Università degli Studi di Padova

MAGNETIC MONOPOLES IN COSMIC MAGNETIC FIELDS: ACCELERATION AND CONSTRAINTS

Speaker: Michele Doro, Takeshi Kobayashi, Daniele Perri

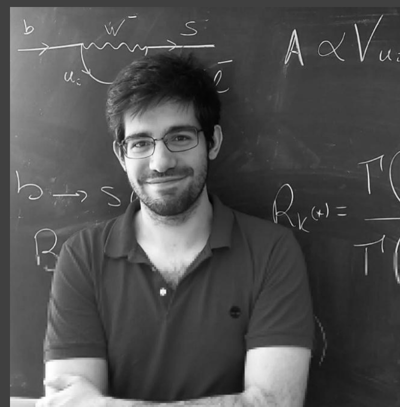
DP, K. Bondarenko, M. Doro, T. Kobayashi
***Phys. Dark Univ.* 46 (2024), 101704**

DP, M. Doro, T. Kobayashi
arXiv:2502.xxxxx

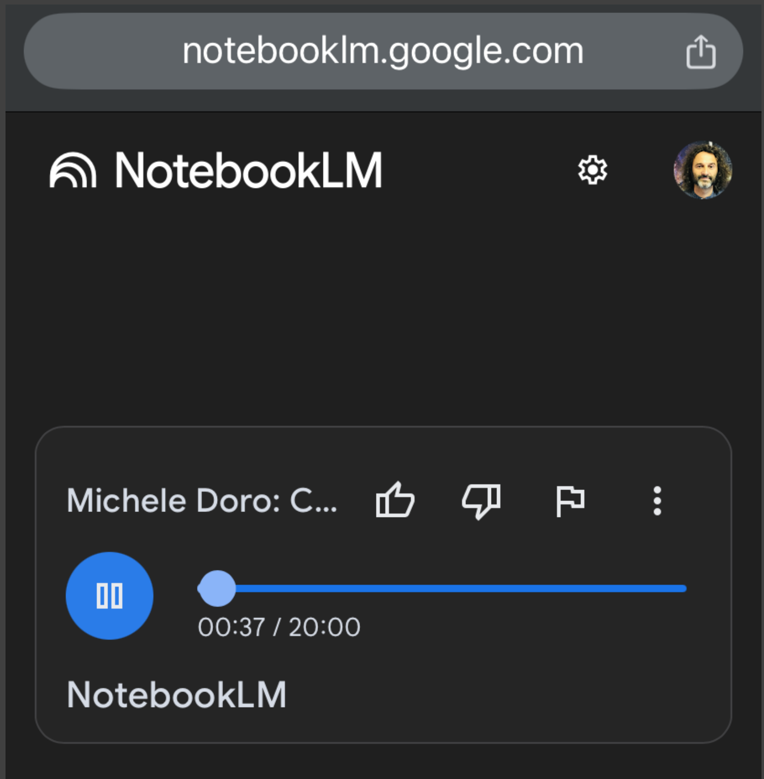
ABOUT MYSELF

Università degli Studi di Padova

- Associate professor at University of Padova
  - Physics Laboratory 1 for Physics BSc
  - General Physics
  - PhD: Remote atmospheric sensing (for astronomy)
- Main collaborators (glimpse at some names):
  - Padova: Elisa Prandini, Ivana Batkovic, Cornelia Arcaro, Davide Miceli, Tommaso Dorigo
  - Abroad: Roberta Zanin, Giacomo D'Amico, Miguel Angel Sanchez Conde, Paolo Giommi, Markus Gaug, …
  - For this work:
    Takeshi Kobayashi,
    Daniele Perri



AI MADE A POSTCAST ON ME ☺



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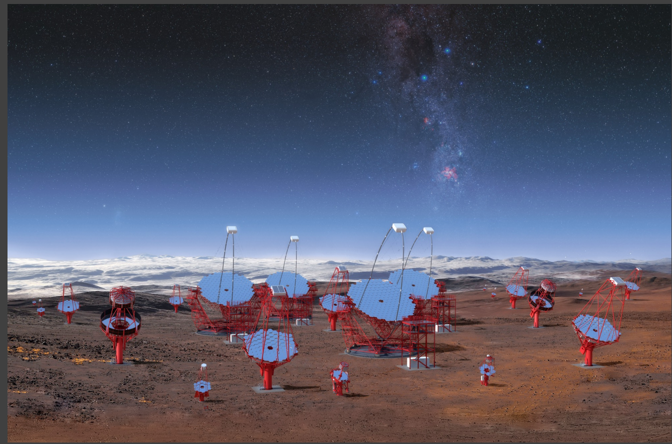
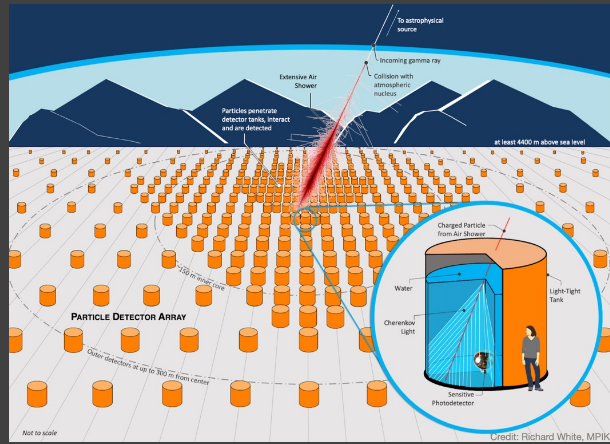
GAMMA-RAY ASTRONOMY





MAGIC: 2003-now

- Mirror and Calibration
- Fundamental Physics: dark matter, ALPs, now blazars
- …

CTAO 2006--now

- Fundamental physics searches
- Atmospheric Calibration

SWGO 2018--now

- Fundamental physics searches
- PeV-simulation outer array

From GeV to PeV…

HOW COSMIC MFS ARE OF INTEREST FOR MAGNETIC MONOPOLES?

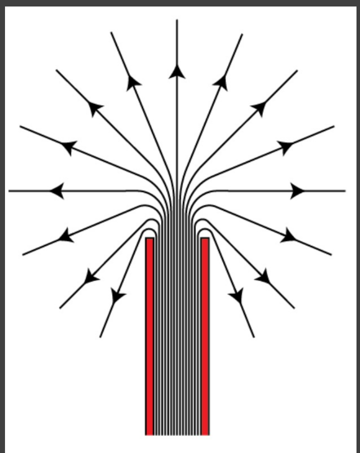
#1 JUST A PRIMER OF MM

Questions to Takeshi …

DIRAC'S CLASSIC MONOPOLE

- 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 (with M=2.4 GeV)
- Magnetic charge:

$$g = 2\pi n/e = ng_{\mathrm{D}}$$



- Maxwell's equations become symmetric

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

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

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

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) → SU(3) × SU(2) × U(1) → SU(3) × U(1)
- MM
  - GUT (early Universe) M>10^16 GeV
  - Intermediate Mass (later) M>10^6 GeV
- The 'T Hooft - Poliakov monopole is a zero-dimensional solitonic solution of the vacuum manifold.

GUT AND INTERMEDIATE MM

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

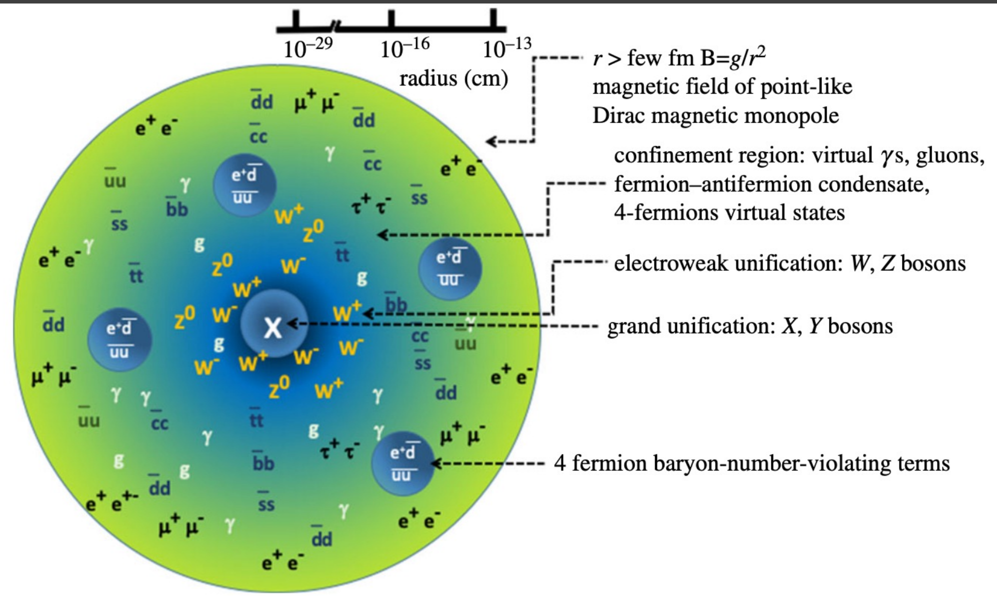


Figure 1. Qualitative picture of the internal structure of a GUT magnetic monopole (modified figure from [11]). The different regions are described in the text.

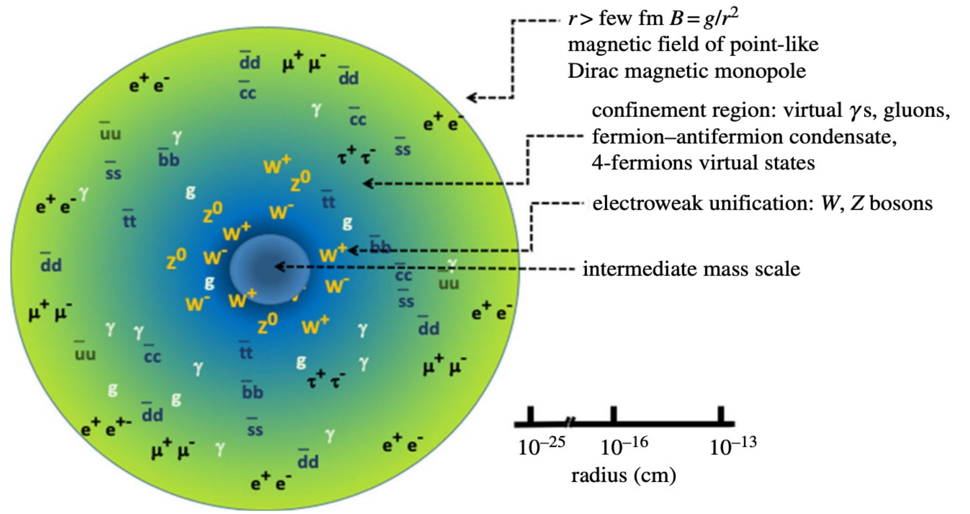


Figure 2. Qualitative picture of an 'intermediate mass magnetic monopole'. The inner region ($r \simeq 10^{-25}$ cm) corresponds to intermediate mass scales; inside this region, one finds the intermediate mass bosons responsible for the symmetry breaking. The outer regions are as in figure 1, but without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

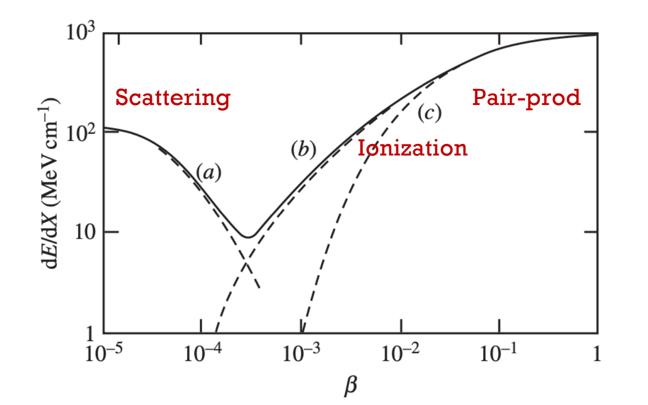
COSMOLOGICAL MONOPOLES indigestion

- 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 indigestion/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

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 varying magnetic field induces a strong electric field. MMs are treated as electrically charged particles with an equivalent speed-dependent electric charge of $g\beta$.
- The search for MMs is naturally based on their speed at the detector.
  - For $\beta \gtrsim 10^{-3}$ the energy loss is mostly through elastic collisions.
  - For $10^{-3} \lesssim \beta \lesssim 10^{-2}$, the medium is seen as a free degenerate gas of electrons (energy level crossings)
  - Relativistic MMs with $\beta \geq 0.1$ ionize and excite atoms. The yield is ~ 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

DIRECT DETECTION OF MONOPOLES

- There are different strategies used for the direct observation of magnetic monopoles:
  - Induction of electric currents into a coil;
  - Energy loss by ionization (Ex. MACRO, IceCube);
  - Catalysis of nucleon decays (only for GUT monopoles).

https://pdg.lbl.gov/

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

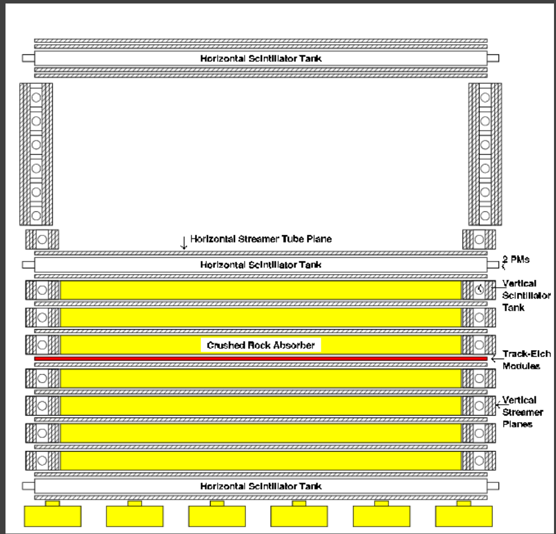
Monopole Production Cross Section — Accelerator Searches

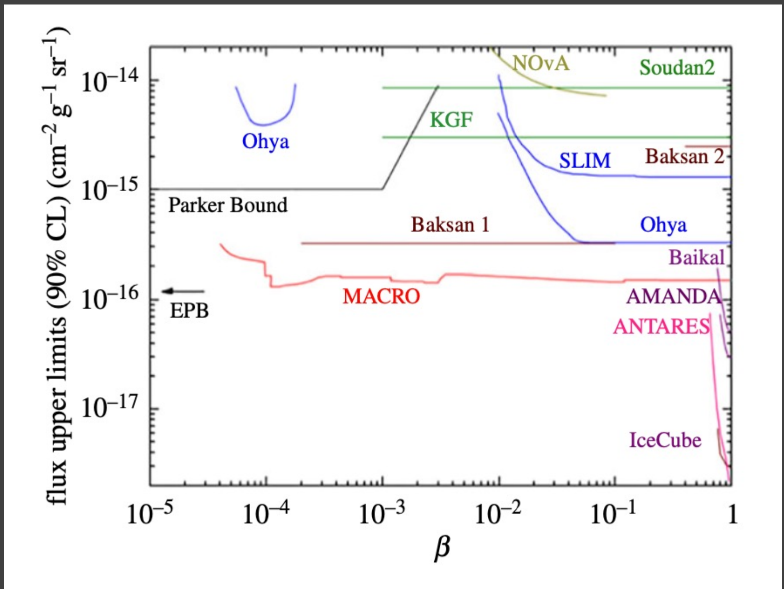
X-SECT (cm^2)	*MASS* (GeV)	*CHG* (g)	*ENERGY* (GeV)	*BEAM*	*DOCUMENT ID*	*TECN*

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

MACRO





- 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.

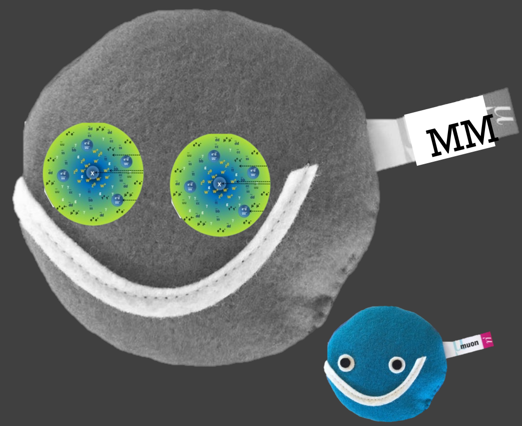
SEARCHES AT ACCELERATORS

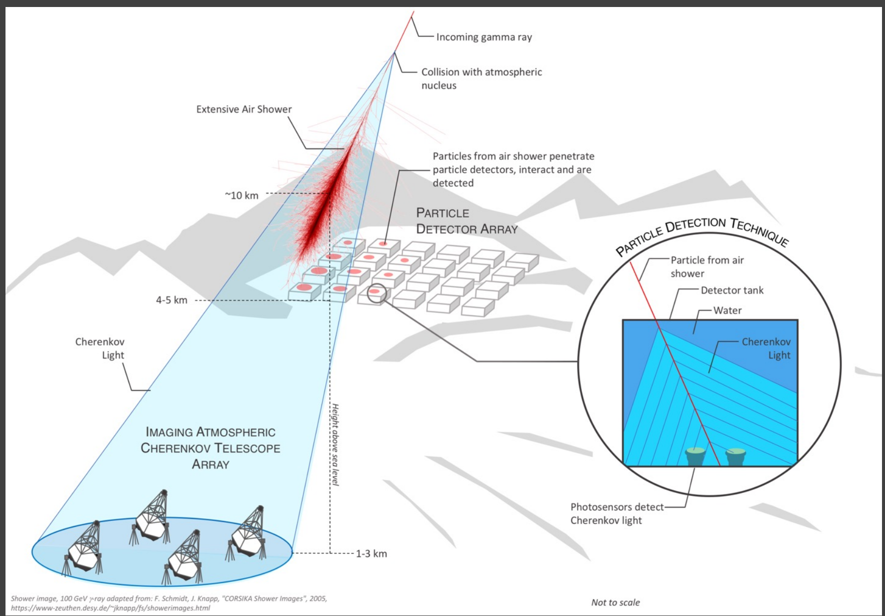
- The ATLAS experiment sought gD MMs with masses of up to 2.5 TeV .
- MM masses as large as 6 TeV have been explored by the MoEDAL experiment*, which has set upper limits to the production of MMs with charges as large as 5gD considering Drell-Yan process

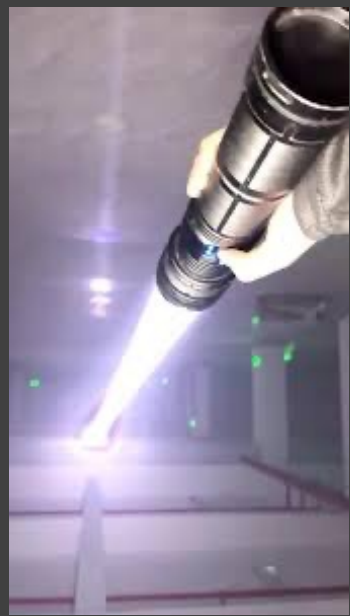
*MoEDAL (Monopole and Exotics Detector at the LHC) is a particle physics experiment at the Large Hadron Collider (LHC)

INDIRECT DETECTION OF MM

- A MM acts as a super-charged muon
  - the ionization yield of a relativistic unit charge MM is (gD/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

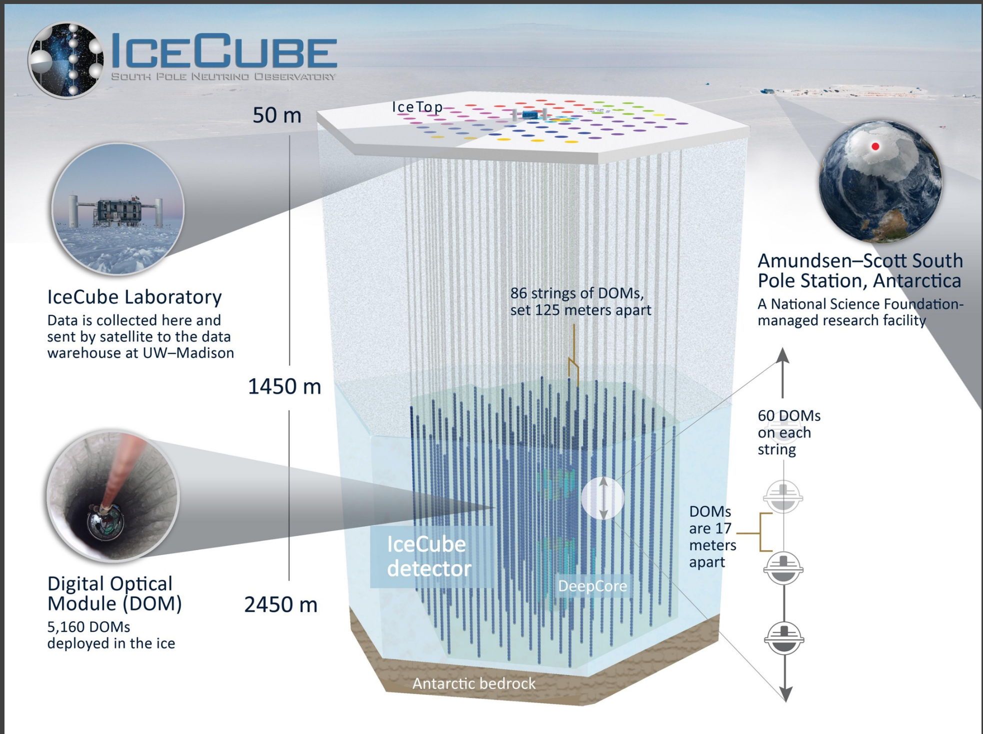
Monopole Density — Astrophysics

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

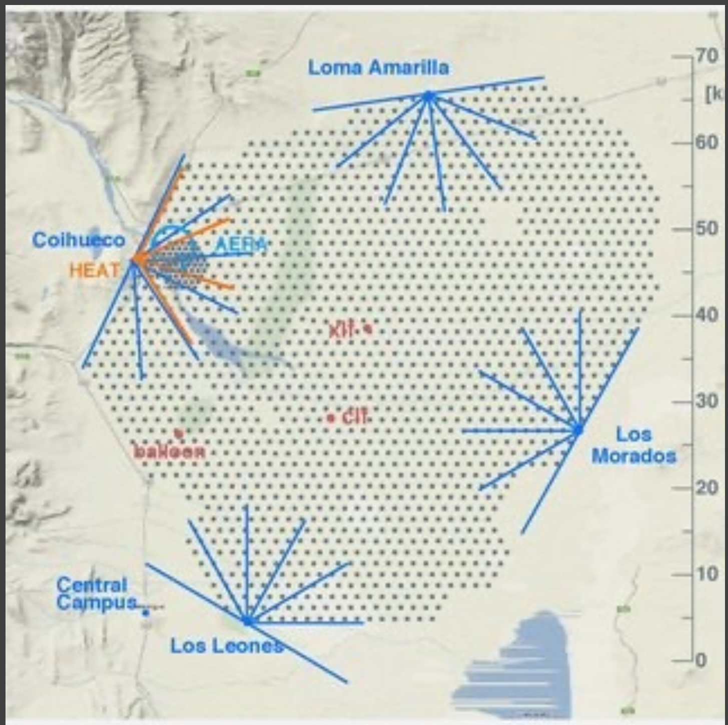
FLUX ($cm^{-2}sr^{-1}s^{-1}$)	MASS (GeV)	CHG (g)	COMMENTS ($\beta = v/c$)	DOCUMENT ID		TECN
<1.3E−20			faint white dwarf	[1] FREESE	99	ASTR
<1.E−16	E17	1	galactic field	[2] ADAMS	93	COSM
<1.E−23			Jovian planets	[1] ARAFUNE	85	ASTR
<1.E−16	E15		solar trapping	BRACCI	85B	ASTR

ICECUBE



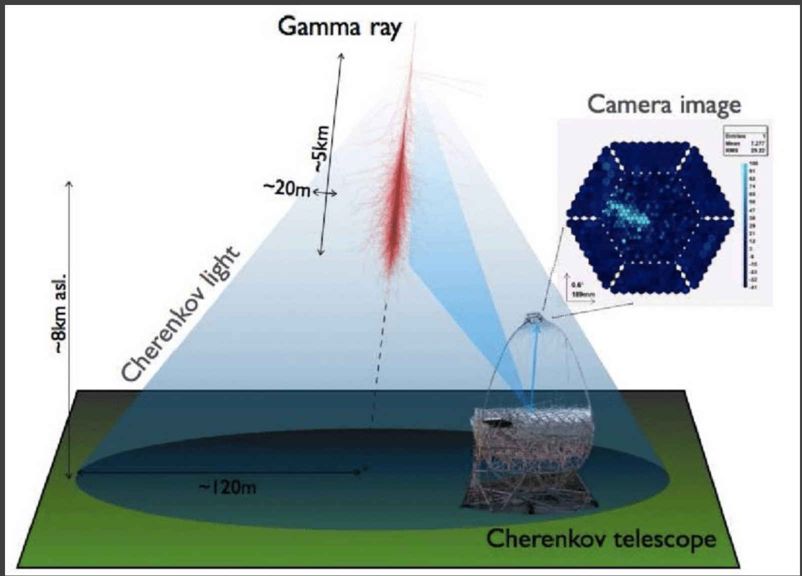
- Located at the South Pole in Antarctica, the IceCube detector is an array of 5160 optical modules arranged in 86 vertical strings deployed into the ice between 1500 m and 2500 m below the surface, with a total volume of 1 km^3.
- A charged particle can emit Cherenkov light in ice
- Core science: astrophysical 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
  - Double signals (from different zone of the atmosphere)
  - No confusion wrt gamma-rays

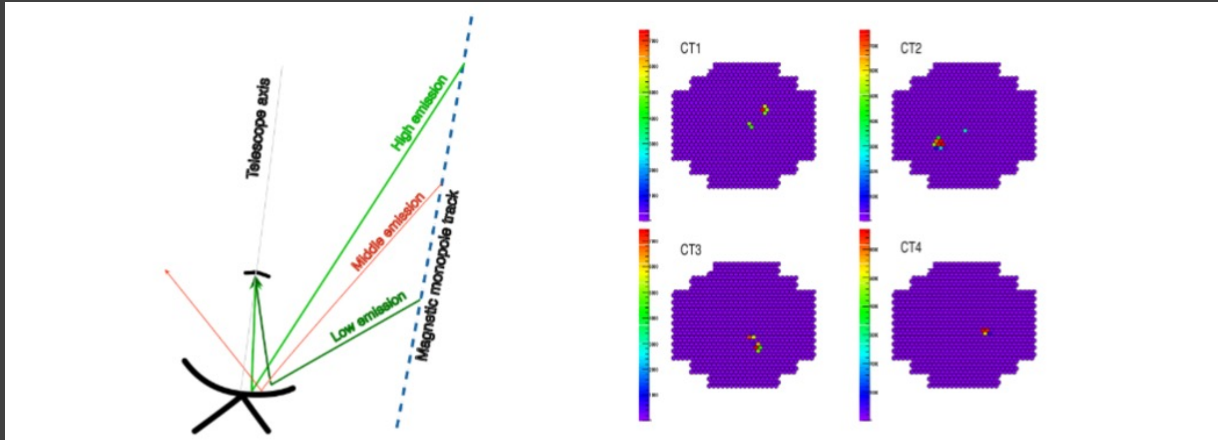
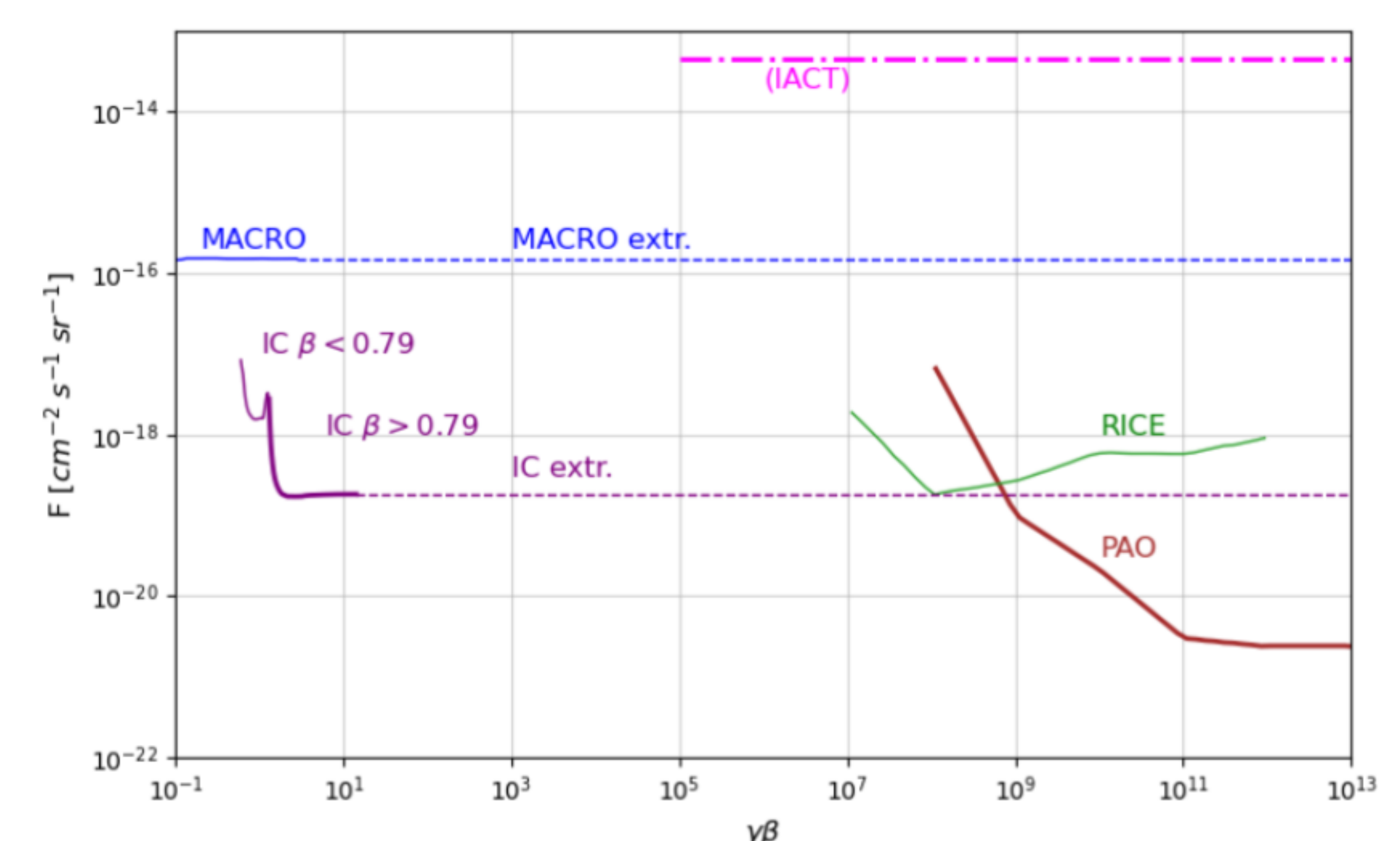


Figure 8.18: Left: Emission scheme from an ultrarelativistic MM emitting Cherenkov radiation throughout the full length of the atmosphere. Right: A simulated MM event on H.E.S.S. cameras. Courtesy of (Spengler, 2009).

- Only preliminary studies from MSc thesis of Gerrit Spengler

CURRENT WORLD-BEST LIMITS



IceCube = Relativistic MMs

PAO=Ultra Relativistic MMs

#2 ACCELERATION OF MM IN COSMIC FIELDS

Yes, sorry for taking so long…

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 –thus the flux density)

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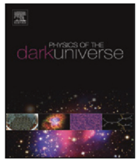
Contents lists available at ScienceDirect

Physics of the Dark Universe

journal homepage: www.elsevier.com/locate/dark



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]

Full model of acceleration in IGMFs

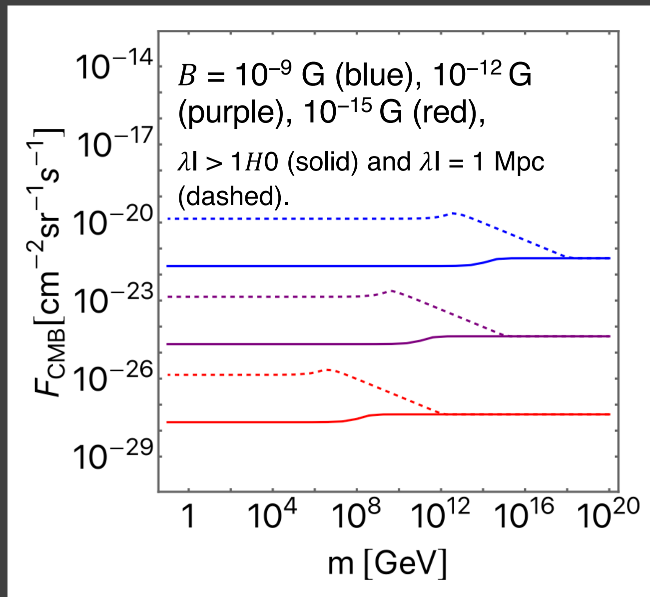
This yields

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

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

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

Threshold for back-reaction

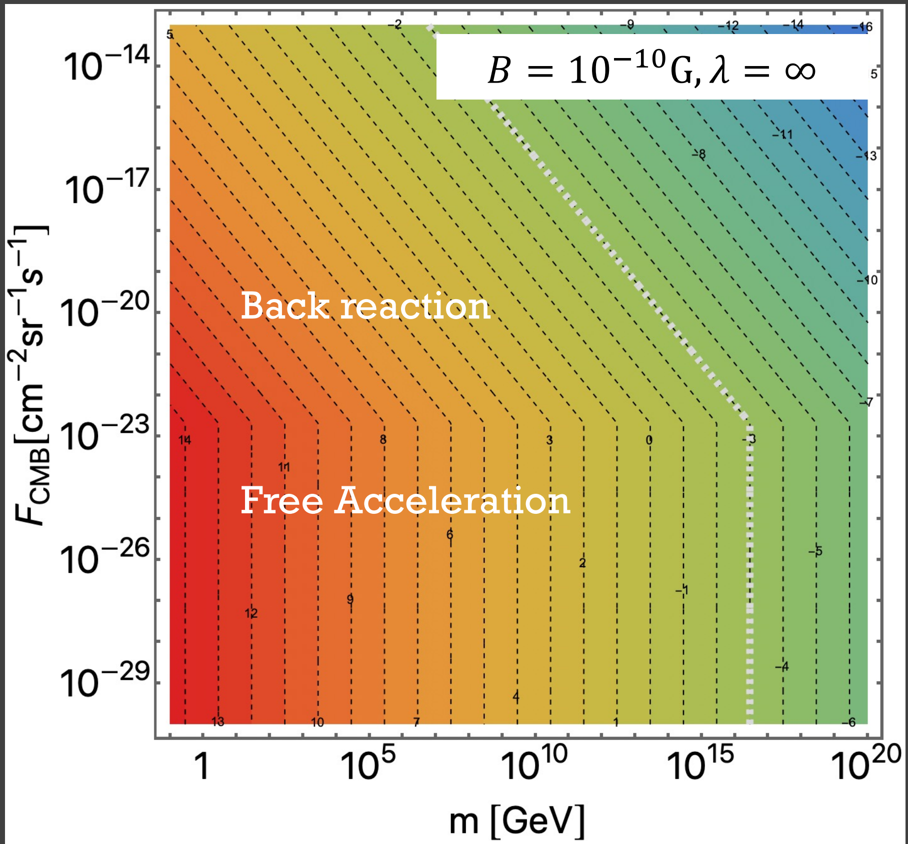


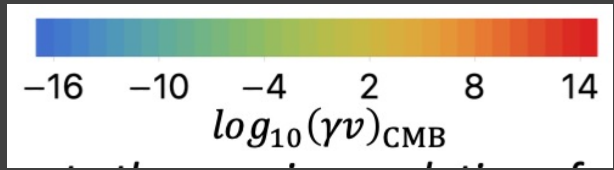
Back-reaction: MM extracts energy from B. It depends on flux

Maximum speed depends on flux:

$$(\gamma v)_{\mathrm{CMB}} \sim min\left(\frac{gB}{mH_0}, \frac{B^2}{4\pi m F_{\mathrm{CMB}}}\right)$$

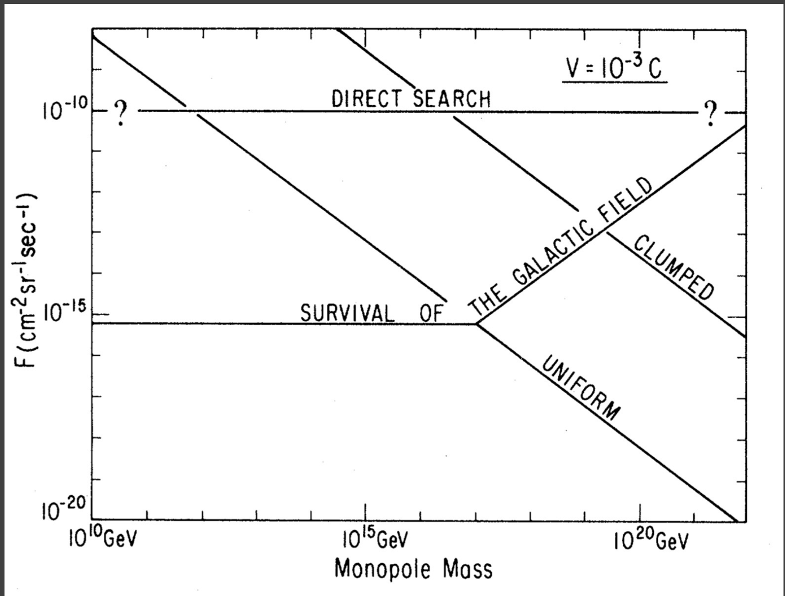
ACCELERATION IN IGMF





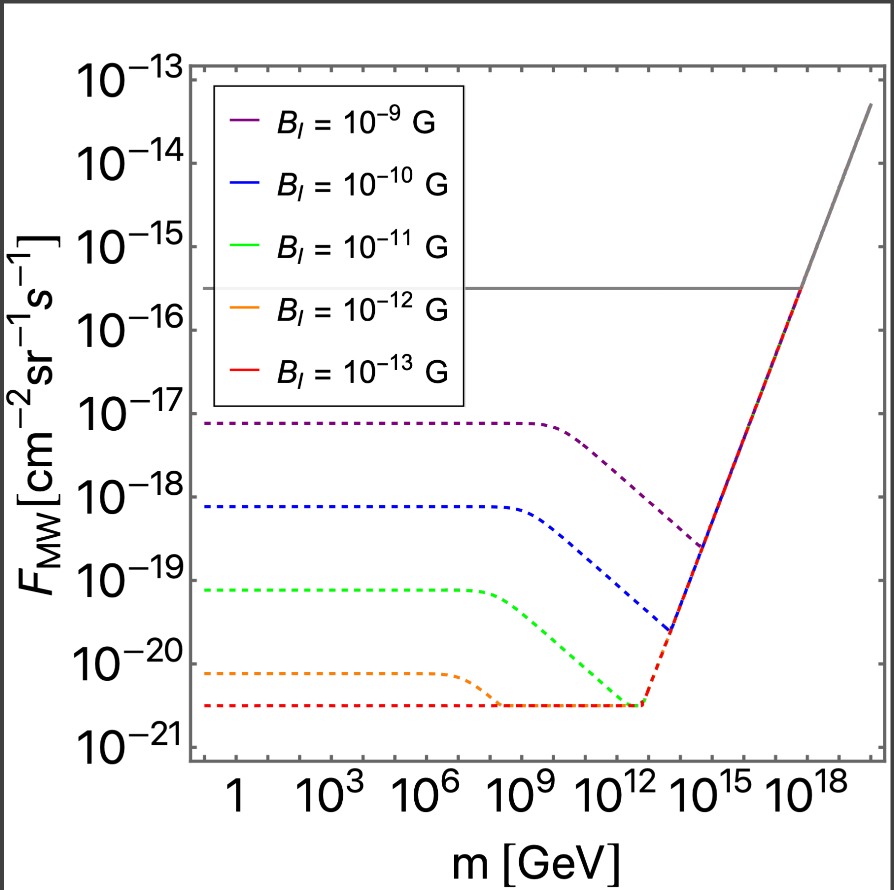
- Depending on the flux, once a model of IGMF is given **MM speed can be related to MM mass**
- **IGMF alone can accelerate MM to ultra-relativistic speeds**

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.

GALACTIC ACCELERATION



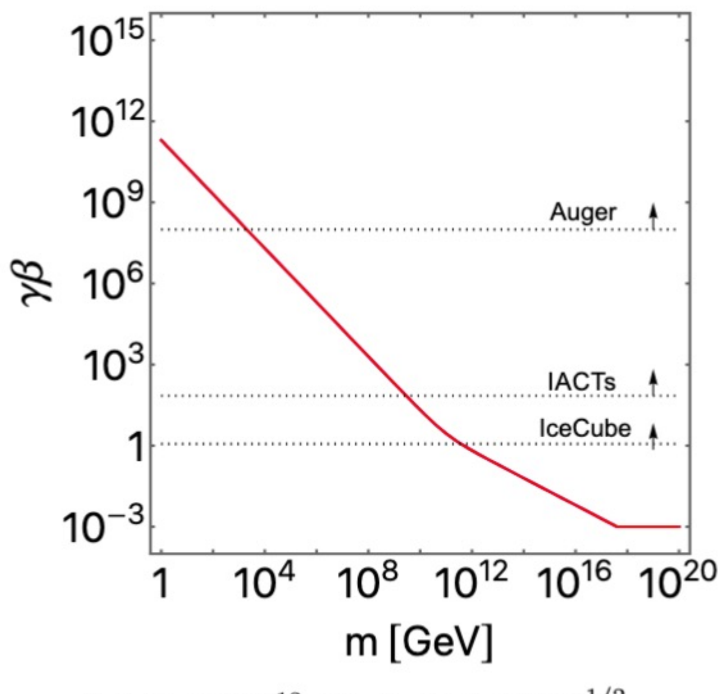
- Observations indicate that the Milky Way hosts GMFs with an average amplitude B ~10−6 G and coherence length λ ~ 1 kpc, within a magnetic region of size R ~ 10 kpc

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

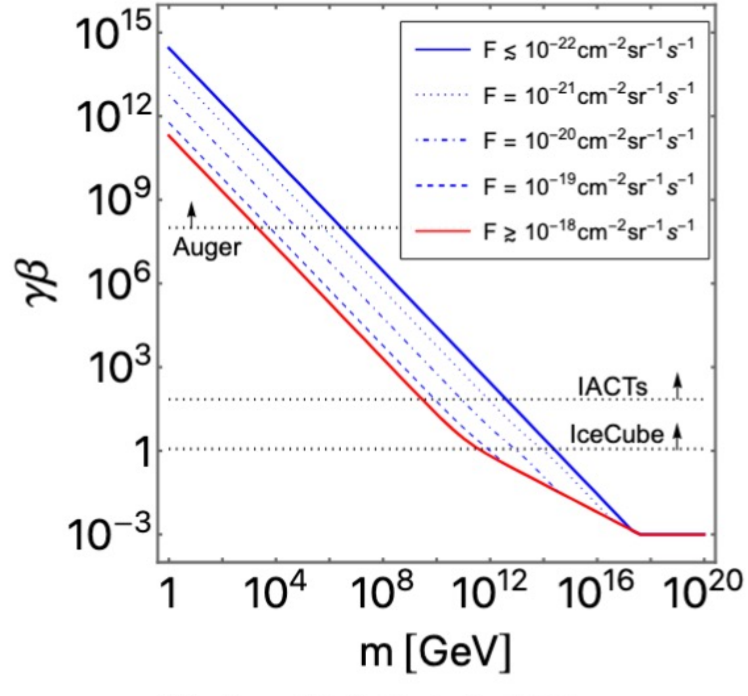
Galactic Parker bounds depend on the monopole incident velocity on the Milky Way (intergalactic acceleration).

PAPER IN PREP.

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



(a) $B_{\rm I} \lesssim 10^{-12}\ G\,[\min\{1, \lambda_{\rm I} H_0\}]^{-1/2}$.

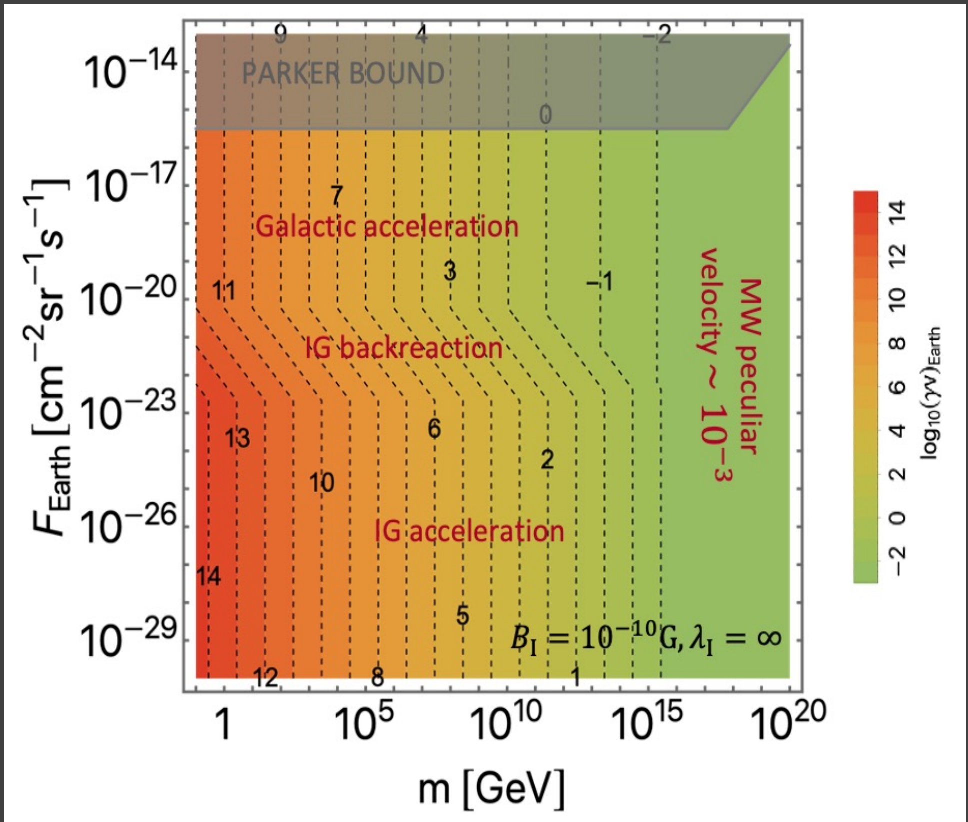


(d) $B_{\rm I} = 10^{-9}\ G,\ \lambda_{\rm I} \gtrsim 1/H_0$.

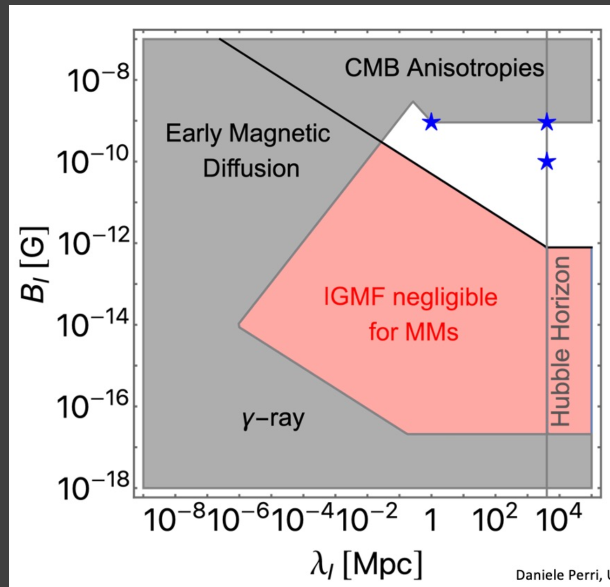
ALL CONSIDERERED

- MM speed at Earth is dominated by maximum accelerator (IGMF, GAL or peculiar velocity)

$$v_{\mathrm{E}} = \max\left\{v_{\mathrm{I}}, v_{\mathrm{G}}, v_{\mathrm{p}}\right\}.$$



- Monopole velocity might be an independent test of IGMFs.



Daniele Perri, U

#3 EXPERIMENTAL MM BOUNDS AND IGMF

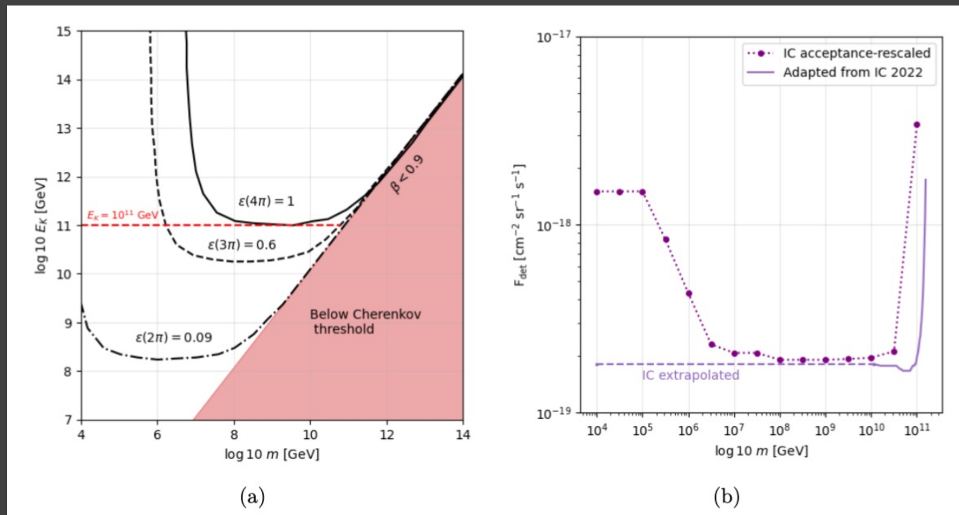
We are almost there

RECASTING OF EXISTING EXPERIMENTAL LIMITS

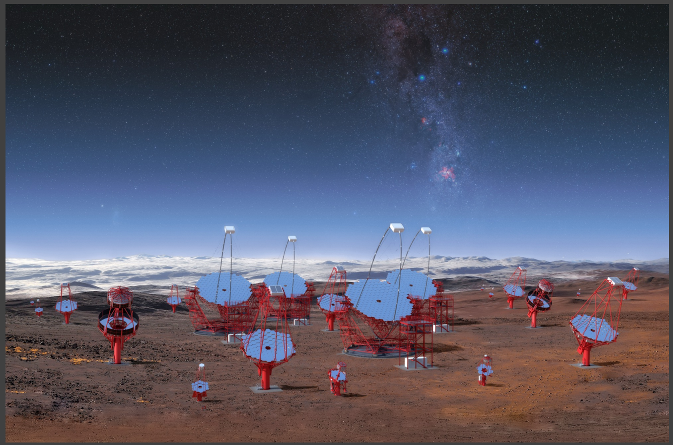
- MACRO, IceCube, PAO, IACTs set limits in dependence of MM speed
- Our model allows to relate MM speed-mass(-flux)
- We recasted published most constraining experimental limits in function of MM mass.
  - Needed to re-compute kinetic energy at the detector, considering detector acceptance

For example:

- IceCube acceptance depends on direction
- MM at different direction requires differnet MM kinetic energies
- (A bit technical)

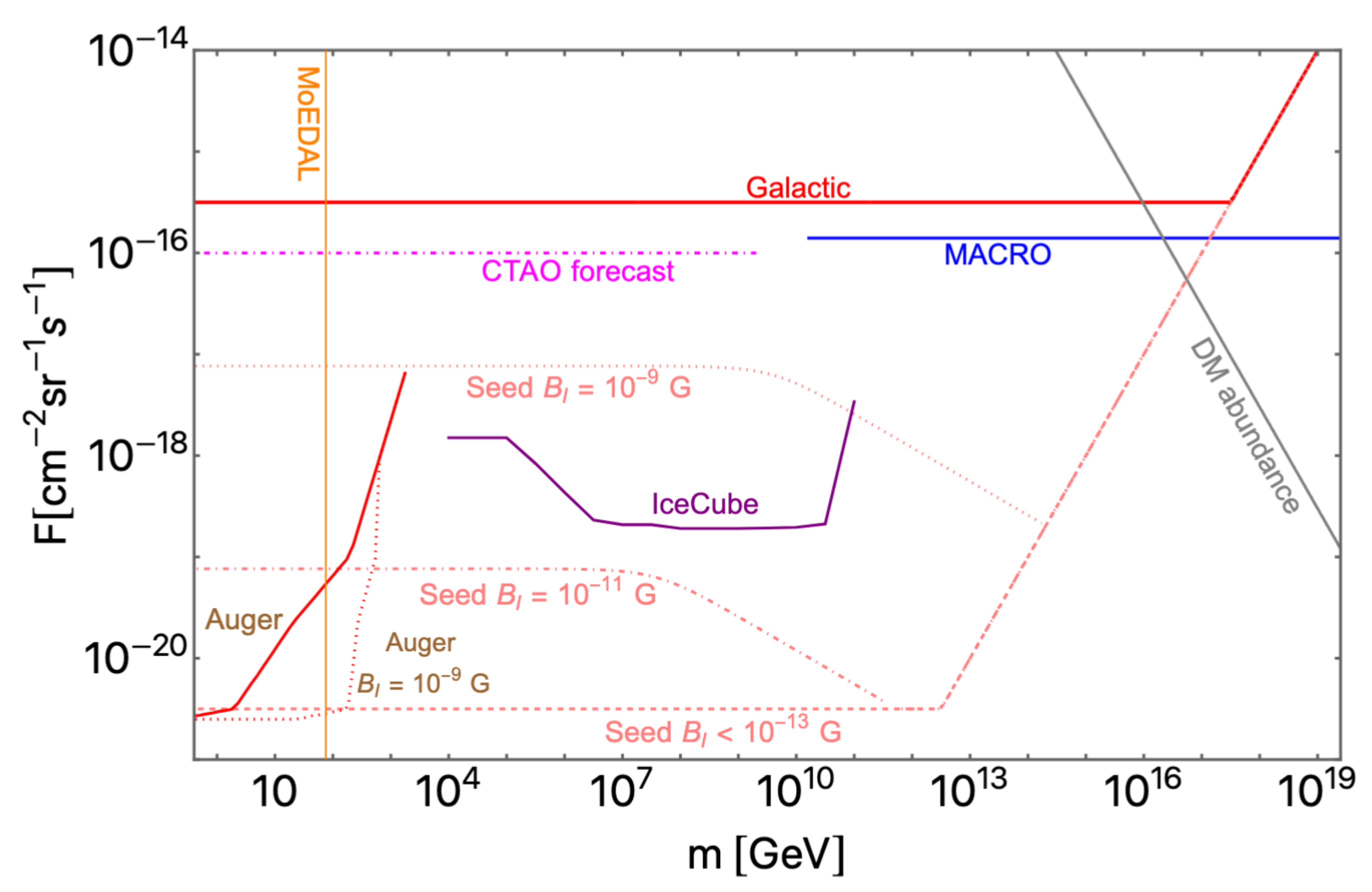


FOCUS ON IACTS



- 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

MM FLUX VS MASS LIMITS

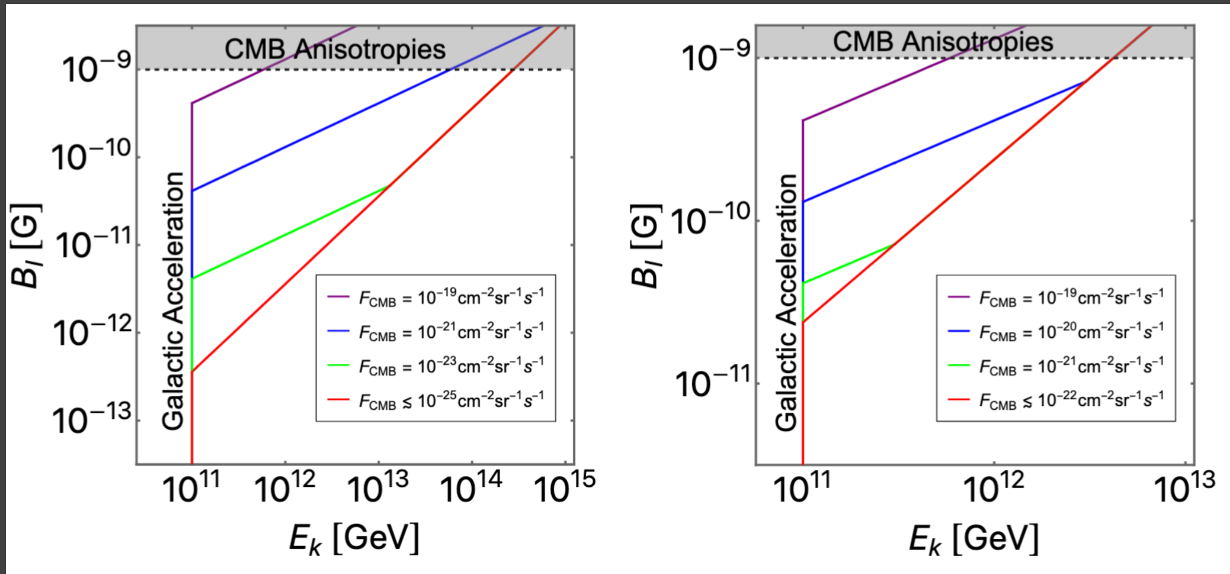


Several points:

- Galactic seed limits competitive depending on B
- Auger limits affected by IGMF acceleration
- CTAO forecast may bridge PAO and IceCube
- …

CONCLUSIONS

- In a coherent cosmic MFs scenario, MMs can be accelerated to ultra-relatitivistic speed depending on mass and flux.
- IGMF or GMF can dominate according to MM mass and flux
- IGMF flux limits can constrain IGMF



(a) $\lambda_I \gtrsim 1/H_0$. (b) $\lambda_I = 1$ Mpc.

Thanks!