DARK MATTER AND FUNDAMENTAL PHYSICS WITH cta

cherenkov telescope array

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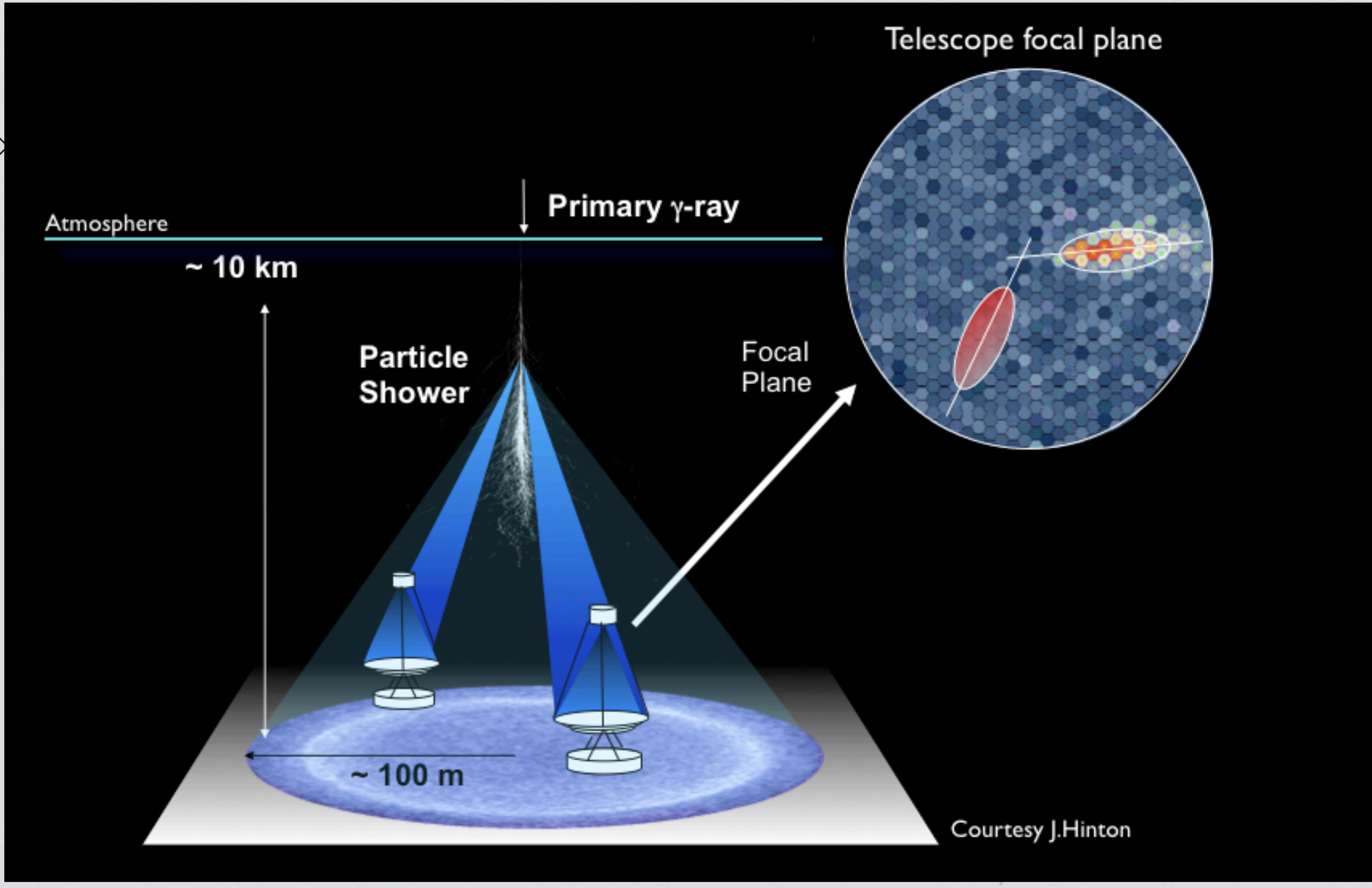
4th Workshop on Air Shower Detection at High Altitude, Napoli 2013

WHERE WE ARE, WHERE TO GO

Towards precision gamma-ray astronomy

The technique



Much larger area than Fermi-LAT, much more background from CRs

The current generation

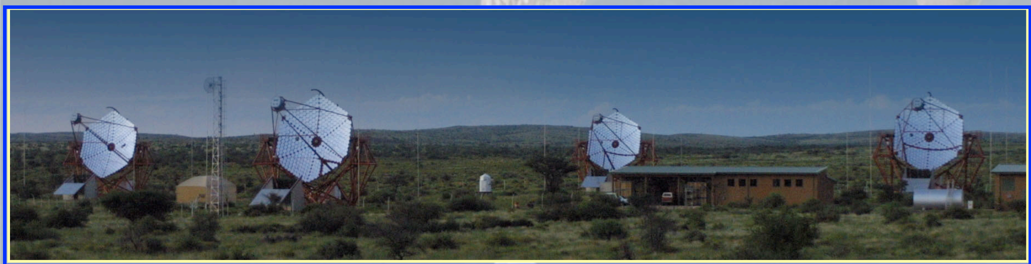
Array 2 telescopes
17m diameters
2200 m asl
>2004

VERITAS (Arizona, USA)

Array 4 telescopes of 12m diam.
Central mast mounting
1800 m asl
>2007

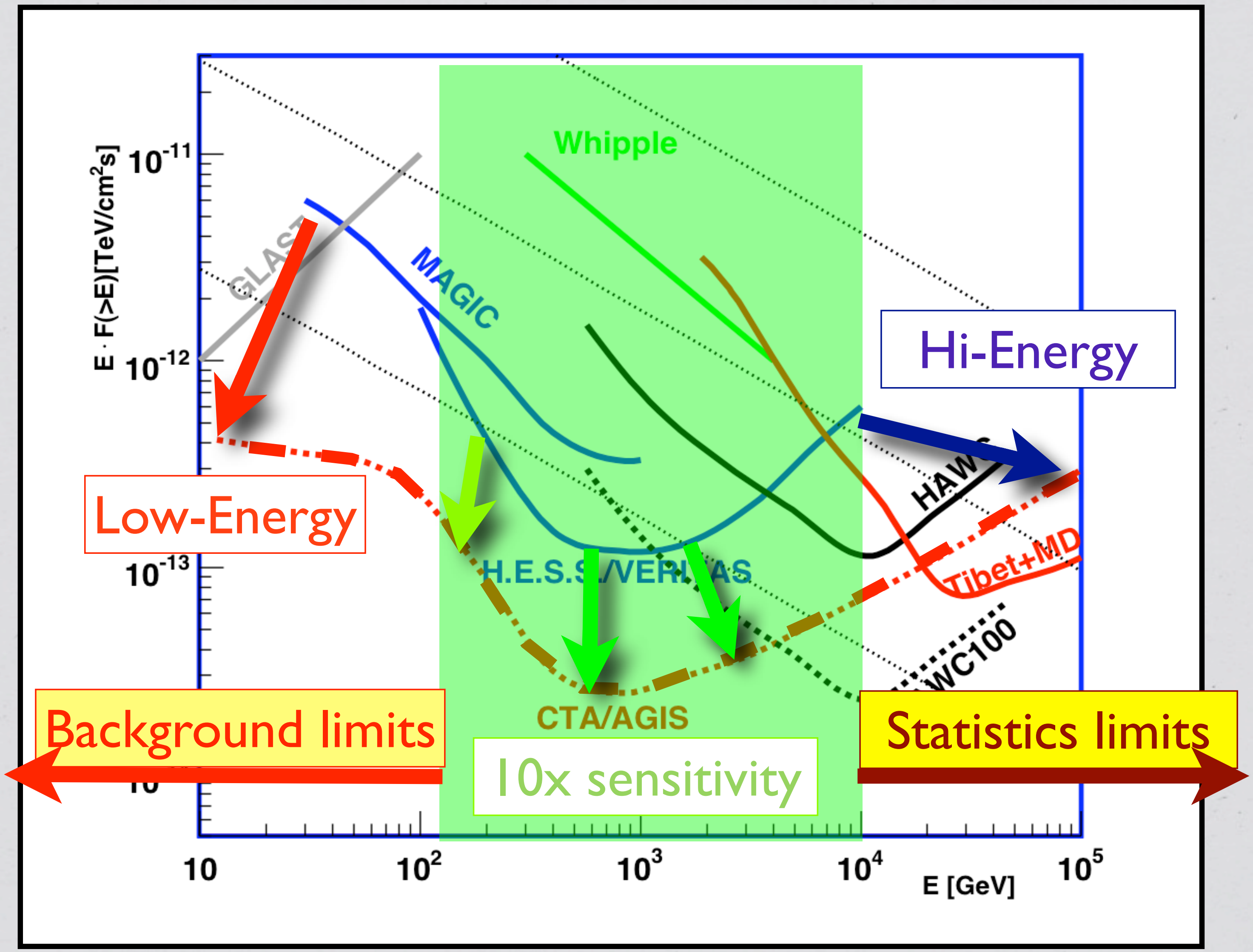
MAGIC (Canary Island, Spain)

HESS (Namibia)

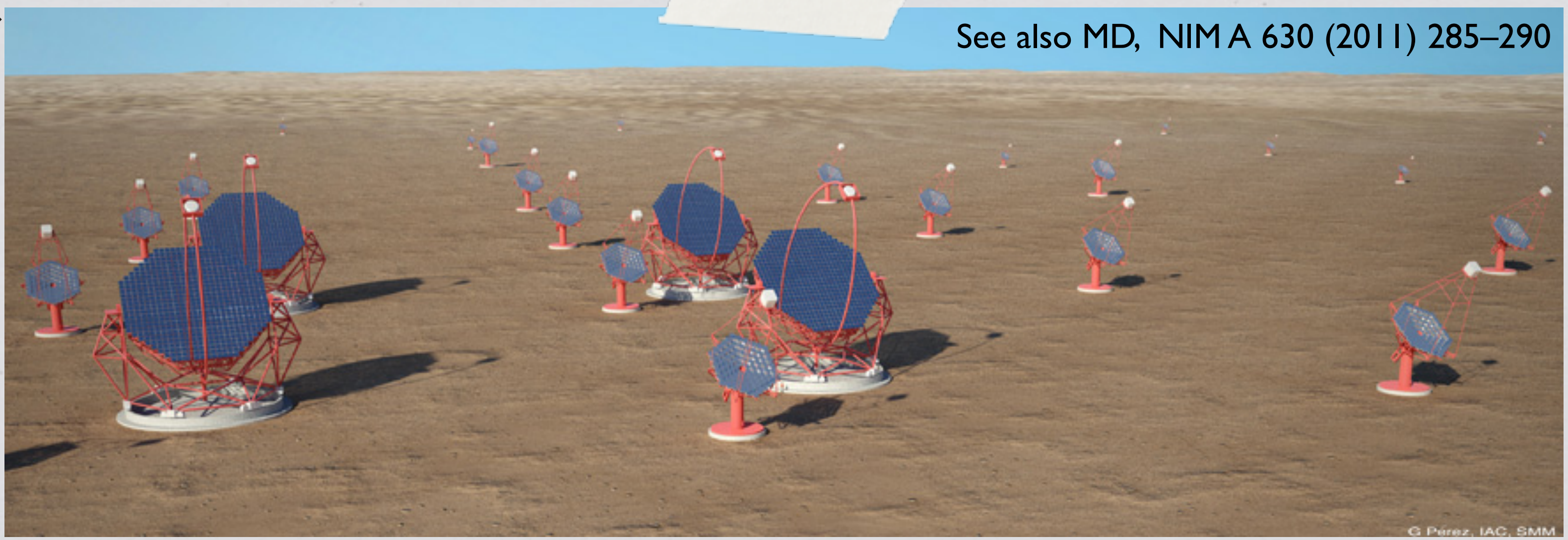


HESS I: Array 4 tel. of 12m
HESS II: 28m diameter (2013?)
1800 m asl
> 2003

IACTS runs on 3 regimes



We have a dream:
precision gamma-ray astronomy



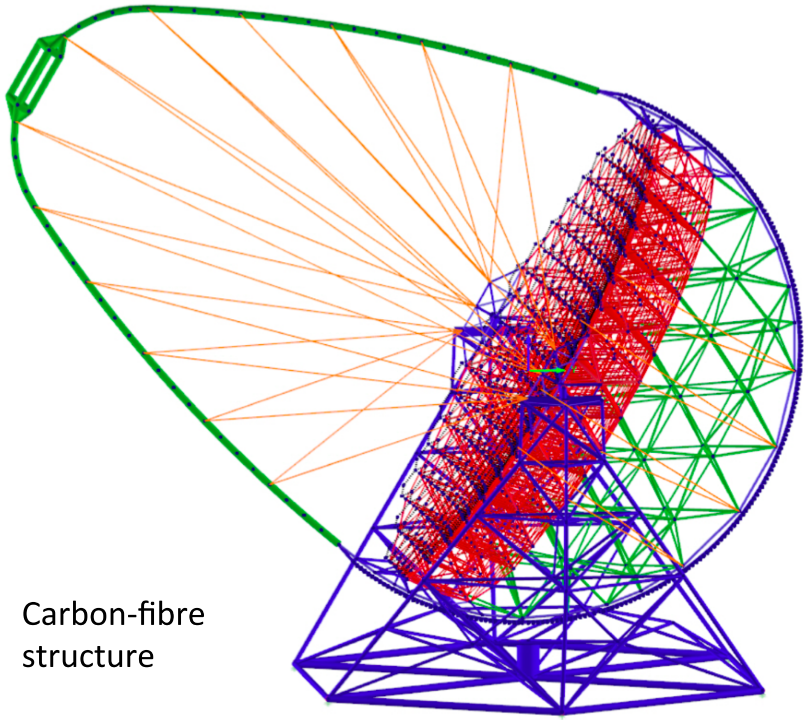
See also MD, NIM A 630 (2011) 285–290

- Have realized what current IACT are (almost) missing:
  - wide energy range
  - angular resolution, FOV
  - sensitivity
- We'll do this with telescopes of 3 different sizes over a large area

The Large Size Telescope(s)

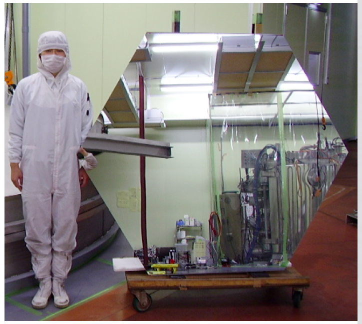
- From 10 GeV to 1 TeV

27.8 m focal length
4.5° field of view
0.1° pixels

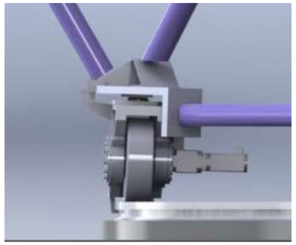


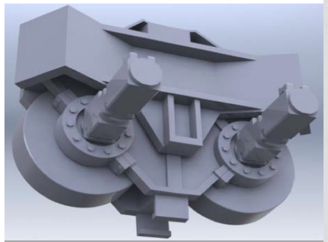
Carbon-fibre
structure

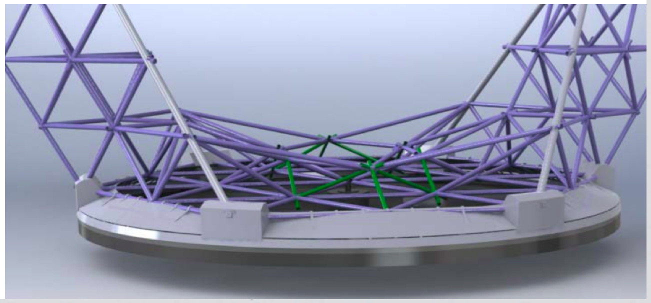
400 m² dish area
1.5 m sandwich
mirror facets



On (GRB) target
in < 20 sec.

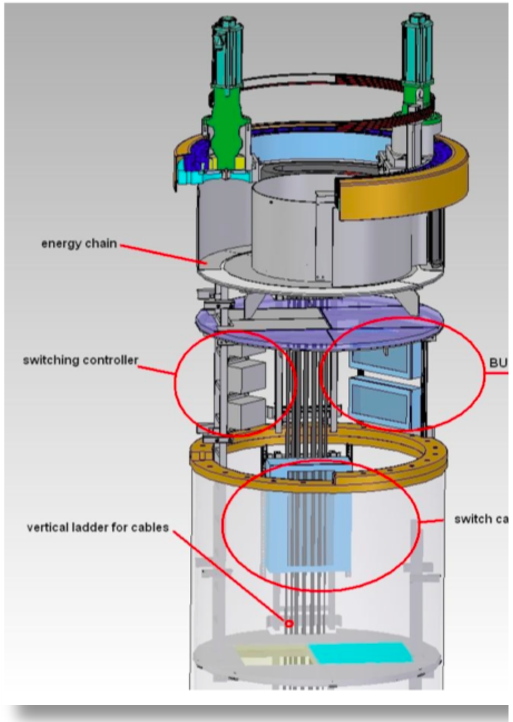




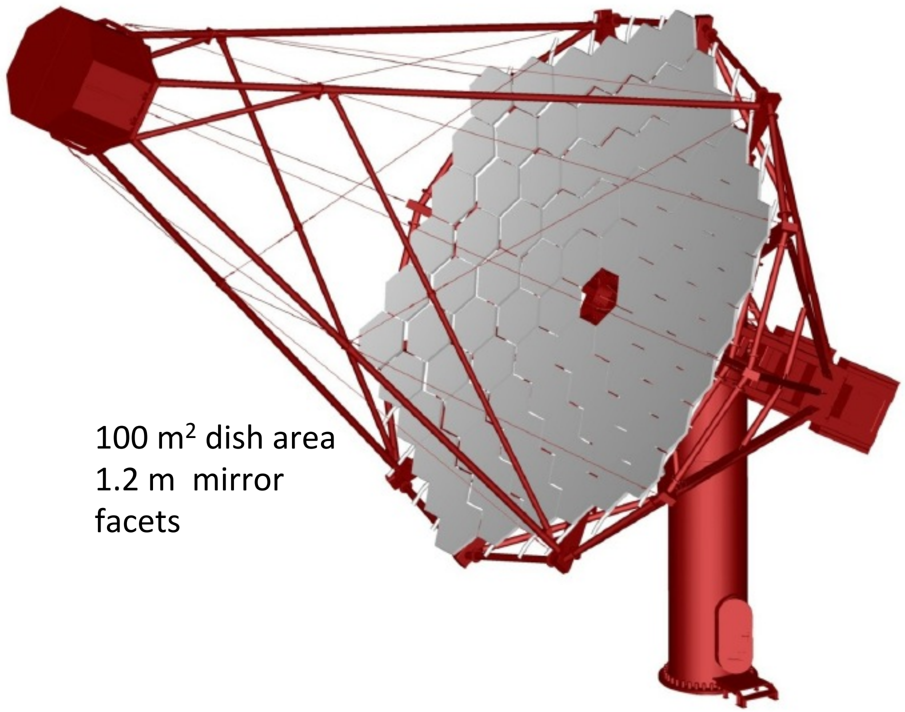


The Medium Size Telescope

- From 100 GeV to 10 TeV



16 m focal length
7-8^{o} field of view
0.18^{o} pixels

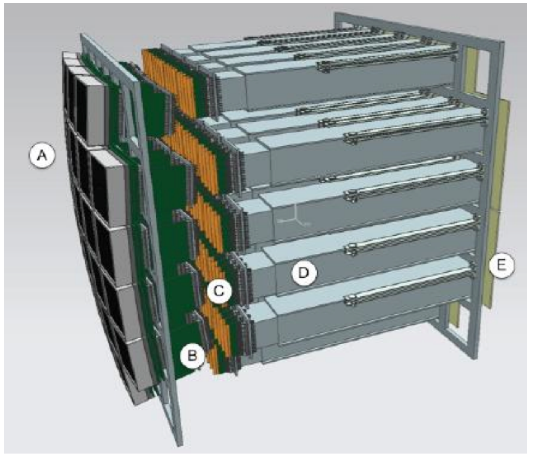


100 m^{2} dish area
1.2 m mirror facets

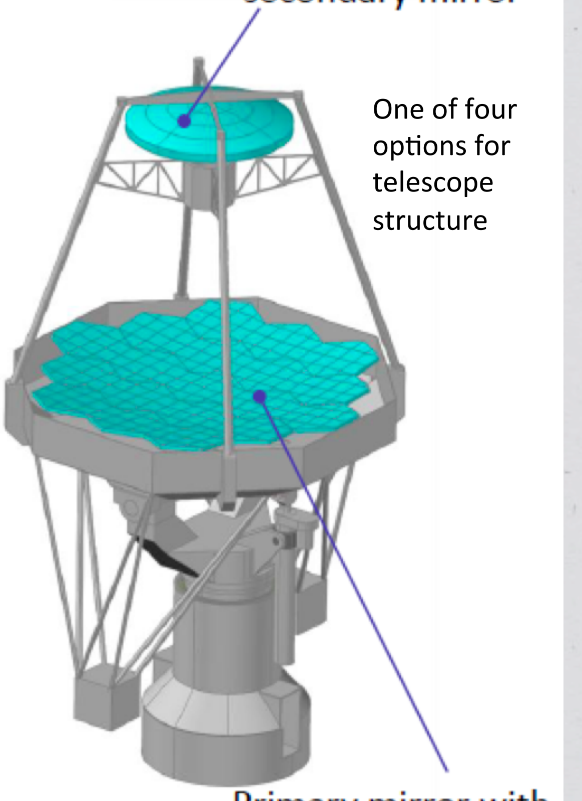
The Small Size Telescope SC

- From 10 to 100 TeV

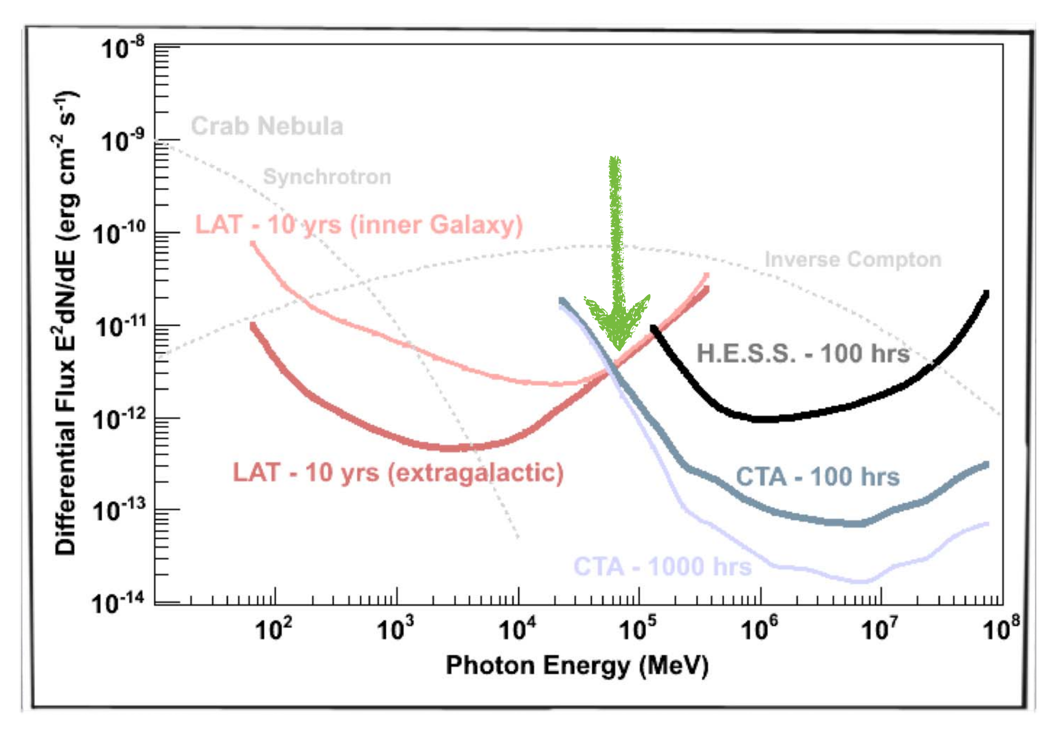
Multi-Anode PMT camera option



Under study:
dual-mirror optics with compact photo sensor arrays
single-mirror optics
PMT-based and silicon-based sensors
➜ Not yet conclusive which solution is most cost-effective



The sensitivity of course



Funk, Hinton

Differential

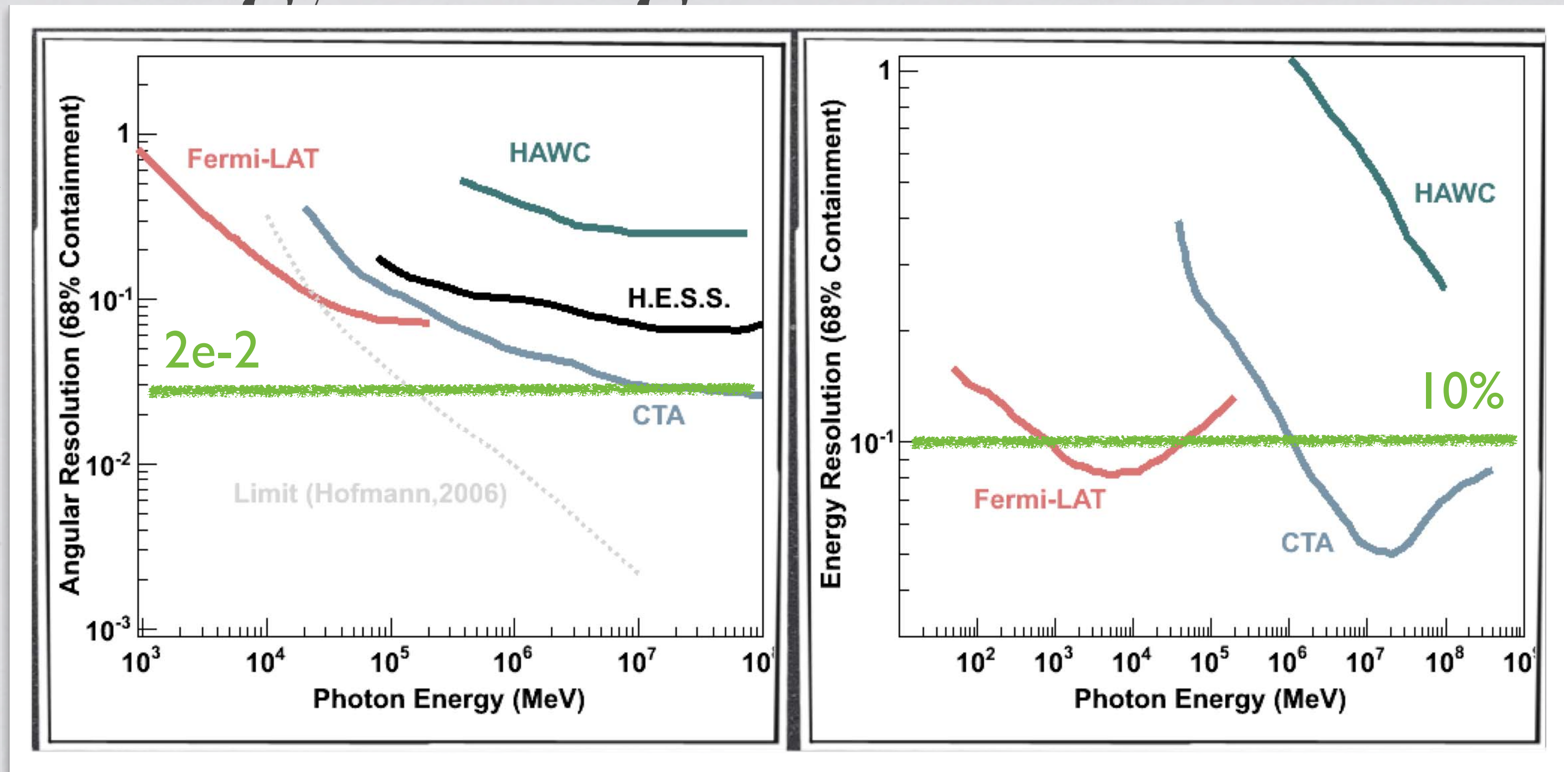
MORE SOURCES
1000 sources expected
(10x now)

VARIABILITY
sub-min scale variation
follow-up obs.

MORPHOLOGY
Galaxy clusters
SNR interactions with
local matter
Galactic Center

CONSOLIDATE TeV ASTRO**NOMY**
VHE full-skymaps
VHE source catalogs

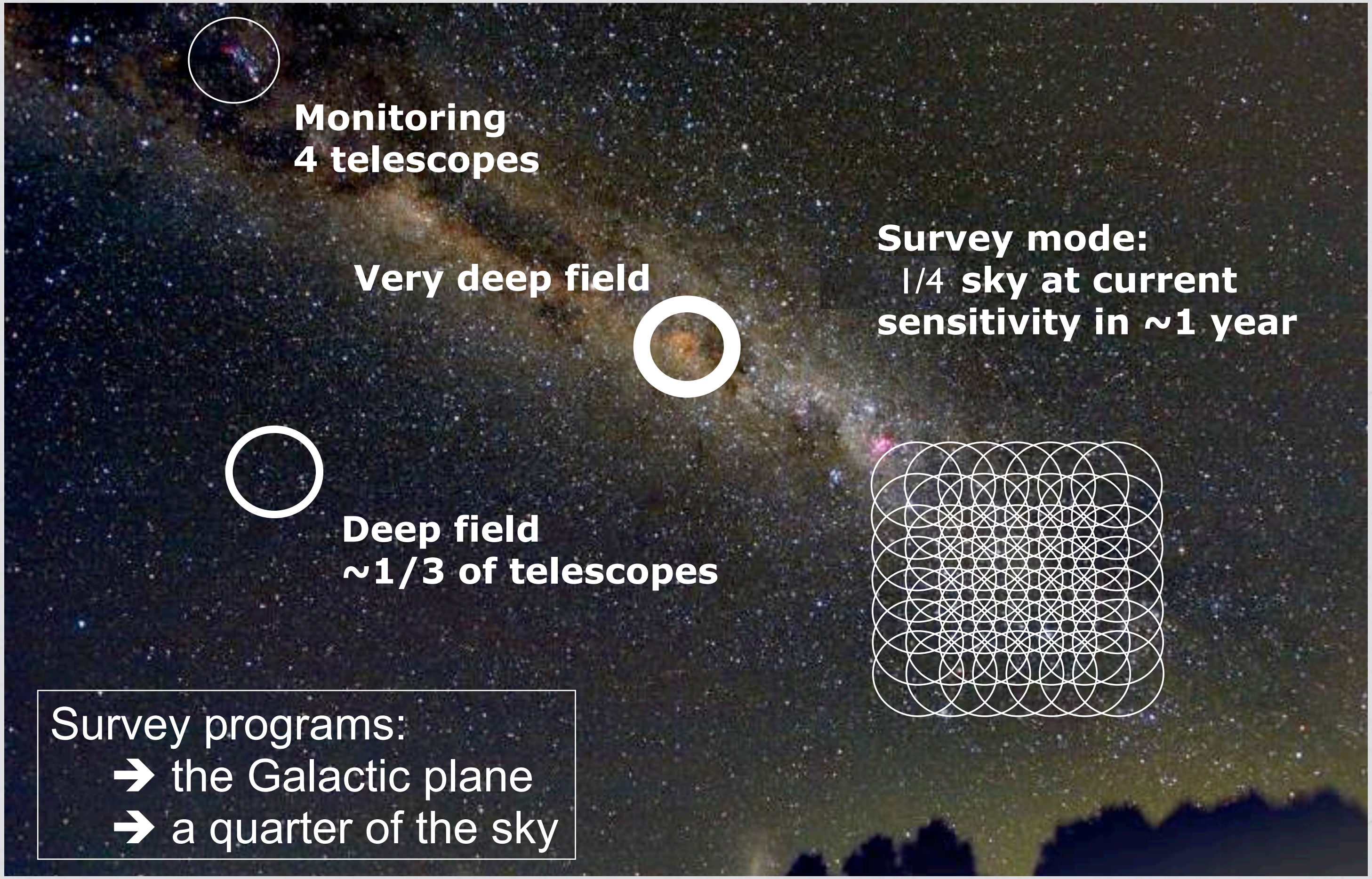
Energy and angular resolution



Funk, Hinton 2012

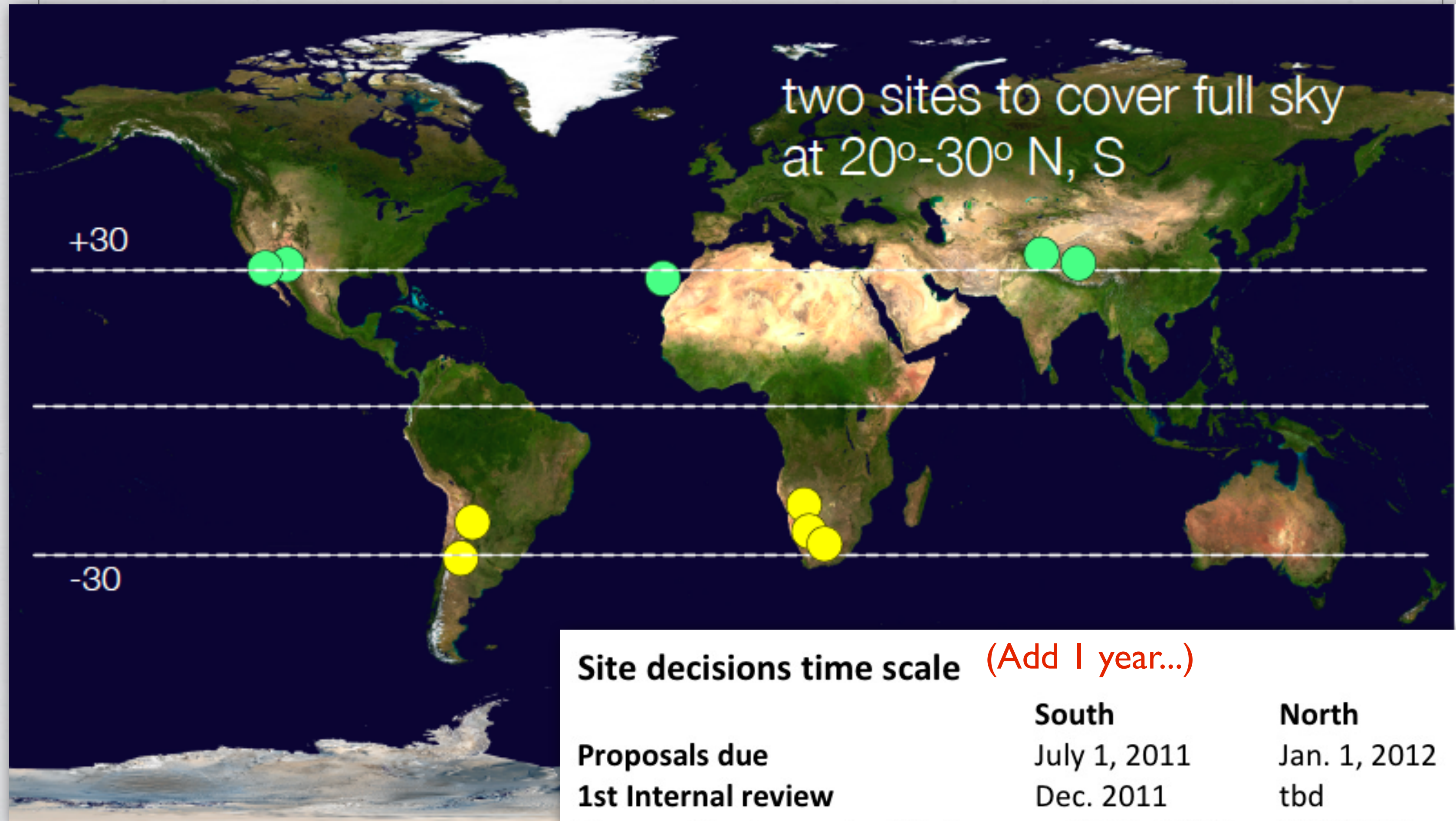
- Angular resolution for morphology
  - source confusion
  - acceleration mechanisms
- Energy resolution
  - Spectral features
  - Spectral discriminations in case of overlapping signals

Flexible observation modes



- Interesting for fundamental physics

Where is CTA?



Site decisions time scale (Add 1 year...)

	South	North
Proposals due	July 1, 2011	Jan. 1, 2012
1st Internal review	Dec. 2011	tbd
Proposal to downselect 2 sites	until Mid 2012	Mid 2012
1st RB Site Committee review	Mid 2012	Mid 2012
Proposed ranking of sites	until Jan. 2013	until Jan. 2013
2nd RB Site Committee review	Jan 2013	Jan 2013

The CTA Collaboration grows

- HESS + MAGIC + VERITAS collaborations + Europe + world interest (Japan, Argentina)
- US AGIS (Advanced Gamma-ray Imaging System) converged to CTA
- already ~150 institutes, ~25 countries (~ 500 scientists)
- Regular meetings since 2007.

CTA singled out in Aspera/APPEC

European funding agencies support construction of CTA

Preparatory phase

Design Concepts for the Cherenkov Telescope Array

The CTA Consortium

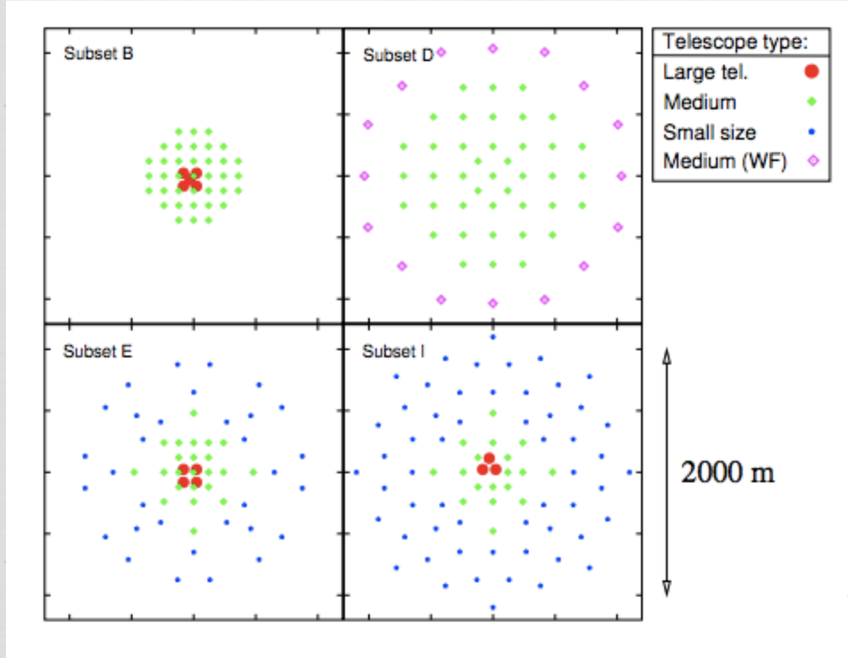
(Submitted on 22 Aug 2010 (v1), last revised 21 Oct 2010 (this version, v2))

Ground-based gamma-ray astronomy has had a major breakthrough with the impressive results obtained using systems of imaging atmospheric Cherenkov telescopes. Ground-based gamma-ray astronomy has a huge potential in astrophysics, particle physics and cosmology. CTA is an international initiative to build the next generation instrument, with a factor of 5-10 improvement in sensitivity in the 100 GeV to 10 TeV range and the extension to energies well below 100 GeV and above 100 TeV. CTA will consist of two arrays (one in the north, one in the south) for full sky coverage and will be operated as open observatory. The design of CTA is based on currently available technology. This document reports on the status and presents the major design concepts of CTA.

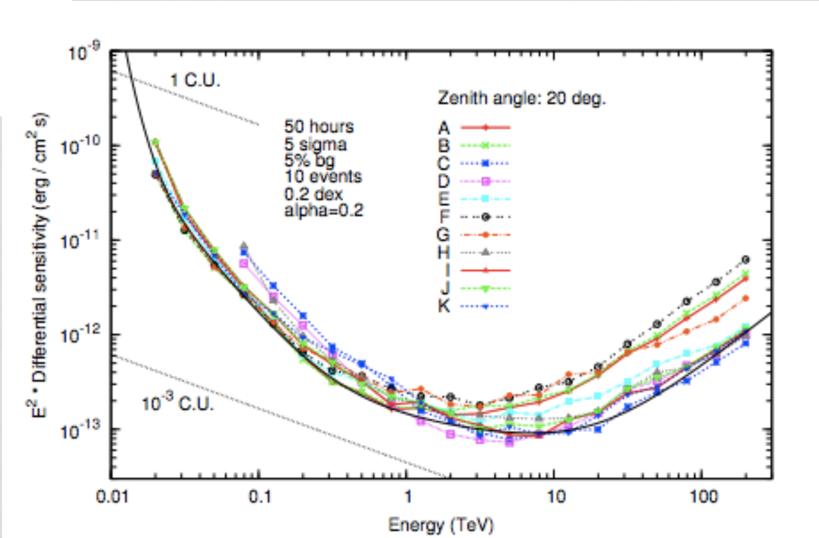
Comments: 120 pages, 54 figures, 5 tables (with minor editorial changes)
Subjects: **Instrumentation and Methods for Astrophysics (astro-ph.IM)**; High Energy Astrophysical Phenomena (astro-ph.HE)
Cite as: arXiv:1008.3703v2 **[astro-ph.IM]**

- FP7-supported Preparatory Phase: Fall 2010 – Fall 2013
  - ➜ Technical design, sites, construction and operation cost
  - ➜ Legal, governance and finance schemes
  - ➜ Small + medium-sized telescope prototypes
- Aim for
  - start of deployment in early 2014
  - first data in 2016/17
  - base arrays complete in late 2018

Test the array layout designs



- Different nr. of LST, MST and SST telescopes
- Different spacing
- Same cost



all leads to different sensitivity

Physics shapes the CTA array

Title	Author	Referees	Status	Draft Link	Accepted Link
DM & Fundamental Physics	M. Doro et al.	A. Murphy, J. Conrad	3/12 Submitted	Submitted version (pdf)	
AGN	H. Sol et al.	G. Romero, M. Persic	4/12 Submitted	Submitted version (pdf)	
EBL	D. Mazin et al.	H. Sol, M. Persic	3/12 Submitted	Submitted version (pdf)	
GRBs	S. Inoue et al.	M. Teshima, G. Romero	24/6/12 SAPO comments to authors	Draft v5.1 (pdf)	
CR/SNRs/Mol.Cloud + Extended/Diffuse Sources	S. Gabici et al.	W. Hofmann, J. Conrad, B. Khelifi	3/12 Submitted	Submitted version (pdf)	
Pulsars&PWN	E. de Ona et al.	B. Khelifi, A. Murphy	2/12 Submitted	Submitted version (pdf)	
MQ/Binaries	J.M. Paredes et al.	R. Ong, M. Persic	2/12 Submitted	Submitted version (pdf)	
Surveys + MW	G. Dubus et al.	H. Sol, M. Martinez	2/12 Submitted	Submitted version (pdf)	
MC	J. Hinton et al.	M. Doro, R. Ong	1/6/12 Draft to SAPO	Draft (pdf)	
Optical Intensity Interferometry with the Cherenkov Telescope Array	D. Dravins et al.	W. Hofmann	04/12 Accepted	Submitted version (pdf)	Accepted version (pdf)
Comparison of Fermi-LAT and CTA in the region between 10-100 GeV	S. Funk, J. Hinton	W. Hofmann, B. Khélifi	2/12 Submitted	Submitted version (pdf)	Accepted version (pdf)
Introducing the CTA Concept	W. Hofmann, M. Martinez	A. Murphy, R. Ong, G. Romero,	22/6/12 Draft to SAPO	Draft (pdf)	

- To be published soon!

THE APP SPECIAL ISSUE

Dark Matter and Fundamental Physics searches with CTA

CTA prospects

MD et al. on behalf of CTA) 2012

Dark Matter and Fundamental Physics with the Cherenkov Telescope Array

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Abstract

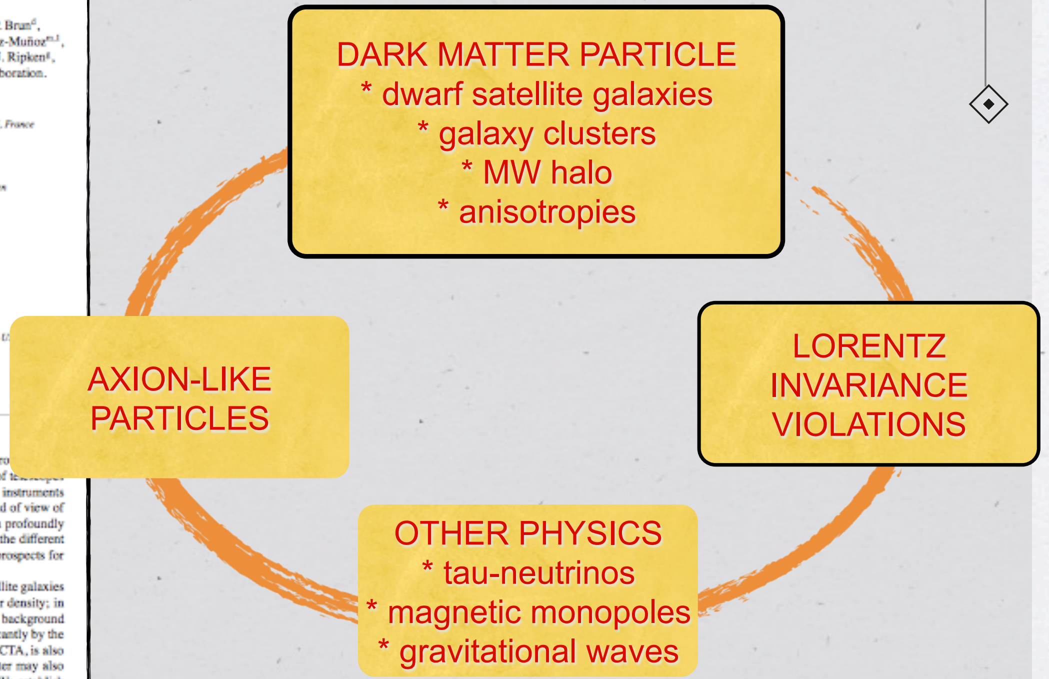
The Cherenkov Telescope Array (CTA) is a project for a next-generation observatory for very high energy (GeV–TeV) gro gamma-ray astronomy, currently in its design phase, and foreseen to be operative a few years from now. Several tens of telescopes of 2–3 different sizes, distributed over a large area, will allow for a sensitivity about a factor 10 better than current instruments such as H.E.S.S, MAGIC and VERITAS, an energy coverage from a few tens of GeV to several tens of TeV, and a field of view of up to 10 deg. In the following study, we investigate the prospects for CTA to study several science questions that can profoundly influence our current knowledge of fundamental physics. Based on conservative assumptions for the performance of the different CTA telescope configurations currently under discussion, we employ a Monte Carlo based approach to evaluate the prospects for detection and characterisation of new physics with the array.

First, we discuss CTA prospects for cold dark matter searches, following different observational strategies: in dwarf satellite galaxies of the Milky Way, which are virtually void of astrophysical background and have a relatively well known dark matter density; in the region close to the Galactic Centre, where the dark matter density is expected to be large while the astrophysical background due to the Galactic Centre can be excluded; and in clusters of galaxies, where the intrinsic flux may be boosted significantly by the large number of halo substructures. The possible search for spatial signatures, facilitated by the larger field of view of CTA, is also discussed. Next we consider searches for axion-like particles which, besides being possible candidates for dark matter may also explain the unexpectedly low absorption by extragalactic background light of gamma-rays from very distant blazars. We establish the axion mass range CTA could probe through observation of long-lasting flares in distant sources. Simulated light-curves of flaring sources are also used to determine the sensitivity to violations of Lorentz Invariance by detection of the possible delay between the arrival times of photons at different energies. Finally, we mention searches for other exotic physics with CTA.

Keywords: CTA, Dark Matter, Dwarf satellite galaxies, Galactic centre, Galactic halo, Galaxy clusters, Axion-like Particles, Lorentz Invariance Violations, Neutrino, Magnetic monopoles, Gravitational Waves

[1]Sent off-print requests to Michele Doro (michele.doro@uab.cat) and Jan Conrad (conrad@fysik.su.se)

Preprint submitted to Astroparticle Physics *June 11, 2012*



TEST MODEL AGAINST CTA PROPOSED ARRAYS

Caveats - prospects for DM

- IF (DM is a particle) {
  - IF (DM is only of one kind) {
    - IF (it is a WIMP) {
      - IF (it is Majorana particle) {
        - IF (no co-annihilation is there) {
          - IF (the profile is cusp or core) {
            - IF (the subhaloes play a role) {
              - IF (we know the annihilation channel) {

then you can make a (robust) prediction!

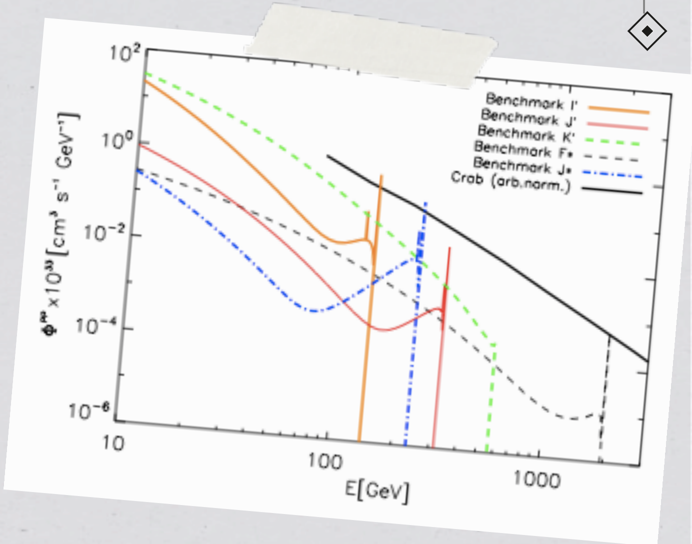
}}}}}}}}

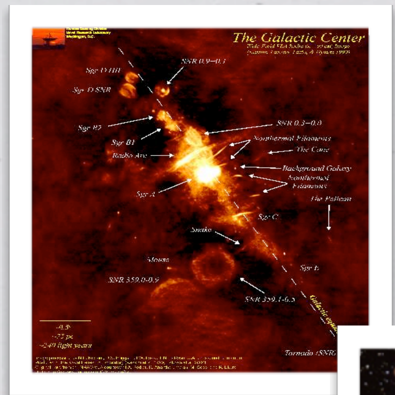
- How to define pessimistic, optimistic and realistic?
- Minimum requirements?
- Which CTA configuration is the best?

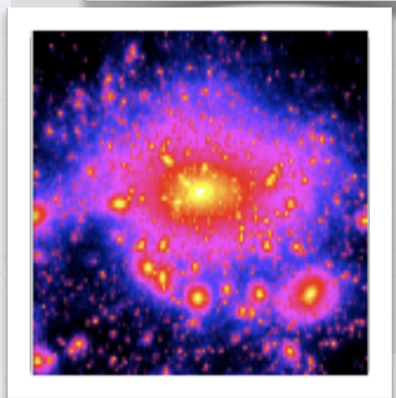
DARK MATTER

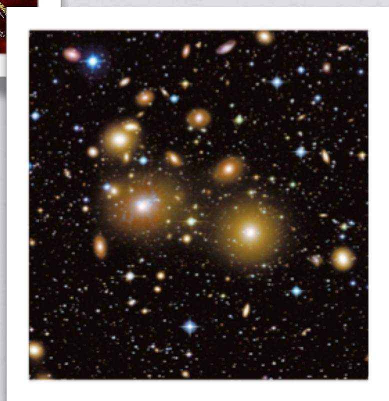
IACT as a (robust) probe for DM

- Few important facts:
  - gamma-ray are expected in many DM model annihilation/decay products
  - they point-back to the source
  - expected universality of DM spectra at different targets
  - DM cutoff in gamma-ray spectra (smoking gun)





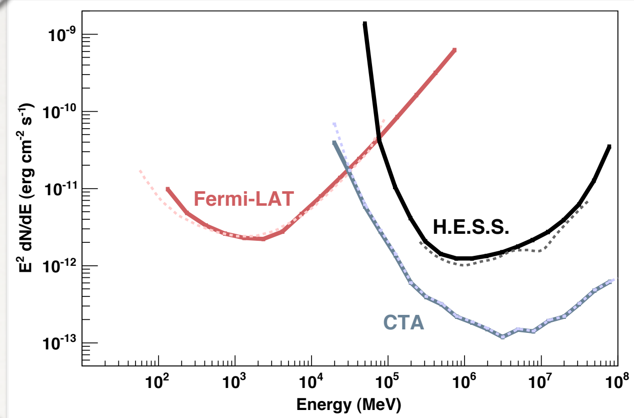


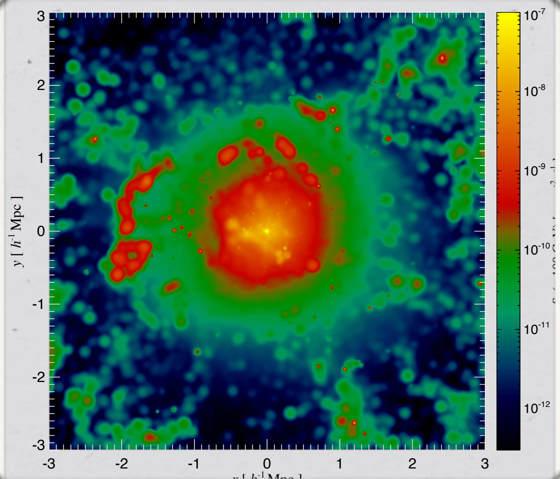


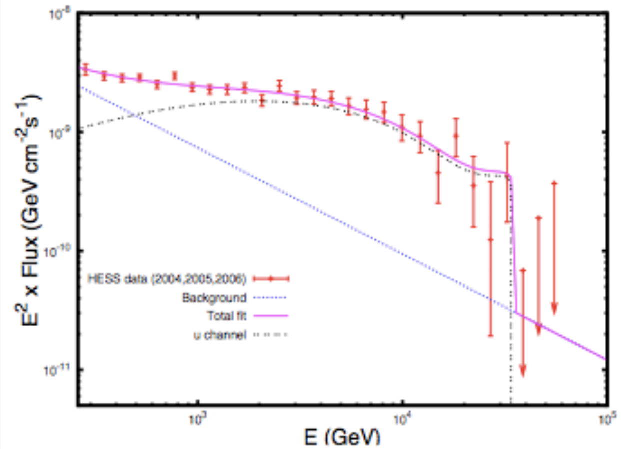
- The Galactic Center and halo
- The dwarf satellite galaxies
- The galaxy cluster
- Other dark spots (IMBH, UFOs)

CTA is welcome for DM searches

- Of course, the **sensitivity**
- **Energy threshold:** more photons per DM annihilation
- **Energy resolution**: Spectral features and discrimination with astrophysical sources
- **FOV and angular resolution**: morphology

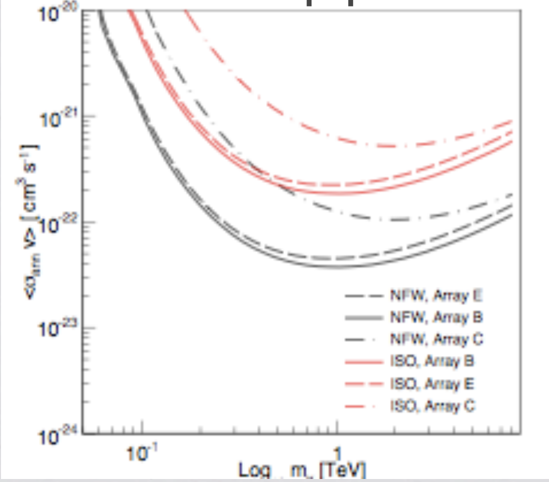




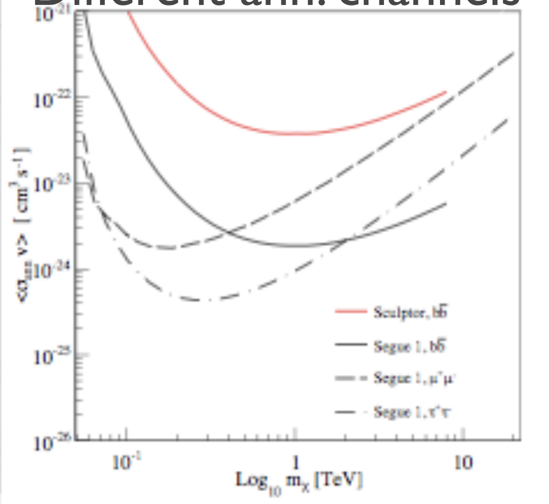


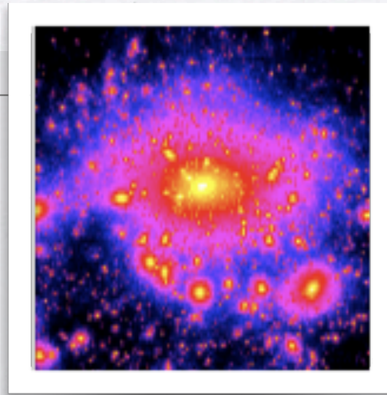
Dwarf spheroidal galaxies

Core-cusp profile



Different ann. channels

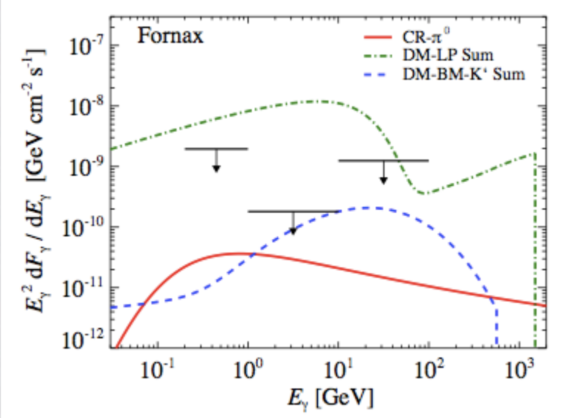


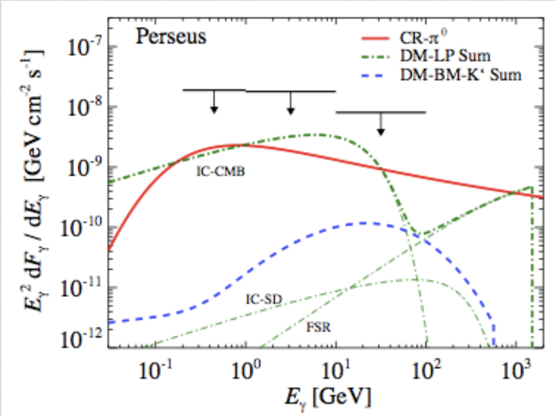


DSG	Dec. [deg]	D [kpc]	$\bar{J}$ [$\mathrm{Gev}^{-2}\,\mathrm{cm}^{-5}$]]	Profile
Ursa Minor	+44.8	66	2.2×10^{18}	NFW
Sculptor	−83.2	79	8.9×10^{17}	NFW
Sculptor	"	"	1.8×10^{17}	ISO
Draco	+34.7	87	7.1×10^{17}	NFW
Willman 1	+51.1	38	8.4×10^{18}	NFW
Segue 1	+16.1	23	1.7×10^{19}	Einasto

- Annihilation spectrum changes prospects
- Improvements wrt to current IACTs is minimal, but analysis not yet optimized on these objects

Galaxy clusters

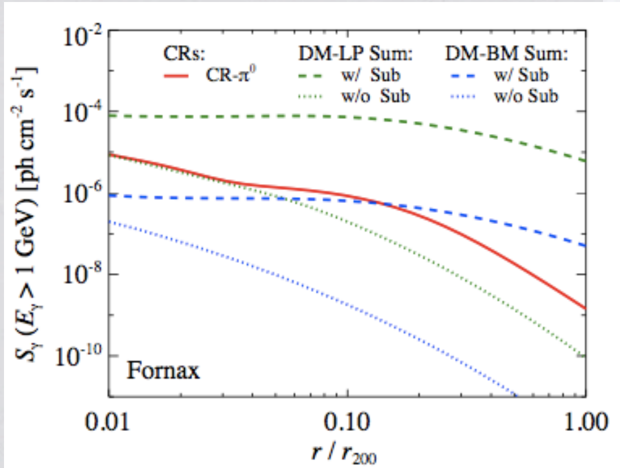




CR-emission is promising in some clusters even with current generation of IACTs

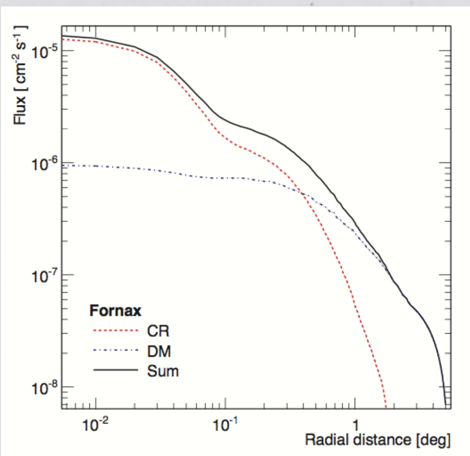
- Complex objects with several gamma-ray sources
  - individual cluster galaxies, see e.g. NGC1275 and IC310 in Perseus by MAGIC
  - CR-induced emission (after pion decay)
  - DM-induced emission from halo

We used:
FORNAX
PERSEUS



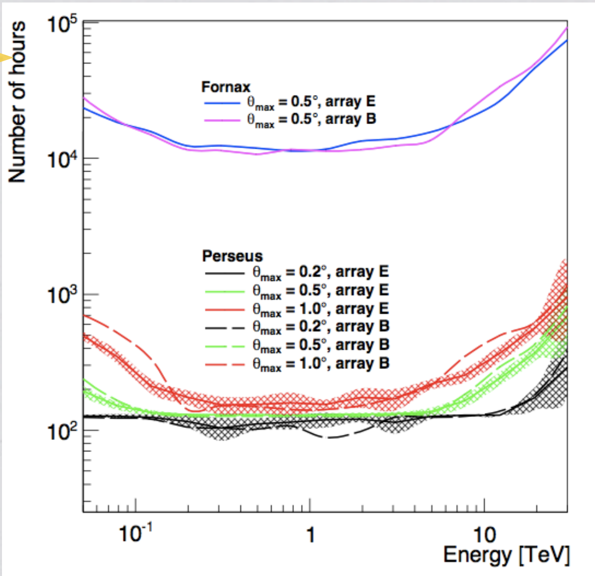
DM emission contributions from substructures
* may be impressive (>1000x)
* can be very extended (5+ deg)

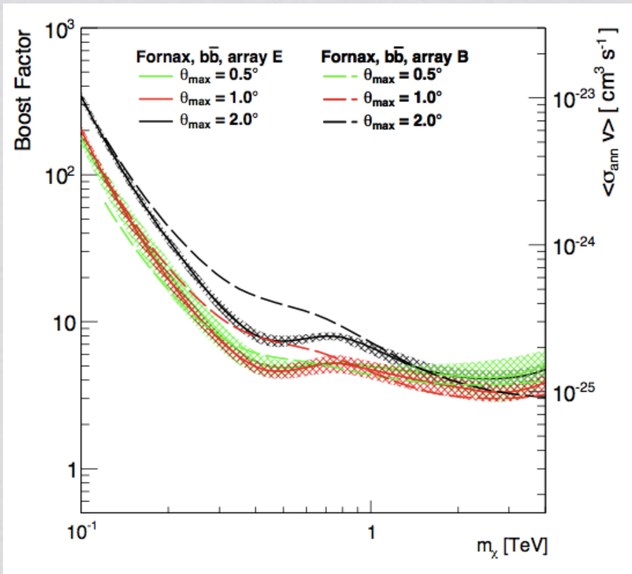
Galaxy clusters



- DM and CR and individual galaxies
  - Different **spectral features**
  - Different **spatial features**
- Analysis cluster-dependent → work to do
- We need to understand very extended MC (5+ deg)

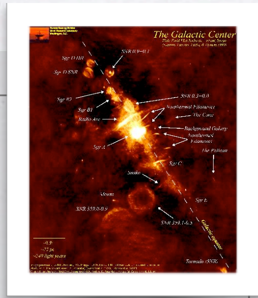
CR only





DM only

Galactic Center halo

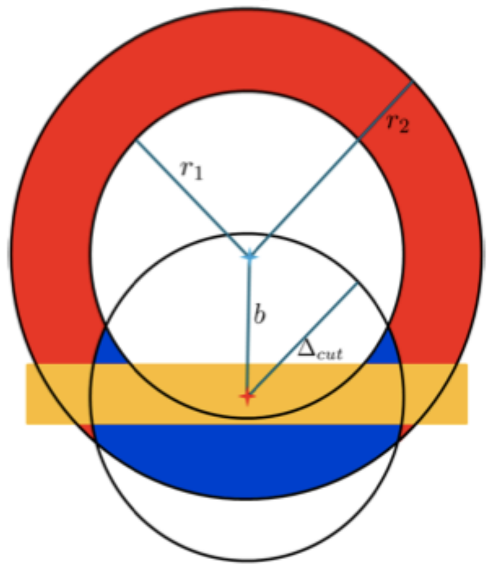


- Galactic center obvious target for DM searches, but crowded region
- Galactic halo at short distance from GC is well-defined
- HESS envisaged a strategy: Abramowski+, et al. PRL 106 (2011) 161301–+.

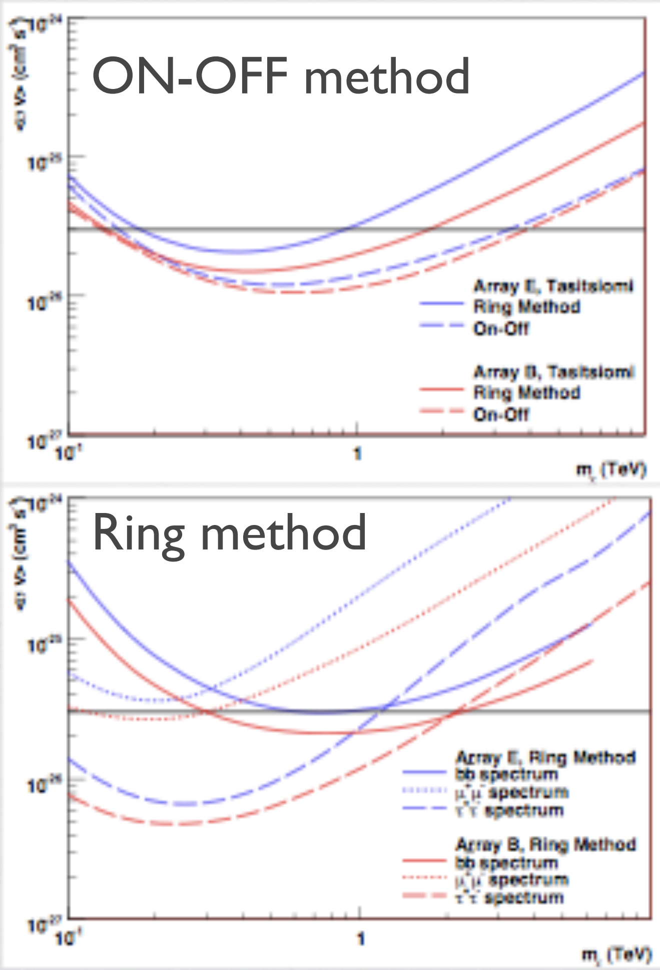
Observation strategy

1. ON-OFF (more sensitive, less robust background control)

2. *Ring Method:*
- The red star denotes the GC
- The blue star marks the pointing of CTA .
- The signal region in blue
- The red annulus is background



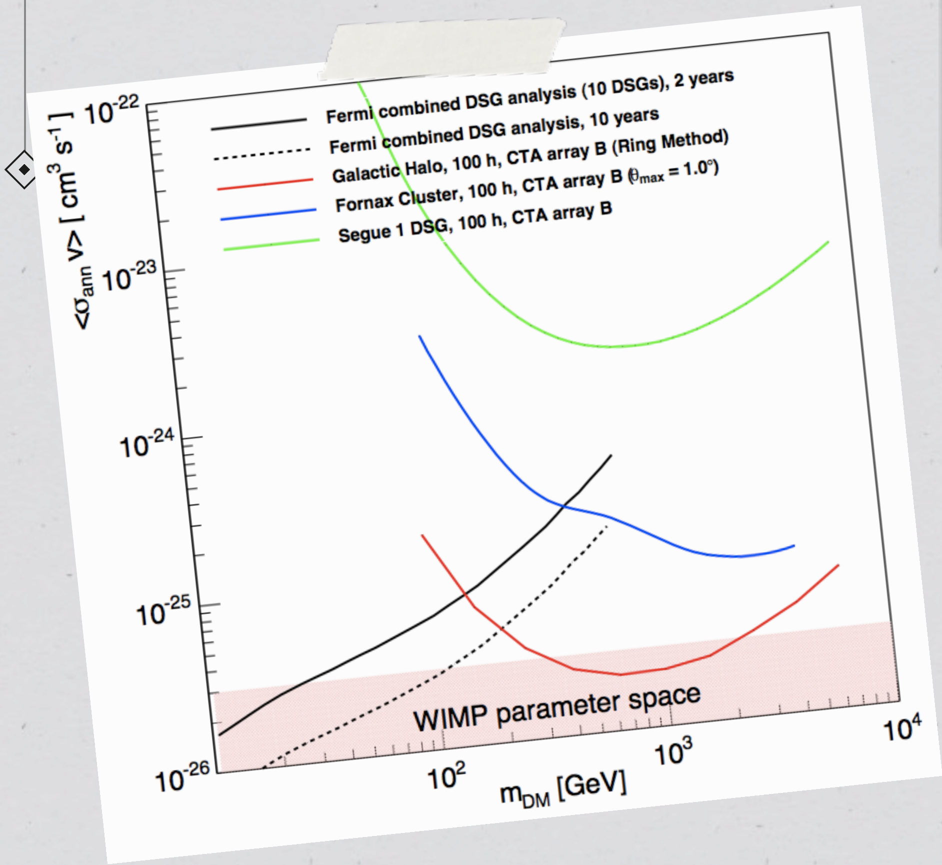
A very good result here



- J-factor from Aquarius
- Two methods tested
  - ON-OFF
  - Ring method
- Several spectra tested
- B, C, E array tested

Exclusion curve below WIMP classical <σ v> (best CTA prospects!)

Comparison



Segue 1 dpsh

Fornax cluster

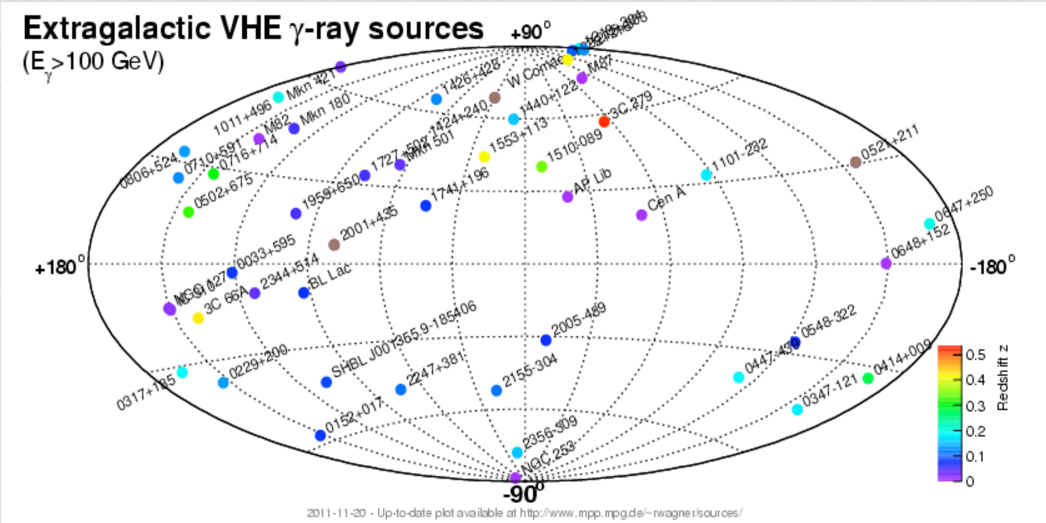
Galactic Halo

- First time **we curb the parameter space**
- **Analysis not yet optimized as well as CTA performance**
- For DM mass above few hundreds GeV CTA outperforms Fermi-LAT

MUCH MORE FUN(DAMENTAL)

Astronomy helps astrophysics

- CTA will observe for sure a lot of AGN (expected 100s), implying:
  - Farther AGN (thanks to low energy threshold)
  - Flares with denser time bins (thanks to sensitivity)
  - Flares with larger energy lever-arm (thanks to energy range)



- And hopefully
  - Longer flares
  - Stronger flares
  - GRBs...

With a population of AGNs and their flares
we can do much fundamental physics (for free)!

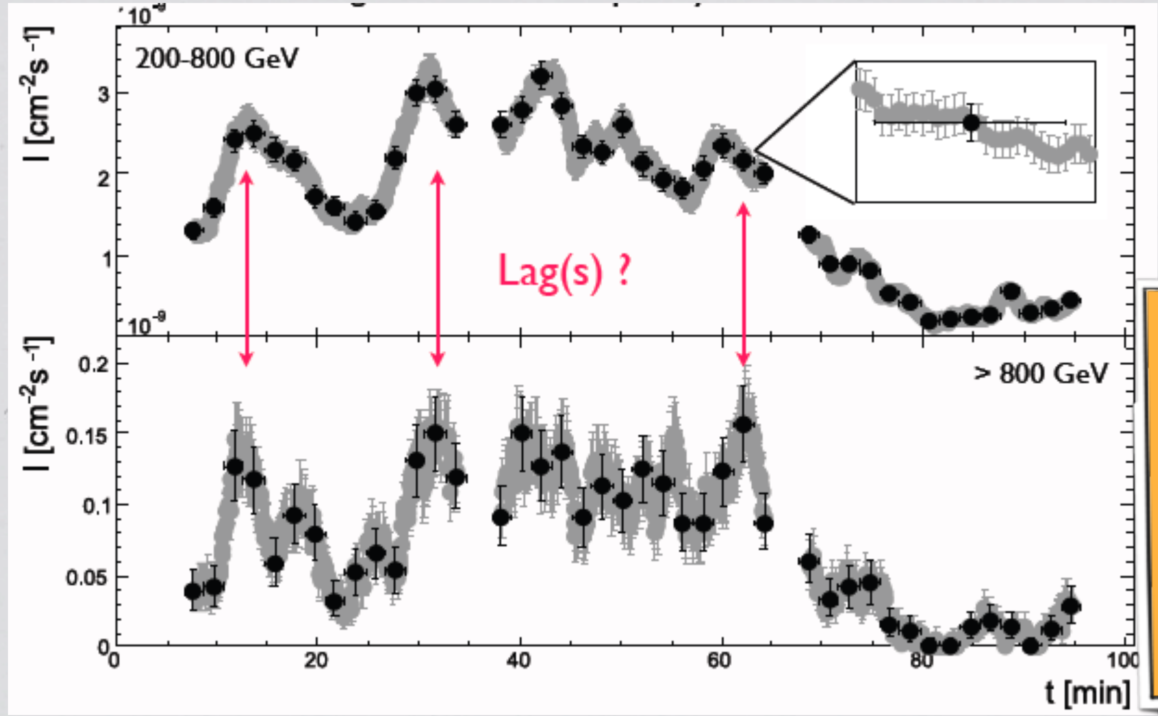
Quantum gravity induced LIV

- QG induced space-time non-unitary dispersion relation:

$$c^2p^2 = E^2\left(1 \pm \xi_1(E/E_P) \pm \xi_2^2(E/E_P)^2 \pm \ldots\right).$$

- photons at different energies travels at different speed: cosmological distances provide amplification

$$\Delta t \simeq \left(\frac{\Delta E}{\xi_\alpha E_P}\right)^\alpha \frac{L}{c}$$



PKS 1255 flare (HESS)

CTA has potential to see such effects every day!

1st or 2nd order?

Time-lag dependence on energy can be linear, **square**, …

$$v = c\left(1 \pm \xi \frac{E}{M_P} \pm \zeta^2 \left(\frac{E}{M_P}\right)^2 + \ldots\right)$$

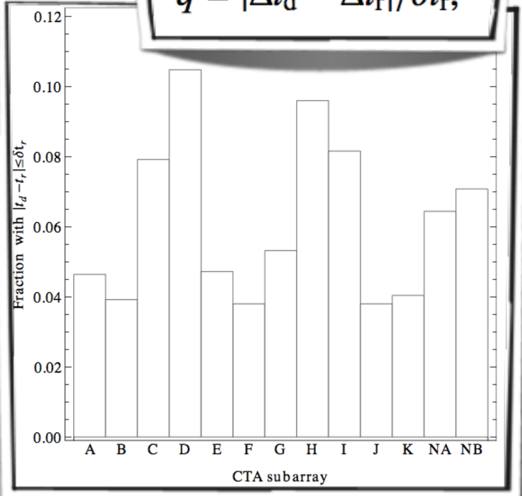
$$\frac{\Delta t}{\Delta E^2} \simeq \frac{3\zeta^2}{2M_P^2 H_0} \int_0^z \frac{(1+z')^2 dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

at TeV, square-dependence means large lever-arm

Telescope	M_P/ξ [GeV]	M_P/ζ [GeV]
MAGIC	0.03×10^{19}	5.7×10^{10}
H.E.S.S.	0.21×10^{19}	6.4×10^{10}
Fermi-LAT	1.50×10^{19}	3.0×10^{10}

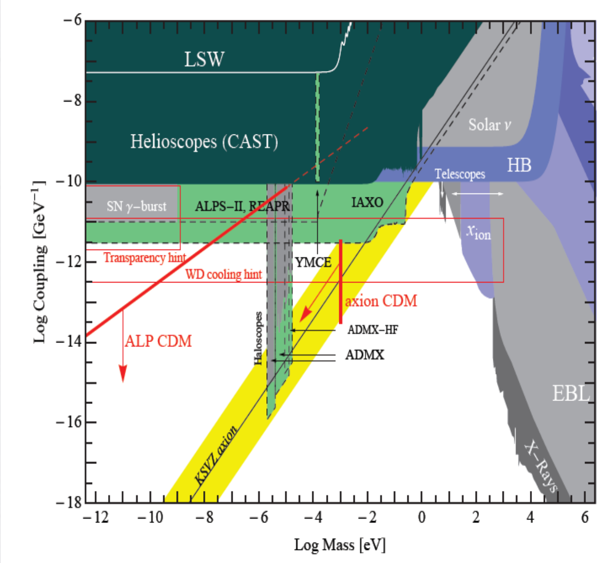
CTA will put much stronger constraints in this regime

$$q = |\Delta t_d - \Delta t_r| / \delta t_r,$$

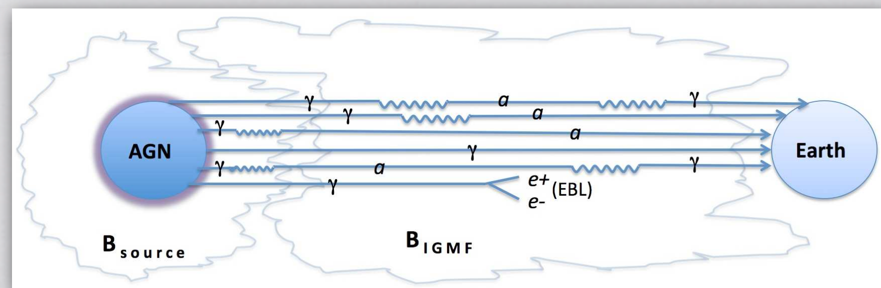


- **2500 light curves (pair) simulated with various properties**
  - redshift 0.03--0.6, slope 1--2.5
  - flux state, observational time, pointing times
- Results:
  - q<1 (6%), q<2 (72%), q<3 (99%)

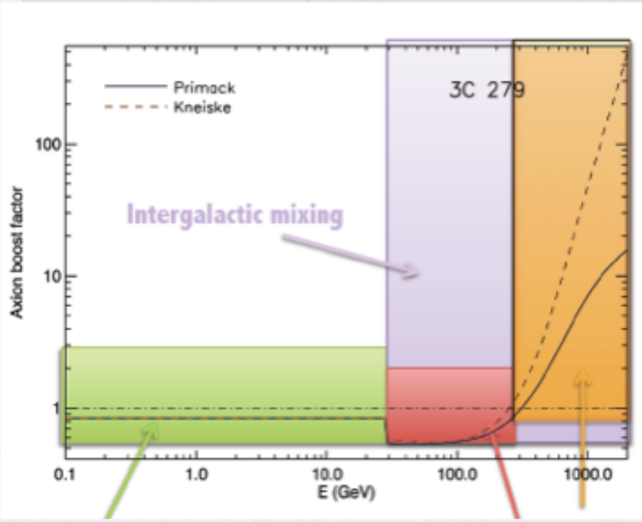
Axion-like particle searches



- Axion-like particle cure several physicists' pains
  - strong-CP problem
  - (a fraction of) DM
  - low-EBL problem/hard far AGN spectra

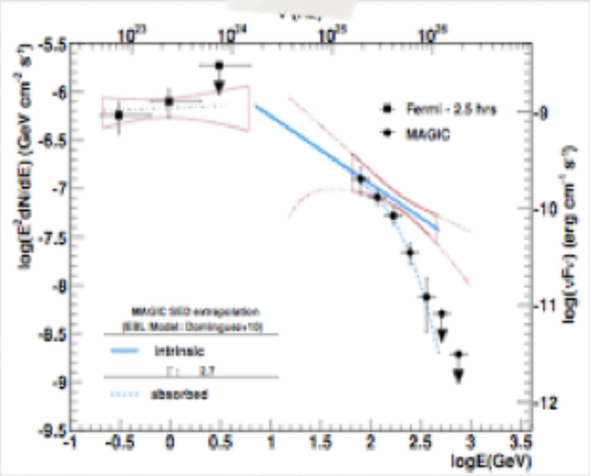


- Photon/ALP oscillation in magnetic field
  - photon/ALP conversion at source (strong B)
  - photon/ALP conversion at IGMF (low B)



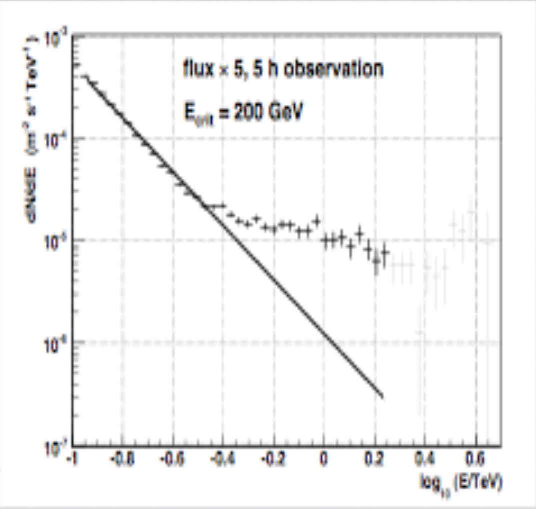
- Mass and coupling
  - Mass u.l.: < 0.02 eV (CAST)
  - Inv. coupling > 0.114 x 1011 GeV

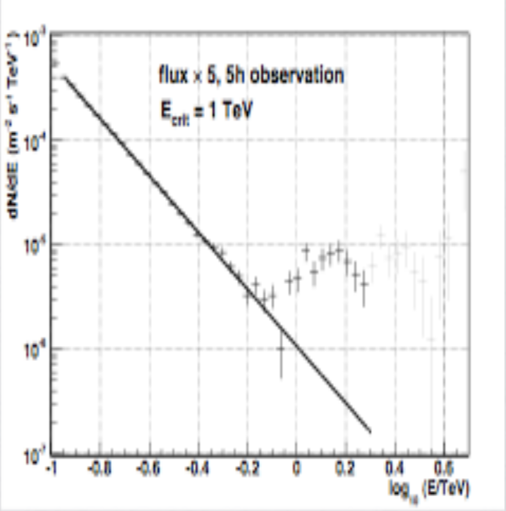
Test-case: PKS 1222+21 (4C +21.35)



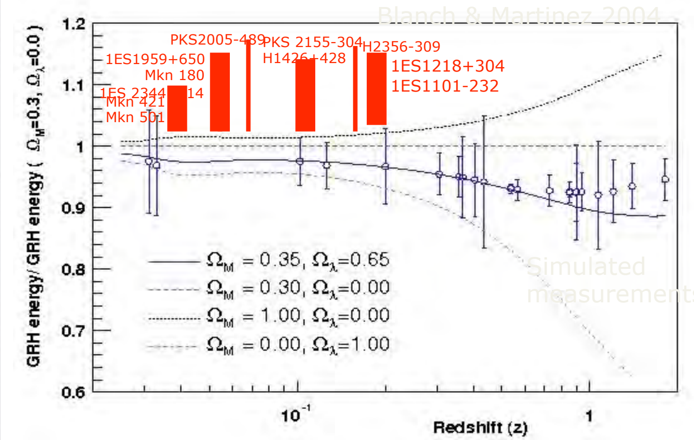
- FSRQ discovered by MAGIC in 2010
  - 2nd farthest VHE source: z=0.432
  - MAGIC+Fermi: can fit to single power-law -2.7(0.3) between 3 and 400 GeV
  - No-sign of any cutoff
  - Most rapid variation ever observed at VHE: Flux doubling-time 8.6min!
  - ~1/2h flare duration

METHOD:
* un-broken power-law
* different flux level
* different flare duration
* E_{crit} scan 0.1-10 TeV
* EBL corrected (Dominguez+)



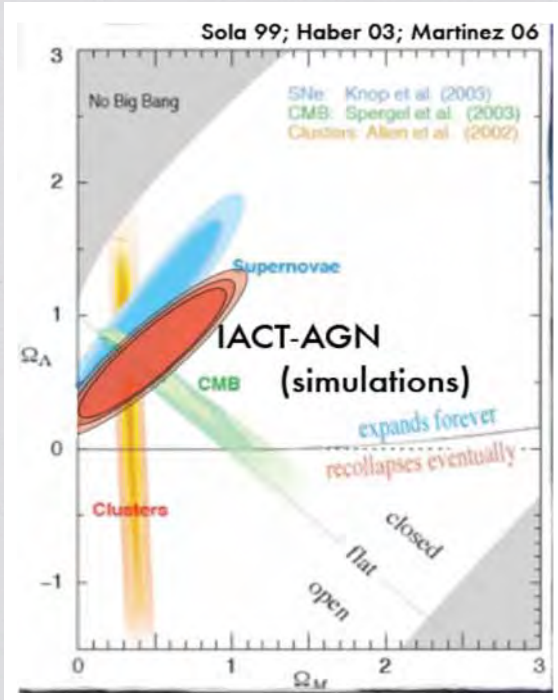


Cosmology with AGN



$$\frac{dl}{dz} = \frac{c}{H_0} \frac{1}{(1+z)\left[(1+z)^2(\Omega_M z+1) - \Omega_\Lambda z(z+2)\right]^{\frac{1}{2}}}$$

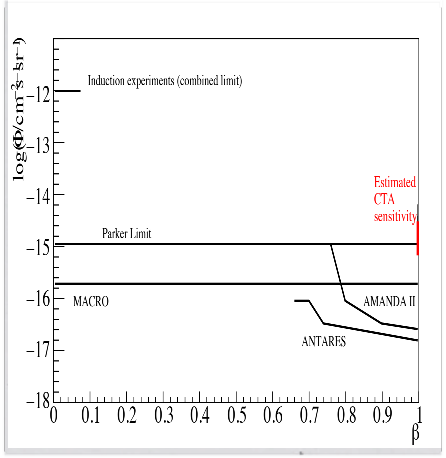
$$\tau(E,z) = \int_0^z dz' \frac{dl}{dz'} \int_0^2 dx \frac{x}{2} \int_{\frac{2m^2c^2}{Ex(1+z)^2}}^{\infty} d\varepsilon \cdot n(\varepsilon,z')\sigma\left[2xE\varepsilon(1+z)^2\right]$$



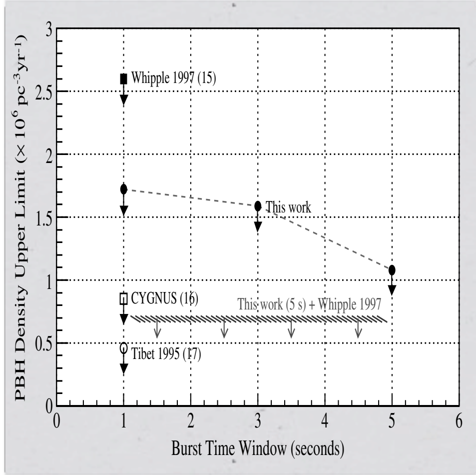
- GRH depends on Hubble constant and cosmological densities. Modulo the EBL, the GRH might be used as a distance estimator (Prandini+2011)
- GRH behaves differently than other observables already used for cosmology measurements.
- EBL constraints are paving the way for the use of AGN to fit Omega_M and Omega_L. Measurements of 20 AGN at z>0.2, cosmological parameters can be fitted.
- Results might improve the 2004 Supernovae result

More dust under the carpet

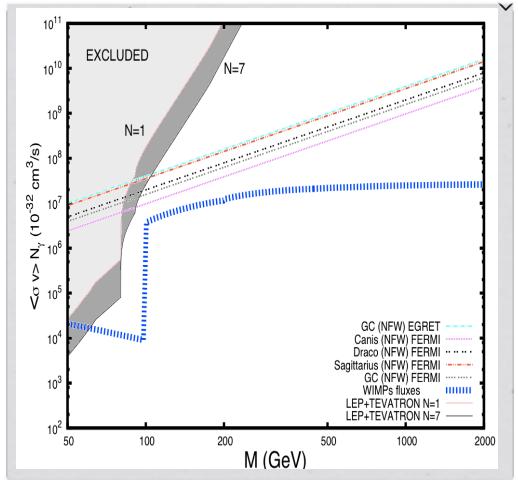
- Is there any strange event in the background we reject (but save on disk)?



Magnetic monopoles (peculiar images)



Primordial black holes (flaring events)



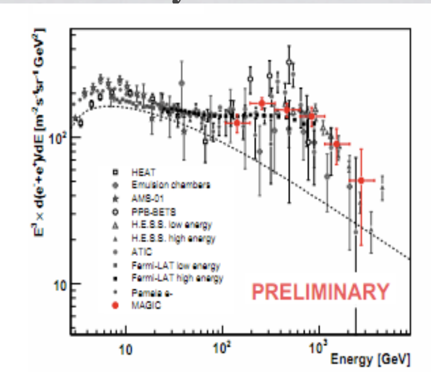
Branons (a-la WIMP)

CTA will collect >100 Hz * 1000 h/year

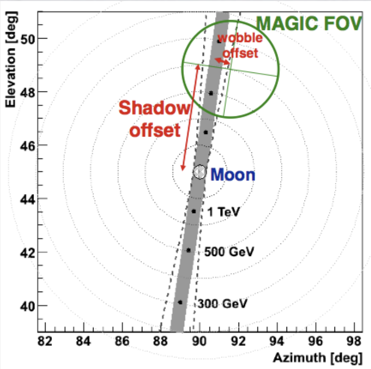
about 10^9 events/year...

A multi-purpose experiment

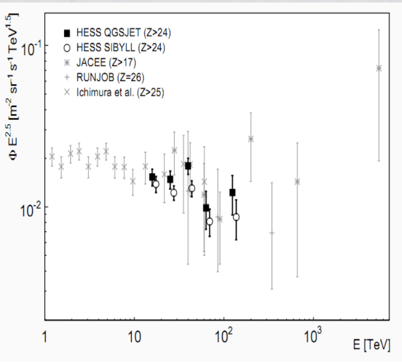
- CTA is a gamma-ray detector? Not only
  - It is a cosmic-ray detector



All-electron searches

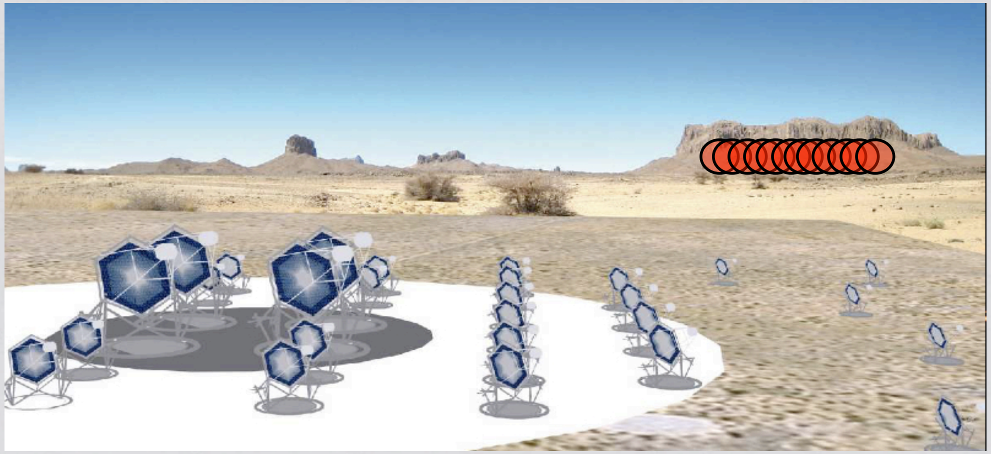


Electron/Positron?



Heavy nuclei

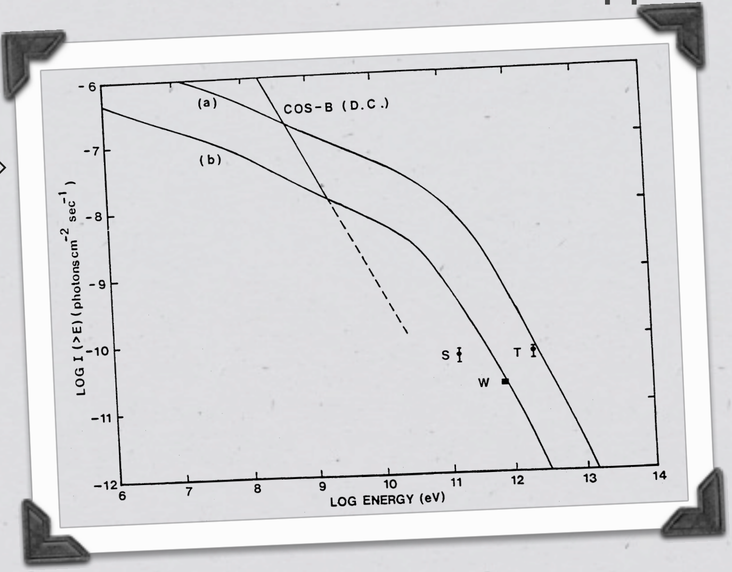
  - It is a neutrino detector?

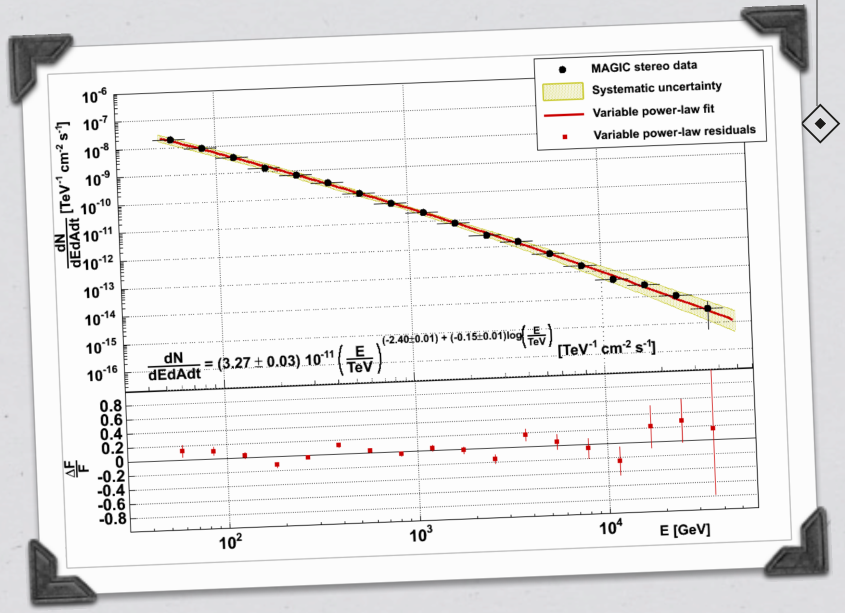


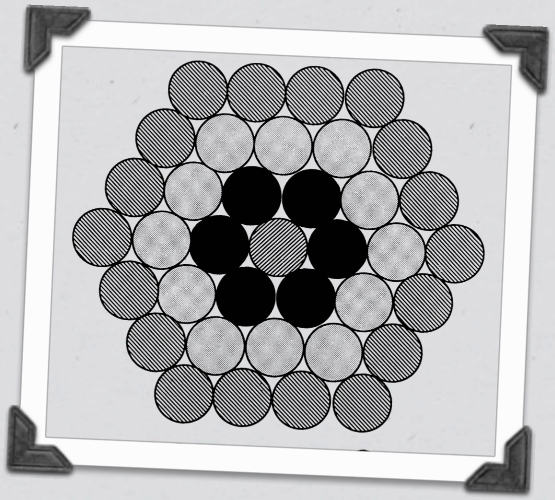
CONCLUSIONS

Family album

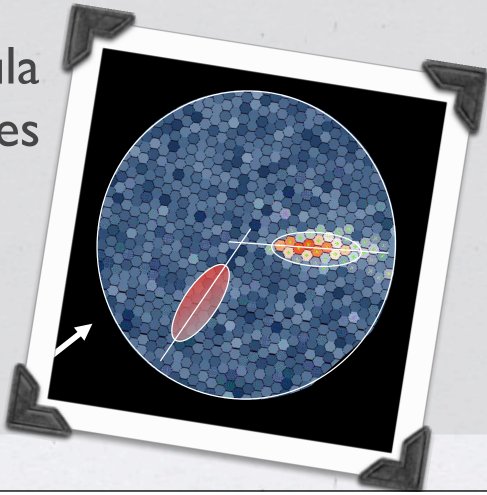
1989: When I first saw
the Crab Nebula with Whipple





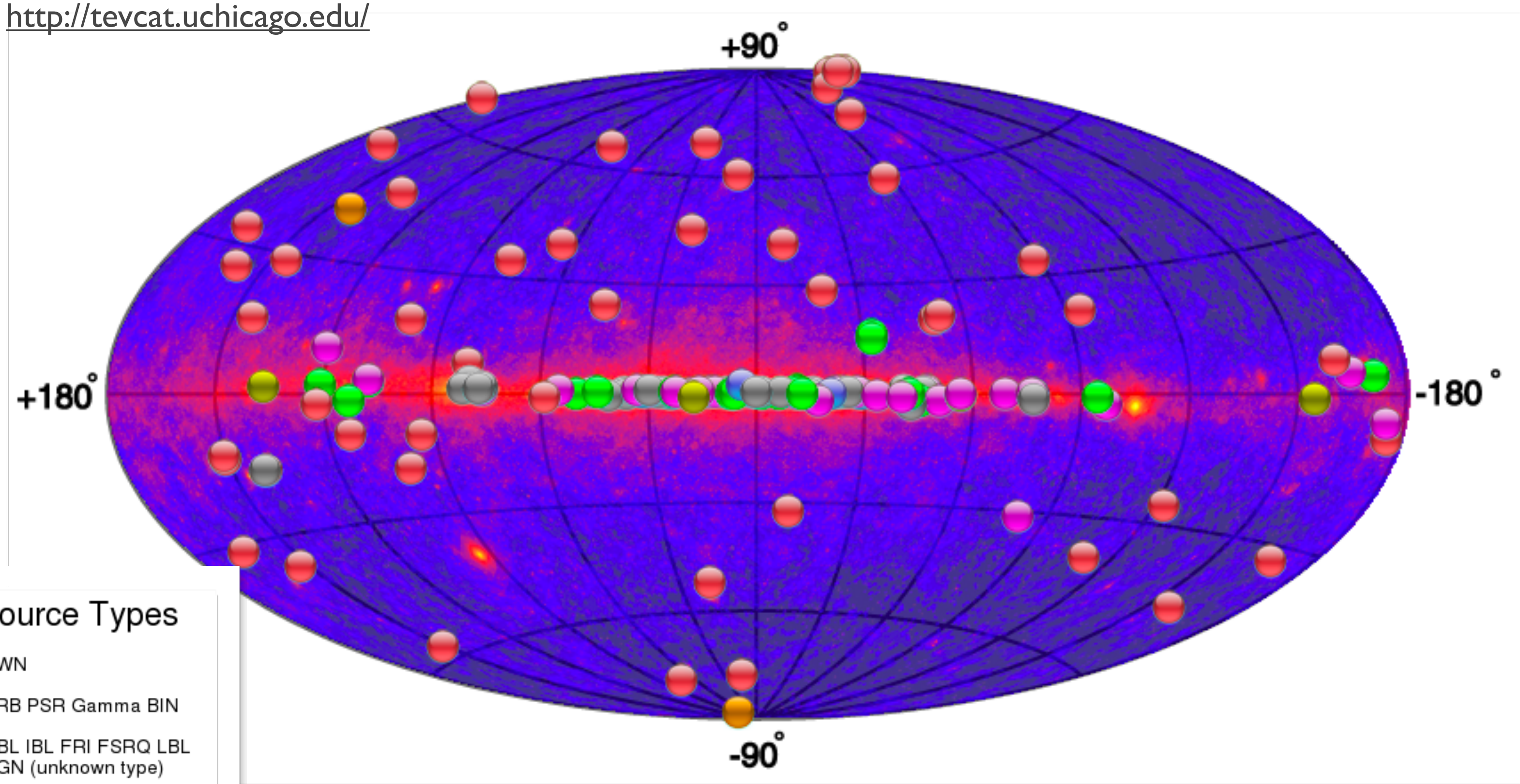


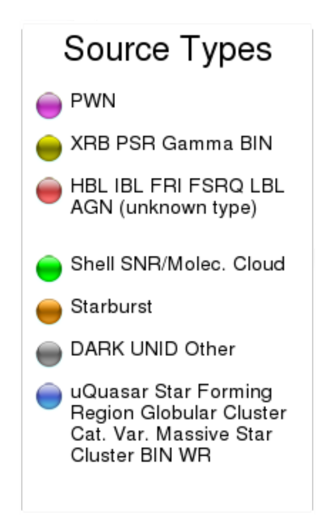
2012: Crab Nebula
with MAGIC eyes



The VHE gamma-ray sky today

http://tevcat.uchicago.edu/

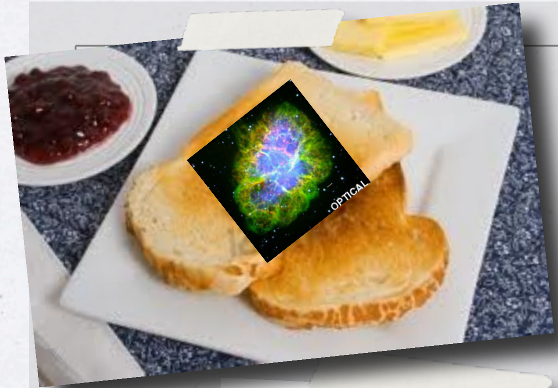




136 sources: ~45 galaxies
~20 SNR, 30 PWN
~25 unidentified

We can expect the unexpected!

Conclusions



- CTA is the perfect experiment for an healthy breakfast:
  - Toasts, jam and butter from astrophysics sources (AGNs, SNRs, PWNs, etc)
  - A cup of **dark** coffee from DM
  - A big cup of milk of archival data where to look for exotic signs
- Between now and then
  - Occasion to create a **VHE scientific community** besides the experimental experience
  - Optimized the analysis and define goals

Thanks!

BACKUPS

Roadmap for CTA-FUND group

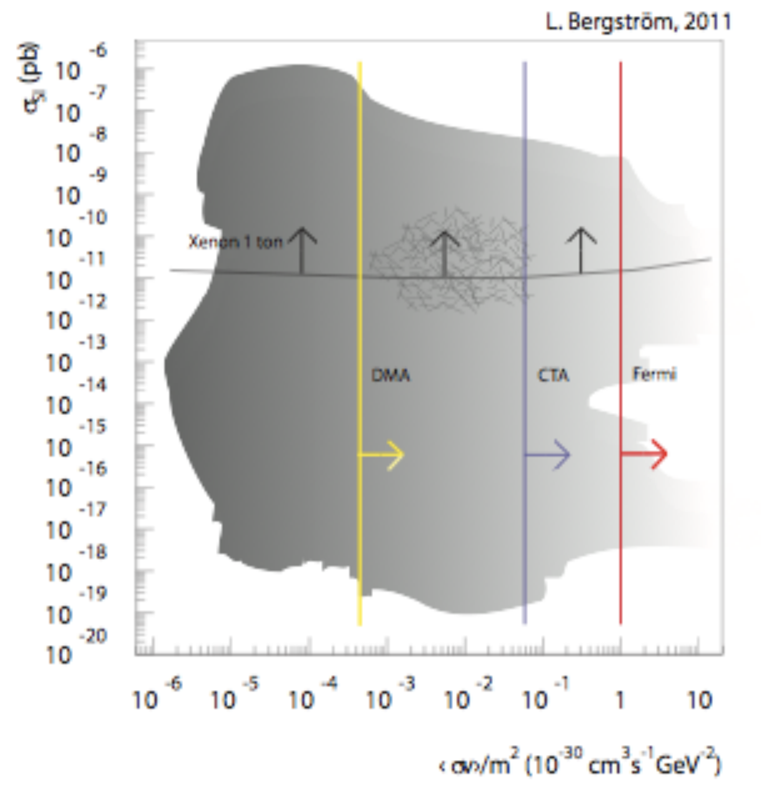
- **Prepare CTA** to fully take into account DM peculiarities
  - spectral features and cutoff + lines
  - morphologies
  - anisotropies
- **Prospects papers** on various targets (**projects**)
  - Galactic center and halo, Dwarfs, Cluster of galaxies, wide-field survey, etc
  - Links with direct detection experiments and accelerators: groups to be formed
  - (React to published papers: i.e., gamma-ray lines from GC region)?

On the other hand, one remark.

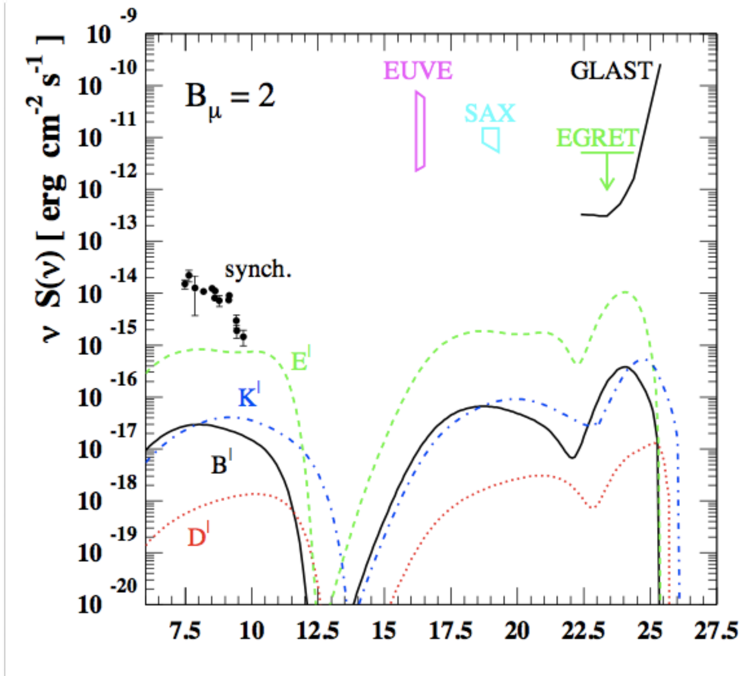
Multi³ DM

Multi³ - A cubic approach to Dark Matter
Multi-messenger Multi-wavelength Multi-experiments
Padova, Department of Physics G.Galilei, March 1-5, 2010

- Multi-experiment approach



- Multi-wavelength approach



Colafrancesco+ 2006

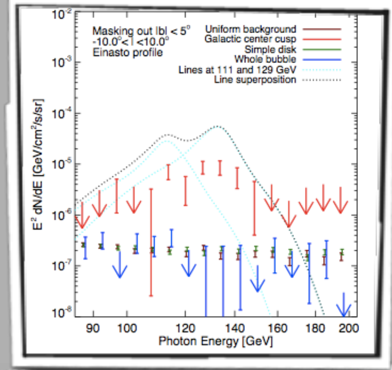
CTA should be prepared for this!

Nature is making drama:
"To WIMP or not to WIMP ?"

LCDM crisis?

"Missing satellite" problem
"core-cusp" problem

Evidence for GeV DM?



Su & Finkbeiner 2012

Evidence for light-DM?

CoGent
+CRESST-II

Astrophysical?

DAMA/LIBRA
+Cogent

Controversies

?

Next few years will tell us more... CTA can be just in time