CTA and the Road Ahead

Jim Buckley
Washington University in St. Louis

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My Postdoc with Trevor

letters to nature

Nature **358**, 477 - 478 (06 August 1992); doi:10.1038/358477a0

Detection of TeV photons from the active galaxy Markarian 421

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PHOTONS of TeV energy have been observed from a few sources in our Galaxy, notably the Crab Nebula[1]. We report here the detection of such photons from an extragalactic source, the giant elliptical galaxy Markarian 421. Mk 421 has a nucleus of the BL Lacertae type[2,3], and emission from it has been observed at radio[4–6], optical[3,6] and X-ray[6–8] frequencies, and most recently in the MeV-GeV bands, by the EGRET detector aboard the Compton observatory[9]. In March–June 1992, we observed Mk 421 with the Whipple Observatory γ-ray telescope[10], a ground-based detector that images Cerenkov light from air showers, and found a signal with statistical significance of 6er above background. The flux above 0.5 TeV is 0.3 of that from the Crab Nebula. The source location agrees with the position of Mk 421 within the angular uncertainty (6 arc minutes) of the Whipple instrument. The fact that we have observed this relatively nearby source (redshift $z = 0.031$), whereas active galaxies and quasars that are brighter at EGRET energies but more distant have not been detected in the TeV energy range, may be consistent with suggestions[11,12] that TeV photons are strongly attenuated by interaction with extragalactic starlight.

- In 1992, while finishing my thesis, my friend Tim McKay (working on CASA-MIA) told me about a paper on the discovery of TeV gamma-rays from Mrk421. Combined with a wonderful talk I had heard by Trevor on the Crab discovery, I remember at that moment deciding I must work for Trevor at Whipple! (When I arrived the signal disappeared).

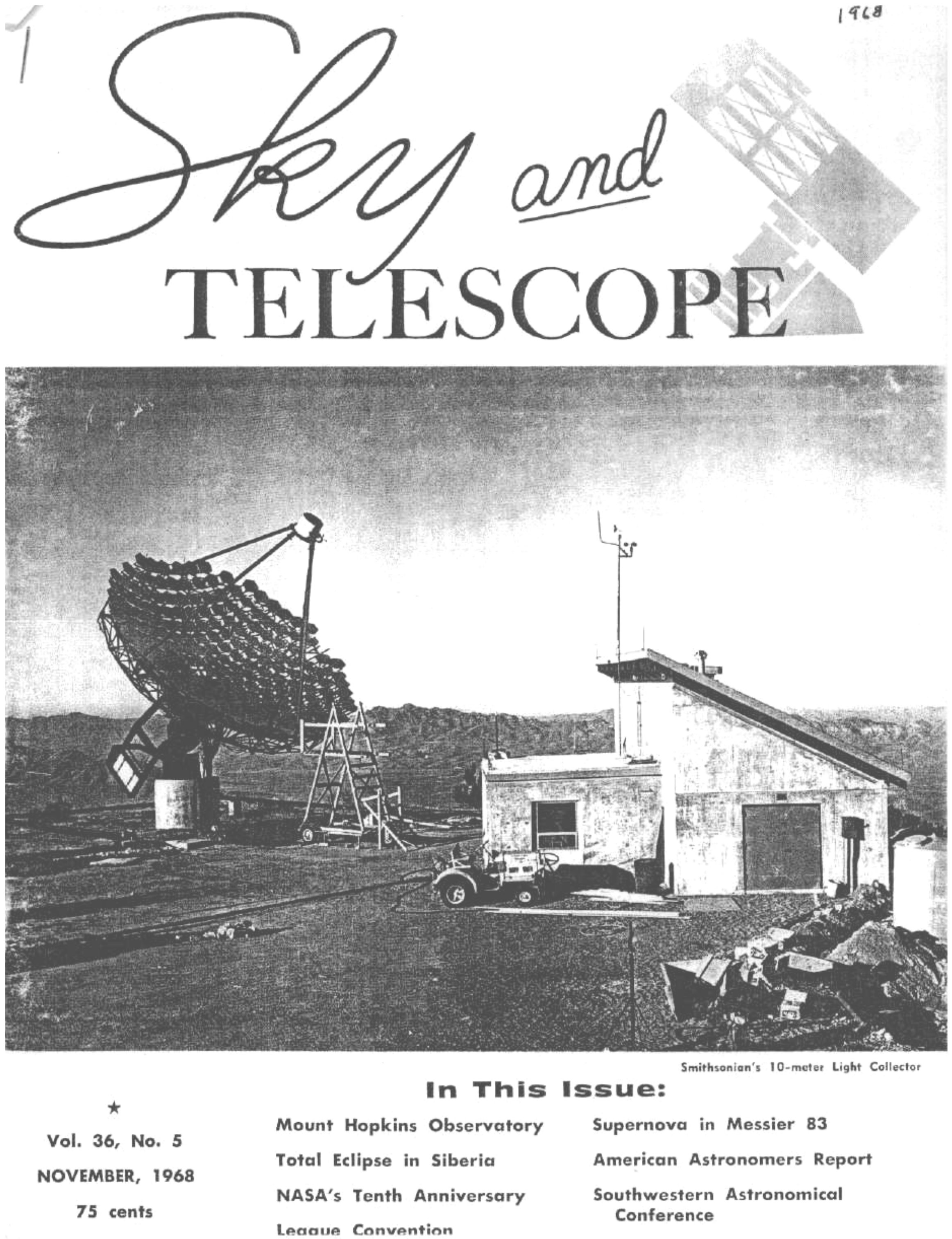
The Road

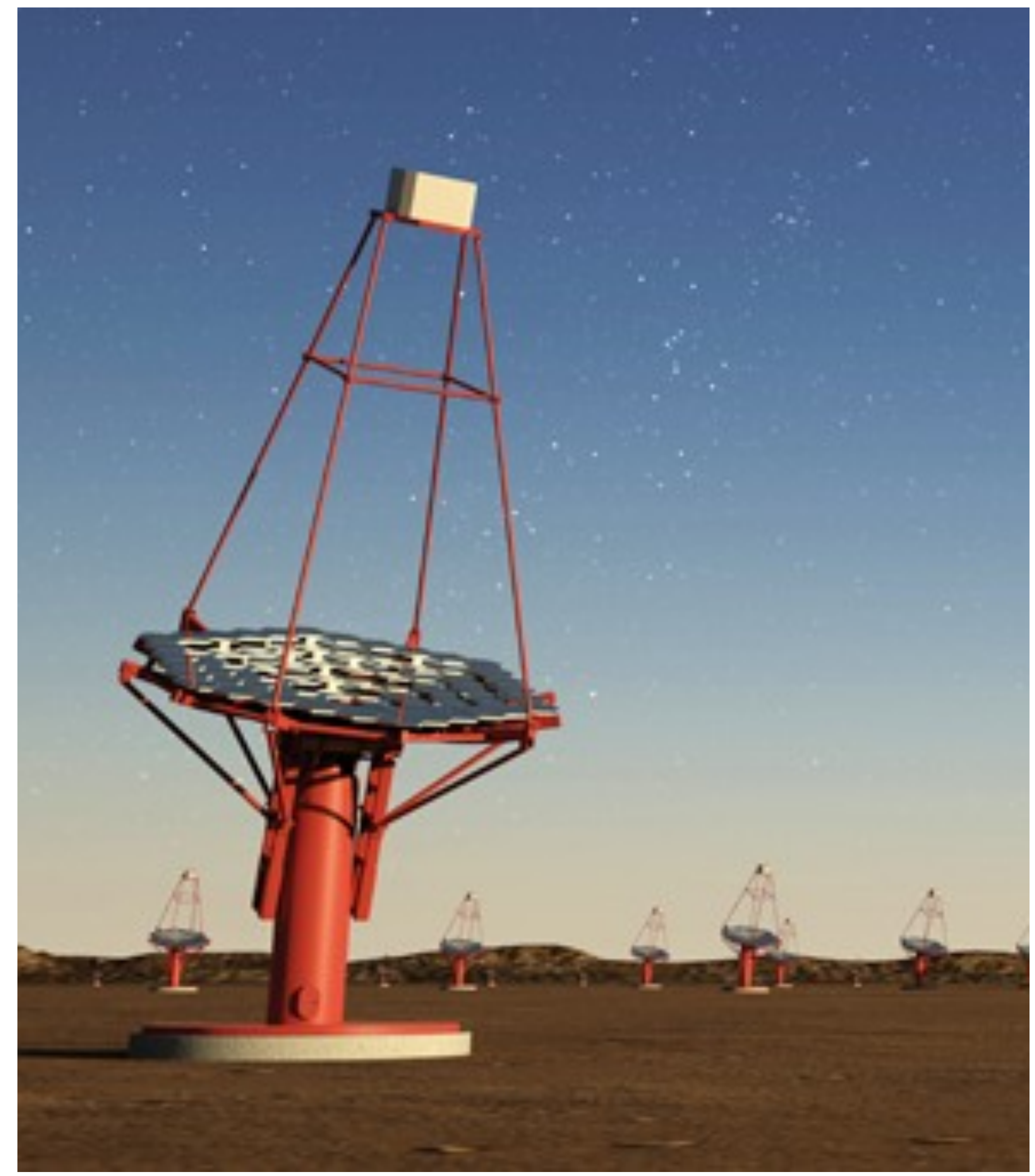
- I remember, after a quick lunch at Trevor's home in Green Valley, I took my first ride up the mountain as Trevor's new postdoc - white knuckled but trying to act calm.
- Trevor was very kind, and told me about all of the "head-to-heads" that occurred over the years and about the merits of having no guard rails, pointing all of the time to the steep drop-off - alternating between trying to put me at ease and to terrify me.
- I soon learned from TCW the great sport of terrifying newcomers with stories about wild animals, scary roads and other dangers.

Working on the Ridge

- Many hazards working on the ridge -
    - Dismal coffee (also at Steward, made by Trevor out of residue of past pots and perhaps mouse droppings).
    - German drivers, Irish drivers, French drivers (and second-hand smoke.)
    - Cows and Javalinas in the road (Mark Chantel's Saturn)
    - Rattle snakes.
    - Bears (Vampire Bears, in particlular)
    - Mountain lions (especially fond of pouncing on new Irish students walking between dorm and 10m - according to TCW)
    - The ghost of Geronimo (fond of slamming doors at 3:00 AM)
    - The *so-called* 11m telescope.
    - Killer deer.
    - Bas van't Sant (biggest risk to Christians or cleaning crew).
    - Arizona pack rats.
    - Trevor's wrath if potential observing time was lost.

IACTs - the Past and Future!



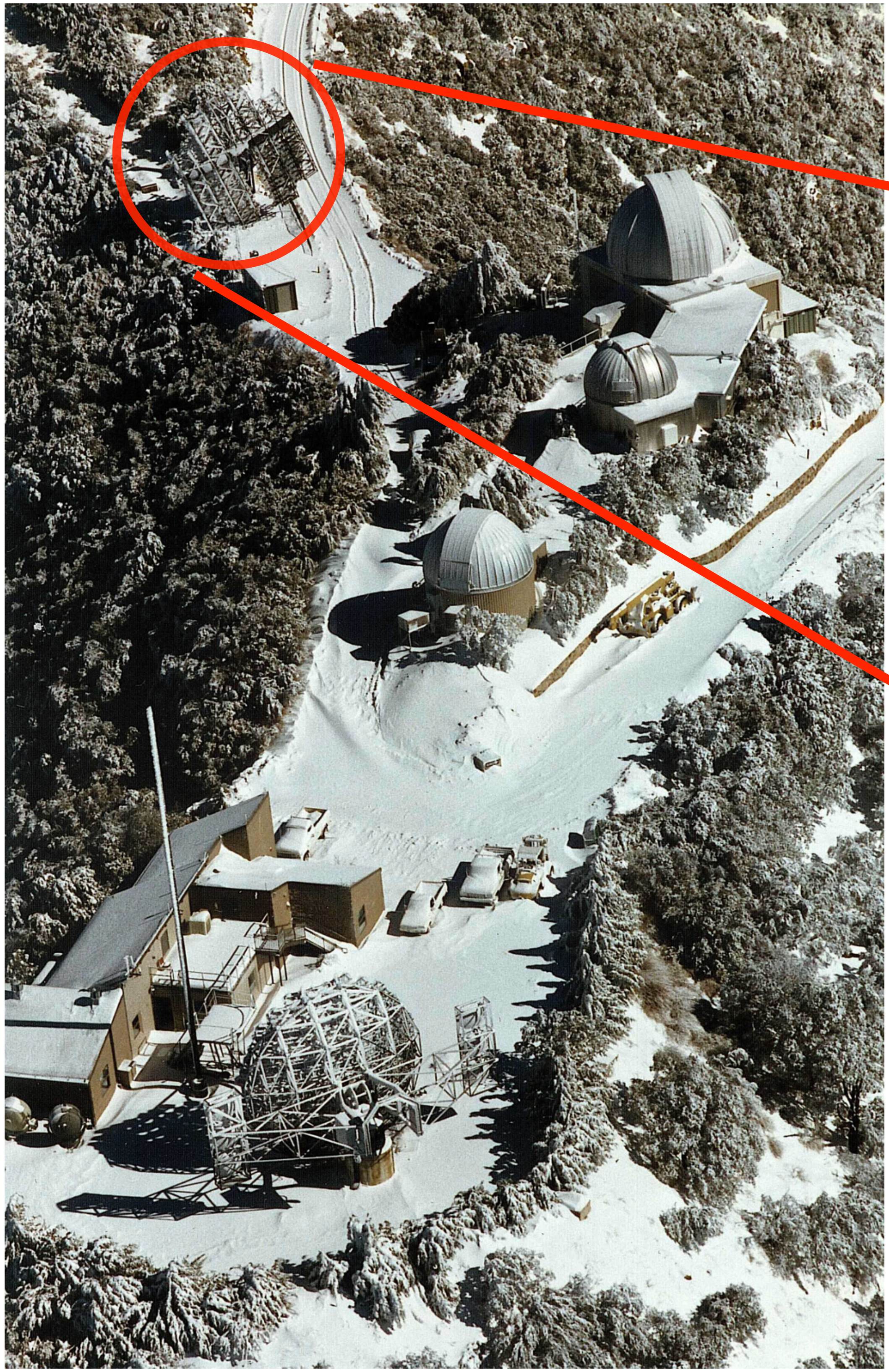


- Since 1968 not much has changed - 10m DC telescopes still rule the gamma-ray sky!

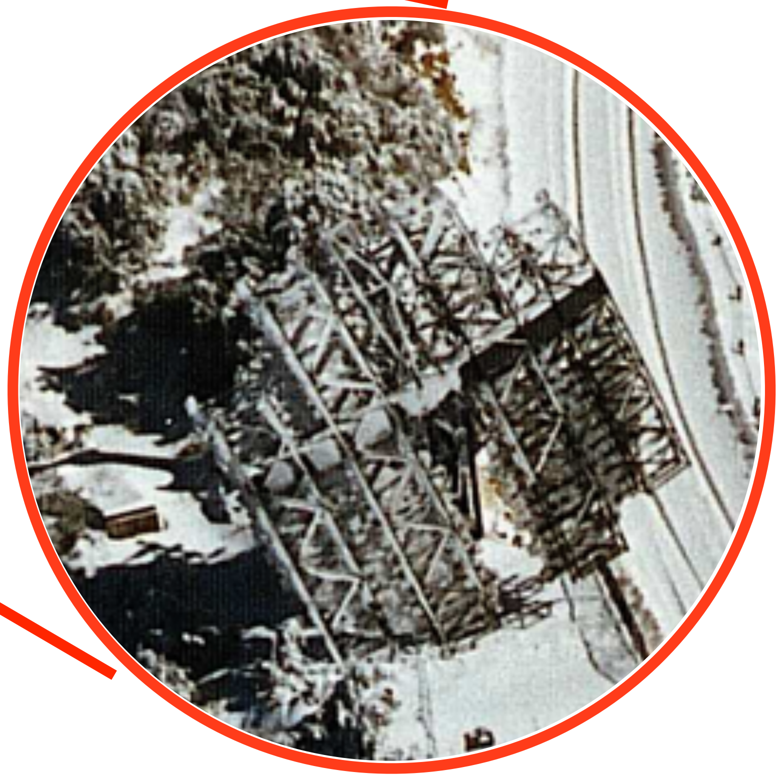
Collaboration with Trevor

- Trevor gave me a lot of freedom to work on science. He also let me quit working on the 11m telescope - a task he specifically hired me to work on! (Would I let my own postdoc do that?).
- During my years in Tucson he and I worked closely on a number of topics:
  - Origin of Cosmic Rays (following up on the exciting suggestion of Drury, Aharonian and Volk, indulging my obsession with IC443)
  - Active Galaxies (we came up with the idea that it was time to turn away from EGRET sources to look at X-ray selected BL Lacs - some from an old Trevor source list)
  - Optical/multiwavelength astronomy with the 48inch and 60inch (encouraging me and Julie to work on this)
- Coming from Chicago, I was somewhat obsessed with the idea of detecting dark matter from the GC - Trevor teased me ruthlessly, but must have really liked the idea. My fascination with null results (from my early years with Trevor) keeps me interested in dark matter.

The 11m



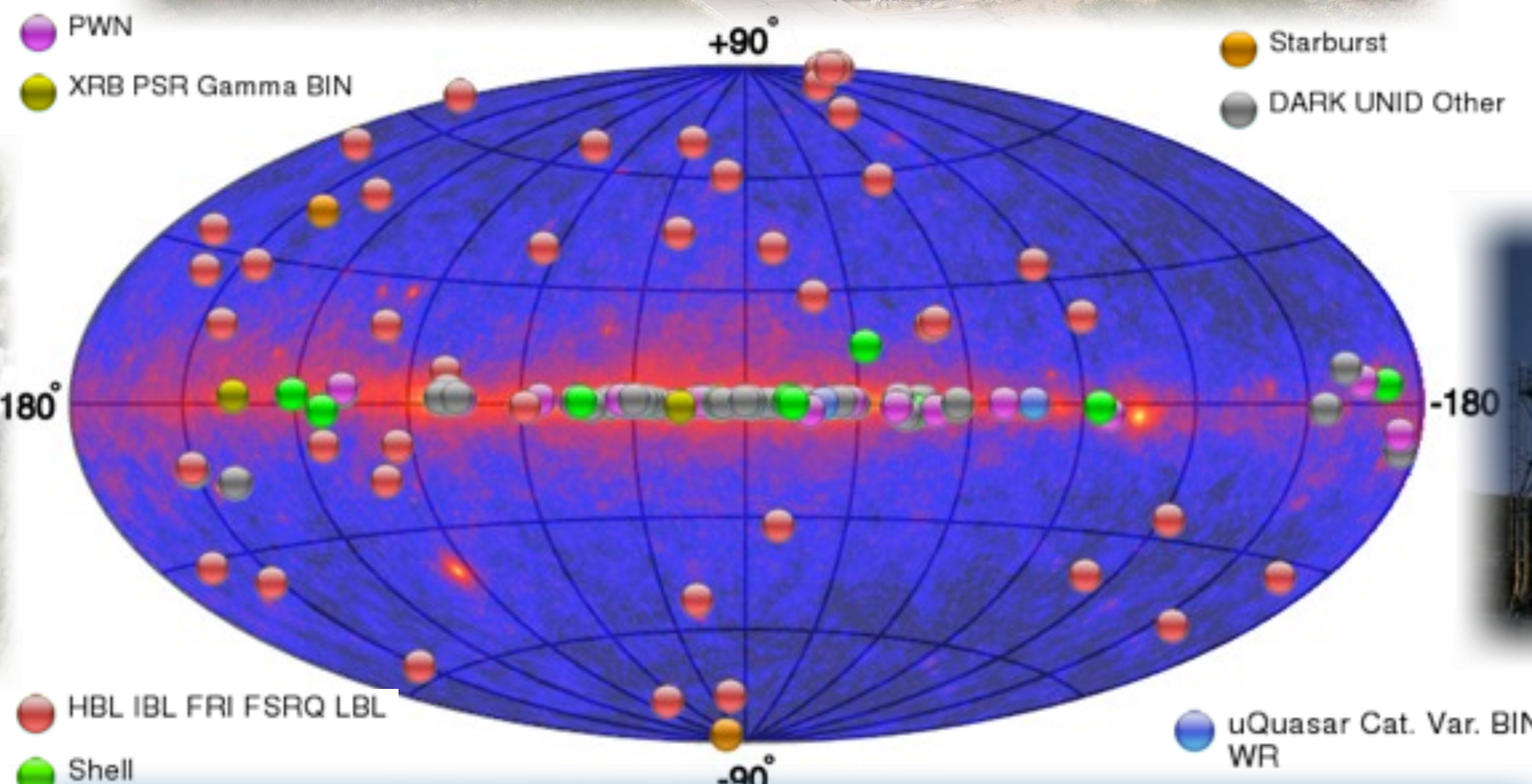
The collapse



I learned many lessons about hardware and data analysis from our failures as well as successes - importance of killing false signals, sometimes the importance of putting telescopes out of their misery (although divine intervention may be required)

VHE Gamma-Ray Status

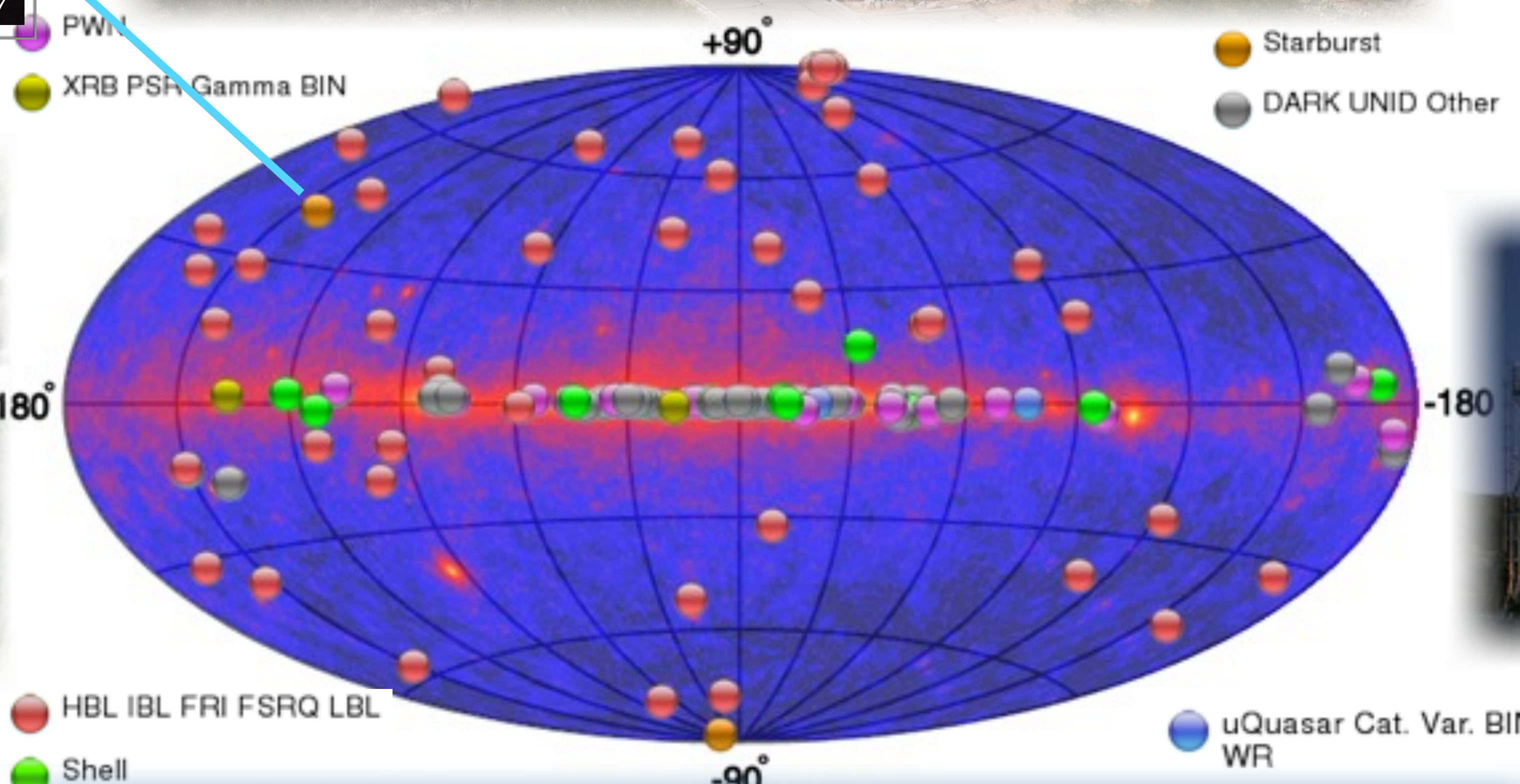
MILAGRO



MAGIC

VHE Gamma-Ray Status

MILAGRO



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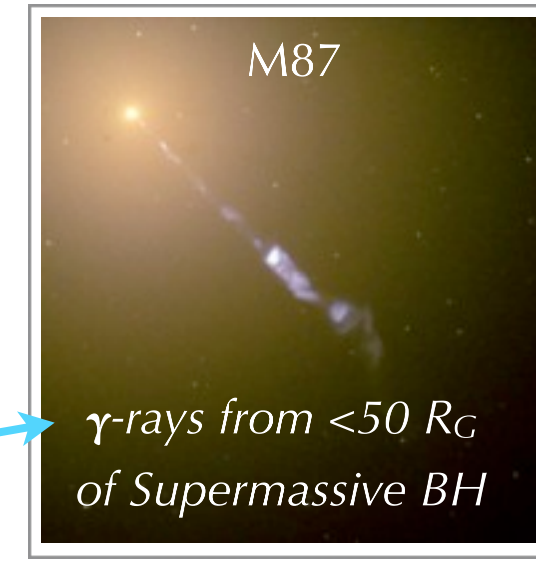

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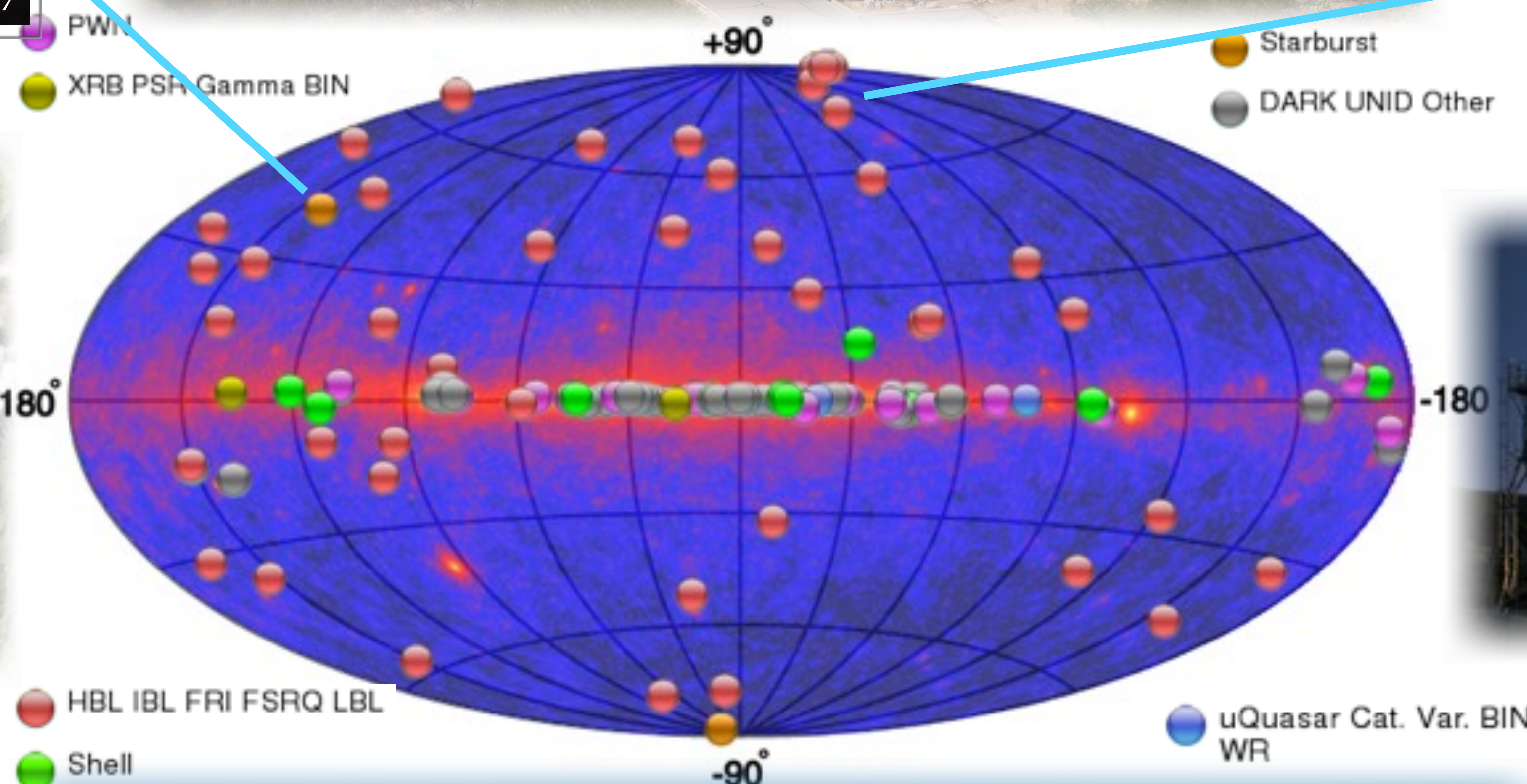

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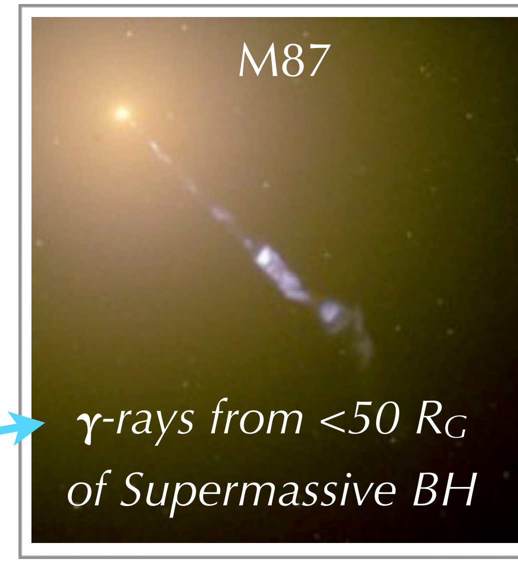

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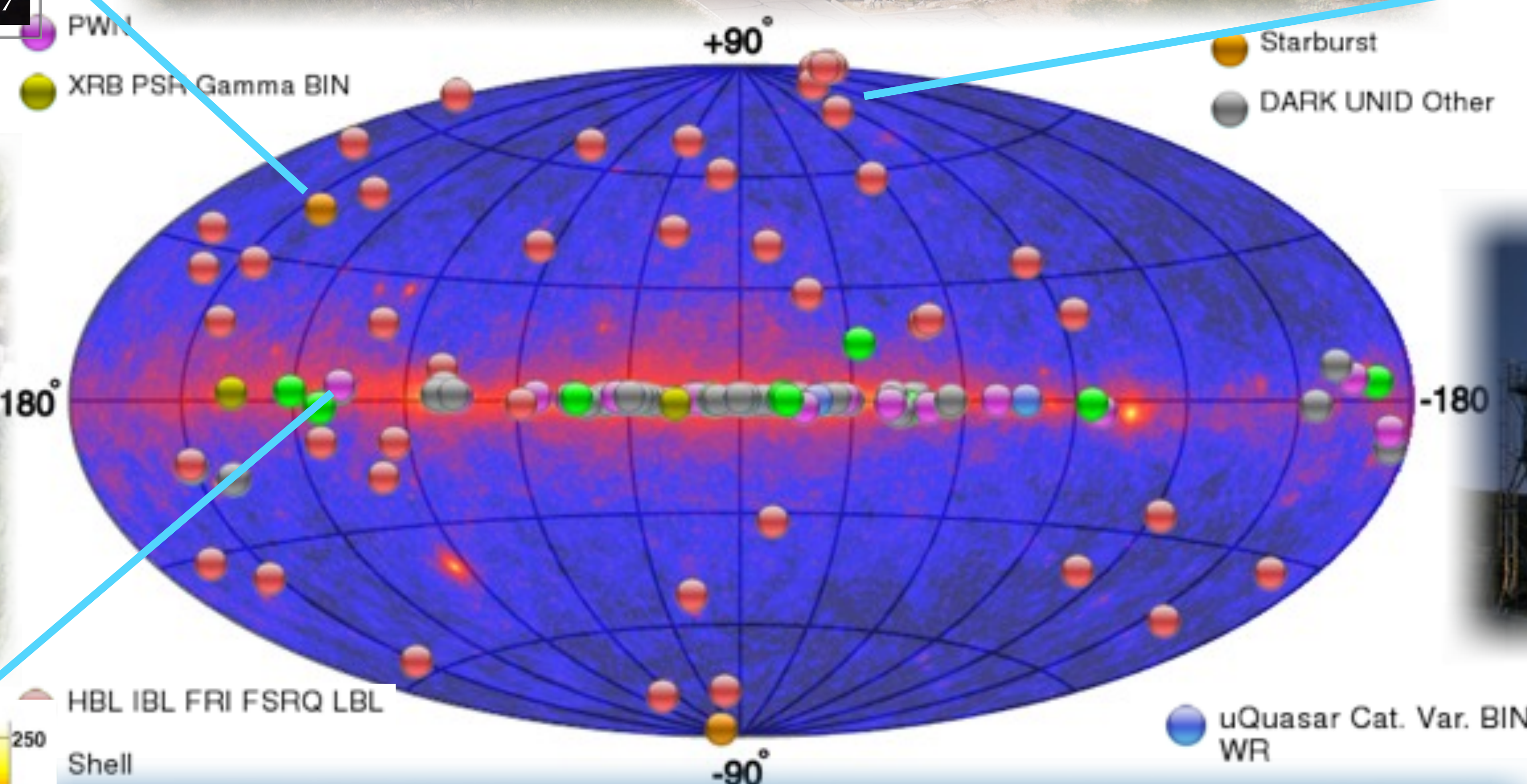

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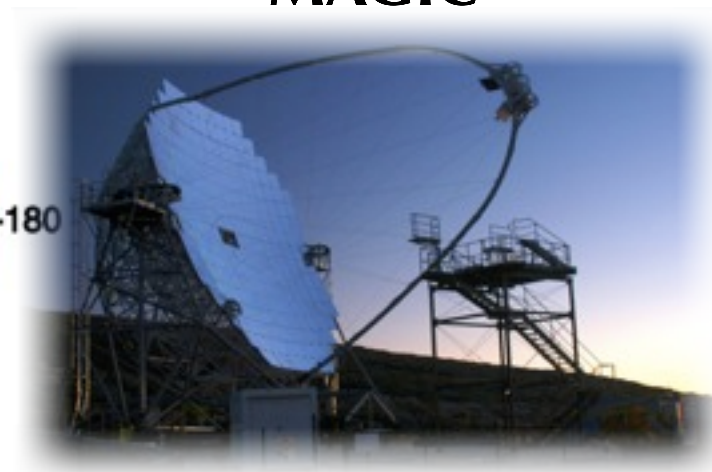

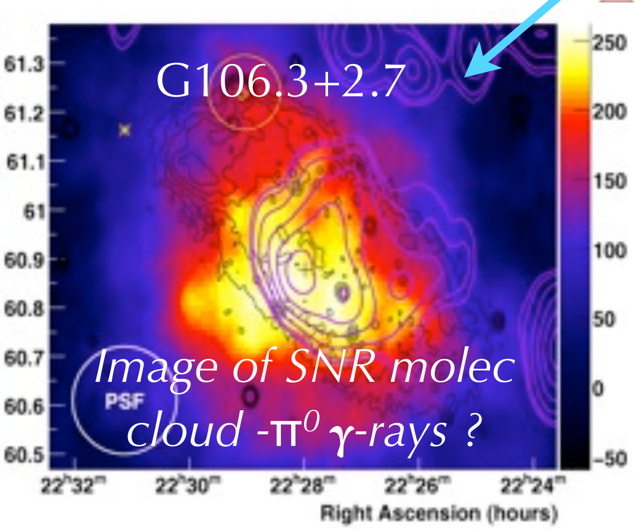

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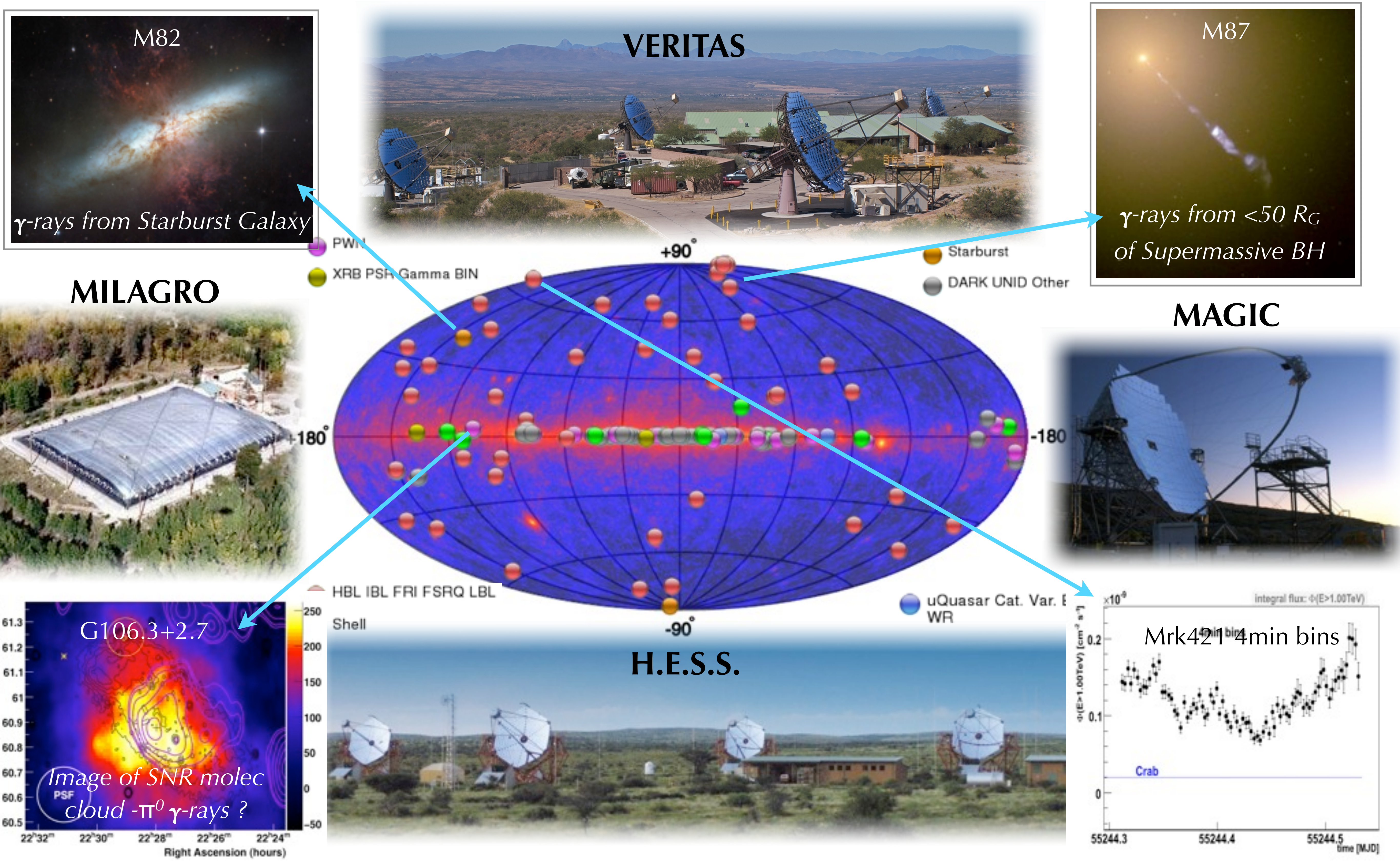
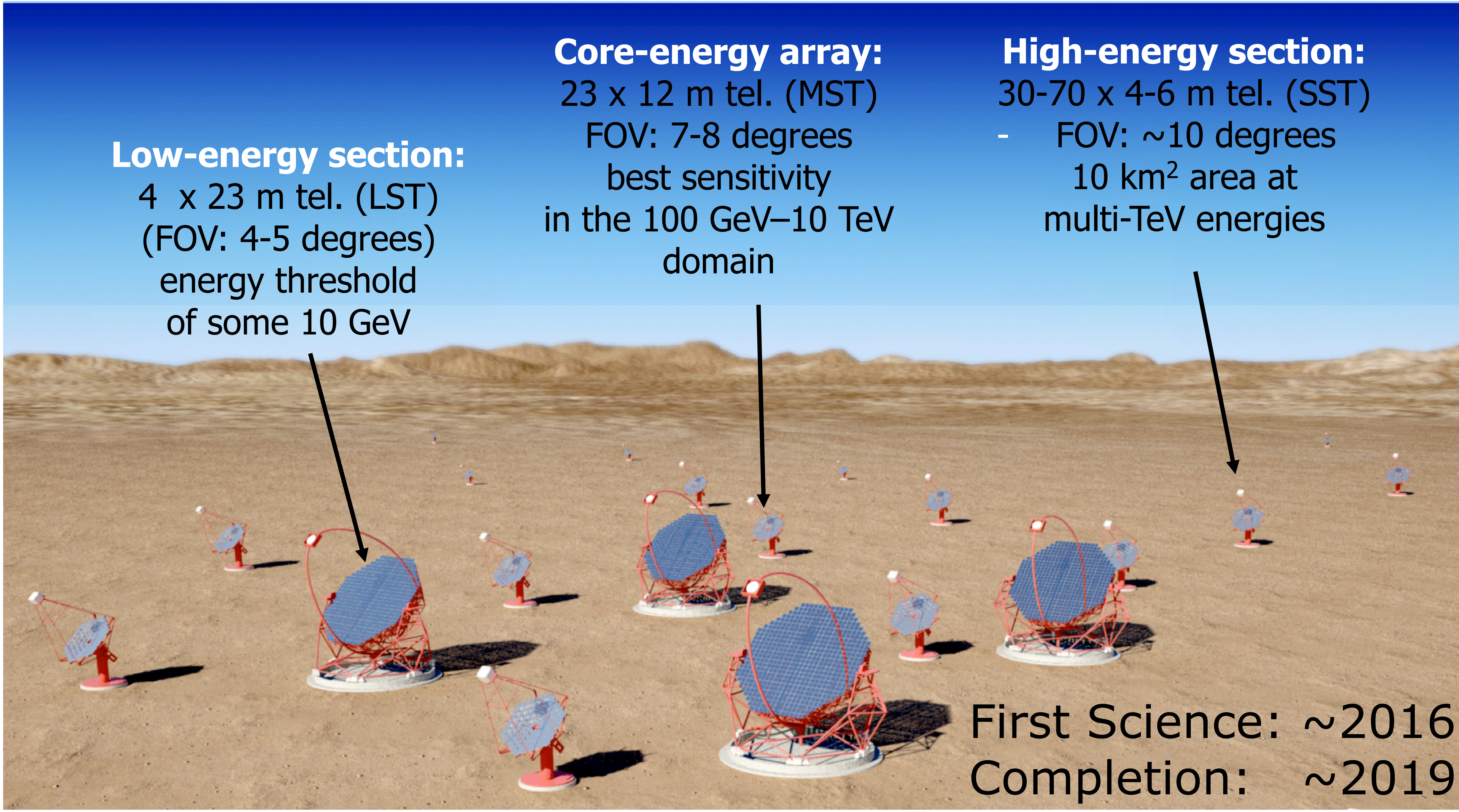


The Future

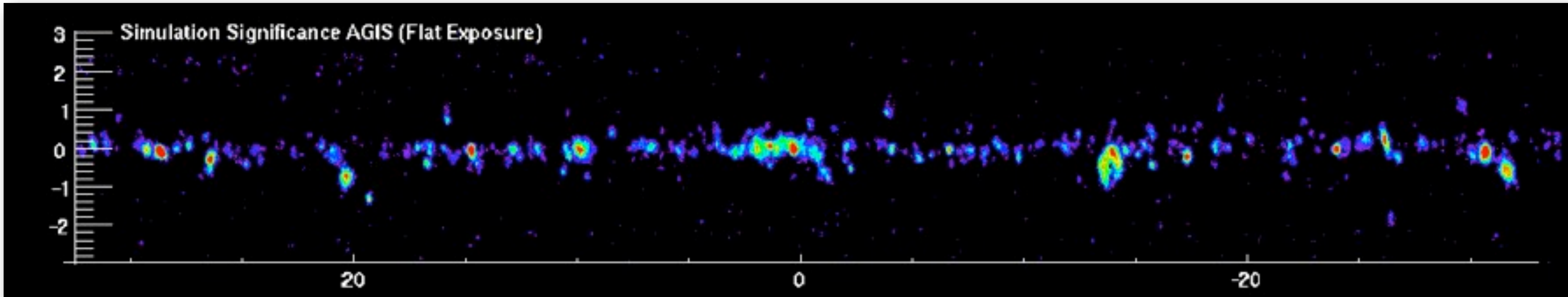
Cherenkov Telescope Array *CTA*



- CTA is being built by an international consortium of ~1000 scientists - *Many Body Physics*

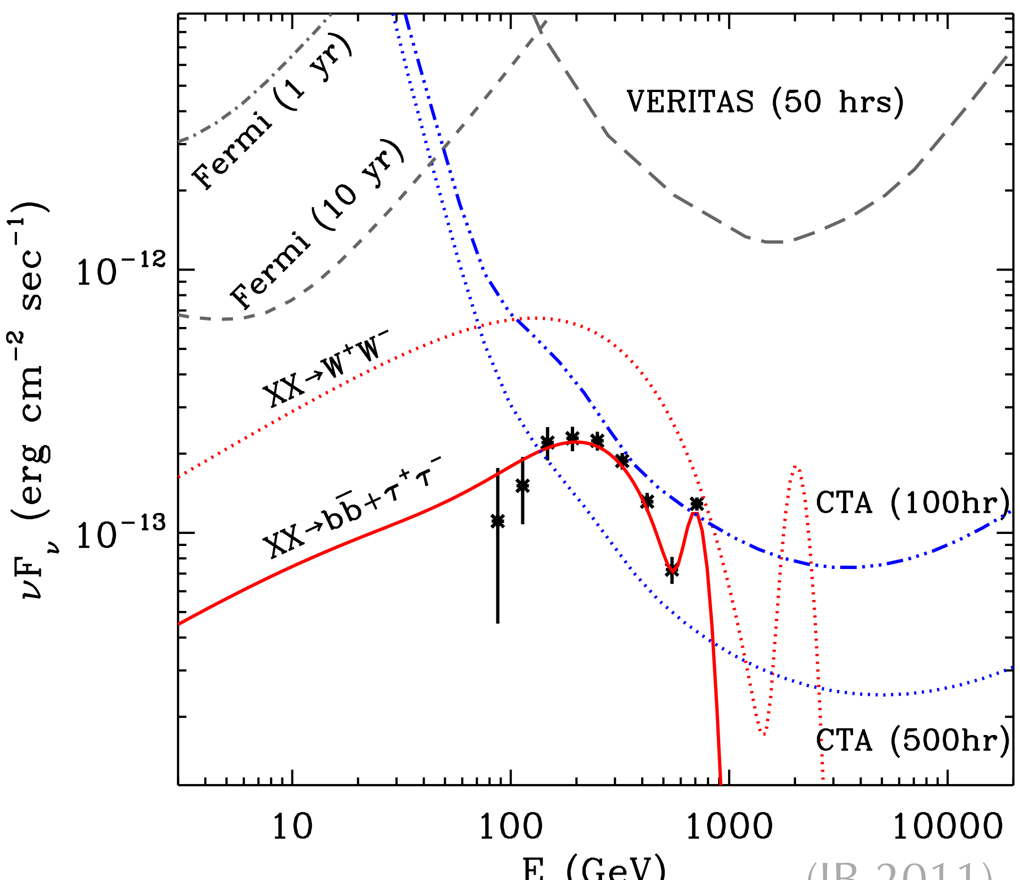
CTA-US Science

Simulated Galactic-plane Sky Map with Improved Angular Resolution, FoV, Sensitivity



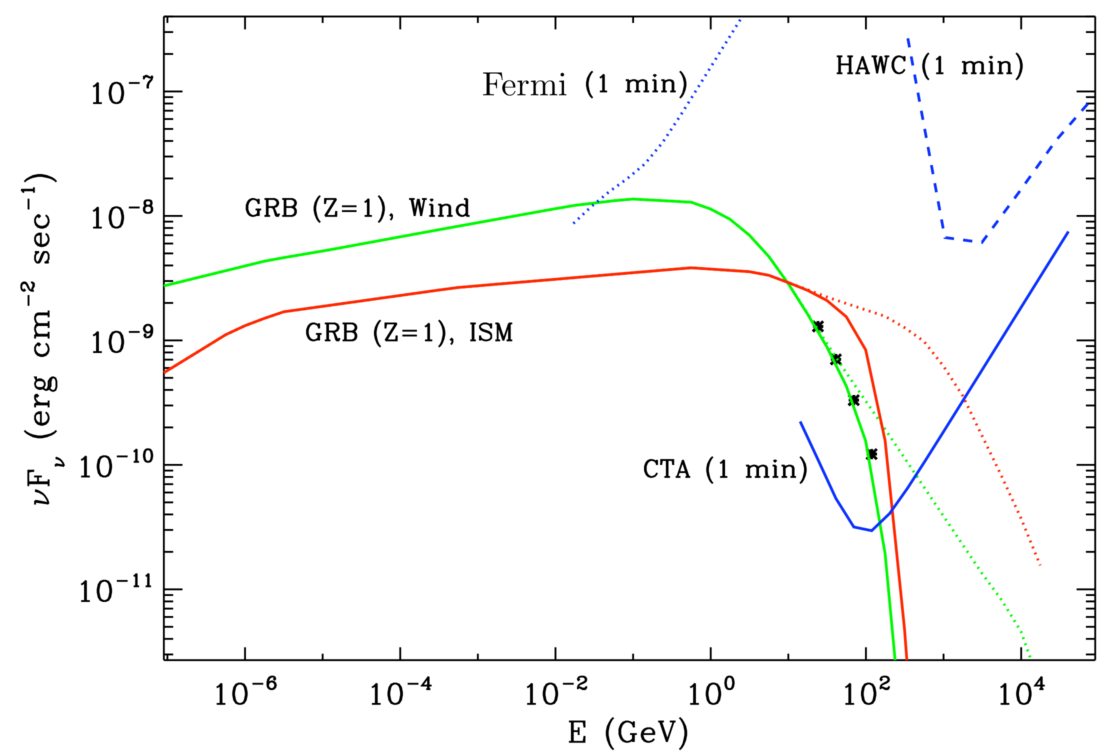
Digel, Funk and Hinton

Dark Matter



(JB 2011)

Larger Redshifts and Rapid Transients



(Buckley et al., APS whitepaper, 2008)

CTA-US Science

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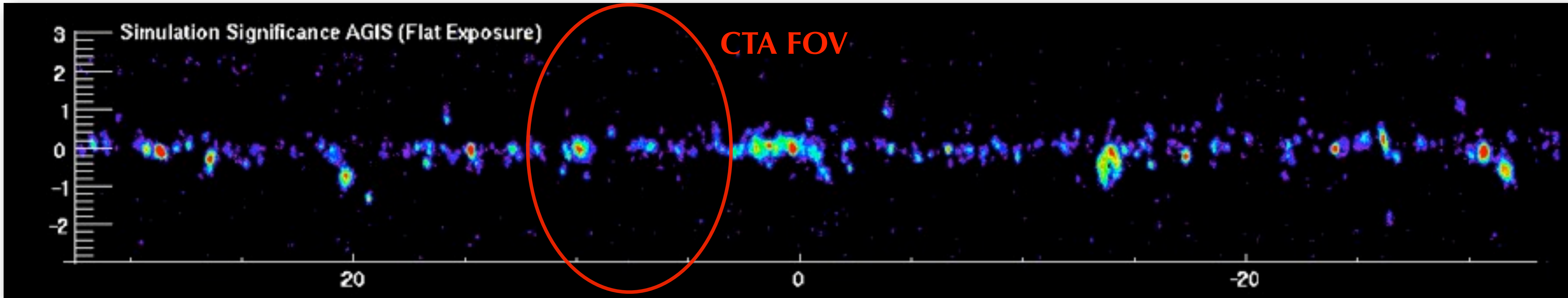

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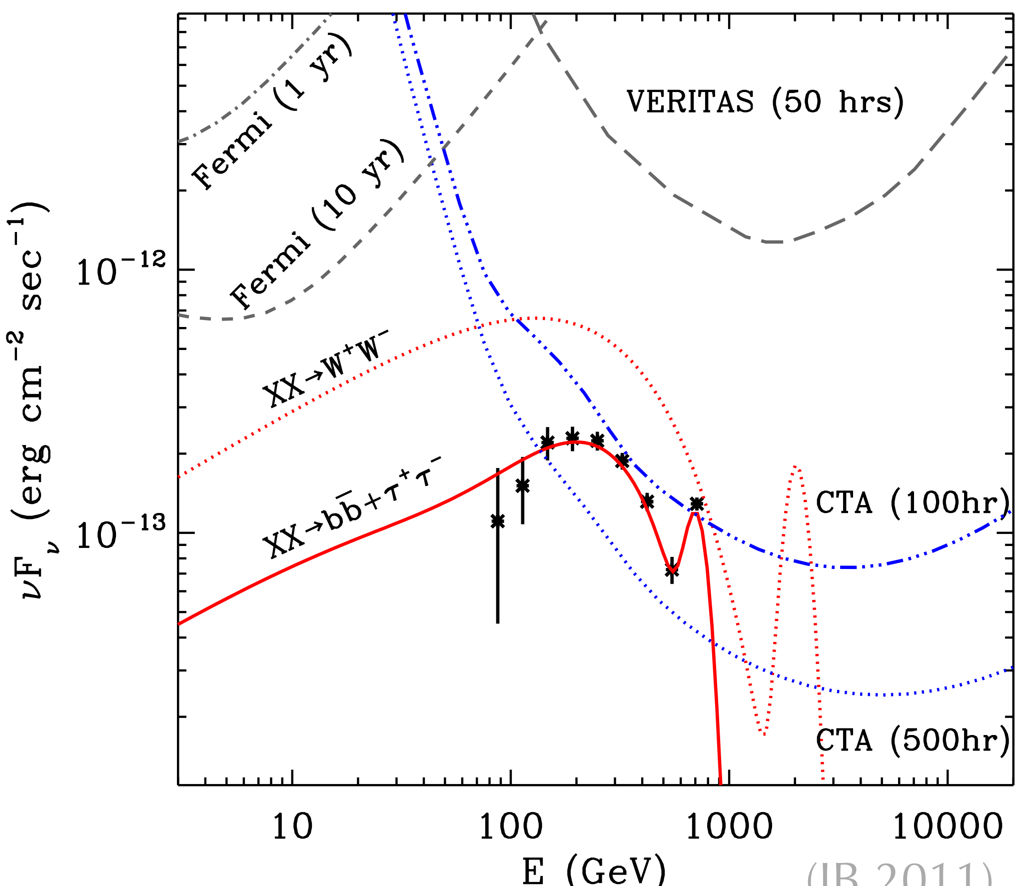

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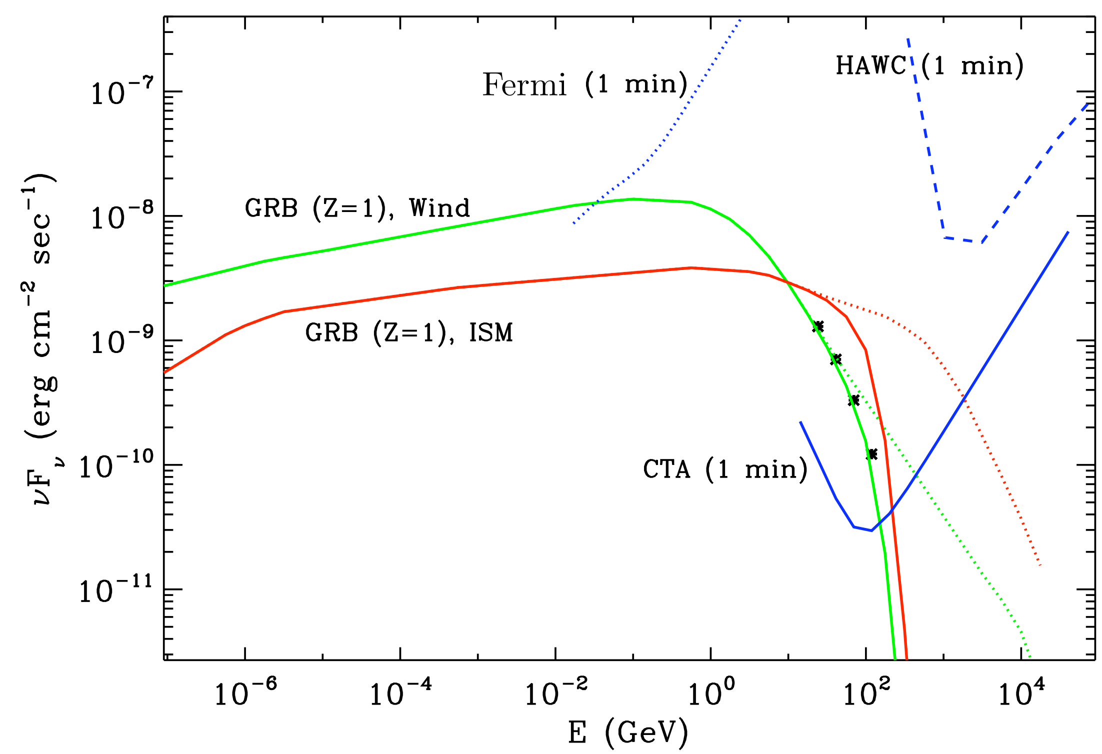


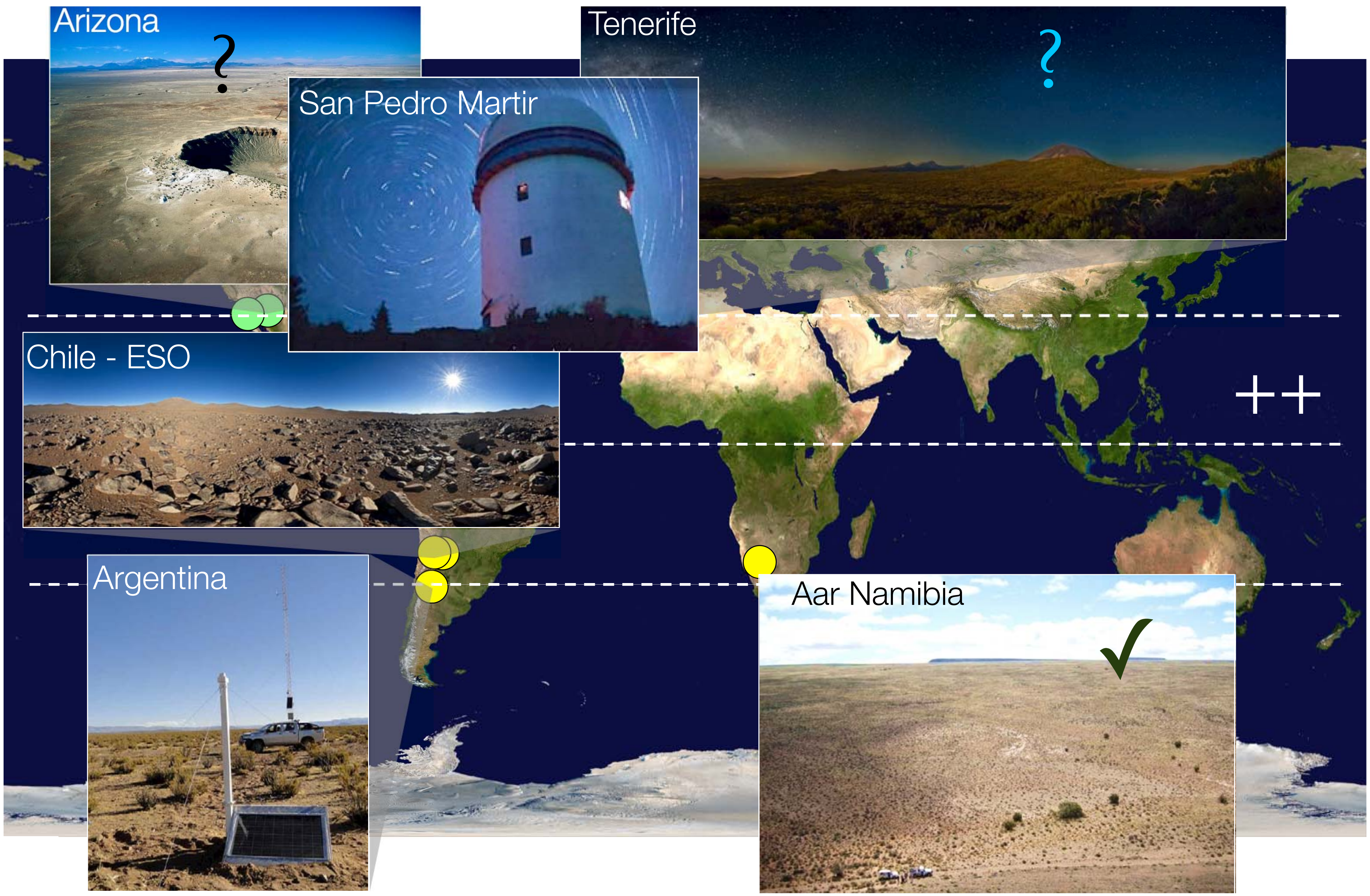
(Buckley et al., APS whitepaper, 2008)

Timeline

NSF MRI and CTA-US timeline

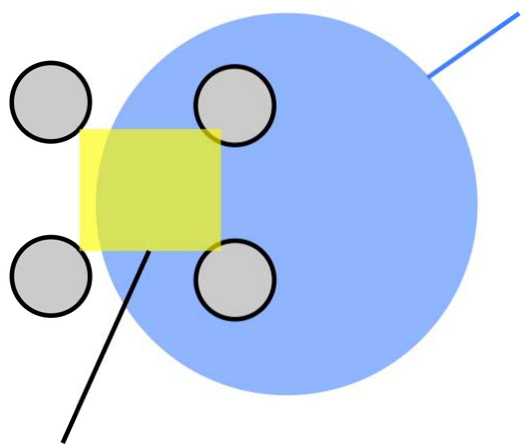
2012-2013	SCT prototype design
2013-2014	SCT prototype construction
2014-2015	SCT prototype commissioning & operation
2016	CTA-US "CTA Extension" construction proposal

CTA Site Selection



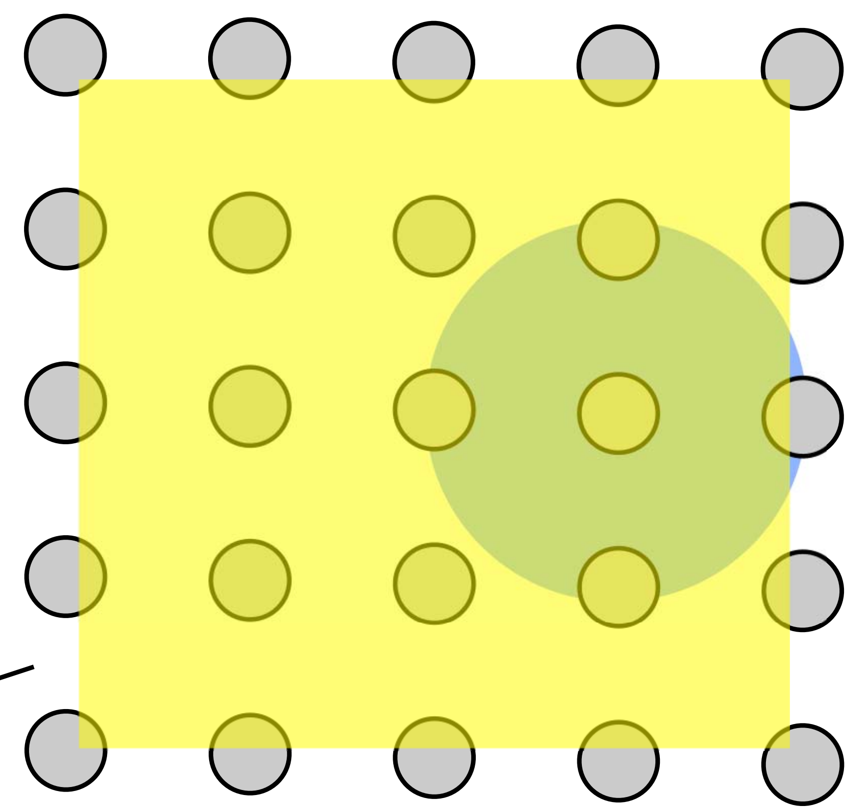
Contained Events

From current arrays to CTA



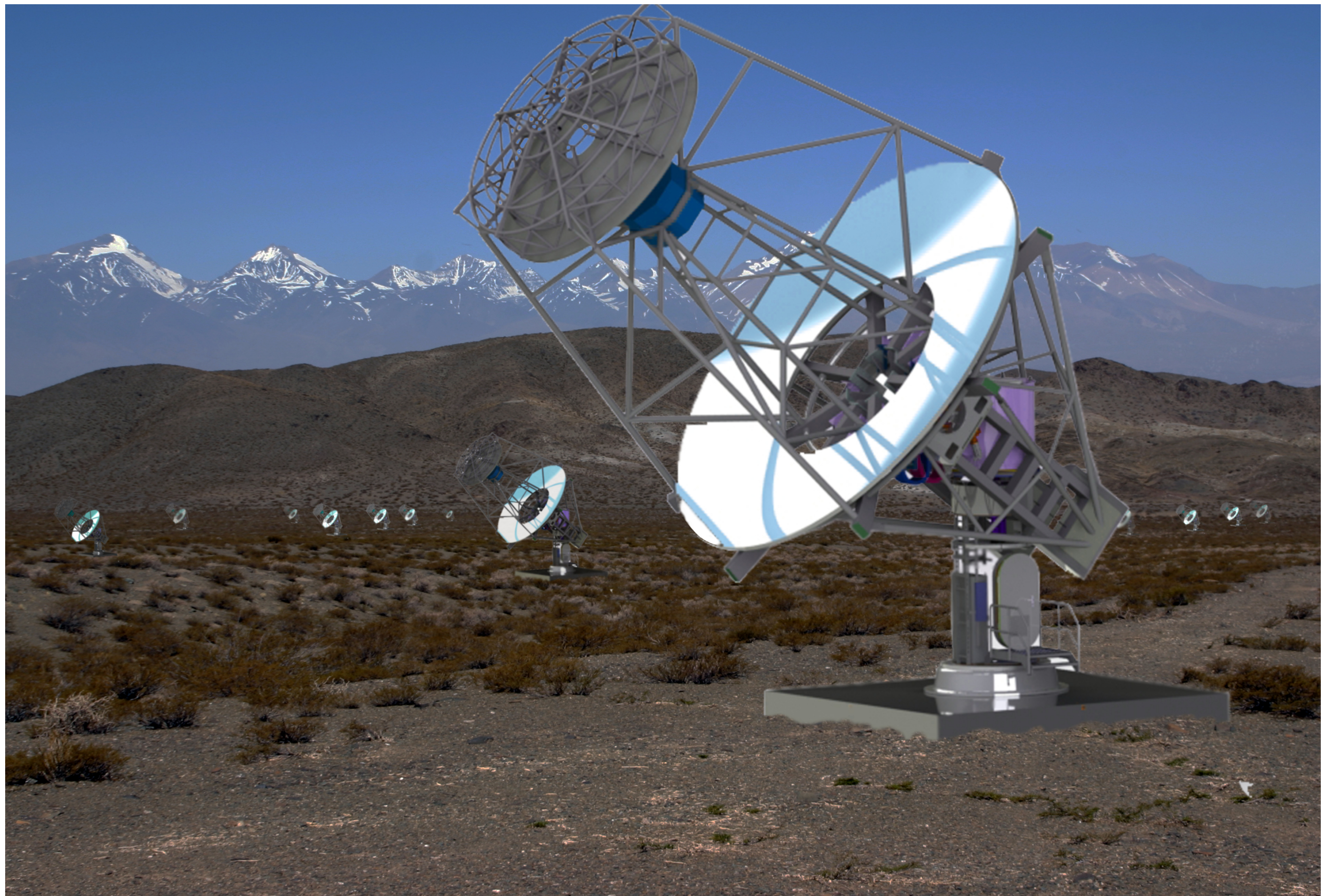
Light pool radius
R ≈100-150 m
≈ typical telescope spacing

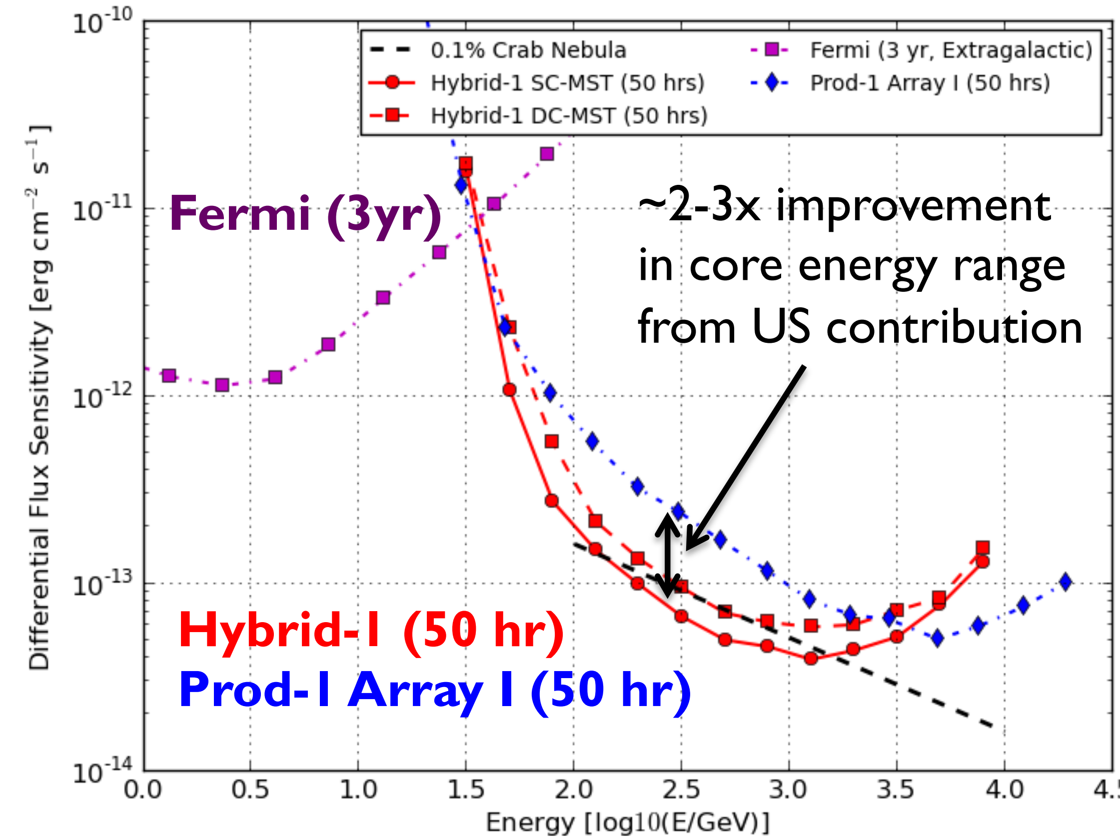
Sweet spot for
best triggering
and reconstruction:
Most shower cores miss it!



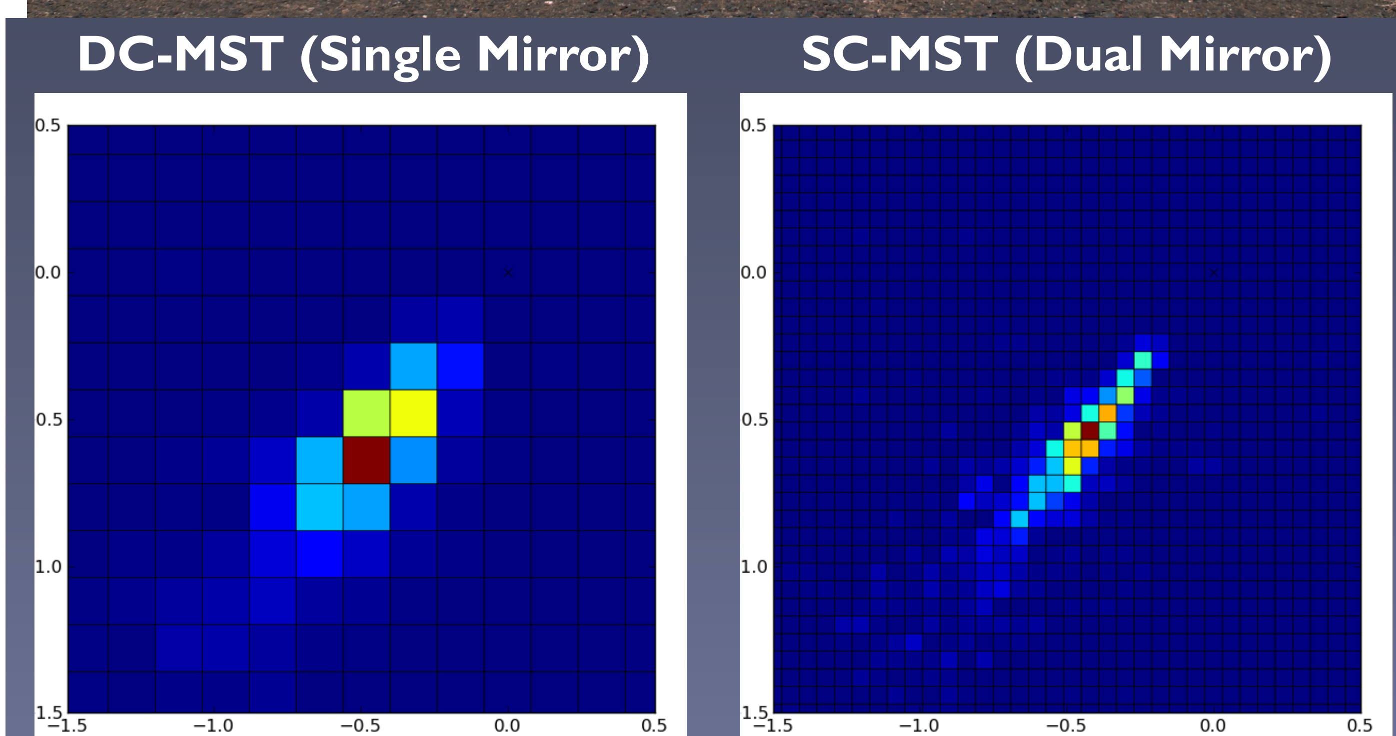
Large detection area
More images per shower
Lower trigger threshold

CTA-US

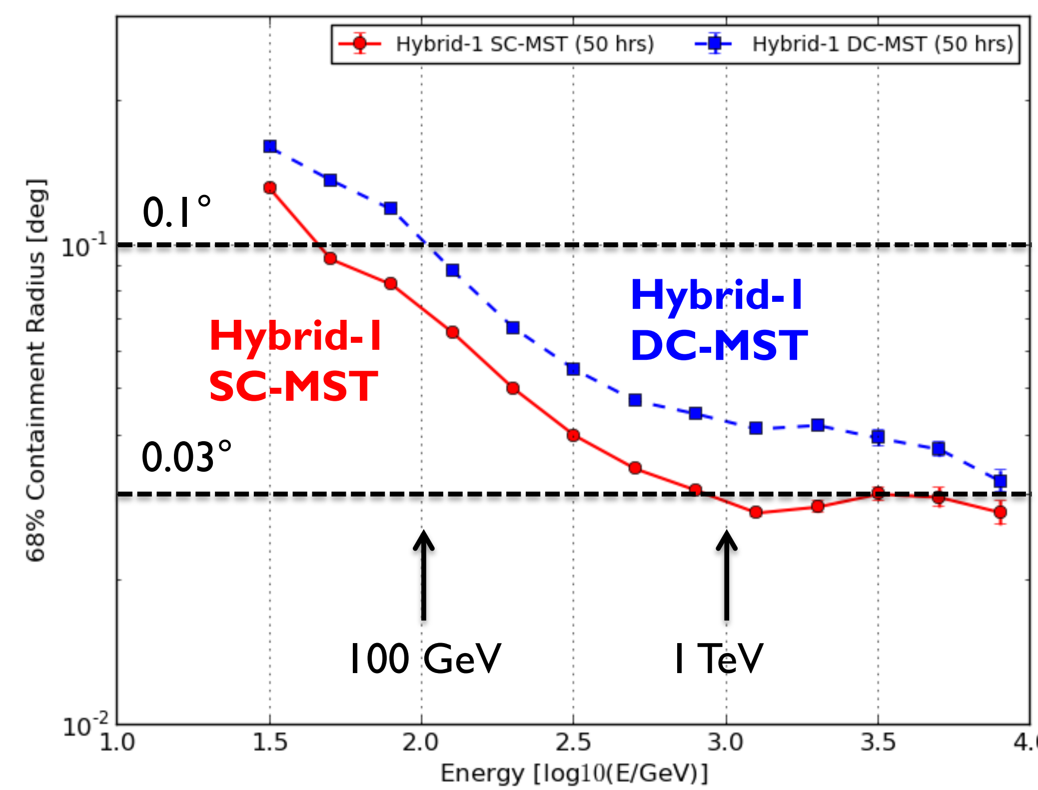




0.1% Crab Nebula
Hybrid-1 SC-MST (50 hrs)
Hybrid-1 DC-MST (50 hrs)
Fermi (3 yr, Extragalactic)
Prod-1 Array I (50 hrs)
Fermi (3yr)
~2-3x improvement in core energy range from US contribution
Hybrid-1 (50 hr)
Prod-1 Array I (50 hr)
Differential Flux Sensitivity [erg cm^{-2} s^{-1}]
Energy [log10(E/GeV)]

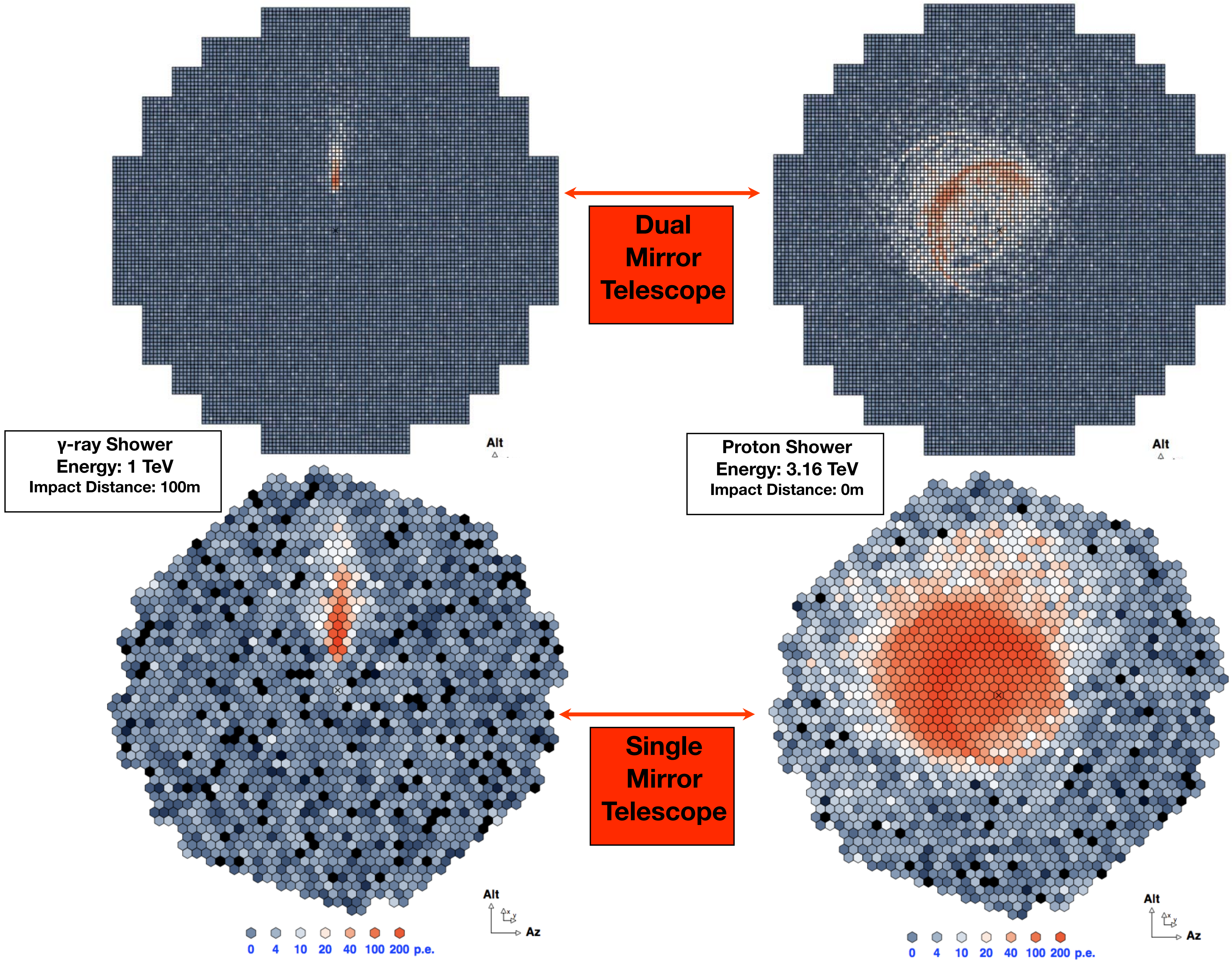


DC-MST (Single Mirror)
SC-MST (Dual Mirror)



Hybrid-1 SC-MST (50 hrs)
Hybrid-1 DC-MST (50 hrs)
0.1°
0.03°
Hybrid-1 SC-MST
Hybrid-1 DC-MST
100 GeV
1 TeV
68% Containment Radius [deg]
Energy [log10(E/GeV)]

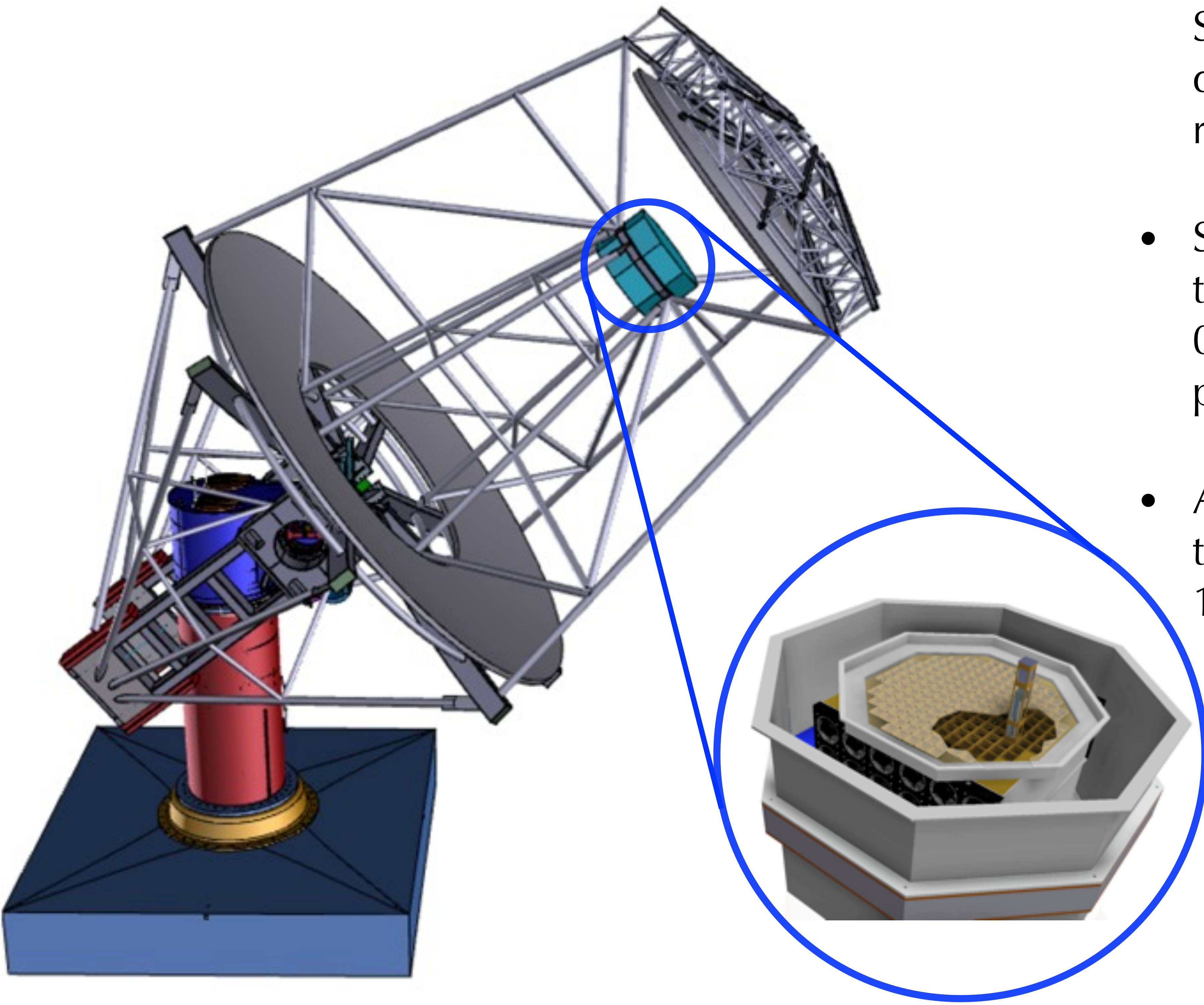
Simulated Images



SCT Prototype

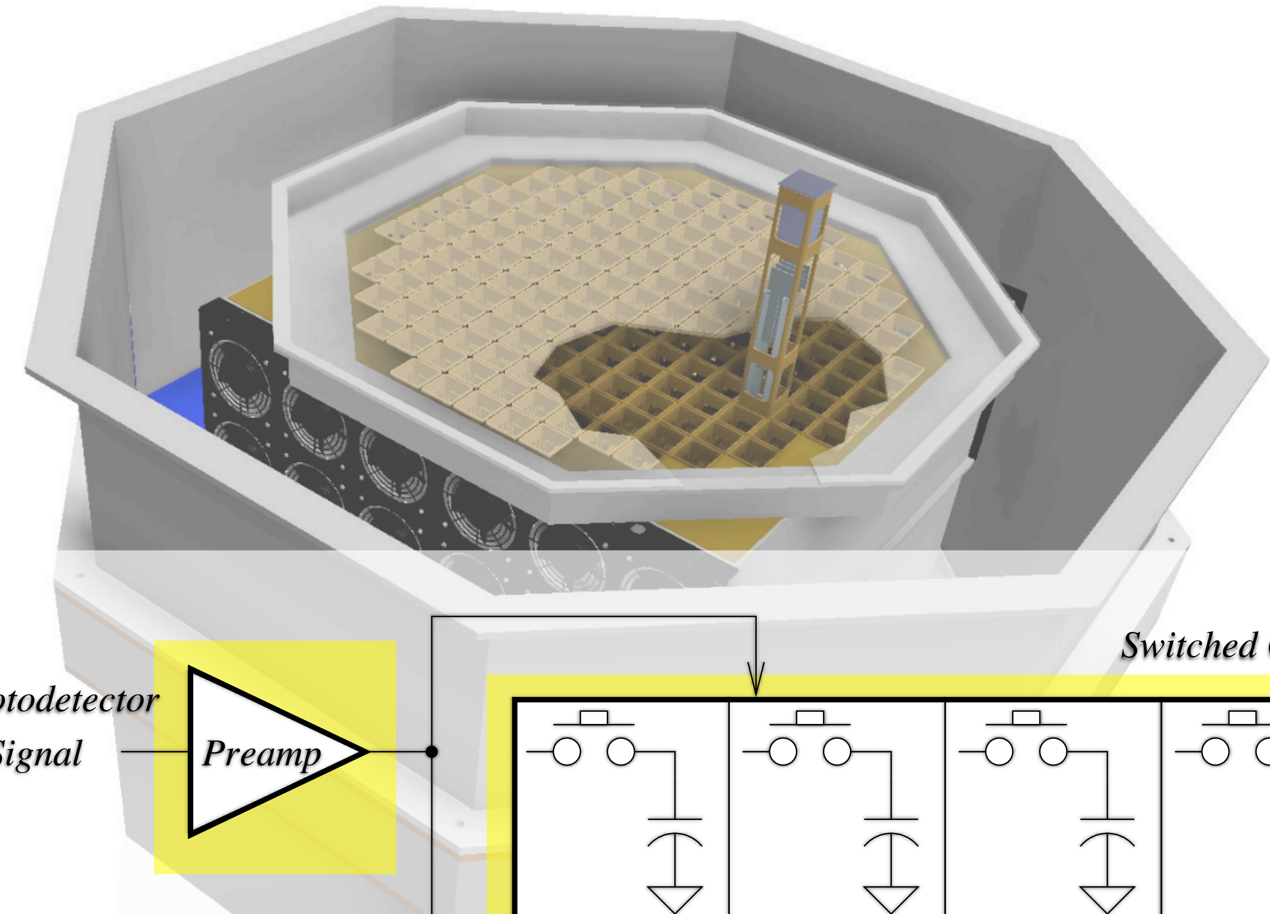
- We are in the second year of a 3-year MRI grant to construct an SCT telescope SCT Prototype will be constructed at the VERITAS site, using old T1 pad.

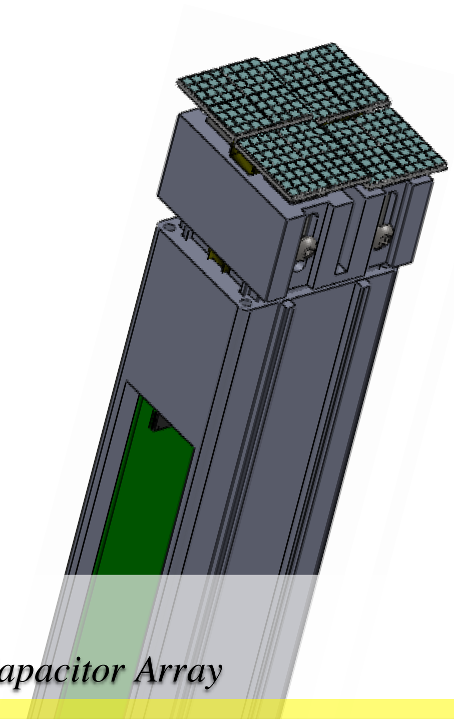
SCT Prototype

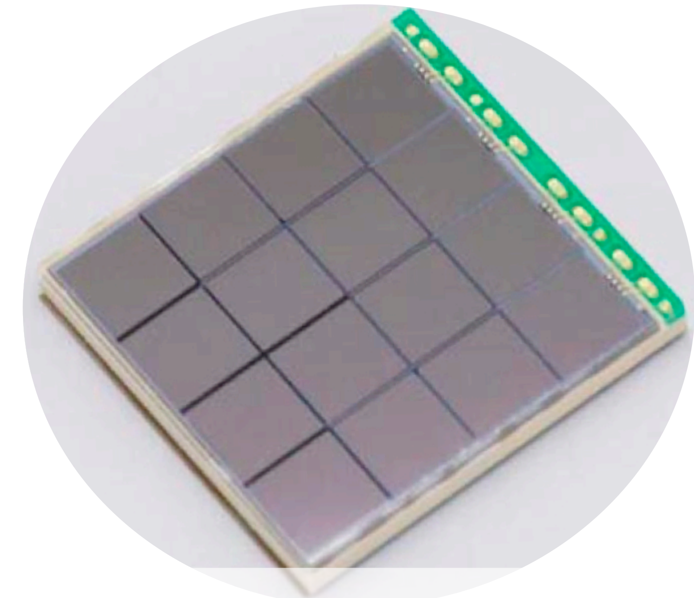


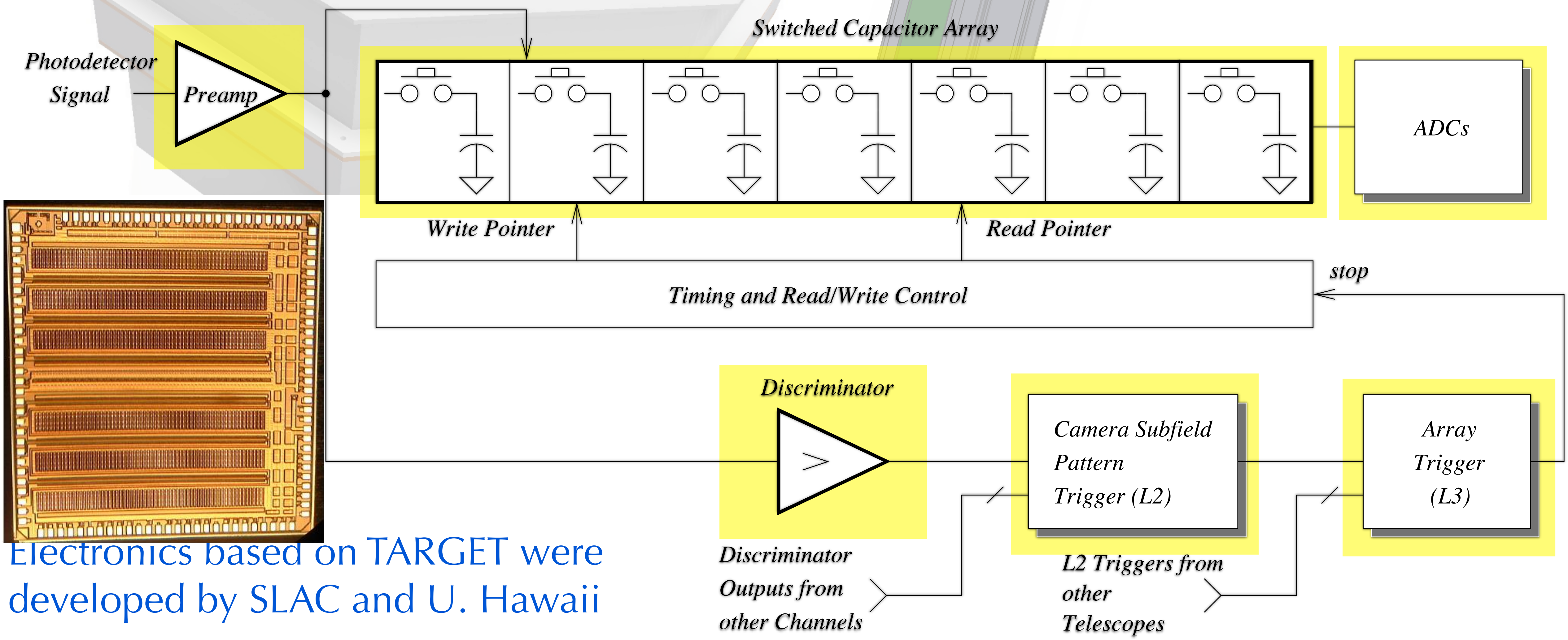
- 10m diameter, 2-mirror Schwarzshild-Couder optical design providing high angular resolution over an 8deg FOV
- Small plate-scale (f/0.58) new technology camera (with 11,000 0.06 degree pixels) cost of ~$70 per pixel.
- As SiPMs improve, could have the same light collection as a 12m DC telescope.

CTA Camera





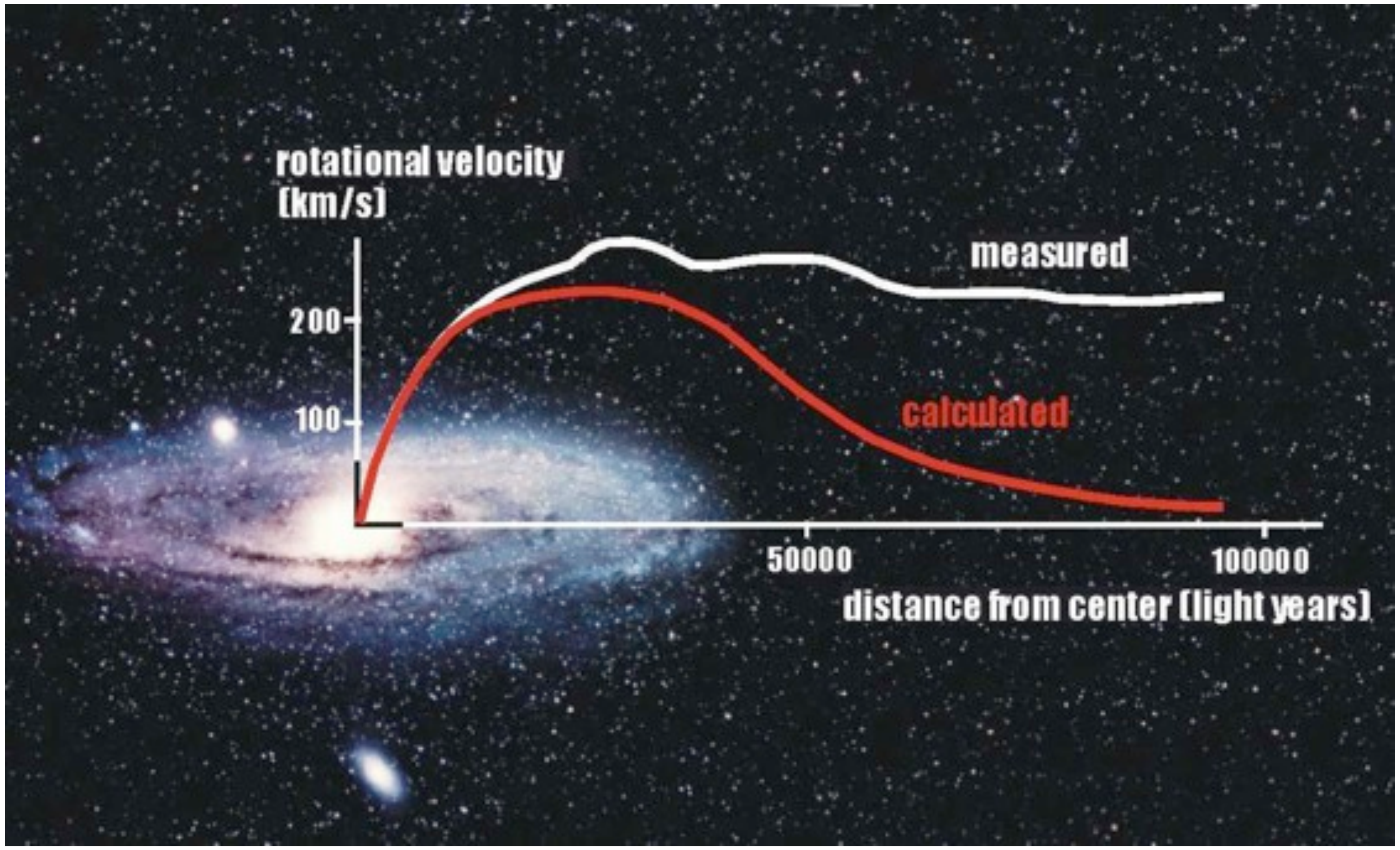




Electronics based on TARGET were developed by SLAC and U. Hawaii


Dark Matter

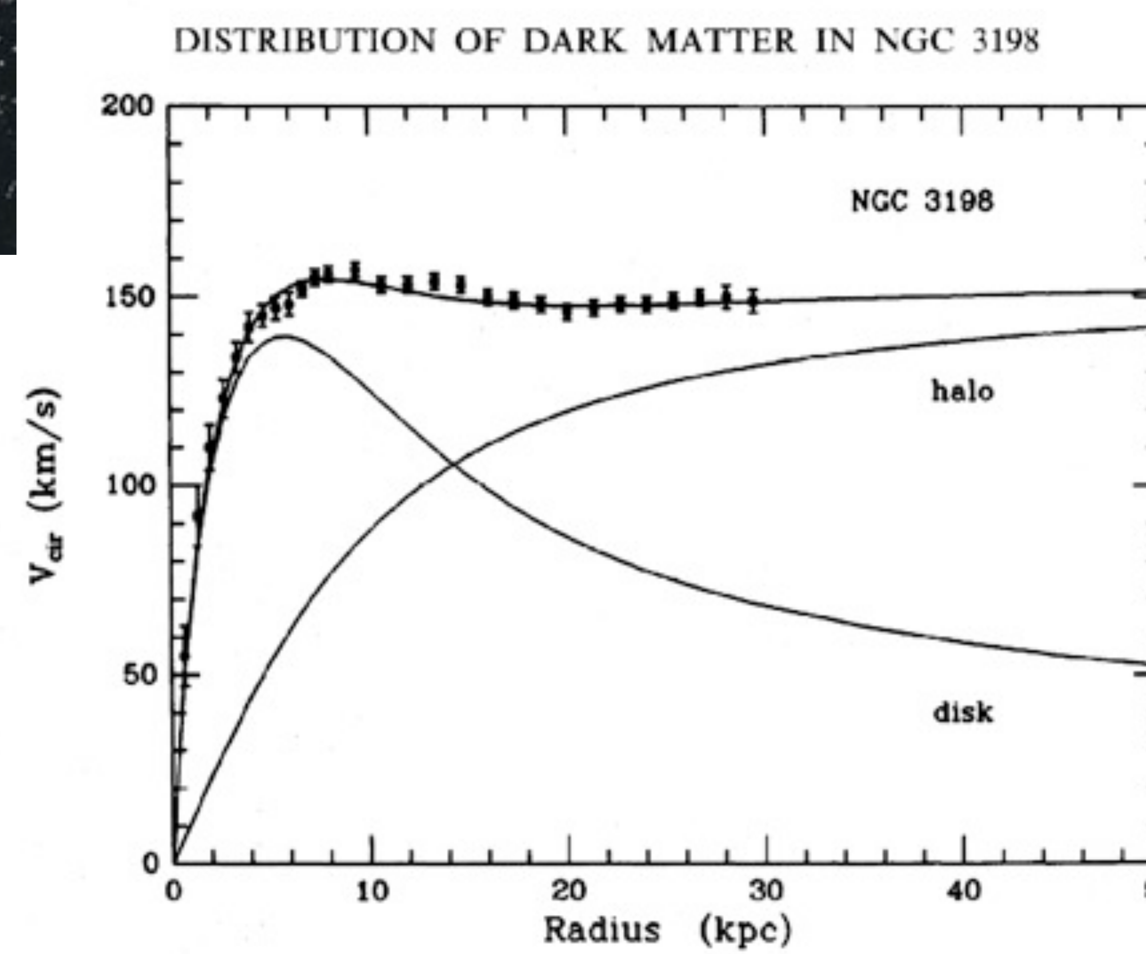
Evidence for Dark Matter



Beyond the stars, the enclosed mass M should be roughly constant

$$\frac{mv^2}{r} = \frac{GmM}{r^2}$$

$$v \sim r^{-1/2}$$



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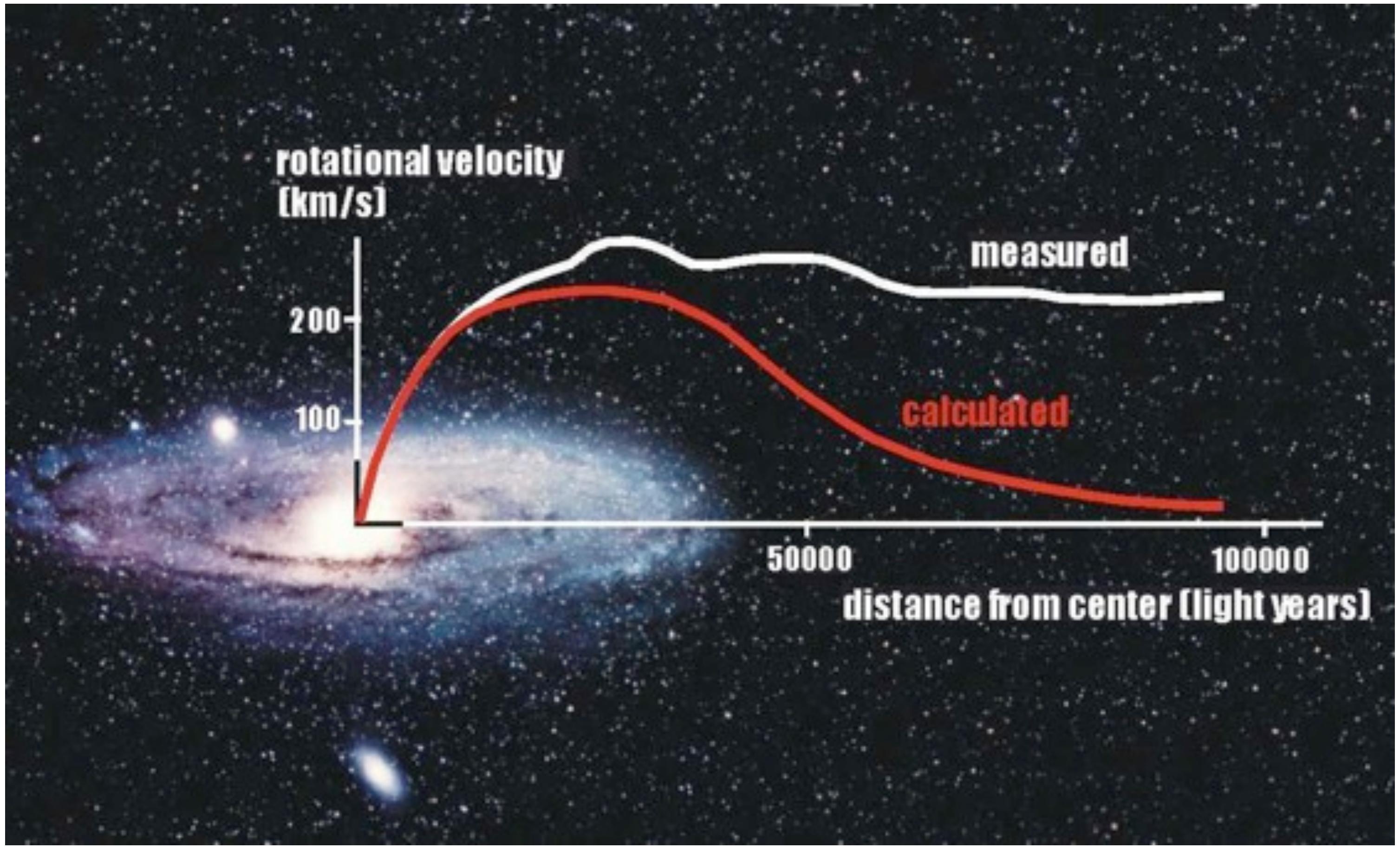


Beyond the stars, the enclosed mass M should be roughly constant

$$\frac{mv^2}{r} = \frac{GmM}{r^2}$$

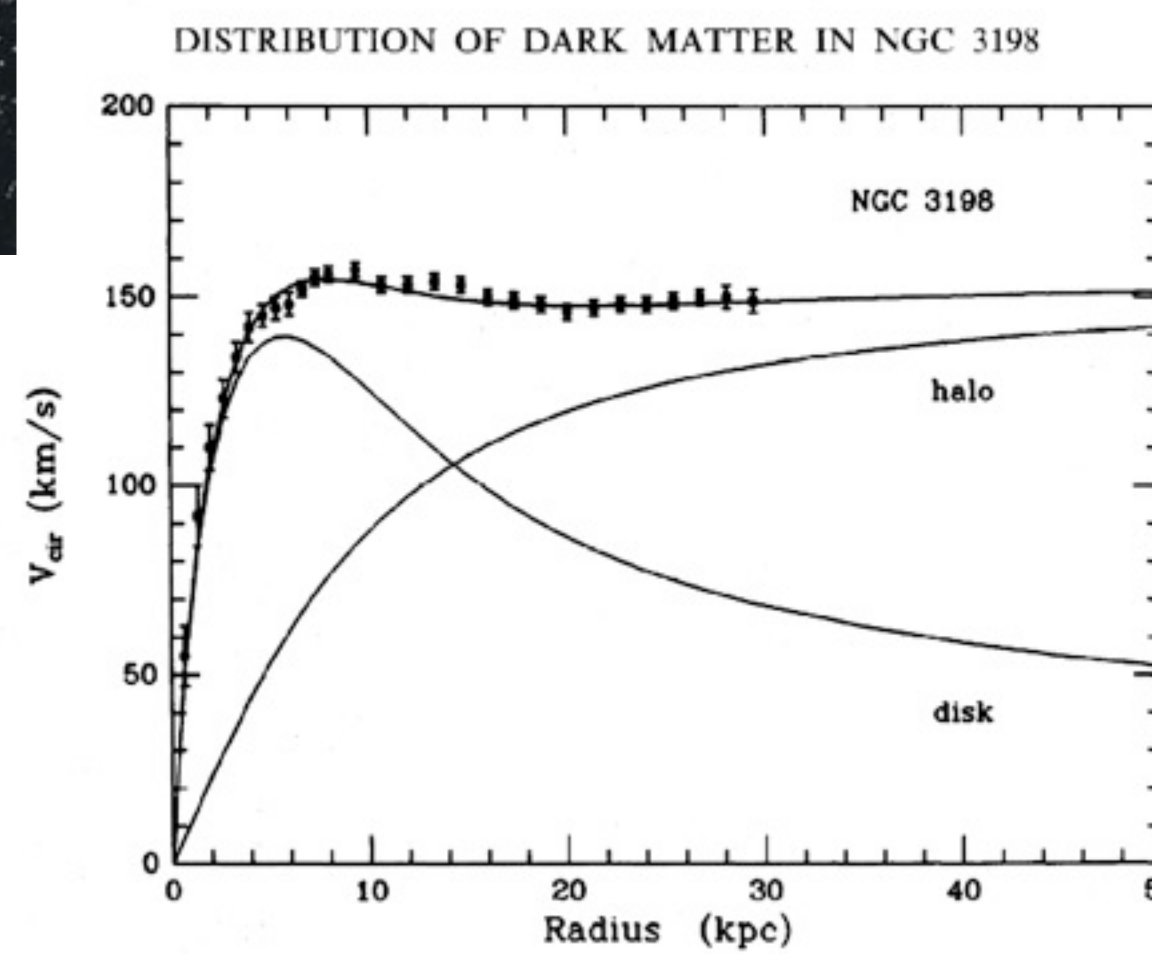
$$v \sim r^{-1/2}$$

$$\frac{mv^2}{r} = \frac{Gm\int_0^r \rho(r')d^3r'}{r^2}$$

if $\rho(r) \sim r^{-2}$ then

$v \sim$ constant $\Rightarrow$

There appears to be a dark halo that extends beyond the distribution of stars, with a mass that exceeds that in stars by a factor of >10

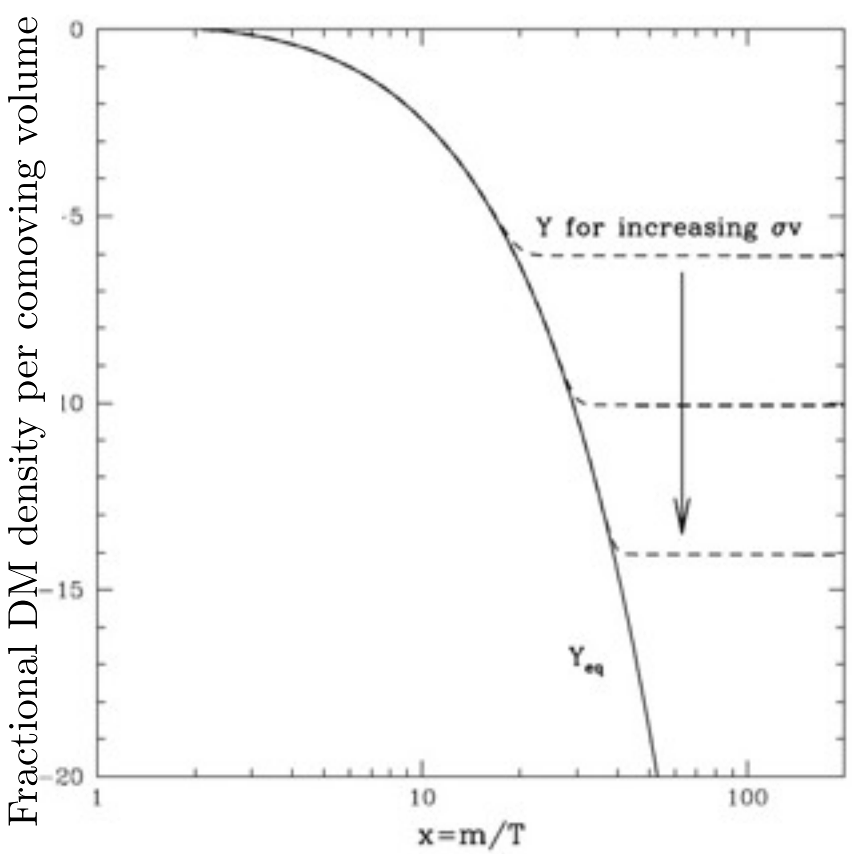


Dark Matter Intro

Gravitational effect of DM is visible in many astrophysical settings (needed to hold galaxies and clusters together)

Bullet cluster image shows gravitational mass inferred from lensing (blue) and X-ray emission from baryonic matter (red).

Not modified gravity, not gas - dark matter behaves like weakly interacting particles

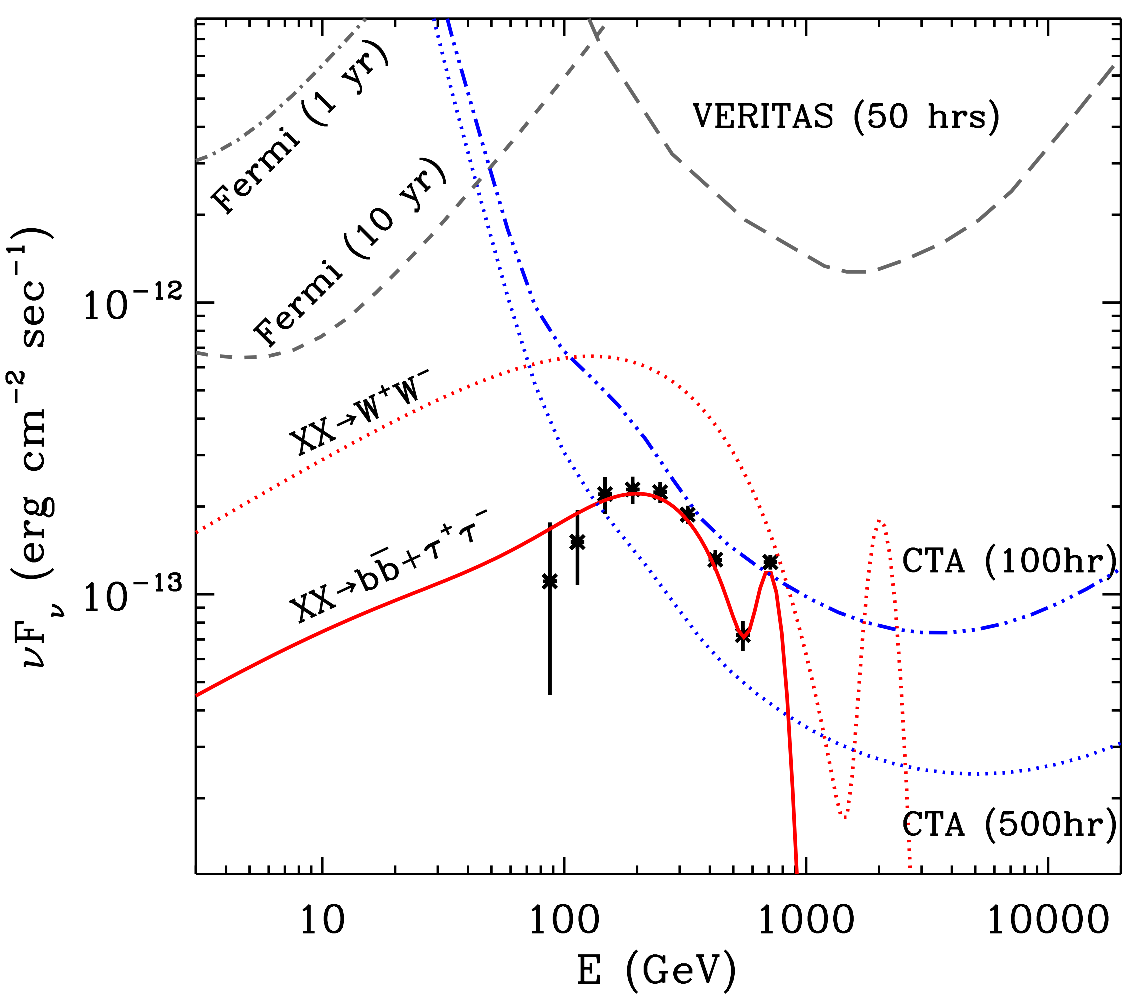


For a thermal relic of the big bang, the larger the annihilation cross section the longer the DM stays in equilibrium and the larger the Boltzmann suppression $\sim e^{-m_\chi/kT}$ before freeze-out.

$$\Omega_\chi \approx \frac{0.1}{h^2}\left(\frac{3\times 10^{-26}\mathrm{cm}^3\mathrm{sec}^{-1}}{\langle\sigma v\rangle}\right)$$

γ-Rays from DM Annihilation

$$E_\gamma \Phi_\gamma(\theta) \approx 10^{-10} \underbrace{\left(E_{\gamma,\mathrm{TeV}} \frac{dN}{dE_{\gamma,\mathrm{TeV}}}\right) \left(\frac{\langle \sigma v \rangle}{10^{-26} \mathrm{cm}^{-3} \mathrm{s}^{-1}}\right) \left(\frac{100\,\mathrm{GeV}}{M_\chi}\right)^2}_{\text{Particle Physics Input}} \underbrace{J(\theta)} \;\mathrm{erg\,cm^{-2} s^{-1} sr^{-1}}$$



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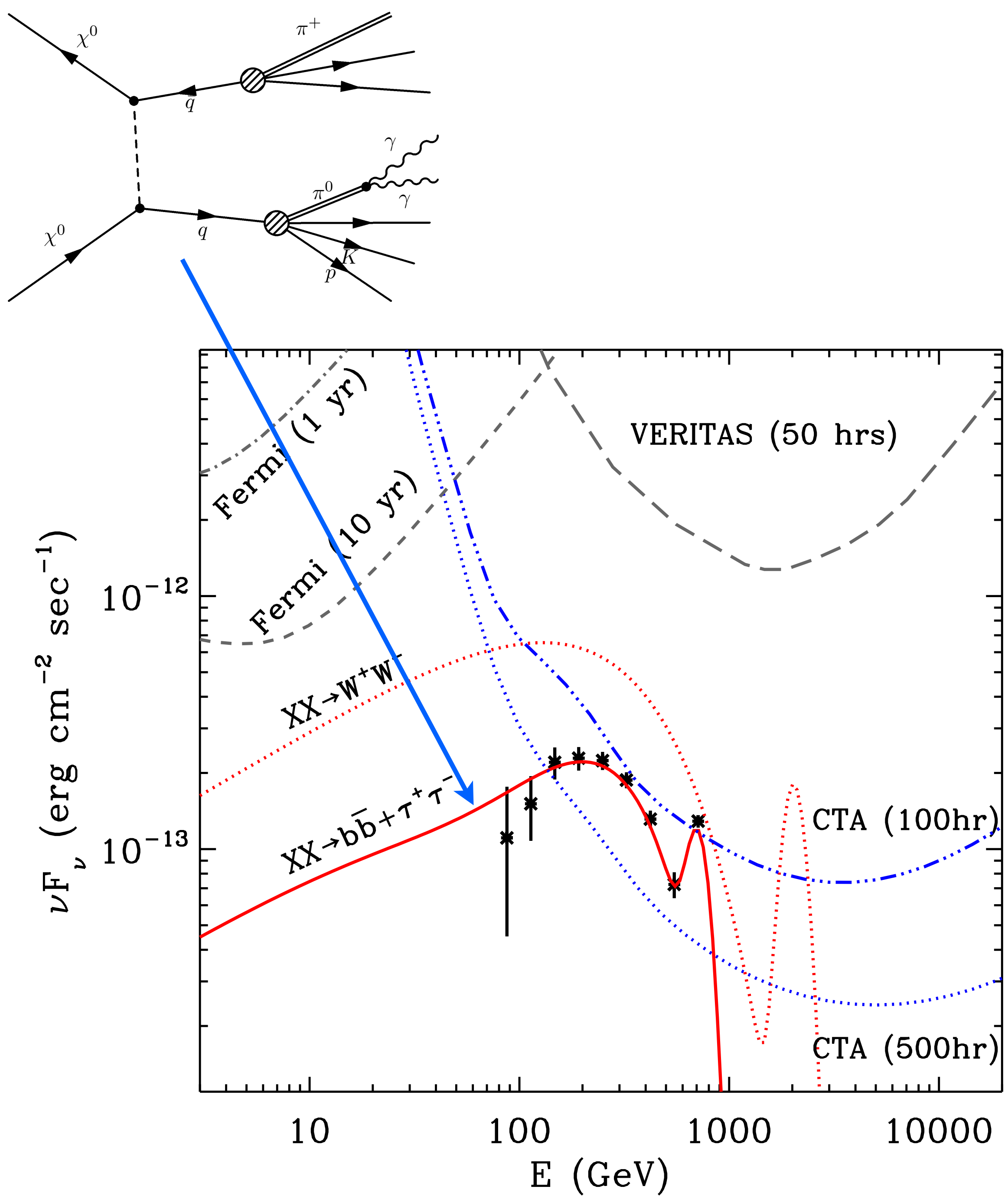

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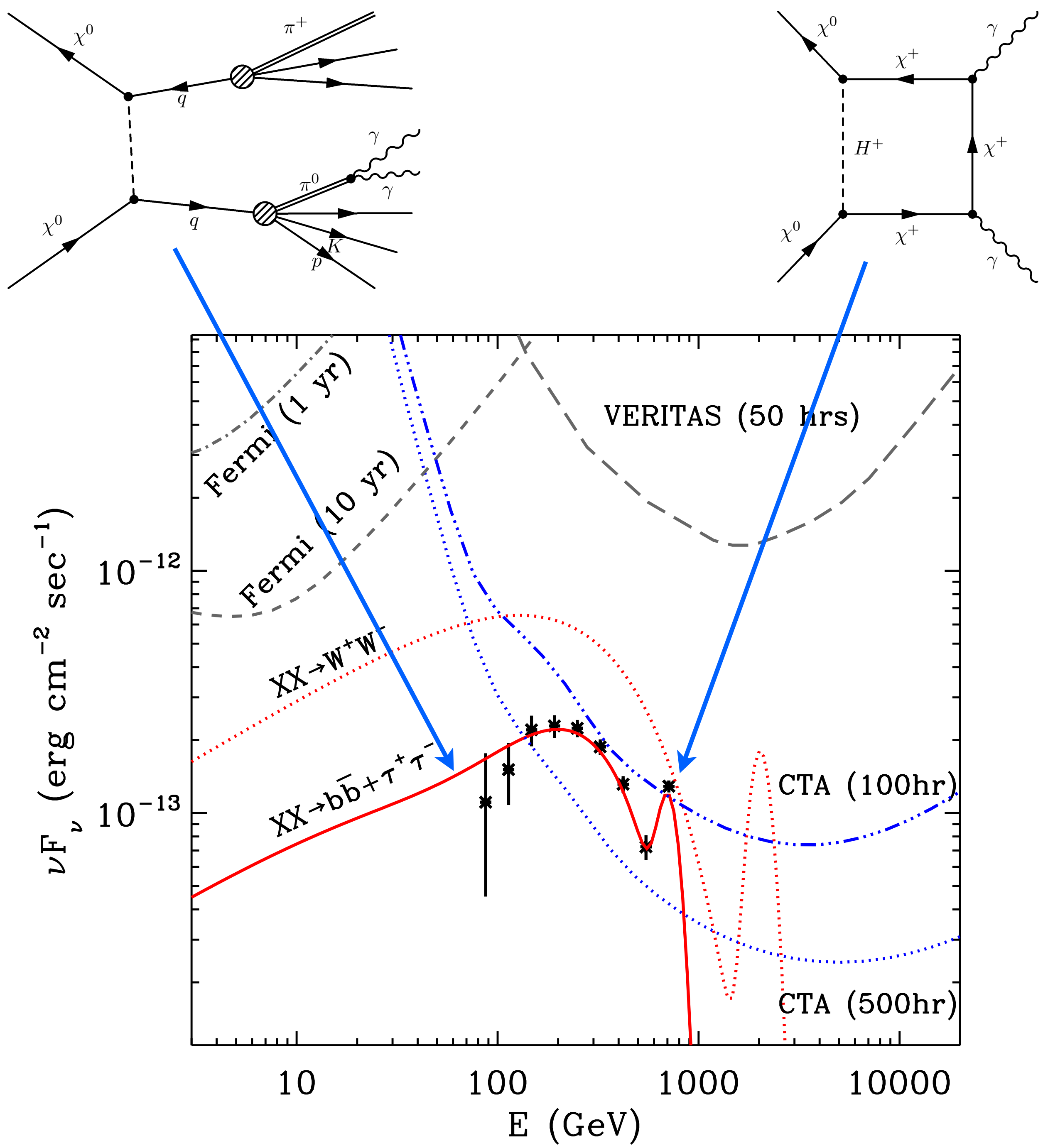

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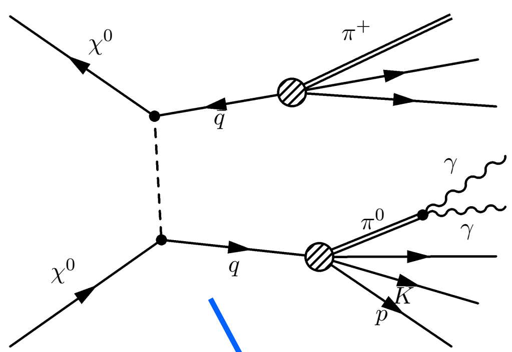
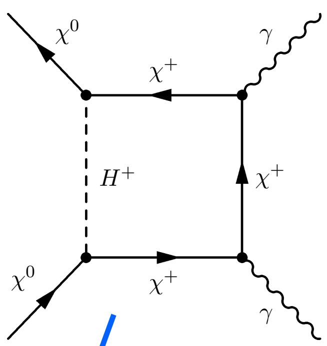
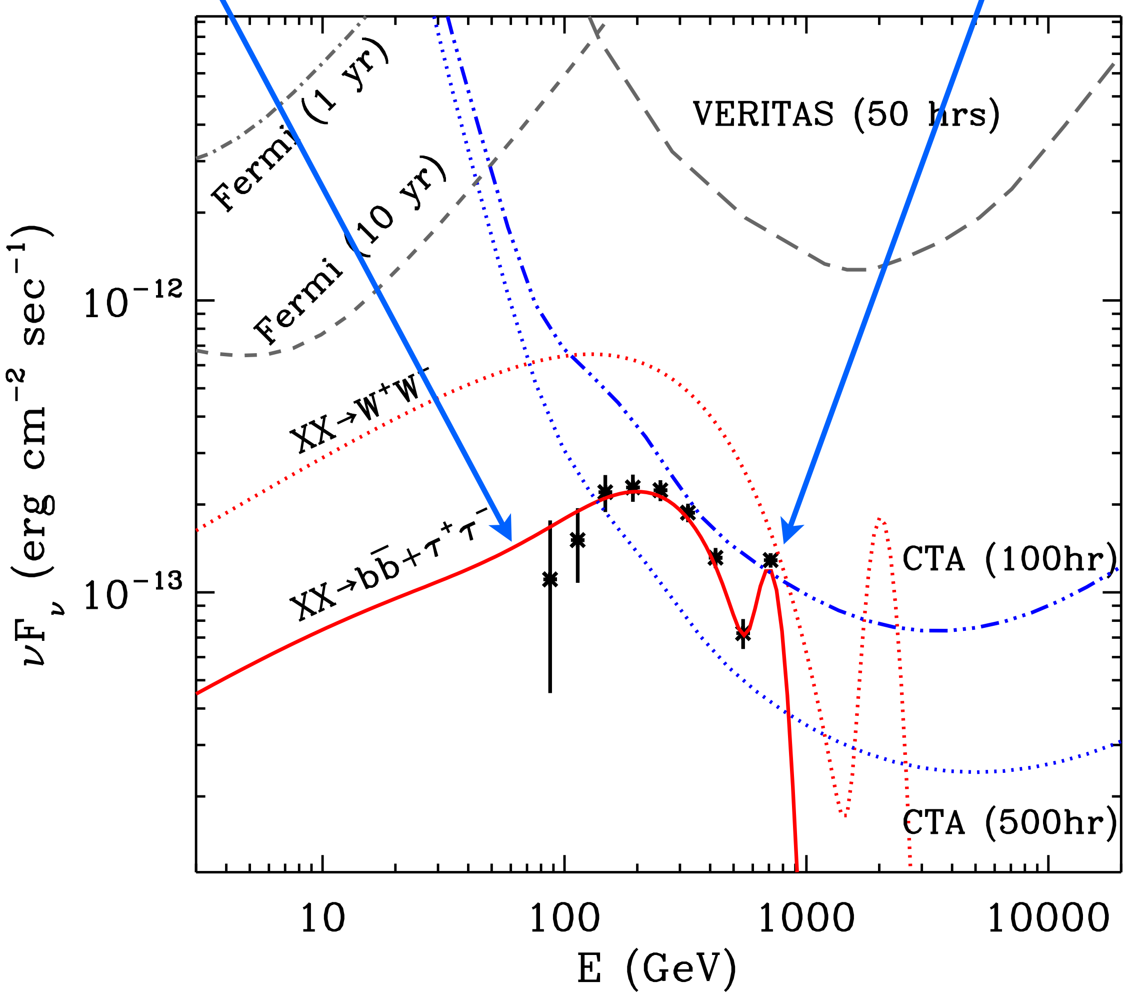
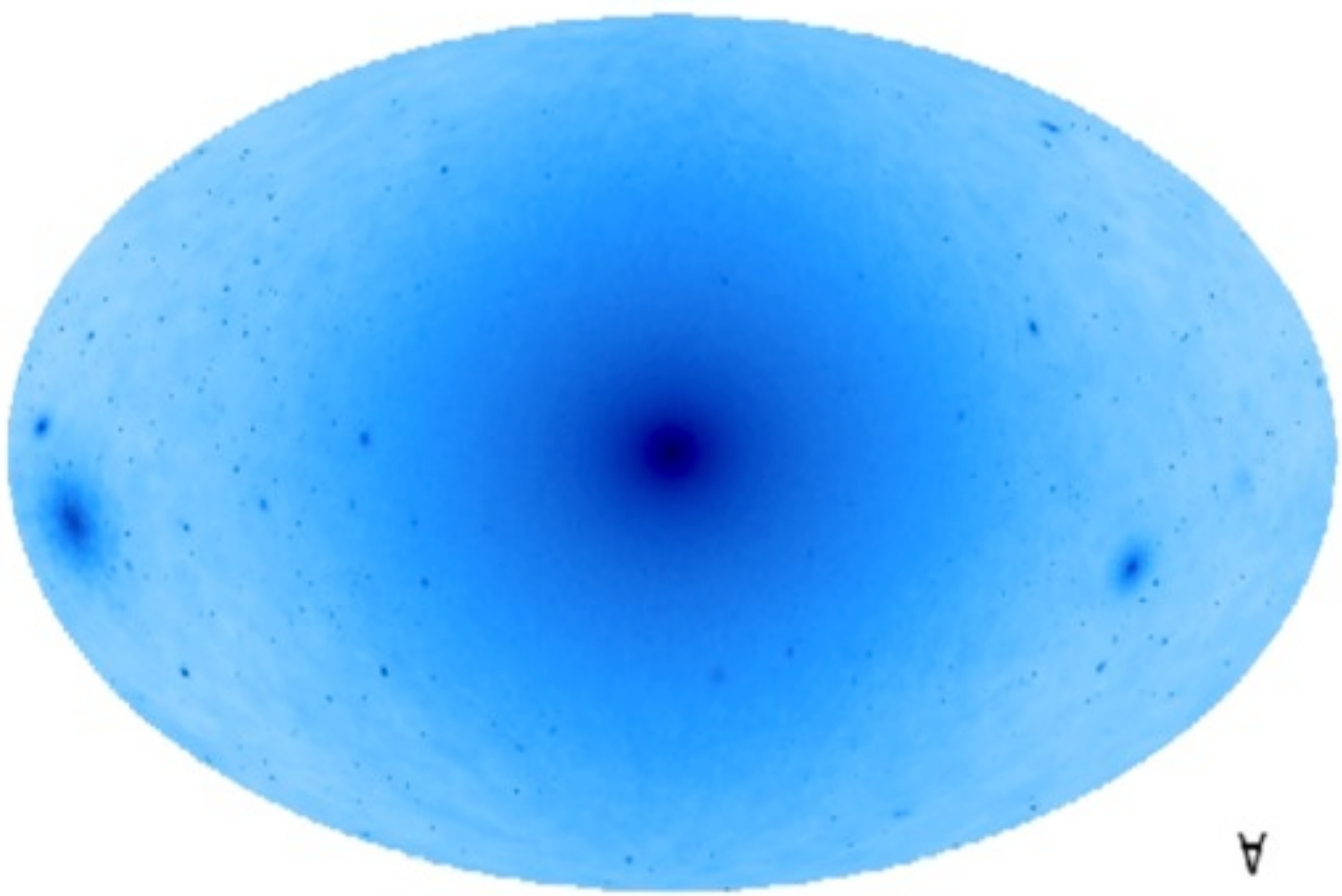
$$\underbrace{J(\theta) = \frac{1}{8.5\,\mathrm{kpc}} \left(\frac{1}{0.3\,\mathrm{GeV/cm^3}}\right)^2 \int_{\text{line of sight}} \rho^2(l)dl(\theta)}_{\text{Astrophysics/Cosmology Input}}$$





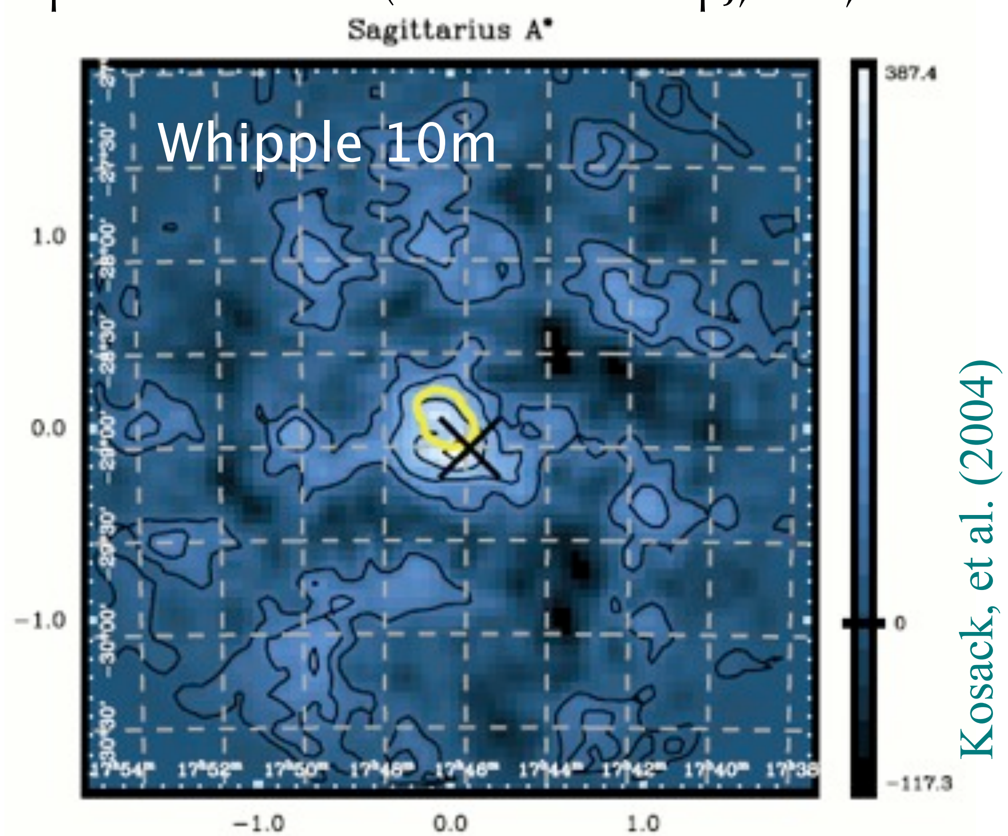




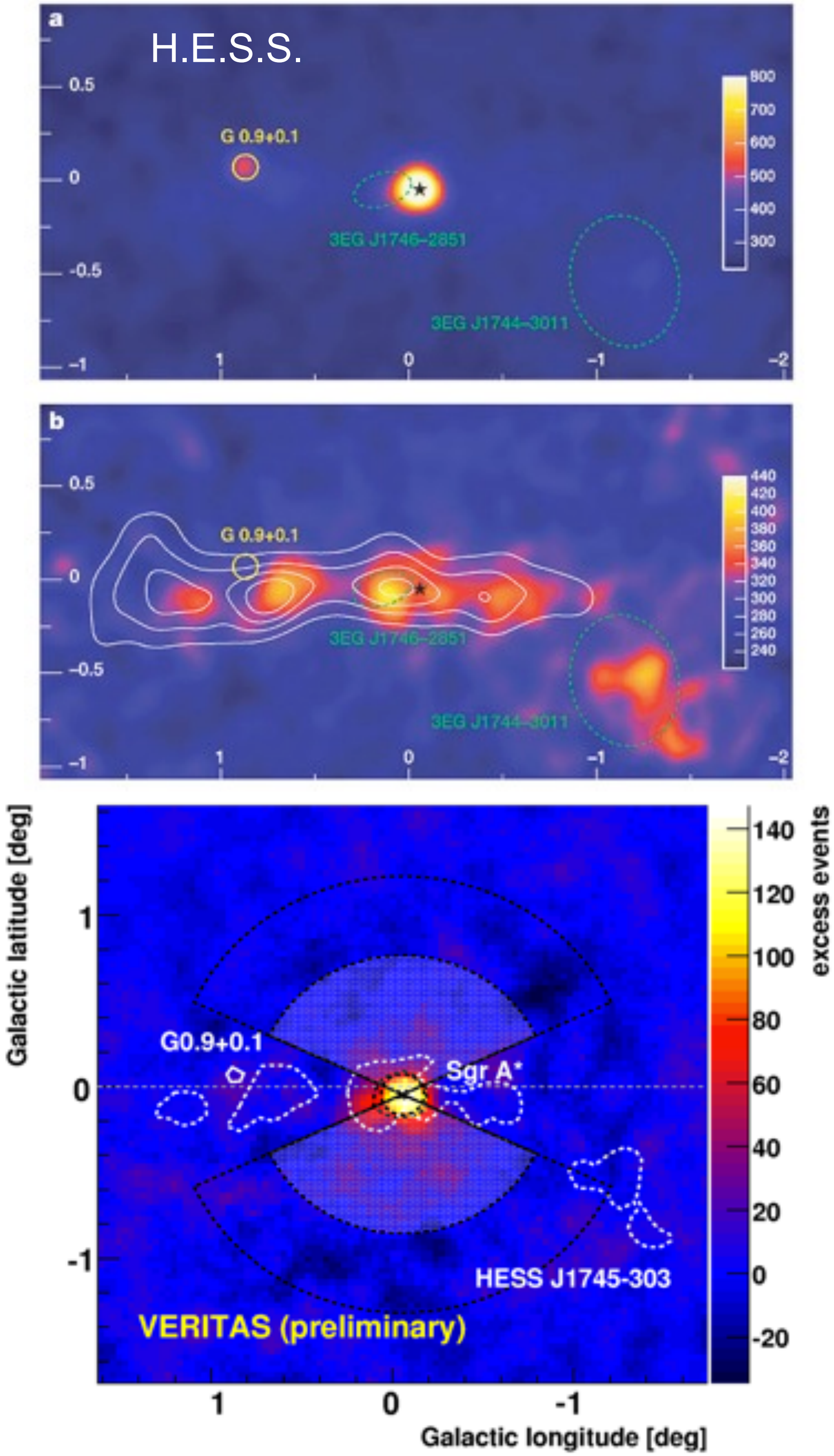
Line-of-sight integral of ρ^2 for a Milky-Way-like halo in the VL Lactea II ΛCDM N-body simulations (Kuhlen et al.)

Galactic Center and Dark Matter

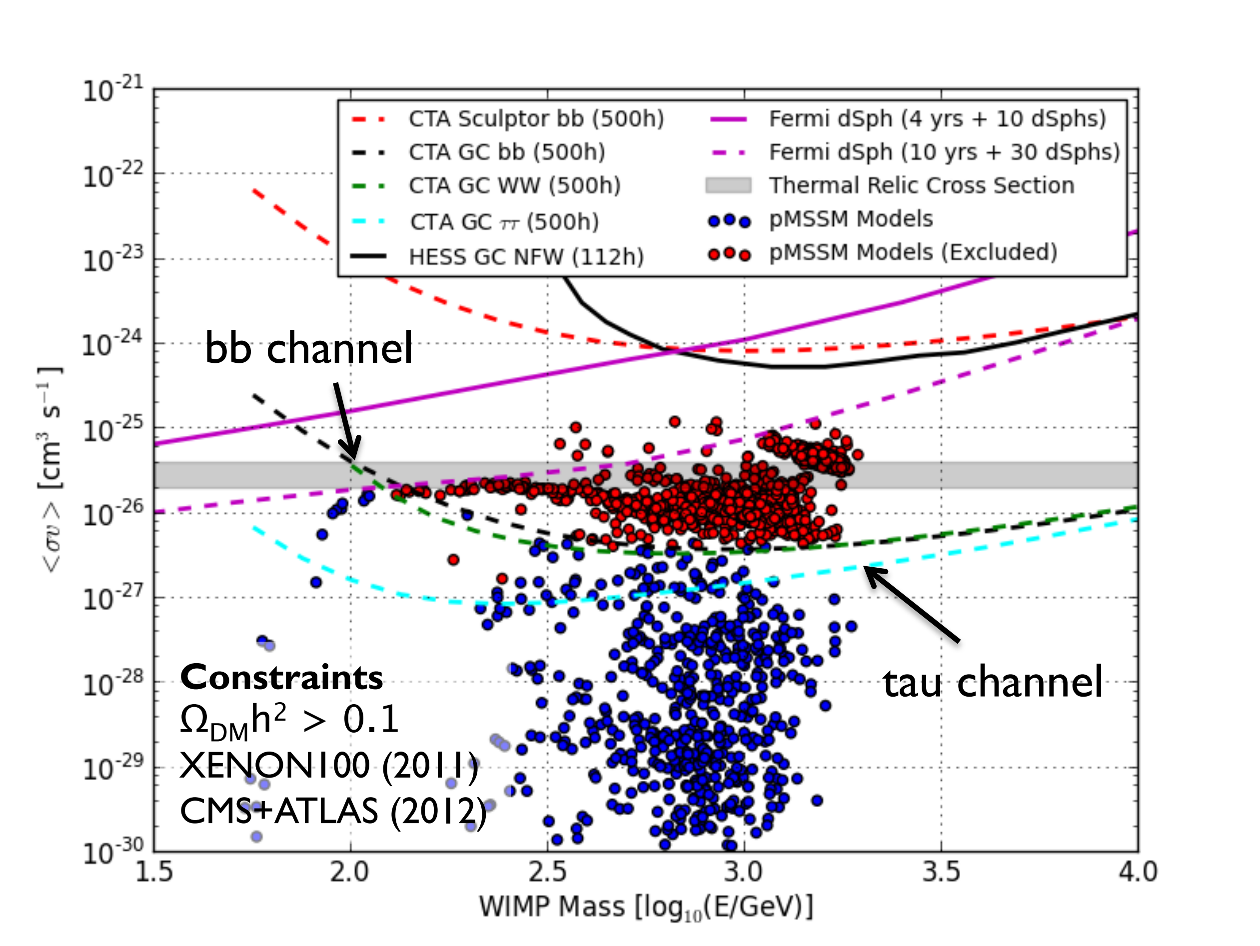
- **EGRET:** 3EG J1746-2851 (Hartman et al. 1999)
- **Whipple 10m (1995-2003, LZA)** - Evidence for GC at 3.7 std. dev., flat spectrum source (Kosack et al. ApJ, 608, L97 2004

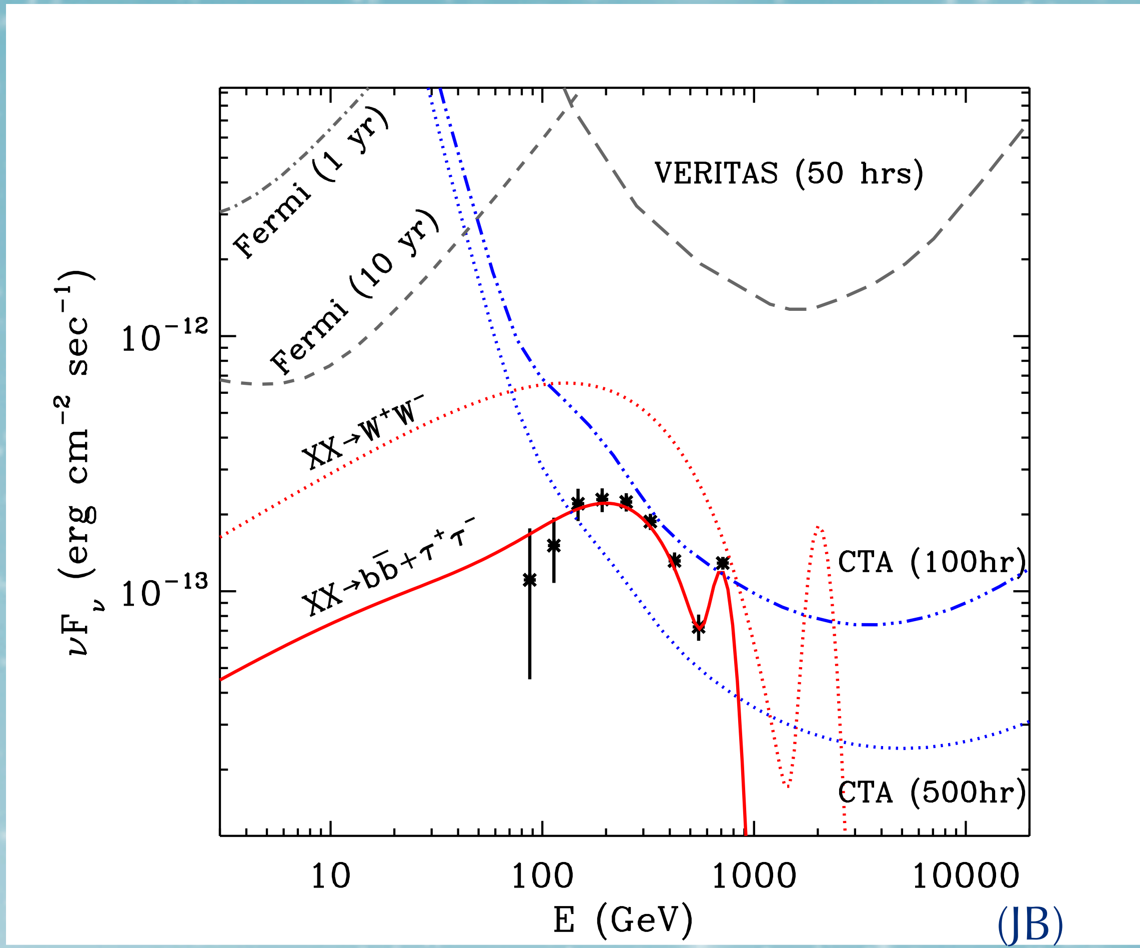


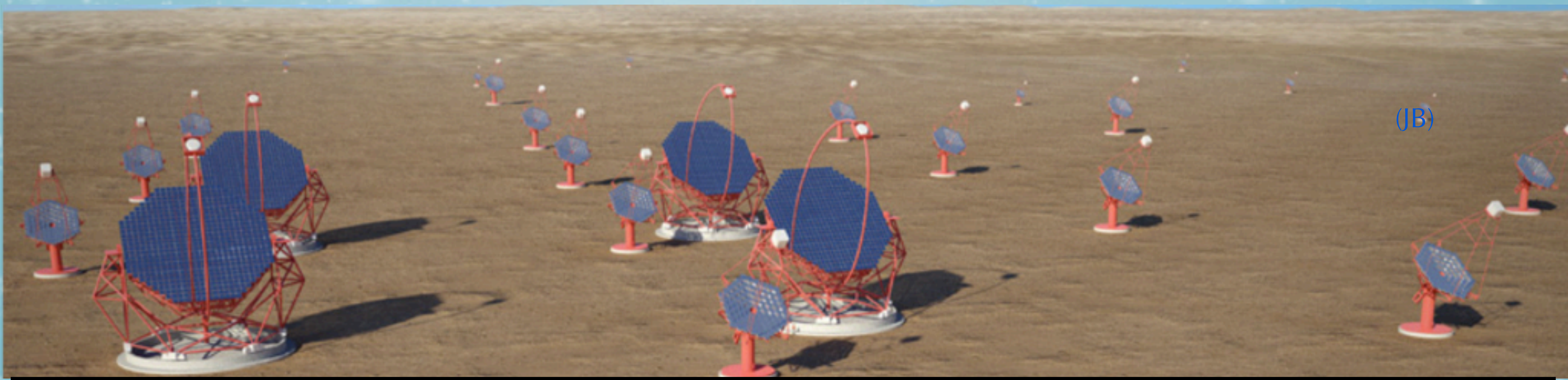
- **H.E.S.S. (2004-2006)** - Now >60 std. dev, dN/dE~E$^{-2.1}$ cutoff ~15 TeV, no variability, within 15 arcsec Sgr A*?, PWN? diffuse emission from molec. clouds dN/dE~E$^{-2.3}$ (Aharonian et al., 2004, A&A, 425, L13; 2006, Nature, 439, 695)



Dark Matter with CTA

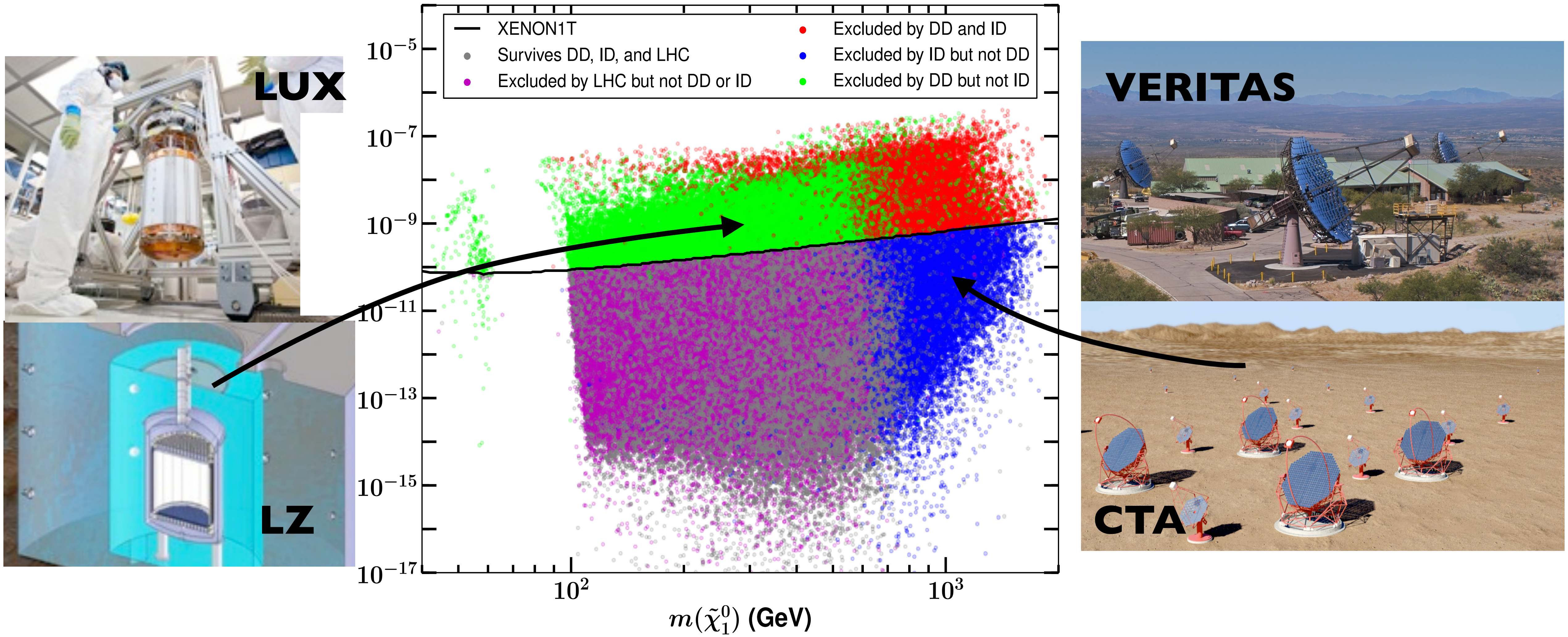






** A CTA like instrument with ~60 Mid-sized telescopes has the sensitivity to probe the natural cross section for WIMP annihilation from 100 GeV to 10 TeV*

CTA, DM and Snowmass

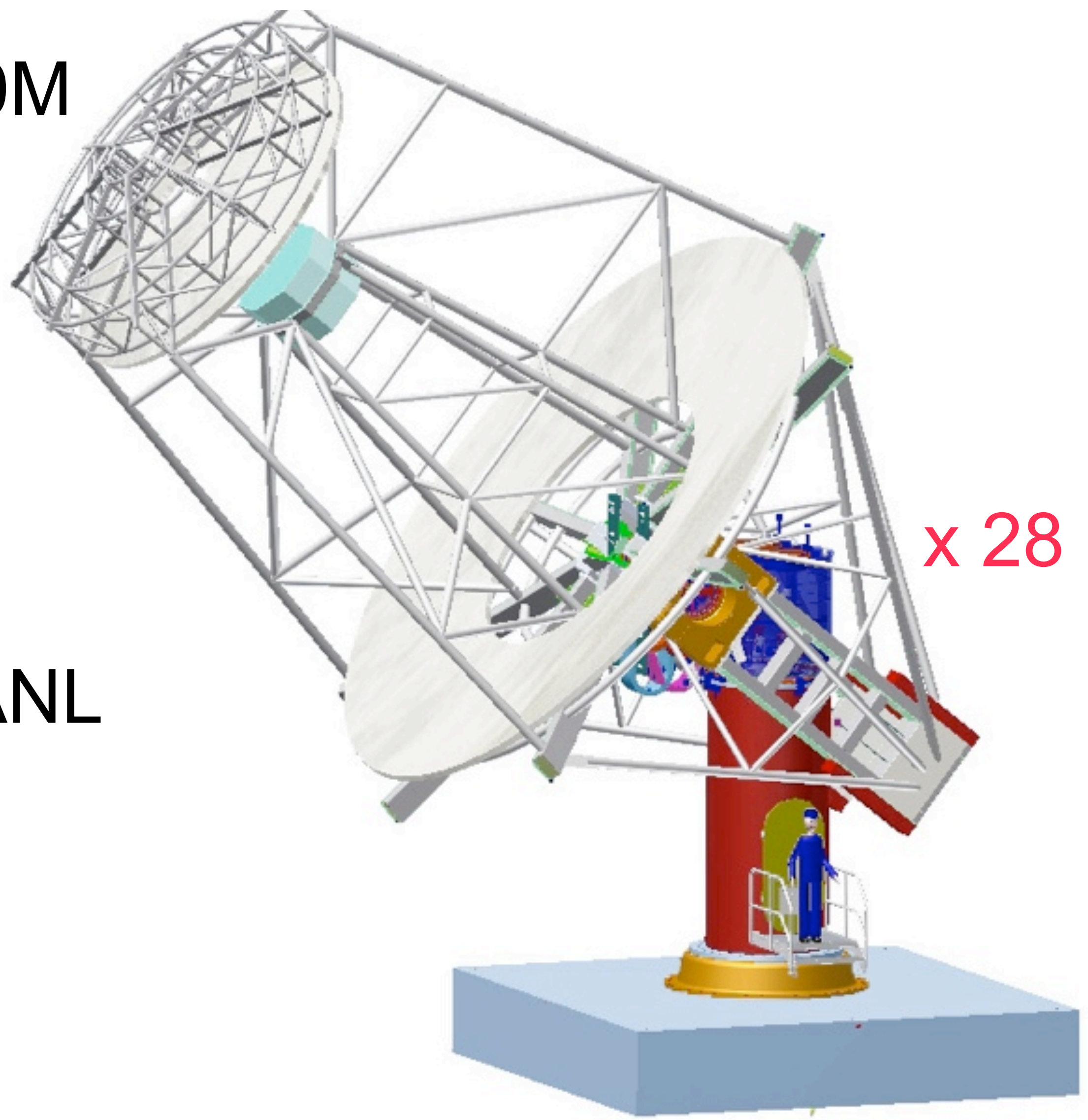


- CTA would provide a powerful new tool for searching for WIMP dark matter. The angular distribution would determine the distribution of dark matter in halos, and the universal spectrum would be imprinted with information about the mass and annihilation channels needed to ID the WIMP.

- A $20M DOE contribution (< a G2 DM experiment) would build the cameras, 2 times that from NSF would build the telescopes.

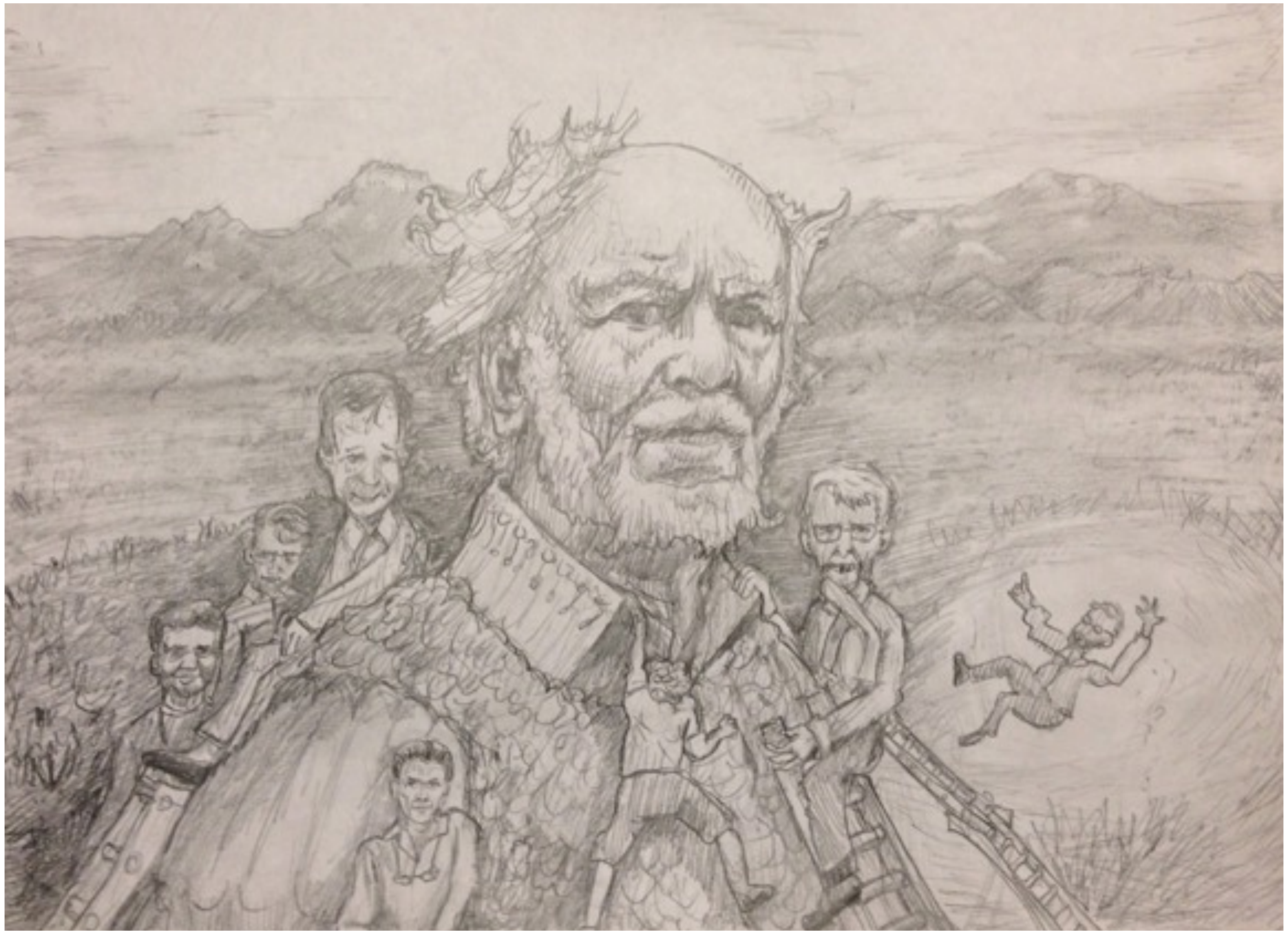
US Contribution to CTA

- Total construction costs: ~$70M
  - Cost per telescope: 2.4M$
  - DOE: cameras: 18.5M$
  - NSF-Phys: 37M$
  - NSF-Astr: 10M$
- DOE groups led by SLAC & ANL
- Secondary optics:
  - Reduction in plate-scale
  - Use cheaper sensors **and**
  - Improve angular resolution



Conclusions

- In the field of gamma-ray astronomy, we are standing on the shoulders of giants...



- The view from the top is always much clearer, and the roads are much smoother after the pioneers have paved the way!

- The climb is still steep, and one has to be careful not to look too far ahead, and keep an eye on your footing.

Backup Slides

Technical Details

Telescope (x 4)
12-m diameter Davies-Cotton
f 1.0, 110 m2 area

Technical Details

Camera (x 4)

499 PMTs, 3.5° FOV

Telescope (x 4)

12-m diameter Davies-Cotton

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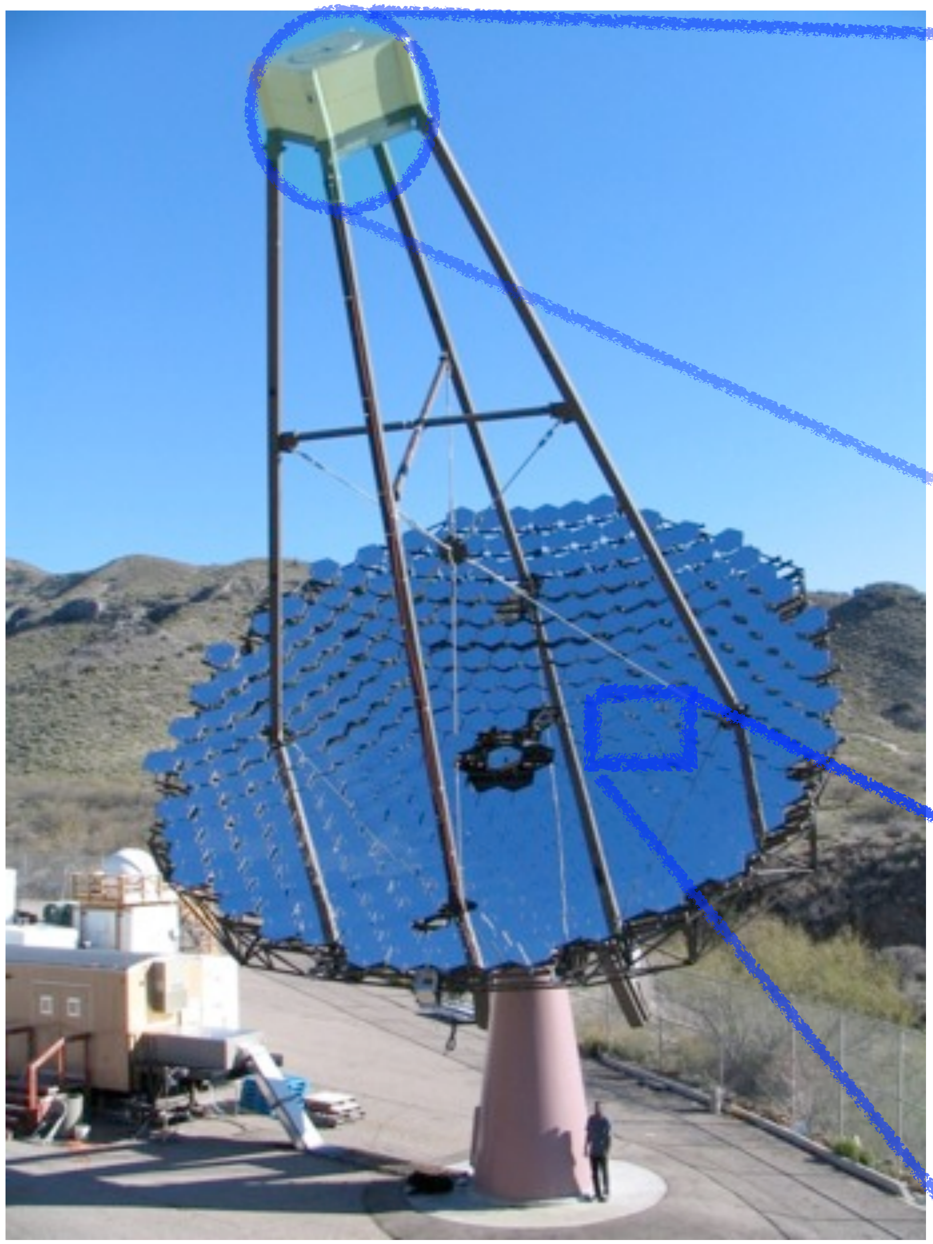

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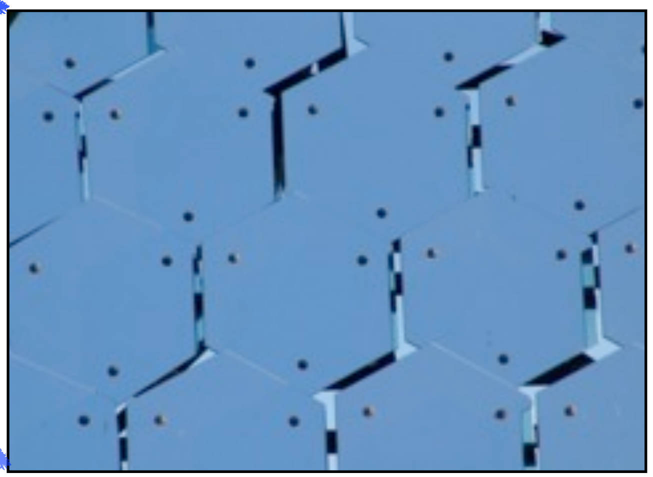

Telescope (x 4)
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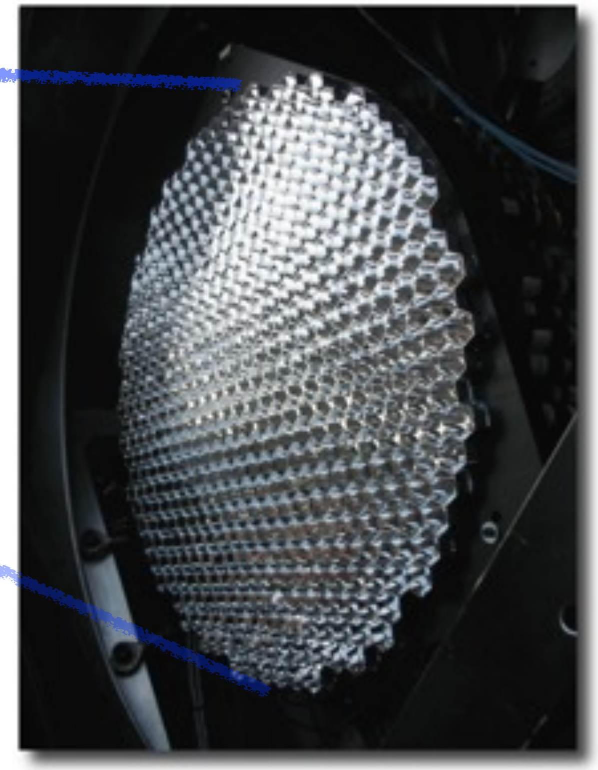
f 1.0, 110 m2 area

Mirror Facets (x 350)
Reflectivity ~ 88%
(Recoated every 2 years)

Technical Details



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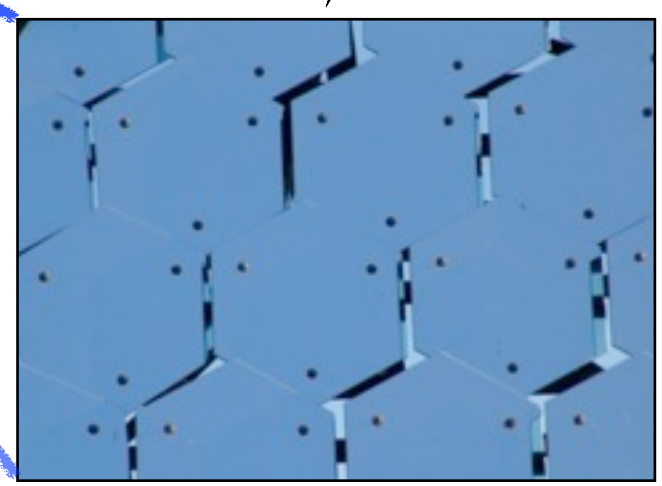

Electronics
500 Msp FADC, CFD trigger, 3-fold adjacent pixels and 2/4 telescope coincidence

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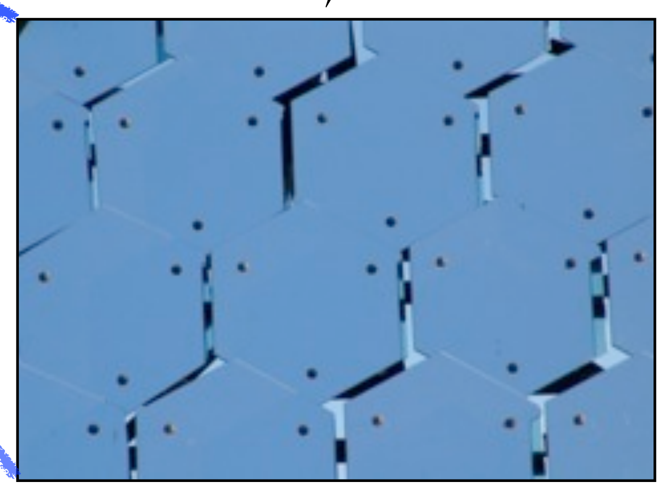

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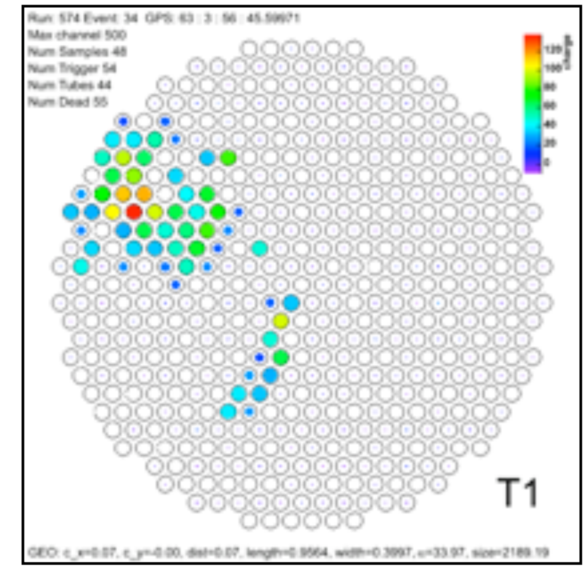

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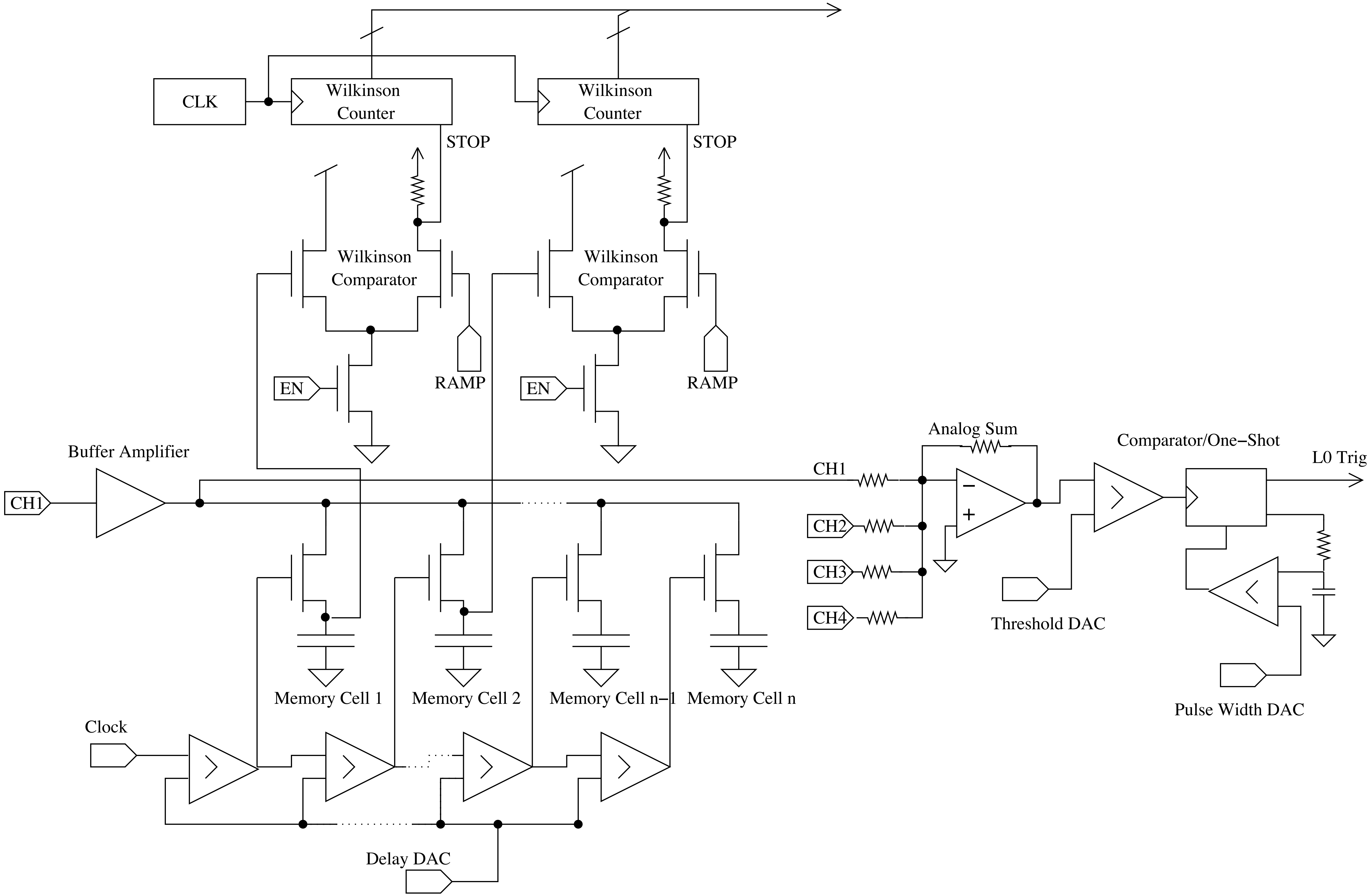
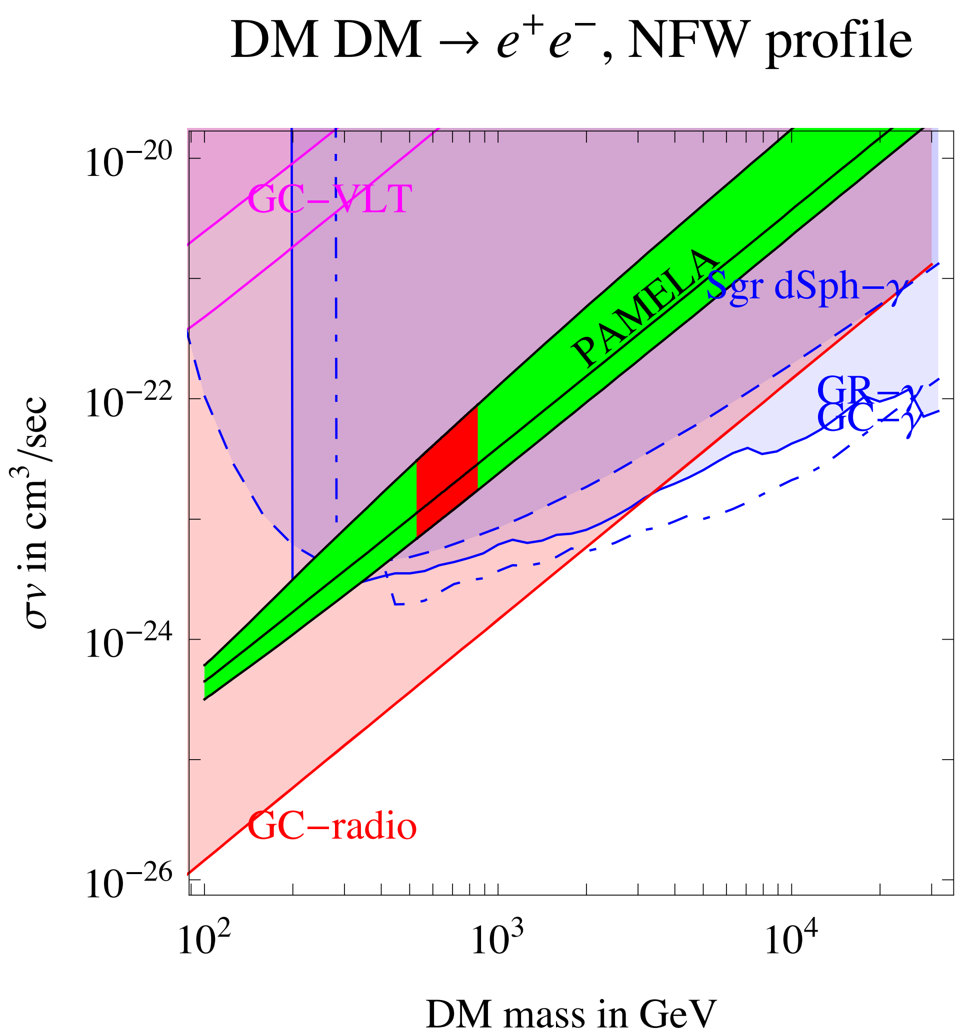
TARGET Design Overview

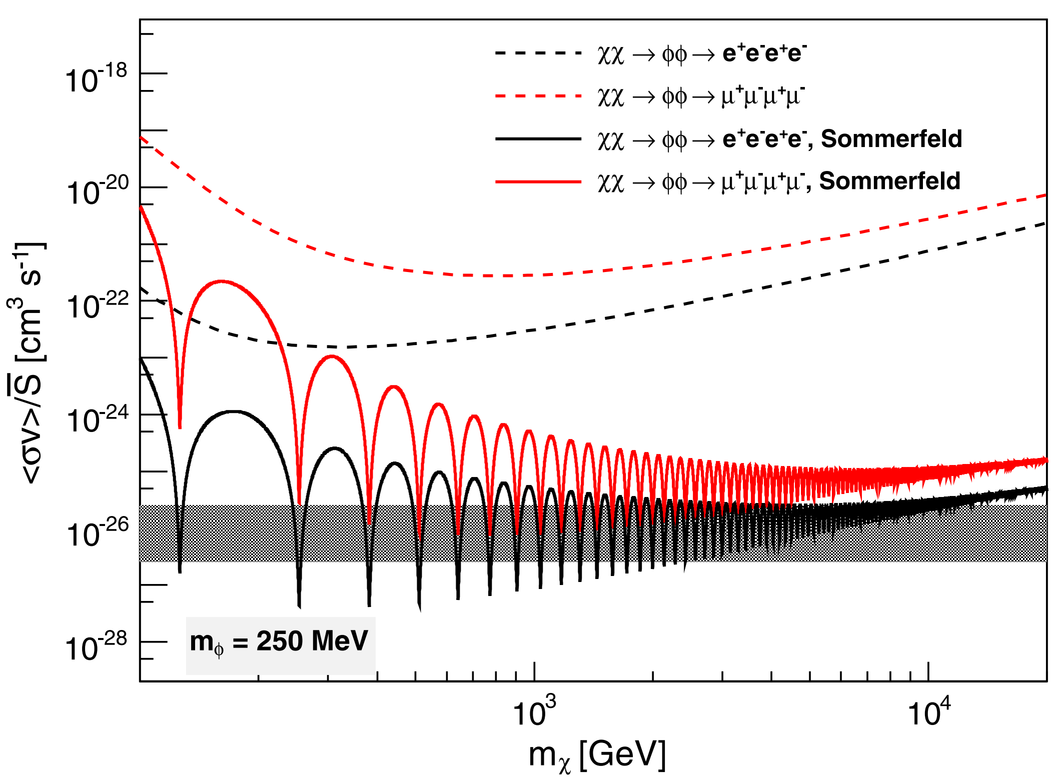


Shedding Light on Positrons



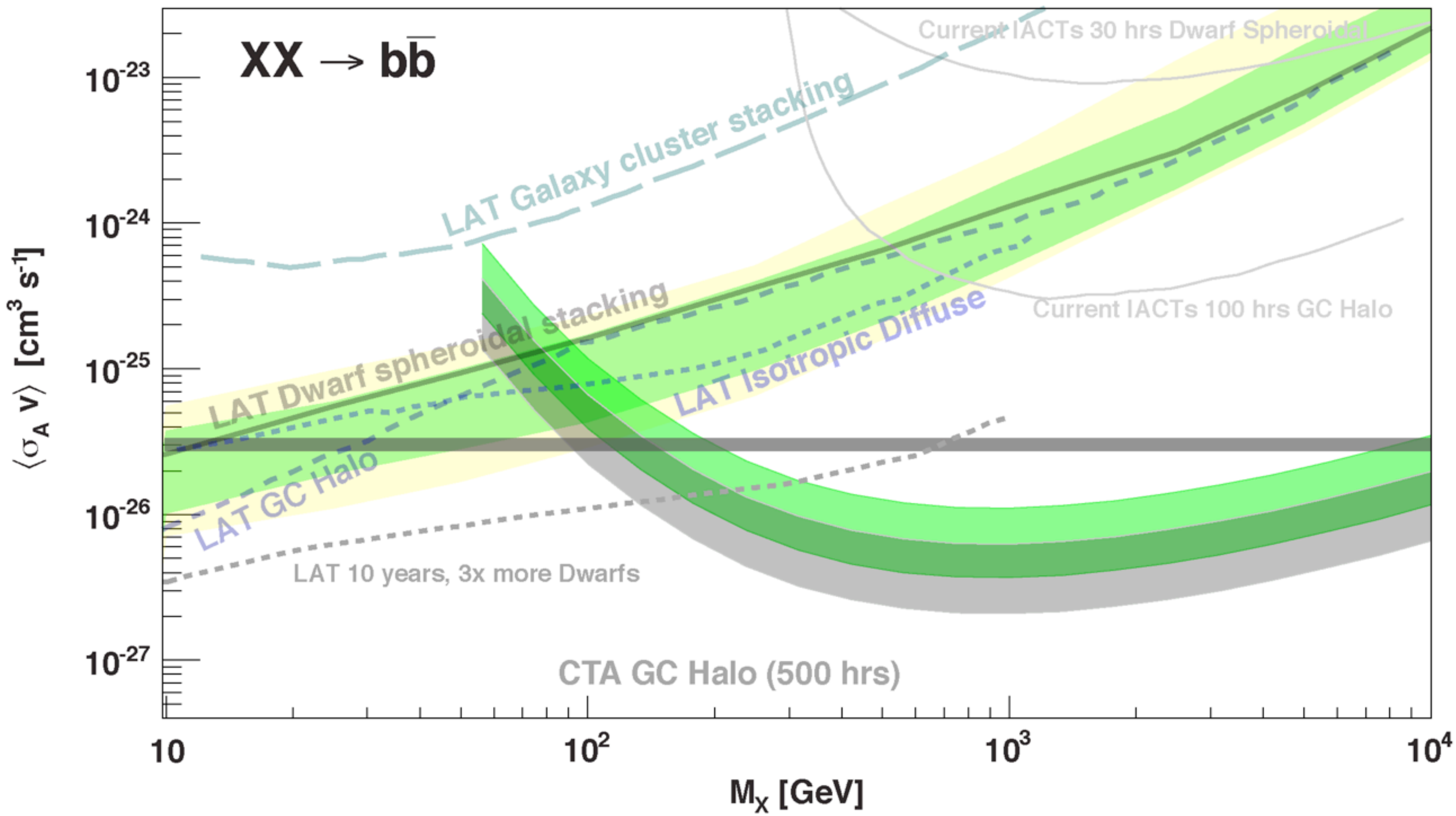
Radio Synchrotron and gamma-ray IC limits for Pamela scenario (Bertone, Cirelli, Strumia and Taoso, arXiv:0811.2744v3). *Note: Radio bounds are sensitive to assumptions about B-fields and diffusion, may be optimistic.*

VERITAS Segue Limits with Sommerfeld Enhancement

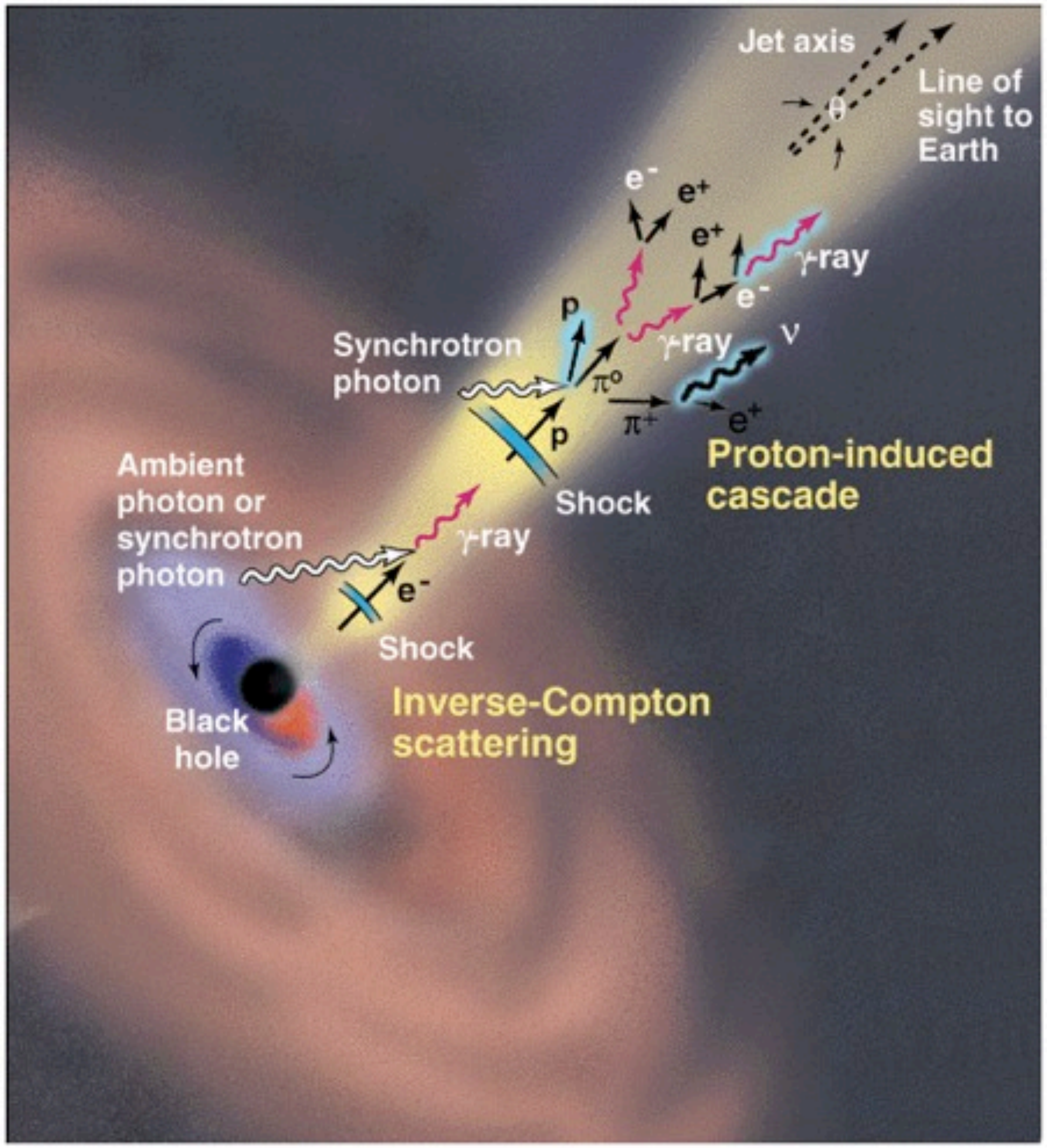


- Pamela excess implies a large radio synchrotron and inverse Compton signal, and a boost in secondary gammas from the GC that are not observed.

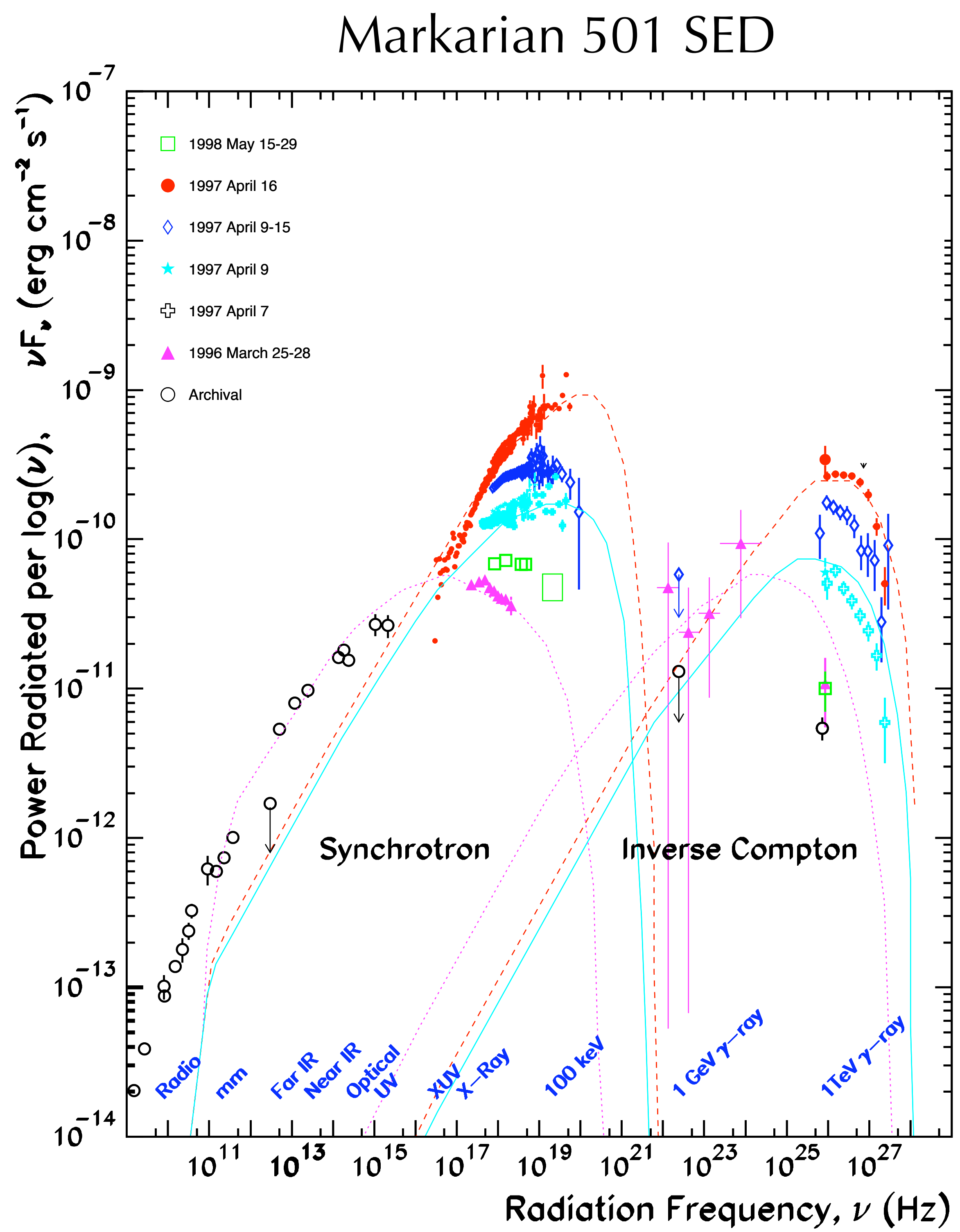
Gamma-Ray Sensitivity



A Typical Source



(Adapted from Buckley, Science, 1998)



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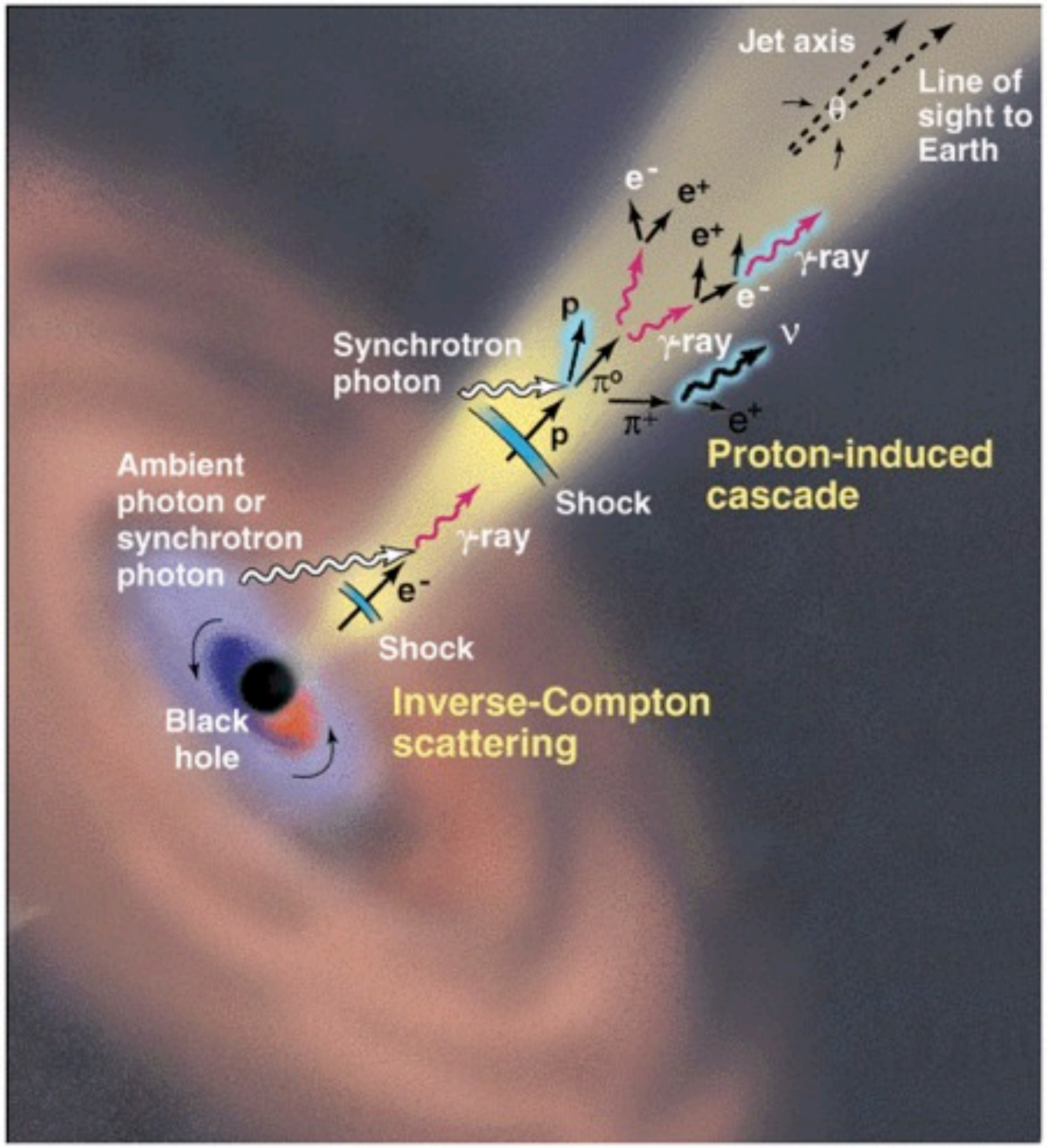

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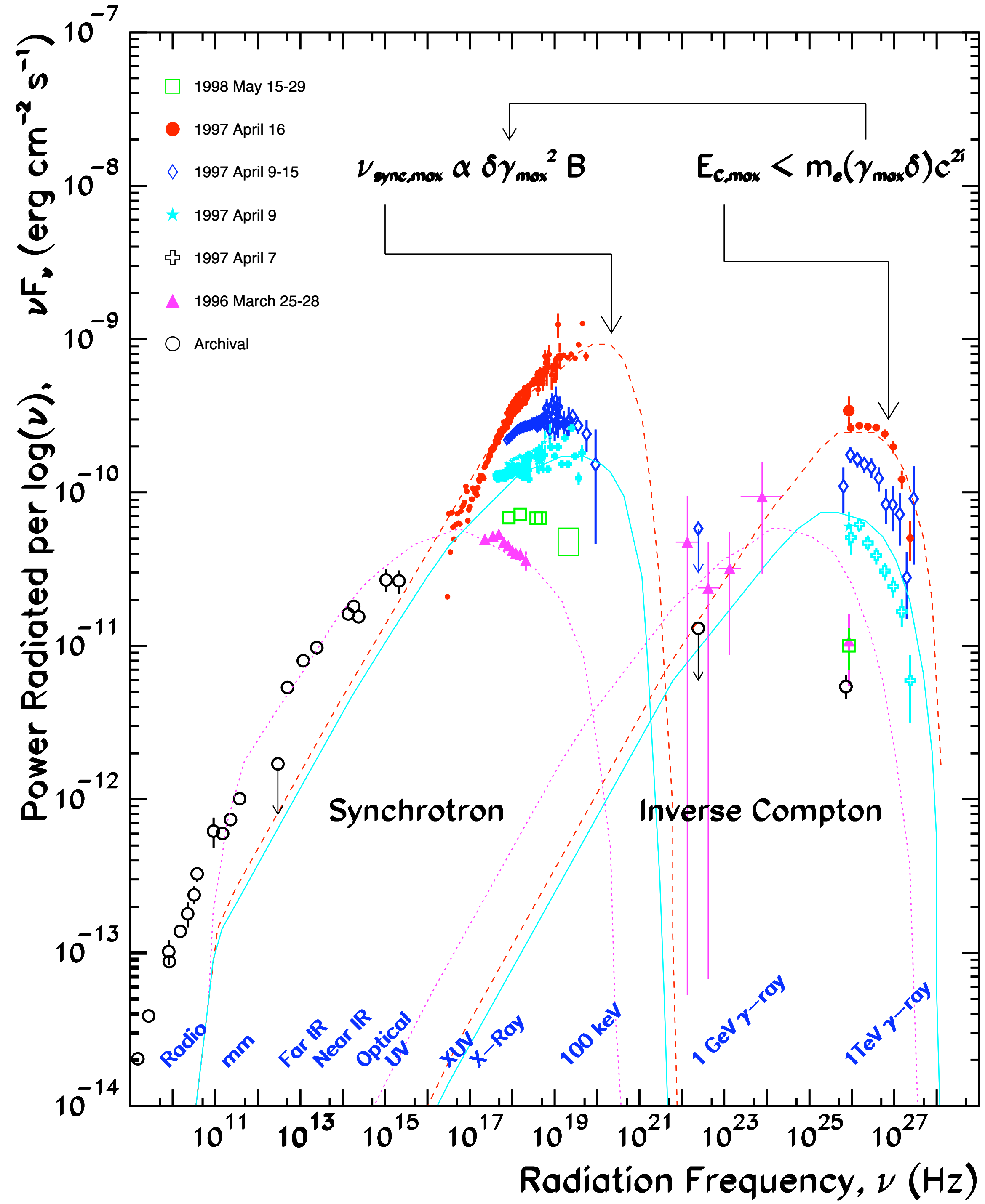
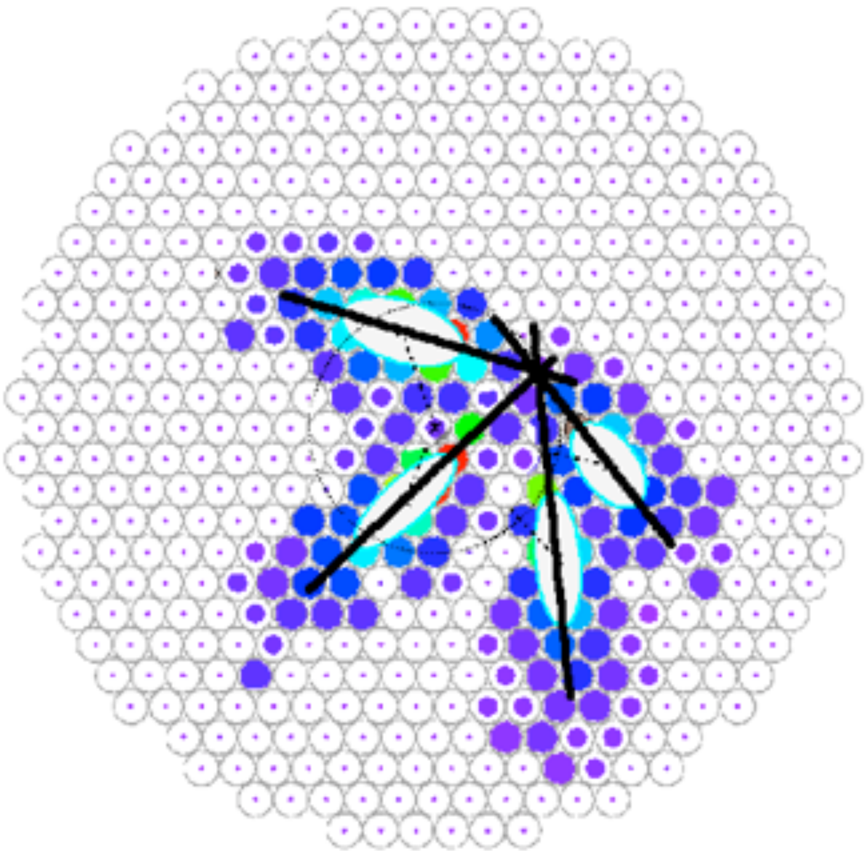
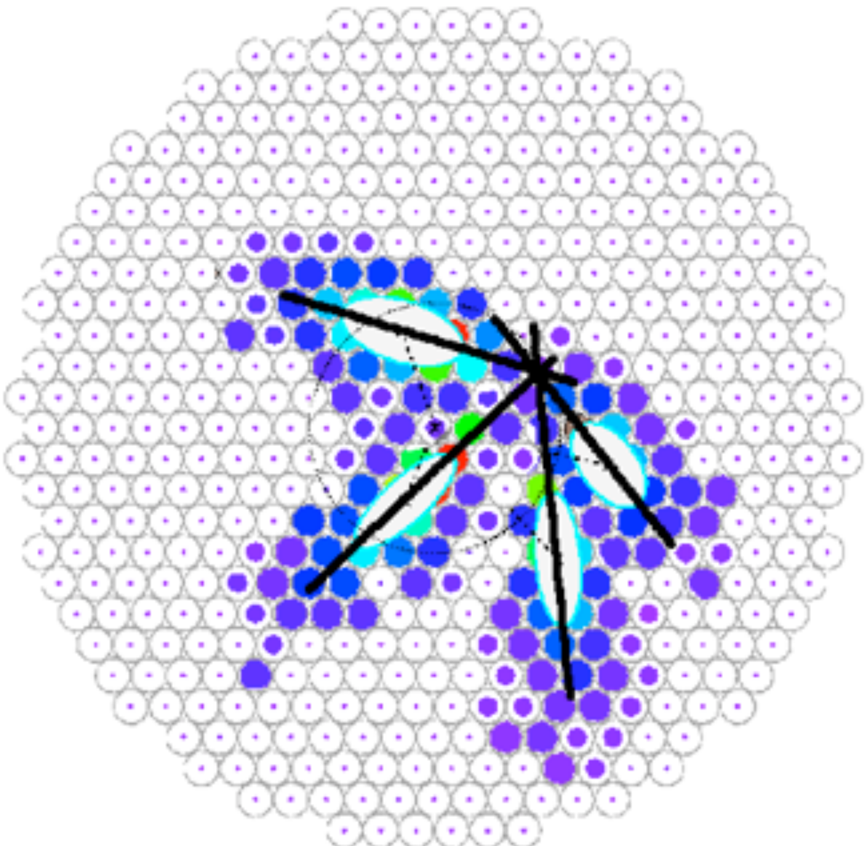
Markarian 501 SED



IACT Arrays

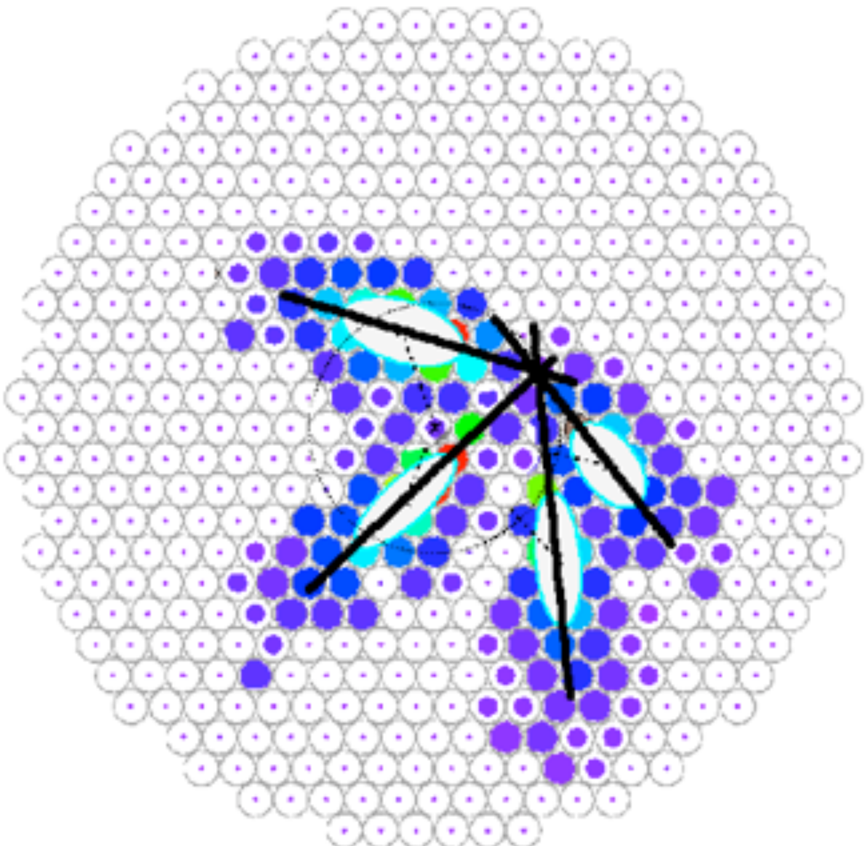


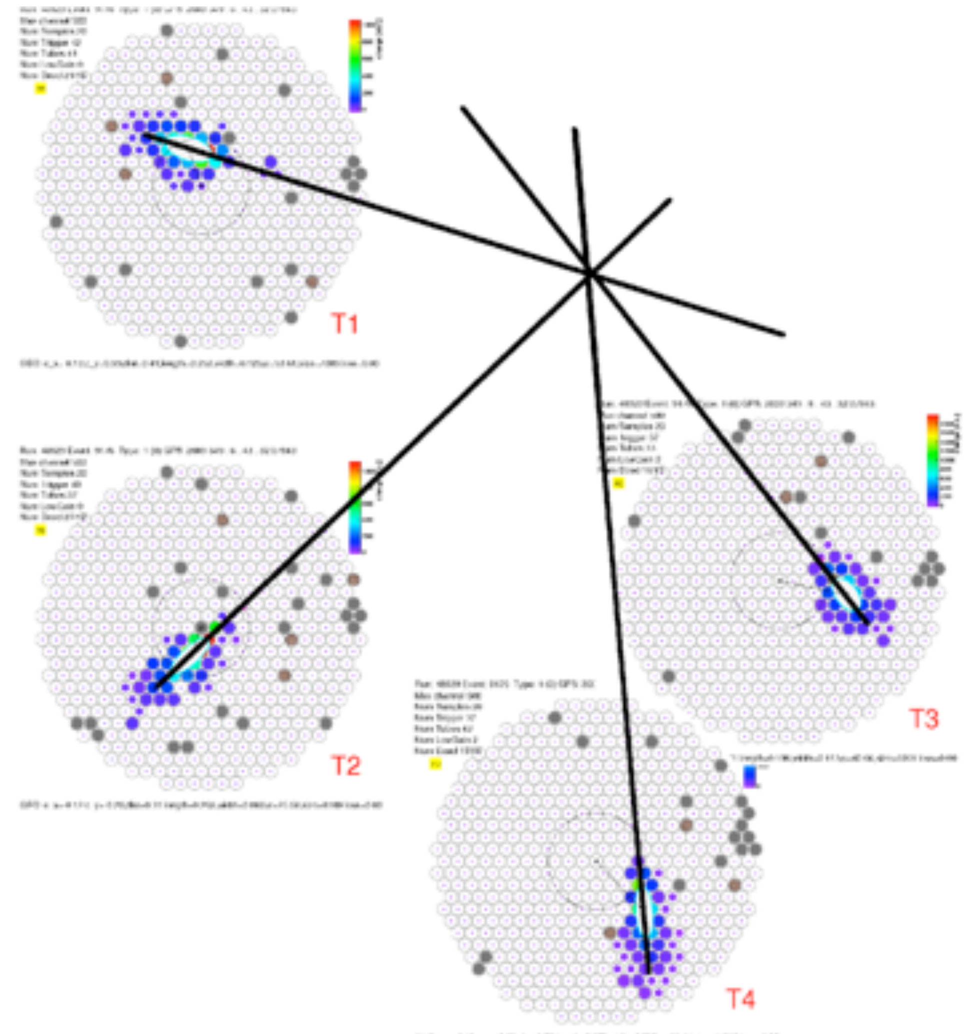
IACT Arrays



- Stereoscopic reconstruction provides point of origin of gamma-rays from intersection of images (like convergence of lines of perspective)

IACT Arrays

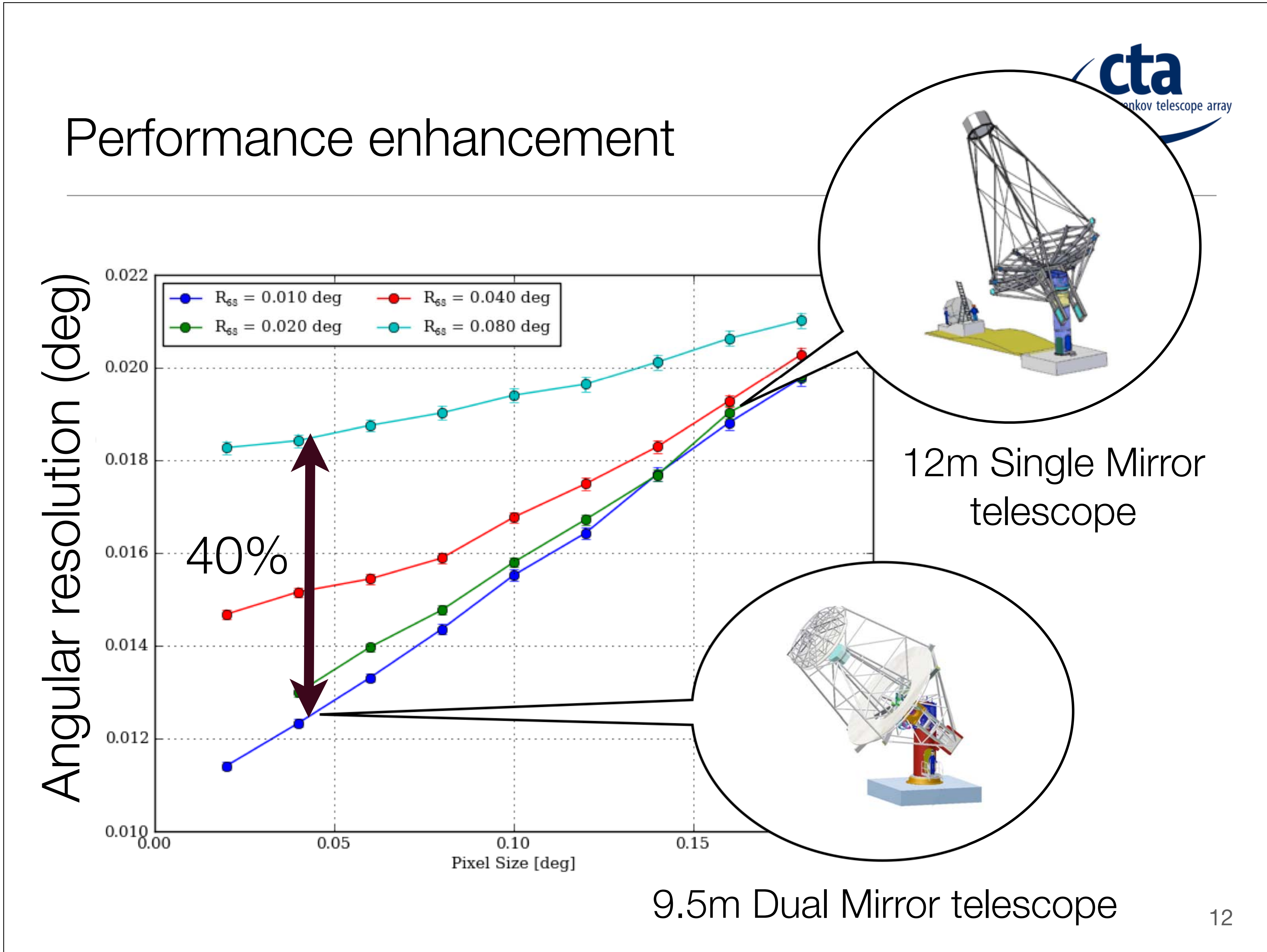




- Stereoscopic reconstruction provides point of origin of gamma-rays from intersection of images (like convergence of lines of perspective)

- Images also converge on impact point on the ground, together with multiple samples of total light providing corrections for the Cherenkov light lateral distribution and good calorimetry

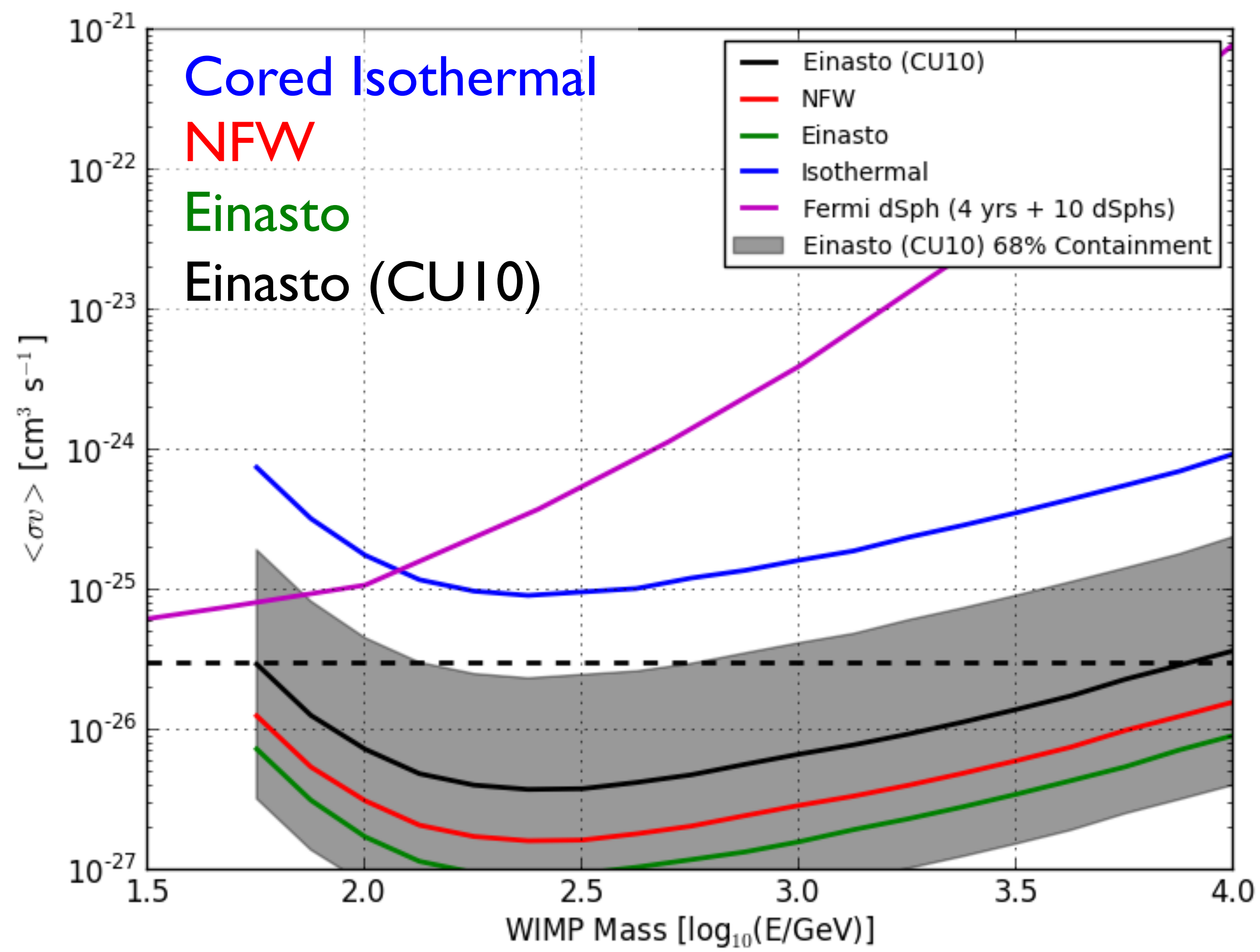
CTA-US Angular Resolution



Snowmass Tough Questions

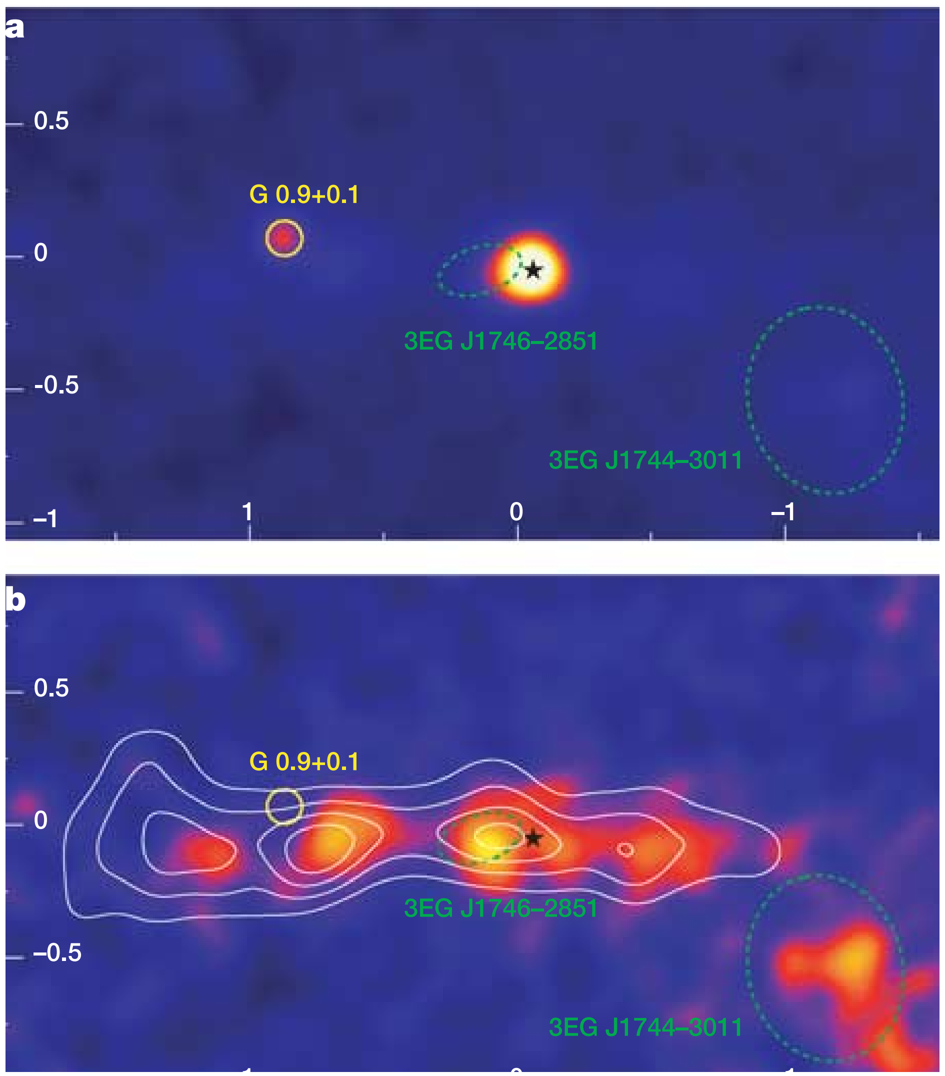
``Can dark matter be convincingly discovered by indirect searches given astrophysical and propagation model uncertainties? Do indirect searches only serve a corroborating role?''

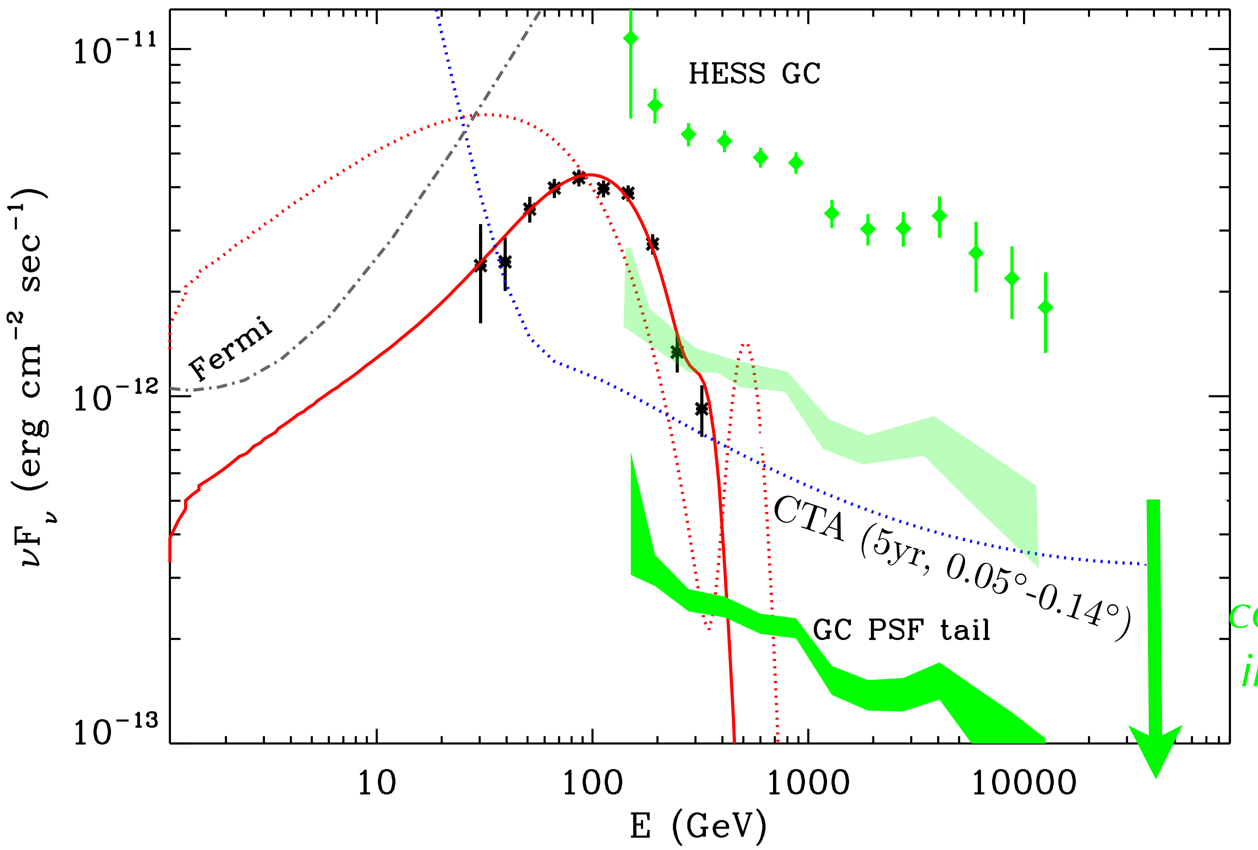
- The primary astrophysical uncertainties come for gamma-ray production come from uncertainties in the halo model. *But even with uncertainties, the limits still reach the natural decoupling cross section.*
- An annihilation line in the gamma-ray spectrum would also provide a smoking gun signature (if detected at high significance!).
- Neutrinos from DM annihilation in the sun would be a smoking gun signature.
- *Wouldn't a hint of a signal of, say 20 TeV neutralinos provide important guidance for the Energy Frontier, and motivate a new 100 TeV accelerator?*



Snowmass Tough Questions

``Given large and unknown astrophysics uncertainties (for example, when observing the galactic center), what is the strategy to make progress in a project such as CTA which is in new territory as far as backgrounds go? How can we believe the limit projections until we have a better indication for backgrounds and how far does Fermi data go in terms of suggesting them? What would it take to convince ourselves we have a discovery of dark matter?"





Dwarf galaxies have almost no known astrophysical backgrounds, for backgrounds the GC is worst case. HESS provides the best data on the GC (below, with point source at Sgr A* subtracted). Better angular resolution can reduce the background from the tail of the PSF function, which dominates over other sources in the plane

Snowmass Tough Questions

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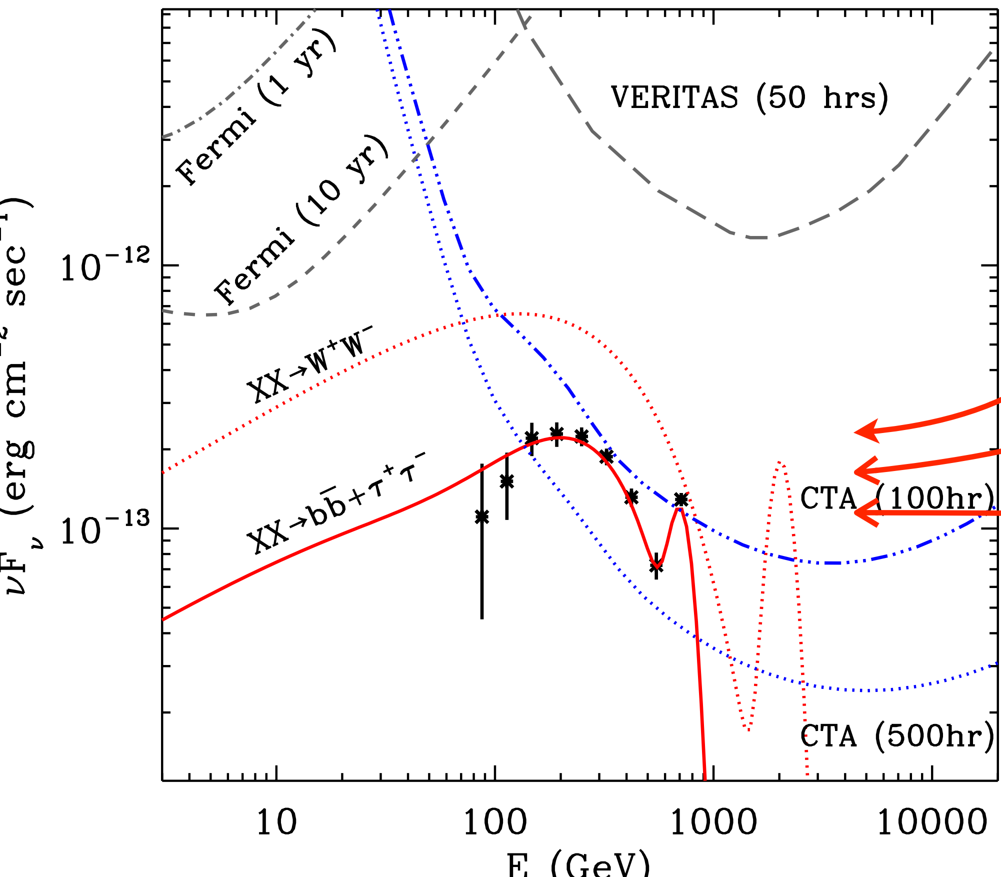
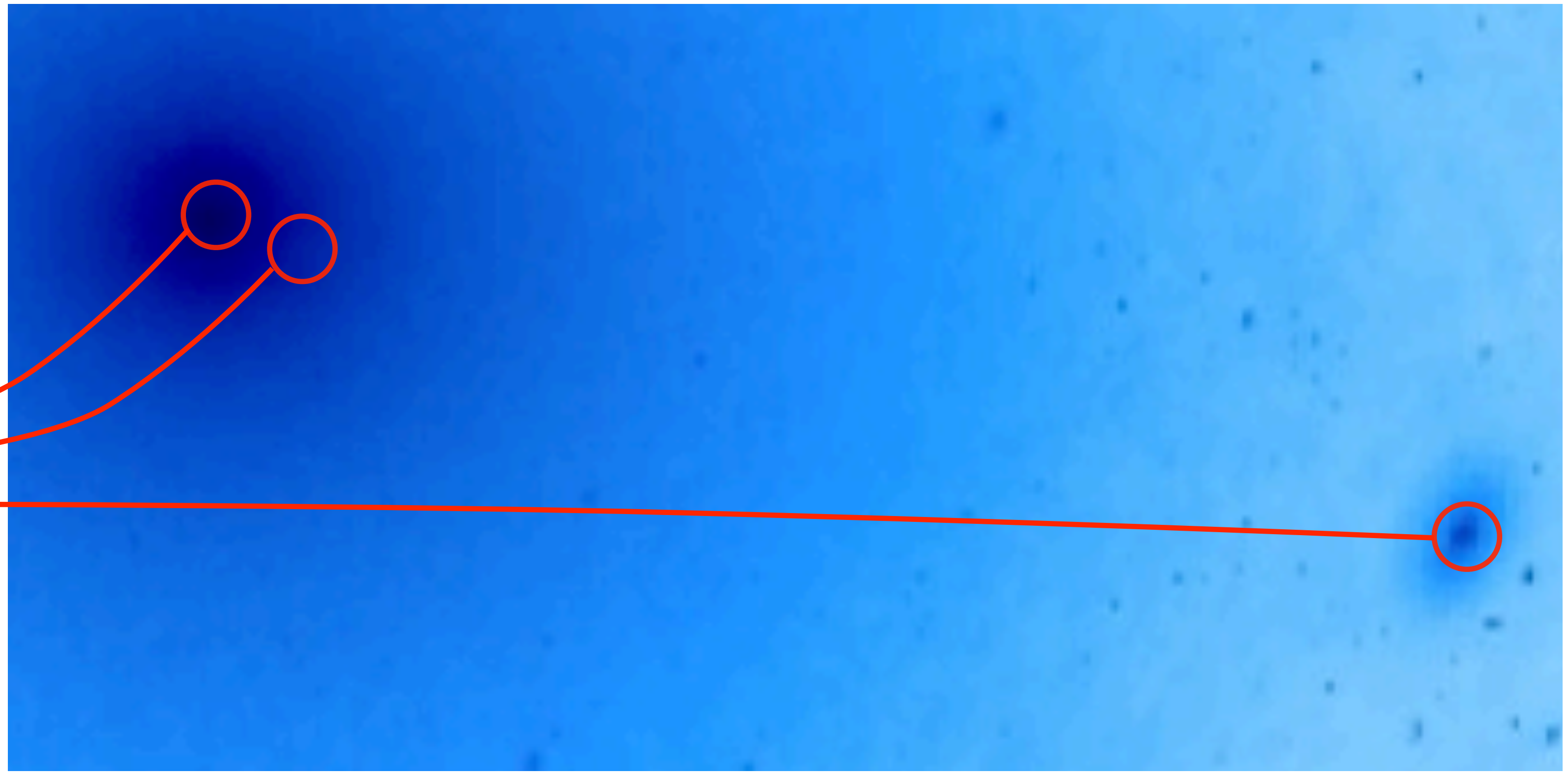
Backgrounds get lower at higher energies, but even at 1-3 GeV with no background subtraction get a limit within $1^\circ \sim 1 \times 10^{-7}\mathrm{cm}^{-2}\,\mathrm{s}^{-1} \Rightarrow \langle \sigma v \rangle = 1.6 \times 10^{-25}\ \mathrm{cm}^3\mathrm{s}^{-1}$

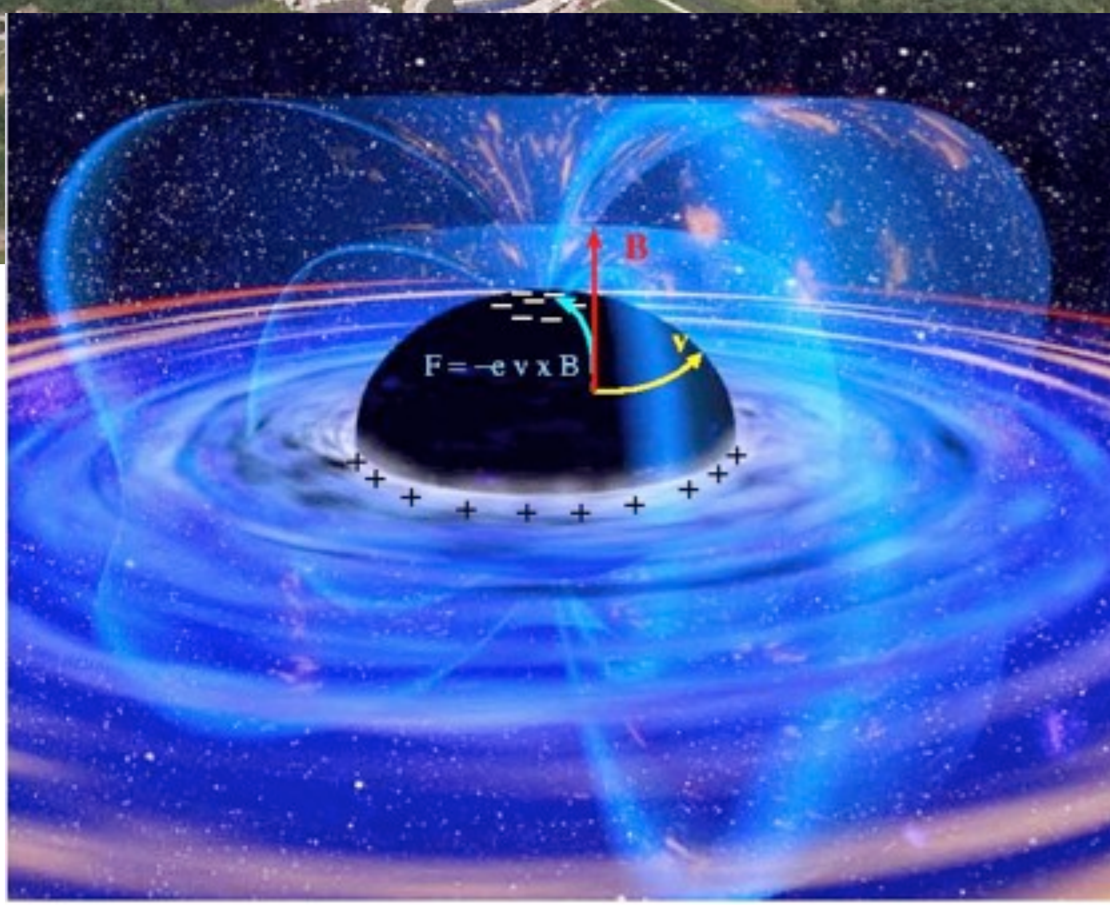
(Tim Linden, SLAC CF meeting)

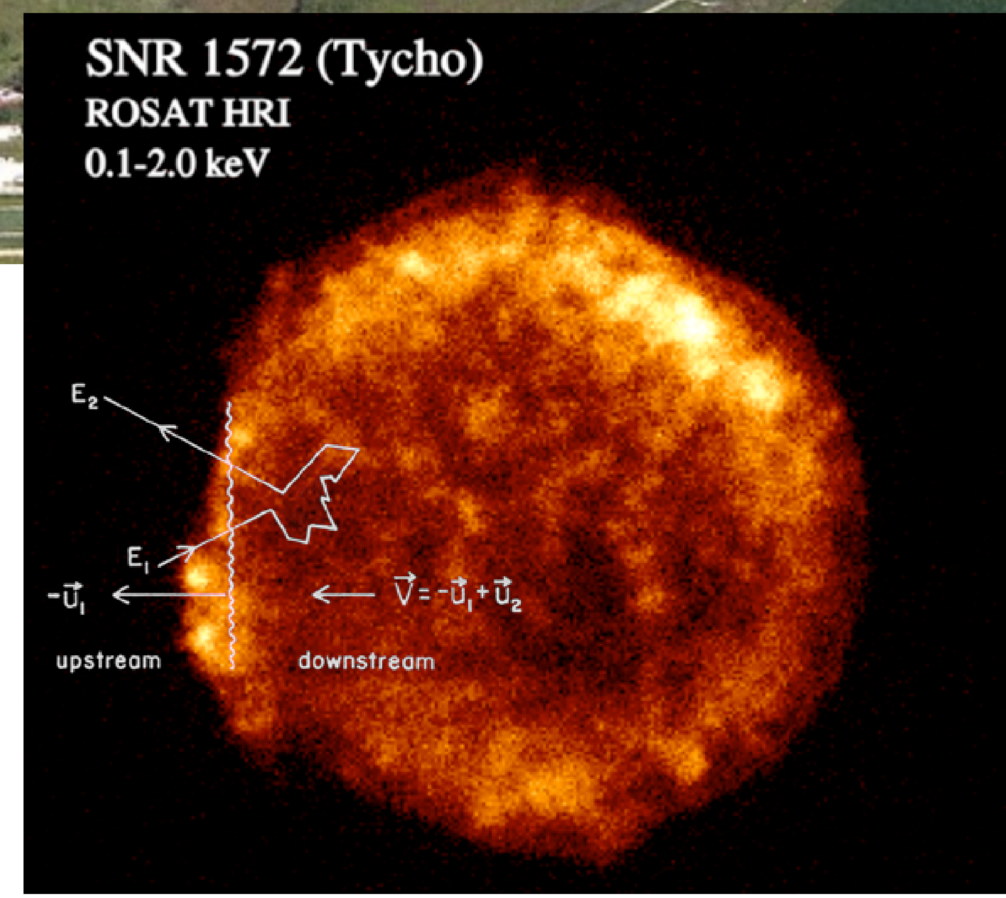




Unlike other astrophysical sources, would see a universal hard spectrum (typically harder by $\sim E^{0.5}$) with a sharp cutoff. The spectral shape would be universal: the same throughout the GC halo, in halos of Dwarf galaxies, with no variability.

Particle Accelerators



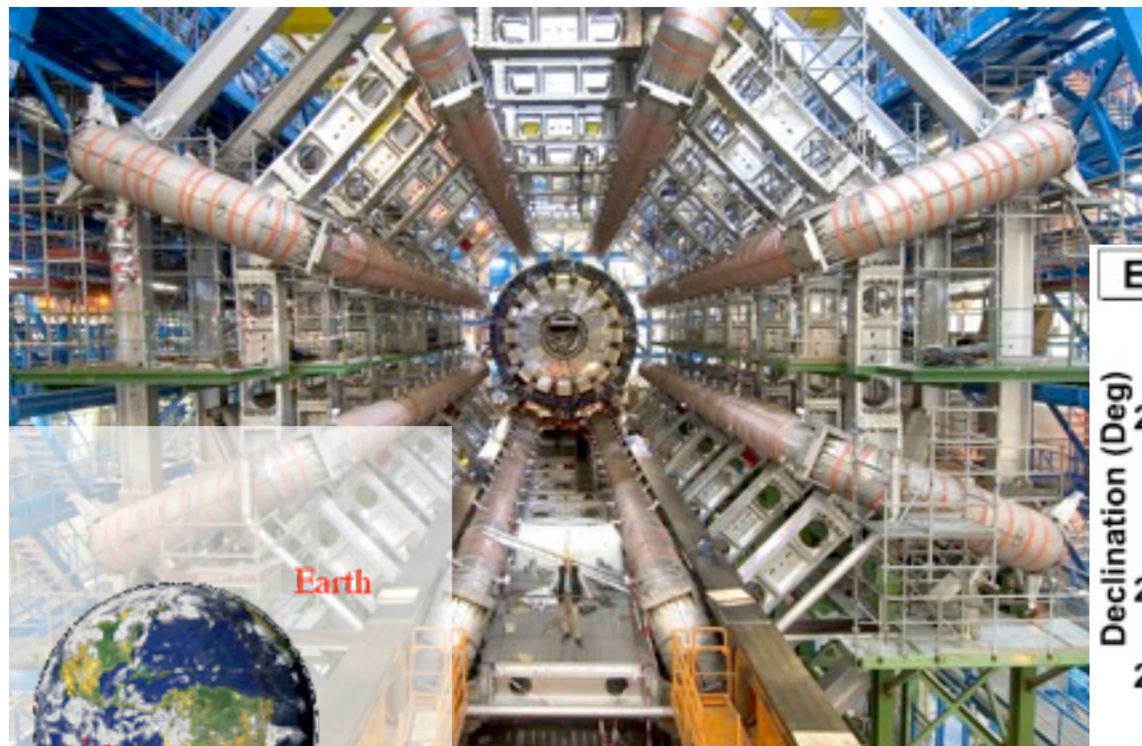


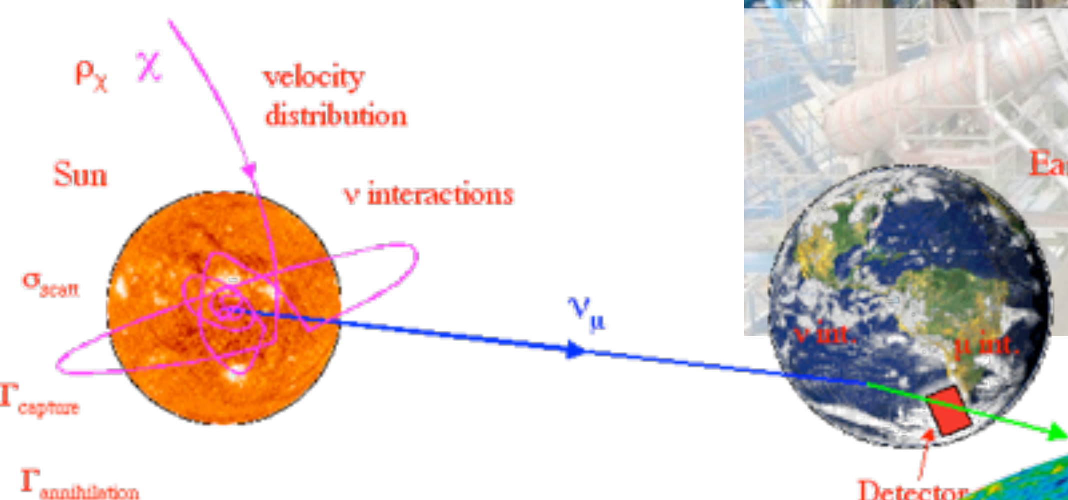
Black hole extended horizon or accretion disk - conductor spinning in a magnetic field - 10^{20} V Generator! (Blandford, Lovelace)

Gamma-ray observations provide direct evidence for acceleration of charged particles up to >tens of TeV in SNR

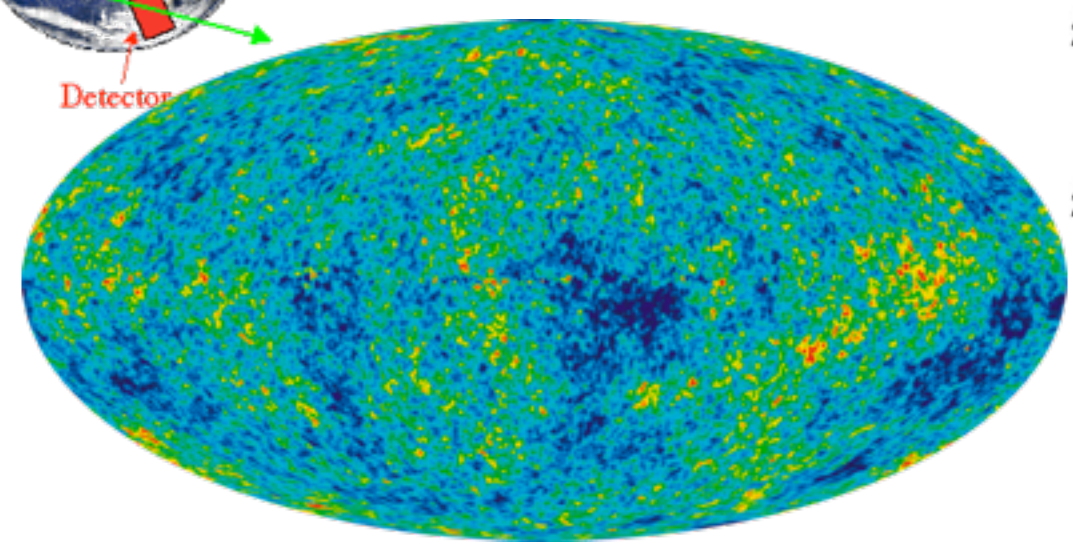
Targets?

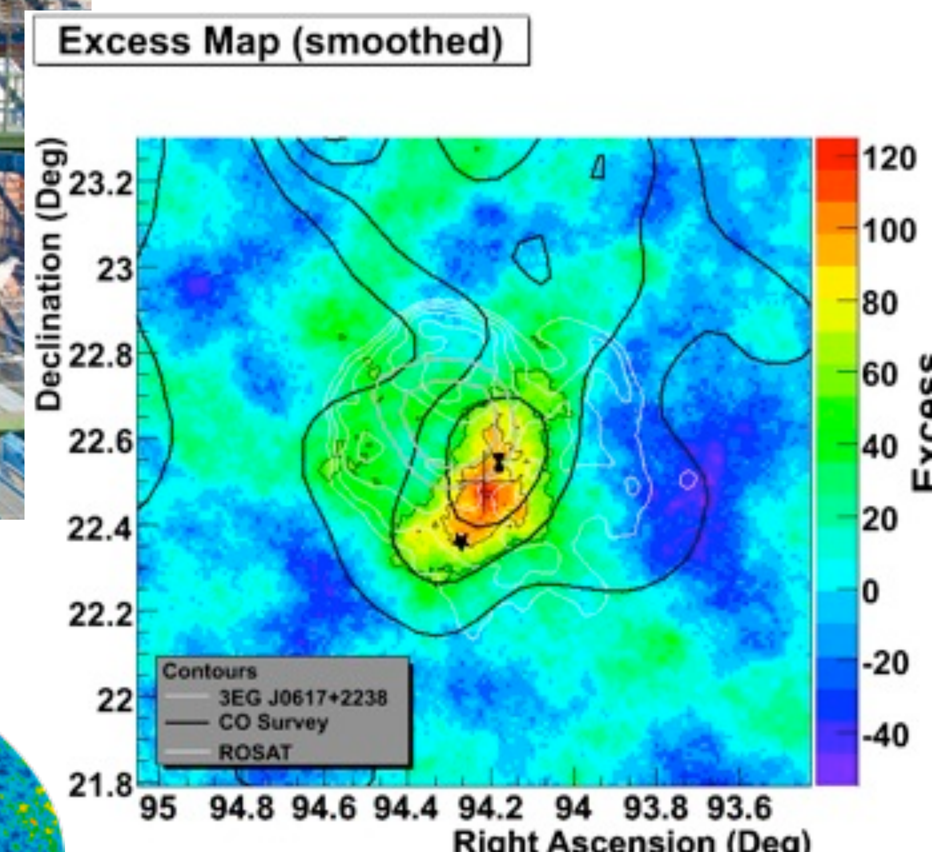
Modern accelerators use colliding beams for higher cm energy
- dark matter halos are matter-antimatter colliding beams!





The sun or earth is sometimes the fixed target!

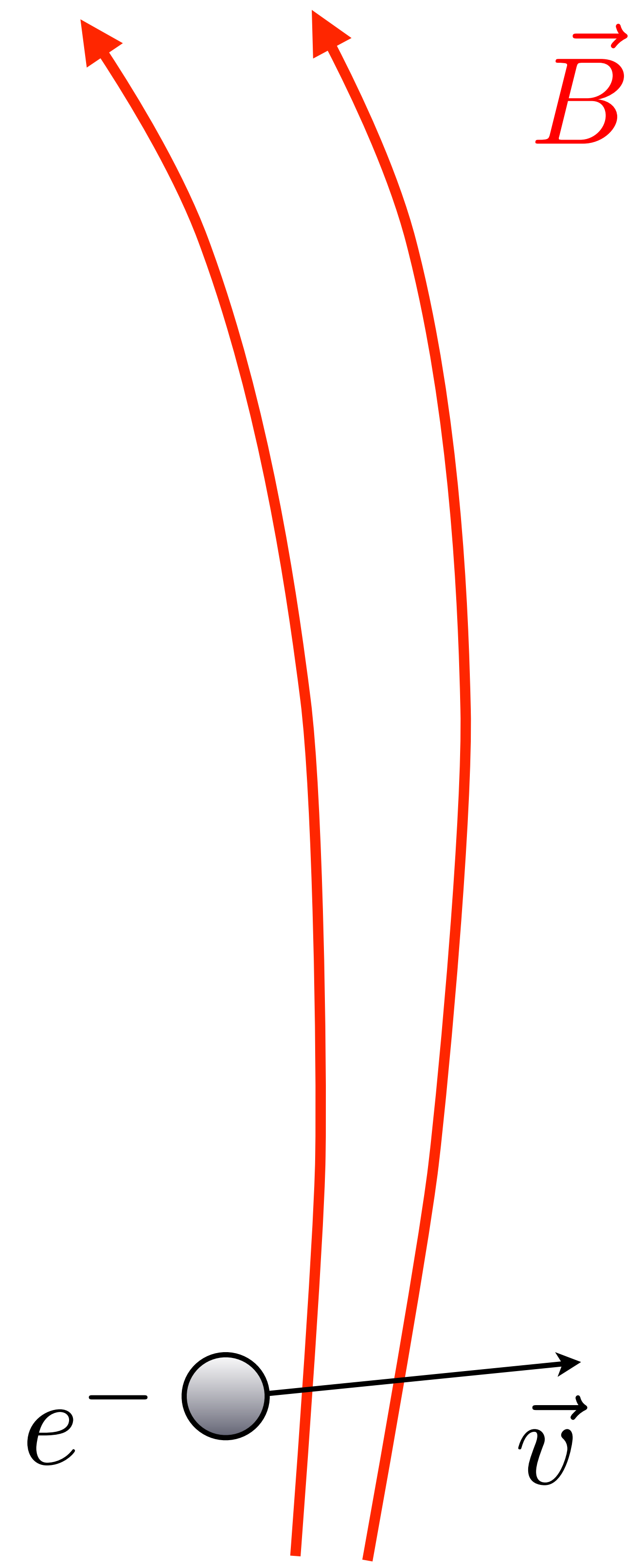




Molecular clouds can be the target

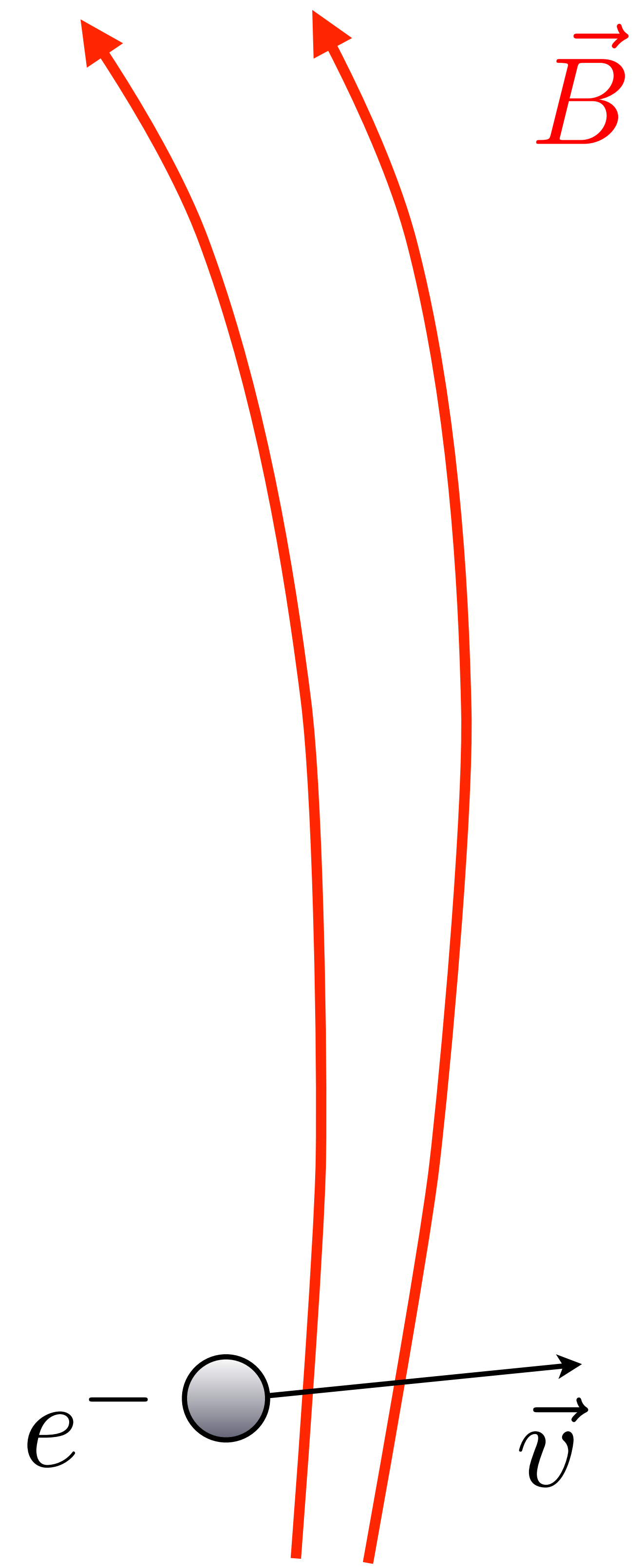
CMB photons and primordial starlight are also targets for high energy cosmic particles

Synchrotron Radiation



Synchrotron Radiation

- Particles are deflected by magnetic fields, causing them to gyrate in circles.



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- Particles are deflected by magnetic fields, causing them to gyrate in circles.
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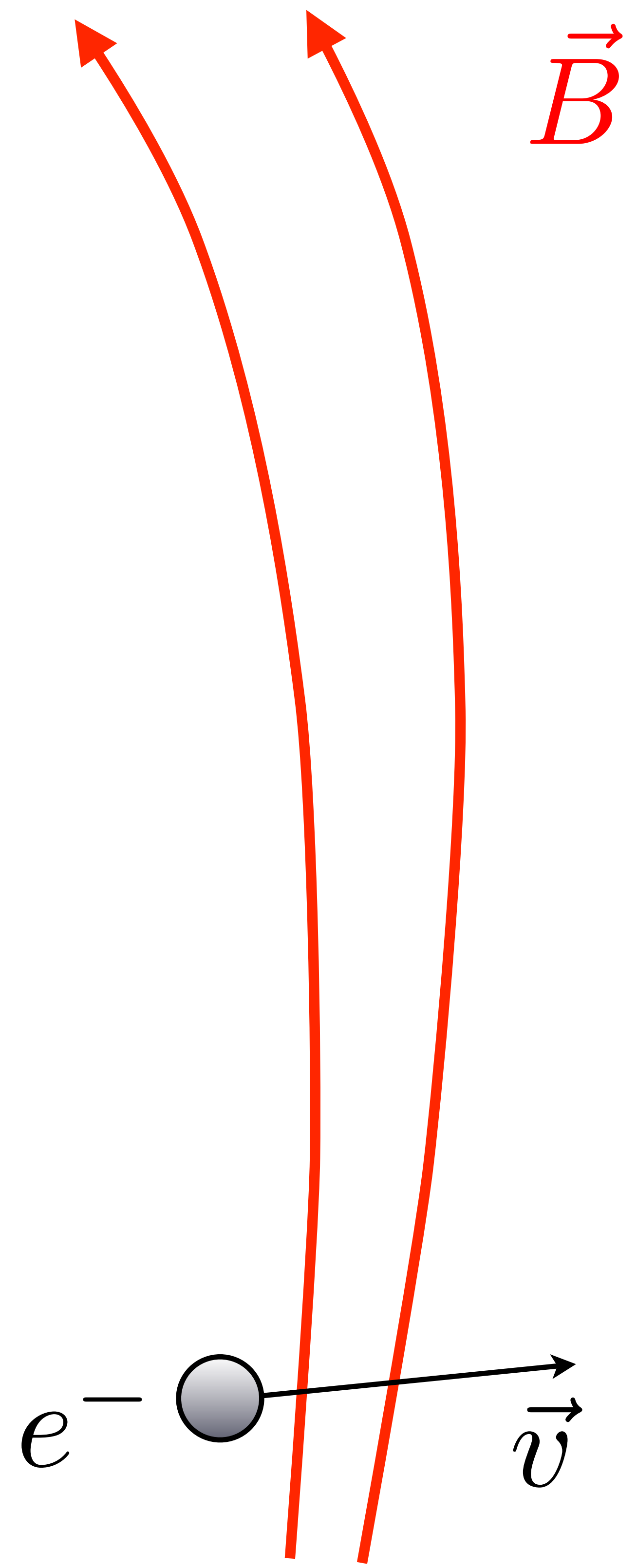

Synchrotron Radiation

- Particles are deflected by magnetic fields, causing them to gyrate in circles.
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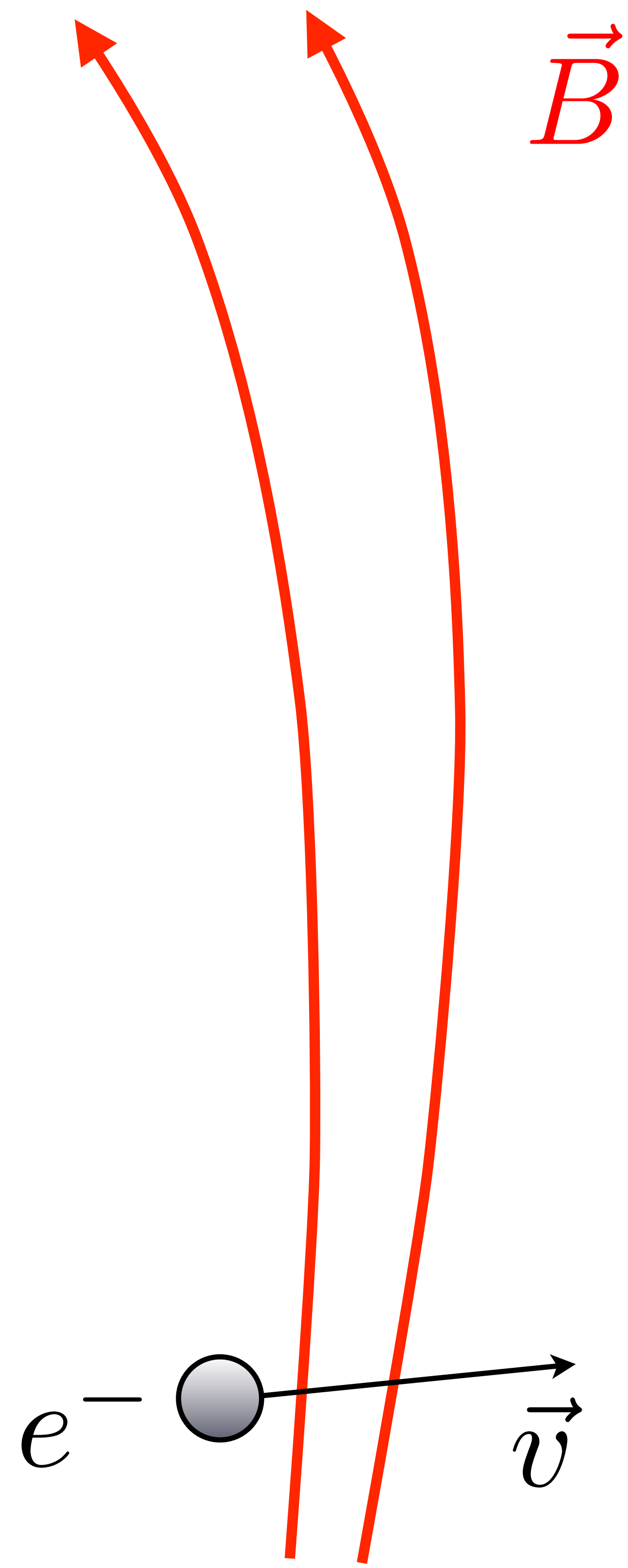
- The emitted "synchrotron radiation" is very different than thermal radiation, having a very broad spectrum that can span radio to X-ray wavelengths



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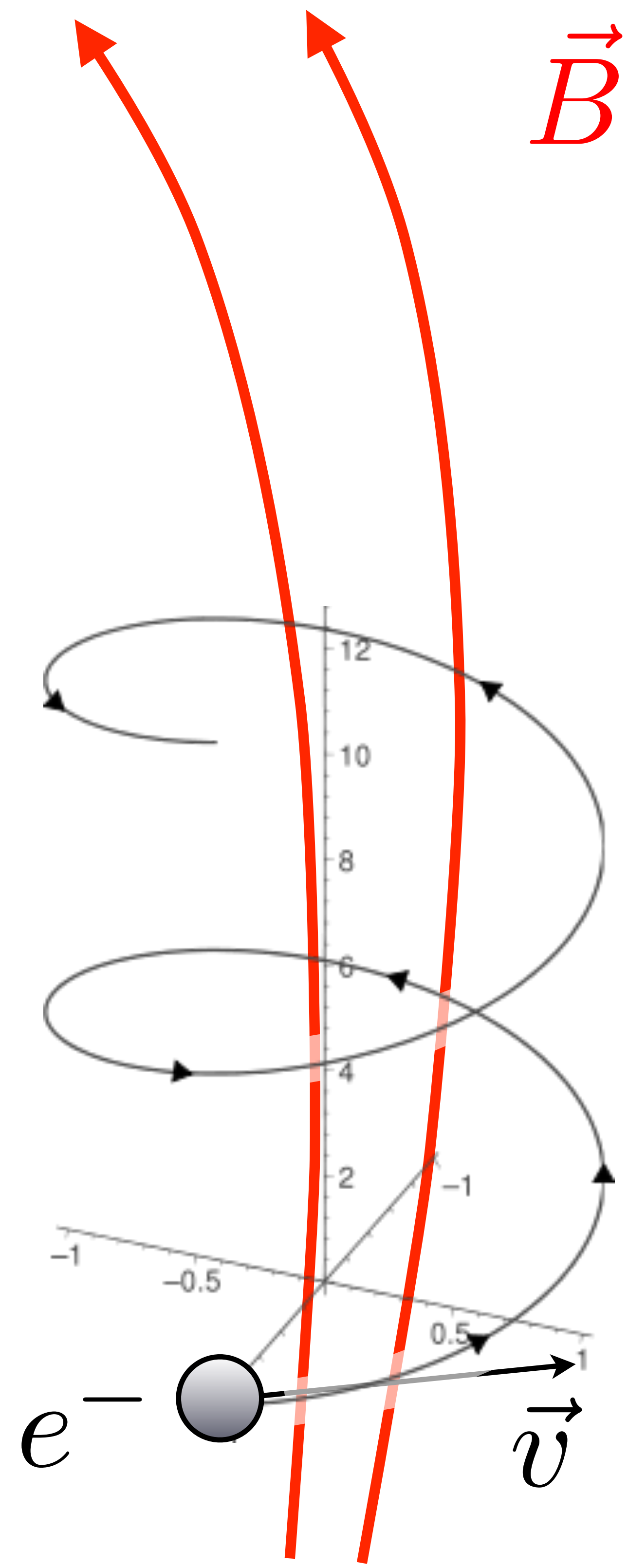

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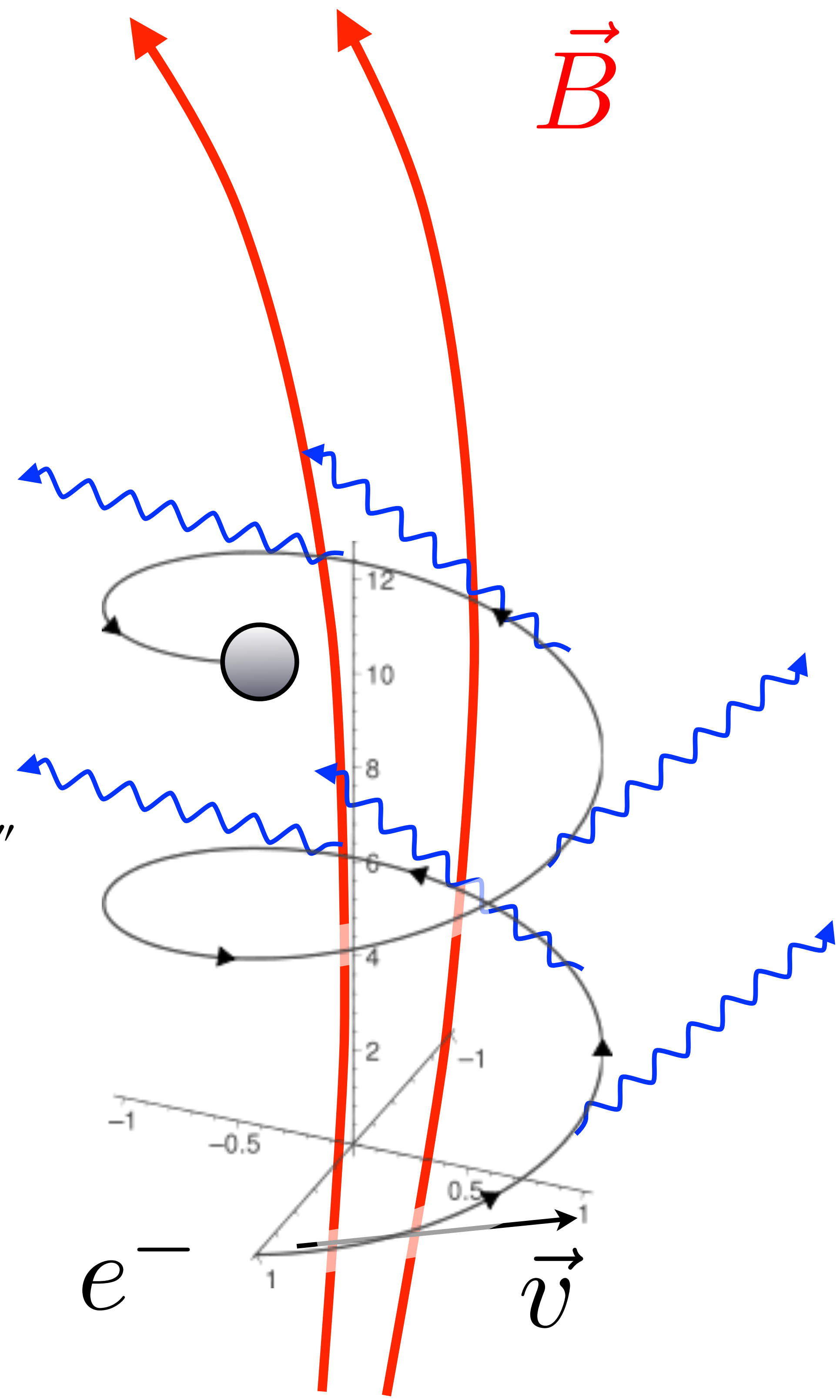
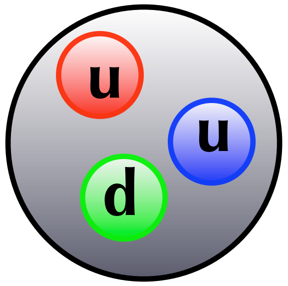


Pion Production

p



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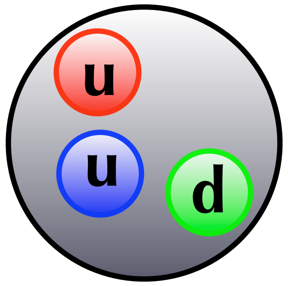
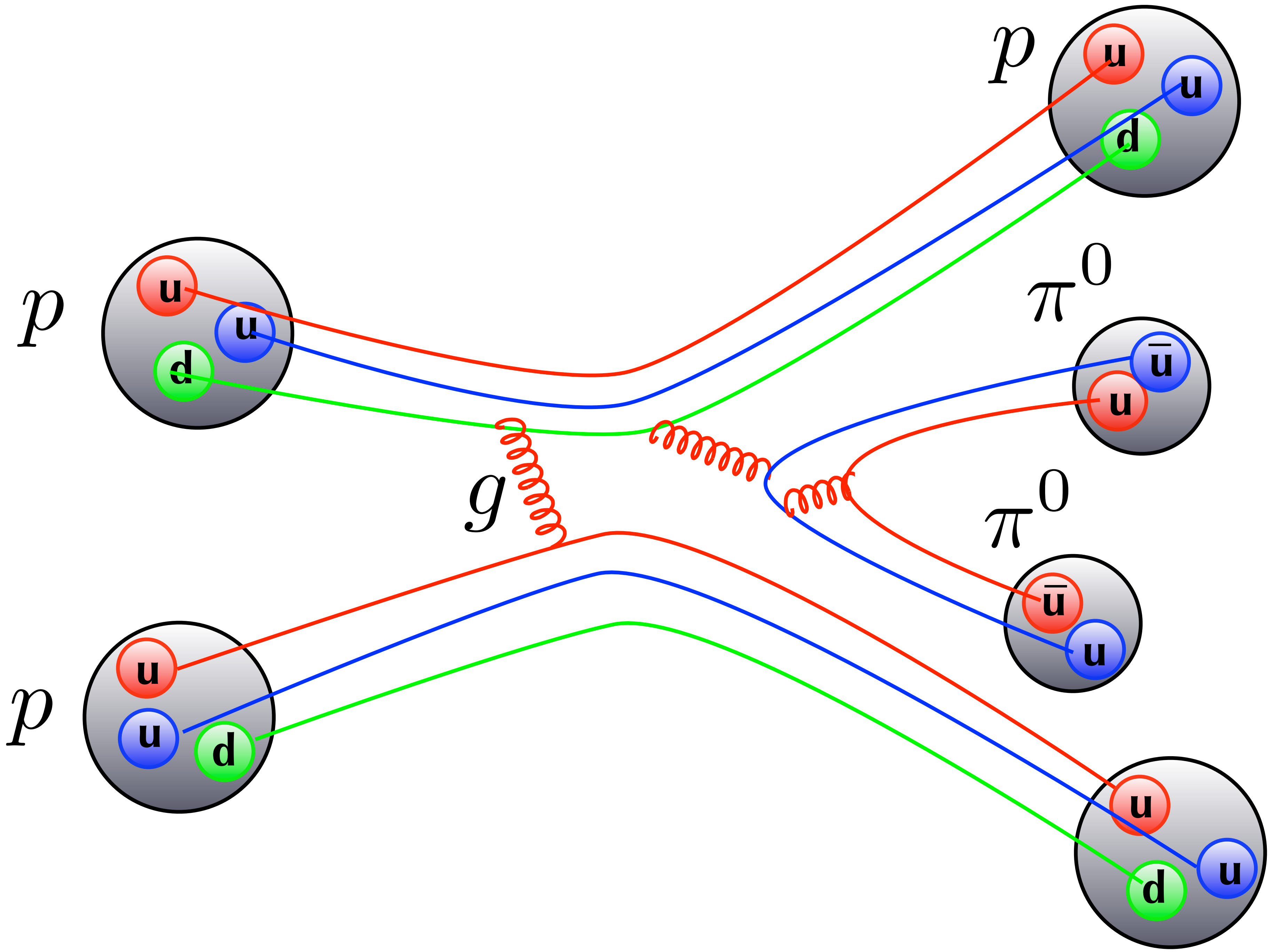


- Protons and other nuclei like bags of quarks, interact by radiating and exchanging gluons. Neutral or charged pions can be formed in interactions.

Pion Production



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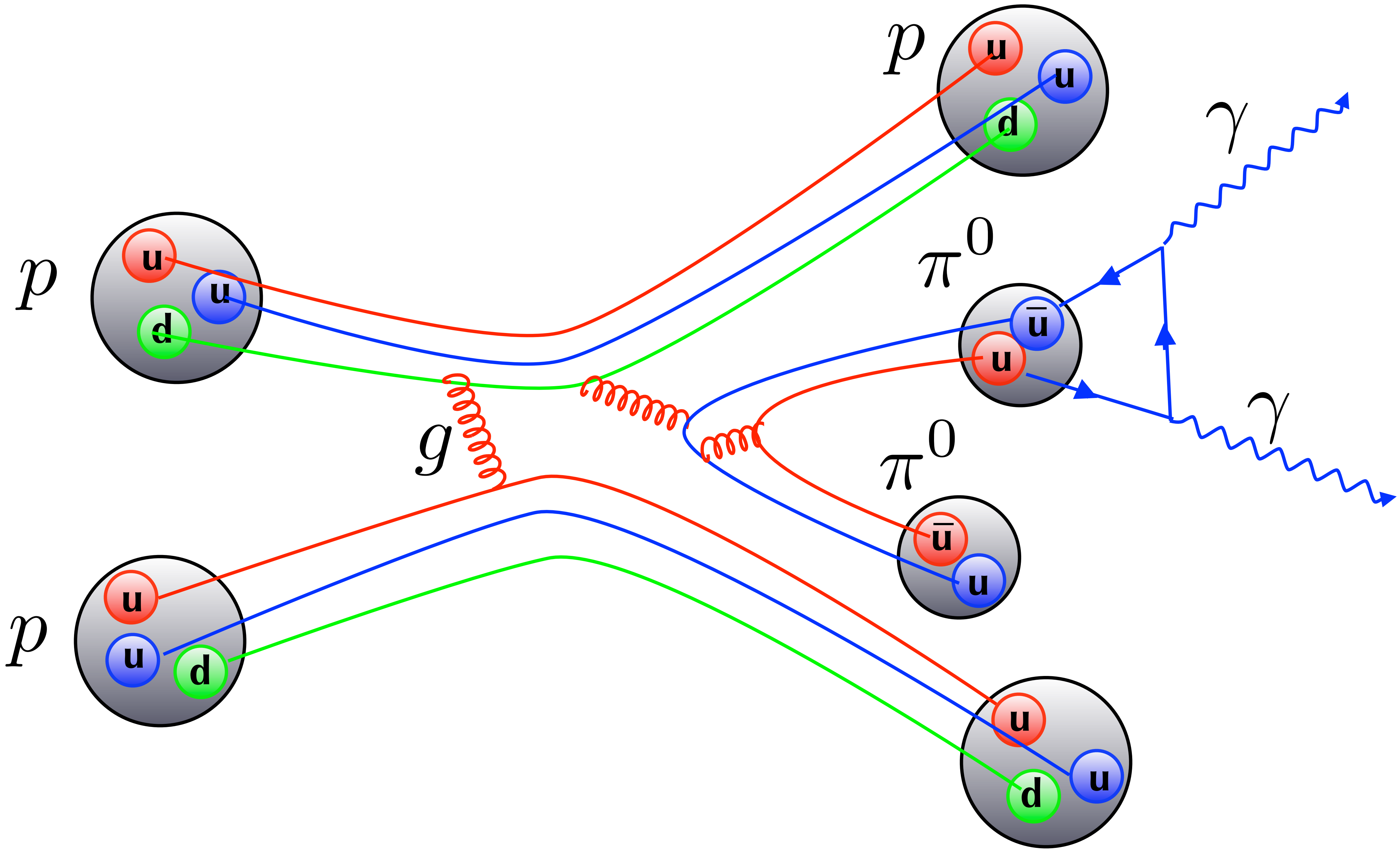

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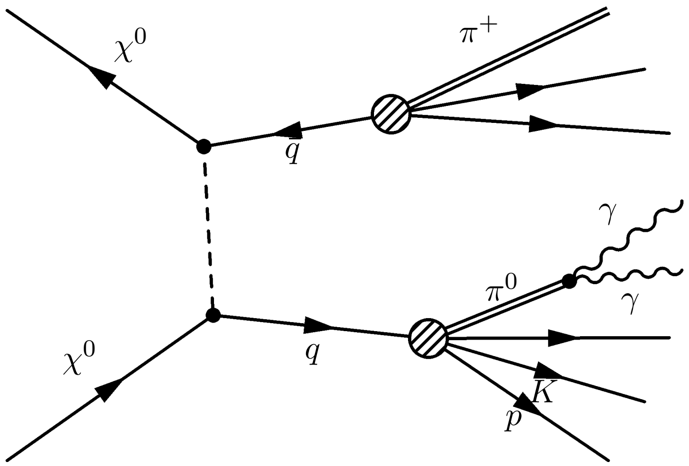
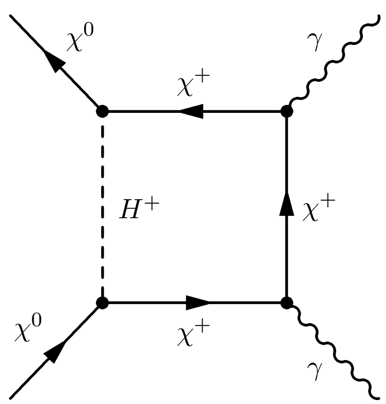
Annihilation Channels

Text

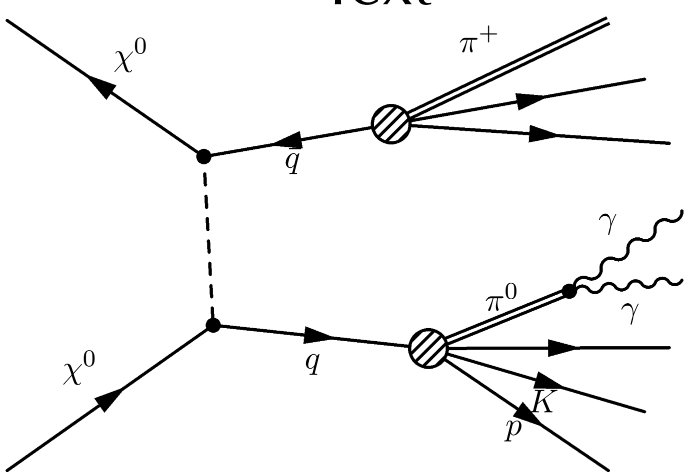


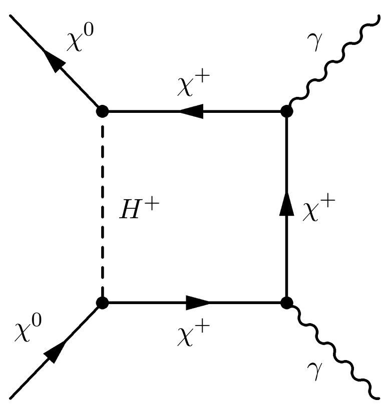


Annihilation Channel	Secondary Processes	Signals	Notes
$\chi\chi \to q\bar{q},\ gg$	$p, \bar{p}, \pi^{\pm}, \pi^0$	p, e, ν, γ	
$\chi\chi \to W^+W^-$	$W^{\pm} \to l^{\pm}\nu_l,\ W^{\pm} \to u\bar{d} \to \pi^{\pm},\ \pi^0$	p, e, ν, γ	
$\chi\chi \to Z^0Z^0$	$Z^0 \to l\bar{l},\ \nu\bar{\nu},\ q\bar{q} \to$ pions	p, e, γ, ν	
$\chi\chi \to \tau^{\pm}$	$\tau^{\pm} \to \nu_\tau e^{\pm}\nu_e,\ \tau \to \nu_\tau W^{\pm} \to p, \bar{p},$ pions	p, e, γ, ν	
$\chi\chi \to \mu^+\mu^-$		e, γ	Rapid energy loss of μs in sun before decay results in sub-threshold νs
$\chi\chi \to \gamma\gamma$ $\chi\chi \to Z^0\gamma$	 Z^0 decay	γ γ	Loop suppressed Loop suppressed
$\chi\chi \to e^+e^-$		e, γ	Helicity suppressed
$\chi\chi \to \nu\bar{\nu}$		ν	Helicity suppressed (important for non-Majorana WIMPs?)
$\chi\chi \to \phi\bar{\phi}$	$\phi \to e^+e^-$	$e^{\pm}$	New scalar field with $m_\chi < m_q$ to explain large electron signal and avoid overproduction of p, γ

Annihilation Channels

Text



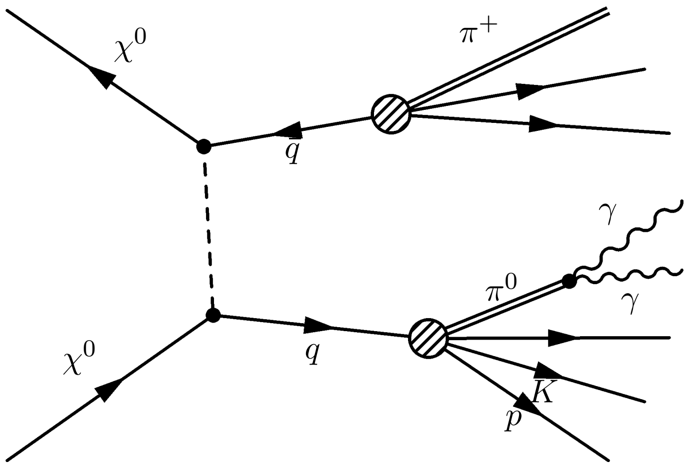


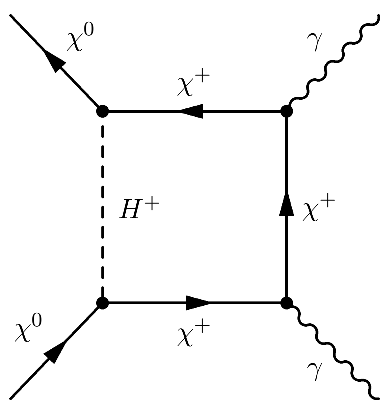
Annihilation Channel	Secondary Processes	Signals	Notes
$\chi\chi \to q\bar{q},\ gg$	$p, \bar{p}, \pi^{\pm}, \pi^0$	p, e, ν, γ	
$\chi\chi \to W^+W^-$	$W^{\pm} \to l^{\pm}\nu_l,\ W^{\pm} \to u\bar{d} \to \pi^{\pm},\ \pi^0$	p, e, ν, γ	
$\chi\chi \to Z^0Z^0$	$Z^0 \to l\bar{l},\ \nu\bar{\nu},\ q\bar{q} \to$ pions	p, e, γ, ν	
$\chi\chi \to \tau^{\pm}$	$\tau^{\pm} \to \nu_\tau e^{\pm}\nu_e,\ \tau \to \nu_\tau W^{\pm} \to p, \bar{p}$, pions	p, e, γ, ν	
$\chi\chi \to \mu^+\mu^-$		e, γ	Rapid energy loss of μs in sun before decay results in sub-threshold νs
$\chi\chi \to \gamma\gamma$ $\chi\chi \to Z^0\gamma$	Z^0 decay	γ γ	Loop suppressed Loop suppressed
$\chi\chi \to e^+e^-$		e, γ	Helicity suppressed
$\chi\chi \to \nu\bar{\nu}$		ν	Helicity suppressed (important for non-Majorana WIMPs?)
$\chi\chi \to \phi\bar{\phi}$	$\phi \to e^+e^-$	$e^{\pm}$	New scalar field with $m_\chi < m_q$ to explain large electron signal and avoid overproduction of p, γ

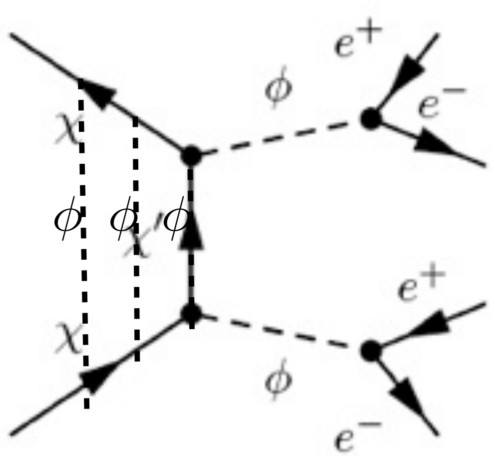
internal/final state bremms
inverse Compton γ's

Annihilation Channels

Text







Annihilation Channel	Secondary Processes	Signals	Notes
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$\chi\chi \to \tau^\pm$	$\tau^\pm \to \nu_\tau e^\pm \nu_e,\ \tau \to \nu_\tau W^\pm \to p, \bar{p}$, pions	p, e, γ, ν	
$\chi\chi \to \mu^+\mu^-$		e, γ	Rapid energy loss of μs in sun before decay results in sub-threshold νs
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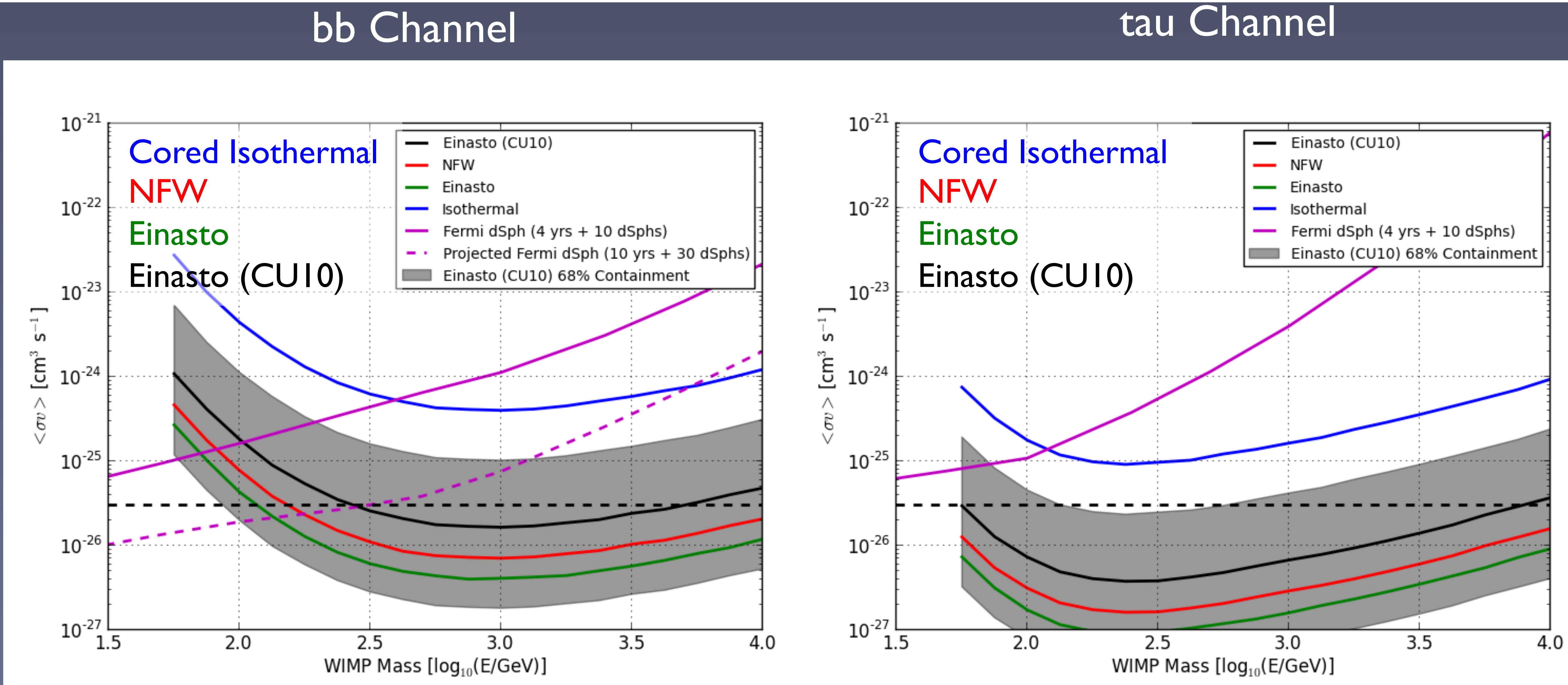
internal/final state bremms
inverse Compton γ's

Halo Uncertainties



500 hour exposure and 3 sigma detection threshold

Specifications

Parameter	Definition
Parameter \ OS Name	Schwarzschild-Couder (SC)
Schwarzschild aplanat q	2/3
Schwarzschild aplanat a	2/3
Focal Length (F) [m]	5.5863
Aperture [m]	9.6638
f/# [1]	f/0.5781
Primary Radius max [m]	4.8319
Primary Radius min [m]	2.1935
Secondary Radius max [m]	2.7081
Secondary Radius min [m]	0.3950
Effective light collecting area /unvignetted [m^2]	50.31
Unvignetted Size [deg]	3.50
Effective light collecting area at FOV edge [m^2]	47.73
Vignetting at the FOV edge [%]	-5.17
Primary projected area [m^2]	58.23
Secondary projected area [m^2]	22.55
Design FOV [deg]	8.00
Design FOV solid angle [deg^2]	50.35
Ideal PSF at the FOV edge (2MAX {RMS}) [arcmin]	3.81
M1 to M2 separation [m]	3/2 * F
M2 to camera separation [m]	1/3 * F
Shadowing by the OSS	Less than 12%
Vignetting by the OSS	TBD

Table 1. Main parameters of the SCT OS designed to provide 8 degree FoV.

Parameter	Definition
Parameter \ OS Name	Schwarzschild-Couder (SC)
FOV [deg]	8.00
FOV solid angle [deg^2]	50.35
Camera FP diameter [m]	0.78
FP plate scale [mm/arcmin]	1.625
FP plate scale [microns/arcsec]	27.083
FP figure	Parabolic
FP sag at the FoV edge [mm]	-22.00
Characteristic photon incidence angle [deg]	51.25
FP figure constants	See [4]
FP distortion constants	See [4]

Table 2. Main parameters of the SCT OS focal plane