Future high-energy gamma-ray observatory: Cherenkov Telescope Array (CTA)

Masaaki Hayashida (ICRR)

IMPU seminar, Nov 27, 2013

Outline

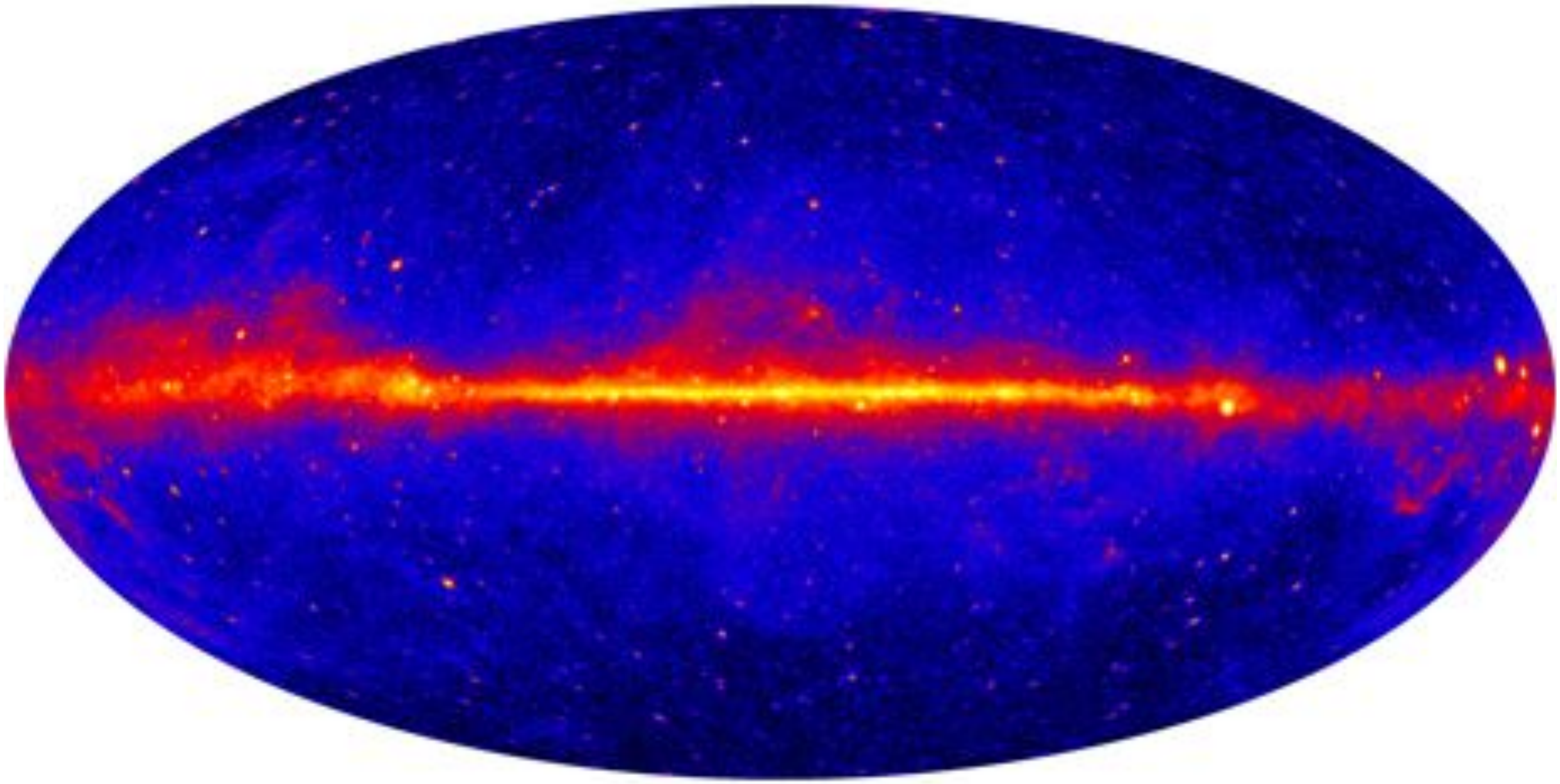
Theme: Cold dark matter (WIMP) search in the gamma-ray observations

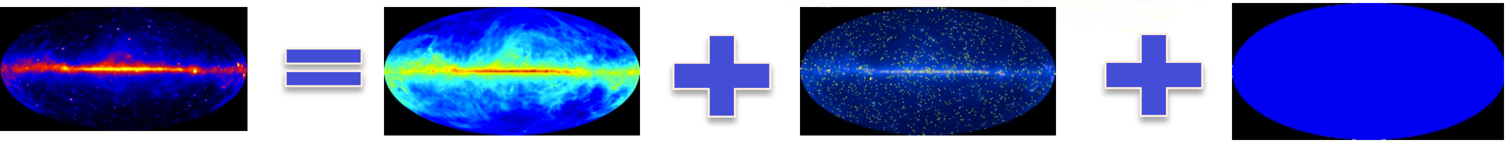
1. a highlight of dark matter study by Fermi-LAT
2. What is CTA?
    1. detection principle of the Cherenkov Telescope
    2. CTA project (design, performance)
3. Prospects for the WIMP search with CTA
    1. dwarf galaxies
    2. Cluster of galaxies
    3. Milky way Halos

Doro et al. 2013, APh, 43, 189 (arXiv:1208.5356)

High energy Gamma-ray Sky

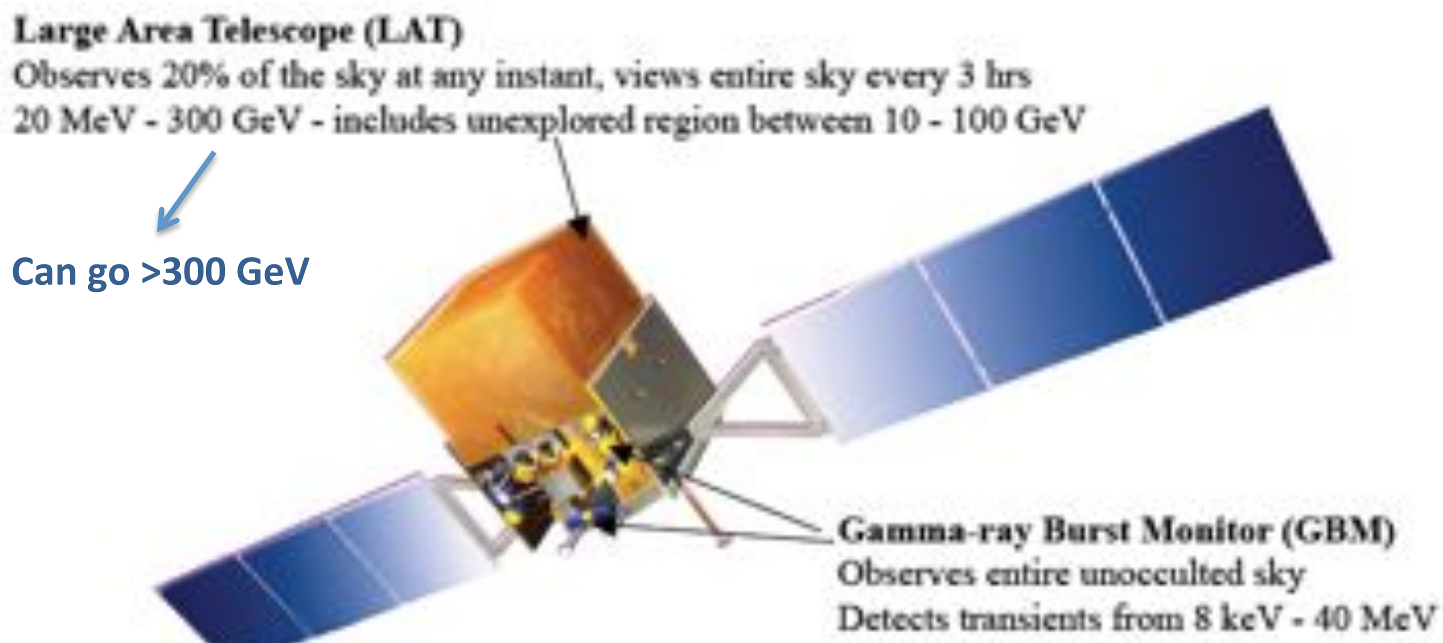
Fermi-LAT (E > 1 GeV)





Fermi Large Area Telescope (LAT)

- On board the Fermi Gamma-ray Space Telescope
  - Launched June 11, 2008
    - Started taking data Aug 2008
  - 5 year mission
    - Mission extended at least through 2016



High energy astrophysics

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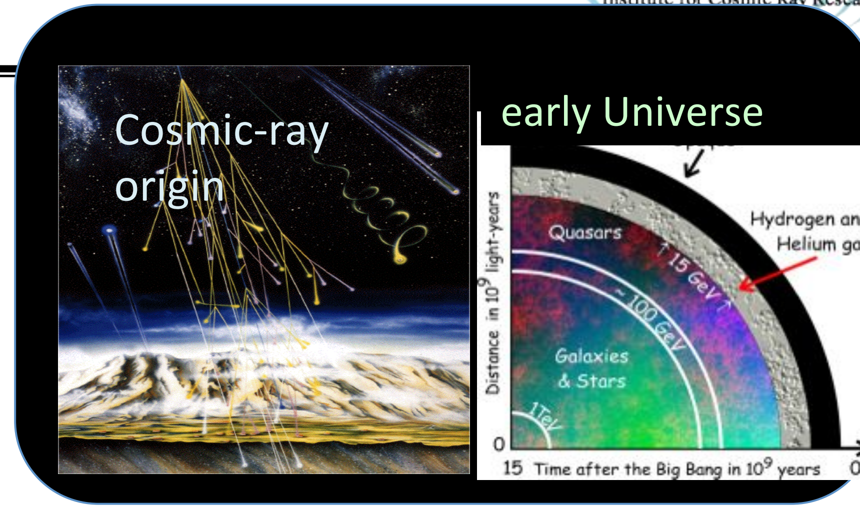
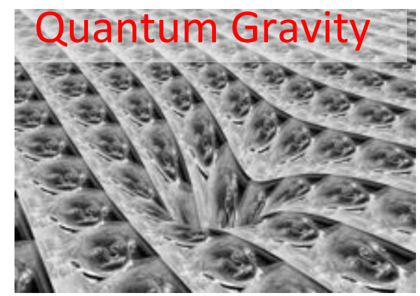
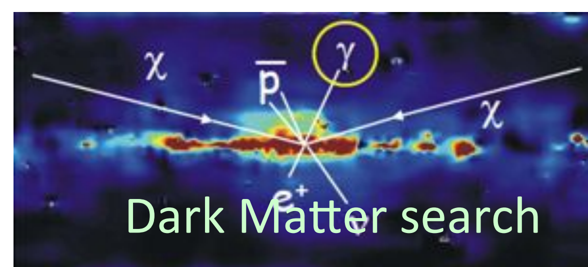
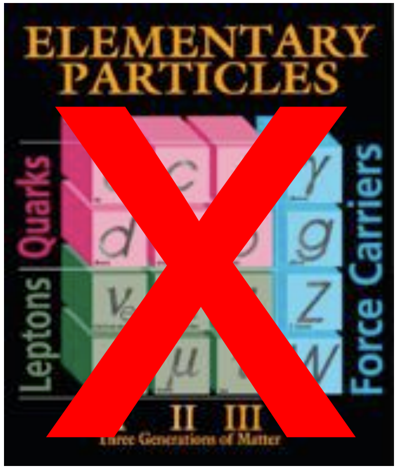


Fundamental physics

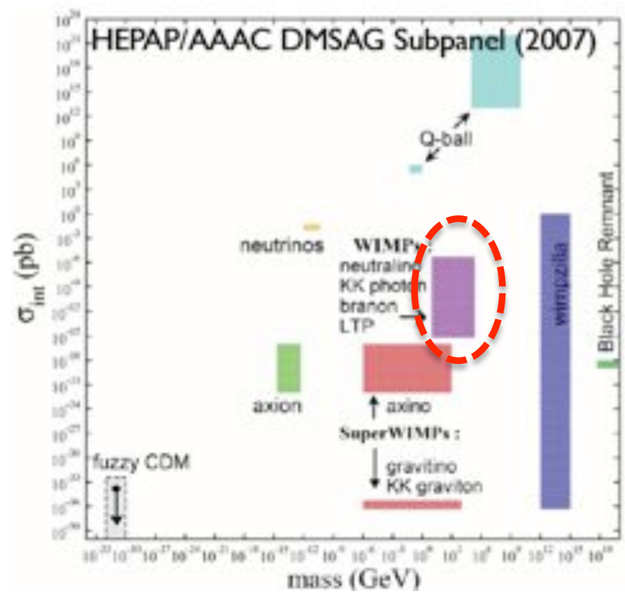




Dark matter candidates



- No known particles are good candidates for dark matter



Here, we focus on

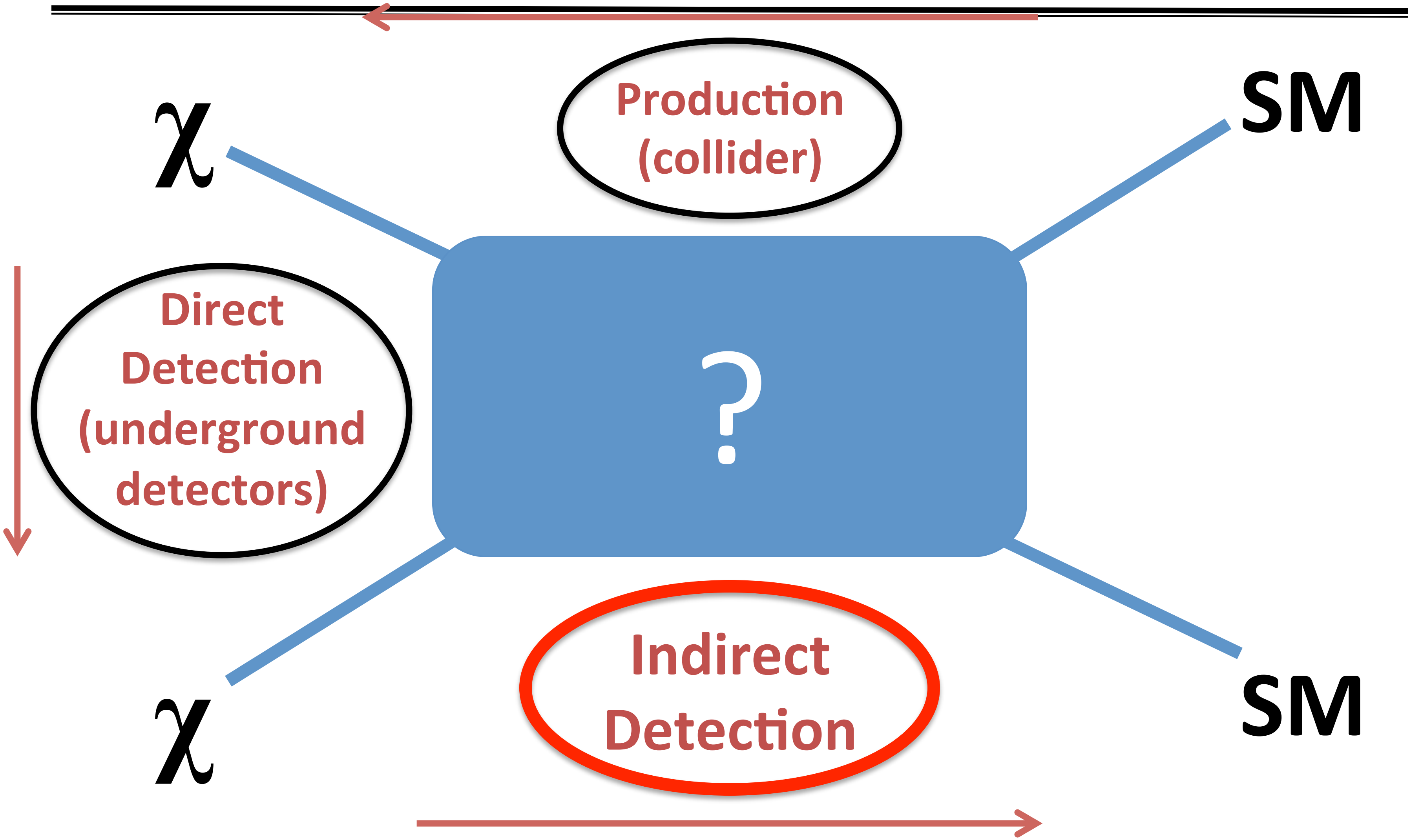
WIMPS

(Weakly Interacting Massive Particles)

"generic" WIMPs has:

- **mass (M_{DM})~ a few 100 GeV**
- **annihilation cross section ($<\sigma v>$) ~ 10^{-26} cm^3/s**

How to Detect WIMPs



Indirect WIMP Signatures

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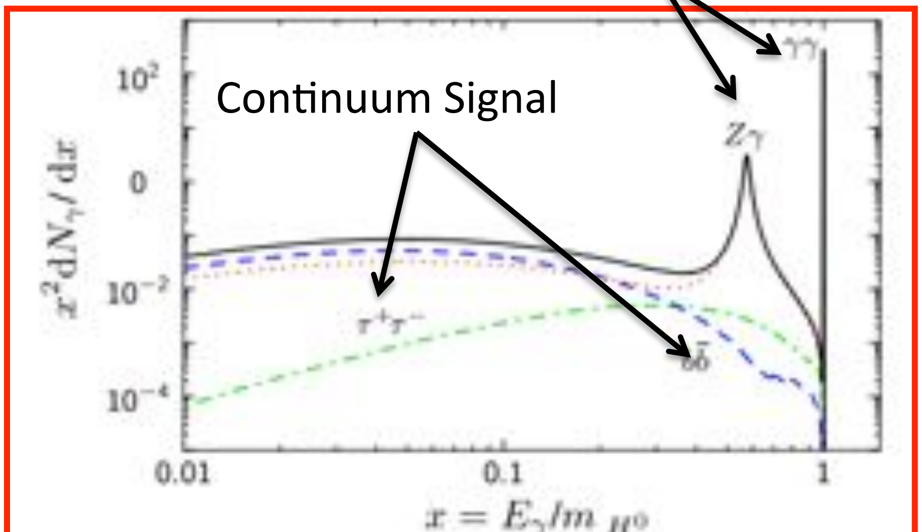
What we observe | Intrinsic Particle Properties | Astrophysics

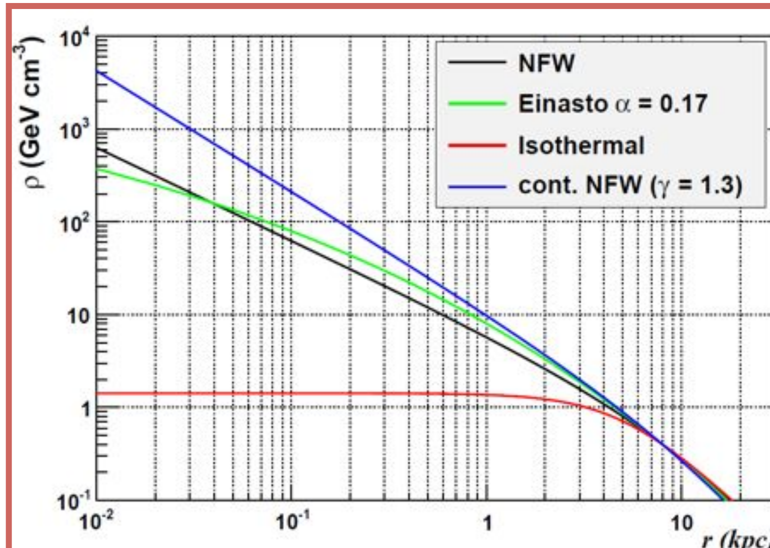
$$\Phi_\chi(E,\psi) = \frac{\langle\sigma_\chi v\rangle}{2}\sum_f \frac{dN_f}{dE}B_f \int_{LOS} dl(\psi)\frac{1}{4\pi}\frac{\rho(l)^2}{m_\chi^2}$$

Smoking gun!!

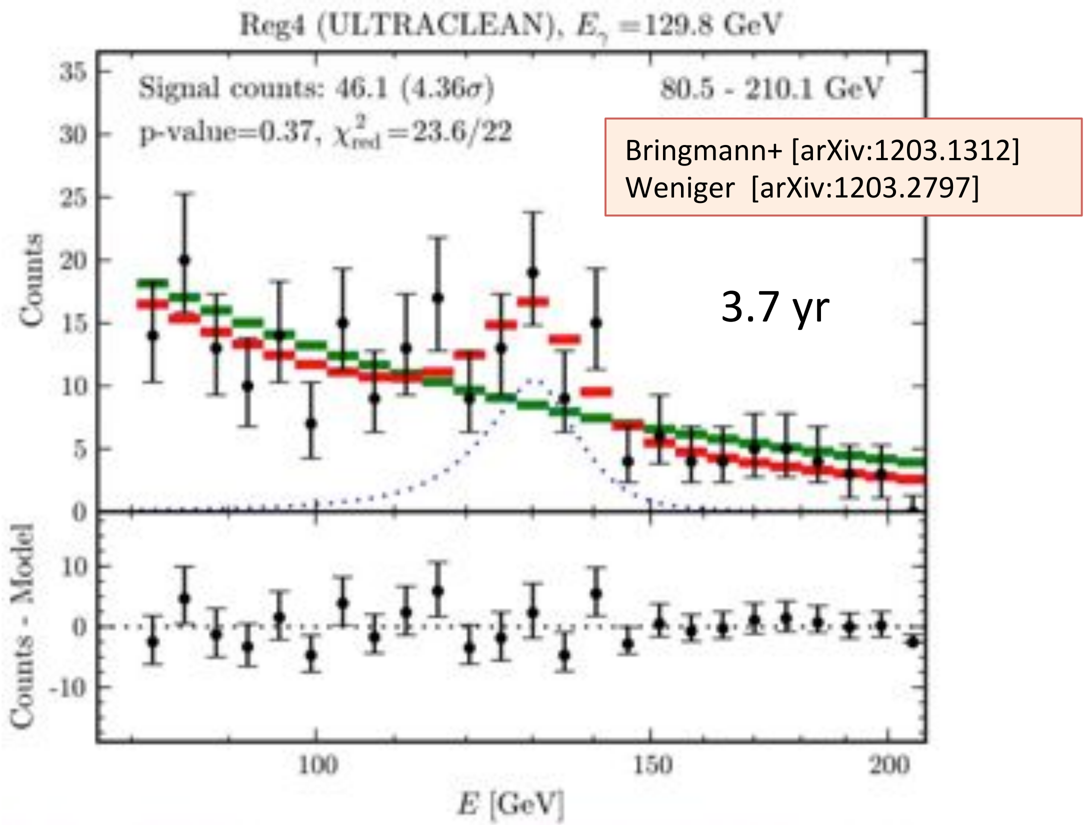
Monochromatic Signal

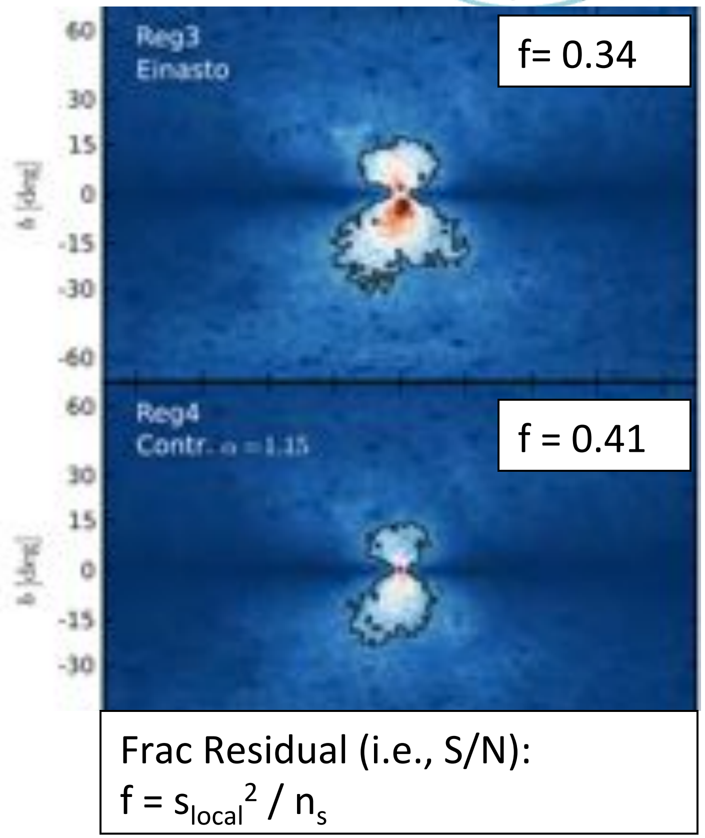
J-factor – Line of sight integral over a ROI





detection of dark matter line?





- Bringmann et al. and Weniger showed evidence for a narrow spectral feature near 130 GeV near the Galactic center (GC)
- Signal is particularly strong in 2 out of 5 test regions, shown above
- Over 4σ, with S/N > 30%, up to ~60% in optimized regions of interest (ROI)

New analysis for line search (by Fermi-LAT collaboration)

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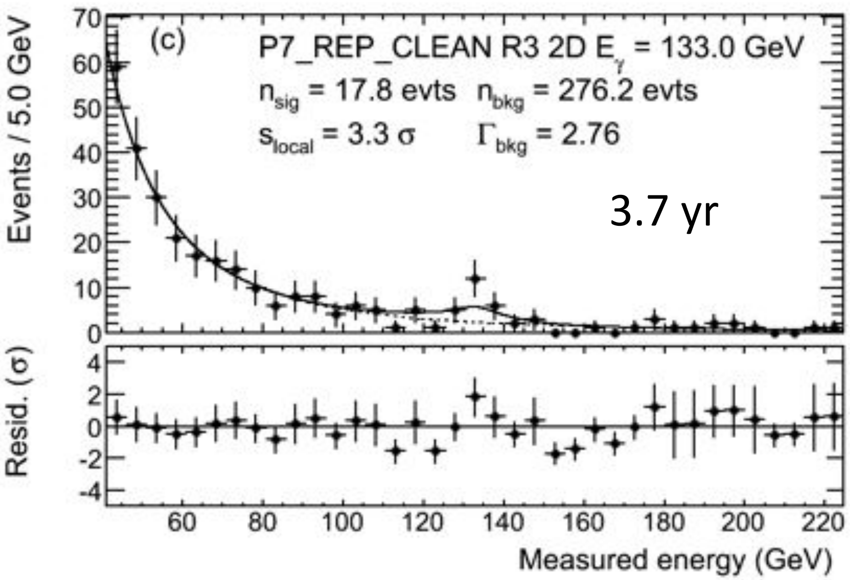
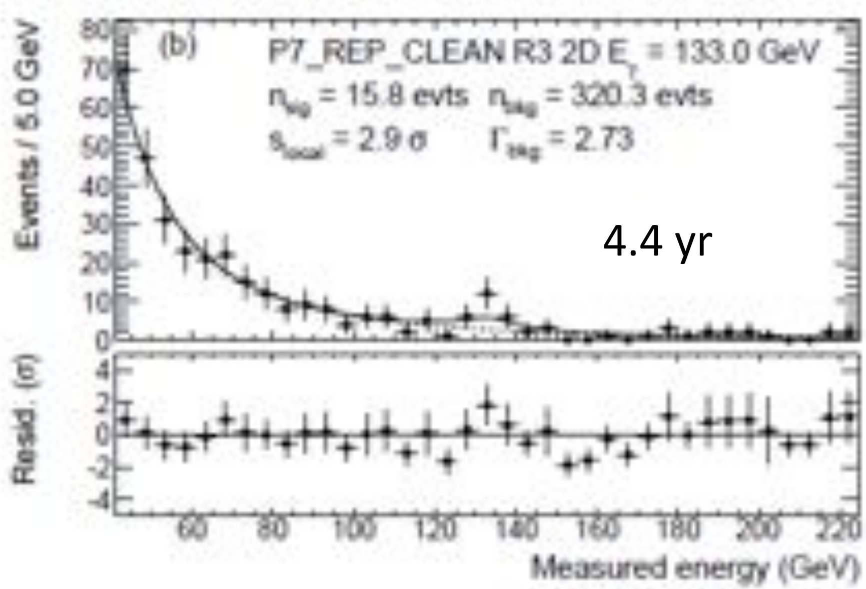


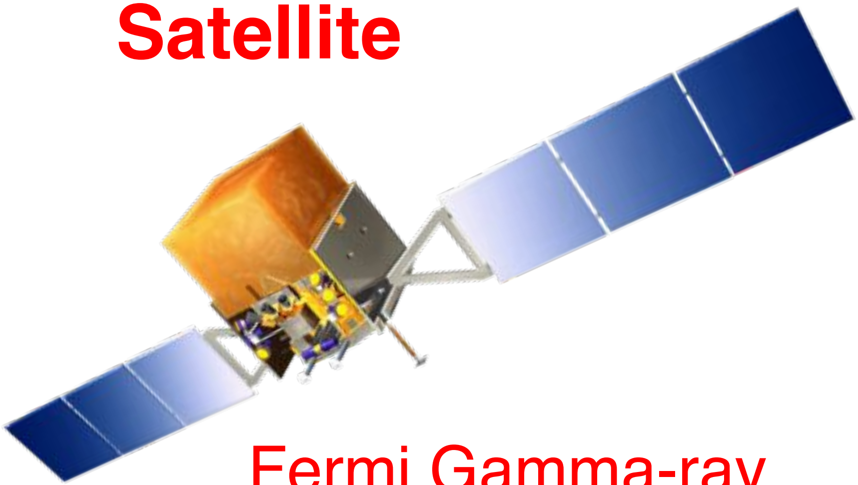


- **Data were reprocessed. Now, the feature can be seen at 133 GeV**
- **s_{local} decreased in 4.4 yr data by ~10% compared to 3.7 yr data**
- **Since spring 2012, feature has decrease**
  - ***More "background-like"***

More observations are needed,,,,,

High-energy γ-ray observations

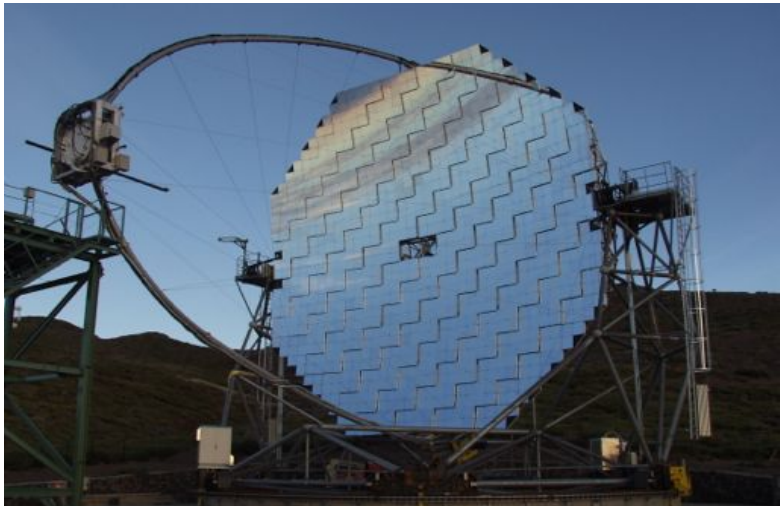
- 0.1 – a few 100 GeV:
  Satellite



Fermi Gamma-ray
Space Telescope

effective area: 1 m^2

- a few 10 GeV
  Imaging Atmospheric Cherenkov Telescope (IACT)
- indirect
- effective area: 10^5 m^2



Satellite vs. Cherenkov telescope

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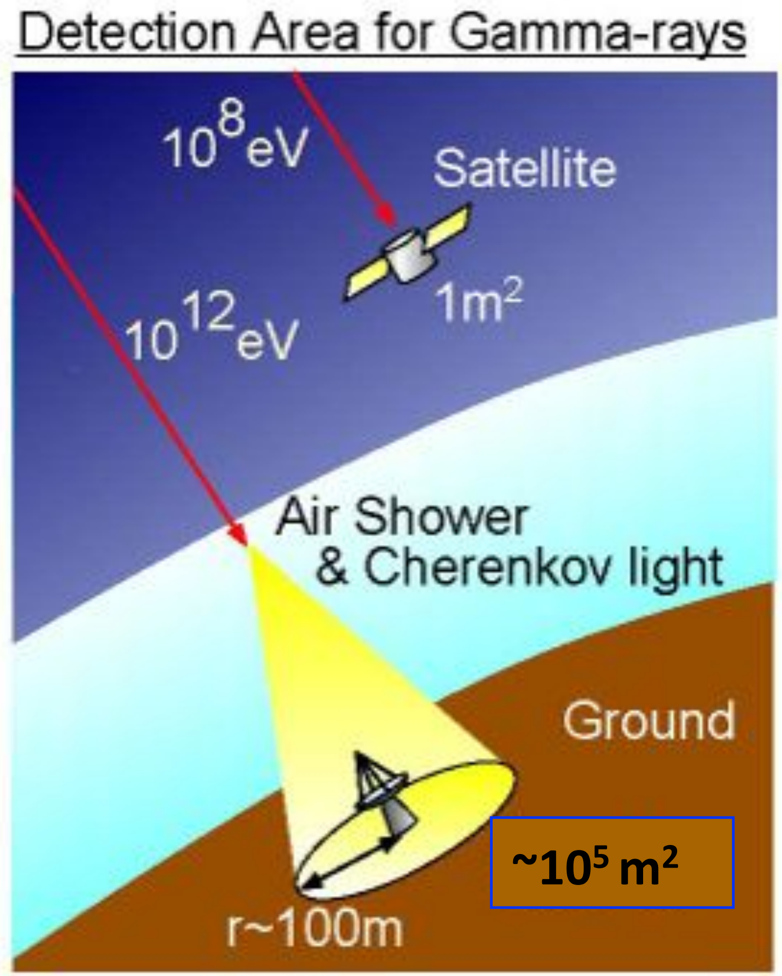
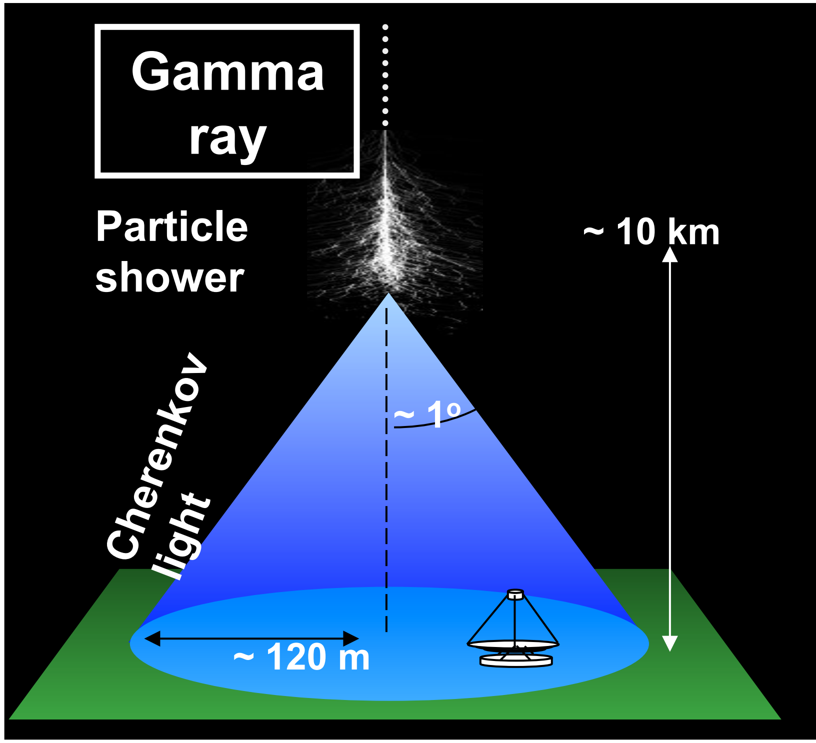
	Satellite Fermi	Ground-based IACTs
Gamma-ray detection	Direct (pair creation)	Indirect (atmospheric Cherenkov)
Energy	Up to a few 100GeV	From a few tens GeV
Positive aspects	High S/N Large FOV	Large area Good ⊿θ
Negative aspects	Small area High cost	Large Background Small FOV duty cycle ~ 10 %



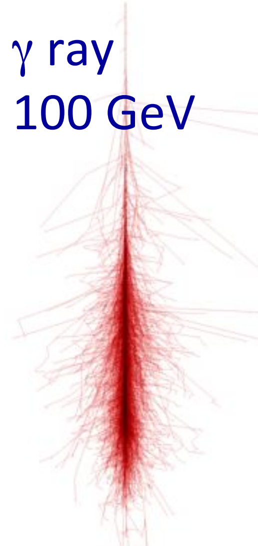
Detection of E>100 GeV γ-rays



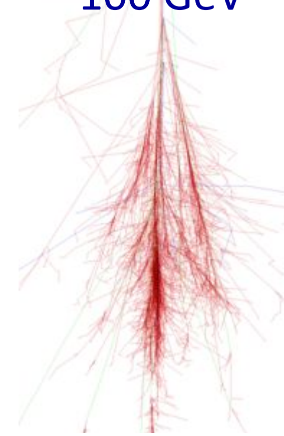
- **Cherenkov light** is emitted by relativistic particles in the shower

- **number of hadron/gamma more than 1000 times**
  -> need to reject hadron events

γ ray
100 GeV



Proton,
100 GeV

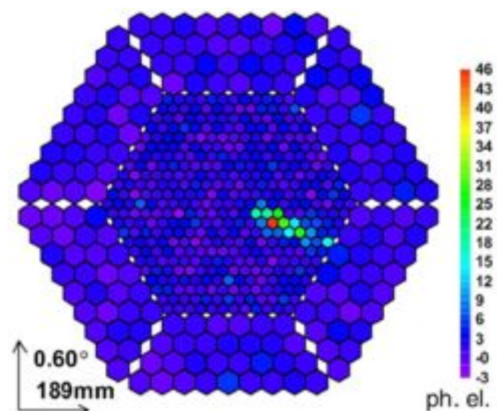


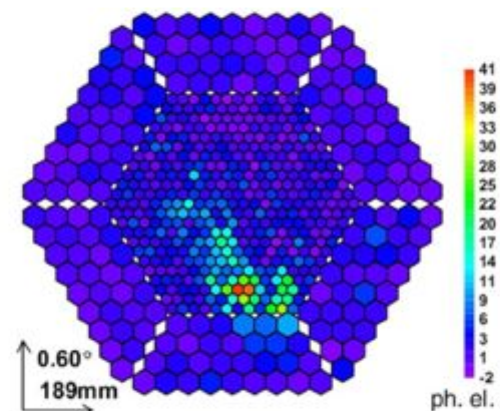
γ showers

- Narrow images
- Aligned towards source direction

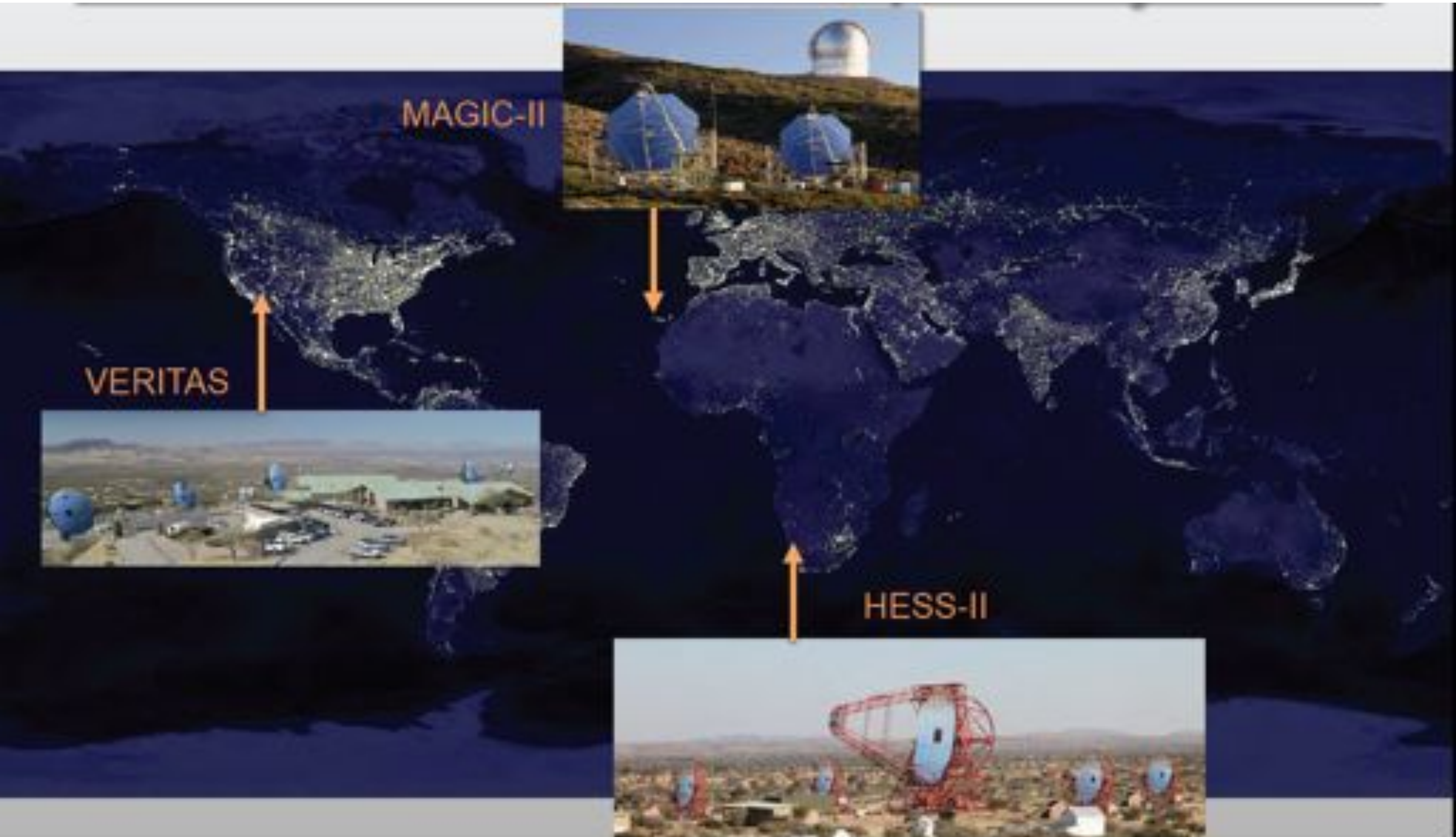
hadronic showers

- Spread images
- Isotropic arrival direction

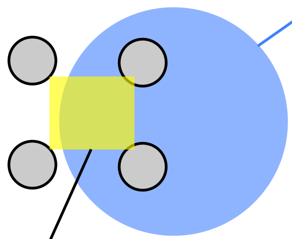




IACTs in currently operation



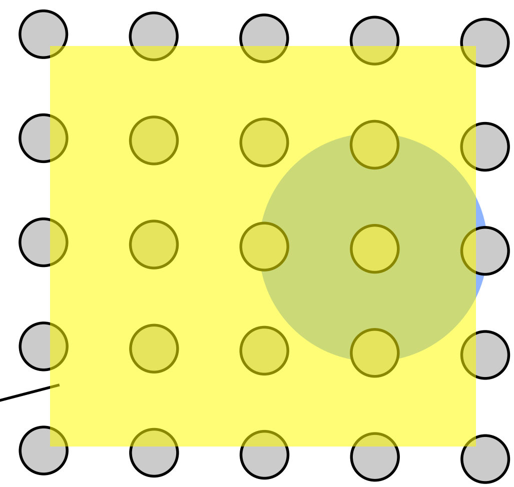
From current array to CTA



Light pool radius
R ≈100-150 m
≈ typical telescope spacing

Sweet spot for
best triggering
and reconstruction:
Most shower cores miss it!

→ *higher sensitivity*



Large detection area
More images per shower
Lower trigger threshold

large telescope → more Cherenkov photon

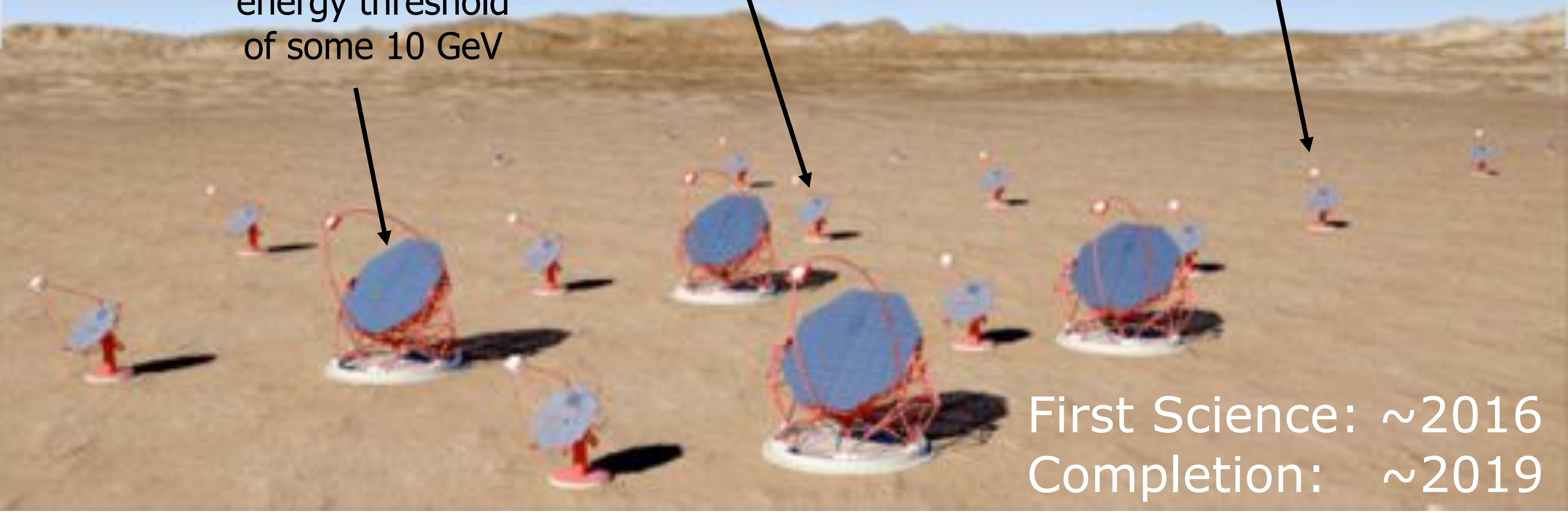
→ *low energy threshold*

The Cherenkov Telescope Array

Core-energy array:
23 x 12 m tel. (MST)
FOV: 7-8 degrees
mCrab sensitivity
in the 100 GeV–10 TeV domain

High-energy section:
30-70 x 4-6 m tel. (SST)
- FOV: ~10 degrees
10 km^2 area at multi-TeV energies

Low-energy section:
4 x 23 m tel. (LST)
(FOV: 4-5 degrees)
energy threshold of some 10 GeV



First Science: ~2016
Completion: ~2019

The Ch

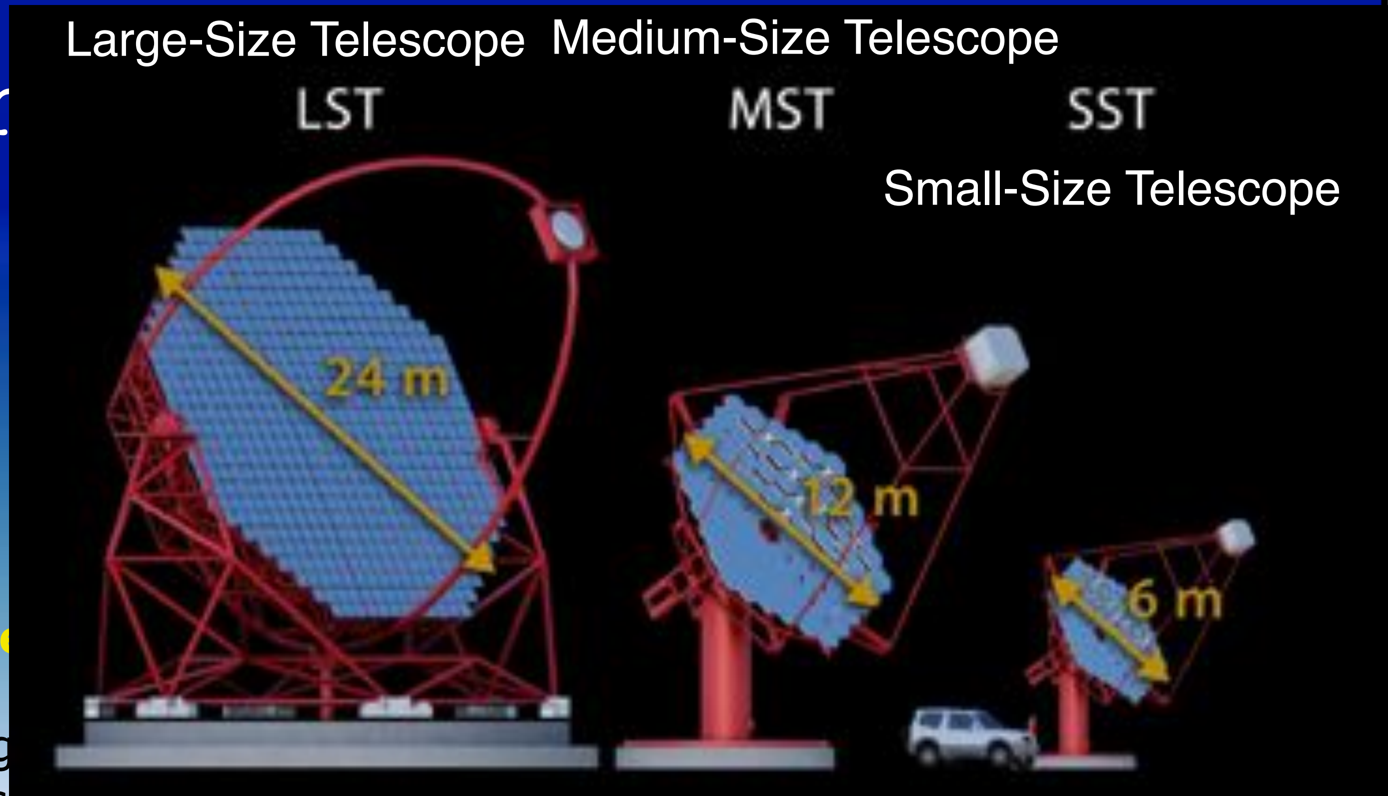
Low-energy s

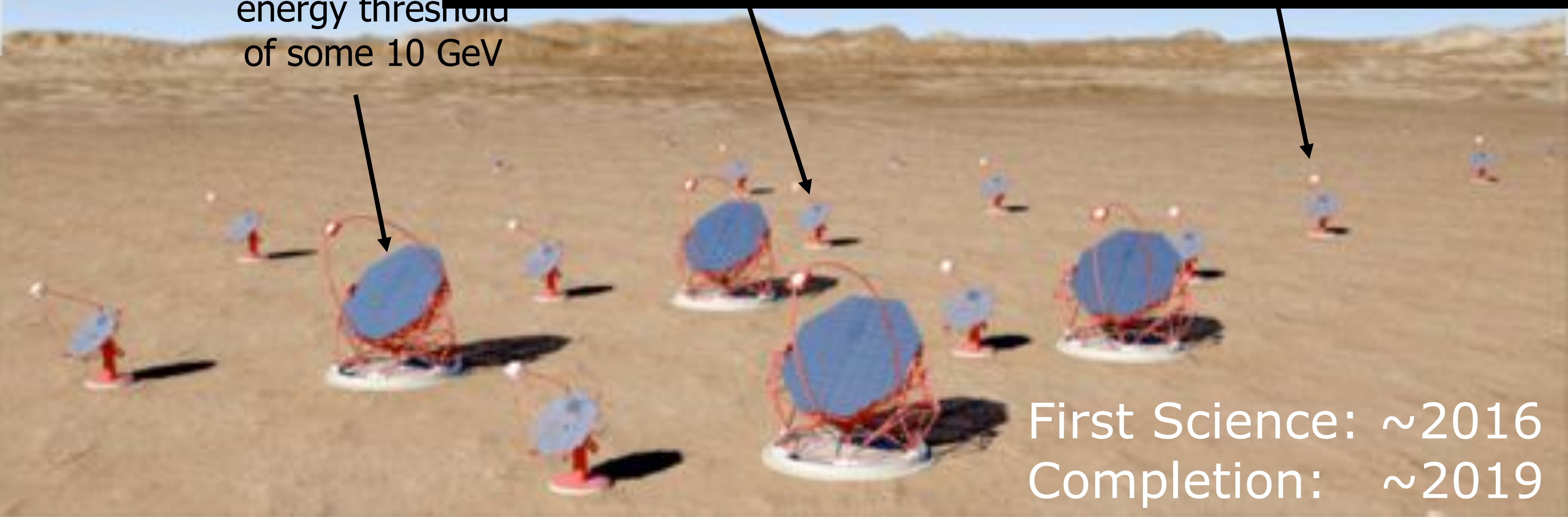
4 x 23 m tel.

(FOV: 4-5 deg

energy threshold

of some 10 GeV





First Science: ~2016

Completion: ~2019

Site candidates

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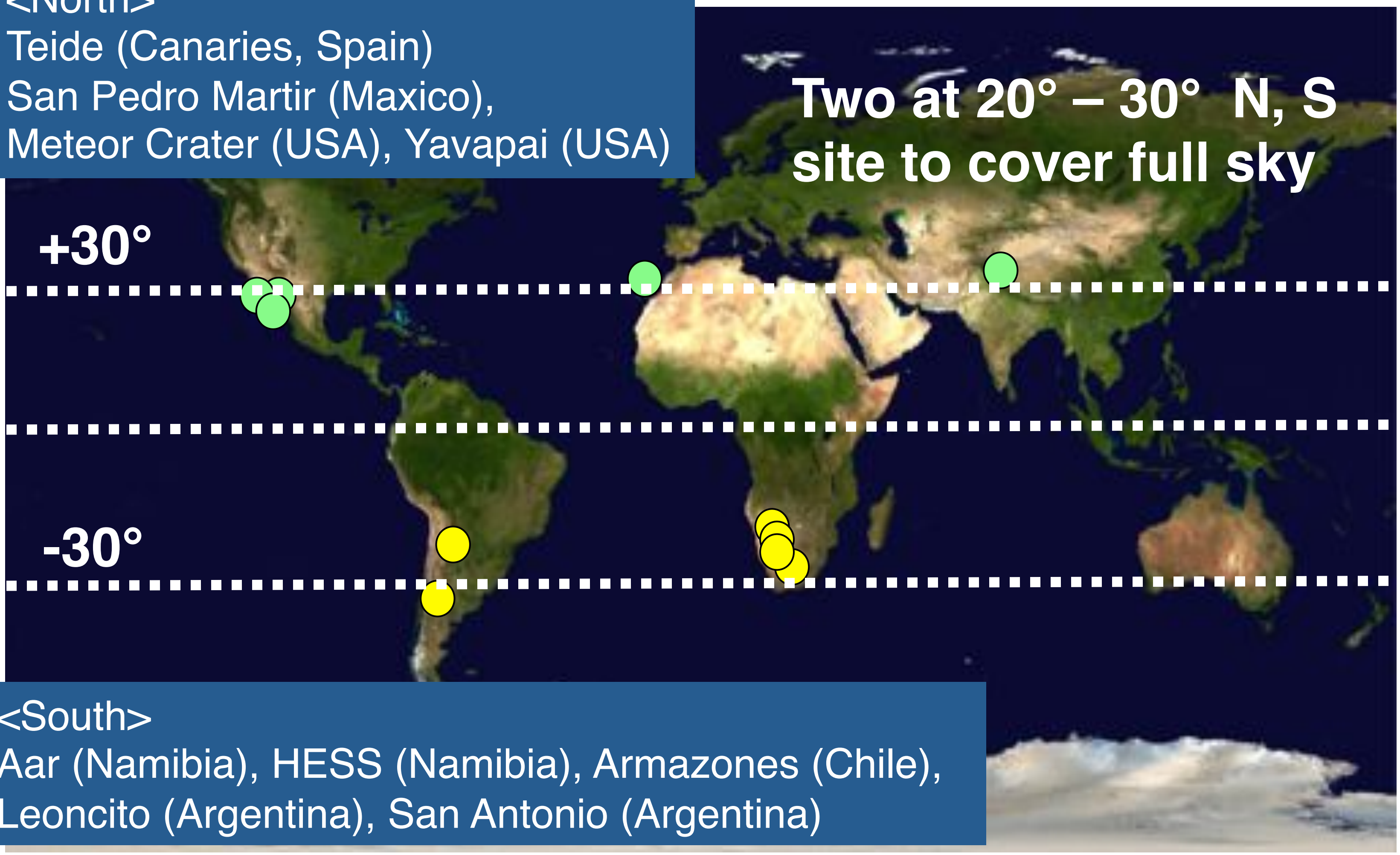
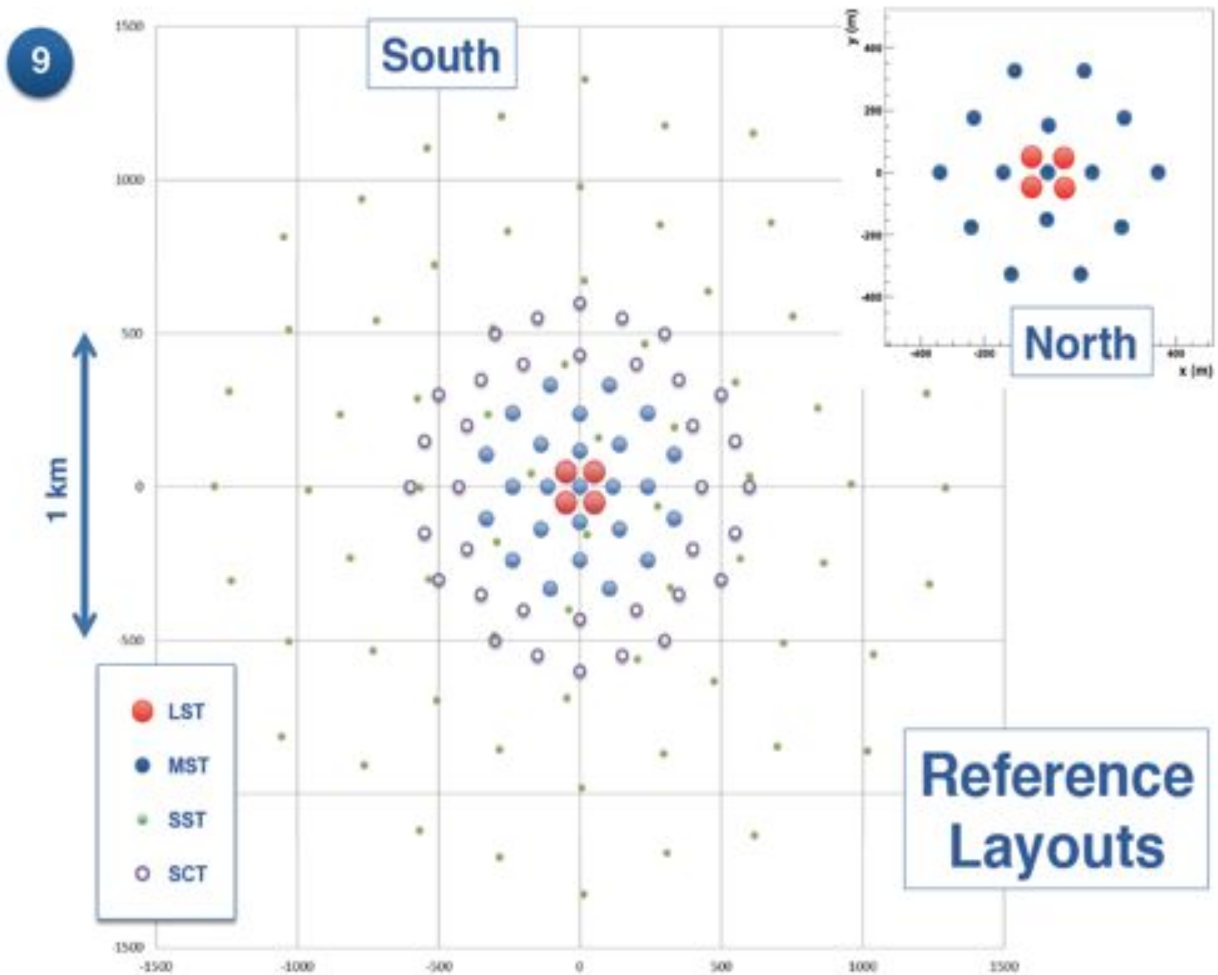
Sites will be selected in early 2014

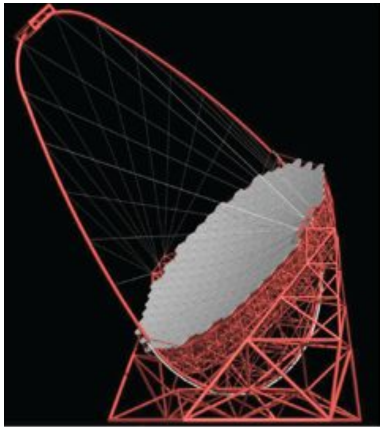
<North>
Teide (Canaries, Spain)
San Pedro Martir (Maxico),
Meteor Crater (USA), Yavapai (USA)

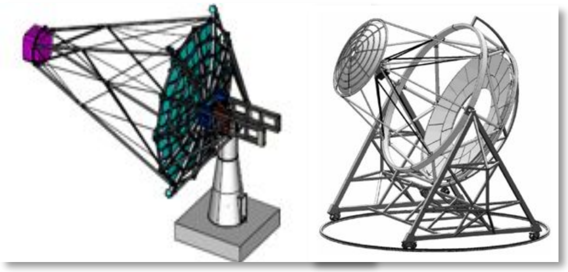


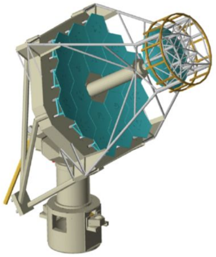
<South>
Aar (Namibia), HESS (Namibia), Armazones (Chile),
Leoncito (Argentina), San Antonio (Argentina)

Possible array configuration




LST 23m

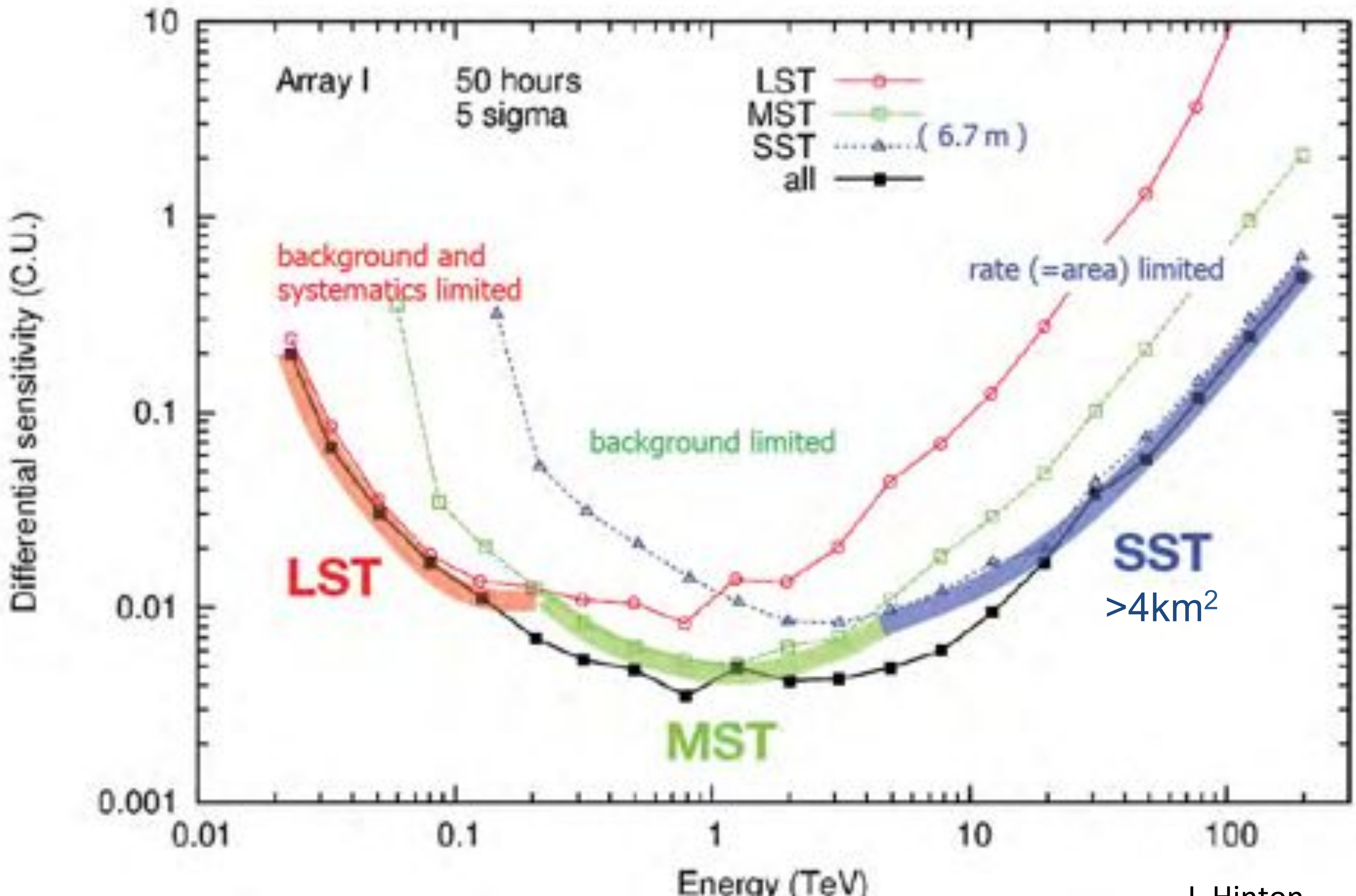

MST 10-12m


SST 4.3m

Telescopes

	SST "small"	MST "medium"	LST "large"	SCT "medium 2-M"
Number	70 (S)	25 (S) 15 (N)	4 (S) 4 (N)	36 (S)
Spec'd range	> few TeV	200 GeV to 10 TeV	20 GeV to 1 TeV	200 GeV to 10 TeV
Eff. mirror area	> 5 m^2	> 88 m^2	> 330 m^2	> 40 m^2
Field of view	> 8°	> 7°	> 4.4°	> 7°
Pixel size ~PSF θ_{80}	< 0.25°	< 0.18°	< 0.11°	< 0.075°
Positioning time	90 s, 60 s goal	90 s, 60 s goal	50 s, 20 s goal	90 s, 60 s goal
Availability	> 97% @ 3 h/week	>97% @ 6 h/week	>95% @ 9 h/week	>97% @ 6 h/week
Target capital cost	420 k€	1.6 M€	7.4 M€	2.0 M€

sensitivity



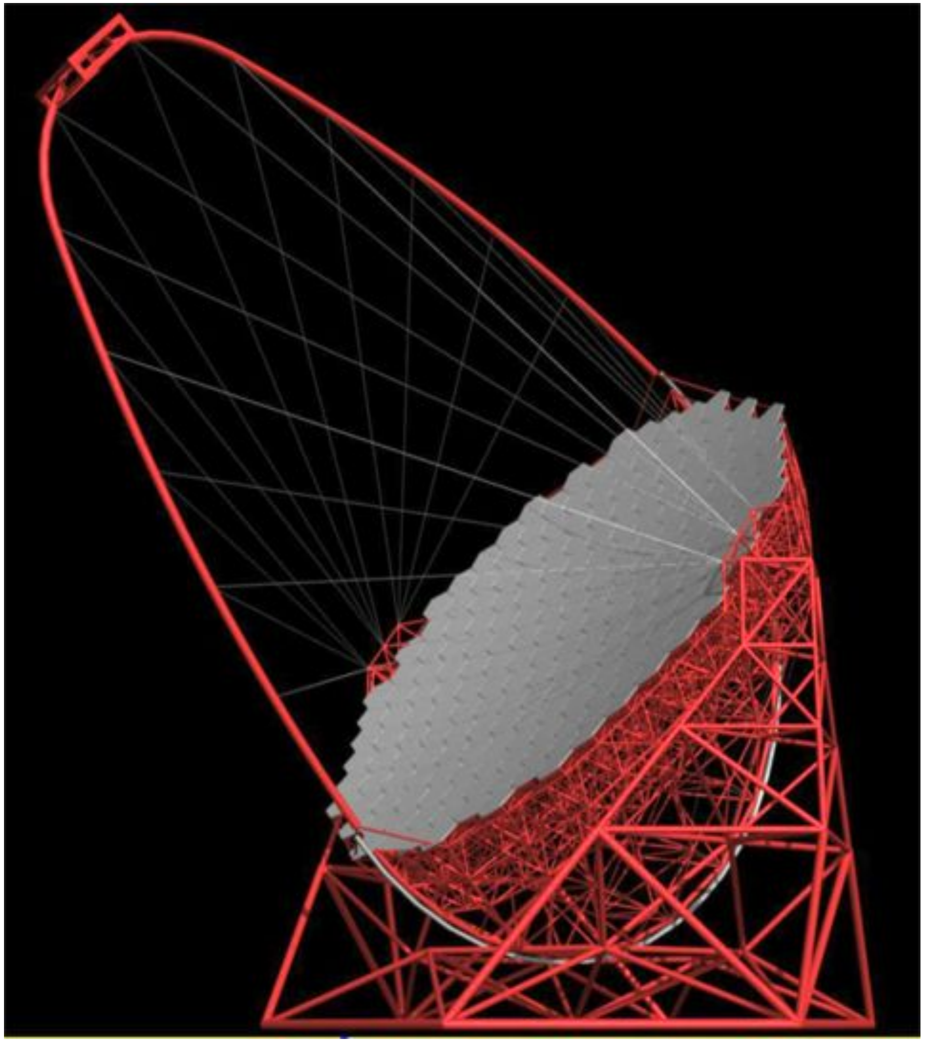
J. Hinton

Japanese contributions to CTA hardware developments

Development of LST

Telescope specification

- Diameter: 23m
- Dish area: ~ 370 m^2
- F/D = 1.2, F=28m
- Dish profile: Parabolic
  - Isochronicity < 0.6 nsec (rms)
- Total weight: ~70 tons
- Fast rotation: 180 deg/ 20sec
- Deformation of mirror dish: <10mm
- Active mirror Control
- Pointing accuracy: 14 arcsec



Designed by MPI Munich and MERO

LST hardware development

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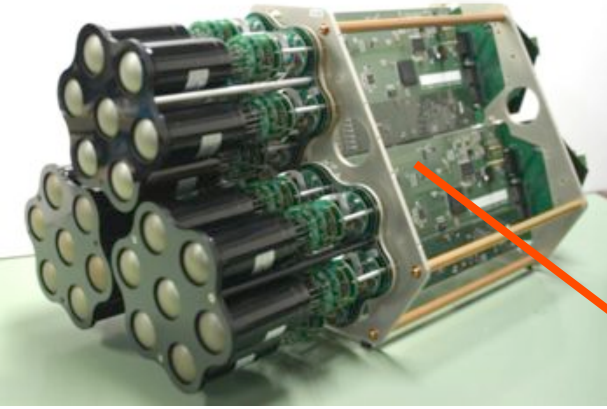
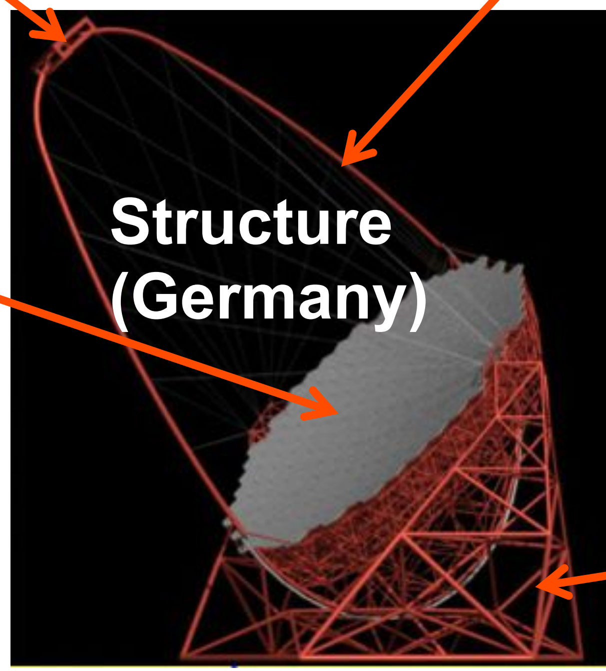
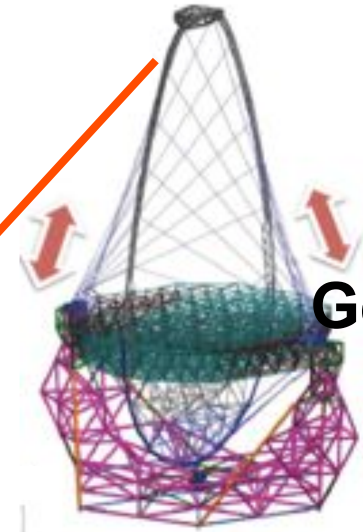
Camera(Japan, Spain)



Mirror(Japan)

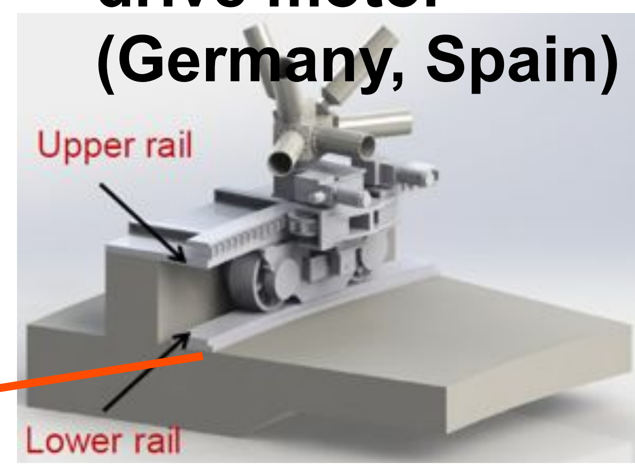


su



(France, Germany)

drive motor (Germany, Spain)



Mirror developments

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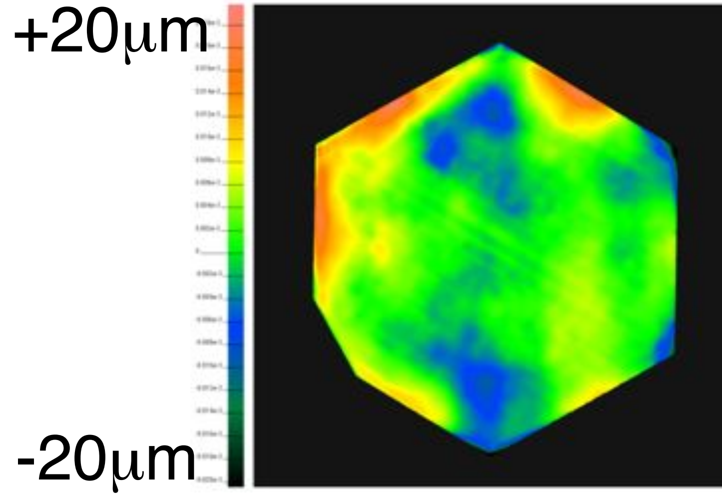
developed in SANKO in Japan

<surface accuracy>

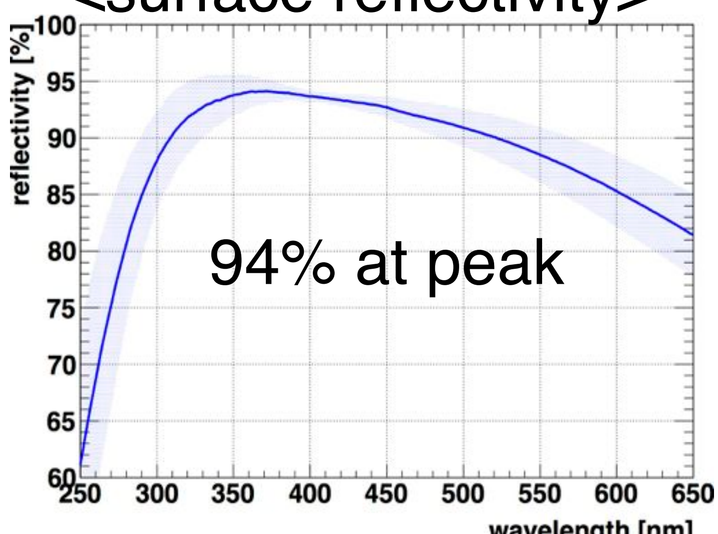


Specification:

- Hex, 1.5m flat-flat (2m2)
- Focal length: 28 m
- PSF: 0.03° (1/3 pixel)
- Weight: 47 kg

<u>200 mirrors for 1 LST</u>

<surface reflectivity>

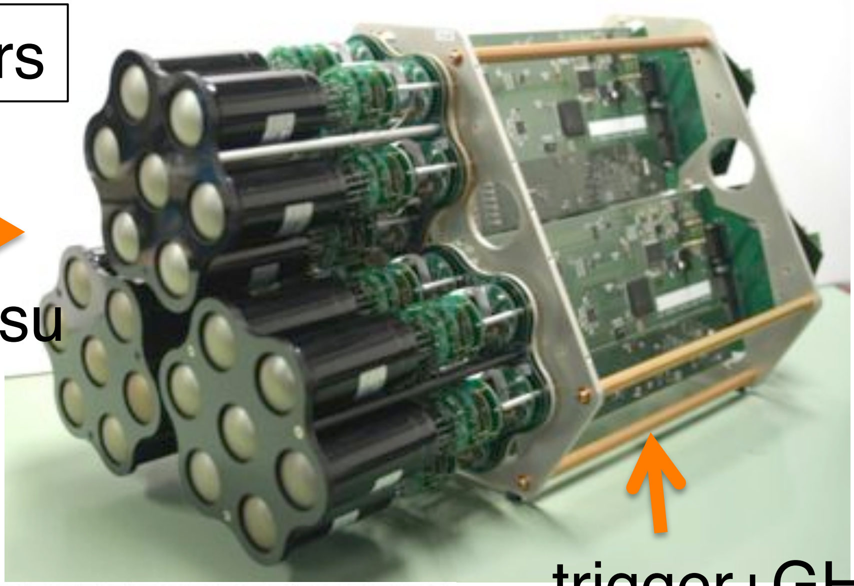


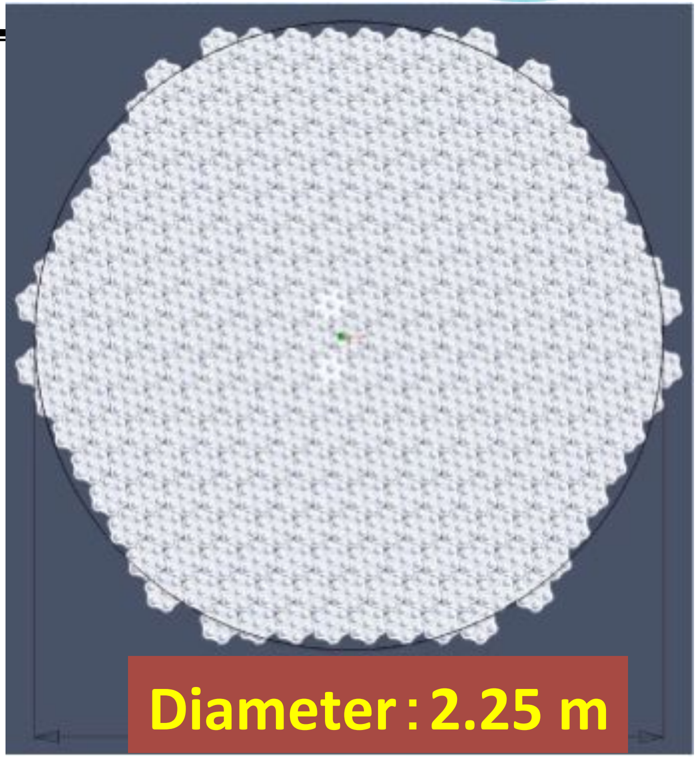
Camera developments

LST-Camera 265 clusters/1855 pixels (0.1°pixel、FOV 4.5°、Weigh< 2 ton)

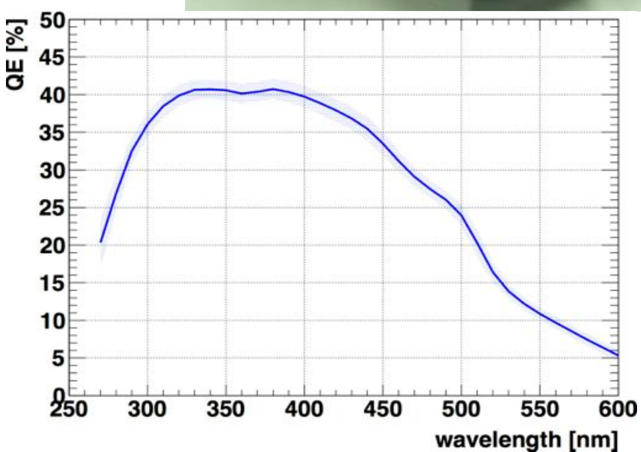
3 clusters

Detectors: PMT (Hamamatsu Photonics)





trigger+GHz Readout

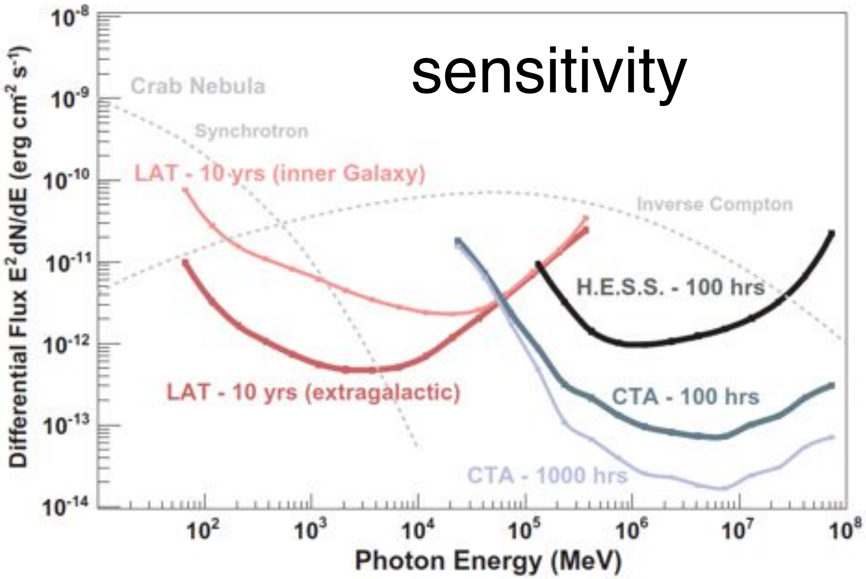


PMT: Quantum efficiency 40% at 350 nm (30-35% in old types)


what can we do with CTA??

Performances: Fermi-LAT and CTA

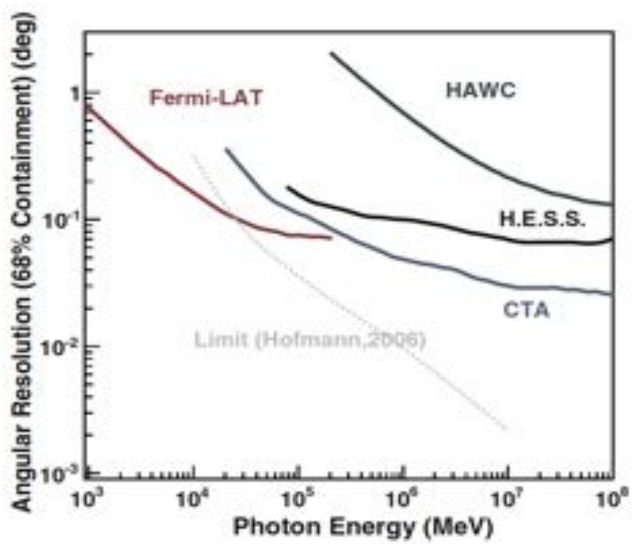
Funk & Hinton (2013)

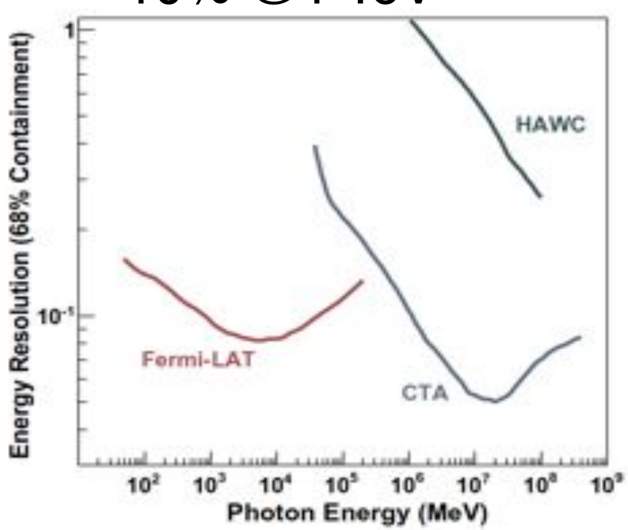


covering 6 decades
crossing at ~ 40 GeV

energy resolution
20% @100 GeV
10% @1 TeV

angular resolution
0.1deg @ 100 GeV





capabilities of CTA

compared to the current Cherenkov telescopes,,,,

1. energy range is extended: 20 GeV to 100 TeV
   - best for >100 GeV WIMPs search
2. increased FOV
   - (5°-8° [CTA] vs 2°-5°[now])
3. better angular resolution
   - (0.1° [CTA] vs 0.2° [now])
4. better energy resolution
   - (10-20 %[CTA] vs 15-30% [now])

Targets for Dark Matter Searches

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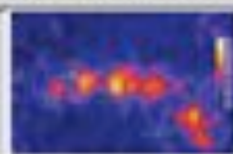
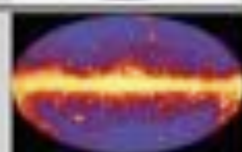
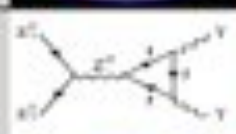
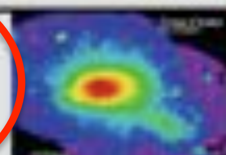
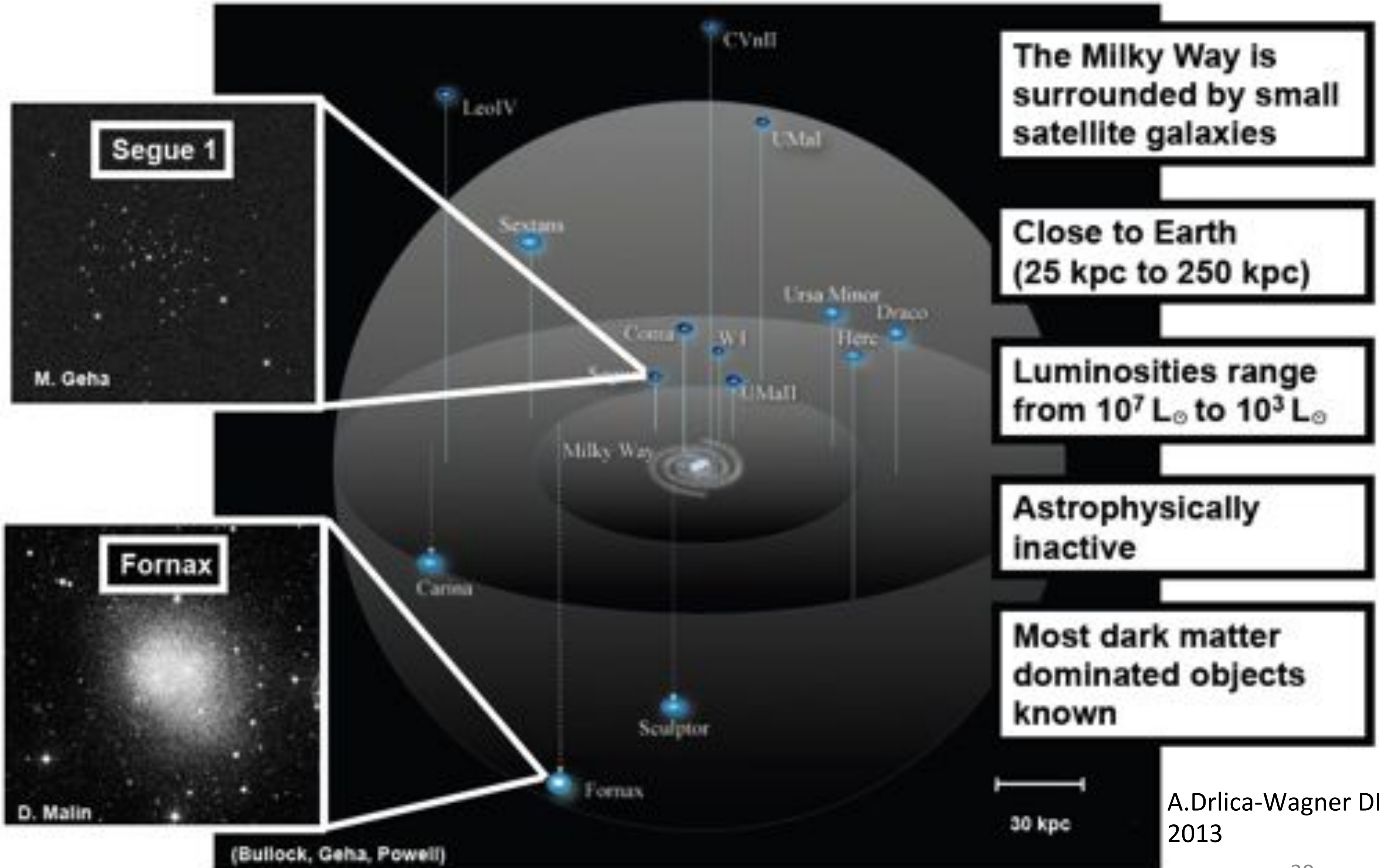
Search Technique		advantages	challenges
Galactic center		Good Statistics	Source confusion/Diffuse background
Satellites, Subhalos		Low background, Good source id	Low statistics
Milky Way halo		Large statistics	Galactic diffuse background
Extra-galactic		Large Statistics	Astrophysics, galactic diffuse background
Spectral lines		No astrophysical uncertainties, good source id	Low statistics
Clusters of Galaxies		Low background, Good source id	Low statistics

E.A. Baltz et al. JCAP07 (2008) 013

DM Search in MW Dwarf Galaxies



A.Drlica-Wagner DPF 2013

Dwarf Galaxy

No gamma-ray background emission is expected!!!

Choice of targets:

- "classical" dSphs:
  - Draco, Ursa Minor (North), Sculptor, Carina (South)
- ultra-faint dSphs: (larger astronomical uncertainties)
  - Coma Berenices, Segue 1, Willman 1

<assumptions>

- NFW and core isothermal DM halo profile
- study annihilation spectra (broad continuum), assuming in turn 100% branching ratio into a specific channel (bb_{var}, $\tau+\tau-$ or $\mu+\mu-$)

Indirect WIMP Signatures

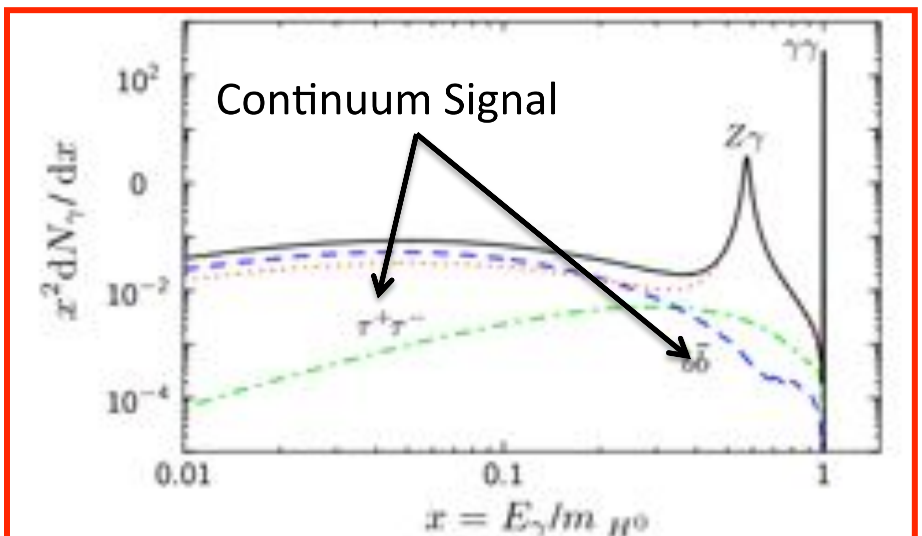
What we observe

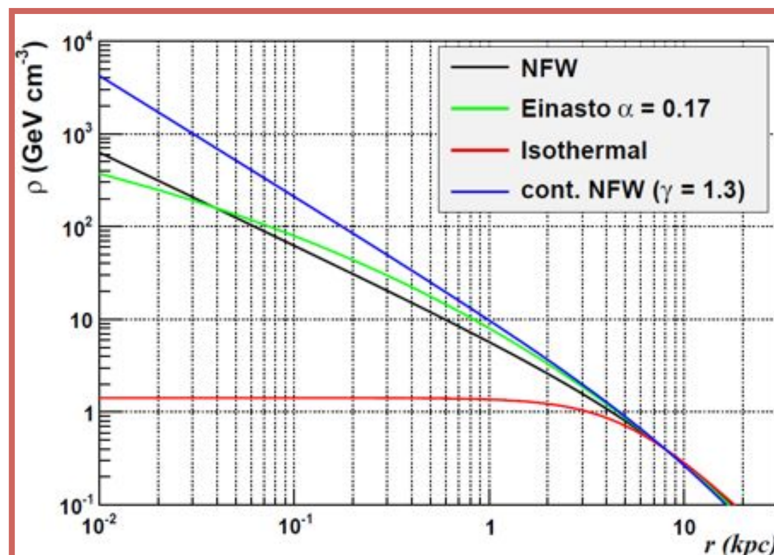
Intrinsic Particle Properties

Astrophysics

$$\Phi_\chi(E,\psi) = \frac{\boxed{\langle\sigma_\chi v\rangle}}{2}\sum_f \frac{dN_f}{dE} B_f \int_{LOS} dl(\psi)\, \frac{1}{4\pi}\frac{\rho(l)^2}{\boxed{m_\chi^2}}$$

J-factor – Line of sight integral over a ROI





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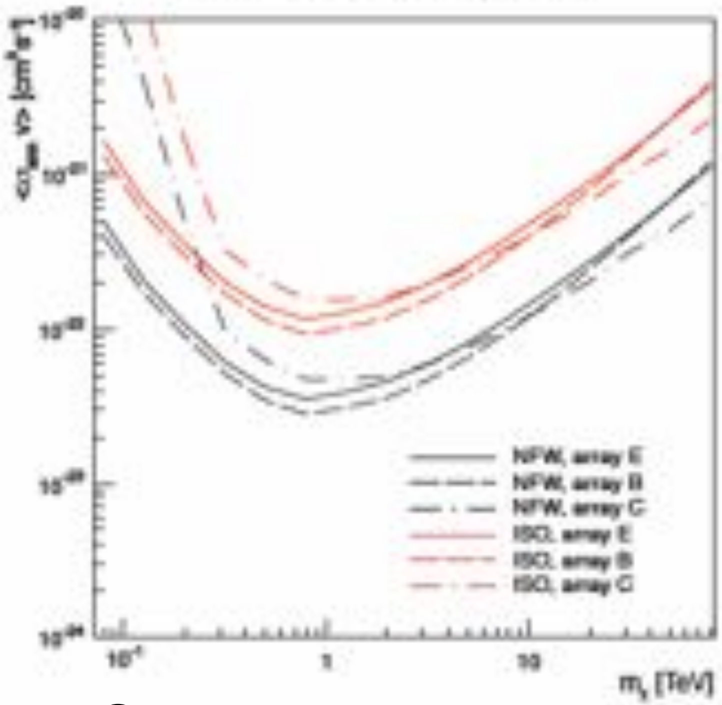
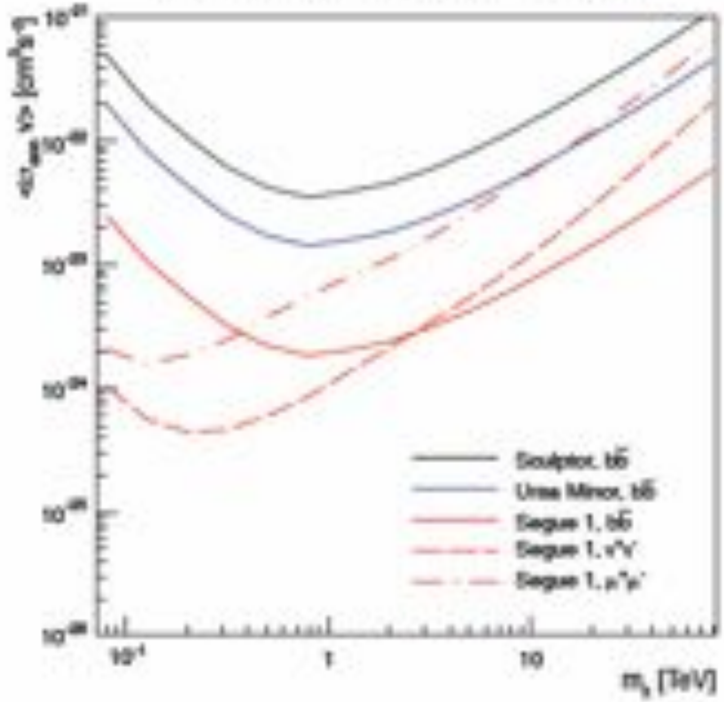
Dwarf Galaxies: 100 hrs

Prospects vs. Profile



Classical vs. Ultra-Faint



Sculptor
("classical")
bb_{var}

dSph	Dec. [deg]	D [kpc]	$\bar{J}$ [$GeV^2\,cm^{-5}$]	Profile
Ursa Minor	+44.8	66	2.2×10^{18}	NFW
Draco	+34.7	87	7.1×10^{17}	NFW
Sculptor	−83.2	79	8.9×10^{17}	NFW
			2.7×10^{17}	ISO
Carina	−22.2	101	2.8×10^{17}	NFW
Segue 1	+16.1	23	1.7×10^{19}	Einasto
Willman 1	+51.1	38	8.4×10^{18}	NFW
Coma Berenices	+23.6	44	3.9×10^{18}	NFW

Charbonnier et al. 2011

Note: 1000 hrs are available in total in 1 year

Dwarf Galaxies: 100 hrs

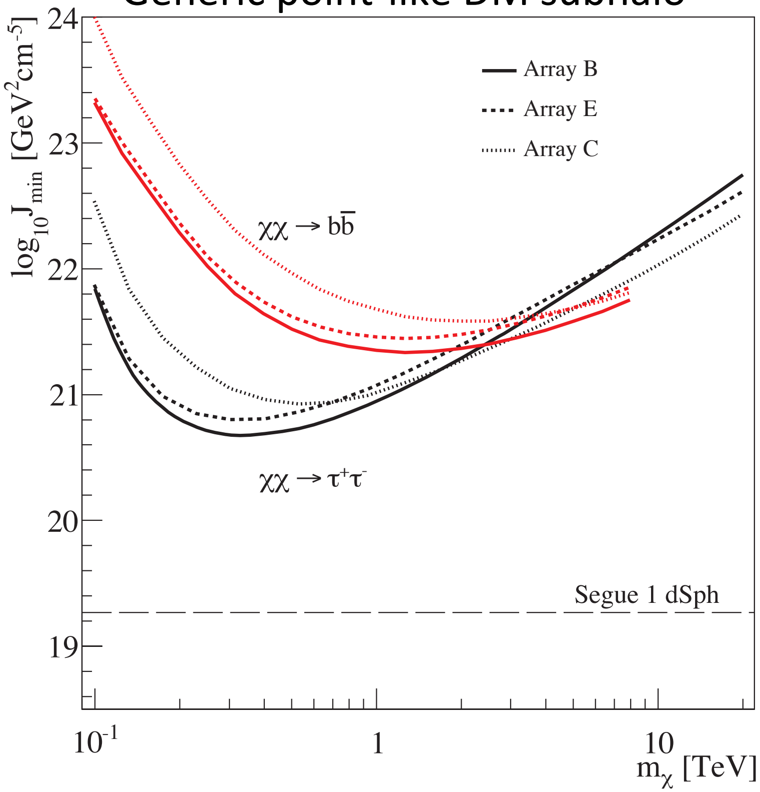
Boost factors required for detection

to reach "thermal cross-section" of <σv>: 3×10^{-26} [cm³/s]

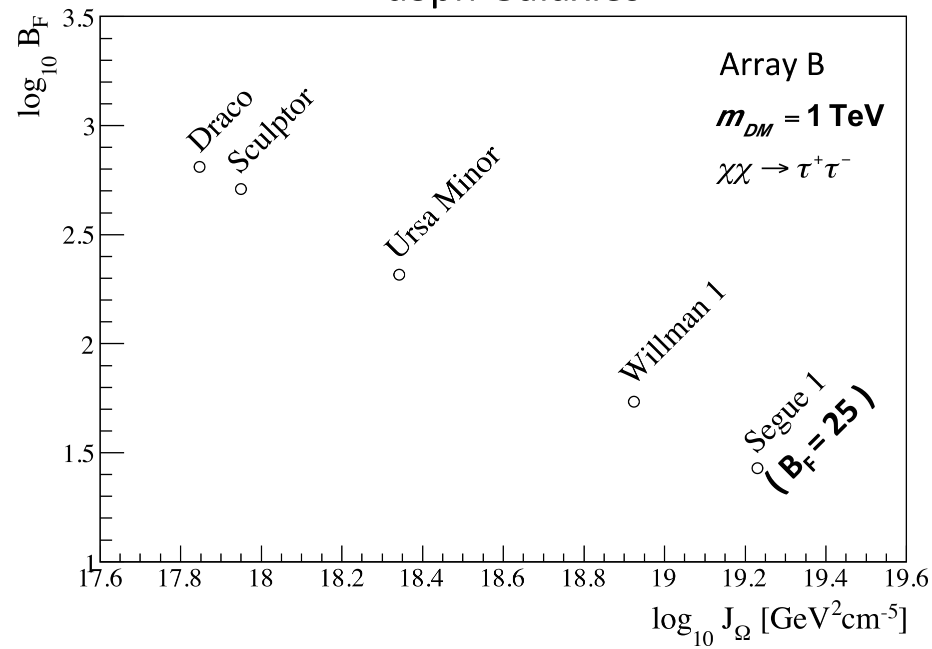
$$\frac{d\Phi}{dE} = B_F \times J(\Delta\Omega) \times \frac{d\Phi^{PP}}{dE}$$

5σ detection in 100h obs.

Generic point-like DM subhalo



dSph Galaxies



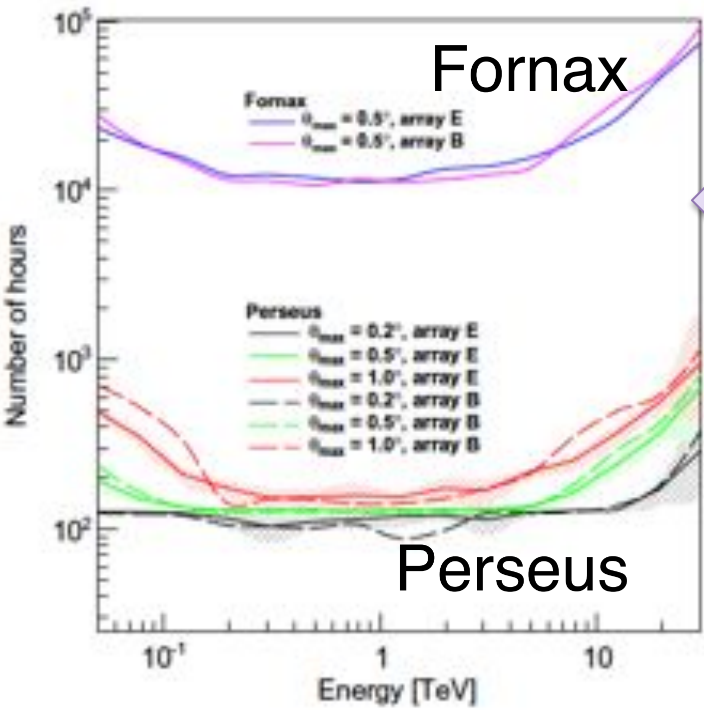
Clusters of Galaxies

cosmic-ray induced γ rays can be contaminated (although no such emission is detected so far.)

- study in two objects
  - Perseus: highest CR-induced photon yield but a low DM content
  - Fornax: opposite reason

  (based on N-body simulation by Pinzke et al. 2011 PRD)
  - assuming the presence of DM subhalos
    - boost factor from subhalos is estimated (Pinzke et al. 2011) 910 for Perseus, 580 for Fornax (for a minimal halo mass of 10^{-6} Msolar)

Cluster of Galaxies

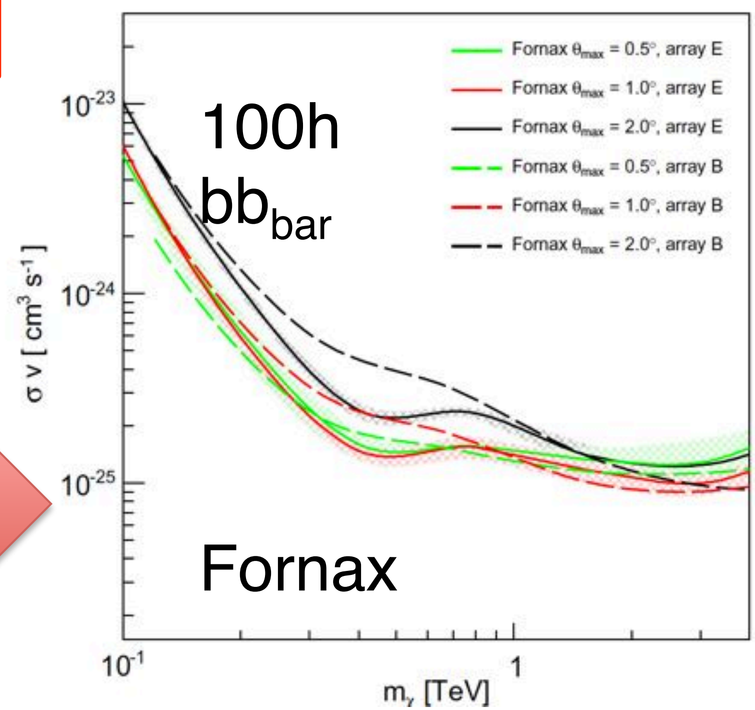


Required obs. time for 5σ detection

Signal

Cosmic rays only

Dark matter only



100h obs., 95%UL

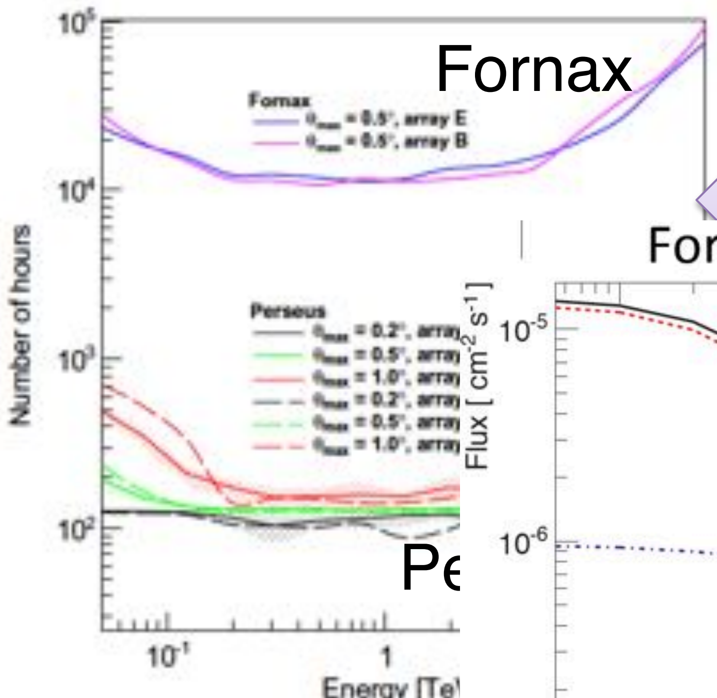
in reality, they are mixed,,,,,,

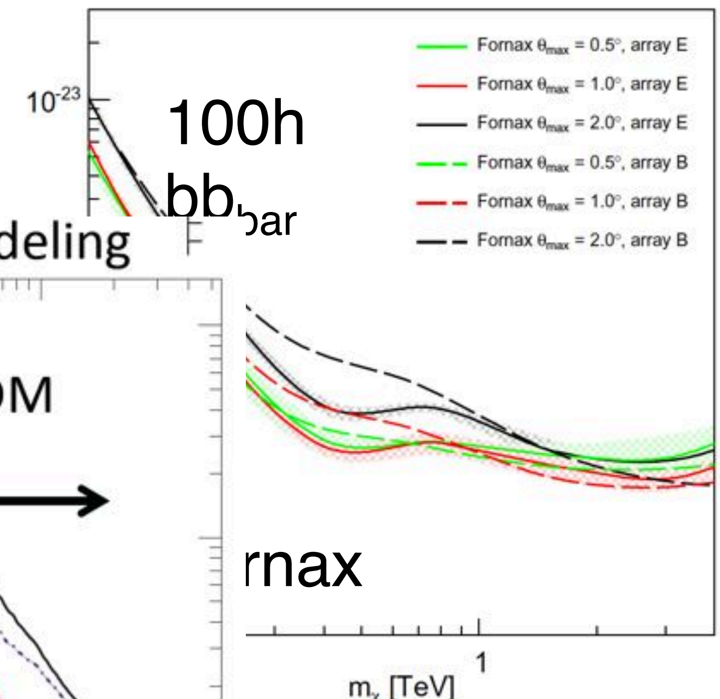
how can we distinguish?

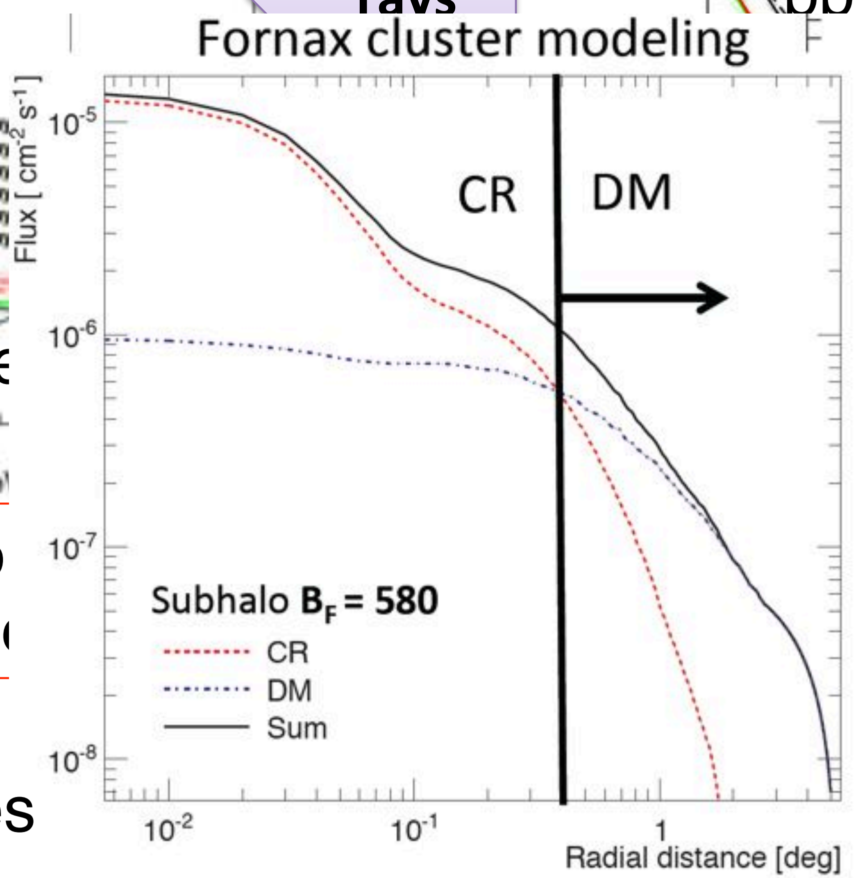
Cluster of Galaxies

Signal

Cosmic rays







Model adapted from Pinzke et al. 2011

Required o
for 5σ dete

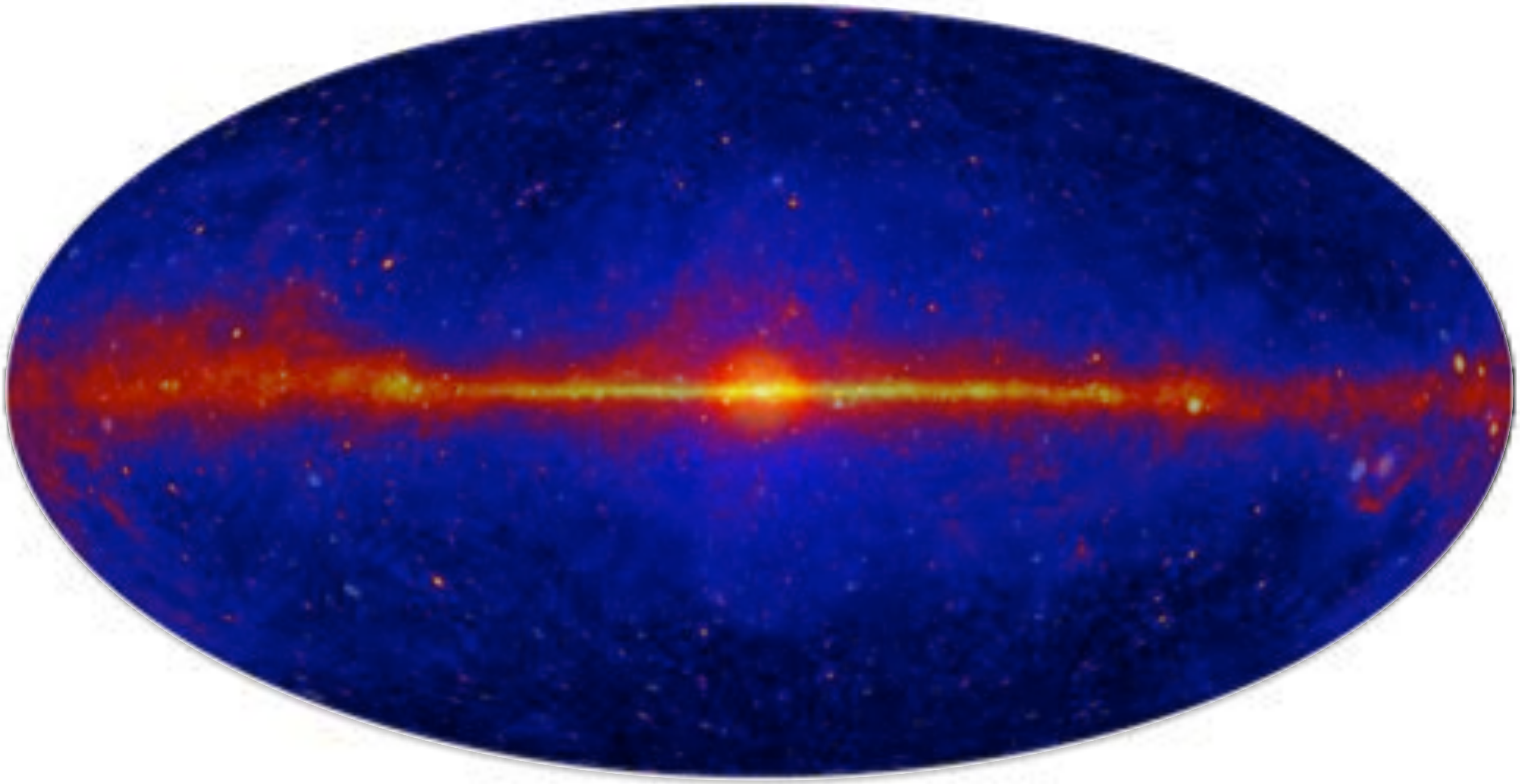
)h obs., 95%UL

spacial profiles are different

DM signal can be more extended

Milky Way halo

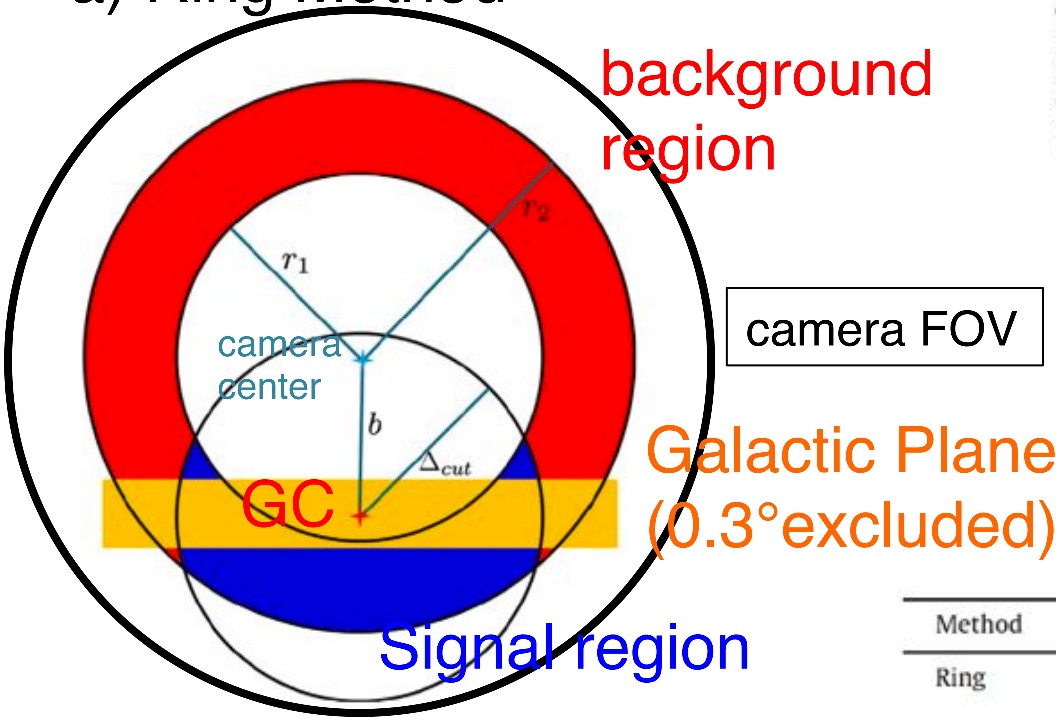
but with the largest astrophysical gamma-ray background,,

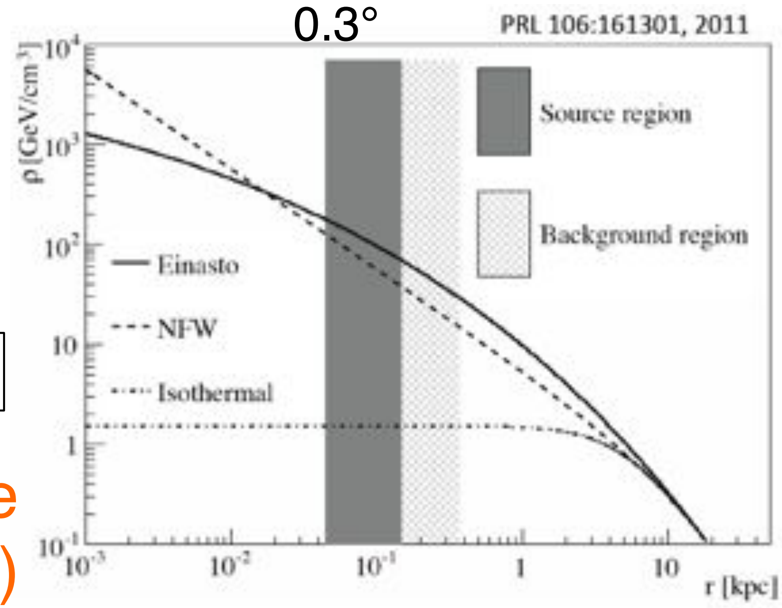


Milky Way Halo simulated by Taylor & Babul (2005)
All-sky map of DM gamma-ray emission (Baltz 2006)

MW Halo: observation strategies

a) Ring Method





Method	Array (TeV)	m_χ	$\bar{J}_s$ (10^{22} GeV^2 cm^{-5})	ΔΩ (sr)
Ring	*E*	Any	4.68	0.00117
	B	Any	4.43	0.00104
On-off	*E*	0.1	16.4	0.00751
		1	19.7	0.01044
		10	28.7	0.02211
On-off	*B*	0.1	16.4	0.00751
		1	22.8	0.01384
		10	28.7	0.02211

b) On-Off Method
(excluding |b| < 0.3 deg)

- more sensitive
- Challenging background control

cf. J~2x10^{19}
Segue 1 (dSph)

MW Halo: prospect

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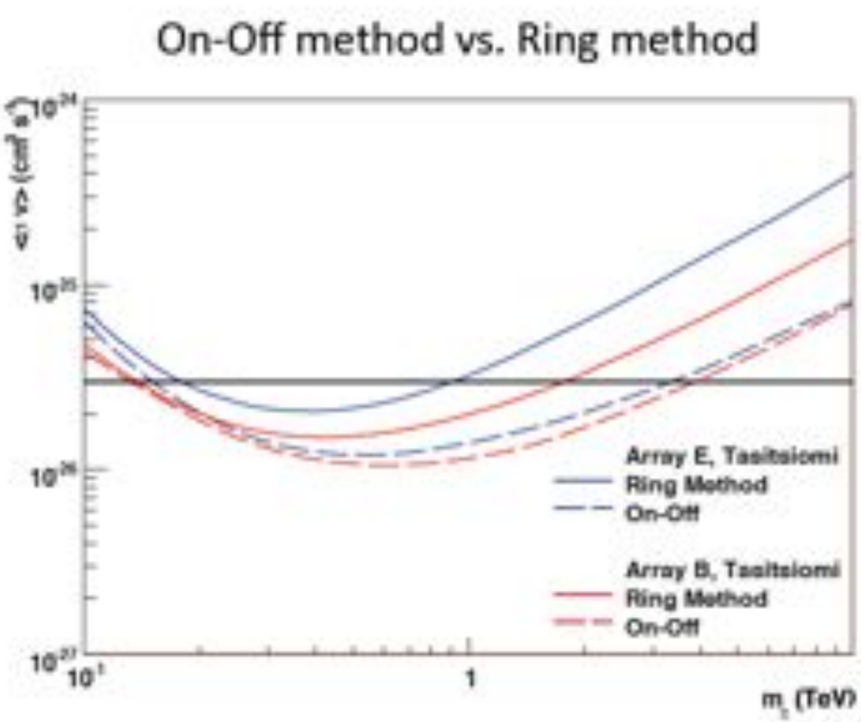
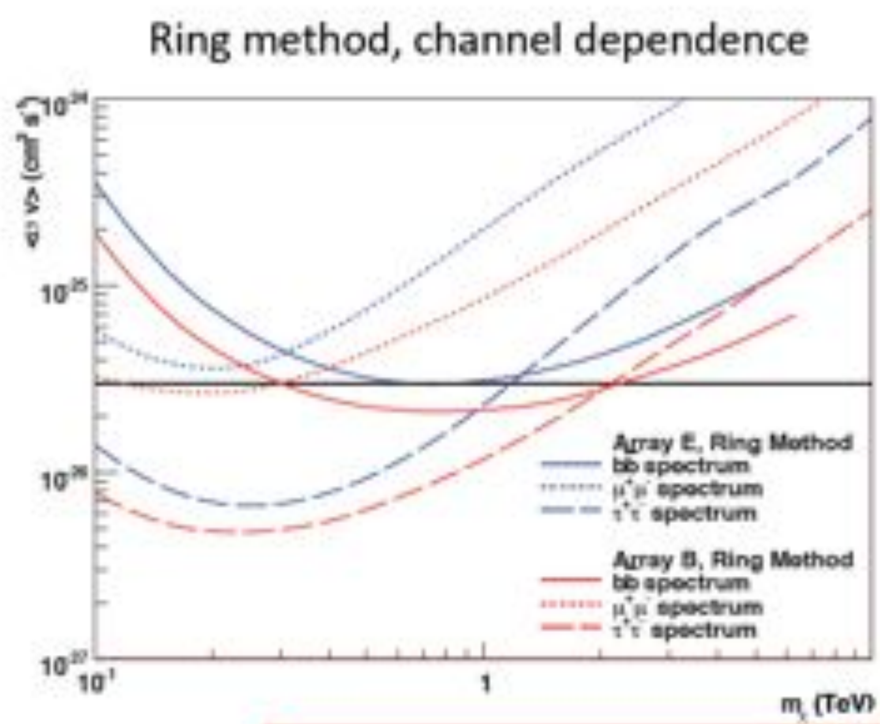
Institute for Cosmic Ray Research
University of Tokyo





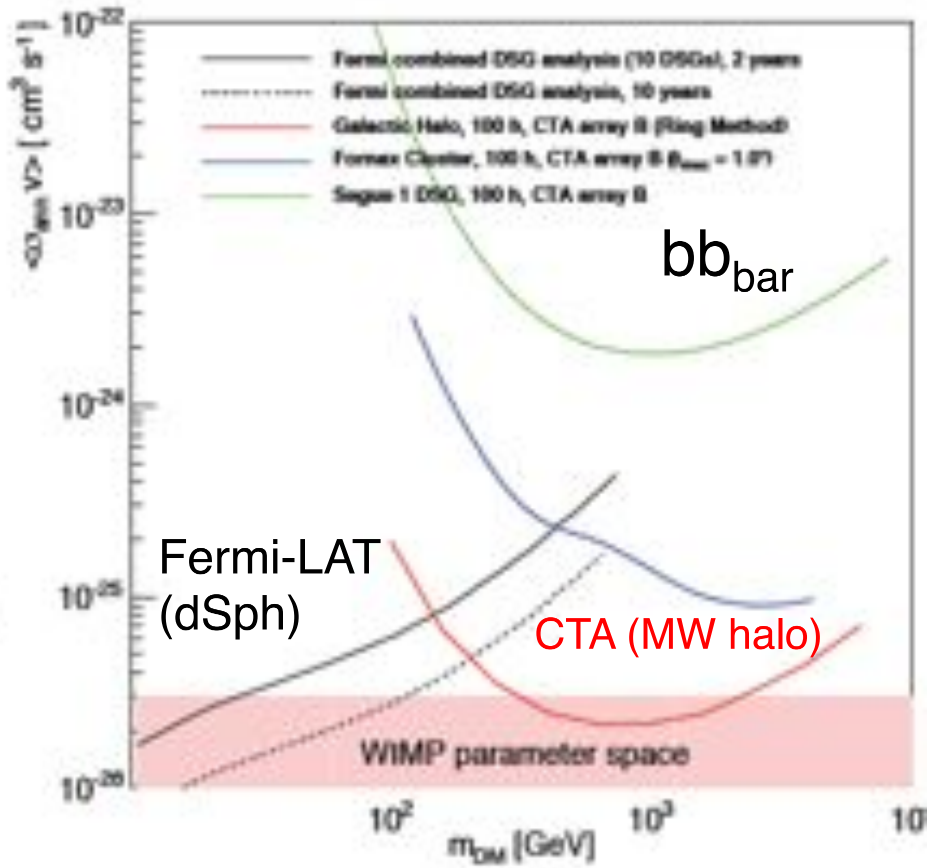
Ring Method: 100h obs.
On-Off Method: 50h+50h obs.

can reach "WMAP" limit space!!

Prospects for the DM search

ICRR Institute for Cosmic Ray Research University of Tokyo

- CTA is the worlwide project for a future VHE gamma-ray **open observatory**, heading toward **starting construction by 2014.**
- dSph Galaxies:
  $\langle \sigma_{ann} v \rangle \sim 10^{-24} cm^3 s^{-1}$
  BF=25 (Segue 1)
- Galaxy Clusters
  $\langle \sigma_{ann} v \rangle \sim 10^{-25} cm^3 s^{-1}$
  CR background, extended emission
- **Galactic Halo**
  $\langle \sigma_{ann} v \rangle \sim 10^{-26} cm^3 s^{-1}$
  Probing the WIMP parameter space!
- **Complementarity** with Fermi-LAT and direct searches



Time schedule

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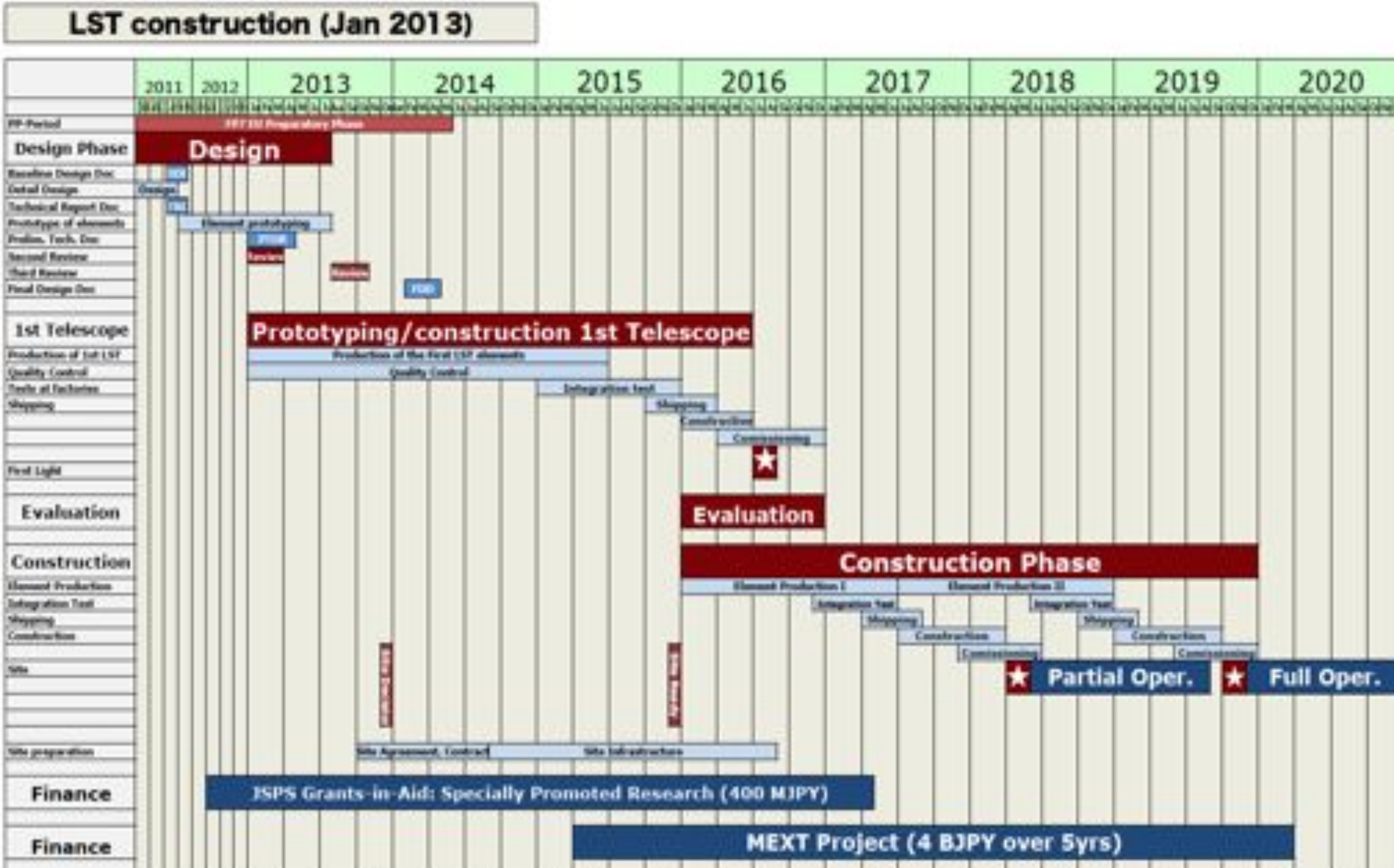
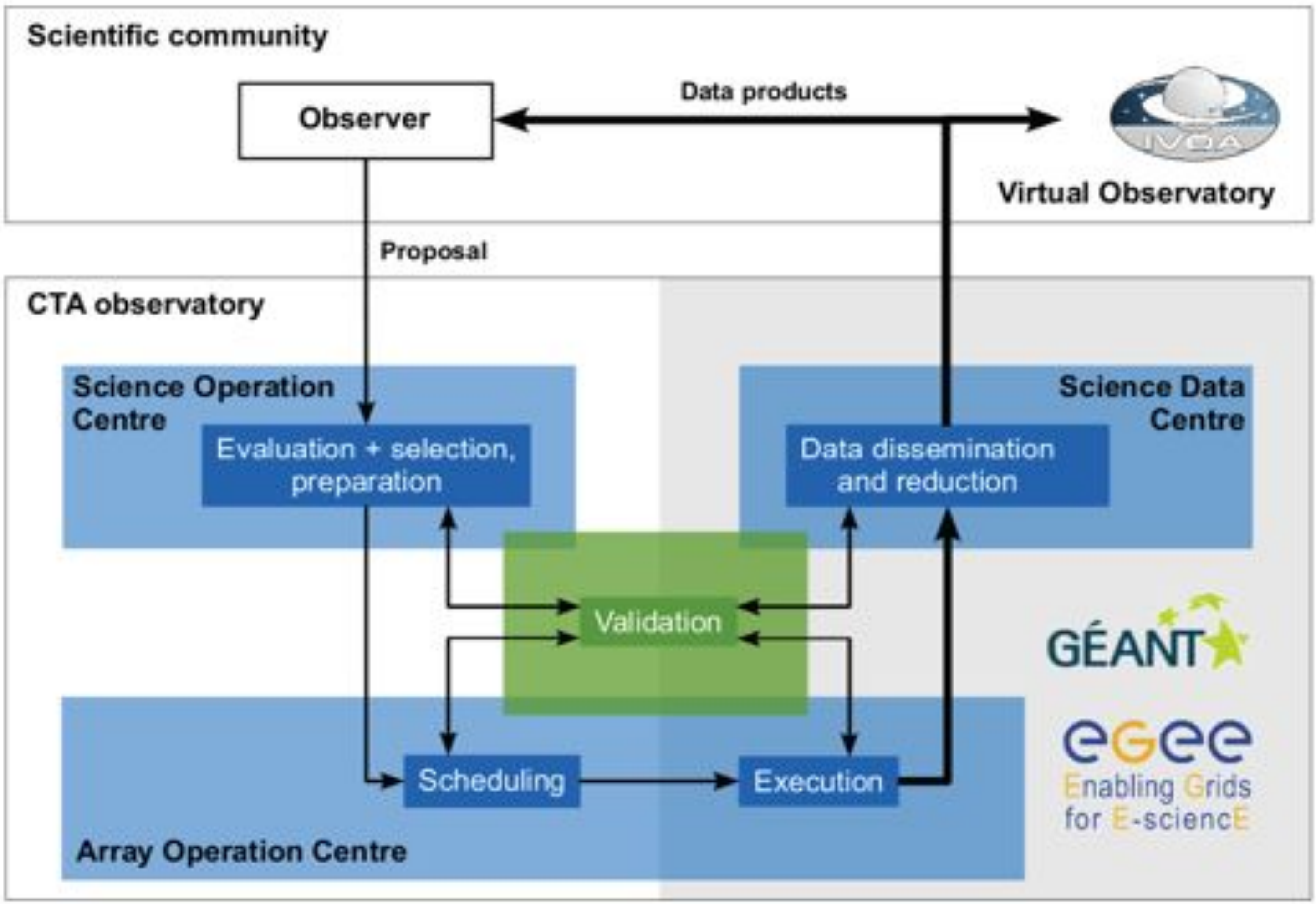


CTA observatory

The first **open observatory** in the field of IACT



Summary

1. CTA will drastically improve the observations in the 20 GeV – 100 TeV band
2. First light will be foreseen in 2016 and the full operation will start 2019
3. CTA-Japan mainly contributes to the LST developments (hardware and MC)
4. CTA can probe “WMAP space” < with the Milky way halo study.
5. CTA will be the open observatory!!!
   You can use it!!!