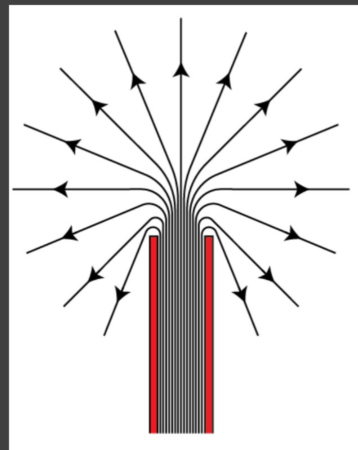
- He was trying to find a way to have a natural explanation for the quantization of the electric charge
- In 1948 he proposed a model for a monopole made of one semi-infinite string solenoid
- Magnetic charge:

$$g = 2\pi n/e = n g_D$$

- Maxwell's equations become symmetric

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$
$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$$



MMS ARE COMMON: T'HOOFT AND POLIAKOV

- In 1974 'T Hooft and Poliakov proposed a model of monopoles as topological defects, which was naturally appearing during phase transitions
- Monopoles are inevitable predictions of Grand Unified Theories: $SU(5) \rightarrow SU(3) \times SU(2) \times U(1) \rightarrow SU(3) \times U(1)$
- MM
  - GUT (early Universe) M>10^16 GeV
  - Intermediate Mass (later) M>10^6 GeV
- The 't Hooft–Polyakov monopole is a finite-energy, topological soliton arising due to the non-trivial topology of the vacuum manifold.

GUT AND INTERMEDIATE MM

Patrizii+ Ann.Rev.Nucl.Part.Sci. 65 (2015)

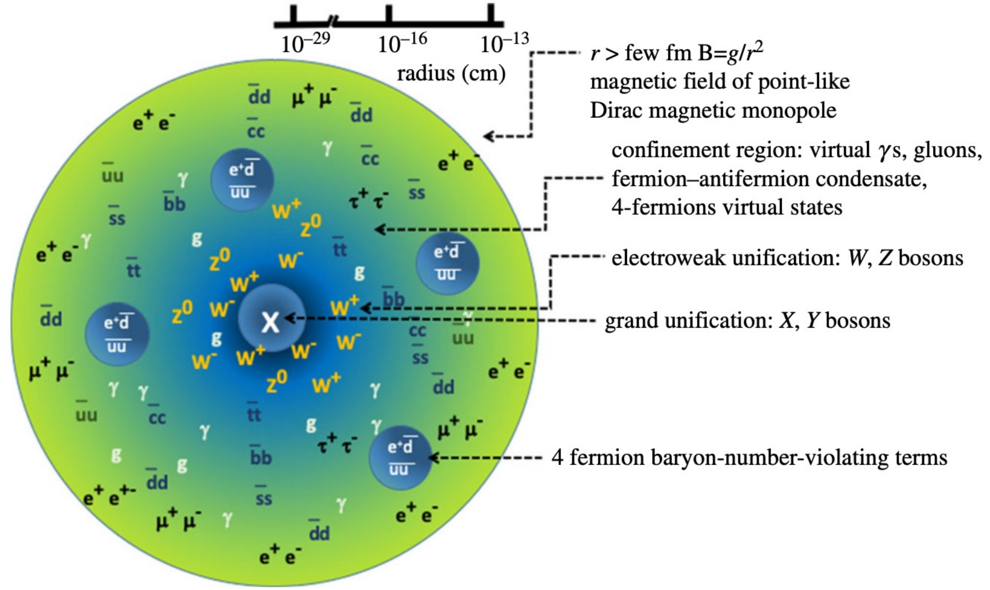


Figure 1. Qualitative picture of the internal structure of a GUT magnetic monopole (modified figure from [11]). The different regions are described in the text.

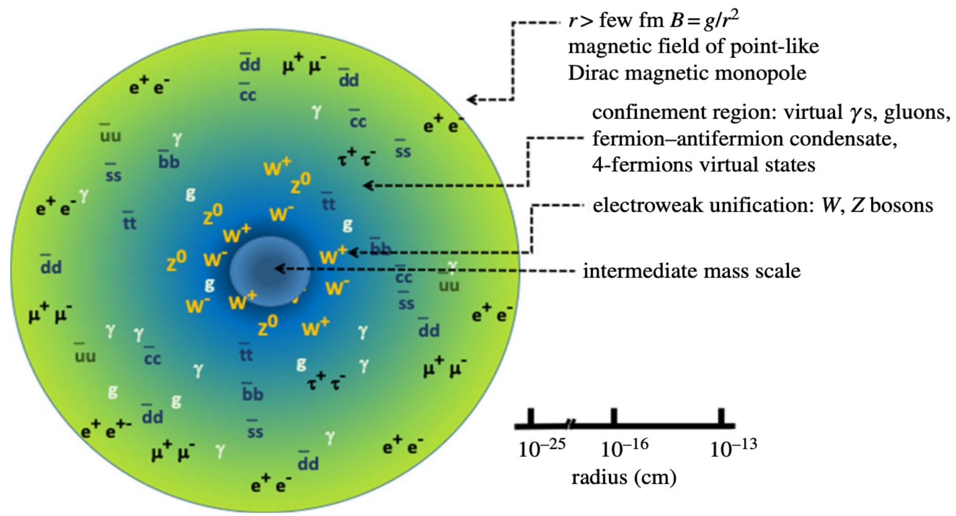


Figure 2. Qualitative picture of an 'intermediate mass magnetic monopole'. The inner region ($r \simeq 10^{-25}$ cm) corresponds to intermediate mass scales; inside this region, one finds the intermediate mass bosons responsible for the symmetry breaking. The outer regions are as in figure 1, but without terms violating baryon number conservation in the fermion–antifermion condensate.

GUT MM foresees proton decay

Inside the core, all the states of the GUT are excited.

ACTUALLY, TOO MANY MAGNETIC MONOPOLES

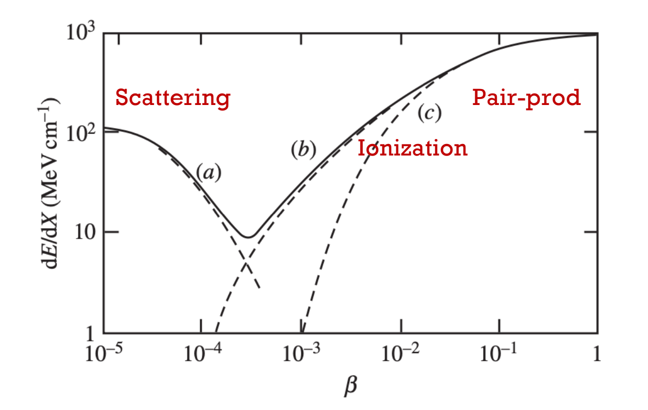
COSMOLOGICAL MONOPOLES crowd

- Monopoles are produced in the early universe during phase transition.
- The abundance of produced monopoles can easily over-dominate the energy density of the universe.
- Inflation provides a good solution to the problem.

GALACTIC MONOPOLES crowd/PARKER BOUND

- The Galaxy presents a magnetic field of ~muG
- The Galactic magnetic field accelerates the monopoles losing its energy;
- The survival of the field provides a bound on the monopole flux today

HOW TO GET THEM: ENERGY LOSS IN MATTER



gy loss (in MeV cm^{-1}) mechanisms of $g = g_D$ MMs in liquid hydrogen versus β. Cu
hydrogen atom scattering; curve (b) corresponds to interactions with energy level
on energy loss [12].

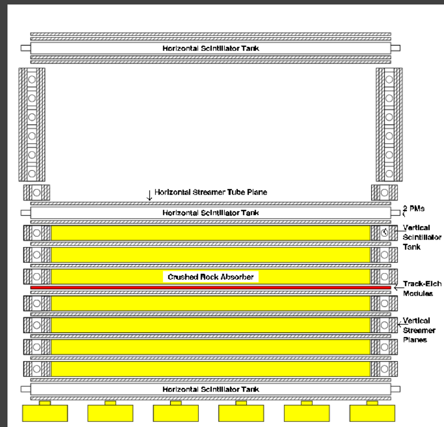
Patrizii+ Ann.Rev.Nucl.Part. Sci. 65 (2015)

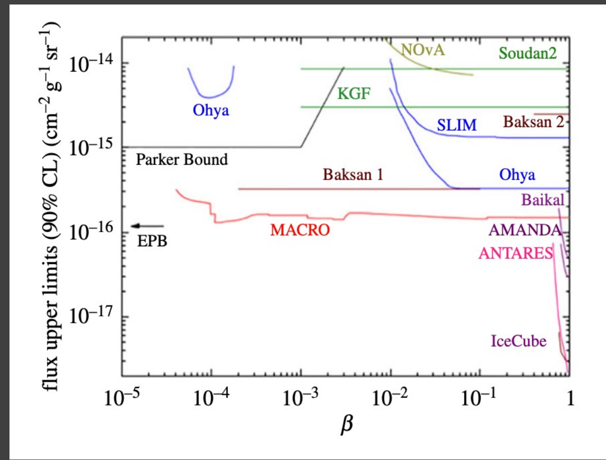
- When MMs cross a medium, the time-varying magnetic field induces a strong electric field. MMs are treated as electrically charged particles with an equivalent speed-dependent electric charge proportional to gβ.
- The search for MMs is naturally based on their speed at the detector.
  - For $\beta \lesssim 10^{-3}$ the energy loss is mostly through elastic collisions with atoms.
  - For $10^{-3} \lesssim \beta \lesssim 10^{-2}$, the medium behaves like a free degenerate gas of electrons (energy level crossings)
  - Relativistic MMs with $\beta \geq 0.1$ ionize atoms. The yield is ~ (g/e)^2=4700 times that of a minimum ionizing particle.
  - Ultra-relativistic MMs, with $\gamma > 10^4$, lose energy mostly by pair production and photo-nuclear radiative processes

HOW TO GET THEM

DIRECT DETECTION OF MONOPOLES

- Induction of electric currents into a coil;
- Energy loss by ionization (Ex. MACRO, IceCube);
- Catalysis of nucleon decays (only for GUT monopoles).





- The Monopole, Astrophysics and Cosmic Ray Observatory (MACRO) was a dedicated instrument for MMs at LNGS until 2000.
- MACRO was composed of three sub-detectors, sensitive to different MM speeds, operated in combination:
  - scintillation counters
  - limited streamer tubes
  - nuclear track detectors
- Upper bounds between $4 \times 10^{-5} \leq \beta < 0.99$ at around 1.4×10^{-16} cm−2s−1sr−1 for masses $\gtrsim 10^{16}$ GeV.

Citation: R.L. Workman *et al.* (Particle Data Group), Prog.Theor.Exp.Phys. **2022**, 083C01 (2022) and 2023 update

Magnetic Monopole Searches

See the related review(s):
Magnetic Monopoles

Monopole Production Cross Section — Accelerator Searches

X-SECT (cm^2)	MASS (GeV)	CHG (g)	ENERGY (GeV)	BEAM	DOCUMENT ID	TECN

https://pdg.lbl.gov/

Monopole Density — Matter Searches

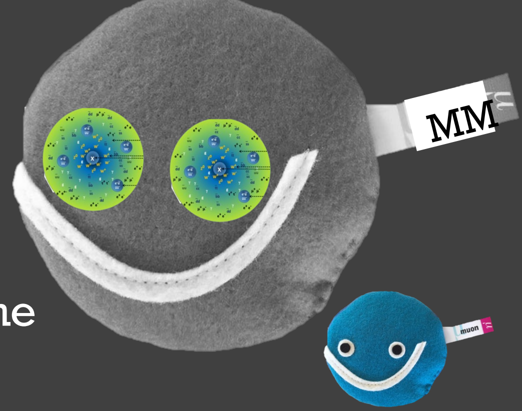
DENSITY	CHG (g)	MATERIAL	DOCUMENT ID		TECN
<9.8E−5/gram	≥ 1	Polar rock	BENDTZ	13	INDU
<6.9E−6/gram	>1/3	Meteorites and other	JEON	95	INDU
<2.E−7/gram	>0.6	Fe ore	[1] EBISU	87	INDU

SEARCHES AT ACCELERATORS

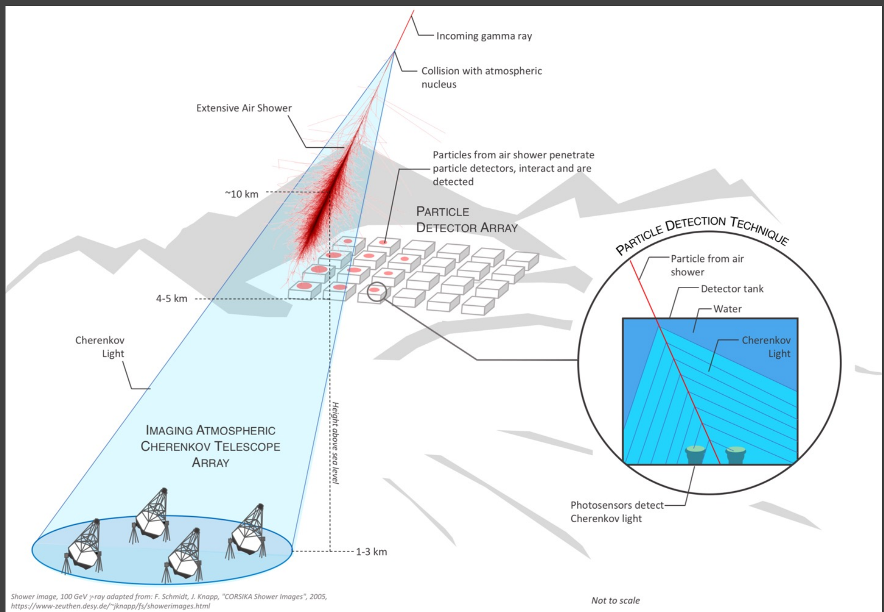
- The ATLAS experiment sought gD MMs with masses of up to 2.5 TeV .
- MM masses as large as 6 TeV have been explored by the MoEDAL experiment*, which has set upper limits to the production of MMs with charges as large as 5gD considering Drell-Yan process

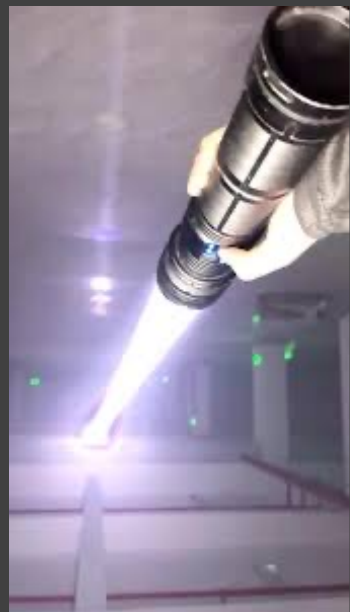
*MoEDAL (Monopole and Exotics Detector at the LHC) is a particle physics experiment at the Large Hadron Collider (LHC)

INDIRECT DETECTION OF MM



- A MM acts as a super-ionizing muon
  - the ionization yield of a relativistic unit charge MM is (g/e)^2 ~ 4700 times that of a MIP
  - Also 4700 times more Cherenkov light than that of a muon with the same speed





https://pdg.lbl.gov/

Monopole Flux — Cosmic Ray Searches

"Caty" in the charge column indicates a search for monopole-catalyzed nucleon decay.

FLUX ($cm^{-2}sr^{-1}s^{-1}$)	MASS (GeV)	CHG (g)	COMMENTS ($\beta = v/c$)	DOCUMENT ID		TECN
<2E-19		1	0.86< β <0.995	[1] ABBASI	22	ICCB
<2E-14	>5E8		6E-4< β <5E-3	[2] ACERO	21	NOVA
<1E-17		Caty	1E-5 < β <1E-3	[3] GAPONENKO	21	BAIK
<1.5E−18		1	β >0.6	[4] ALBERT	17	ANTR
<2.5E−21		1	1E8< γ <1E13	[5] AAB	16	AUGE

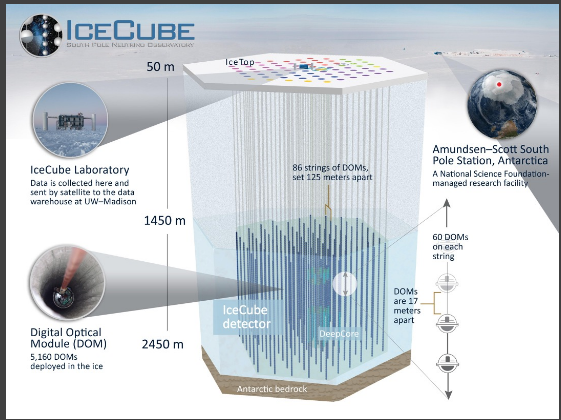
Monopole Density — Astrophysics

DENSITY	CHG (g)	MATERIAL	DOCUMENT ID		TECN
<1.E−9/gram	1	sun, catalysis	[1] ARAFUNE	83	COSM
<6.E−33/nucl	1	moon wake	SCHATTEN	83	ELEC

Monopole Flux — Astrophysics

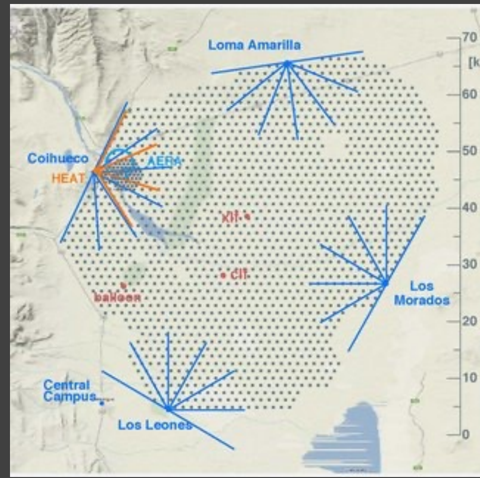
FLUX ($cm^{-2}sr^{-1}s^{-1}$)	MASS (GeV)	CHG (g)	COMMENTS ($\beta = v/c$)	DOCUMENT ID		TECN
<1.3E−20			faint white dwarf	[1] FREESE	99	ASTR
<1.E−16	E17	1	galactic field	[2] ADAMS	93	COSM
<1.E−23			Jovian planets	[1] ARAFUNE	85	ASTR
<1.E−16	E15		solar trapping	BRACCI	85B	ASTR

ICECUBE



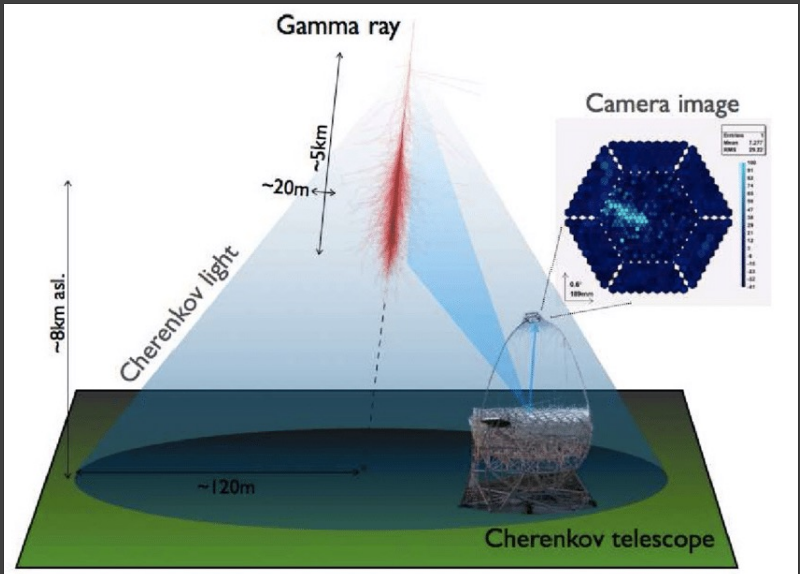
- Located at the South Pole in Antarctica, the IceCube detector is an array of 5160 optical modules arranged in 86 vertical strings deployed into the ice between 1500 m and 2500 m below the surface, with a total volume of 1 km^3.
- A charged particle can emit Cherenkov light in ice
- Core science: astrophysical neutrinos, but can see MMs above beta>0.5
- Several publications assuming supermassive MMs

PIERRE AUGER OBSERVATORY (PAO)



- PAO is the largest (3, 000 km2) ultra-high-energy cosmic-ray detector currently in operation.
- Surface-detector array of water tanks that samples the charged particles from atmospheric showers and 24 fluorescence detectors with a field-of-view of 30◦.
- PAO is sensitive to ultra-relativistic gamma>10^8 MMs
- Several papers published assuming light enough MMs

IACTS



- Very peculiar signature from MM in IACTs:
  - Super-bright events
  - Sometimes Double signals (from different zone of the atmosphere)
  - No confusion wrt gamma-rays

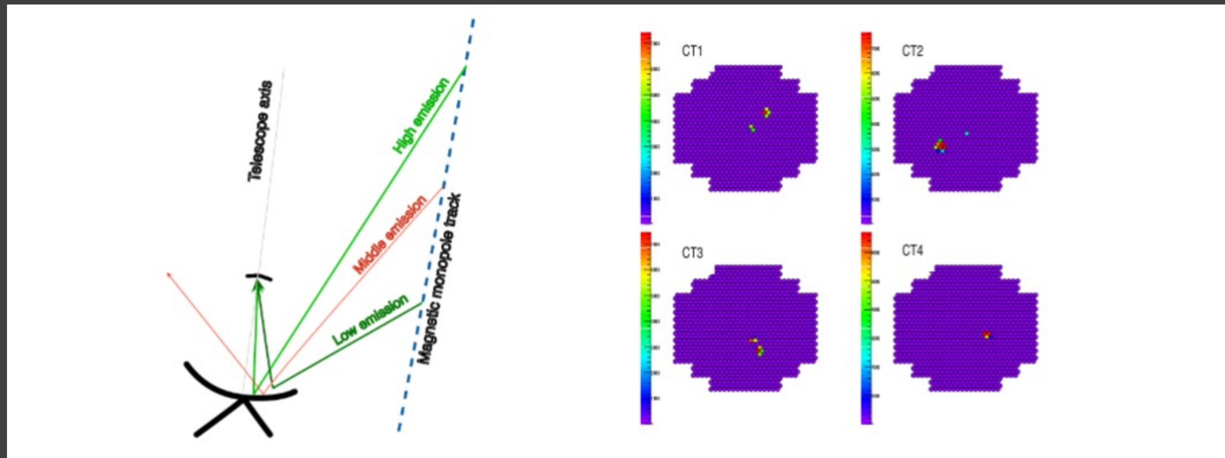
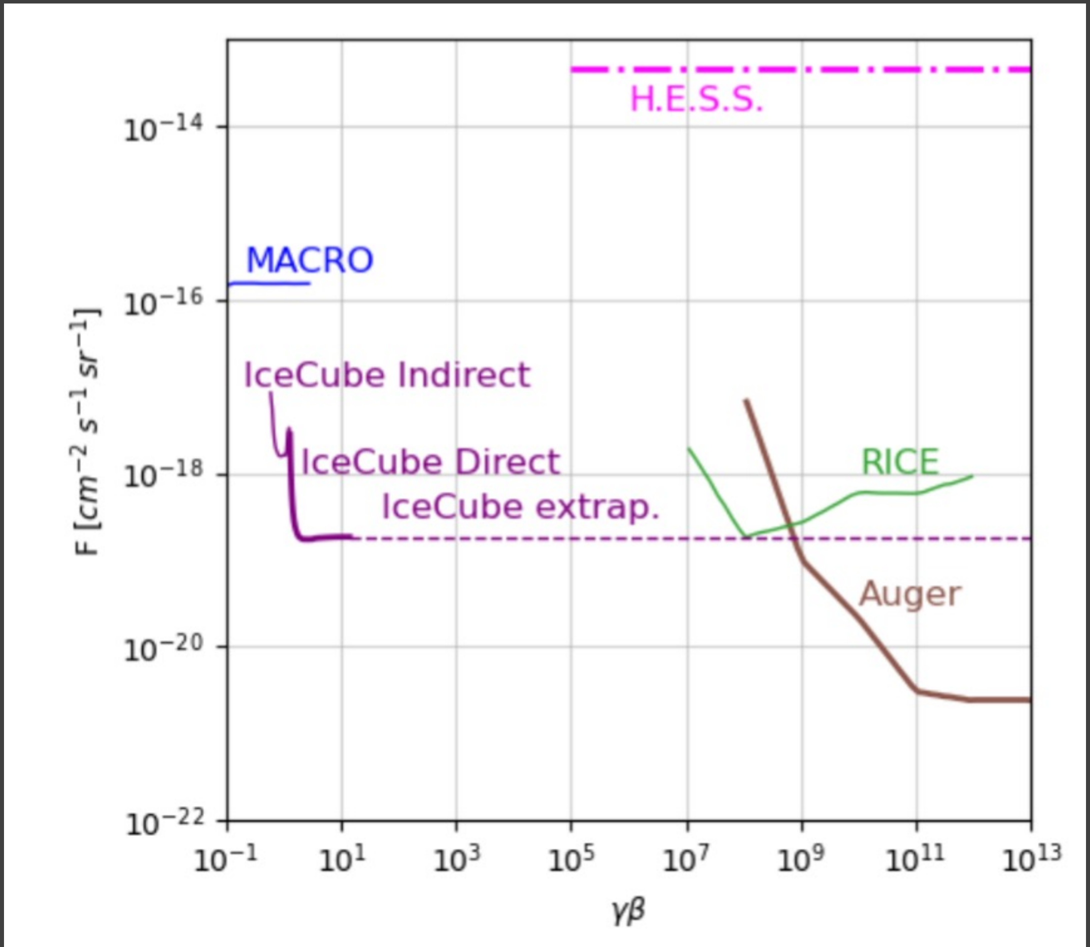


Figure 8.18: Left: Emission scheme from an ultrarelativistic MM emitting Cherenkov radiation throughout the full length of the atmosphere. Right: A simulated MM event on H.E.S.S. cameras. Courtesy of (Spengler, 2009).

- Only preliminary studies from MSc thesis of Gerrit Spengler

CURRENT WORLD-BEST LIMITS



IceCube = Relativistic MMs

PAO=Ultra Relativistic MMs

← In terms of speed

#2 ACCELERATION OF MM IN COSMIC FIELDS

MM AND MAGNETIC FIELDS

- The evolutions of magnetic monopoles and cosmic magnetic fields are strictly coupled throughout the universe's history.

Cosmic magnetic fields accelerate the monopoles

$$m \frac{d}{dt}(\gamma v) = gB$$

↔

Accelerated monopoles extract energy from cosmic magnetic fields

↓

Monopole bounds are affected by the acceleration

↓

The survival of cosmic magnetic fields might lead to new bounds

If one defines a model for cosmic MFs, one can compute the acceleration of MMs in function of the MM mass (and considering the back-reactions)

ACCELERATION

https://arxiv.org/abs/2401.00560

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Full length article

Monopole acceleration in intergalactic magnetic fields

Daniele Perri [a,b,c,*], Kyrilo Bondarenko [a,b,c], Michele Doro [d,e], Takeshi Kobayashi [a,b,c,f]

This yields

$$(\gamma v)_0 \sim \frac{g B_\mathrm{I}}{m H_0}. \qquad (2.10)$$

Inhomogeneous IGMF. With sub-horizon coherence lengths, $\lambda_\mathrm{I} < 1/H_0$, the present-day velocity takes the forms,

$$(\gamma v)_0 \sim \begin{cases} \frac{g B_\mathrm{I} \lambda_I}{m} \frac{1}{(\lambda_\mathrm{I} H_0)^{1/2}} & \text{for } m < \frac{g B_\mathrm{I} \lambda_\mathrm{I}^{1/2}}{H_0^{1/2}}, \\ \left(\frac{g B_\mathrm{I} \lambda_\mathrm{I}}{m}\right)^{2/3} \frac{1}{(\lambda_I H_0)^{1/3}} & \text{for } \frac{g B_\mathrm{I} \lambda_\mathrm{I}^{1/2}}{H_0^{1/2}} < m < \frac{g B_\mathrm{I}}{\lambda_\mathrm{I} H_0^2}, \\ \frac{g B_\mathrm{I}}{m H_0} & \text{for } m > \frac{g B_\mathrm{I}}{\lambda_\mathrm{I} H_0^2}. \end{cases} \qquad (2.11)$$

- We have explored IGMF/GMF:
  - IGMF: current bounds on intensity, $\lambda_I = 1 Mpc \text{ or } > 1/H_0$
  - GMF: Jannson and Farrar models

- In short:
  - Define B strengths and coherence length
  - Compute acceleration in function of MM mass
  - Consider back-reaction on B field (flux dependent)
  - Check which dominates!

IGMF LIMITS

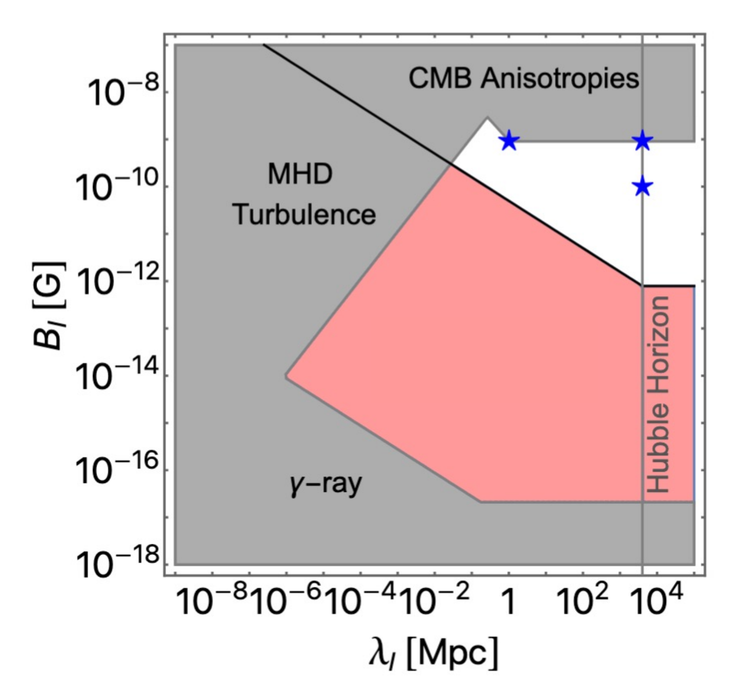
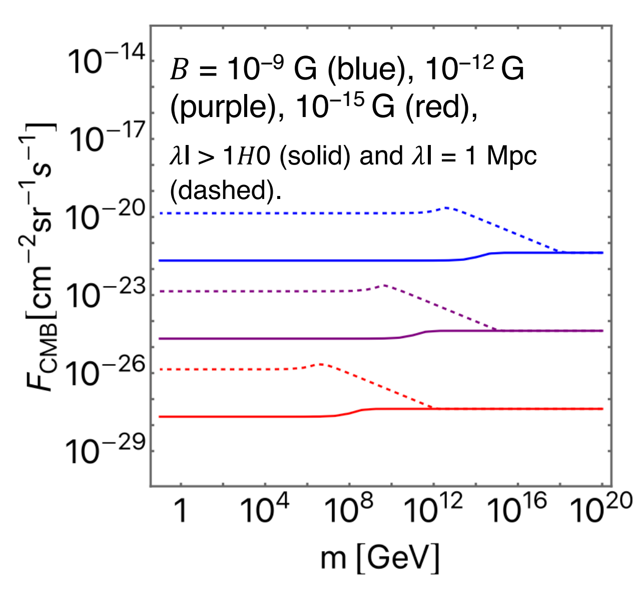


Figure 1: Parameter space of IGMF strength and coherence length. The gray region is excluded by various constraints [28]. The red region shows where IGMFs have negligigle effects on the MM velocity at Earth. The blue stars indicate benchmark values that are used in Fig. 2.

- Current limits on intensity
  - From above, mostly by CMB anisotropies (~1e-9 G)
  - From below by gamma-ray experiments
    - G-ray halos around blazars,
    - TeV→ GeV signal reprocess (due to pair production+synchrotron)
    - Delayed signal emission
- On coherent lengths
  - Small values excludes by turbulence

Durrer:2013pga,AlvesBatista:2021sln,Neronov:2021xua

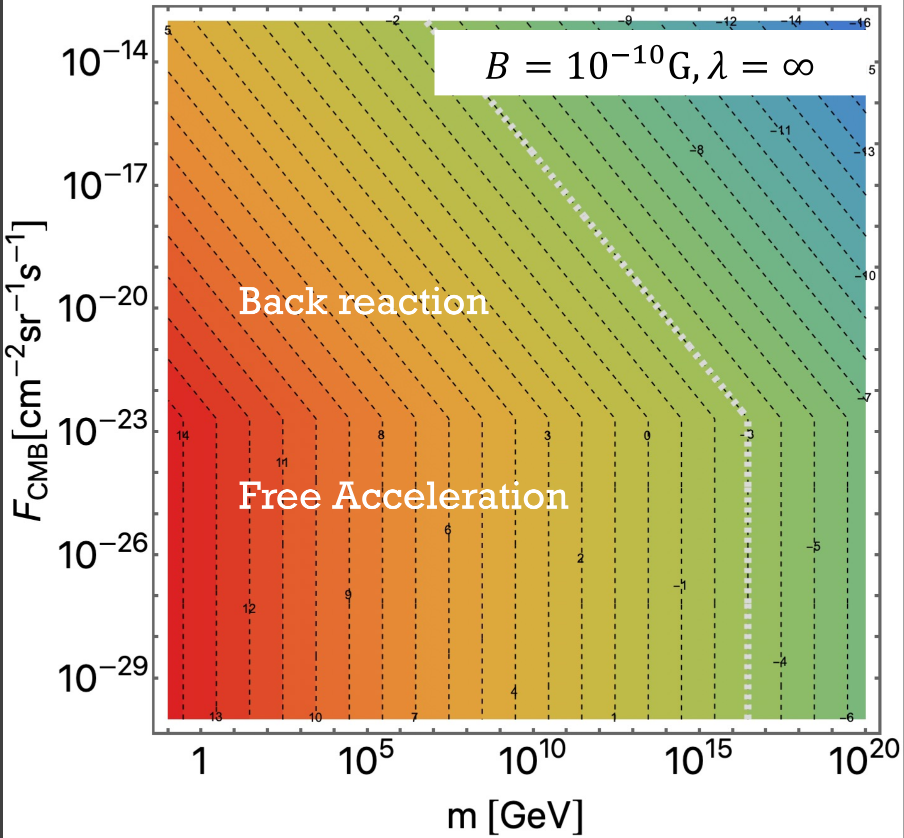
BACK REACTION

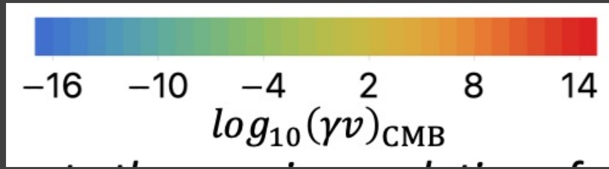


- MM extracts energy from B.
- This depends on their flux / their mass
- ← Threshold for back-reaction
- Higher B allows for larger MM fluxes
- Larger λ_I allows for larger fluxes

As a result, the maximum speed depends on flux: $max(v_{MW}, v_{IGMF}, v_{GMF})$

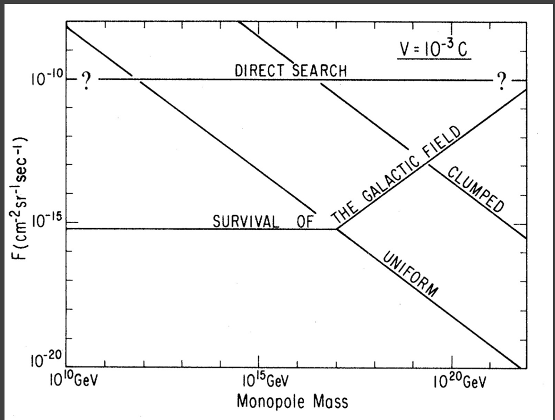
ACCELERATION IN IGMF

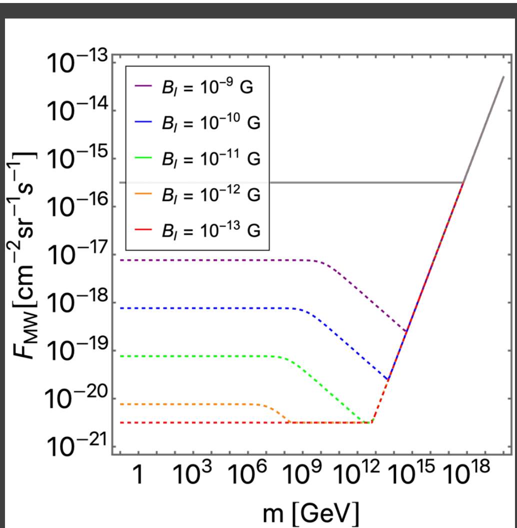




- IGMF alone can accelerate MM to ultra-relativistic speeds

GALACTIC MAGNETIC FIELDS





- In 1970 Parker proposed a bound on the monopole flux today inside our Galaxy:
  - The Galaxy presents a magnetic field of~2×10^(−6) G;
  - The Galactic magnetic field accelerates the monopoles losing its energy;
  - The survival of the field provides a bound on the monopole flux today.
- The bound can be even extended considering the seed field of the Galaxy.

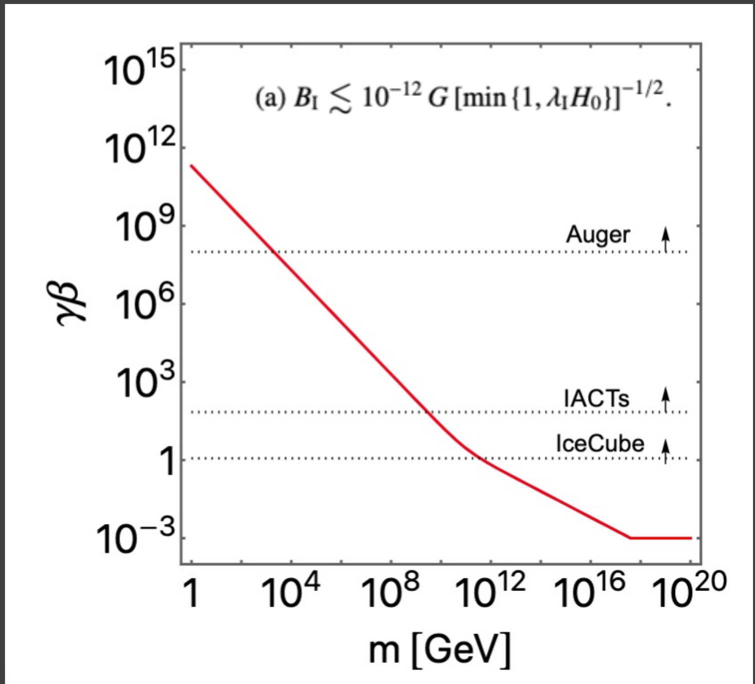
← Seed Parker bounds are weakened by acceleration into IGMF

Acceleration in GMF

$$m\,(\gamma_G - 1) \sim g B_G \sqrt{R \lambda_G} \sim 10^{11}\,\mathrm{GeV} \left(\frac{g}{g_D}\right).$$

SPEED-MASS RELATION (DEP. FLUX)

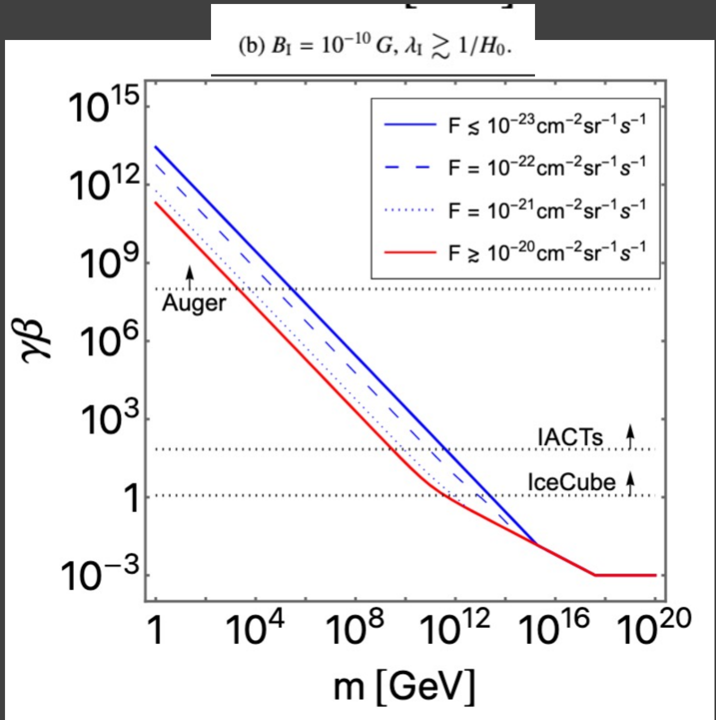
- One can compute the speed-mass relation for different scenarios of IGMF (and flux)



(a) $B_I \lesssim 10^{-12}\,G\,[\min\{1, \lambda_I H_0\}]^{-1/2}$.

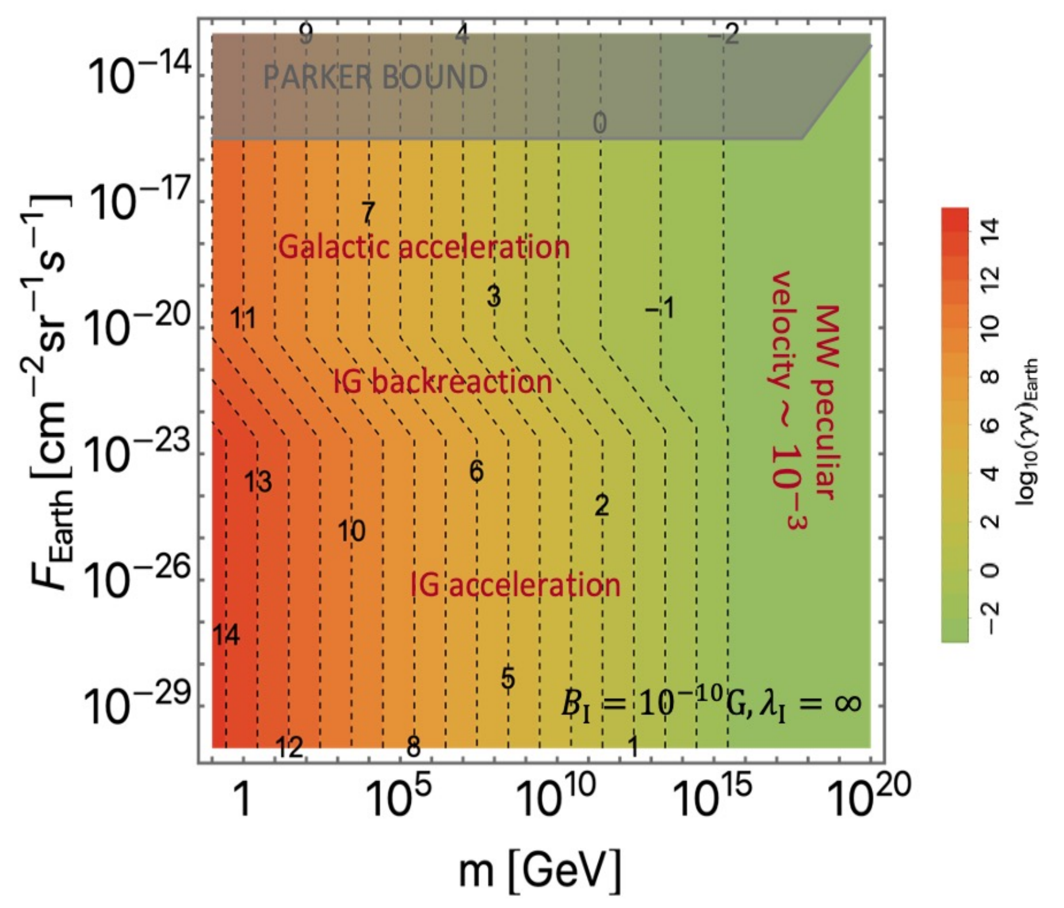
← Weak IGFM
GMF dominates
No back-reaction

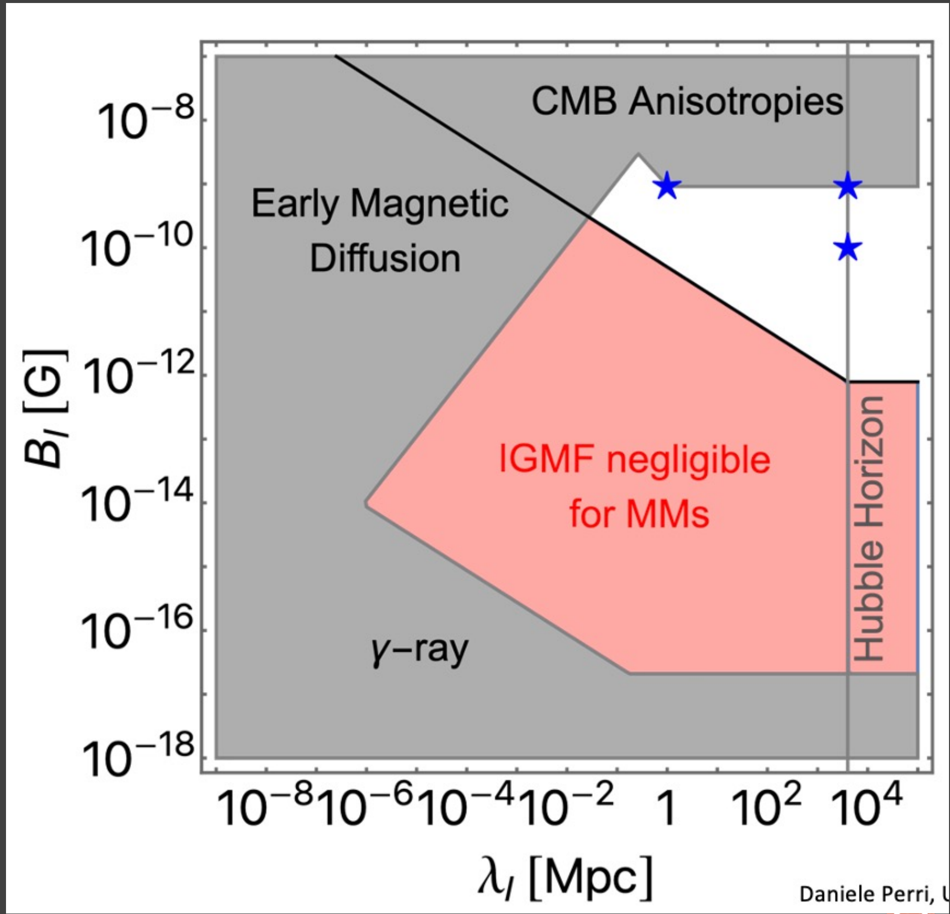
Strong IGMF →
IGMF contributes
Back-reaction matter



(b) $B_I = 10^{-10}\,G, \lambda_I \gtrsim 1/H_0$.

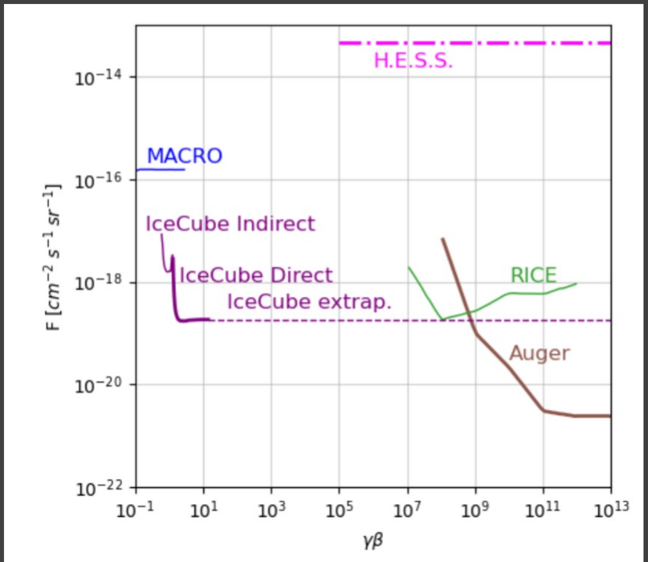
ALL CONSIDERERED

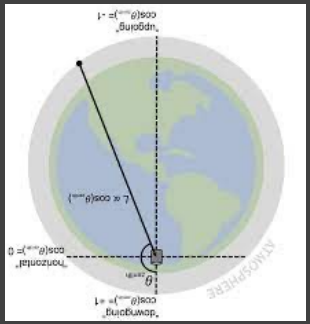




#3 RE-CAST EXPERIMENTAL BOUNDS

FROM SPEED-LIMITS TO MASS-LIMITS

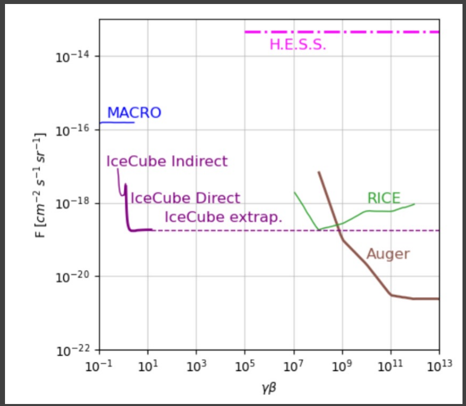


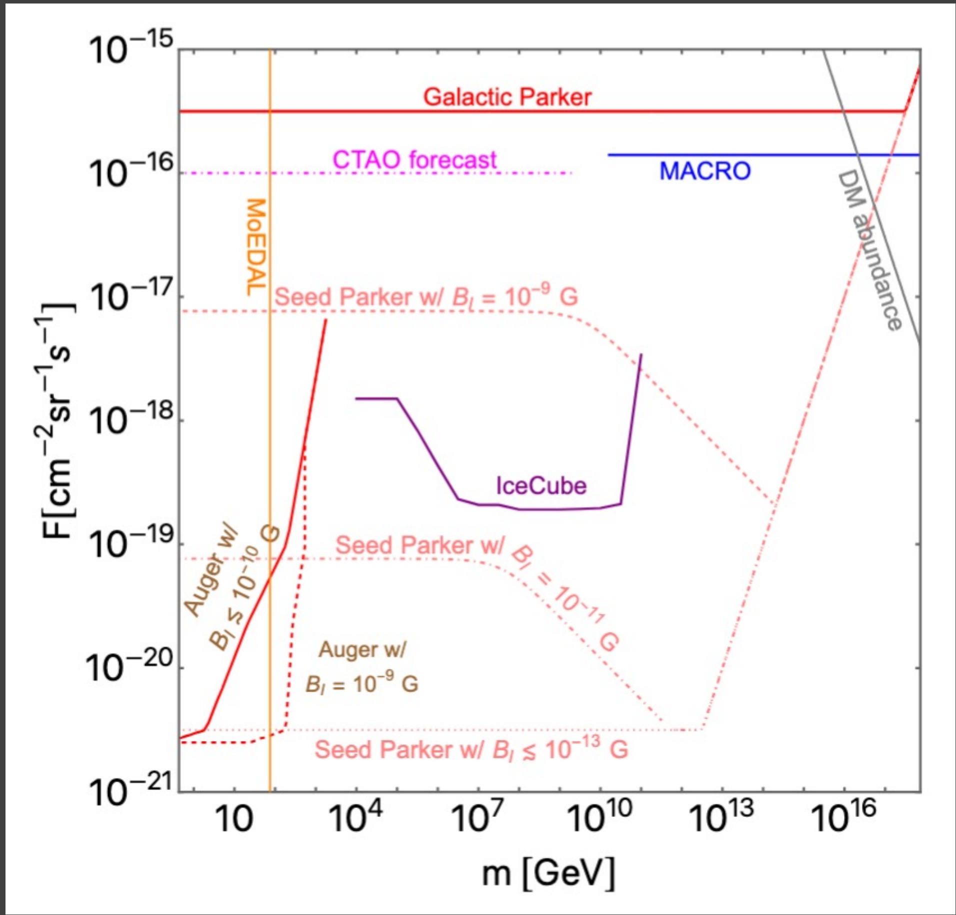


- Assuming a model of IGMF one can related speed to mass
- Terrestrial experiments required relativistic and ultra-relativistic speeds
- One should consider 'kinetic energy at the detector'
  - Compute energy loss in matter (if required)
  - Acceptance direction depedent
- E.g. MMs are clearly seen by IC only if coming from below
- Small kinetic energy MMs are lost (and this depends on the angle)
- Similar argument for MACRO
- We carefully checked Icecube and MACRO acceptance

RESULTS

Ah! I need a navigator!





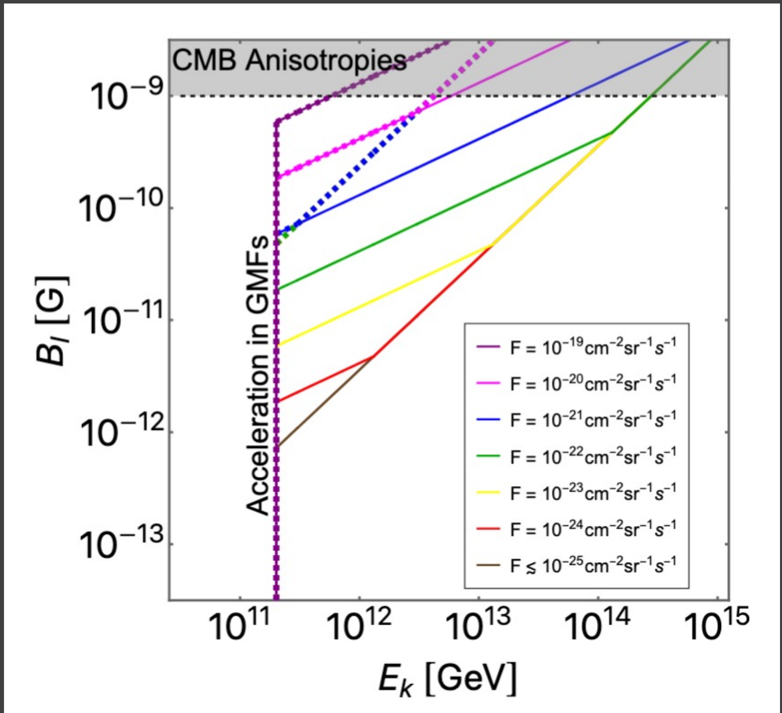
In terms of mass →

1/ Instruments have different mass sensitivity

2/ Seed Parker bounds significantly modulated by IGMF strength

3/ For small fluxes, IGMFs must be considered

BONUS

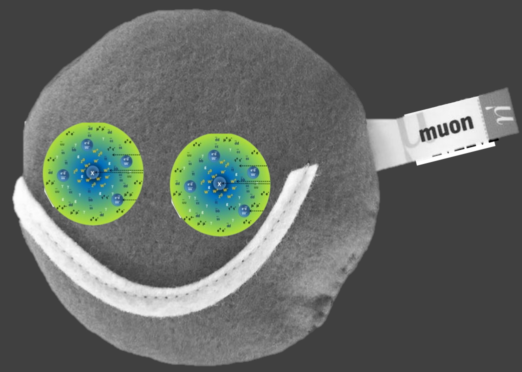


- The argument can be reversed
- A MM flux limit, assuming a certain kinetic energy, could be translated into an IGMF limit

CONCLUSIONS

TAKE-HOME

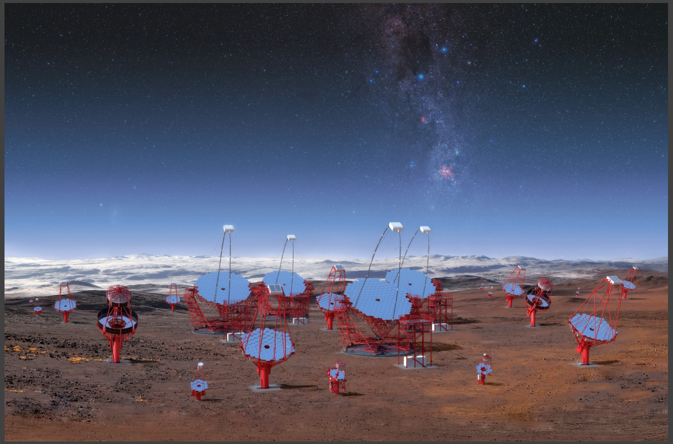
- We have developed a framework that computes the relation MM mass-speed in cosmic MFs (that includes back-reaction)
- We have made assumptions on MFs, if better models come out, more accurate estimations can be made
- Strong IGMFs impact MM acceleration (could contribute, could dominate)
- Terrestrial instruments are sensitive to different MM mass (related to their formation mechanisms)



Thanks!

BACKUPS

FOCUS ON IACTS



- Only MSc work from Gerrit Spengler (2009) for H.E.S.S. data
  - Simplified Monte Carlo, strong data selection
- Cherenkov Telescope Array Observatory will improve
  - Larger FOV
  - Larger effective area
  - Longer exposure
- All considered, sensitivity can improve 200 times wrt H.E.S.S. and on wider MM speed range
- A topic so far not investigated by current IACTs