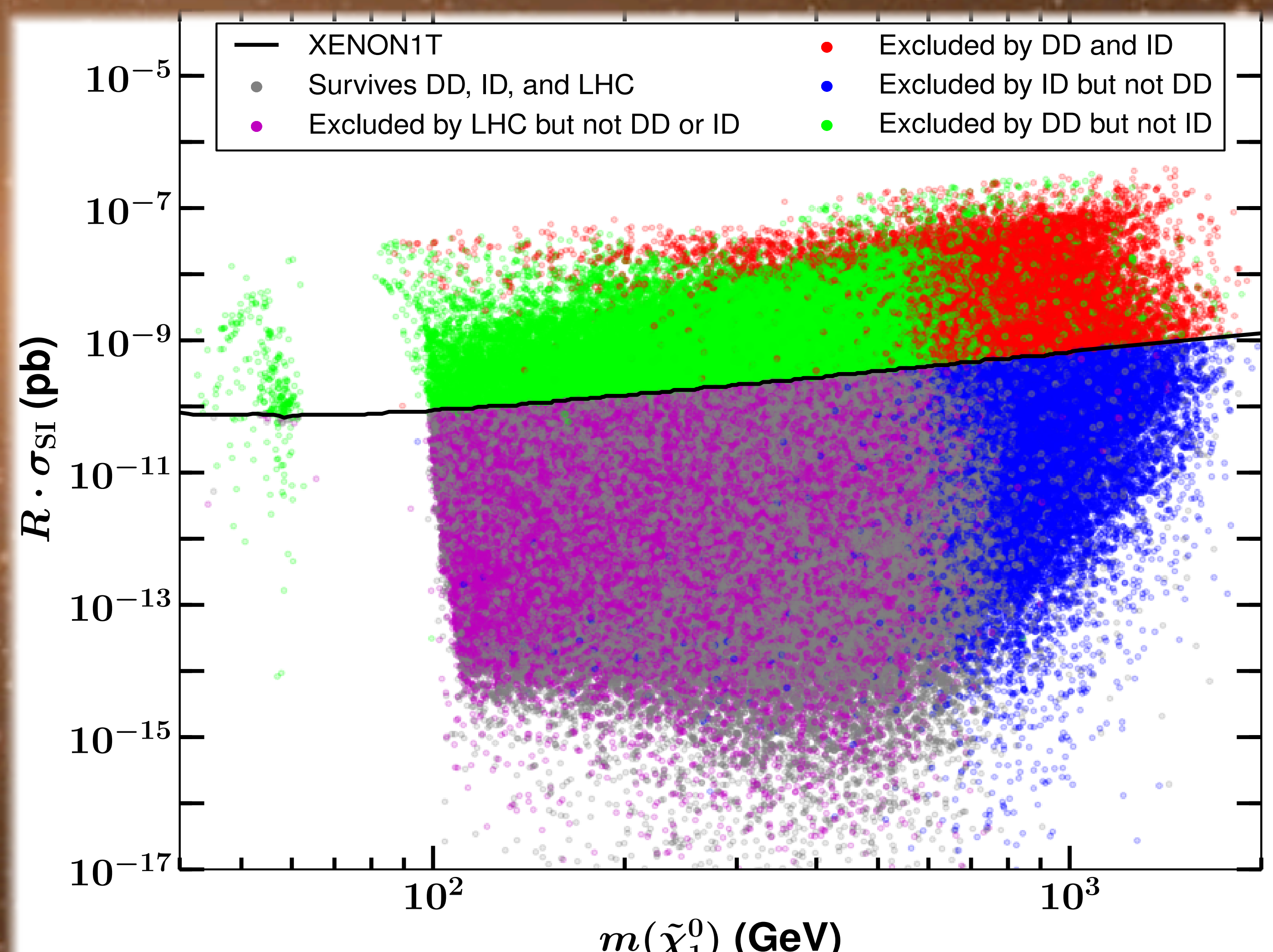
Dark Matter
Indirect Detection (CF2) Summary
Jim Buckley
for the Snowmass CF2 working group



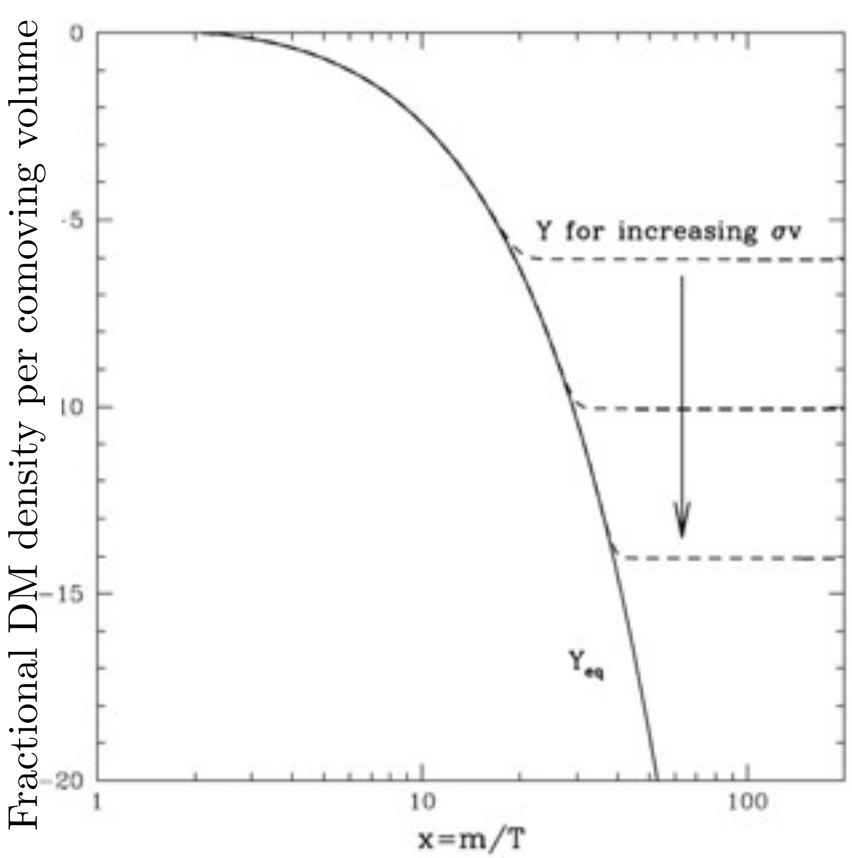
M. Cahill-Rowley, R. Cotta, A. Drlica-Wagner, S. Funk, J. Hewett, A. Ismail, T. Rizzo and M. Wood (SLAC and Irvine Particle Theory groups)

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

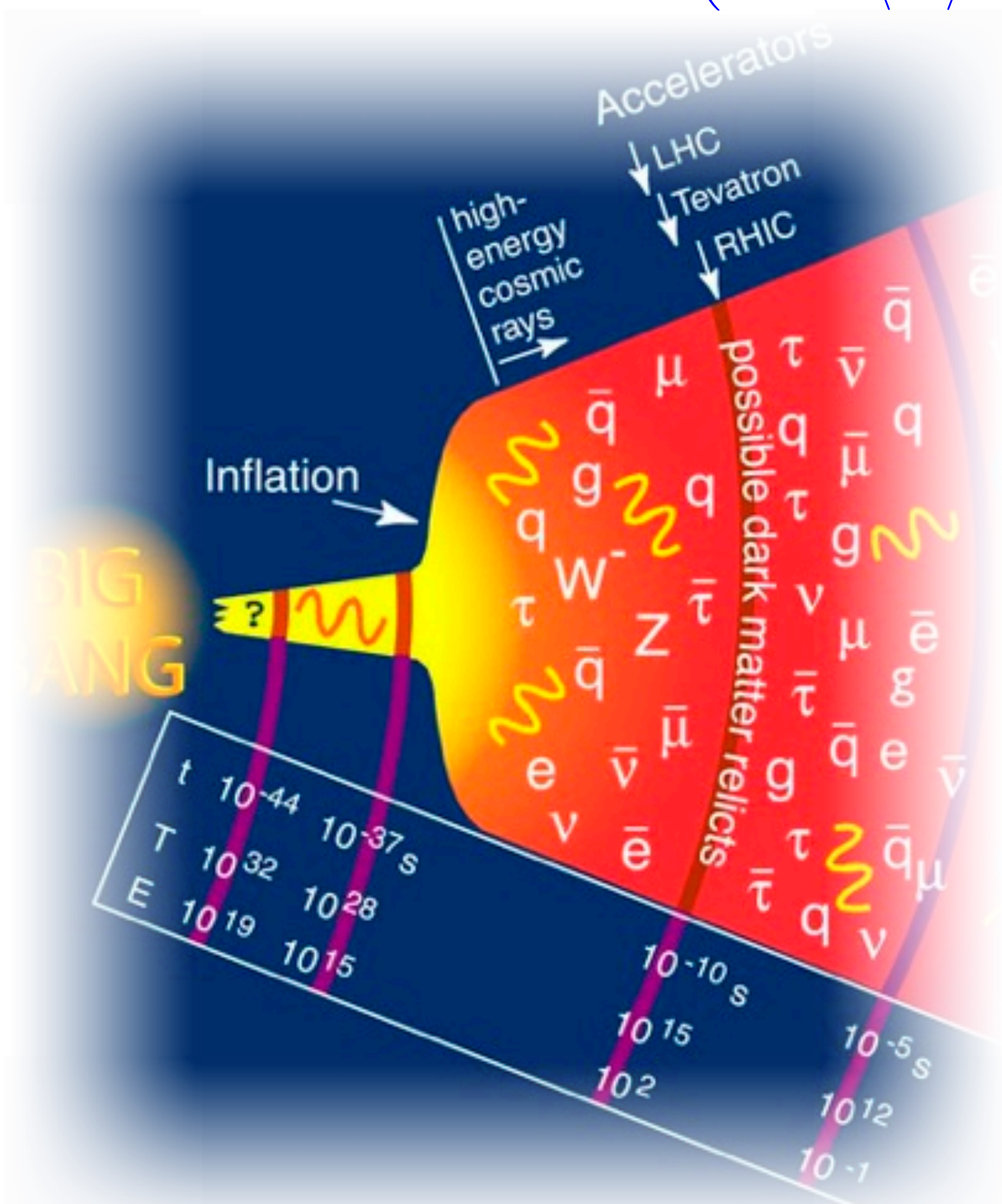


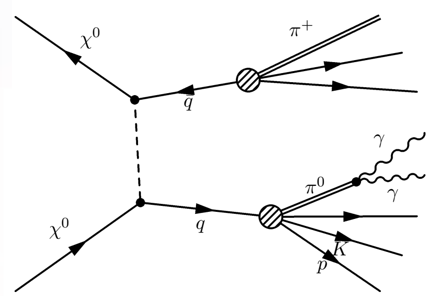
For a thermal relic of the big bang, the larger the annihilation cross section the longer the DM stays in equilibrium and the larger the Boltzmann suppression $\sim e^{-m_\chi/kT}$ before freeze-out.

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

Indirect Detection Cross Section

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





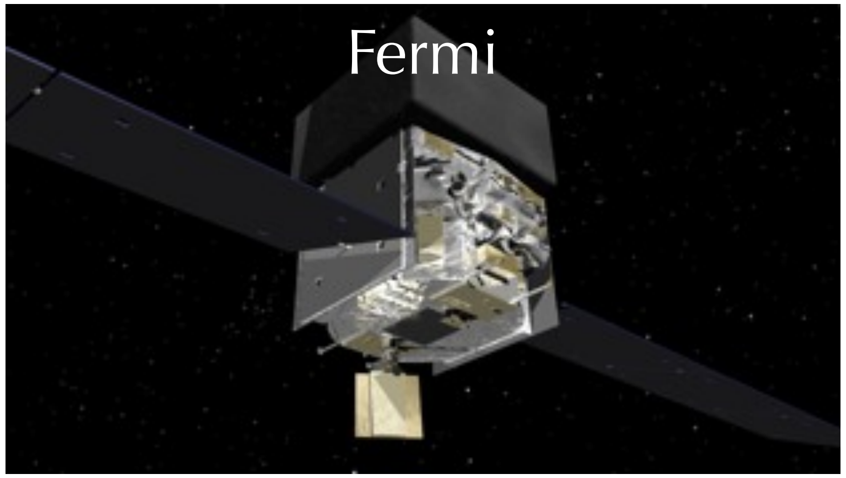
Annihilation Channel	Secondary Processes	Signals
$\chi\chi \to q\bar{q},\ gg$	$p,\bar{p},\pi^\pm,\pi^0$	p,e,ν,γ
$\chi\chi \to W^+W^-$	$W^\pm \to l^\pm\nu_l,\ W^\pm \to u\bar{d} \to \pi^\pm,\ \pi^0$	p,e,ν,γ
$\chi\chi \to Z^0Z^0$	$Z^0 \to l\bar{l},\ \nu\bar{\nu},\ q\bar{q} \to$ pions	p,e,γ,ν
$\chi\chi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

- The same interactions of WIMPs with standard model particles in the early universe (holding WIMPs in thermal equilibrium) 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 is closely related to the decoupling cross section:* $\sim n_\chi^2\langle\sigma v\rangle$

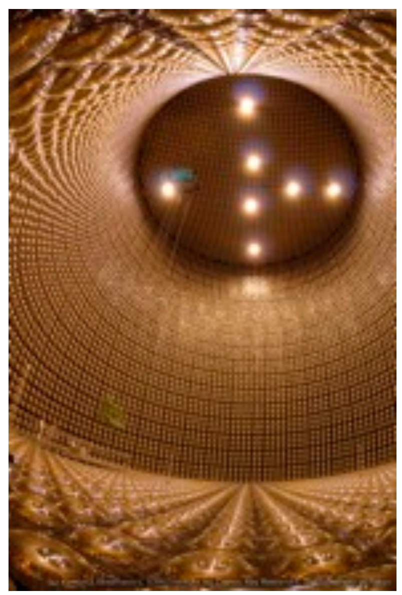
** Gamma-ray production by annihilation in the present universe is closely related to the decoupling cross section in the early universe with a natural scale* $\langle\sigma v\rangle \approx 3\times 10^{-26}\mathrm{cm}^3\mathrm{sec}^{-1}$

Indirect Detection

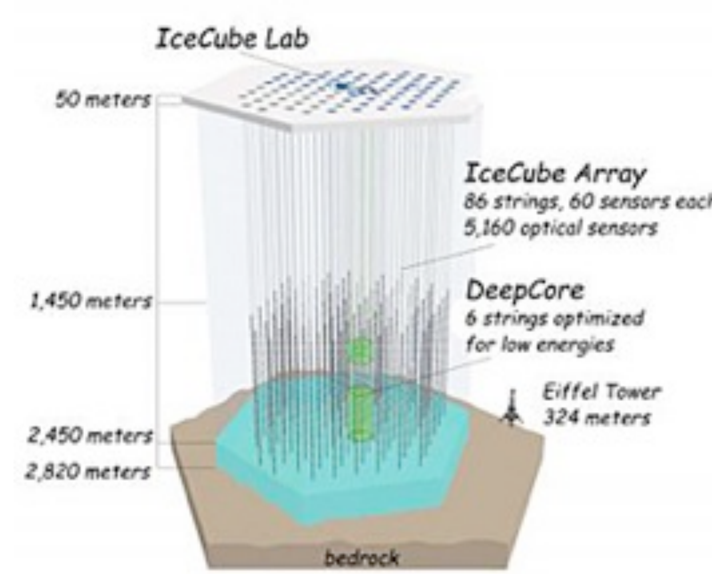


γ

Super-K

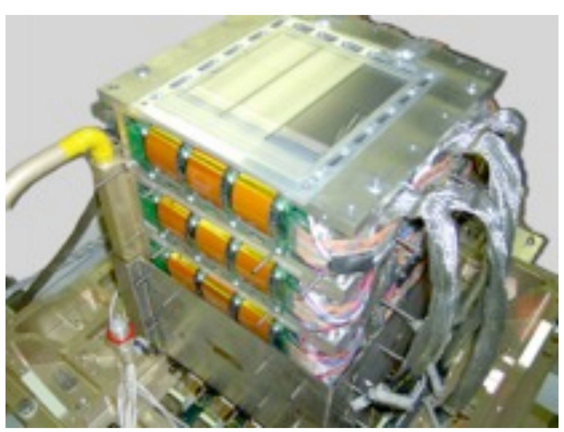


ν



ICECUBE

PAMELA



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

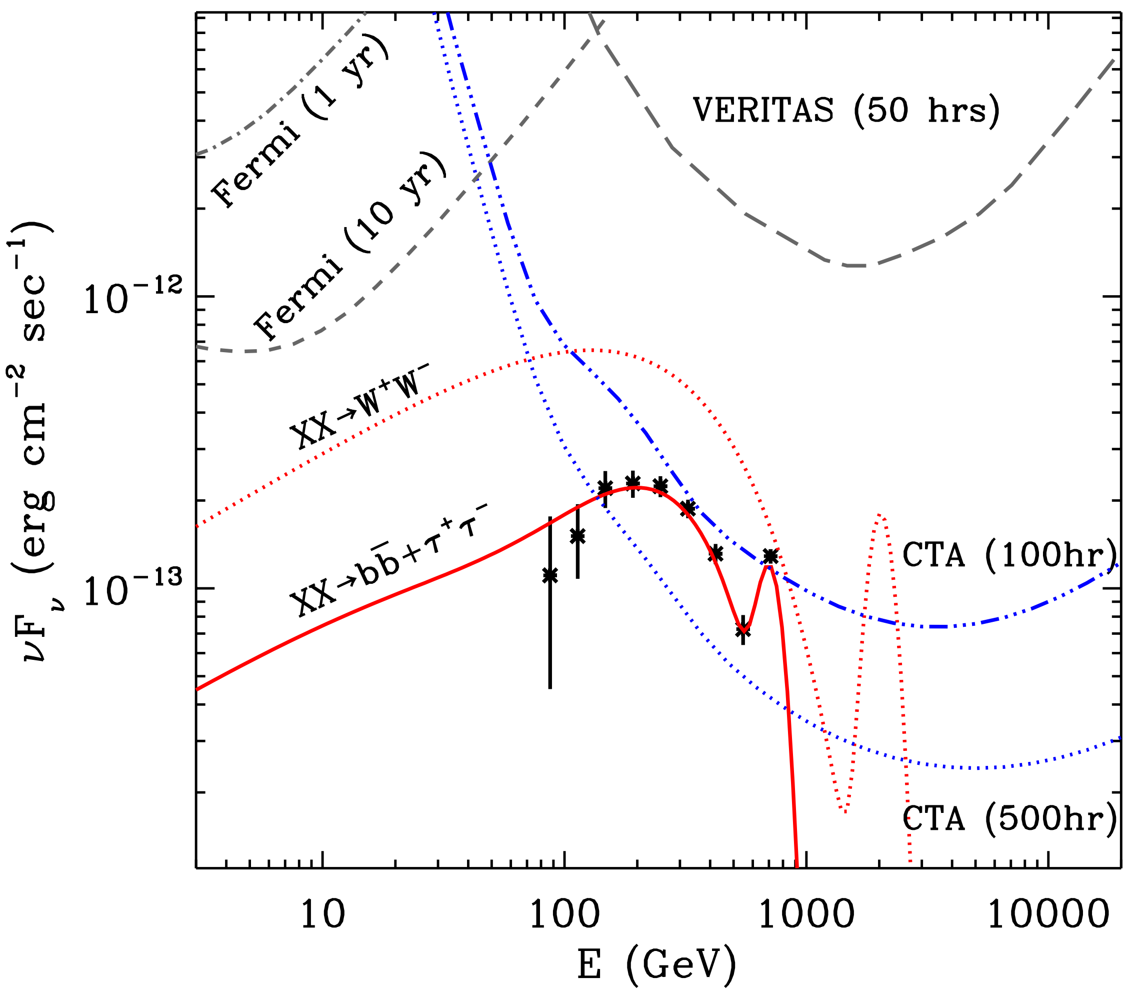
AMS

Current and Planned Experiments

Status	Experiment	Target	Location	Major Support	Comments
Current	AMS	e^+/e^-, anti-nuclei	ISS	NASA	Magnet Spectrometer, Running
	Fermi	Photons, e^+/e^-	Satellite	NASA, DOE	Pair Telescope and Calorimeter, Running
	HESS	Photons, e^-	Namibia	German BMBF, Max Planck Society, French Ministry for Research, CNRS-IN2P3, UK PPARC, South Africa	Atmospheric Cherenkov Telescope (ACT), Running
	IceCube/ DeepCore	Neutrinos	Antarctica	NSF, DOE, International *Belgium, Germany, Japan, Sweden)	Ice Cherenkov, Running
	MAGIC	Photons, e^+/e^-	La Palma	German BMBF and MPG, INFN, WSwiss SNF, Spanish MICINN, CPAN, Bulgarian NSF, Academy of Finland, DFG, Polish MNiSzW	ACT, Running
	PAMELA	e^+/e^-	Satellite		
	VERITAS	Photons, e^+/e^-	Arizona, USA	DOE, NSF, SAO	ACT, Running
Planned	CALET	e^+/e^-	ISS	Japan JAXA, Italy ASI, NASA	Calorimeter
	CTA	Photons	ground-based (TBD)	International (MinCyT, CNEA, CONICET, CNRS-INSU, CNRS-IN2P3, Irfu-CEA, ANR, MPI, BMBF, DESY, Helmholtz Association, MIUR, NOVA, NWO, Poland, MICINN, CDTI, CPAN, Swedish Research Council, Royal Swedish Academy of Sciences, SNSF, Durham UK, NSF, DOE	ACT
	GAMMA-400	Photons	Satellite	Russian Space Agency, Russian Academy of Sciences, INFN	Pair Telescope
	GAPS	Anti-deuterons	Balloon (LDB)	NASA, JAXA	TOF, X-ray and Pion detection
	HAWC	Photons, e^+/e^-	Sierra Negra	NSF/DOE	Water Cherenkov, Air Shower Surface Array
	PINGU	Neutrinos	Antarctica	NSF	Ice Cherenkov

Gamma 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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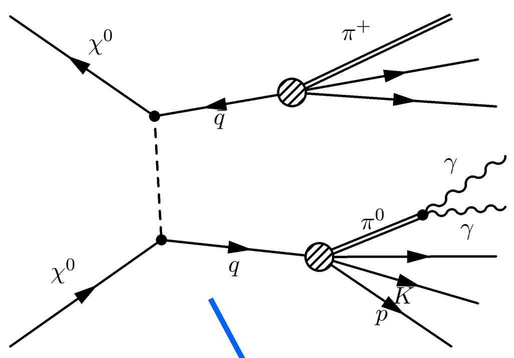

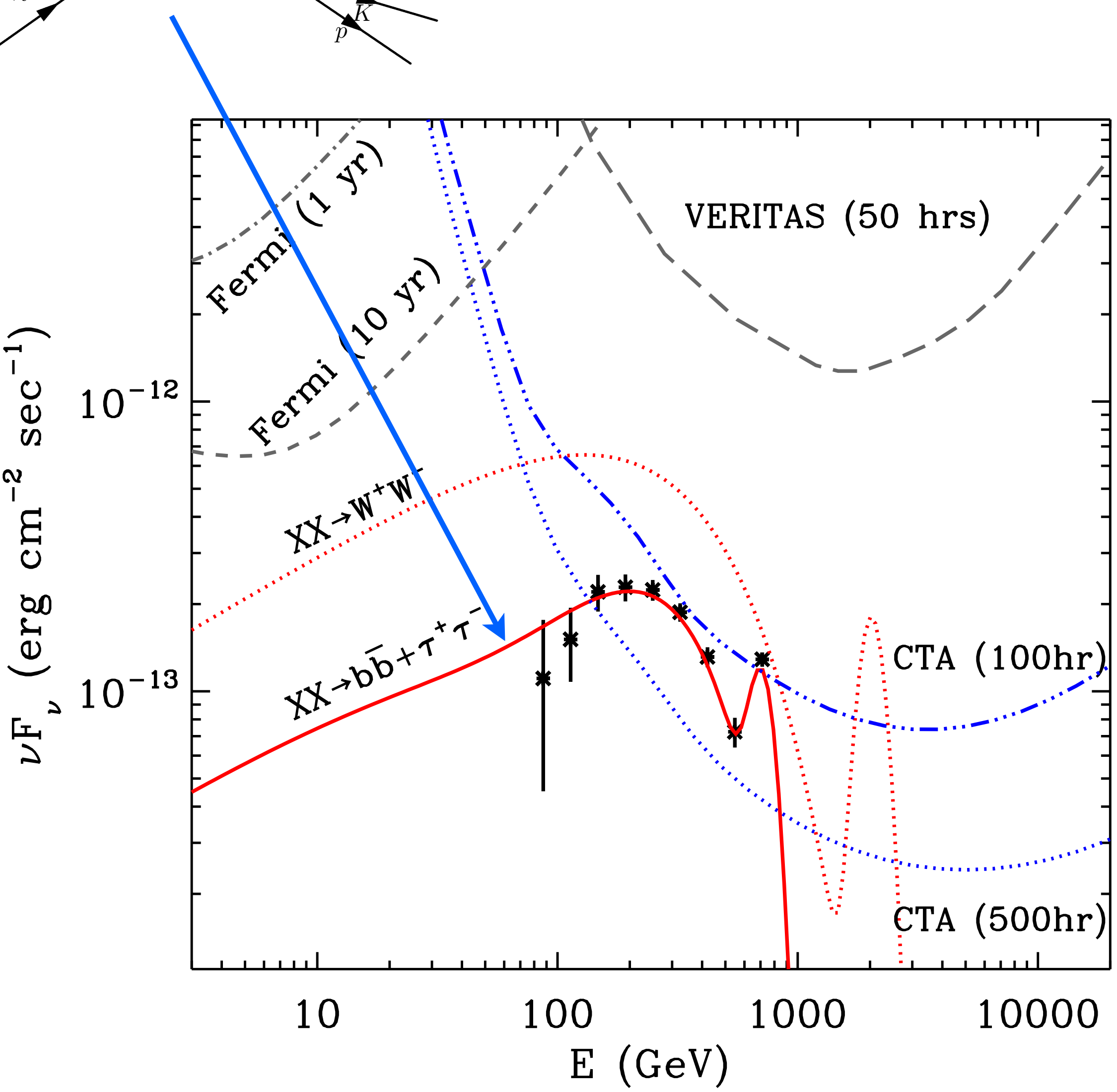

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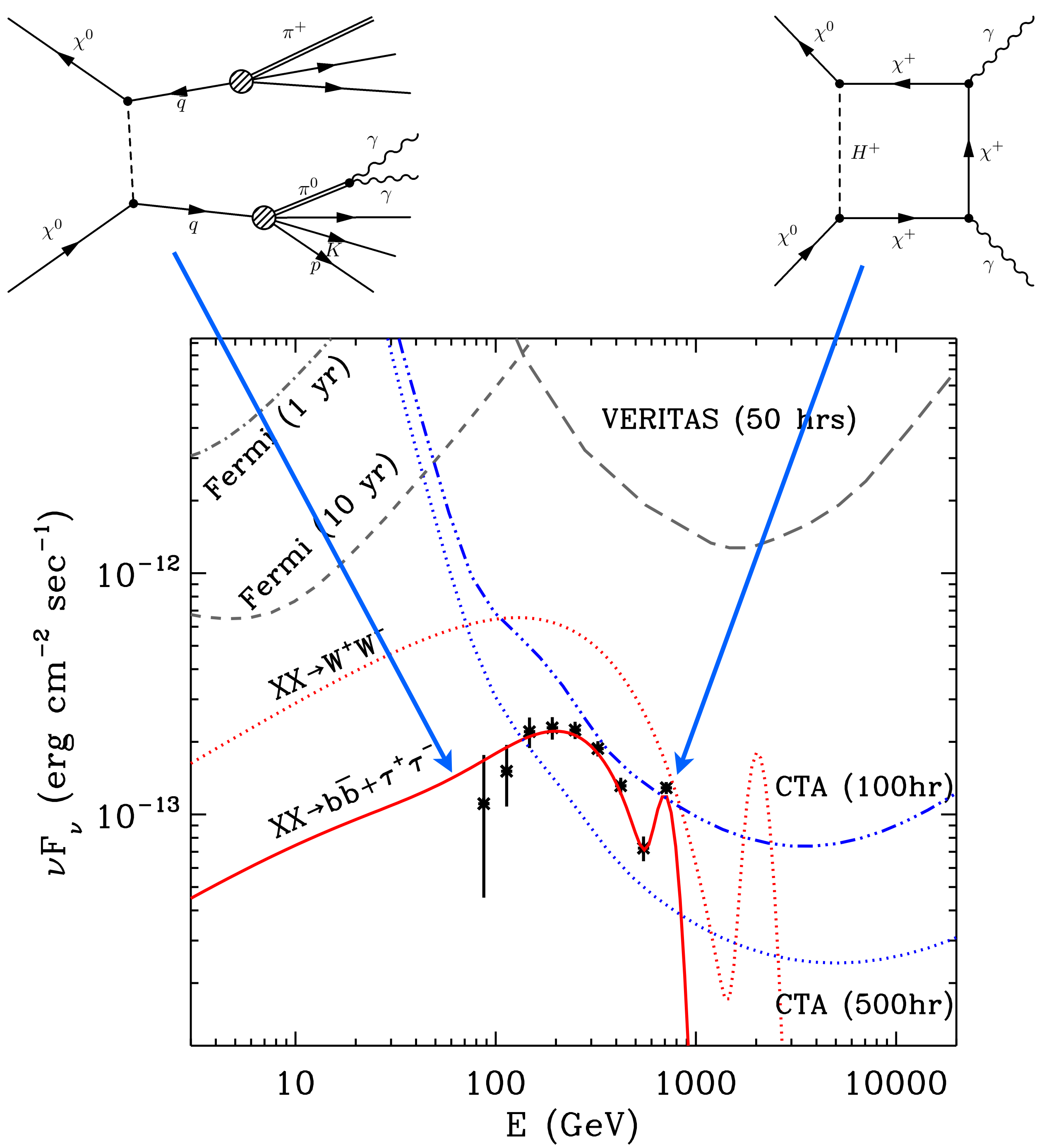

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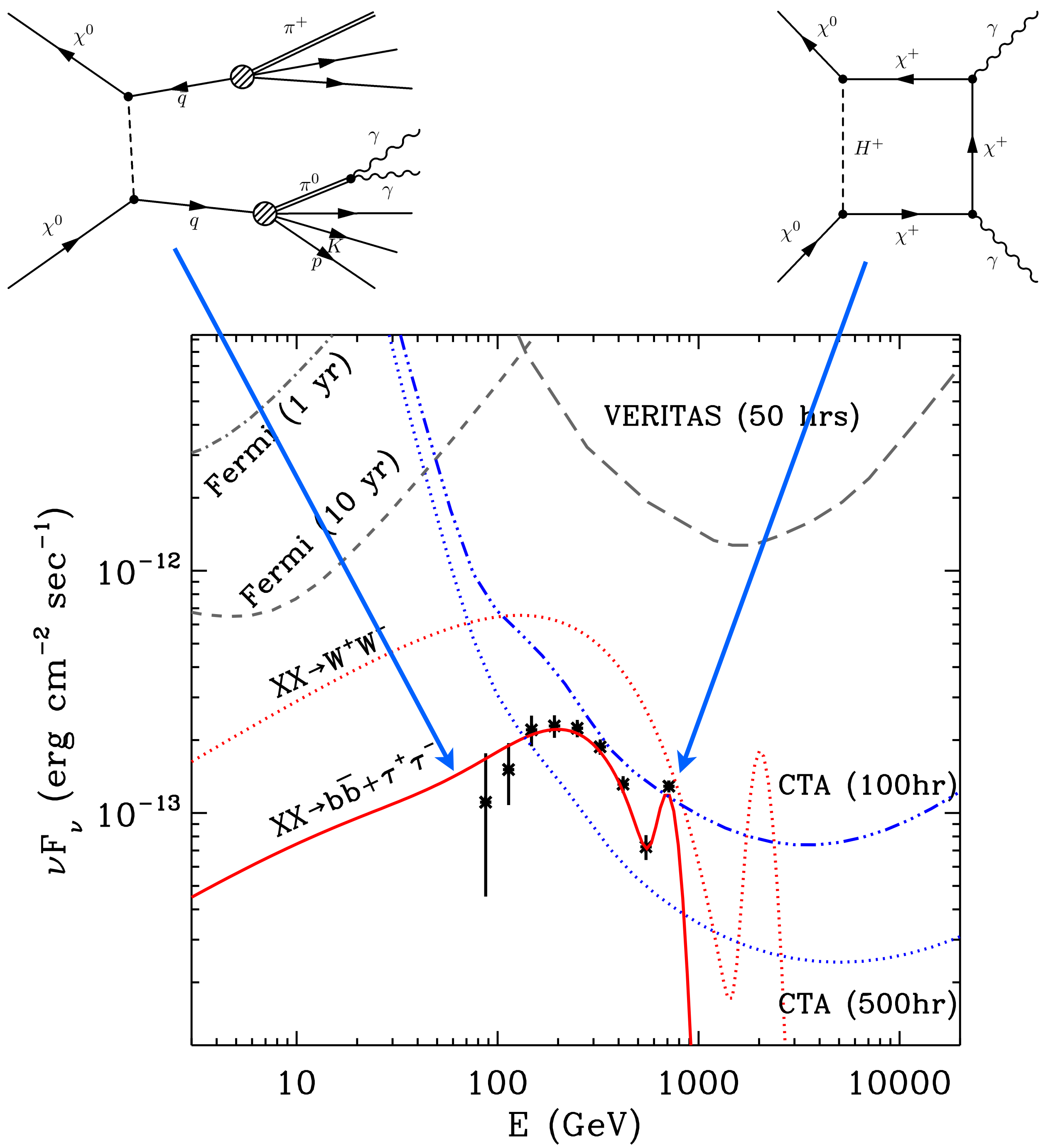
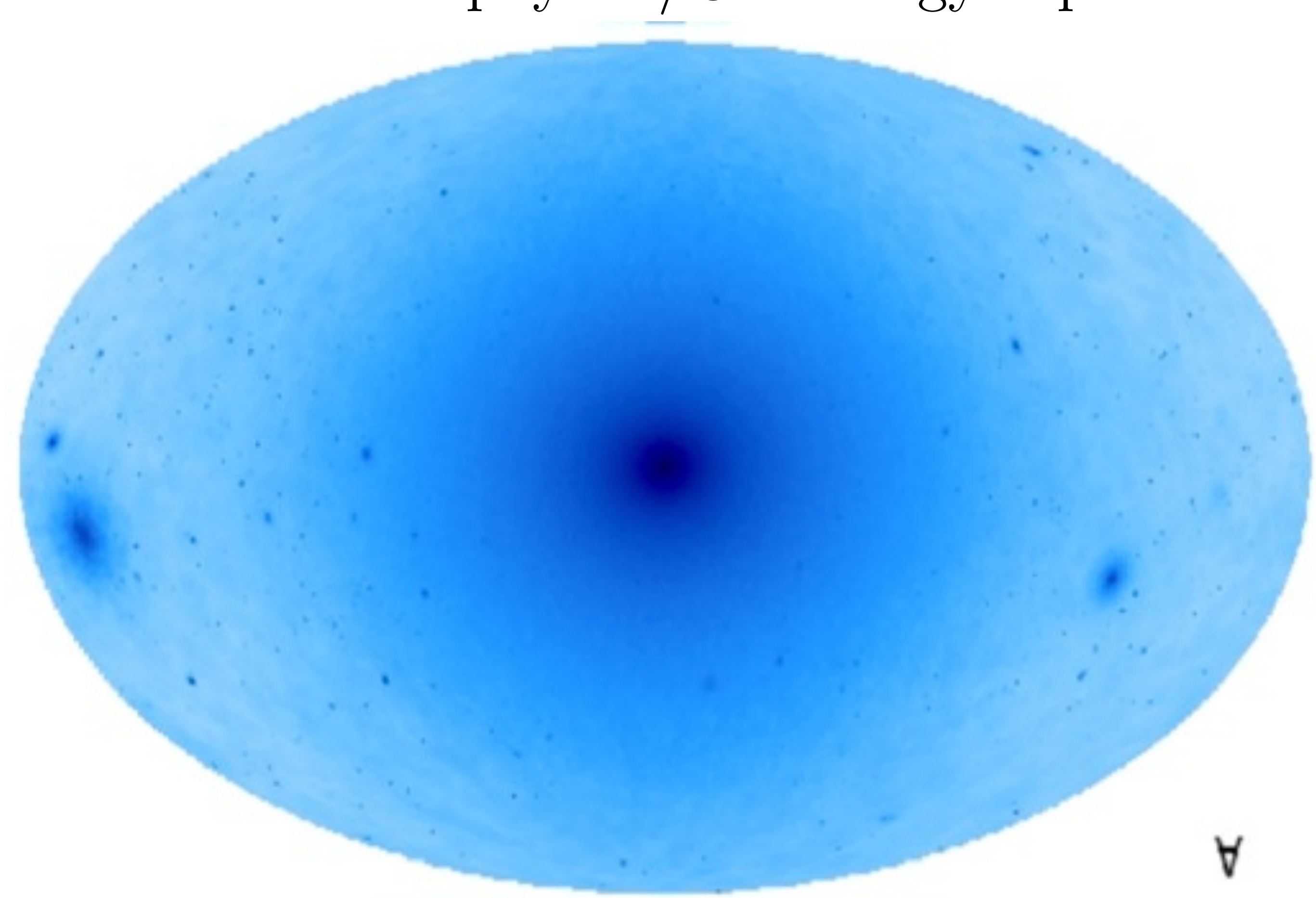
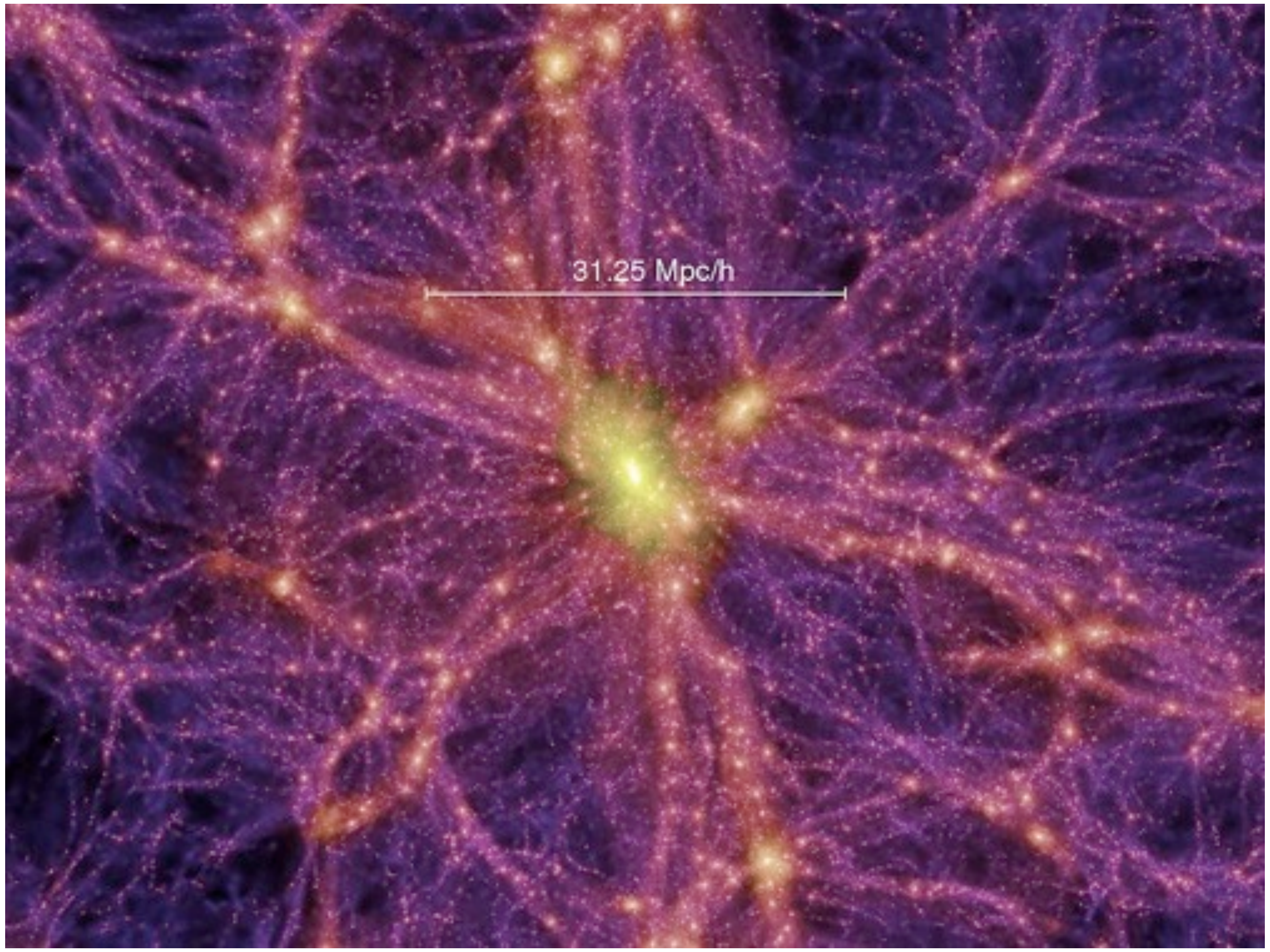
$$J(\theta) = \underbrace{\frac{1}{8.5\,\mathrm{kpc}} \left(\frac{1}{0.3\,\mathrm{GeV/cm^3}}\right)^2 \int_{\text{line of sight}} \rho^2(l)\,dl(\theta)}_{\text{Astrophysics/Cosmology Input}}$$



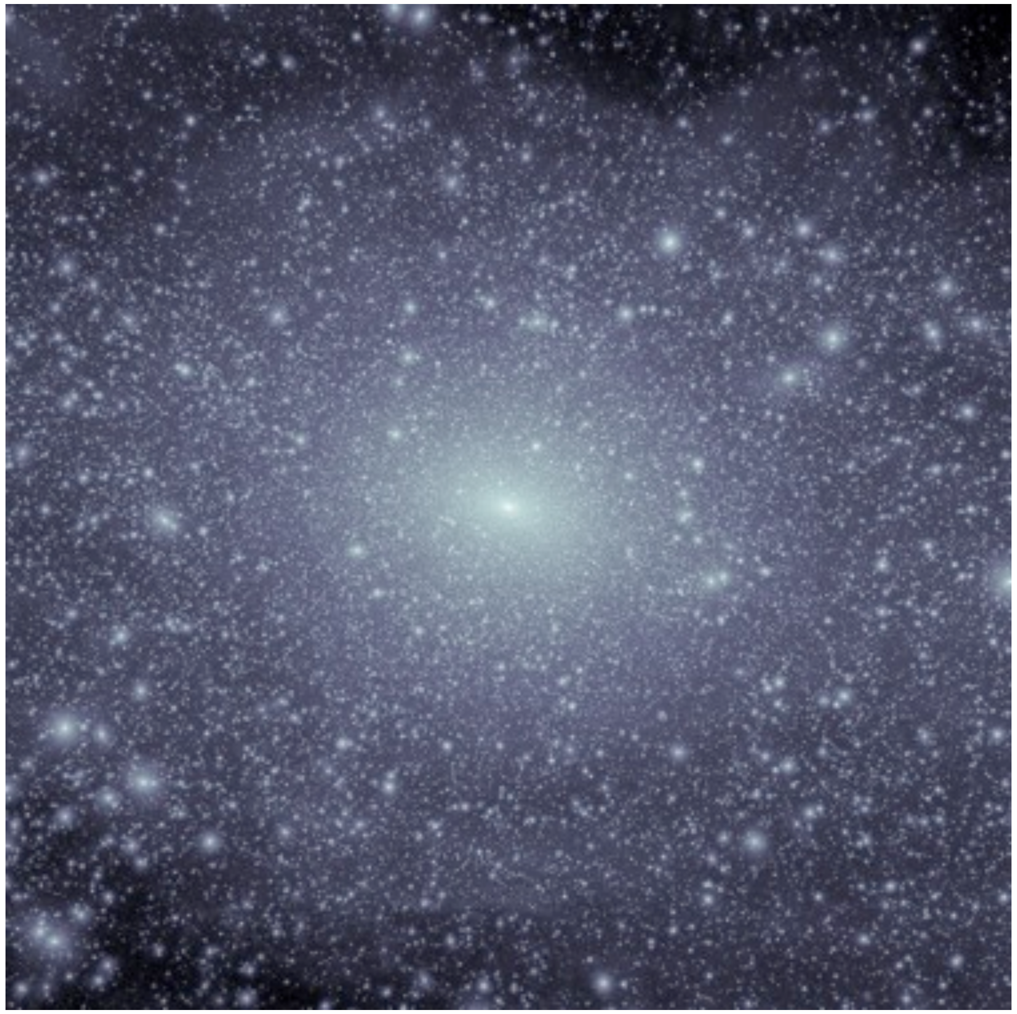


Line-of-sight integral of ρ^2 for a Milky-Way-like halo in the VL Lactea II ΛCDM N-body simulations (Kuhlen et al.)

Dark Matter Halos



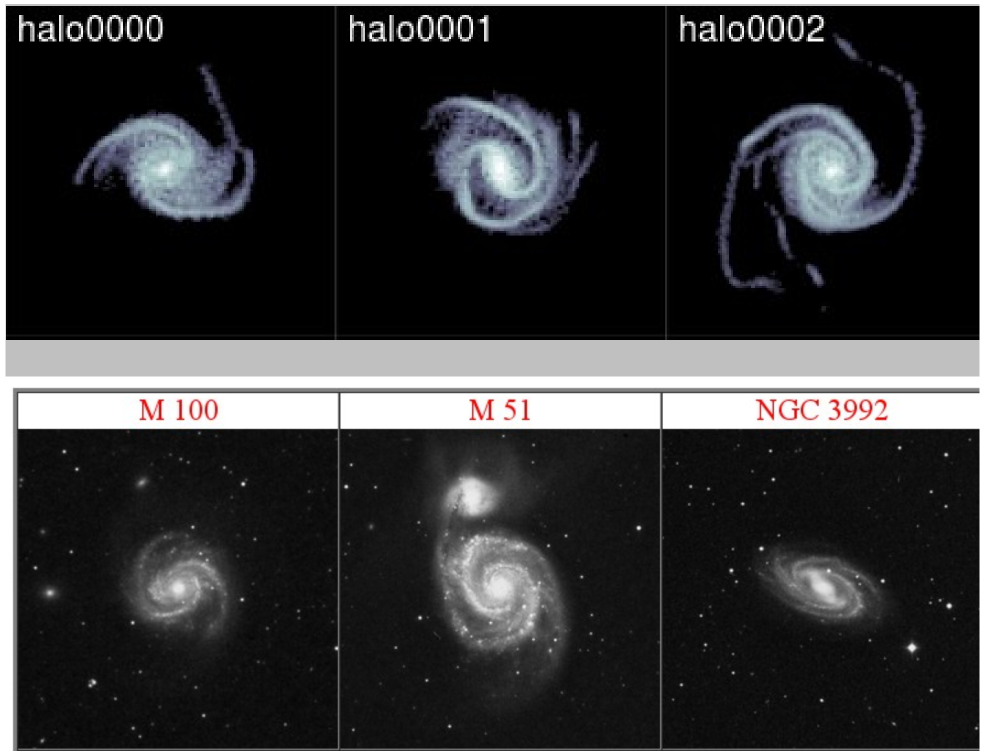
(Millenium simulation)

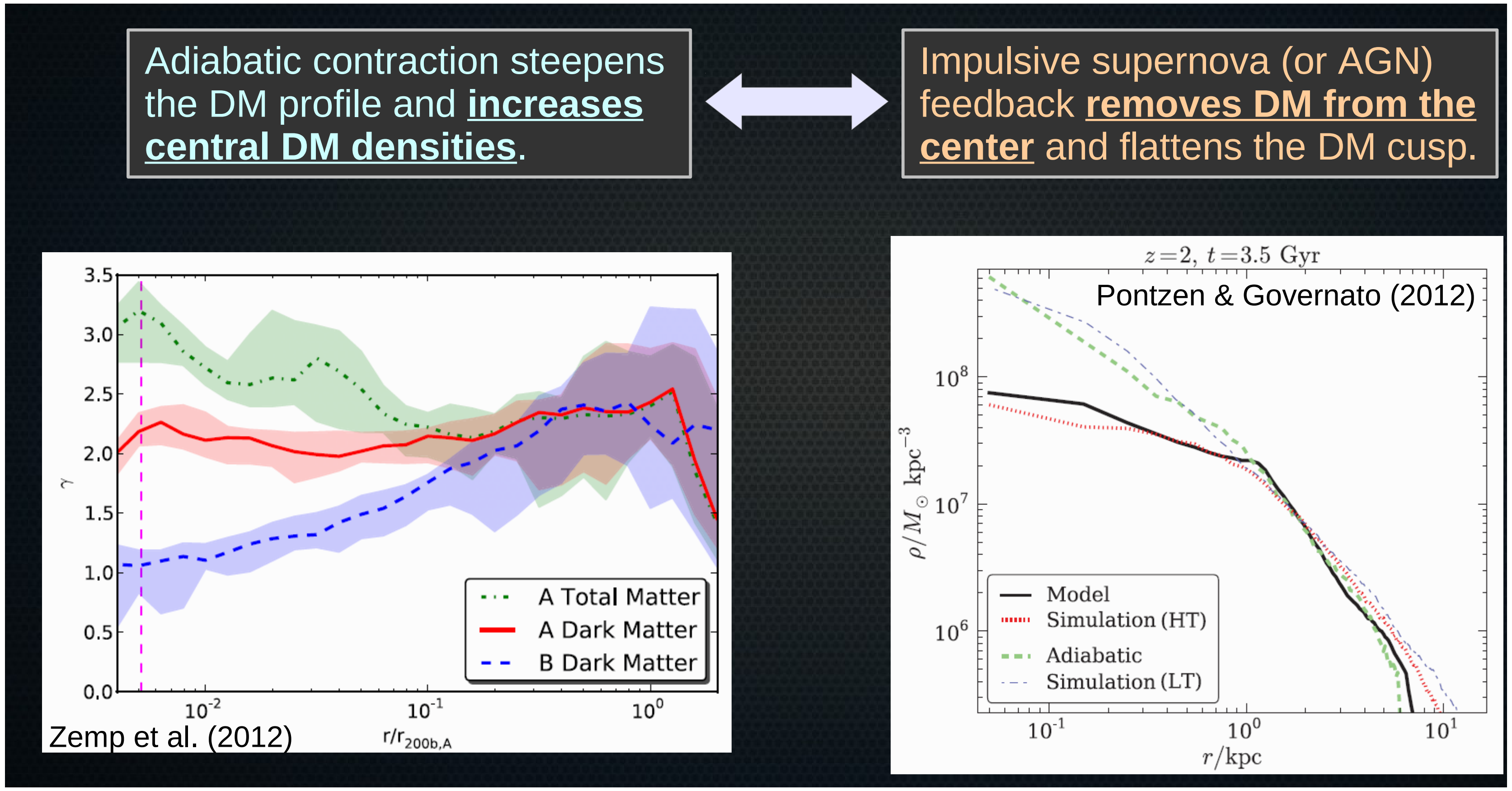


(VL Lactea II Simulation)

- N-body simulations now include 10s of billions of non-interacting particles, revealing information down to sub-kpc scales.
- Starting from initial conditions provided by ΛCDM cosmology, one obtains a picture of the present day universe which agrees very well with observed large scale structure

Baryonic Feedback

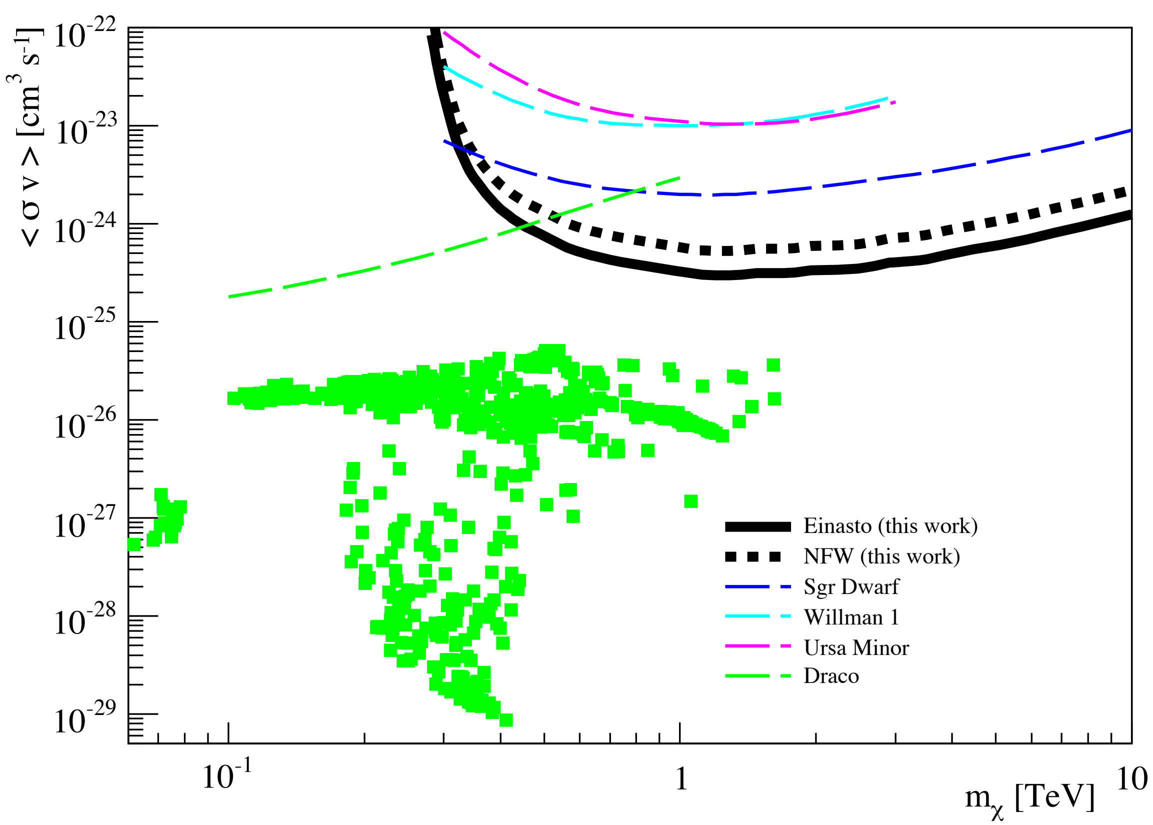




- N-body simulations with LCDM in remarkable agreement with observations, but some problems - too many dwarf galaxies, cored halos in dwarfs.
- Adding Baryons to N-body simulations starting to give amazing results - similar morphology, Tully-Fisher relation.
- Including interplay of baryonic matter may either result in cored halos with reduced signals, or cusped halos with a huge enhancement.

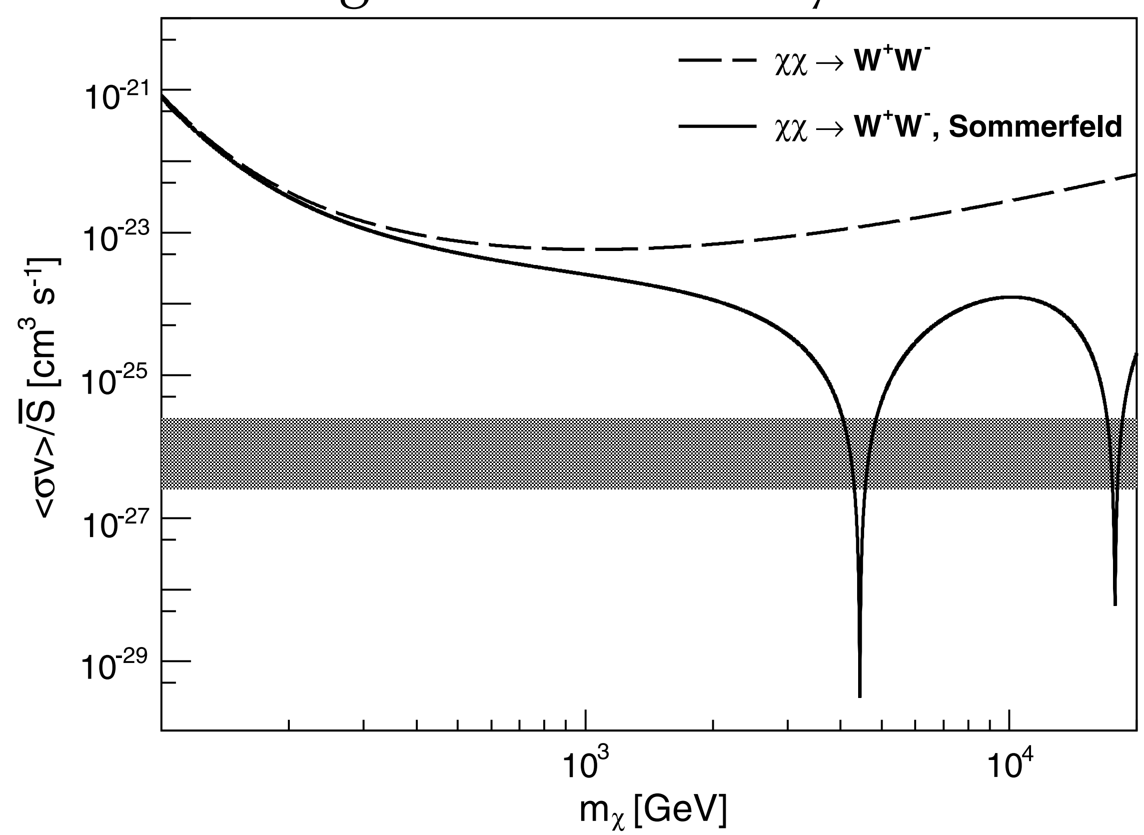
ACT DM Constraints

GC Limits



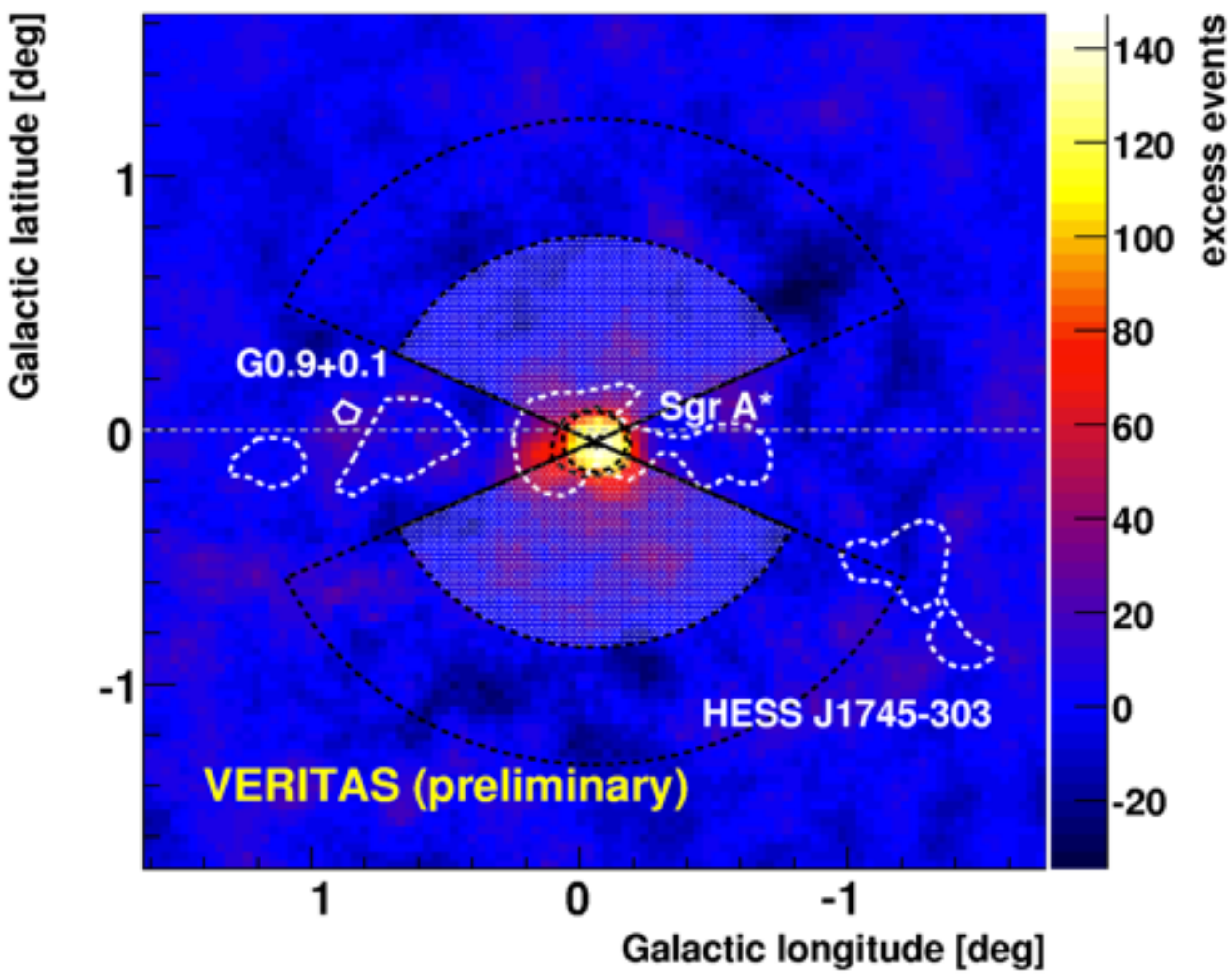
(Aharonian et al. for the HESS collaboration, PRL 106, 1301)

Segue Dwarf Galaxy Limits

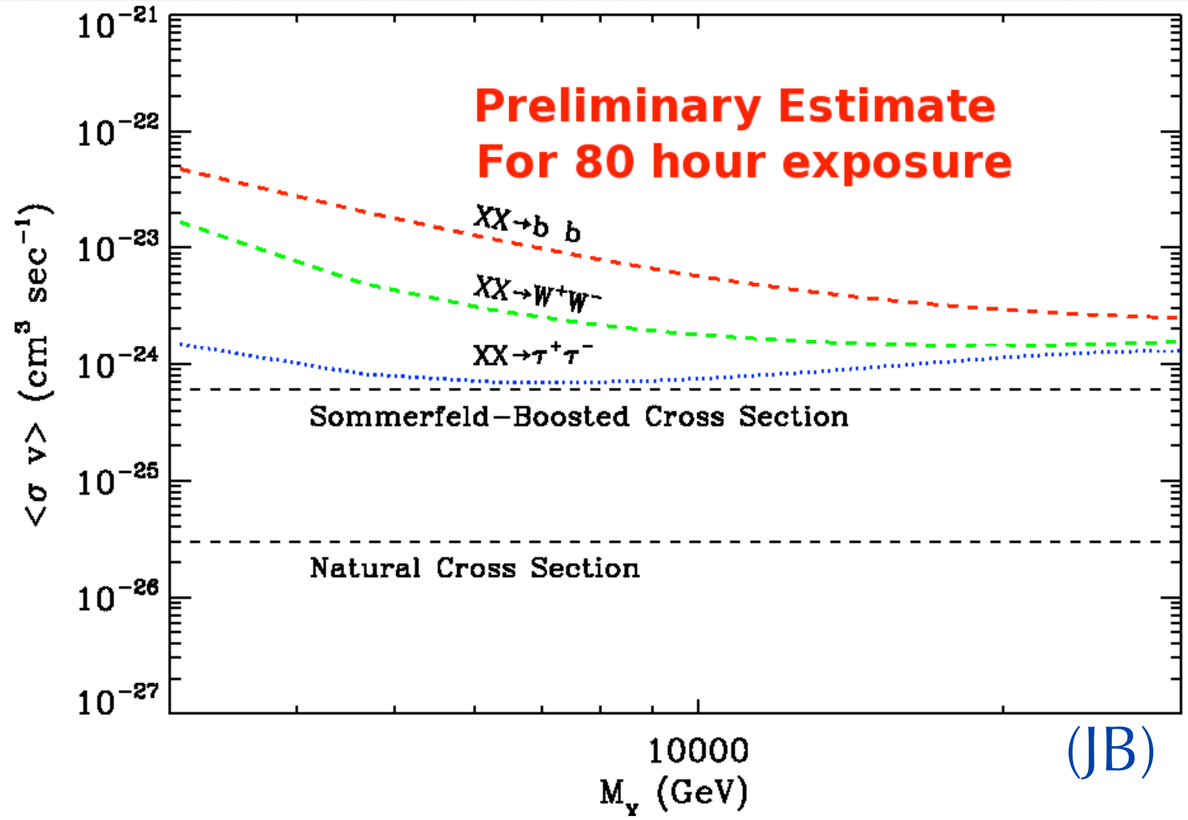


(Aliu et al. for the VERITAS collaboration, PRD 85, 062001)

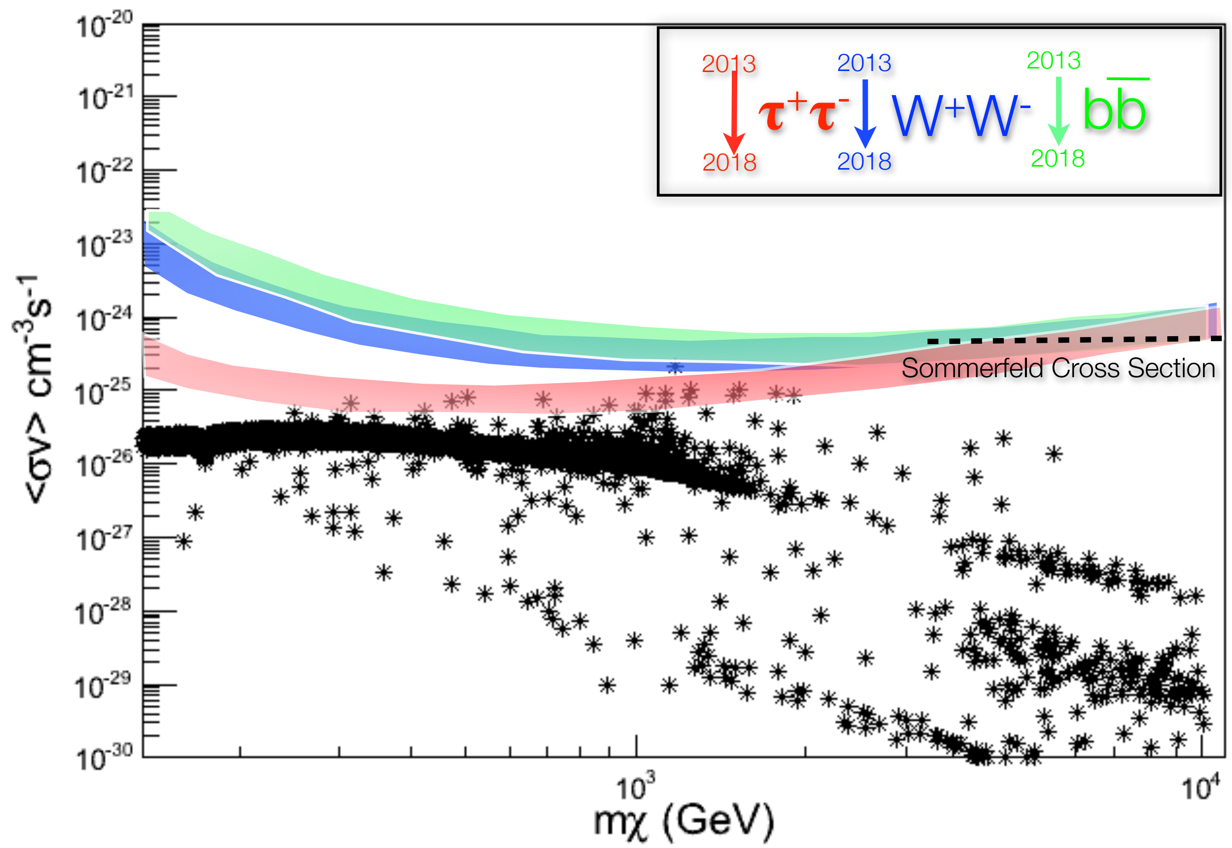
VERITAS Projections



(SLAC CF Workshop Talk by A. Smith)

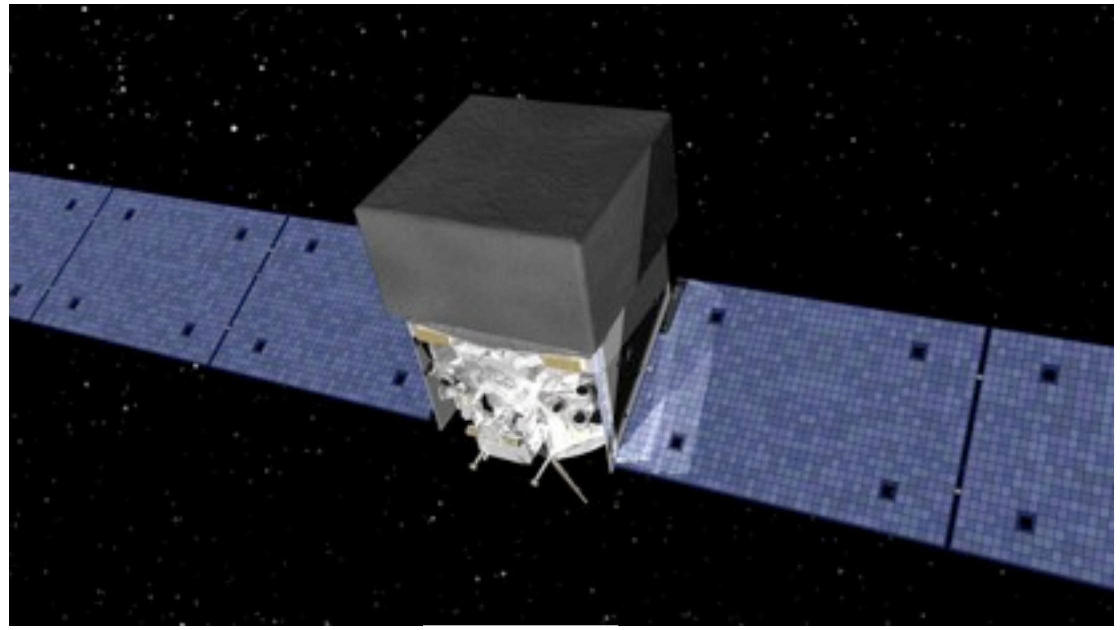


(JB)

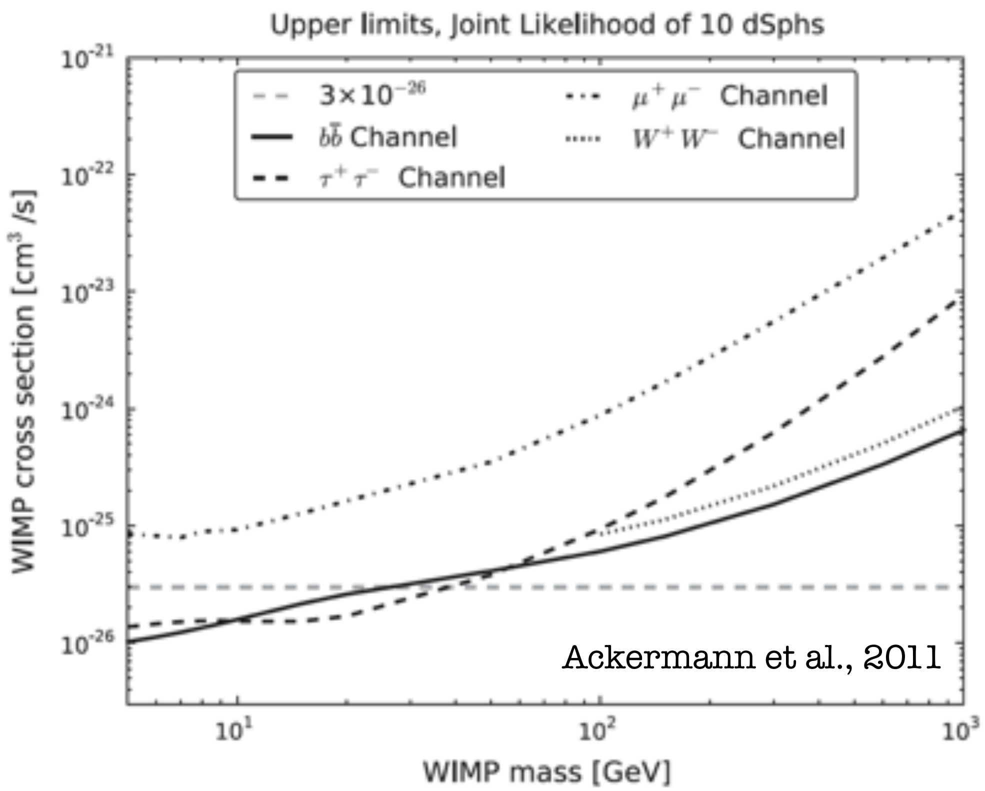


- With another 5 years, can push limits with VERITAS down into interesting cross-section regime

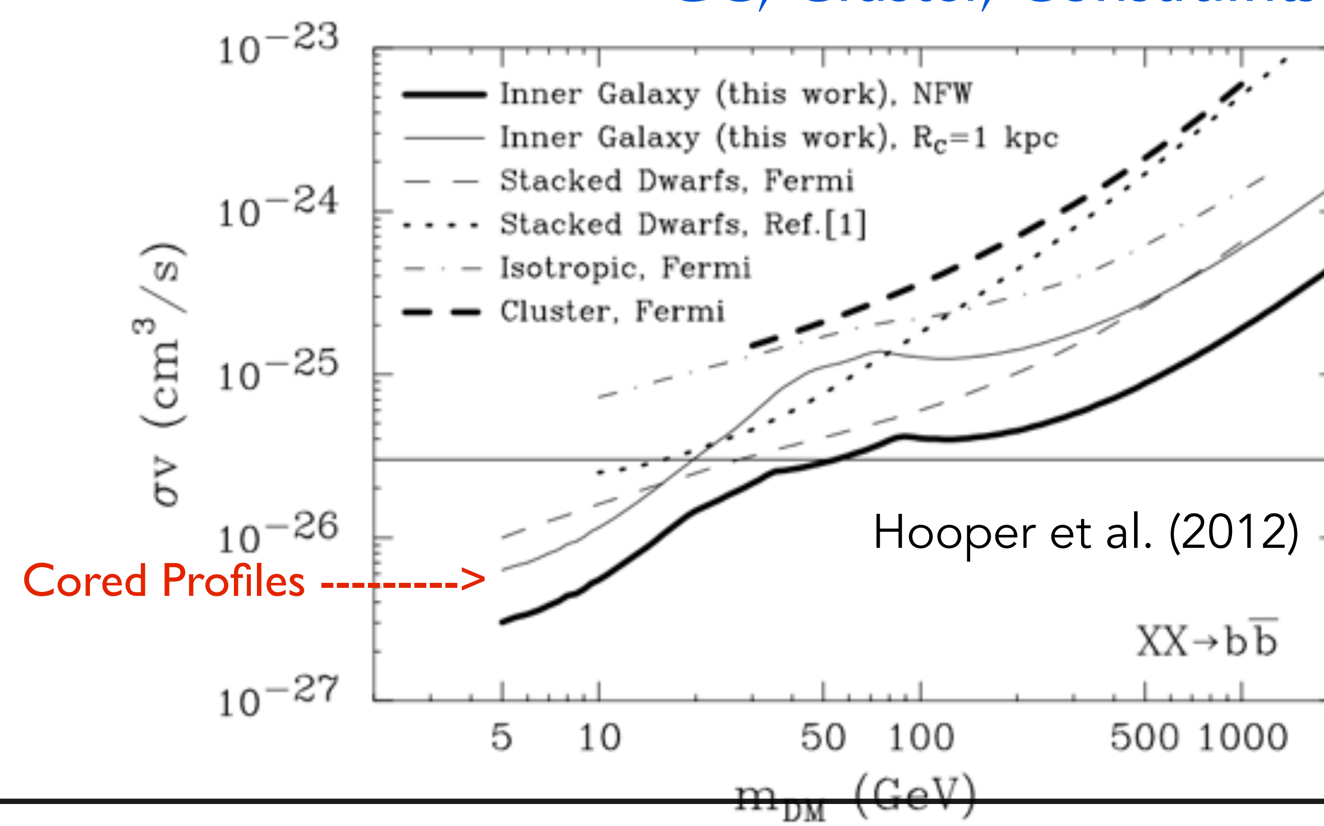
Fermi LAT DM Constraints



Dwarf Constraints

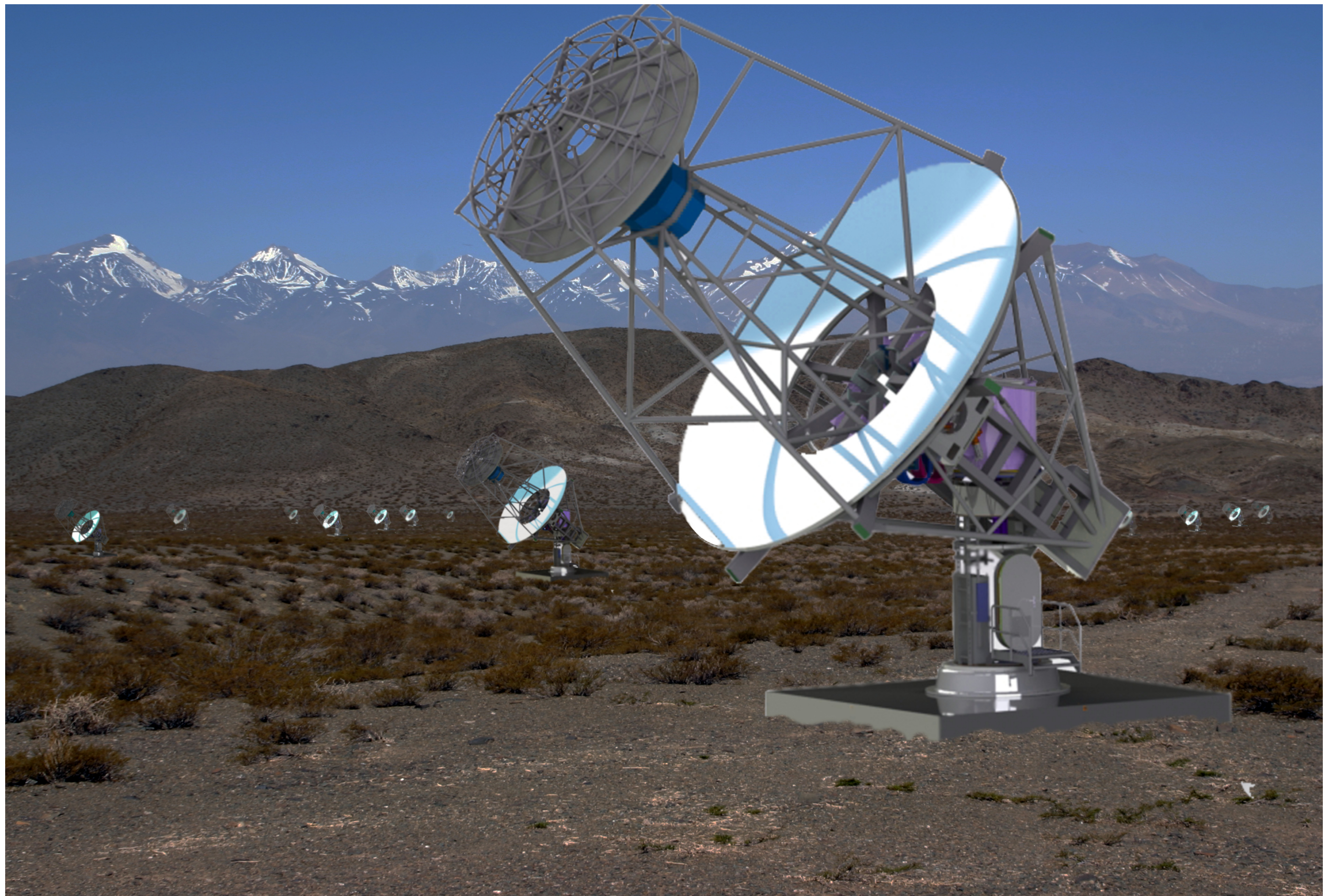


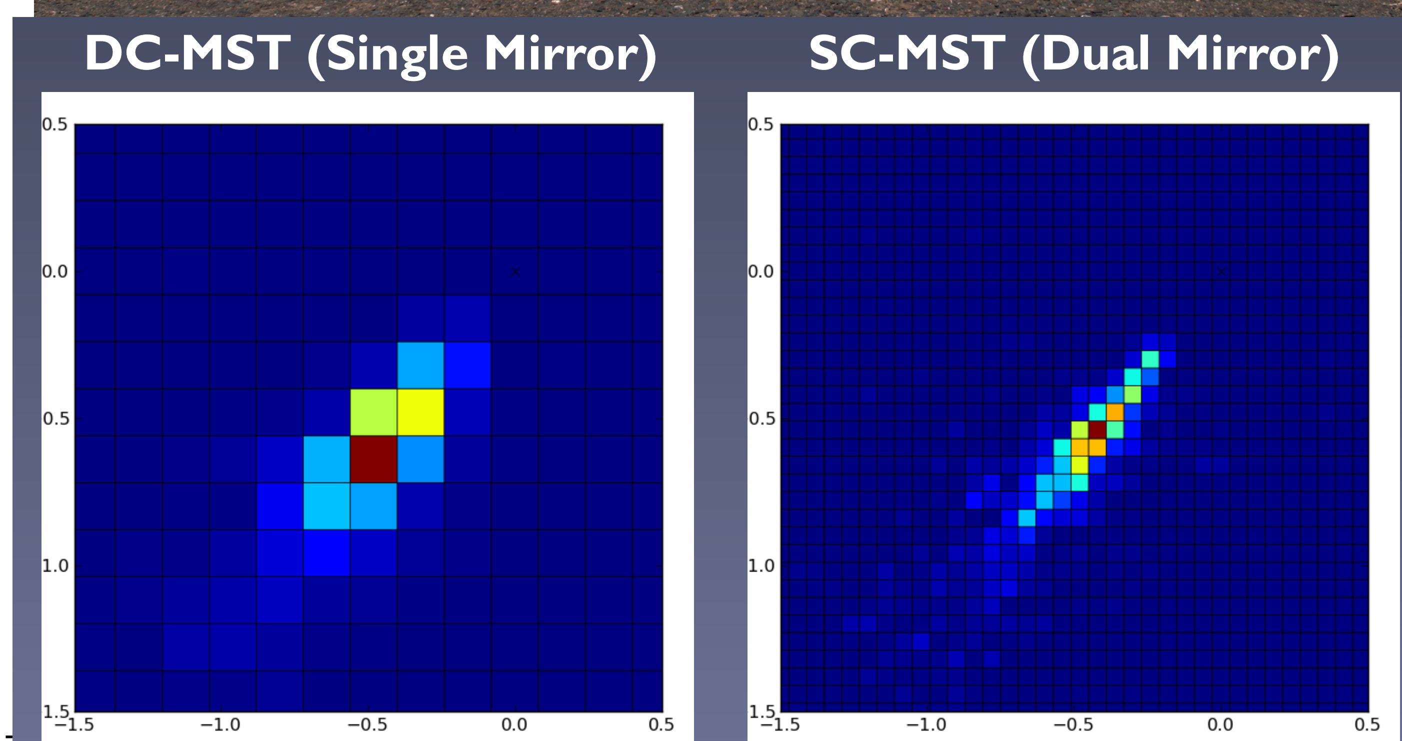
GC, Cluster, Constraints



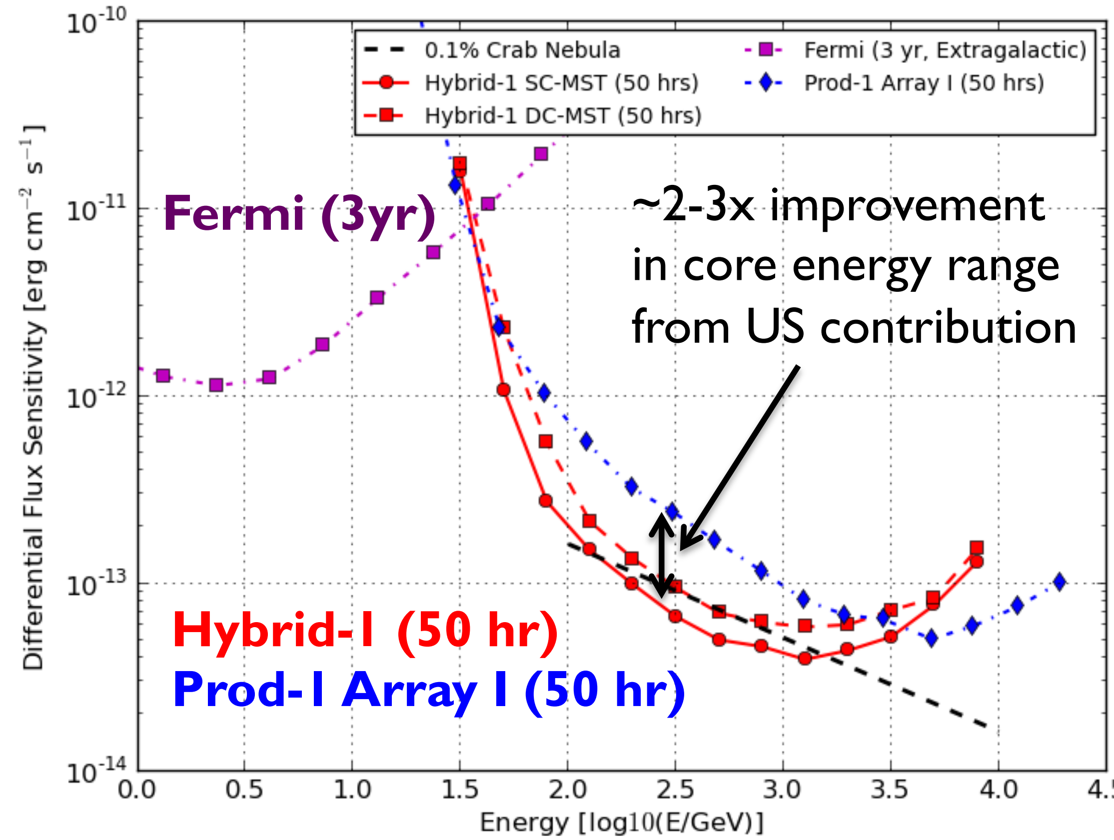
**Enormous progress since last Snowmass meeting! We are beginning to probe natural cross section at low mass (<20 GeV) and pull within 1-2 orders of magnitude for 100GeV-1TeV WIMPs.*

CTA-US

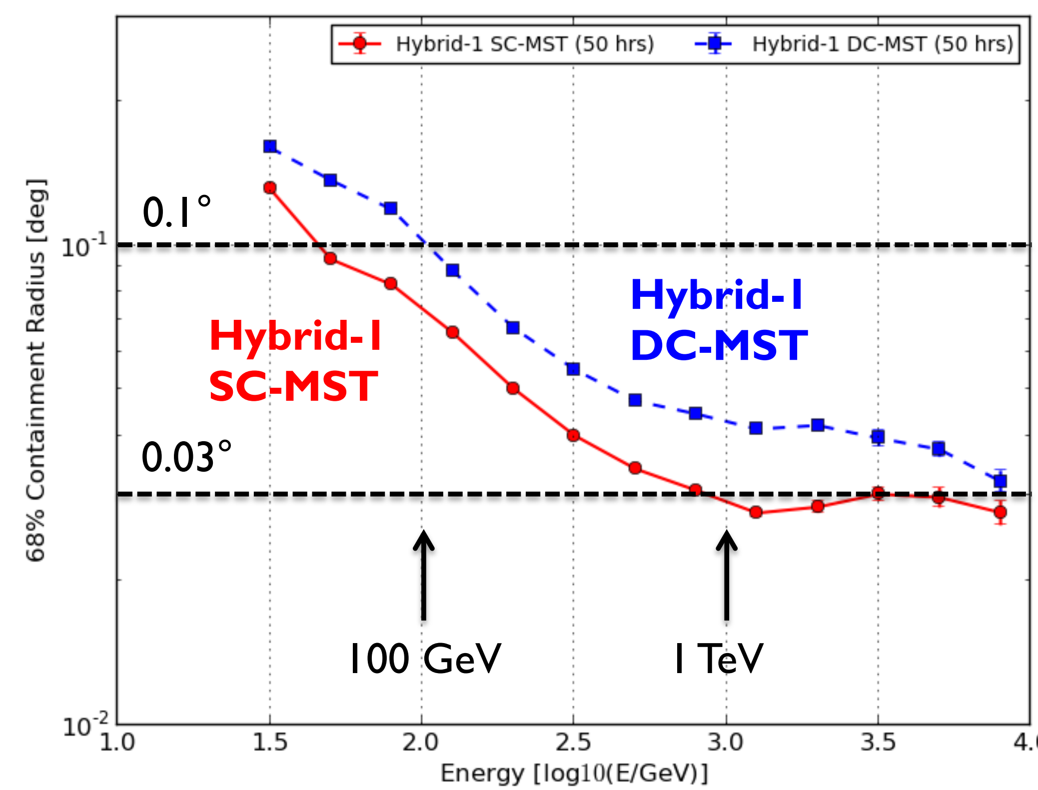




DC-MST (Single Mirror)
SC-MST (Dual Mirror)
0.5
0.0
0.5
1.0
1.5
−1.5
−1.0
−0.5
0.0
0.5

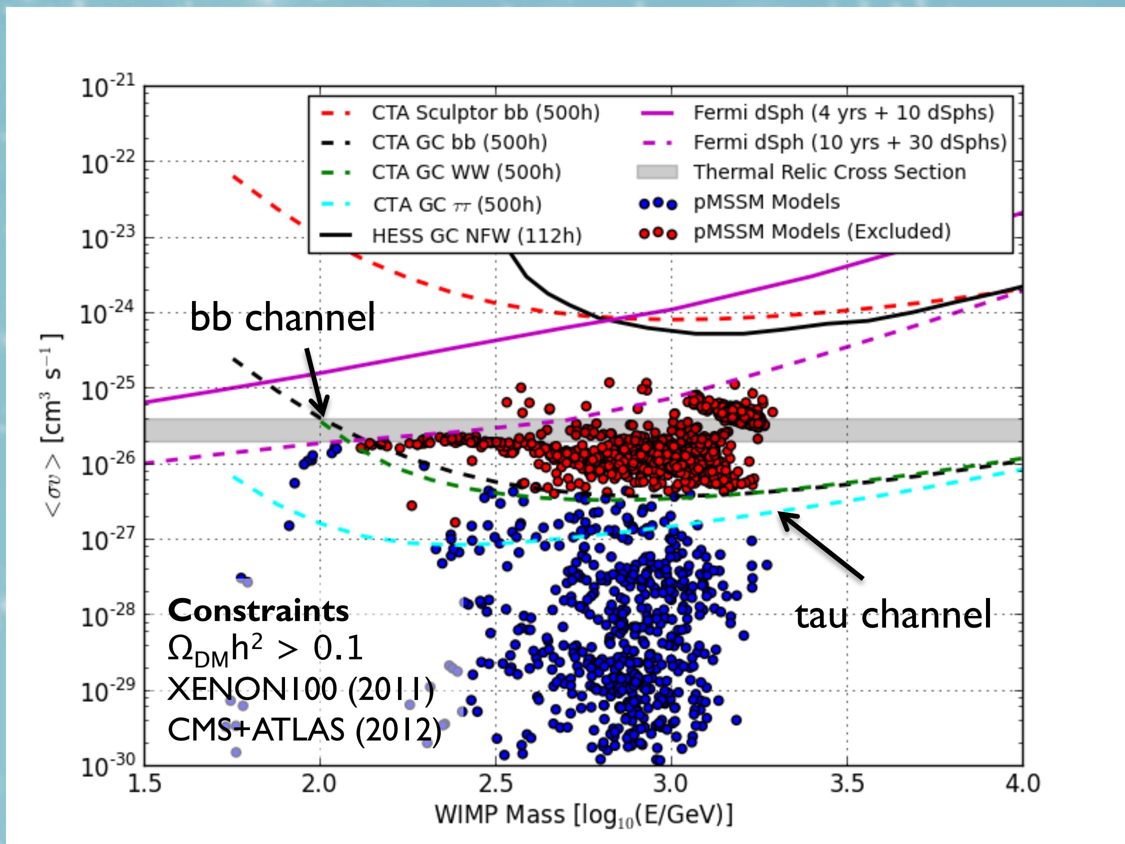


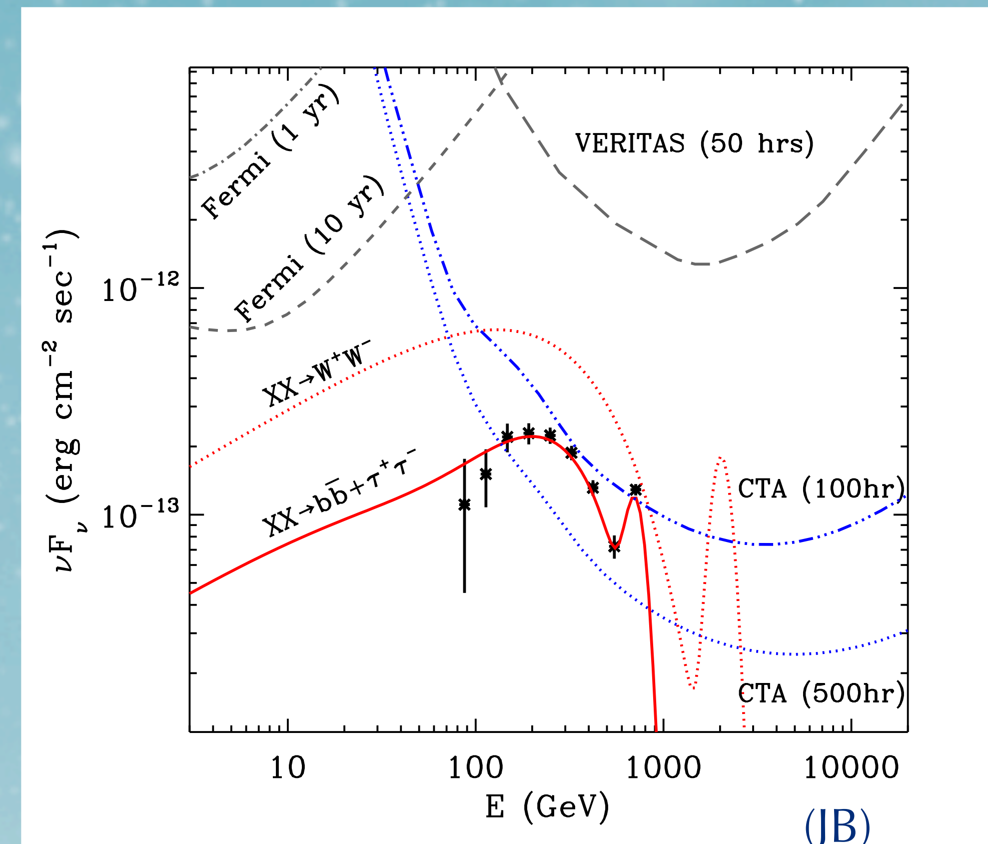
0.1% Crab Nebula
Hybrid-1 SC-MST (50 hrs)
Hybrid-1 DC-MST (50 hrs)
Fermi (3 yr, Extragalactic)
Prod-1 Array I (50 hrs)
Fermi (3yr)
~2-3x improvement
in core energy range
from US contribution
Hybrid-1 (50 hr)
Prod-1 Array I (50 hr)
Differential Flux Sensitivity [erg cm^{-2} s^{-1}]
Energy [log10(E/GeV)]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5

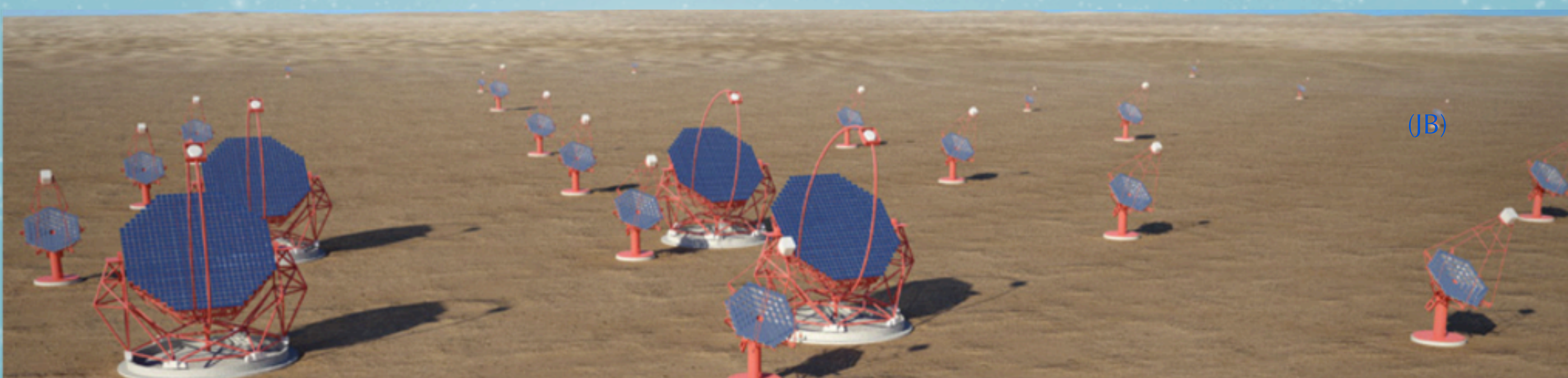


Hybrid-1 SC-MST (50 hrs)
Hybrid-1 DC-MST (50 hrs)
0.1°
0.03°
Hybrid-1
SC-MST
Hybrid-1
DC-MST
100 GeV
1 TeV
68% Containment Radius [deg]
Energy [log10(E/GeV)]
10^{-1}
10^{-2}
1.0
1.5
2.0
2.5
3.0
3.5
4.0

CTA

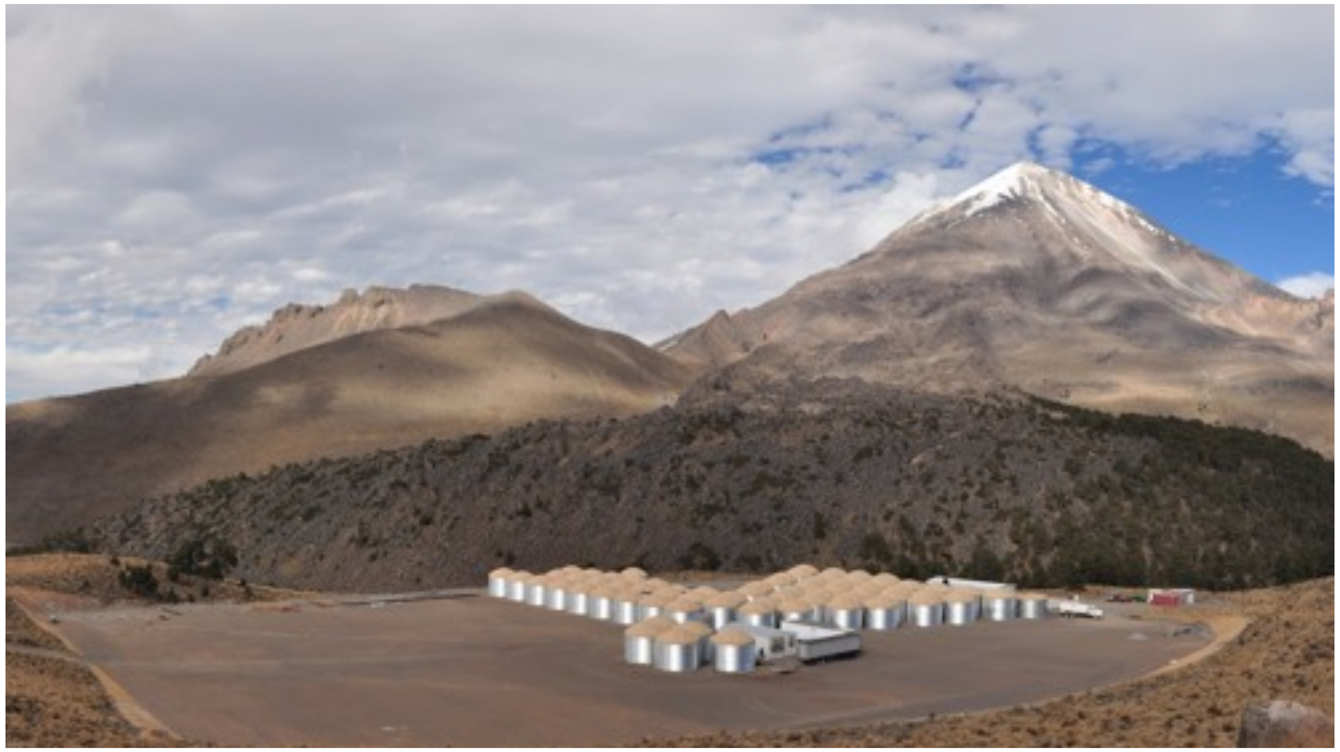


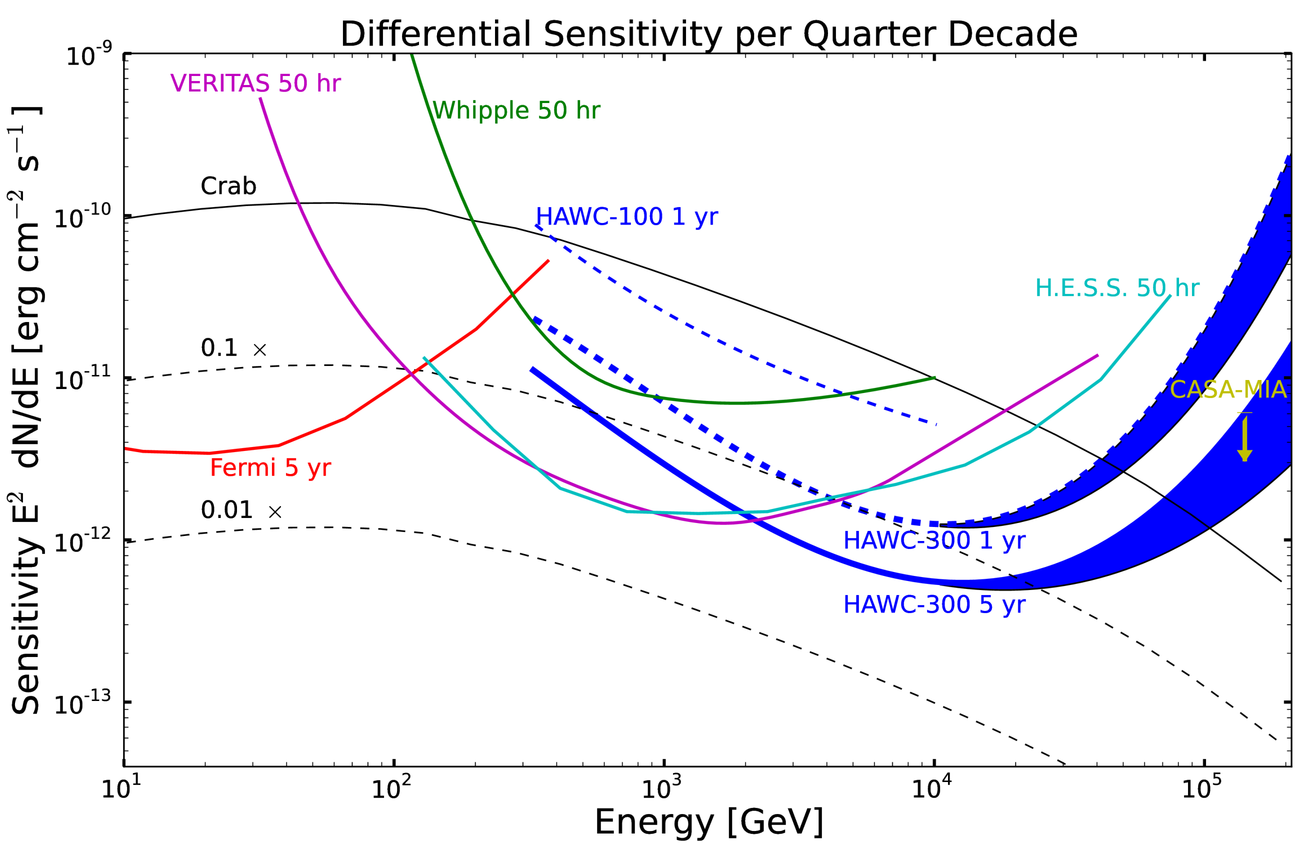


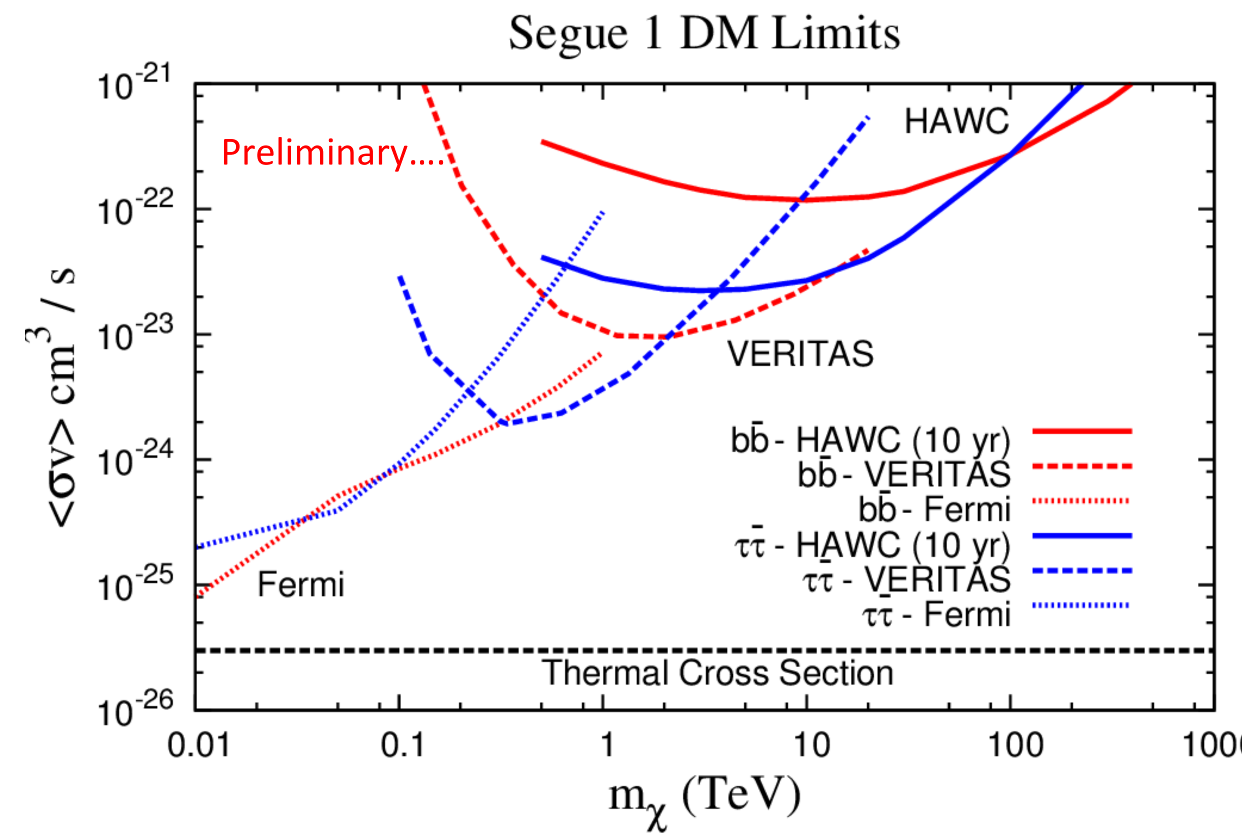


** A CTA like instrument with ~60 Mid-sized telescopes has the sensitivity to probe the natural cross section for WIMP annihilation from 100 GeV to 10 TeV - But this requires a US contribution*

HAWC







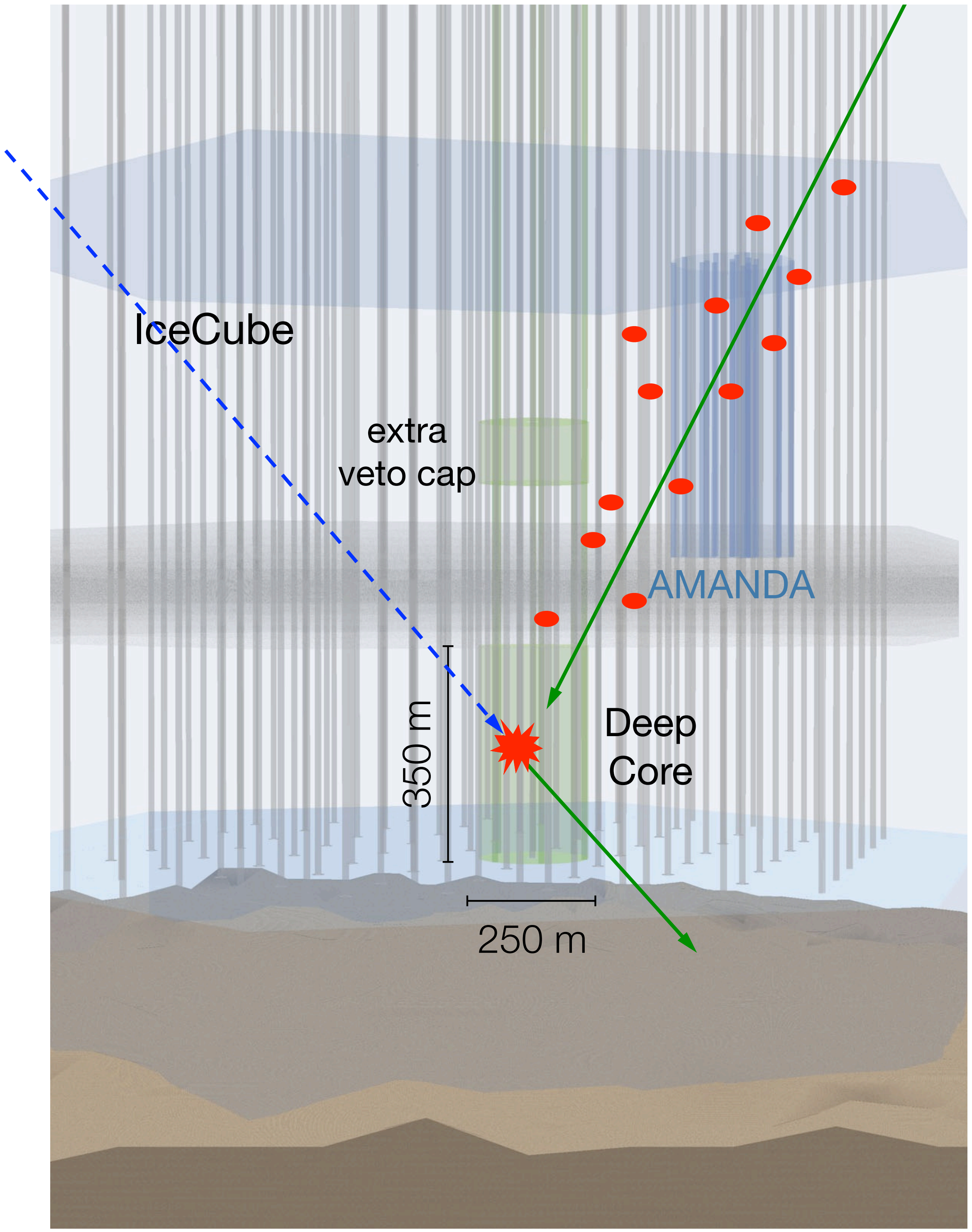
Fermi:
Ackermann et al. PRL 107:241302 (2011)

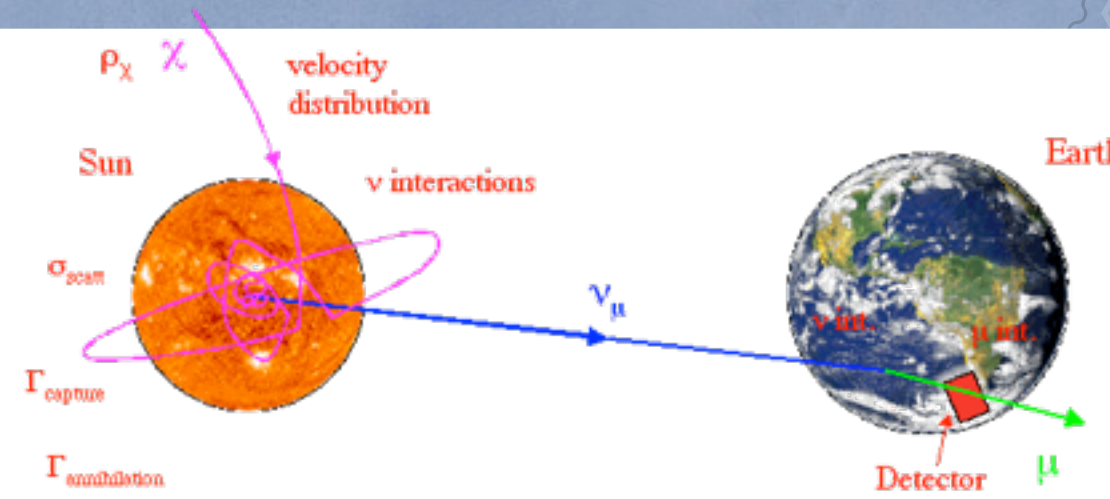
Spectra: P. Harding.

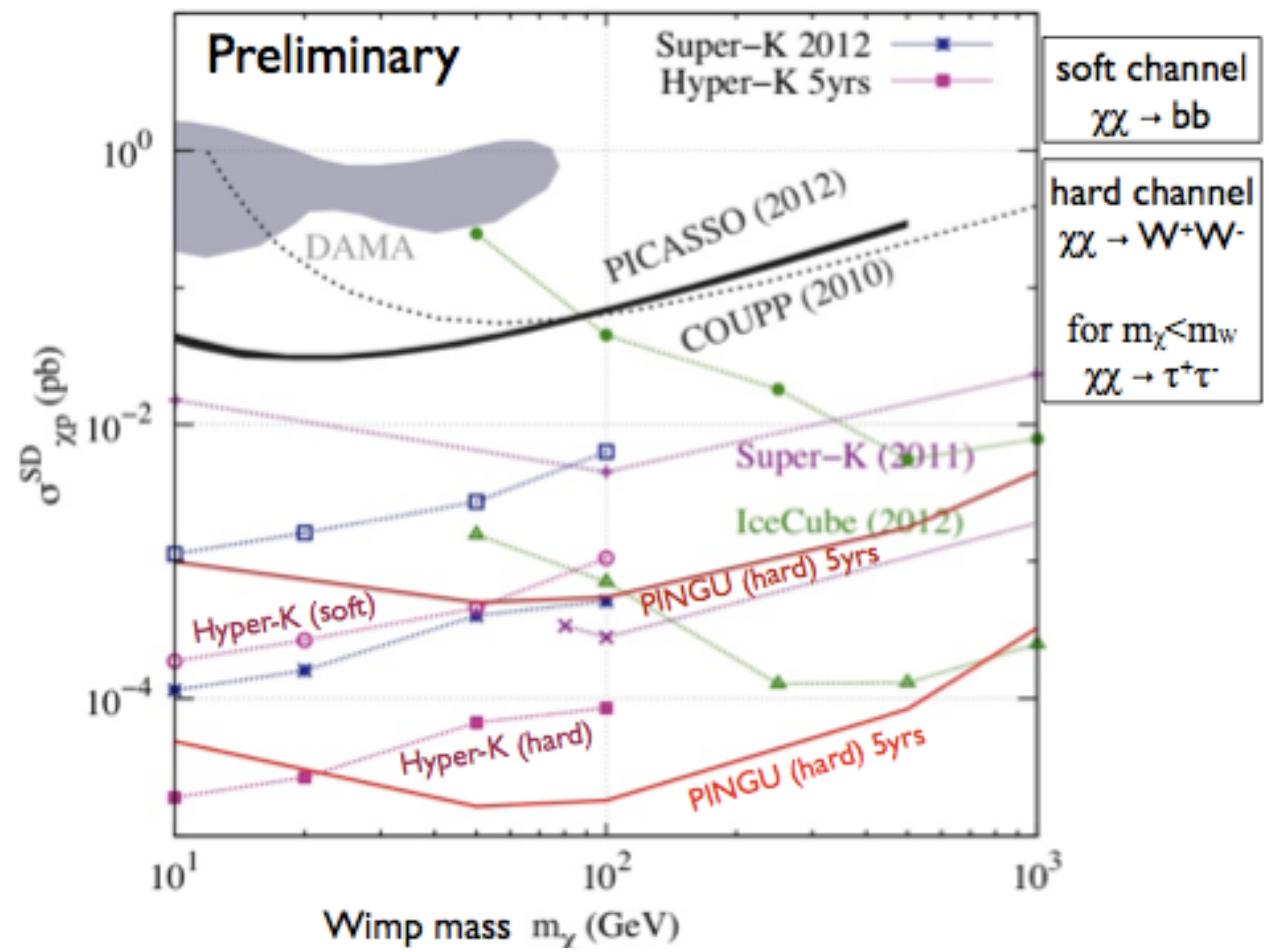
VERITAS:
Aliu et al. PRD 85:062001 (201

(Pretz, 2013, SLAC CF Meeting)

Future Neutrino Detectors

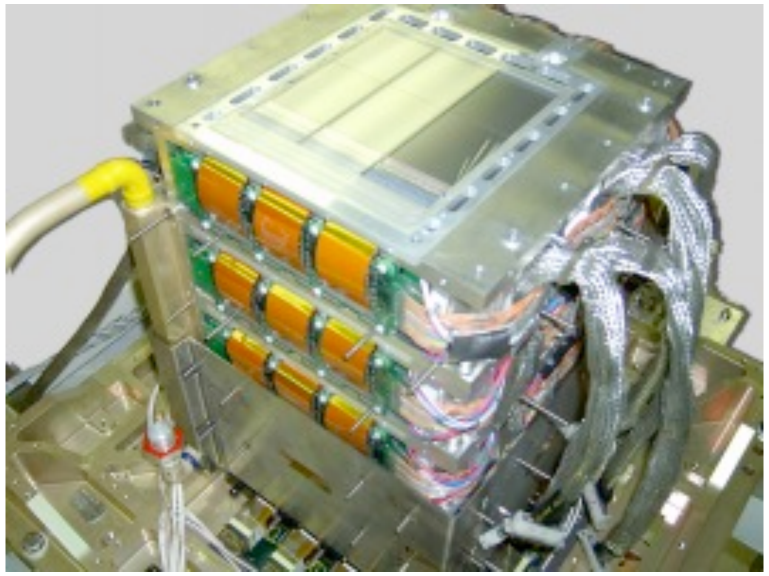


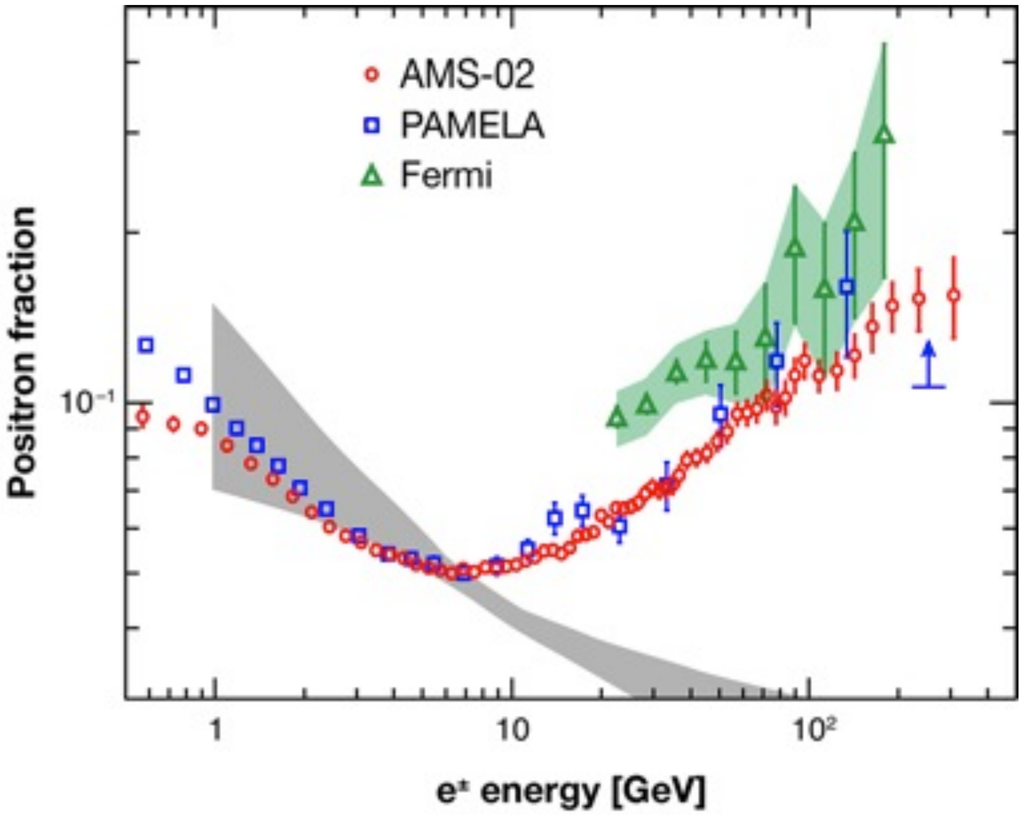




** Future neutrino experiments like the PINGU enhancement to IceCube/DeepCore offer the possibility of discovery of a smoking-gun signal (high energy neutrinos from the sun), and may provide some of the best constraints on spin dependent cross sections.*

Positron Results

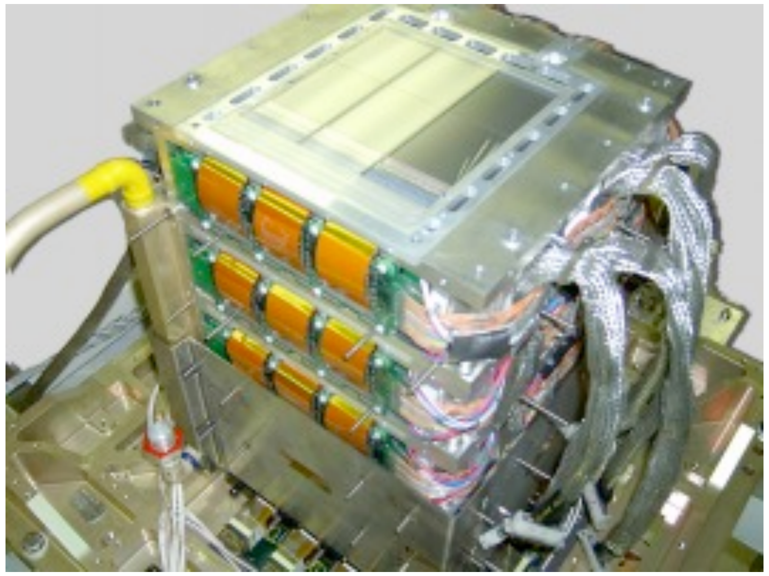


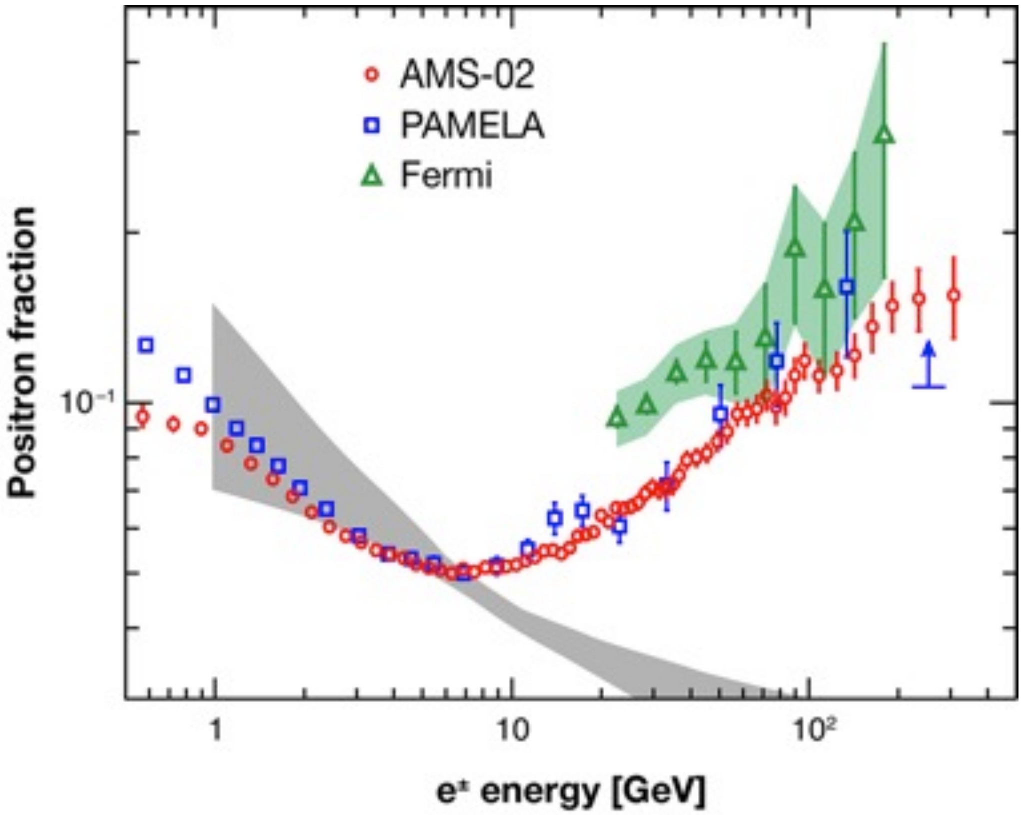


New dark sector force carrier giving a Sommerfeld enhancement, hadronic channels kinematically inaccessible (e.g., Arkani-Hamed, Finkbeiner, Slayter and Weiner, 1999, PRD 79, 015014)

- Pamela results on positron excess are now confirmation by Fermi (using geomagnetic field) and AMS result.
- Signal may also be explained by some cosmic-ray propagation models, or by astrophysical sources such as pulsars.
- A DM interpretation requires a combined astrophysical/particle physics boost of 100 or more.

Positron Results





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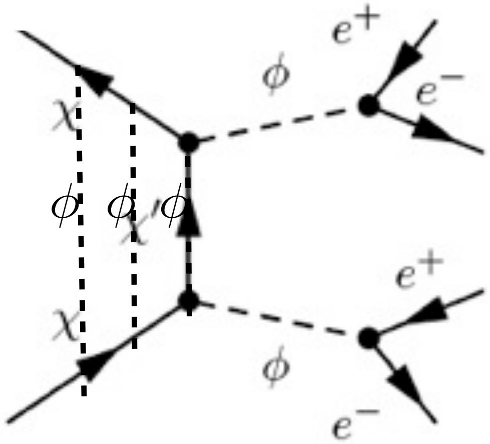

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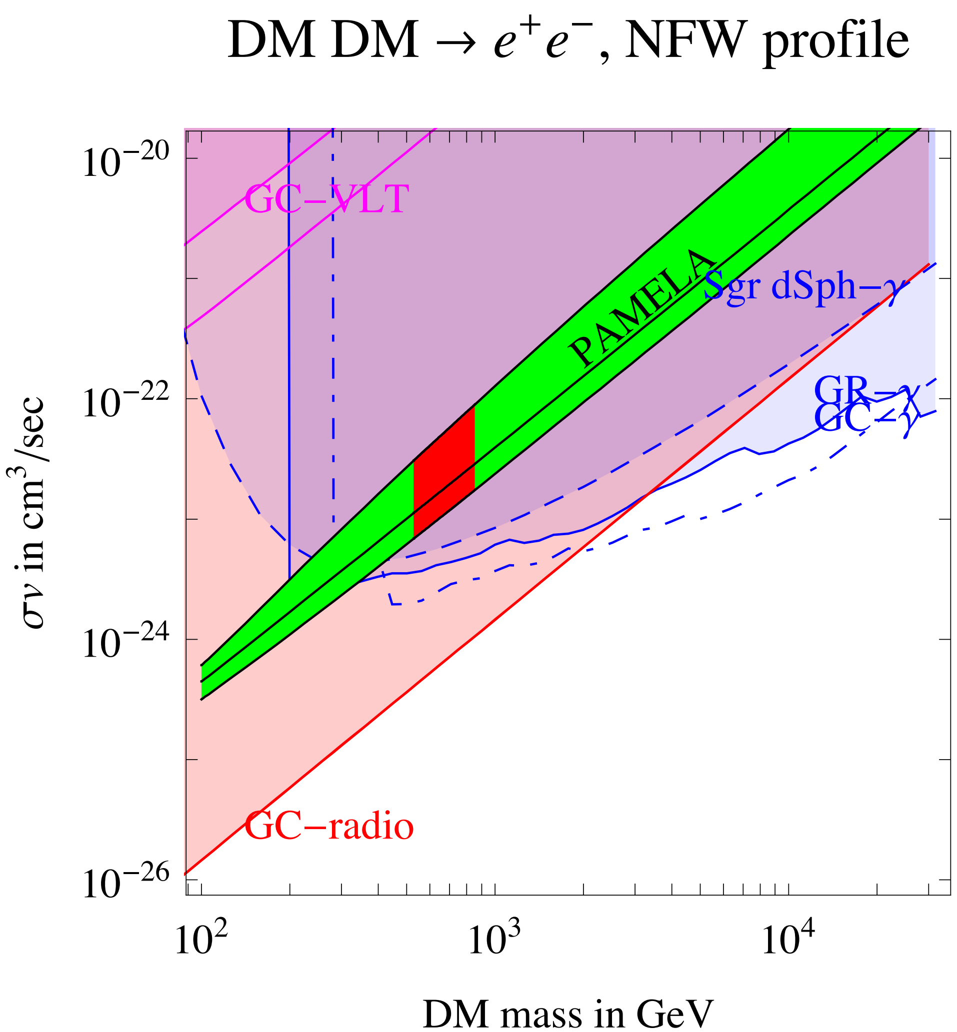
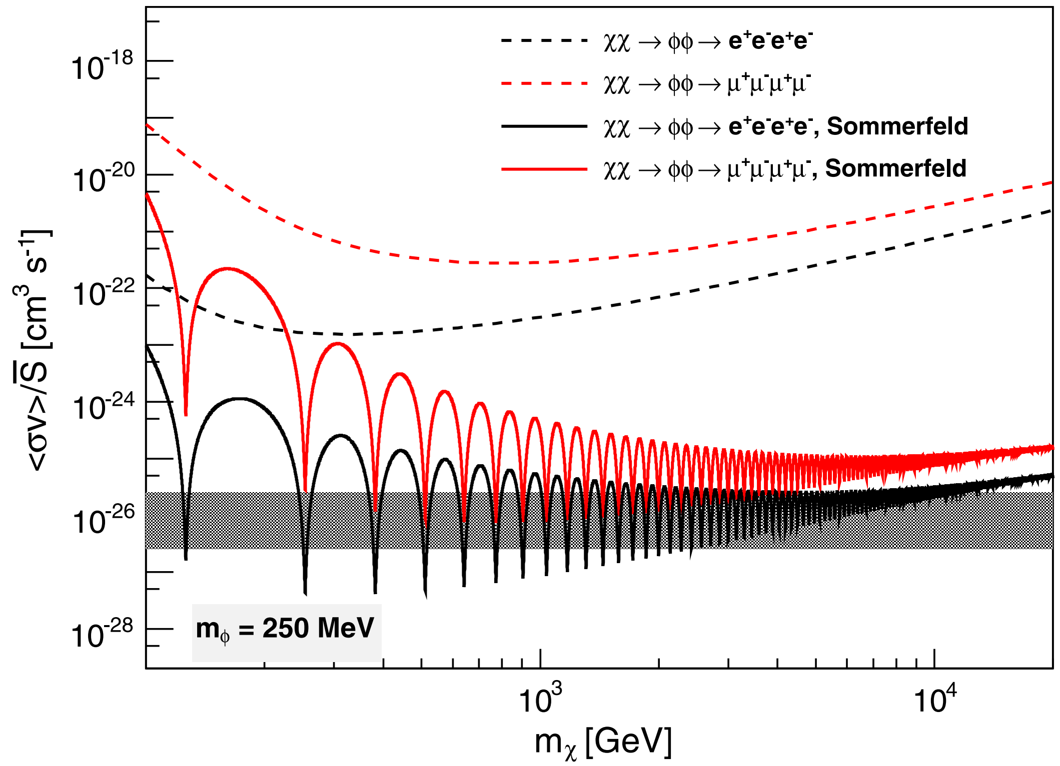
Shedding Light on Positrons



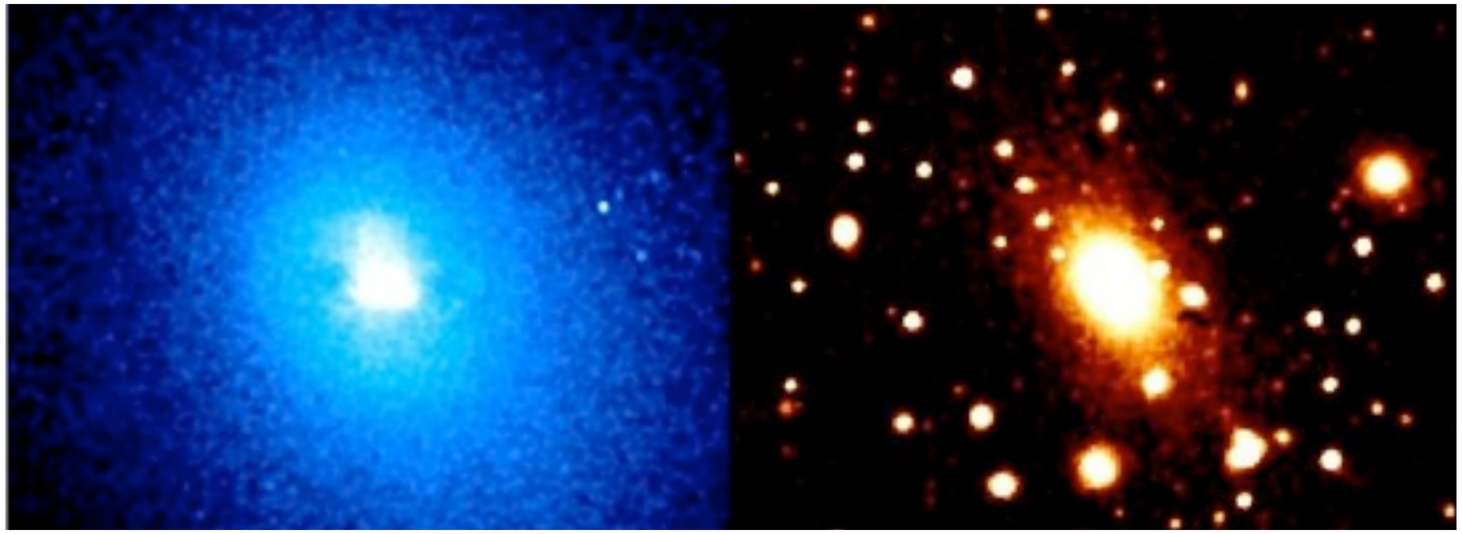
Radio Synchrotron and gamma-ray IC limits for Pamela scenario (Bertone, Cirelli, Strumia and Taoso, arXiv:0811.2744v3). *Note: Radio bounds are sensitive to assumptions about B-fields and diffusion, may be optimistic.*

VERITAS Segue Limits with Sommerfeld Enhancement

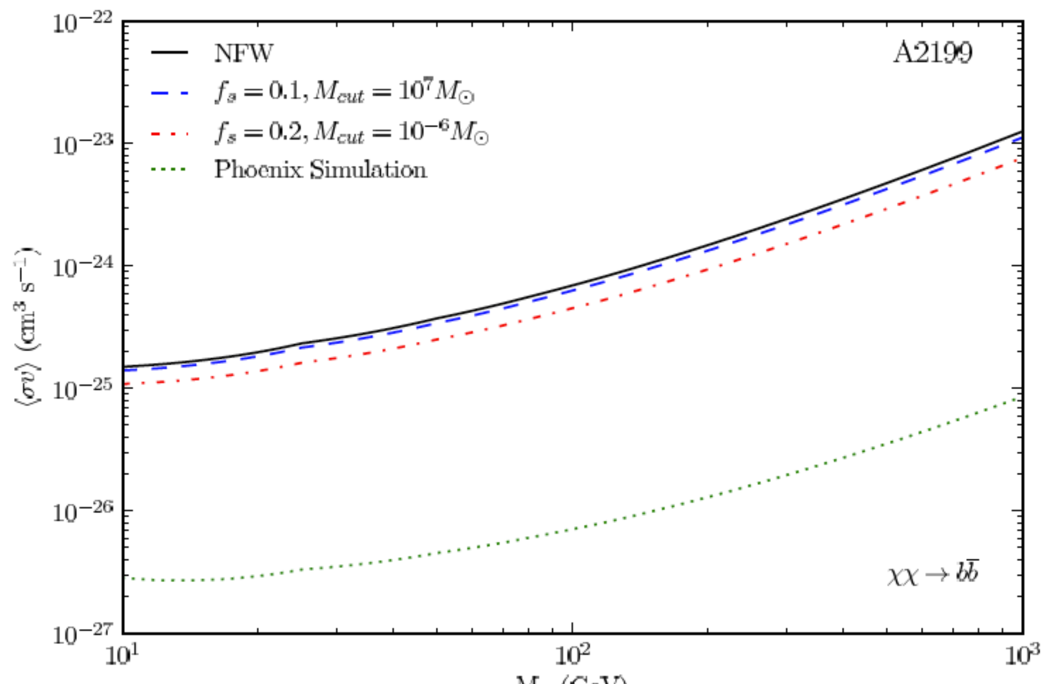


- Pamela excess implies a large radio synchrotron and inverse Compton signal, and a boost in secondary gammas from the GC that are not observed.

Astrophysical Constraints



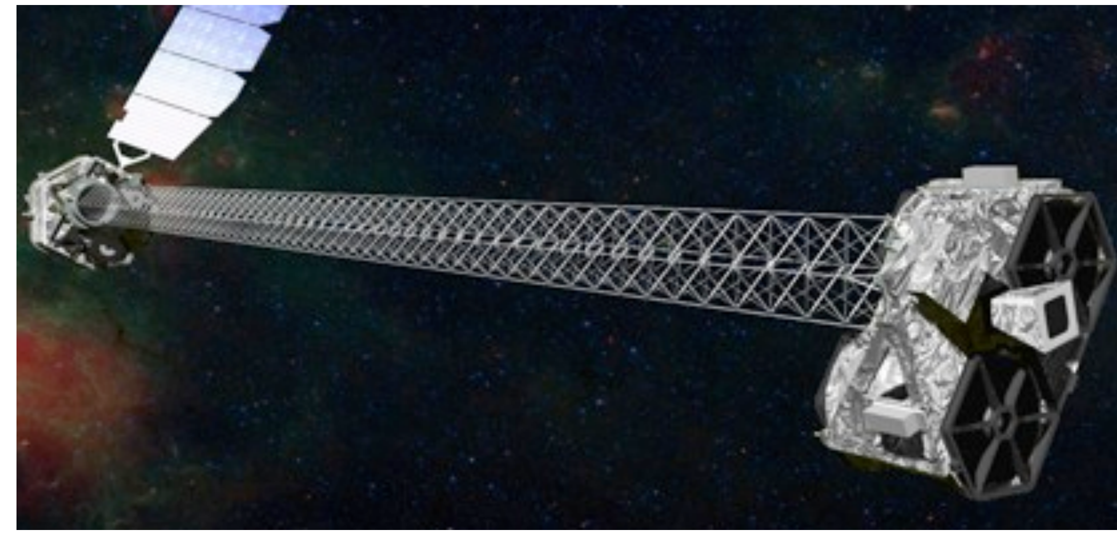
Radio Constraints on Galaxy Cluster (A2199)

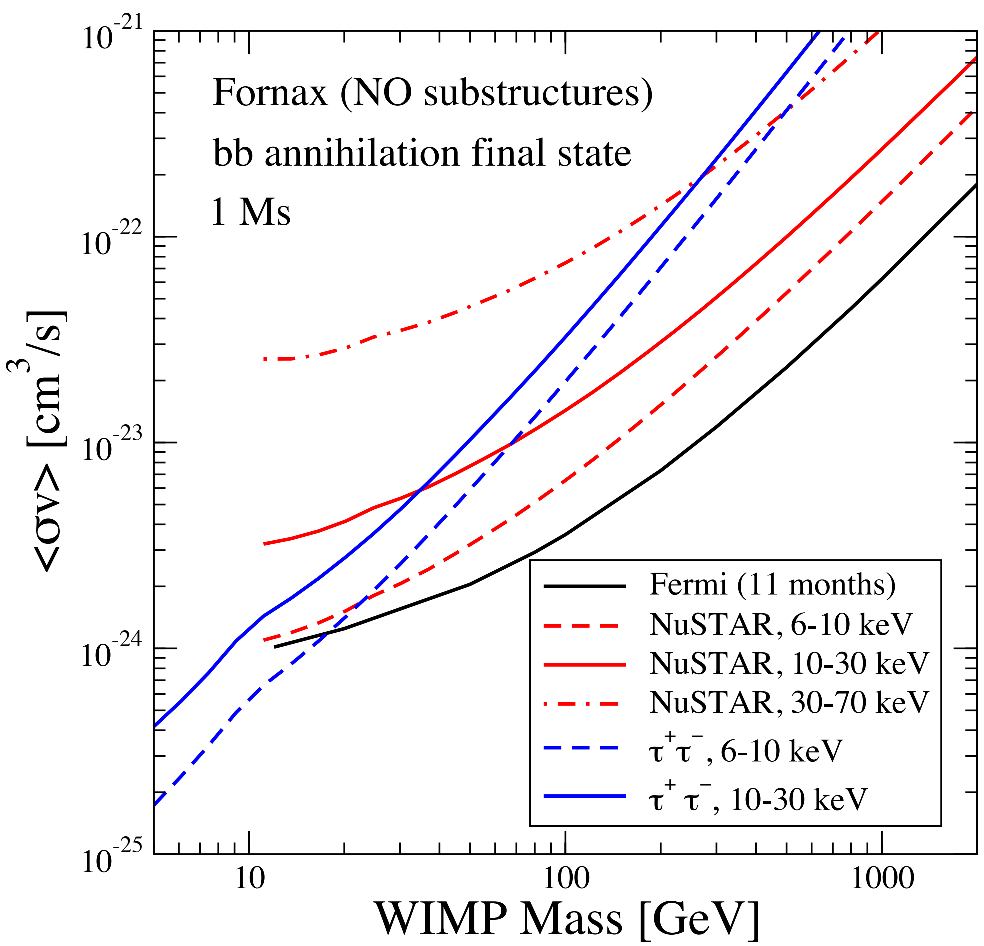


(SLAC CF Talk by T. Jeltema)

- 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



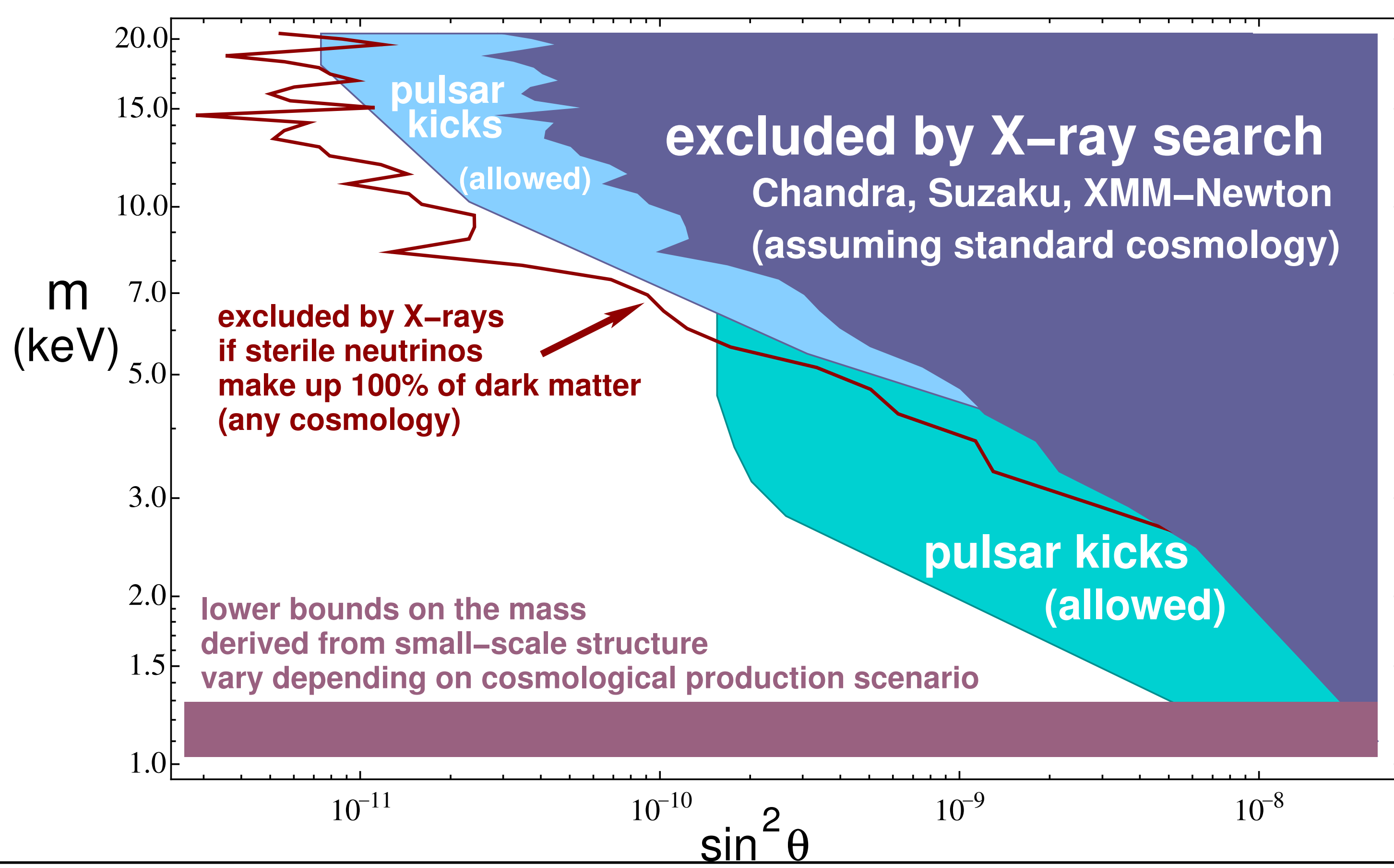


Sterile Neutrinos

Chandra

Suzaku

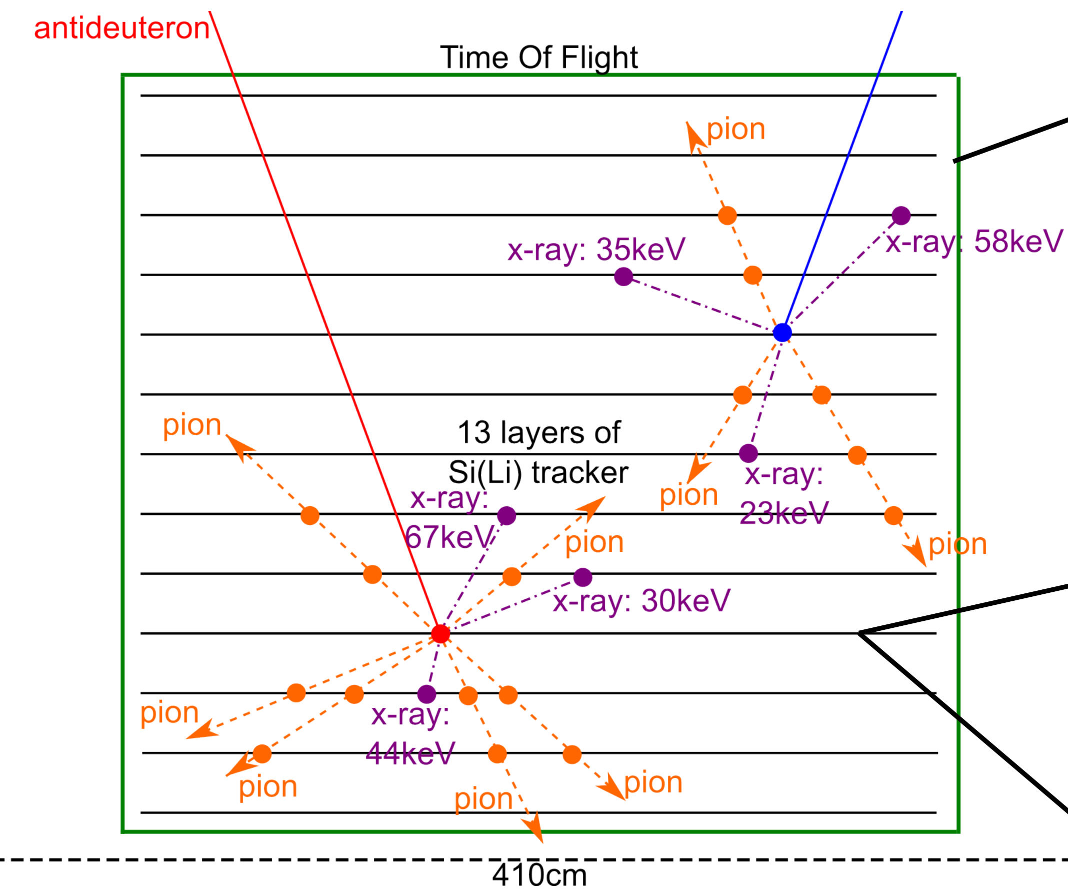
XMM/Newton

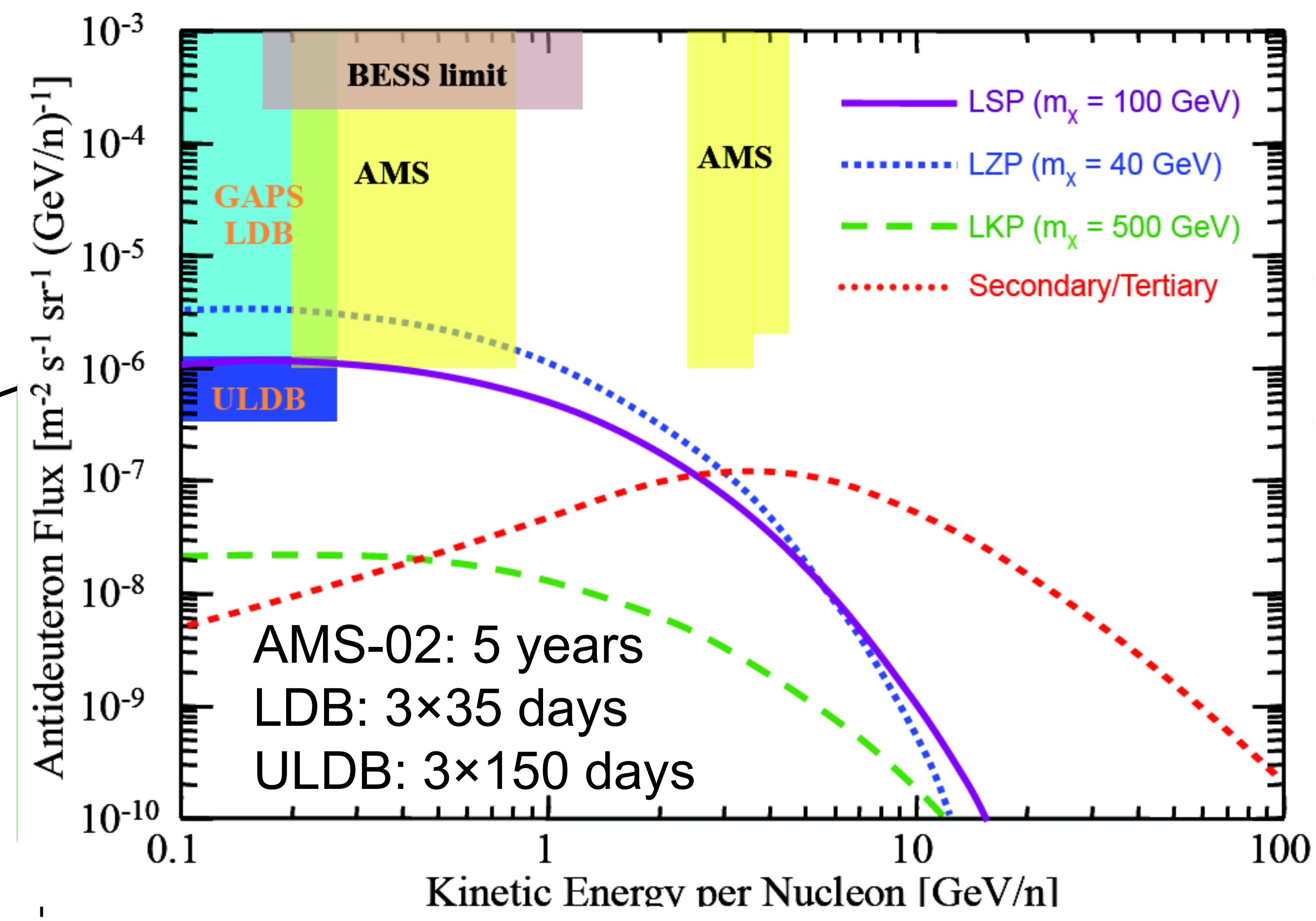


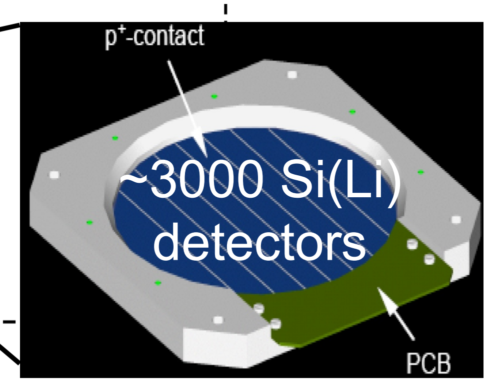
(Loewenstein et al, Astrophys.J. 700 (2009) 426-435; Astrophys.J. 714 (2010) 652-662; Astrophys.J. 751 (2012) 82; Kusenko, Phys.Rept. 481 (2009) 1-28)

Antideuteron Measurements

(SLAC CF Workshop talk by P. von Doetinchem)

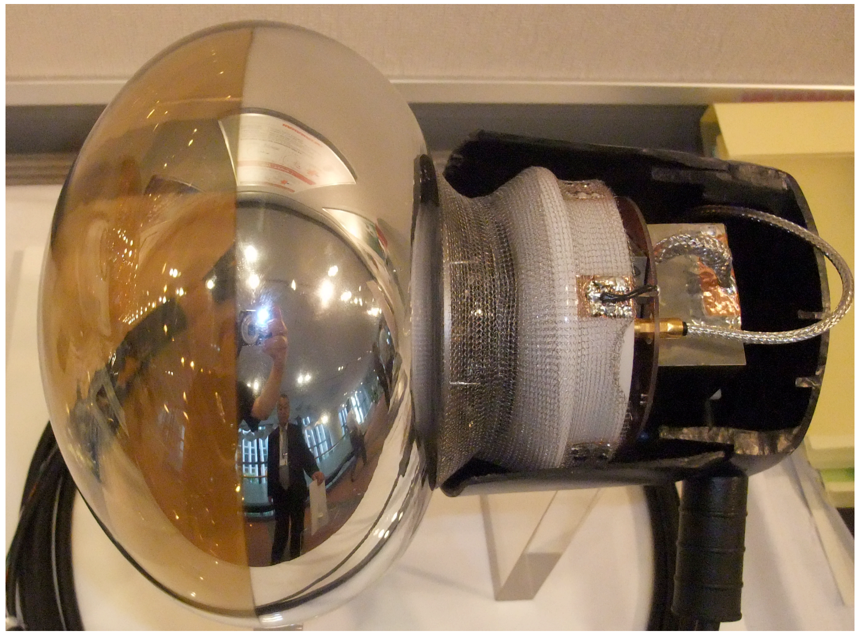




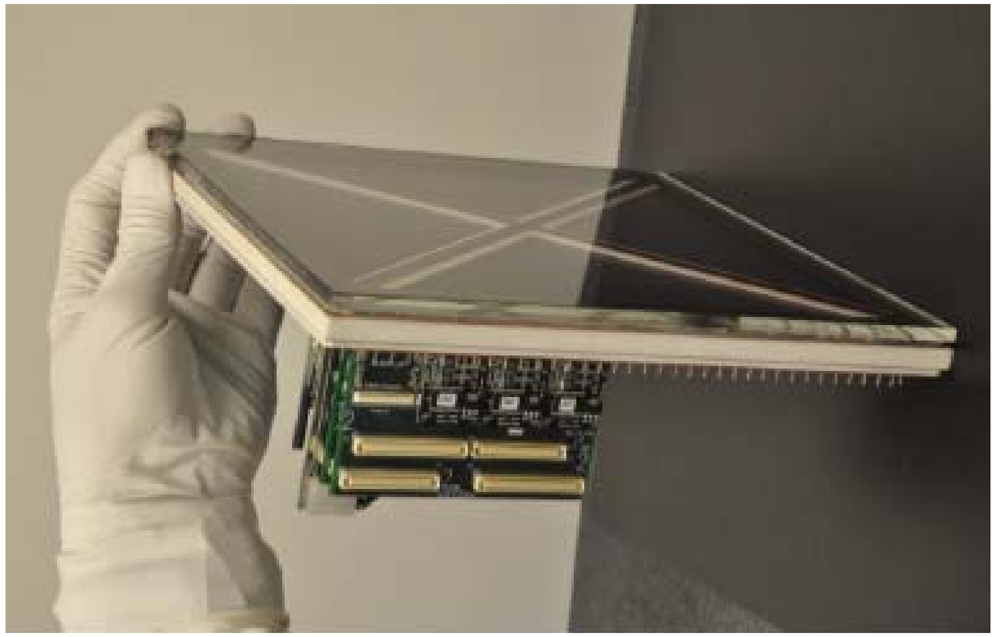


- GAPs looks for anti-deuterons (hard to produce as CR secondaries), uses TOF, X-rays from short-lived exotic atom, pion star from annihilation

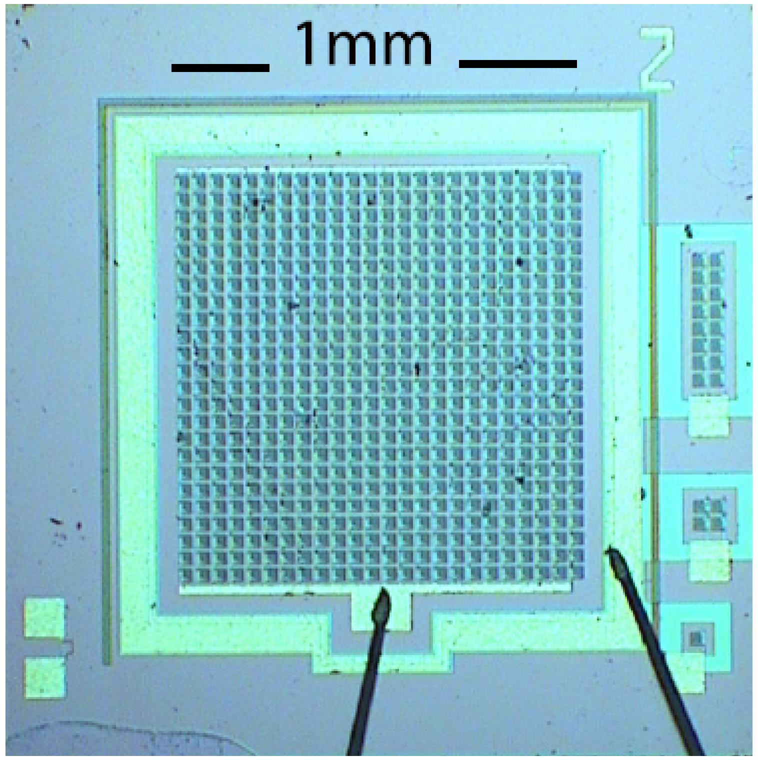
Technical Developments



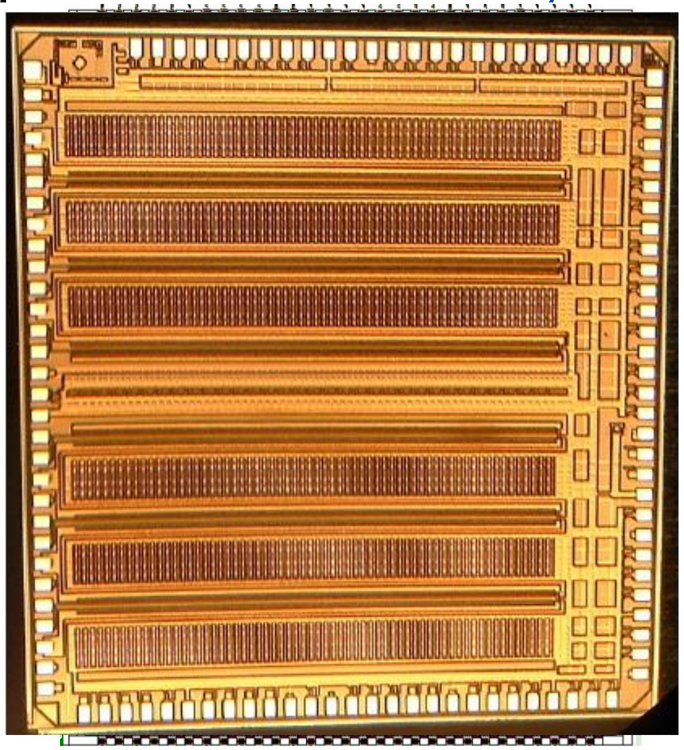
Large-Area HPMT (Masahi Yokoyama)



LAPPD psec timing, 8″ square photodetector, (K. Byrum)



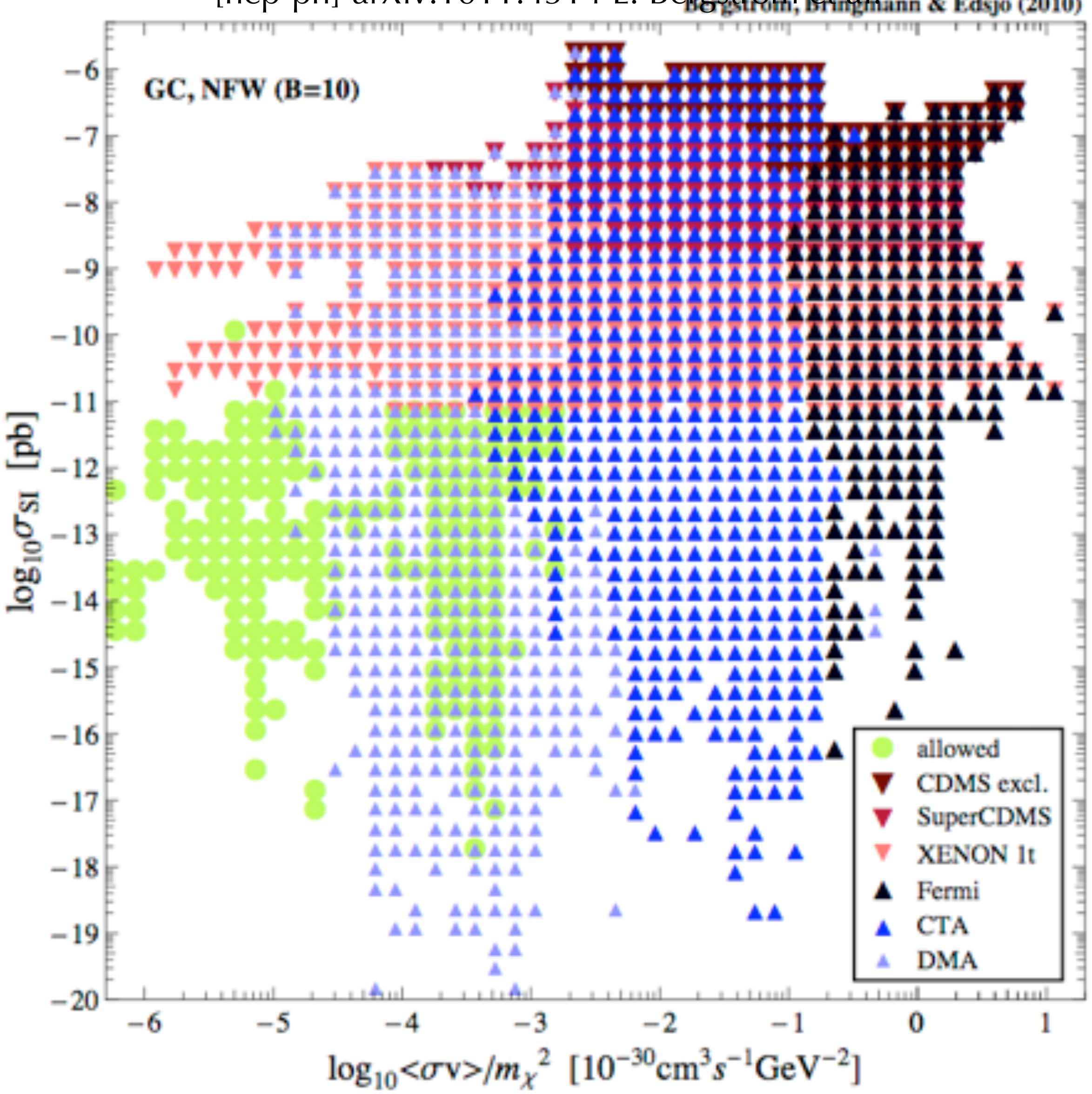
SiPMs, (N. Otte)



- Analog pipeline ASICs (K. Nishimura)

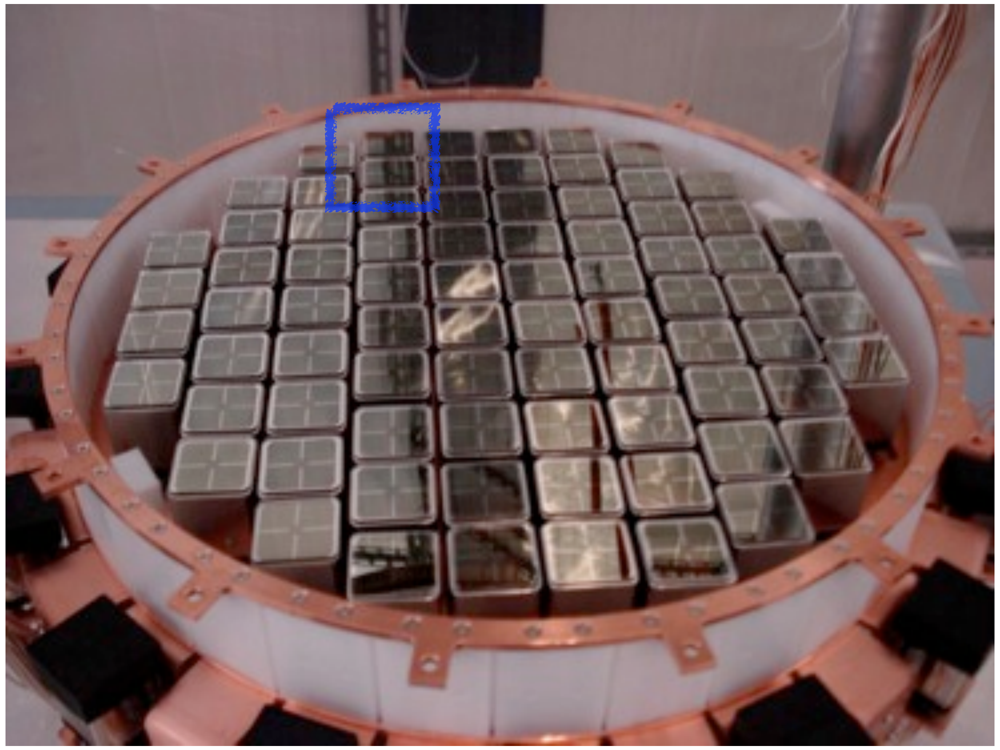
Direct and Indirect Detection

[hep-ph] arXiv:1011.4514 L. Bergstrom et al.



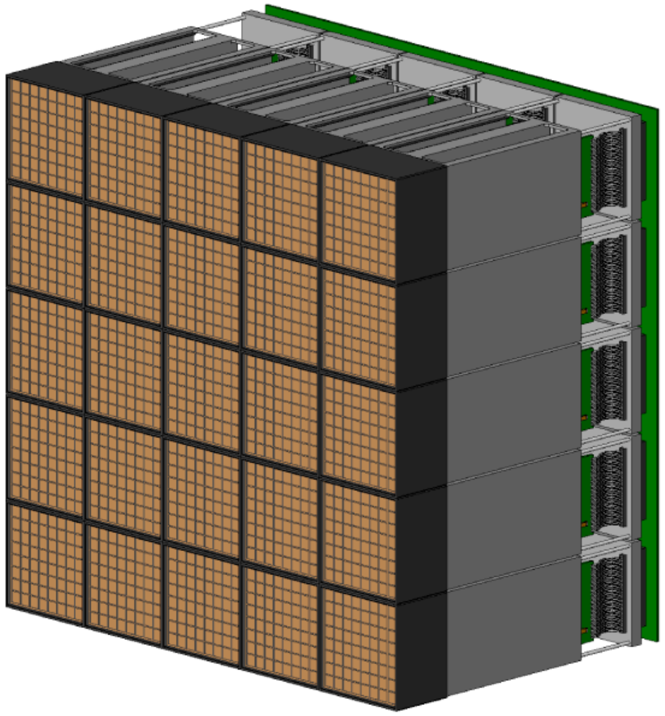
- Scientific complementarity

- Technical complementarity

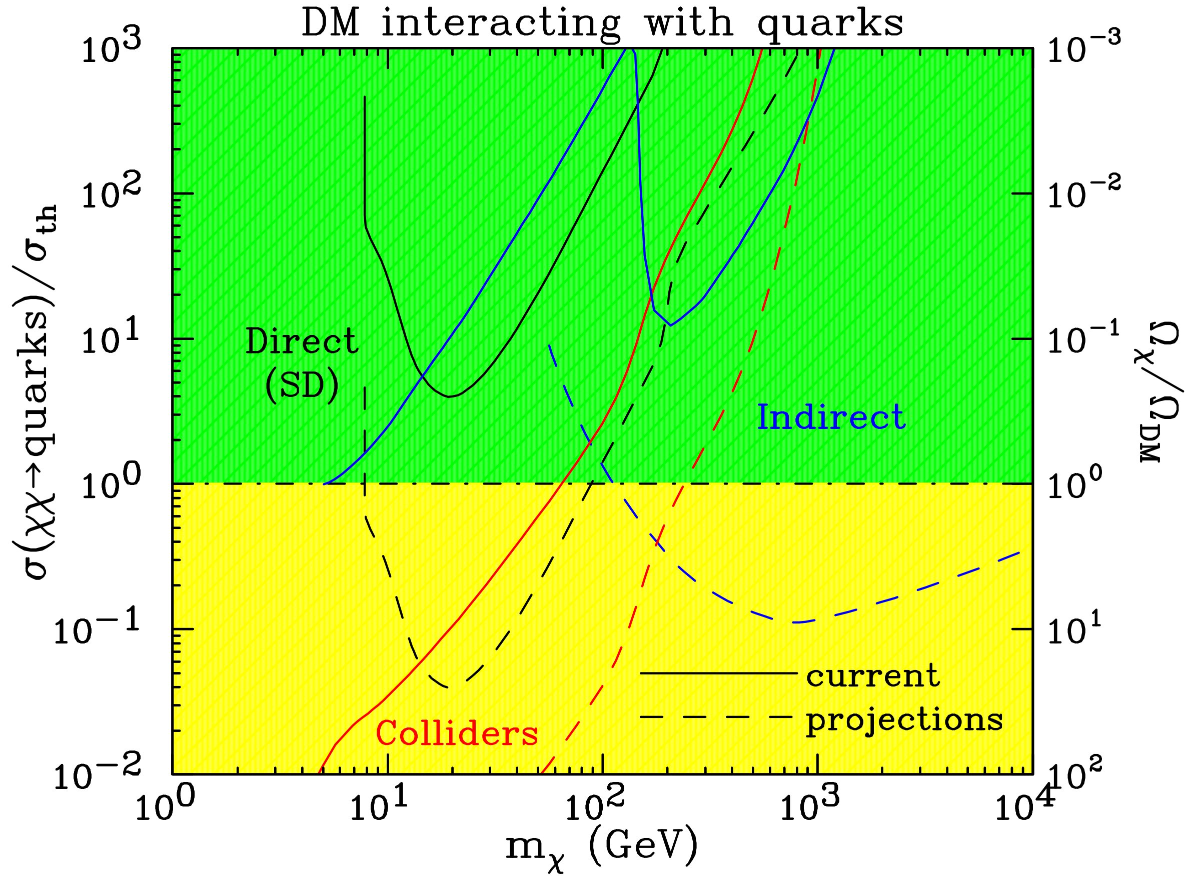


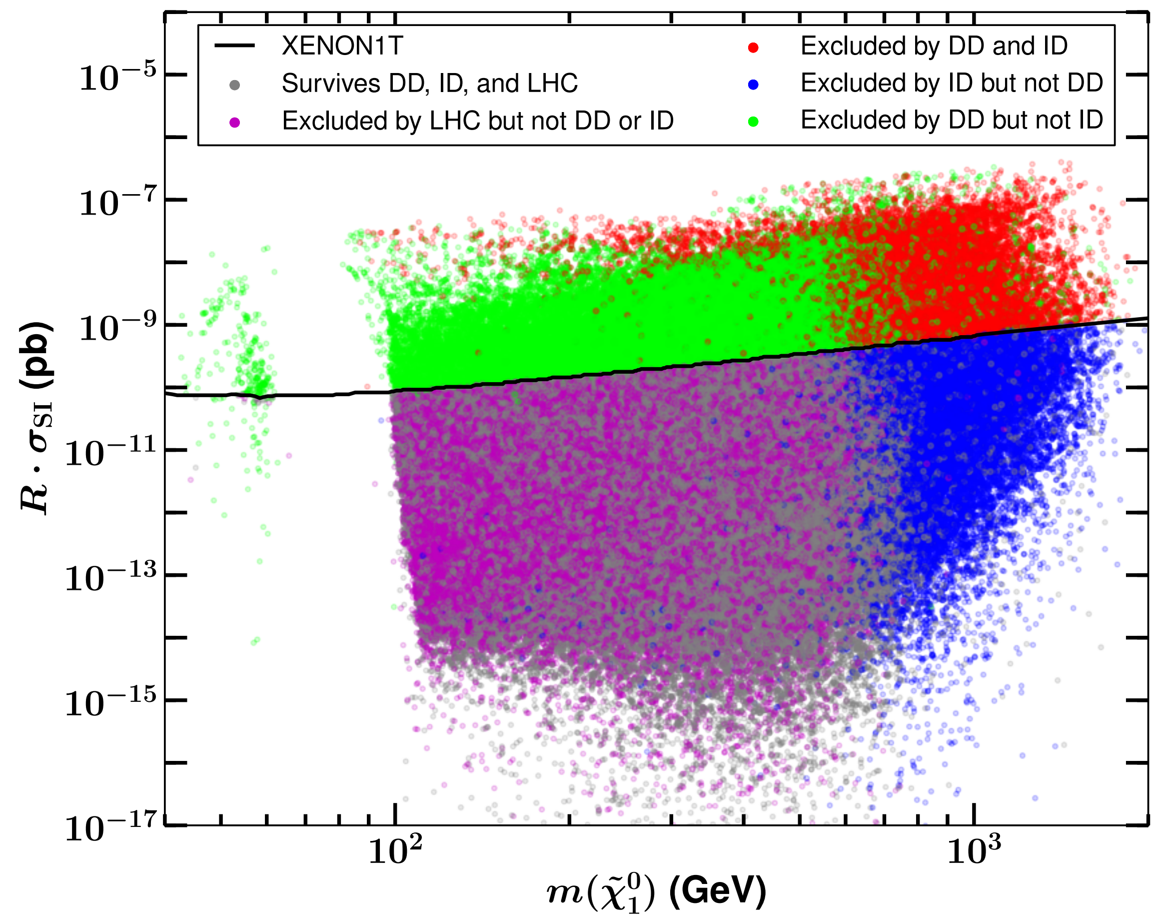
Xenon100 Detector

Proposed CTA SC camera module with 25 2″ MAPMTs



CF2 Key Findings



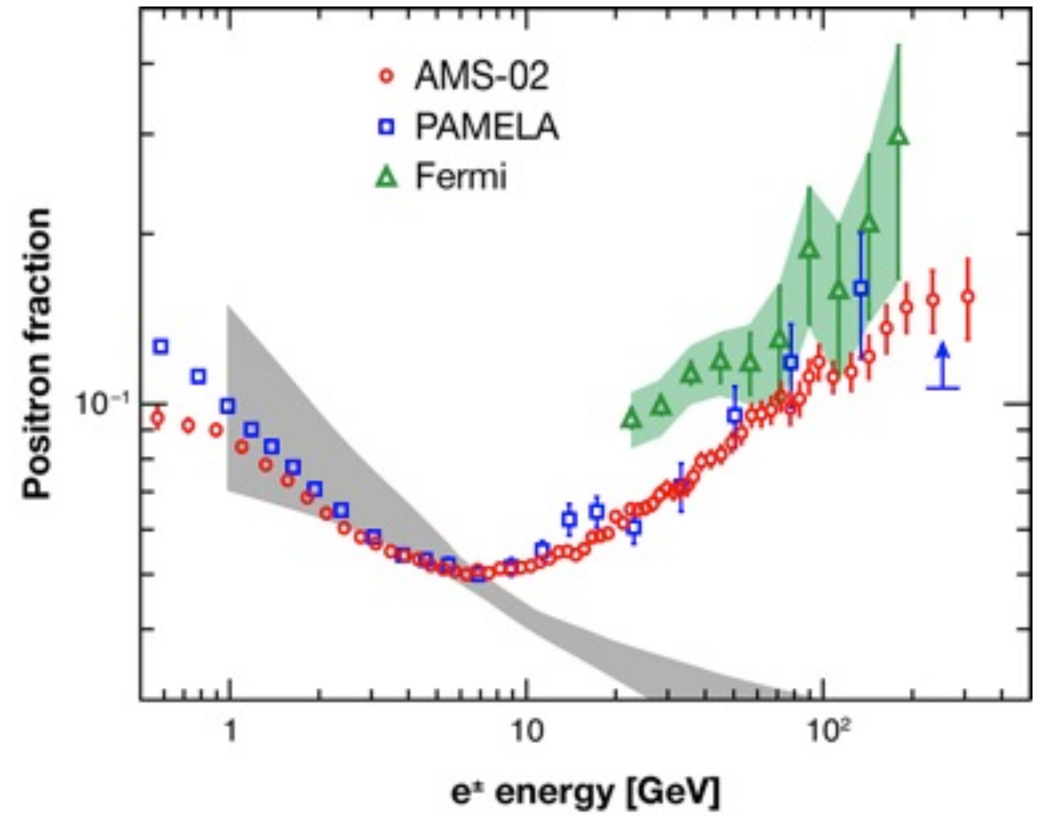


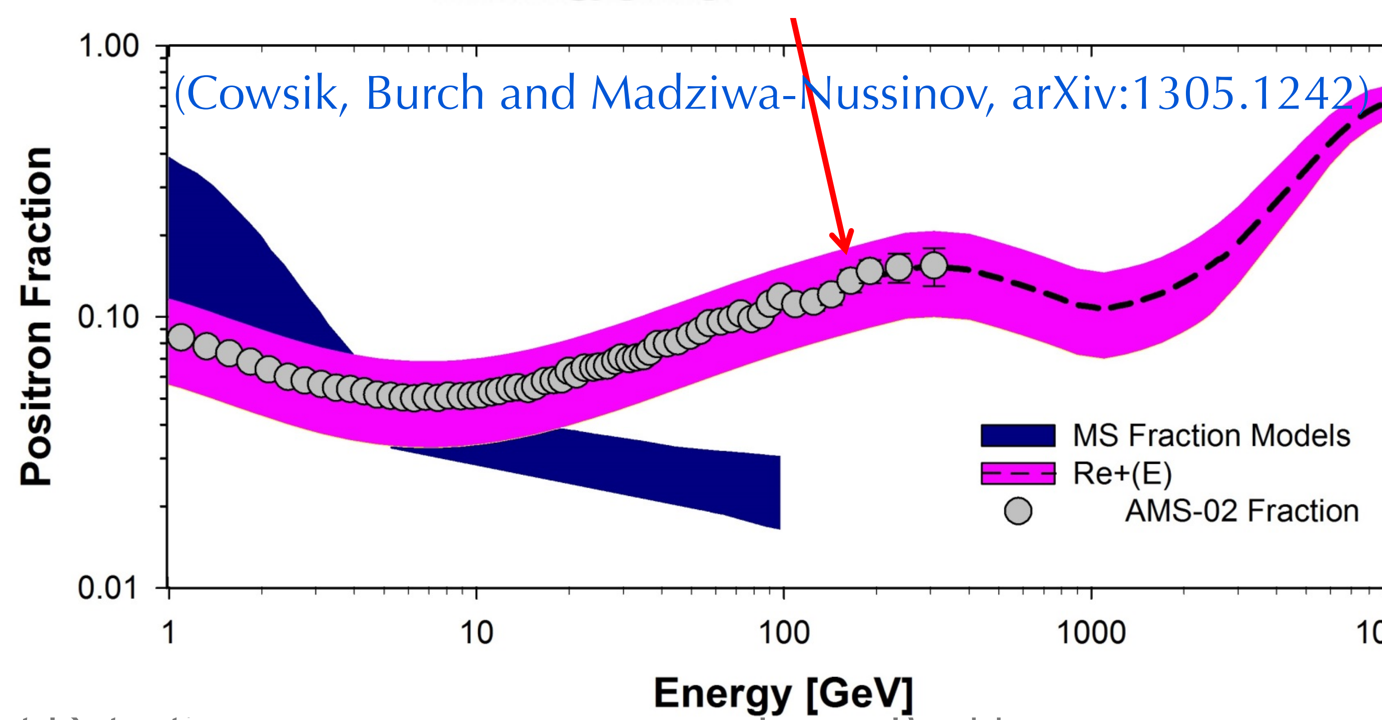
- Detailed theoretical studies with PMSSM, contact operators, realistic halo models are resulting in quantitative estimates of sensitivity, showing the complementary reach of different techniques.
- CTA, with the U.S. enhancement, would provide a powerful new tool for searching for WIMP dark matter. 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 neutrino experiments like the PINGU enhancement to IceCube/DeepCore offer the possibility of a smoking-gun signal (high energy neutrinos from the sun), and may provide some of the best constraints on spin dependent cross sections.
- Other astrophysical constraints such as low-frequency radio (synchrotron from electrons) or X-rays (inverse Compton scattering by electrons, sterile neutrino decay) can provide very powerful tests for DM annihilation for certain annihilation channels and provide constraints on decaying dark matter.

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?

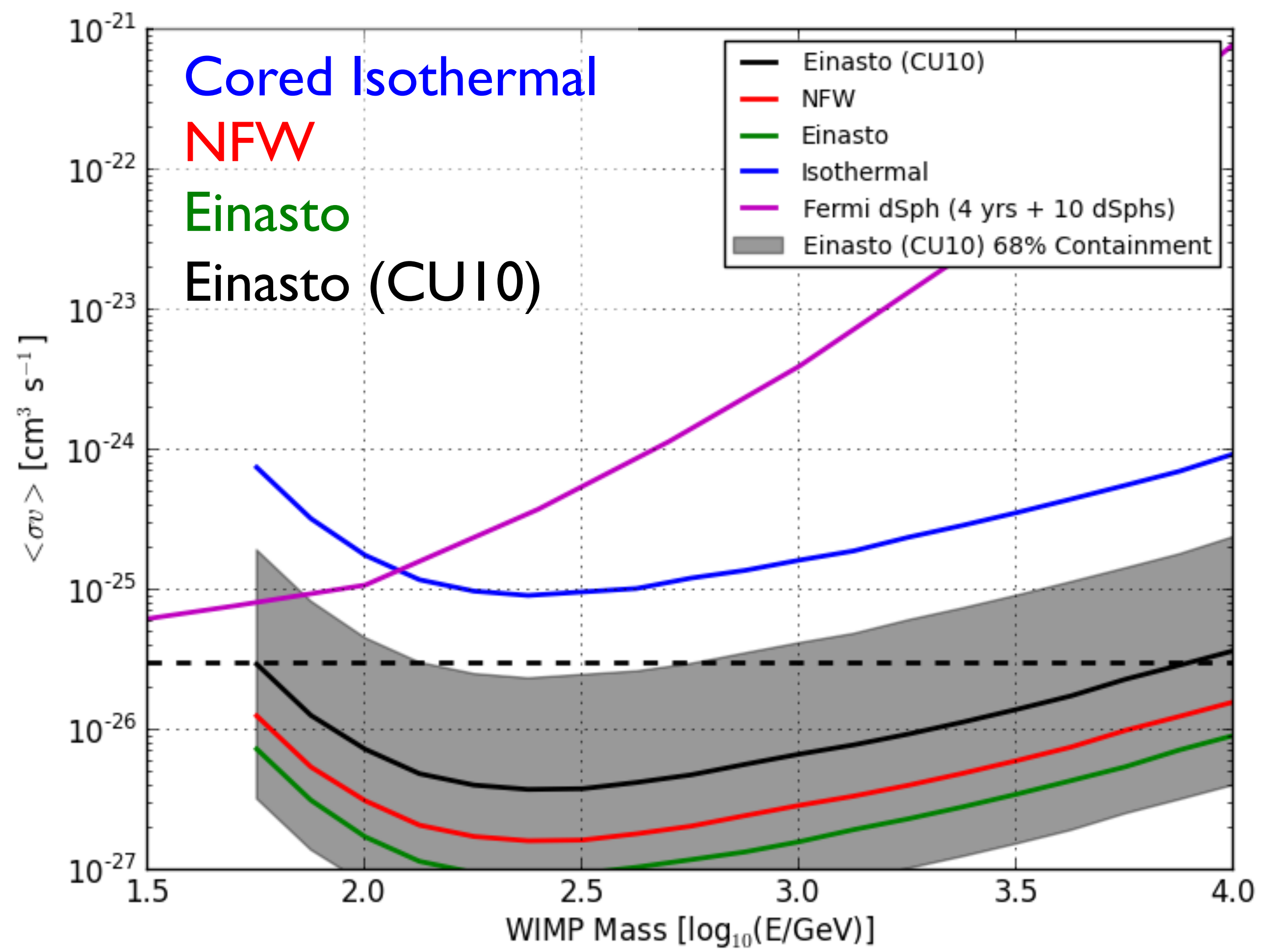




Snowmass Tough Questions

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

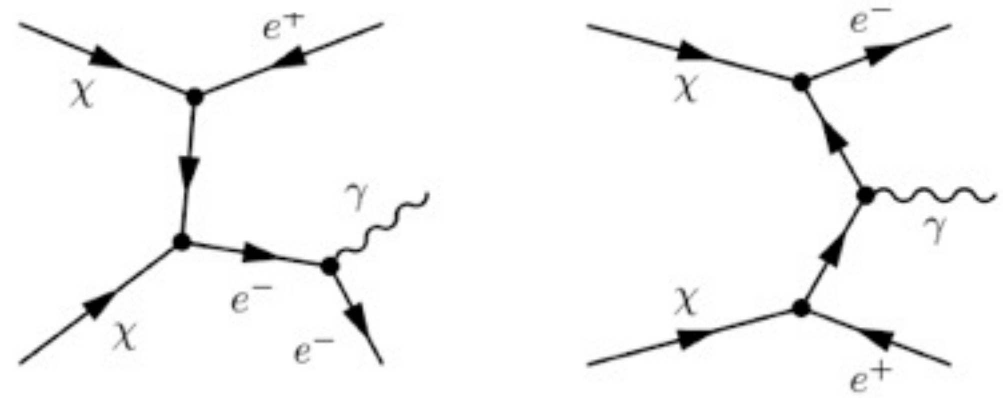
- The primary astrophysical uncertainties come for gamma-ray production come from uncertainties in the halo model. *But even with uncertainties, the limits still reach the natural decoupling cross section.*
- An annihilation line in the gamma-ray spectrum would also provide a smoking gun signature (if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



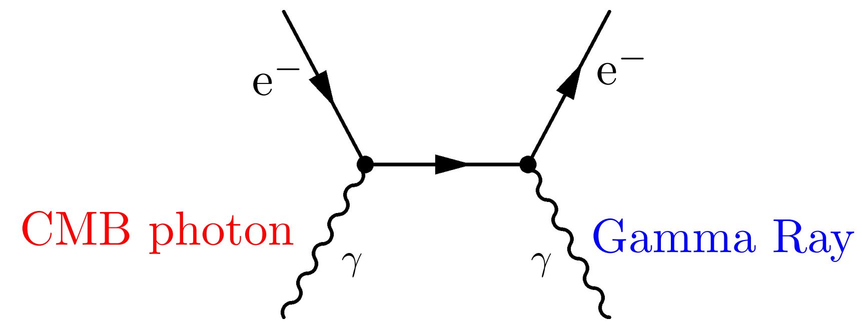
Boosts

- 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:

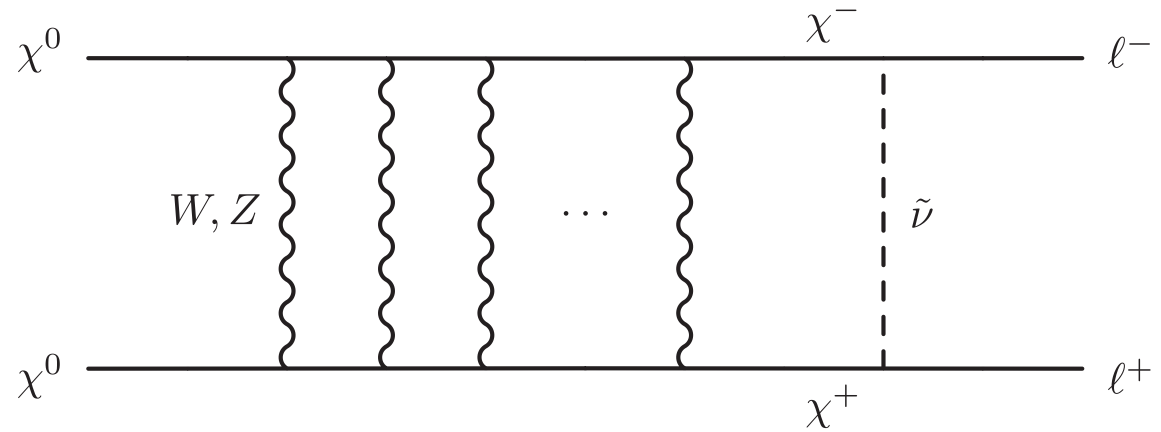
Final-state radiation, or internal bremsstrahlung may lead to a gamma-ray peak near the kinematic cutoff, improving sensitivity of higher threshold ground-based instruments.



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



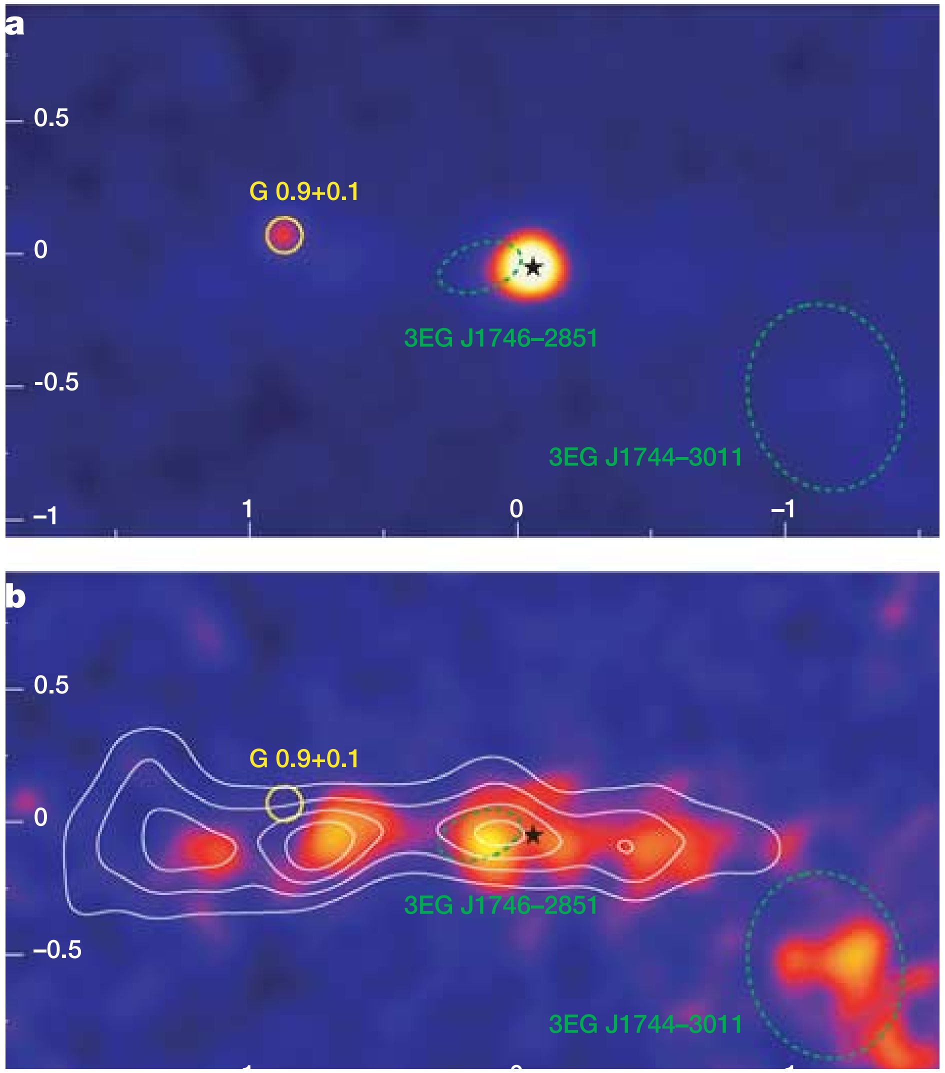
Above a few TeV, W and Z exchange can produce a Yukawa like potential that boosts cross section at low velocities compared with higher-velocity interactions in early universe

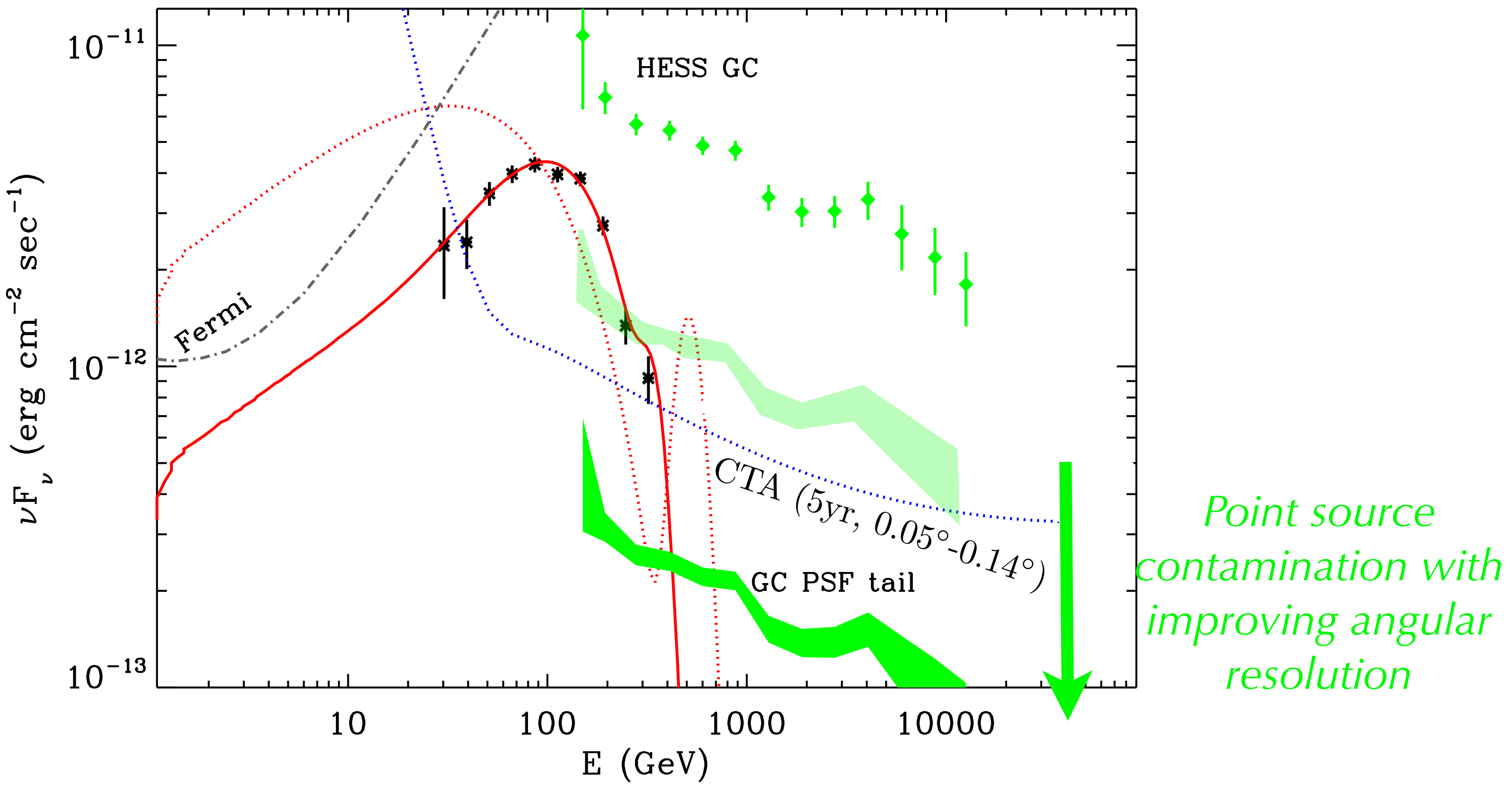


Lattanzi and Silk, PRD 79, 083523 (2009), Profumo (2005)

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?''





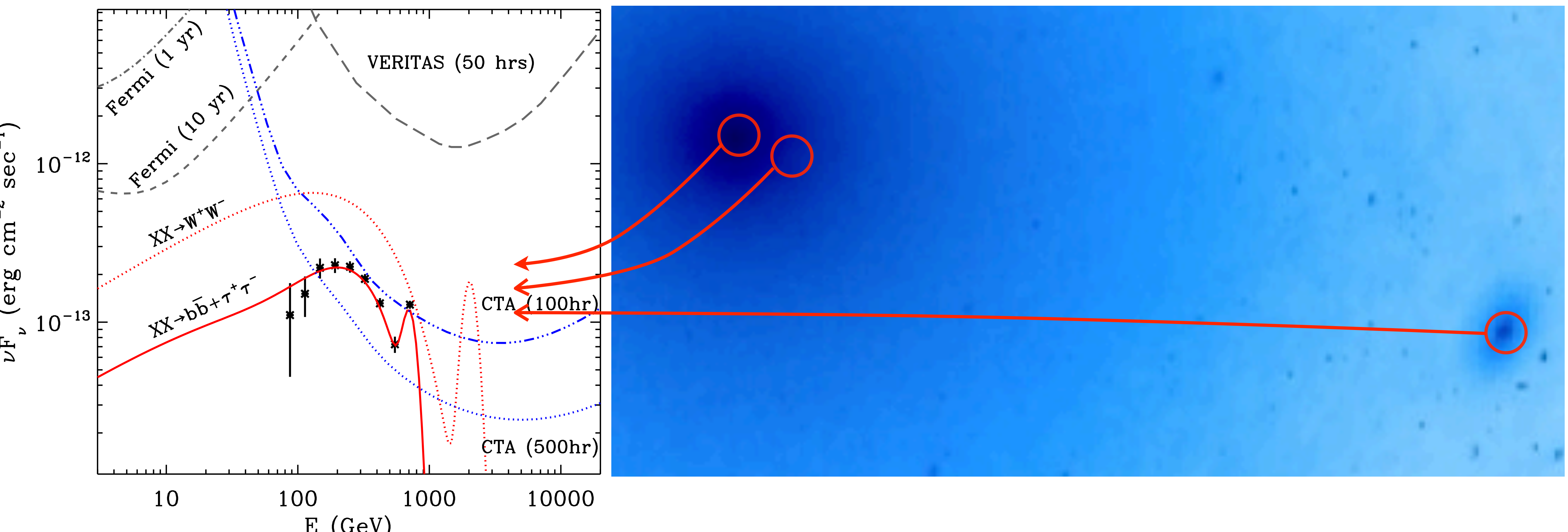
Dwarf galaxies have almost no known astrophysical backgrounds, for backgrounds the GC is worst case. HESS provides the best data on the GC (below, with point source at Sgr A* subtracted). Better angular resolution can reduce the background from the tail of the PSF function, which dominates over other 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 $1^\circ \sim 1 \times 10^{-7}\mathrm{cm}^{-2}\,\mathrm{s}^{-1} \Rightarrow \langle\sigma v\rangle = 1.6 \times 10^{-25}\ \mathrm{cm}^{3}\mathrm{s}^{-1}$

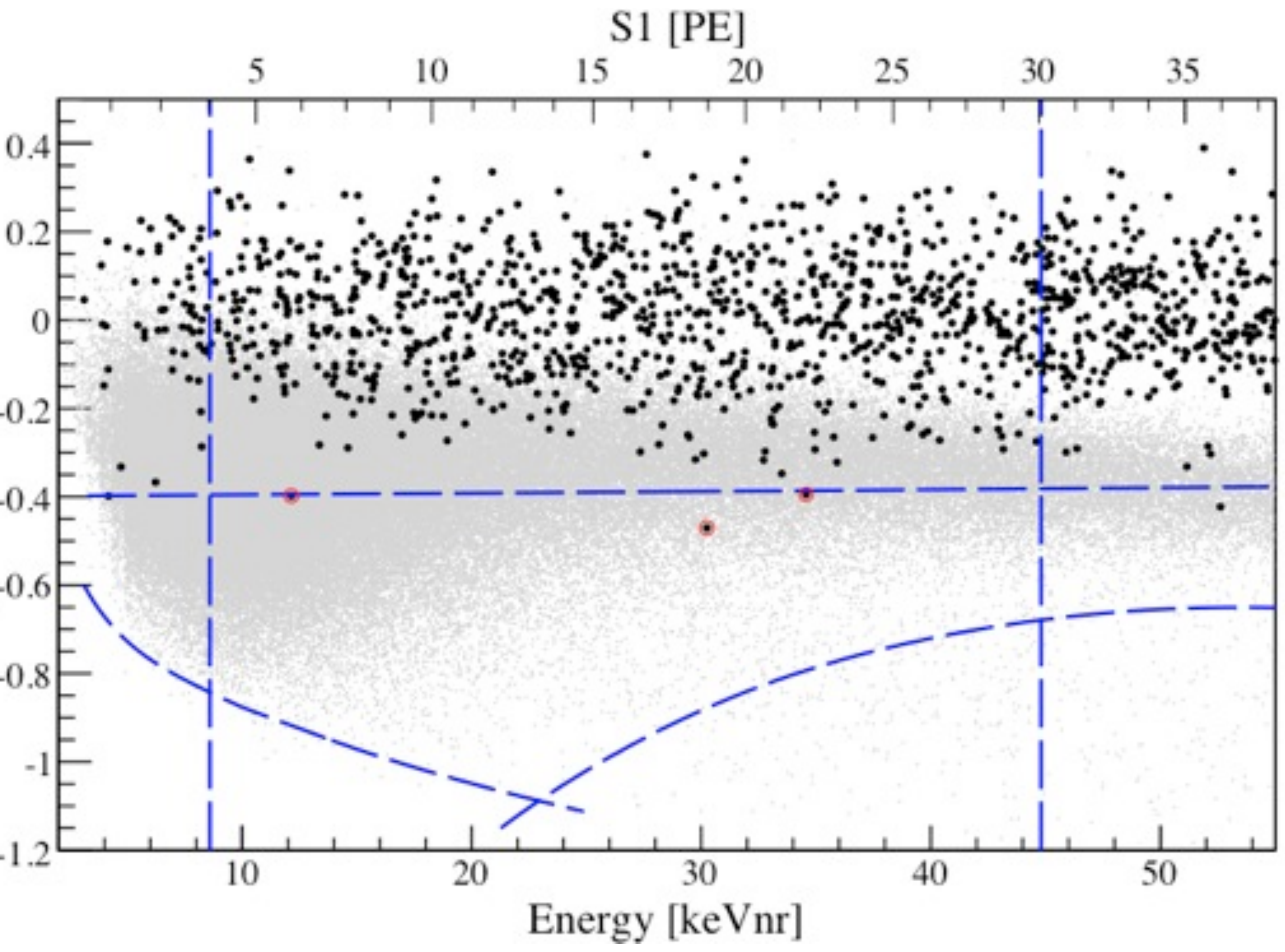
(Tim Linden, SLAC CF meeting)



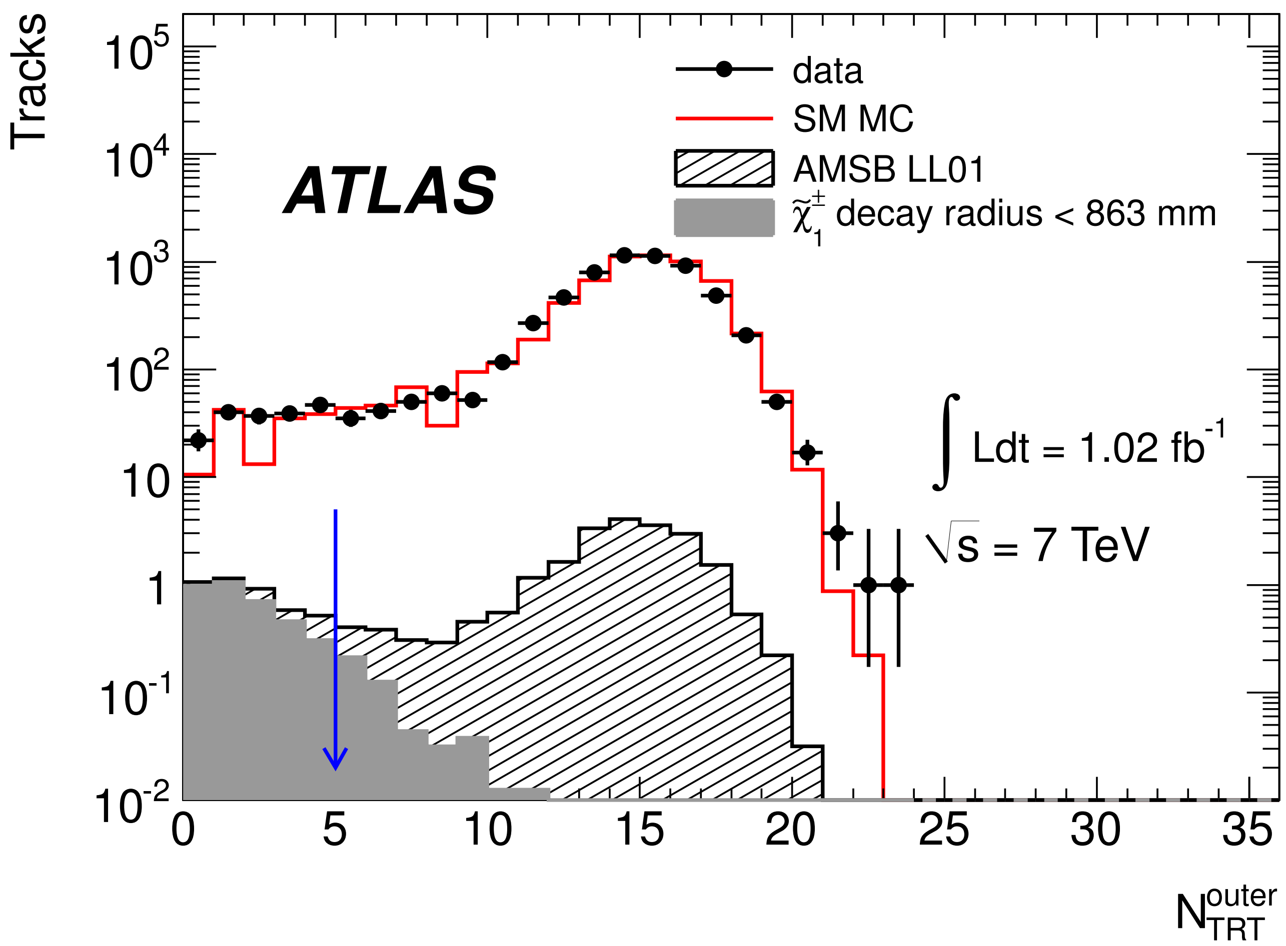
Unlike other astrophysical sources, would see a universal hard spectrum (typically harder by ~$E^{0.5}$) with a sharp cutoff. The spectral shape would be universal: the same throughout the GC halo, in halos of Dwarf galaxies, with no variability.

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.

Backup Slides

Gamma-400 and CALET

	Space-based instruments			
	Fermi LAT	AMS-2	GAMMA-400	CALET
Energy range, GeV	0.02-300	10-1000	0.1-3,000	10-10,000
Field-of-view, sr	2.4	0.4	1.2	
Effective area, m^2	0.8	0.2	~0.4	~0.1
Angular resolution (E>100 GeV)	0.2°	1.0°	~0.01°	0.1°
Energy resolution (E>100 GeV)	10%	2%	~1%	2%

Gamma-400 is a pair-conversion telescope with a deep (25 X_0) calorimeter

CALET is an imaging calorimeter with ~0.12 m^2 sr

Good energy resolution for lines

Angular resolution helps with removal of point source backgrounds

Hard to compete with Fermi-LAT and AMS on exposure

VERITAS Array

VERITAS Array

- *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)

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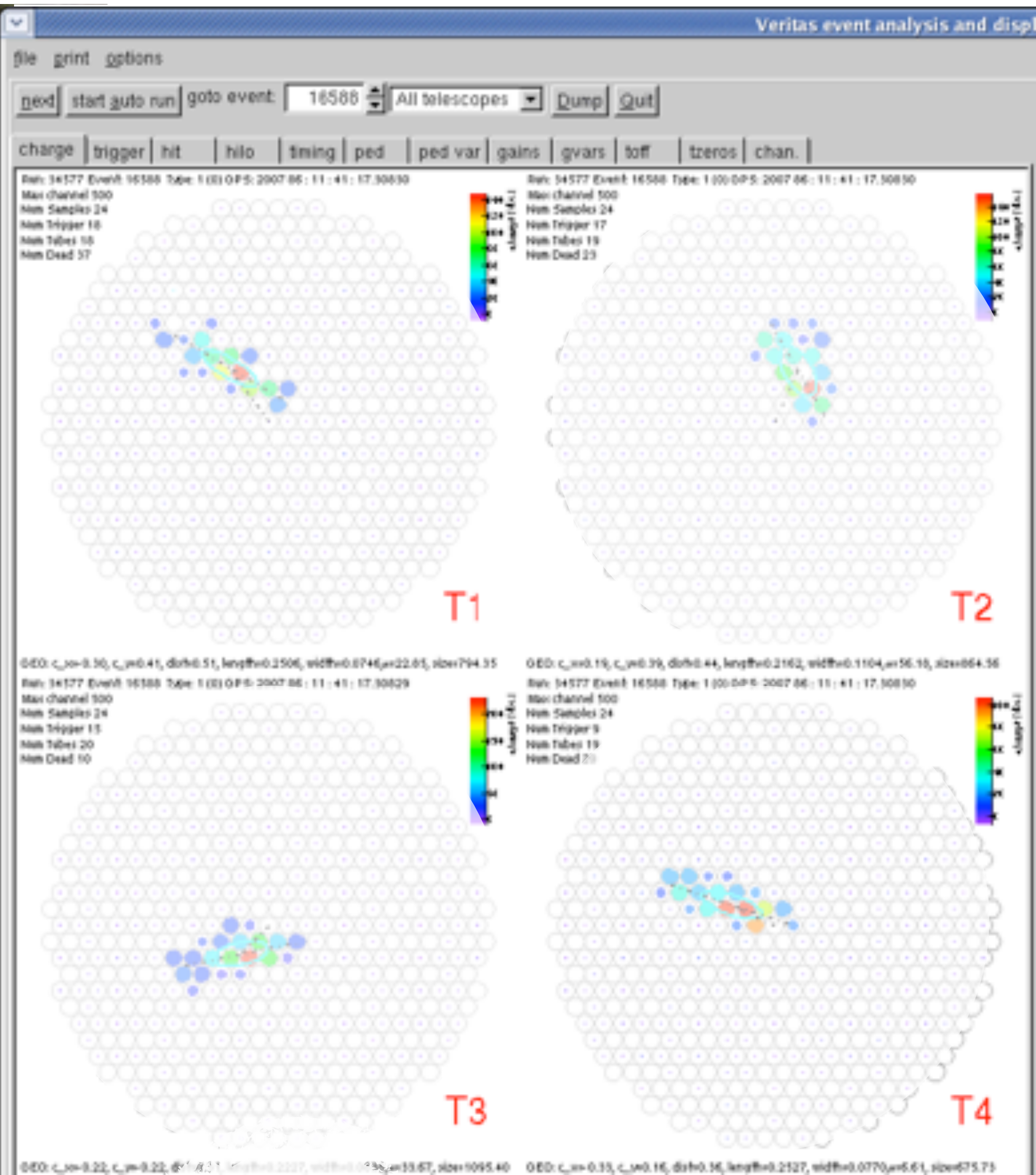

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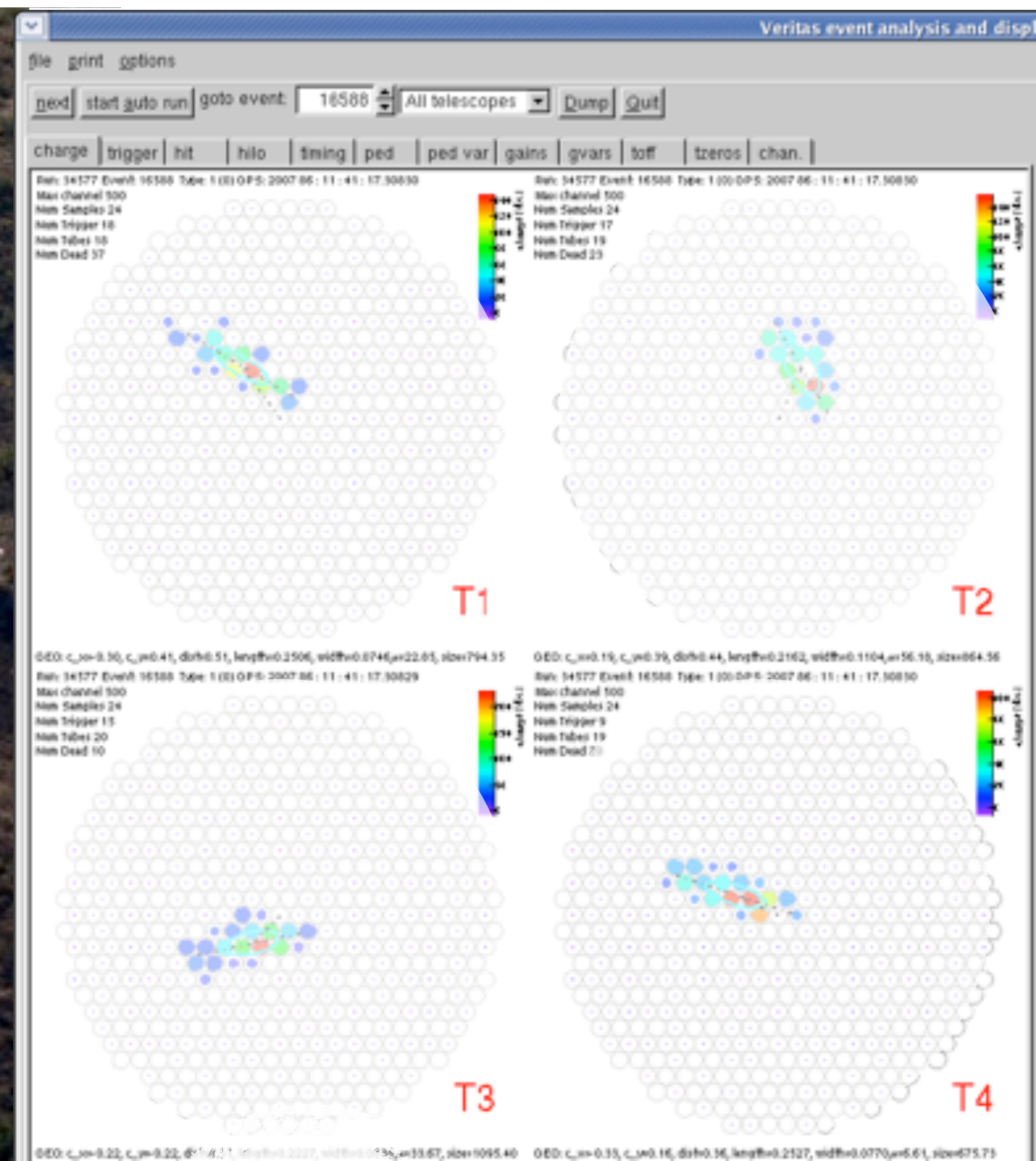

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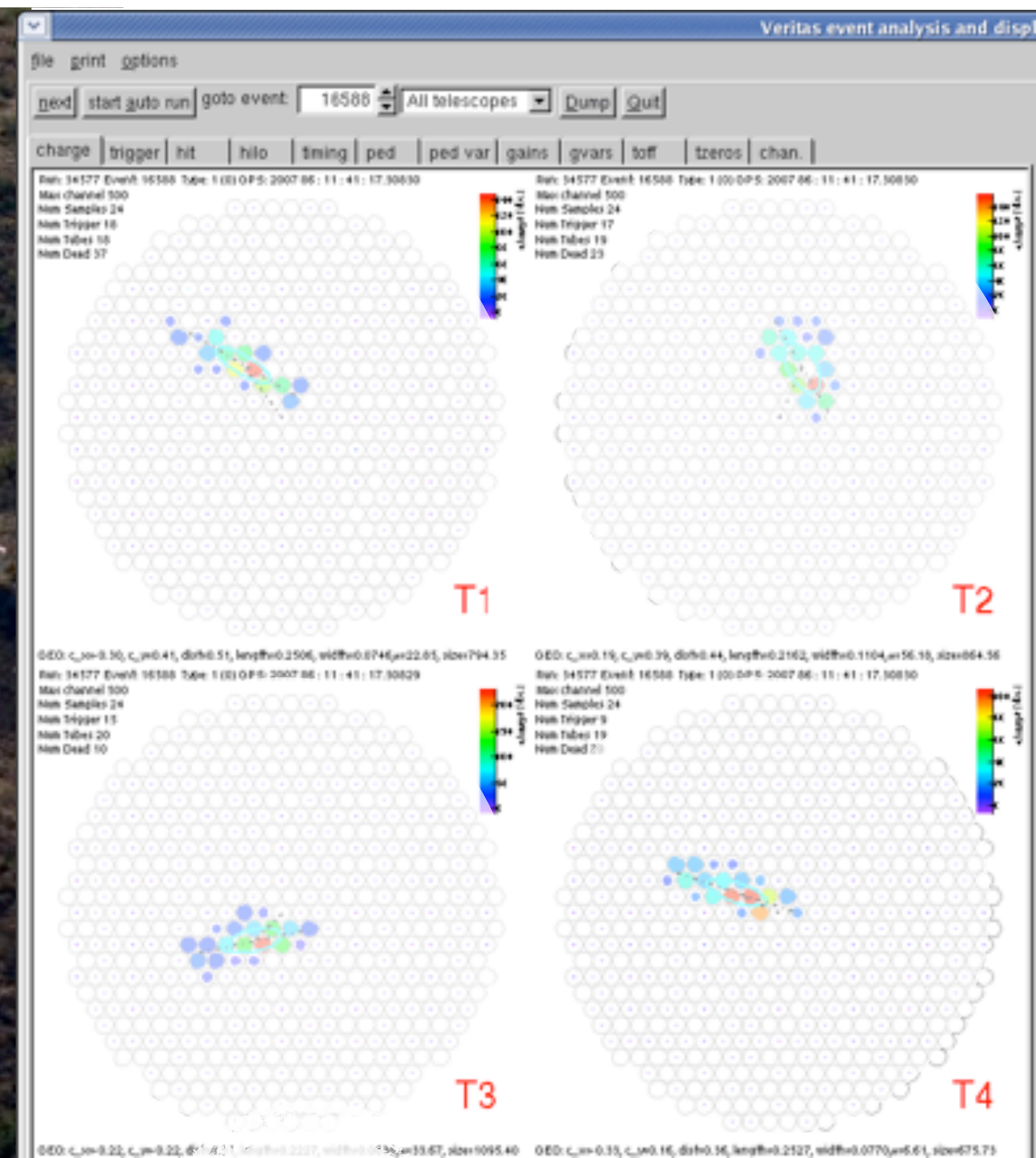

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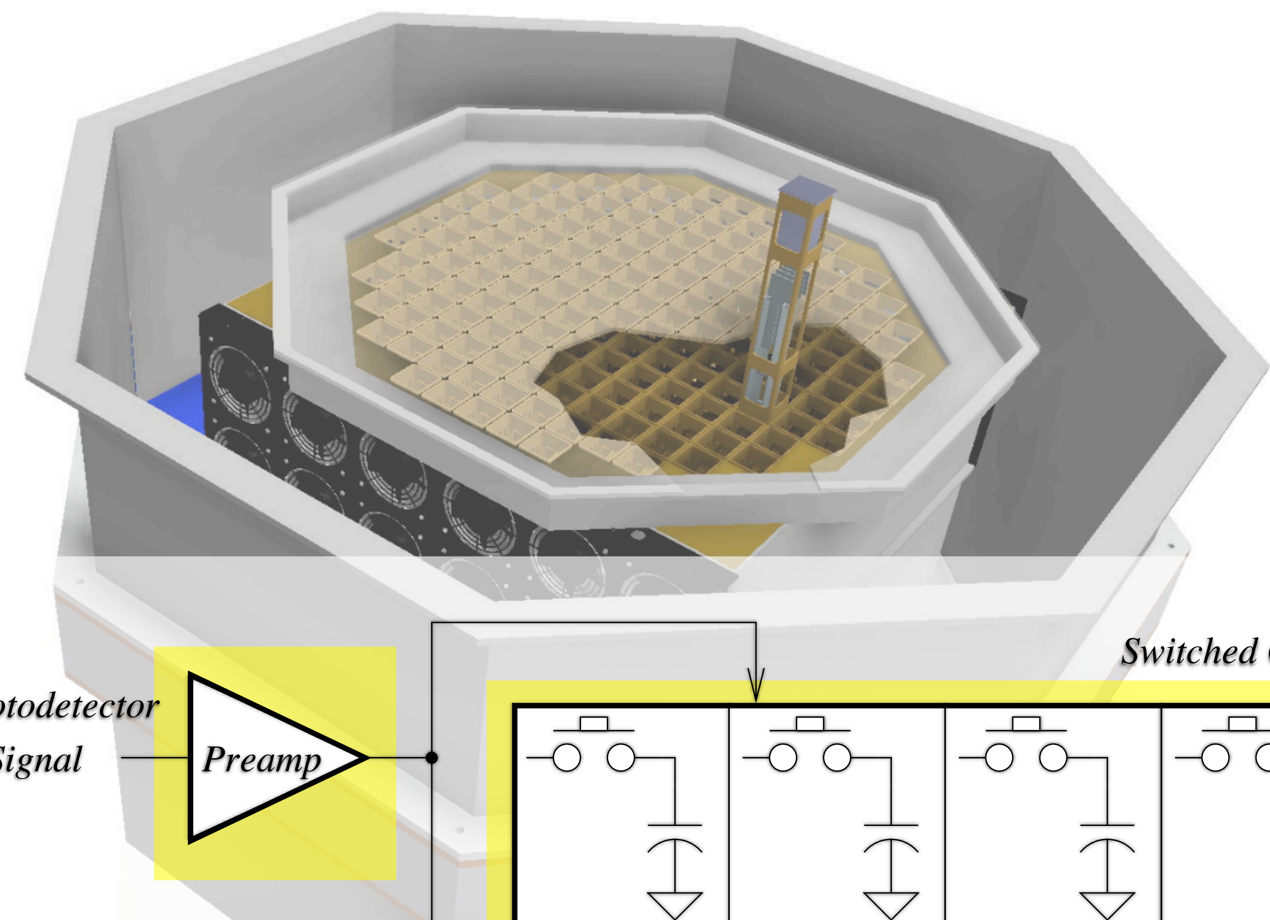
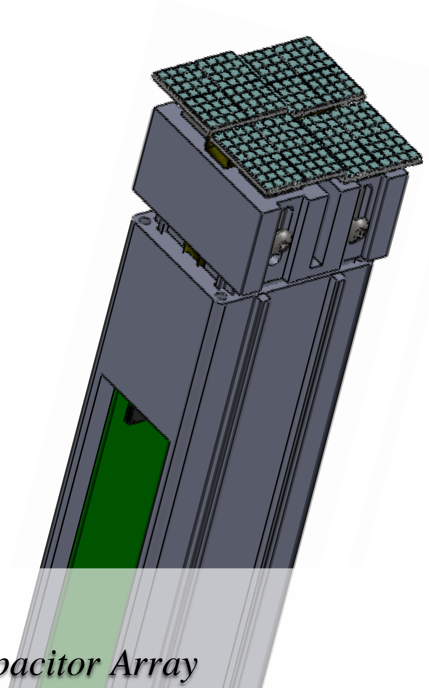
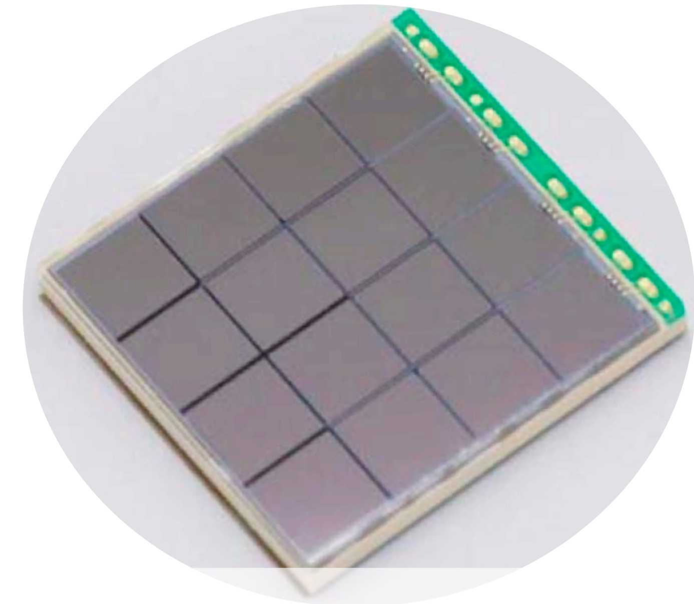
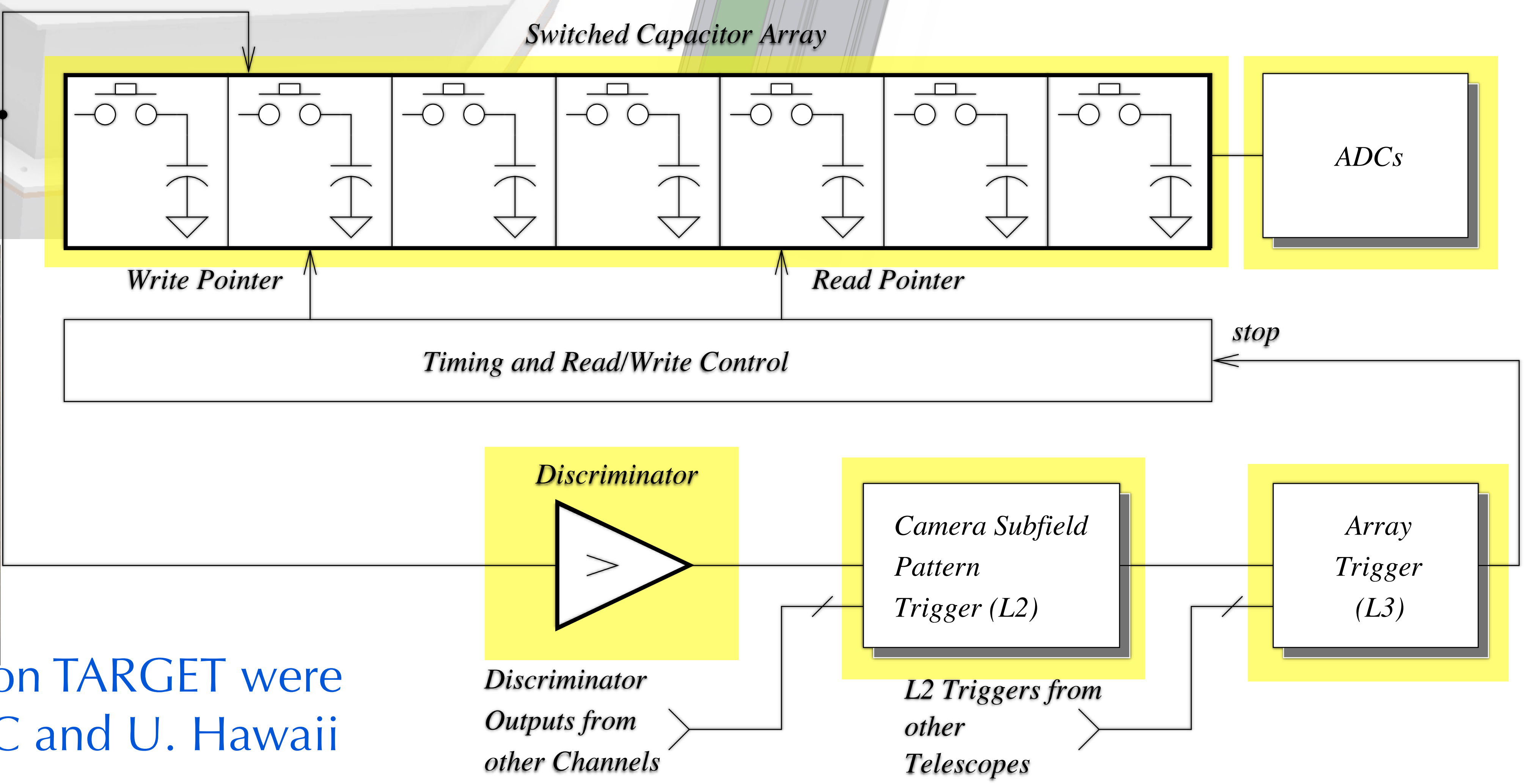
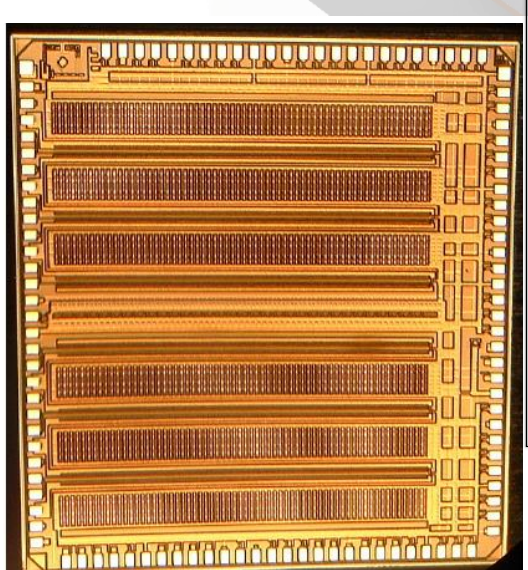
CTA Camera





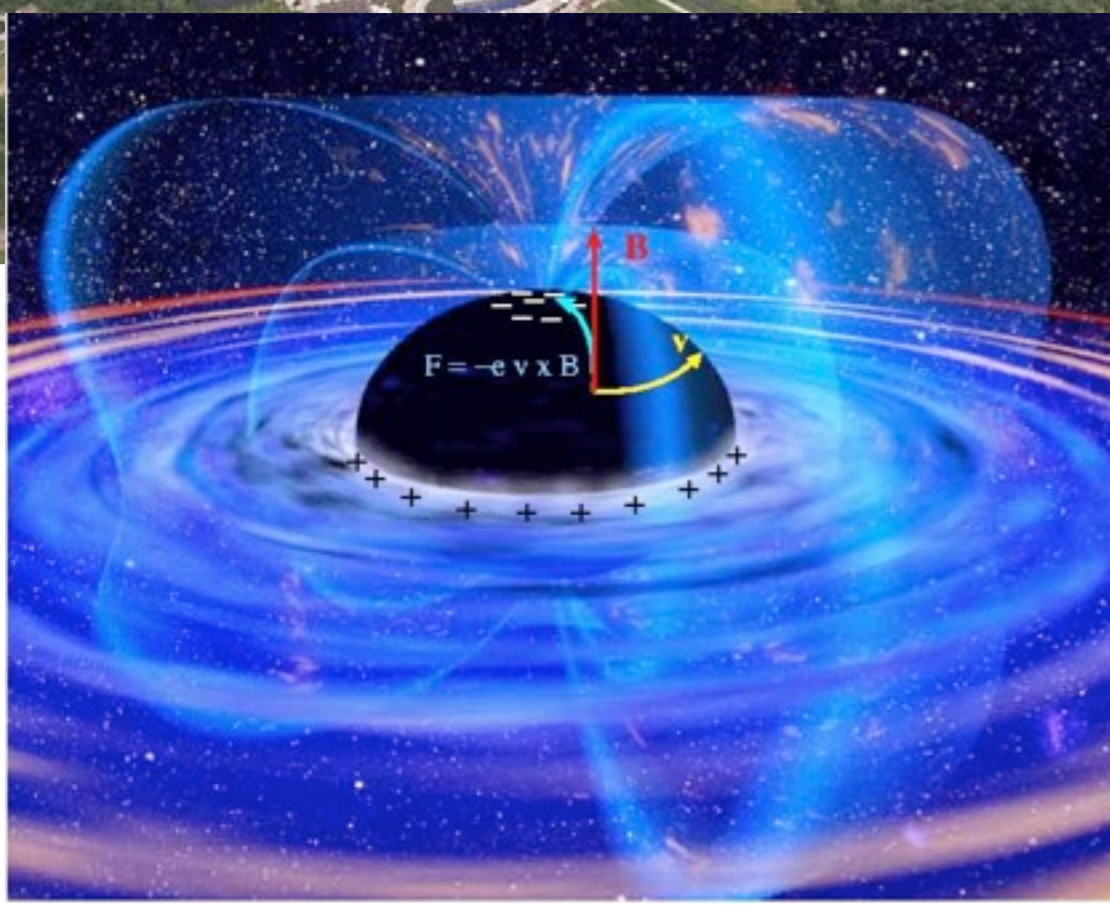


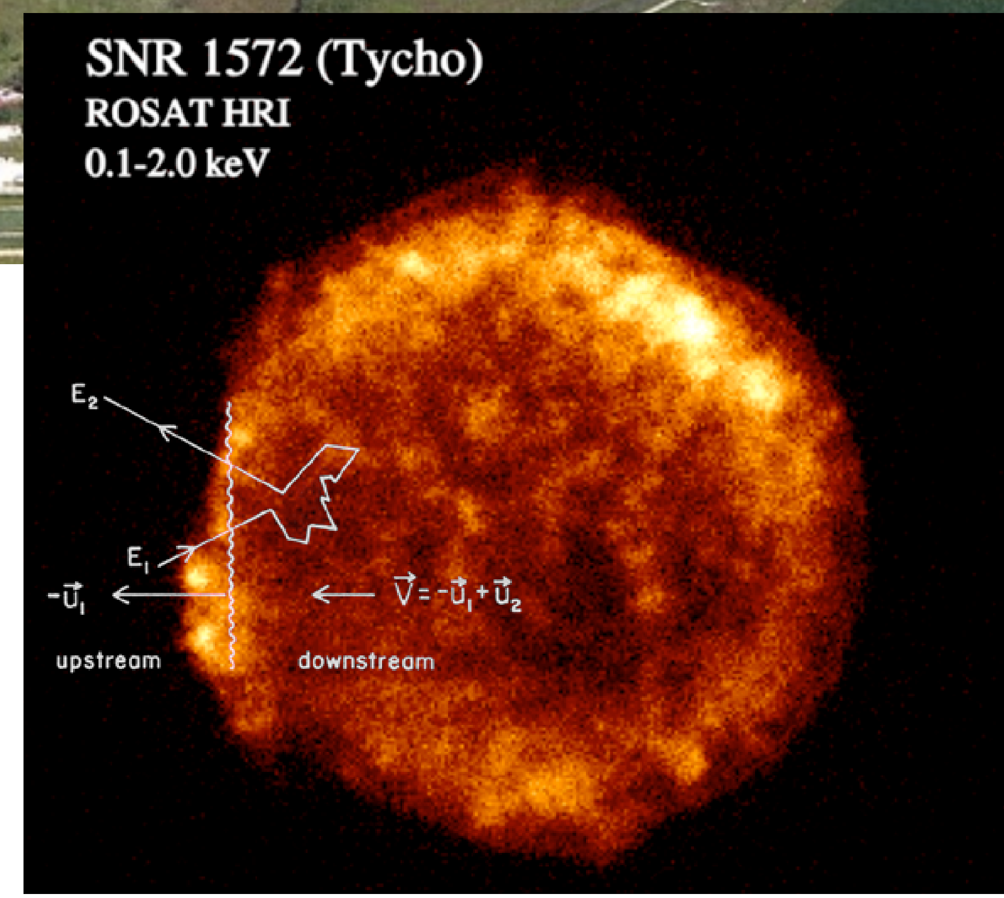




Electronics based on TARGET were developed by SLAC and U. Hawaii

Particle Accelerators



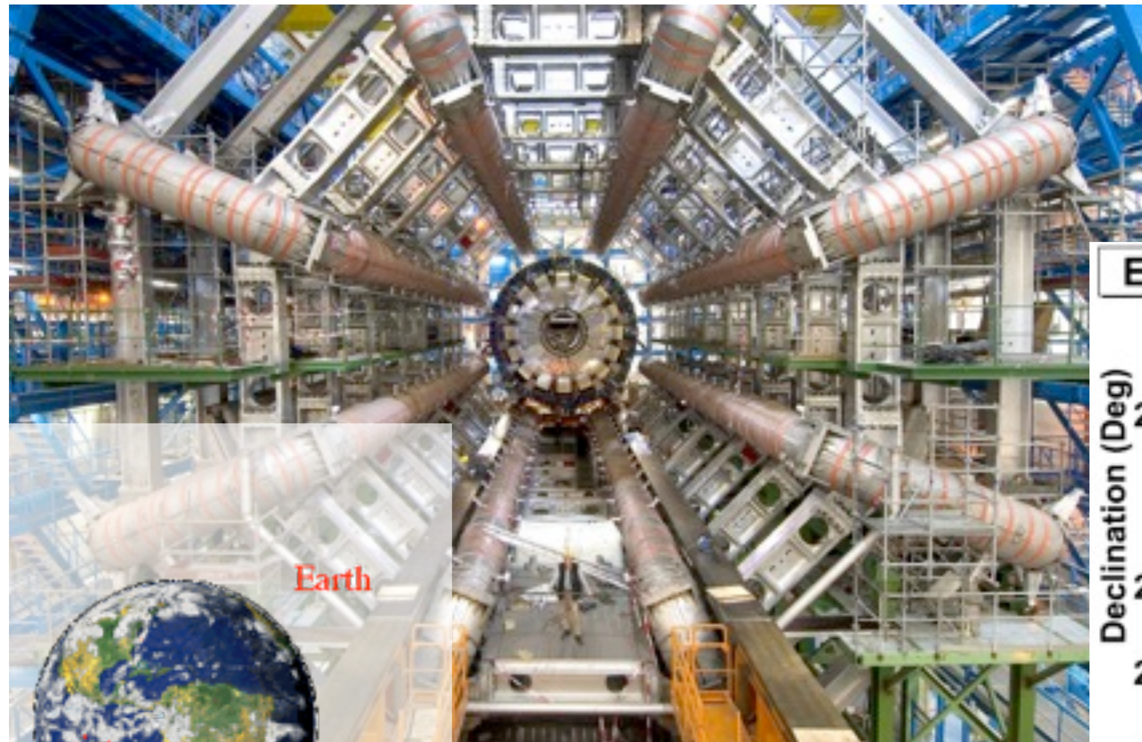


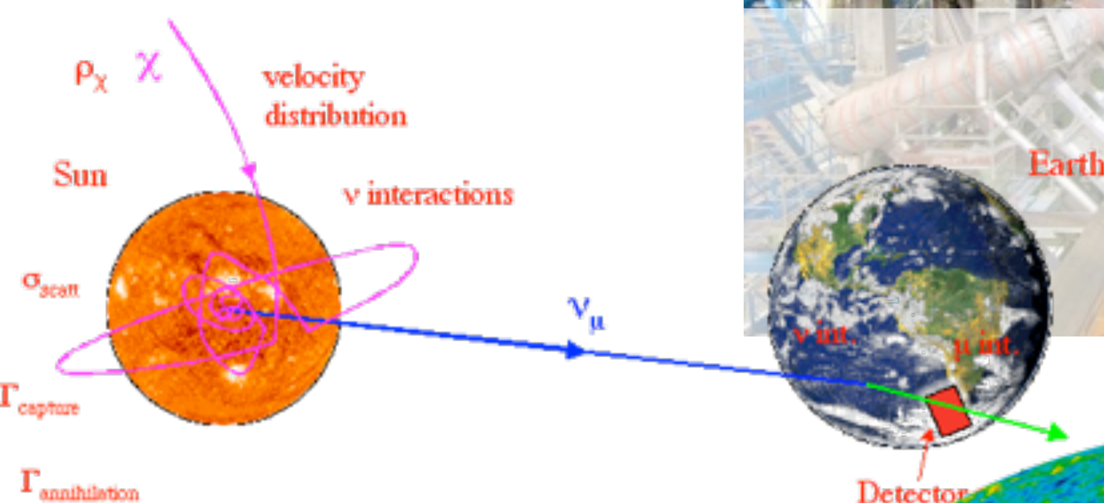
Black hole extended horizon or accretion disk - conductor spinning in a magnetic field - 10^{20} V Generator! (Blandford, Lovelace)

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

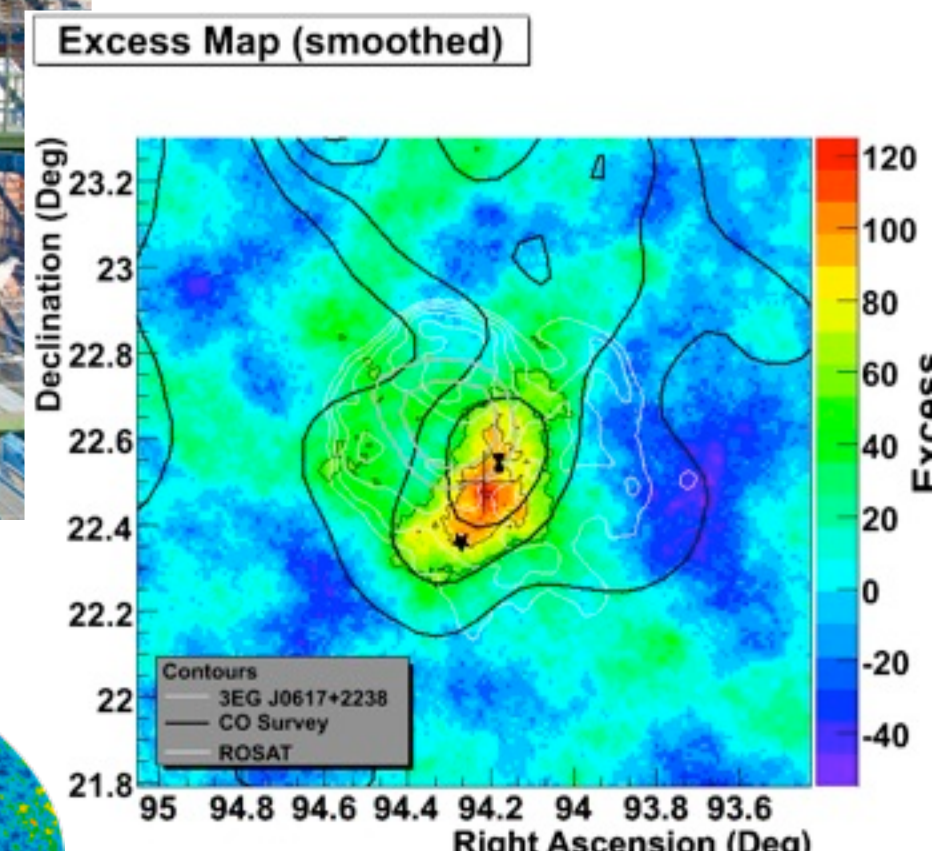
Targets?

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

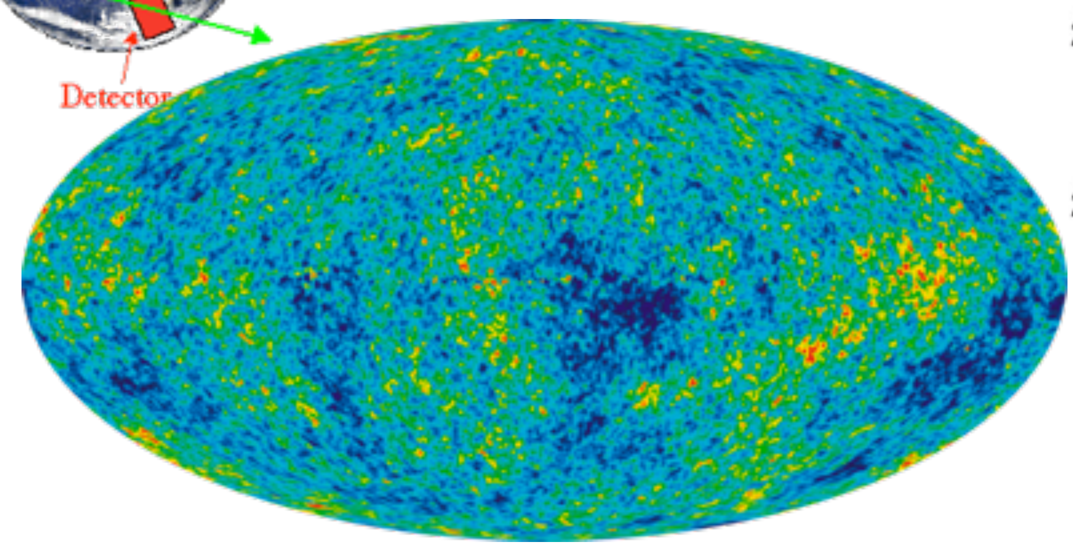




The sun or earth is sometimes the fixed target!

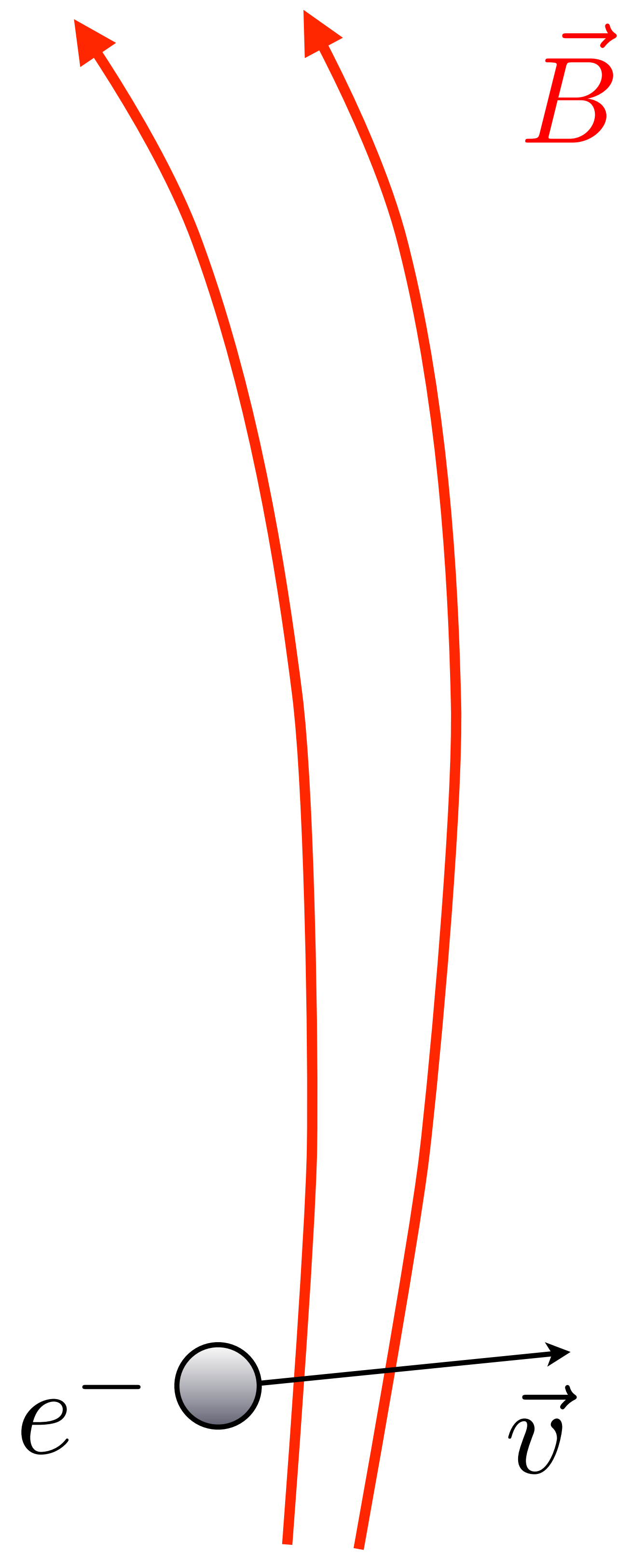


Molecular clouds can be the target



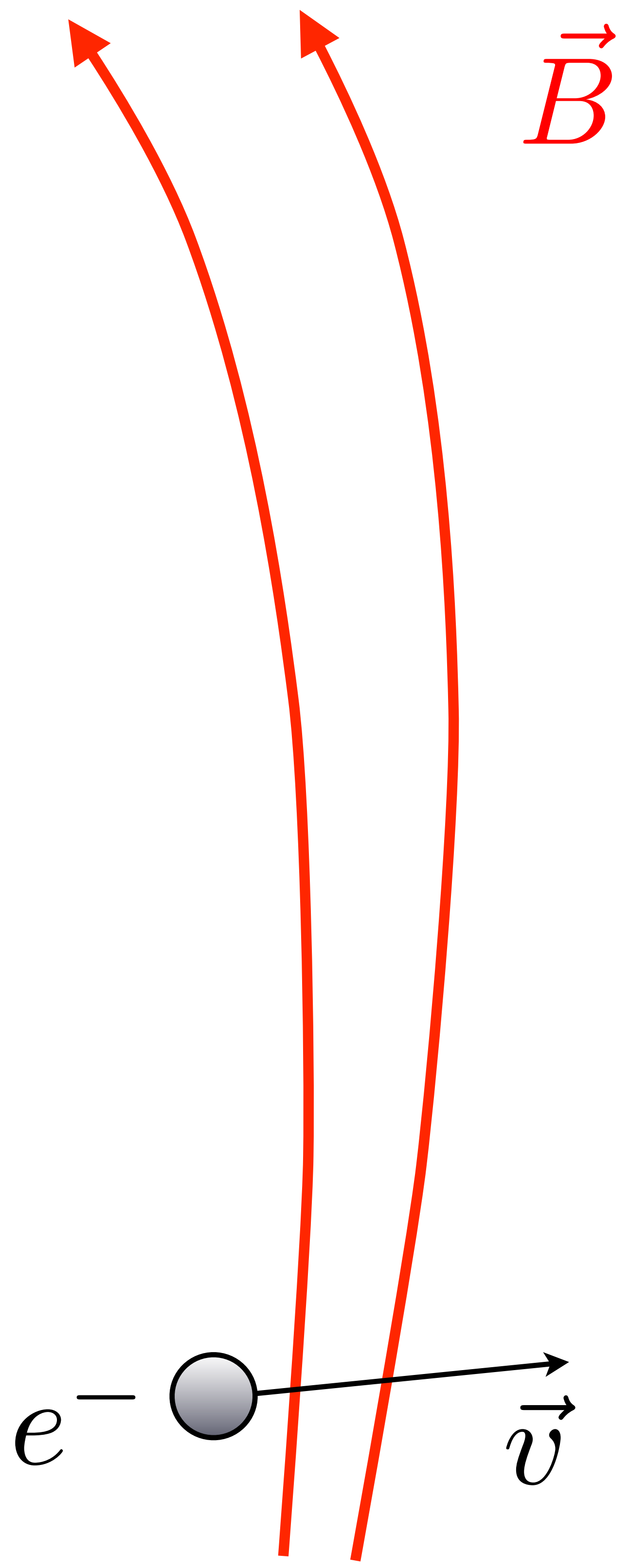
CMB photons and primordial starlight are also targets for high energy cosmic particles

Synchrotron Radiation



Synchrotron Radiation

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



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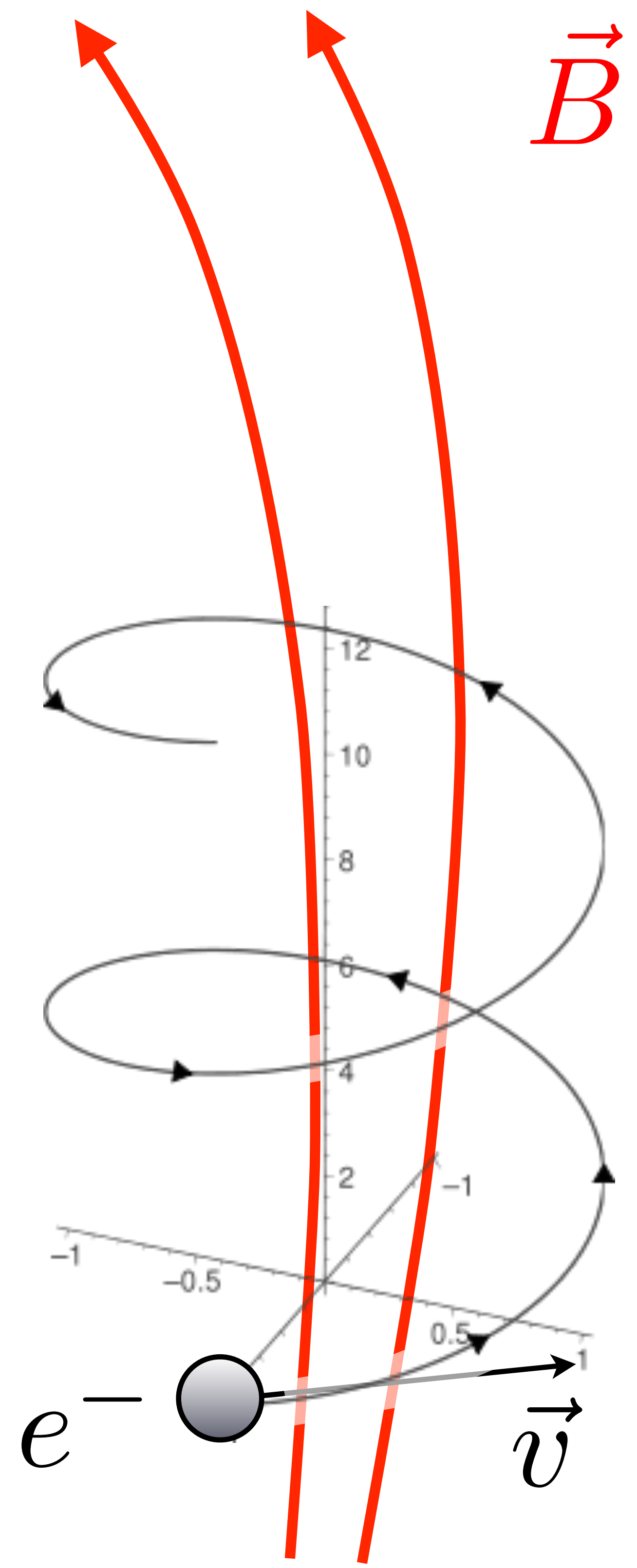
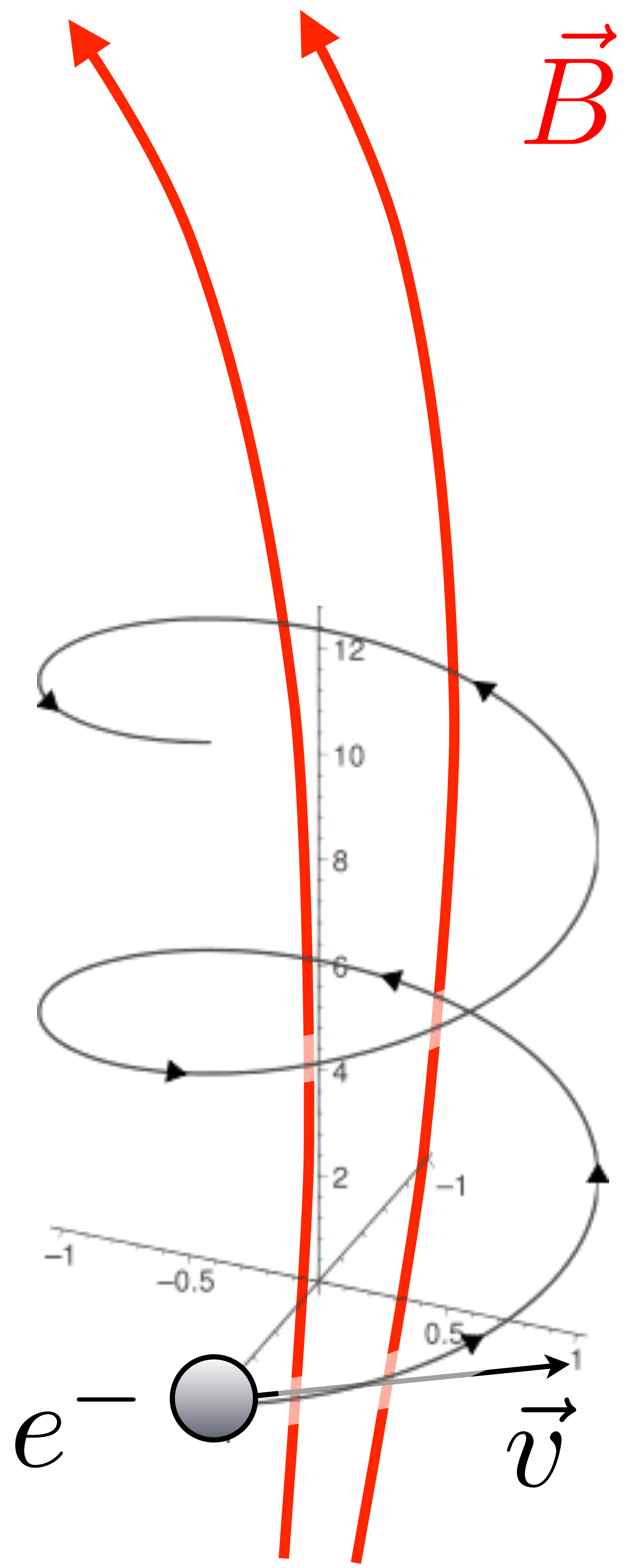


Synchrotron Radiation

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



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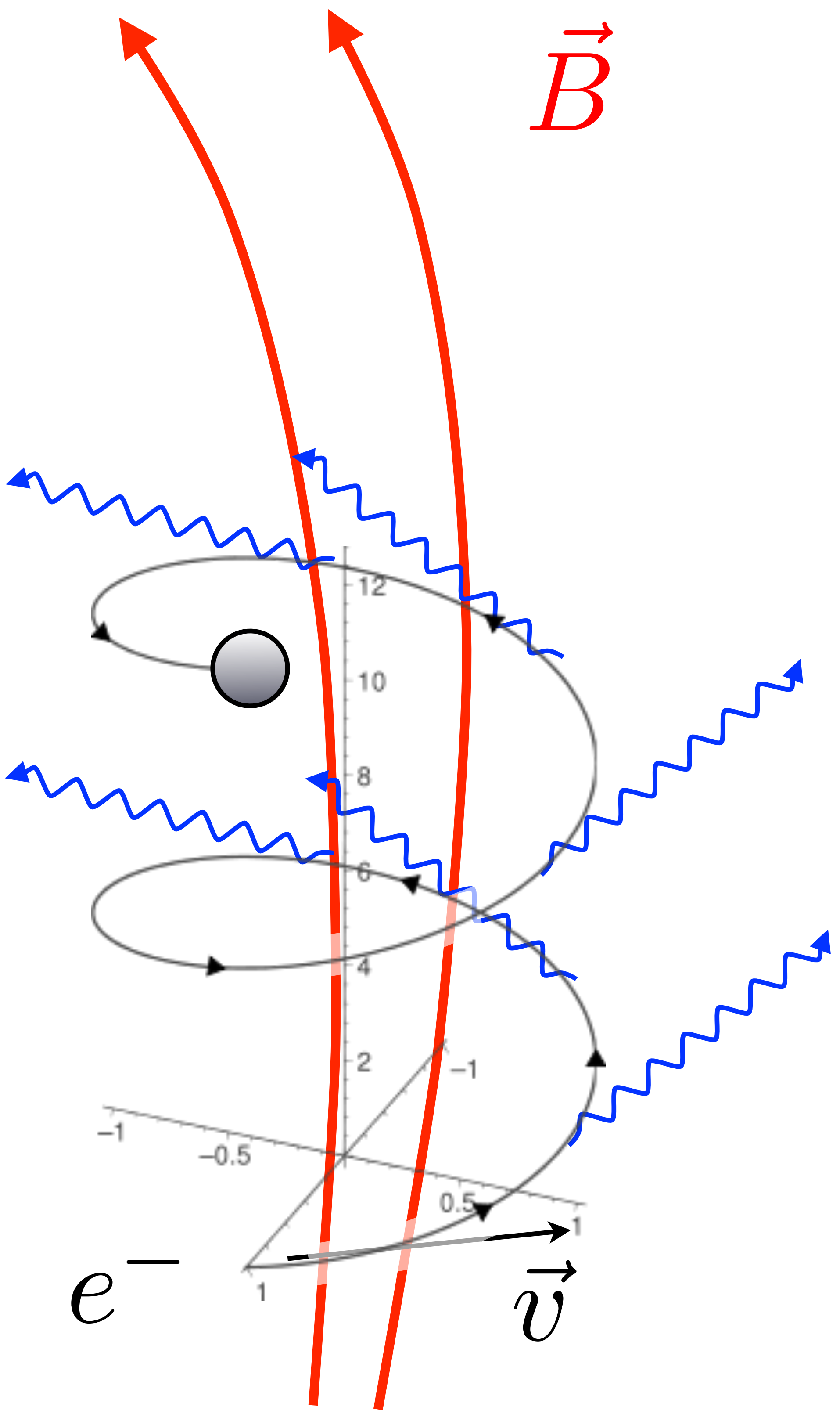
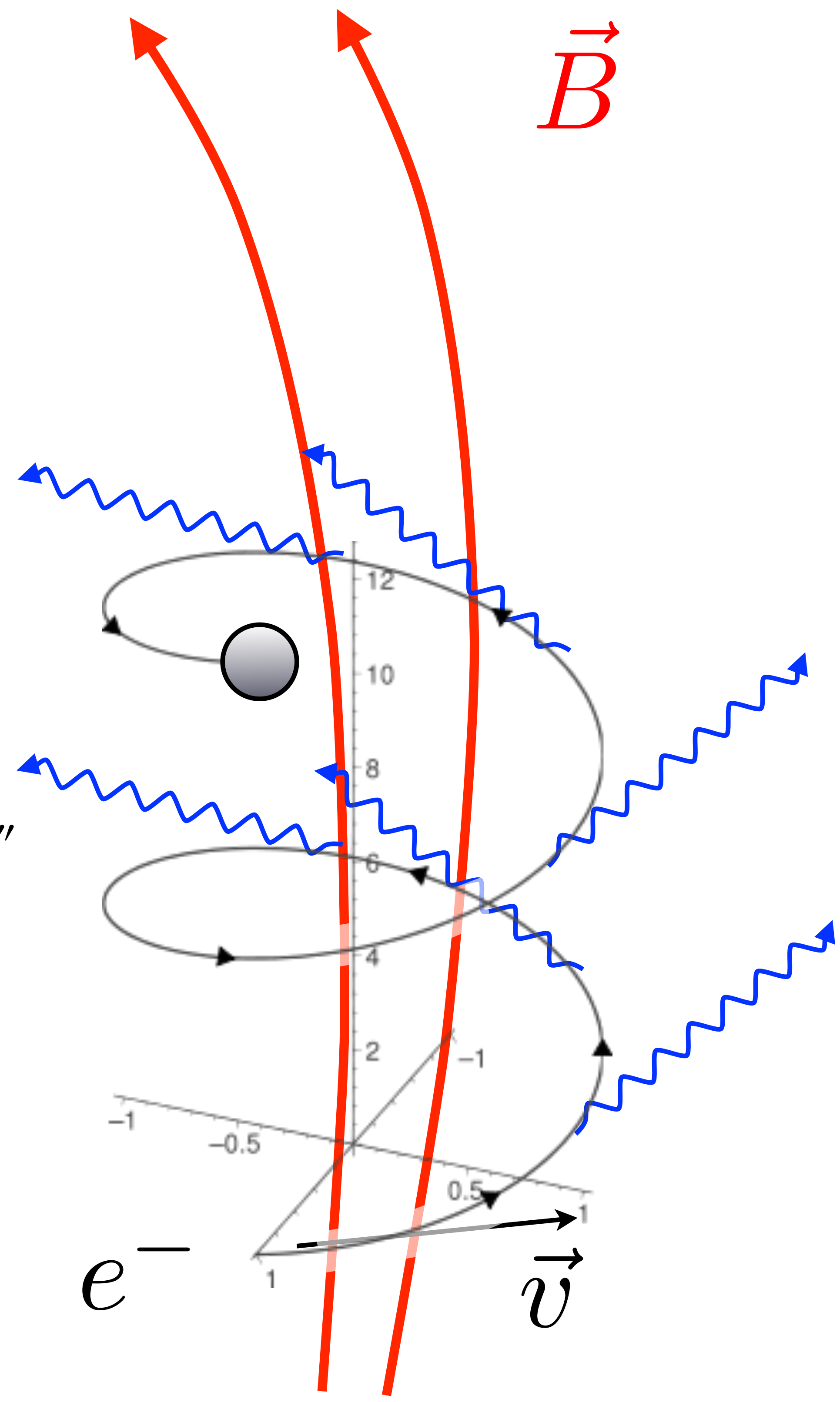
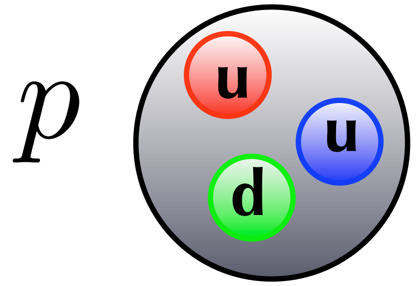


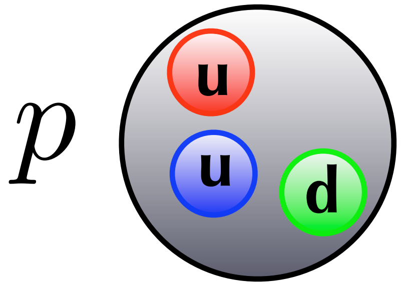
Synchrotron Radiation

- 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.

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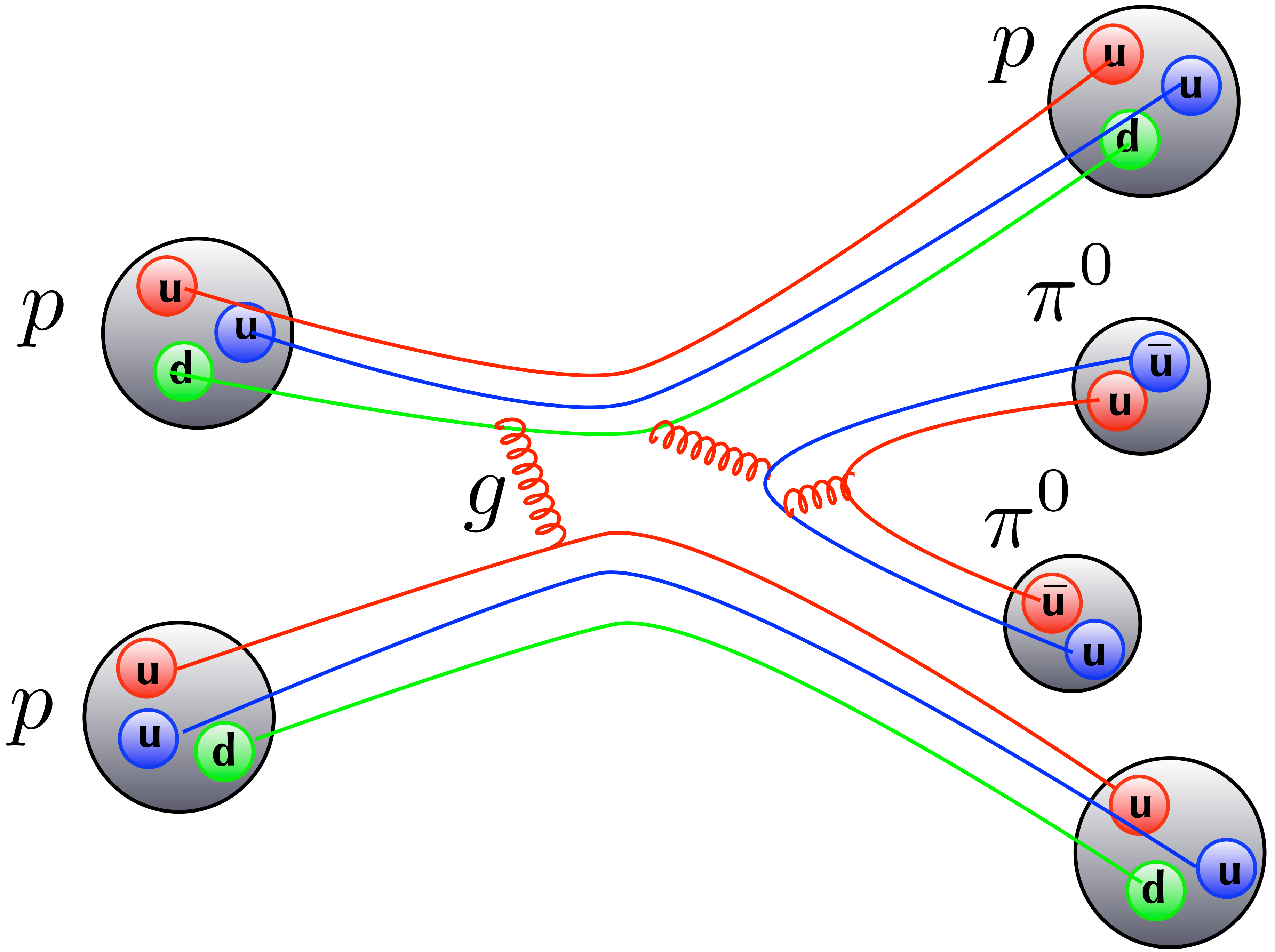

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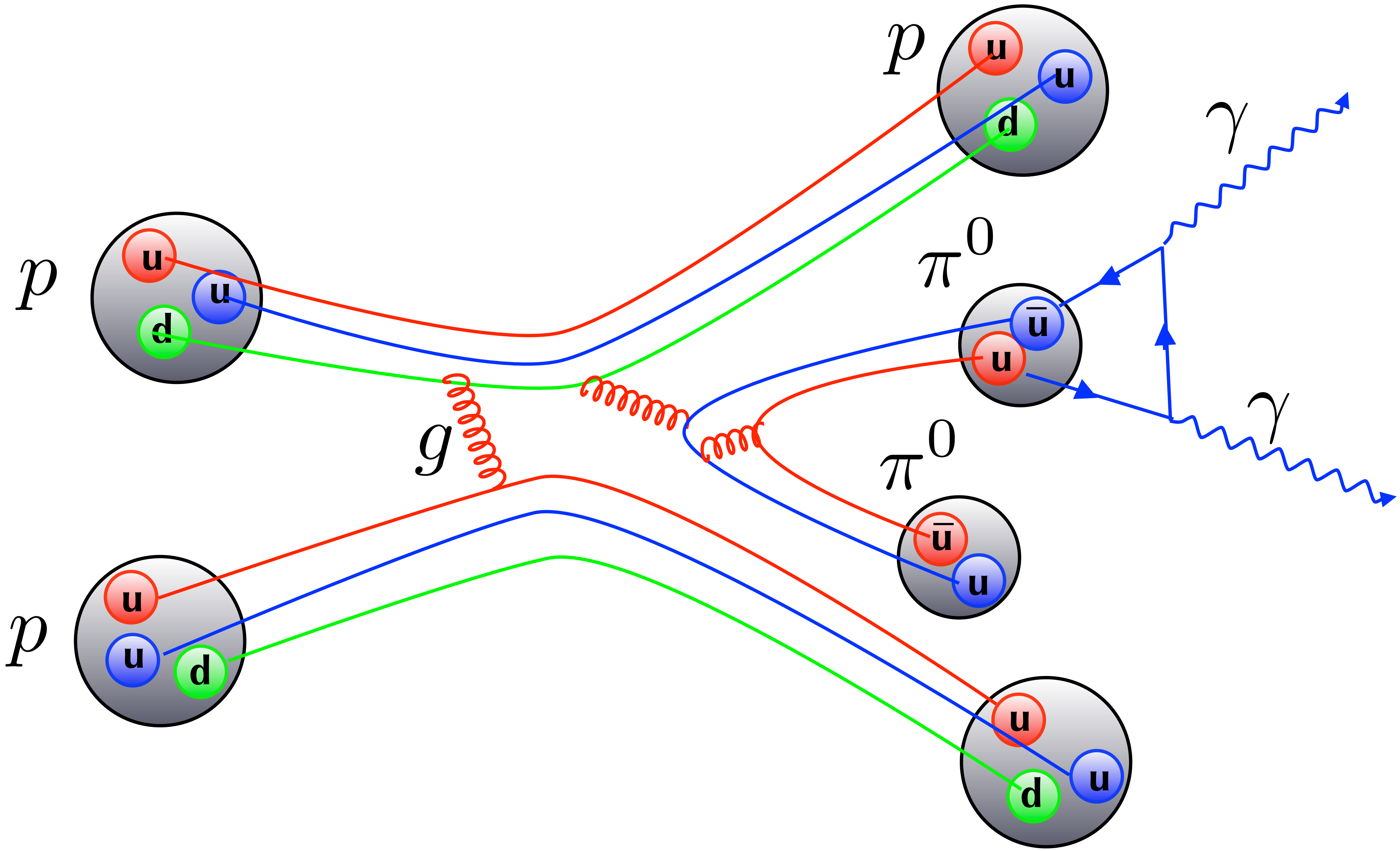

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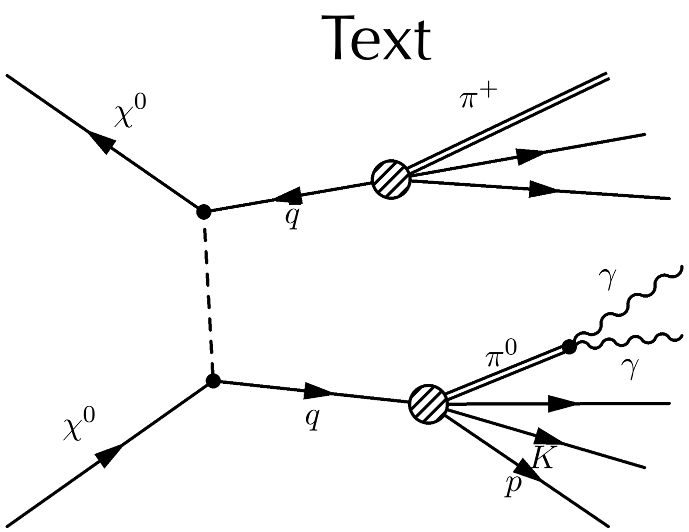
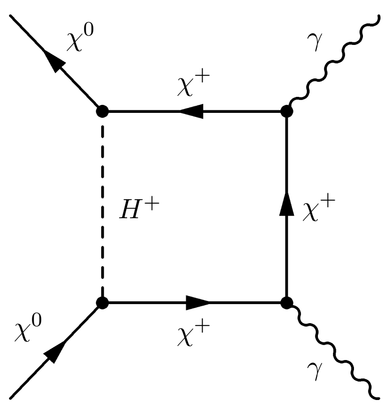
Annihilation Channels

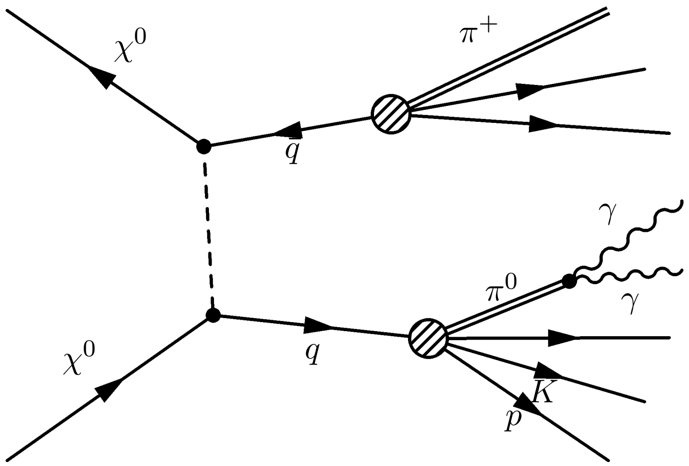


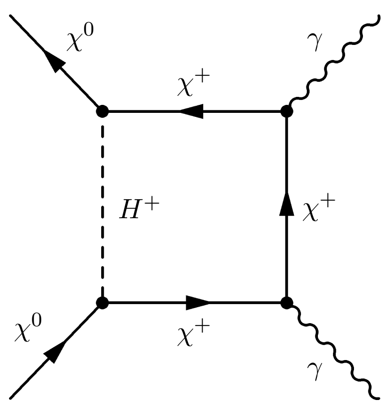


Annihilation Channel	Secondary Processes	Signals	Notes
$\chi\chi \rightarrow q\bar{q},\ gg$	$p, \bar{p}, \pi^{\pm}, \pi^0$	p, e, ν, γ	
$\chi\chi \rightarrow W^+W^-$	$W^{\pm} \rightarrow l^{\pm}\nu_l,\ W^{\pm} \rightarrow u\bar{d} \rightarrow \pi^{\pm},\ \pi^0$	p, e, ν, γ	
$\chi\chi \rightarrow Z^0Z^0$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

Annihilation Channels

Text





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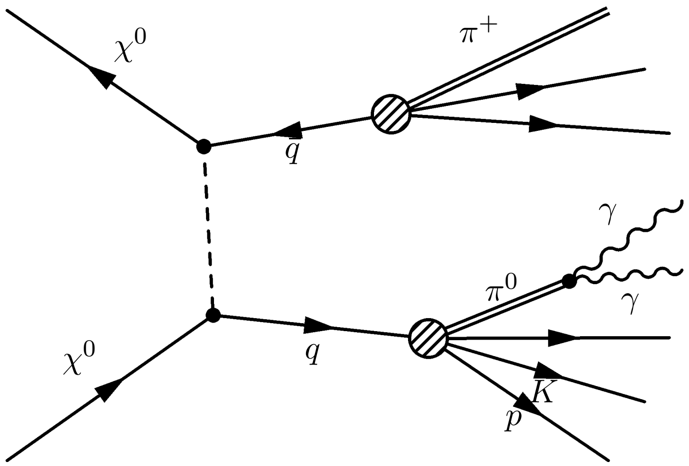
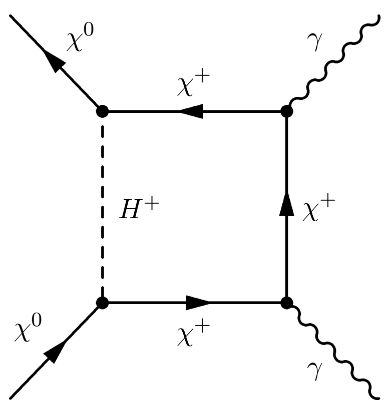
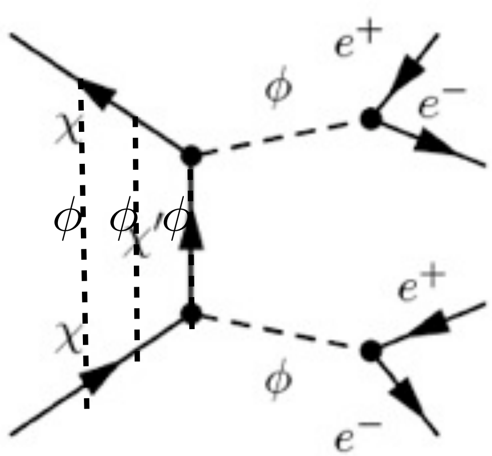
internal/final state bremms
inverse Compton γ's

Annihilation Channels

Text







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