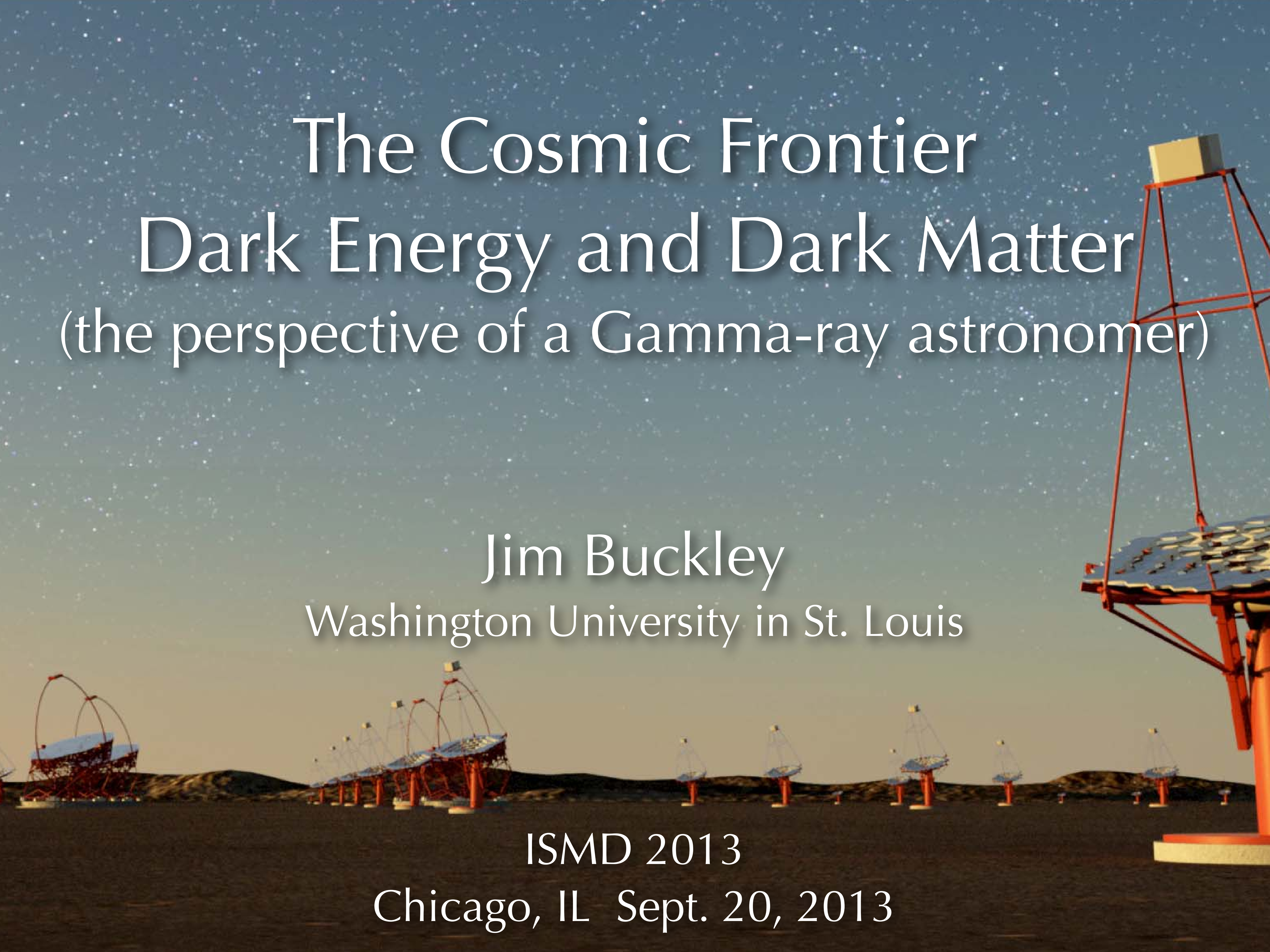
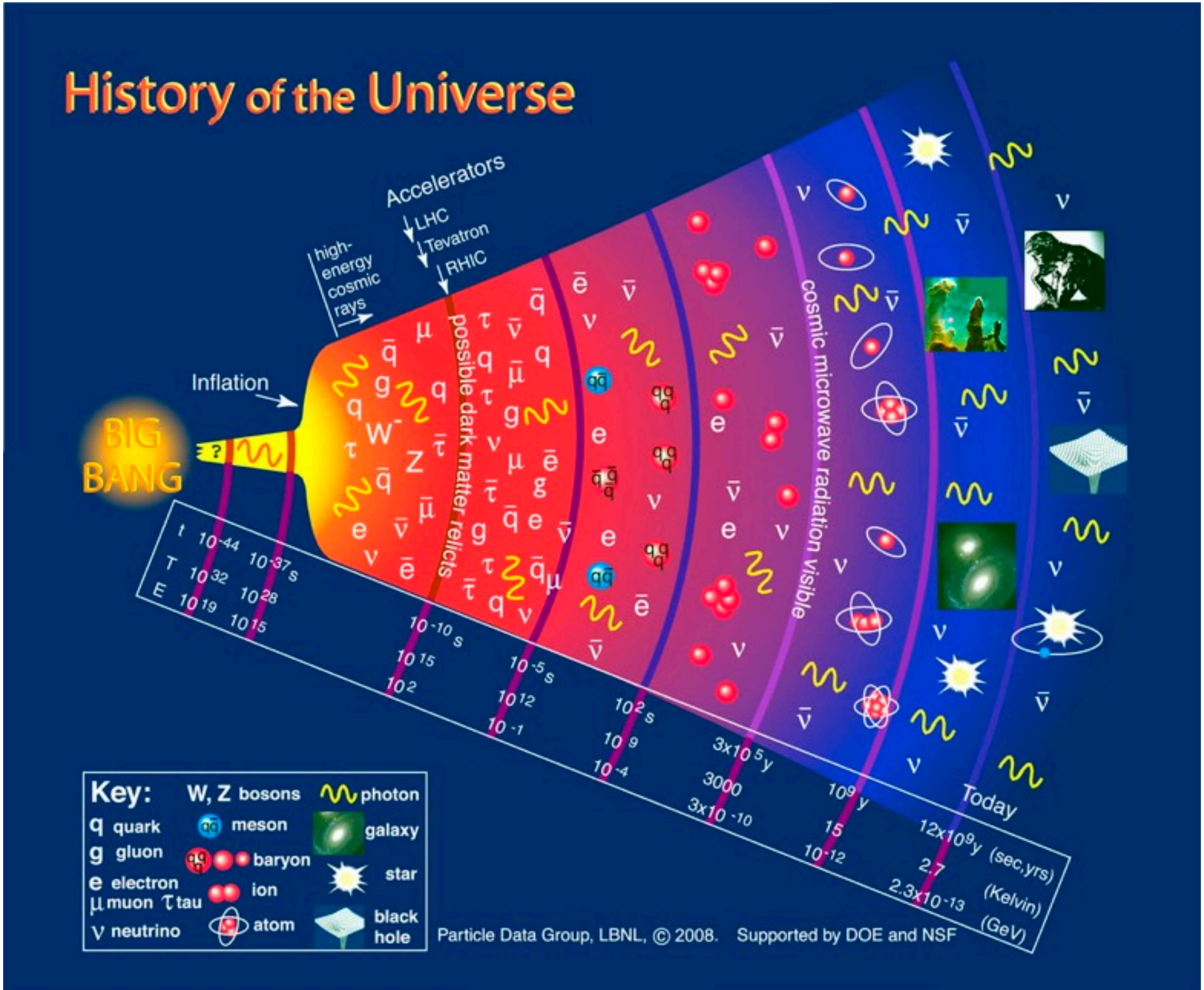
The Cosmic Frontier
Dark Energy and Dark Matter
(the perspective of a Gamma-ray astronomer)

Jim Buckley
Washington University in St. Louis



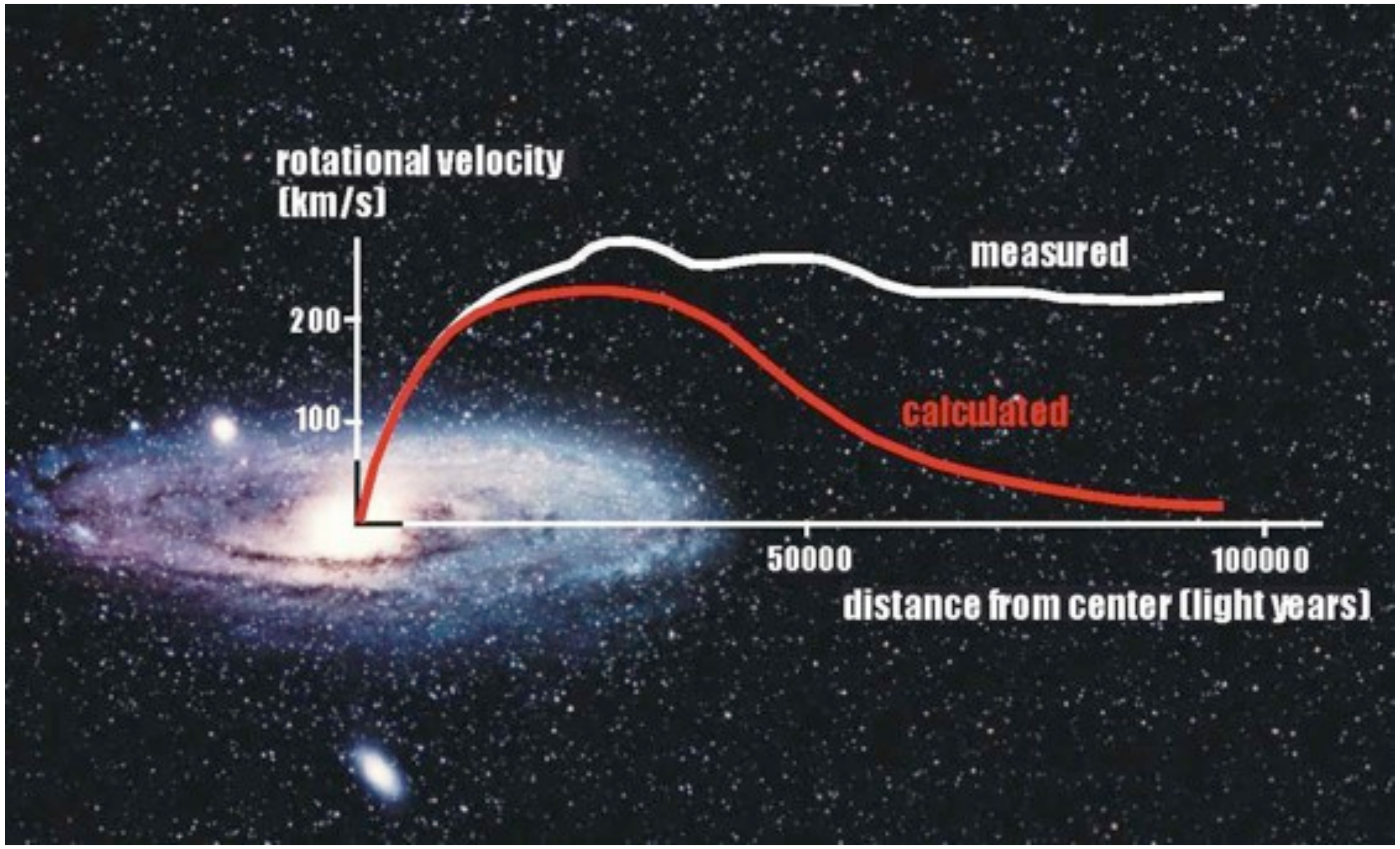
ISMD 2013
Chicago, IL Sept. 20, 2013

Cosmology



History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
µ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008.
Supported by DOE and NSF

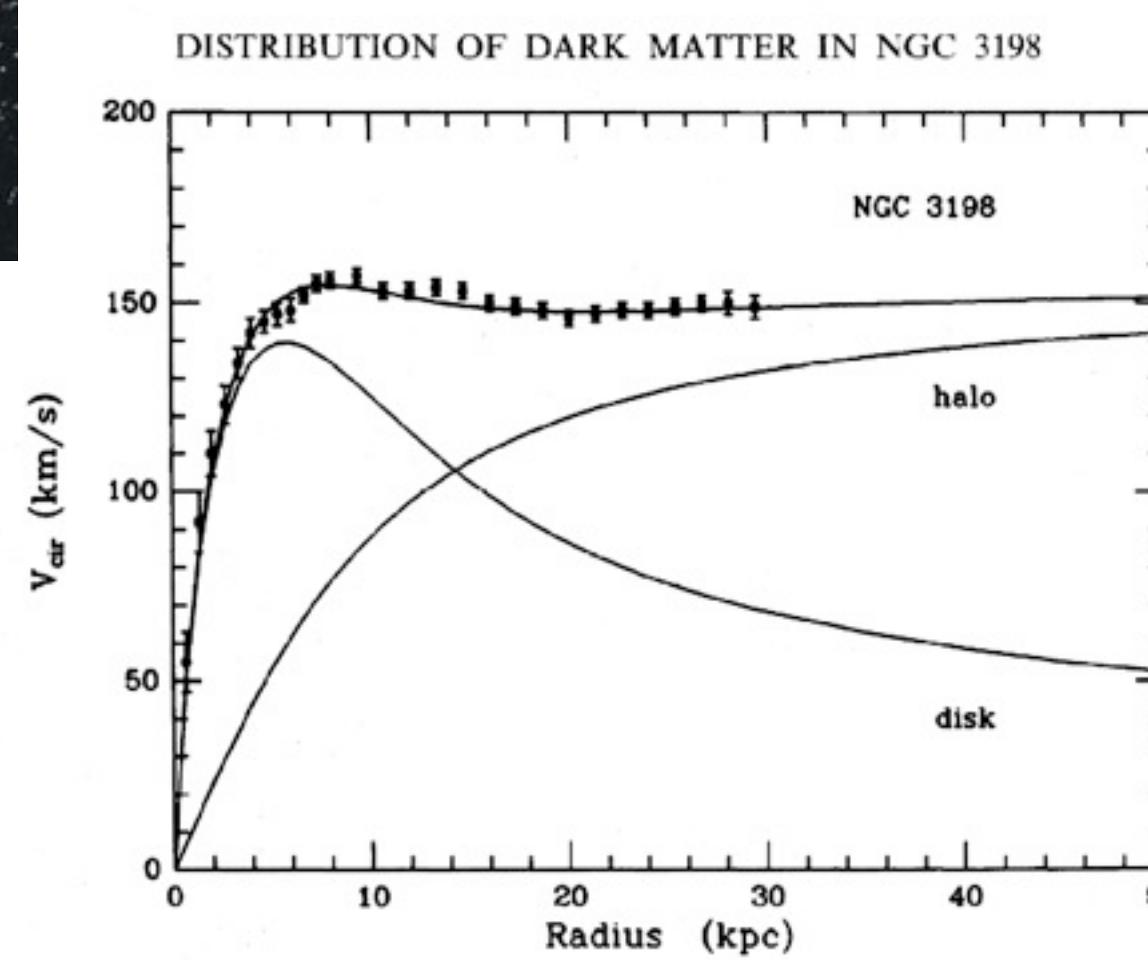
Evidence for Dark Matter



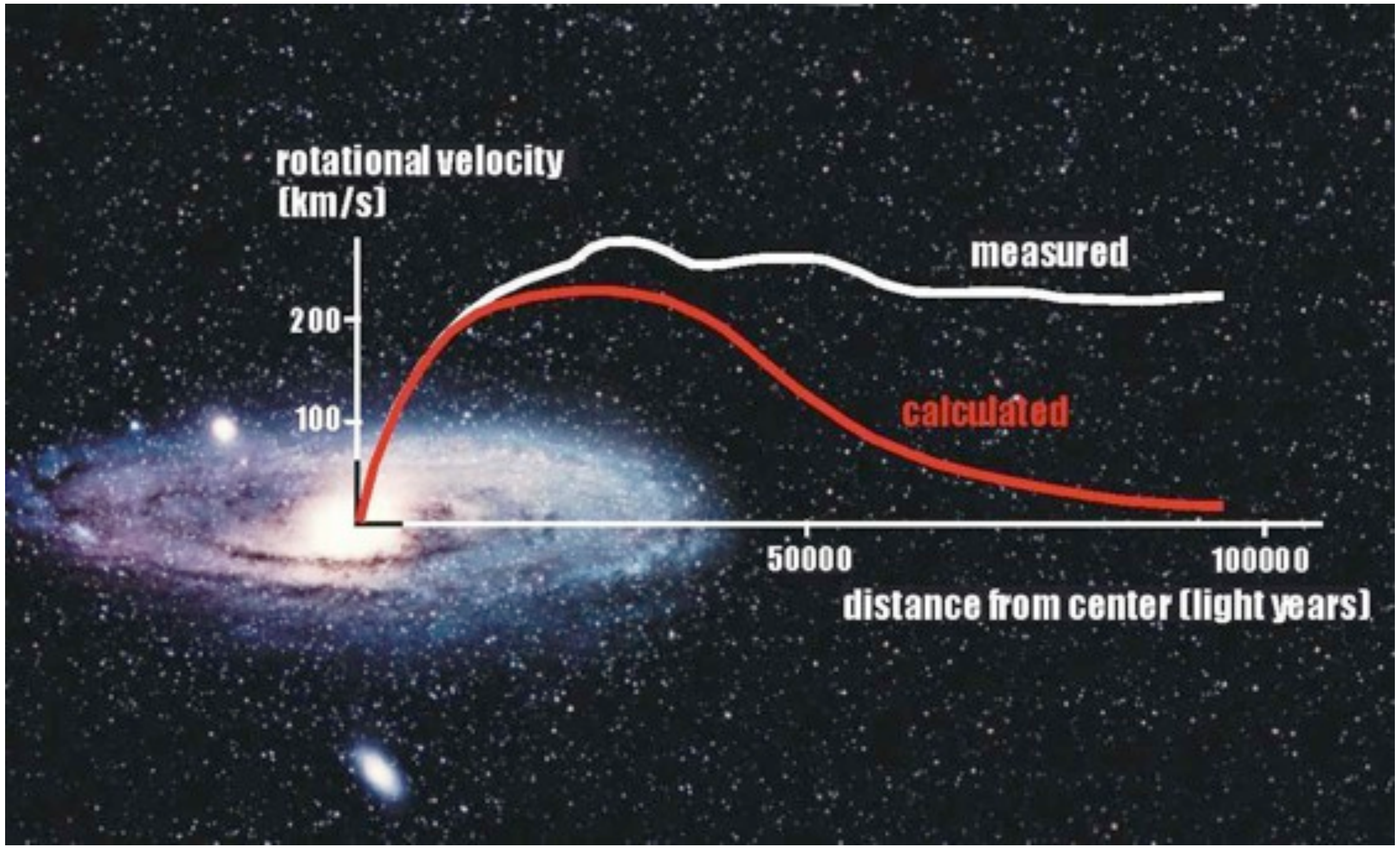
Beyond the stars, the enclosed mass M should be roughly constant

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

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



Evidence for Dark Matter



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

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

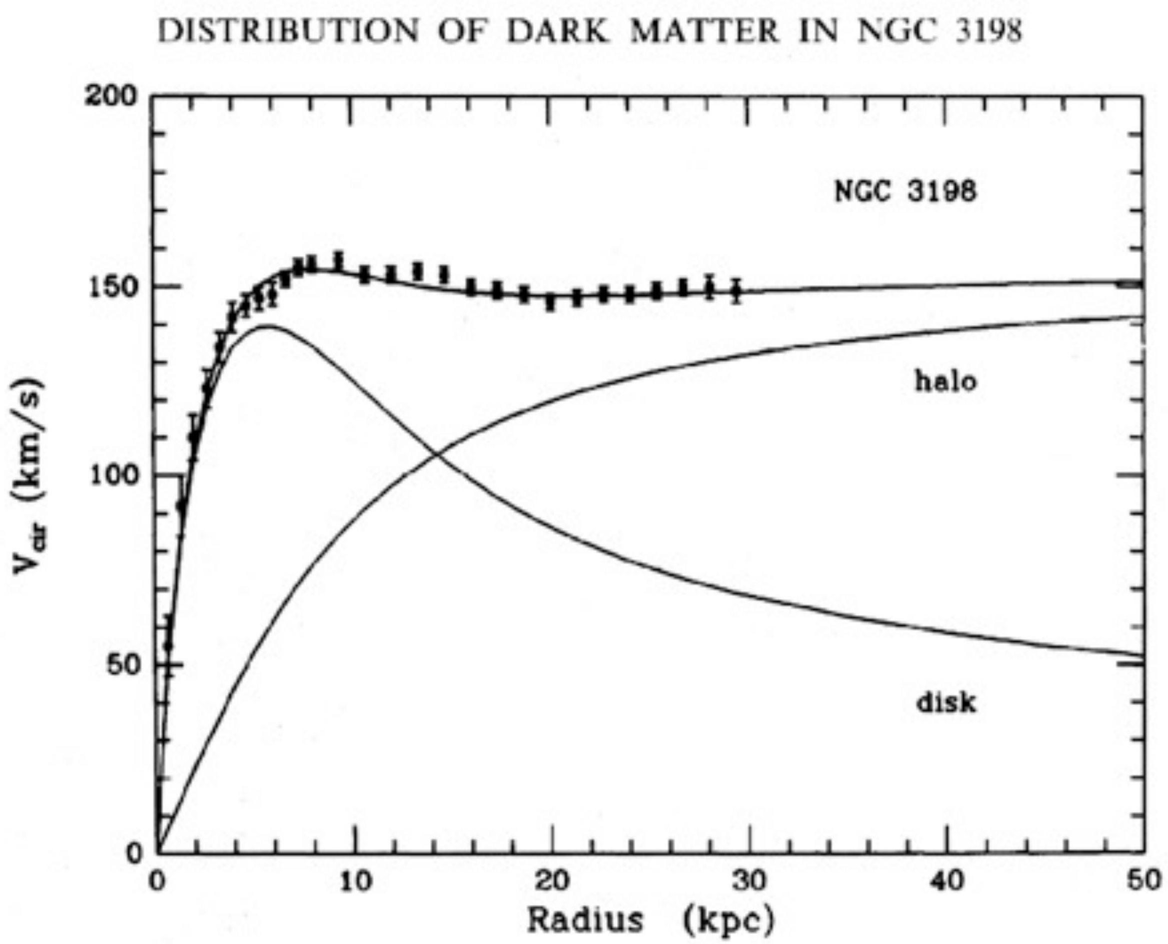
$v \sim \text{constant} \Rightarrow$

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

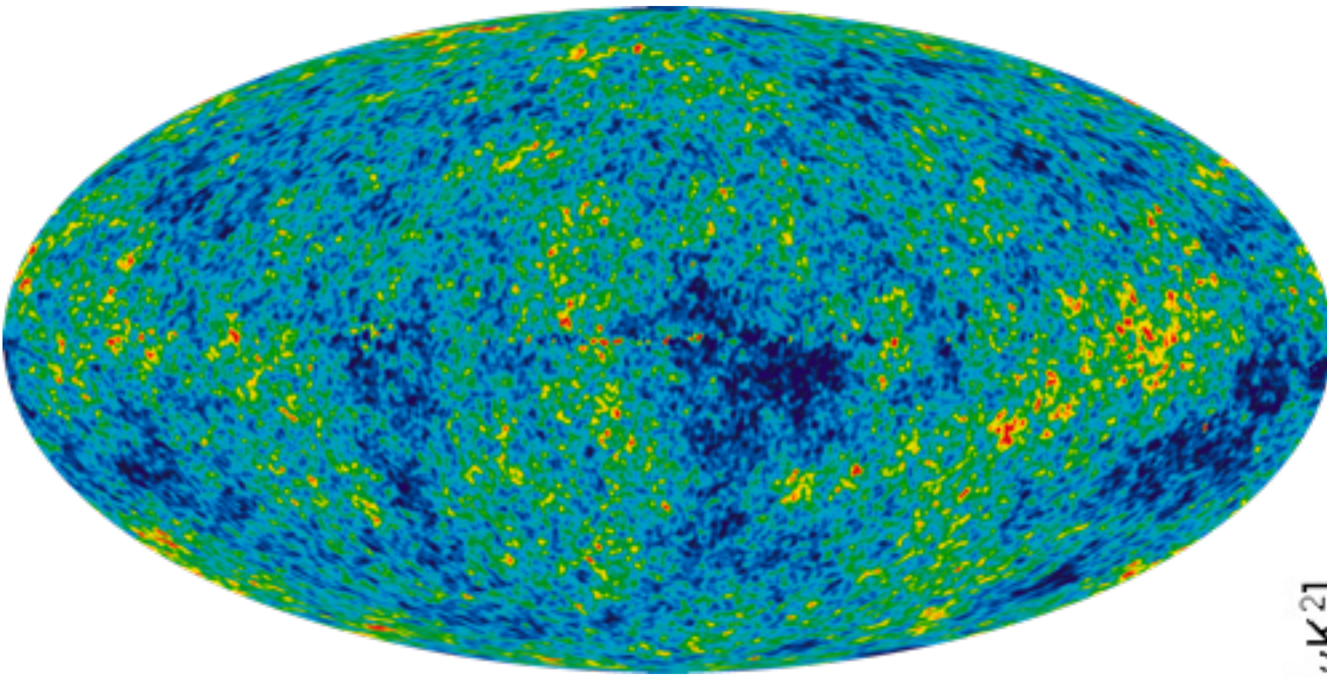
Beyond the stars, the enclosed mass M should be roughly constant

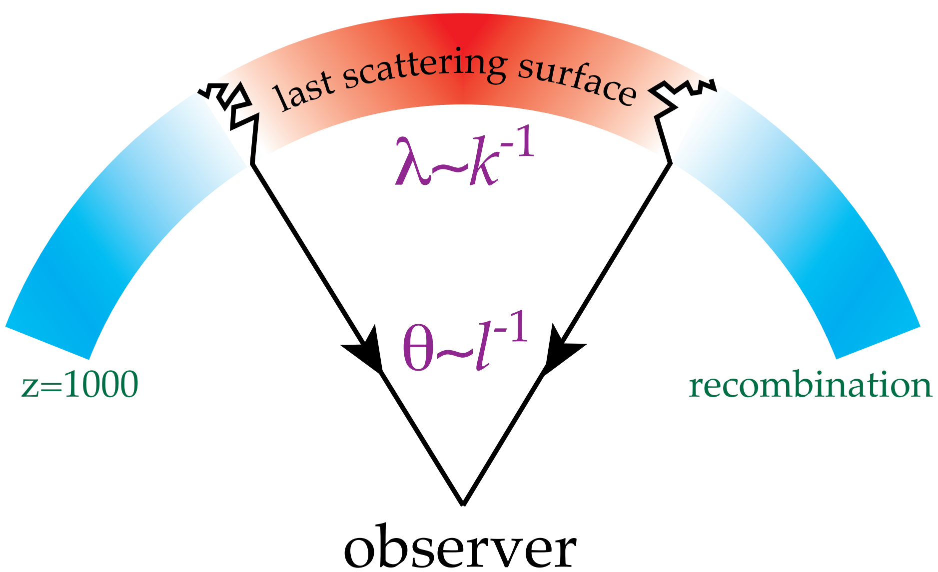
$$\frac{mv^2}{r} = \frac{GmM}{r^2}$$

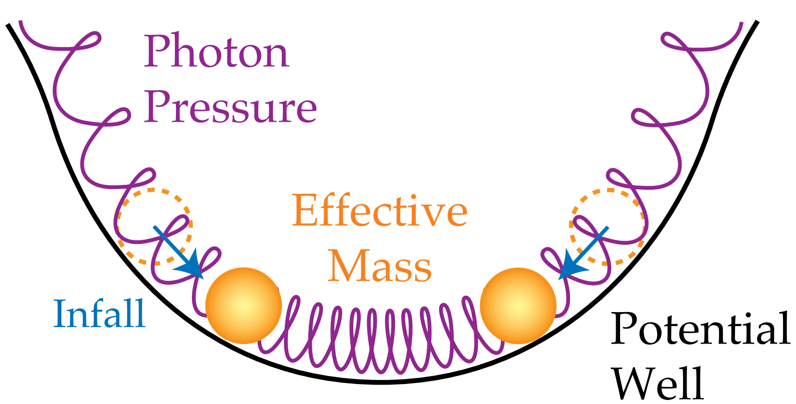
$$v \sim r^{-1/2}$$

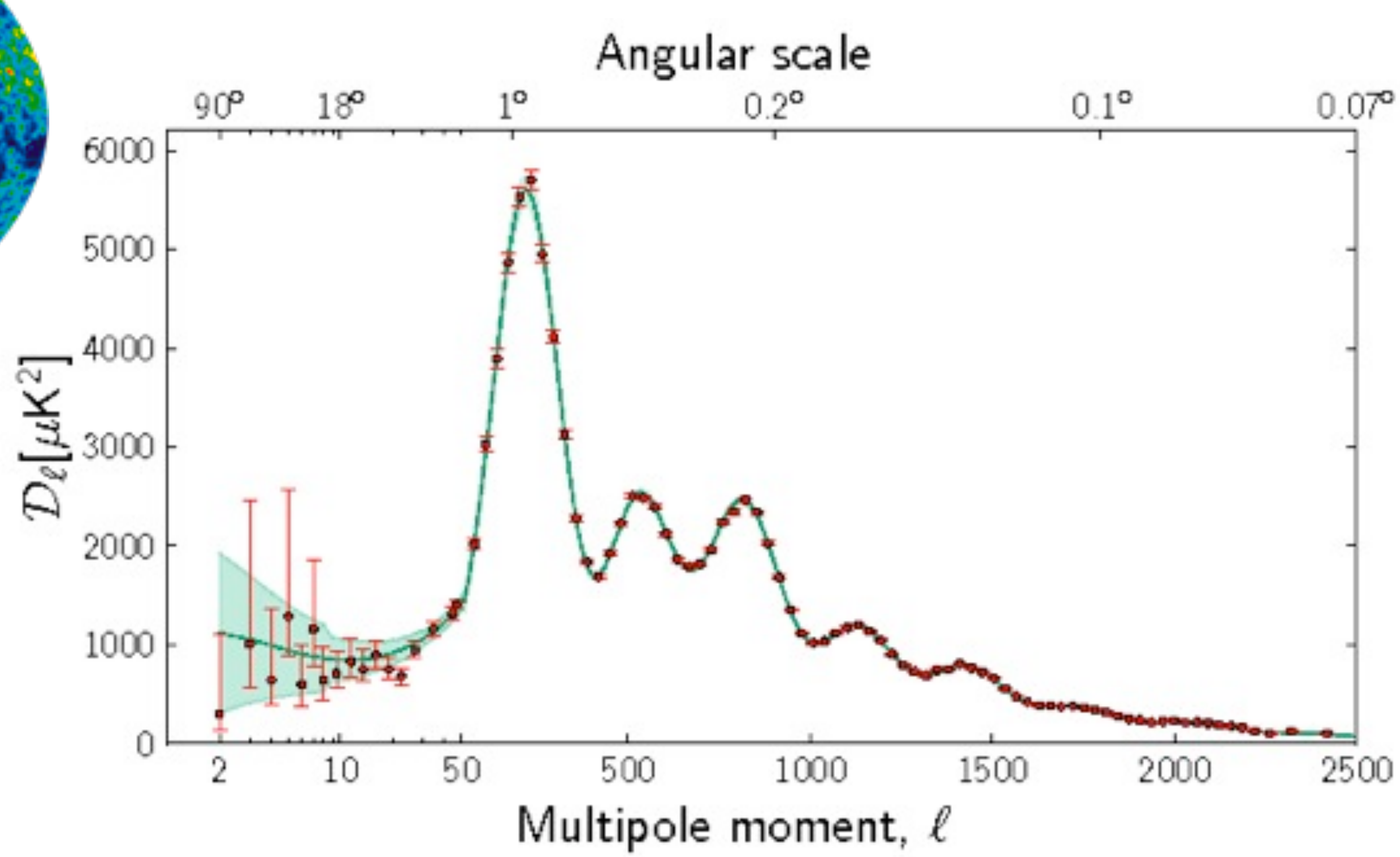


CMB



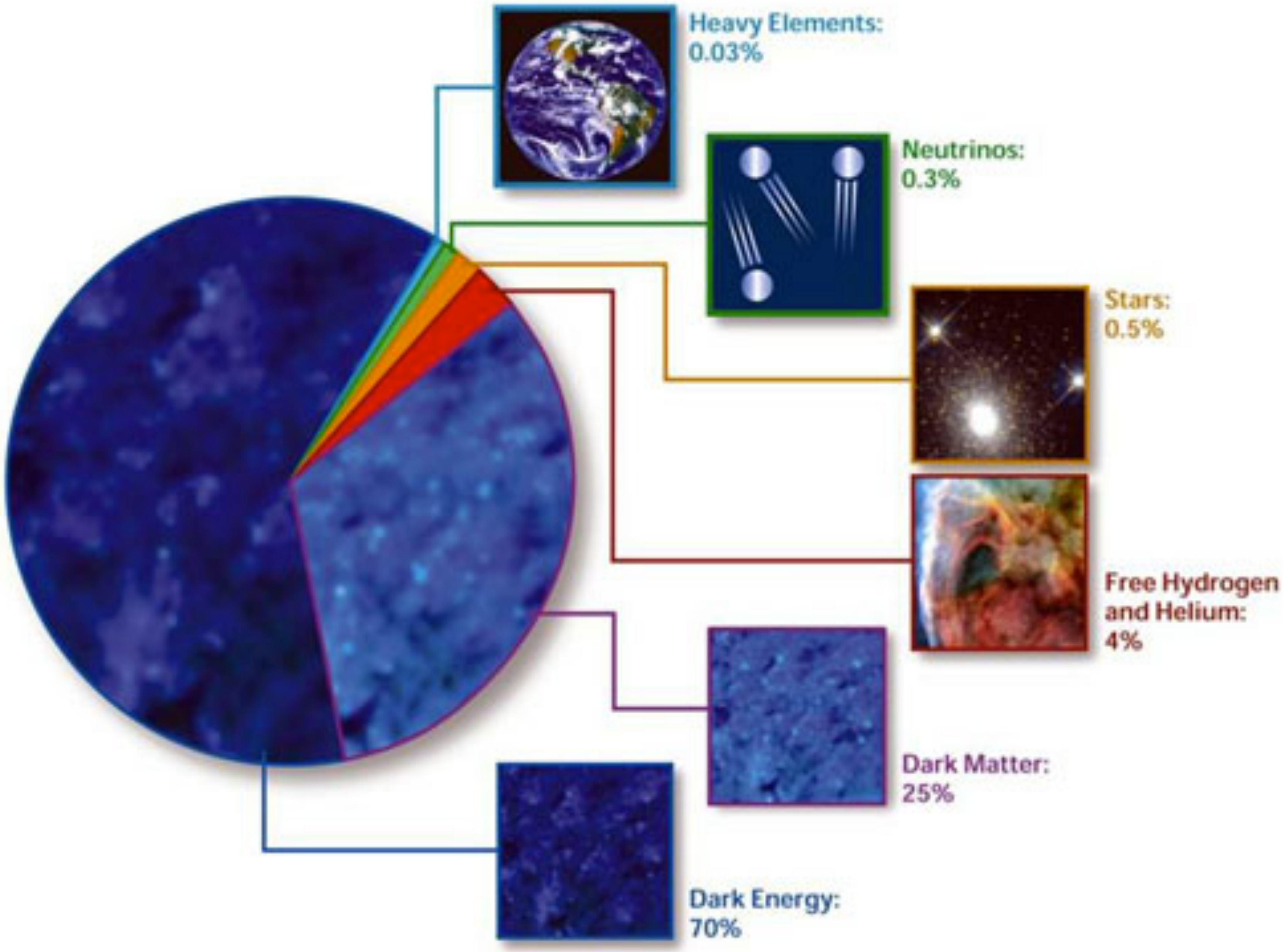






- Power spectrum of the CMB reveals curvature of the universe from the size of the Horizon at decoupling (**Ω**=1)
- Acoustic peaks give ratio of total gravitating mass to pressure (provided by radiation acting on baryonic matter)

The Cosmic Frontier

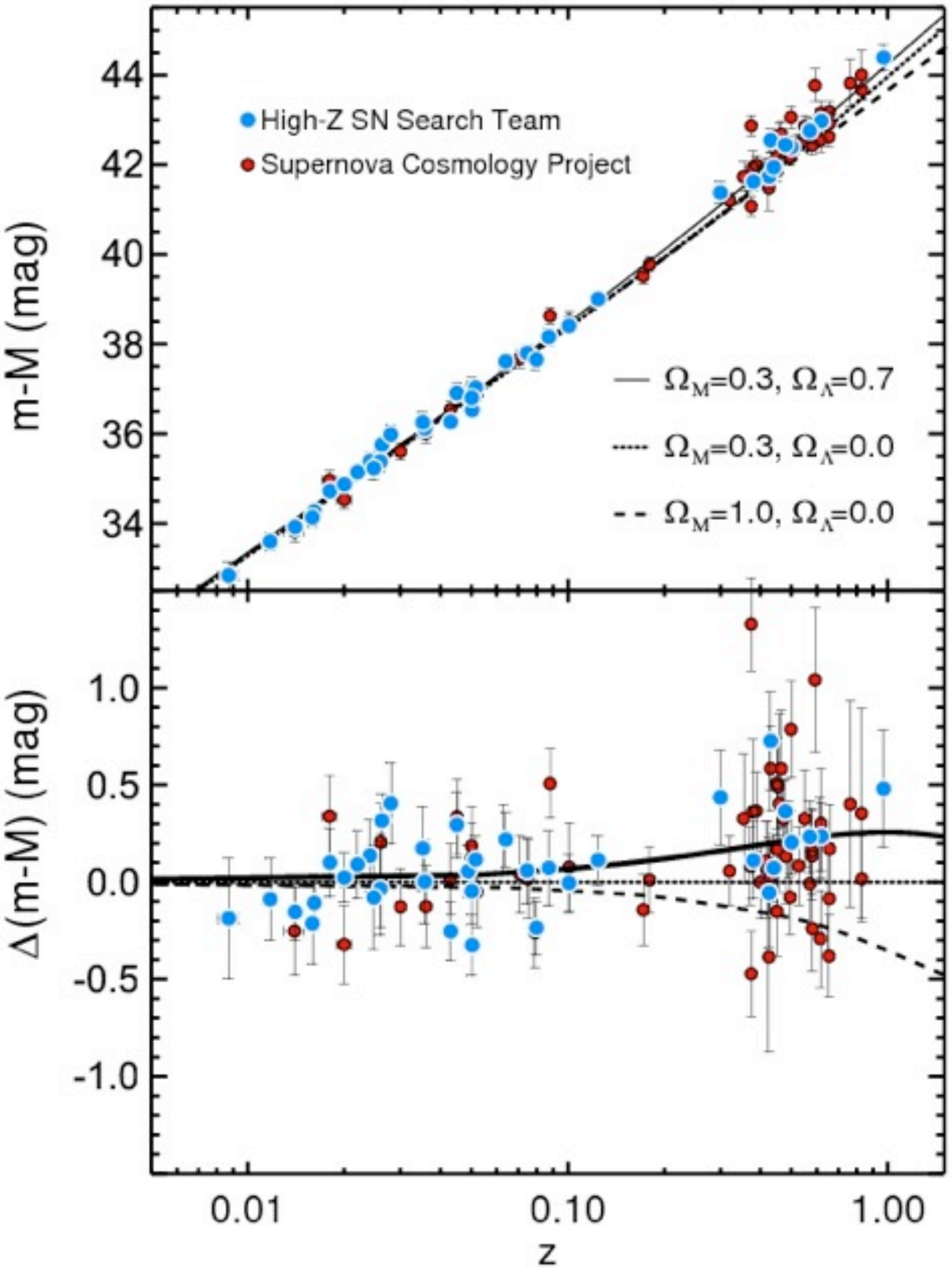


- Cosmic Frontier Experiments are largely focused on two big questions: what is the nature of the *Dark Energy* and *Dark Matter* (the majority of our universe).
- With the embarrassing agreement of experiments (LHC) with the Standard Model of particle physics, best evidence for new particles and fields comes from the Cosmos!

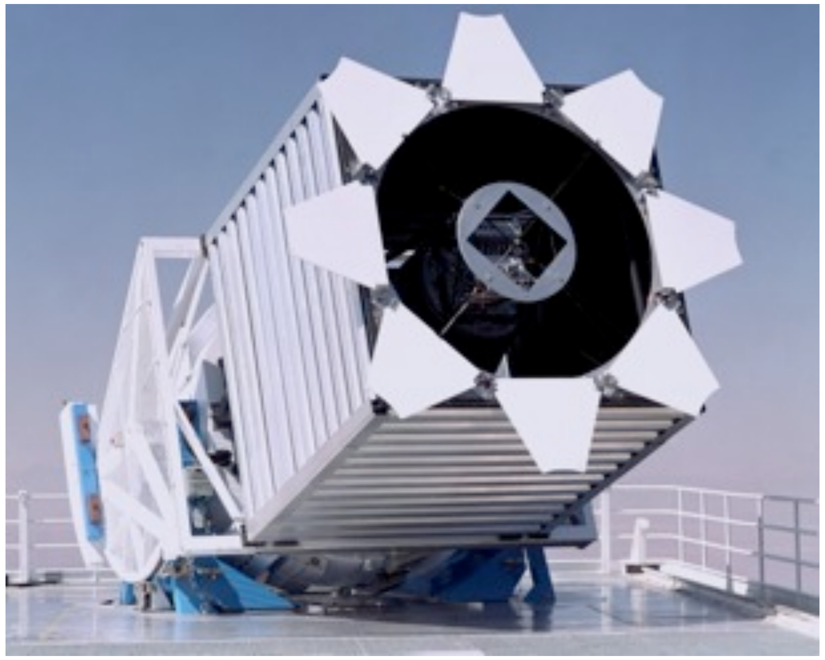
Part 1: Dark Energy Experiments

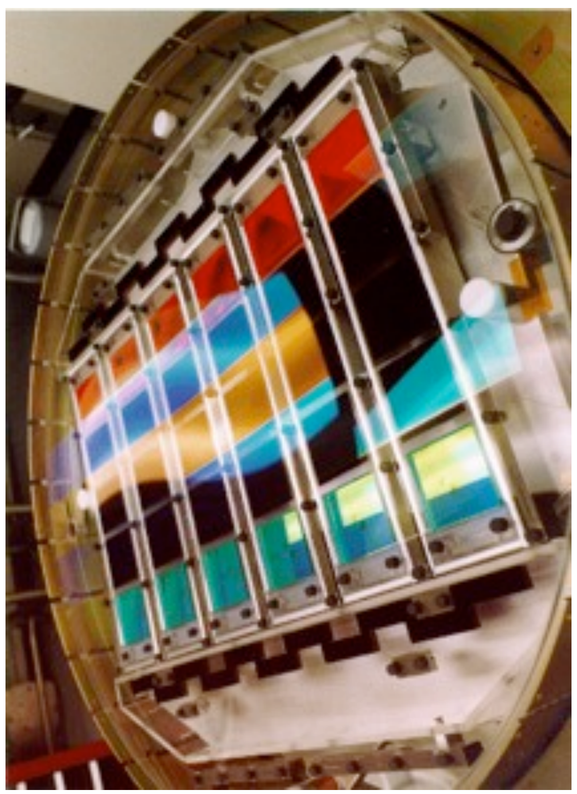
Hubble Diagram

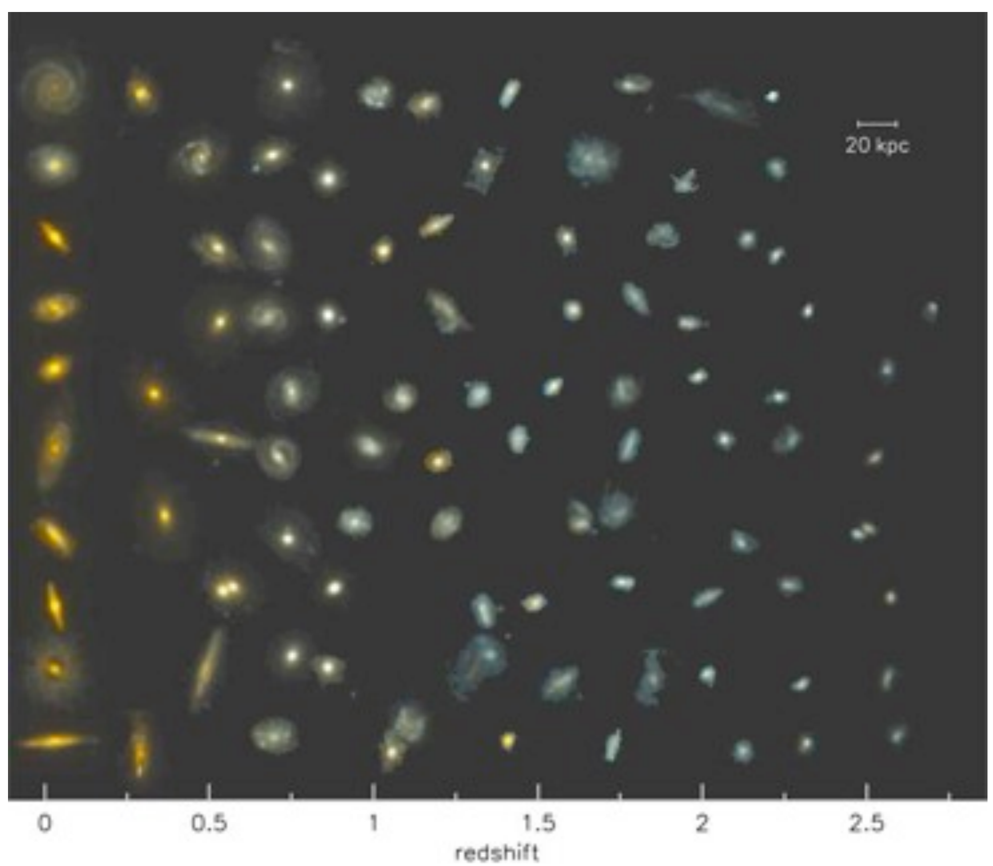
- The modern Hubble diagram not only show that the universe is expanding, but that the rate of expansion is *increasing*, something self gravity should not do!



Wide-Field Optical Telescopes



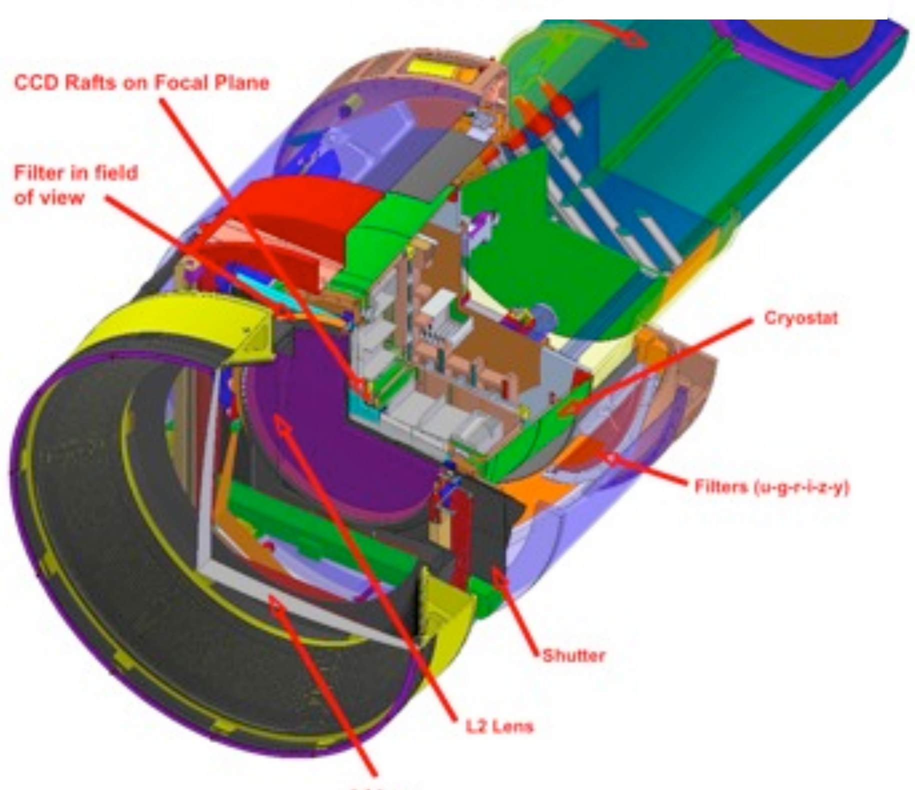


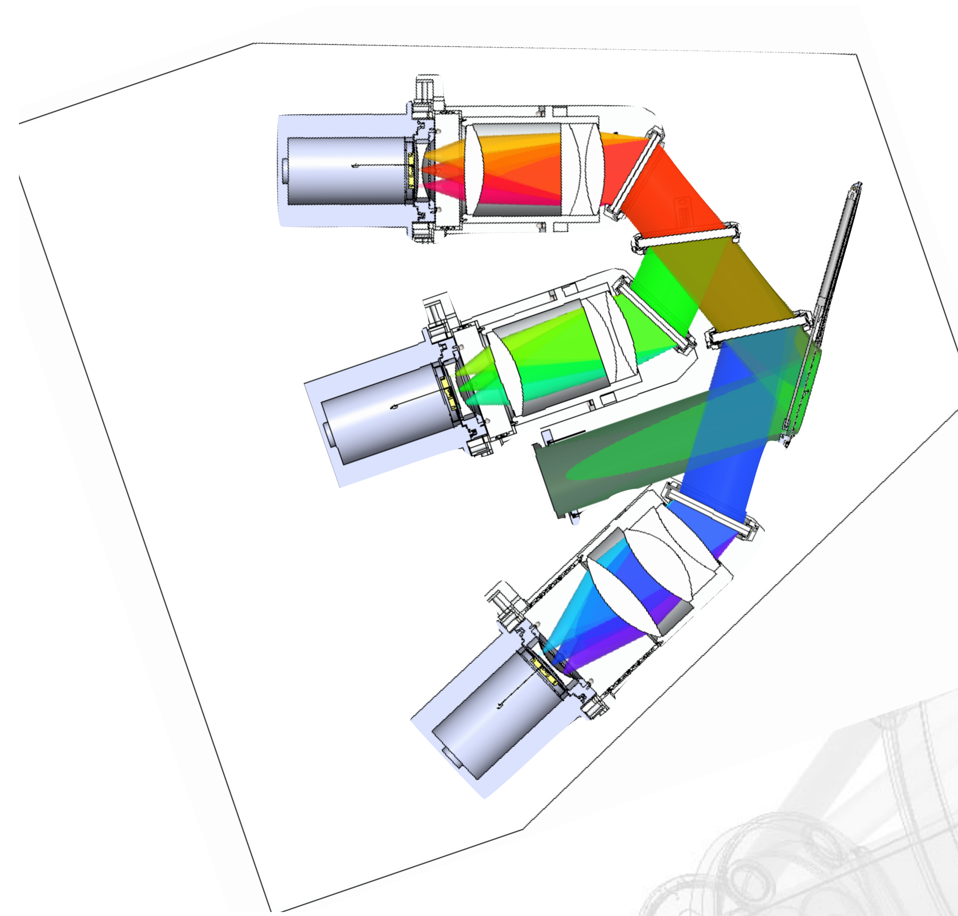


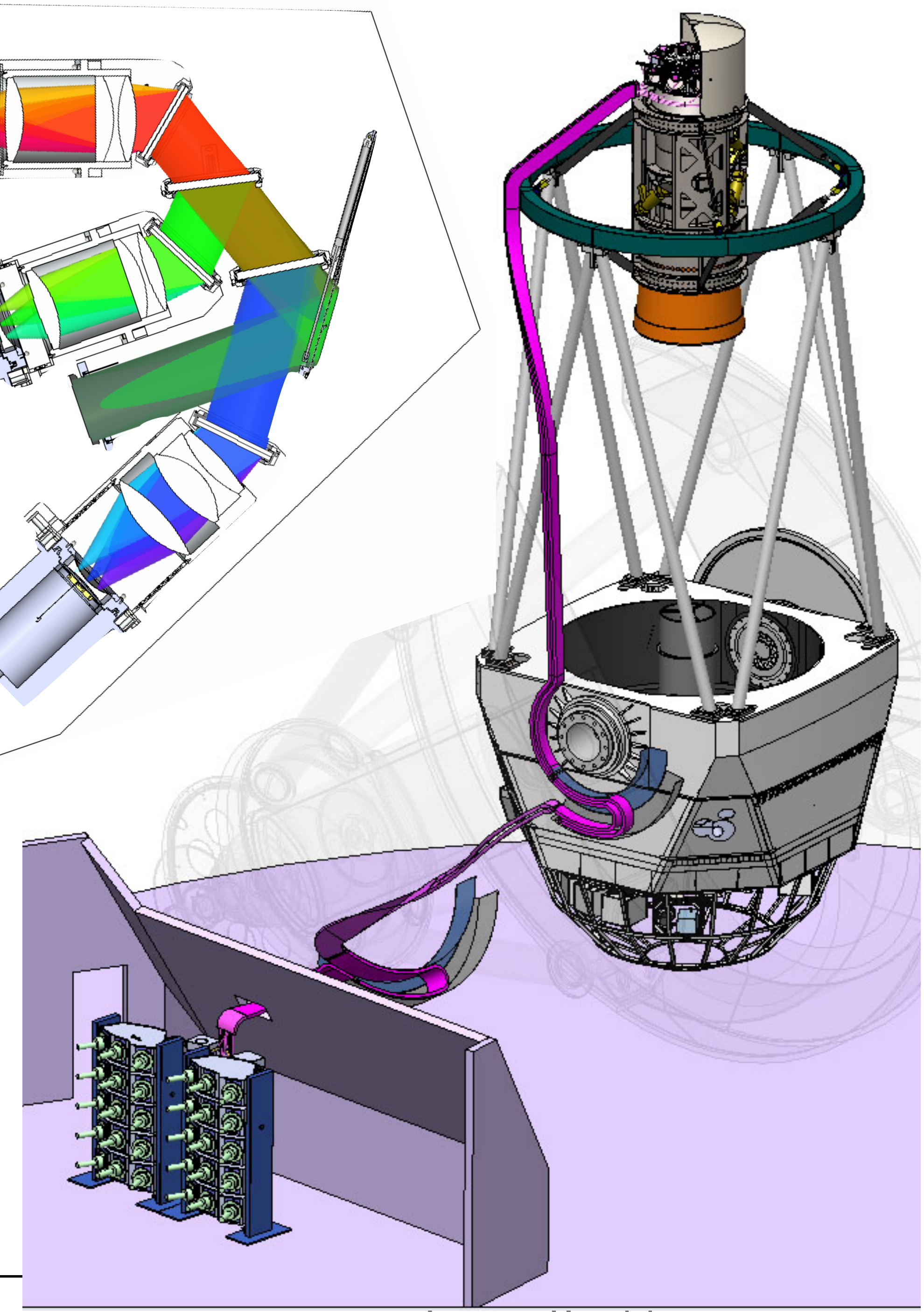
- **Sloan** has provided an incredible wealth of data on galaxies (930,000 galaxies and 120,000 quasars) and valuable information about galaxy structure and evolution, cosmology and (for us gamma-ray astronomers) a bunch of new DM dominated dwarf galaxies.

Dark Energy Experiments

- **LSST:** an 8.4m telescope with a 3.5deg FoV and 3.2 Gigapixel camera will cover whole sky 8 times. Will do Dark Energy (SNae, BAO), Dark Matter (microlensing) science + lots of astronomy.
- **MS_DESI:** 4m Mayall telescope on Kitt Peak, 3deg FoV, 5000 robotic fibers fed to high resolution spectrometers for third dimension (redshift) in large scale structure surveys.







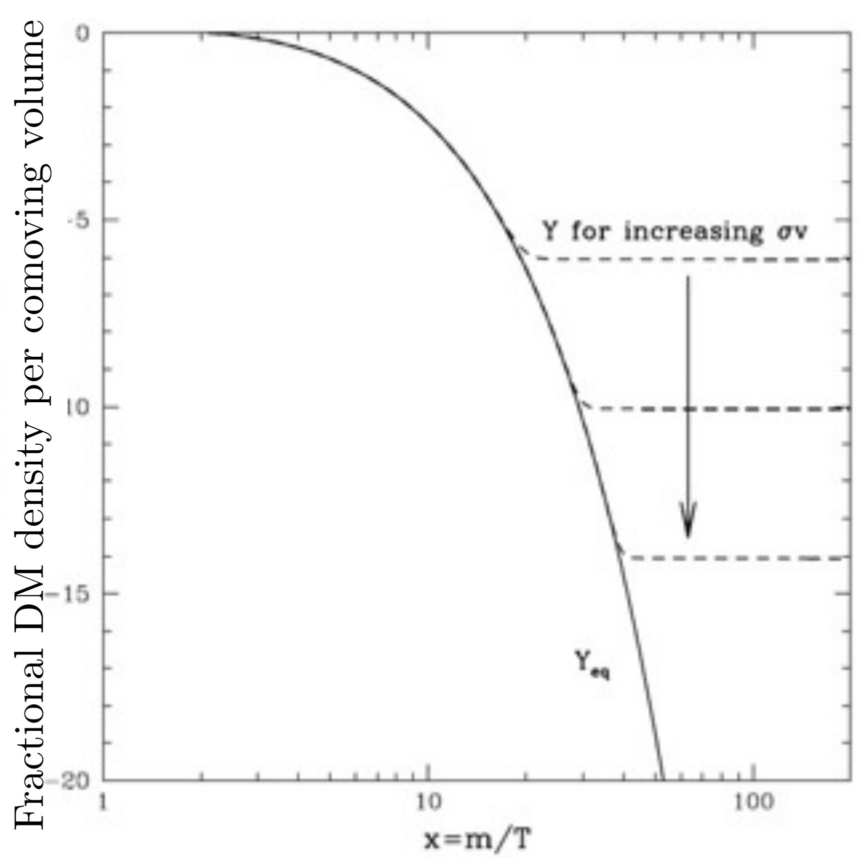
Part 2: Dark Matter Experiments: Direct and Indirect Detection

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



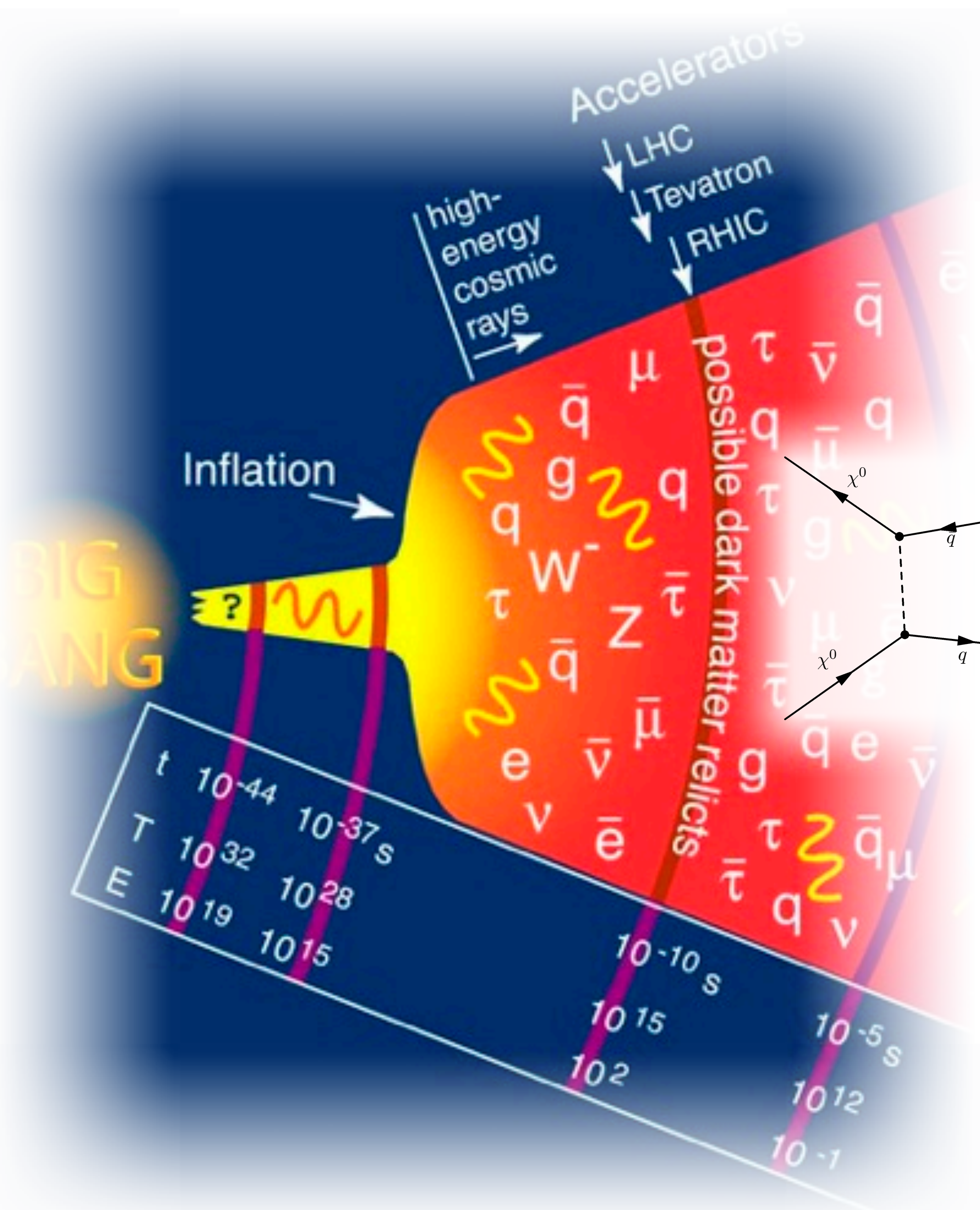
For a thermal relic of the big bang, the larger the annihilation cross section the longer the DM stays in equilibrium and the larger the Boltzmann suppression $\sim e^{-m_\chi/kT}$ before freeze-out.

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

Indirect Detection Cross Section

DM relic abundance : $\Omega_\chi \approx \frac{0.1}{h^2}\left(\frac{3\times10^{-26}\mathrm{cm^3sec^{-1}}}{\langle\sigma v\rangle}\right)$

Annihilation Channel	Secondary Processes	Signals
$\chi\chi \rightarrow q\bar{q},\ gg$	$p, \bar{p}, \pi^\pm, \pi^0$	p, e, ν, γ
$\chi\chi \rightarrow W^+W^-$	$W^\pm \rightarrow l^\pm\nu_l,\ W^\pm \rightarrow u\bar{d} \rightarrow \pi^\pm,\ \pi^0$	p, e, ν, γ
$\chi\chi \rightarrow Z^0Z^0$	$Z^0 \rightarrow l\bar{l},\ \nu\bar{\nu},\ q\bar{q} \rightarrow$ pions	p, e, γ, ν
$\chi\chi \rightarrow \tau^\pm$	$\tau^\pm \rightarrow \nu_\tau e^\pm\nu_e,\ \tau \rightarrow \nu_\tau W^\pm \rightarrow p, \bar{p}$, pions	
$\chi\chi \rightarrow \mu^+\mu^-$		e, γ
$\chi\chi \rightarrow \gamma\gamma$		γ
$\chi\chi \rightarrow Z^0\gamma$	Z^0 decay	γ
$\chi\chi \rightarrow e^+e^-$		e, γ

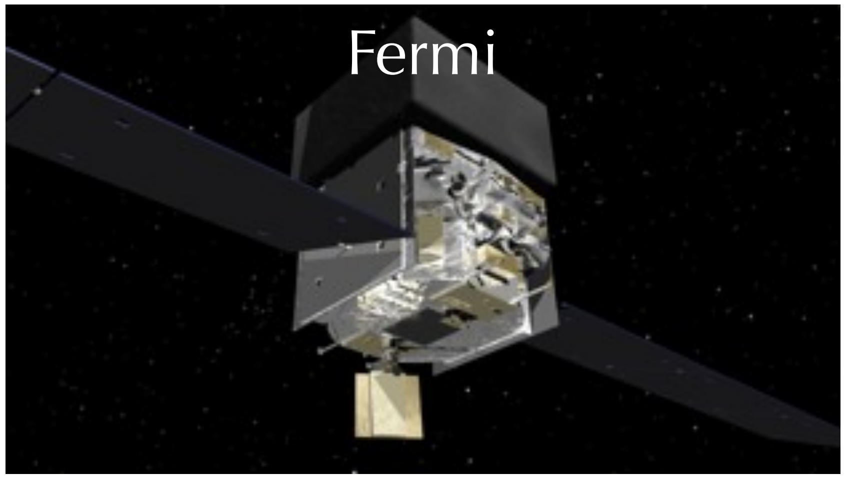


- The same interactions of WIMPs with standard model particles in the early universe imply interactions in the current universe.

- While the cross-section for a specific interaction (e.g., scattering off a nucleon) or annihilation channel is indirectly related to this decoupling cross section, *almost all annihilation channels produce photons and the total annihilation rate to photons* $\sim n_\chi^2\langle\sigma v\rangle$ *is closely related to the decoupling cross section:*

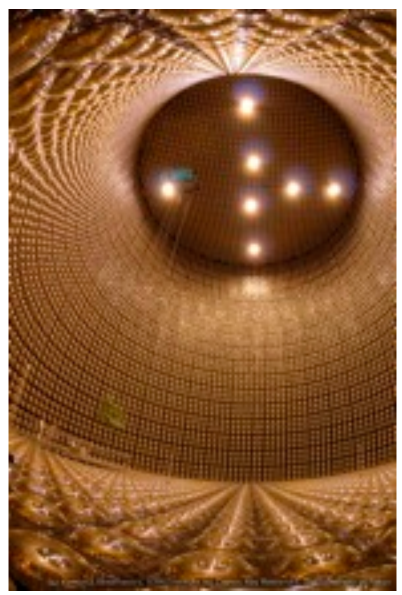
** Gamma-ray production by annihilation in the present universe is closely related to the decoupling cross section in the early universe with a natural scale* $\langle\sigma v\rangle \approx 3\times10^{-26}\mathrm{cm^3sec^{-1}}$

Indirect Detection

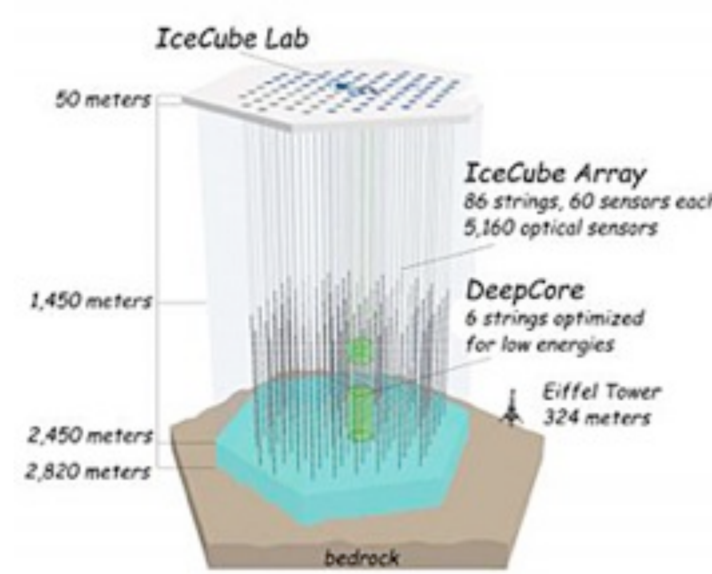


γ

Super-K

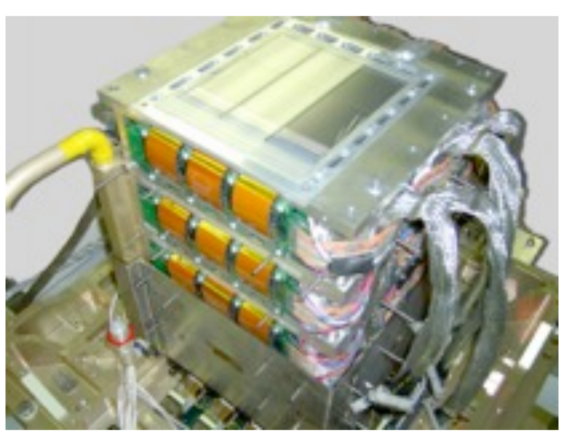


ν



ICECUBE

PAMELA



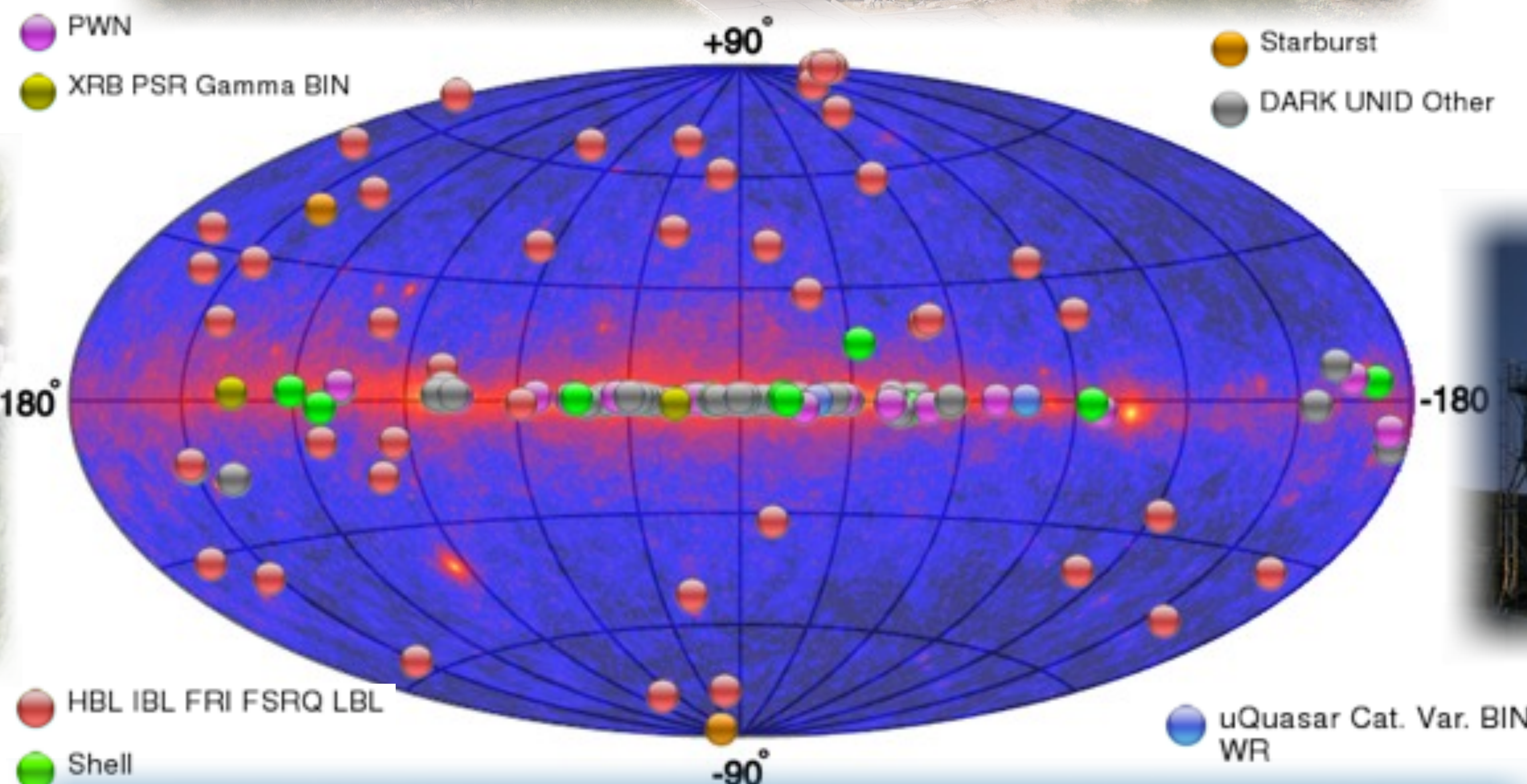
$e^-, e^+, p, \bar{p}$

AMS

VHE Gamma-Ray Status

VERITAS

MILAGRO

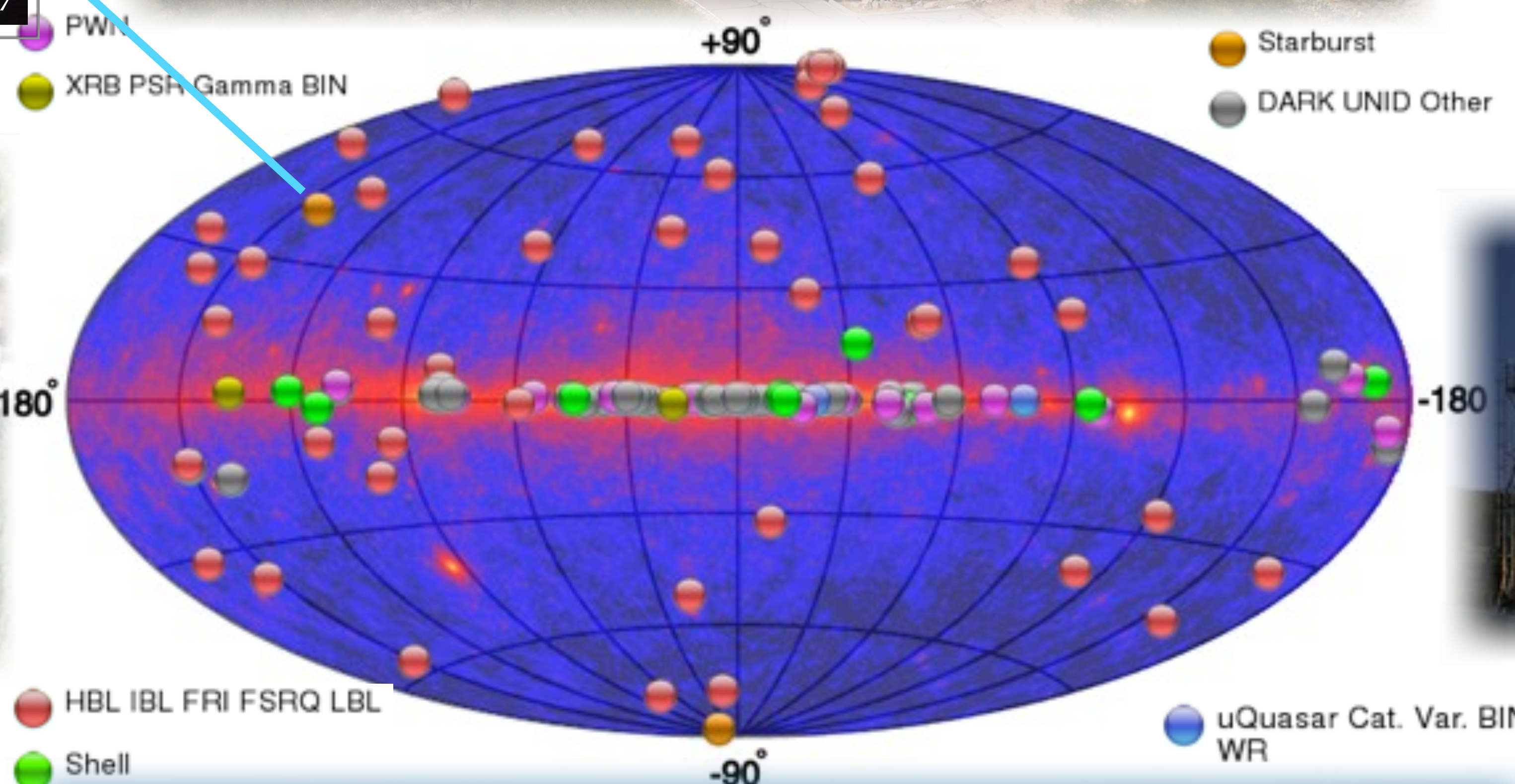


MAGIC

H.E.S.S.

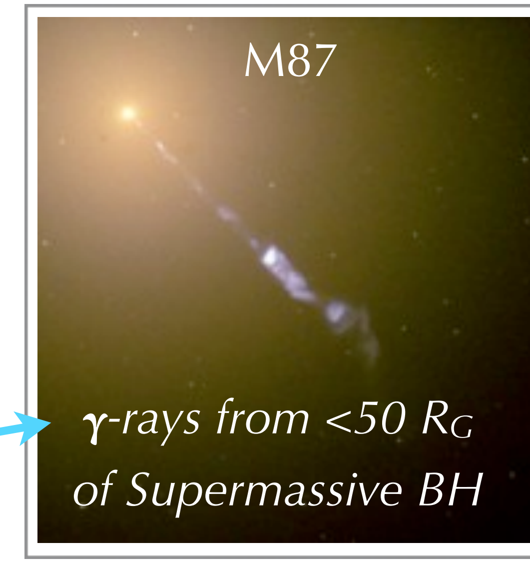
VHE Gamma-Ray Status

MILAGRO

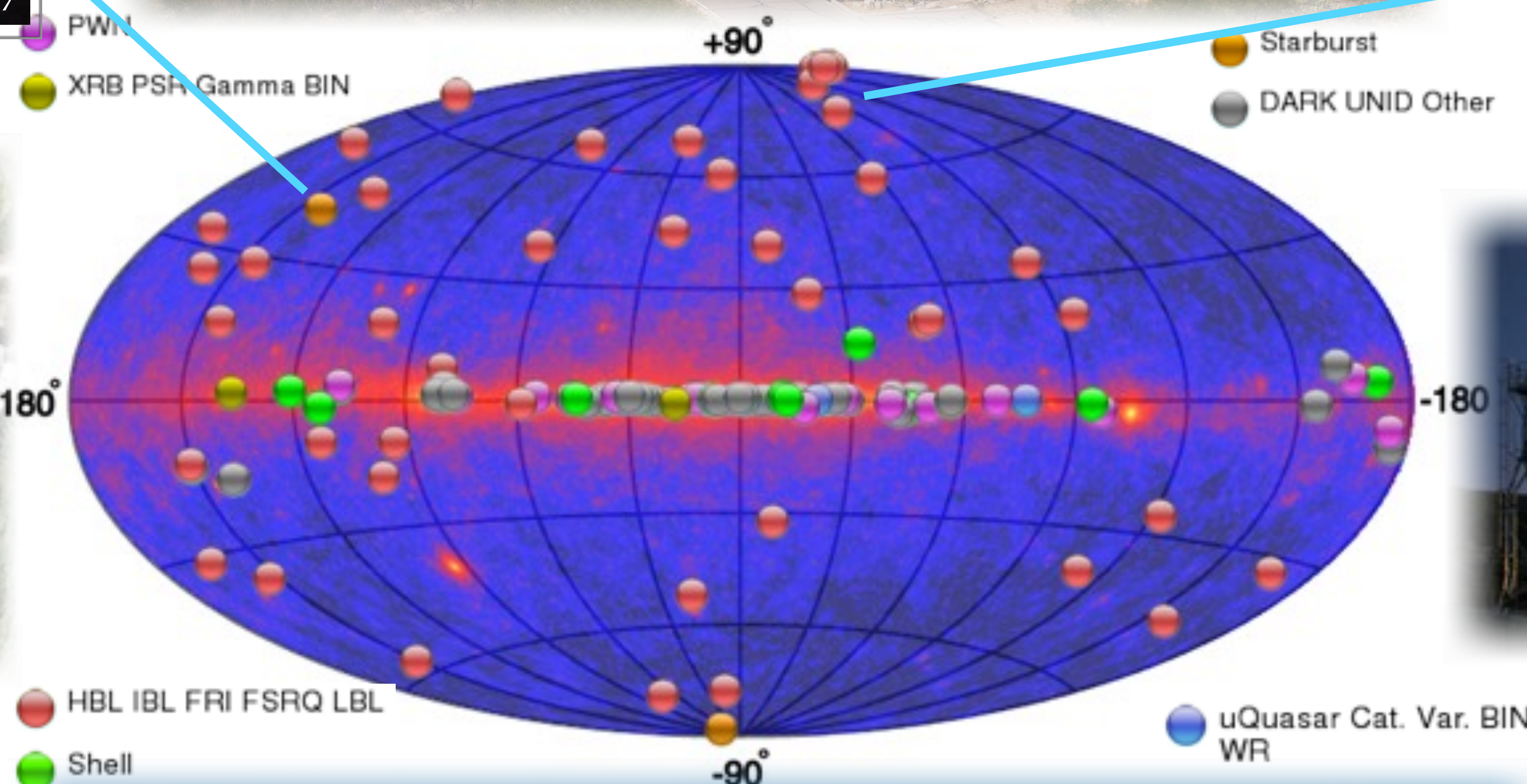


MAGIC

VHE Gamma-Ray Status

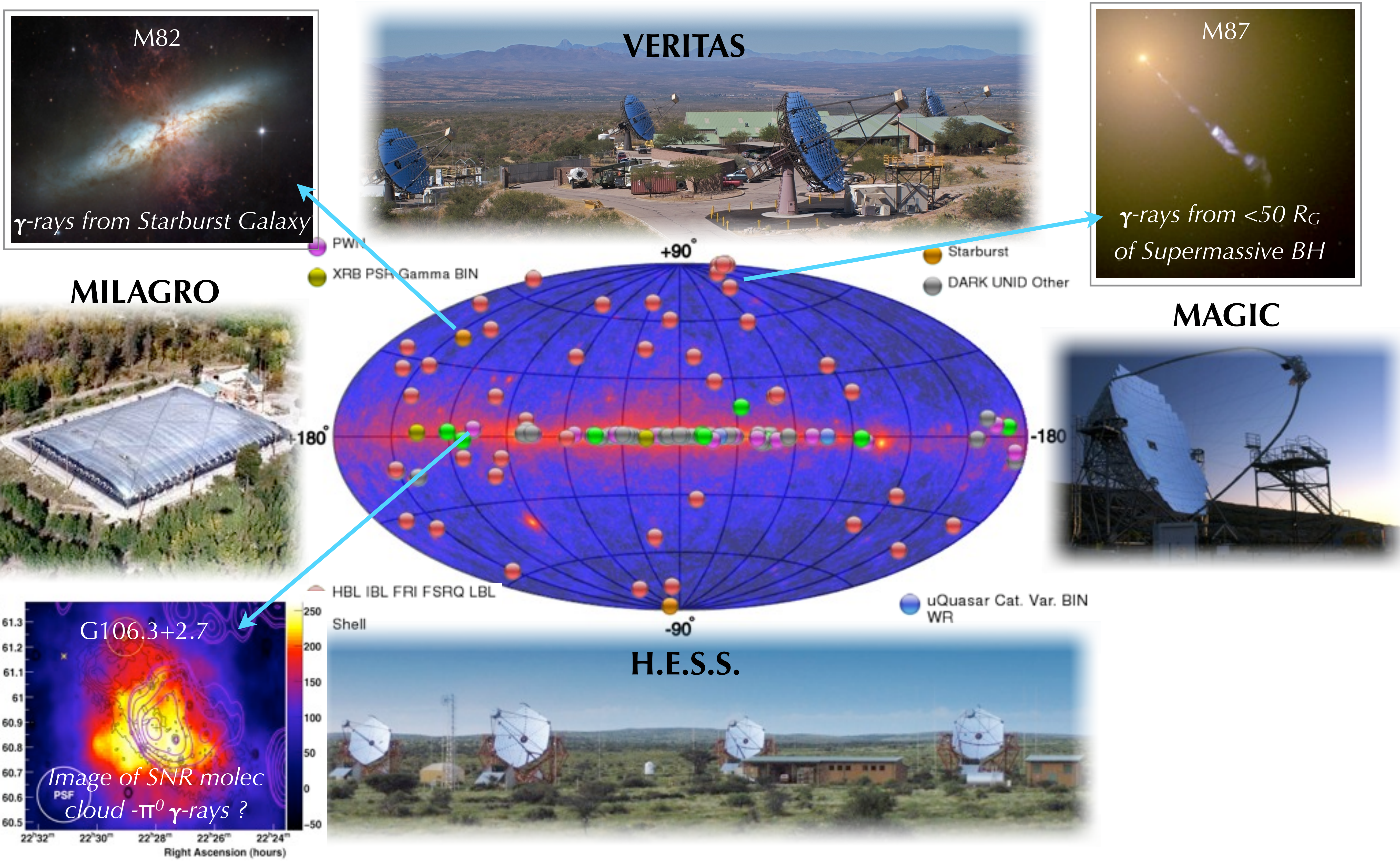


MILAGRO

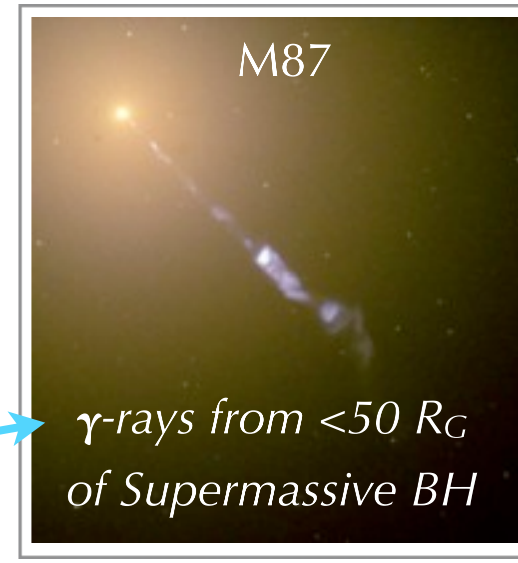


MAGIC

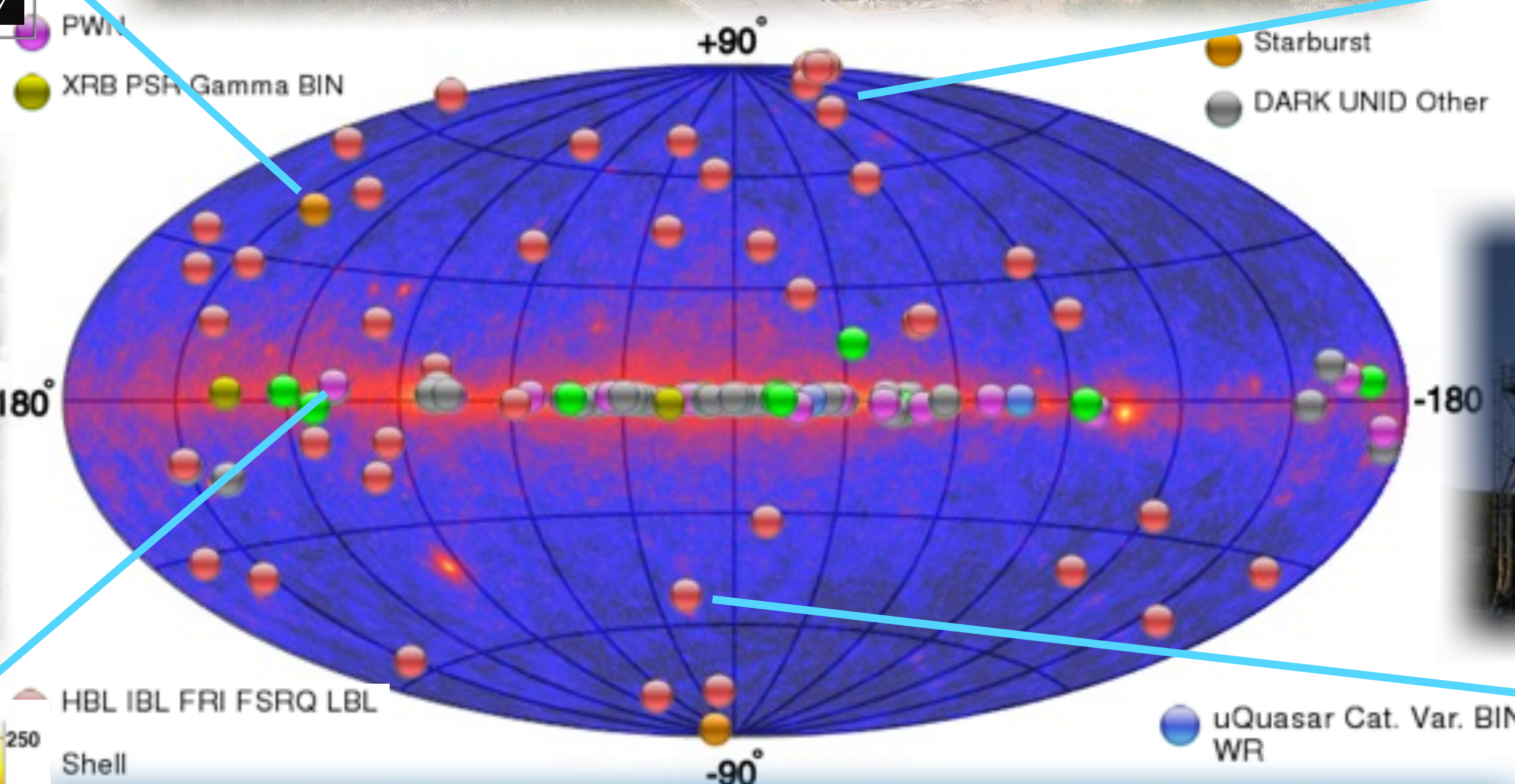
VHE Gamma-Ray Status



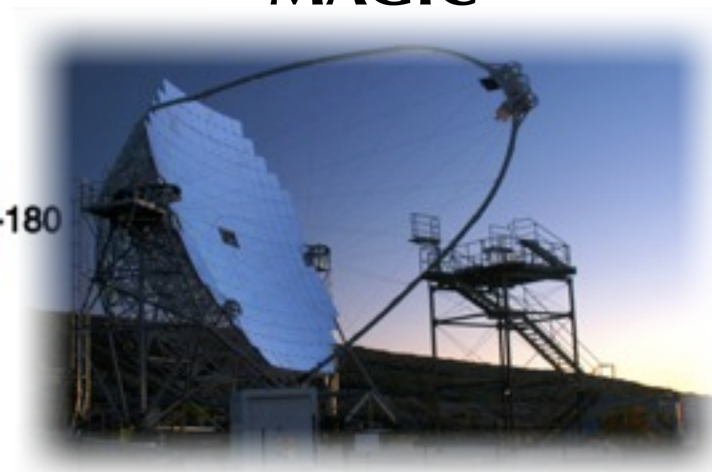
VHE Gamma-Ray Status

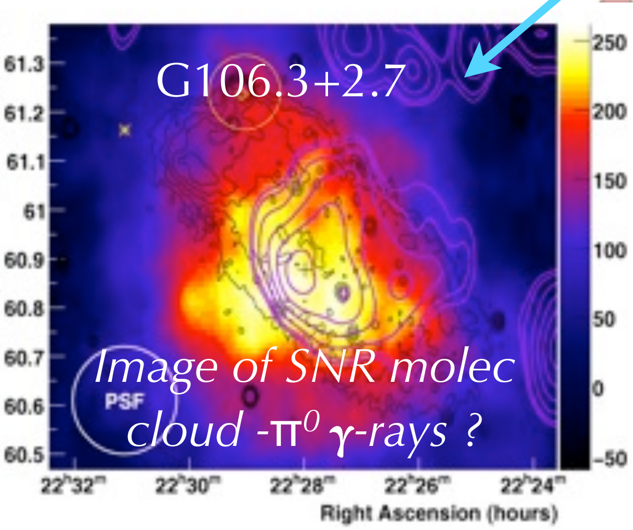


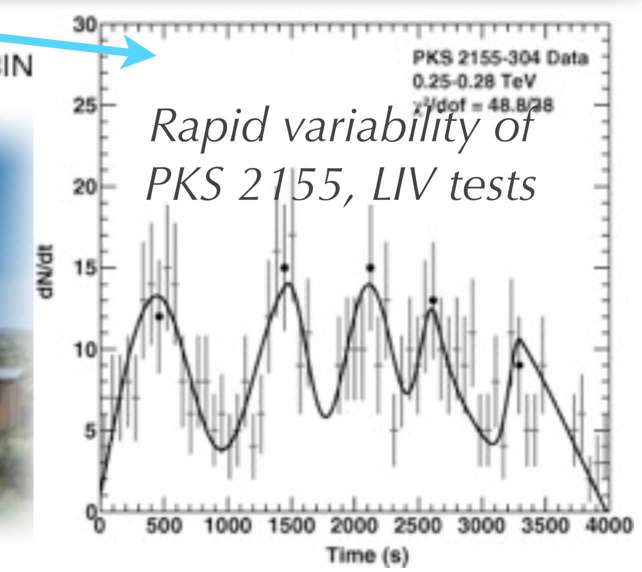
MILAGRO



MAGIC

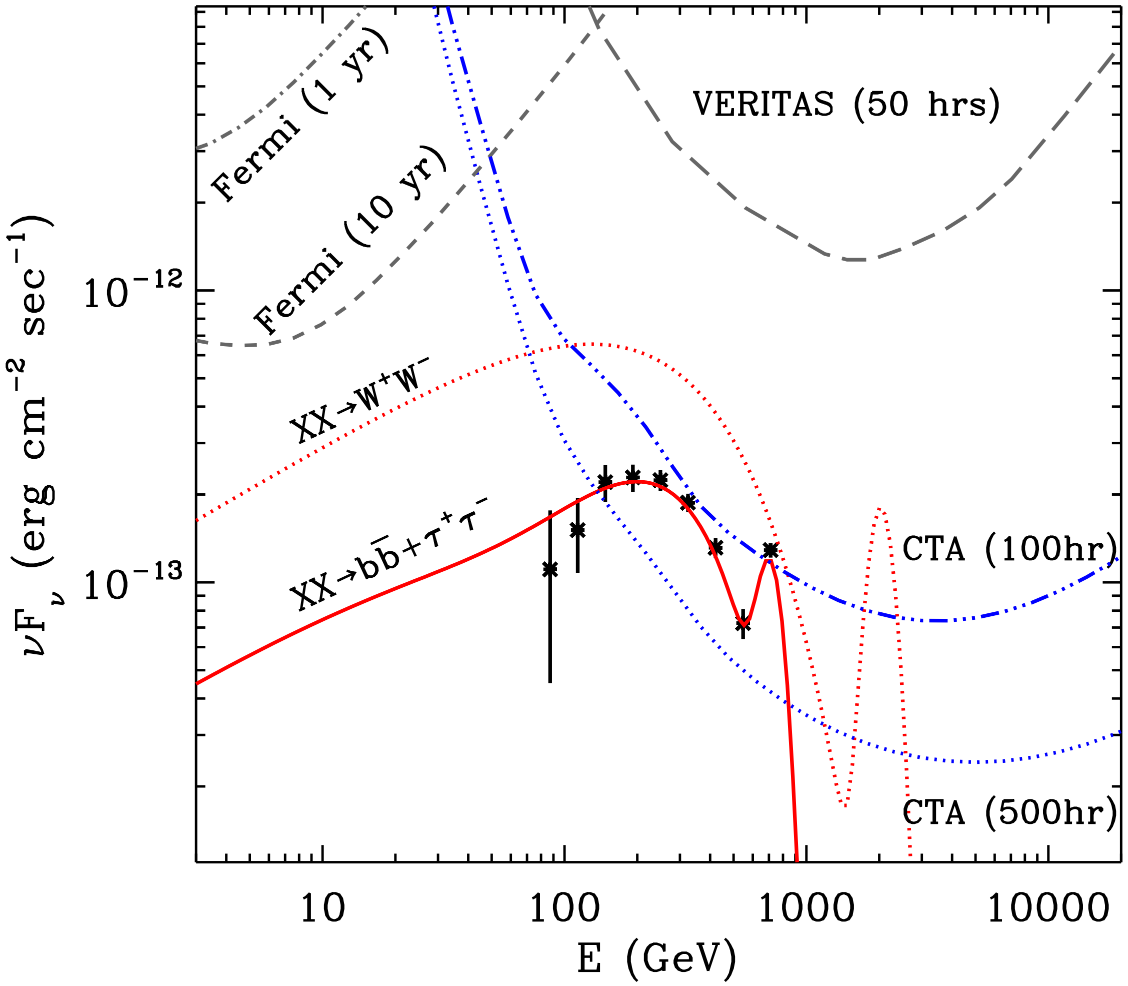






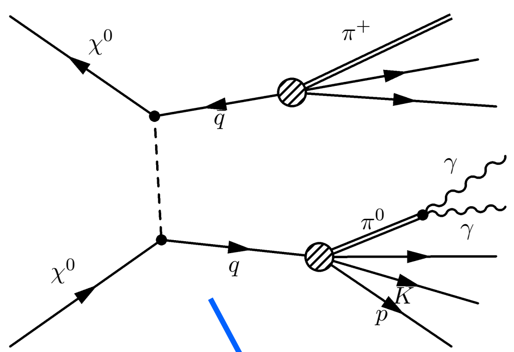
γ-Rays from DM Annihilation

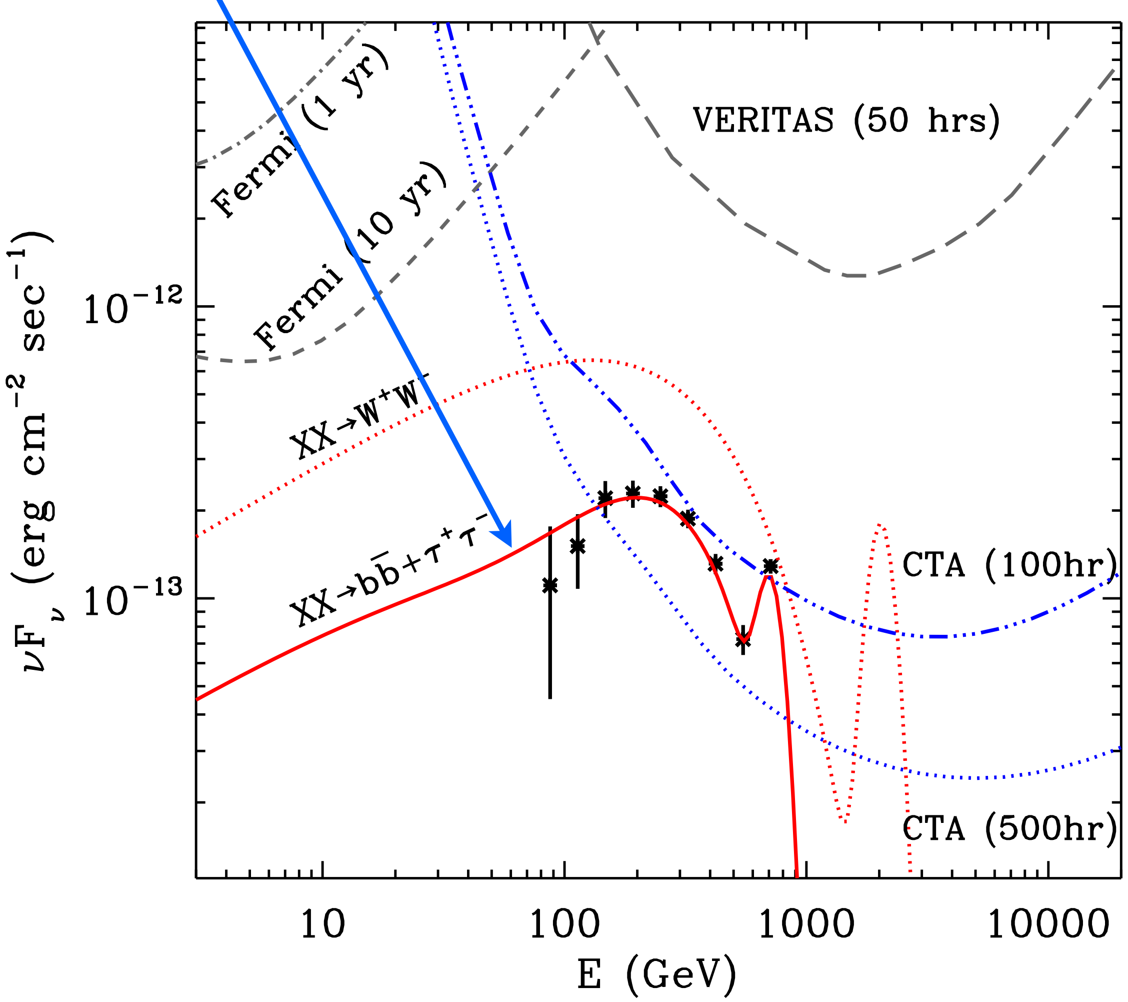
$$E_\gamma \Phi_\gamma(\theta) \approx 10^{-10} \underbrace{\left(E_{\gamma,\mathrm{TeV}} \frac{dN}{dE_{\gamma,\mathrm{TeV}}}\right) \left(\frac{\langle \sigma v \rangle}{10^{-26}\mathrm{cm}^{-3}\mathrm{s}^{-1}}\right) \left(\frac{100\,\mathrm{GeV}}{M_\chi}\right)^2}_{\text{Particle Physics Input}} \underbrace{J(\theta)}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



γ-Rays from DM Annihilation

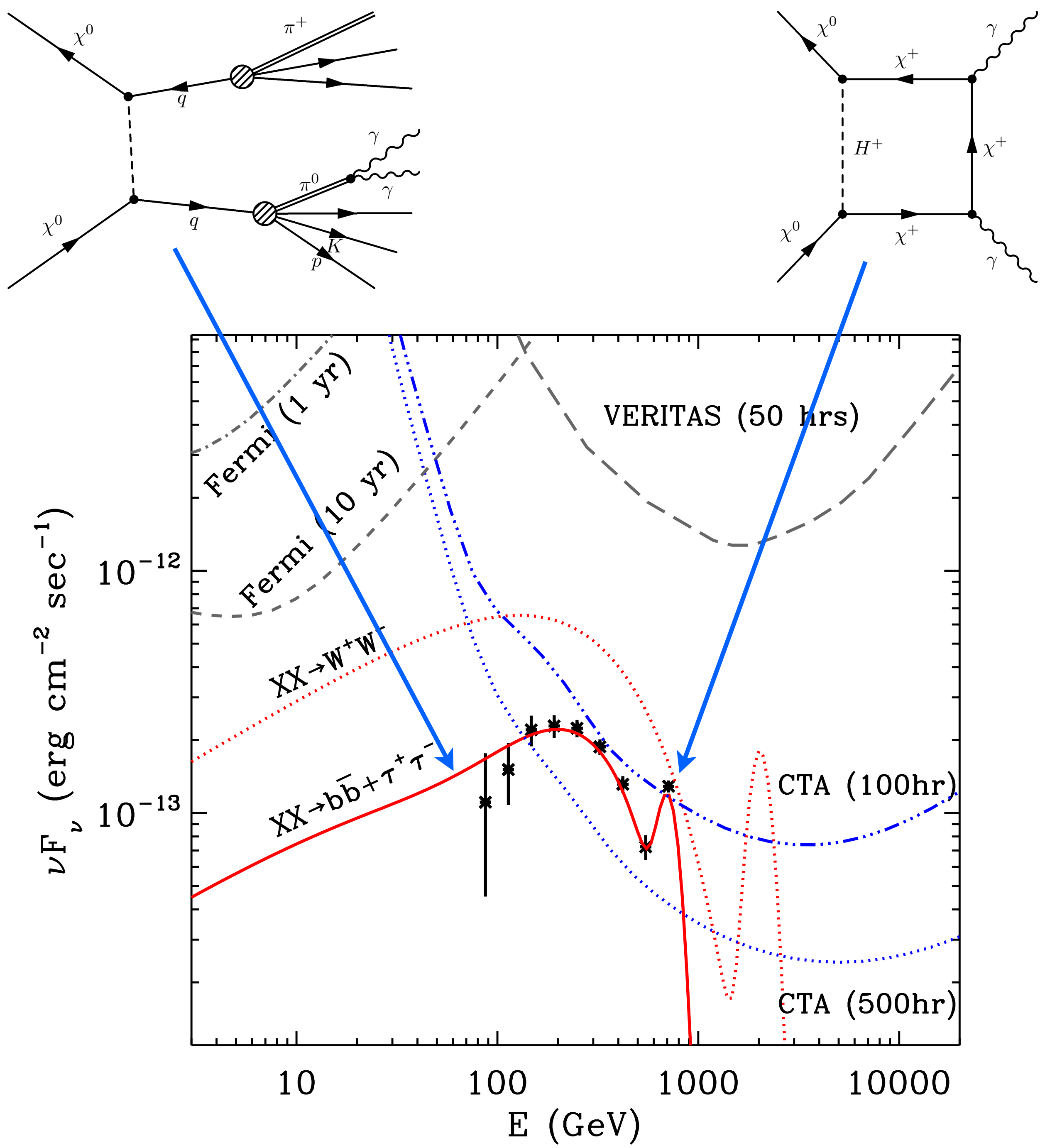
$$E_\gamma \Phi_\gamma(\theta) \approx 10^{-10} \underbrace{\left(E_{\gamma,\mathrm{TeV}} \frac{dN}{dE_{\gamma,\mathrm{TeV}}}\right) \left(\frac{\langle \sigma v \rangle}{10^{-26}\mathrm{cm}^{-3}\mathrm{s}^{-1}}\right) \left(\frac{100\,\mathrm{GeV}}{M_\chi}\right)^2}_{\text{Particle Physics Input}} \underbrace{J(\theta)}\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





γ-Rays from DM Annihilation

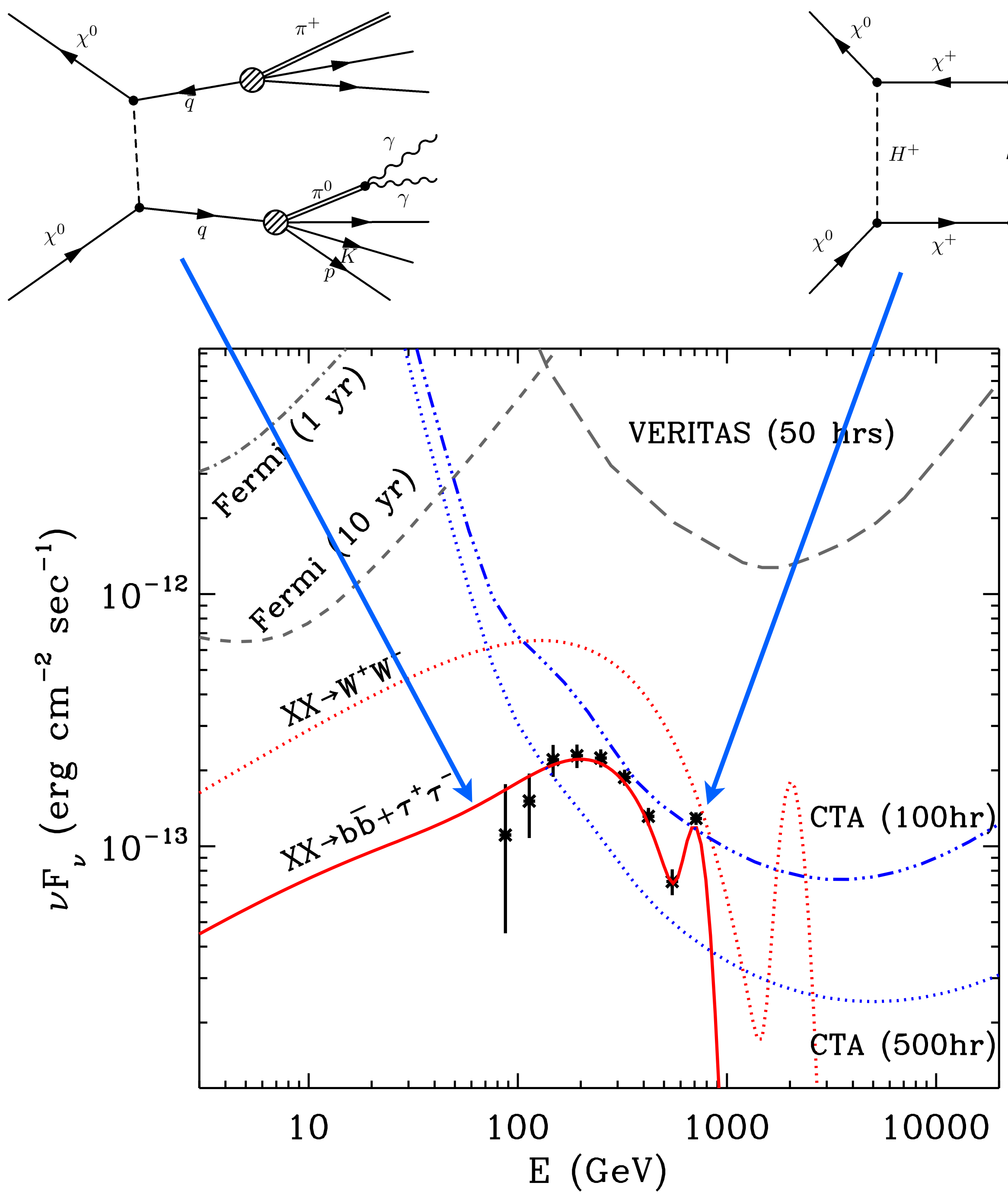
$$E_\gamma \Phi_\gamma(\theta) \approx 10^{-10} \underbrace{\left(E_{\gamma,\mathrm{TeV}} \frac{dN}{dE_{\gamma,\mathrm{TeV}}}\right) \left(\frac{\langle \sigma v \rangle}{10^{-26}\mathrm{cm}^{-3}\mathrm{s}^{-1}}\right) \left(\frac{100\,\mathrm{GeV}}{M_\chi}\right)^2}_{\text{Particle Physics Input}} \underbrace{J(\theta)}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

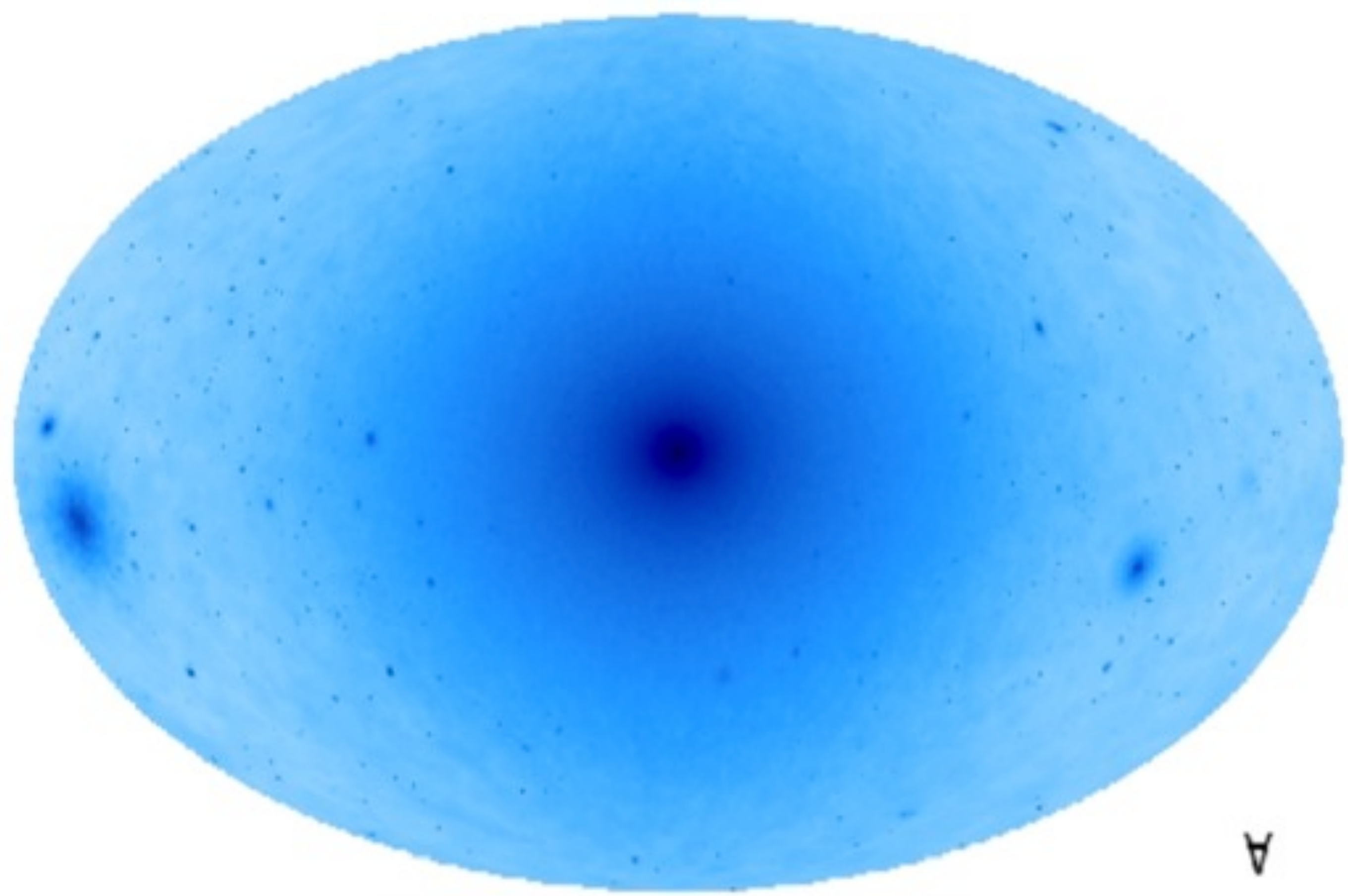


γ-Rays from DM Annihilation

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

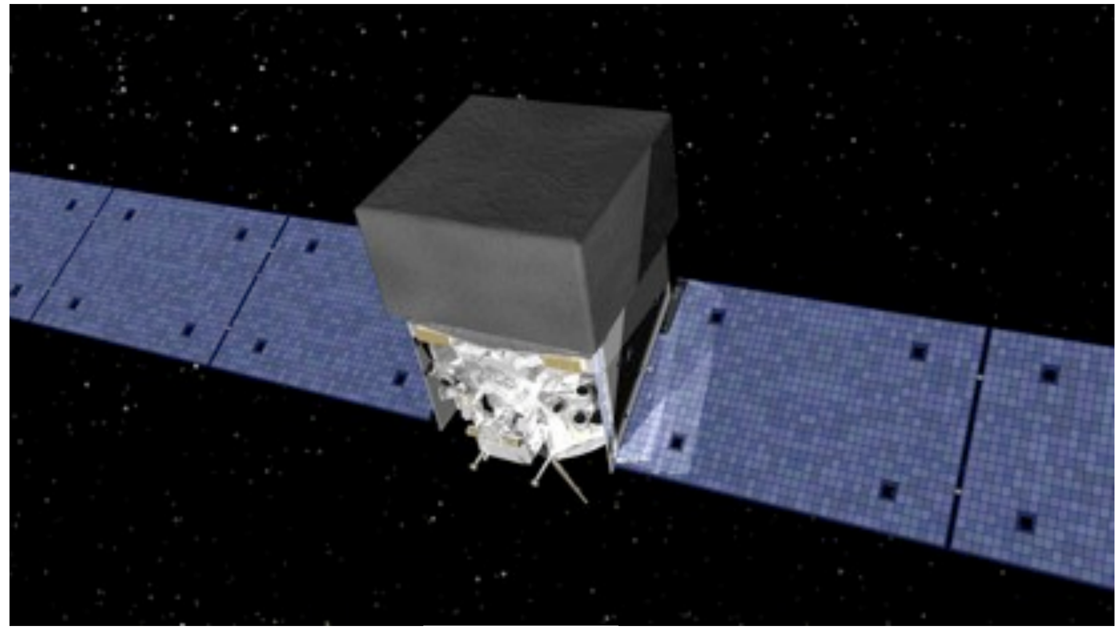
$$J(\theta) = \underbrace{\frac{1}{8.5\,\mathrm{kpc}} \left(\frac{1}{0.3\,\mathrm{GeV/cm^3}}\right)^2 \int_{\text{line of sight}} \rho^2(l)dl(\theta)}_{\text{Astrophysics/Cosmology Input}}$$



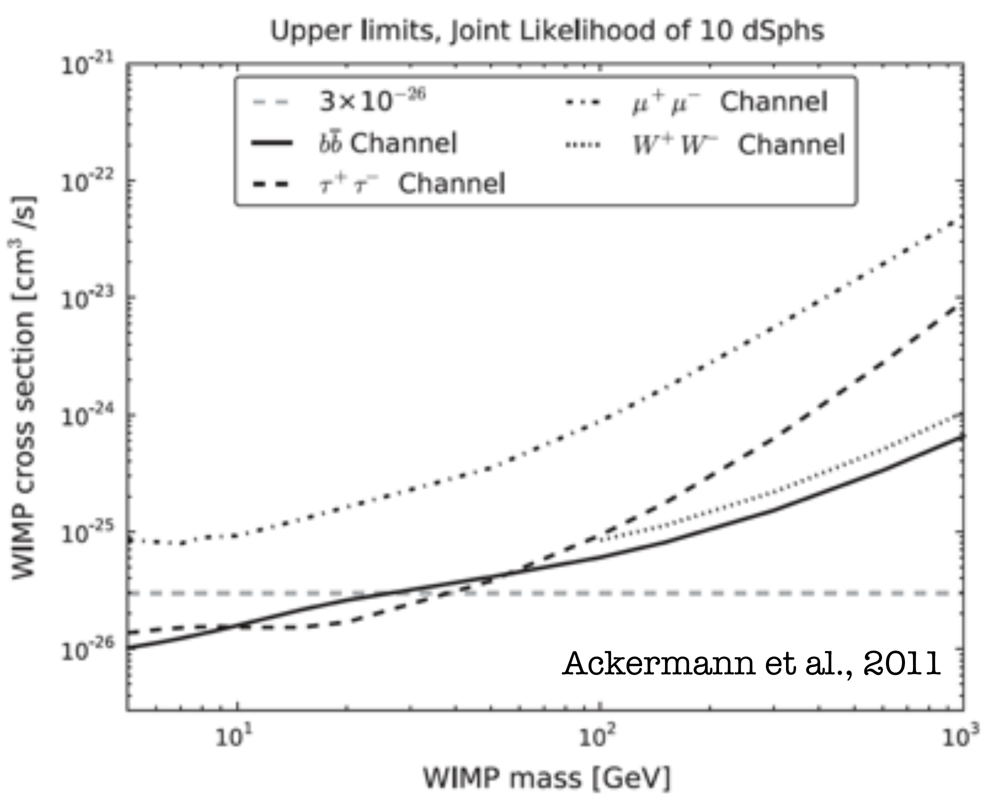


Line-of-sight integral of ρ^2 for a Milky-Way-like halo in the VL Lactea II ΛCDM N-body simulations (Kuhlen et al.)

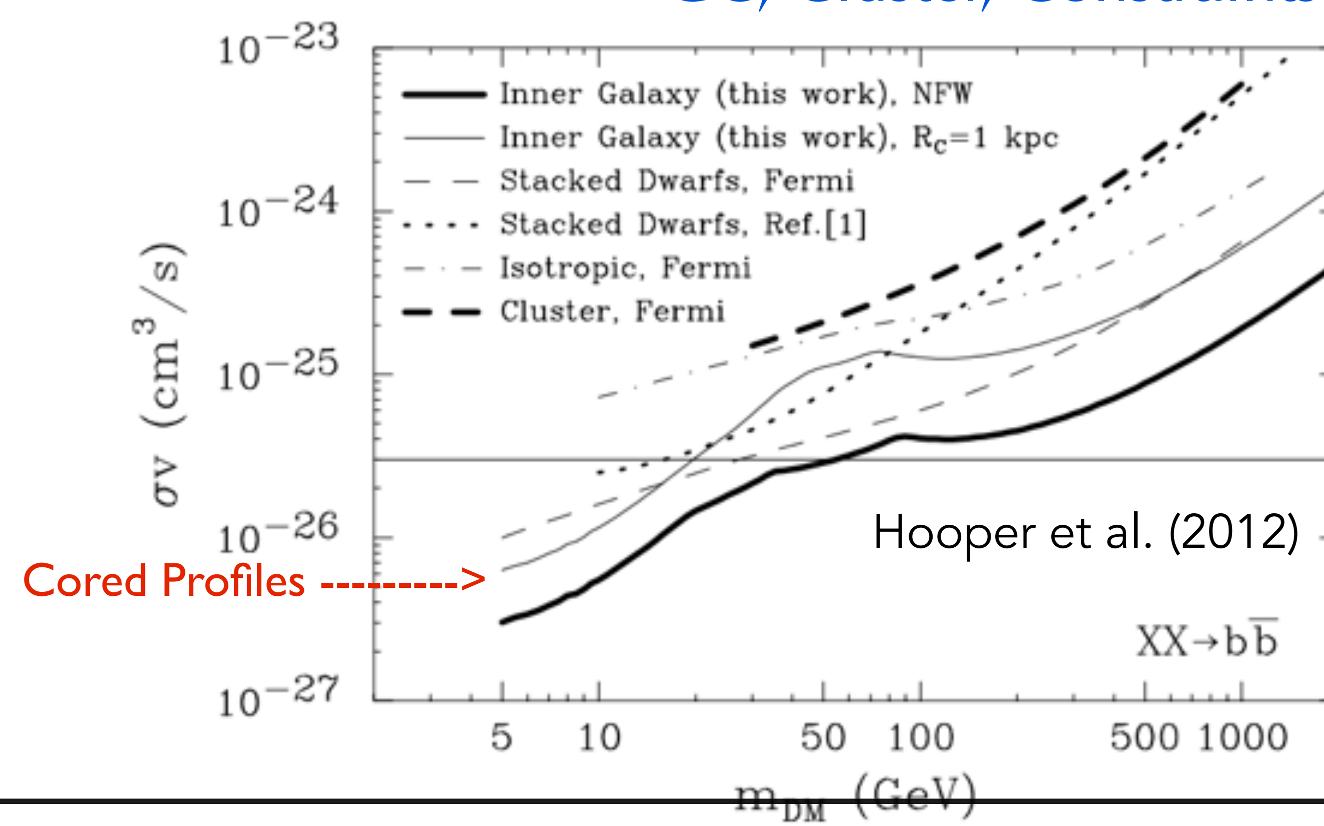
Fermi LAT DM Constraints



Dwarf Constraints

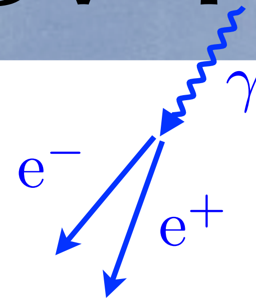


GC, Cluster, Constraints

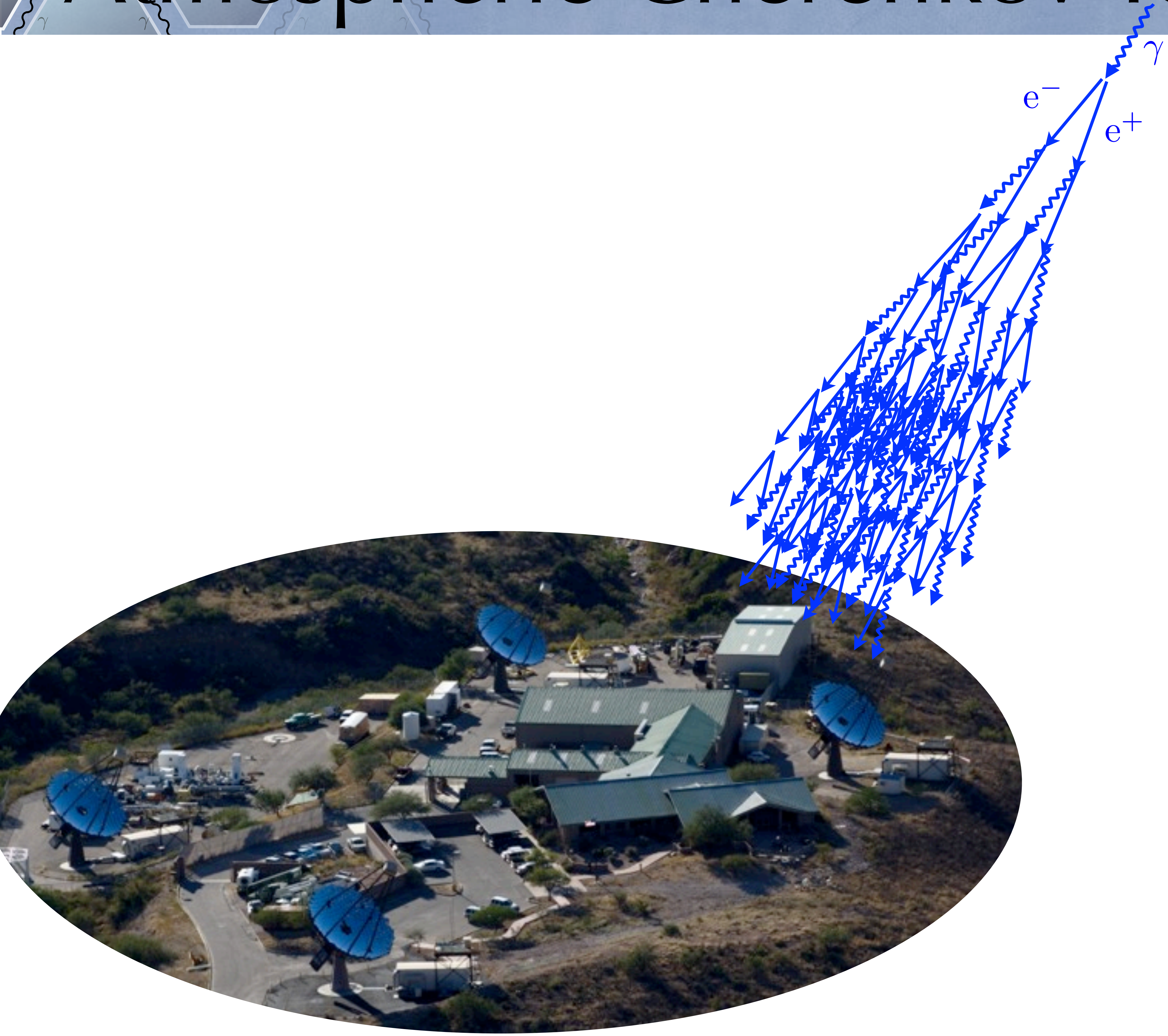


**Enormous progress since last Snowmass meeting! We are beginning to probe natural cross section at low mass (<20 GeV) and pull within 1-2 orders of magnitude for 100GeV-1TeV WIMPs.*

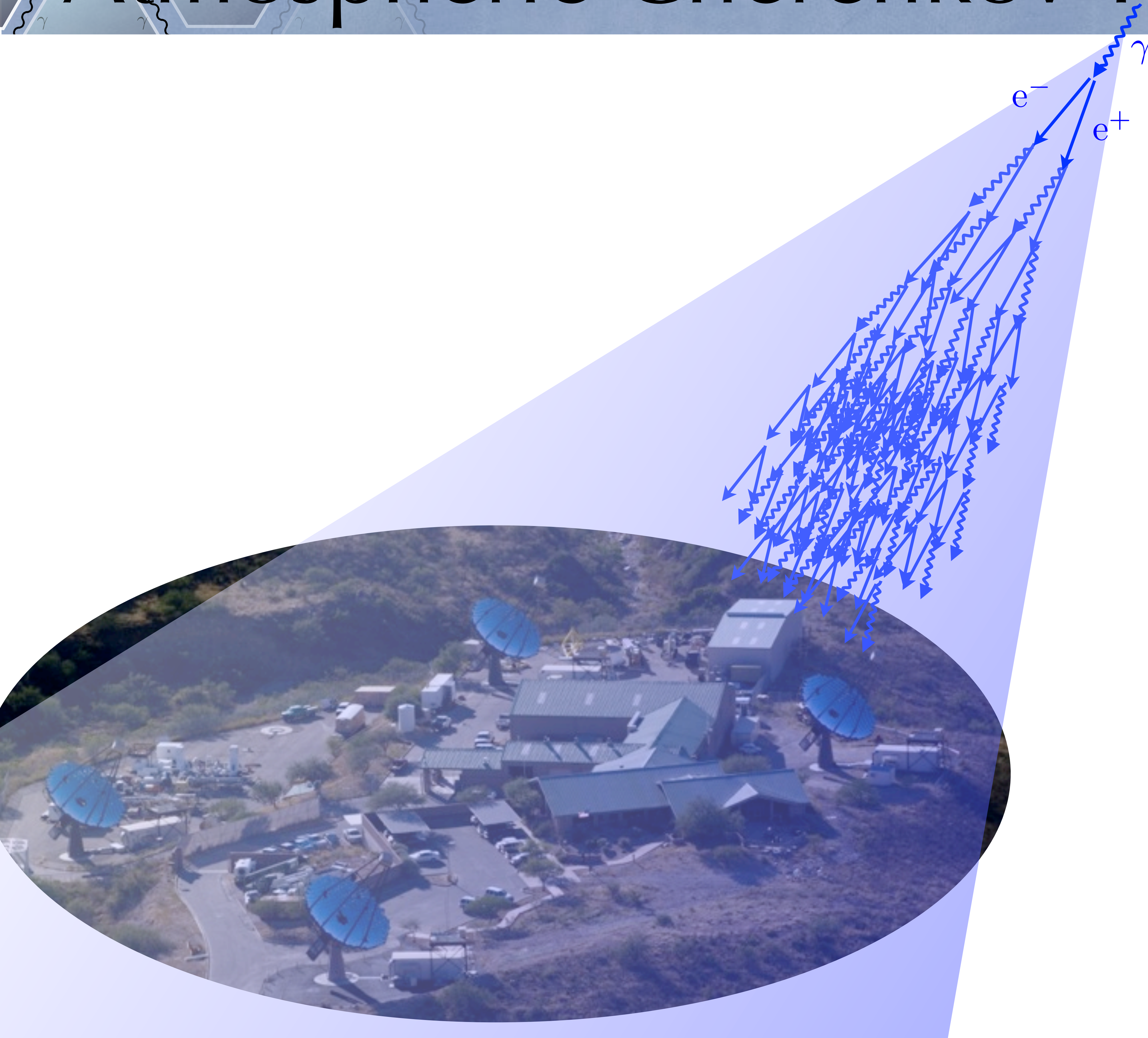
Atmospheric Cherenkov Telescopes



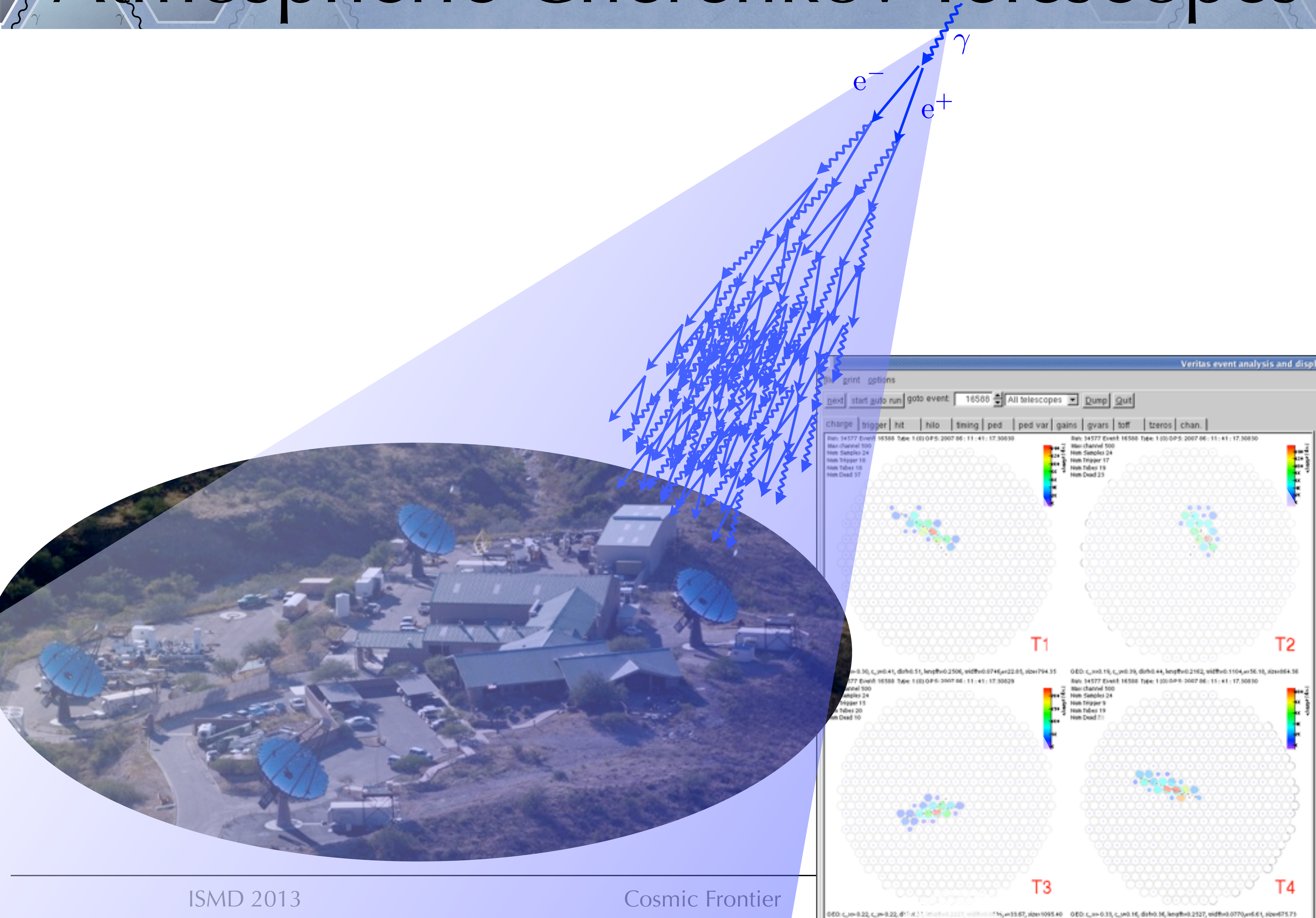
Atmospheric Cherenkov Telescopes



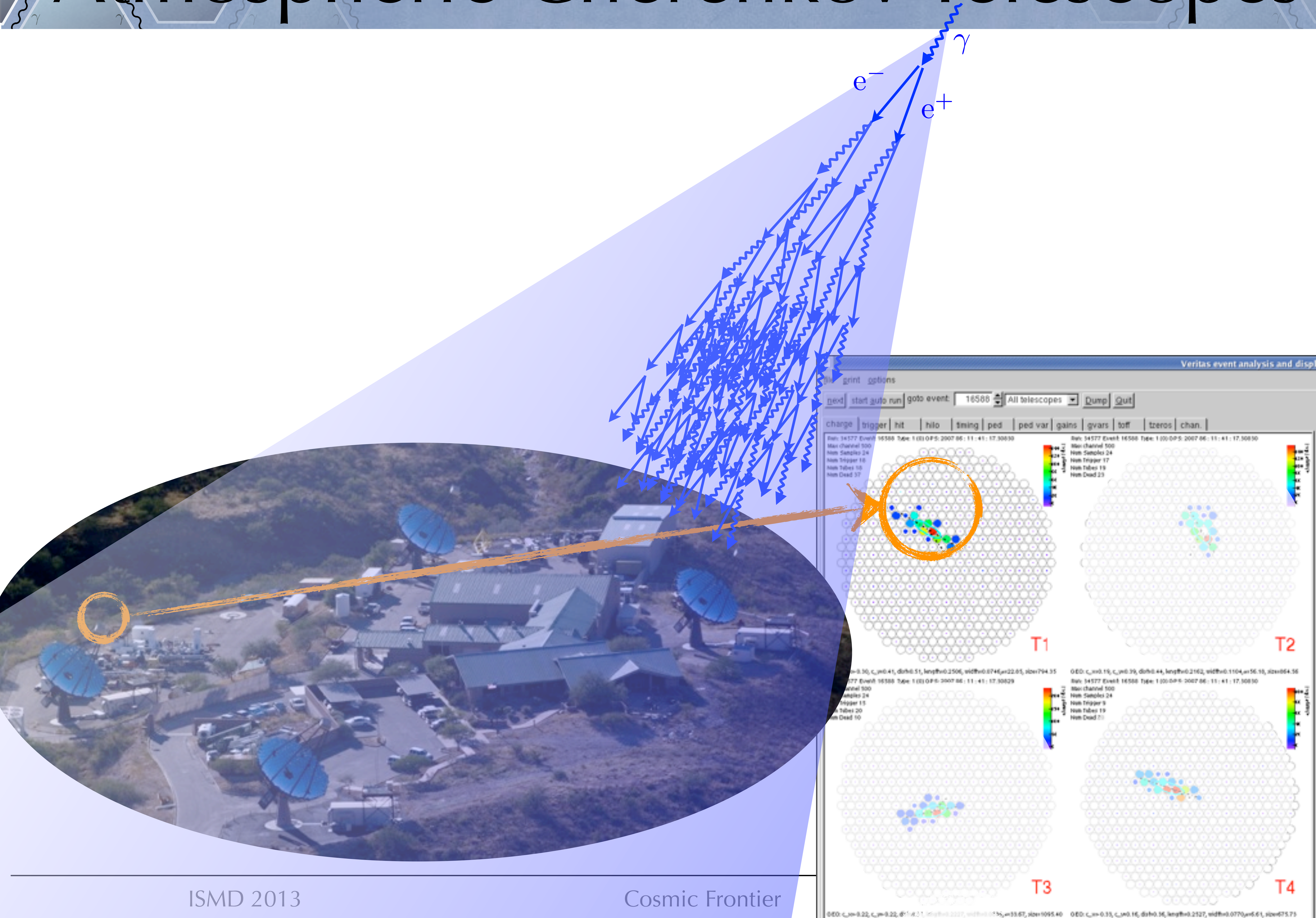
Atmospheric Cherenkov Telescopes



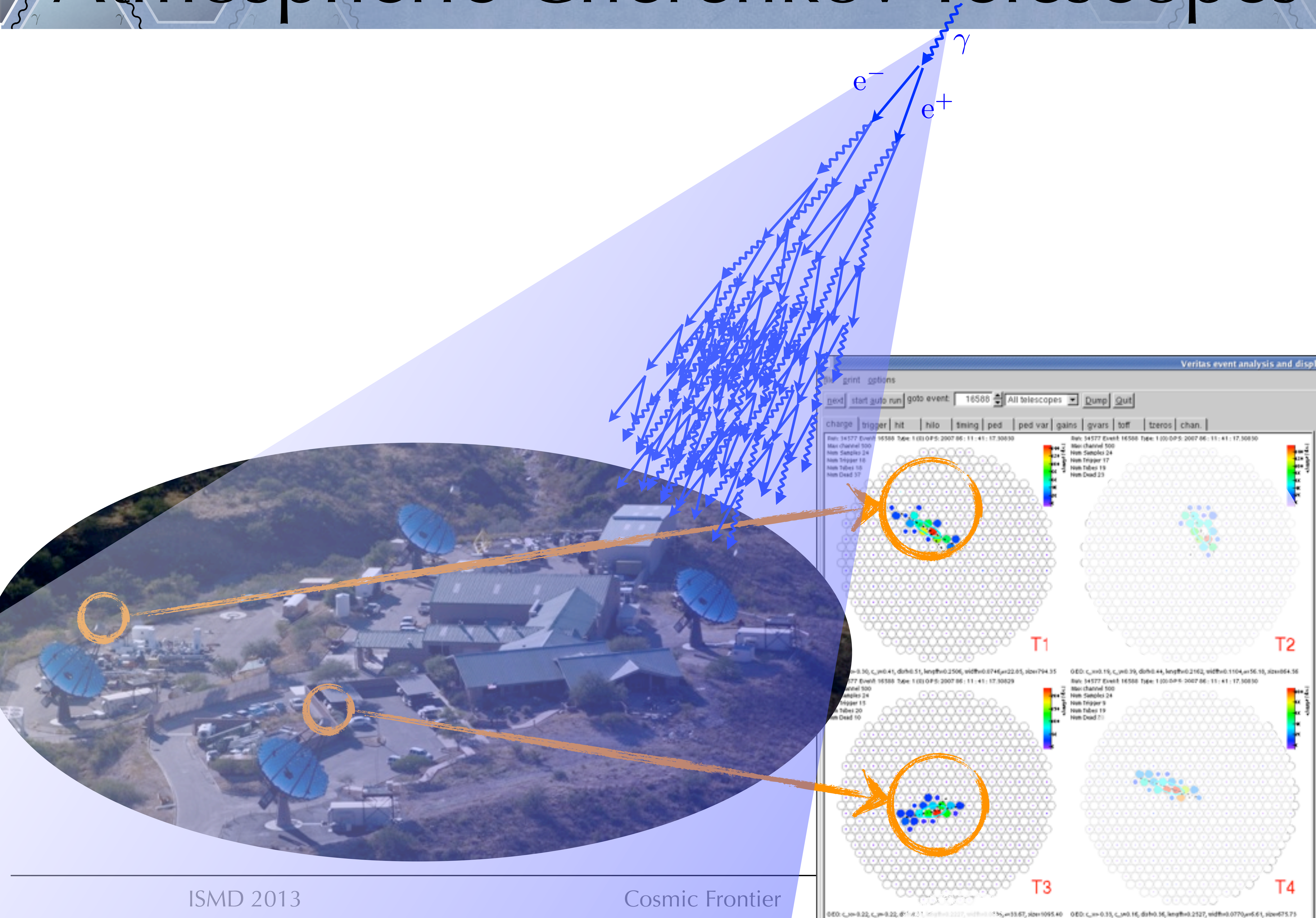
Atmospheric Cherenkov Telescopes



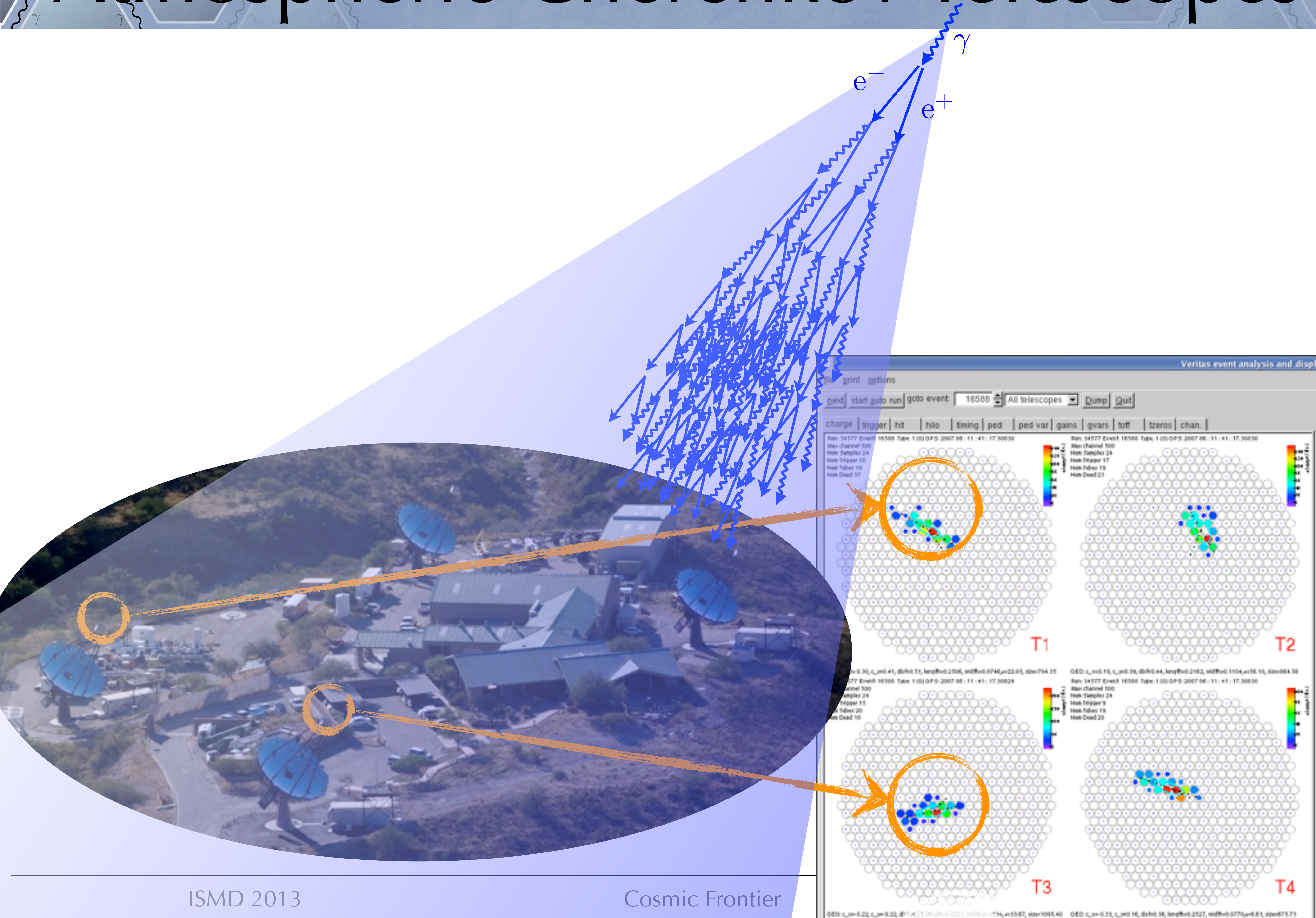
Atmospheric Cherenkov Telescopes



Atmospheric Cherenkov Telescopes

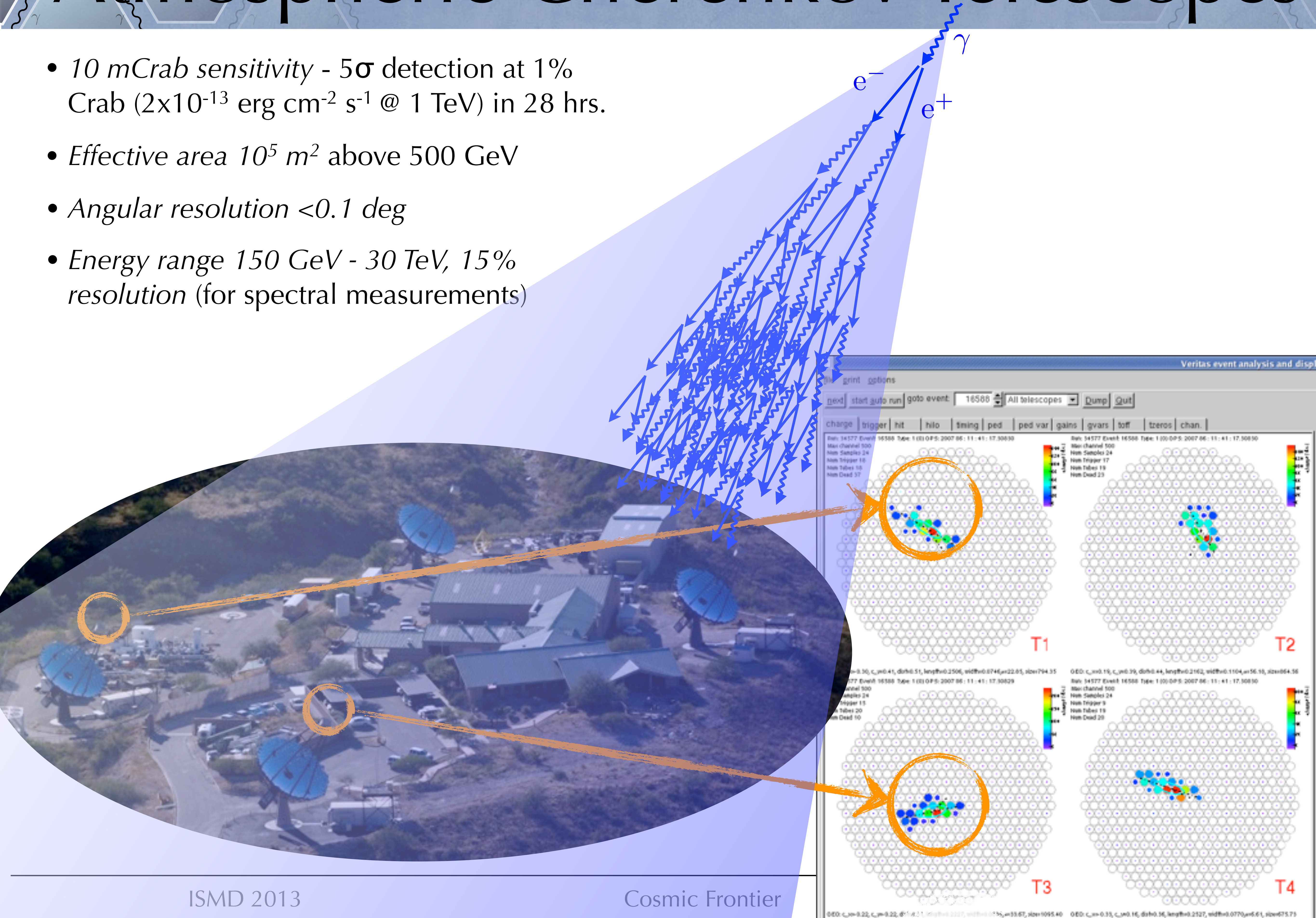


Atmospheric Cherenkov Telescopes



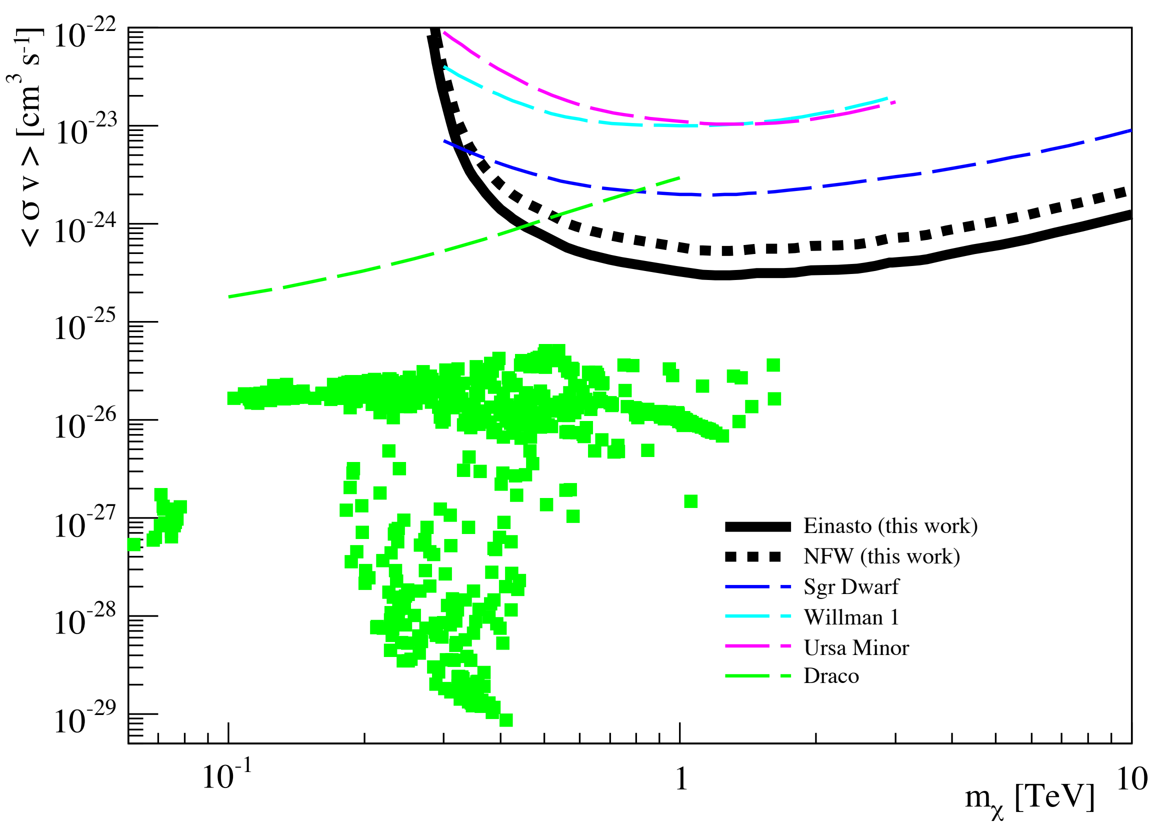
Atmospheric Cherenkov Telescopes

- *10 mCrab sensitivity* - 5σ detection at 1% Crab (2×10^{-13} erg cm^{-2} s^{-1} @ 1 TeV) in 28 hrs.
- *Effective area 10^5 m^2* above 500 GeV
- *Angular resolution <0.1 deg*
- *Energy range 150 GeV - 30 TeV, 15% resolution* (for spectral measurements)



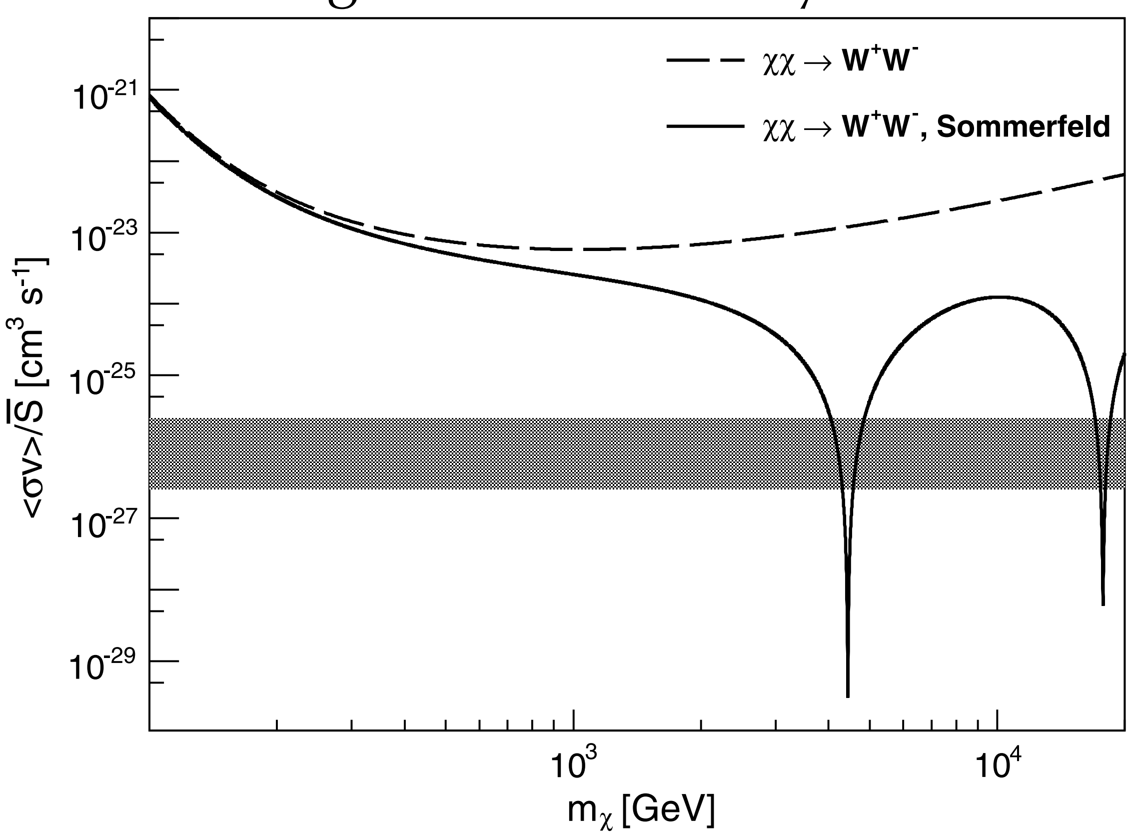
ACT DM Constraints

GC Limits



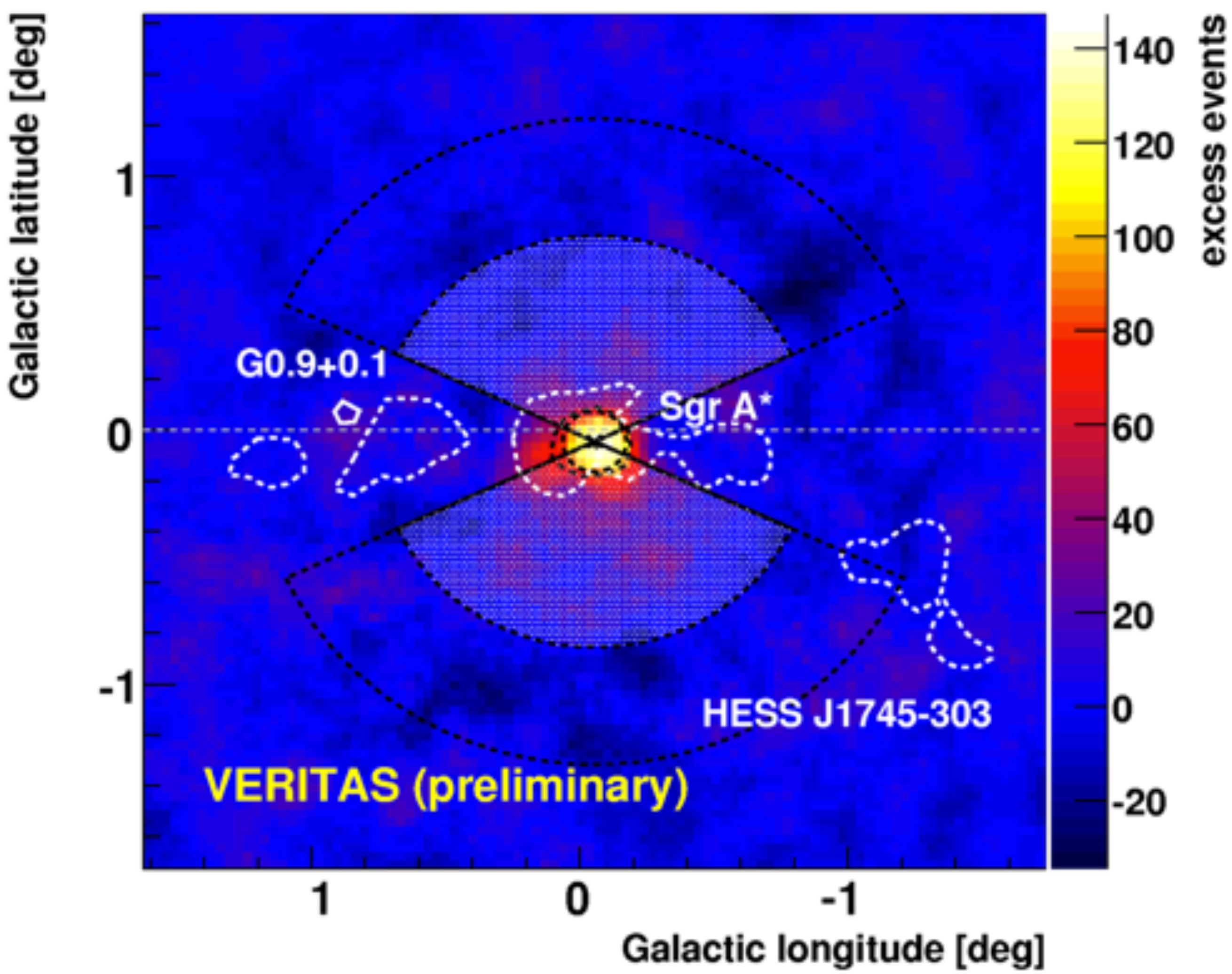
(Aharonian et al. for the HESS collaboration, PRL 106, 1301)

Segue Dwarf Galaxy Limits



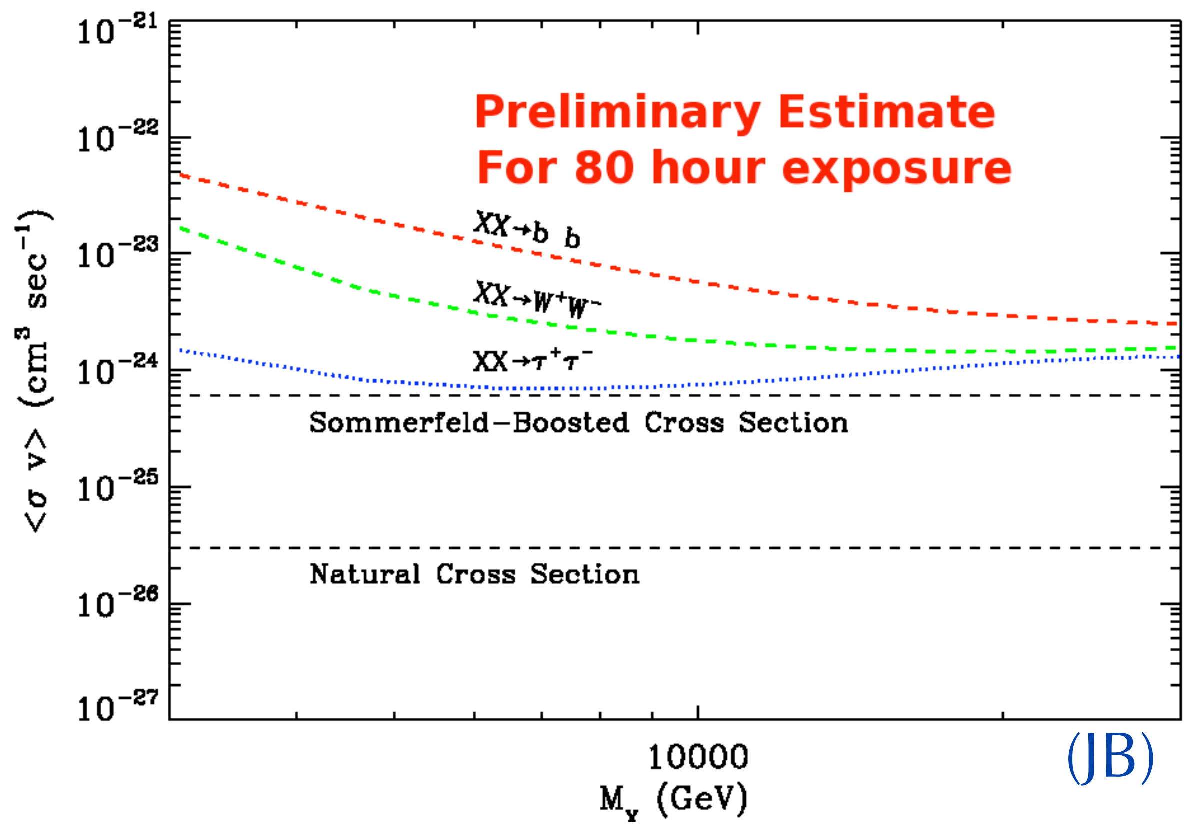
(Aliu et al. for the VERITAS collaboration, PRD 85, 062001)

VERITAS Projections

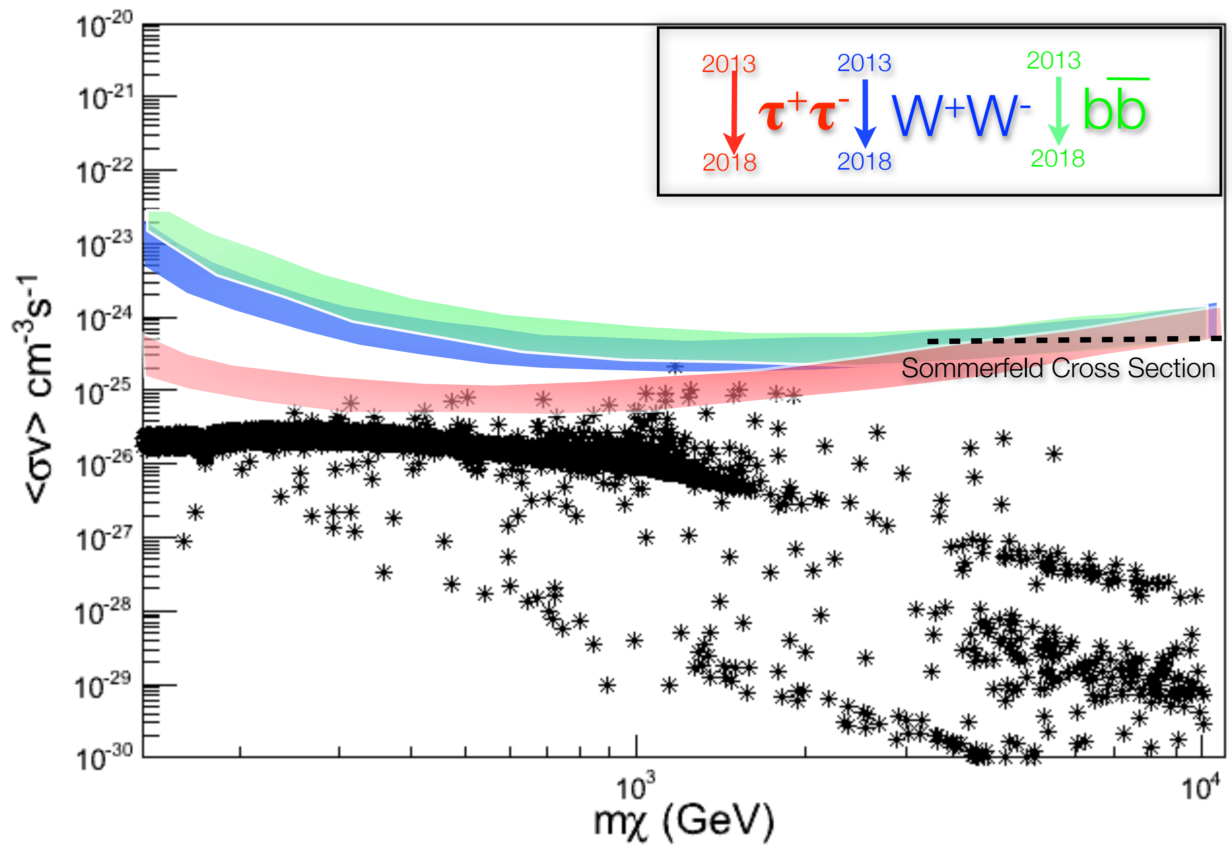


(SLAC CF Workshop Talk by A. Smith)

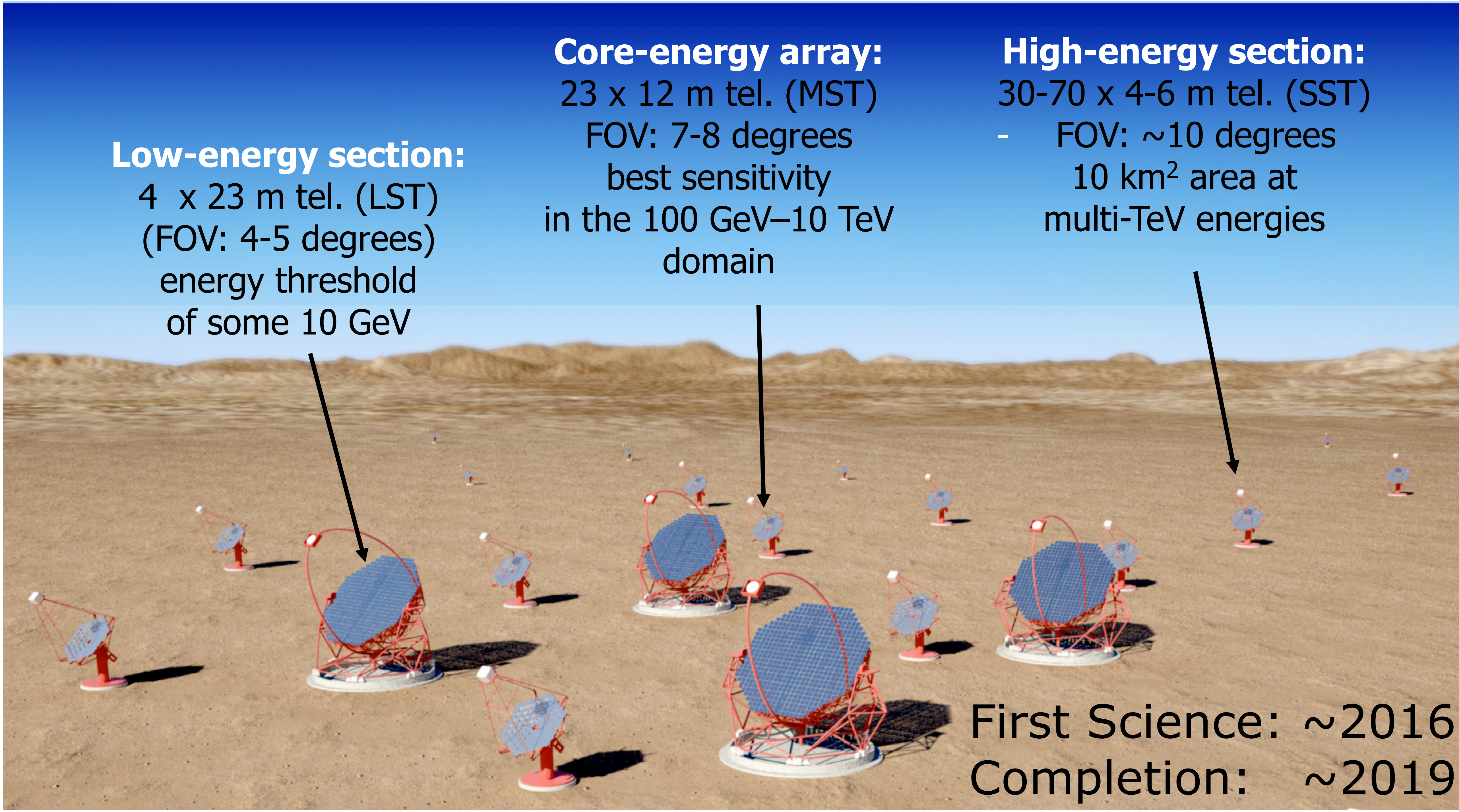
- With another 5 years, can push limits with VERITAS down into interesting cross-section regime



(JB)

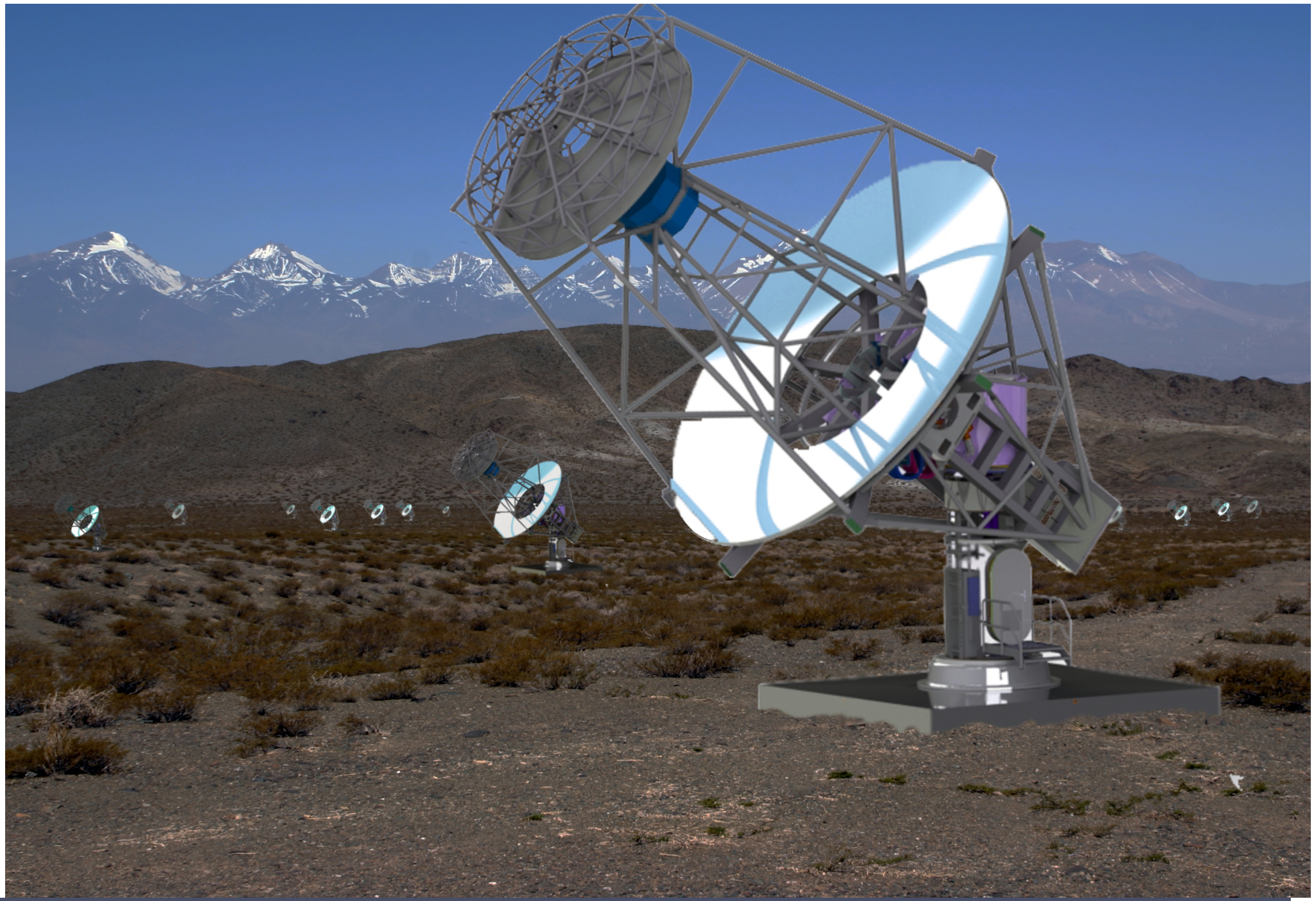


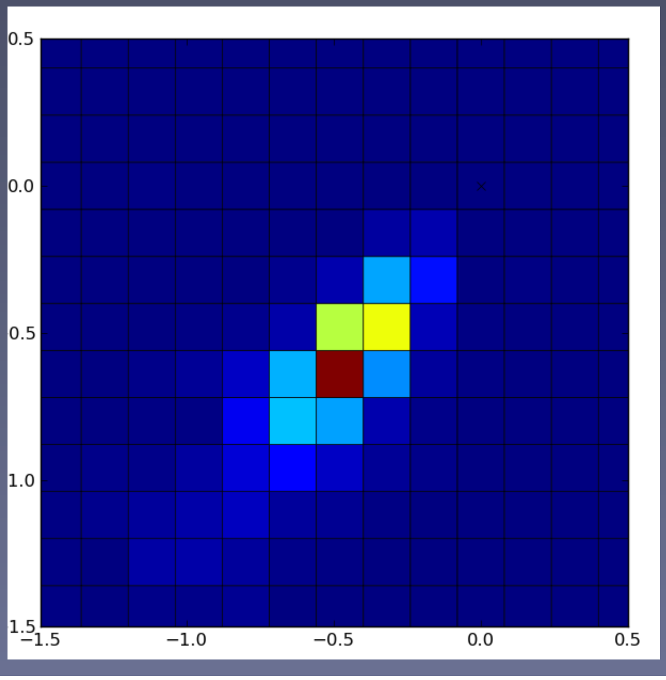
Cherenkov Telescope Array CTA



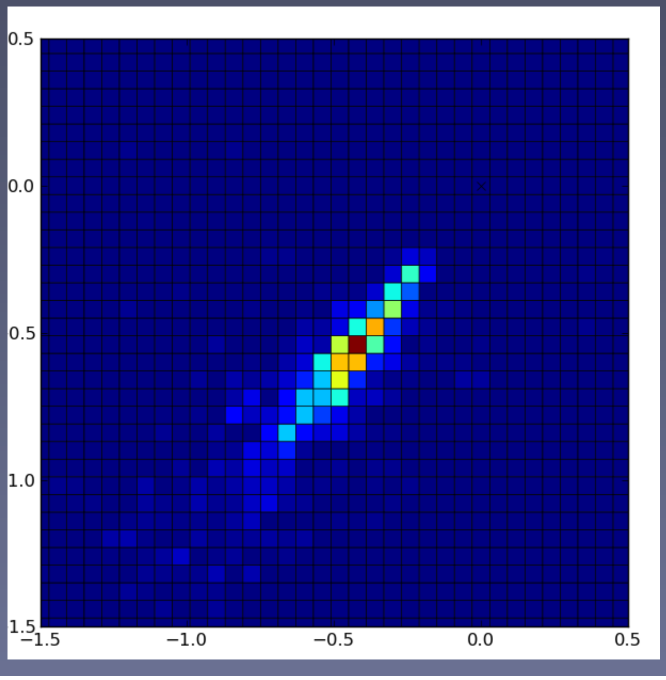
- CTA is being built by an international consortium of ~800 scientists - *Many Body Physics*

CTA-US

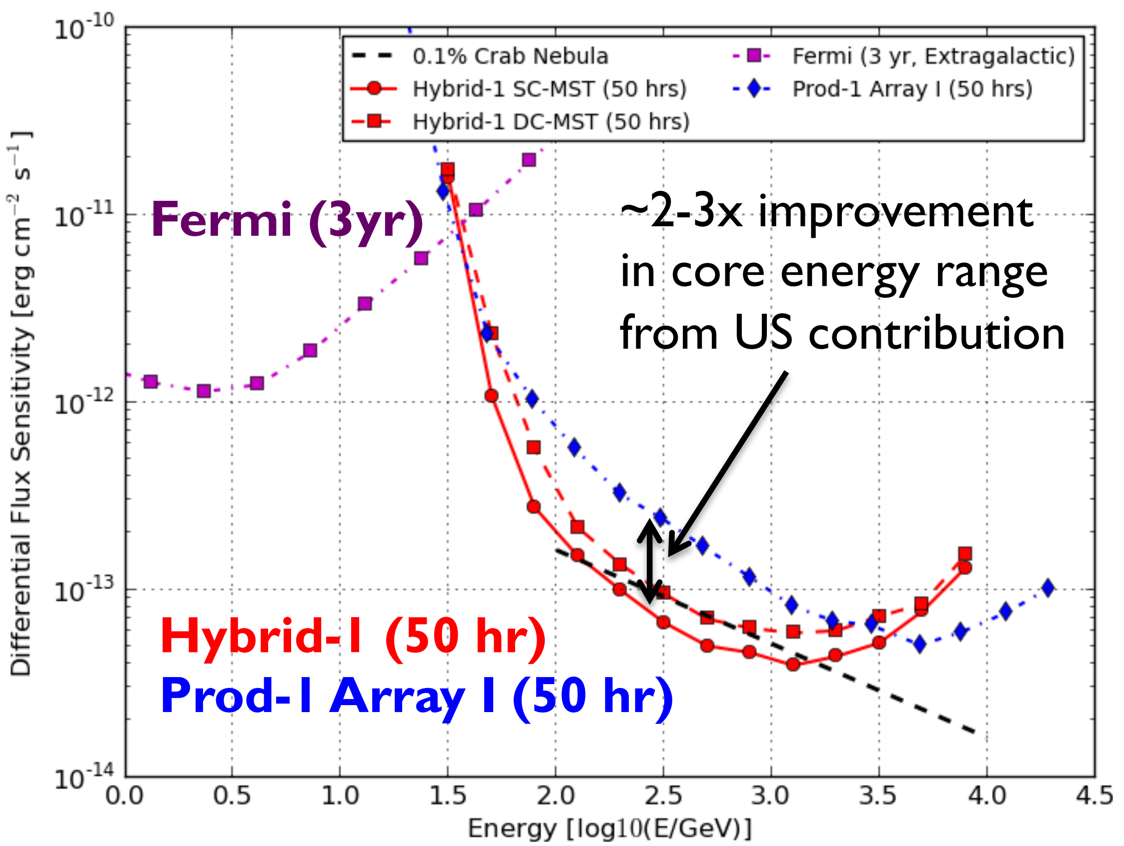




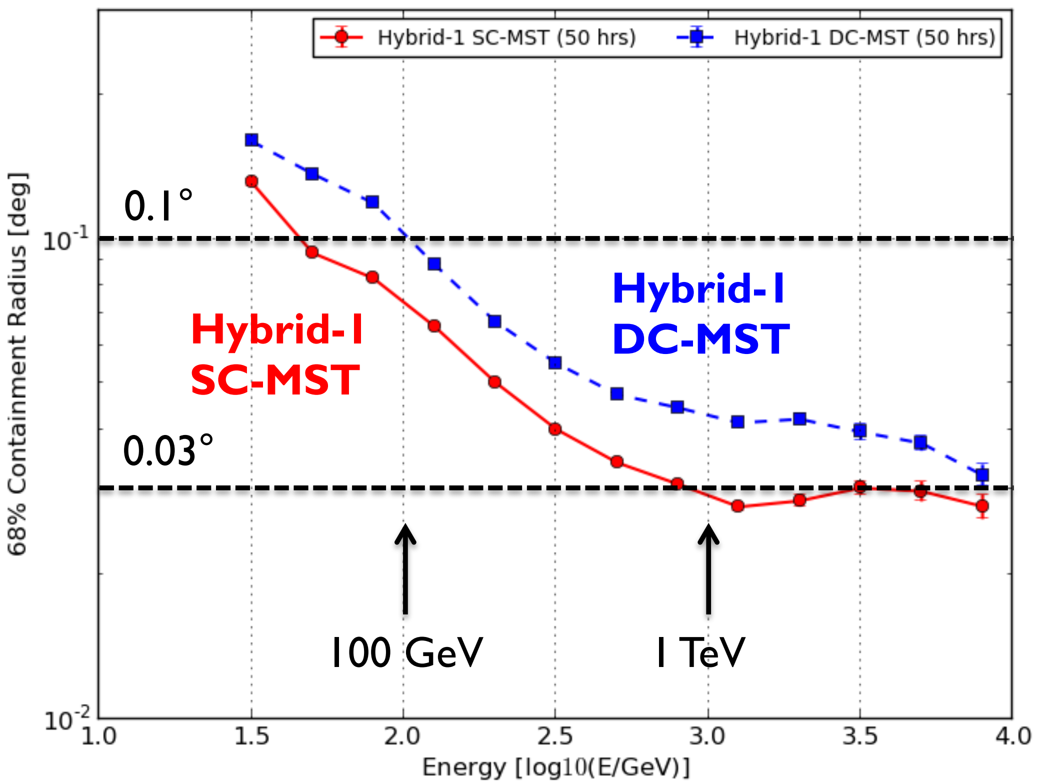
DC-MST (Single Mirror)
0.5
0.0
0.5
1.0
1.5
−1.5
−1.0
−0.5
0.0
0.5



SC-MST (Dual Mirror)
0.5
0.0
0.5
1.0
1.5
−1.5
−1.0
−0.5
0.0
0.5

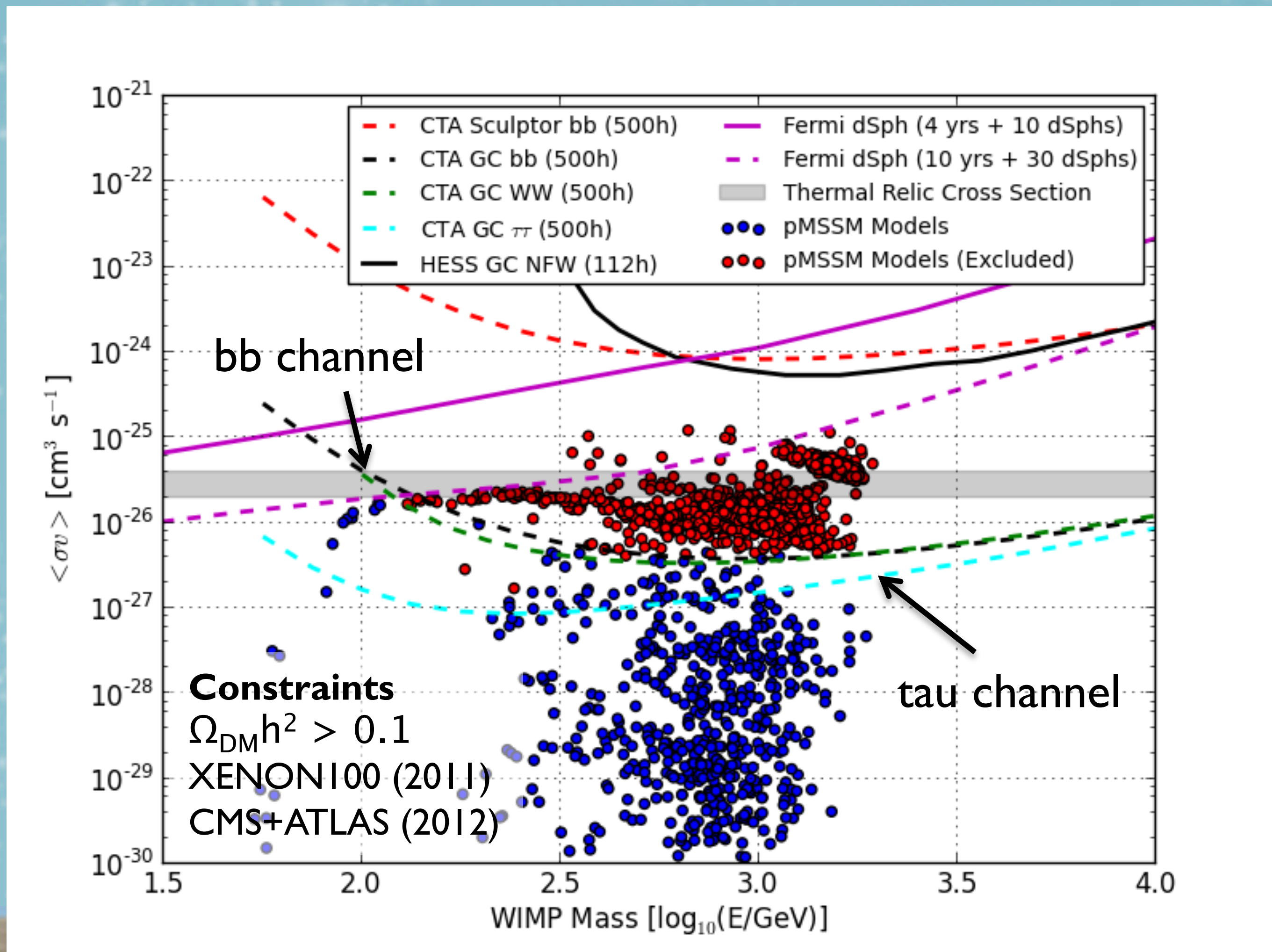


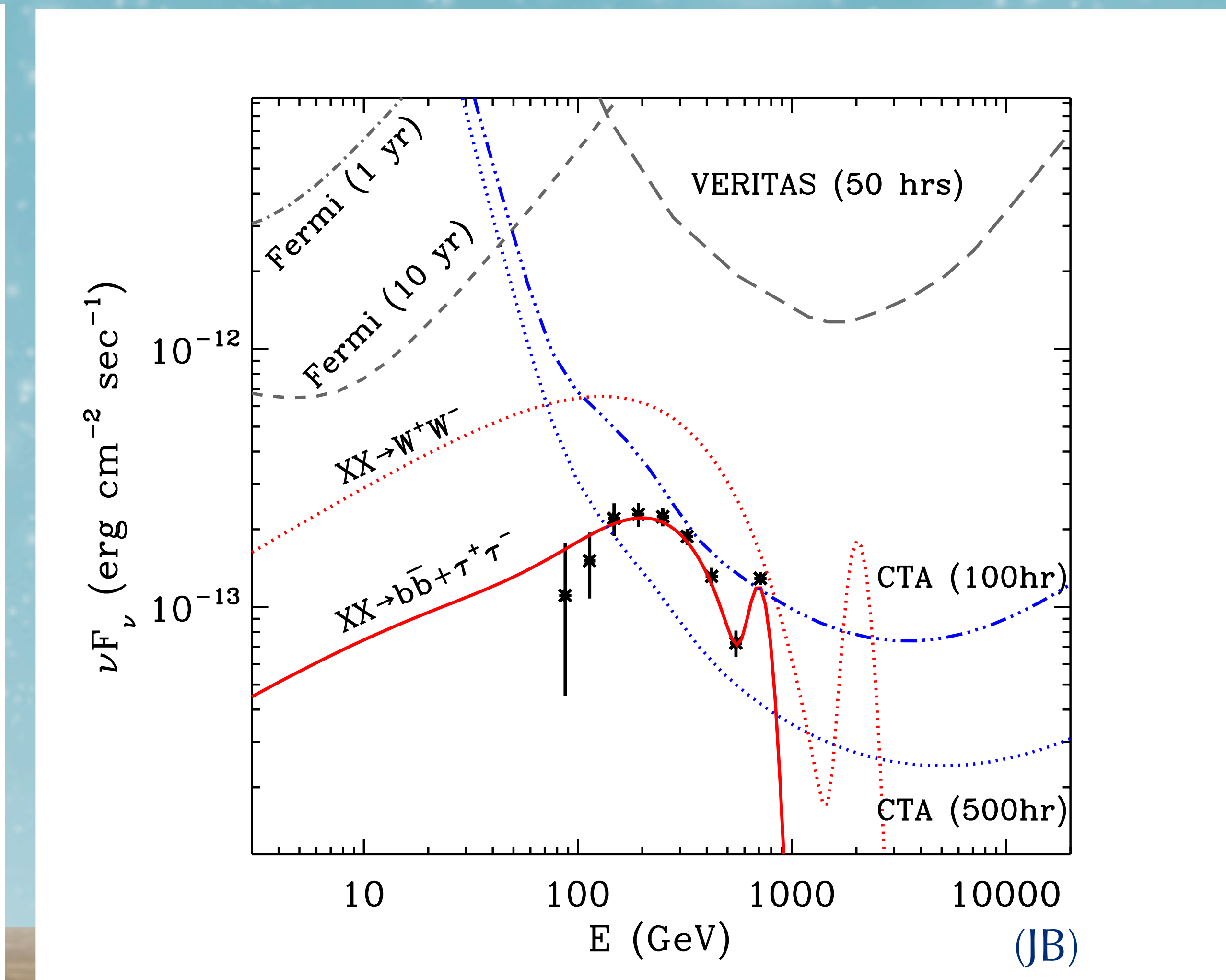
0.1% Crab Nebula
Hybrid-1 SC-MST (50 hrs)
Hybrid-1 DC-MST (50 hrs)
Fermi (3 yr, Extragalactic)
Prod-1 Array I (50 hrs)
Fermi (3yr)
~2-3x improvement
in core energy range
from US contribution
Hybrid-1 (50 hr)
Prod-1 Array I (50 hr)
Differential Flux Sensitivity [erg cm⁻² s⁻¹]
Energy [log10(E/GeV)]

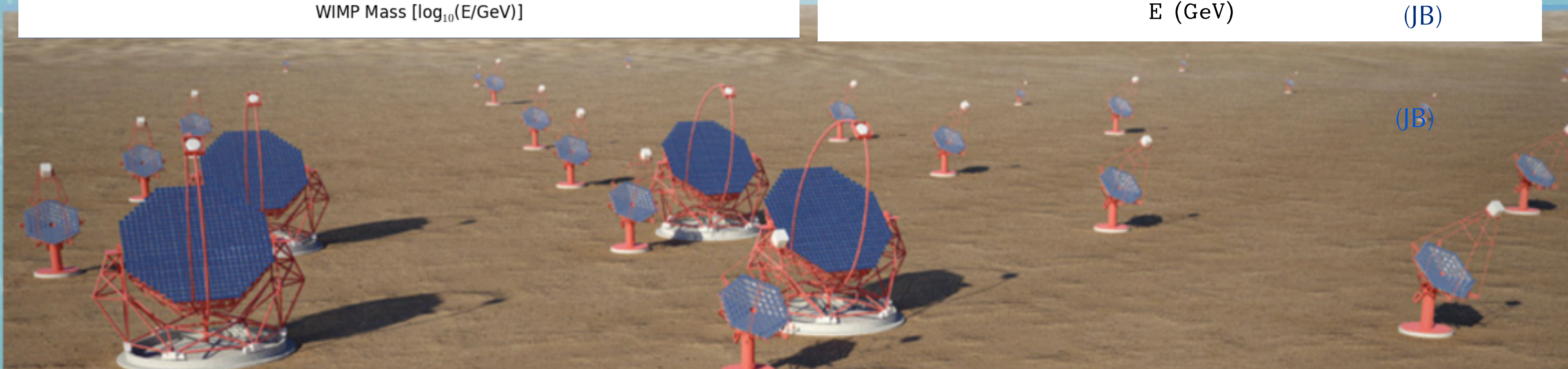


Hybrid-1 SC-MST (50 hrs)
Hybrid-1 DC-MST (50 hrs)
0.1°
0.03°
Hybrid-1
SC-MST
Hybrid-1
DC-MST
100 GeV
1 TeV
68% Containment Radius [deg]
Energy [log10(E/GeV)]

CTA

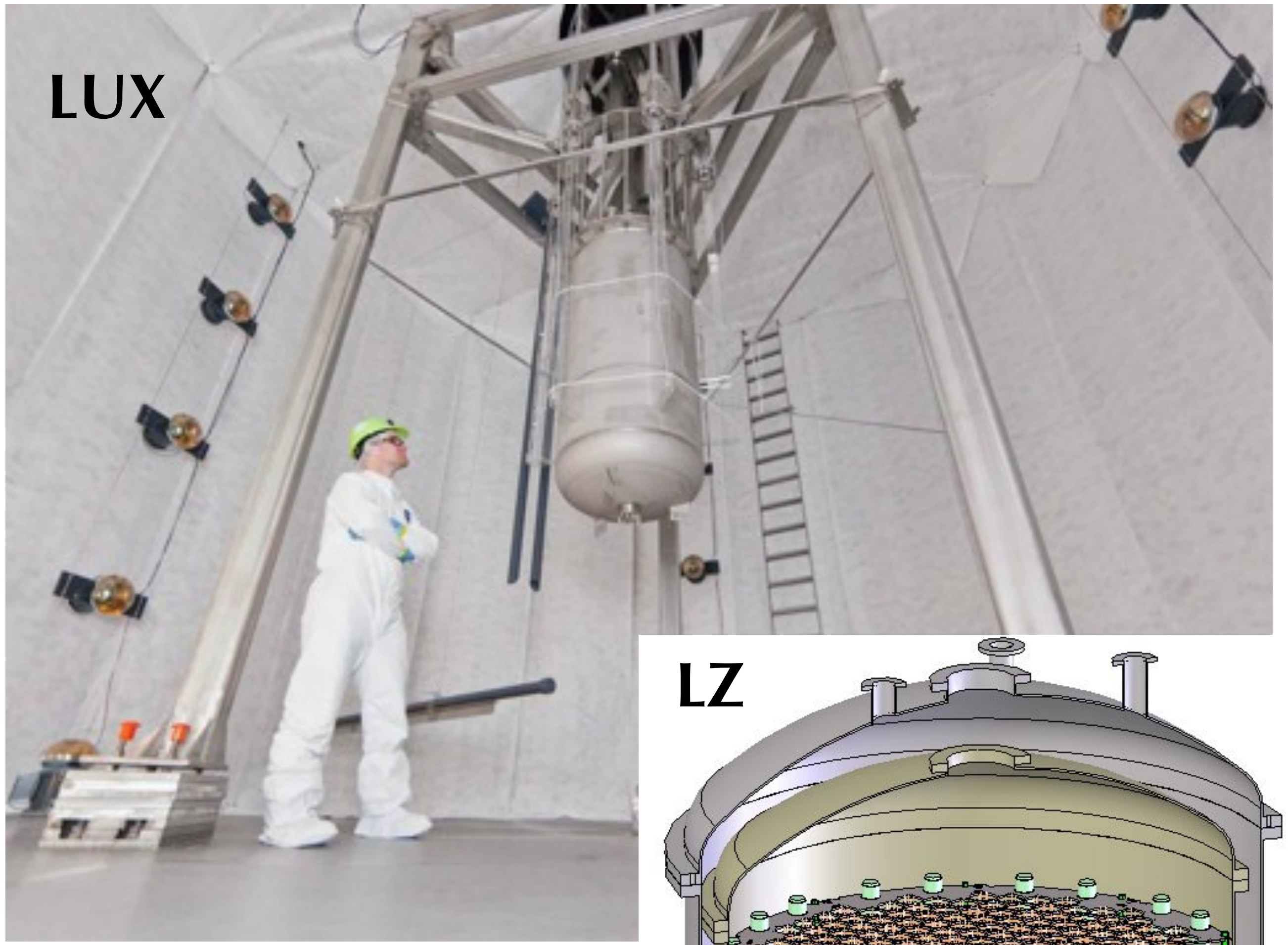


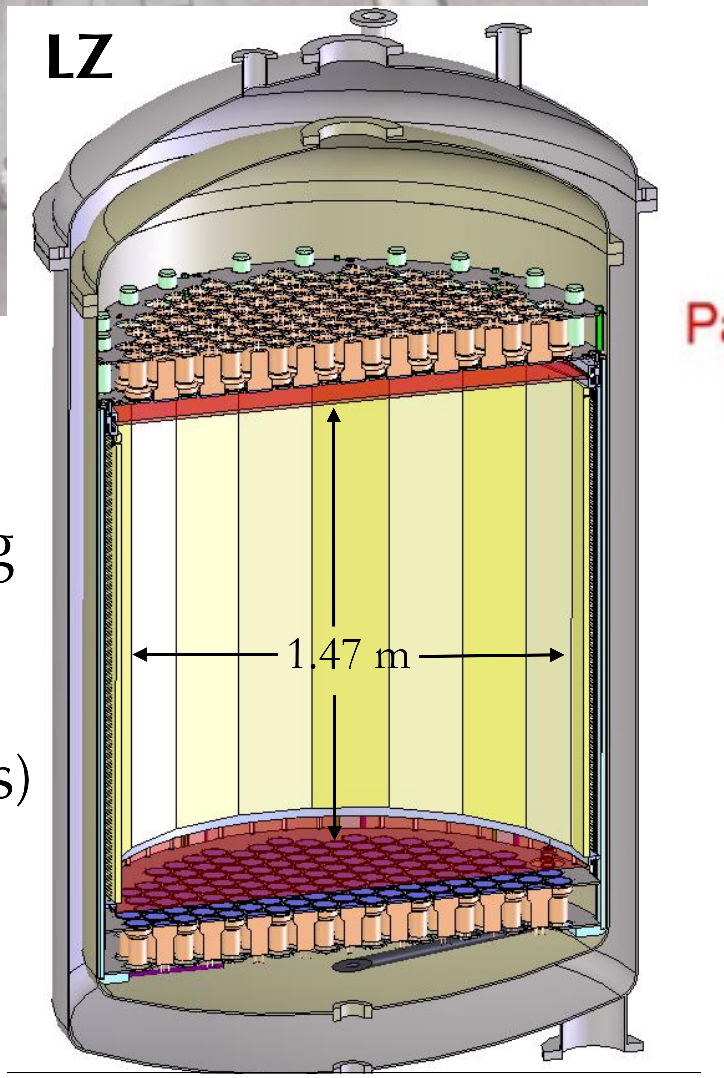




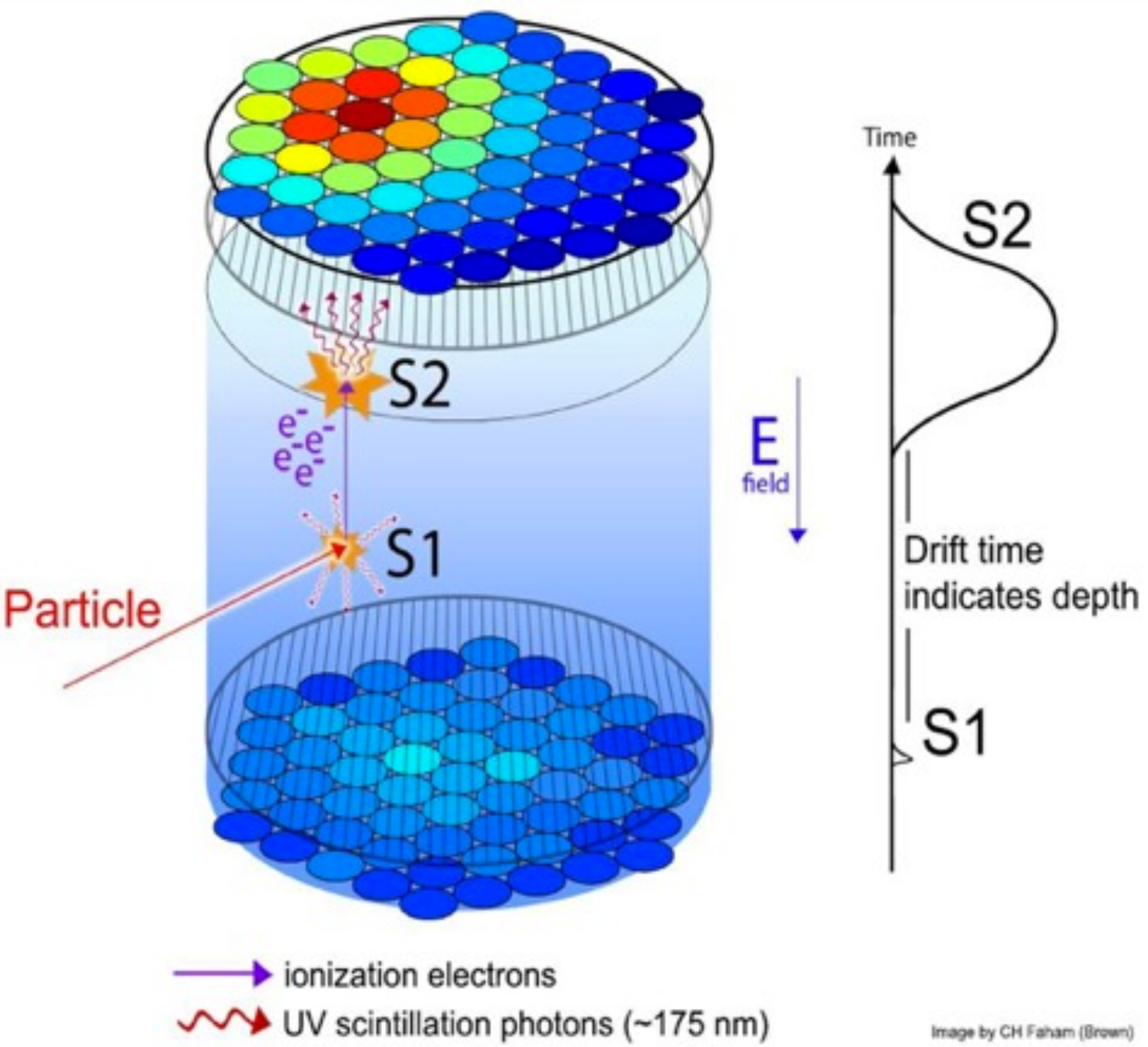
** A CTA like instrument with ~60 Mid-sized telescopes has the sensitivity to probe the natural cross section for WIMP annihilation from 100 GeV to 10 TeV - But this requires a US contribution*

Direct Detection



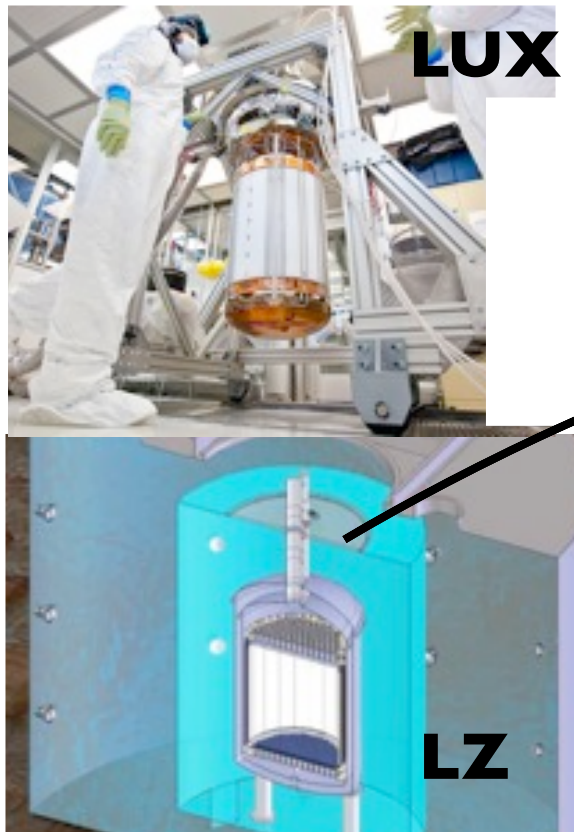


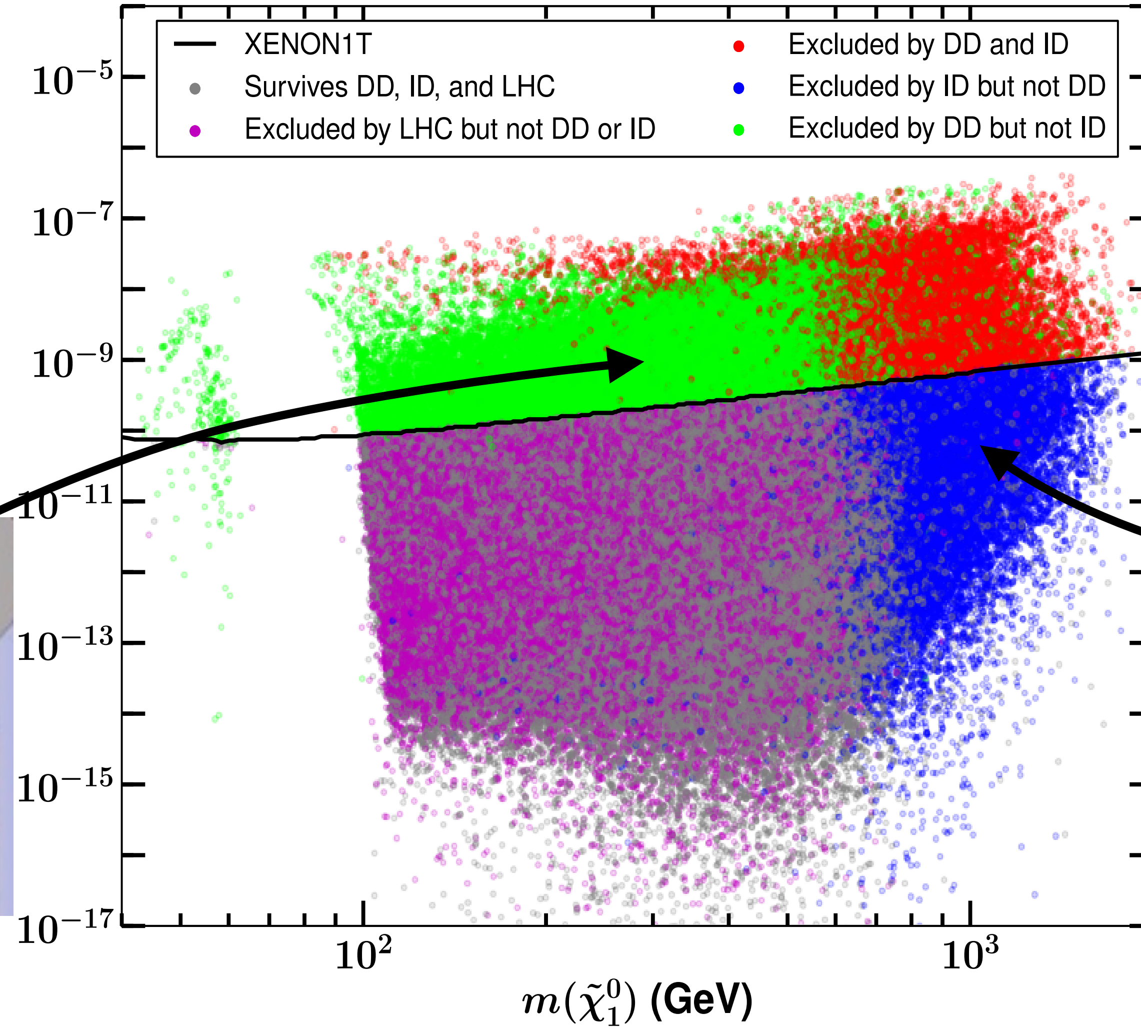
2-Phase Liquid Xenon Dark Matter Detectors

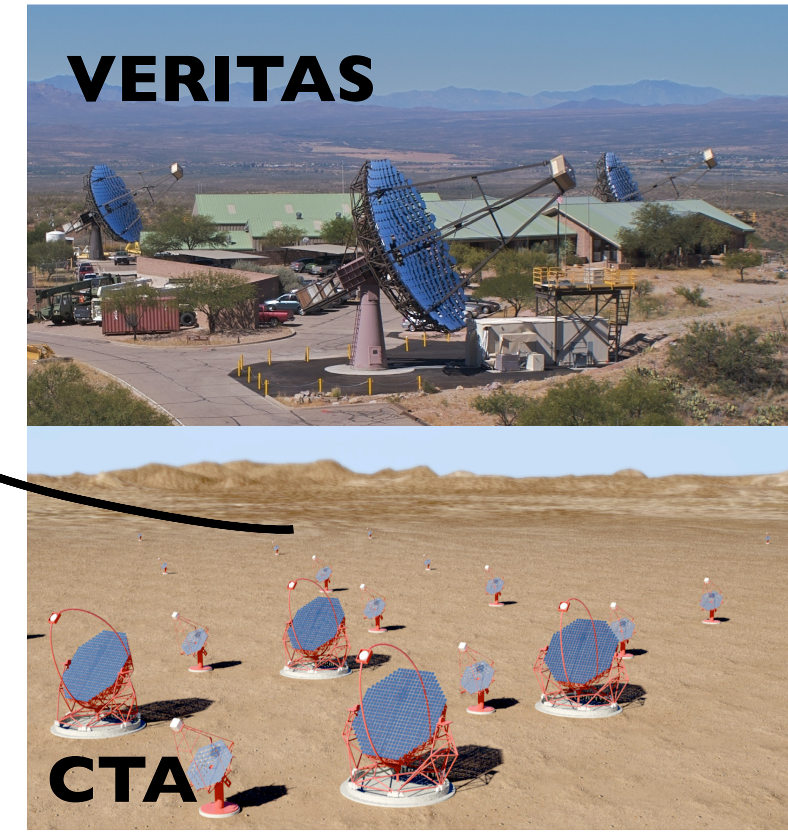


LXe Experiments currently have ~100s kg mass, next generation will have tons (e.g., LZ with 7 tons)

Conclusions



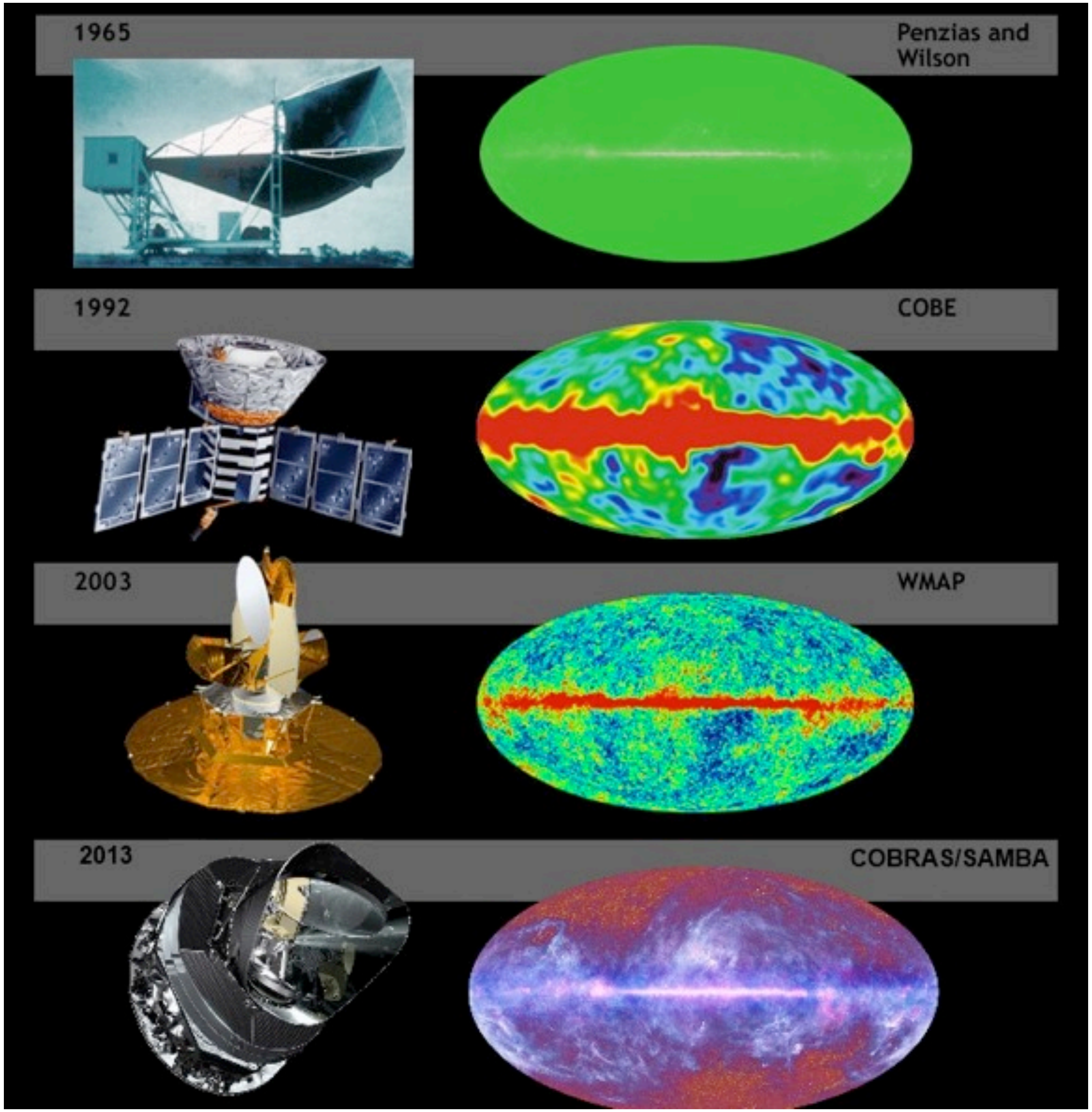




- Detailed theoretical studies with PMSSM, contact operators, realistic halo models are resulting in quantitative estimates of sensitivity, showing the complementary reach of different techniques.
- CTA, with the U.S. enhancement, would provide a powerful new tool for searching for WIMP dark matter. 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.
- Future Direct Detection Experiments are also cutting deeply into natural parameter space, soon to be limited by *pp* and atmospheric neutrinos - exciting enough that it is making at least one astronomer start working underground!

Backup Slides

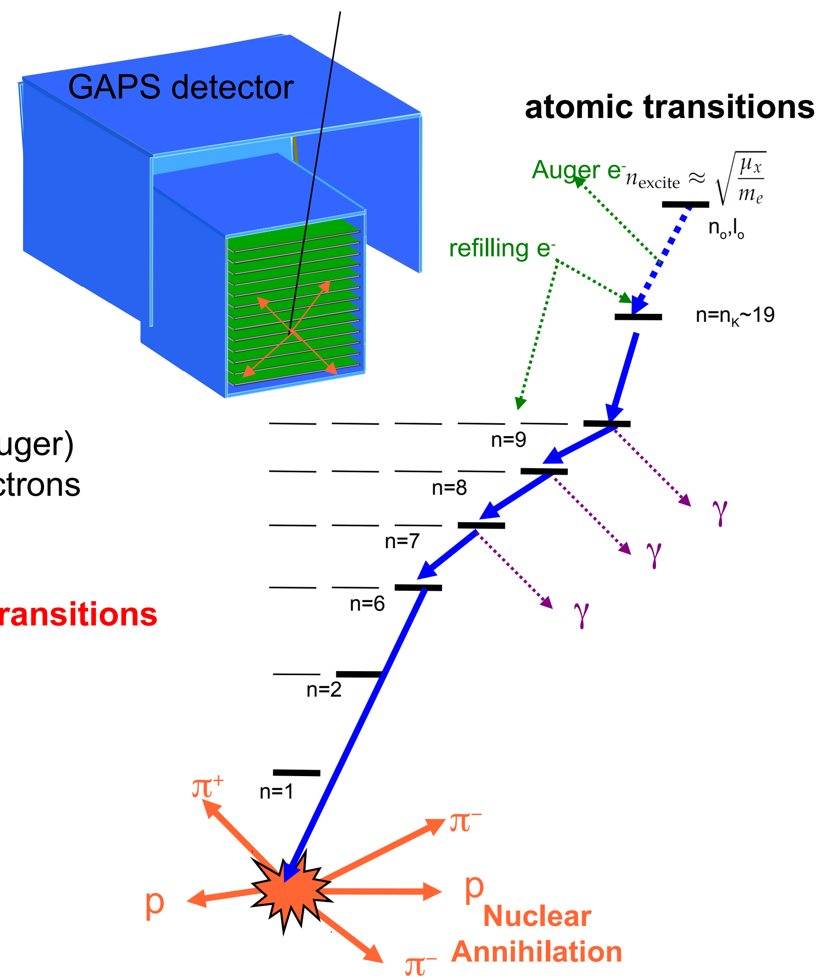
CMB Experiments

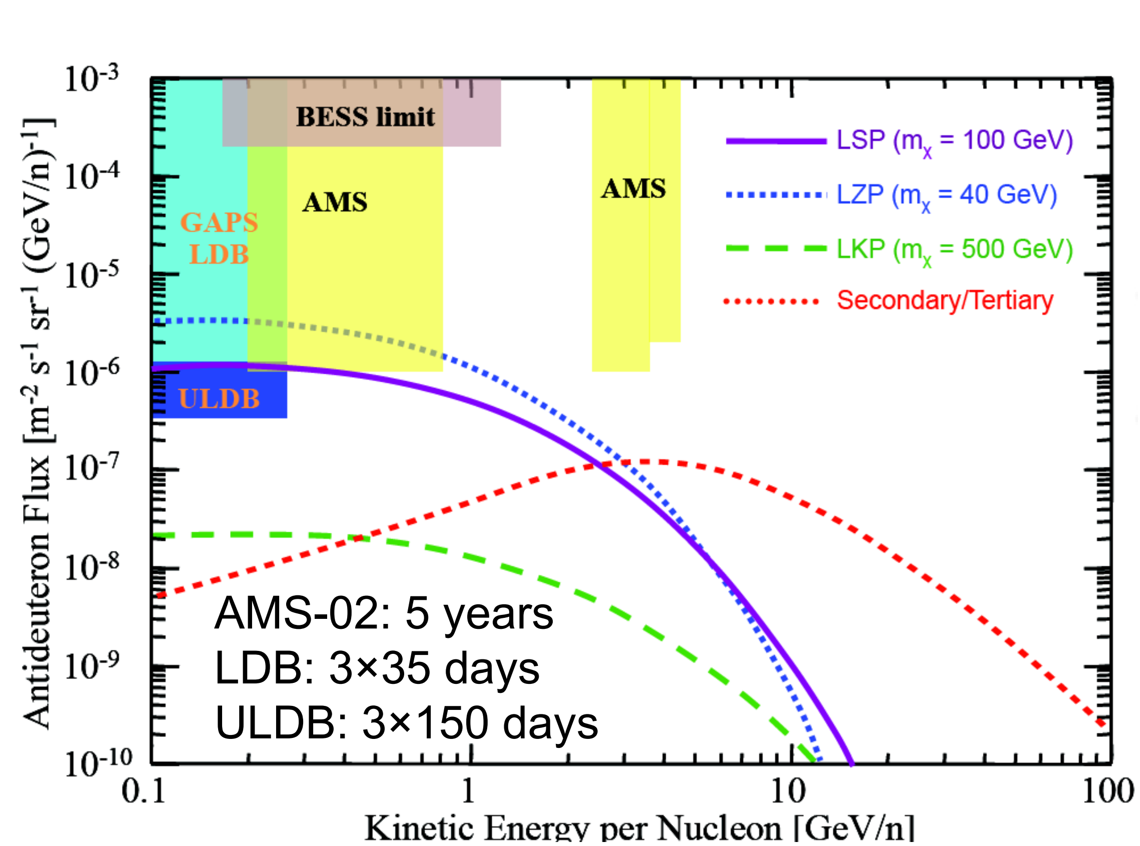


GAPS

Novel approach for antideuteron identification

- antideuteron slows down and stops in material
- large chance for creation of an excited exotic atom (E_{kin}~E_I)
- deexcitation:
  - fast ionisation of bound electrons (Auger) → complete depletion of bound electrons
  - Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via **characteristic X-ray transitions**
- nucleus-antideuteron annihilation: **pions and protons**
- exotic atomic physics understood (tested in KEK 2004/5 testbeam)

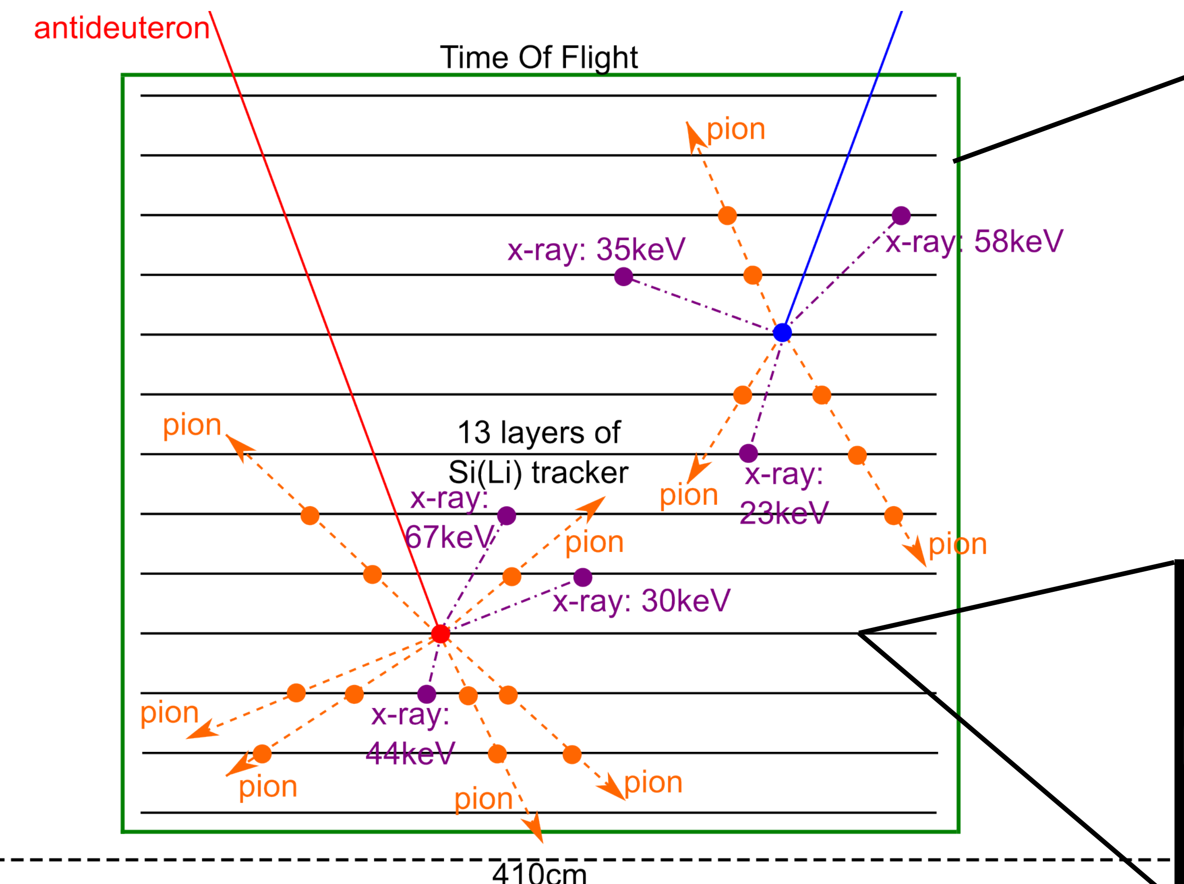


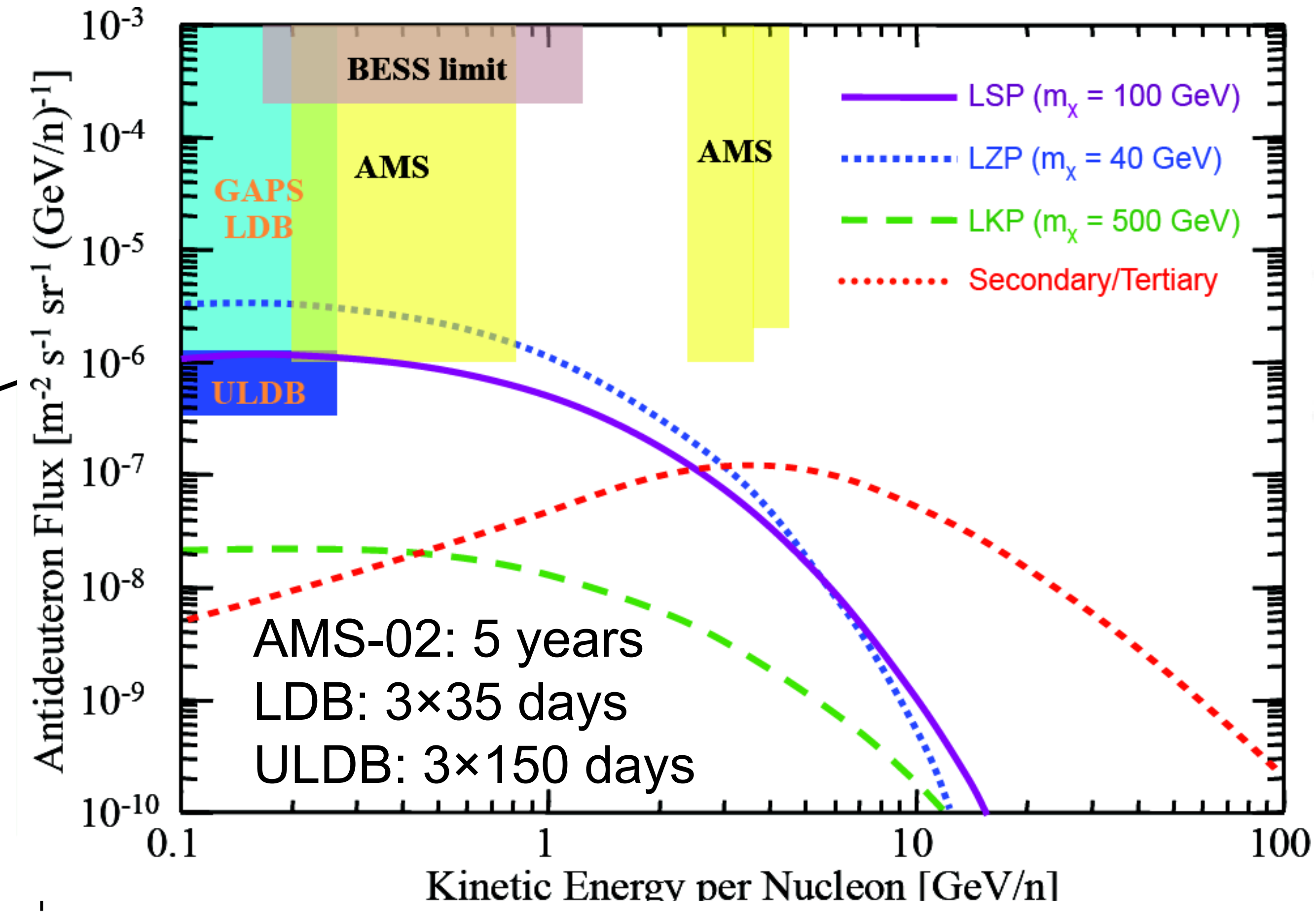


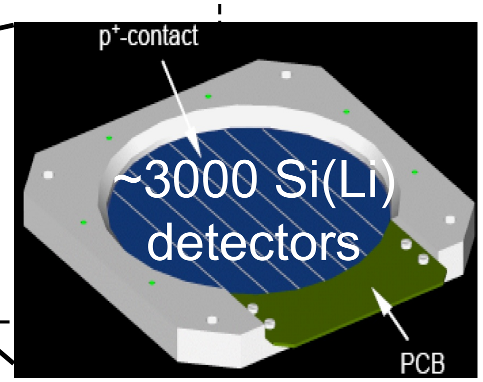
Ph. von Doetinchem **GAPS** March 13 - p6

Antideuteron Measurements

(SLAC CF Workshop talk
by P. von Doetinchem)

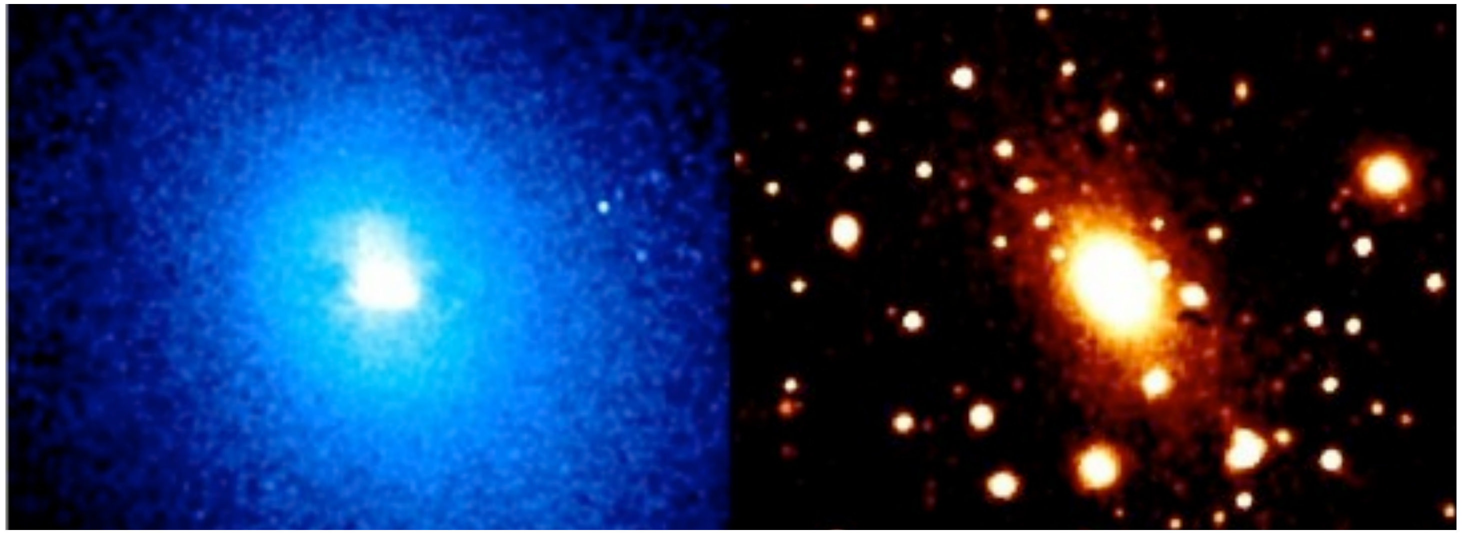




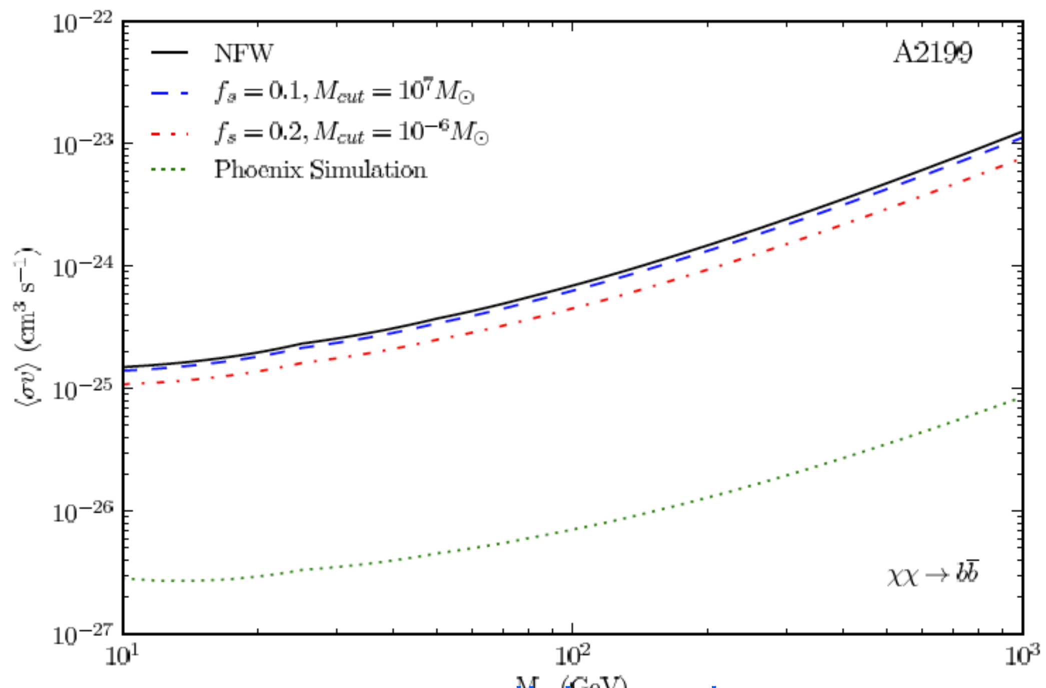


- GAPs looks for anti-deuterons (hard to produce as CR secondaries), uses TOF, X-rays from short-lived exotic atom, pion star from annihilation

Astrophysical Constraints



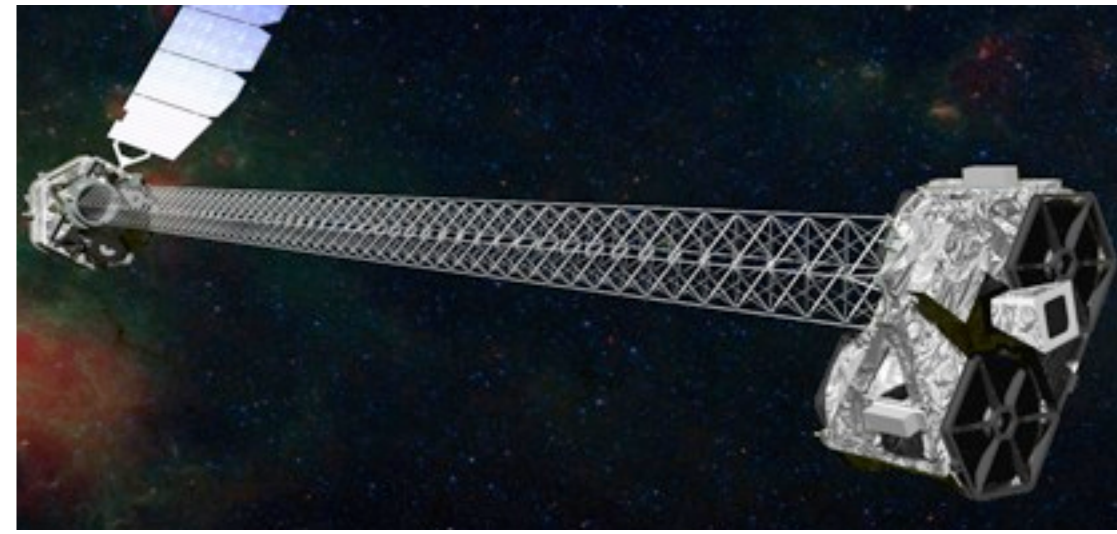
Radio Constraints on Galaxy Cluster (A2199)

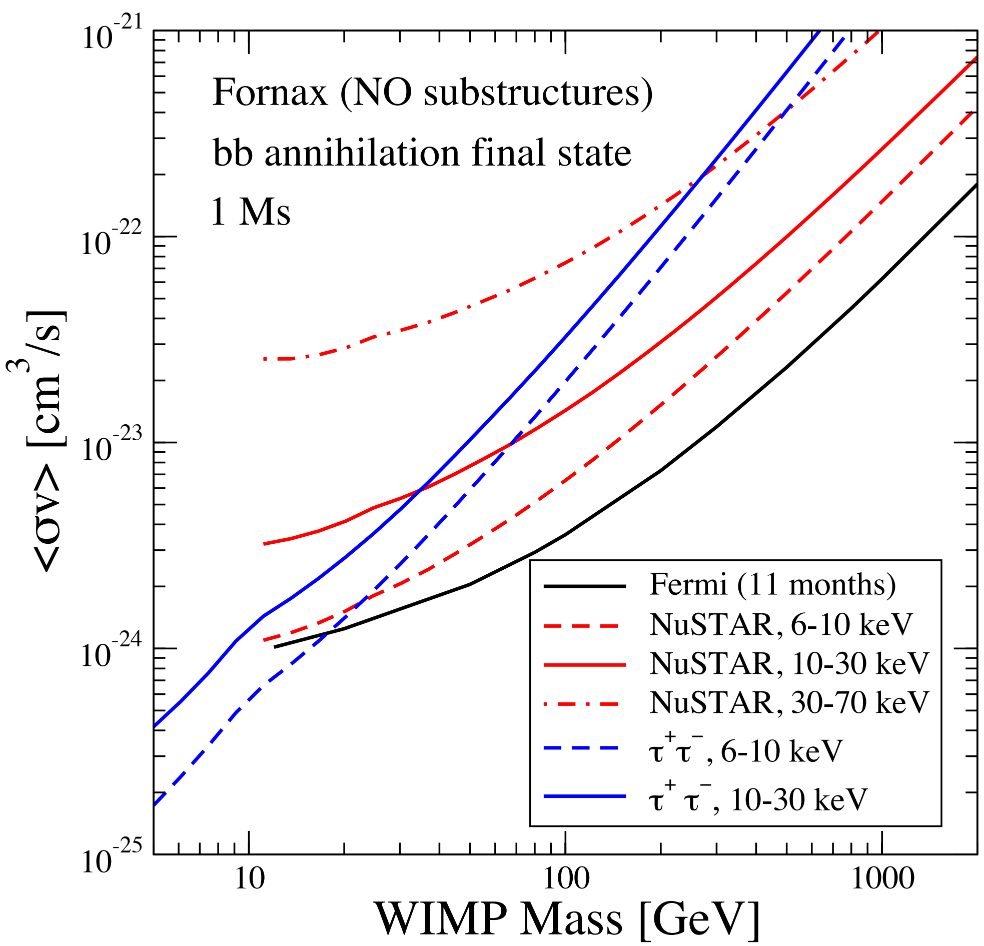


(SLAC CF Talk by T. Jeltema)

- When the magnetic field and diffusion are understood, radio constraints on DM can be important.
- Electrons up-scatter CMB photons, producing a measurable X-ray signal and DM constraints

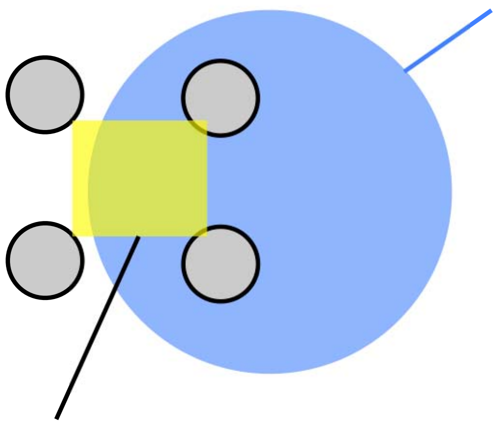
X-Ray (NuSTAR) constraints on Fornax cluster compared with Fermi gamma-ray constraints





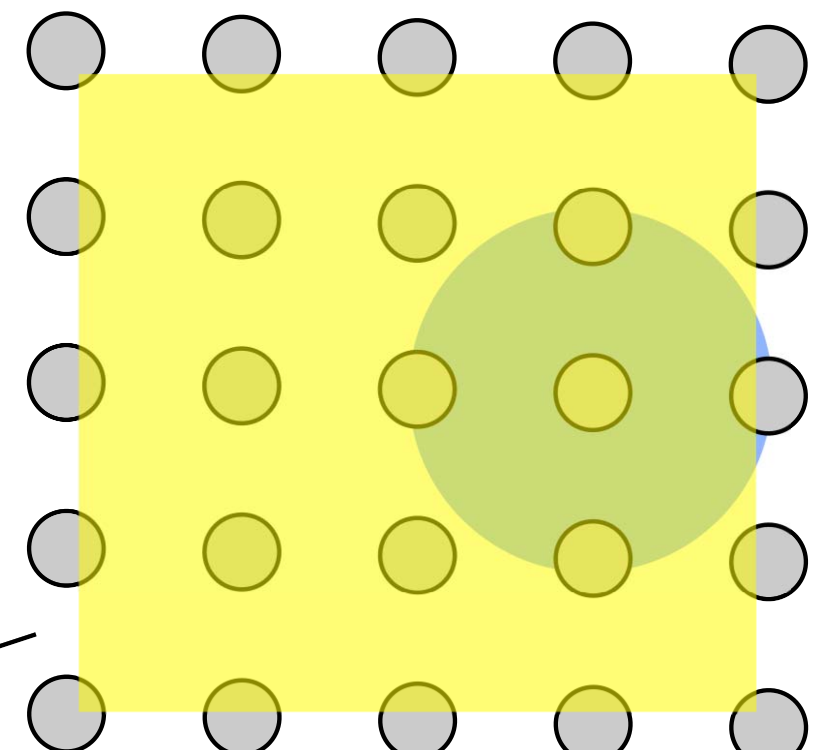
Contained Events

From current arrays to CTA



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

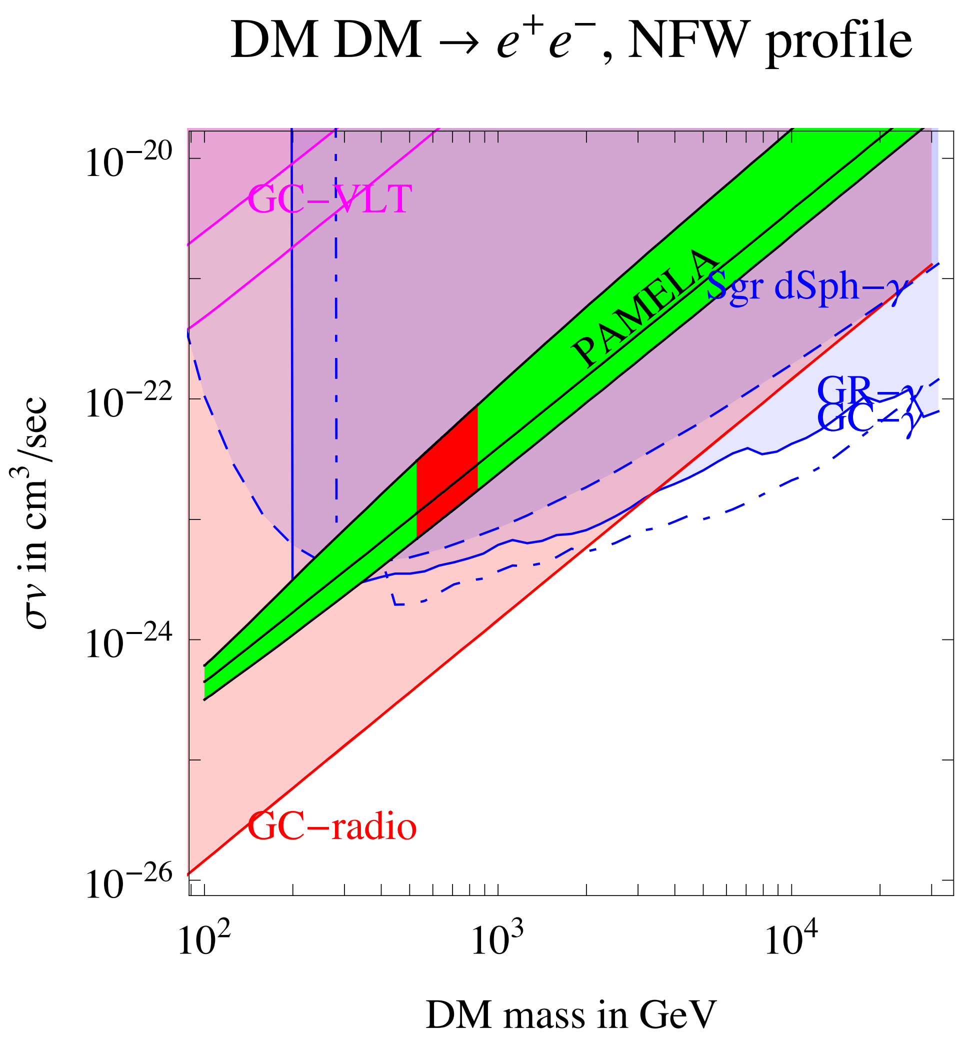
Sweet spot for
best triggering
and reconstruction:
Most shower cores miss it!



Large detection area
More images per shower
Lower trigger threshold

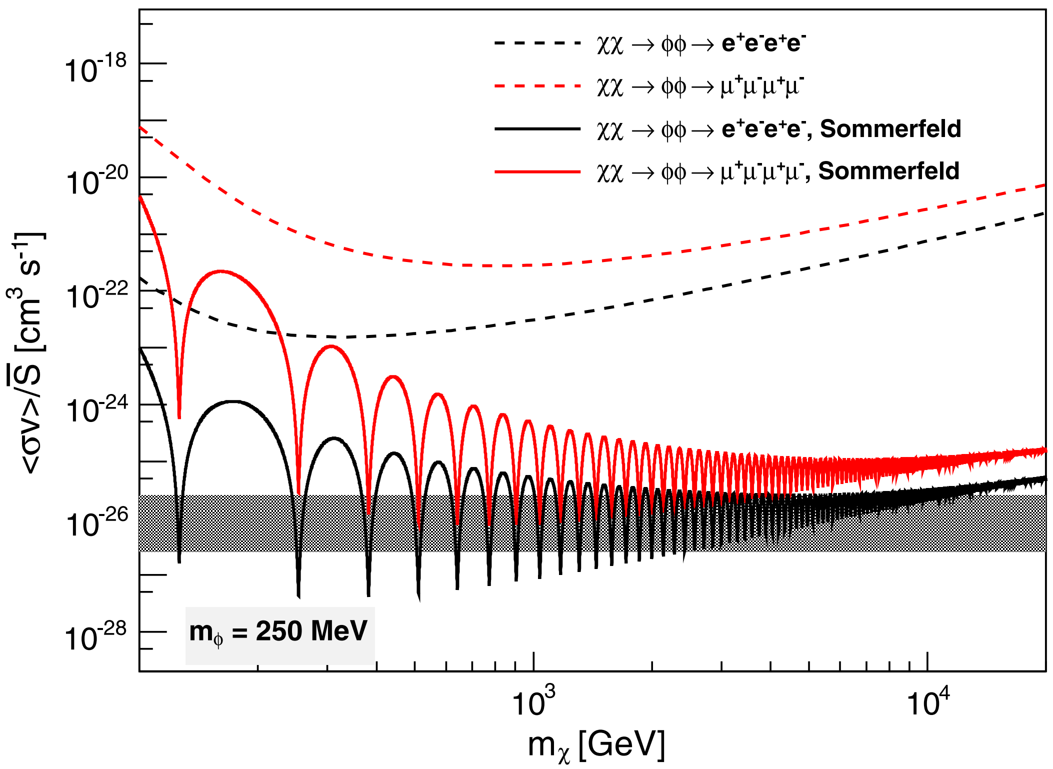
3

Shedding Light on Positrons



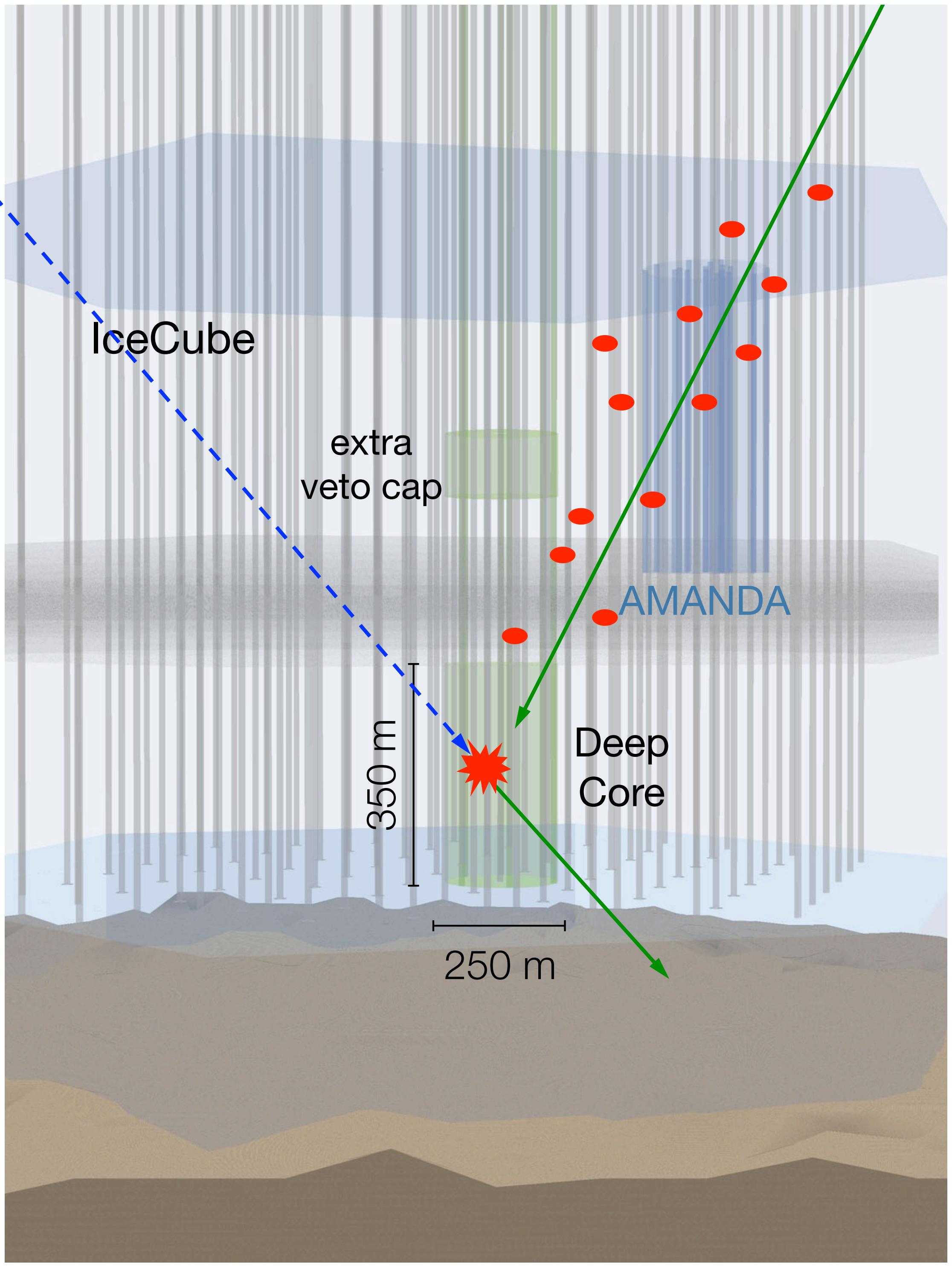
Radio Synchrotron and gamma-ray IC limits for Pamela scenario (Bertone, Cirelli, Strumia and Taoso, arXiv:0811.2744v3). *Note: Radio bounds are sensitive to assumptions about B-fields and diffusion, may be optimistic.*

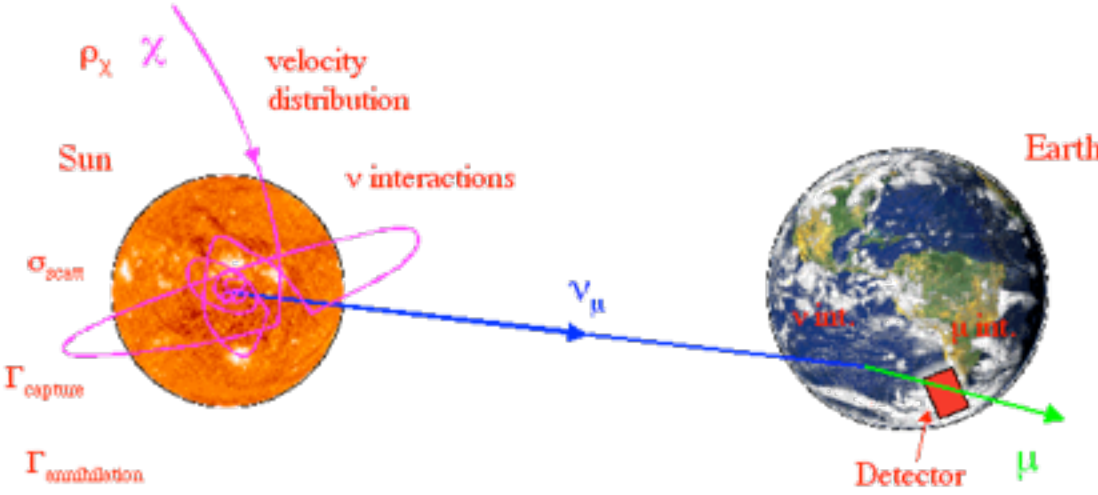
VERITAS Segue Limits with Sommerfeld Enhancement

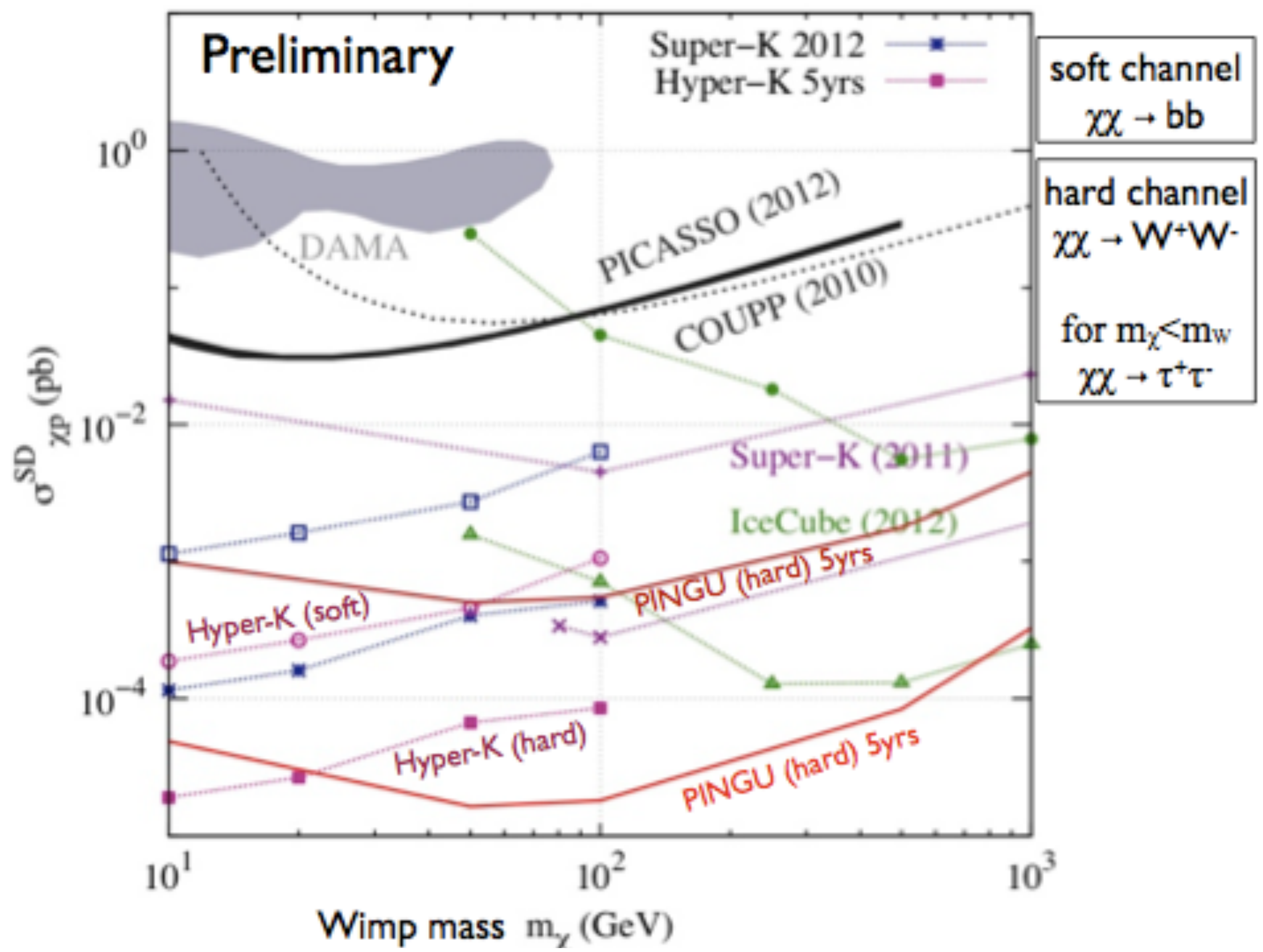


- Pamela excess implies a large radio synchrotron and inverse Compton signal, and a boost in secondary gammas from the GC that are not observed.

Future Neutrino Detectors

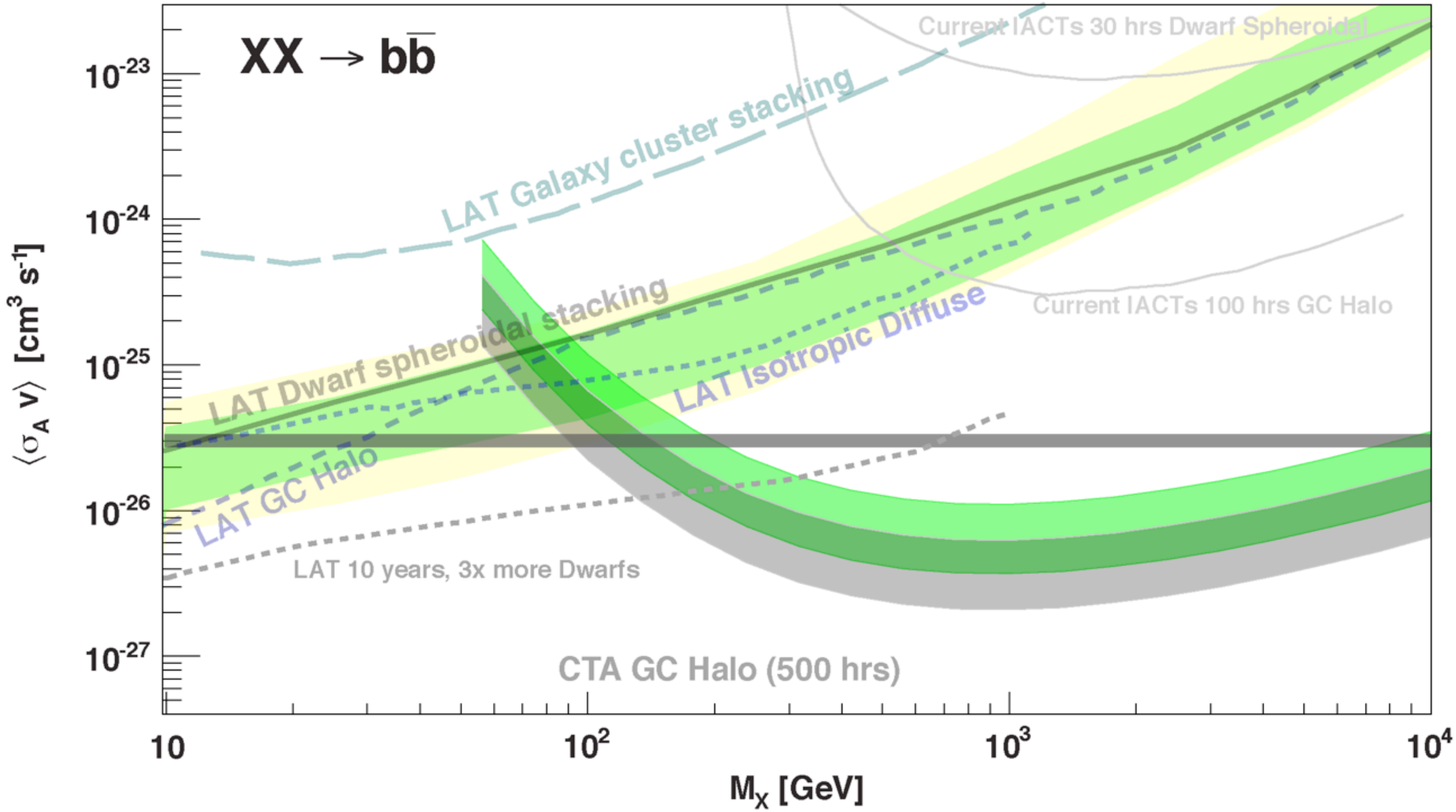






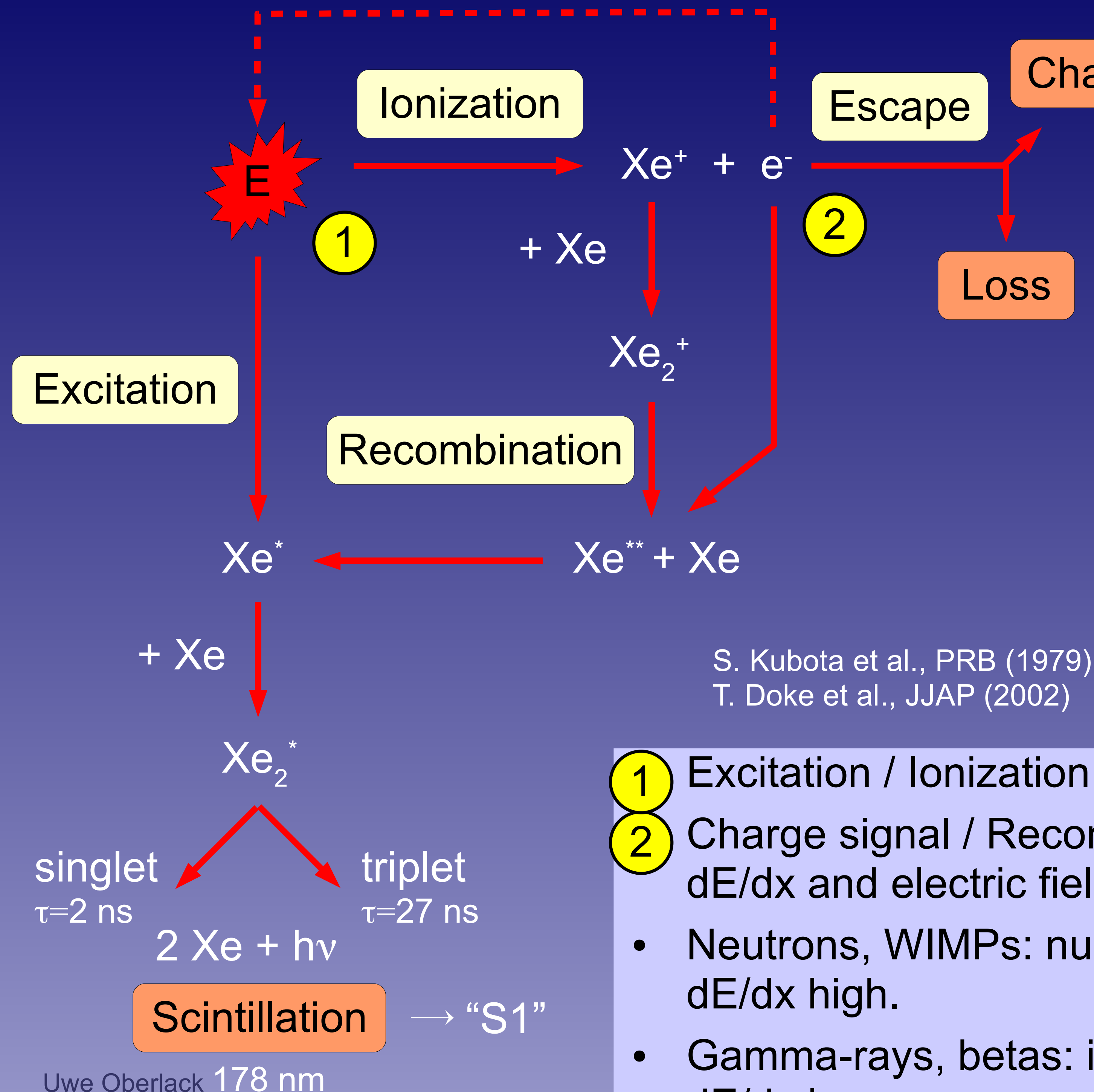
* *Future neutrino experiments like the PINGU enhancement to IceCube/DeepCore offer the possibility of discovery of a smoking-gun signal (high energy neutrinos from the sun), and may provide some of the best constraints on spin dependent cross sections.*

Gamma-Ray Sensitivity



LXe Detectors

Ionization and Scintillation in LXe



S. Kubota et al., PRB (1979)
T. Doke et al., JJAP (2002)

Excitation Scintillation:

$$Xe^* + Xe \rightarrow Xe_2^*$$
$$Xe_2^* \rightarrow 2\,Xe + h\nu$$

Recombination Scintillation:

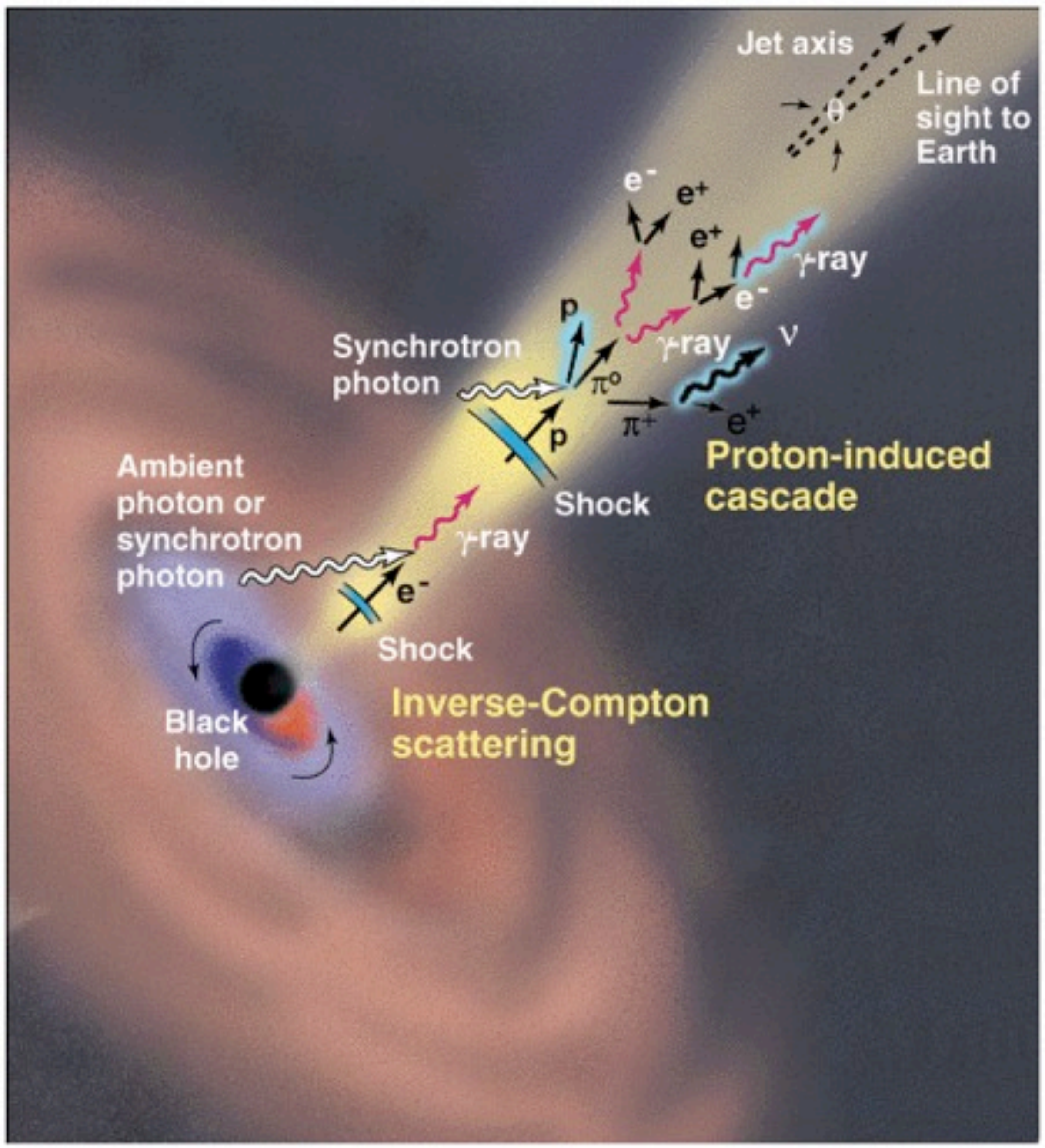
$$Xe^+ + Xe \rightarrow Xe_2^+$$
$$Xe_2^+ + e^- \rightarrow Xe^{**} + Xe$$
$$Xe^{**} \rightarrow Xe^* + \text{heat}$$
$$Xe^* + Xe \rightarrow Xe_2^*$$
$$Xe_2^* \rightarrow 2\,Xe + h\nu$$

1. Excitation / Ionization depends on dE/dx.
2. Charge signal / Recombination depends on dE/dx and electric field.

- Neutrons, WIMPs: nuclear recoil O(10 keV), dE/dx high.
- Gamma-rays, betas: interactions with electrons, dE/dx low.

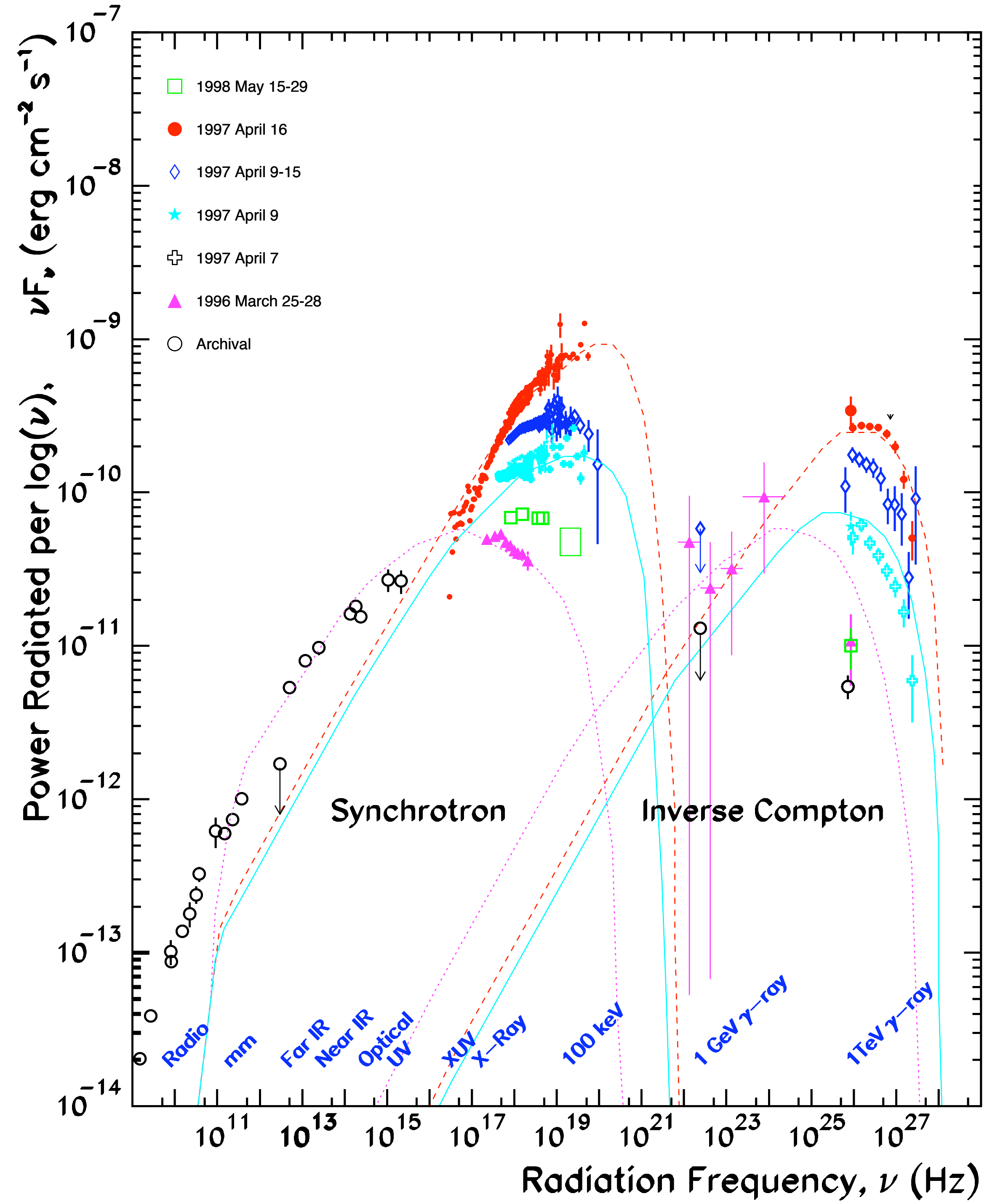
(from Uwe Oberlack, Rice)

A Typical Source

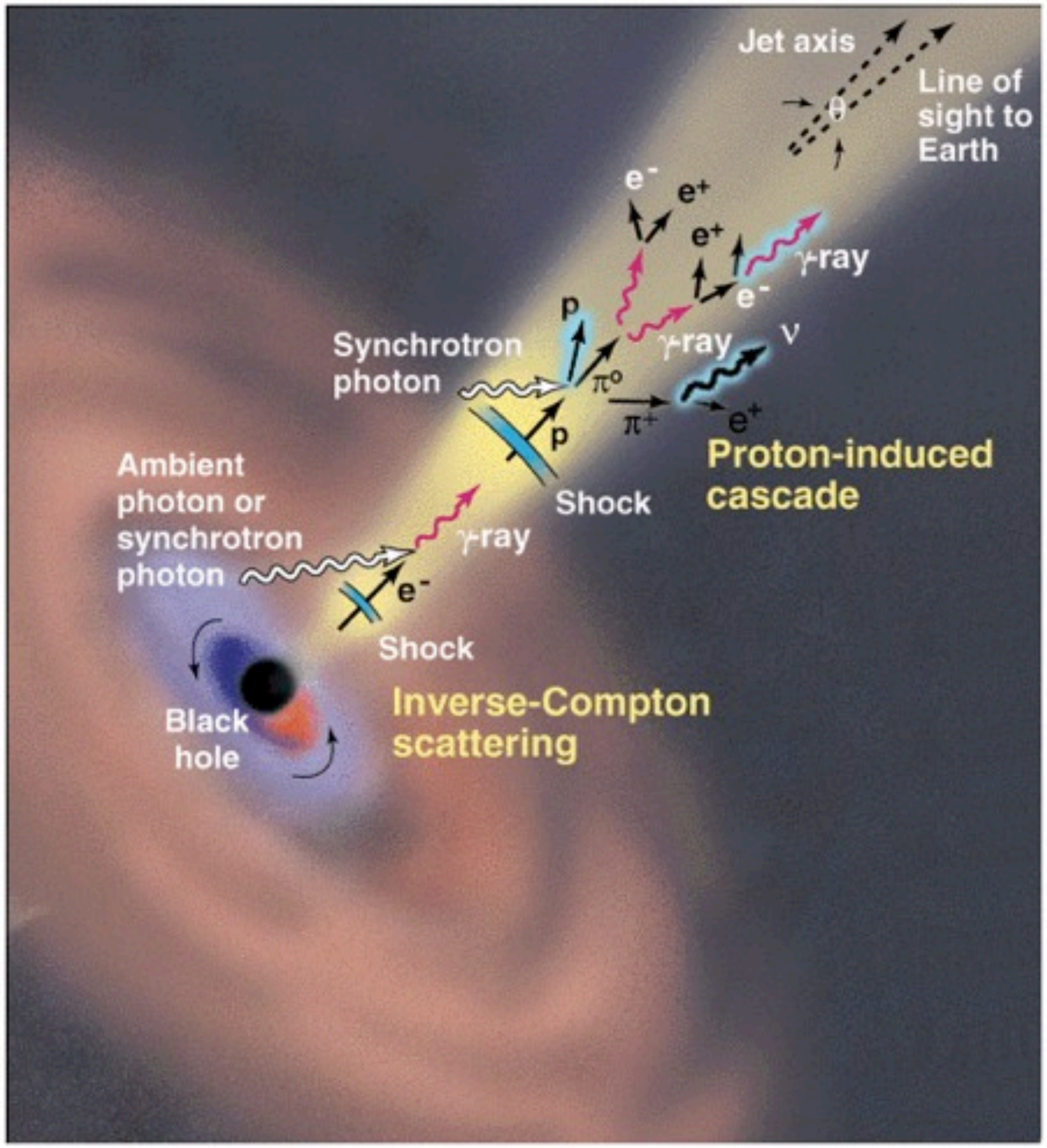


(Adapted from Buckley, Science, 1998)

Markarian 501 SED

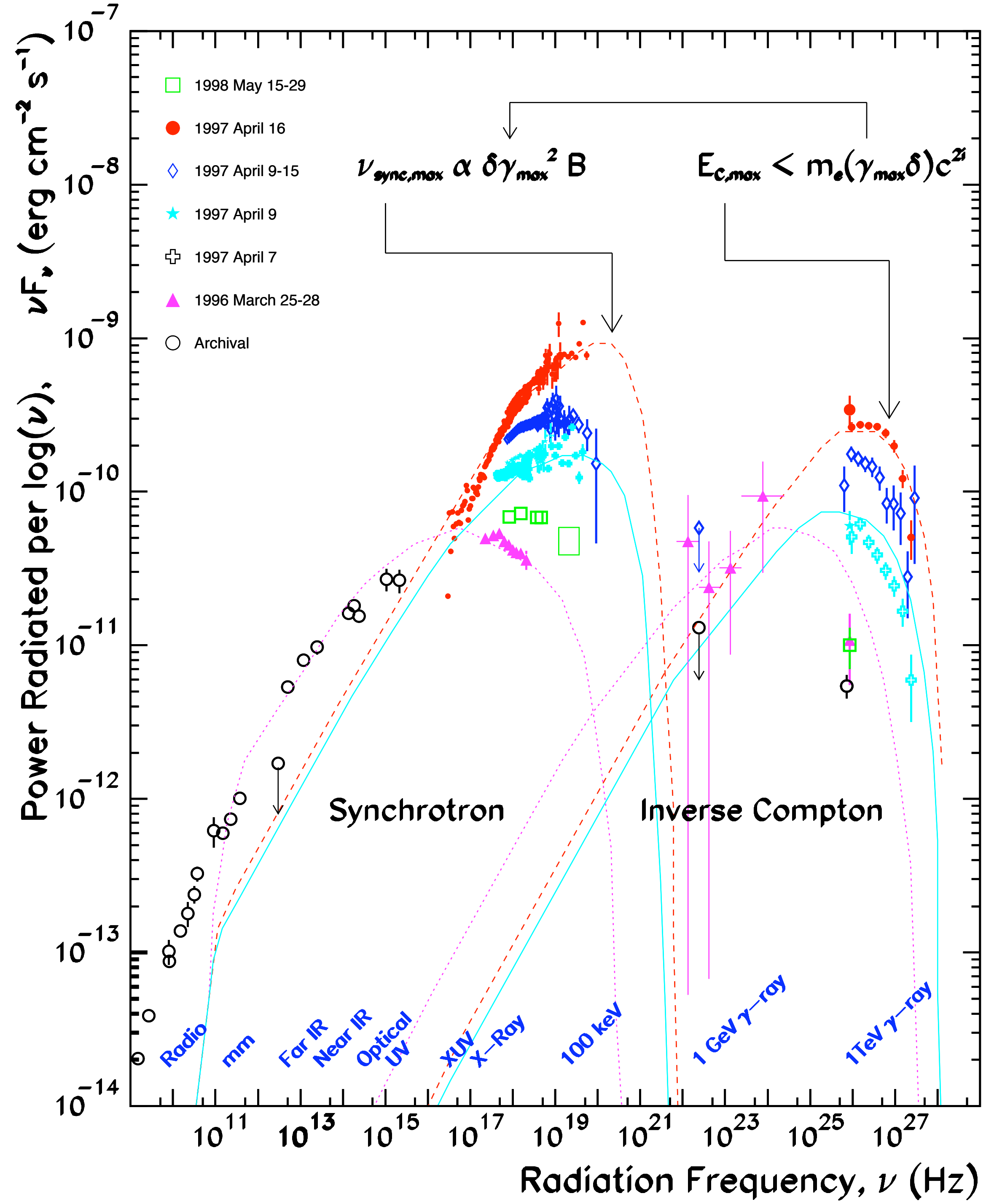


A Typical Source



(Adapted from Buckley, Science, 1998)

Markarian 501 SED



Technical Details

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

Technical Details

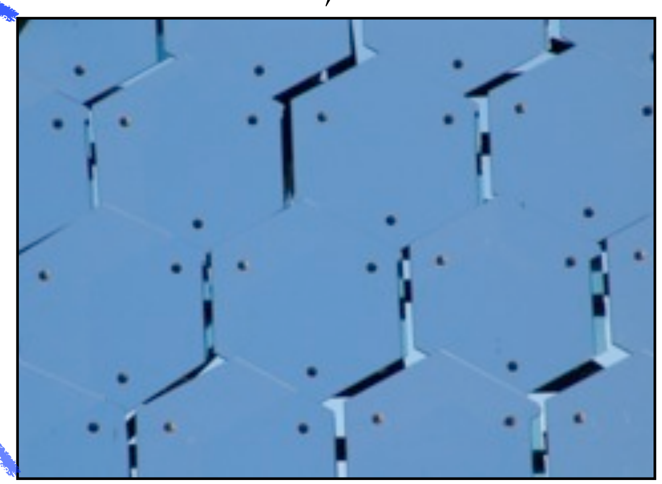
Camera (x 4)
499 PMTs, 3.5° FOV

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

Technical Details

Camera (x 4)

499 PMTs, 3.5° FOV



Telescope (x 4)

12-m diameter Davies-Cotton

f 1.0, 110 m2 area

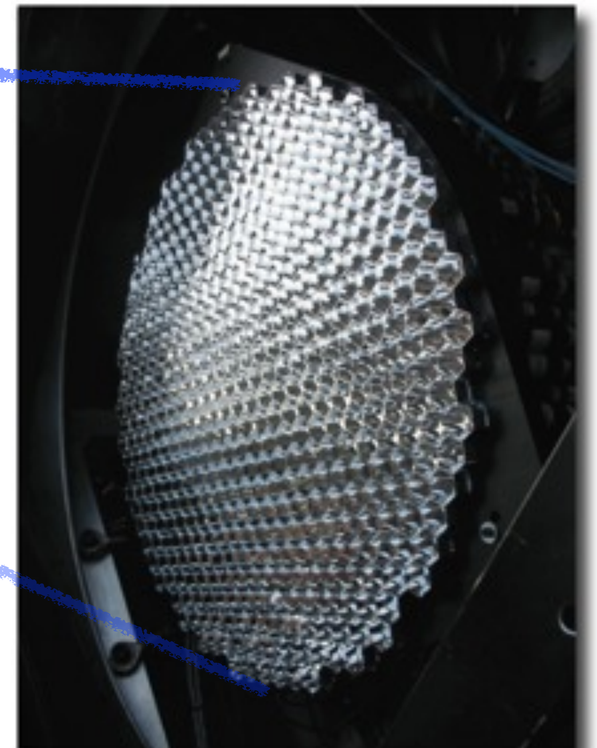
Mirror Facets (x 350)

Reflectivity ~ 88%

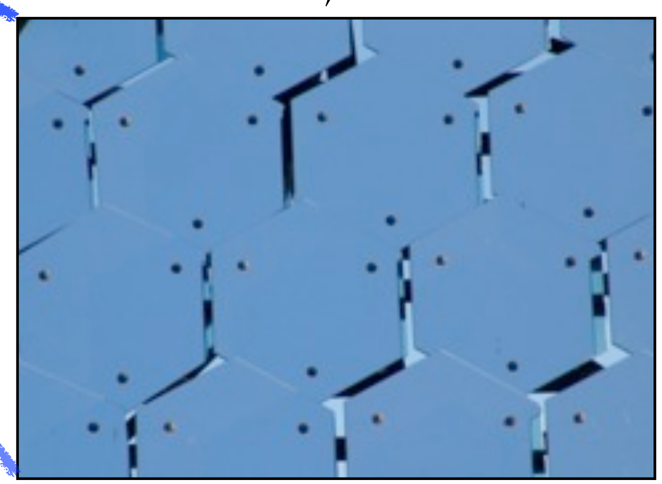
(Recoated every 2 years)

Technical Details

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



Camera (x 4)
499 PMTs, 3.5° FOV



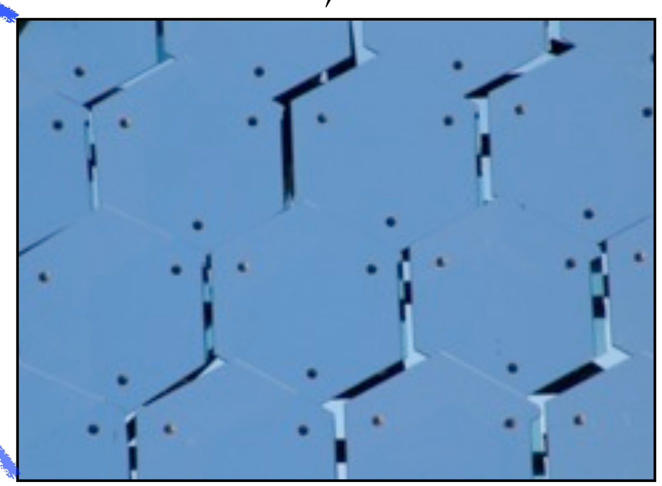
Mirror Facets (x 350)
Reflectivity ~ 88%
(Recoated every 2 years)

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

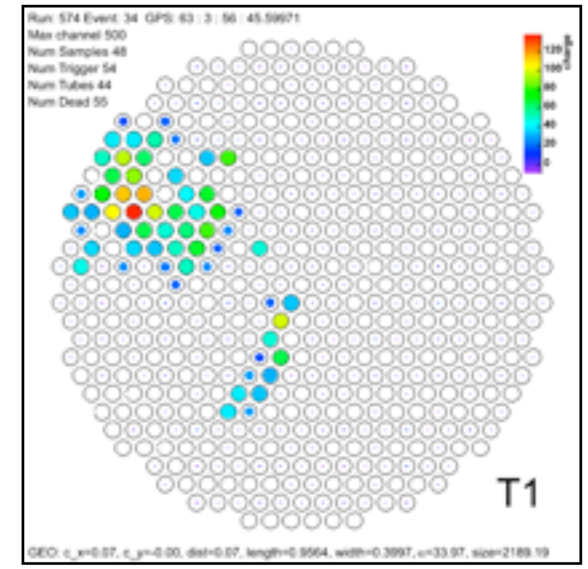
Technical Details

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

Camera (x 4)
499 PMTs, 3.5° FOV

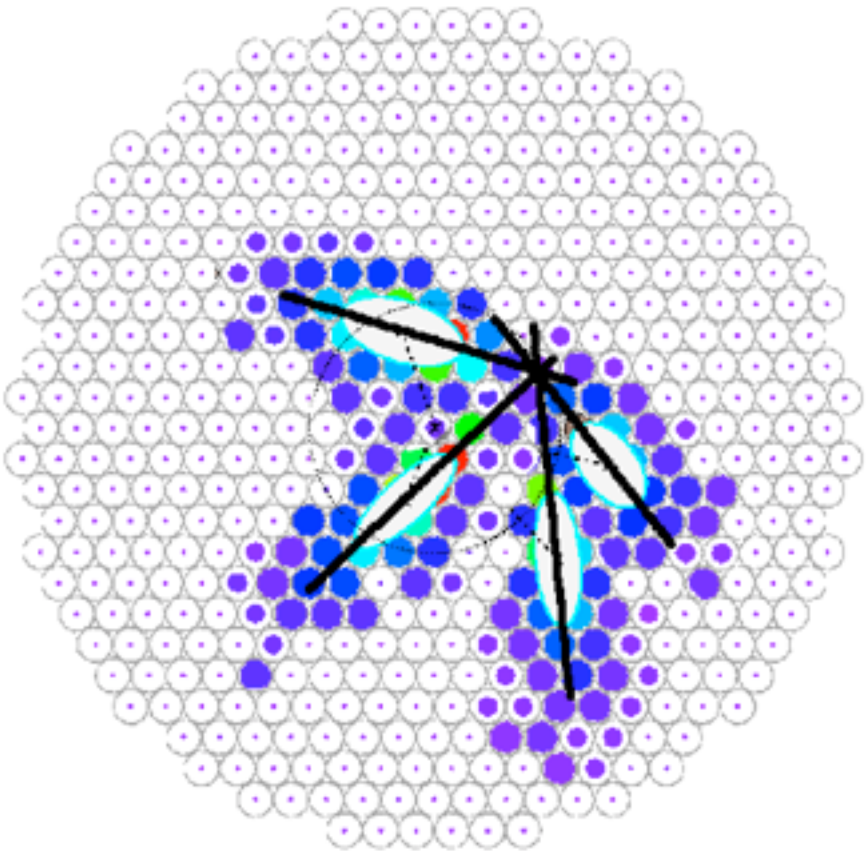


Mirror Facets (x 350)
Reflectivity ~ 88%
(Recoated every 2 years)

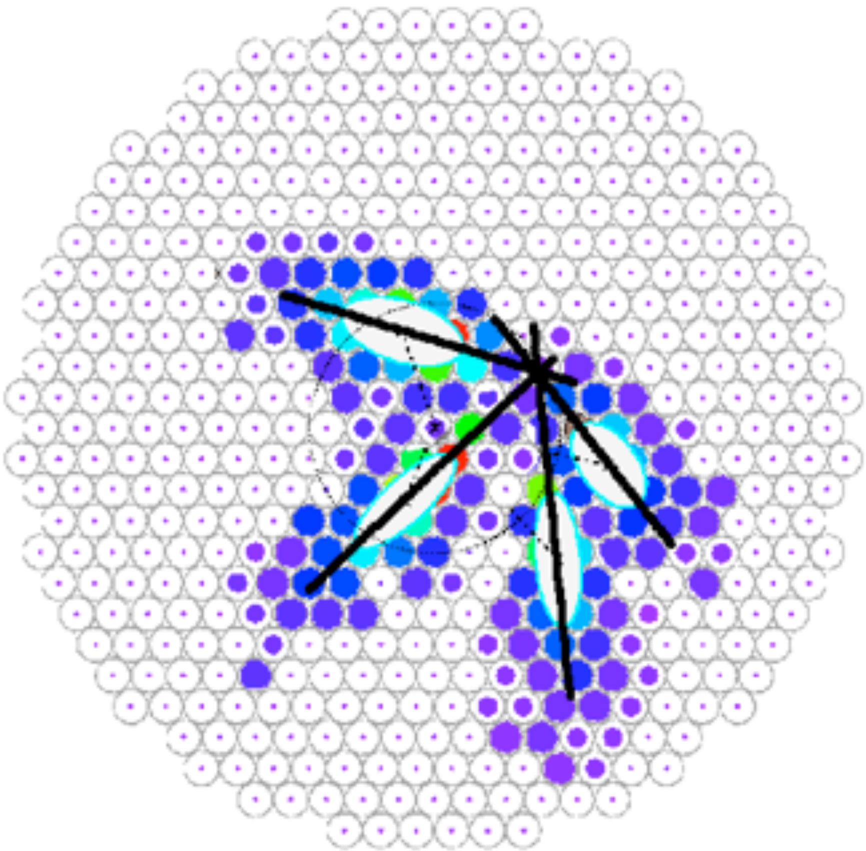


Electronics
500 Msp FADC, CFD trigger, 3-fold adjacent pixels and 2/4 telescope coincidence

IACT Arrays

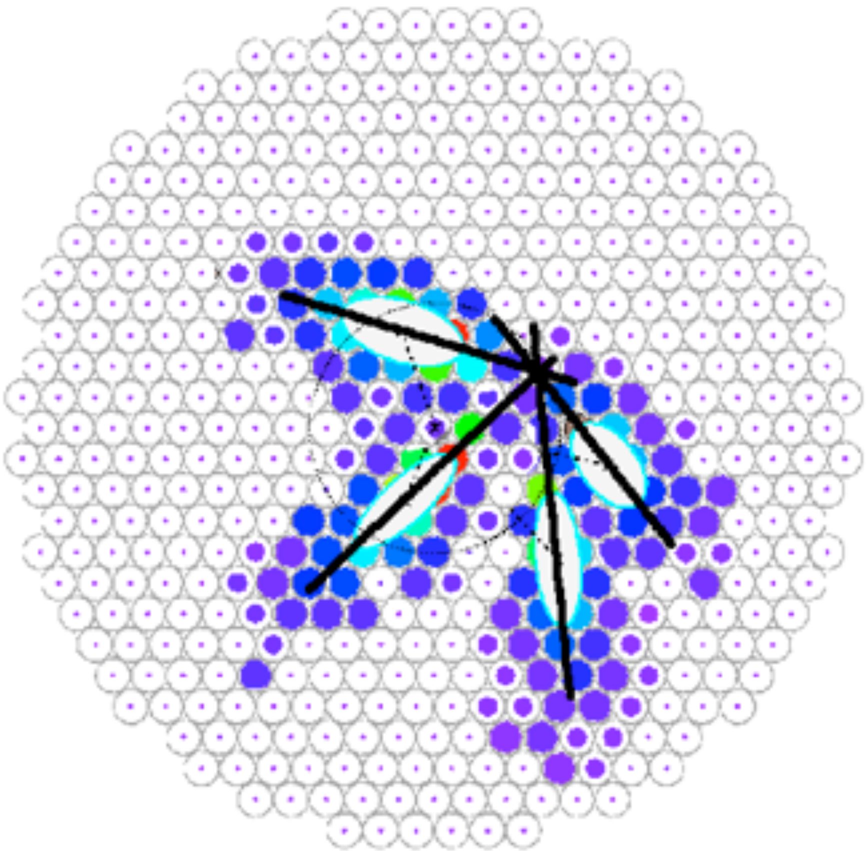


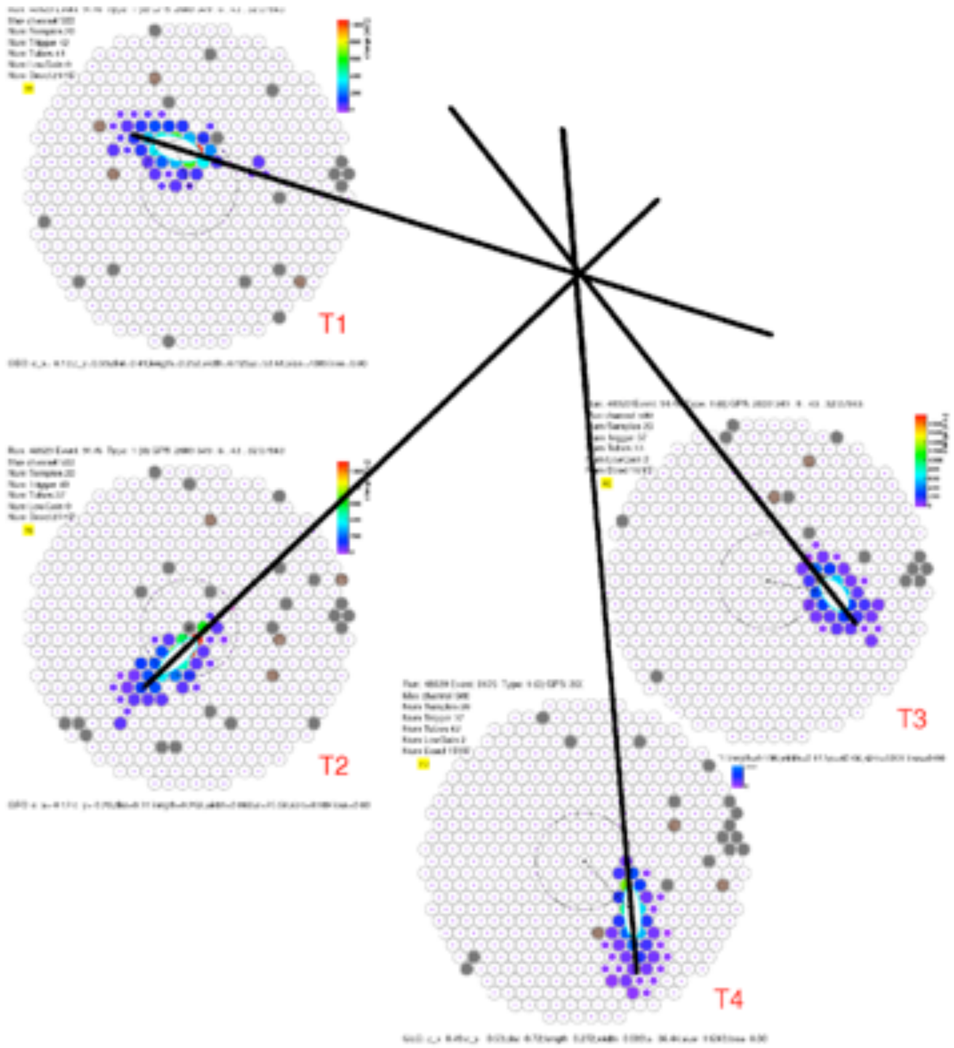
IACT Arrays



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

IACT Arrays

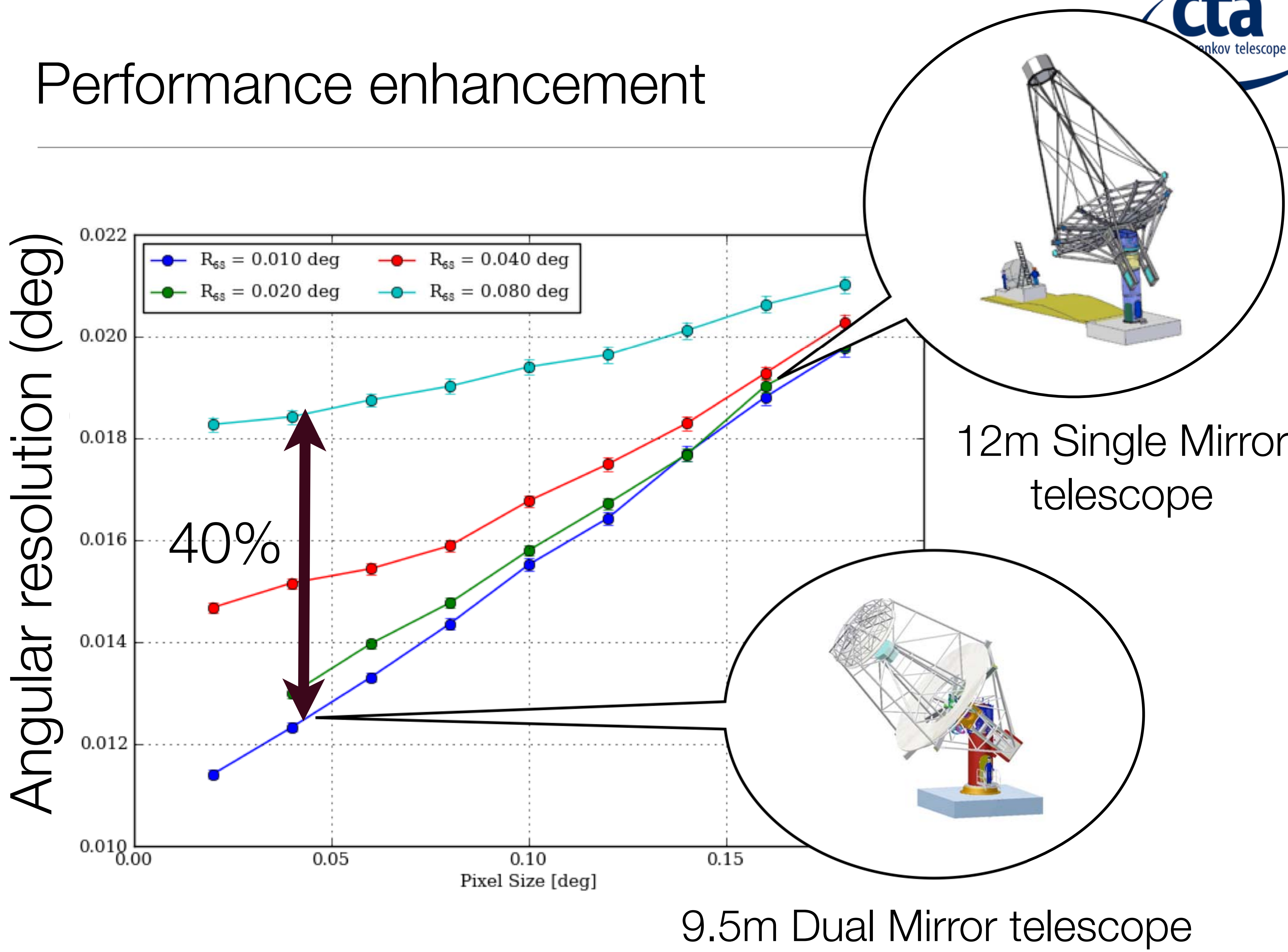




- Stereoscopic reconstruction provides point of origin of gamma-rays from intersection of images (like convergence of lines of perspective)
- Images also converge on impact point on the ground, together with multiple samples of total light providing corrections for the Cherenkov light lateral distribution and good calorimetry

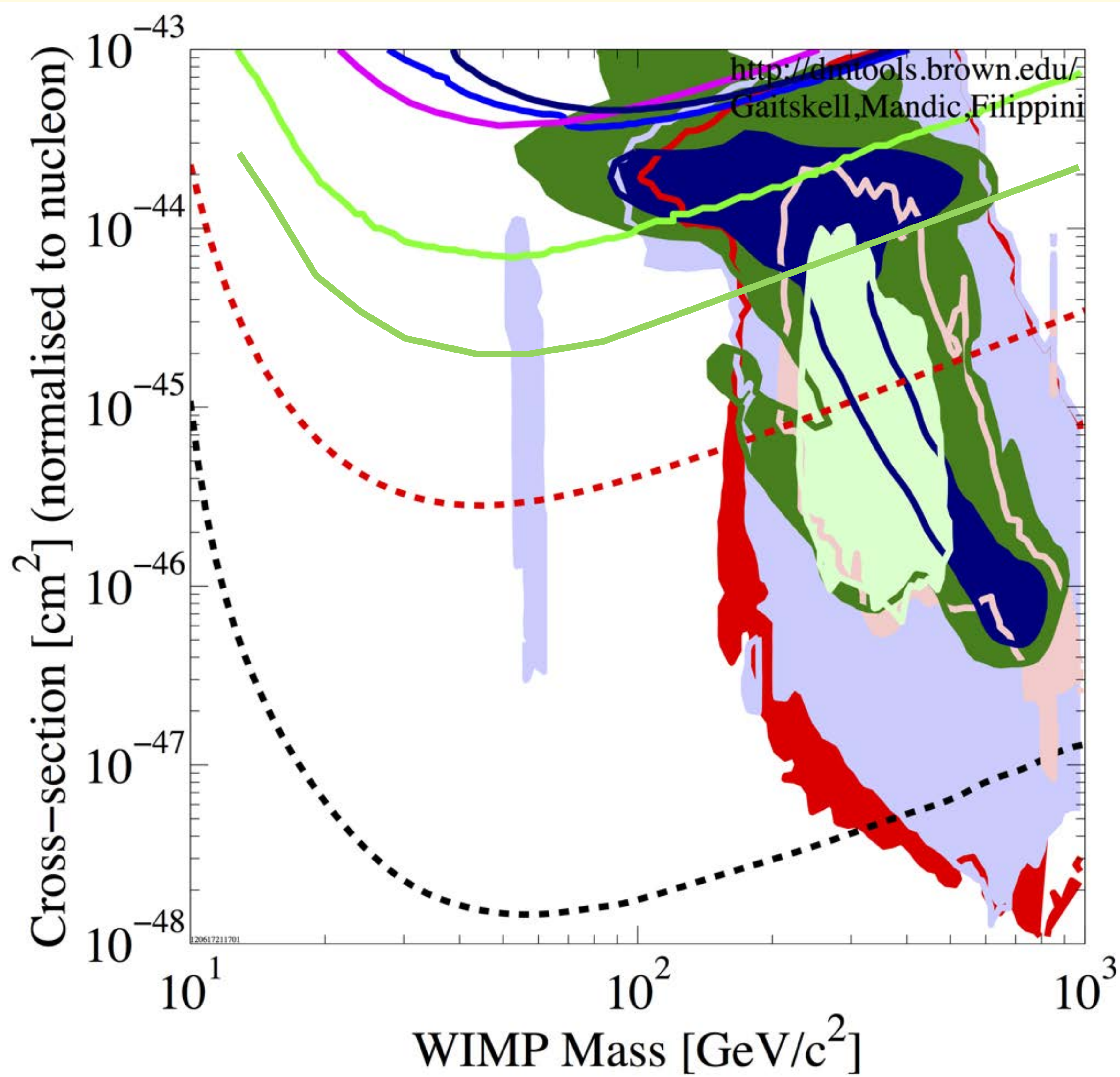
CTA-US Angular Resolution

Performance enhancement



12

Projected Reach



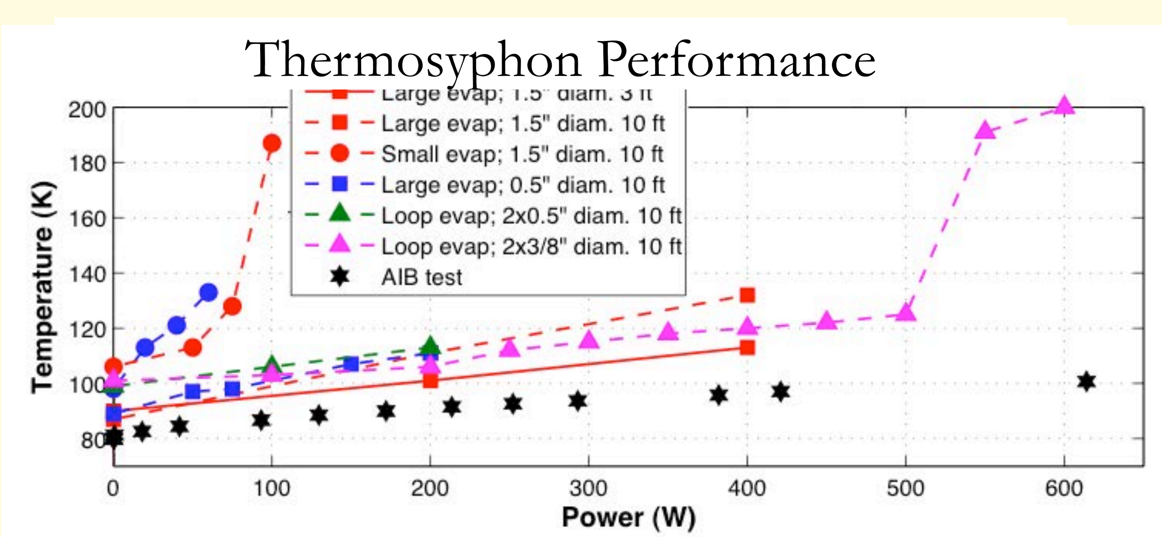
XENON100 -
(old! - new by hand)

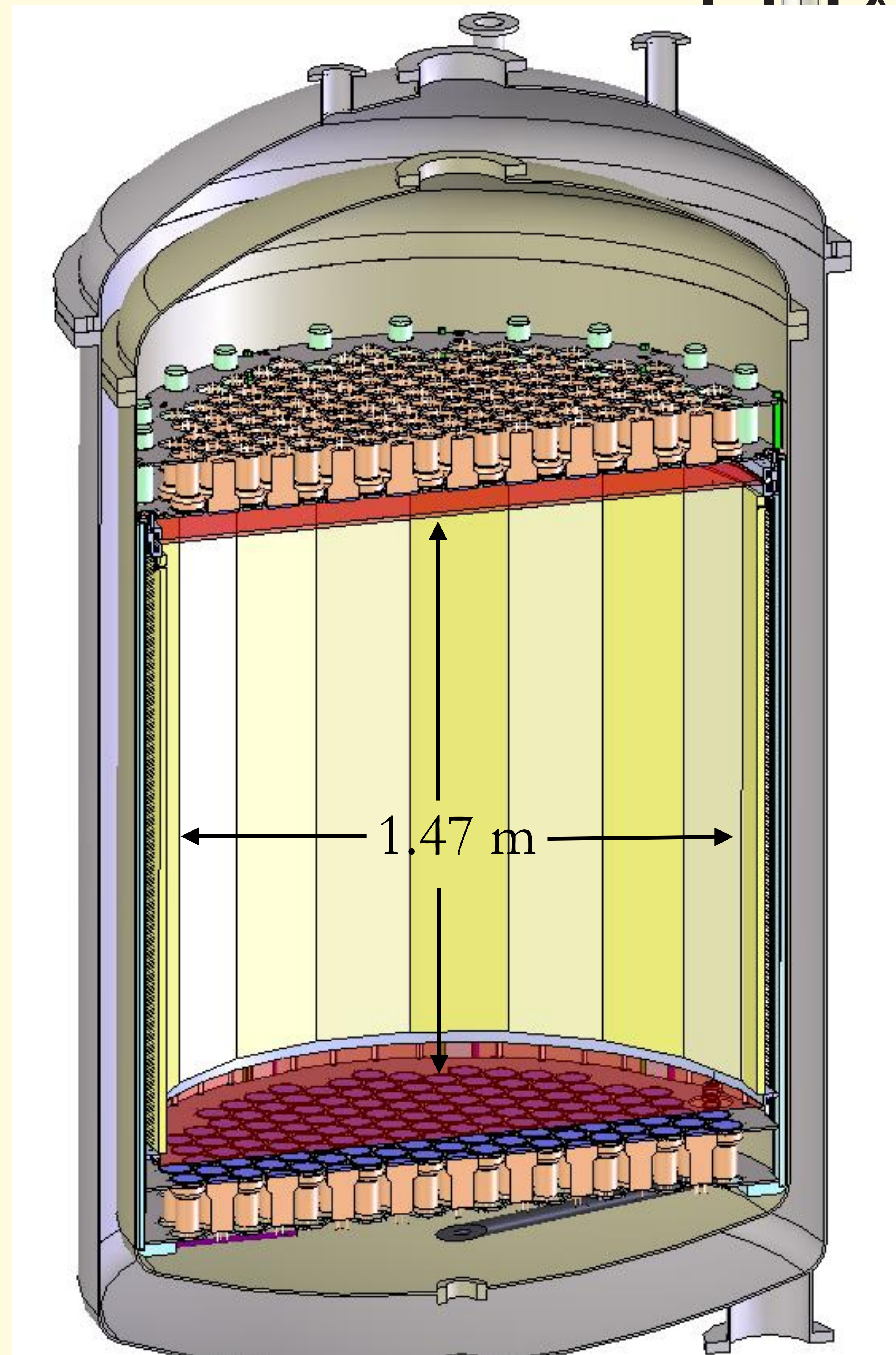
LUX

LZ

Xe detector system

- 7 tons fully active, ~8.4 tons total
- Xe vessel + interior assembled on surface
  - Vessel just fits, slung under Yates cage
- Ultra-low background Ti vessels
- Thermosyphon cryogenics
- Highly integrated purification system
- Active Xe skin

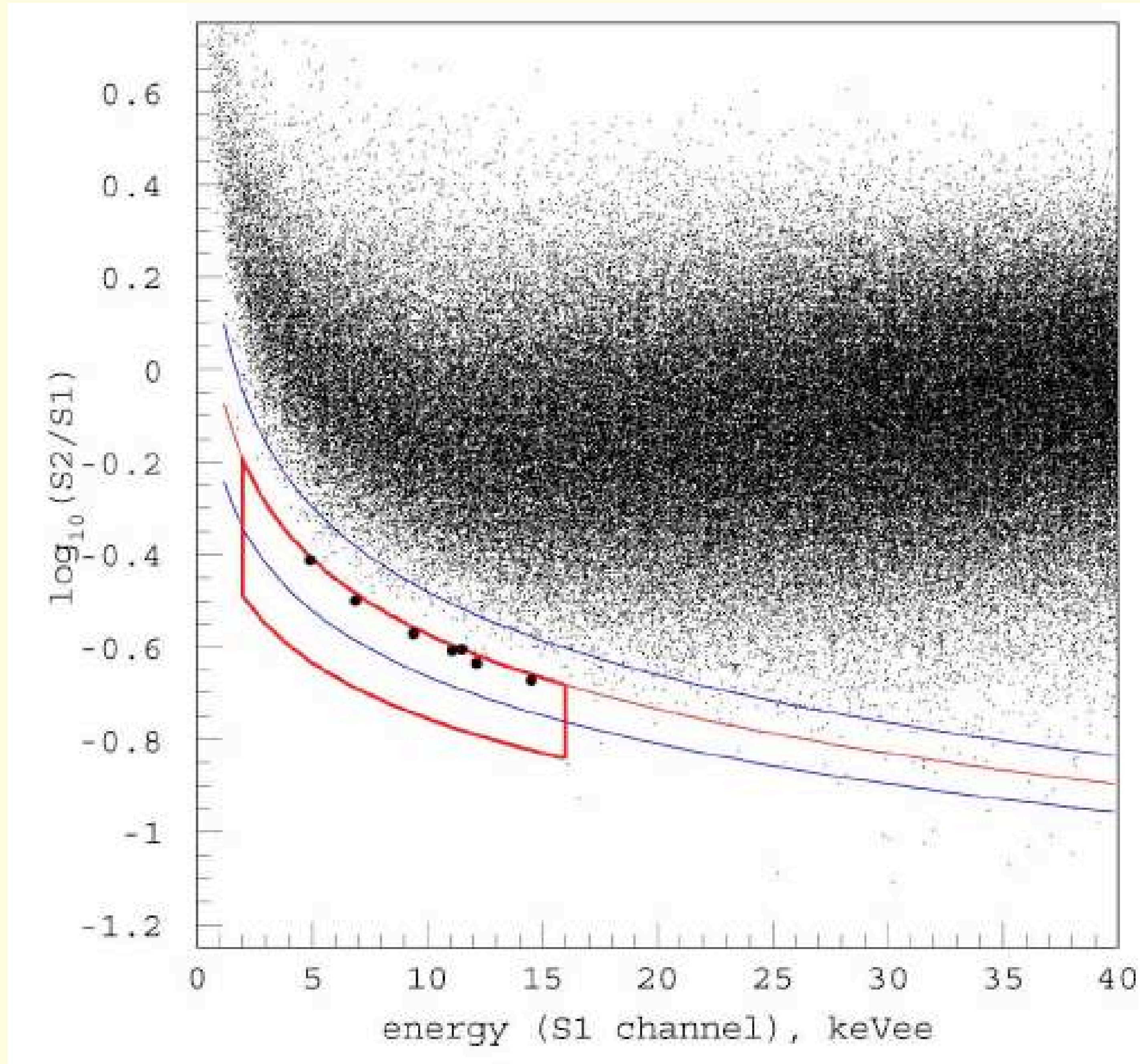




Discrimination of electron recoil backgrounds

- 99.5% baseline assumption gives 3.6 events from pp neutrinos in 1000 days
  - Also determines fiducial mass
- Statistical:
  - Fluctuations in S1 and S2 signals.
- Tails:
  - Presumably due to pathological event topologies ("gamma-X")
  - Two-layer veto - strong tag

ZEPLIN III - 10^4 Discrimination

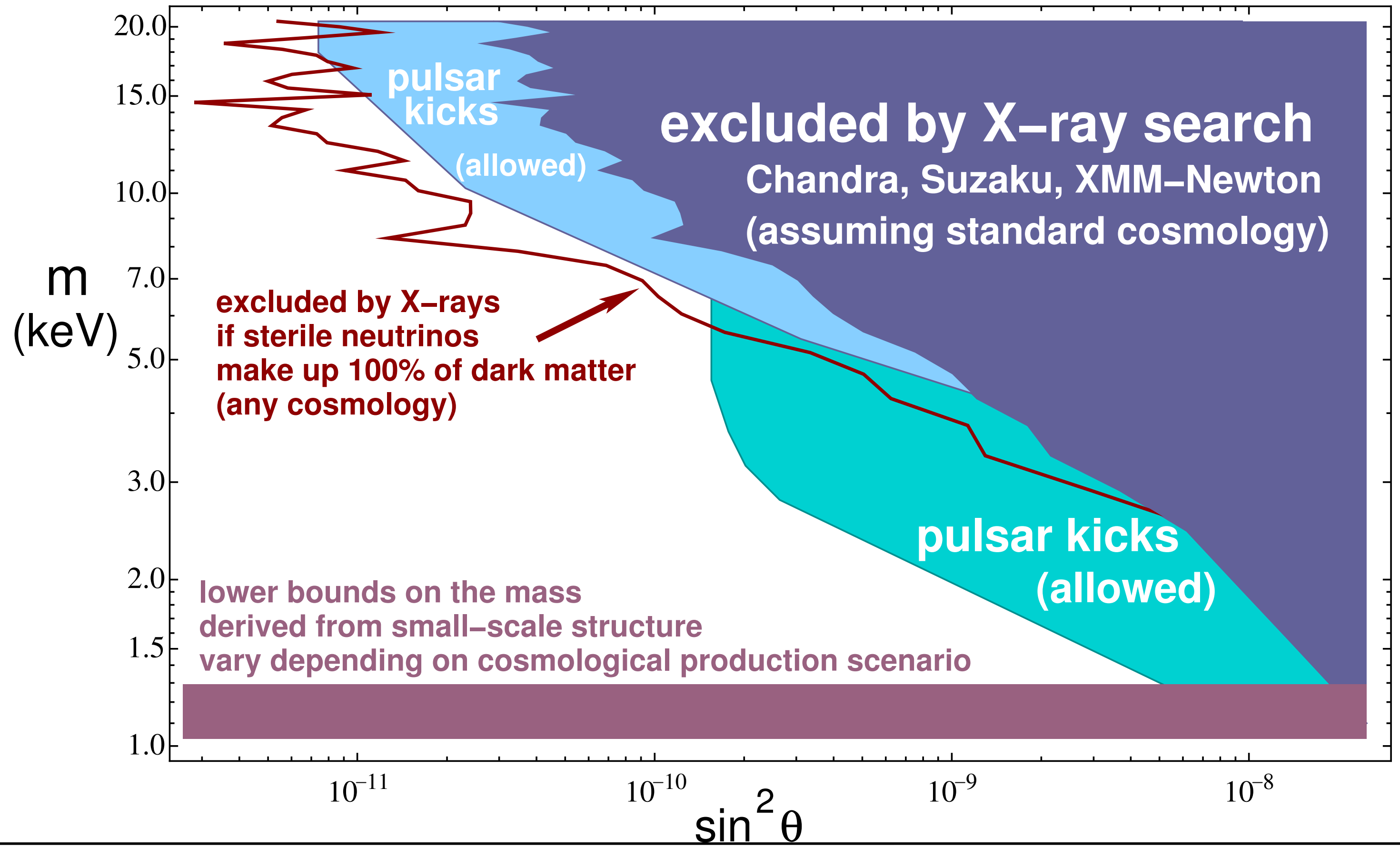


Sterile Neutrinos

Chandra

Suzaku

XMM/Newton

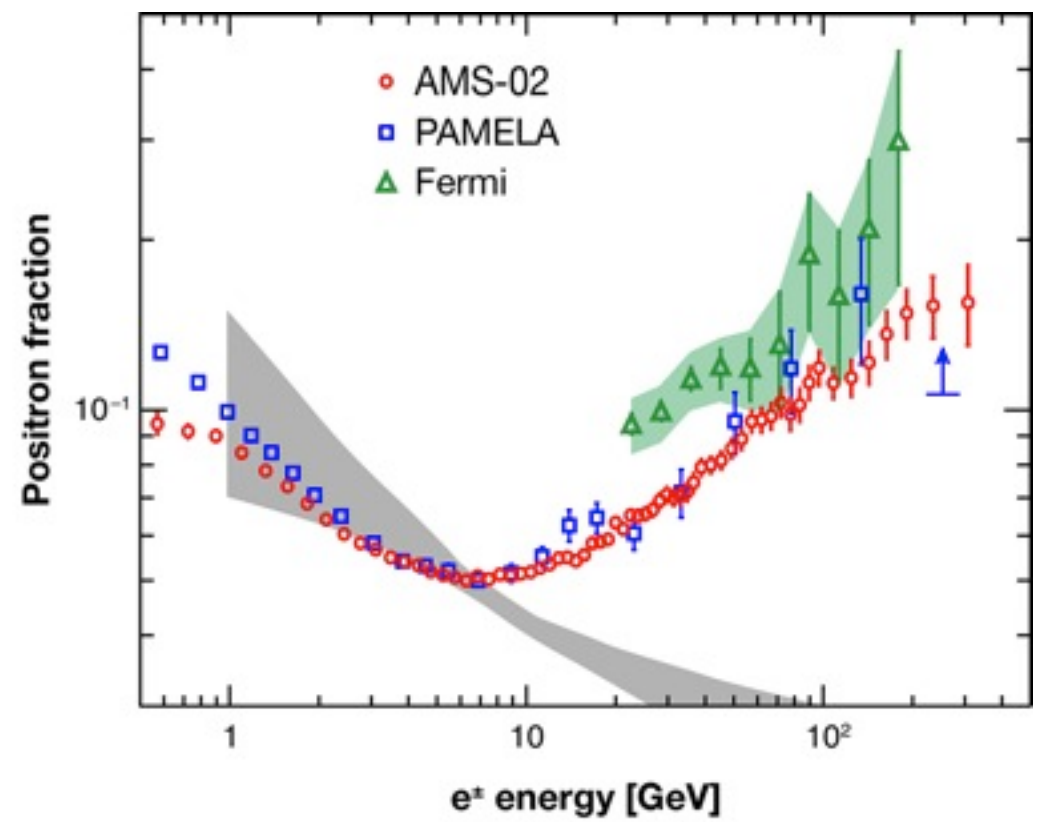


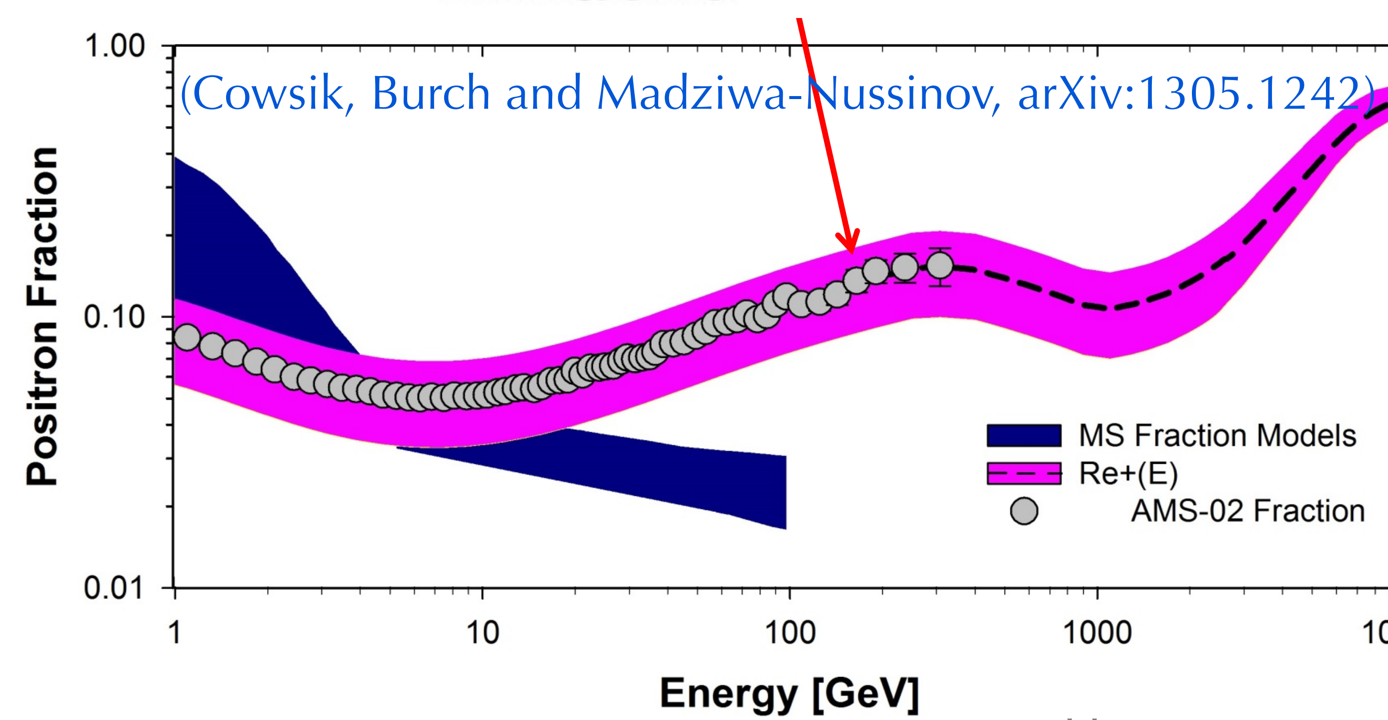
(Loewenstein et al, Astrophys.J. 700 (2009) 426-435; Astrophys.J. 714 (2010) 652-662; Astrophys.J. 751 (2012) 82; Kusenko, Phys.Rept. 481 (2009) 1-28)

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?''

- Extracting a DM signal from positron measurements does depend on backgrounds from *secondaries produced in cosmic ray propagation*, or *astrophysical sources such as pulsars*. The measured positron excess is orders of magnitude above the generic expectations for WIMP annihilation. However, a spectral feature (with a sharp cutoff) would be a strong indication of a signal.
- While Isotropy may argue against a new astrophysical source, a nearby subhalo is probably necessary to boost the electron annihilation signal - can we have it both ways?

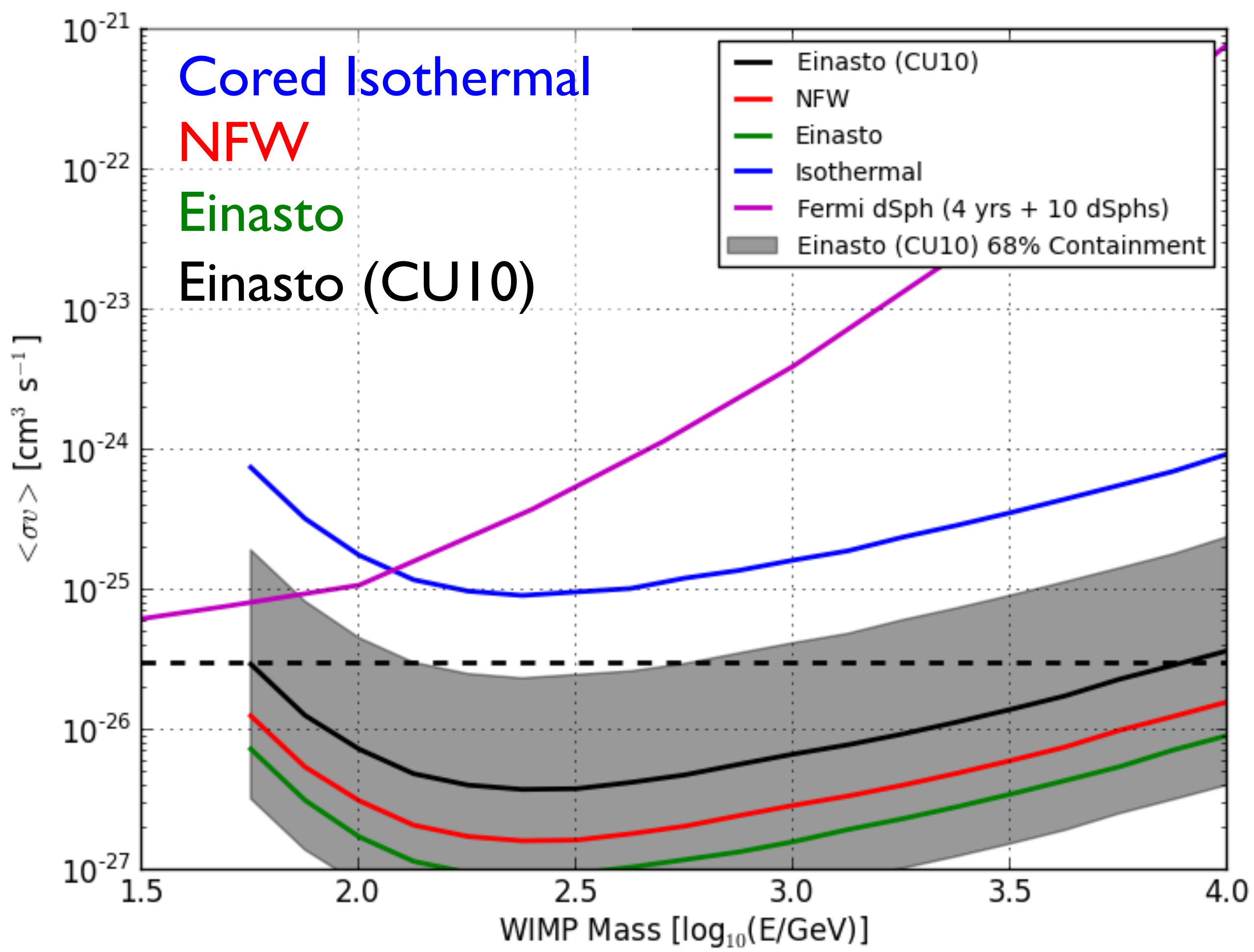




Snowmass Tough Questions

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

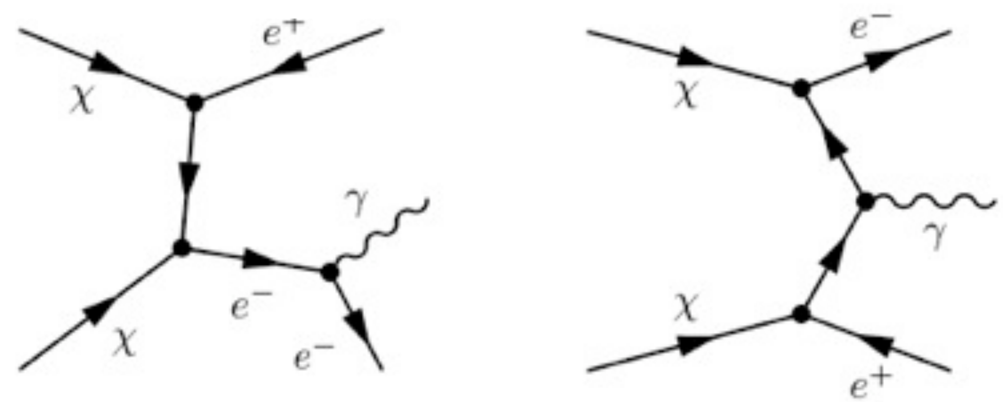
- The primary astrophysical uncertainties come for gamma-ray production come from uncertainties in the halo model. *But even with uncertainties, the limits still reach the natural decoupling cross section.*
- An annihilation line in the gamma-ray spectrum would also provide a smoking gun signature (if 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?*



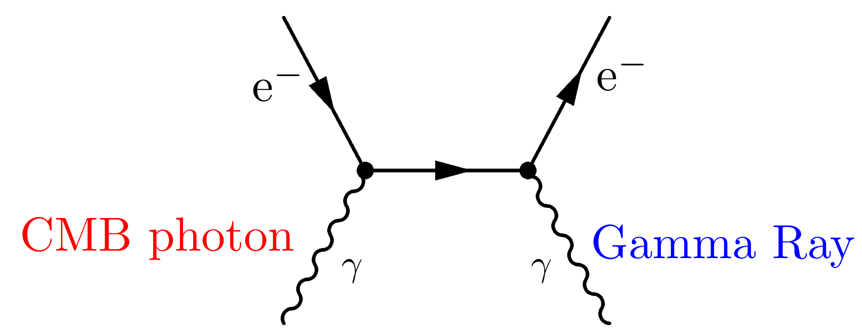
Boosts

- It is often assumed that astrophysical uncertainties make gamma-ray detection worse - cored halos, annihilation channels with the lowest gamma-ray production - but a large number of *boosts* are possible, even generic:

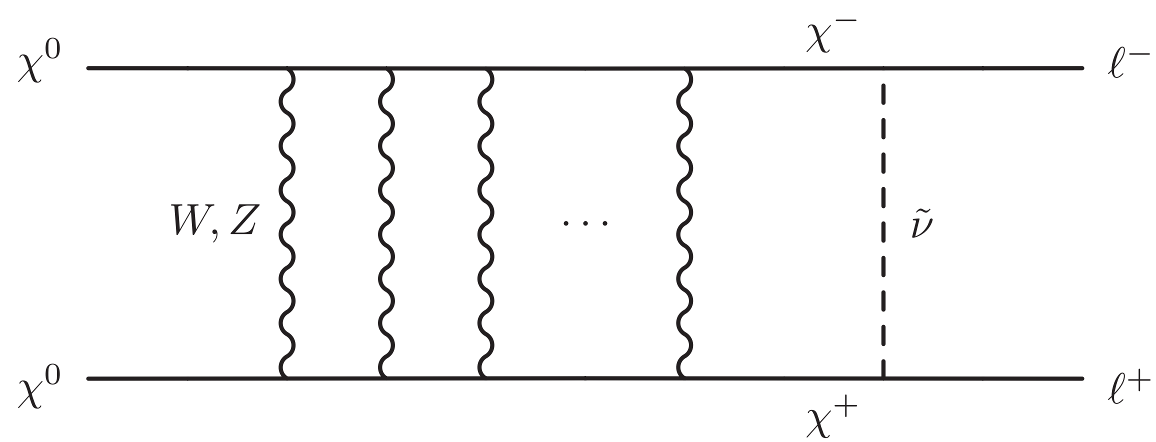
Final-state radiation, or internal bremsstrahlung may lead to a gamma-ray peak near the kinematic cutoff, improving sensitivity of higher threshold ground-based instruments.



Secondary electrons can produce additional high energy gamma-rays by inverse Compton scattering.



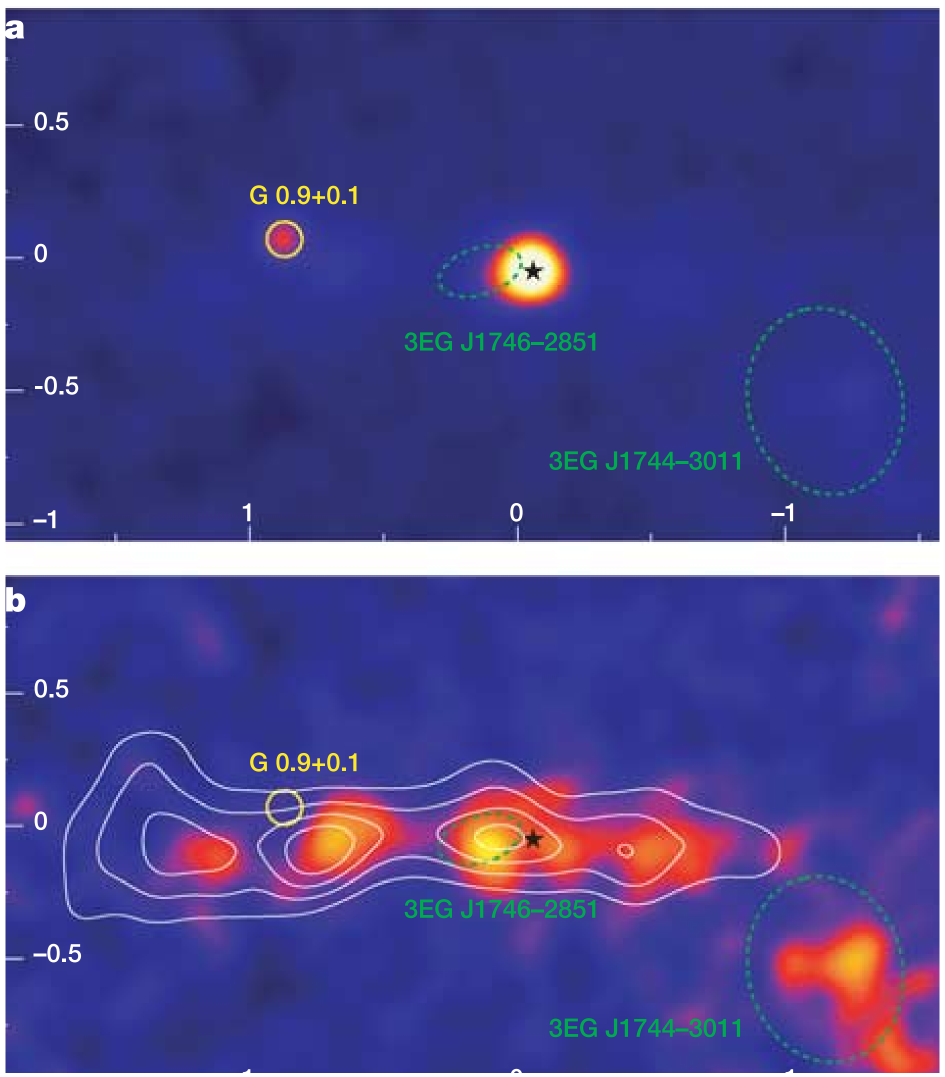
Above a few TeV, W and Z exchange can produce a Yukawa like potential that boosts cross section at low velocities compared with higher-velocity interactions in early universe

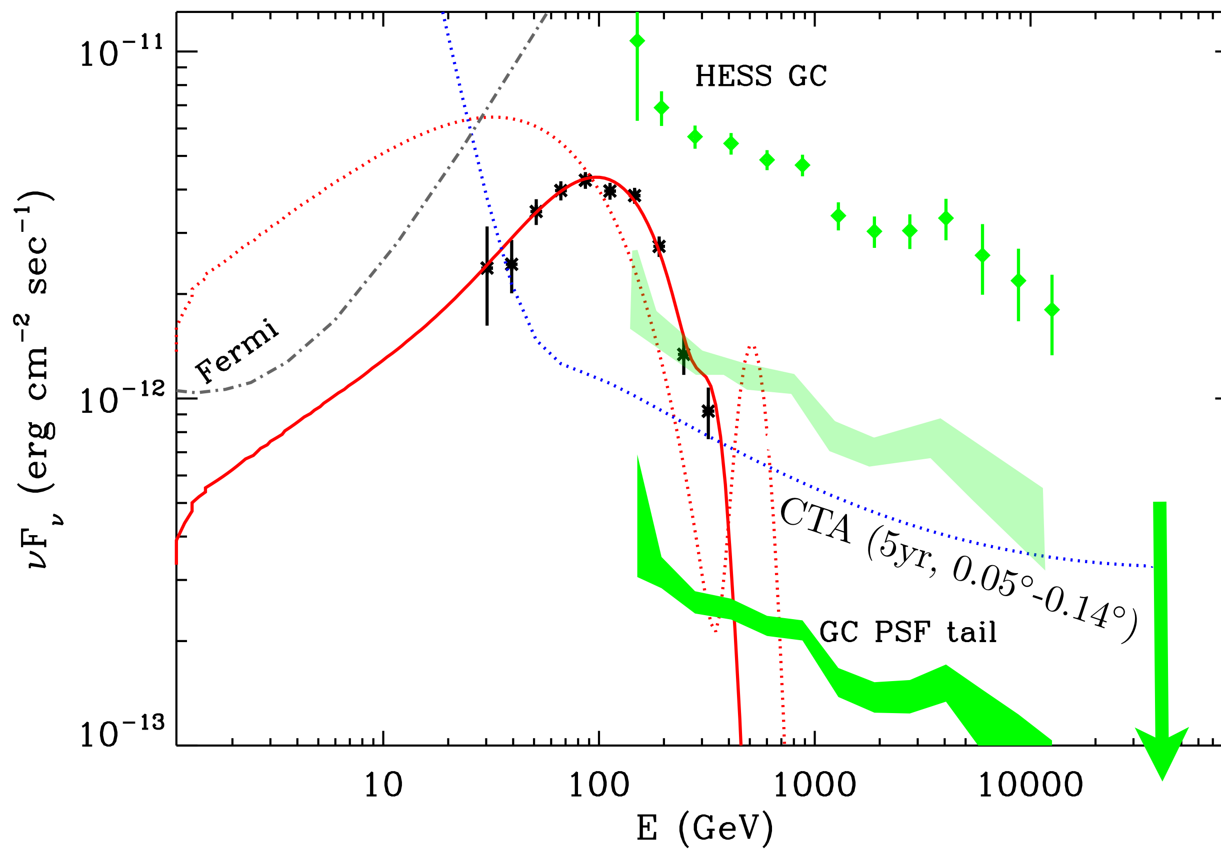


Lattanzi and Silk, PRD 79, 083523 (2009), Profumo (2005)

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?''





Point source contamination with improving angular resolution

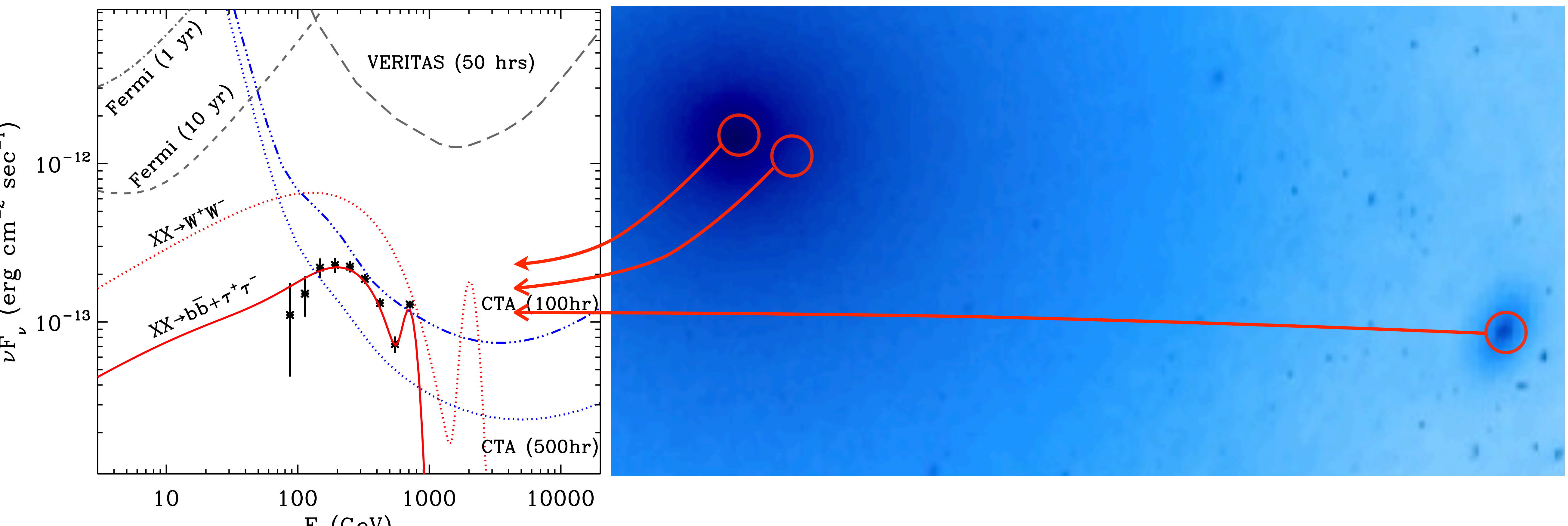
Dwarf galaxies have almost no known astrophysical backgrounds, for backgrounds the GC is worst case. HESS provides the best data on the GC (below, with point source at Sgr A* subtracted). Better angular resolution can reduce the background from the tail of the PSF function, which dominates over other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

Snowmass Tough Questions

``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?''

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

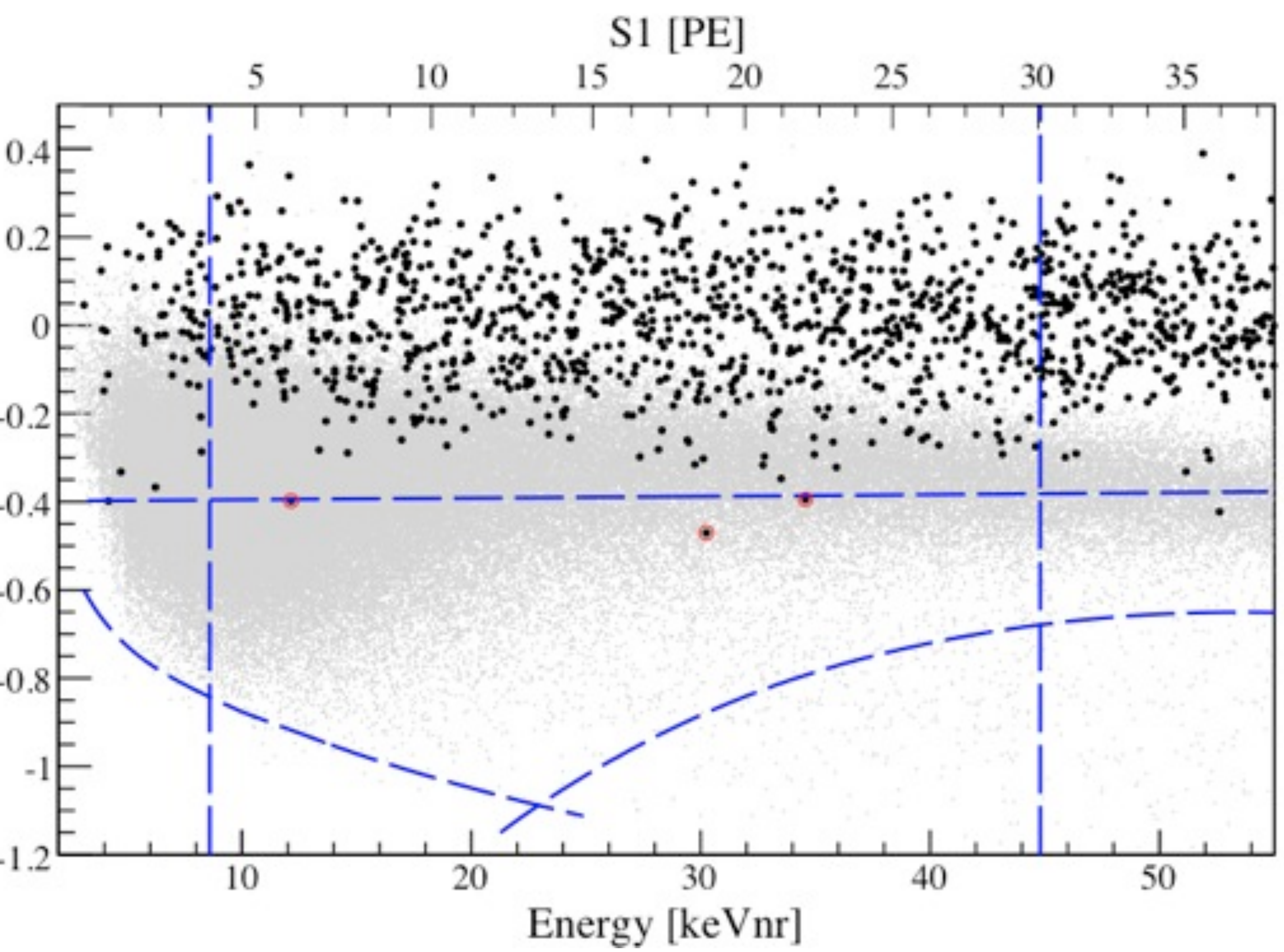
(Tim Linden, SLAC CF meeting)



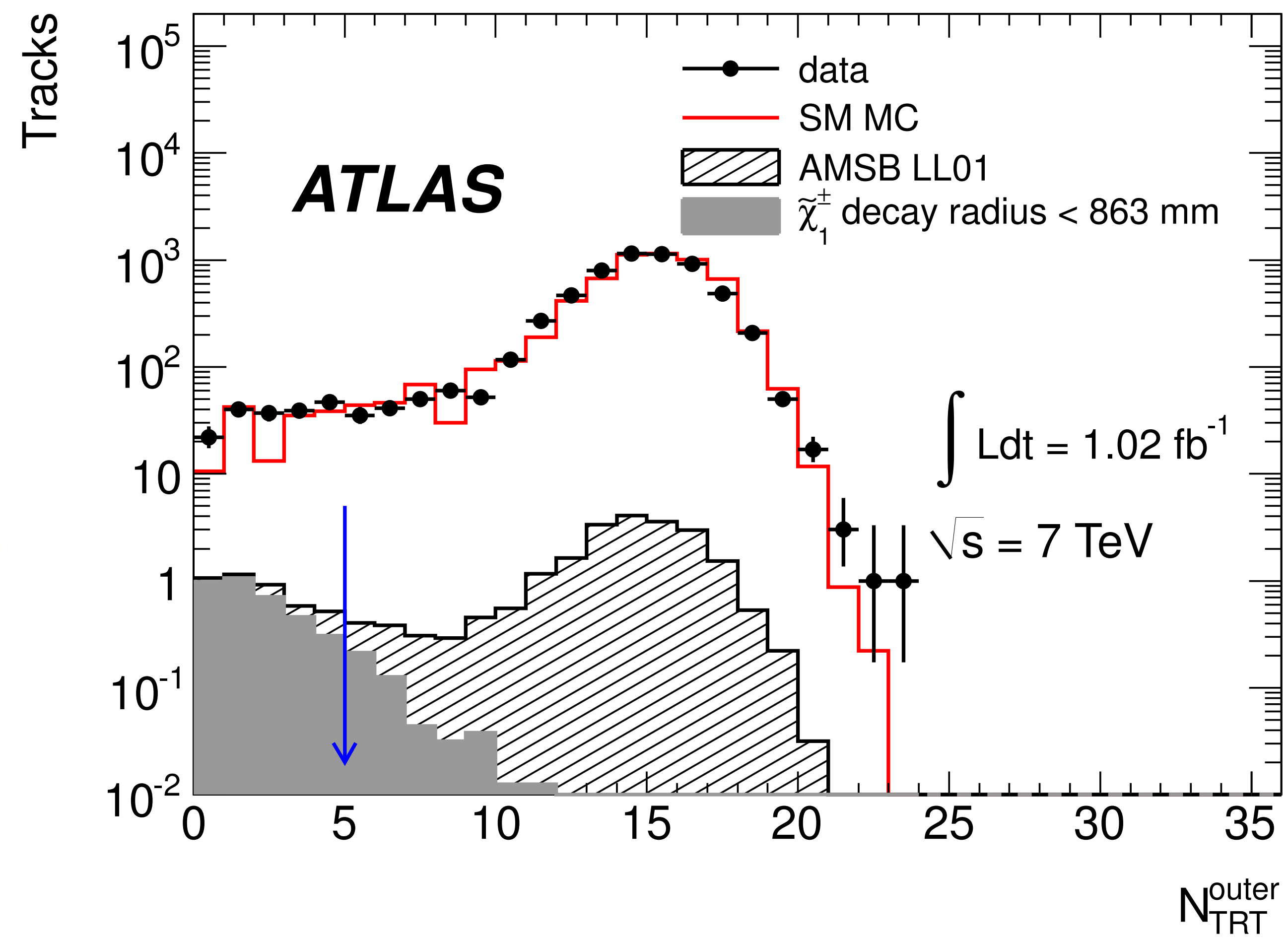
Unlike other astrophysical sources, would see a universal hard spectrum (typically harder by ~$E^{0.5}$) with a sharp cutoff. The spectral shape would be universal: the same throughout the GC halo, in halos of Dwarf galaxies, with no variability.

Background?

Xenon-100 Direct Detection Data

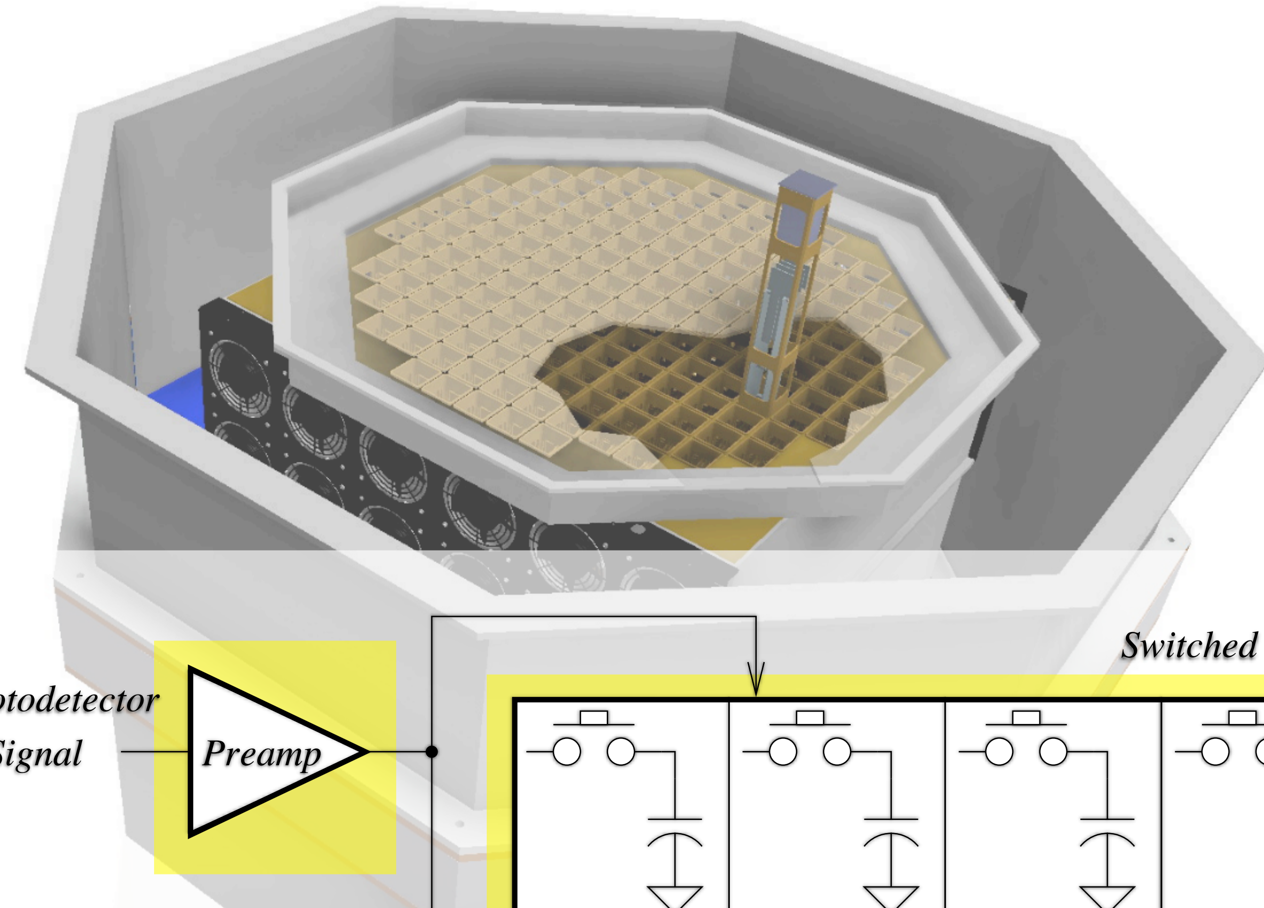
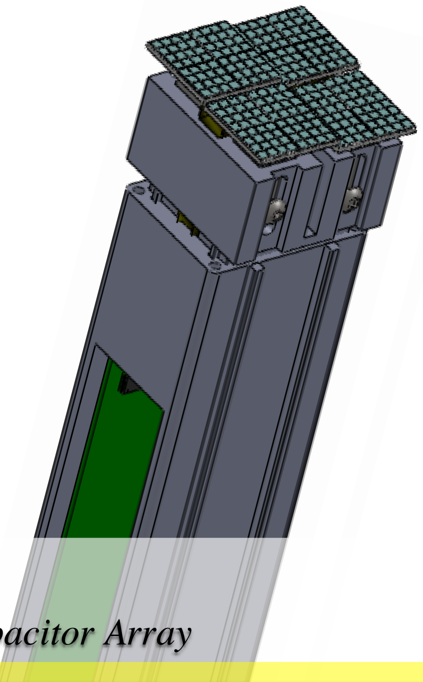
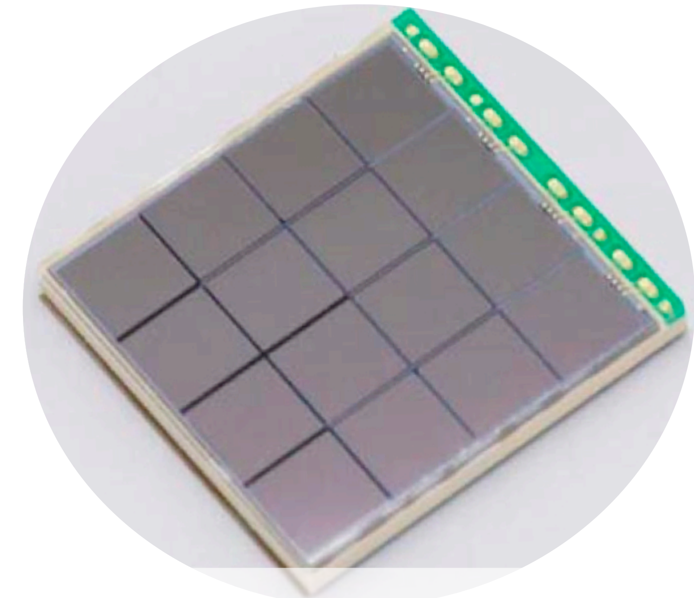
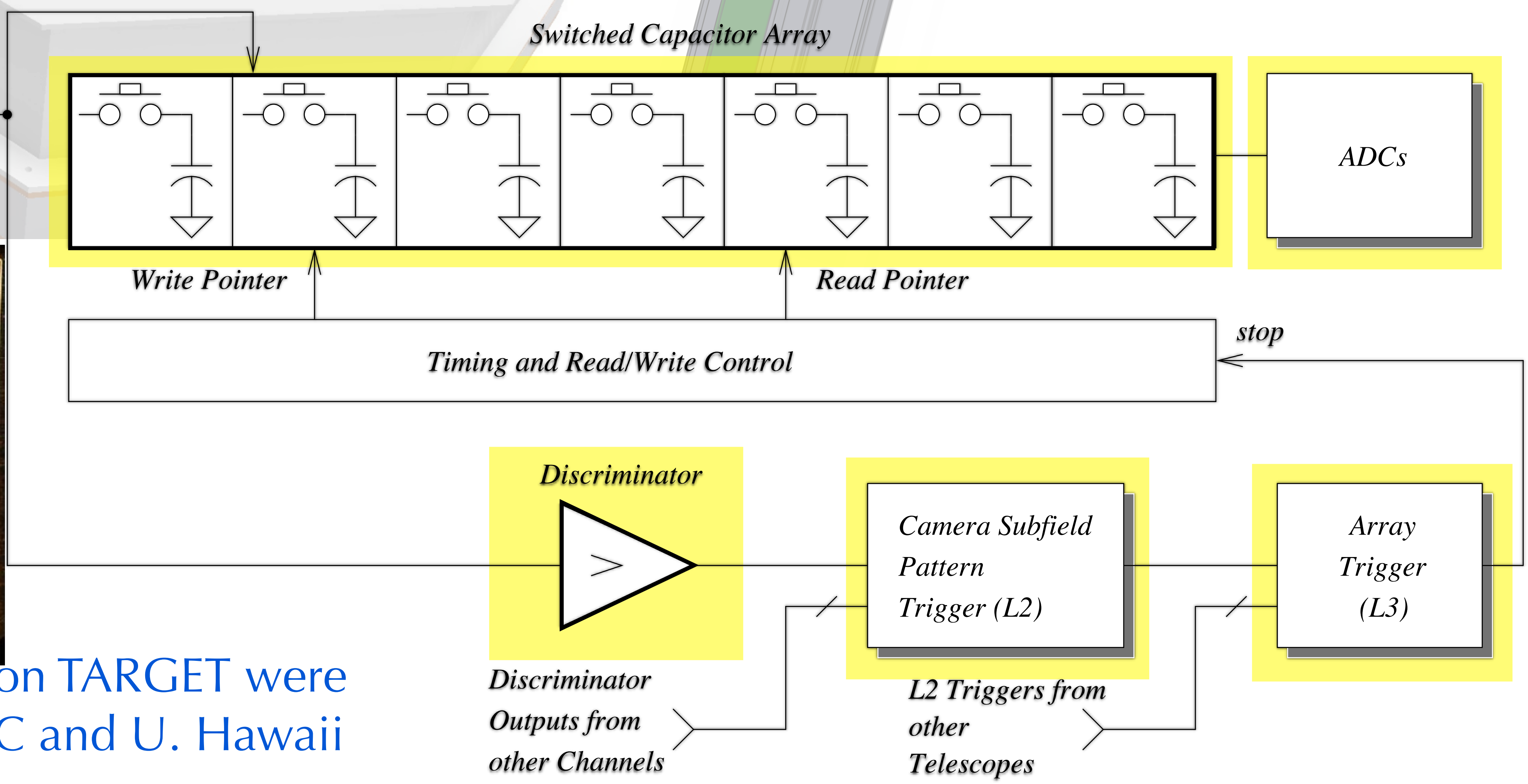


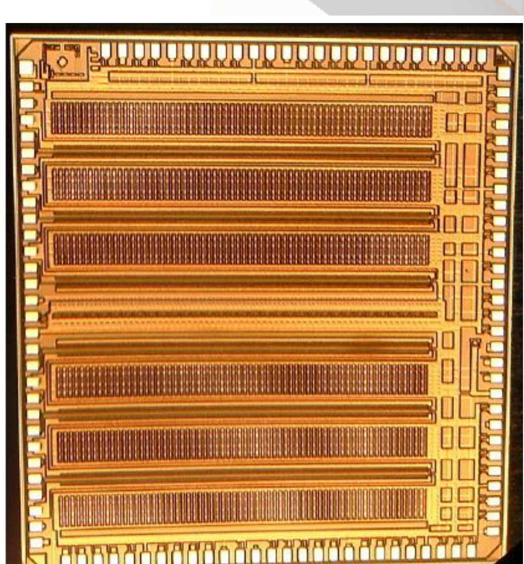
ATLAS Collider Data



- Upper limits are straightforward, but demonstrating that there is a signal and not a misidentified background is hard - this is true for DD, ID and Colliders.

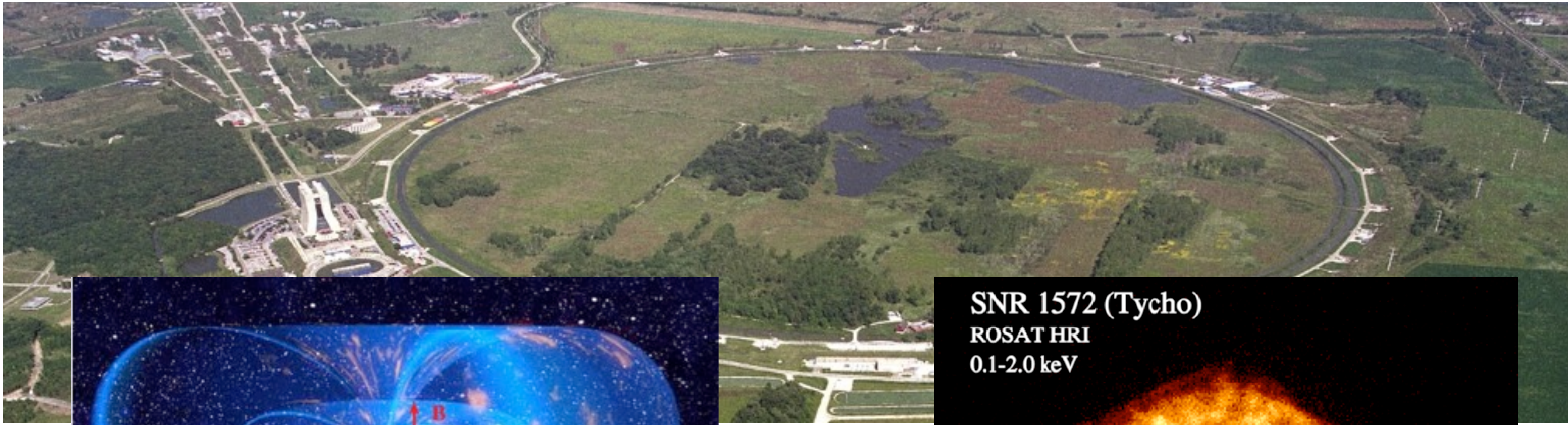
CTA Camera

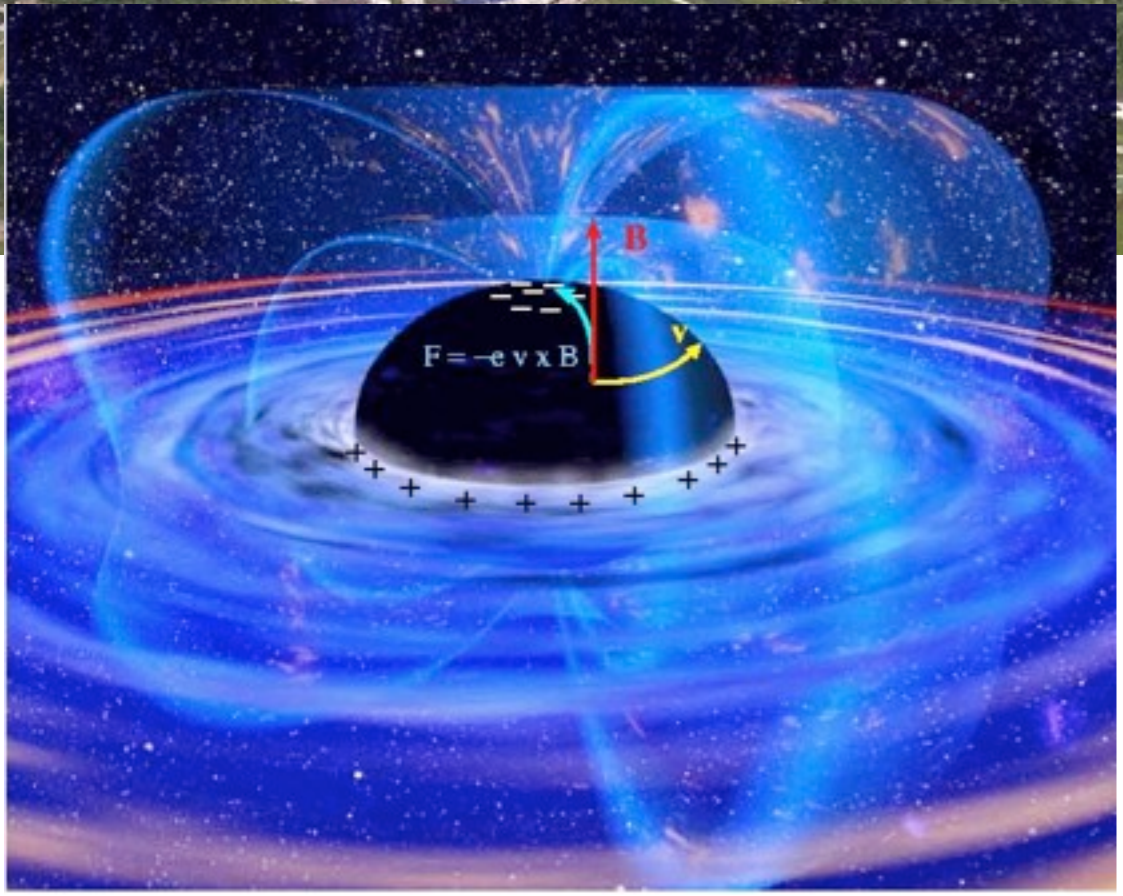







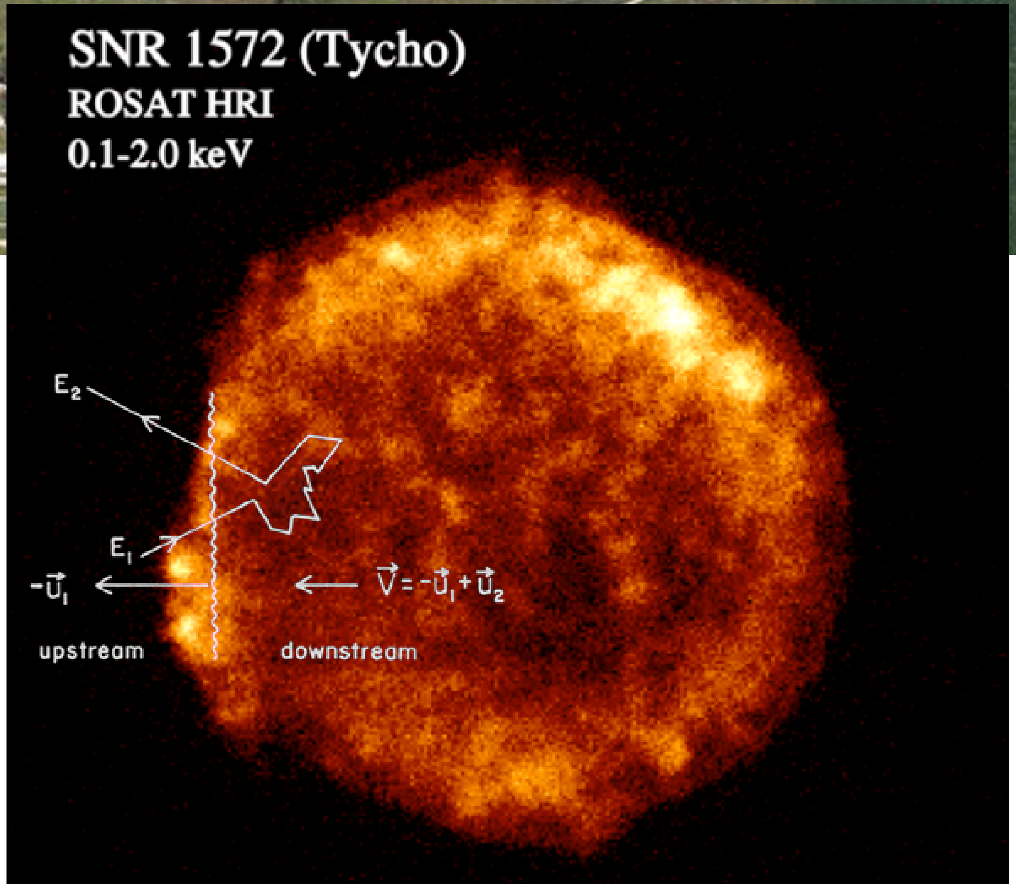
Electronics based on TARGET were developed by SLAC and U. Hawaii

Particle Accelerators





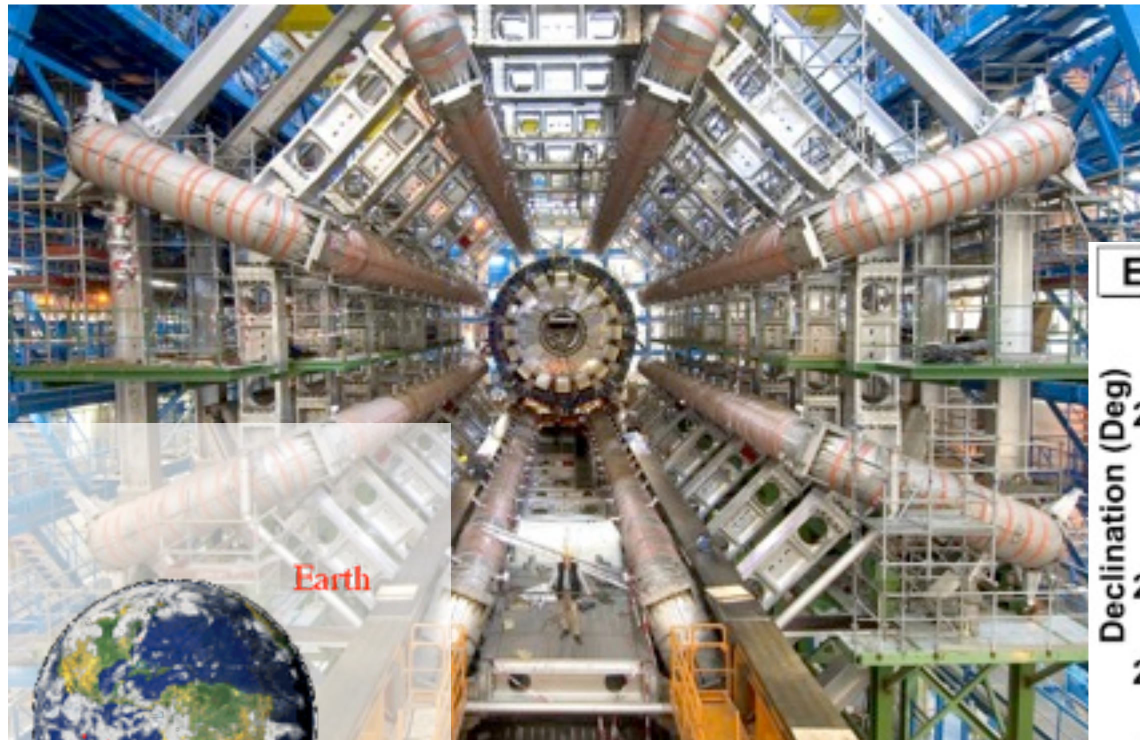
Black hole extended horizon or accretion disk - conductor spinning in a magnetic field - 10^{20} V Generator! (Blandford, Lovelace)

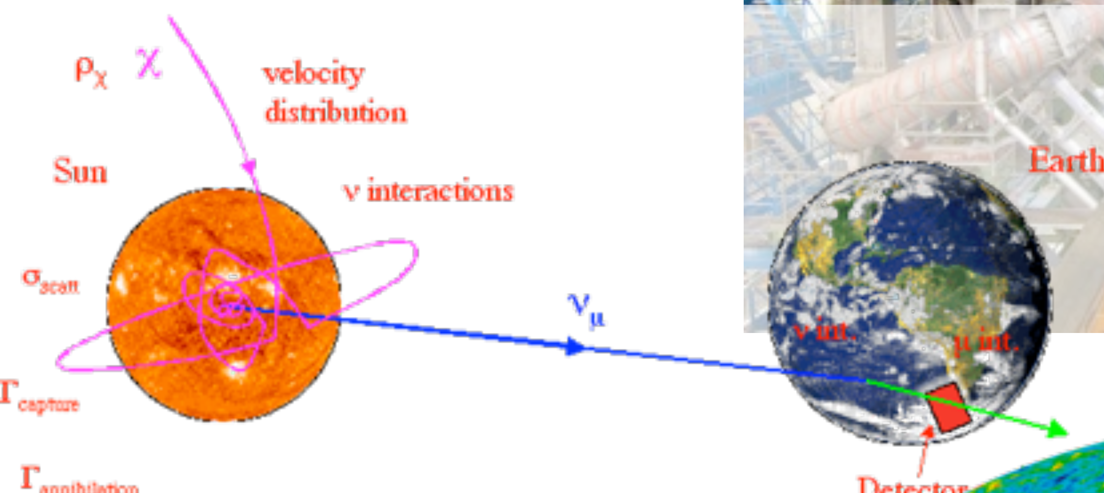


Gamma-ray observations provide direct evidence for acceleration of charged particles up to >tens of TeV in SNR

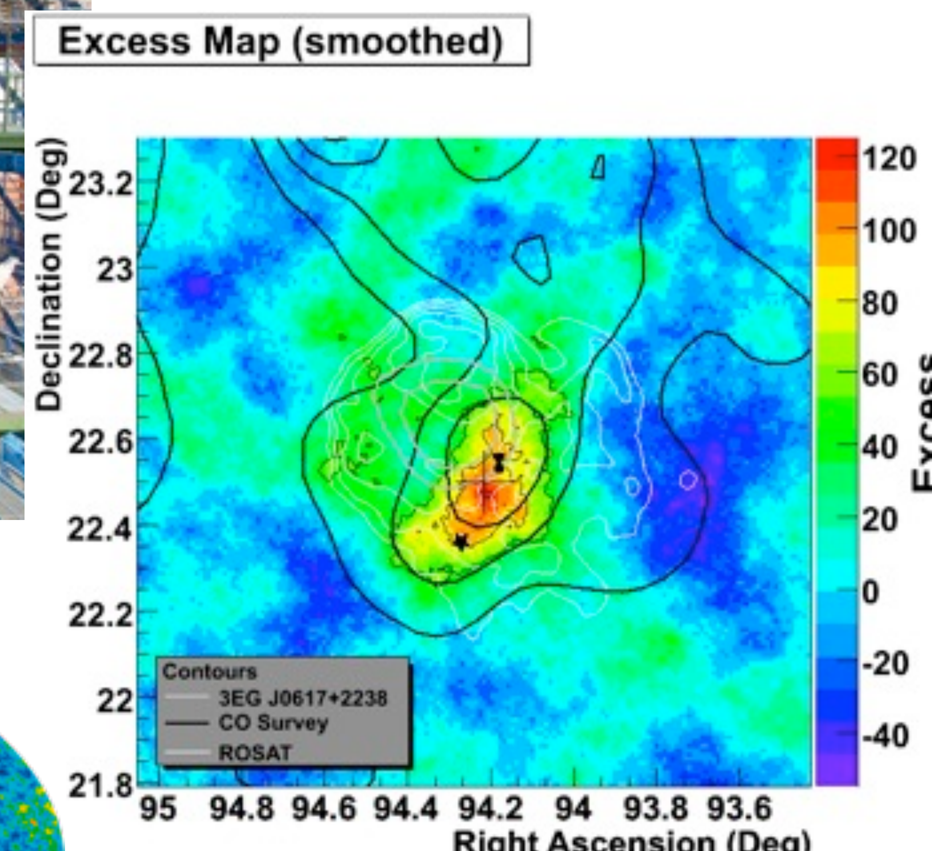
Targets?

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

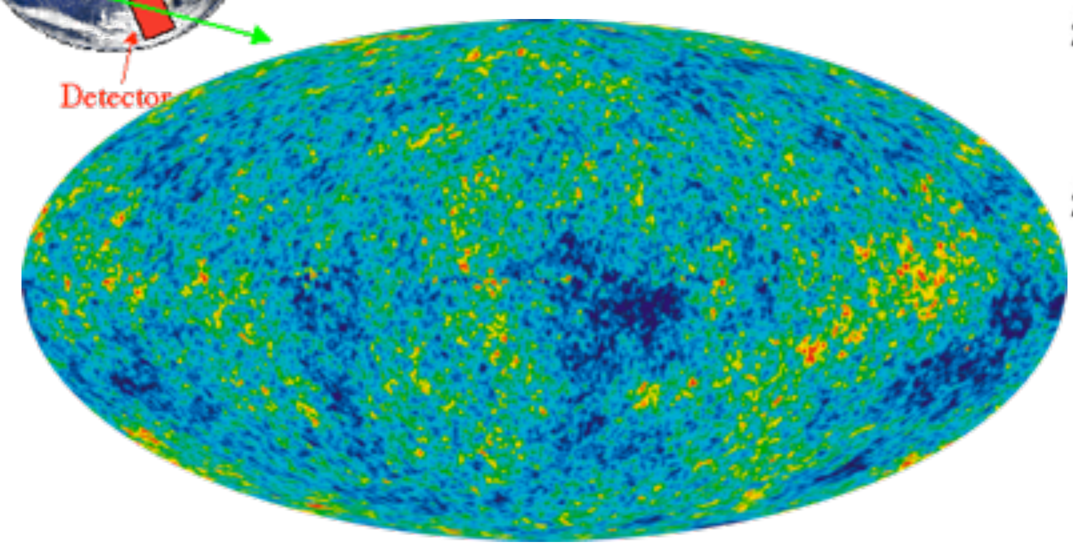




The sun or earth is sometimes the fixed target!

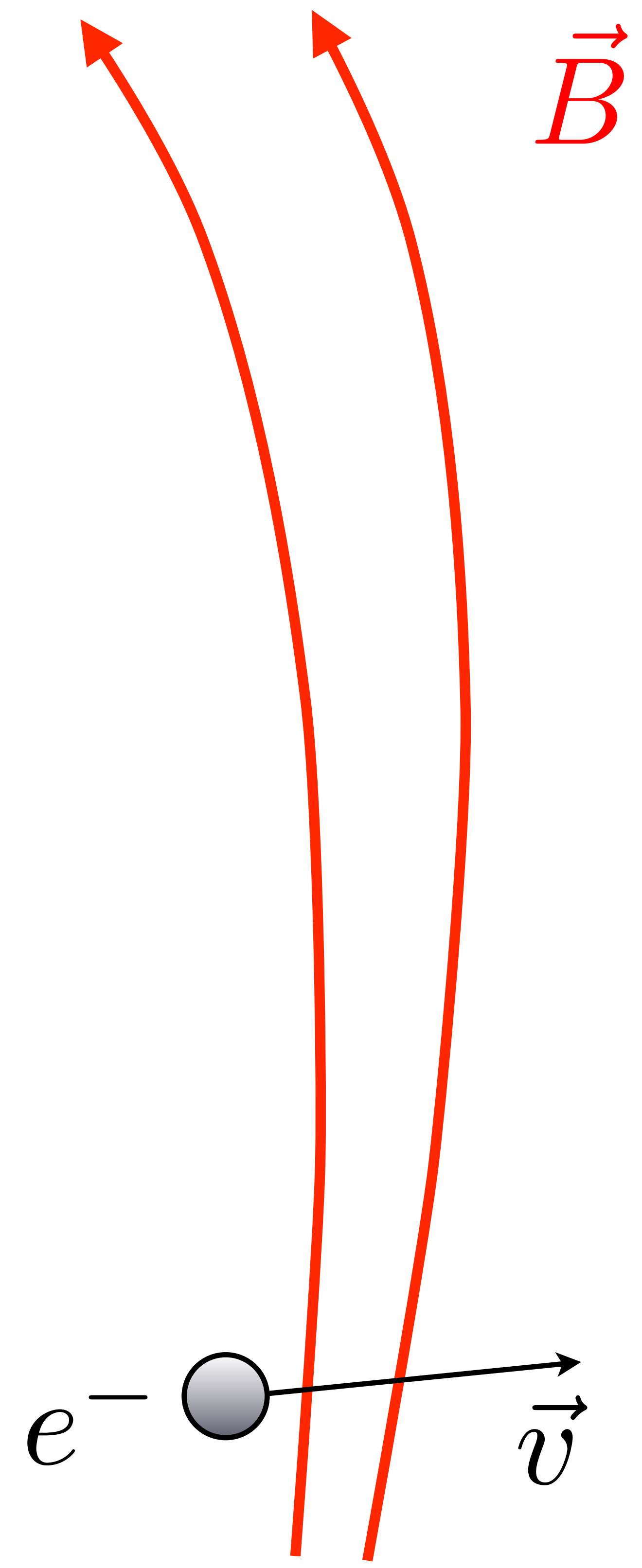


Molecular clouds can be the target



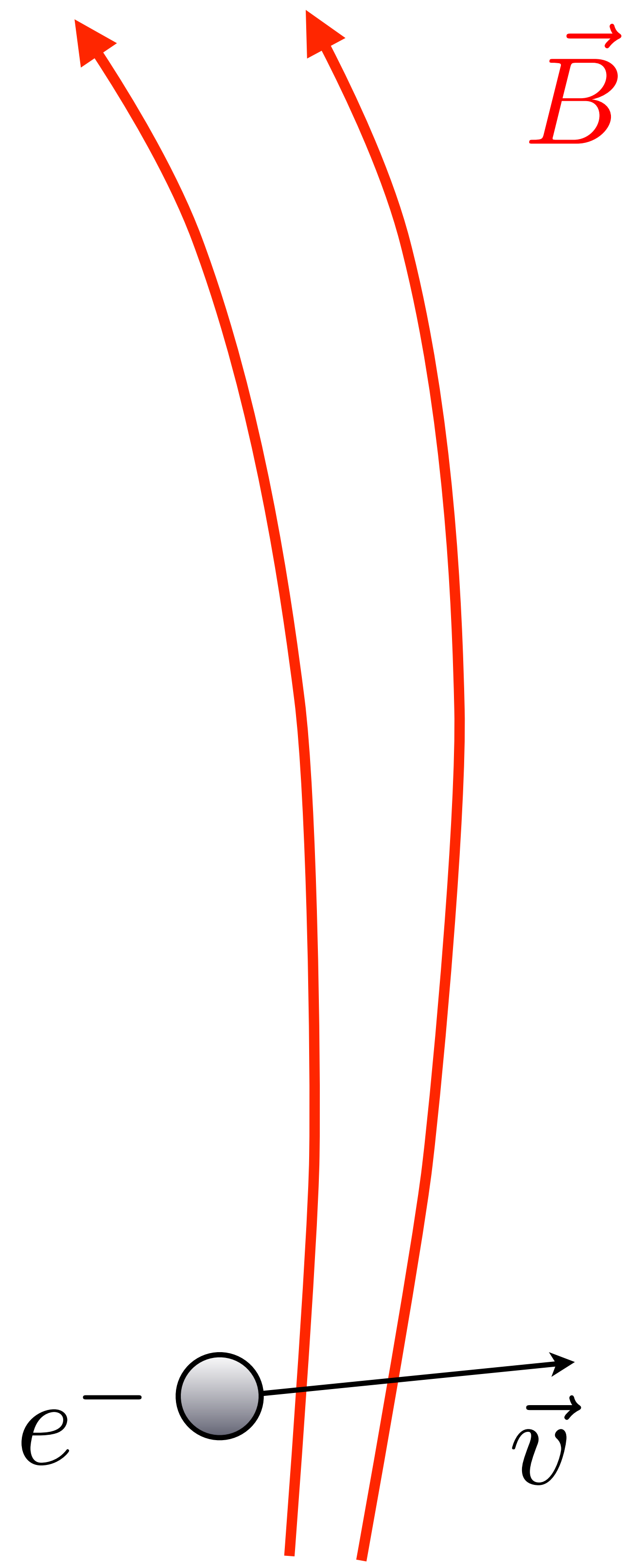
CMB photons and primordial starlight are also targets for high energy cosmic particles

Synchrotron Radiation



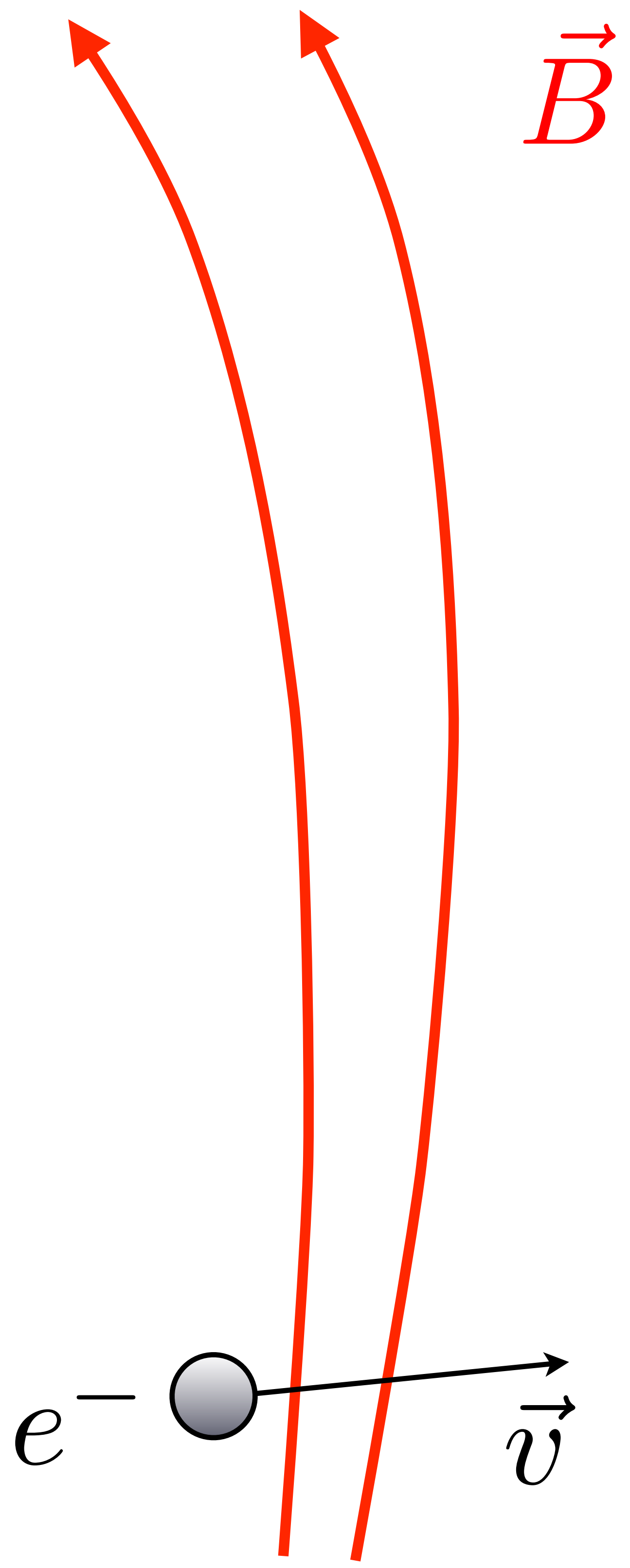
Synchrotron Radiation

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



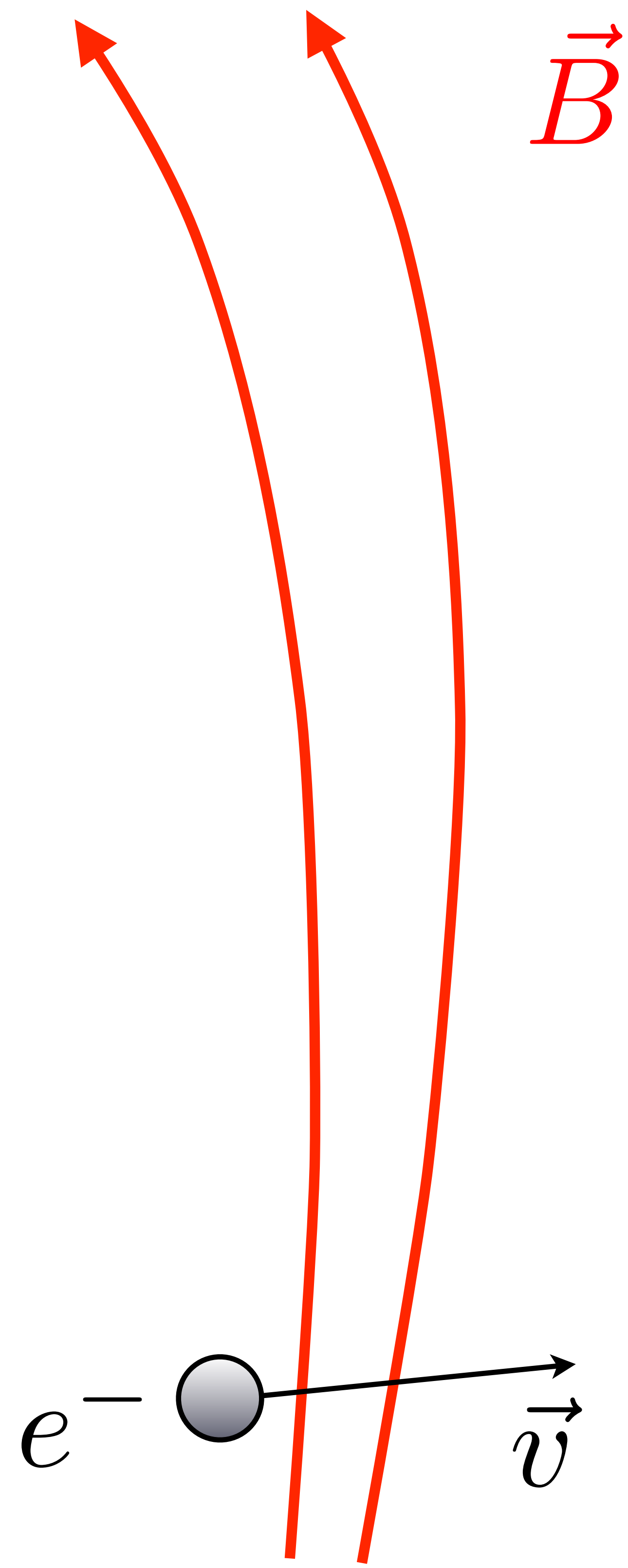
Synchrotron Radiation

- Particles are deflected by magnetic fields, causing them to gyrate in circles.
- Circular motion implies acceleration giving radiation



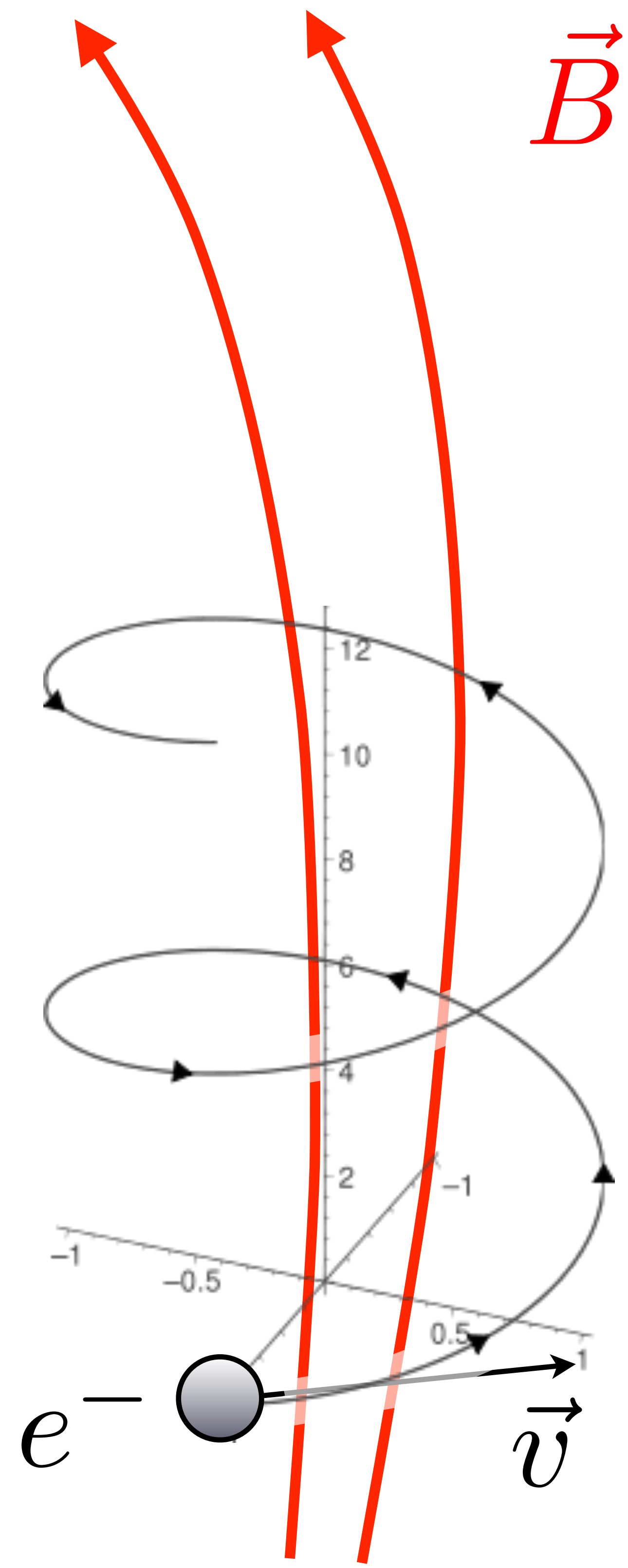
Synchrotron Radiation

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



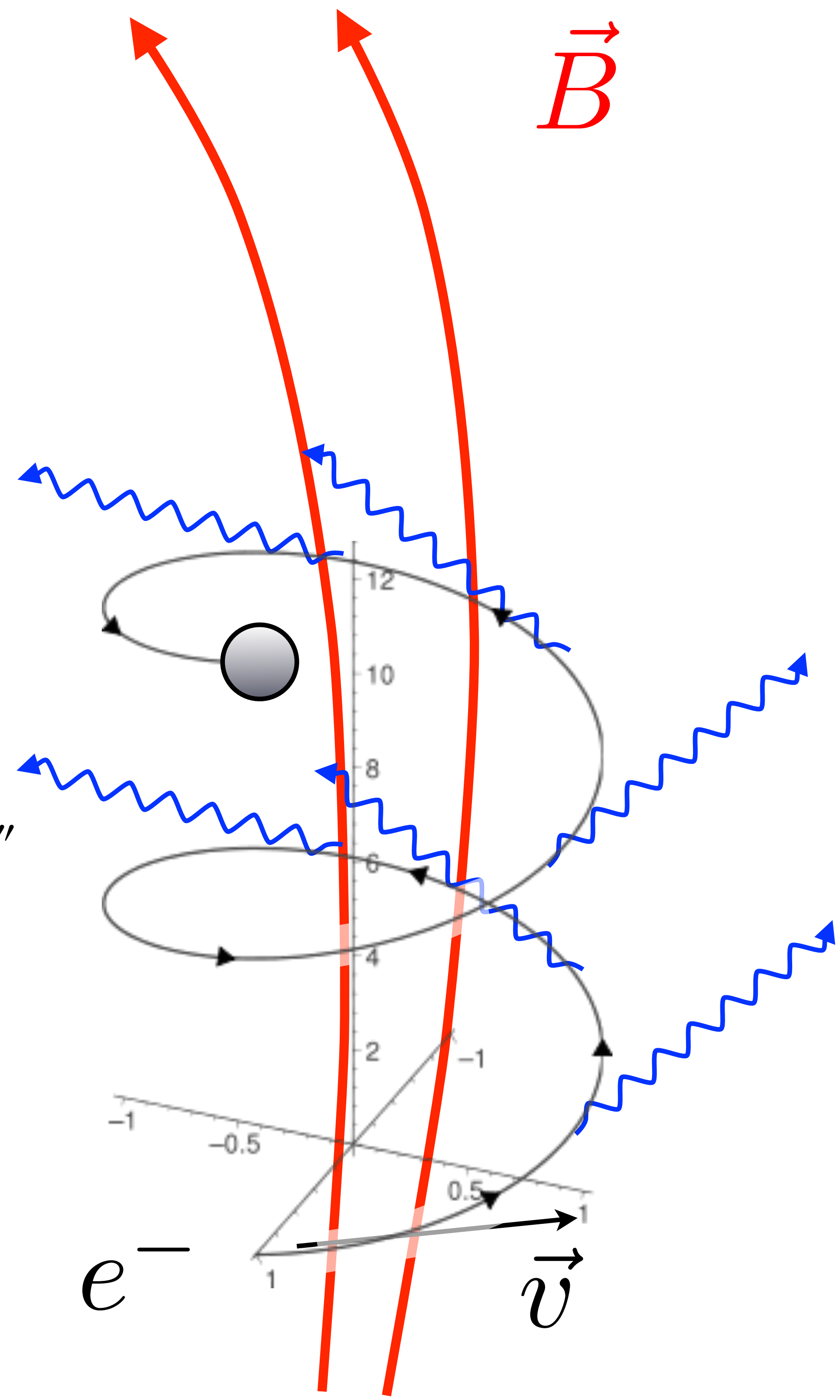
Synchrotron Radiation

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

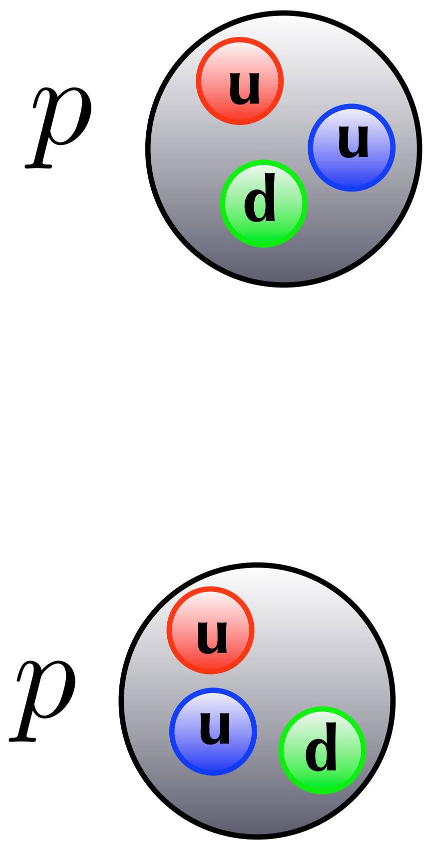


Synchrotron Radiation

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

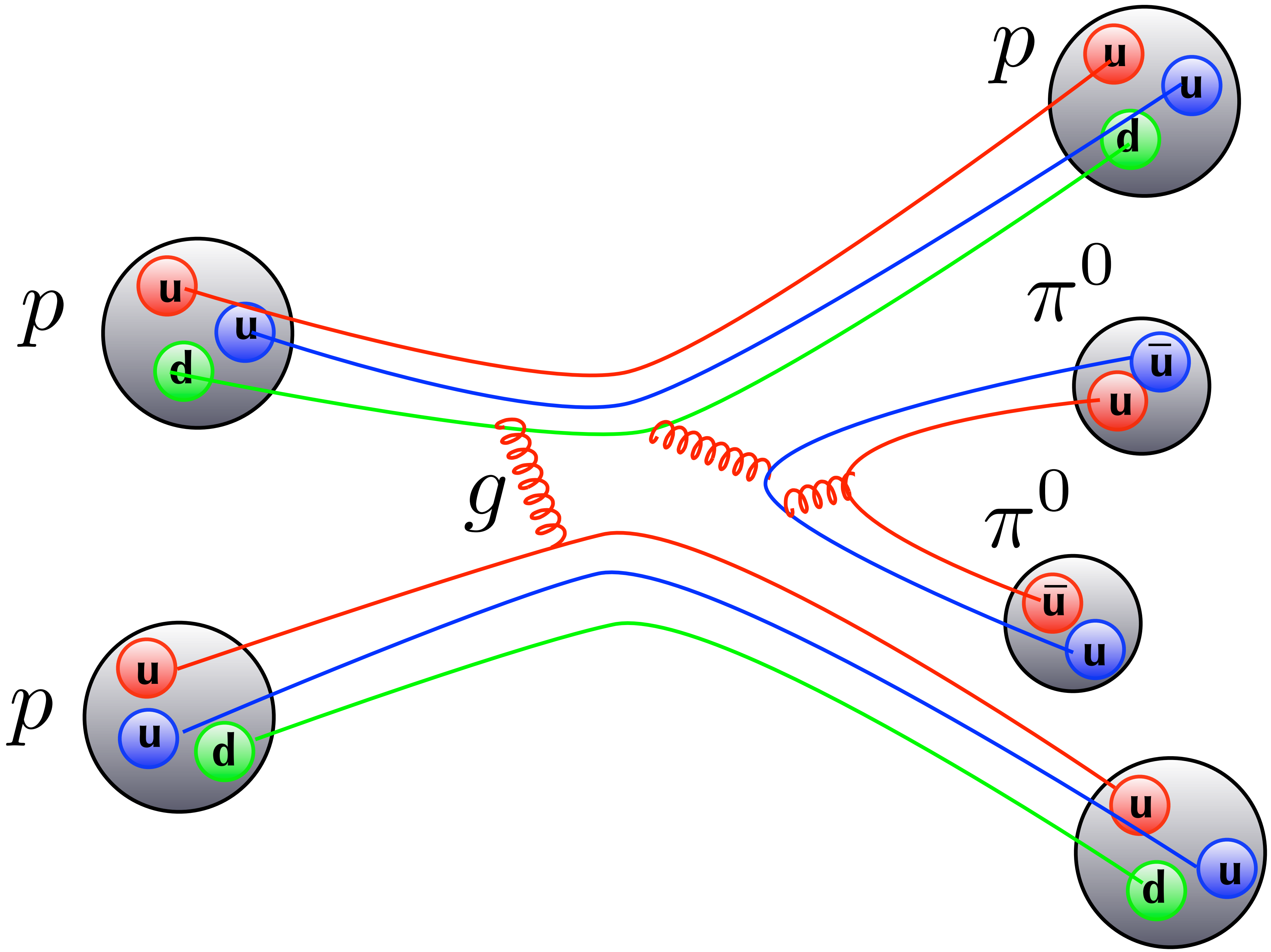


Pion Production



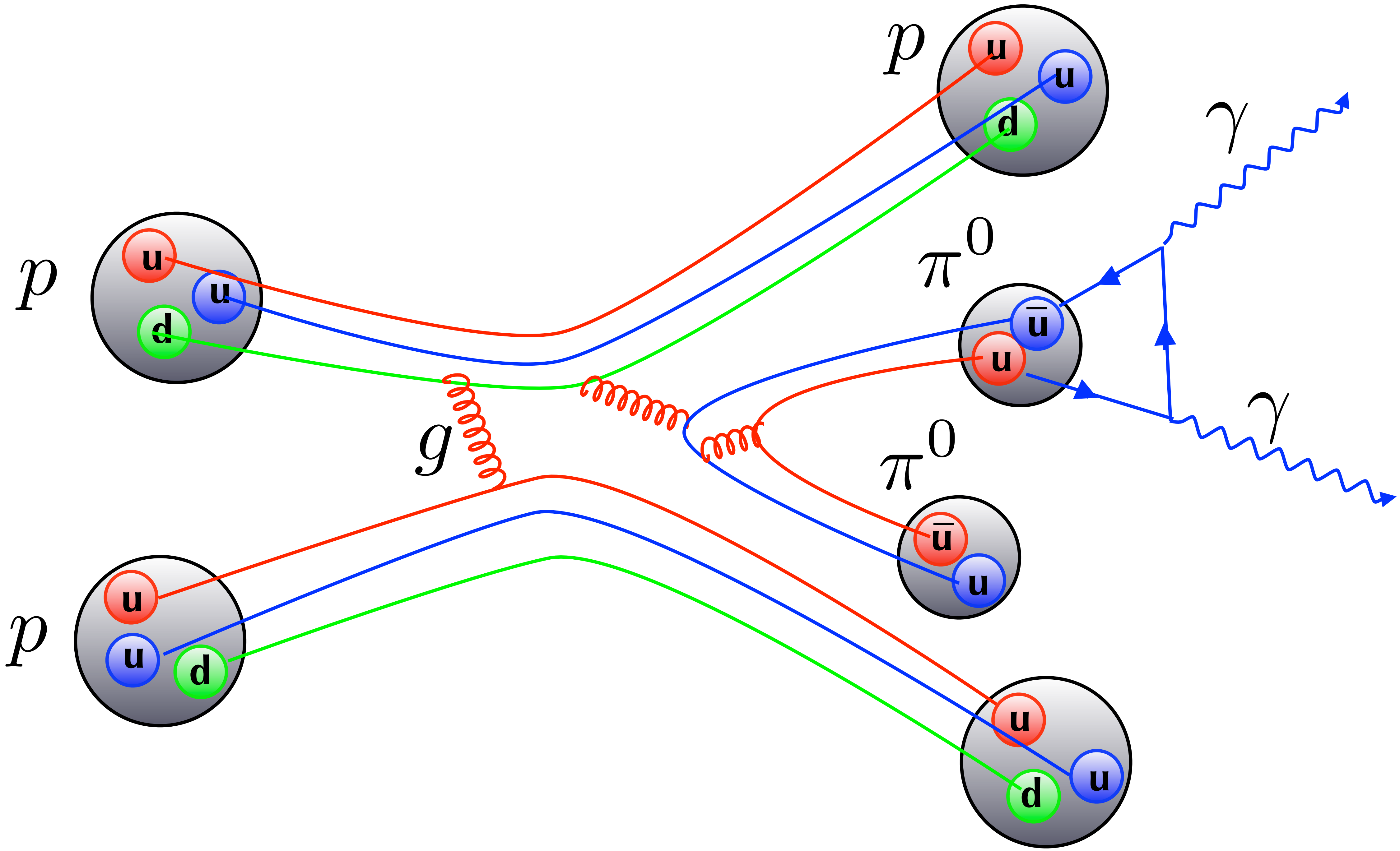
- Protons and other nuclei like bags of quarks, interact by radiating and exchanging gluons. Neutral or charged pions can be formed in interactions.

Pion Production



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

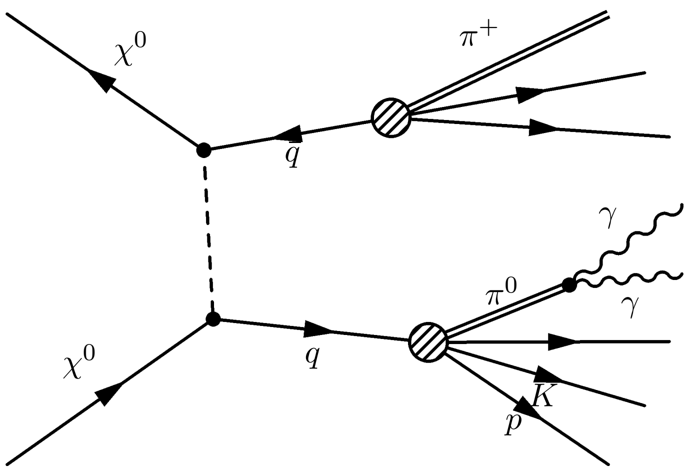
Pion Production

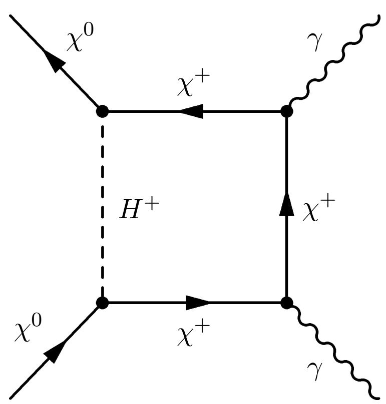


- Protons and other nuclei like bags of quarks, interact by radiating and exchanging gluons. Neutral or charged pions can be formed in interactions.

Annihilation Channels

Text

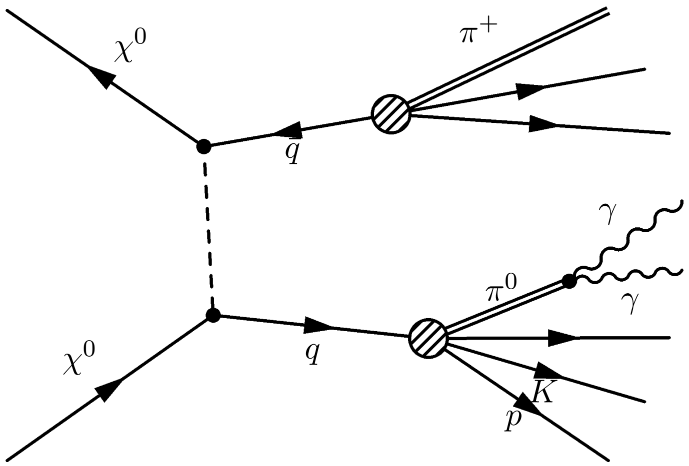


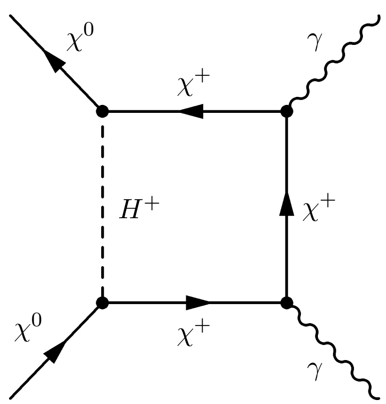


Annihilation Channel	Secondary Processes	Signals	Notes
$\chi\chi \to q\bar{q},\ gg$	$p, \bar{p}, \pi^{\pm}, \pi^0$	p, e, ν, γ	
$\chi\chi \to W^+W^-$	$W^{\pm} \to l^{\pm}\nu_l,\ W^{\pm} \to u\bar{d} \to \pi^{\pm},\ \pi^0$	p, e, ν, γ	
$\chi\chi \to Z^0Z^0$	$Z^0 \to l\bar{l},\ \nu\bar{\nu},\ q\bar{q} \to$ 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

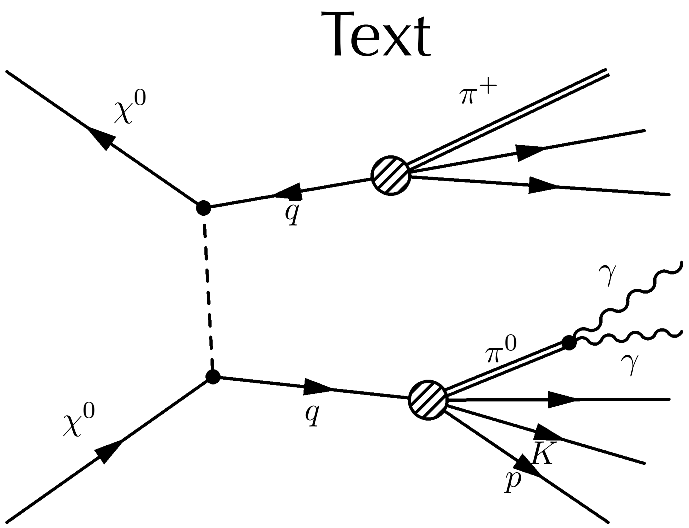


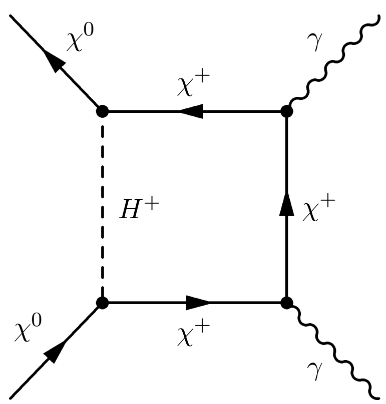


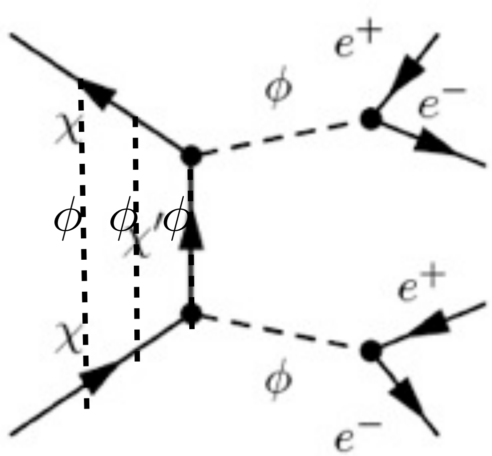
Annihilation Channel	Secondary Processes	Signals	Notes
$\chi\chi \to q\bar{q},\ gg$	$p, \bar{p}, \pi^{\pm}, \pi^0$	p, e, ν, γ	
$\chi\chi \to W^+W^-$	$W^{\pm} \to l^{\pm}\nu_l,\ W^{\pm} \to u\bar{d} \to \pi^{\pm},\ \pi^0$	p, e, ν, γ	
$\chi\chi \to Z^0Z^0$	$Z^0 \to l\bar{l},\ \nu\bar{\nu},\ q\bar{q} \to$ 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





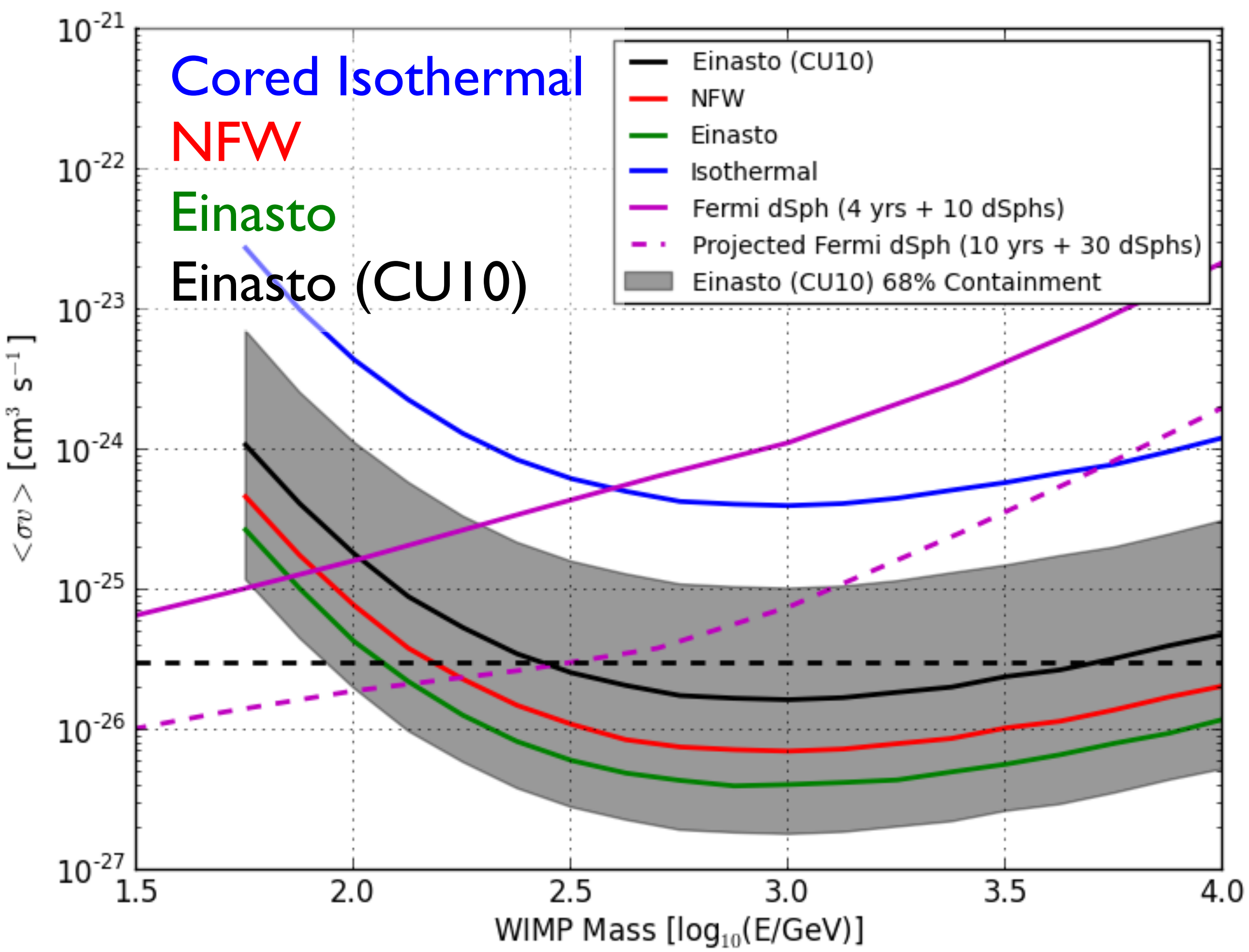


Annihilation Channel	Secondary Processes	Signals	Notes
$\chi\chi \to q\bar{q},\ gg$	$p, \bar{p}, \pi^{\pm}, \pi^0$	p, e, ν, γ	
$\chi\chi \to W^+W^-$	$W^{\pm} \to l^{\pm}\nu_l,\ W^{\pm} \to u\bar{d} \to \pi^{\pm},\ \pi^0$	p, e, ν, γ	
$\chi\chi \to Z^0Z^0$	$Z^0 \to l\bar{l},\ \nu\bar{\nu},\ q\bar{q} \to$ 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

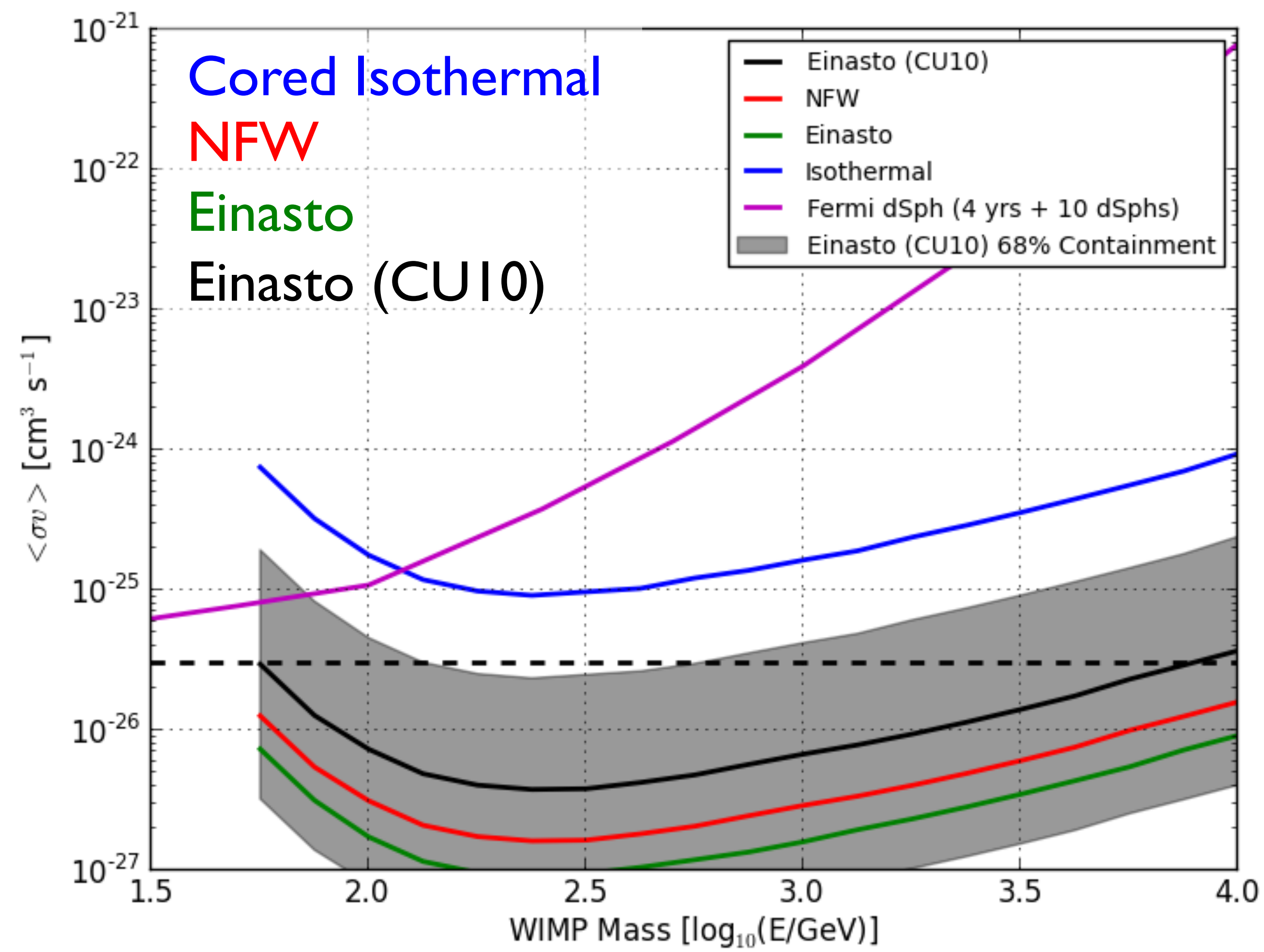
internal/final state bremms
inverse Compton γ's

Halo Uncertainties

bb Channel



tau Channel



500 hour exposure and 3 sigma detection threshold