SOME TOPICS OF FUNDAMENTAL PHYSICS ATTAINABLE WITH IACTS

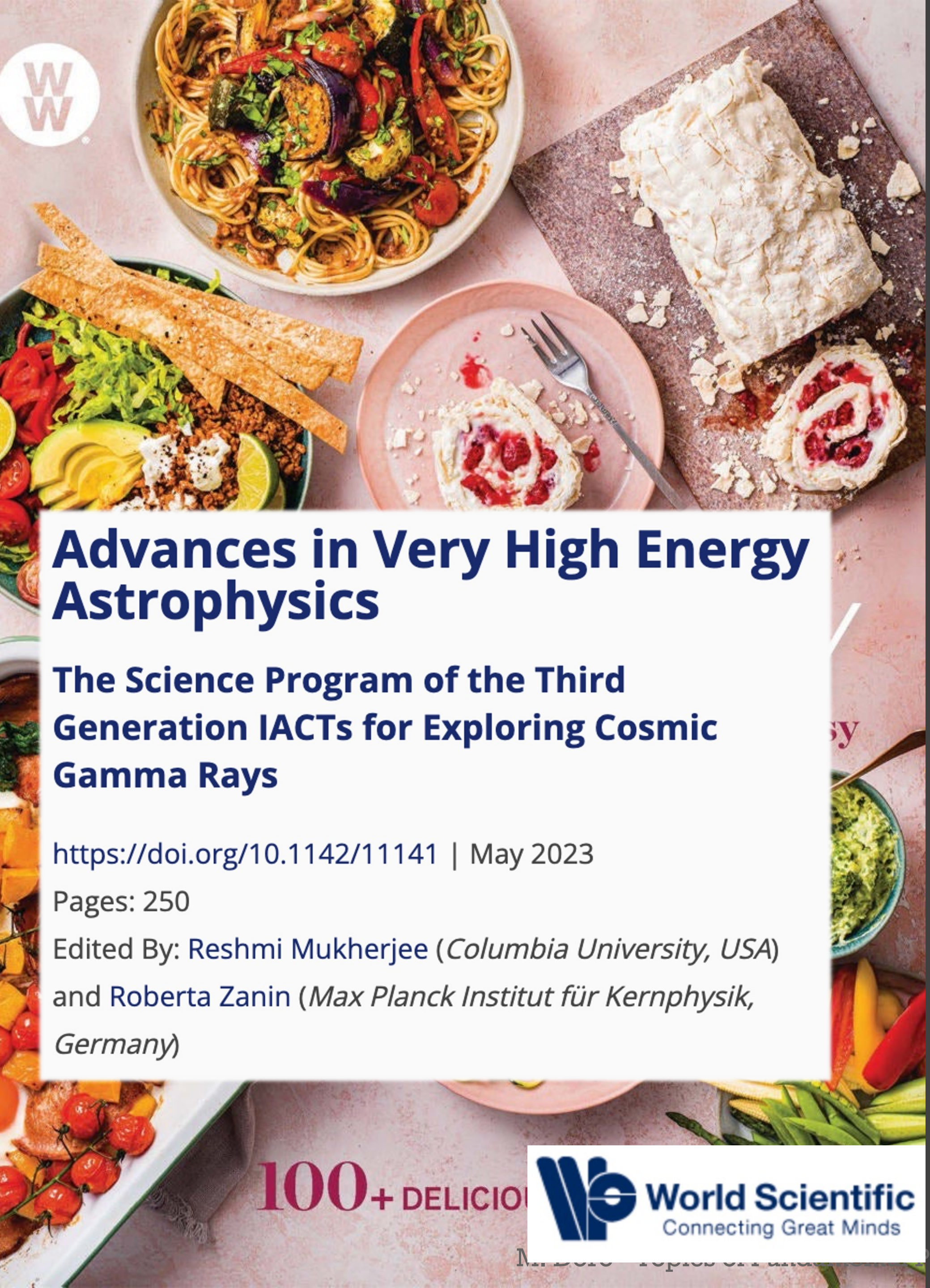
Michele Doro, University of Padova

michele.doro@unipd.it

OUTLINE

- Gamma-rays recap
- IACTs recap
- Finger food recipes: DM, ALP and more
- After dinner

FROM OUR COOKBOOK



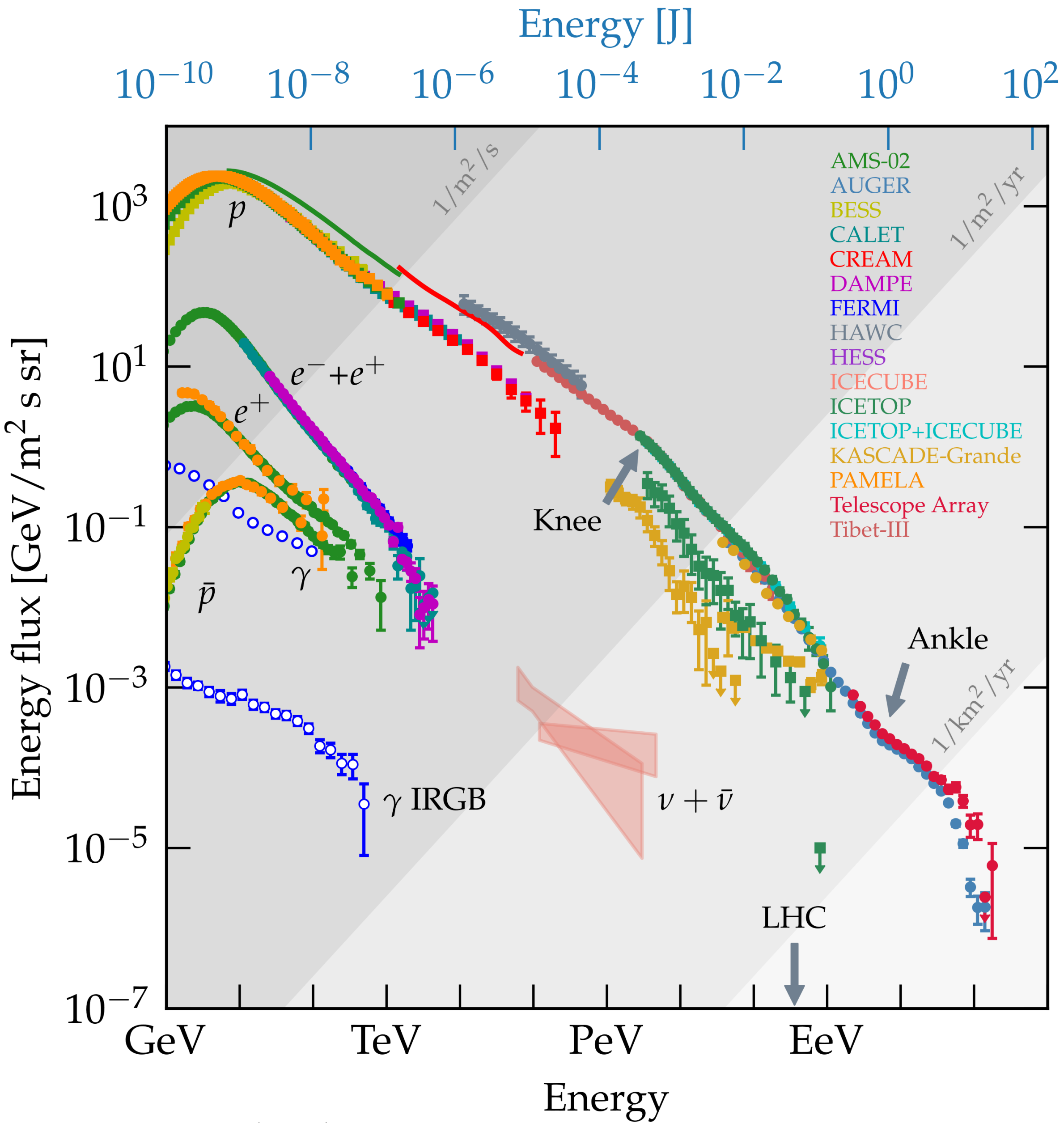
‘Dark matter and fundamental physics with IACTs’

https://arxiv.org/abs/2111.01198

#1 ASTROPHYSICAL GAMMA-RAY PROBES

Why they are best suited for fundamental physics (and can't possibly do that at CERN)

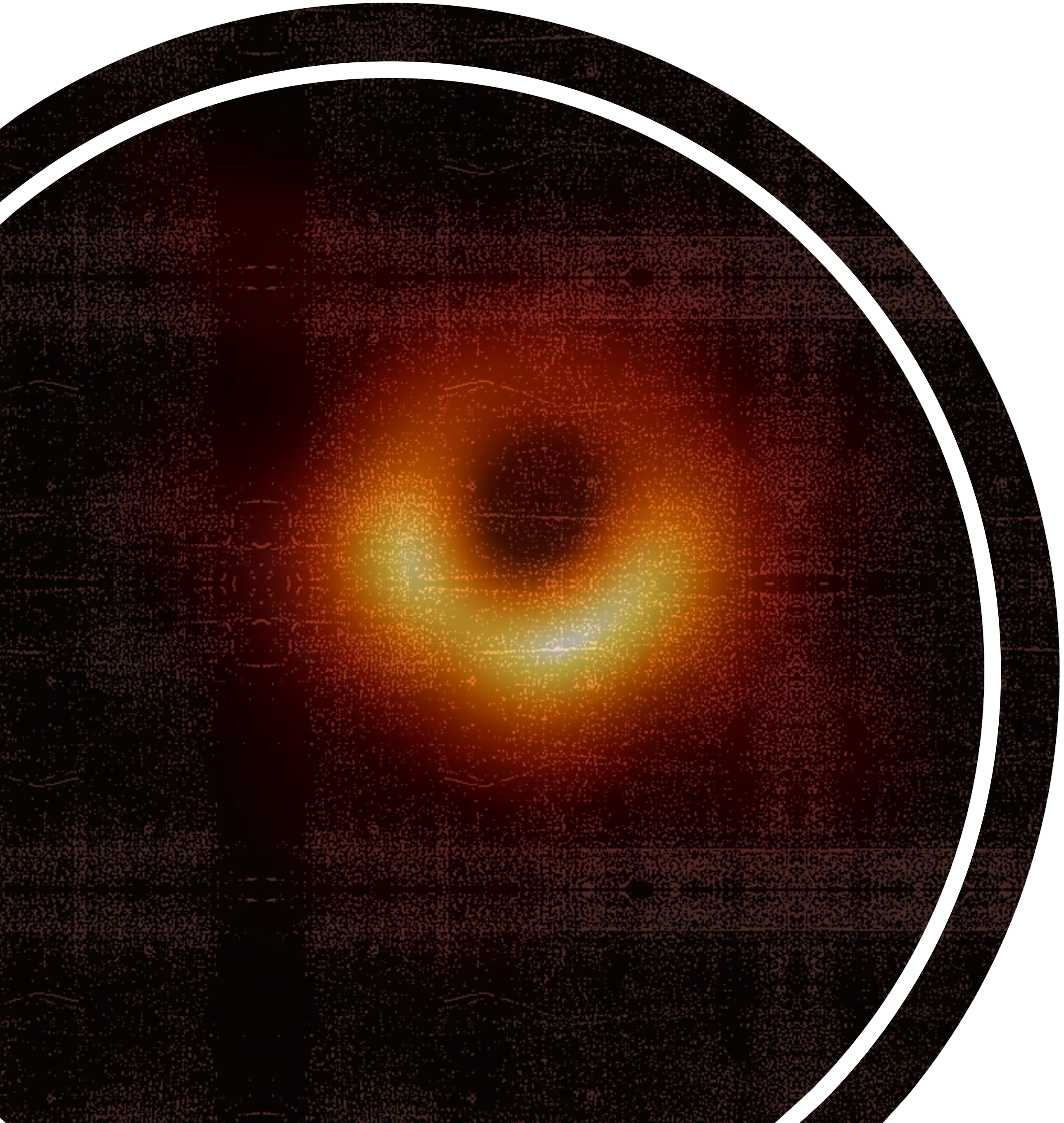
4



Evoli, Carmelo. (2018). The Cosmic-Ray Energy Spectrum. Zenodo. https://doi.org/10.5281/zenodo.2360277

1/ A NEVERENDING POWERFUL ENGINE

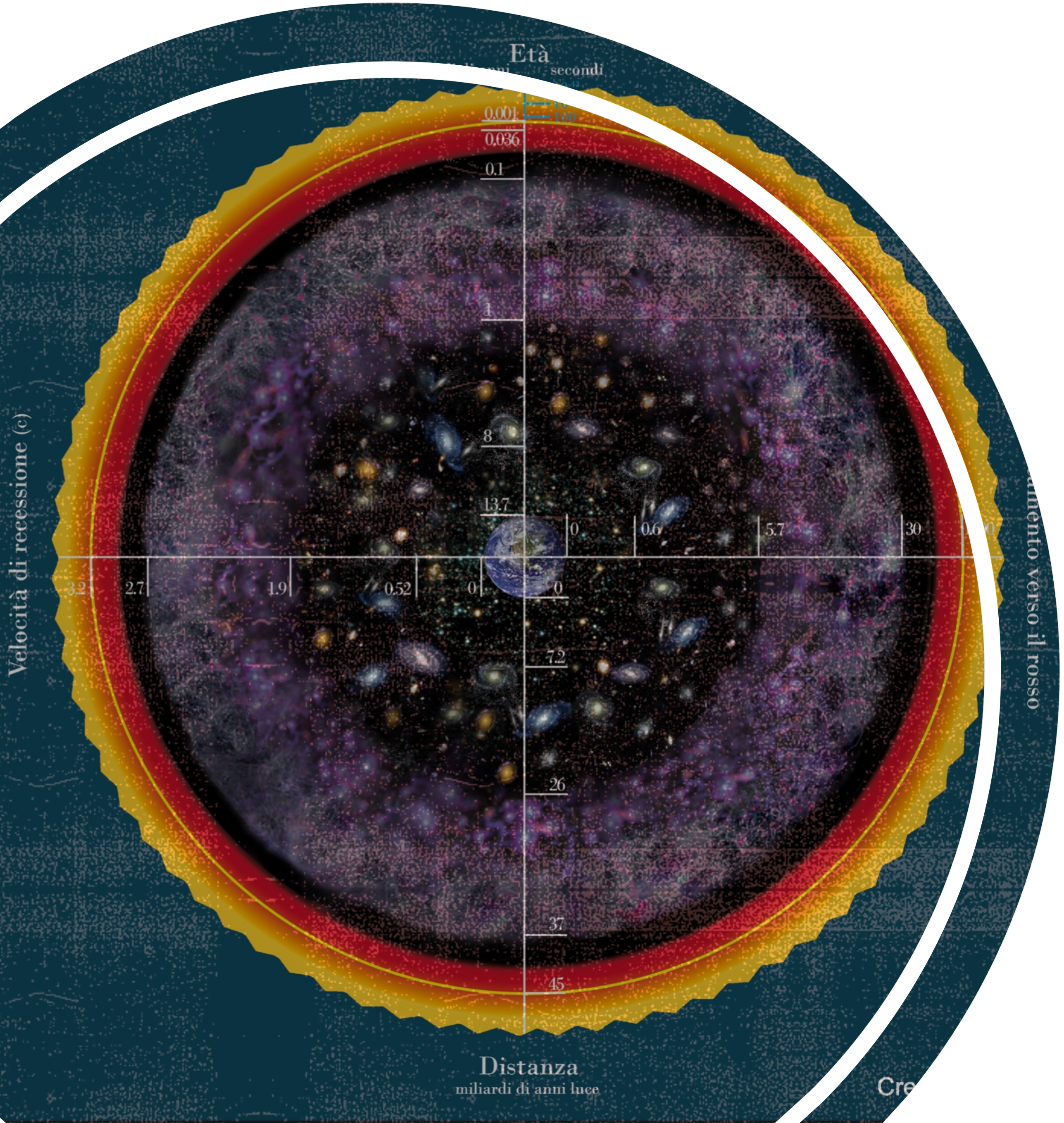
- Cosmic rays power up gamma rays
- Immense energy budget, e.g. a GRB can give 10^{53} erg/s
- Acceleration (and emission) for kyears



2/ PARTICLE INJECTION THROUGH GRAVITY

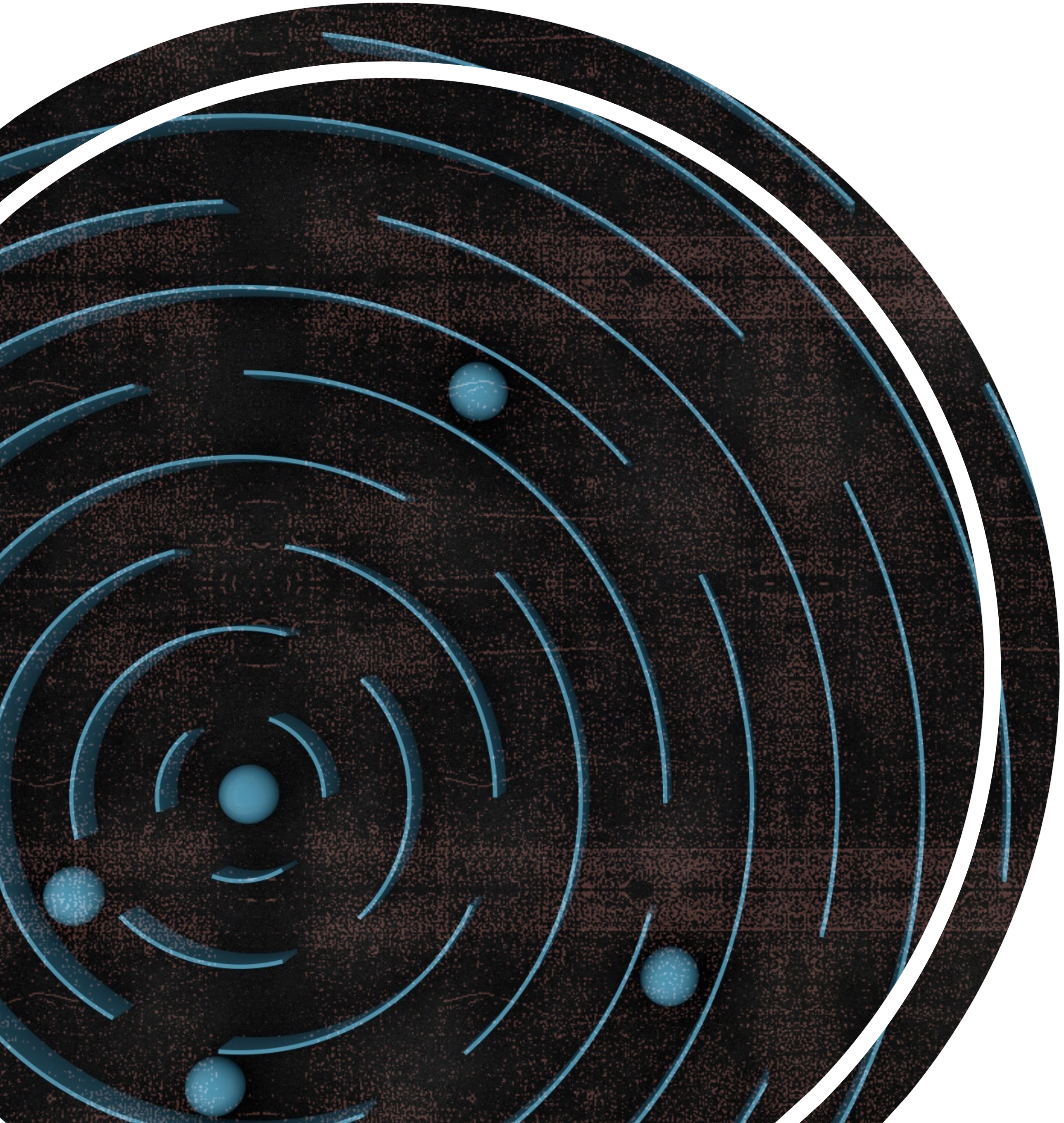
We can use the inevitable gravity infall

- Capture→ increase cross sections
- Energy budget → e.g. around BH, NS, GRB
- Efficient energy conversion



3/ A HUGE FIDUCIAL VOLUME

- Signals from CMB and further
- Several direct emitters but also vast ‘beam dumps’
  - particle and radiation fields everywhere

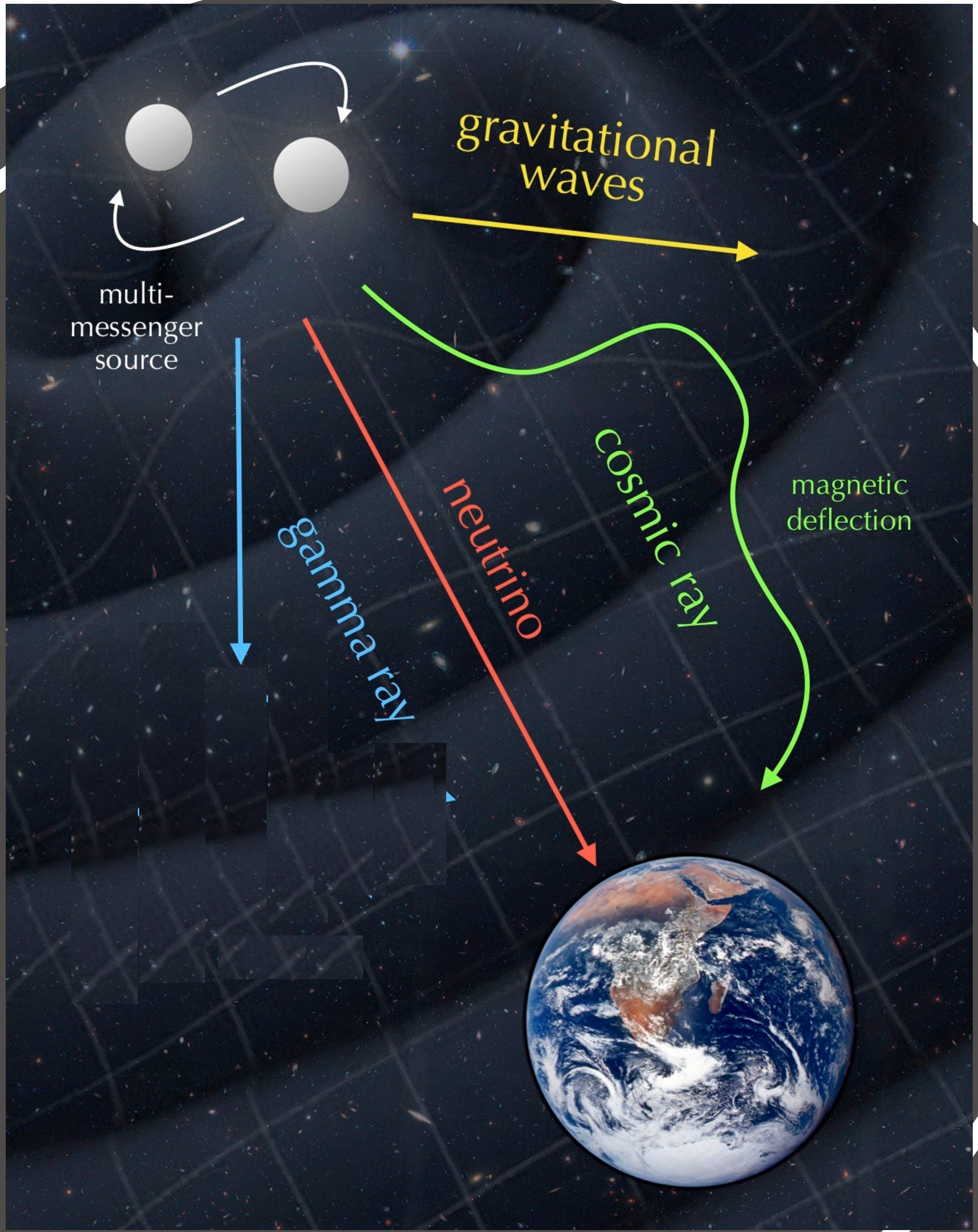


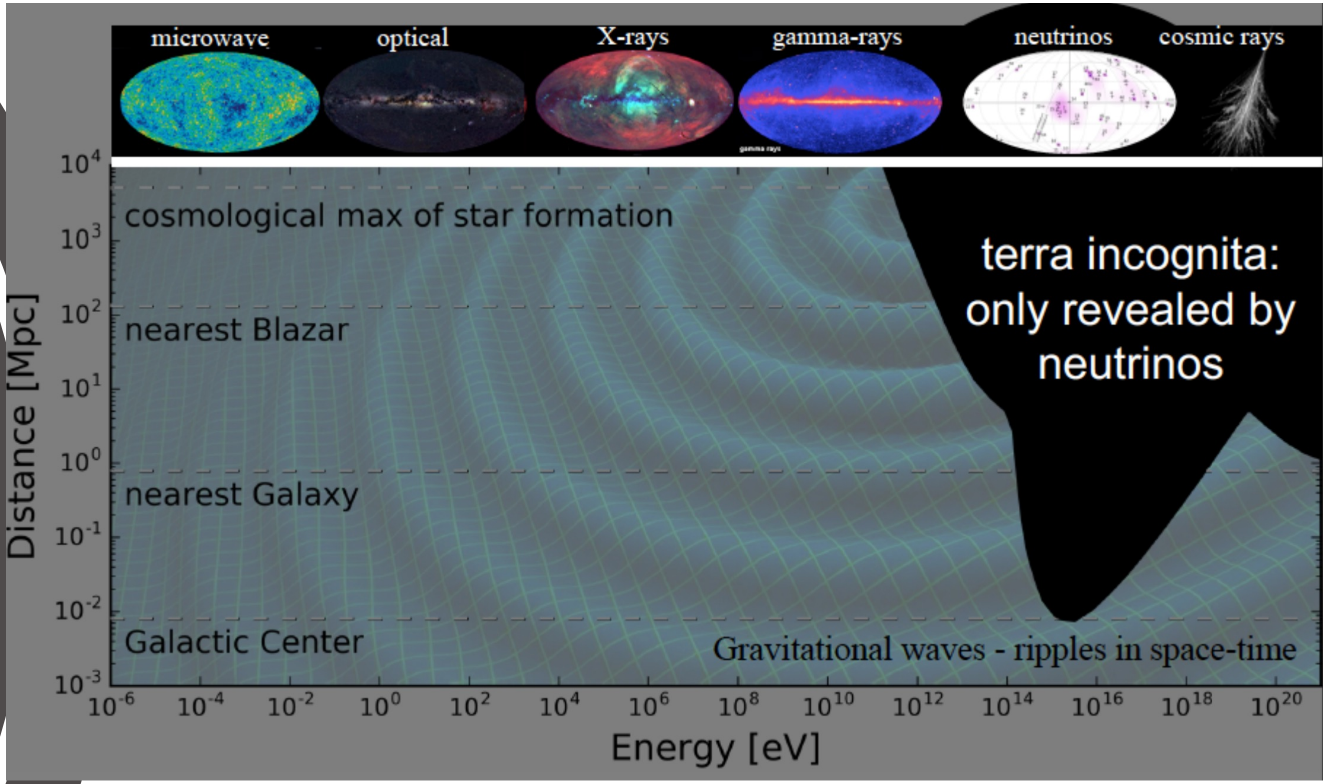
3/ TIME OF FLIGHT AND TRACKING

- We can trace particle interactions from similar targets at different times

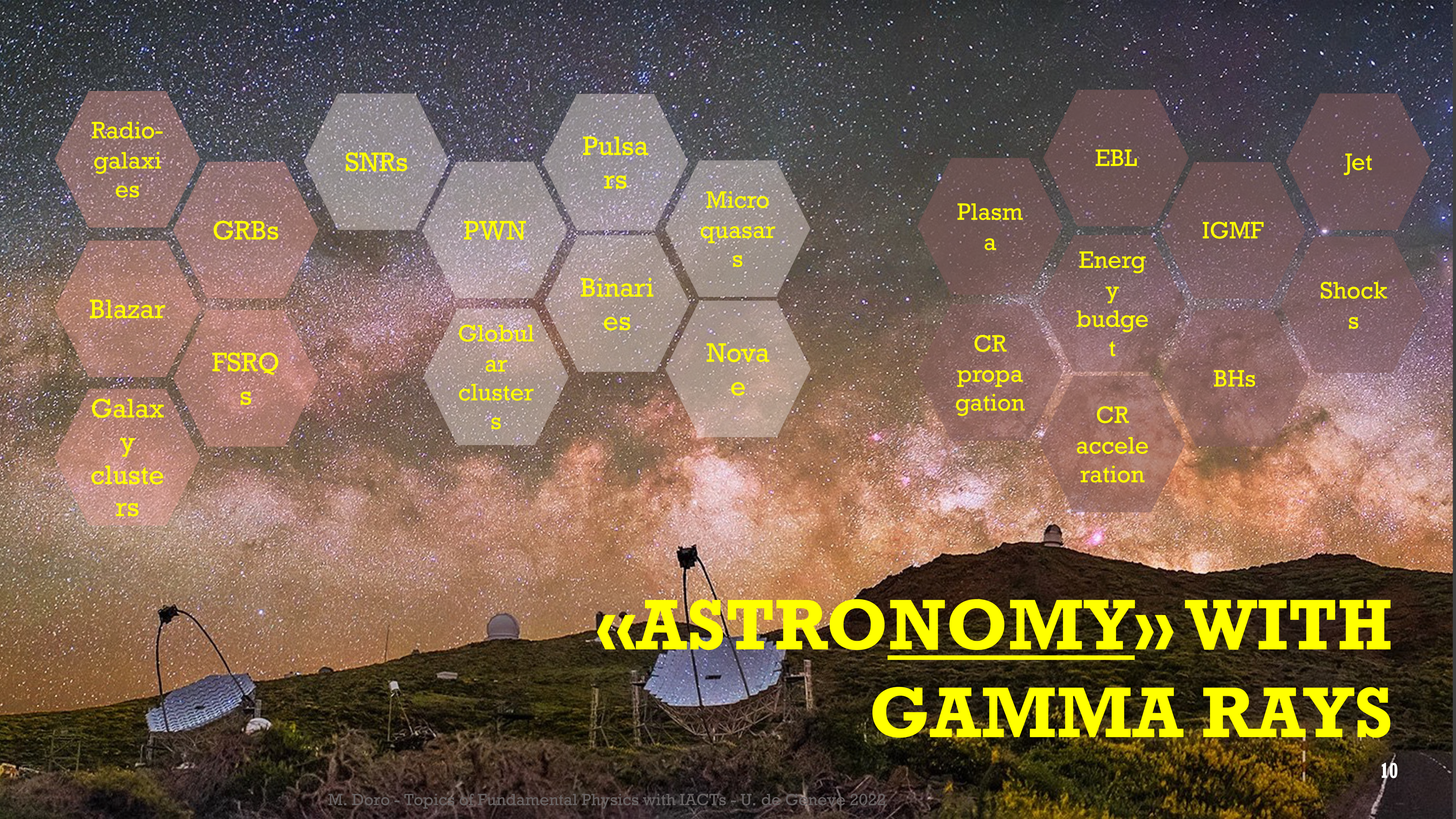
- For free:
  - back when Universe was not as it was now
  - Also events have time structure

4/ VARIOUS SENSING SYSTEM





F. Halzen


Radio-galaxies
GRBs
Blazar
FSRQs
Galaxy clusters
SNRs
PWN
Globular clusters
Pulsars
Binaries
Microquasars
Novae
Plasma
CR propagation
EBL
Energy budget
CR acceleration
IGMF
BHs
Jet
Shocks
«ASTRONOMY» WITH GAMMA RAYS

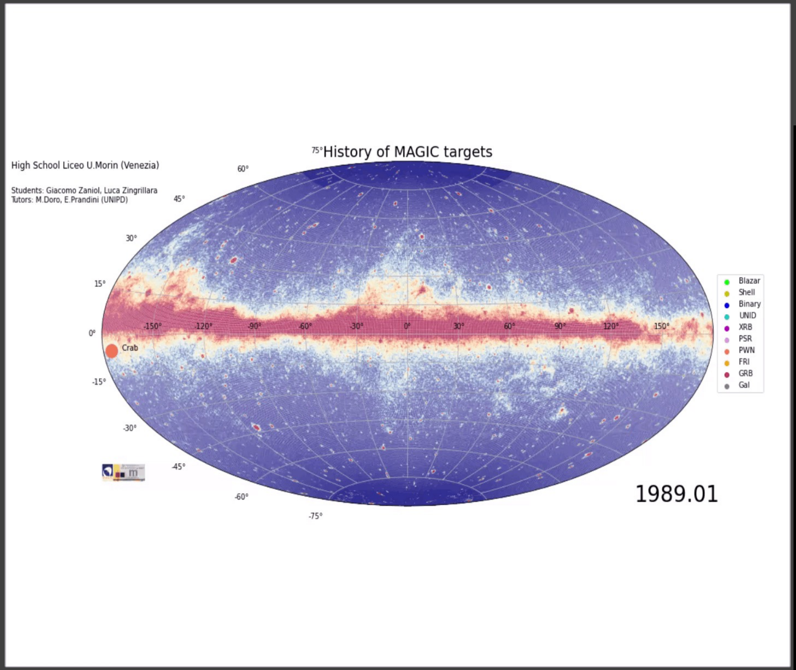
#2 IACTS

A great instrumental success of the last decade.

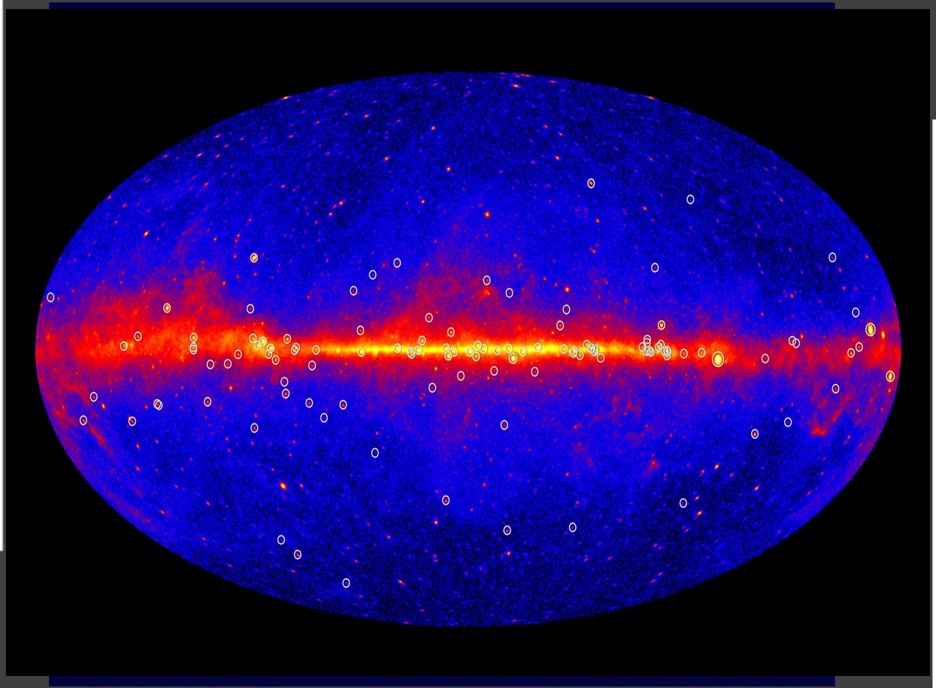
Some basic info to get the rest clearly

GAMMA-RAY SKY: "3 REVOLUTIONS IN 3 DECADES"

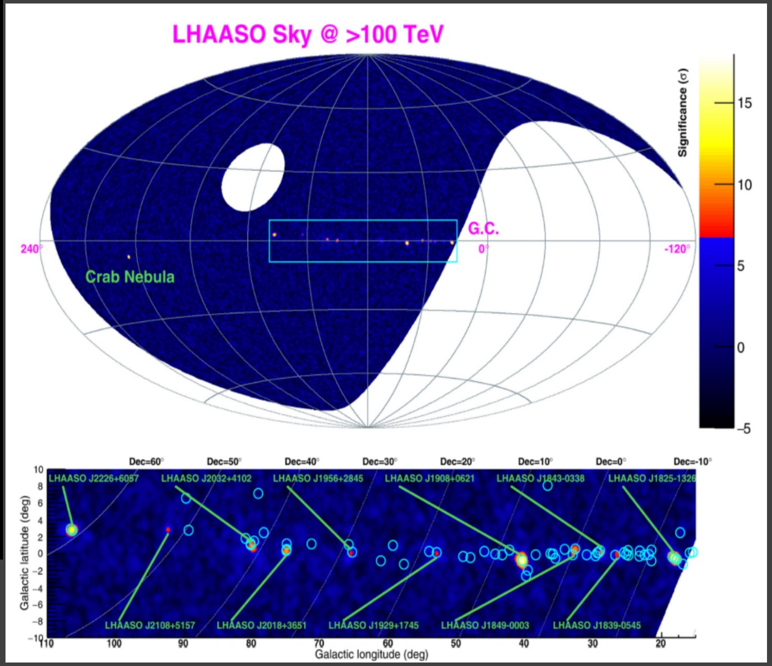
Cit. F. Aharonian



TeV revolution (IACT, 2000)



GeV revolution (AGILE, FERMI, 2010)



PeV revolution (LHAASO, 2020)

GAMMA RAY (COSMIC-RAY) DETECTORS

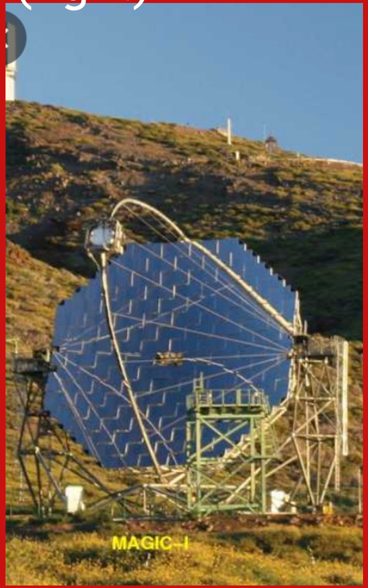
ENERGY

<MeV range
Balloons-borne detectors

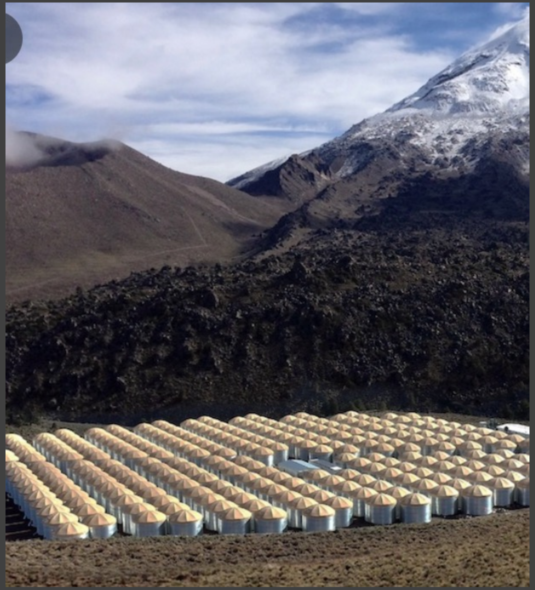
Just cosmic rays

MeV-GeV range
Satellite-borne detectors

TeV range
Ground-based detectors (light)



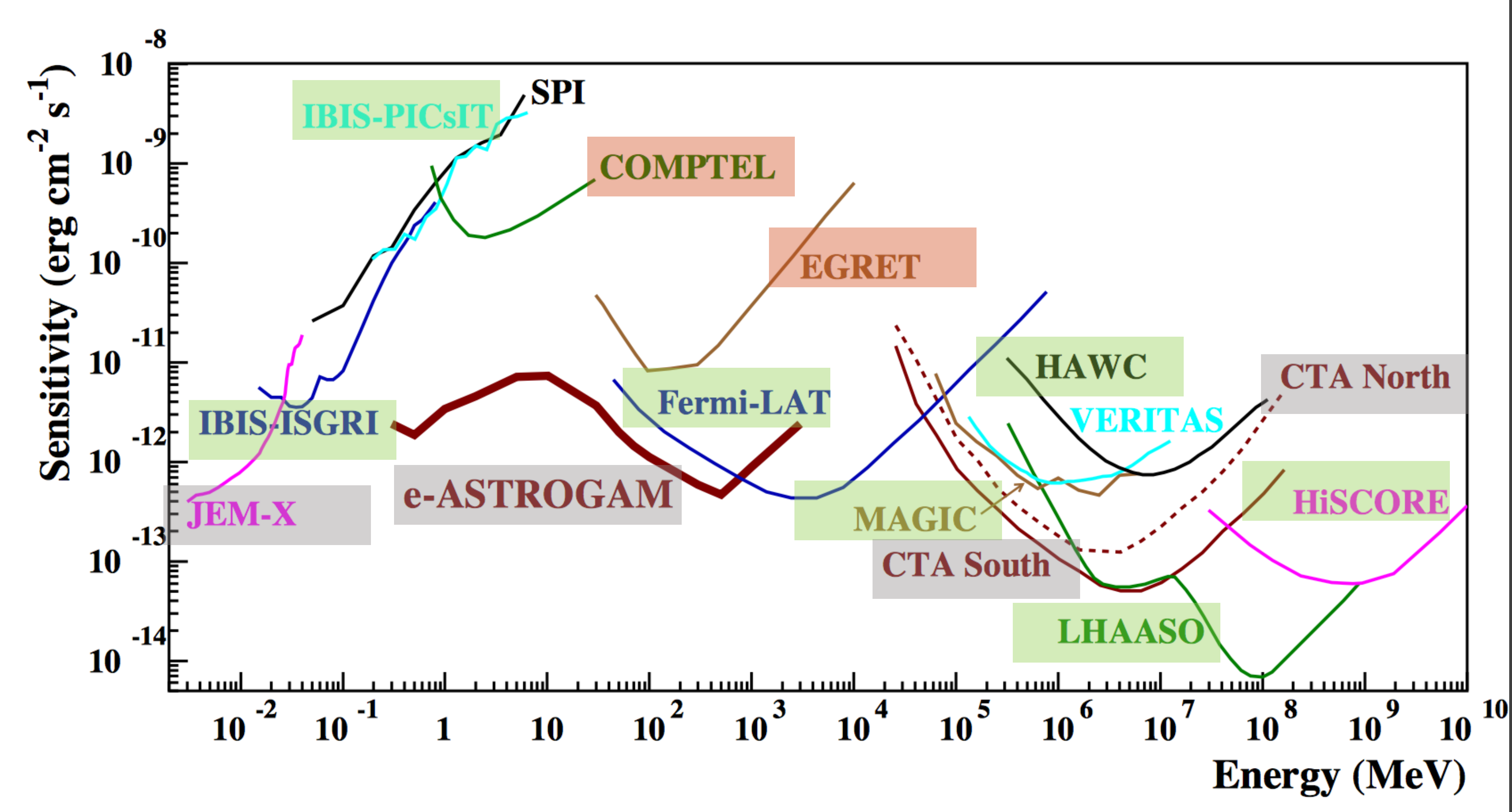
TeV-PeV range
Compact Ground-based detectors (particles)



>PeV range
Wide Ground-based detectors (particles)

IACTS AND FRIENDS

Plot from de Angelis+ https://arxiv.org/abs/1611.02232



Past

Present

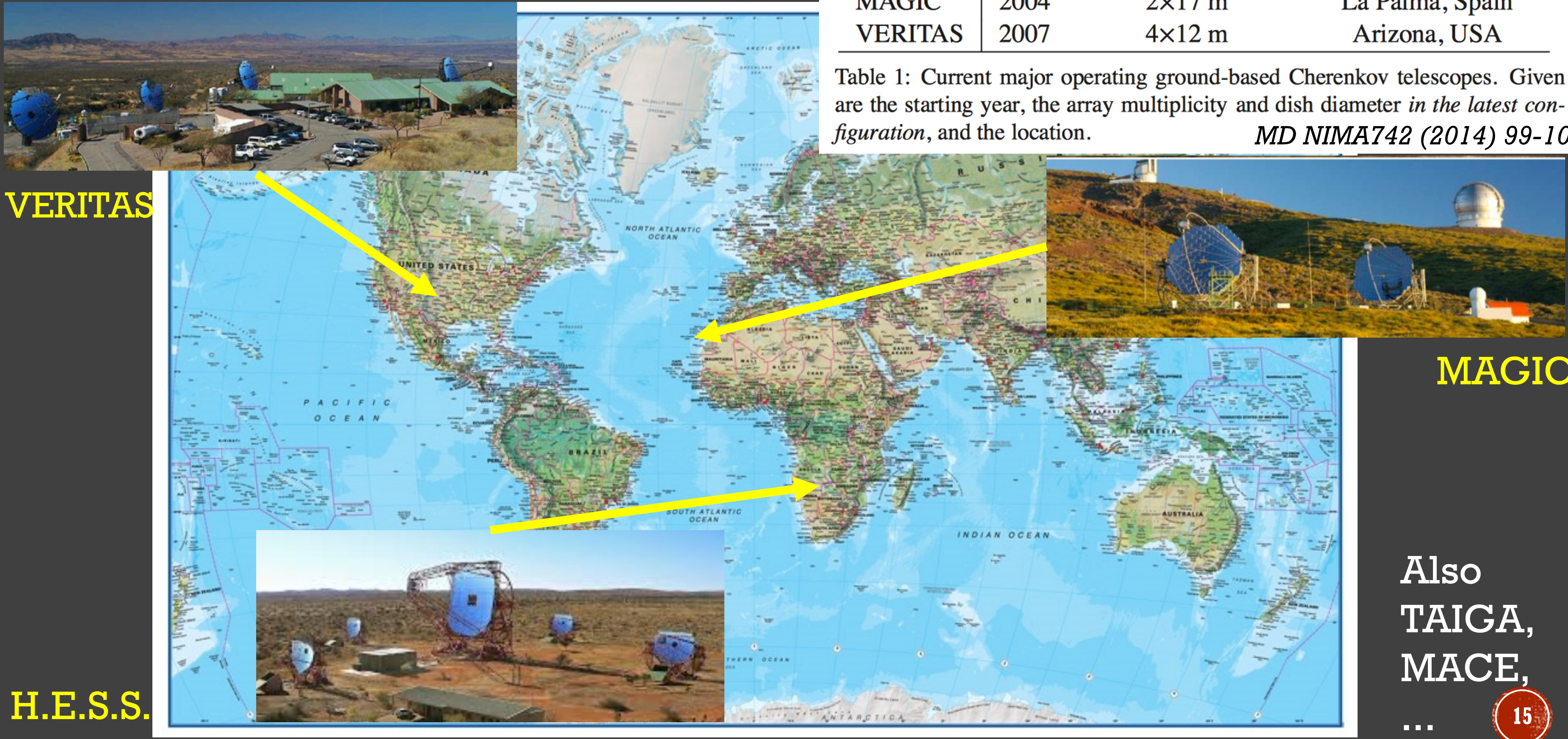
Future

MAJOR IACTS

IACT	Year	Nr. tels & diameter	Location
~~Whipple~~	~~1968~~	~~1×12 m~~	~~Arizona, USA~~
H.E.S.S.	2003	4×12 m+1×28 m	Gambserg, Namibia
MAGIC	2004	2×17 m	La Palma, Spain
VERITAS	2007	4×12 m	Arizona, USA

Table 1: Current major operating ground-based Cherenkov telescopes. Given are the starting year, the array multiplicity and dish diameter *in the latest configuration*, and the location.

MD NIMA742 (2014) 99-106



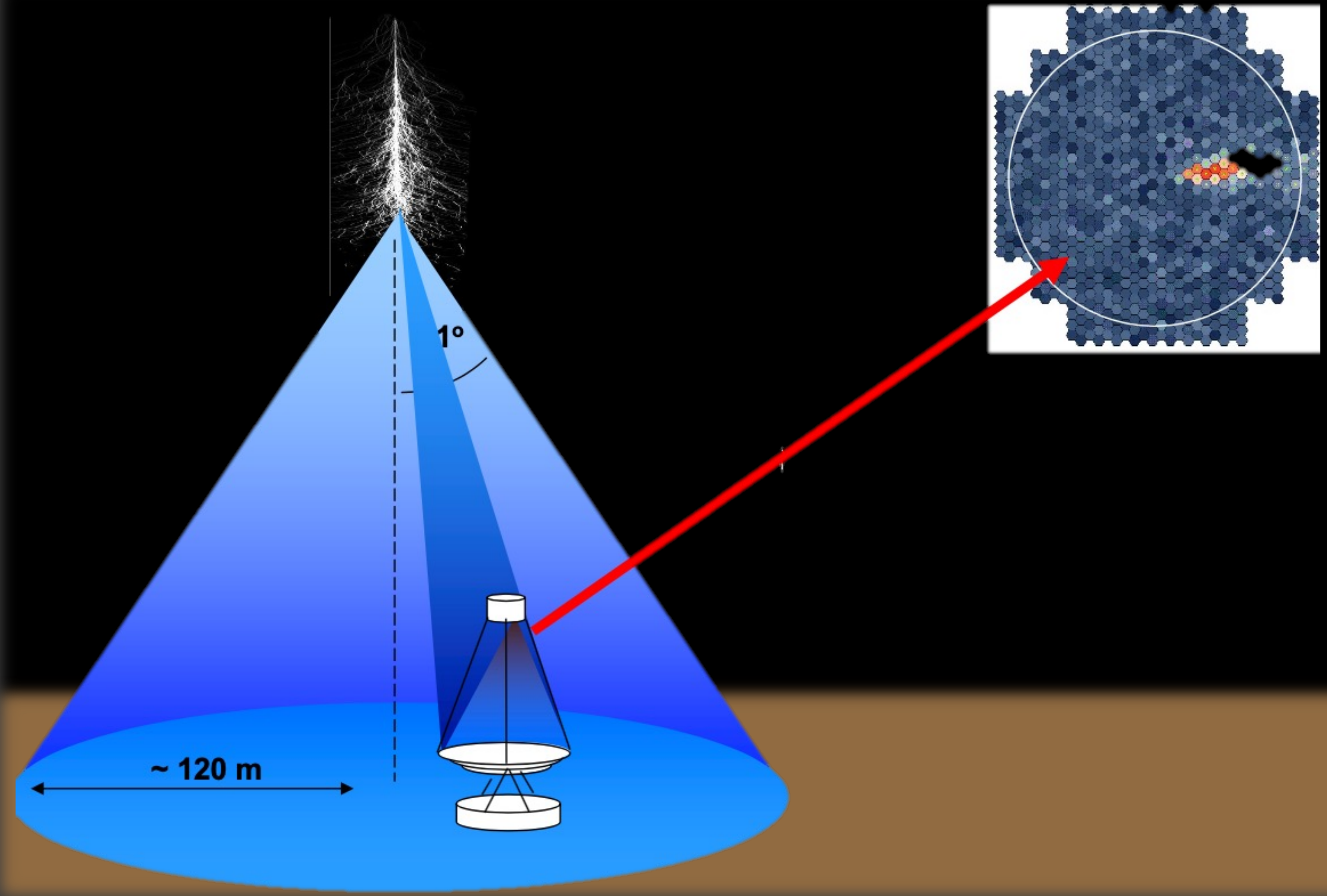
VERITAS

MAGIC

H.E.S.S.

Also TAIGA, MACE, …

#1 GROUND-BASED IMAGING CHERENKOV



1. Primary gamma-rays pair-produce after few radiation lengths at 10-20 km asl
2. Shower of electrons dies off after few interaction lengths: particle do not reach ground
3. Cherenkov light emitted by ‘superluminal’ electrons v>c/n
4. Cherenkov photons pool at ground

IACTS

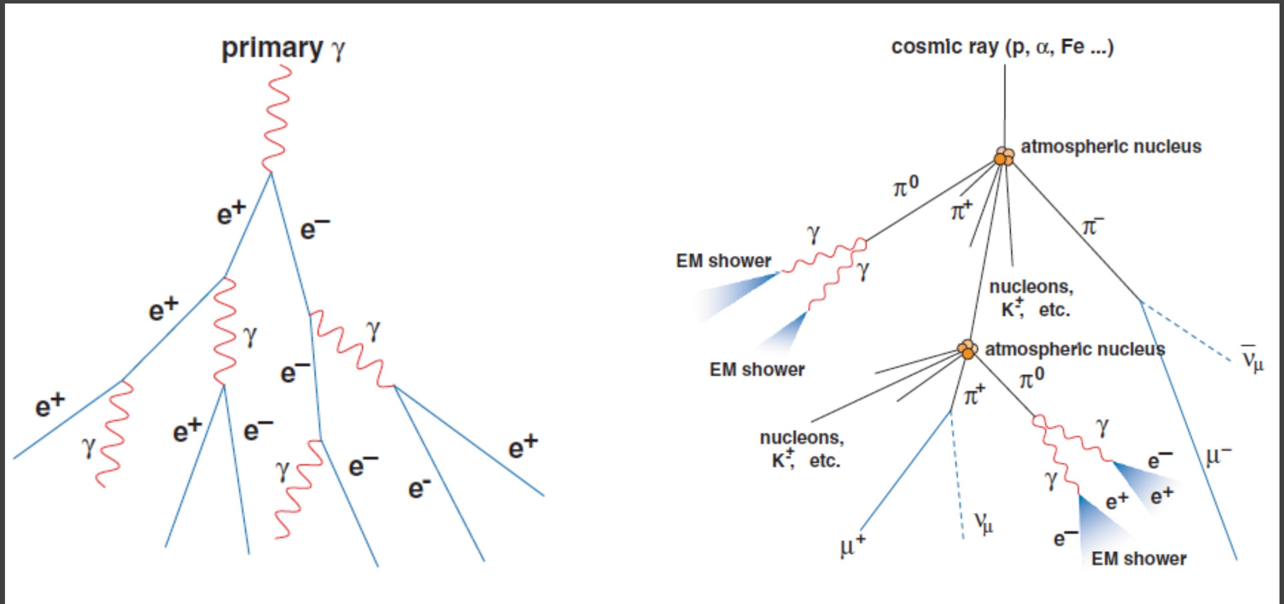
- **Array** of telescopes
  - **10^5** square meter effective area
  - **FOV** about 5 deg / **PSF** = 0.1 deg
  - Picosecond relative **timing** precision

- During data-taking, e.g., MAGIC acquires @ **200 Hz.**
  - *These are mostly hadronic showers. Gamma-rays are less than 1/1000 of this rate.*

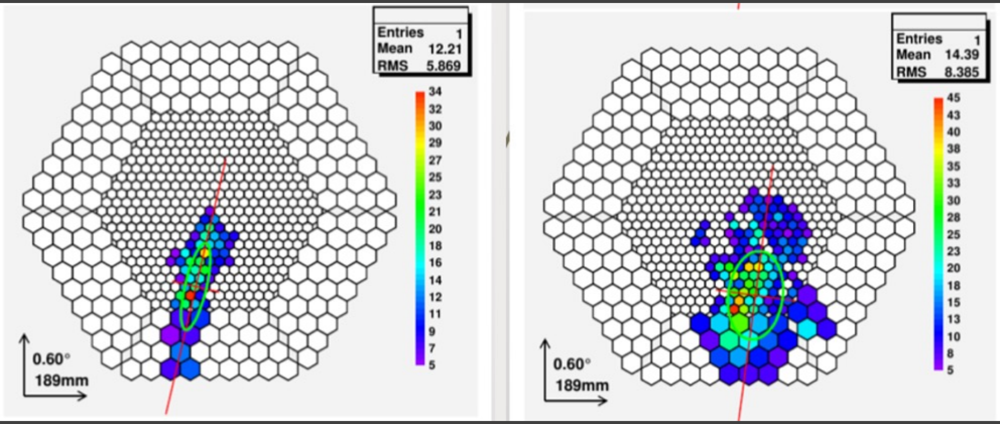
- During data reconstruction, **only 1/1000 hadronic events survive** (very energy dependent)

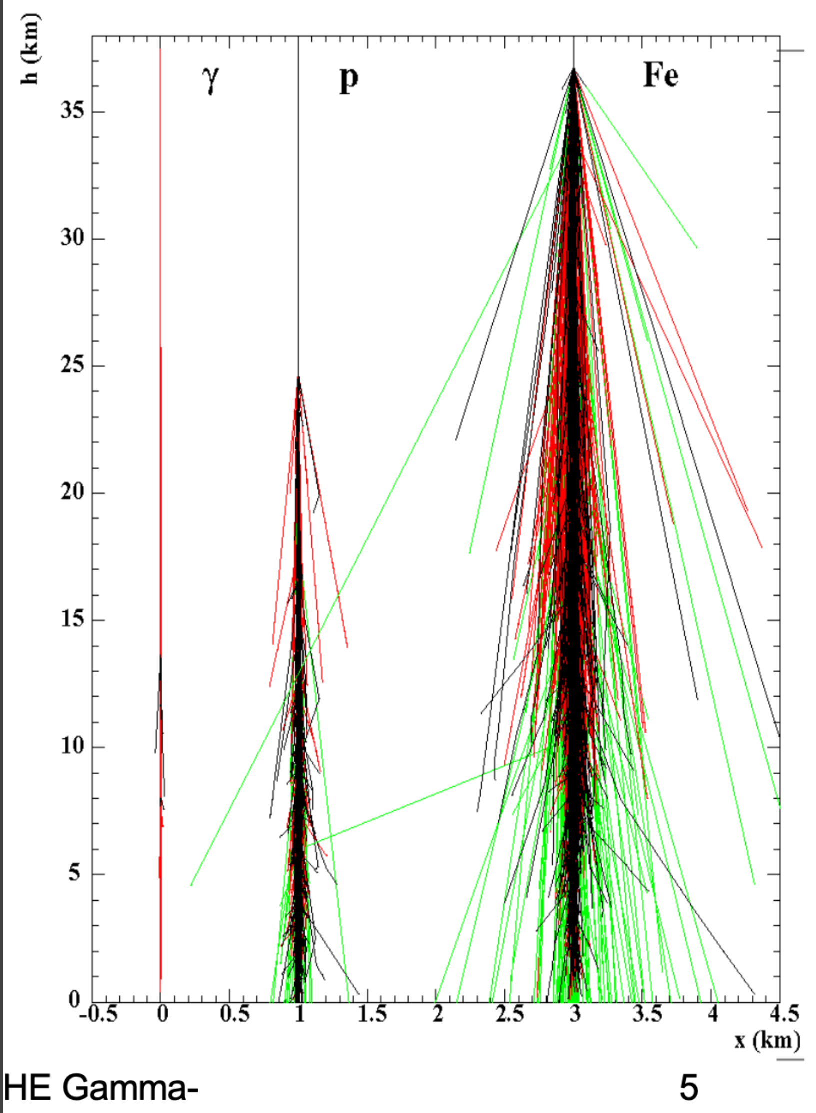
THERE'S MORE THAN JUST GAMMAS

- Ample bkg: 1 to 1000 gammas/protons

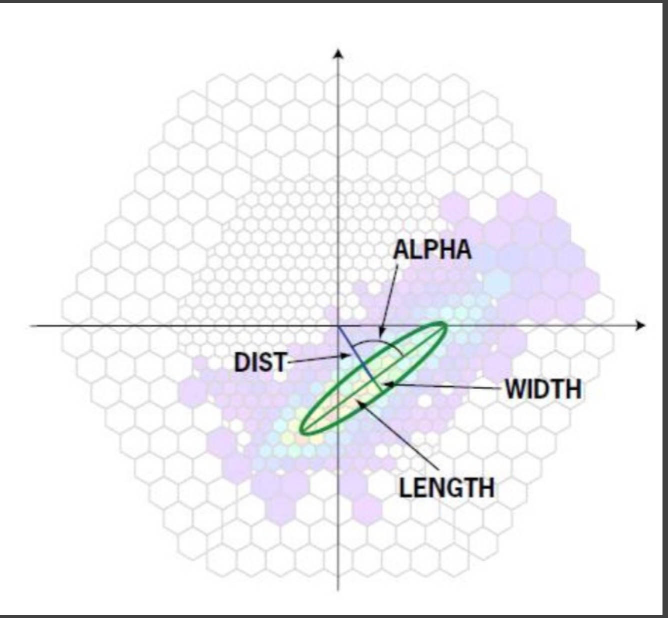


- Selection based on image momenta (Hillas criteria)





EVENT TAGGING

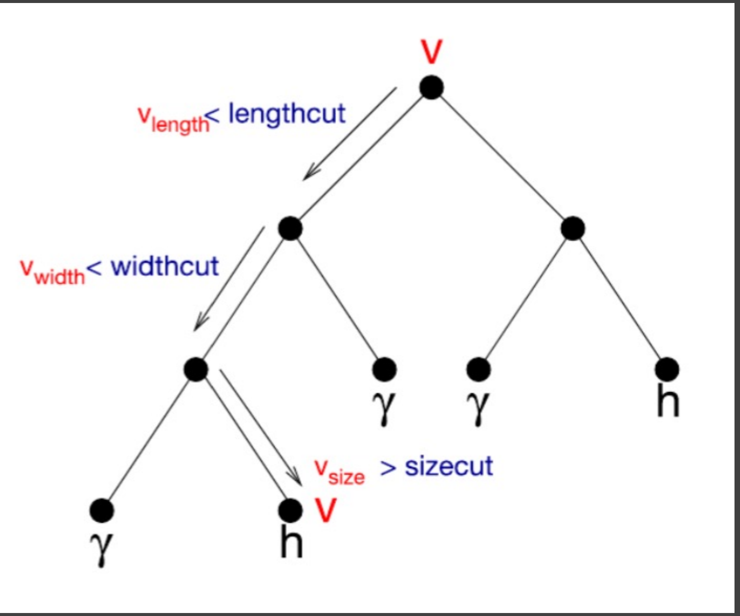


1

You "clean" the image and extract shape parameters

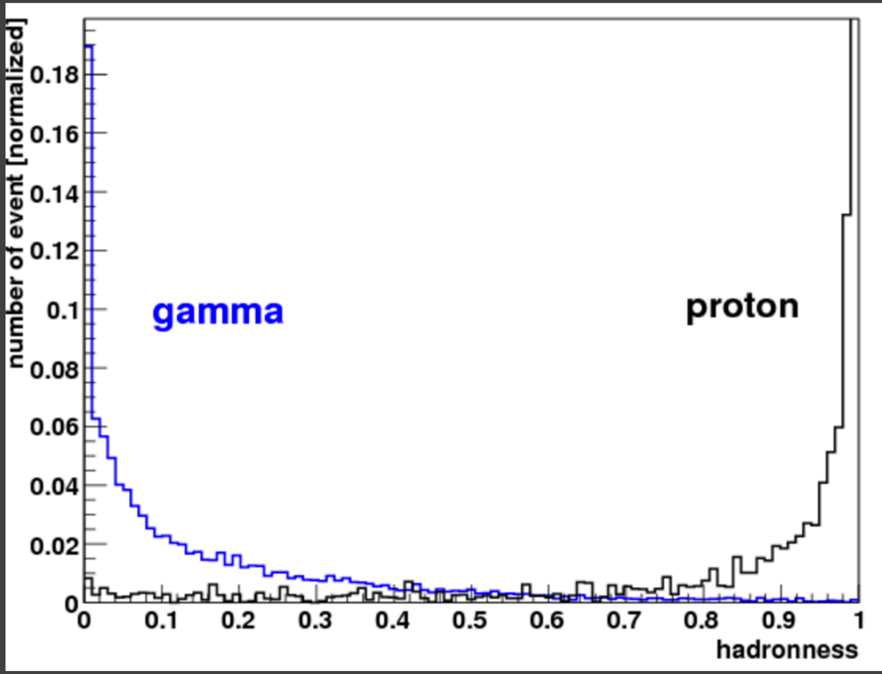
2

You make a Random Forest is a collection of decision trees, by comparing with Monte Carlo



3

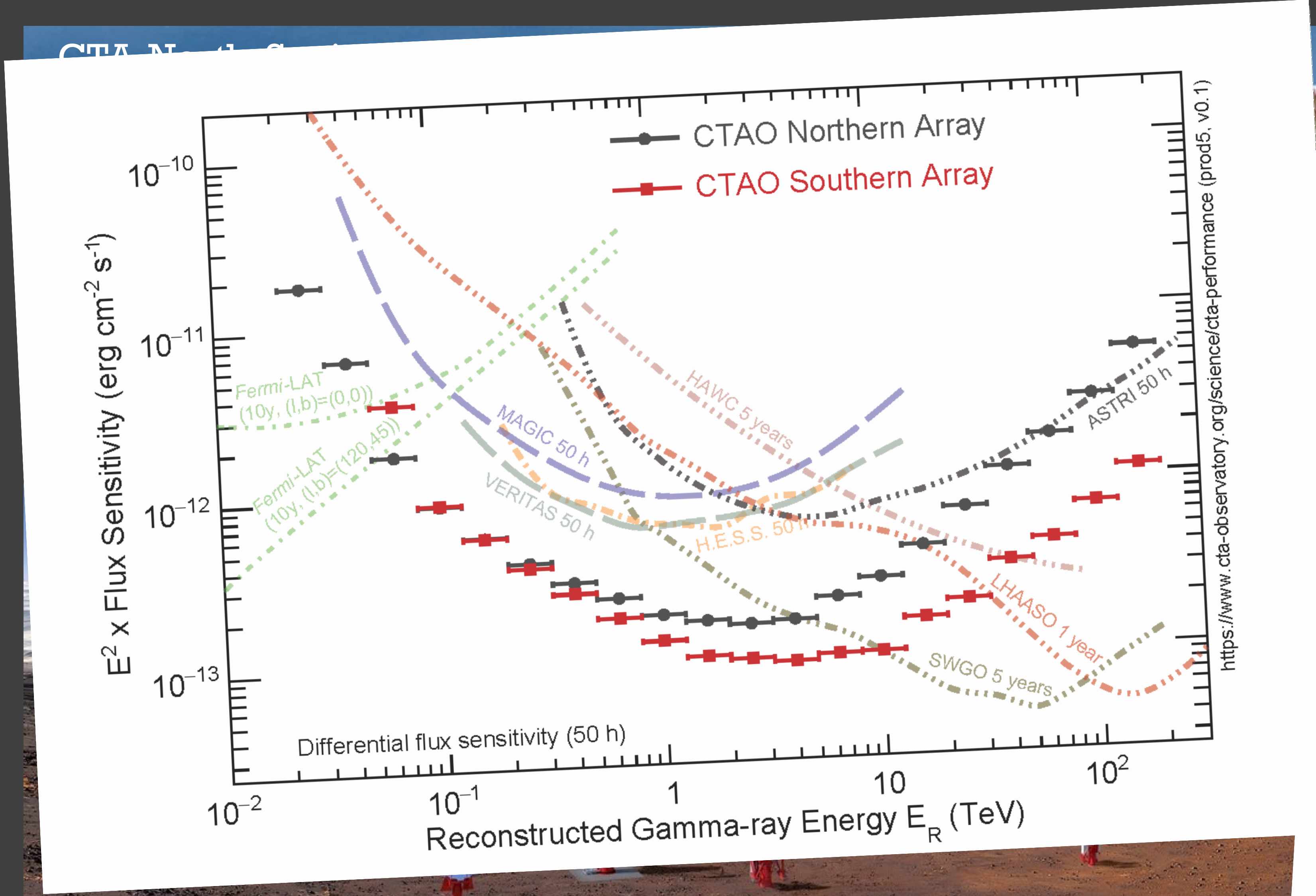
You have classified events according to "gammaness" and start to make cuts

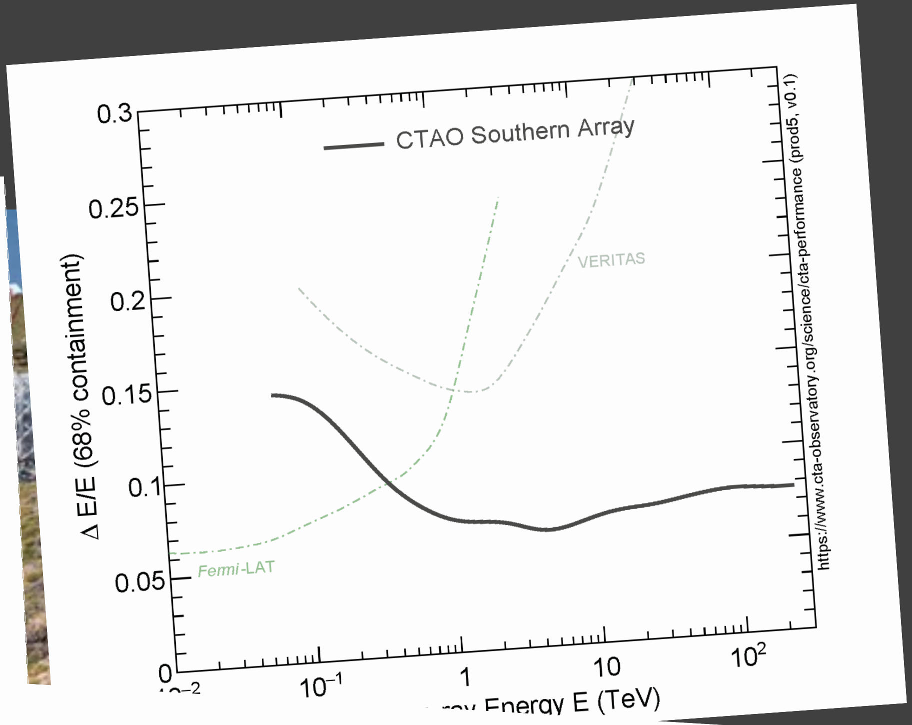


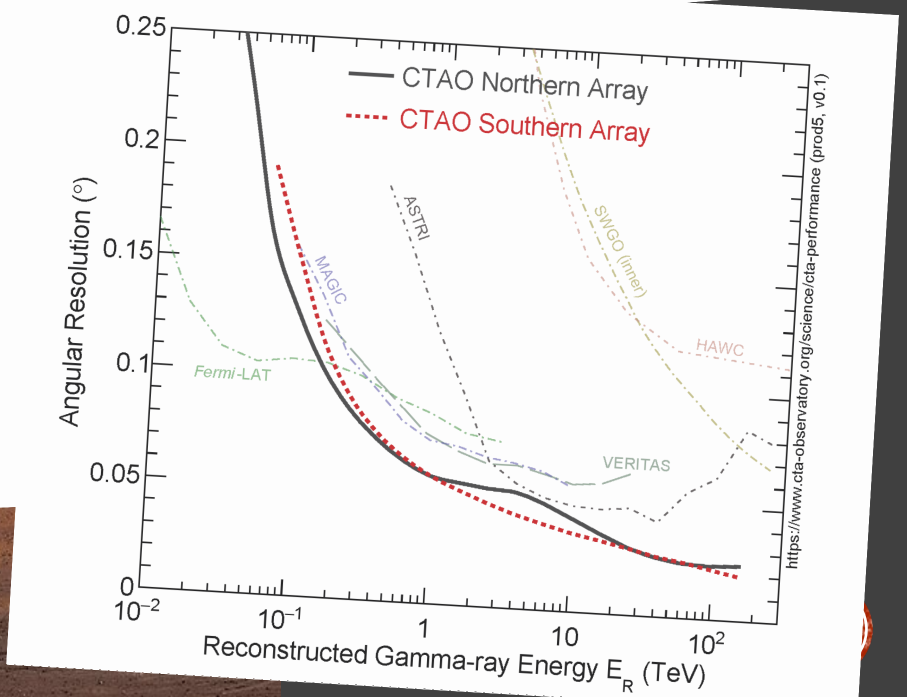
A LOT OF 'LEFTOVERS'

- **Background events rate**
  - One large night: 8h*3600s*200 = 5.76 MEvents
  - **Lifetime: 12 Gevents**
- In the case of MAGIC **these billions of events are safely stored** in the database
- ← **Is this really trash**? Can there be something peculiar in these leftovers?

THE CTA REVOLUTION







https://www.cta-observatory.org/science/ctao-performance

MENU FOR IACTS

- For large volumes, high energies
  - Dark Matter particles
  - Axion Like Particles
  - Magnetic monopoles and quark nuggets
  - Primordial black holes
  - UHE neutrinos
- For long distances, flares
  - LIV
- For synpoptic view
  - Hubble constant

DARK MATTER

Better served cold

A TEV DM CLAIM (2006)

TABLE II. The approximate energy distribution of events reported by CACTUS compared to the prediction from various annihilating dark matter scenarios. The CACTUS observations appear to be consistent with a ~500 GeV dark matter particle annihilating to $b\bar{b}$, a ~300 GeV dark matter particle annihilating to W^+W^-, or a ~200 GeV dark matter particle annihilating to $\tau^+\tau^-$. In the last column, the number of events which EGRET should have seen is given for each case.

	Total	>100 GeV	>125 GeV	EGRET
CACTUS observation	30 000	7000	4000	–
600 GeV, $b\bar{b}$	30 000	9000	5000	290
500 GeV, $b\bar{b}$	30 000	7700	3900	400
400 GeV, $b\bar{b}$	30 000	6000	2700	630
400 GeV, W^+W^-	30 000	9200	5100	280
300 GeV, W^+W^-	30 000	7100	3500	470
200 GeV, W^+W^-	30 000	4000	1300	1100
300 GeV, $\tau^+\tau^-$	30 000	15 000	9500	2.8
200 GeV, $\tau^+\tau^-$	30 000	9200	4200	7.2
150 GeV, $\tau^+\tau^-$	30 000	5000	1300	16

- CACTUS (Converted Atmospheric Cherenkov Telescope Using Solar-2) was a ACT located in California.
- It was originally a solar power plant called Solar Two, converted to an observatory in 2001, installing a 6 meter secondary that imaged the field onto an array of 80 PMTs.

Bergstrom Hooper Phys.Rev.D 73 (2006)

...AFTER ~15 YEARS

MD, M.A. Sanchez-Conde, M. Huetten. https://arxiv.org/abs/2111.01198

Table 8.1 – continued from previous page

Target	Year	Time [h]	IACT	Limit	Ref.
Segue 1	2008 – 2009	29.4	MAGIC‡	Ann.	Aleksić et al. (2011)
	2010 – 2011	(47.8)	VERITAS	A.+D.	Aliu et al. (2012)
	2010 – 2013	(92.0)		Ann.	Archambault et al. (2017)
	2010 – 2013	157.9	MAGIC	A.+D.	Aleksić et al. (2014)
				Ann.	Ahnen et al. (2016b)
	2010 – 2018	184	VERITAS	–	Kelley-Hoskins (2018)
Boötes 1	2009	14.3	VERITAS	Ann.	Acciari et al. (2010)
		(14.0)		Ann.	Archambault et al. (2017)
Coma Berenices	2010 – 2013	(8.6)	H.E.S.S.	Ann.	Abramowski et al. (2014)
	2010 – 2013	10.9		Ann.	Abdalla et al. (2018a)
	< 2018	37	VERITAS	–	Kelley-Hoskins (2018)
	2018	50.2	MAGIC	Ann.	Maggio et al. (2021)
Fornax	2010	6.0	H.E.S.S.	Ann.	Abramowski et al. (2014)
				Ann.	Abdalla et al. (2018a)
Ursa Major II	2014 – 2016	94.8	MAGIC	Ann.	Ahnen et al. (2018a)
Triangulum II*	2014 – 2016	62.4	MAGIC	Ann.	Acciari et al. (2020)
	< 2018	181	VERITAS	–	Kelley-Hoskins (2018)
Segue II	< 2018	19	VERITAS	–	Kelley-Hoskins (2018)
Canes Ven I	< 2018	14	VERITAS	–	Kelley-Hoskins (2018)
Canes Ven II	< 2018	14	VERITAS	–	Kelley-Hoskins (2018)
Hercules	< 2018	13	VERITAS	–	Kelley-Hoskins (2018)
Sextans	< 2018	13	VERITAS	–	Kelley-Hoskins (2018)
Draco II	< 2018	10	VERITAS	–	Kelley-Hoskins (2018)
Leo I	< 2018	7	VERITAS	–	Kelley-Hoskins (2018)
Leo II	< 2018	16	VERITAS	–	Kelley-Hoskins (2018)
Leo IV	< 2018	3	VERITAS	–	Kelley-Hoskins (2018)
Leo V	< 2018	3	VERITAS	–	Kelley-Hoskins (2018)
Reticulum II	2017 – 2018	18.3	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Tucana II	2017 – 2018	16.4	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Tucana III*	2017 – 2018	23.6	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Tucana IV*	2017 – 2018	12.4	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Grus II*	2018	11.3	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Dark satellites					
1FGL J2347.3+0710	2010	8.3	MAGIC	–	Nieto et al. (2011a)
1FGL J0338.8+1313	2010-2011	10.7	MAGIC	–	Nieto et al. (2011a)
2FGL J0545.6+6018	2013-2015	8.5	VERITAS	Ann.	Nieto (2015)
2FGL J1115.0-0701	2013-2015	13.8	VERITAS	Ann.	Nieto (2015)
H3FHL J0929.2-4110	2018-2019	7.8	H.E.S.S.†	Ann.	Abdallah et al. (2021a)
3FHL J1915.2-1323	2018 – 2019	3.0	H.E.S.S.†	Ann.	Abdallah et al. (2021a)
3FHL J2030.2-5037	2018 – 2019	8.8	H.E.S.S.†	Ann.	Abdallah et al. (2021a)
3FHL J2104.5+2117	2018 – 2019	5.5	H.E.S.S.†	Ann.	Abdallah et al. (2021a)

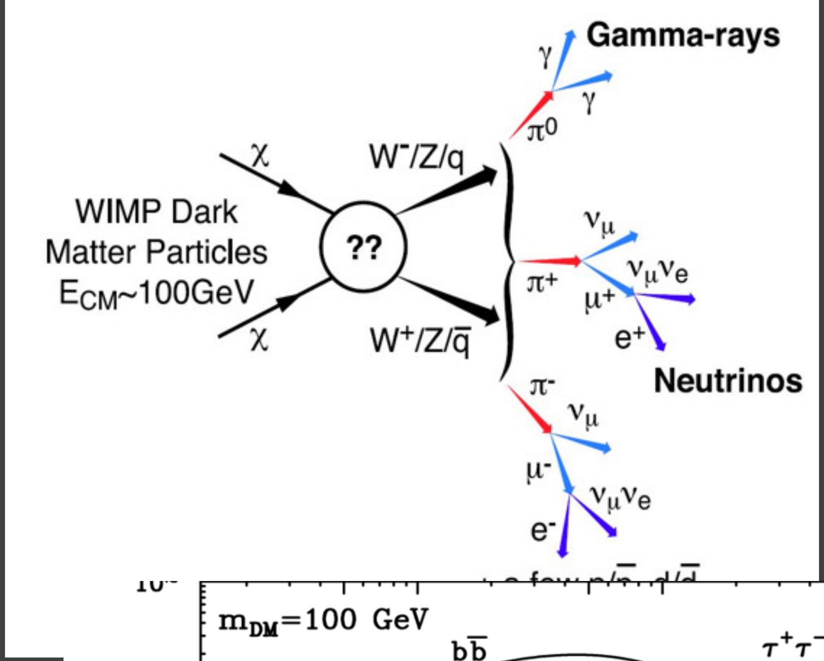
Table 8.1 – Continued on next page

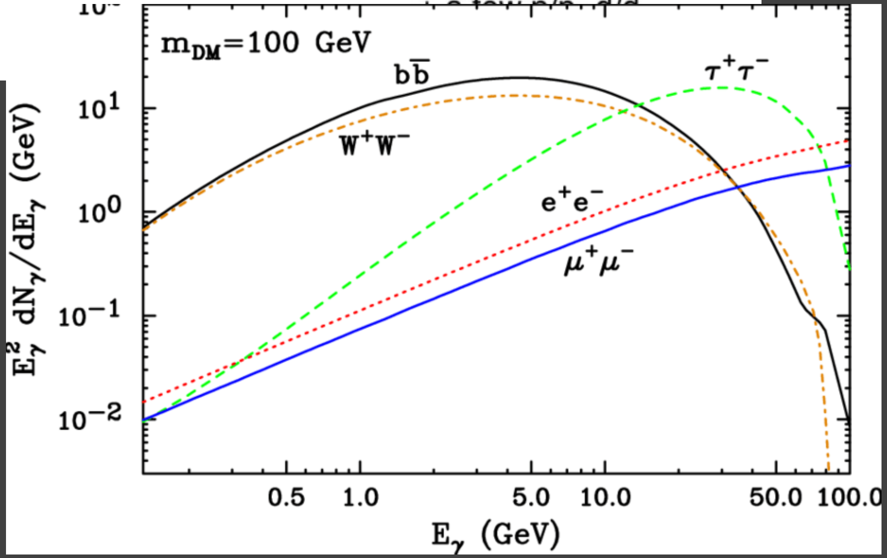
Target	Year	Time [h]	IACT	Limit	Ref.
The Milky Way central region & halo					
MW Centre	2004	(48.7)	H.E.S.S.	Ann.	Aharonian et al. (2006)
MW Inner Halo	2004 – 2008	(112)	H.E.S.S.	Ann.	Abramowski et al. (2011)
	2010	9.1		Ann.	Abramowski et al. (2015)
	2004 – 2014	254		Ann.	Abdallah et al. (2016)
	2014 – 2020	546	H.E.S.S.†	Ann.	Montanari et al. (2021)
MW Outer Halo	2018	10	MAGIC	Decay	Ninci et al. (2019)
Dwarf Satellite Galaxies					
Draco	2003	7.4	Whipple	Ann.	Wood et al. (2008)
	2007	7.8	MAGIC‡	Ann.	Albert et al. (2008b)
	2007	(18.4)	VERITAS	Ann.	Acciari et al. (2010)
	2007 – 2013	(49.8)		Ann.	Archambault et al. (2017)
	2007 – 2018	114		–	Kelley-Hoskins (2018)
	2018	52.6	MAGIC	Ann.	Maggio et al. (2021)
Ursa Minor	2003	7.9	Whipple	Ann.	Wood et al. (2008)
	2007	(18.9)	VERITAS	Ann.	Acciari et al. (2010)
	2007 – 2013	(60.4)		Ann.	Archambault et al. (2017)
	2007 – 2018	161		–	Kelley-Hoskins (2018)
Sagittarius	2006	(11.0)	H.E.S.S.	Ann.	Aharonian et al. (2008)
	2006 – 2012	90		Ann.	Abramowski et al. (2014)
	2006 – 2012	(85.5)		Ann.	Abdalla et al. (2018a)
Canis Major	2006	9.6	H.E.S.S.	Ann.	Aharonian et al. (2009a)
Willman 1	2007 – 2008	13.7	VERITAS	Ann.	Acciari et al. (2010)
		(13.6)		Ann.	Archambault et al. (2017)
	2008	15.5	MAGIC‡	Ann.	Aliu et al. (2009)
Sculptor	2008	(11.8)	H.E.S.S.	Ann.	Abramowski et al. (2011)
				Ann.	Abdalla et al. (2018a)
	2008 – 2009	12.5		Ann.	Abramowski et al. (2014)
Carina	2008 – 2009	(14.8)	H.E.S.S.	Ann.	Abramowski et al. (2011)
	2008 – 2009	(12.7)		Ann.	Abramowski et al. (2014)
	2008 – 2010	22.9		Ann.	Abdalla et al. (2018a)

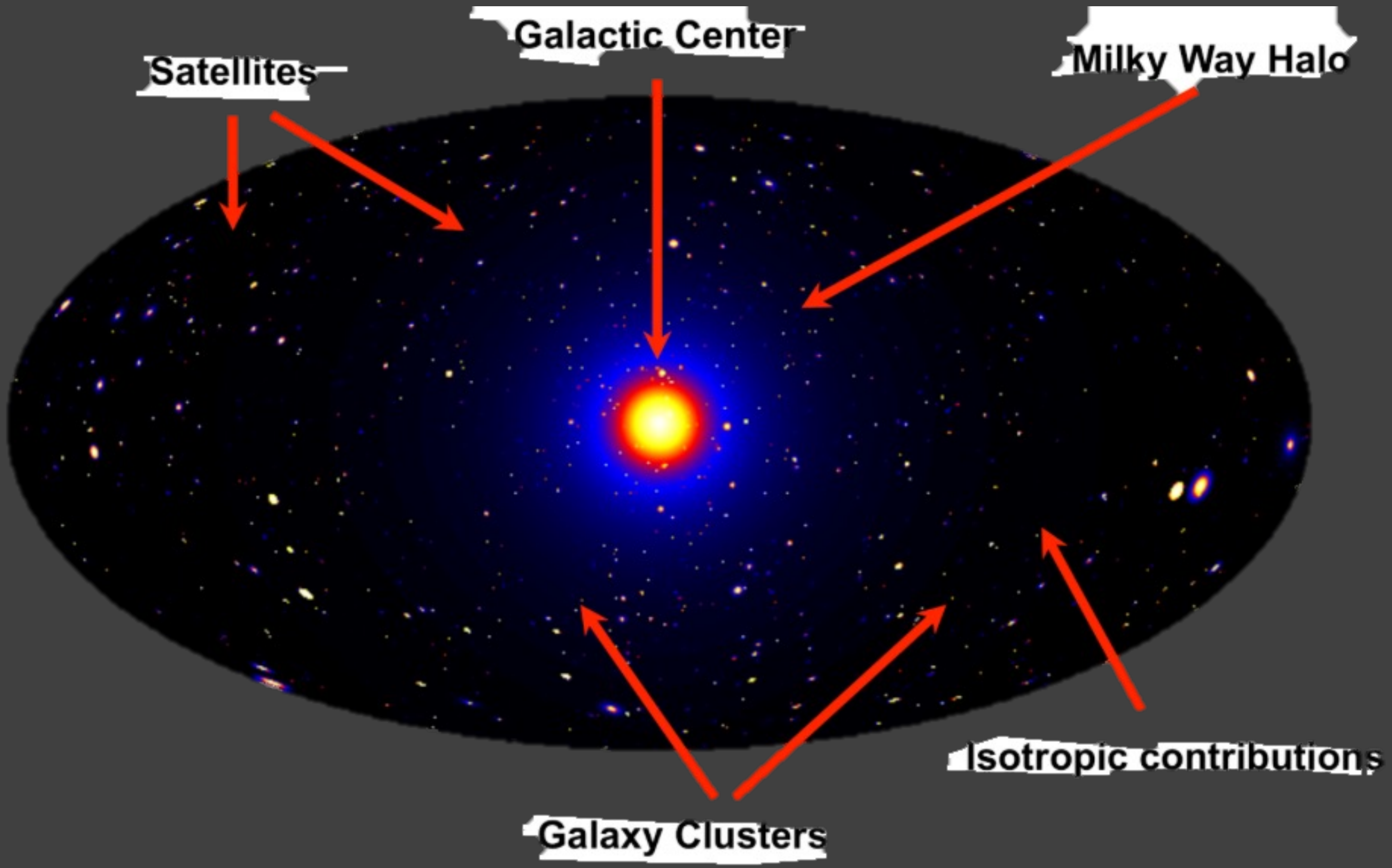
Table 8.1 – continued from previous page

Target	Year	Time [h]	IACT	Limit	Ref.
Intermediate Mass Black Holes					
Galactic Plane Survey	2004 – 2007	400	H.E.S.S.	Ann.	Aharonian et al. (2008a)
	2005 – 2006	25	MAGIC‡	Ann.	Doro et al. (2007)
Globular Clusters					
M15	2002	0.2	Whipple	Ann.	Wood et al. (2008)
	2006 – 2007	15.2	H.E.S.S.	Ann.	Abramowski et al. (2011)
NGC 6388	2008 – 2009	27.2	H.E.S.S.	Ann.	Abramowski et al. (2011)
Other galaxies					
M33	2002 – 2004	7.9	Whipple	Ann.	Wood et al. (2008)
M32	2004	6.9	Whipple	Ann.	Wood et al. (2008)
WLM	2018	18.2	H.E.S.S.†	Ann.	Abdallah et al. (2021b)
Galaxy Clusters					
Abell 2029	2003 – 2004	6.1	Whipple	–	Perkins et al. (2006)
Perseus (Abell 426)	2004 – 2005	13.5	Whipple	–	Perkins et al. (2006)
	2008	24.4	MAGIC‡	Ann.	Aleksić et al. (2010)
	2009 – 2017	202.2	MAGIC	Decay	Acciari et al. (2018)
Fornax (Abell S0373)	2005	14.5	H.E.S.S.	Ann.	Abramowski et al. (2012)
Coma (Abell 1656)	2008	18.6	VERITAS	Ann.	Arlen et al. (2012)
Line searches					
MW Inner Halo	2004 – 2008	(112)	H.E.S.S.	Ann.	Abramowski et al. (2013c)
	2014	15.2	H.E.S.S.†	Ann.	Abdalla et al. (2016)
	2004 – 2014	(254)	H.E.S.S.	Ann.	Abdalla et al. (2018b)
	2013 – 2019	204	MAGIC	Ann.	Inada et al. (2021)
Segue 1 dSph	2010 – 2013	(157.9)	MAGIC	A.+D.	Aleksić et al. (2014)
Five dSph galaxies	2006 – 2012	(137.1)	H.E.S.S.	Ann.	Abdalla et al. (2018a)
Five dSph galaxies	2007 – 2013	(229.8)	VERITAS	Ann.	Archambault et al. (2017)
WLM	2018	(18.2)	H.E.S.S.†	Ann.	Abdallah et al. (2021b)
Charged particles					
All-electron	2004 – 2007	239	H.E.S.S.	–	Aharonian et al. (2008b, 2009b)
	2009 – 2012	296	VERITAS	–	Archer et al. (2018)
	2009 – 2010	14	MAGIC	–	Borla Tridon et al. (2011)
Moon shadow	2010 – 2011	20	MAGIC	–	Colin et al. (2011)
	2014	1.2	VERITAS	–	Bird et al. (2016)

SEVERAL TARGETS



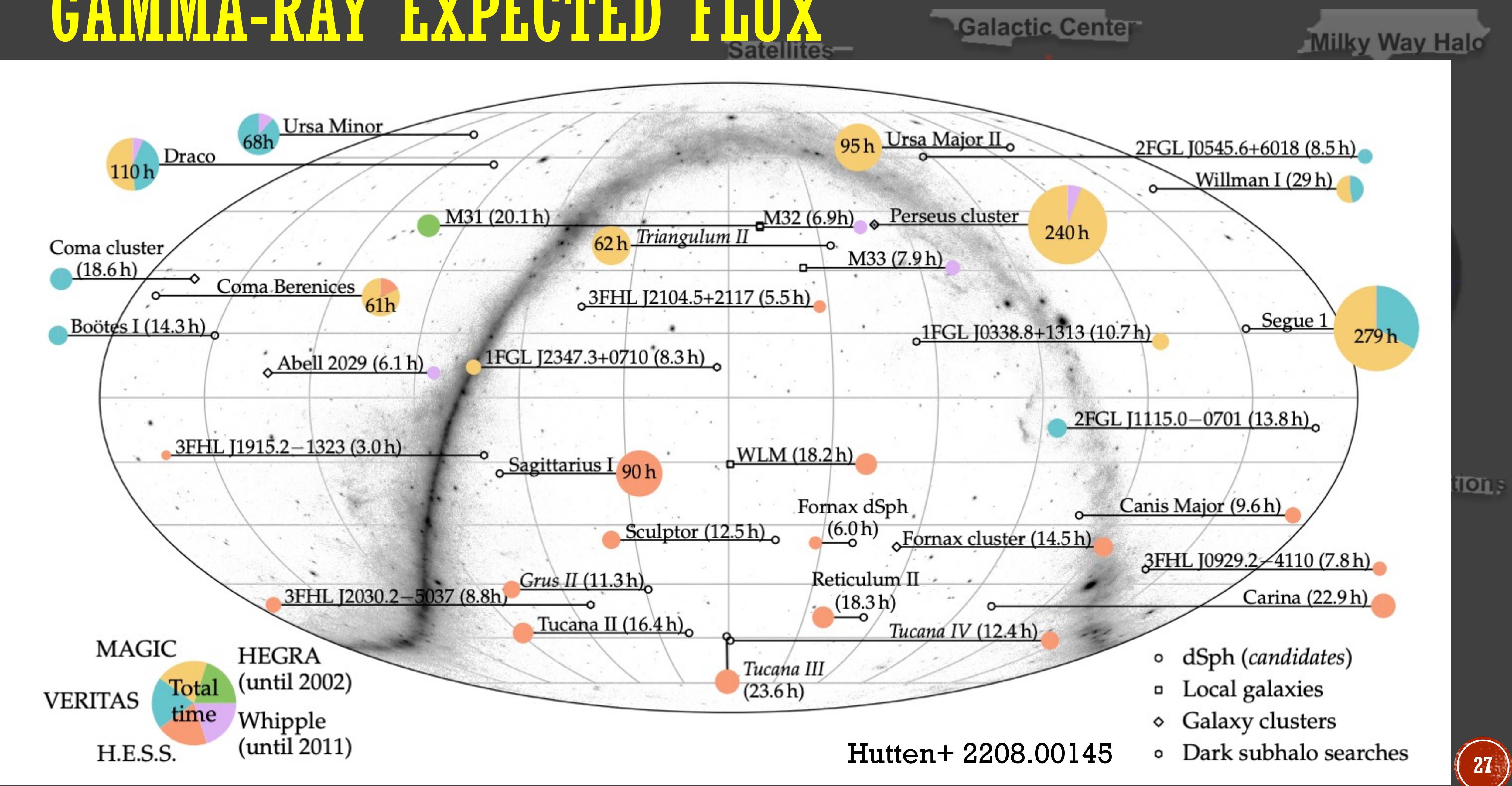




One theory

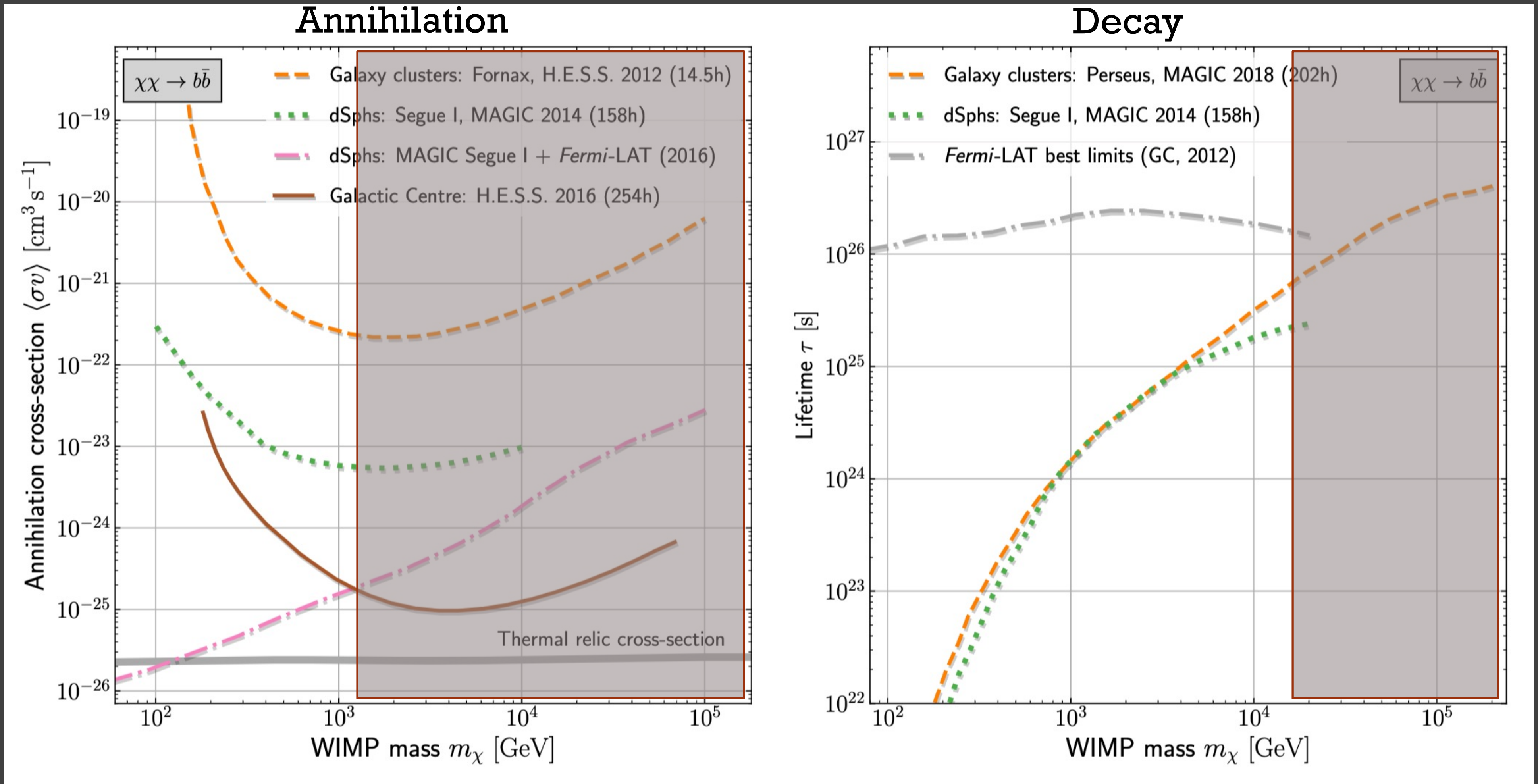
- Same spectra = multiple signatures
- Smoking gun detection and identification!

GAMMA-RAY EXPECTED FLUX



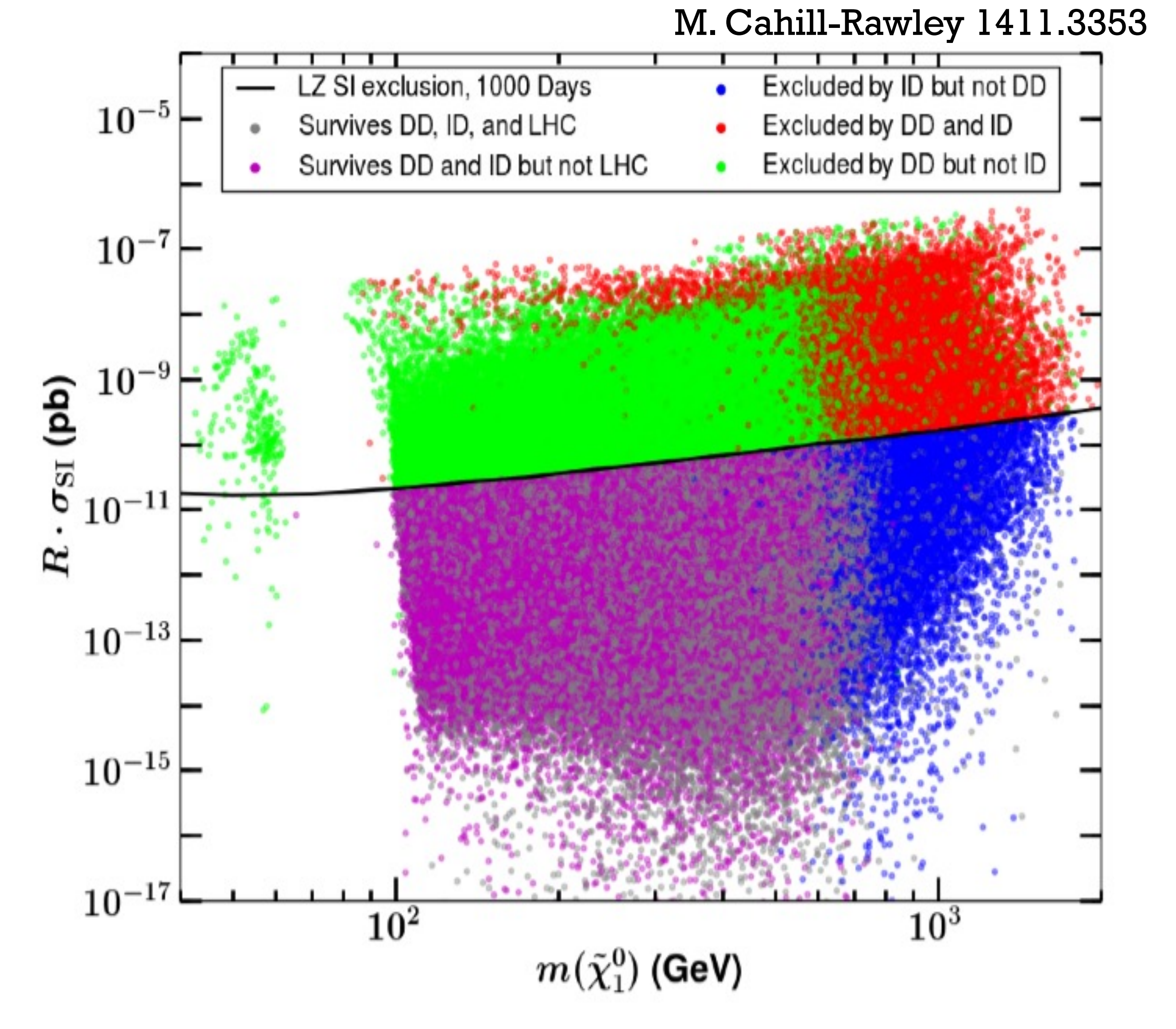
Hutten+ 2208.00145

IACT SUMMARY SO FAR



MD, M.A. Sanchez-Conde, M. Huetten. 2111.01198

STILL WORTH IT…COMPLEMENTARITY



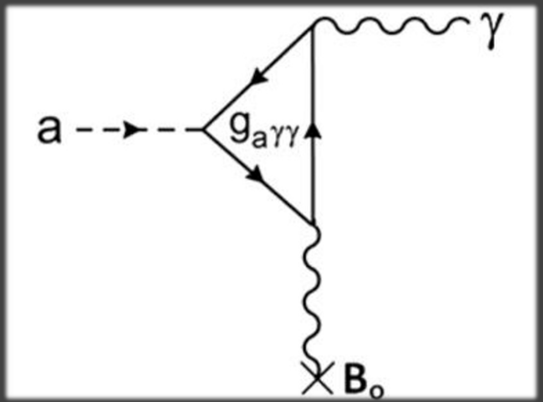
- Also…upper limit at ~100 TeV is not impenetrable:
- DM particles can be ultra-heavy --> 10 PeV (Tak+ in prep)

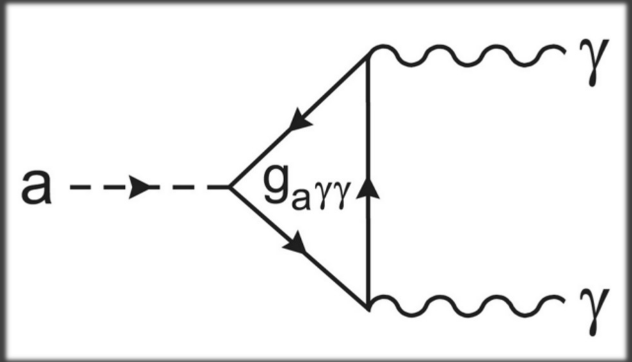
AXION LIKE PARTICLES

The fix your every meal

AXIONS AND AXIONS LIKE PARTICLES

- Peccei (1977): a new particle to fix the missing CP (the axion), but too heavy not to be detected





- A general axion is the ALP (invisible axion, Weinberg, 1978, Wilczek, 1978) arises in several theories BSM
  - Mixes with photons (in magnetic fields)
  - Decays in photons

ASTROPHYSICAL AXION LIKE PARTICLES

Ivana Batkovic

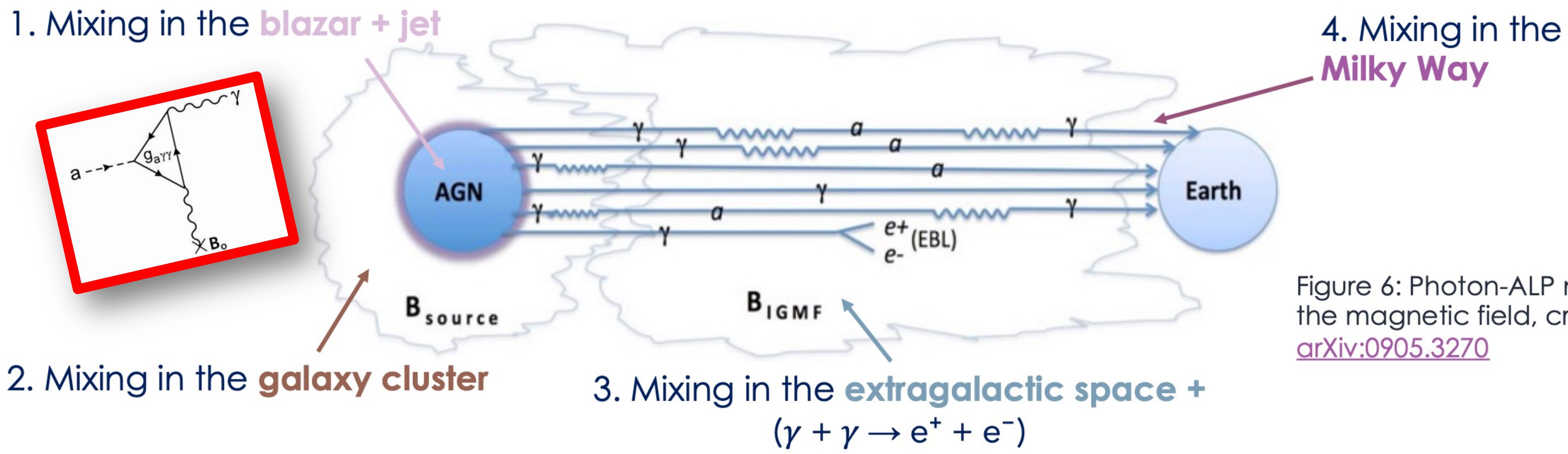


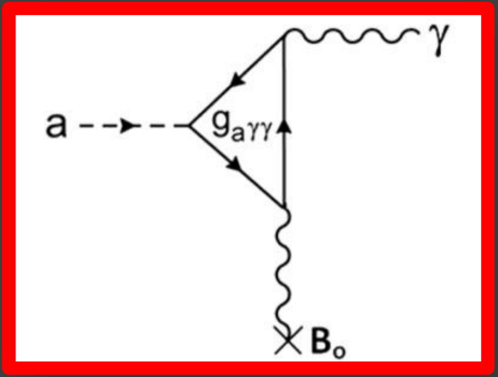
Figure 6: Photon-ALP mixing in the magnetic field, credit: arXiv:0905.3270

KNOWLEDGE OF THE **MAGNETIC FIELDS** IS FUNDAMENTAL FOR PRODUCING THE **ALPS** MODELS!

- ALP can travel very long distances unabsorbed, while gamma rays do not (EBL)

ALP-B MIX AND OBSERVABLE EFFECTS

Used to explain unusual low EBL…



$$E_{crit} = 2.5\ GeV \frac{|m^2_{a,neV} - \omega^2_{pl,,neV}|}{G_{11} B_{\mu G}}$$

- E~Ec wiggles
- E>Ec full mix

- Spectral Wiggles

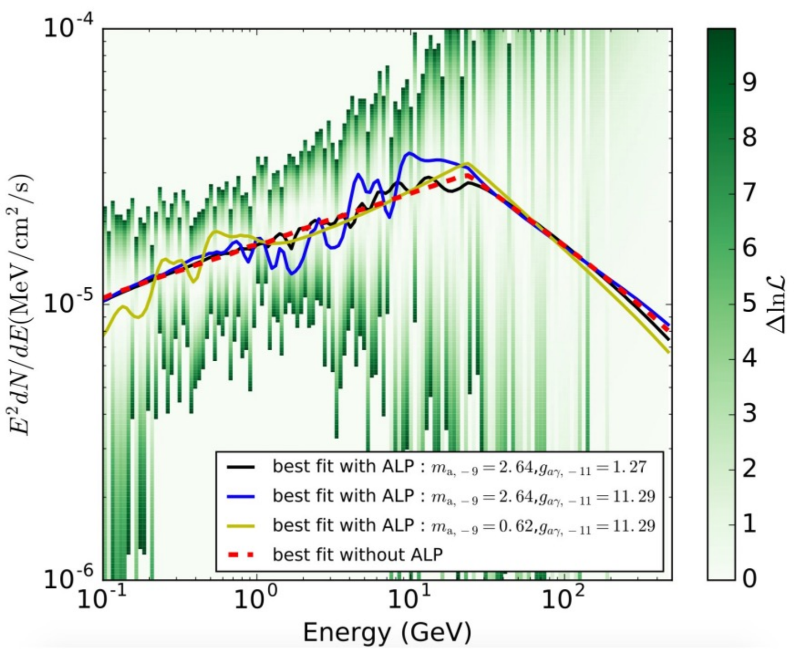


Figure 3: Spectrum fit of PKS2155-304 w & w/o ALPs, arXiv:1311.3148

- Photon recovery

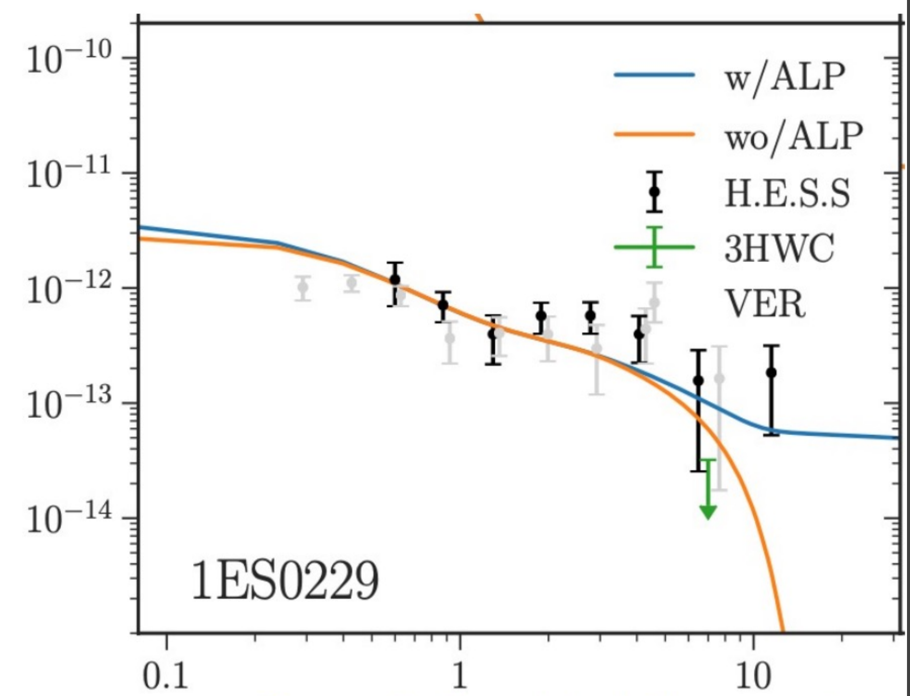
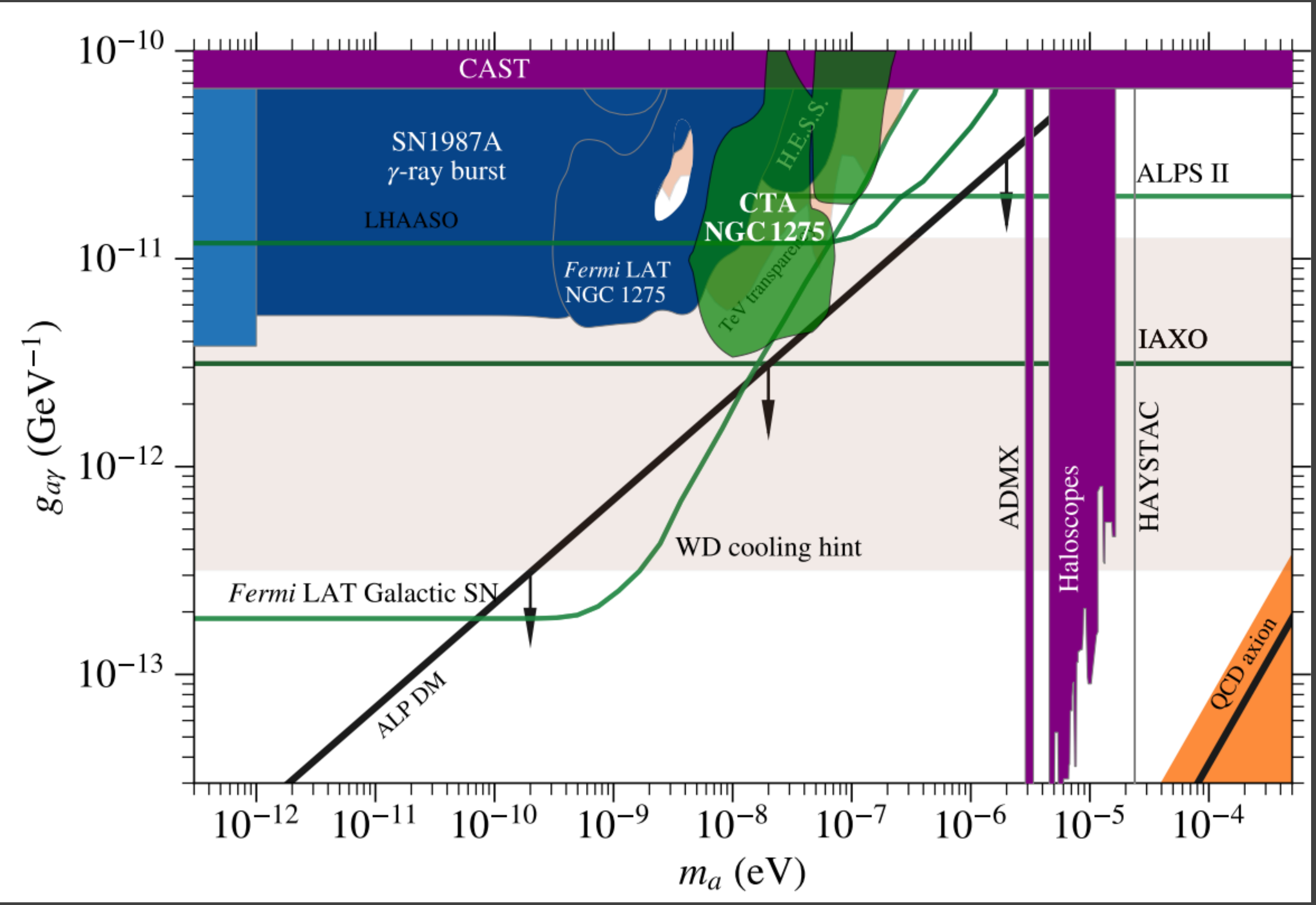


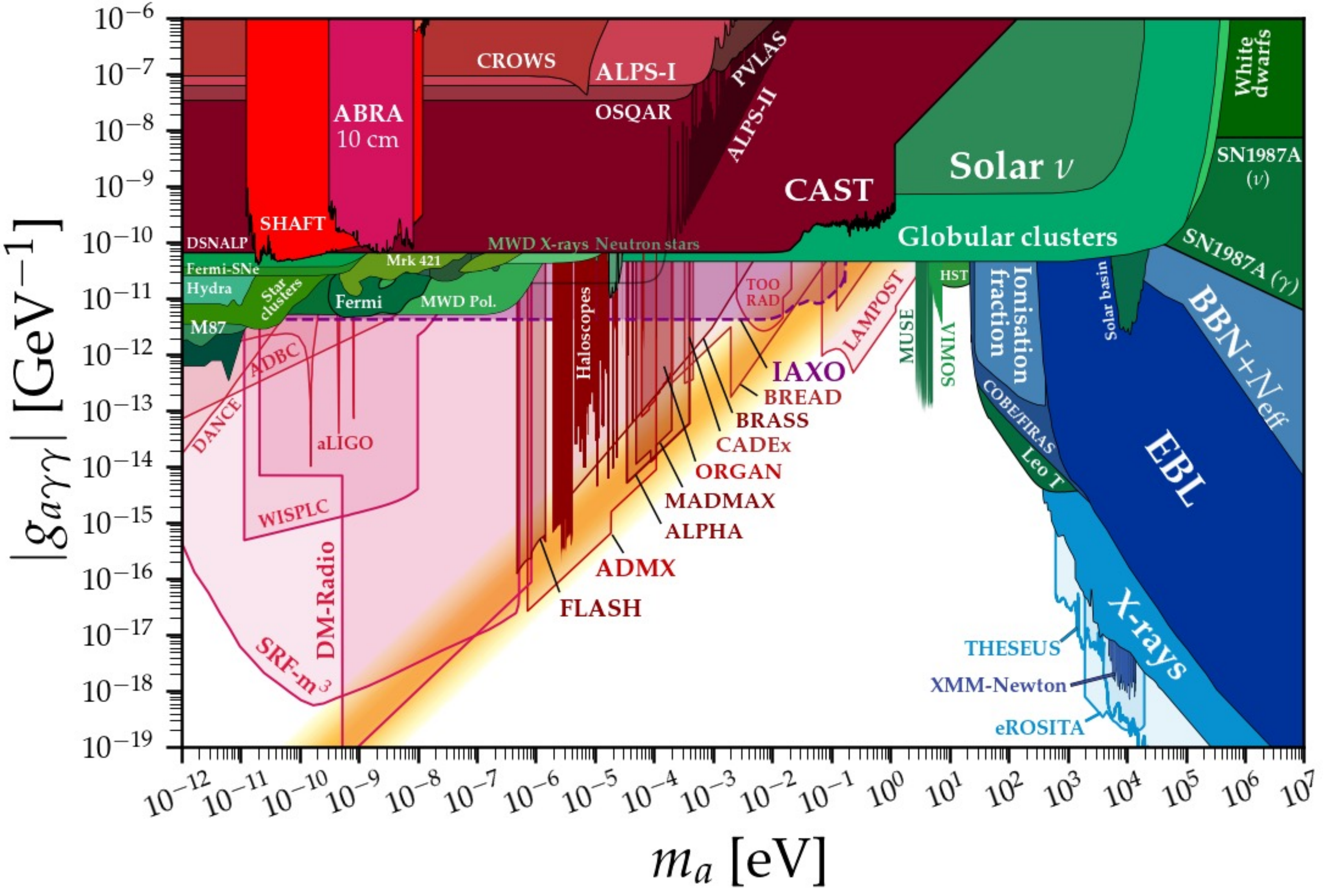
Figure 4: Simulated flux spectra w & w/o ALPs; Jacobsen et al., arXiv:2203.04332

GAMMA-RAY LIMITS

CTA coll. , *JCAP* 02 (2021) 048 • e-Print: 2010.01349

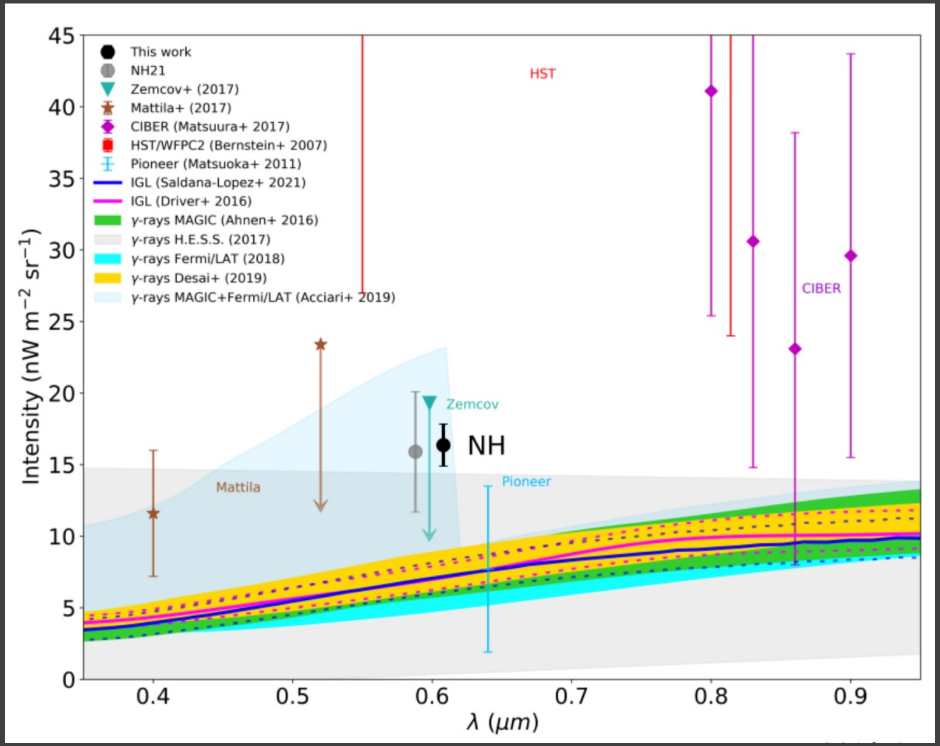


- CTA reach
  - 250h NGC1275 (Perseus GC)
- Probing neV ALP
- Galaxy cluster
- Blazars jets



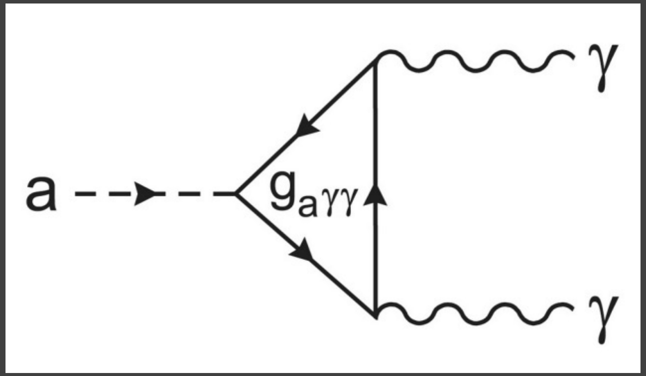
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]
CROWS
ALPS-I
PVLAS
ALPS-II
OSQAR
ABRA 10 cm
SHAFT
DSNALP
CAST
Solar ν
White dwarfs
SN1987A (ν)
Globular clusters
SN1987A (γ)
MWD X-rays
Neutron stars
Mrk 421
Fermi-SNe
Hydra
Star clusters
Fermi
MWD Pol.
M87
Haloscopes
TOO RAD
LAMPOST
HST
MUSE
VIMOS
Ionisation fraction
Solar basin
BBN+N_{eff}
EBL
COBE/FIRAS
Leo T
X-rays
IAXO
BREAD
BRASS
CADEx
ORGAN
MADMAX
ALPHA
ADMX
FLASH
ADBC
DANCE
aLIGO
WISPLC
DM-Radio
SRF-m^3
THESEUS
XMM-Newton
eROSITA

ALP FIXES YOU EVERY MEAL



- Lauer+ 2022 "Anomalous Flux in the Cosmic Optical Background Detected with New Horizons Observations"

- A decaying ALP at eV scale…



…used to explain unusual high EBL…

MAGNETIC MONOPOLES AND QUARK NUGGETS

Caution! Hot!

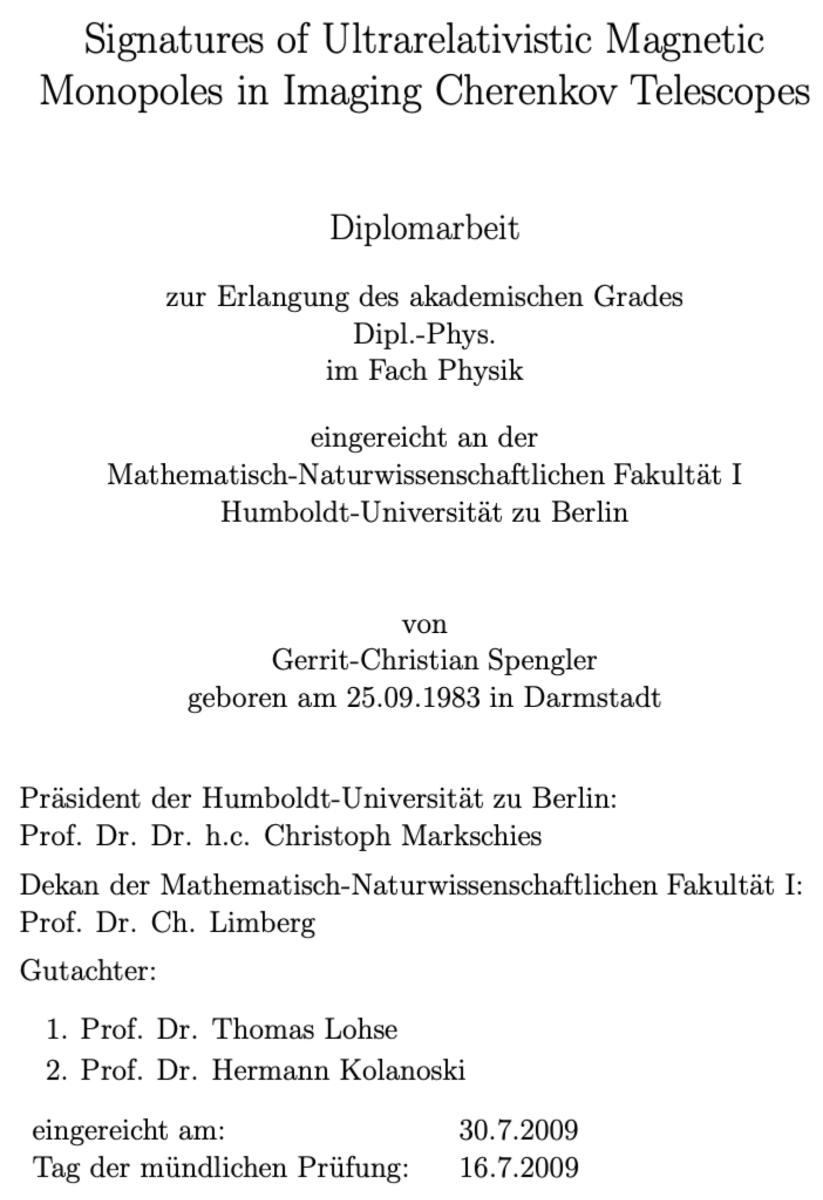
G. Spengler, BSc

MAGNETIC MONOPOLES

- **In 1931, Dirac MM** to explain electric charge quantization. Later on, many theories predict its existence
- Tamm and Frank (1937), Tompkins (1965), etc: MM will produce 4700 times the Cherenkov light of an electron, without producing any secondary particle

$$\frac{d^2N}{dxd\lambda}^{\text{Air}}_{\text{Monopole}} \approx 4700 \frac{d^2N}{dxd\lambda}_{\text{Electric}}$$

- Cherenkov emission happens deep in atmosphere and only $\gamma > 10^3$ and $m > 1\, TeV$ can be probed (ultrarelativistic MM)


Signatures of Ultrarelativistic Magnetic Monopoles in Imaging Cherenkov Telescopes

Diplomarbeit

zur Erlangung des akademischen Grades
Dipl.-Phys.
im Fach Physik

eingereicht an der
Mathematisch-Naturwissenschaftlichen Fakultät I
Humboldt-Universität zu Berlin

von
Gerrit-Christian Spengler
geboren am 25.09.1983 in Darmstadt

Präsident der Humboldt-Universität zu Berlin:
Prof. Dr. Dr. h.c. Christoph Markschies

Dekan der Mathematisch-Naturwissenschaftlichen Fakultät I:
Prof. Dr. Ch. Limberg

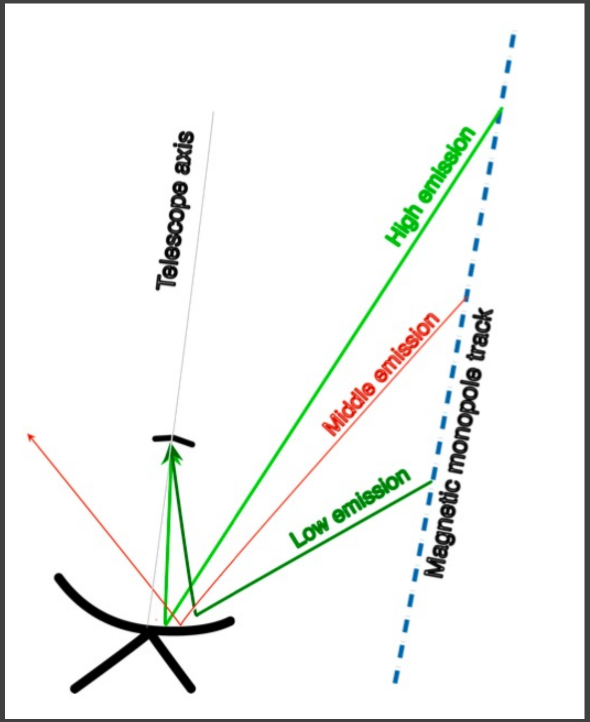
Gutachter:

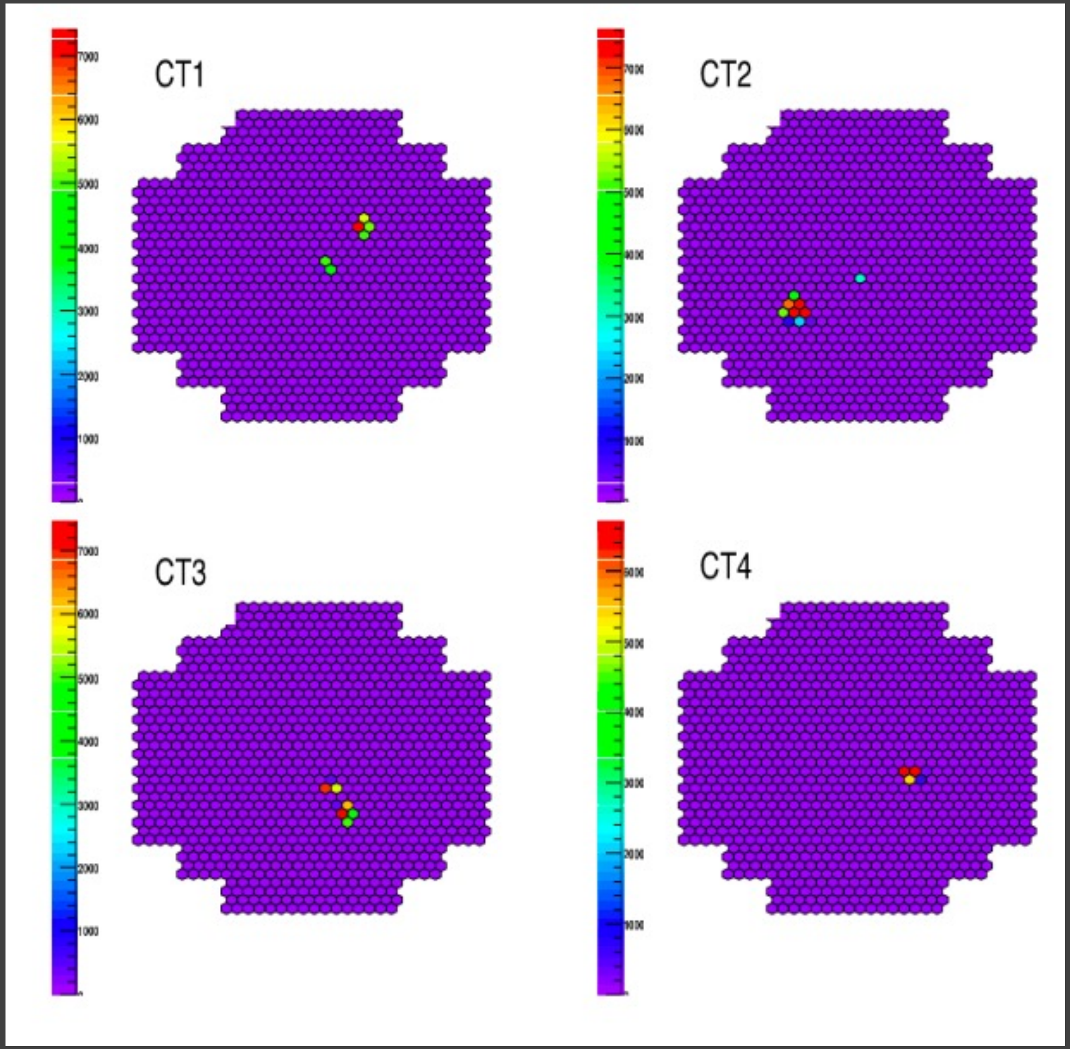
1. Prof. Dr. Thomas Lohse
2. Prof. Dr. Hermann Kolanoski

eingereicht am: 30.7.2009
Tag der mündlichen Prüfung: 16.7.2009

SIGNATURES AT IACTS

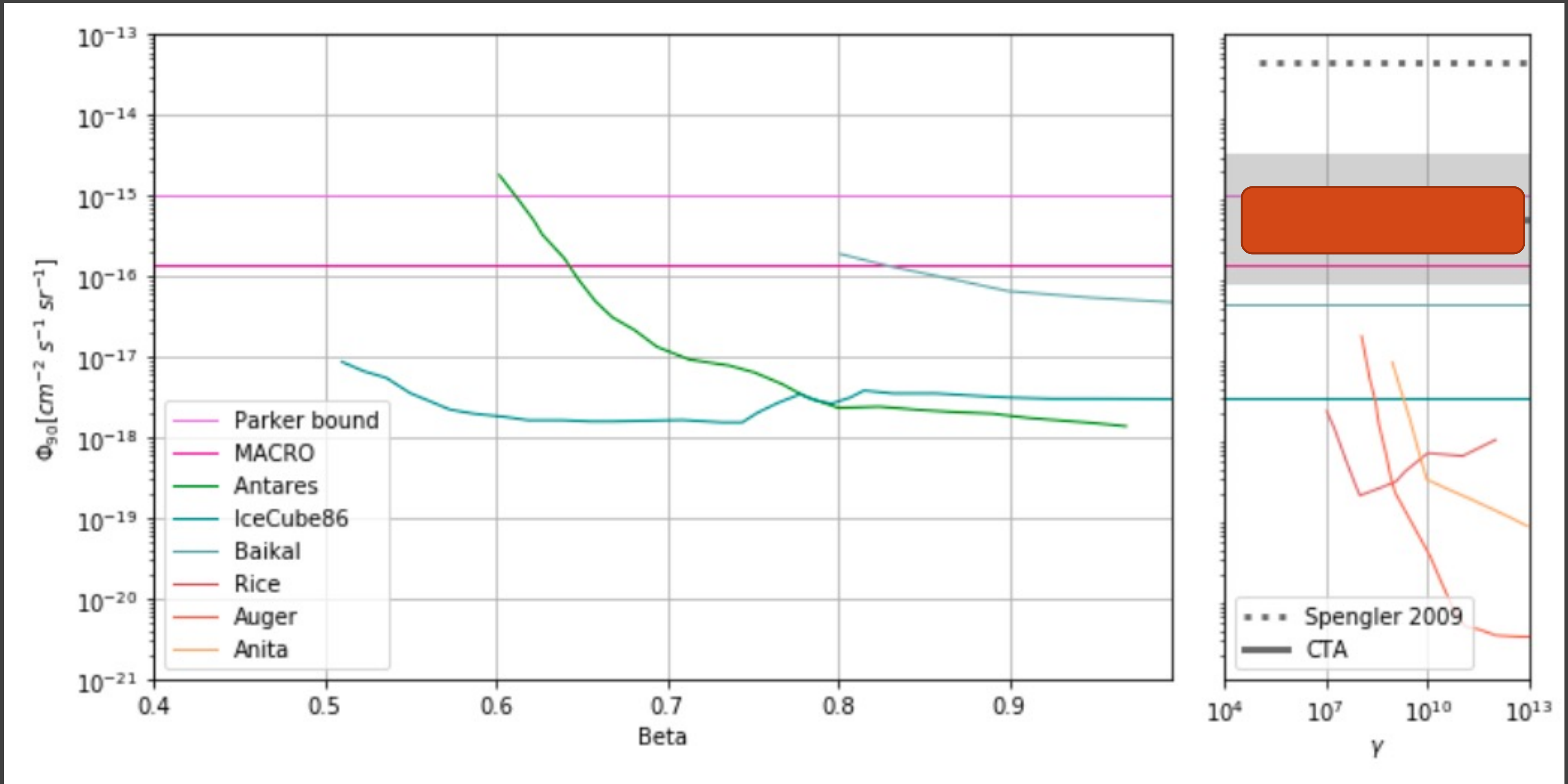
G. Spengler, BSc and Spengler+ ICRC 2011





- Very peculiar rare events in IACTs
- Strong risk of throw-away from plate

PROSPECTS



←Estimated CTA sensitivity

(MD+ Astroparticle Physics 43 (2013) 189–214)

QUARK NUGGETS/STRANGELETS…?

Kyle Lawson (British Columbia U.). Nov 2010.
Published in **Phys.Rev. D83 (2011) 103520**

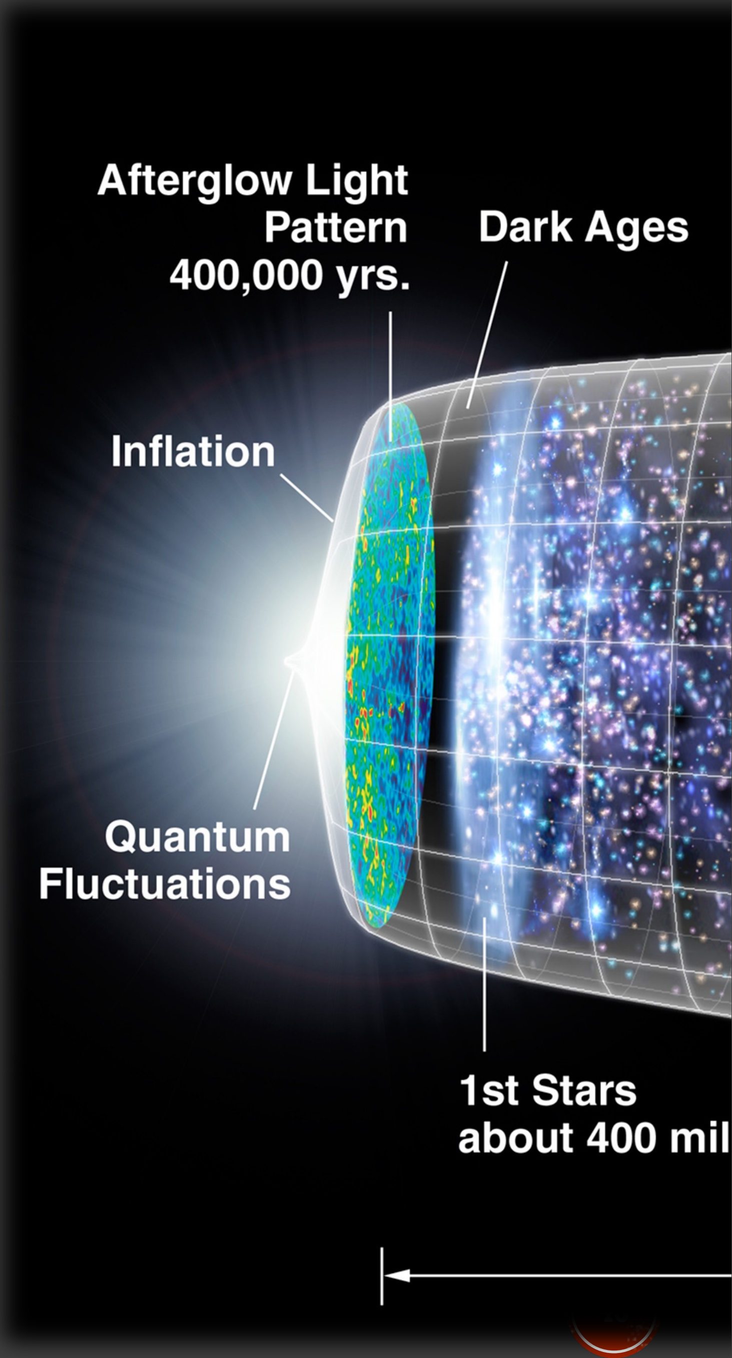
- Quark nuggets are **stable bound states of quarks or antiquarks** generated in the early universe: 10^{20} quarks inside.
  - Globally neutral, with expected **charge excess on the surface**: nuggets will be dressed with leptons
- Big and heavy…
- **When crossing the atmosphere**, the energy deposited by annihilations can be quite large : **an extensive air shower will be produced**.
  - K. Lawson 2009-2015 papers+

PRIMORDIAL BLACK HOLES

They pop!

FACTS

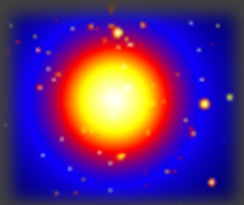
- Several mechanisms to generate BHs of non-stellar-collapse origin in the early Universe [e.g. Sasaki+ 2018]
  - Collapse of overdensities
  - Phase transition
- Mass range at truly all scales, from Planck to Sun^n
- Do they evolve?
  - Accretion, interaction with DM [hot!]
  - Evaporation (Hawking 1974)
- They can constitute a fraction of DM



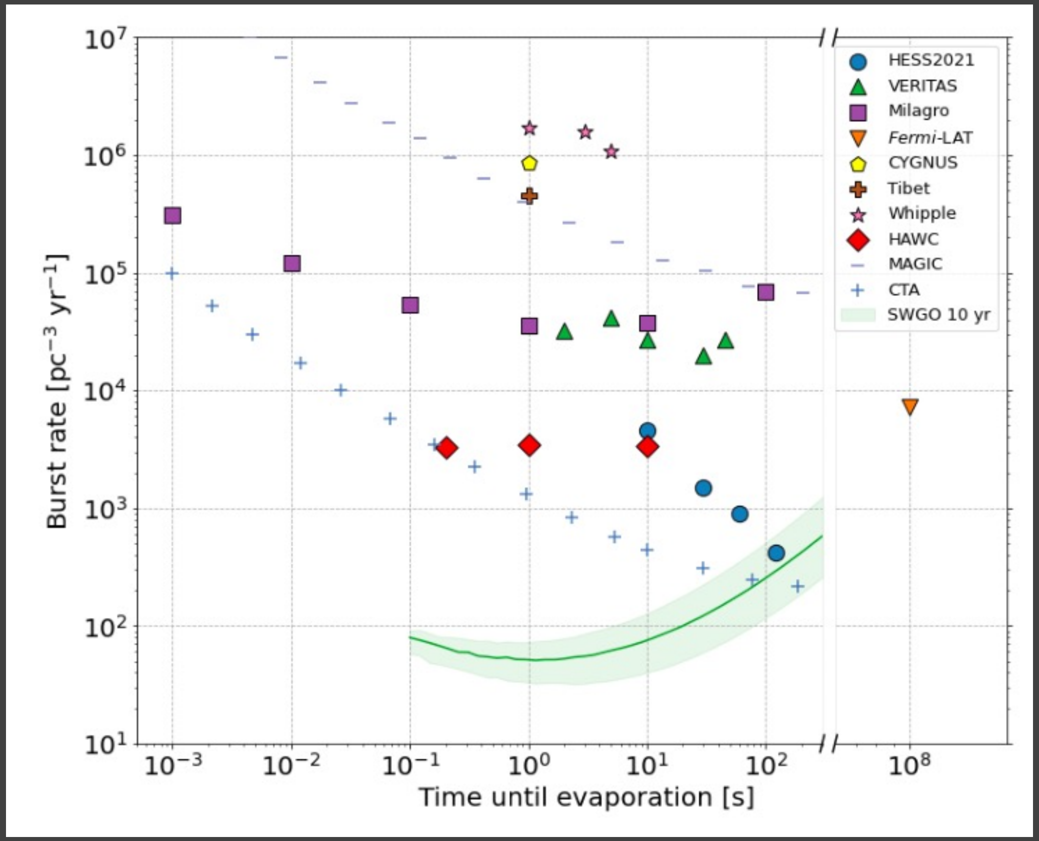
PBH EVAPORATION

$$\tau_{\rm BH}(M) = \frac{G^2 M^3}{\hbar\, c^4} \sim 10^{10} \left(\frac{M}{10^{15}\rm g}\right)^3 \; [\rm yr]$$

Evaporation time



- IACTs: Observable as serendipity flashes in gamma-rays

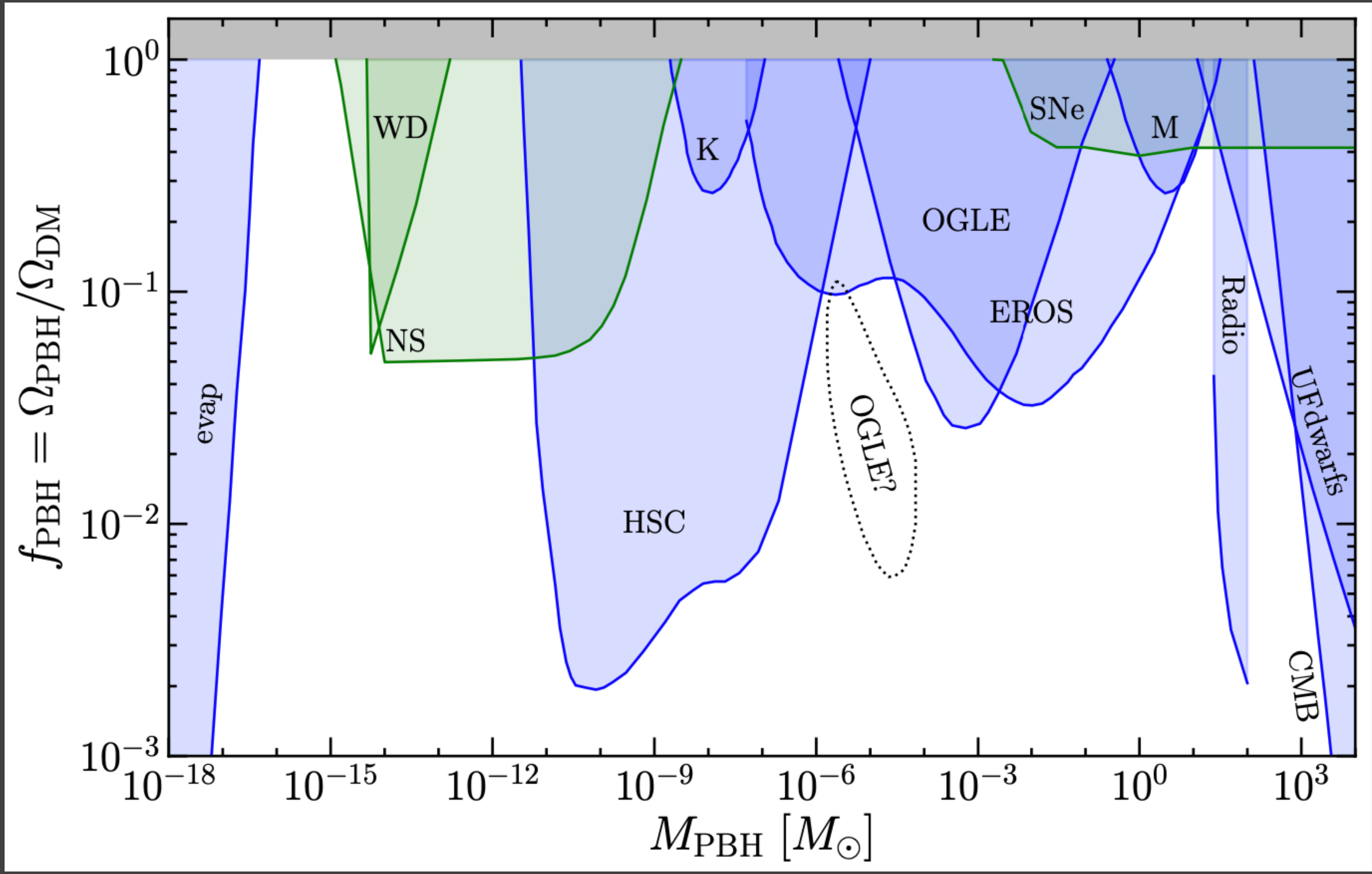


Lopez Coto, MD, + JCAP 08 (2021) 040

- 3 regimes:
  - PBH < 10^{15}g dead by now…
  - PBH ~ 10^{15}g evaporating today!
  - PBH > 10^{15}g still around!
- Naïve scenarios, it depends…

PBH LIMITS

https://github.com/bradkav/PBHbounds



- IACTs limits are buried within Fermi-LAT limits
- However
  - theoretical mapping not complete
  - Events could be left in the plate

UHE NEUTRINOS

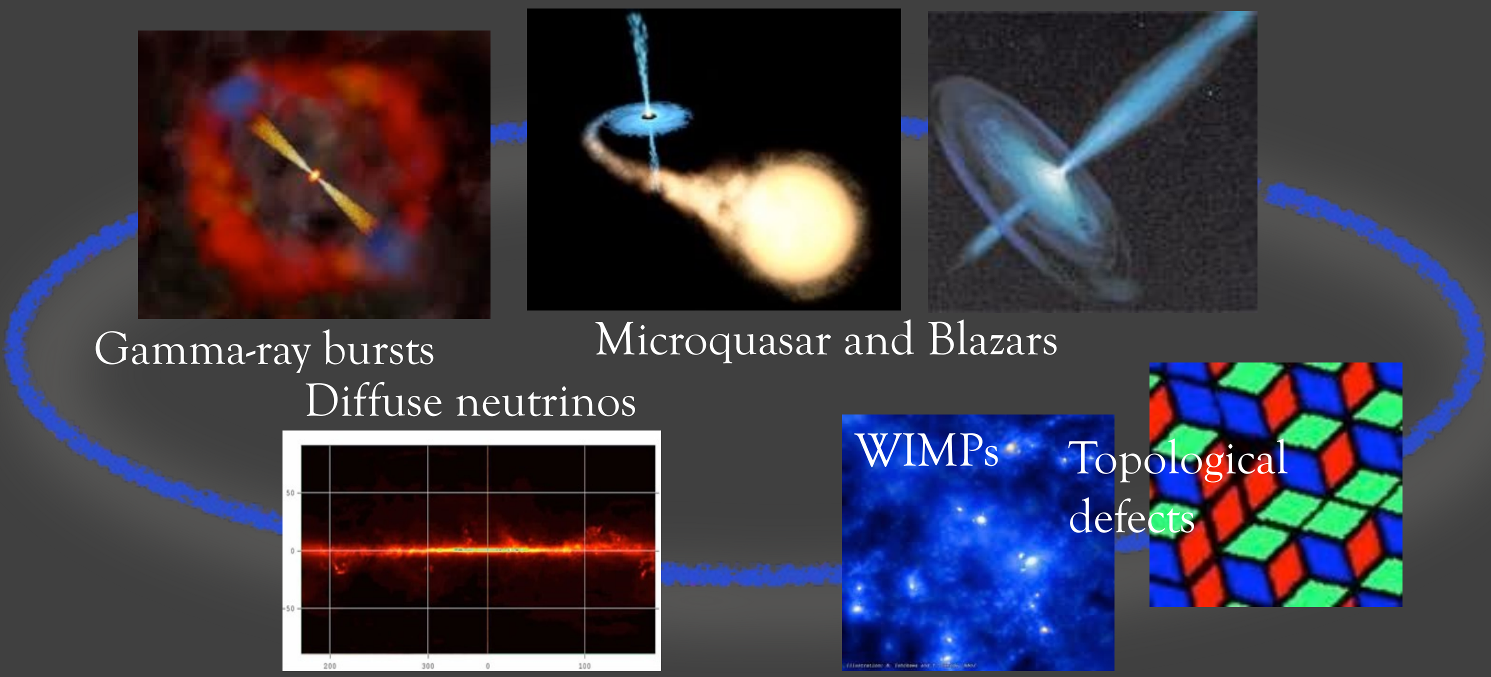
Light meal

HIGH-ENERGY NEUTRINOS

MAGIC +, *Science* 361 (2018) 6398

Point-like and diffuse emitters

Exotic emitters



Pions production
(at source or propagation)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n\,\pi^+ \\ p\,\pi^0 \end{cases}$$

$$pp \longrightarrow pp\pi^+\pi^-\pi^0$$

Fargion, 1997

Neutrinos production
(at source or propagation)

$$\pi^+ \longrightarrow \mu^+\nu_\mu$$

$$\mu^+ \longrightarrow \bar{\nu}_\mu e^+ \nu_e$$

$$(\nu_e : \nu_\mu : \nu_\tau) = (1:2:0)\,.$$

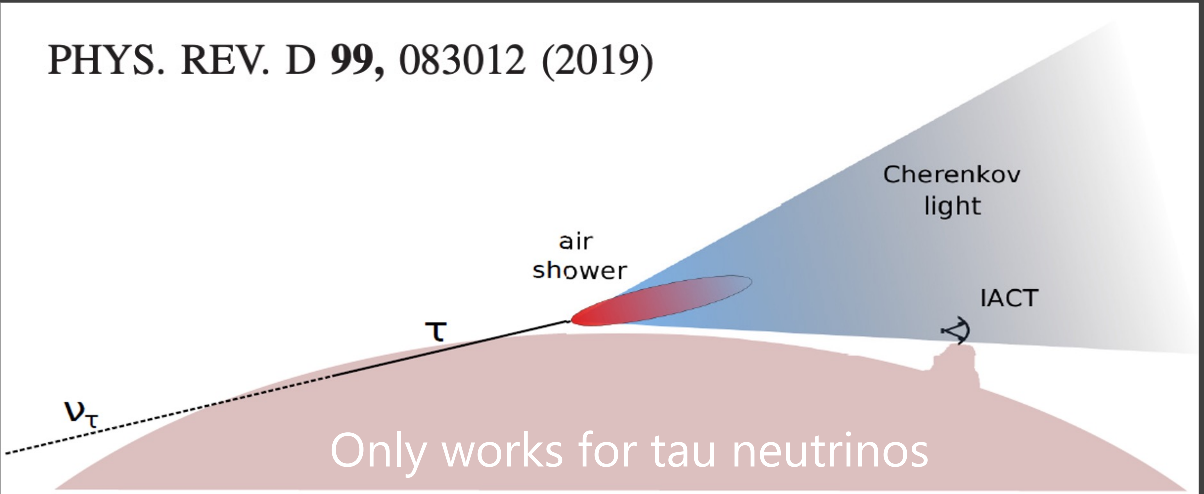
$\ldots$and $\nu_\tau\ldots$

* At the source if charmed mesos are produced

* At the Earth, after flavor mixing

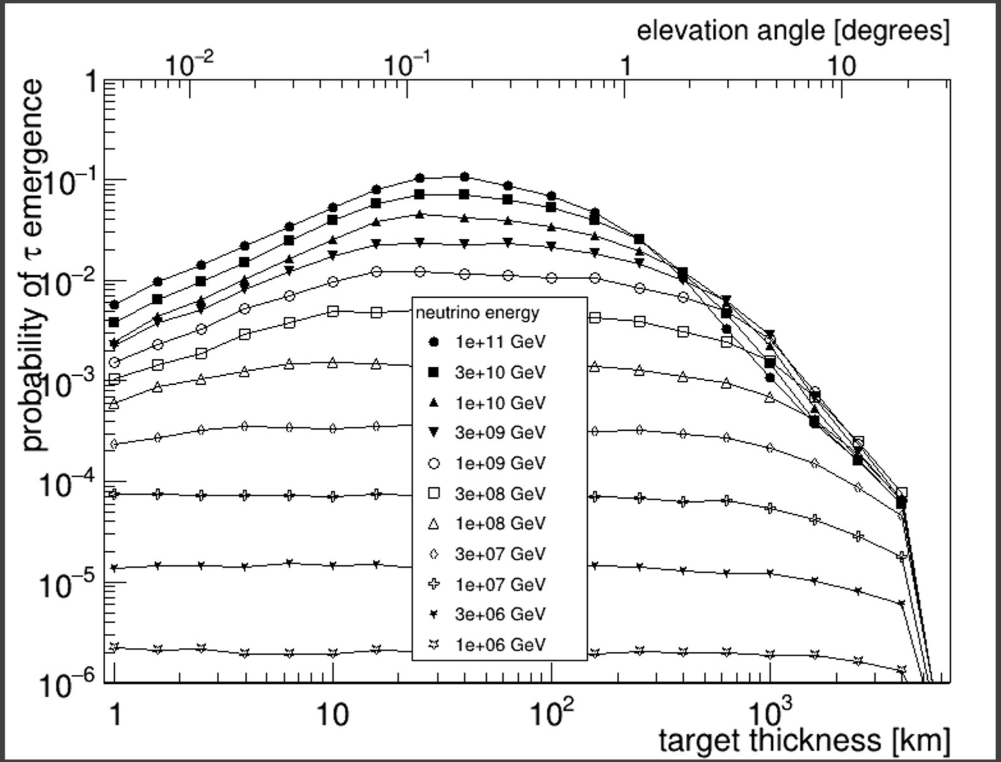
$$(\nu_e : \nu_\mu : \nu_\tau)_{Earth} = (1:1:1)$$

EARTH-SKIMMING TAU NEUTRINOS



- The emerging UHE **tauons** can generate e.m. **atmospheric (sub)showers**

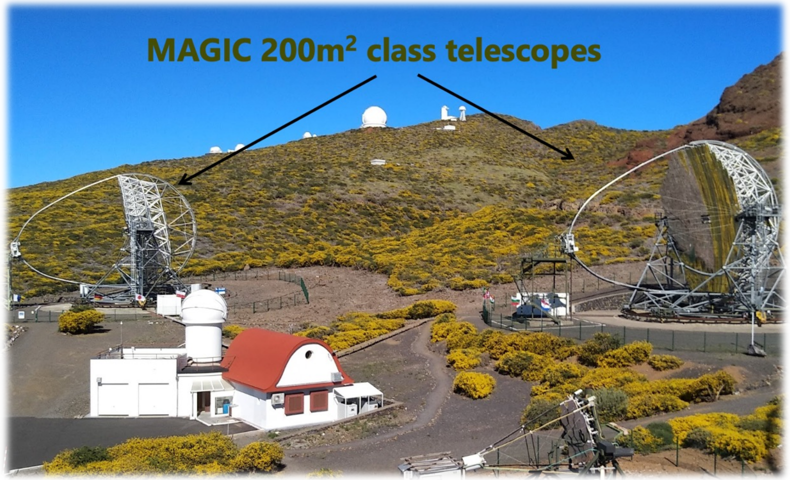
Decay	Secondaries	Probability	Air-shower
$\tau \to \mu^- \bar{\nu}_\mu \nu_\tau$	μ^-	17.4%	weak showers
$\tau \to e^- \bar{\nu}_e \nu_\tau$	e^-	17.8%	1 Electromagnetic
$\tau \to \pi^- \nu_\tau$	π^-	11.8%	1 Hadronic
$\tau \to \pi^- \pi^0 \nu_\tau$	$\pi^-, \pi^0 \to 2\gamma$	25.8%	1 Hadronic, 2 Electromagnetic
$\tau \to \pi^- 2\pi^0 \nu_\tau$	$\pi^-, 2\pi^0 \to 4\gamma$	10.79%	1 Hadronic, 4 Electromagnetic
$\tau \to \pi^- 3\pi^0 \nu_\tau$	$\pi^-, 3\pi^0 \to 6\gamma$	1.23%	1 Hadronic, 6 Electromagnetic
$\tau \to \pi^- \pi^- \pi^+ \nu_\tau$	$2\pi^-, \pi^+$	10%	3 Hadronic
$\tau \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$	$2\pi^-, \pi^+, \pi^0 \to 2\gamma$	5.18%	3 Hadronic, 2 Electromagnetic



10^6-10^{10} GeV UHE nu-tau, when crossing 1-100 km of rock have significant **probability of emerge as tau-lepton**

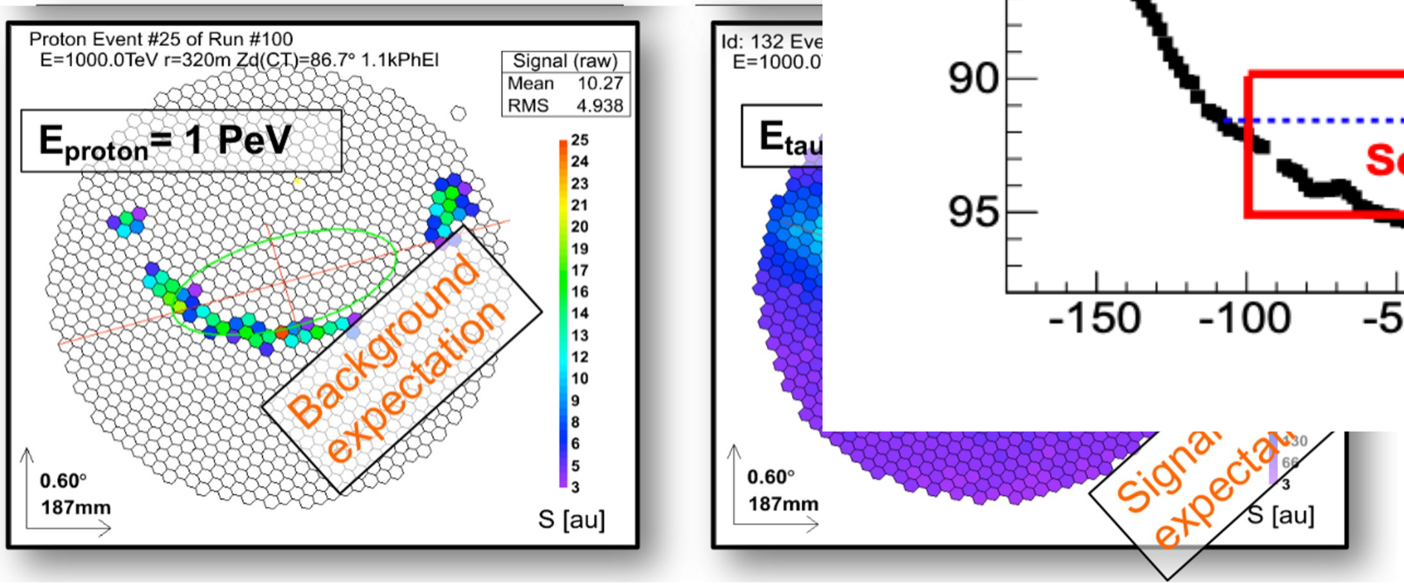
DEMONSTRATED BY MAGIC

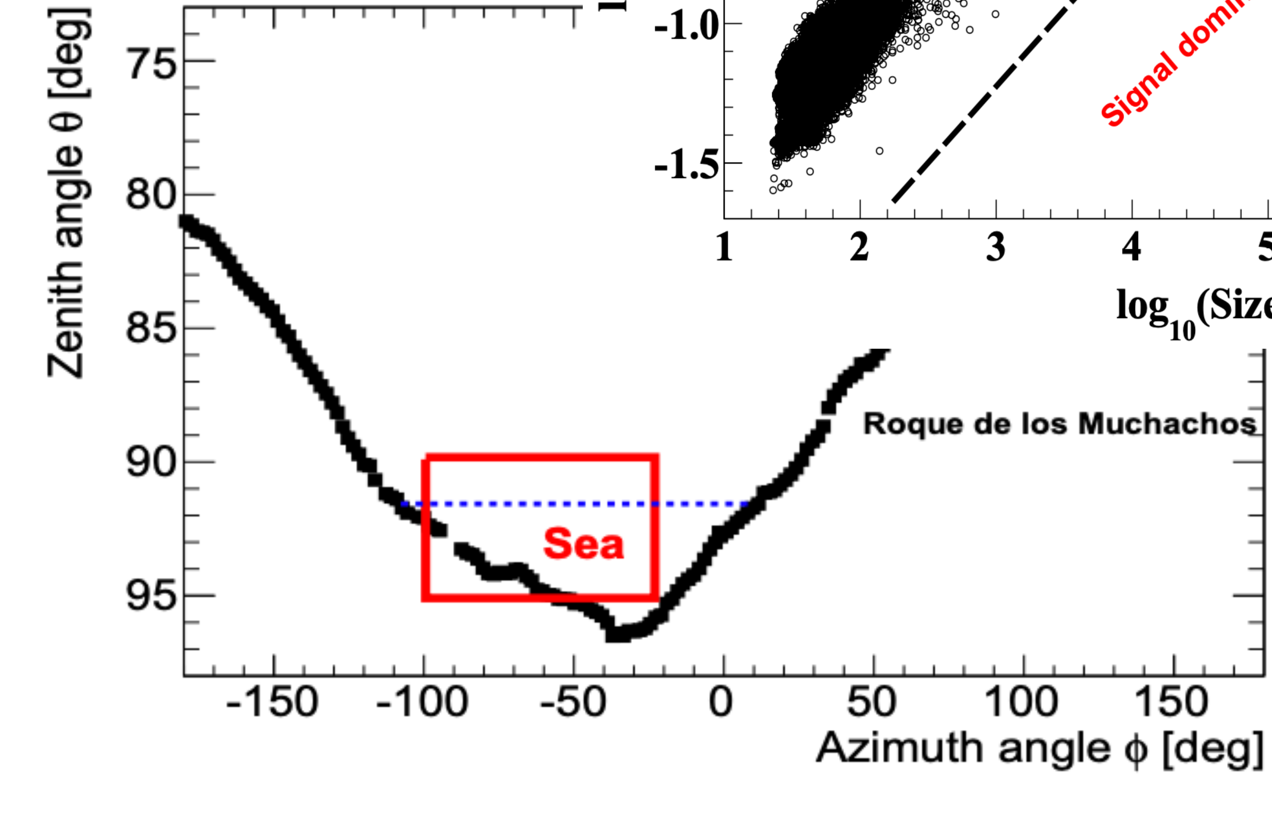
MAGIC (2018), Astropart.Phys. 102,77-88. [Dariusz Gora+]

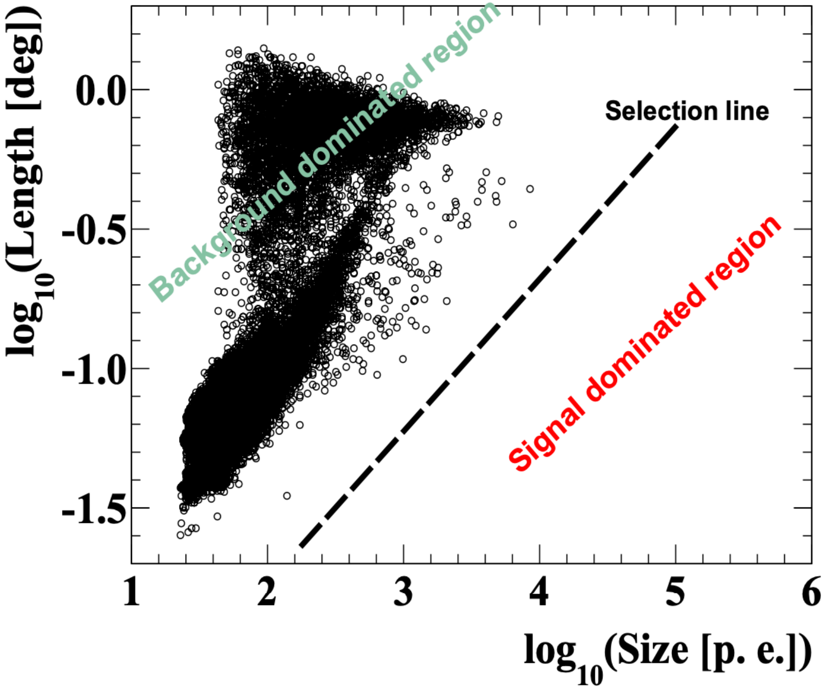


Proton injected at the top of the atmosphere

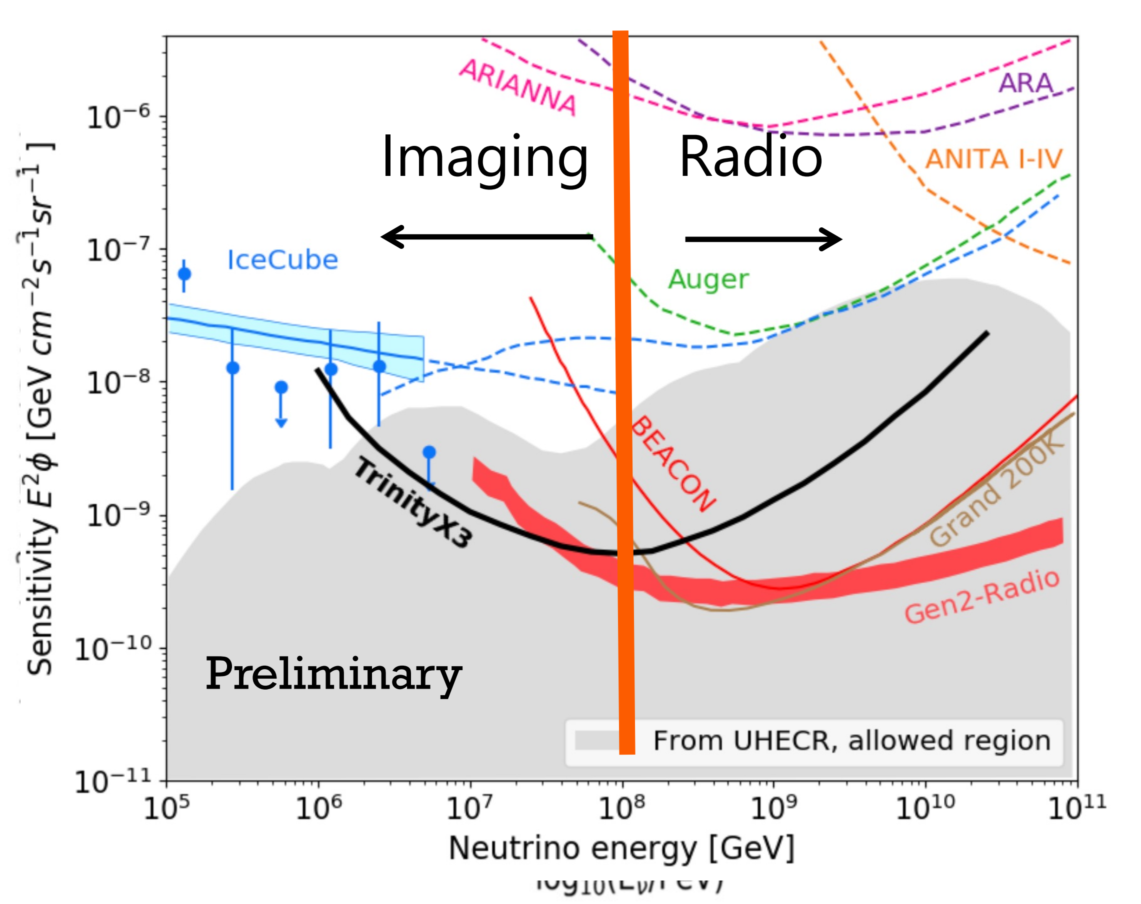
(~800 km to the detector for 87°)



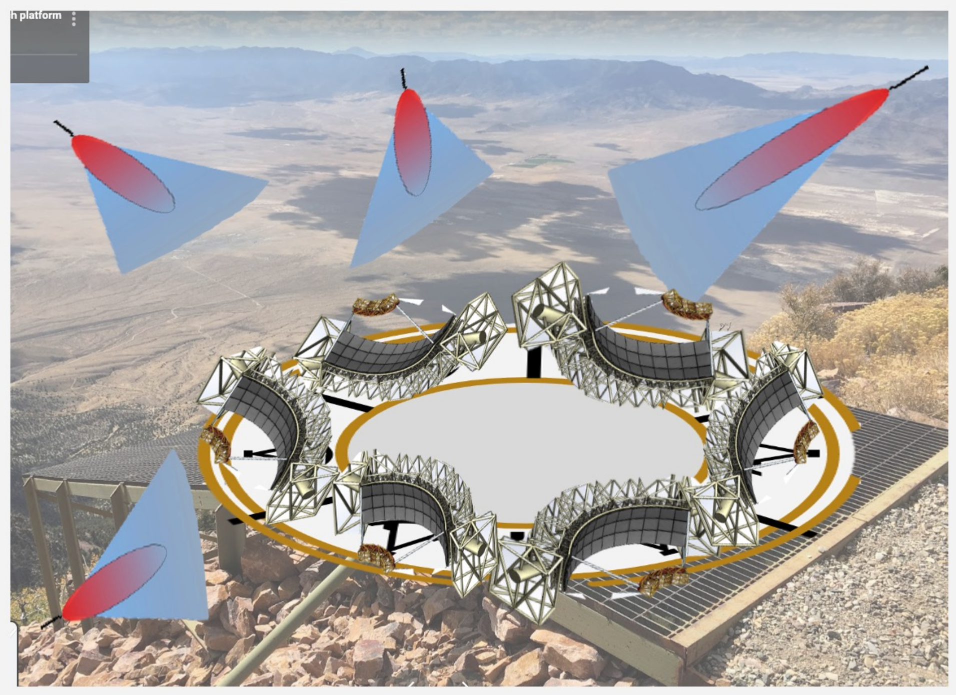




RESULTS AND OUTLOOK: TRINITY



- Trinity telescopes (PI: N. Otte)
  - 6x telescopes
  - 60x5 FOV
  - Waiting for neutrinos



https://www.youtube.com/watch?v=OC8GcuyFsqA

Brown, MD, others ICRC 2021

LORENTZ INVARIANCE

Calories depends on how fast you eat

ENERGY-DEPENDENT TIME DELAY

$$v_\gamma = \frac{\partial E_\gamma}{\partial p_\gamma} \simeq c\left[1 + \sum_{n=1}^{\infty} \eta_n \frac{n+1}{2}\left(\frac{E}{E_{QG,n}}\right)^n\right]$$

- Several theories predict E-dependent group speed of light. Related to vacuum properties
- Energy dependence can be
  - Superluminal/subluminal
  - Linear/quadratic/…
  - Proportional/Stochastic

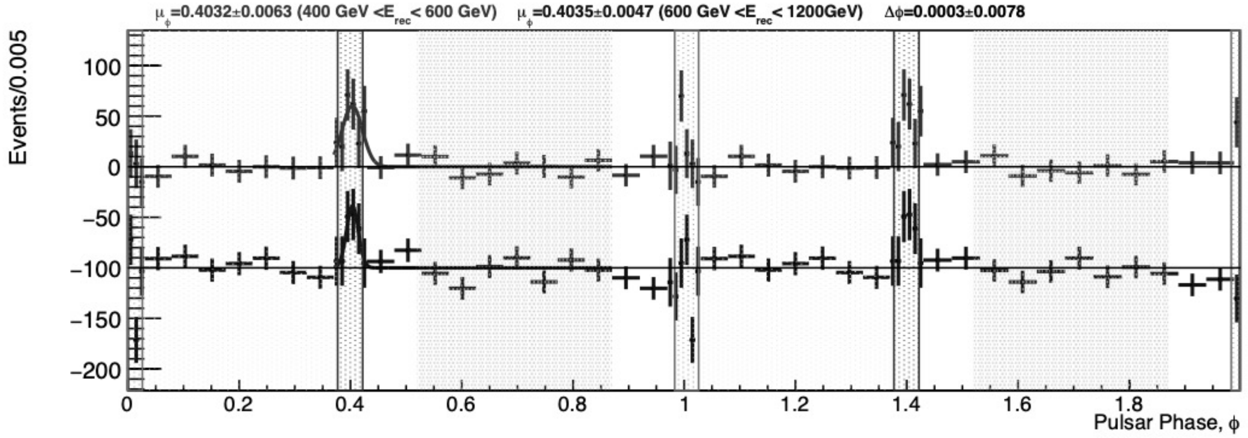


Fig. 7.9. The Crab pulsar folded light curve as measured by MAGIC. Two periods are shown, for high and low gamma-ray energies. The shaded areas define the pulse and inter-pulse regions. **Extracted from Ahnen *et al.* [2017b].**

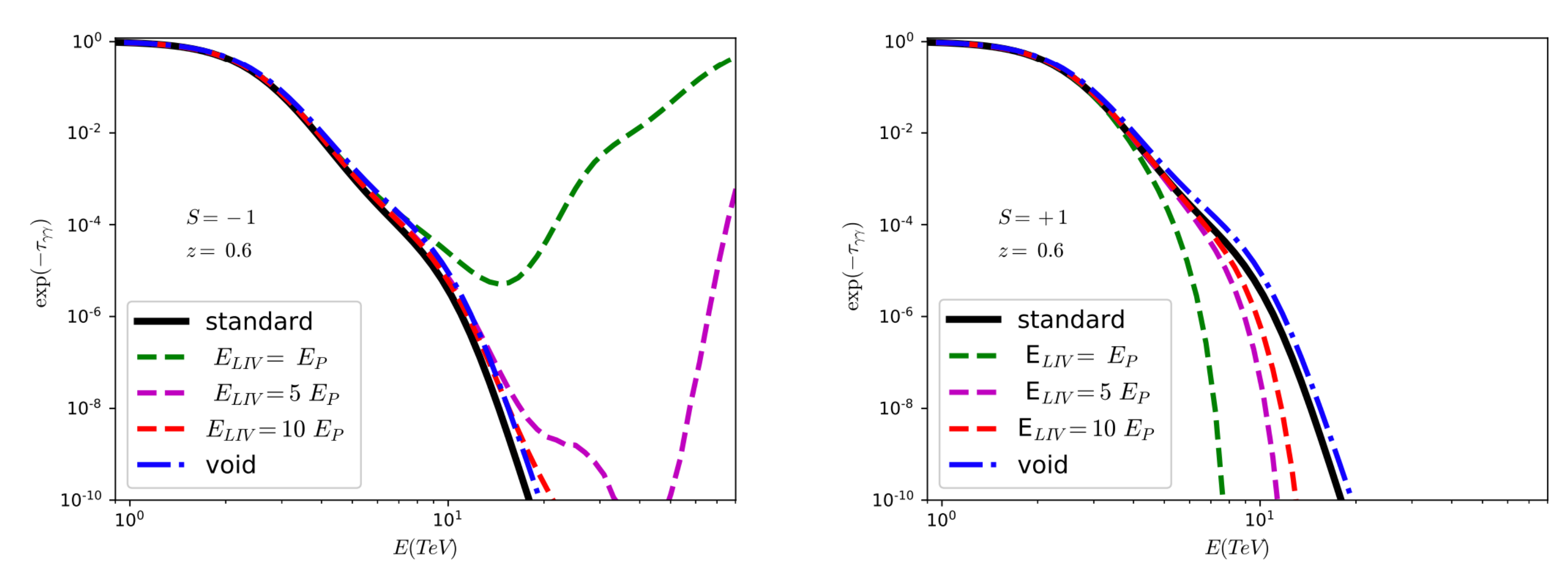
- Tiny effect at earth, but long-distances allows for accumulation: GRBs, AGN flares, pulsar
- Best limits for quadratic dependence

PAIR PRODUCTION CROSS-SECTION MODIFIED

$$\epsilon'_{\rm th} = \frac{2m_{\rm e}^2c^4}{E'(1-\cos\theta')} - \frac{\eta_n}{2(1-\cos\theta')}\left(\frac{E'}{E_{{\rm QG},n}}\right)^n E',$$

De los Heros, Terzic
https://arxiv.org/abs/2209.06531

- LIV modified the cross-section for pair production.



- Spectra distorted at high energies according to distance and LIV scale

HUBBLE CONSTANT

Let's digest this dinner

LIGHT FROM DISTANCE LADDER

- 1/ Compare the integrated galaxy light to the VHE optical depth [Biteau, Williams 2015 Astrophys.J. 812 (2015)]

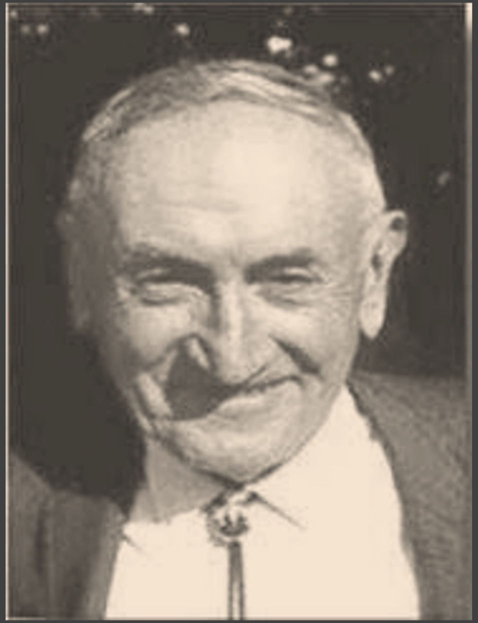
- 2/ Galaxy counts from VHE observation assuming EBL models [Dominguez, Prada 2013, Astrophys.J.Lett. 771]

- Compatible

To appear in Mukherjee, Zanin +

DINNER SERVED

“Fritz, what do you say?"



TASTE GOOD!

- Tens of astro-laboratories with varying distance, age, energy, B-field, stability → pick your favorite
- Several theories BSM involving gamma-rays (decay, annihilation, conversion) → pick your guy

BUT, WHO PAYS THE DINNER?

- Limits are model dependent (accuracy? likeliness?)
- Are we leaning anything at all…?

IACT 'LEFTOVERS'

- Several studies I showed used IACT leftovers!
- CTA will generate a huge amount of 'waste' that cannot be saved (PB)
- It is of utmost importance to
  - Envisage search pipeline for new hidden physics signal NOW!
  - Not to throw it away forever

AFTER DINNER, HAVING DRINKED TOO MUCH, GOING BACK HOME

Thanks!