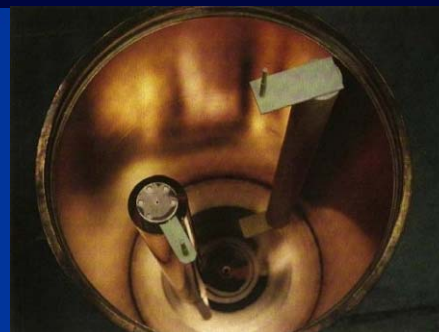
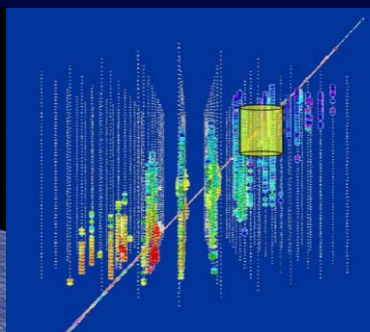
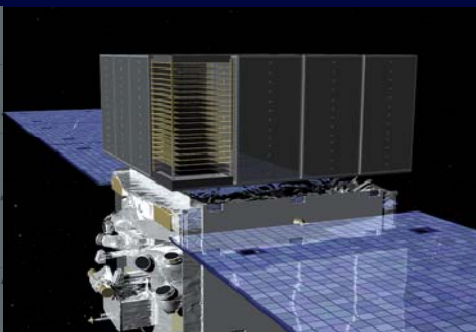
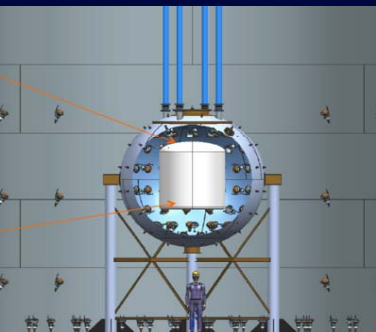


Astroparticle Results

Rene A. Ong (UCLA)

Nobel Symposium on LHC Results, May 2013



Astroparticle Physics Overview

Astroparticle Physics encompasses a wide variety of topics:

1) New Particles/Interactions (BSM)

- ✓ Dark Matter, Weakly Interacting Slim Particles (WISPs)
- Other relics (PBH's, GUT particles, etc.)
- Lorentz Invariance Violation
- etc.

2) VHE Astrophysics (VHE = Very High Energy, $E > 10^{12}$ eV)

- ✓ Point/diffuse sources of VHE γ -rays, CR's and ν 's.
- Origin of cosmic rays
- ✓ Intergalactic radiation fields
- etc.

3) Particle Properties

- Neutrino properties (atm., solar, SN, and relic ν)
- ✓ Proton, photon and ν interactions at ultrahigh energies
- etc.

4) Cosmology (a field in its own right)

Outline

Selected set of topics in three general areas:

A. Very High Energy (VHE) Astrophysics

- VHE sources of γ -rays (and possibly neutrinos and CR's)

B. AP Topics Connected to LHC

- Proton-Proton Cross Section at 70 TeV
- WIMP DM – Direct and Indirect Detection Results & LHC

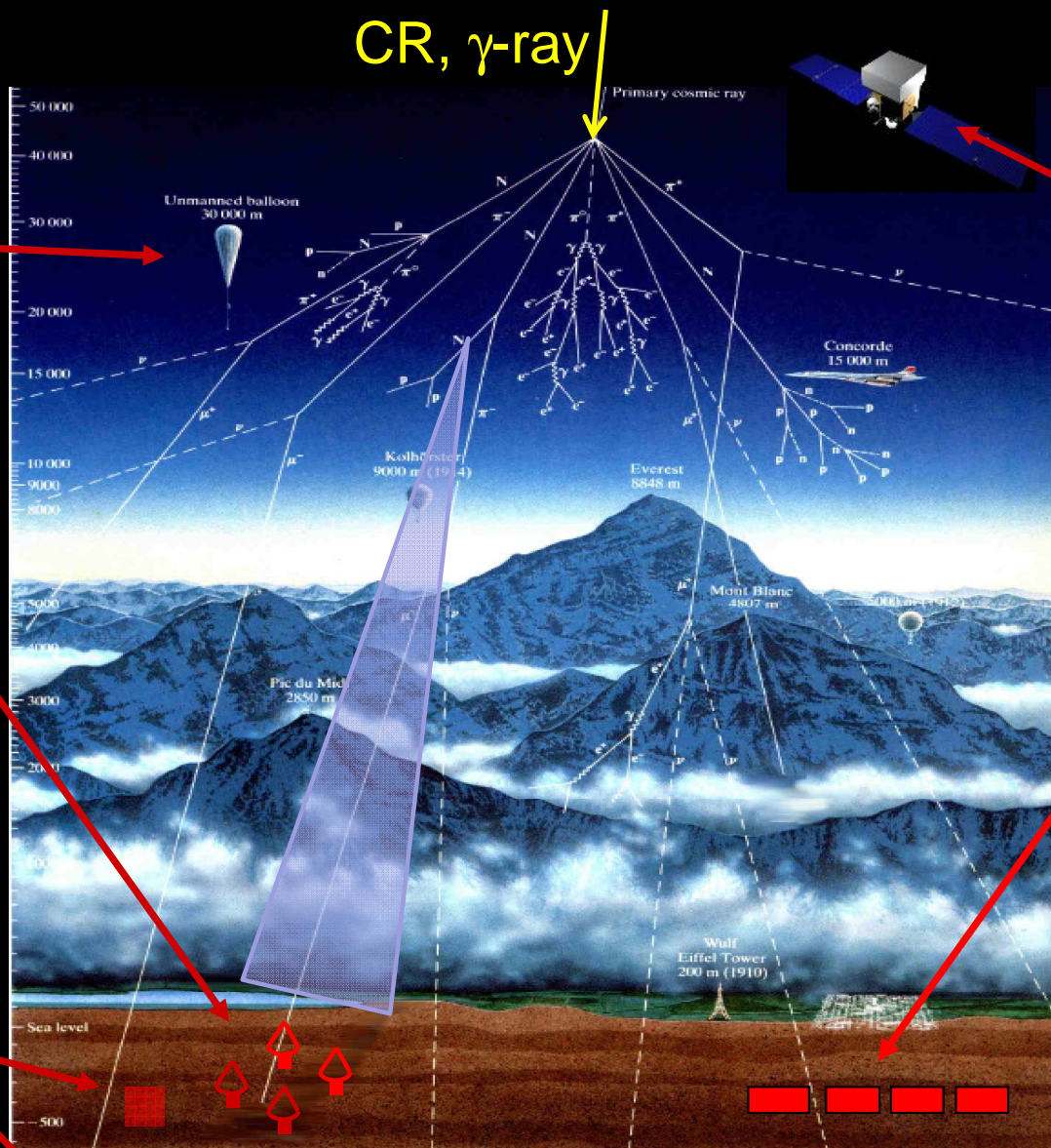
C. Other Topics (possibly connected to LHC)

- Axions and axion like particles (ALPs)

Future Projects and Summary

(note: some overlap with talk by Lars Bergstrom)

Many Detectors, Many Techniques



Balloon Instruments

ANITA

Atmospheric Cherenkov Telescopes

HESS, VERITAS
MAGIC ...

Ground or Underground Detectors

CDMS, Xenon ...
ADMX, CAST ...

Satellite Instruments

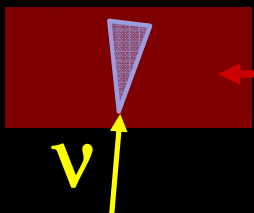
Fermi, AMS
PAMELA ...

Air Shower Arrays

Auger ...

IceCube ...

Ice/Water Cherenkov Detectors

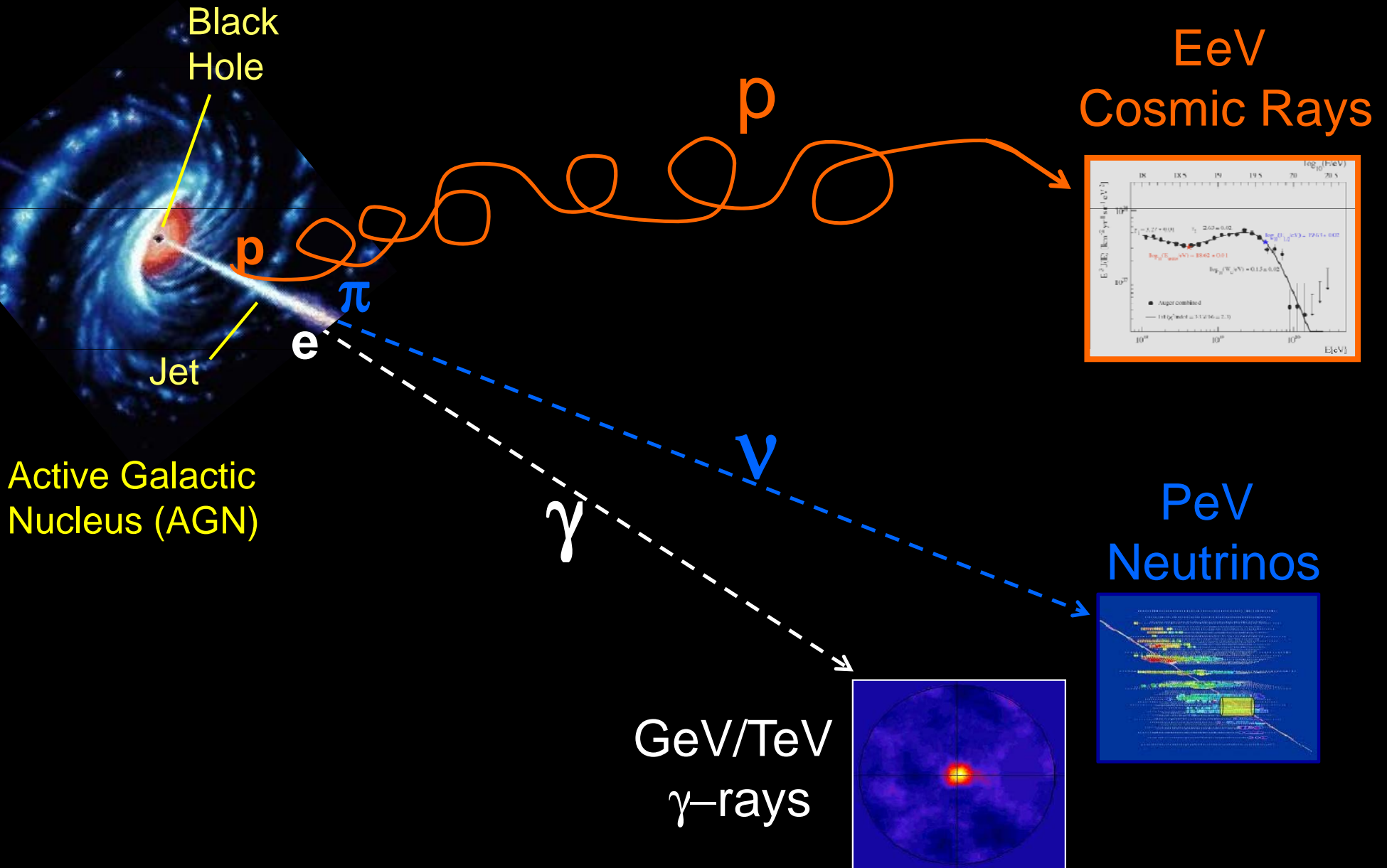


Outline

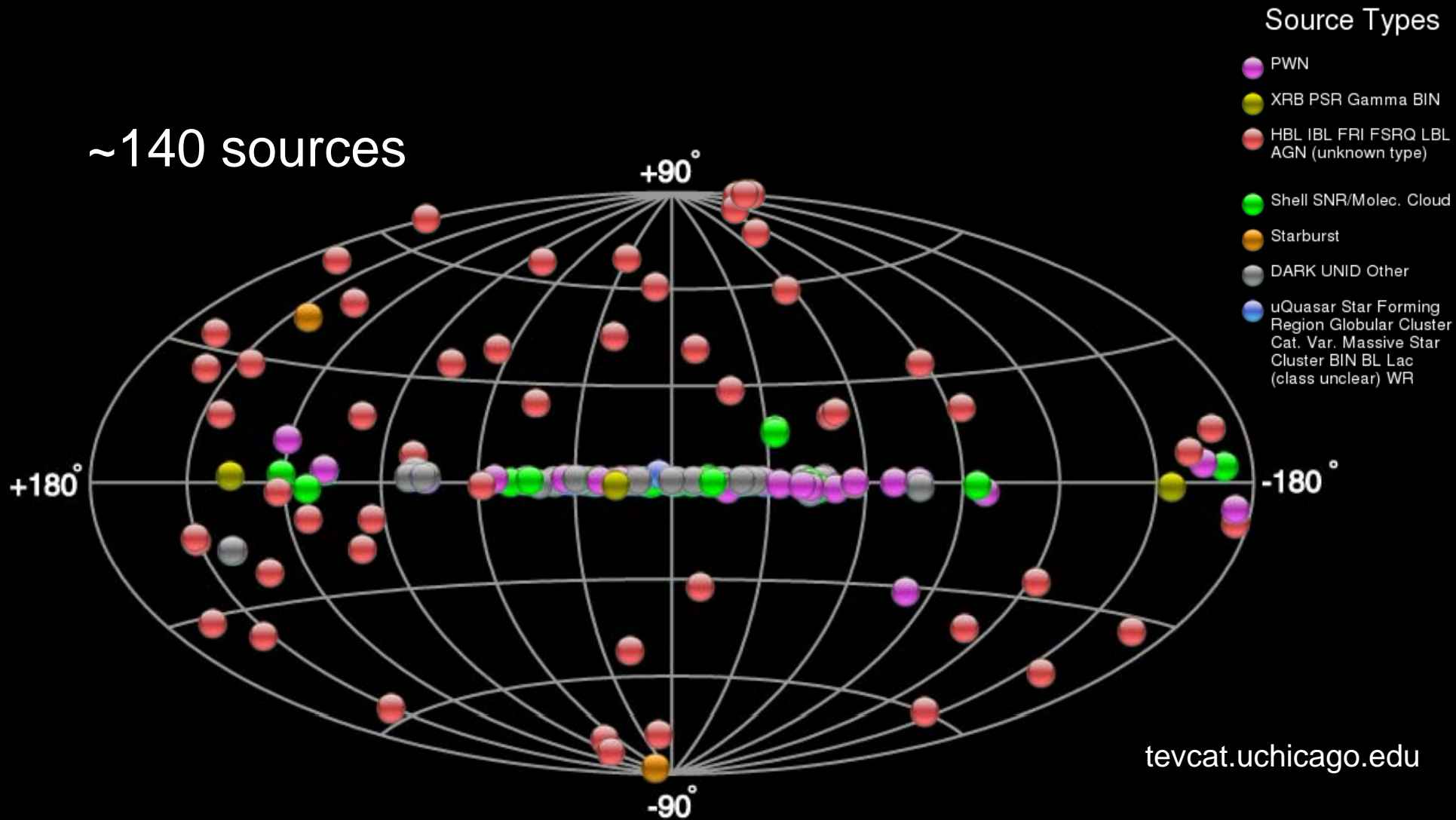
A. Very High Energy (VHE) Astrophysics

- VHE sources of γ -rays (and possibly neutrinos and CR's)

VHE Multi-Messenger Astrophysics

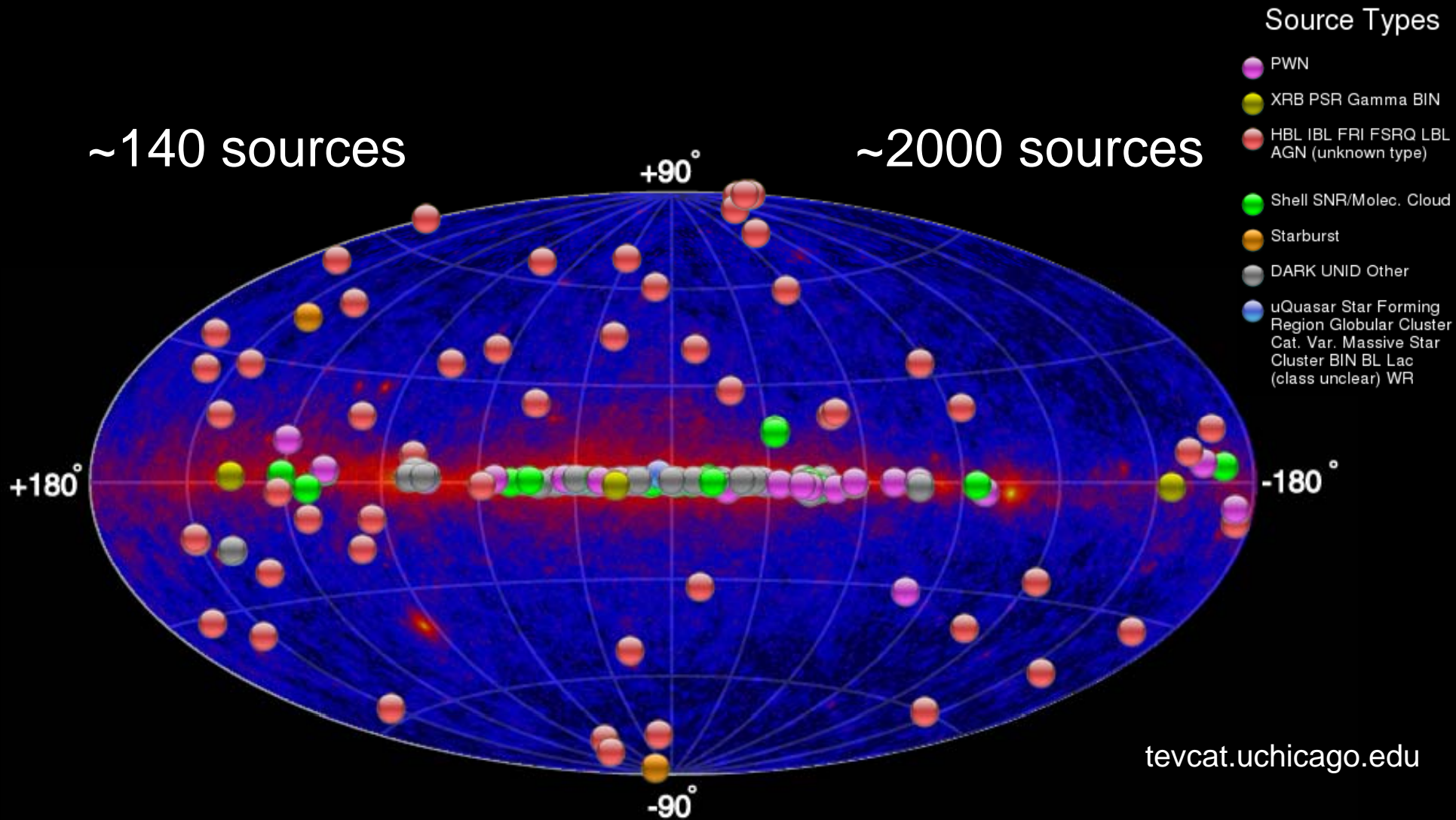


TeV γ -ray Sky c2013

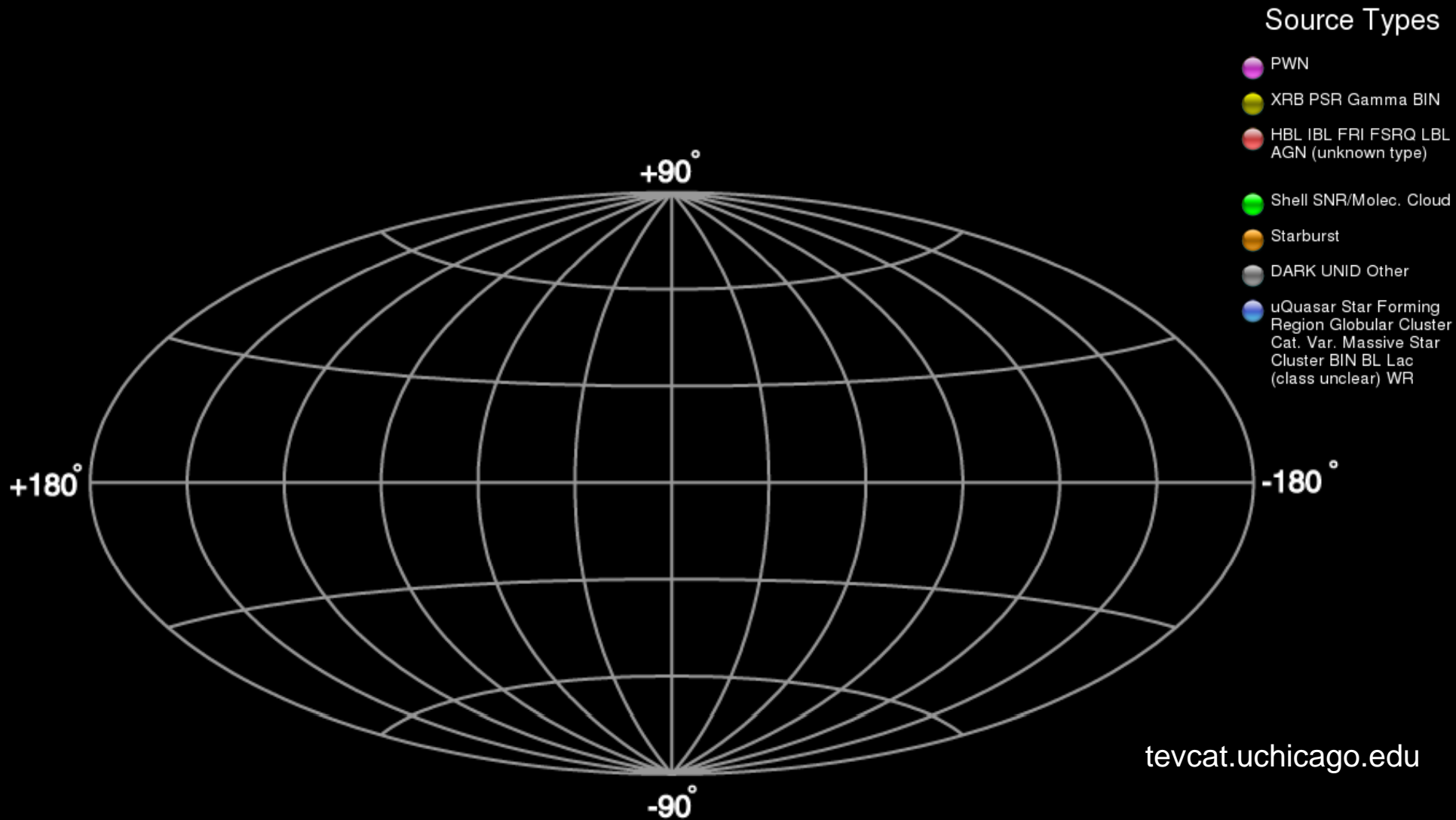


- Almost all discoveries made by atm. Cherenkov telescopes
- Detailed information from spectra, images, variability, MWL ...

VHE γ -ray Sky c2013 + HE γ -ray Sky



VHE/UHE ν Sky c2013

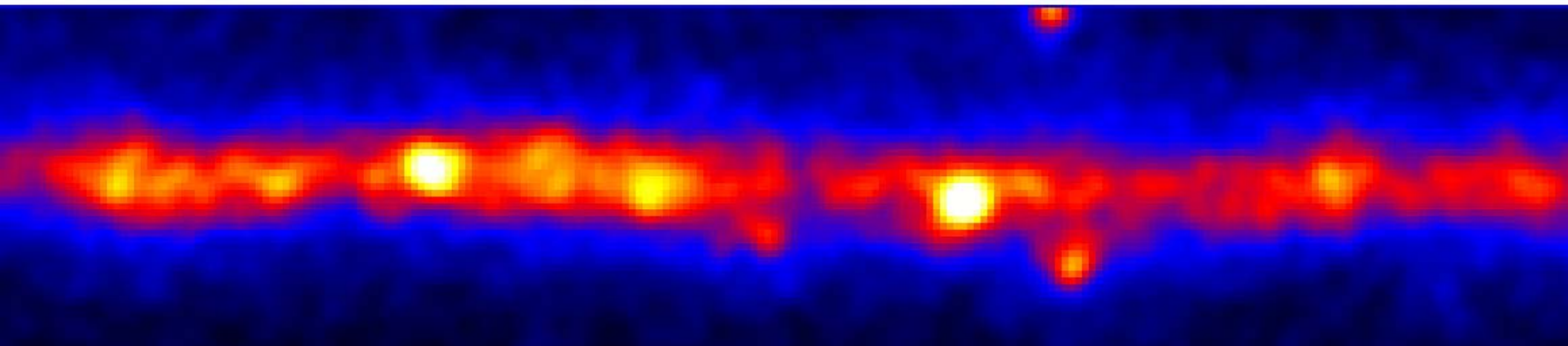
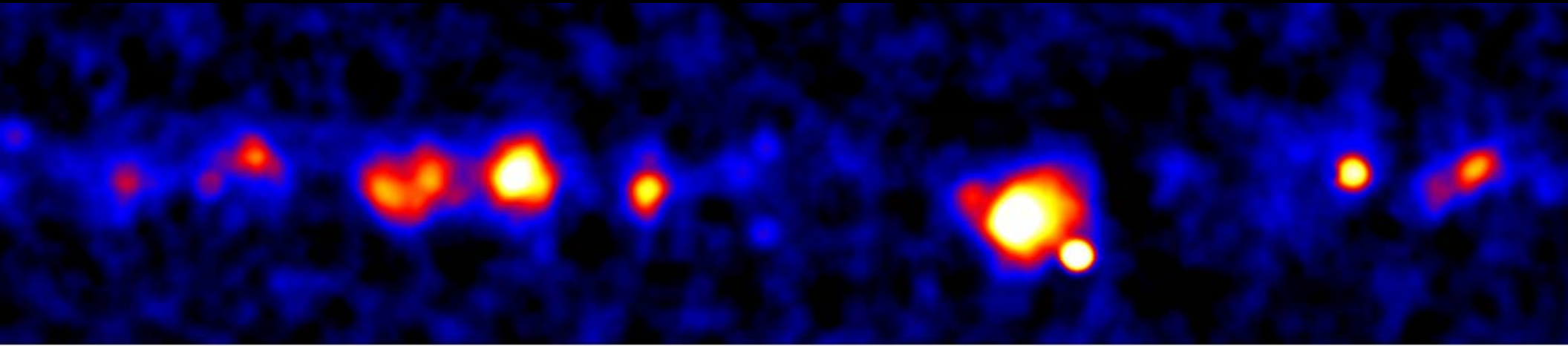


- Neutrino detections should be coming soon !

The High Energy Milky Way

Extended sources, size typically few 0.1°
few 10 pc

H.E.S.S. (TeV)



Fermi-LAT (GeV)

Courtesy of W. Hofmann

The Many Faces of TeV Particle Acceleration

Pulsars



NS dynamo

AGN



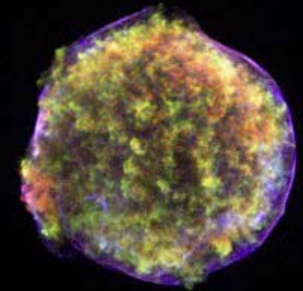
Jets powered by accretion or unipolar Induction. UHECR's ?

Star Forming Regions



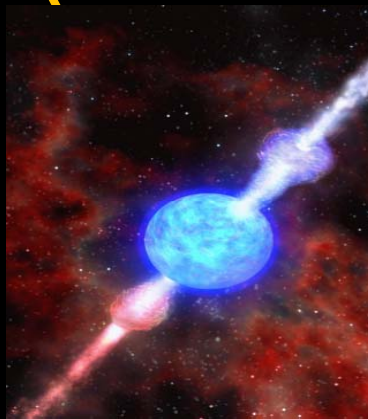
SNRs, cosmic rays, molecular clouds.

Supernova Remnants



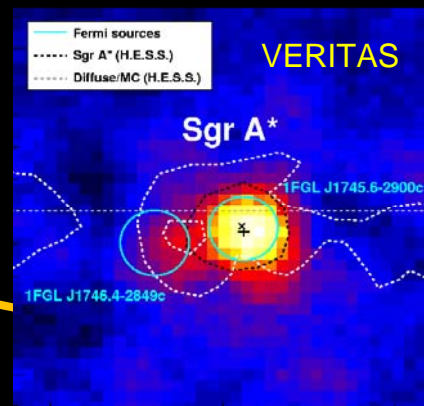
Fermi Acceleration

Gamma-Ray Bursts



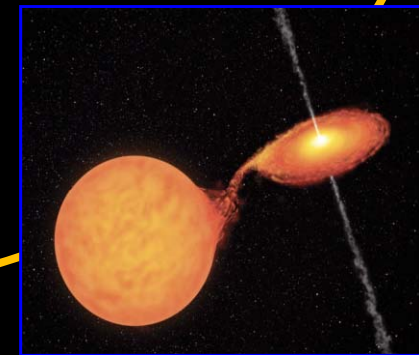
Star collapse → relativistic jets

Unidentifieds



???

Binary Systems



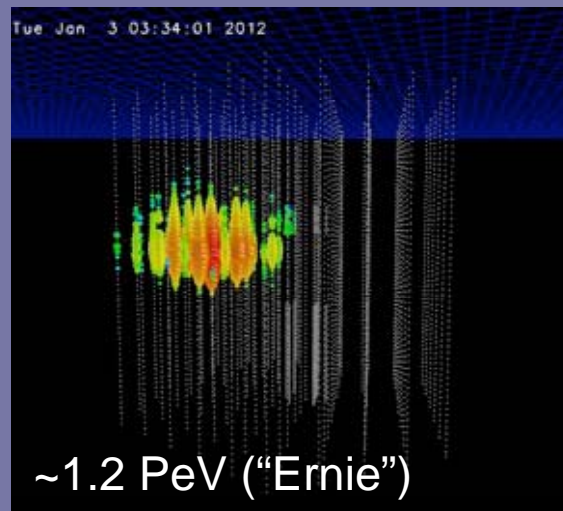
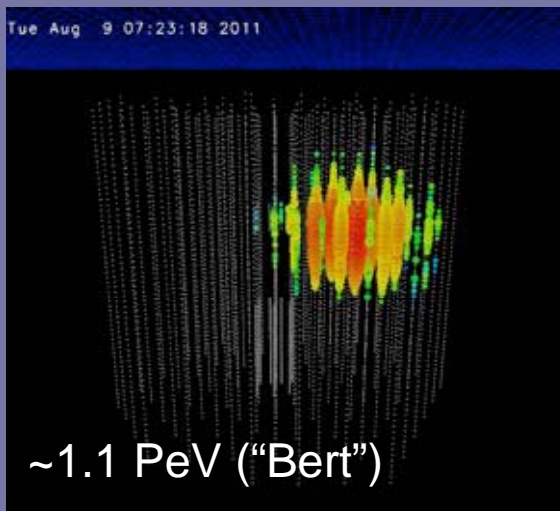
Accretion jets or stellar winds

Latest IceCube Results

Simple Search for Diffuse ν 's

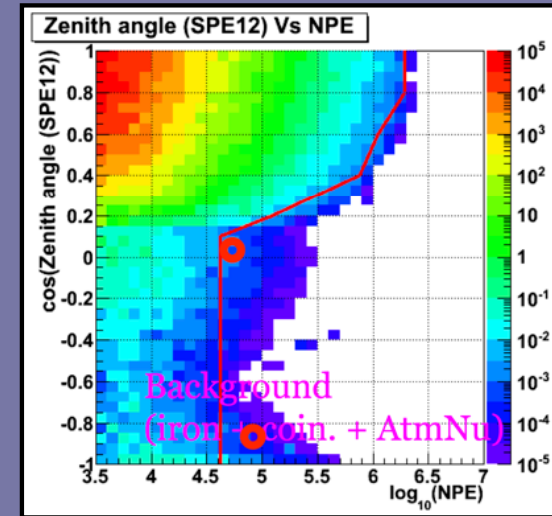
- Look at events all directions
- Look for upward ($E > 1$ PeV) and downward ($E > 100$ PeV) events

Find 2 events (0.08 exp. bkgnd)

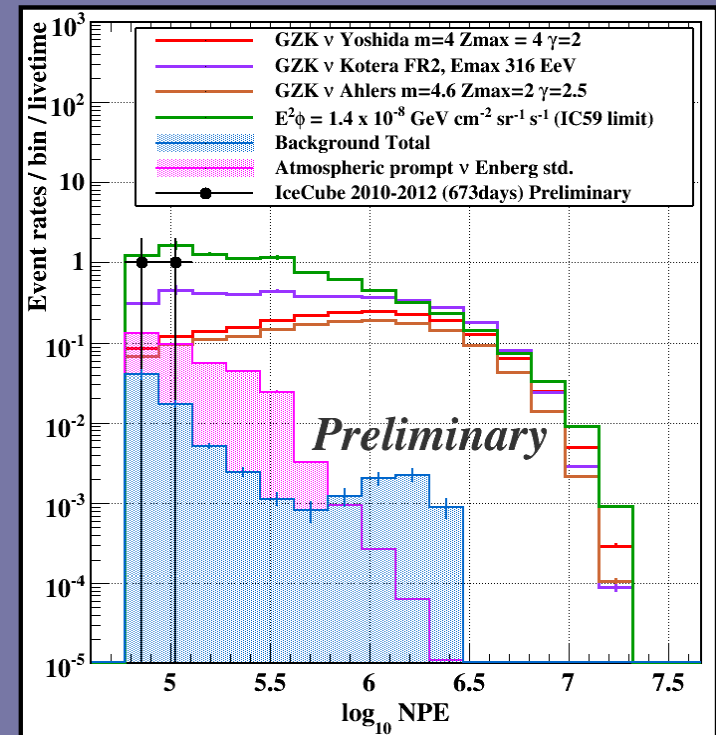


Not consistent with atm. background nor consistent with expected cosmogenic ν .

... perhaps the "tip of the iceberg" ?!



C. Kopper, LLWI 2013



Outline

B. AP Topics Connected to LHC

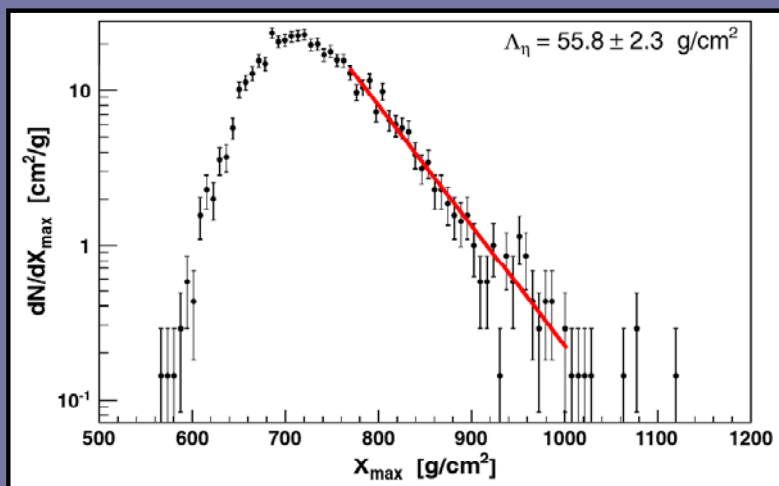
- Proton-Proton Cross Section at 70 TeV
- WIMP DM – Direct and Indirect Detection Results & LHC

P-P Cross-Section @ 60 TeV (Auger)

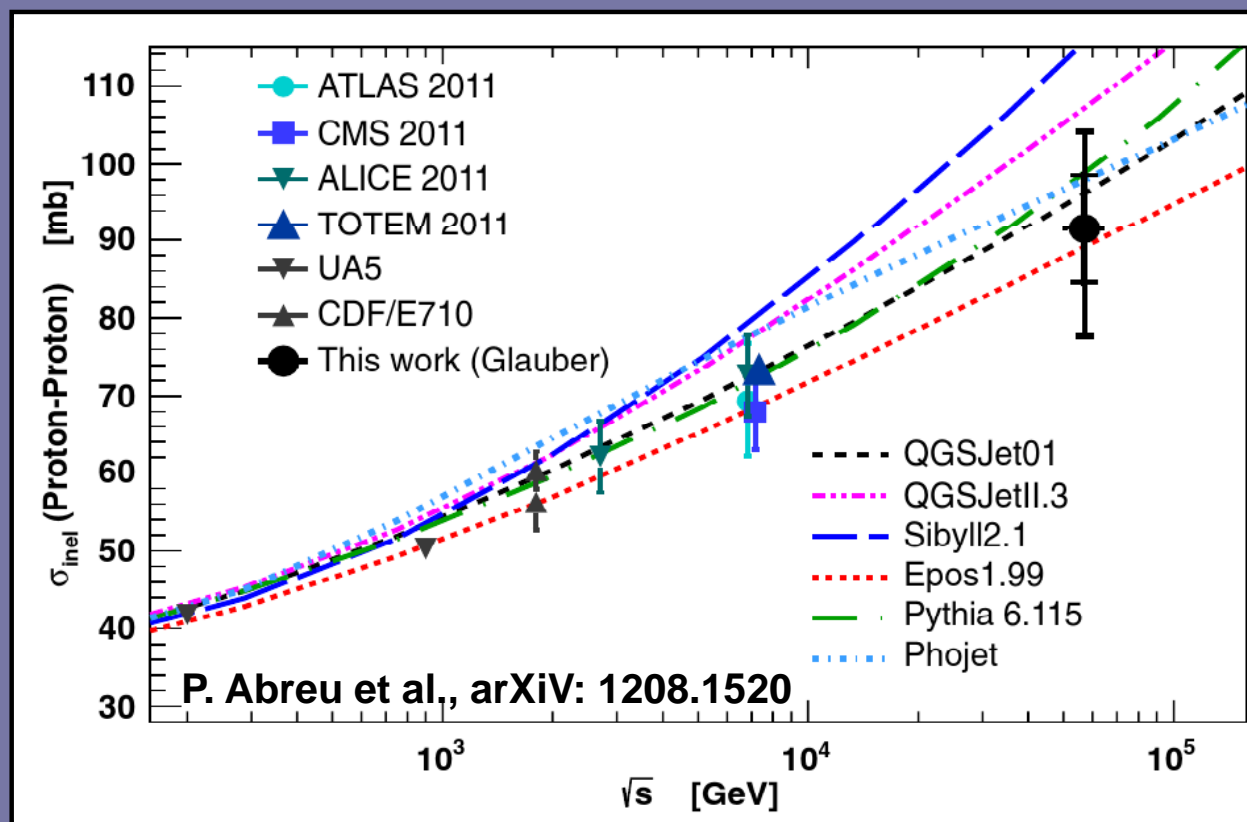
Auger measures p-air collisions at $E_{\text{lab}} \sim 10^{18}\text{-}10^{18.5}\text{eV}$

- Cross-section scales with dn/dx_{max} , where x_{max} = point of max shower development.
- Glauber formalism to infer pp cross-section.

$$\frac{dN}{dX_{\text{max}}} \propto \exp\left(\frac{X_{\text{max}}}{\Lambda_{\eta}}\right)$$



dn/dx_{max} distribution



Auger results consistent with smooth extrapolation from LHC.

Dark Matter

Postulated in the 1930's, dark matter (DM) remains one of the deepest mysteries of science.

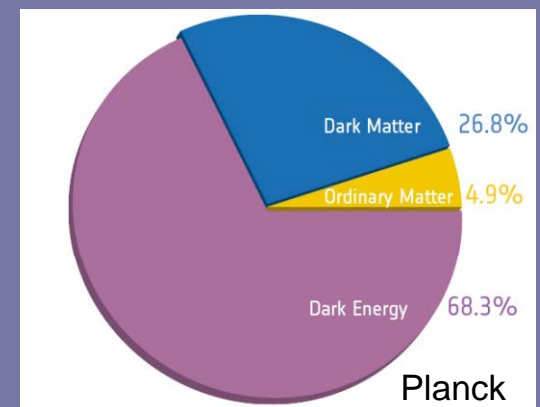
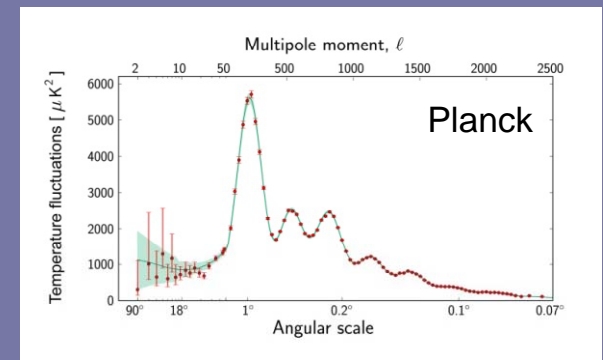
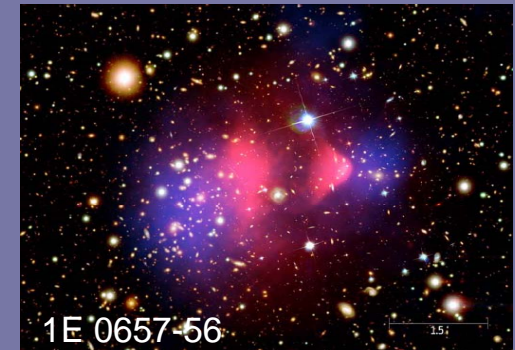
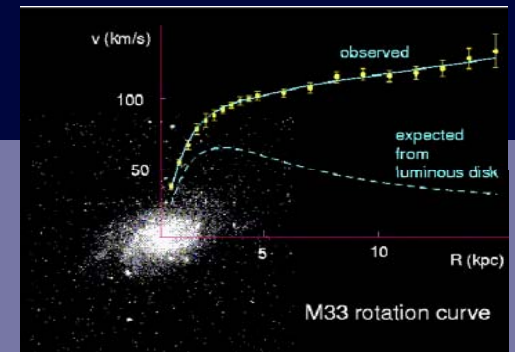
There is now overwhelming evidence for existence of DM.

What we do know:

Dark matter:

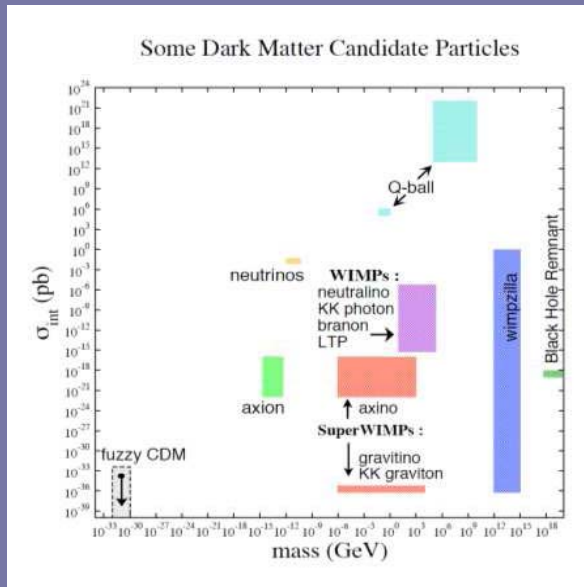
- is non-baryonic
- is non-relativistic (cold or warm)
- is stable on cosmological times
- has v. weak interaction with SM matter
- comprises ~85% of the matter in Universe

One of the clearest indications for physics beyond the standard model !

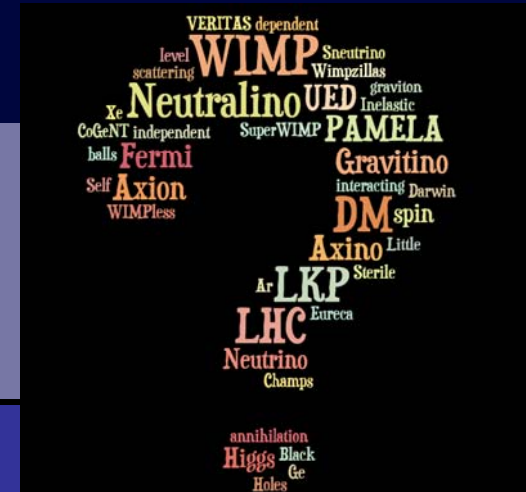


What is Dark Matter ?

We don't know ... many candidates !



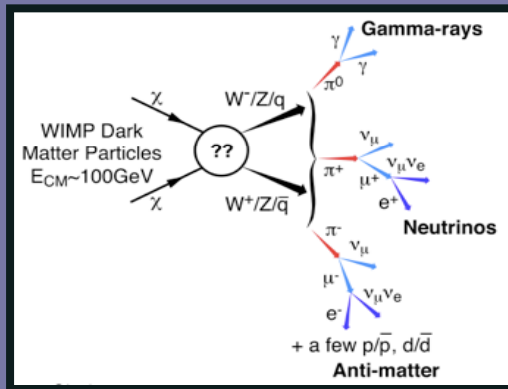
Candidate	Mass Range	“Bonus”
WIMP	1 – 10 ⁴ GeV	“WIMP miracle” (new physics ~WI scale)
Axion	1 μeV – 1 meV	Strong CP problem (PQ symmetry)
Sterile ν	various	Accel./reactor ν experiments
Many others	various	



Cold dark matter (CDM) is attractive and fits much of the astrophysical/cosmological data, but ...

1. CDM has well-known problems (e.g. missing satellites, cusps ...)
 - “warm” DM, “fuzzy” DM, self-interacting DM, ...
2. DM might consist of multiple constituents, i.e.
 - “Dark Sector”, such as asymmetric DM

WIMP DM Complementary Approaches

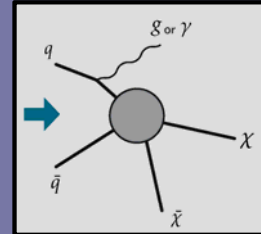
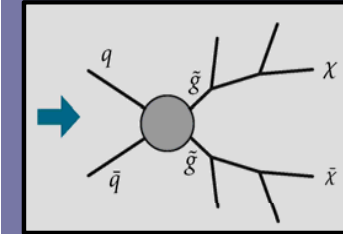
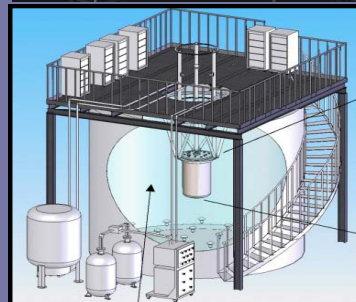
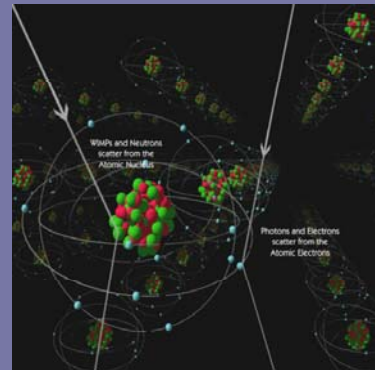
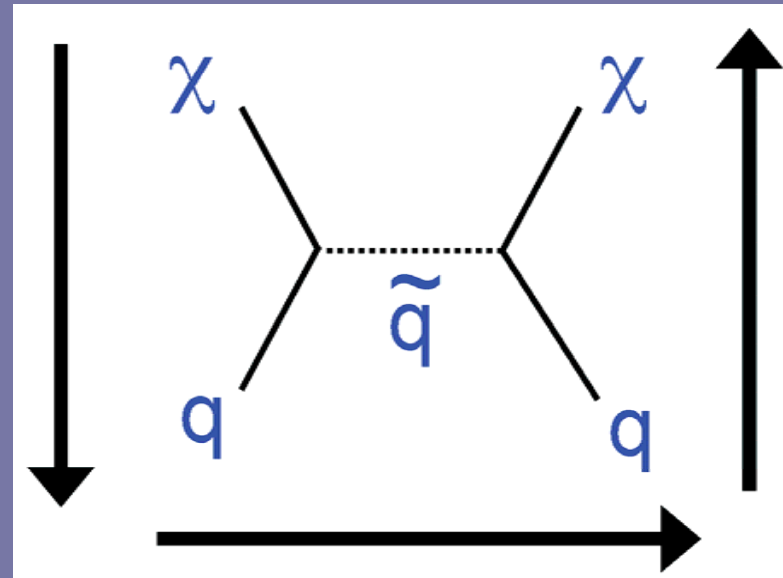


WIMP annihilation
 In the cosmos

Indirect Detection

WIMP-Nucleon
 Elastic scattering

Direct Detection



Heavy particle prod.
 MET + jets
 Weak pair prod.
 MET + monojet

LHC Production

WIMP Direct Detection

$$\text{Detection rate } R \propto N \frac{\sigma_{\chi N}}{m_{\chi}} \rho_{\chi} \int_{v_{\min}}^{v_{\text{esc}}} \frac{f(v) dv}{v}$$

Particle Physics **Astrophysics**

Particle Physics:

Elastic scattering of WIMPs off nuclei

- Spin-independent (coherent) $\sim A^2$
- Spin-dependent (target has net spin)

Astrophysics:

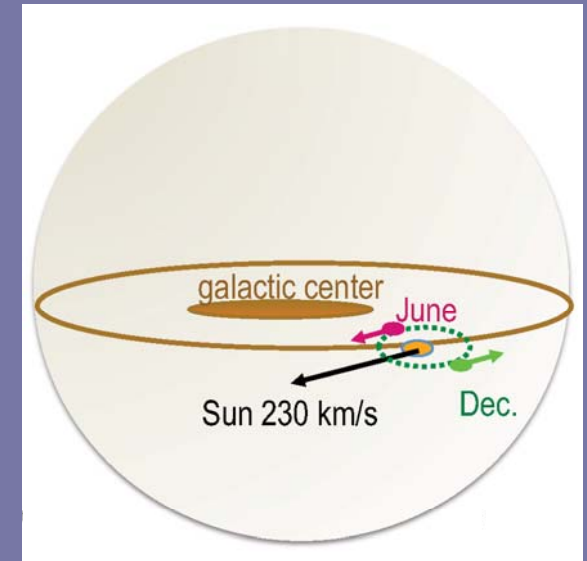
Isothermal, spherical halo with MB velocity dist,
 $f(v)dv$, for $v_0 \sim 230$ km/s and $\rho_{\chi} \sim 0.3$ GeV/cm³

Signals:

- Counting (eliminate SM interactions)
- Annual modulation
- Diurnal modulation

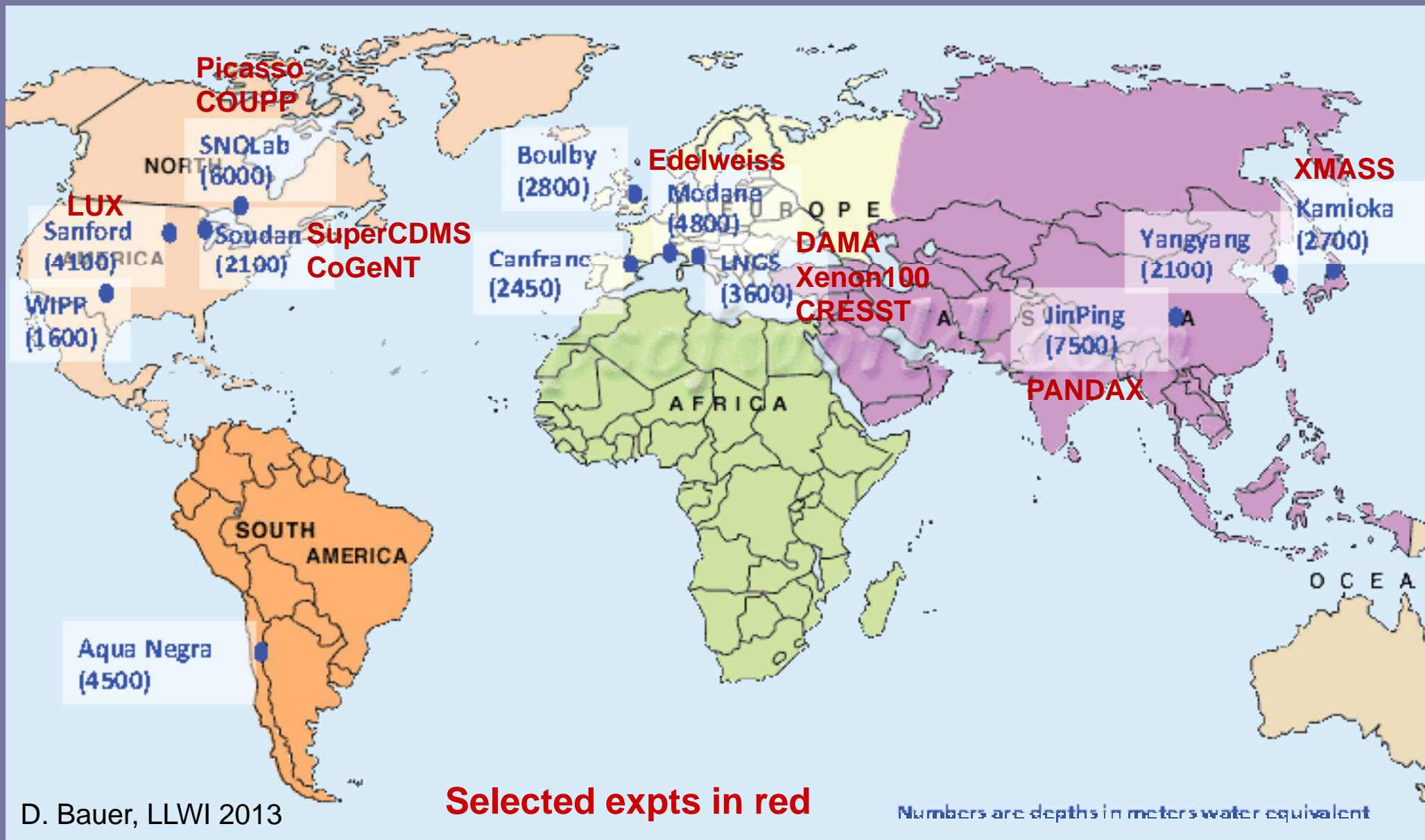
Challenges:

- Very low bkgnd required
- Low E threshold (<25 keV)
- Stable, large mass detectors



D. Bauer, LLWI 2013

Underground Labs & Some Expts



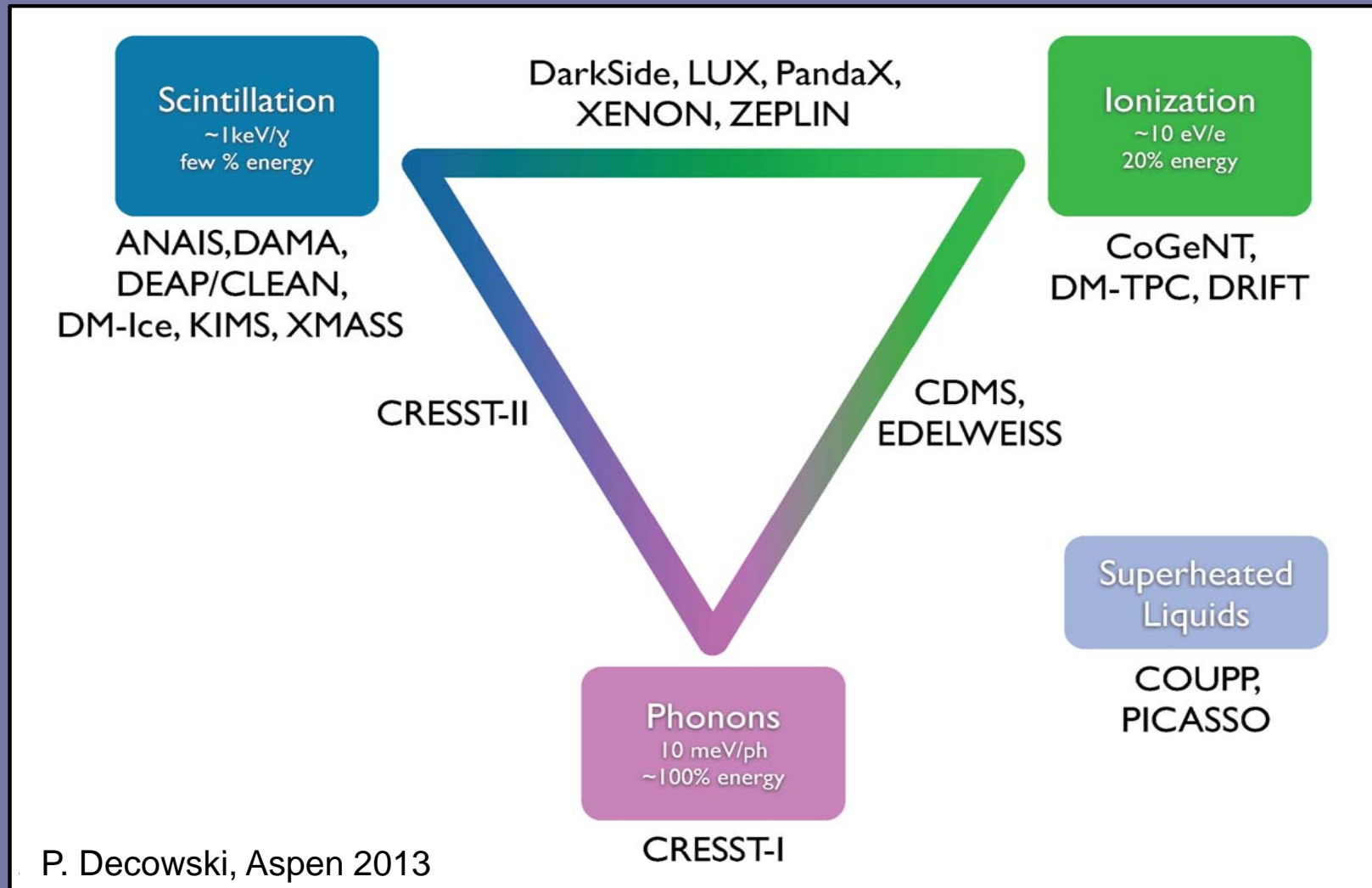
D. Bauer, LLWI 2013

Selected expts in red

Numbers are depths in meters water equivalent

There are ~20 operational (or soon to be operational) experiments !

Detection Techniques by Experiment

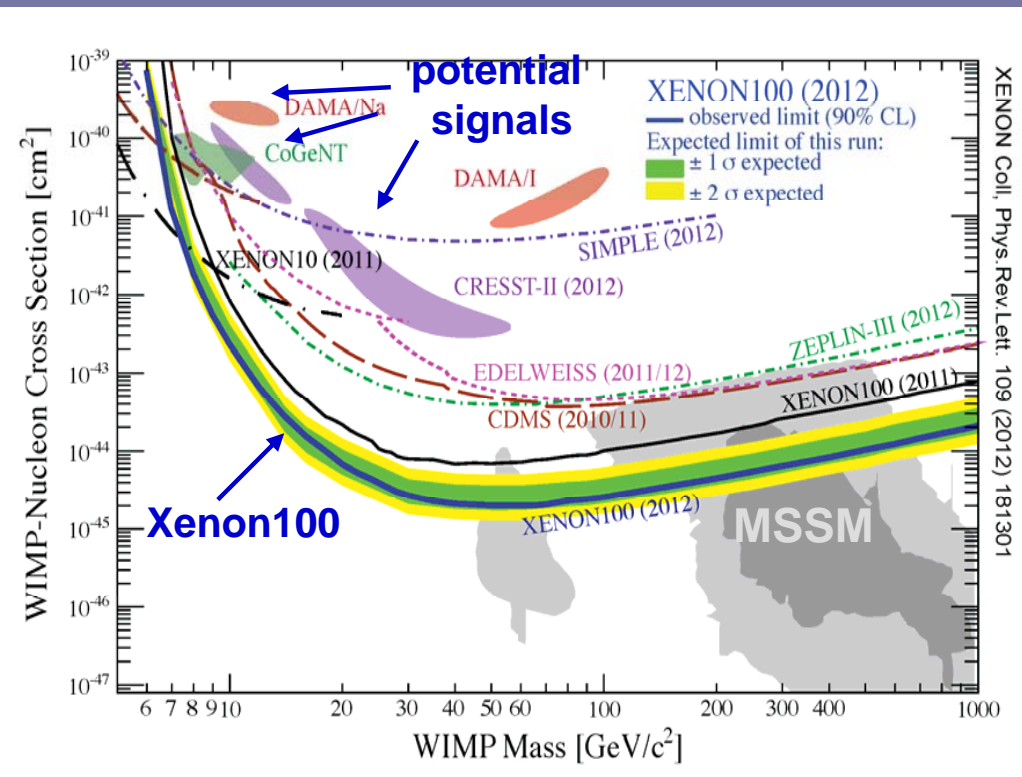


The use of two detection techniques allows for cleaner separation of nuclear recoils from background.

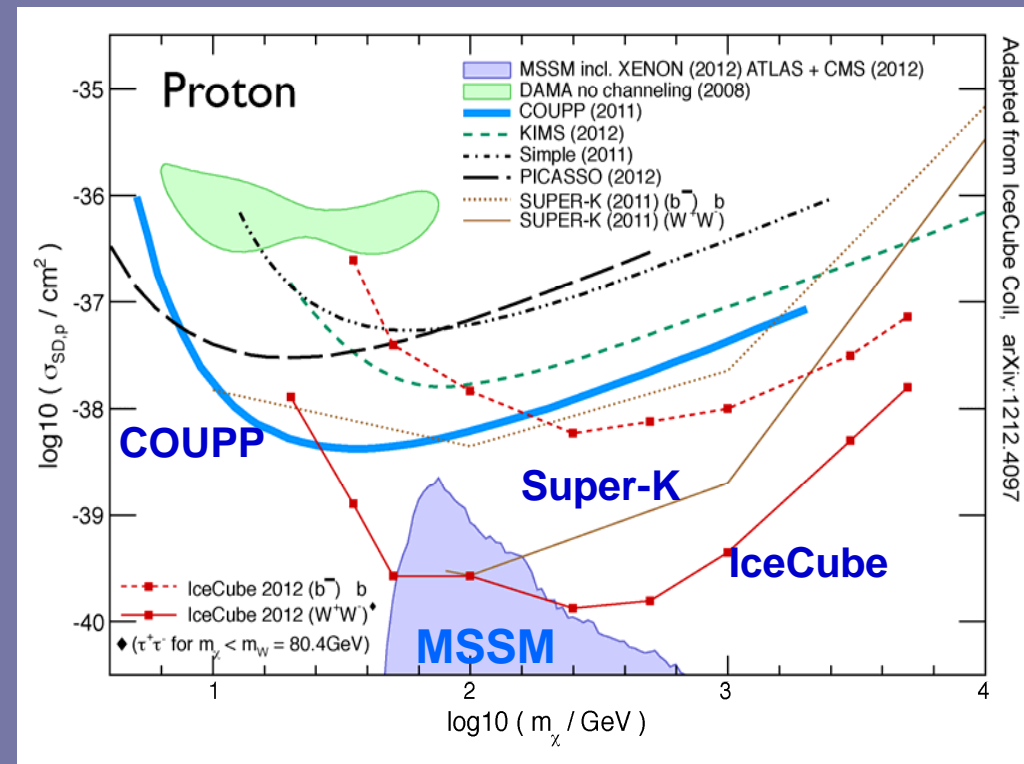
Also important is use of different targets – different A, properties.

WIMP Direct Detection Limits

Spin Independent



Spin Dependent



(Potential signals: DAMA/LIBRA, CRESST, CoGeNT – see backup slides)

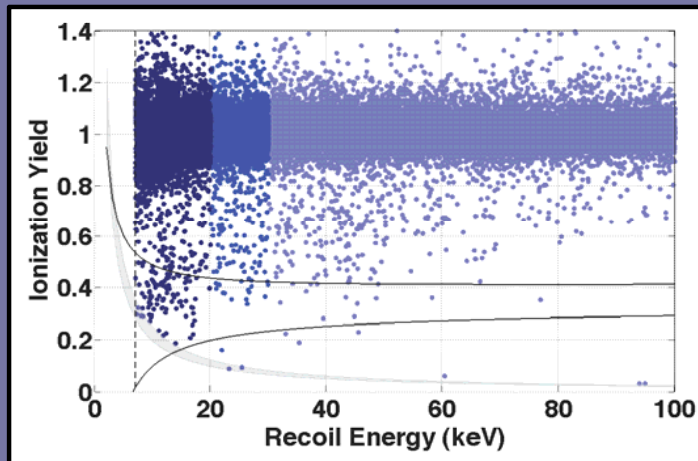
SuperCDMS Results (2013)

SuperCDMS

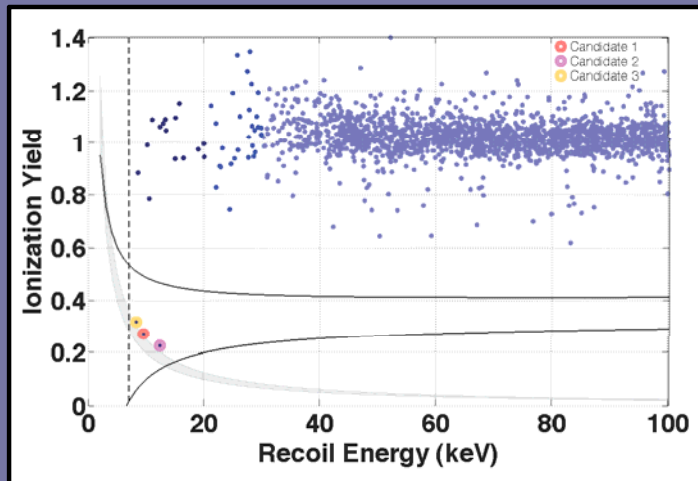
Si detectors, more sensitive below 15 GeV

Prob for 3 evts from bgnd $\sim 5.4\%$, but
Prob for measured energies $\sim 0.19\%$.

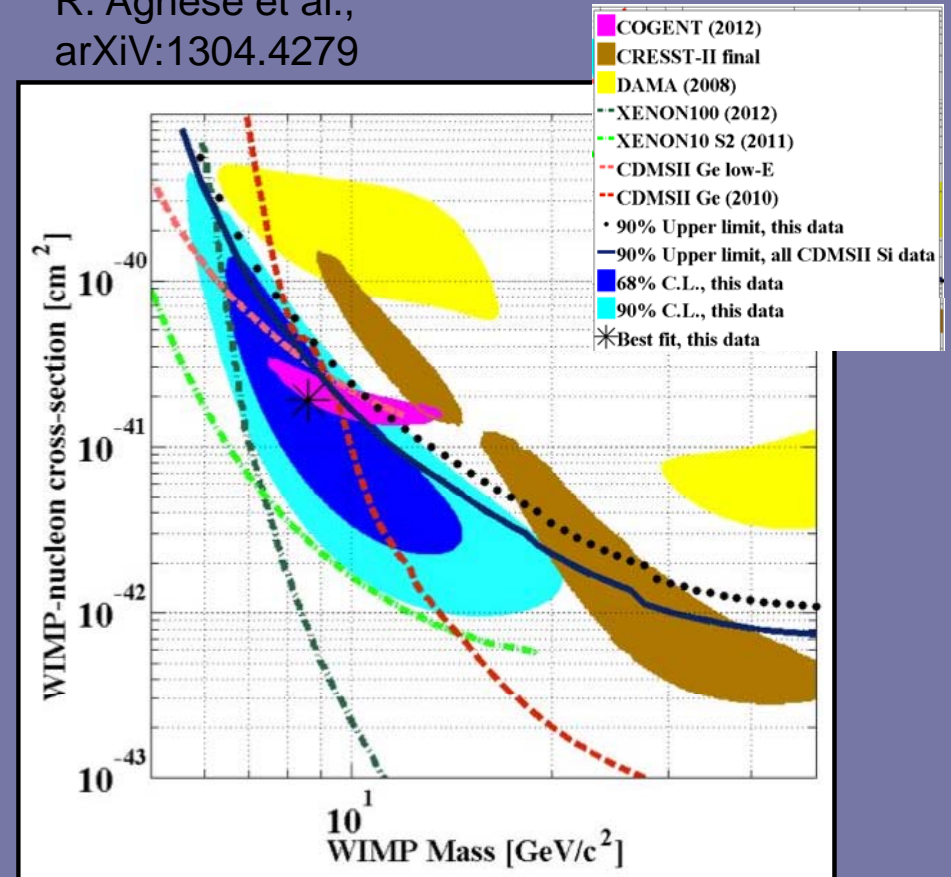
Before
timing cut



After
timing cut



R. Agnese et al.,
arXiv:1304.4279

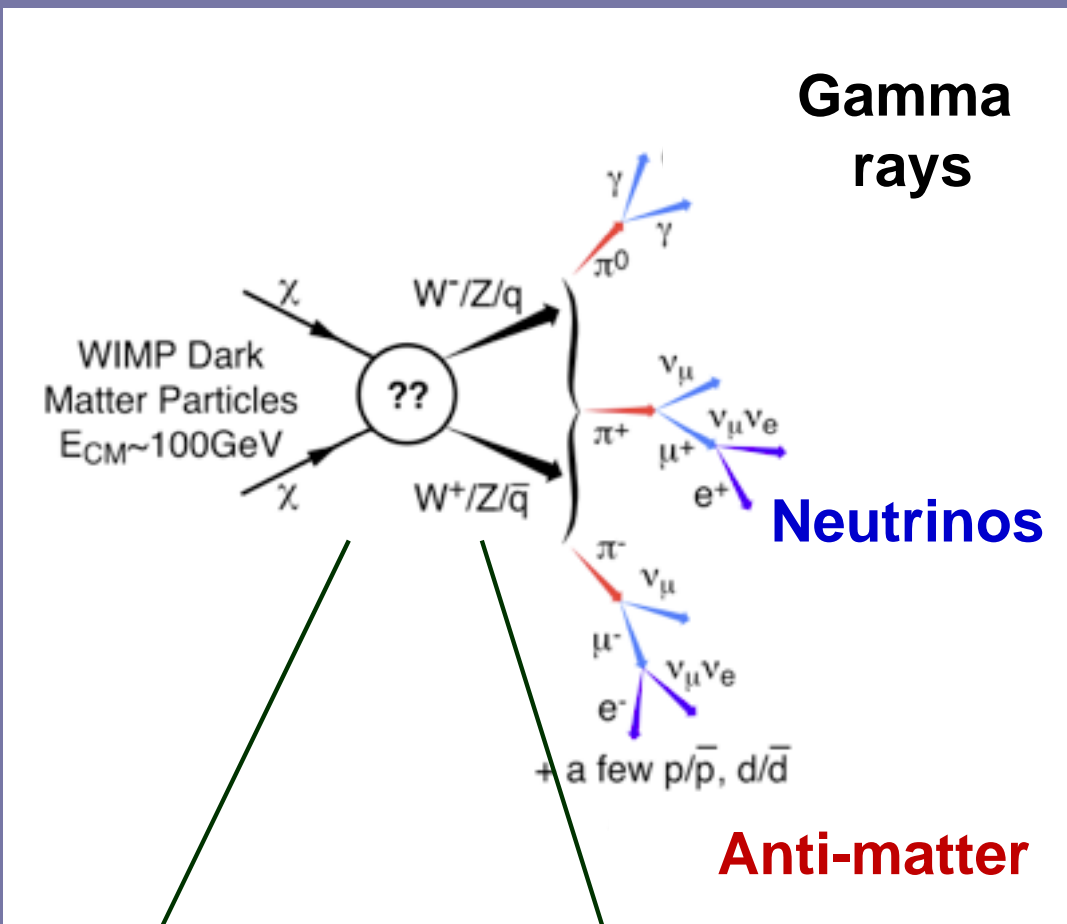


Max. likelihood @ $m = 8.6 \text{ GeV}$,
 $\sigma = 1.9 \times 10^{-41} \text{ cm}^2$

Not yet statistically significant.

WIMP Indirect Detection

WIMP Annihilation



Particle Physics
 (Uncertainty from m_χ , decay modes, etc.)

$\gamma\gamma$
 $Z\gamma$
 γ (cont.)

GeV Fermi, AGILE (Satellite)

TeV HESS, MAGIC VERITAS (Atm. Cherenkov)

ν
 from Sun

GeV-TeV IceCube, Antares Super-K (Ice/Water Cherenkov)

e^+, \bar{p}, \bar{d}
 in CR

GeV-TeV PAMELA, Fermi, AMS (Satellite)

WIMP Indirect Detection: γ -rays

- Gamma rays from DM annihilation:

particle physics

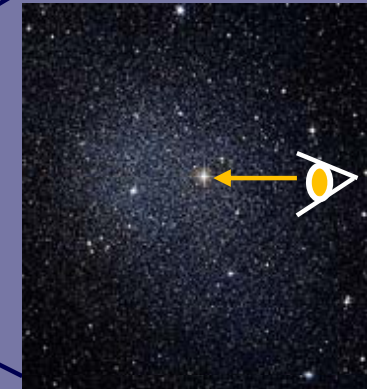
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi} \frac{\langle \sigma_{ann} v \rangle}{2m_{WIMP}^2} \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f$$

$$\times \int_{\Delta\Omega(\phi, \theta)} d\Omega' \int_{los} \rho^2(r(l, \phi')) dl(r, \phi')$$

DM distribution

DM distribution

Line-of-sight Integral
(Uncertainty from unknown DM profile)



Where to look:

The Galactic Center

- Brightest spot in the sky
- Considerable astrophysical backgrounds

The Galactic Halo

- High statistics
- Requires detailed model of galactic backgrounds

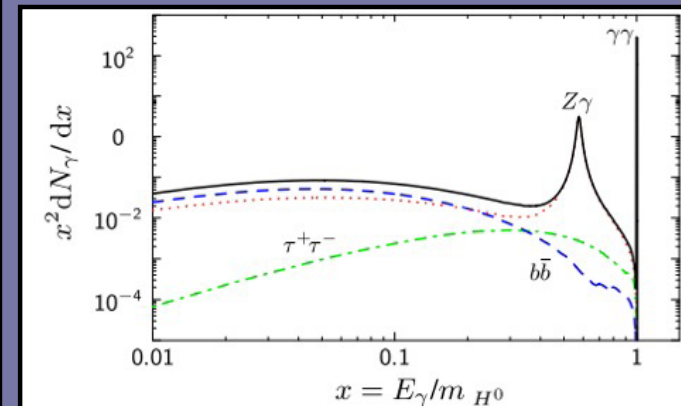
Isotropic Background

- High statistics
- potentially difficult to identify

Dwarf Galaxies

- Less signal
- Low backgrounds

What to look for:

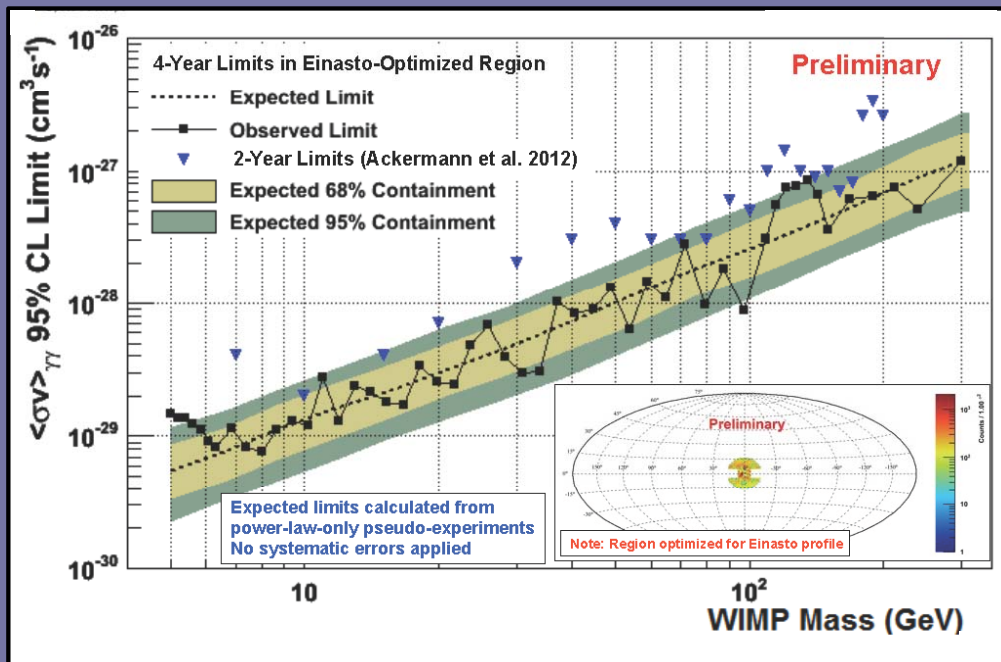


D. Hooper,
Aspen 2013

WIMP Limits: γ -rays

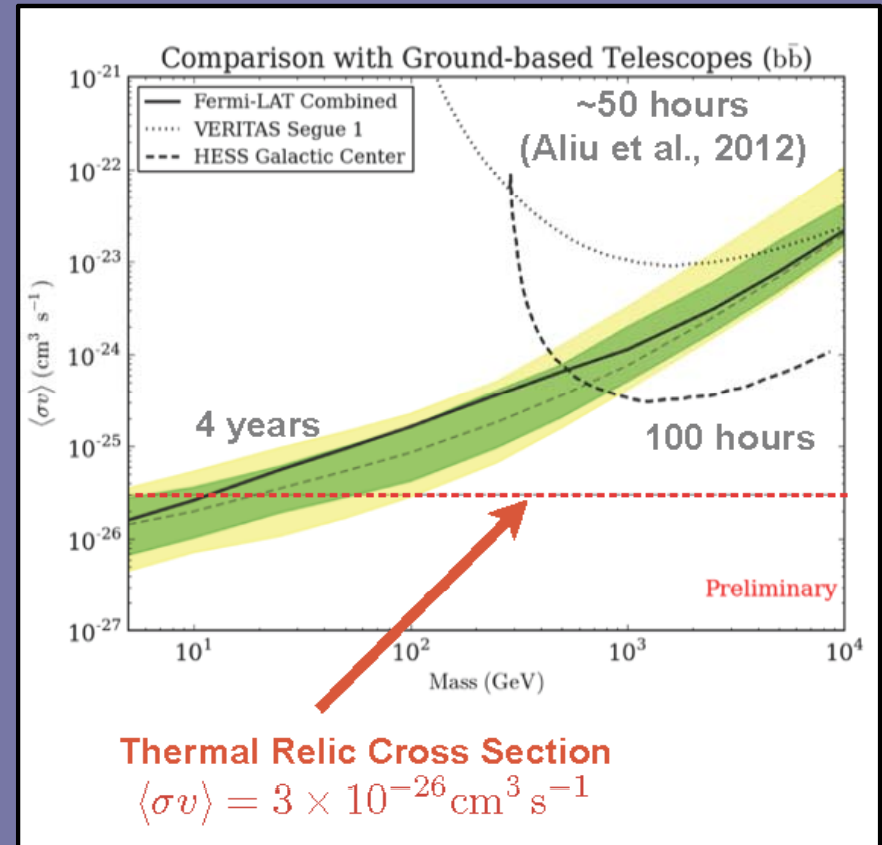
Fermi

$\gamma\gamma$ line limits



A. Drlica-Wagner, APS 2013

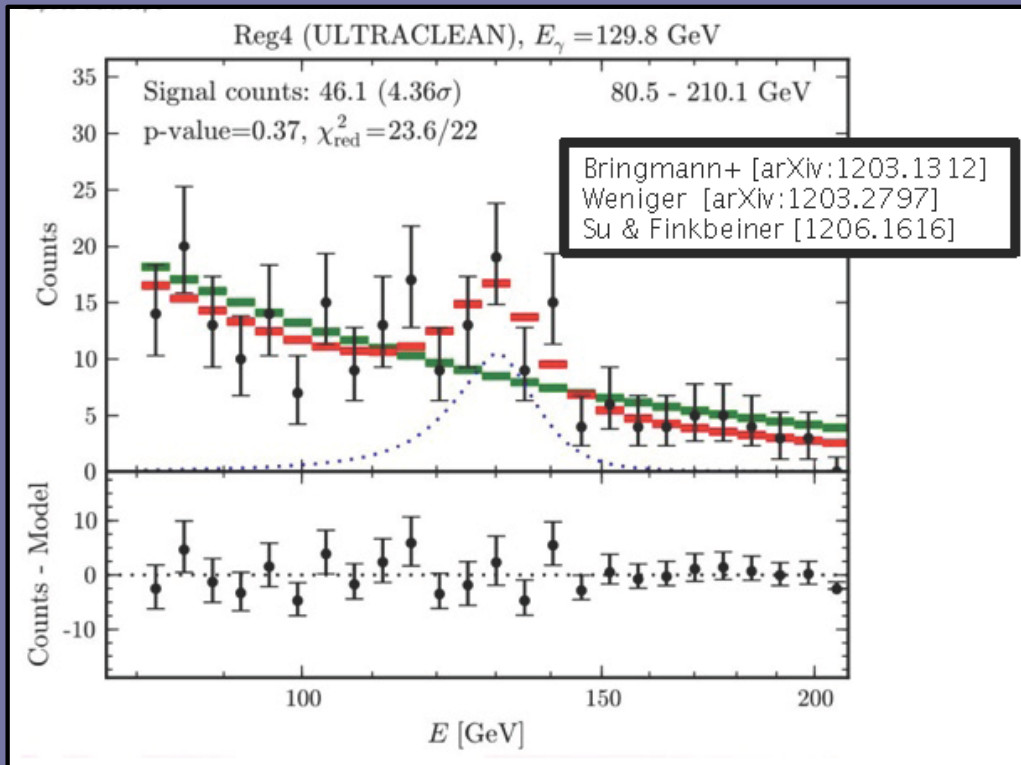
Fermi, HESS, VERITAS
Gal. center, dwarf galaxies



No evidence for a signal in gamma rays,
for standard thermal WIMP $m > 10$ GeV. But ...

130 GeV WIMP Line in Fermi Data ?

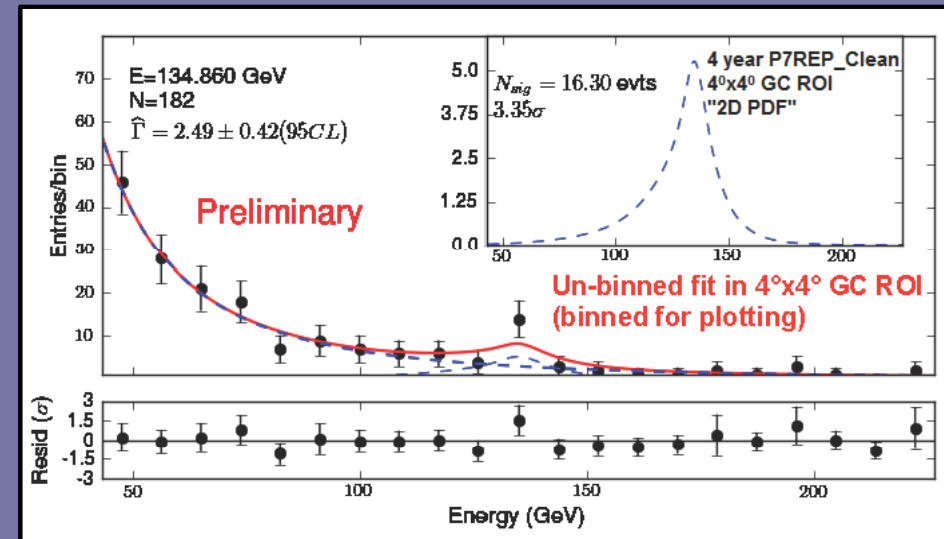
Line evidence:



Analysis done using public data & tools

- Feature near 130 GeV
- Near to (but displaced from) the Galactic center
- 4.6σ (local), 3.2σ (global)

However:



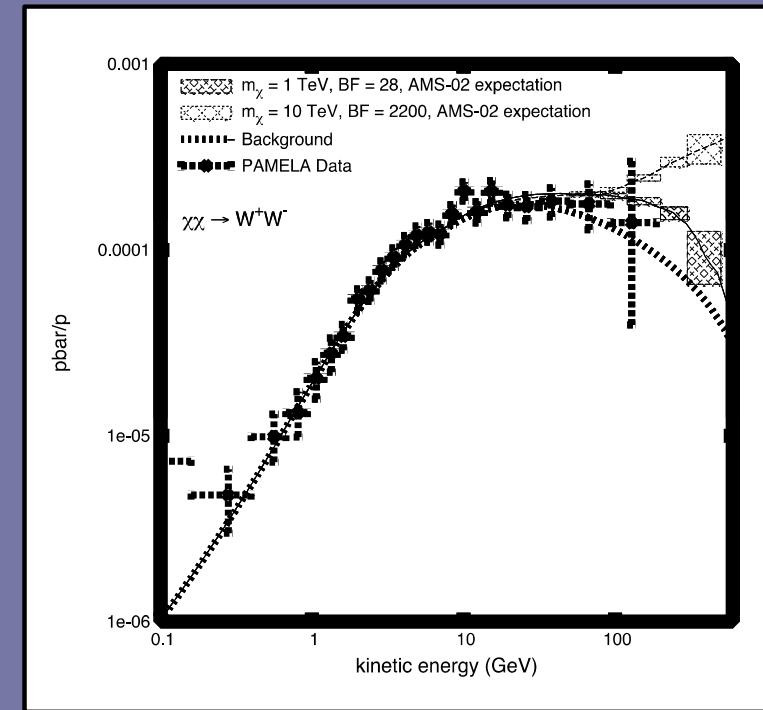
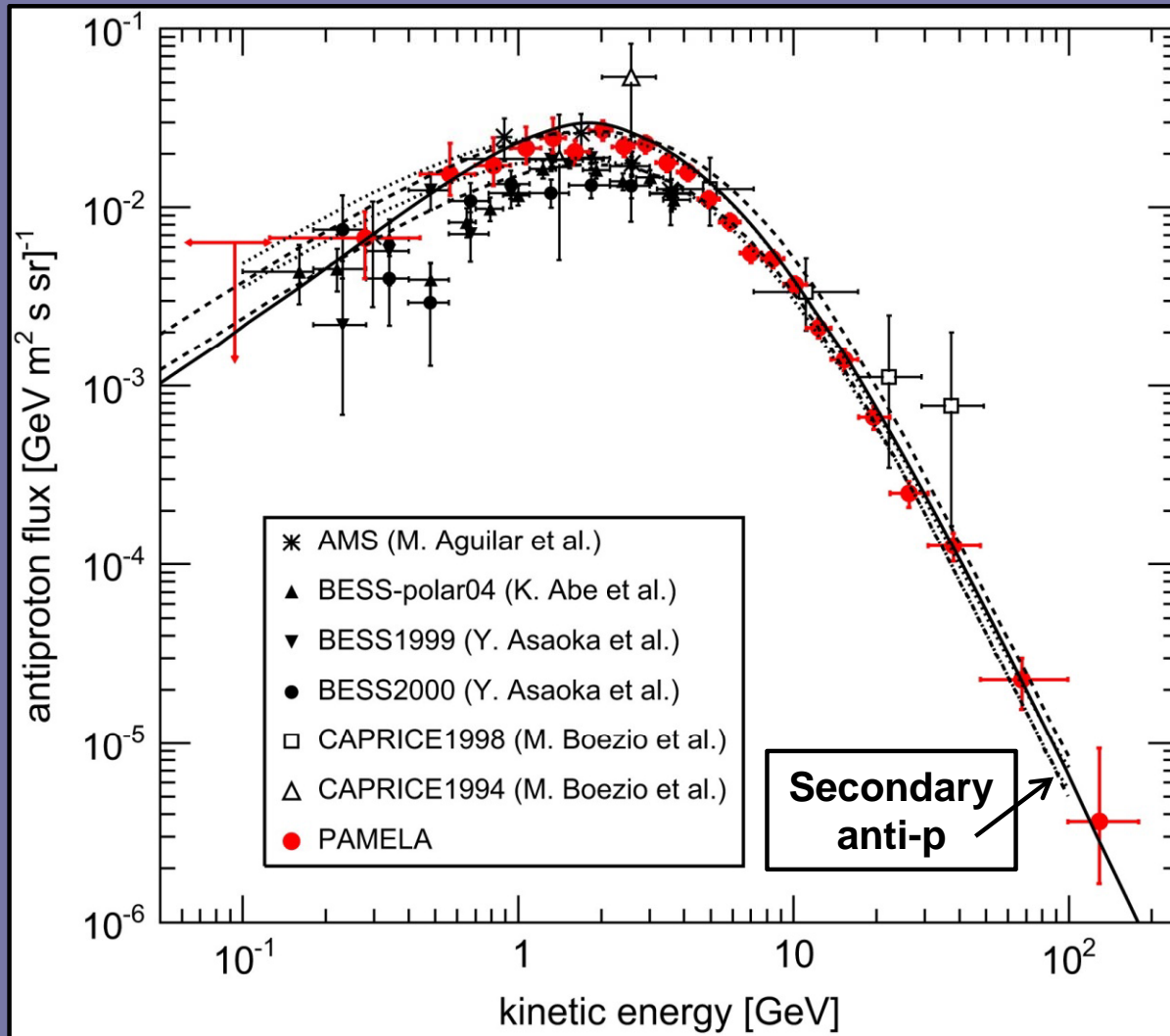
A. Drlica-Wagner, APS 2013

Analysis done by Fermi-LAT team:

- Re-processed data, includes better calibration, reconstruction
- $3.4\text{-}3.7\sigma$ (local), $\sim 2\sigma$ (global)
- "Peak" seen in Earth limb data, largely at incident $\cos(\theta) \sim 0.7$.

Systematic Effect ?

Anti-Protons



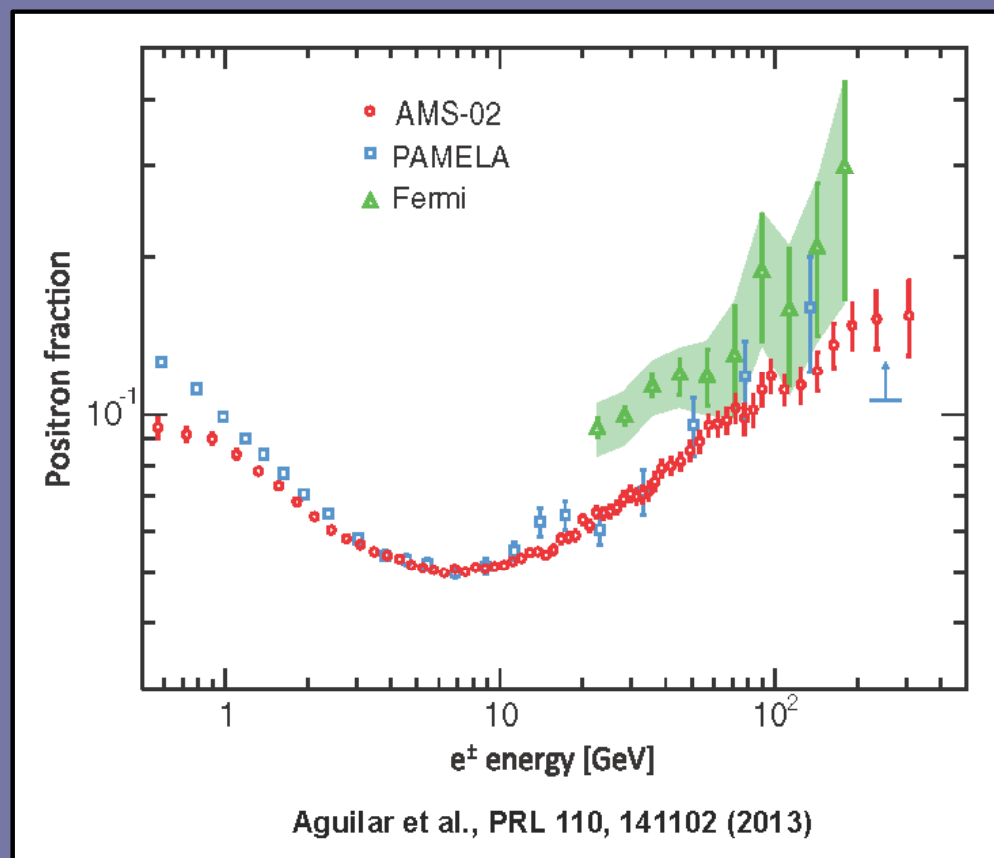
Future AMS-02 sensitivity
(note: $\text{p-bar}/\text{p}$ is plotted)

O. Adriani et al., PRL 105, 121101 (2010)

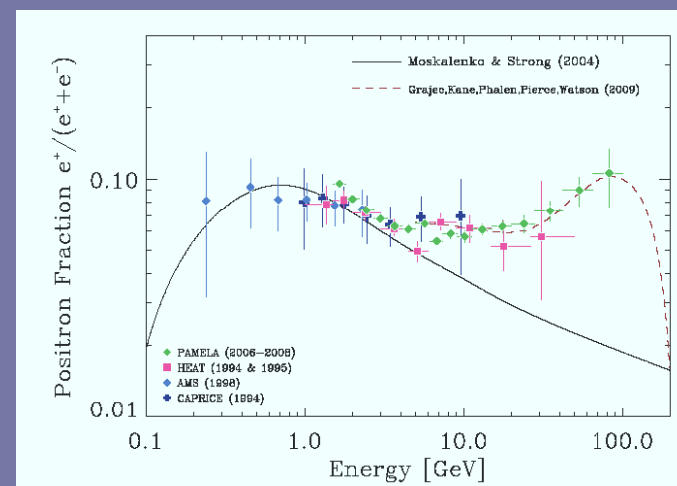
No evidence in anti-protons

But ... what about Positrons ?

Clear rise in e^+ fraction at high E :
(including very recent results from AMS-02)



But, astrophysical sources possible:



Local pulsar

(Yuskel, Kistler, & Stanev,
PRL **103**, 051101 (2009)).

But ... “leptophilic” models largely ruled out by γ -ray and ν results
(see backup slides). Anti-deuteron signal would be much more
compelling.

WIMP Detection Summary

Trying to make sense of all the results:

Technique	Experiment(s) with “Signal”	Features	Difficulties with DM hypothesis
Direct Detection Spin-independent	DAMA, CRESST, CoGeNT	Low E Annual modulation	Possible unknown bkgnds & large modulation; seemingly ruled out by Xenon100, Super-CDMS.
Direct Detection Spin-independent	Super-CDMS	Low E Si detectors only	Near threshold, not significant yet.
Direct Detection Spin-dependent	No Signal		
γ -rays Dwarf galaxies	No Signal		
γ -rays Galactic center	Fermi-LAT	Line near 130 GeV	Hard to account for strength of line signal; possible systematic? Not very significant.
Anti-Protons	No Signal		
Positrons	PAMELA, Fermi, AMS	Rising e+ fraction above 10 GeV	Requires “leptophilic” models and large σ . Possible astrophysical source(s). DM hypothesis ruled out by γ -ray, ν results.
Neutrinos Sun	No Signal		

Plus, more results not listed here !

WIMP Detection Summary

Trying to make sense of all the results:

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γ -rays Dwarf galaxies	No Signal		
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Anti-Protons	No Signal		
Positrons	PAMELA, Fermi, AMS	Rising e+ fraction above 10 GeV	Requires "leptophilic" models and large σ . Possible astrophysical source(s). DM hypothesis ruled out by γ -ray, ν results.
Neutrinos Sun	No Signal		

No Clear Indications for DM

Plus, more results not listed here !

WIMP Comparisons to LHC

Making comparisons between:

- Direct detection results
- Indirect detection results
- LHC results

is, of course, non-trivial; no generic prescriptions and many DOF.

Two general approaches:

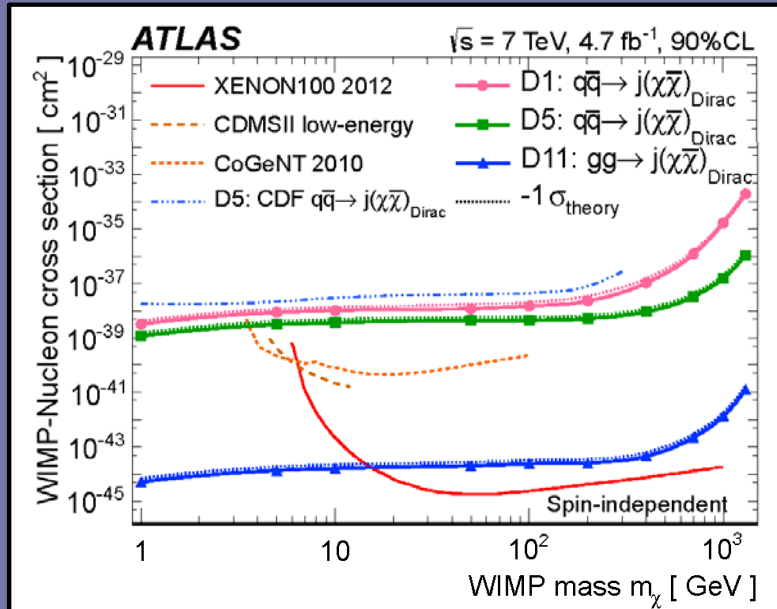
1. Compare in context of specific models (e.g. MSSM)
2. Compare using generalized models (e.g. effective field theory models)

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D

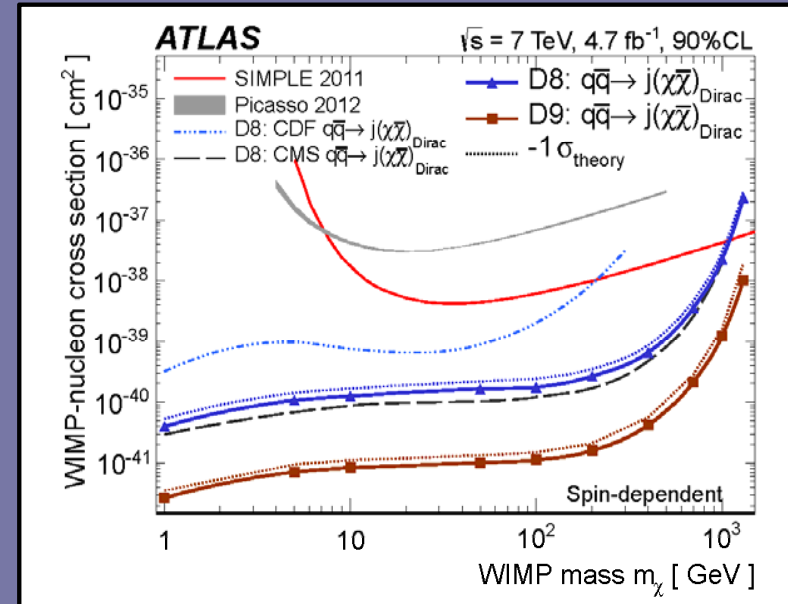
Operators for Dirac WIMP

Some LHC Results and Comparisons

σ_{scatt} spin-ind

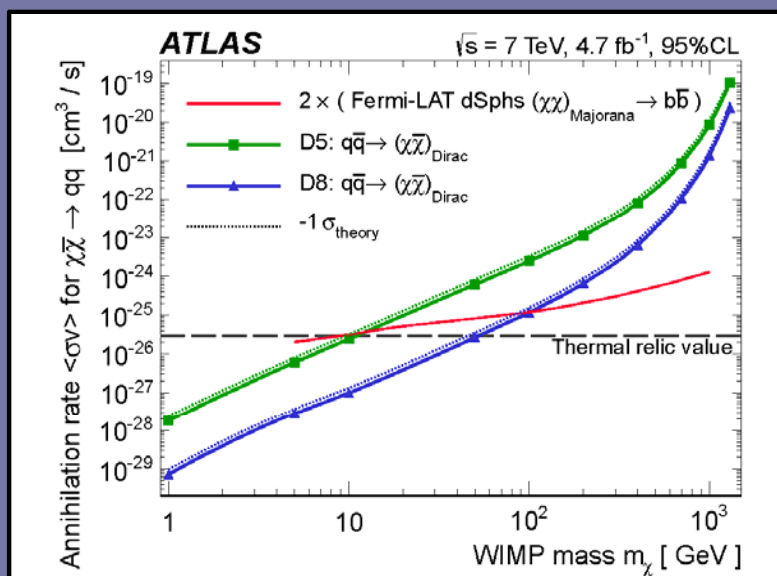


σ_{scatt} spin-dep



ATLAS Collab., arXiv: 1210:4491v2.

$\langle \sigma_{\text{anh}} v \rangle$

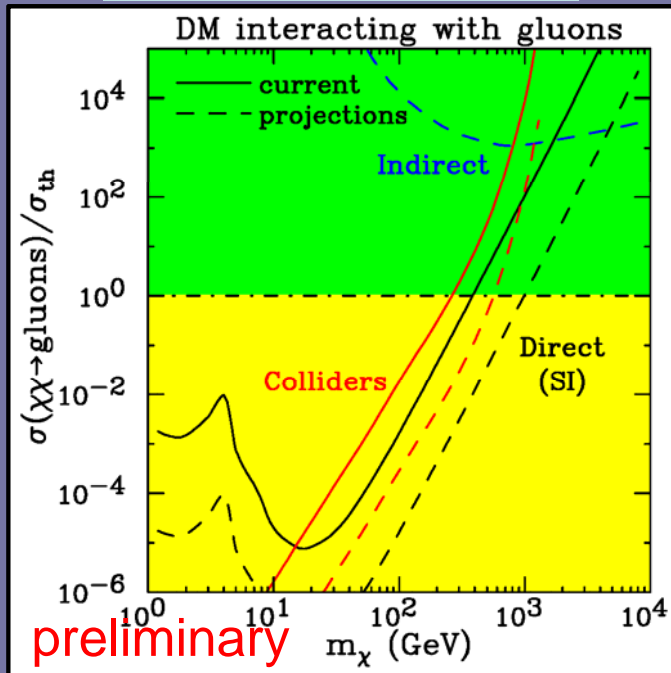


- For some operators, LHC limits are quite constraining for $m_\chi < 100 \text{ GeV}$.
- For others, direct or indirect detectors are more constraining.
- Similar results for CMS (see CMS PAS EXO-12-048, <http://cds.cern.ch/record/1525585>)

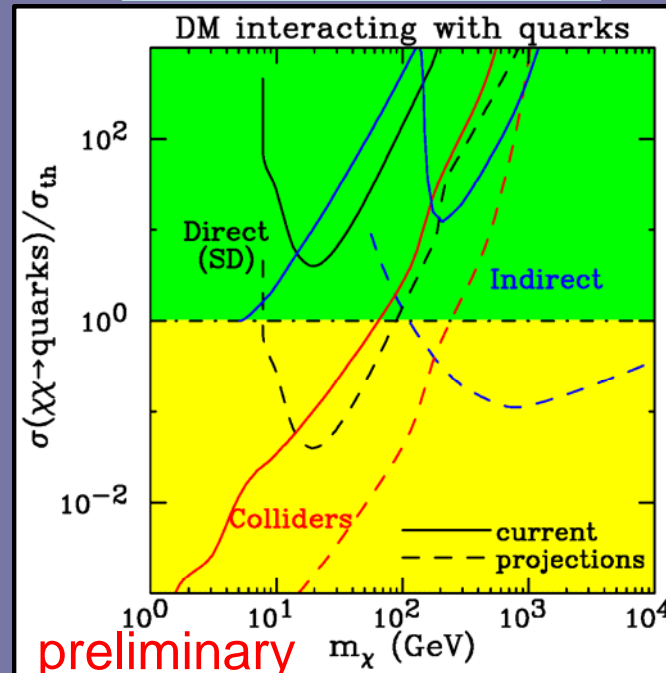
WIMPs: a More General Framework

D. Bauer et al., “Dark Matter in the Coming Decade: Complementary Paths to Discovery and Beyond,” White Paper for Snowmass 2013.

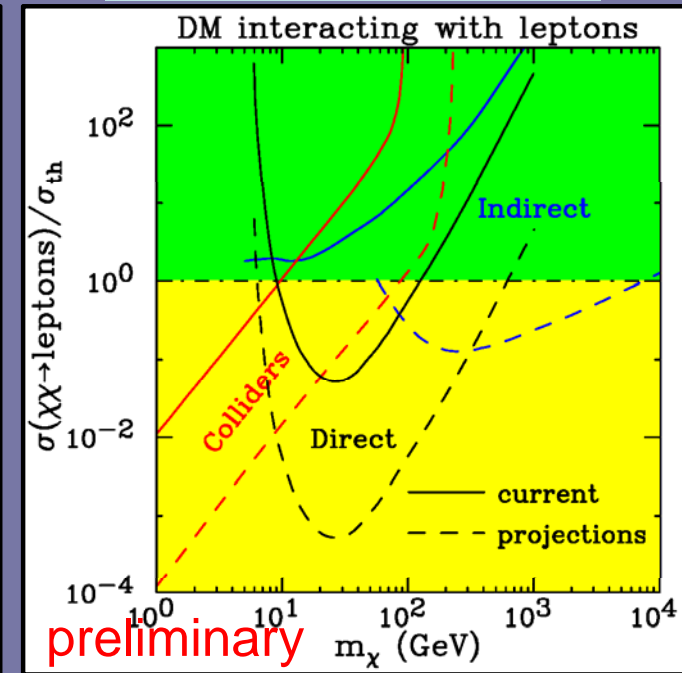
Gluon Interactions



Quark Interactions



Lepton Interactions



1.0 = expected thermal relic cross-section

- For gluon/quark interactions, LHC competitive or dominates at energies below ~few 100 GeV.
- For gluon and lepton interactions, direct expts. are important.
- For quark and lepton interactions, indirect expts are important.

Outline

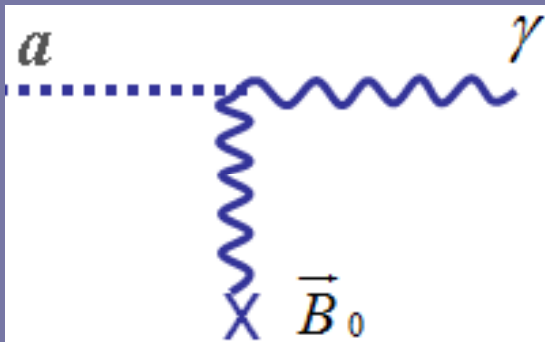
C. Other Topics (possibly connected to LHC)

- Axions and axion like particles (ALPs)

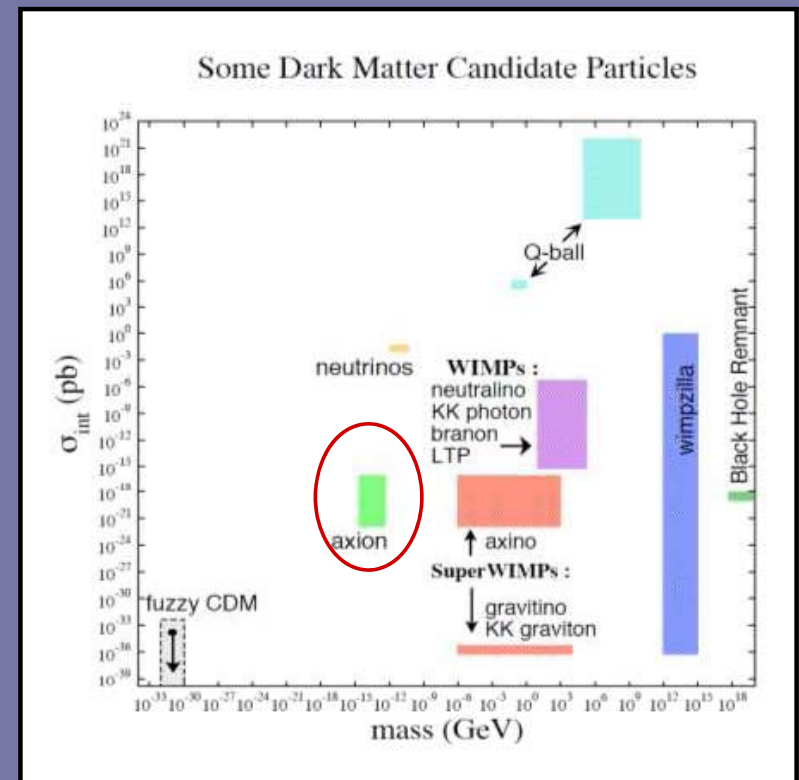
Axions as Dark Matter

- Axion motivated by strong CP problem (PQ symmetry).
- Constraints (astrophysics, accelerators) on the axion coupling (and mass).
- For a stable relic axion, and a DM candidate:
 e.g. for $n_a \sim 2 \times 10^{13} / \text{cm}^3$ and $m_a = 20 \mu\text{eV}$, $\Omega_a \sim 0.23$.
- Axion: neutral pseudoscalar boson
 (light cousin of π^0)

Produced/detected via Primakoff effect
 (Sikivie):



$$\mathcal{L}_{a\gamma\gamma} = g_\gamma a \vec{E} \cdot \vec{B}_0$$

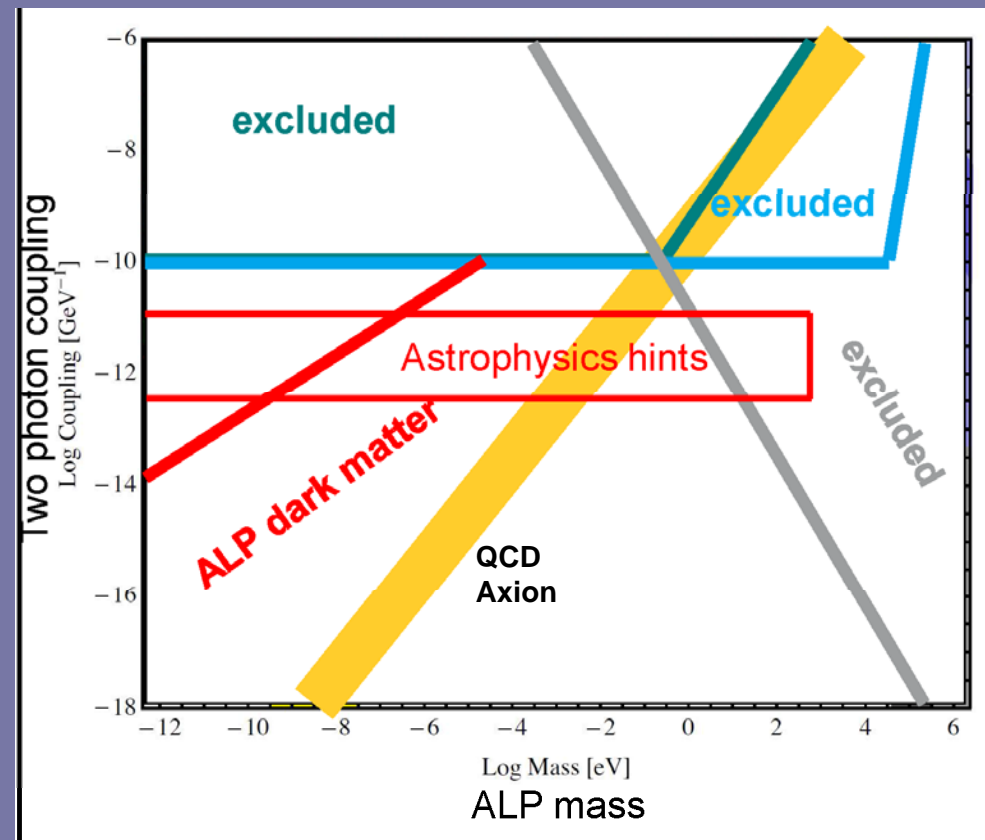


Extension to ALPs

WISPs: ALPs, hidden photons, chameleons, etc. are components of a “hidden sector”, inspired by string theory extensions of SM.

ALPs = Axion-like-particles

A. Lindner, DPG 2013



Coupling-mass diagram for axions and ALPs.

Axion/ALP Current/Future Limits

A. Lindner, DPG 2013

Laboratory Axions

- “Light-shining-through-walls” (OSQAR, LIPSS, ALPS ...)

Solar Axions

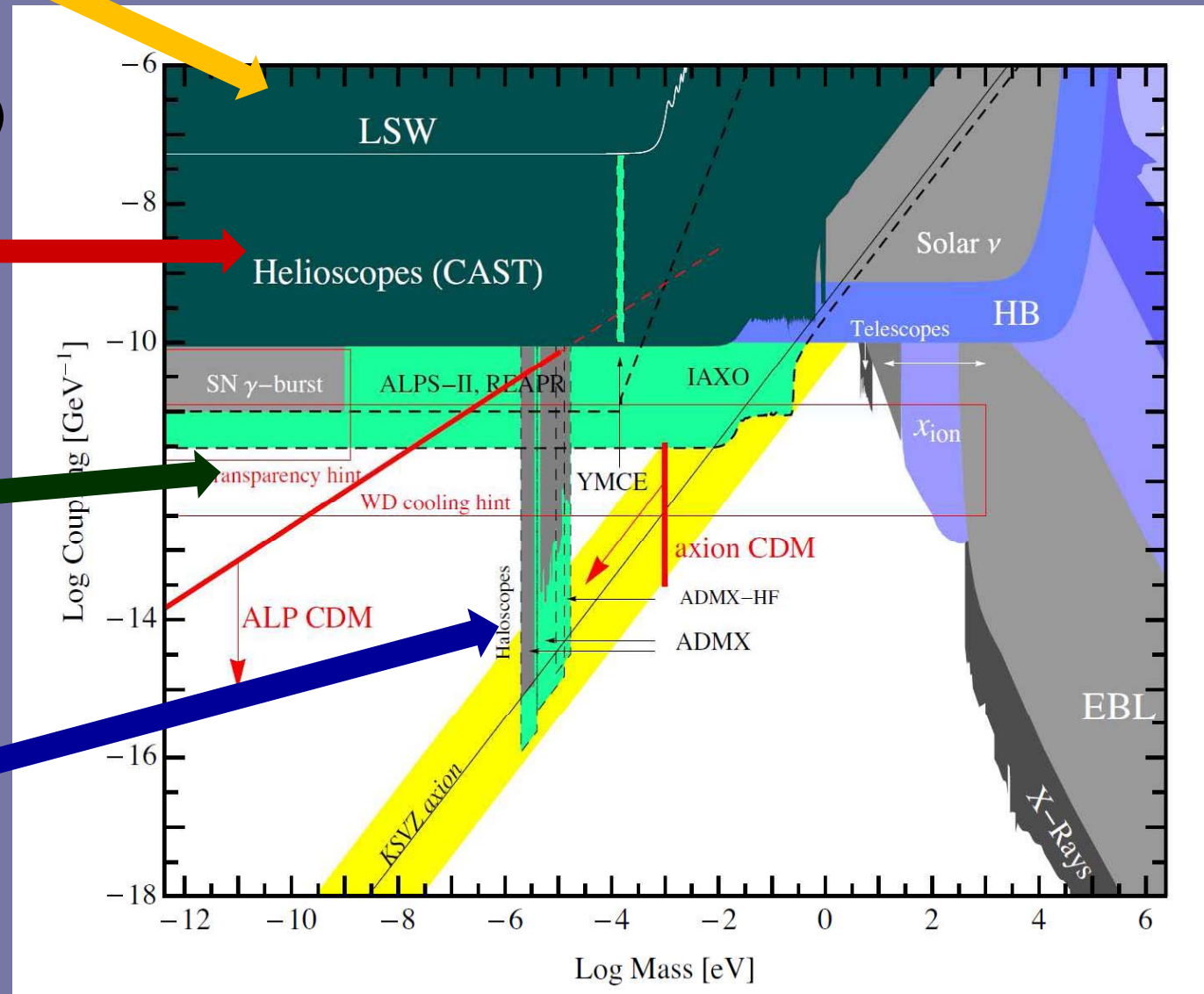
- Helioscopes (CAST, Tokyo ...)

Cosmic ALPs

- γ -ray Telescopes (Fermi, VERITAS ...)

DM Halo Axions

- Haloscopes (ADMX)

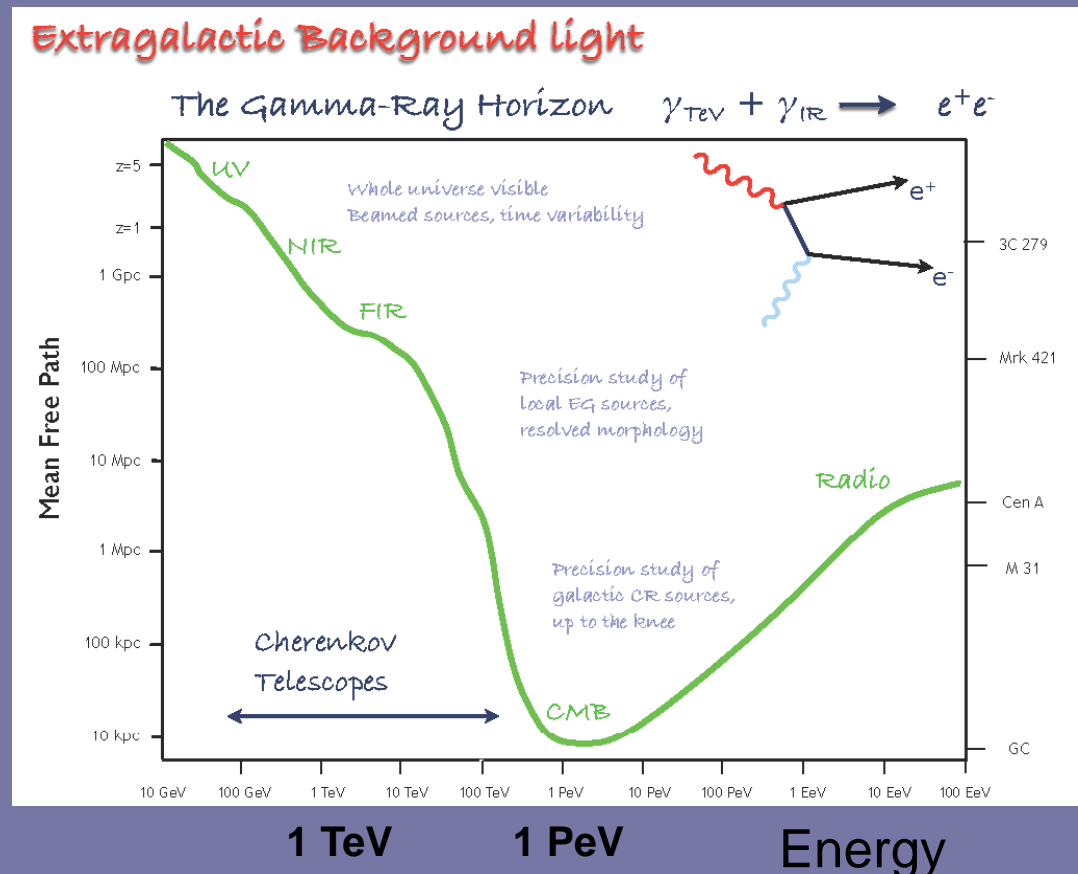
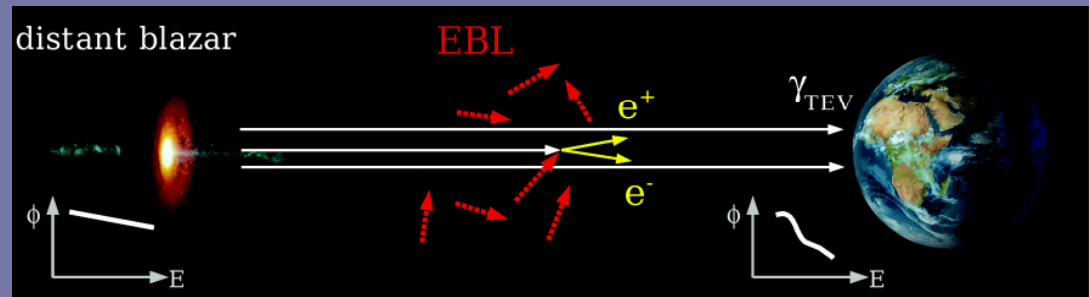


VHE γ -rays as Cosmological Probes

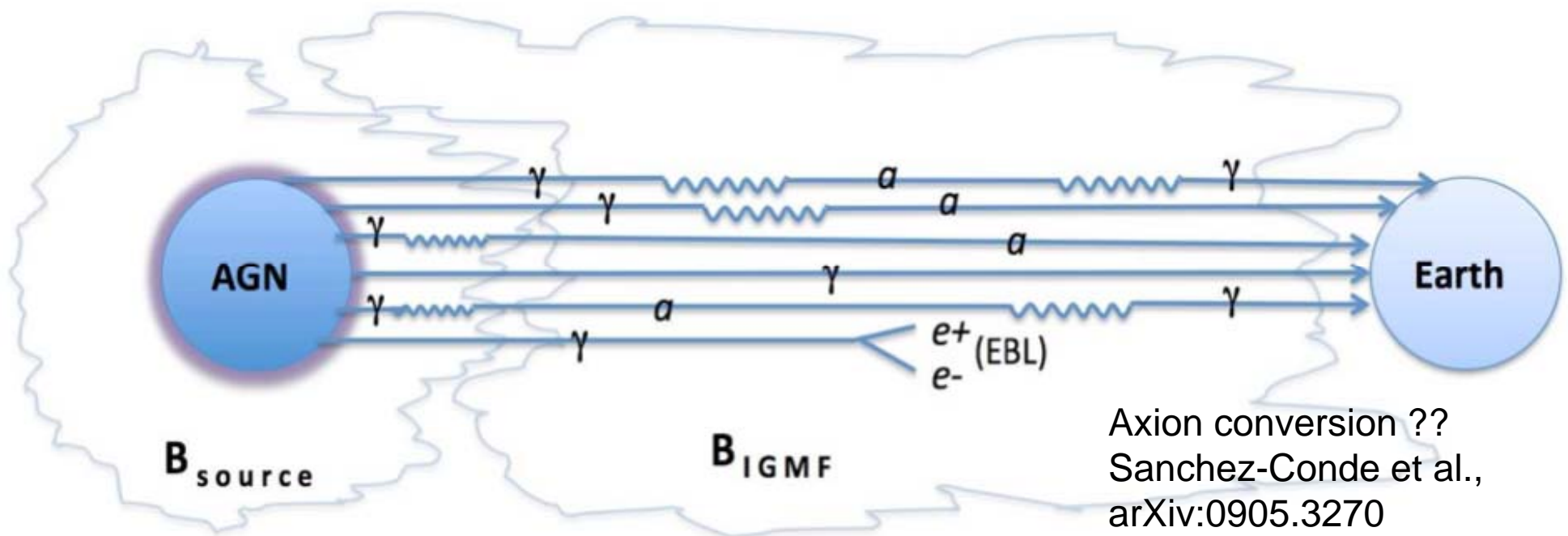
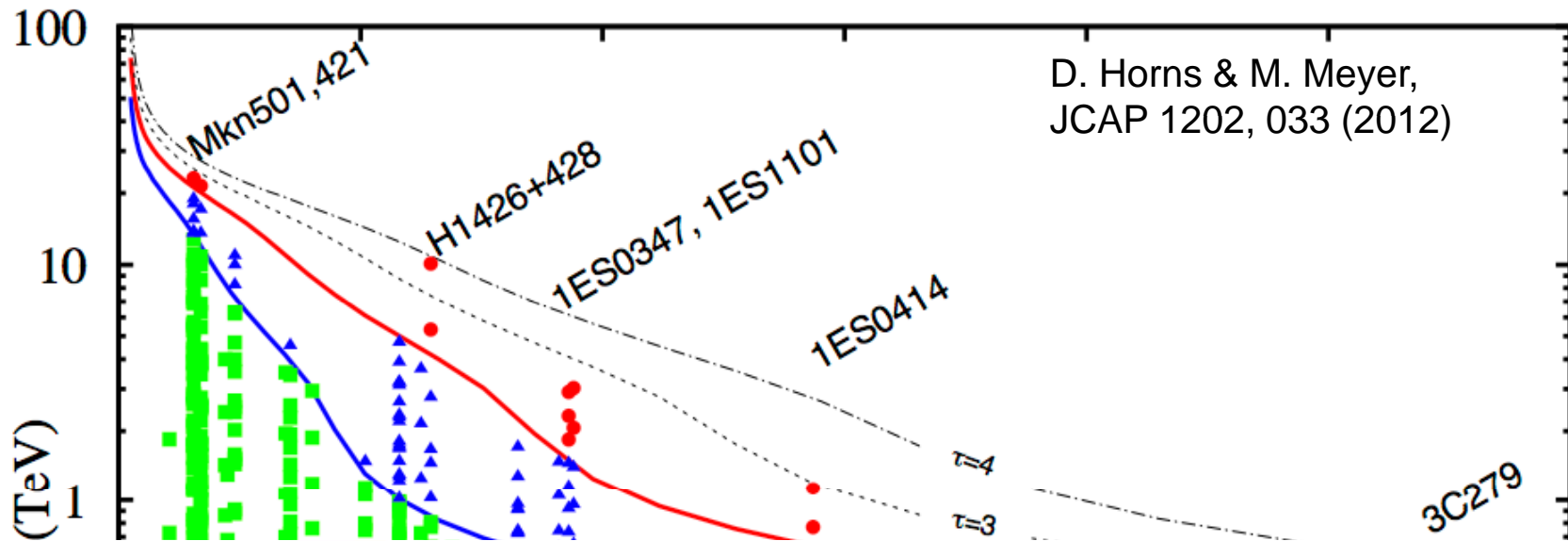
Extragalactic Background Light (EBL):

- Optical/IR diffuse background produced by all star-formation throughout history of universe.
- $\gamma\gamma$ interaction probes EBL density & uniformity.
- Potential way to measure tiny extragalactic magnetic field (EGMF).

$$B \sim 10^{-9} - 10^{-18} \text{ G}$$

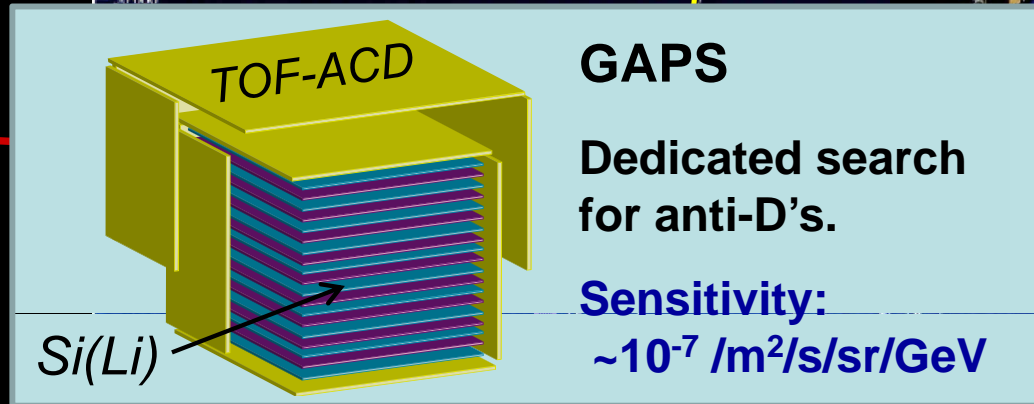


Is the Universe too Transparent ?



(Some) Future Experiments

CR, γ -ray



Balloon Instruments

ANITA **GAPS**

Atmospheric Cherenkov

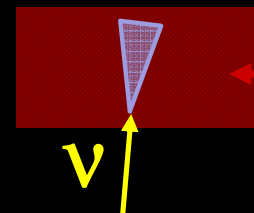
Cherenkov Telescope Array (CTA)

γ -rays, 30 GeV–300 TeV; factor 10 sensitivity improvement



Underground Detectors

CDMS, Xenon ...
ADMX, CAST ...
Many Discussed



Satellite Instruments

Fermi, AMS
PAMELA ...
Gamma-200
DAMPE

IceCube ...

Ice/Water Cherenkov Detectors

SUMMARY

- A tremendous amount of activity exists in astroparticle physics. There are new results from a wide variety of experiments.
- VHE γ -rays have opened a new window in astrophysics. TeV particle acceleration is ubiquitous in the cosmos and needs to be understood. VHE neutrino astronomy is likely to follow soon.
- WIMP dark matter is being increasingly constrained by LHC, direct and indirect measurements. Interesting anomalies exist, but none (as yet) provide convincing evidence for dark matter.
- Numerous other dark matter candidates remain viable. Some (e.g. axions and ALPs) are being pursued by new projects with improved sensitivity. What other well-motivated candidates remain?
- There are a large number of future experiments being planned or proposed. A common thread is the wish for “large scale” (> 40 M€) instruments. Not all of these will be realized.

QUESTIONS

- 1) What is required to eliminate the generic thermal WIMP picture for dark matter? (or, can the WIMP scenario be falsified?).
- 2) If LHC does not clearly see any new physics, are there other accelerator experiments that can shed light on dark matter? (If so, how?).
- 3) When can we say that we have determined the origin of cosmic rays?
- 4) What is the appropriate balance of accelerator and non-accelerator projects in particle physics?

Some of the Topics Not Covered

- Proton decay
- Sterile neutrinos
- Cosmic electrons
- DM astrophysics – local density, cusps, streams, etc.
- The Galactic center
- Fermi “bubbles”
- WMAP/Planck “haze”
- Fermi “haze”
- Primordial black holes
- UHE Cosmic Rays
- GUT-scale particles
- Lorentz invariance violation (LIV)
- Relic neutrinos
- Extragalactic magnetic field (EGMF)
- Origin of cosmic rays (real progress made here !)
- ...

BACKUP

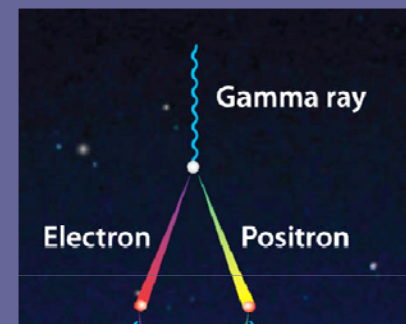
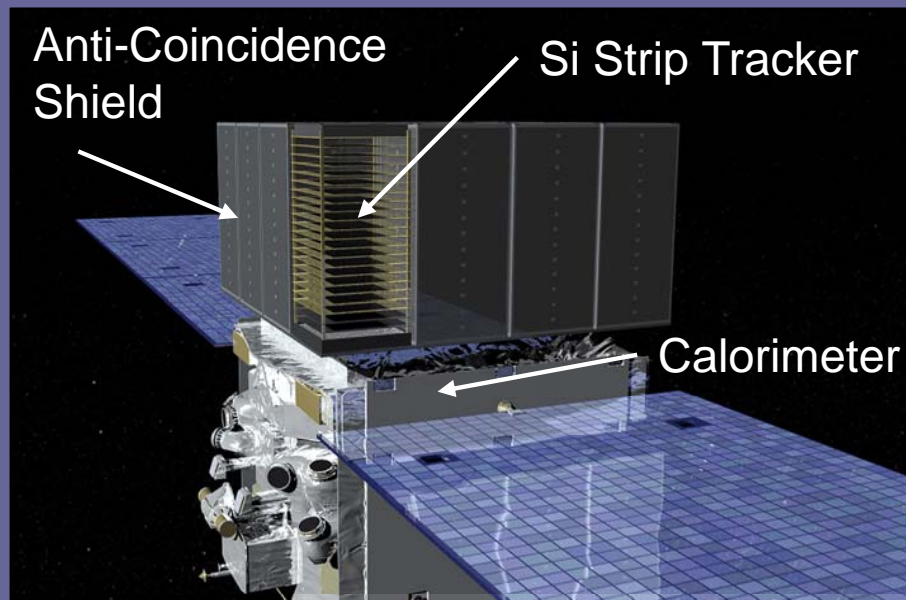
Some of the Experiments

GeV and TeV γ -ray Telescopes

GeV

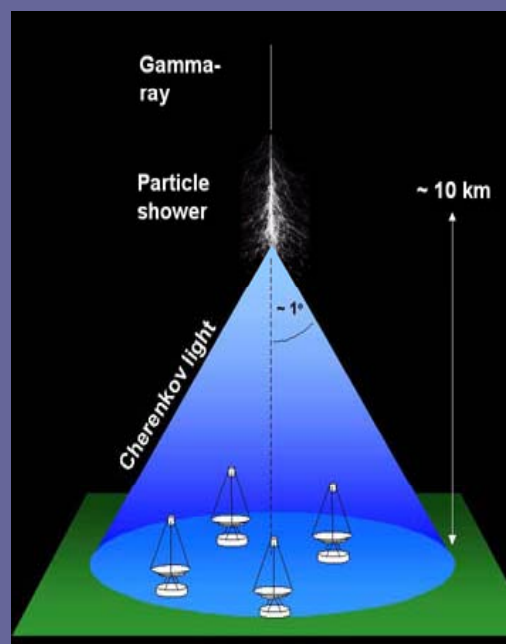
Fermi-LAT

- $E = 30 \text{ MeV} - 300 \text{ GeV}$
- $A \sim 1 \text{ m}^2$
- 2.5 sr FOV
- $0.3^\circ - 1.5^\circ$ resolution



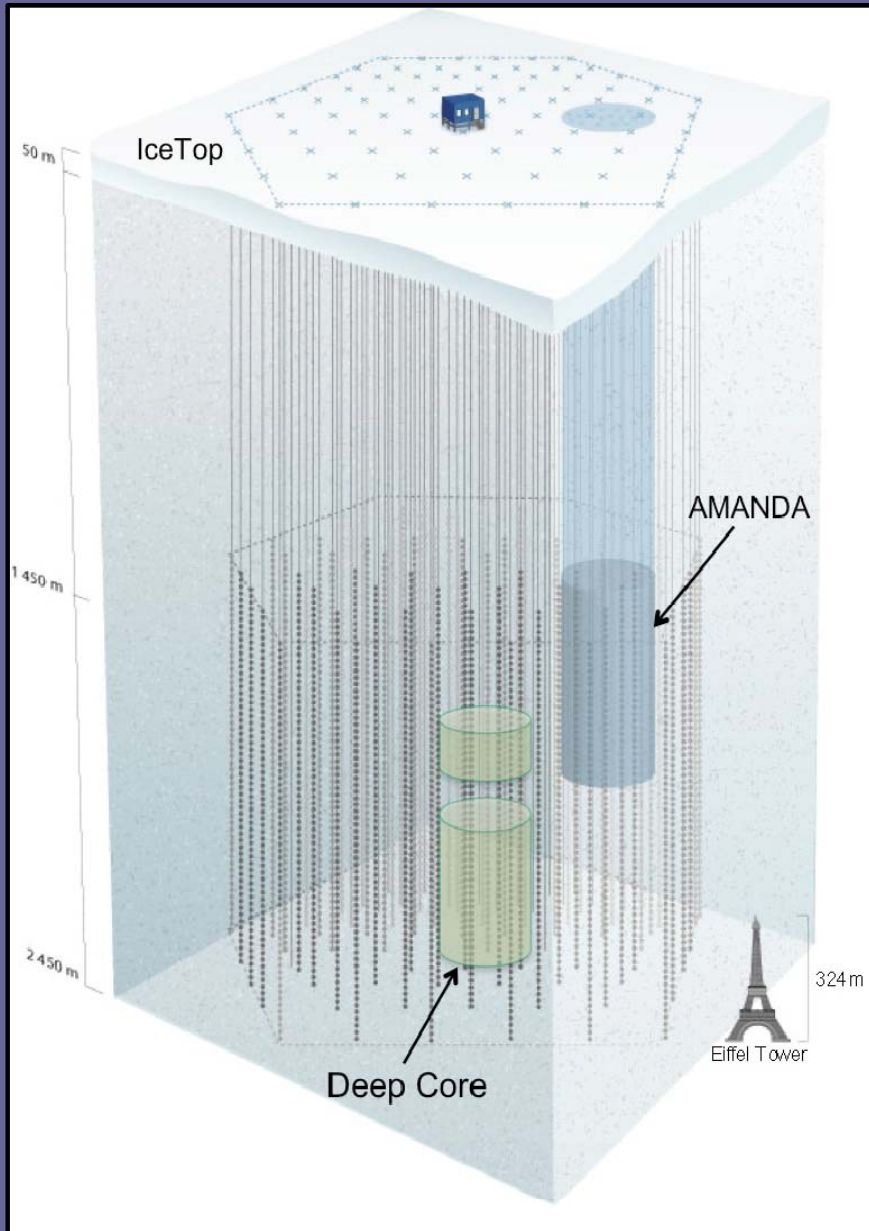
Atm. Cherenkov Telescopes

- $E > 50 \text{ GeV}$
- $A \sim 1 \times 10^5 \text{ m}^2$
- $\sim 4^\circ$ FOV
- $< 0.1^\circ$ resolution

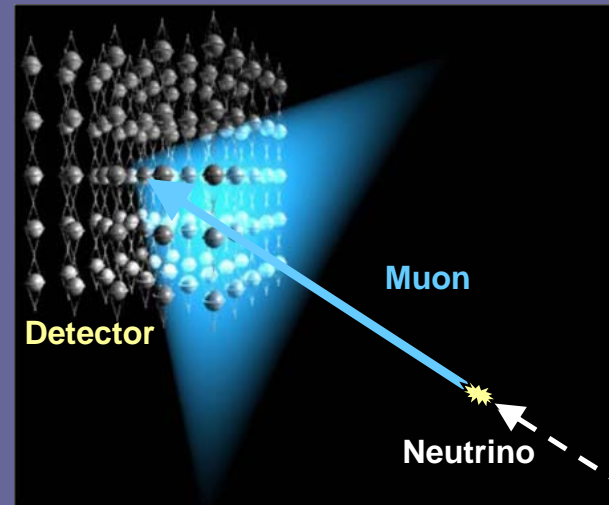


VERITAS @ Mt. Hopkins AZ, USA

IceCube: ν Detector at South Pole



Schematic of IceCube at South Pole



TeV muon-neutrino detection

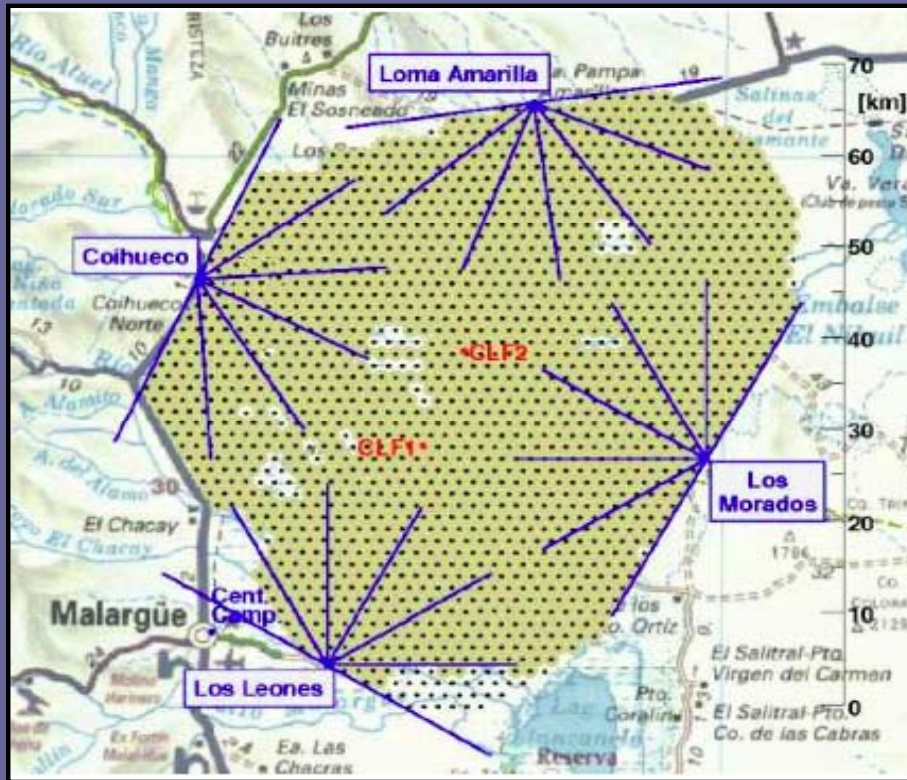


Installing an IceCube string

km³ Neutrino Detector

- Ice-Cherenkov technique
- Energy range: 10^{11} - 10^{17} eV
- 86 strings x 60 optical modules
- IceTop for air showers
- Deep Core for low energies

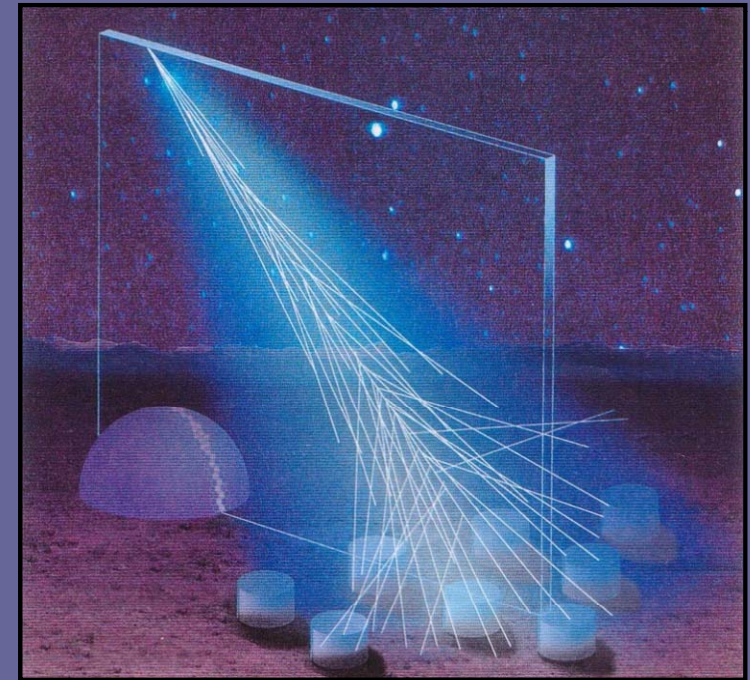
Auger Project for Ultrahigh Energies



Auger Project in Mendoza, Argentina

3000 km² air shower array

- $E > 10^{17}$ eV
- Surface array of 1600 detectors
- 24 fluorescence detectors, 4 locations



Surface array & fluorescence detection



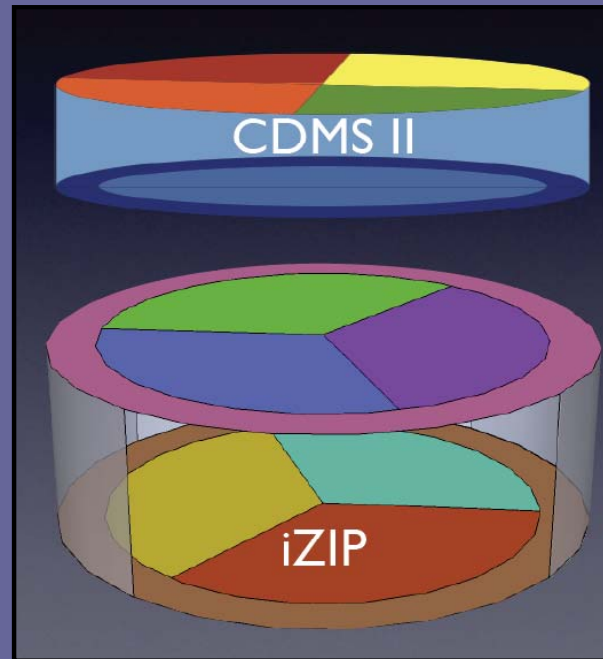
A surface detector & fluorescence station

Super CDMS (LNGS)

Ge or Si crystals: ionization and phonon signals
 $T < 50$ mK
(EDELWEISS II similar)



One detector

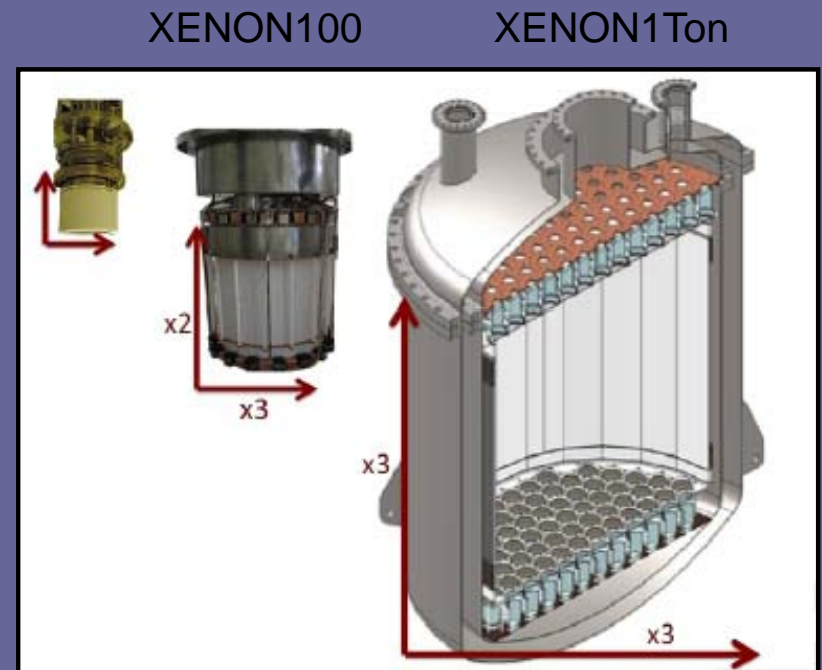
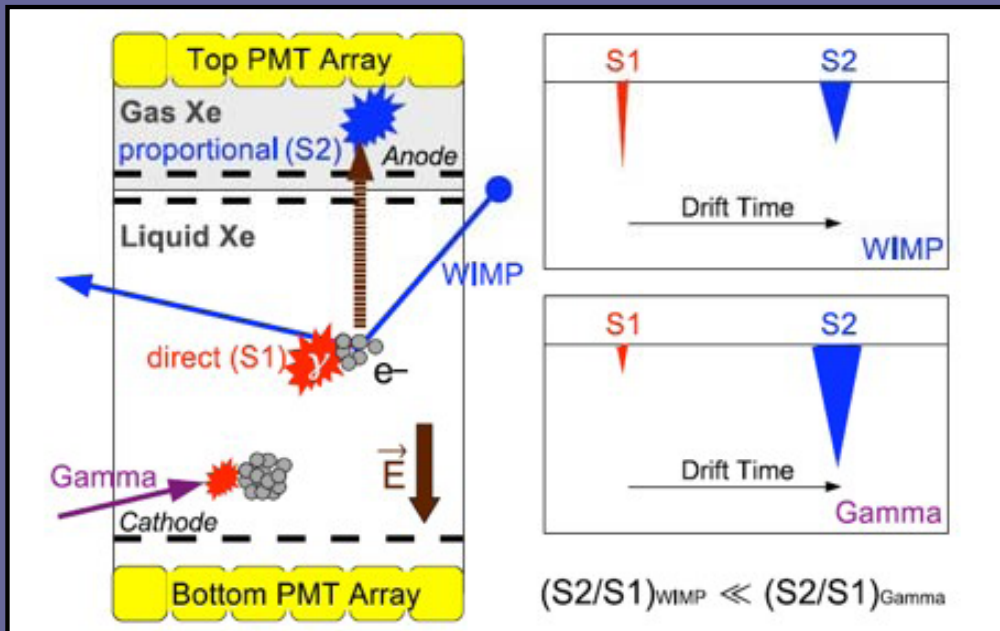


Interleaved
ionization/photon
sensors

- Low energy threshold (< 10 keV)
- Excellent energy resolution ($< 1\%$)
- Proven event-by-event background discrimination
- (Surface events mimic nuclear recoil)

Xenon100 (Gran Sasso)

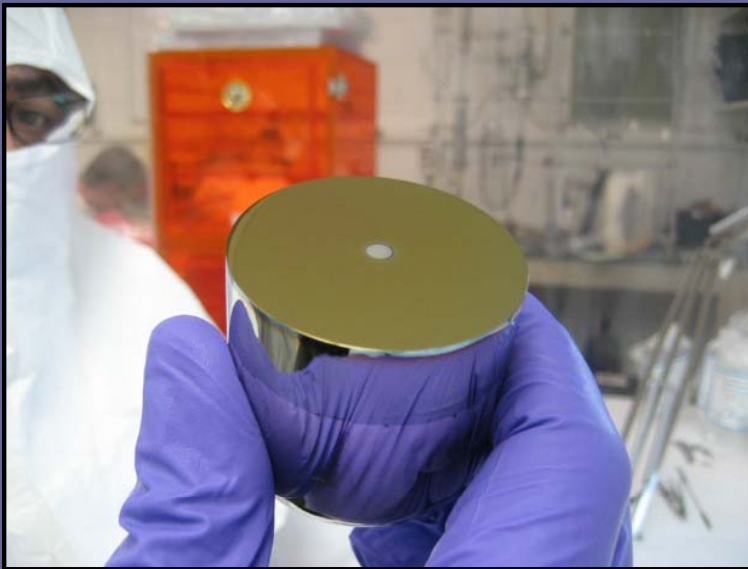
Dual phase Xe: Ionization and scintillation signals
3D track reconstruction (TPC)
(LUX, PandaX similar)



- Good self-shielding, pure and homogeneous material
- Large A \rightarrow large rate, but less sensitive at lower E
- Straightforward to scale to larger volumes
- (Weaker detector discrimination, maintaining high purity LXe required)

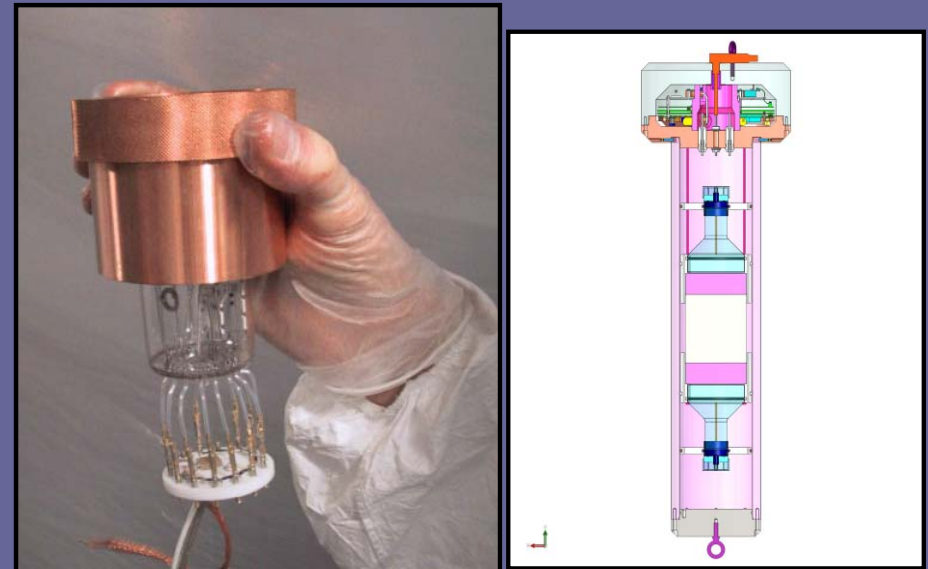
Other Direct Detection Experiments

Solid state ionization detectors
Ultrapure Ge @ 77K
CoGeNT



- V. low E threshold
- Low intrinsic bkgnd
- (Hard to distinguish NR from ER)
- (Pulse shape to discriminate surface from bulk events)

Scintillating Crystals
NaI (TI)
DAMA/LIBRA, DM-ICE

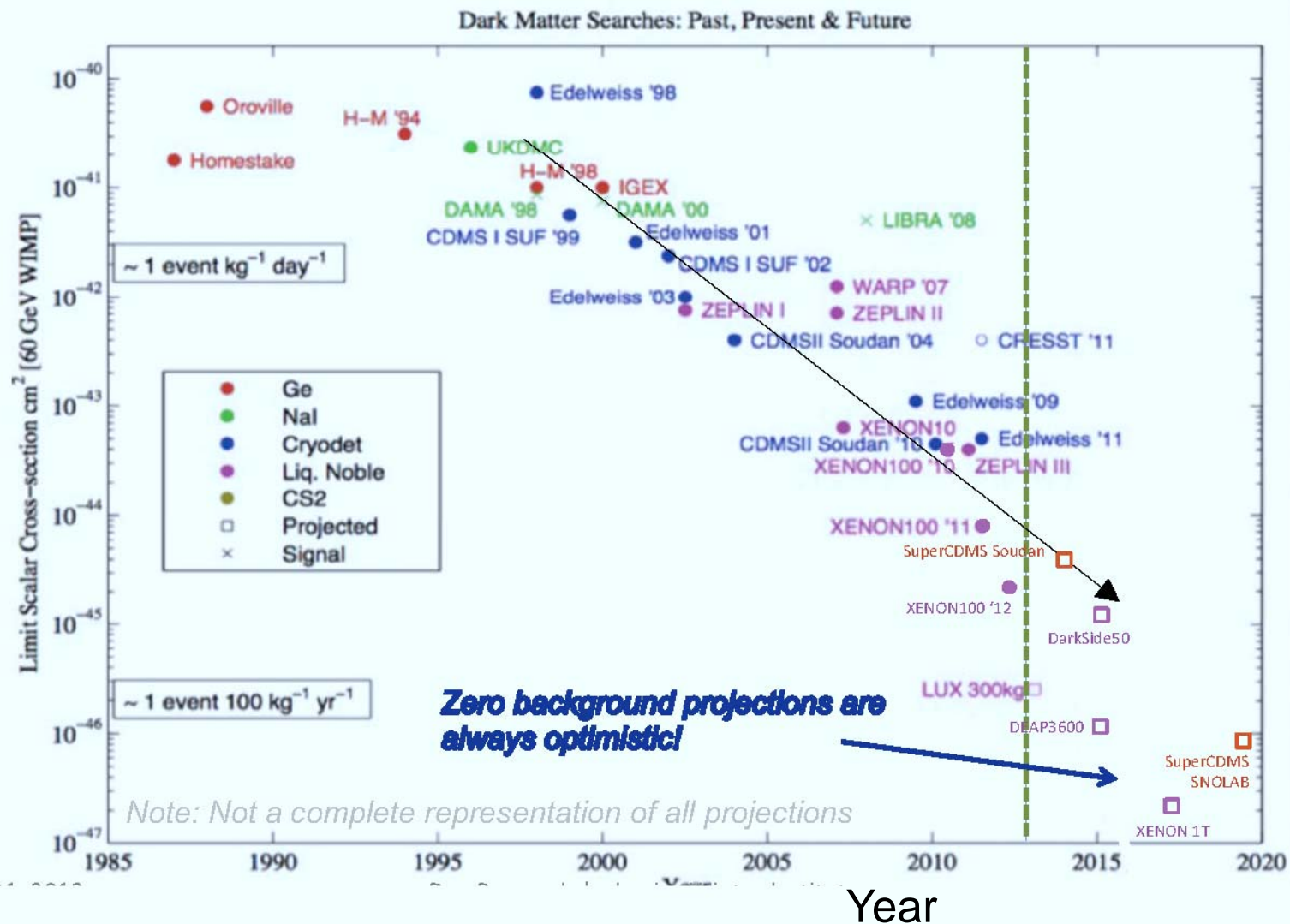


- keV E threshold
- Large mass \rightarrow large signal
- (No event-by-event discrimination)
- (Large residual bkgnds, annual modulation required)

Evolution of DM Detectors

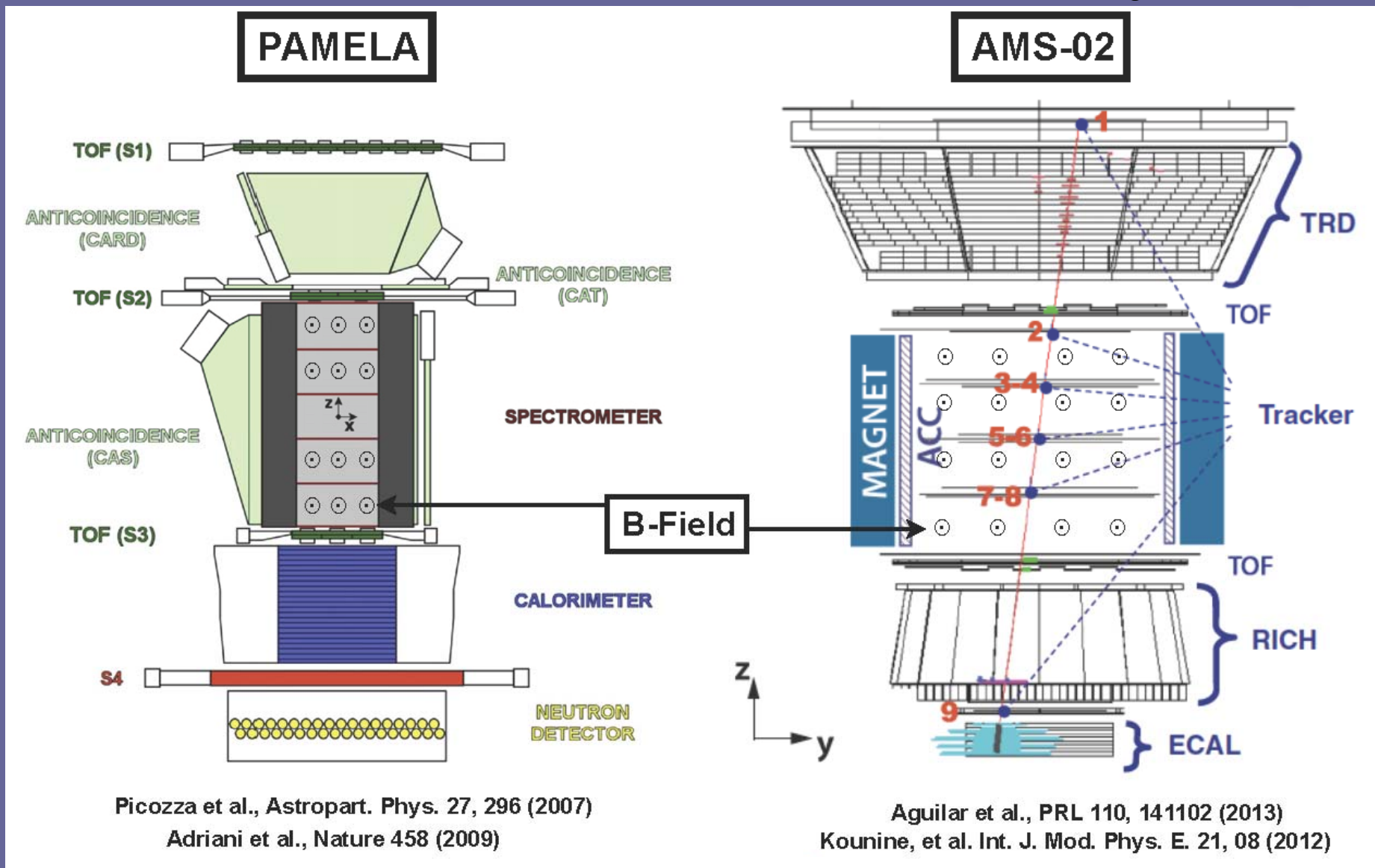
Moore's Law for Direct Detection

Sensitivity roughly doubled every ~18 months for the past decade



Anti-Matter Space Detectors

A. Drlica-Wagner, APS 2013



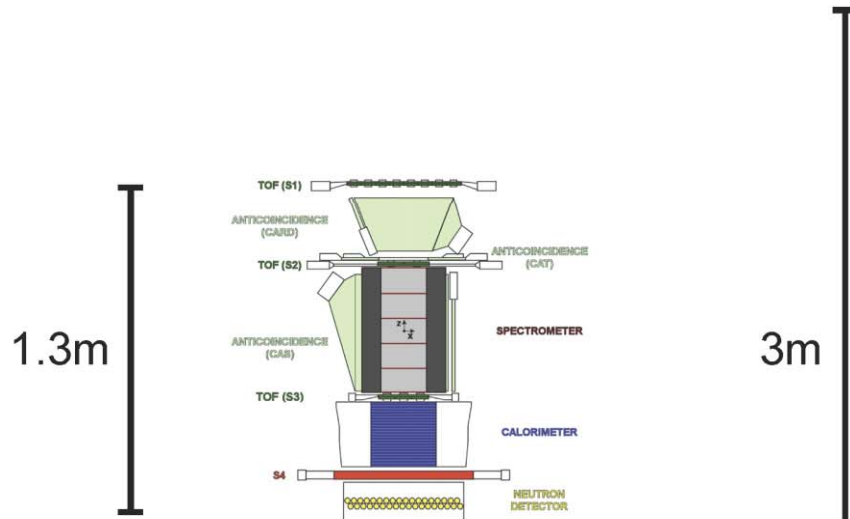
e detected by shower shape
e⁺ detected by magnet

e detected by shower shape *and* TRD
e⁺ detected by magnet

Anti-Matter Space Detectors

A. Drlica-Wagner, APS 2013

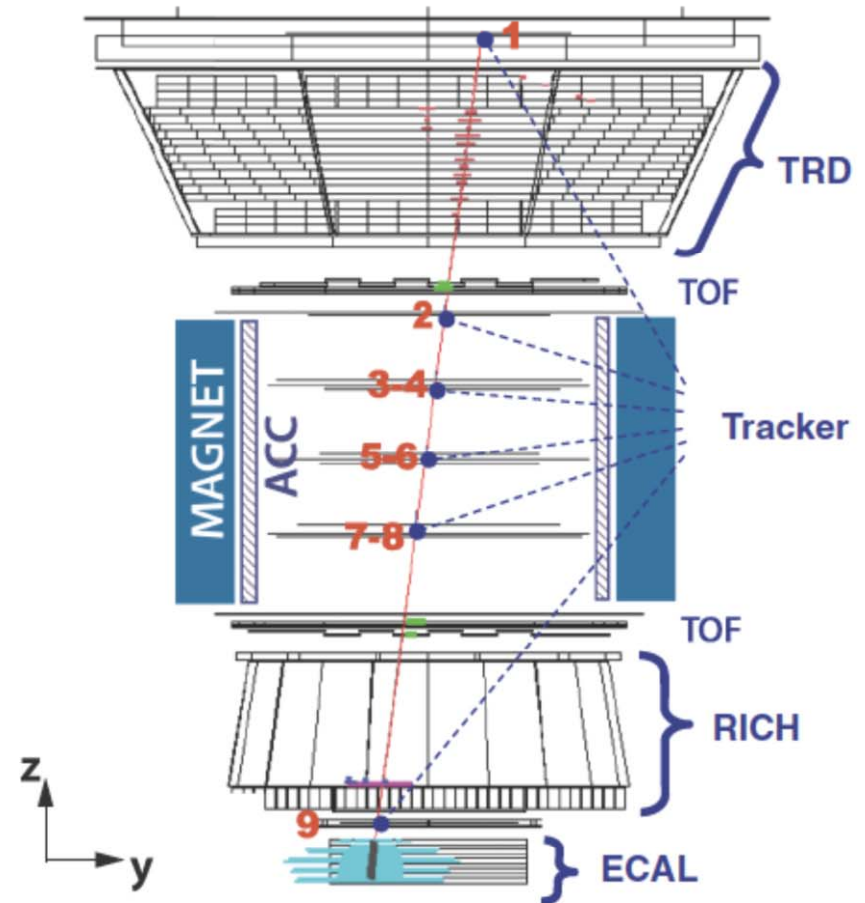
PAMELA



Picozza et al., *Astropart. Phys.* 27, 296 (2007)
 Adriani et al., *Nature* 458 (2009)

e detected by shower shape
 e⁺ detected by magnet

AMS-02



Aguilar et al., *PRL* 110, 141102 (2013)
 Kounine, et al. *Int. J. Mod. Phys. E.* 21, 08 (2012)

e detected by shower shape *and* TRD
 e⁺ detected by magnet

Axions

Original motivation – to explain the “strong CP” problem

- QCD contains CP violating term for non-zero θ

$$L_\theta = \frac{\theta g_s^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

- Expect EDM(n) $\sim 10^{-15}$ e-cm; current limit 10^{11} below this!
- Peccei-Quinn introduce dynamical field, which produces an effective potential to drive θ to zero.
- The quantum of the field is a particle, the axion (Weinberg-Wilczek).

Axion mass:

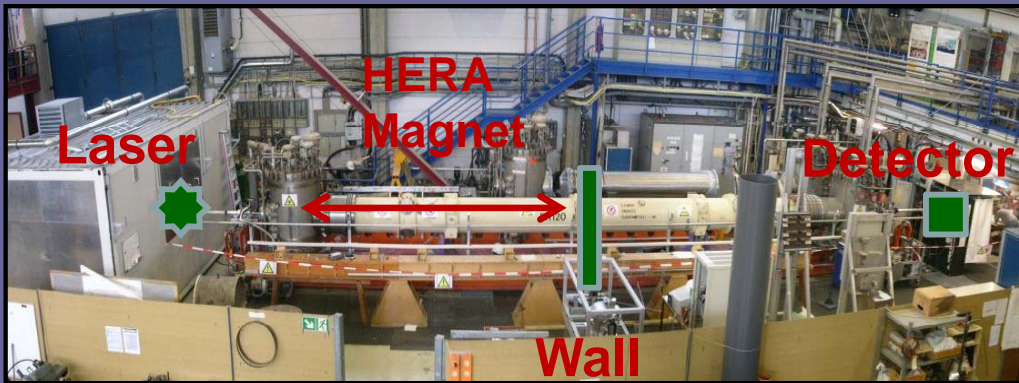
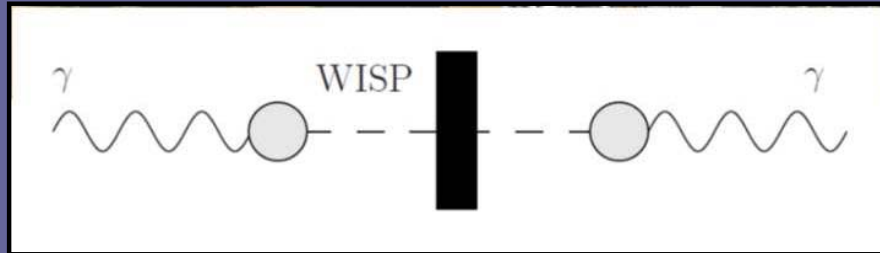
$$m_a = 6\mu\text{eV} \frac{10^{12}\text{GeV}}{f_a}$$

f_a = decay constant

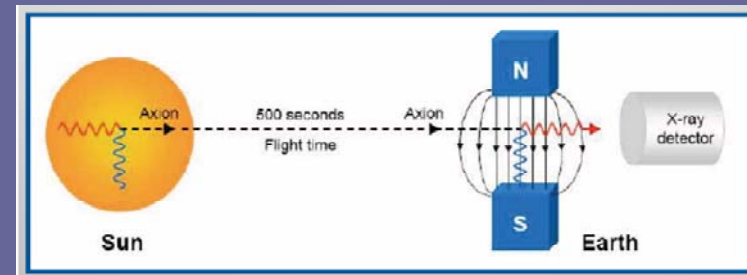
Interactions scale as $1 / f_a$

Laboratory & Solar Axion Expts

ALPS (DESY)



CAST (CERN)

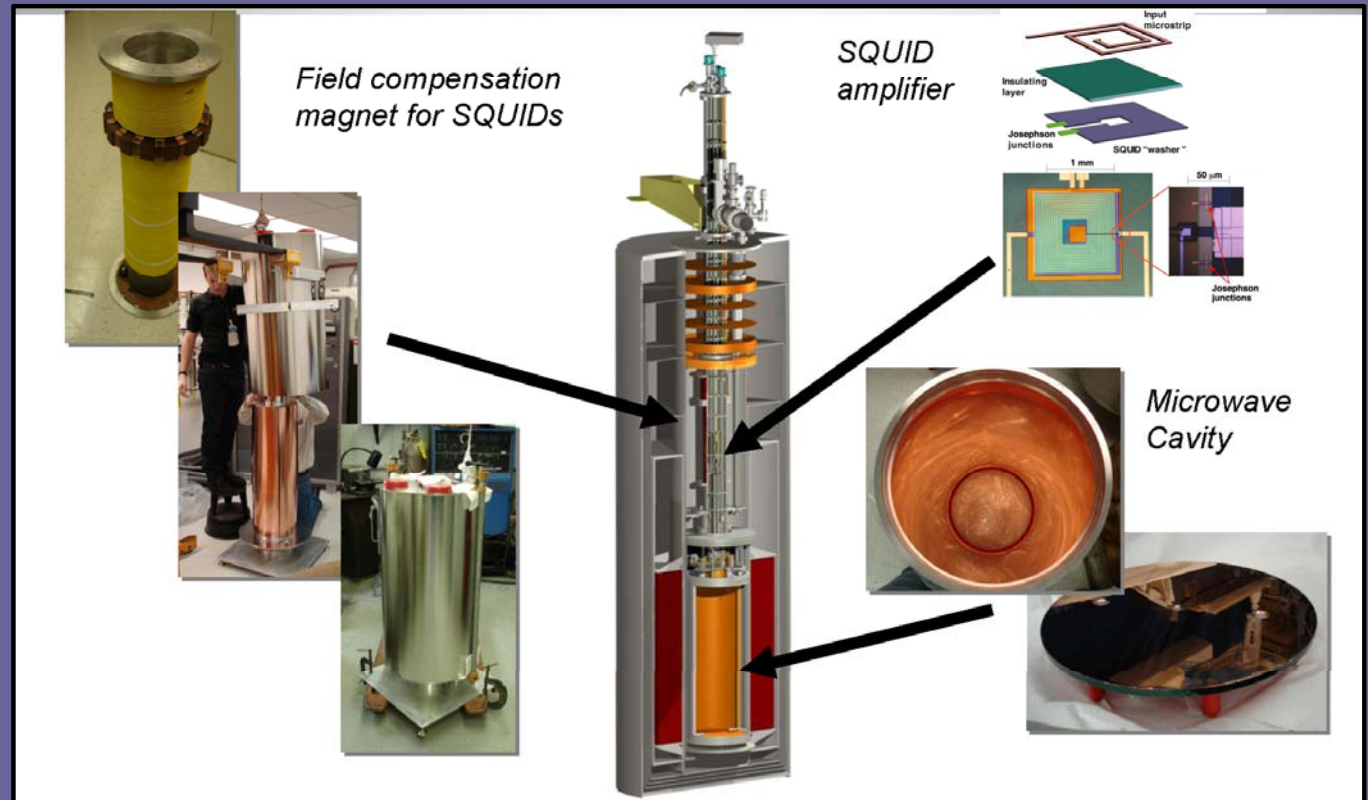
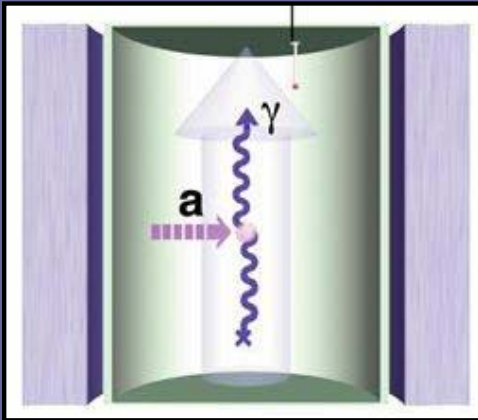


- HERA magnet
- ALPS-I search in 2010
- Search for conversion to X-rays
- Upgrade to laser, magnet and cavity (ALPS-II).

- Decommissioned LHC magnet
- Tracks Sun (3 hrs/day)
- Search for conversion to X-rays
- Future experiment IAXO (LLNL)

DM Haloscope (ADMX)

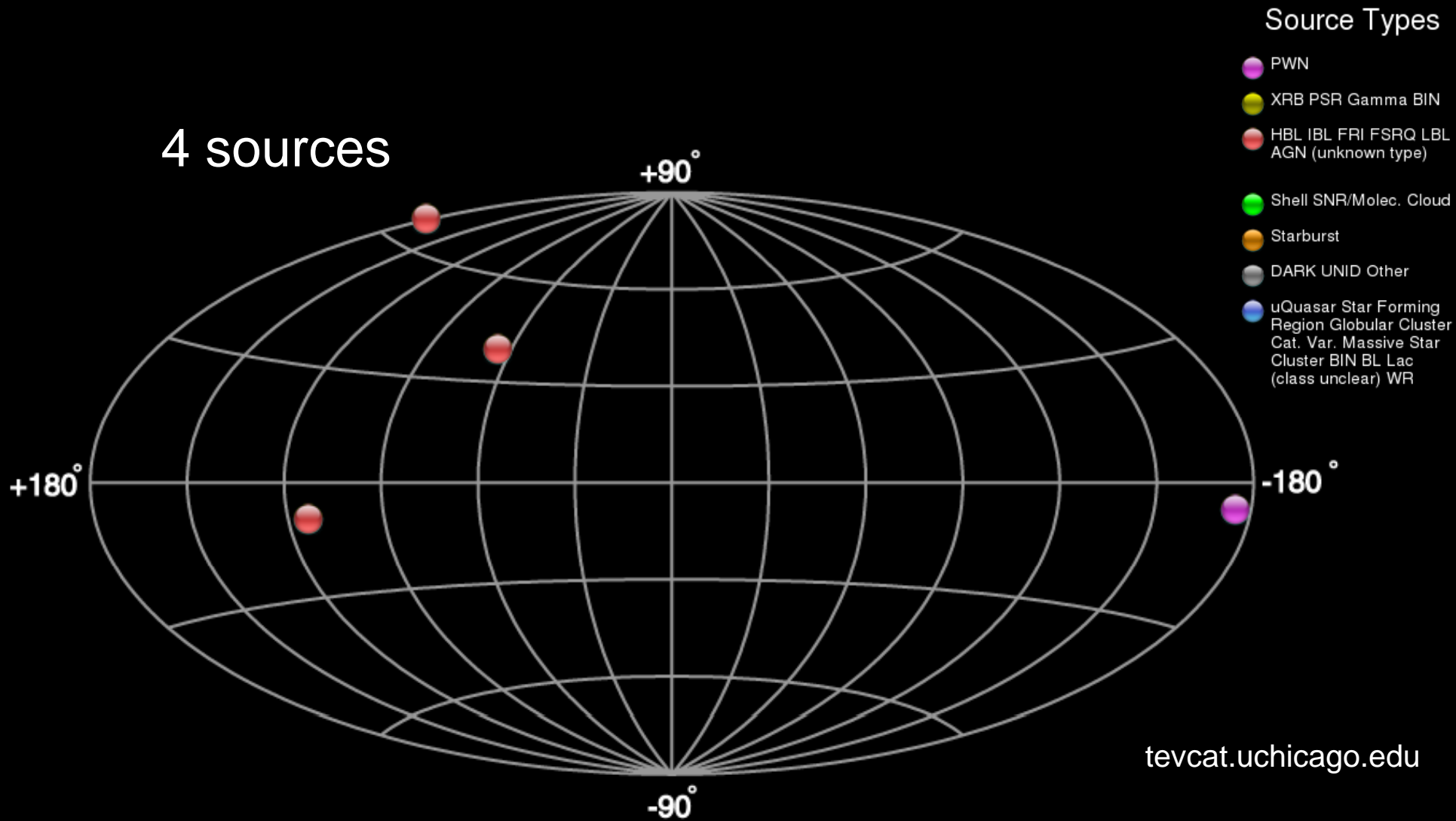
ADMX (U. Washington)



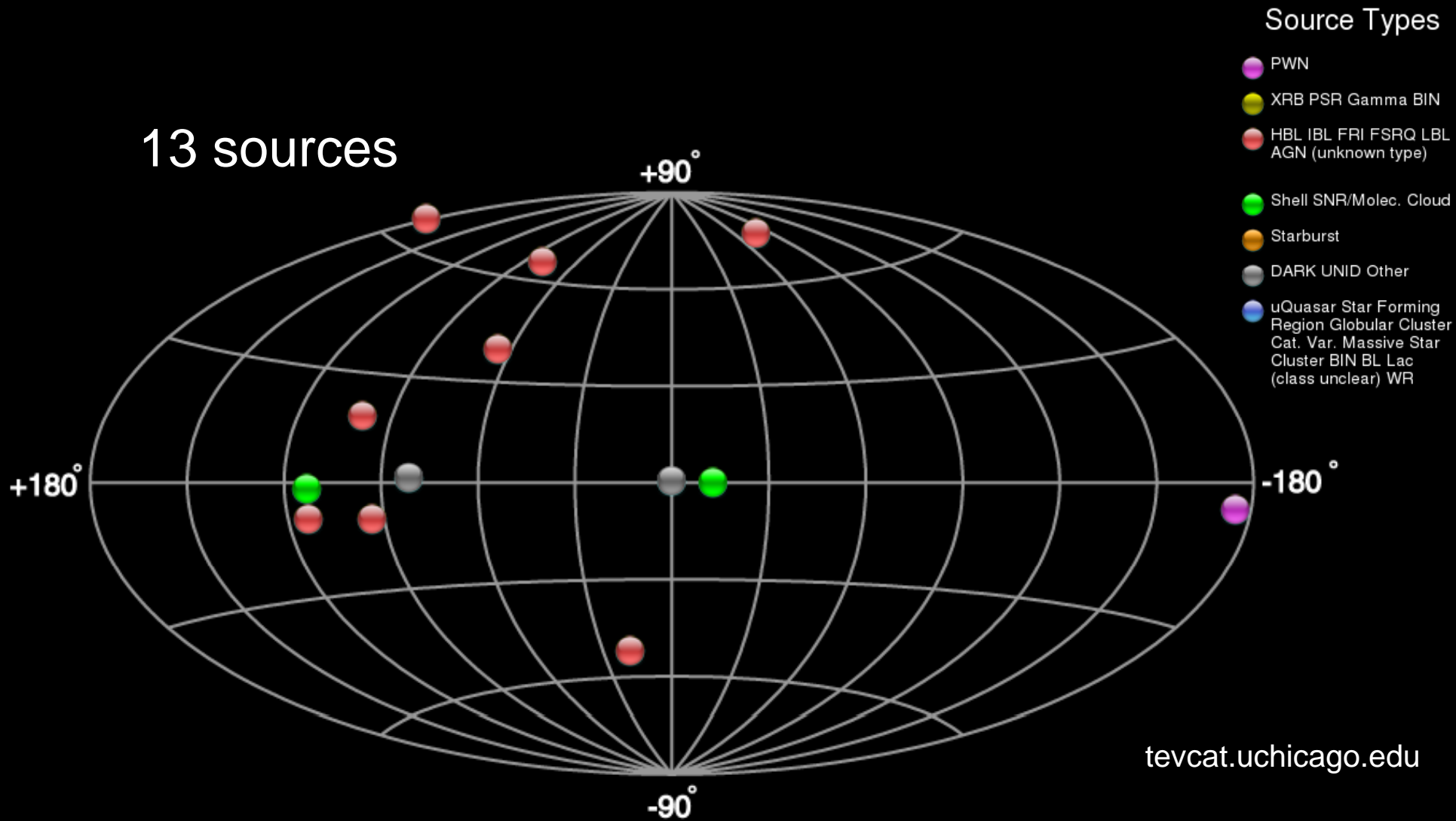
- Microwave cavity DM axion search
- Phase II construction underway
- Operation by 2015
- Cover $m_a = 2-40 \mu\text{eV}$ range

VHE γ -ray, CR and ν Astrophysics

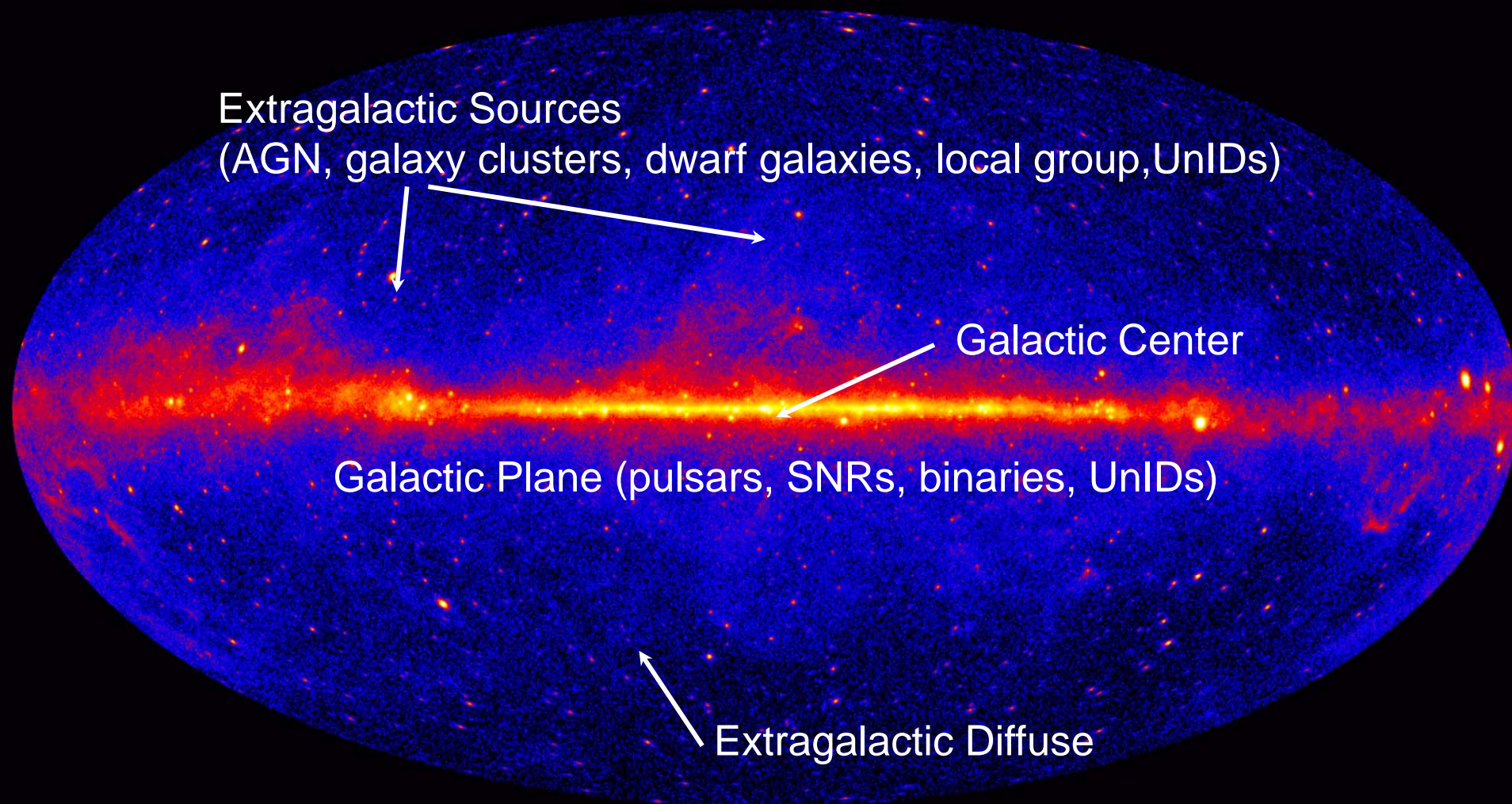
TeV γ -ray Sky c1997



TeV γ -ray Sky c2005

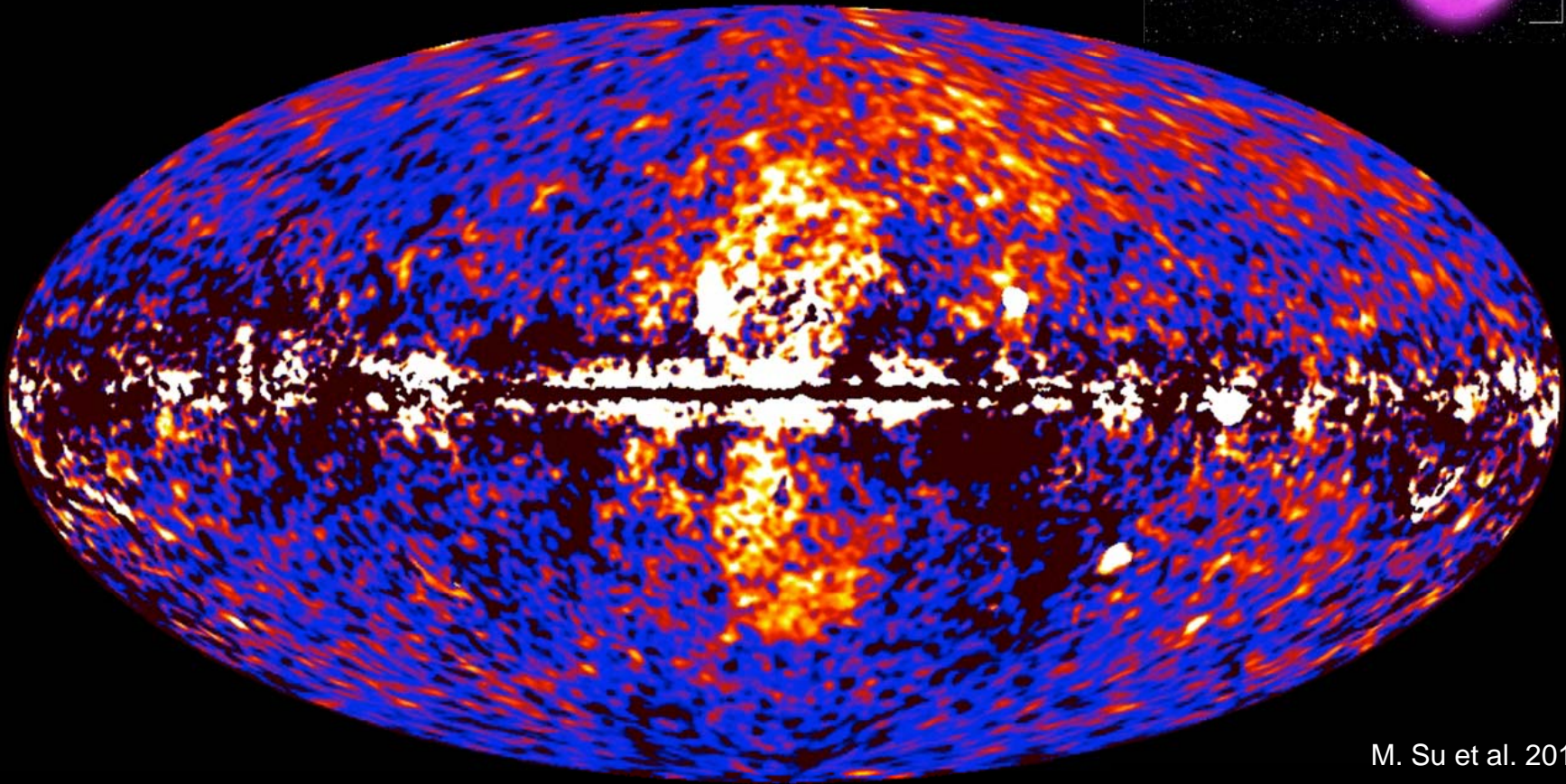
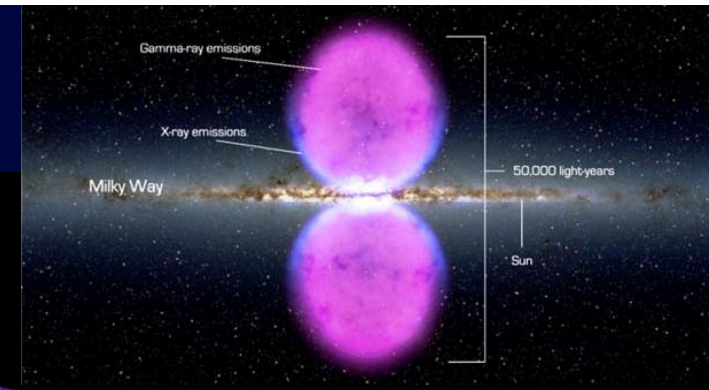


The GeV Sky (c 2012)



- Three-year γ -ray sky seen by Fermi-LAT

Fermi Bubbles

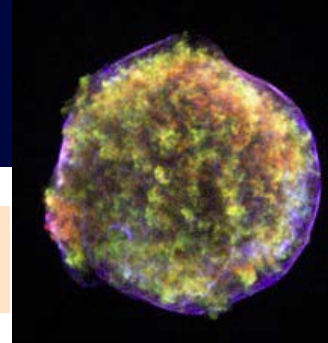


M. Su et al. 2010

Complete Surprise !

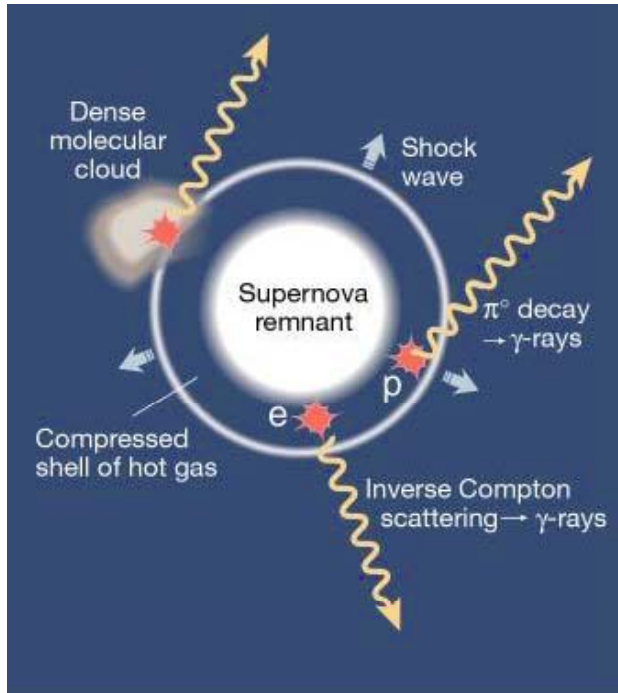
- Very extended (10 kpc) with hard spectrum.
- Related to earlier history of Galactic center ?

SNRs: Origin of Cosmic Rays



Tycho, age = 440y,
D = 2-5 kpc

General Picture



Recent Data from Tycho's SNR

V. Acciari et al., 2011

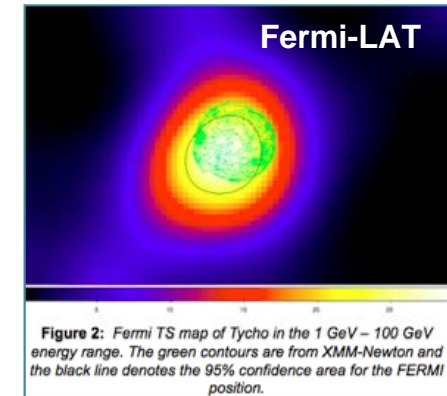
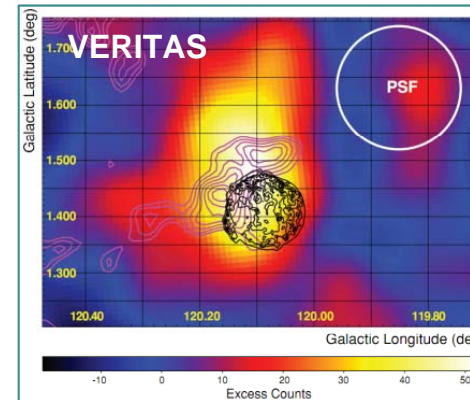
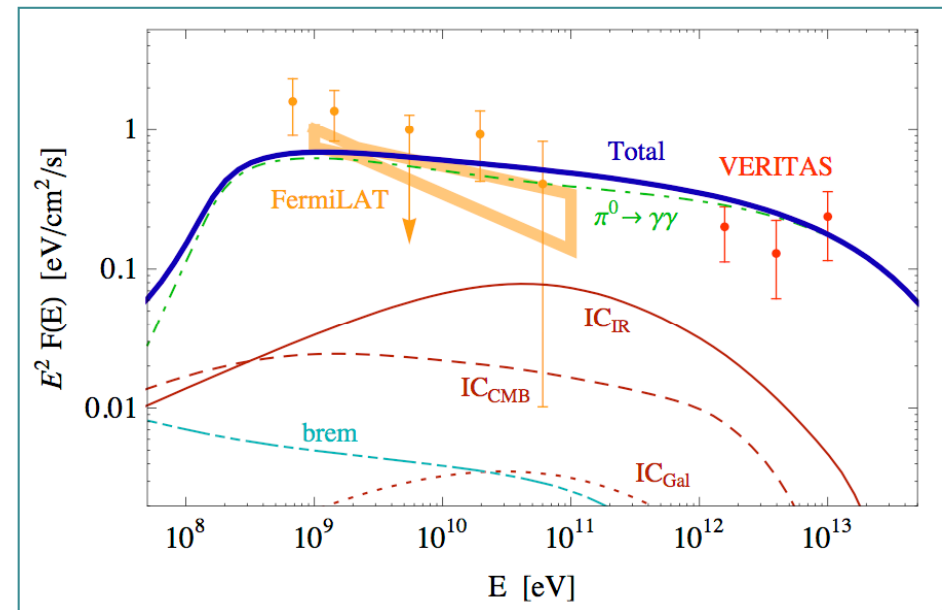


Figure 2: Fermi TS map of Tycho in the 1 GeV – 100 GeV energy range. The green contours are from XMM-Newton and the black line denotes the 95% confidence area for the FERMI position.

F. Giordano et al., 2011

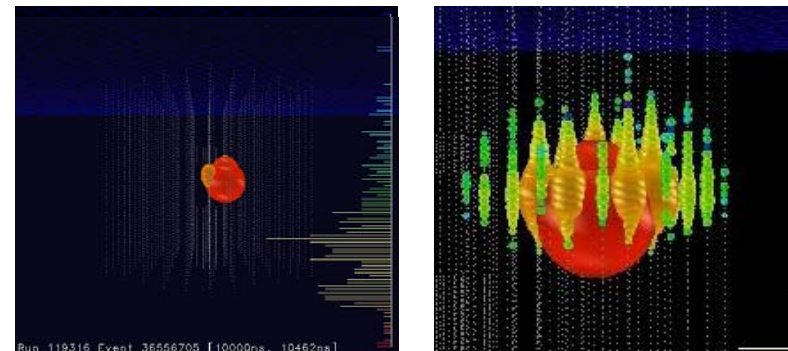
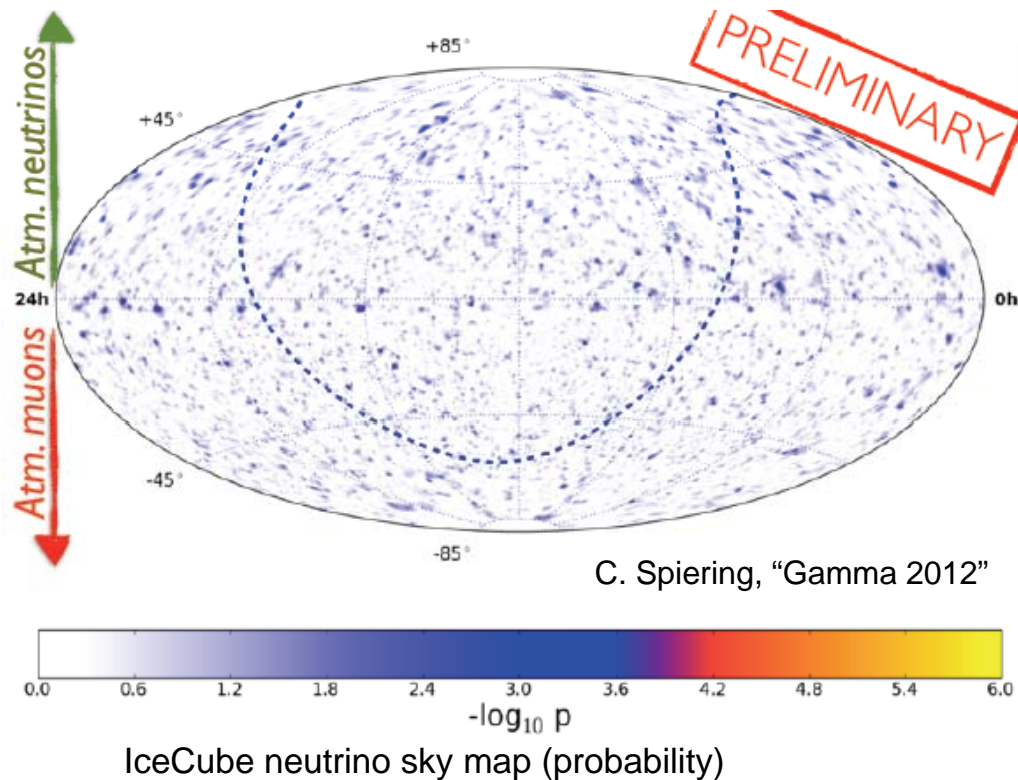
Standard paradigm for CR's

- Gives luminosity, spectral shape.
- Several SNRs now provide evidence for hadron acceleration.
- but ... more evidence needed.



Morlino & Caprioli, 2011

Latest Neutrino Results



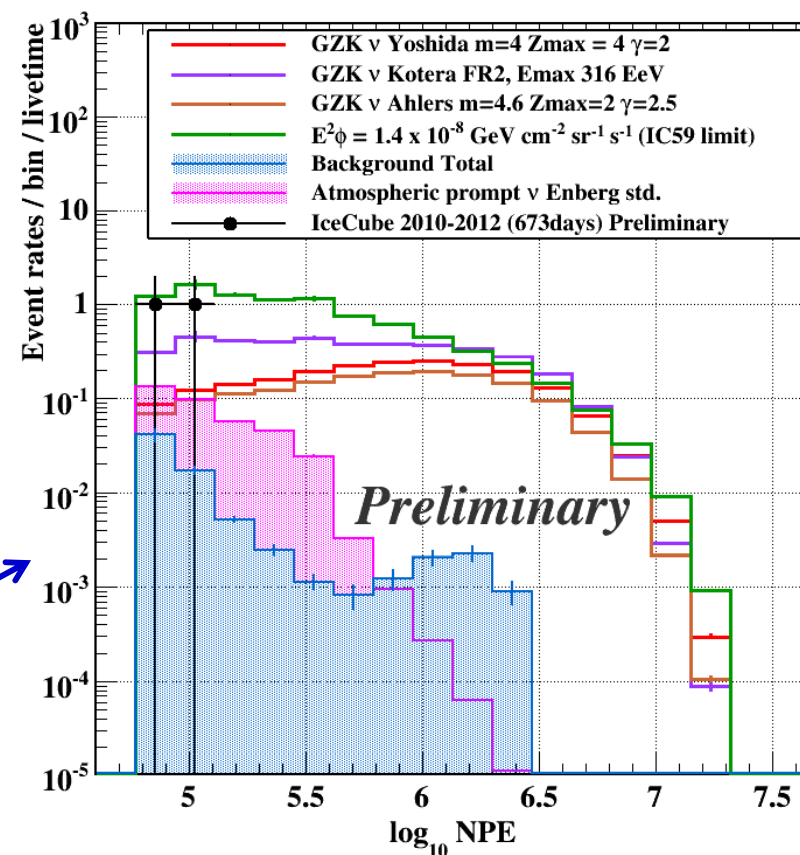
Event displays of one PeV diffuse neutrino event

No ν 's detected from point sources.

- Limits now well below initial estimates.

Diffuse Search: 2 detected events

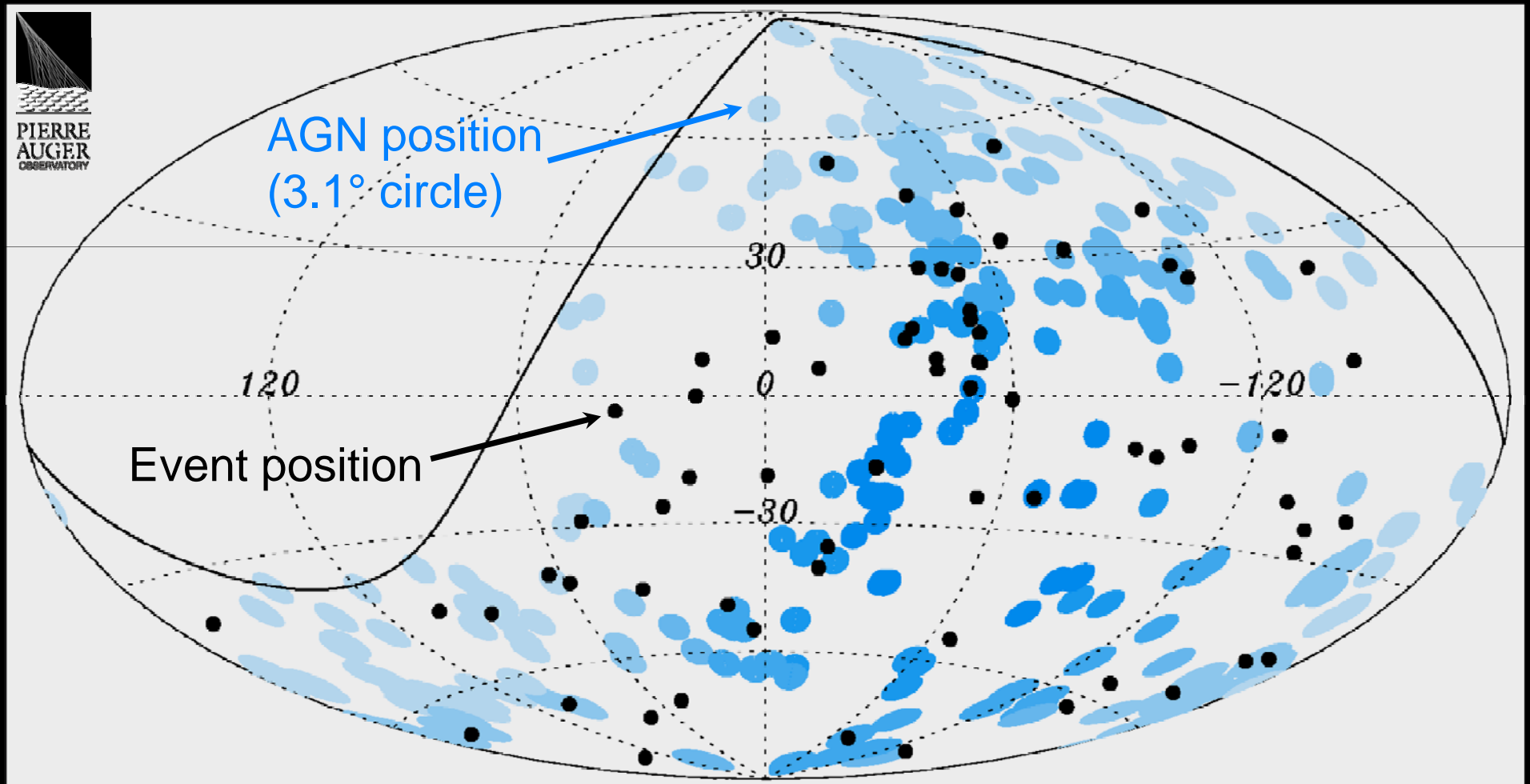
- 0.14 expected from background
- $E > 10^{15}$ eV



Number of photoelectrons detected by IceCube for two shower events, with models/bkgfn.

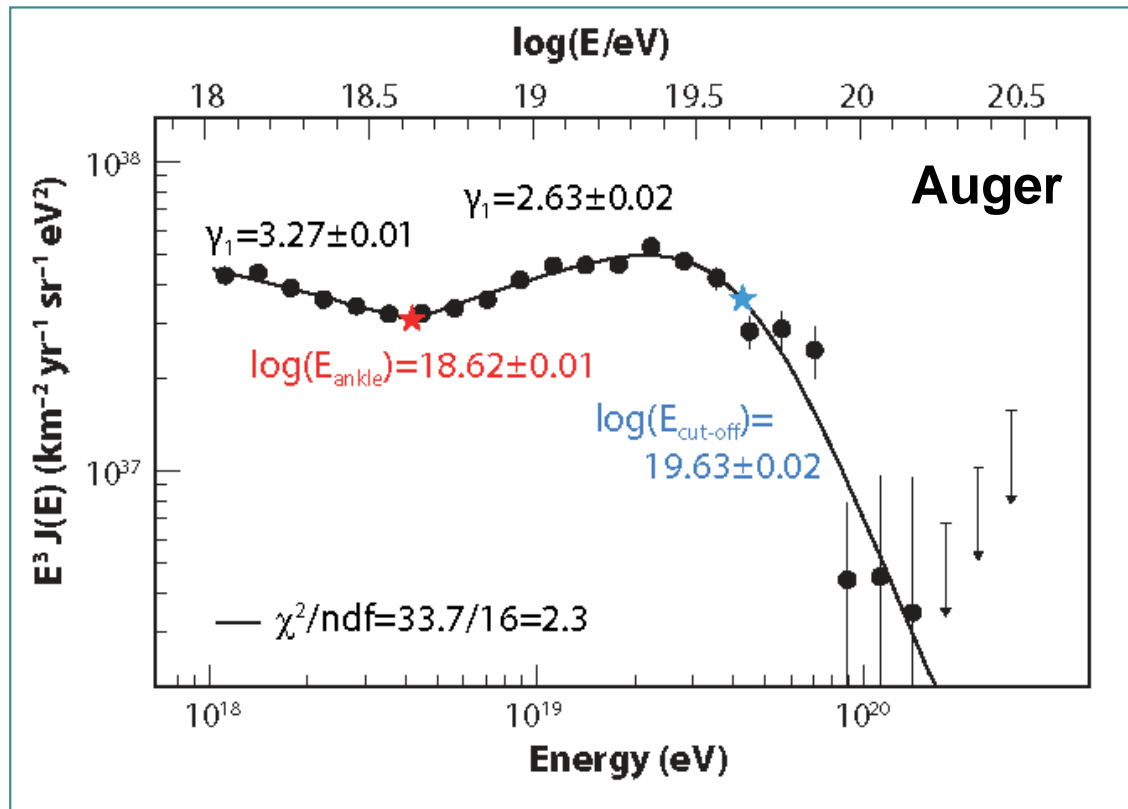
The 10^{19} eV Sky (c 2012)

P. Abreu et al., 2010

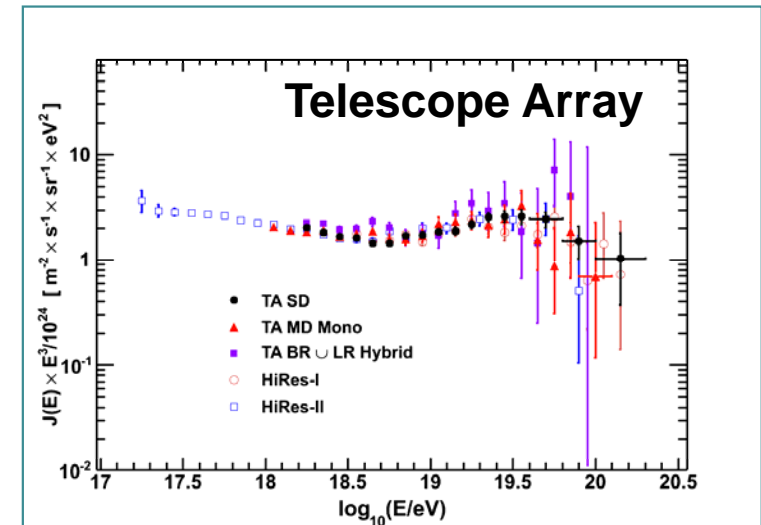


- EeV sky seen by Auger ($E > 55$ EeV), 69 events.
- Additional 25 events from Telescope Array ($E > 57$ EeV).

CR's at the Highest Energies



S. Westerhoff, "COSPAR 2012"



S. Westerhoff, "COSPAR 2012"

Origin is still unknown

- Auger and Telescope Array agree on spectrum – clear cutoff $\sim 6 \times 10^{19} \text{eV}$
→ Unclear if GZK effect or source acceleration limit
- Weakly correlated with nearby AGN/matter

WIMP Direct Detection

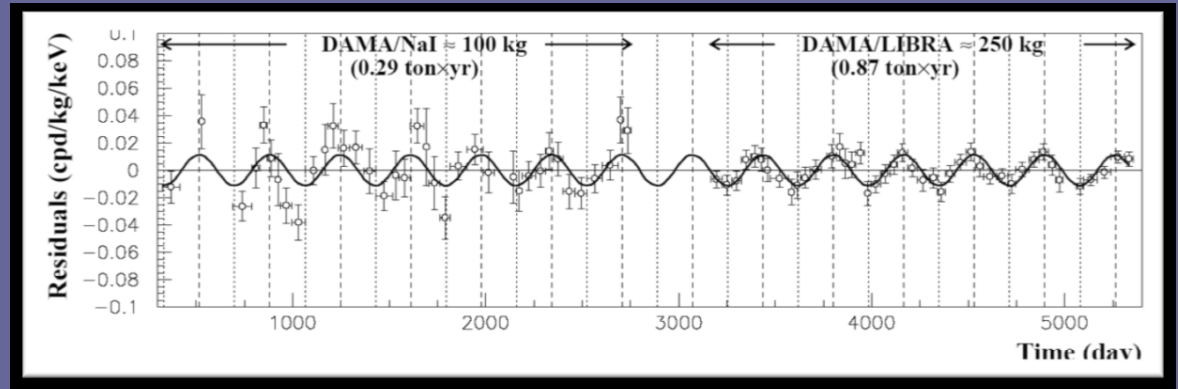
WIMP Evidence: Direct Detection

R. Bernabei et al., arXiv:1002.1028

DAMA/LIBRA

Ann. Modulation is $\sim 9\sigma$ effect

Is it due to DM ?



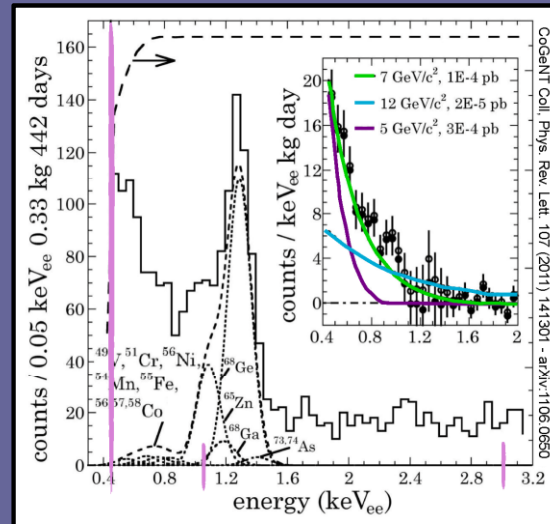
CoGeNT

442 live days

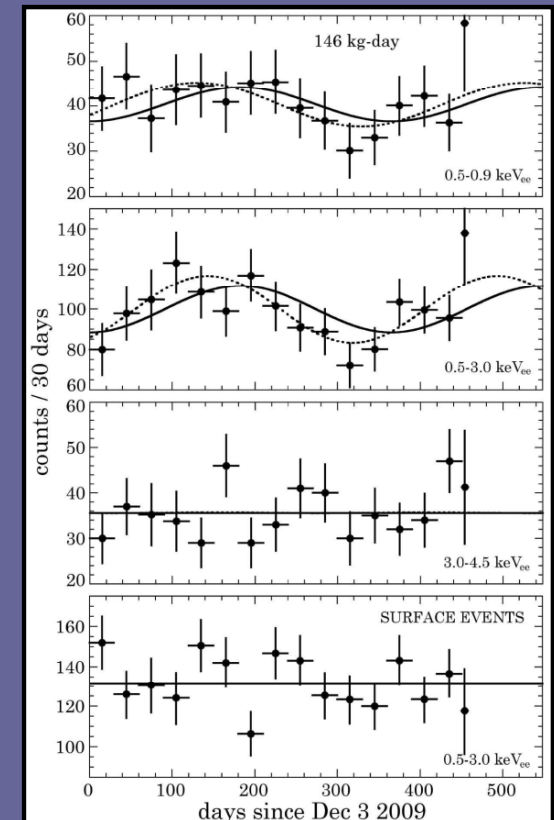
Low E threshold & extensive Bkgnd studies

2.8σ annual modulation
(4-5 times expected amount)

Continuing to take data ...

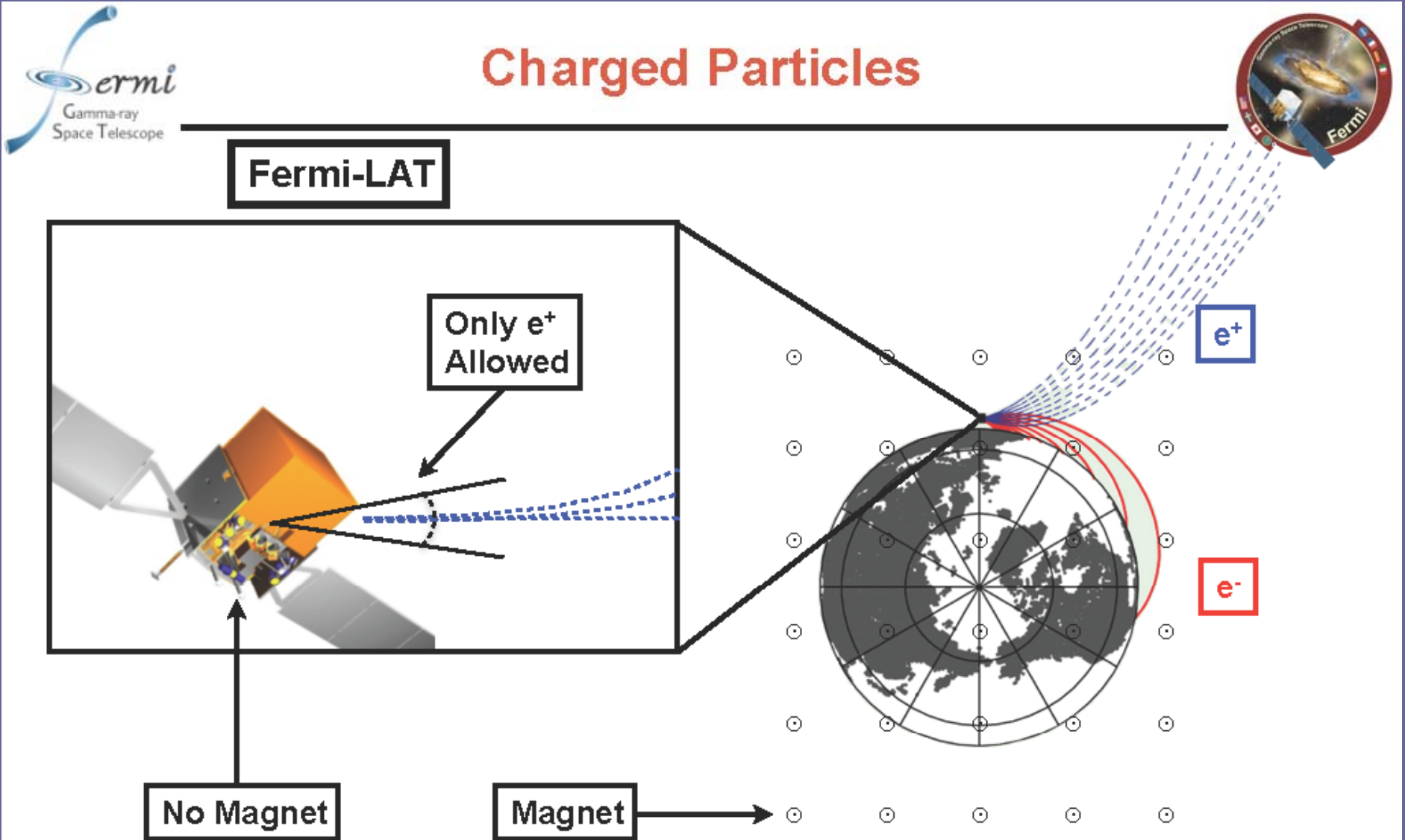


C.E. Aalseth et al.,
PRL 107, 141301 (2011)



DM Indirect Detection

Fermi e^+ Detection Technique

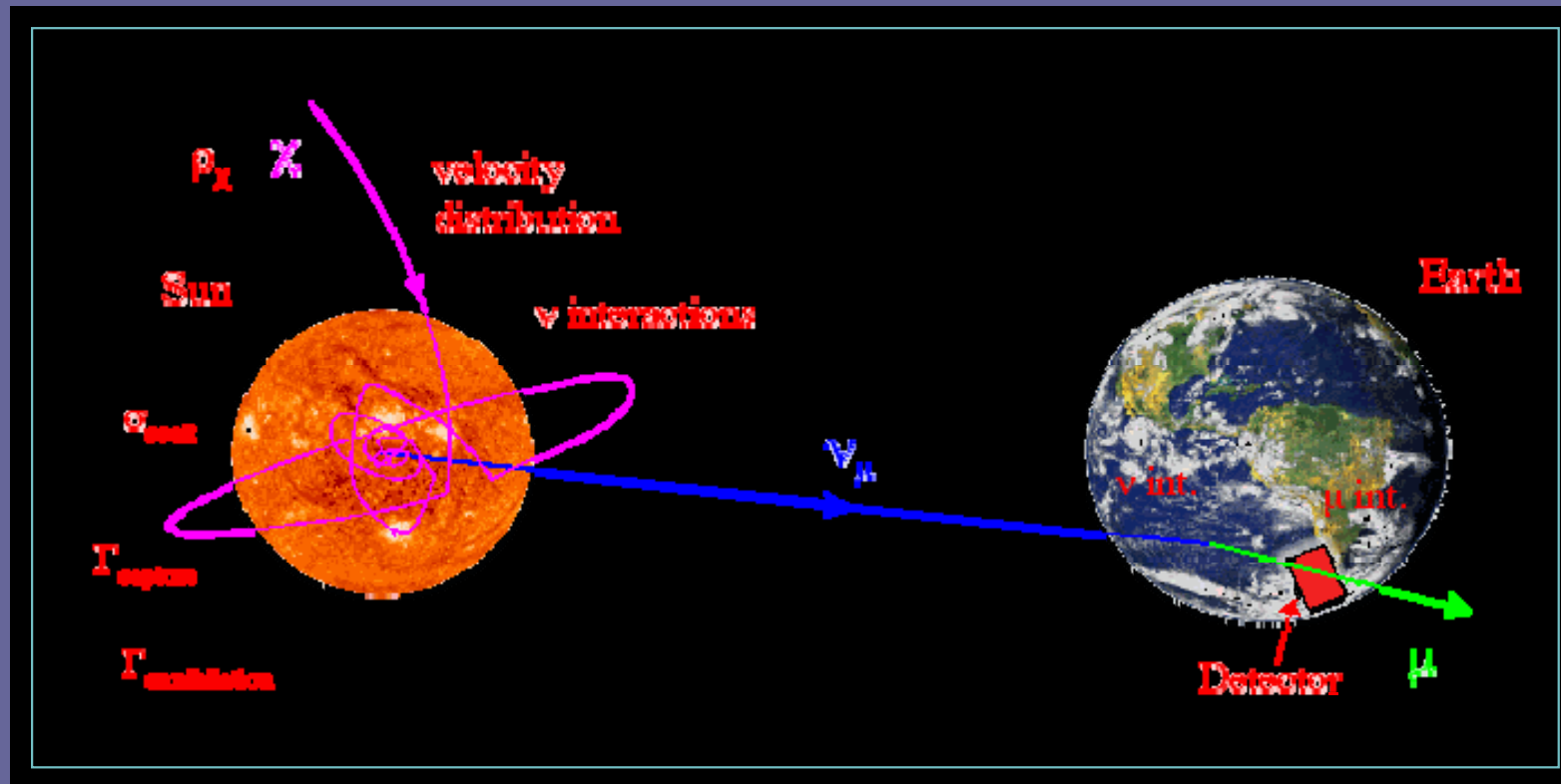


Ackermann et al., PRL 108, 1 (2012)

Daniel & Stephens, PRL 15, 769 (1965)

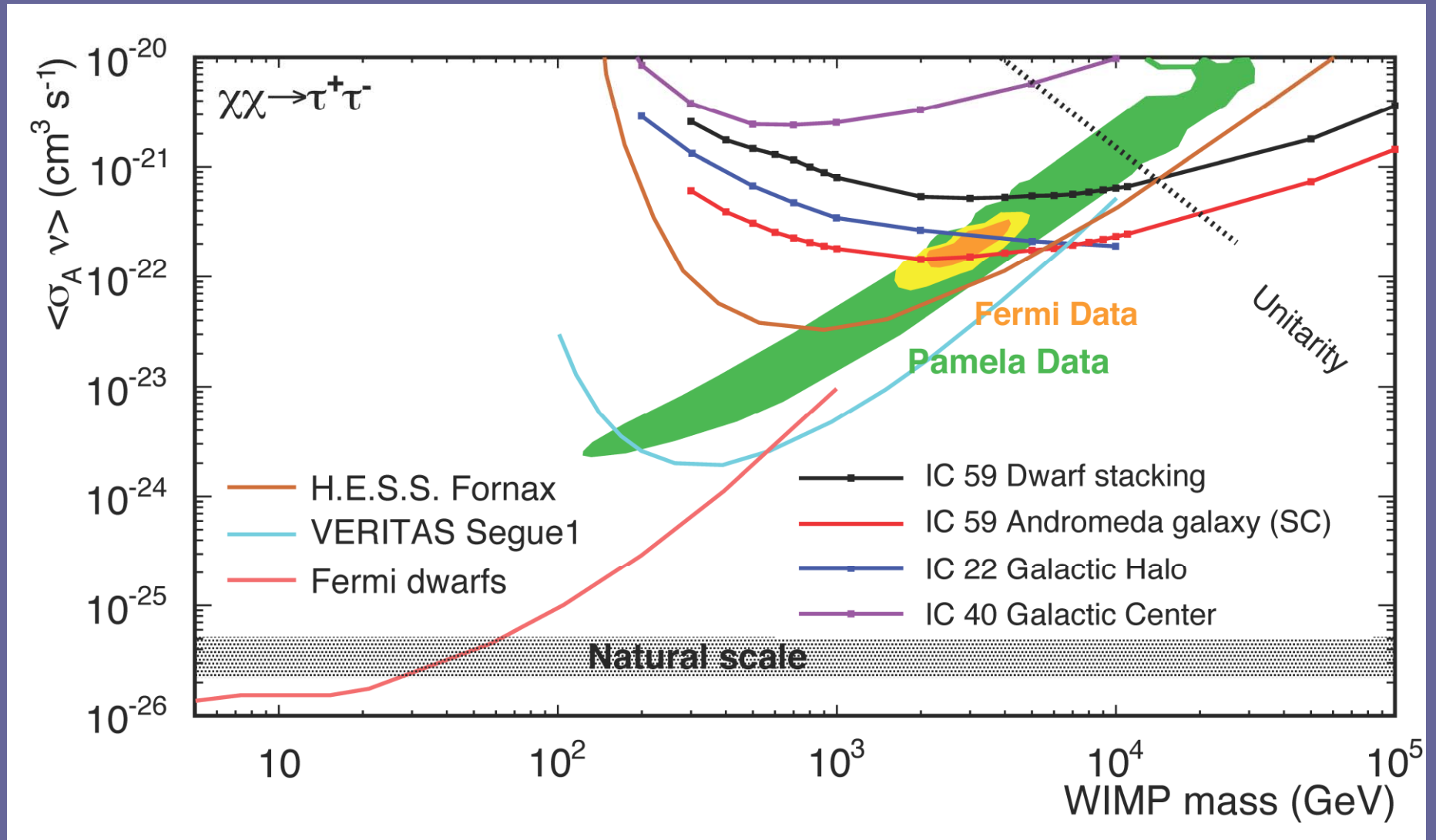
Müller & Tang, ApJ. 312, 183 (1987)

Neutrino WIMP Detection



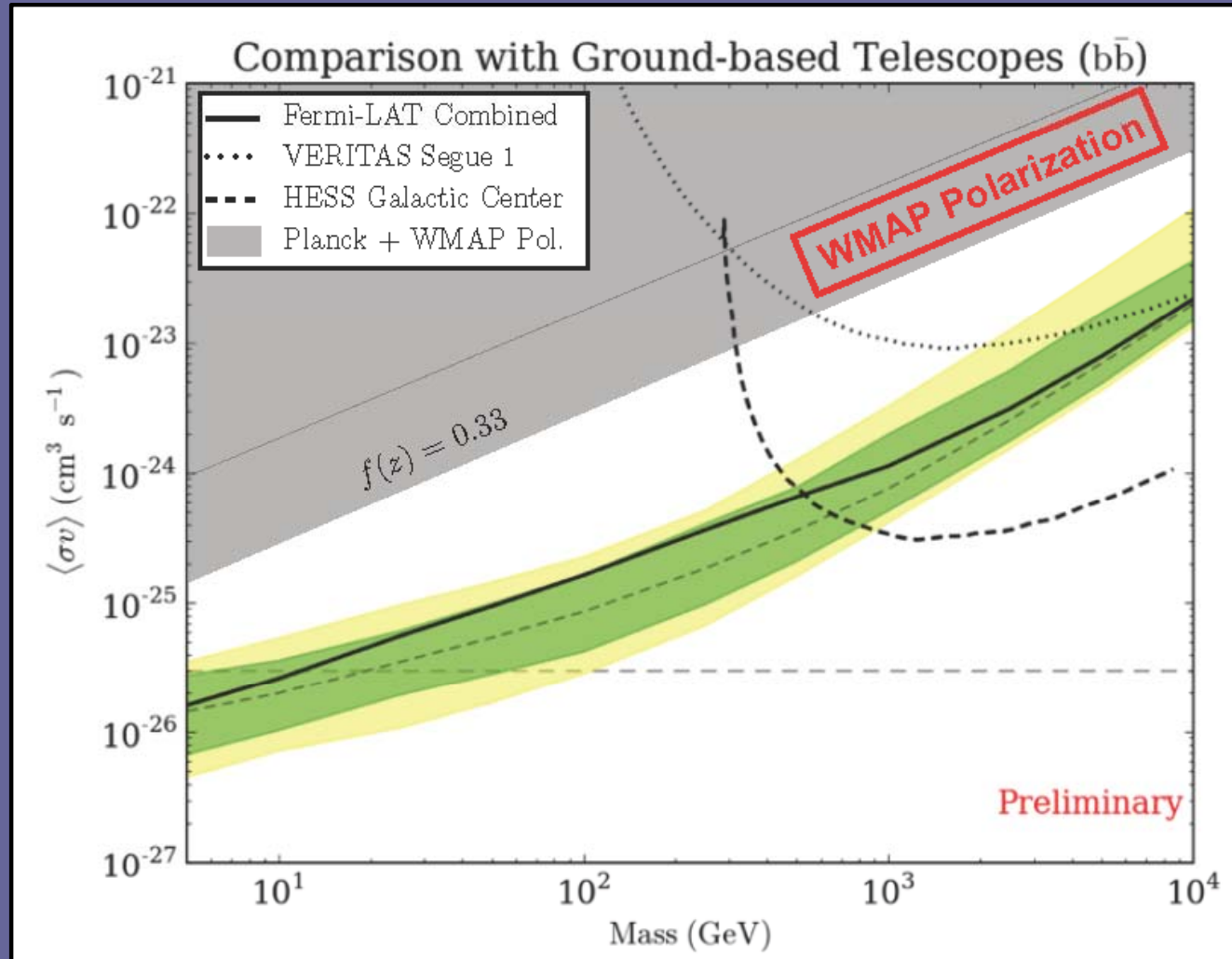
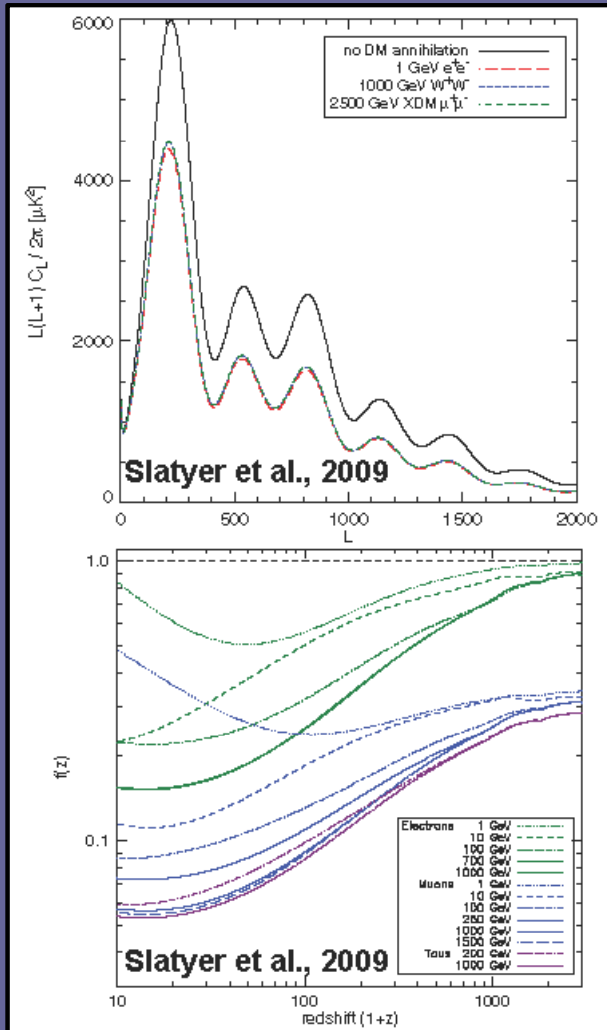
- WIMPs scatter off nuclei in Sun and get captured (σ_{SI} or σ_{SD}).
- WIMP annihilation produces primary or secondary neutrinos.
- Neutrinos detected on Earth in water or ice Cherenkov detectors.

Constraints on Leptophilic Scenario



CMB Constraints

- CMB power spectrum sensitive to energy injected near recombination
- Limit DM annihilation $\langle \sigma v \rangle$ from power spectrum



Some pMSSM Comparisons (Future)

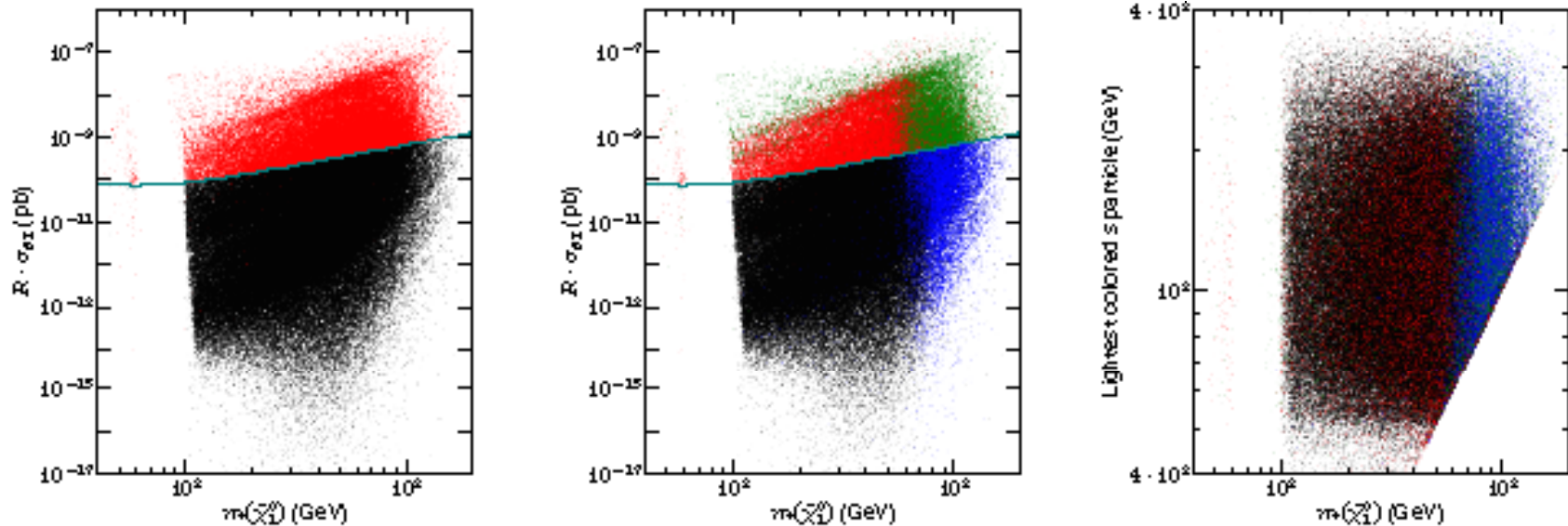
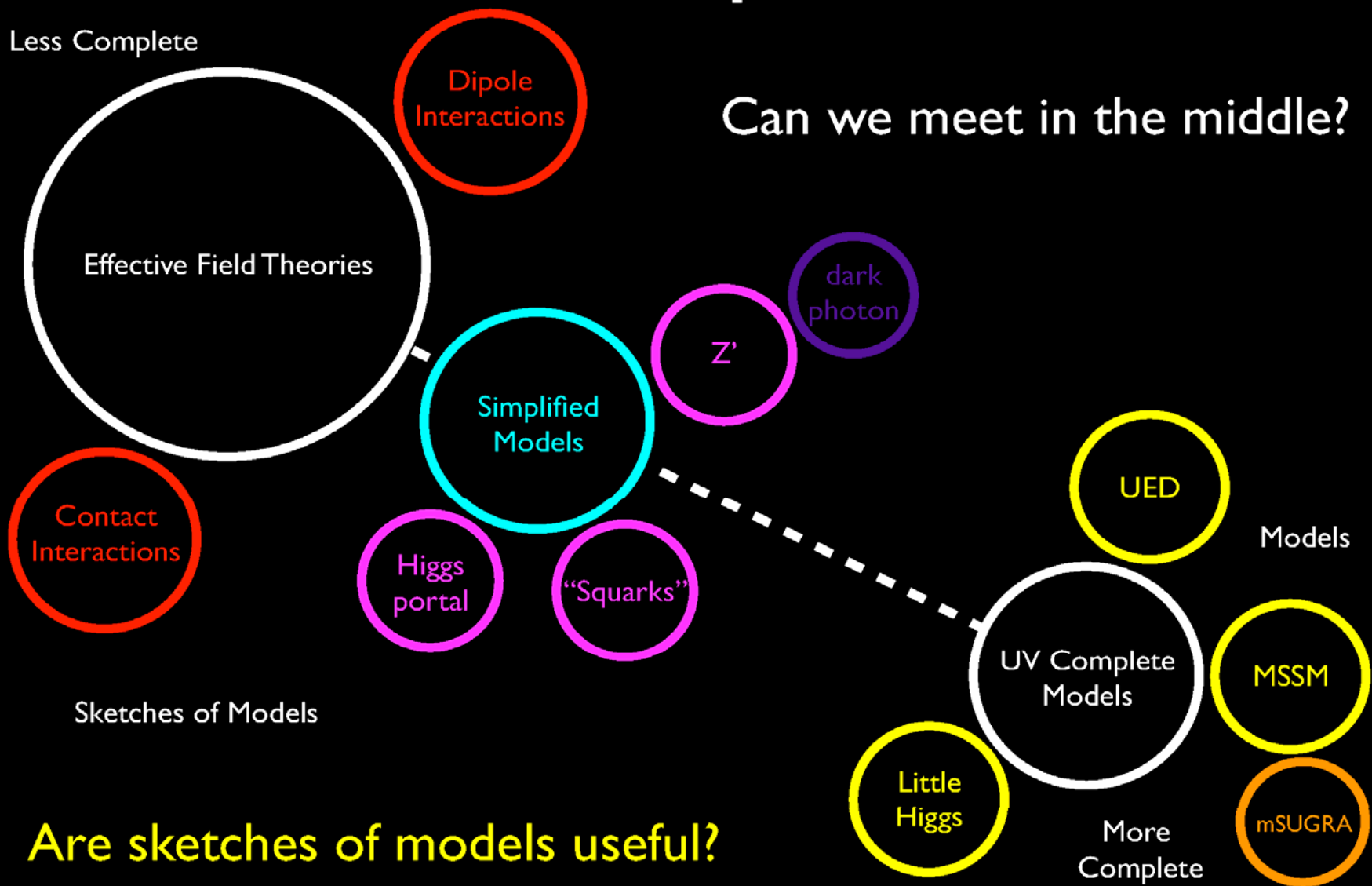


FIG. 3: Results from a model-independent scan [60] of the full parameter space in the minimal supersymmetric model (MSSM), presented in the $(m_\chi, \sigma_{\text{SI}}^p)$ plane (left and middle panels) or the $(m_\chi, m_{\text{LCSP}})$ plane (right panel). The models are divided into categories, depending on whether dark matter can be discovered in future direct detection experiments (red points), indirect detection experiments (blue points) or both (green points).

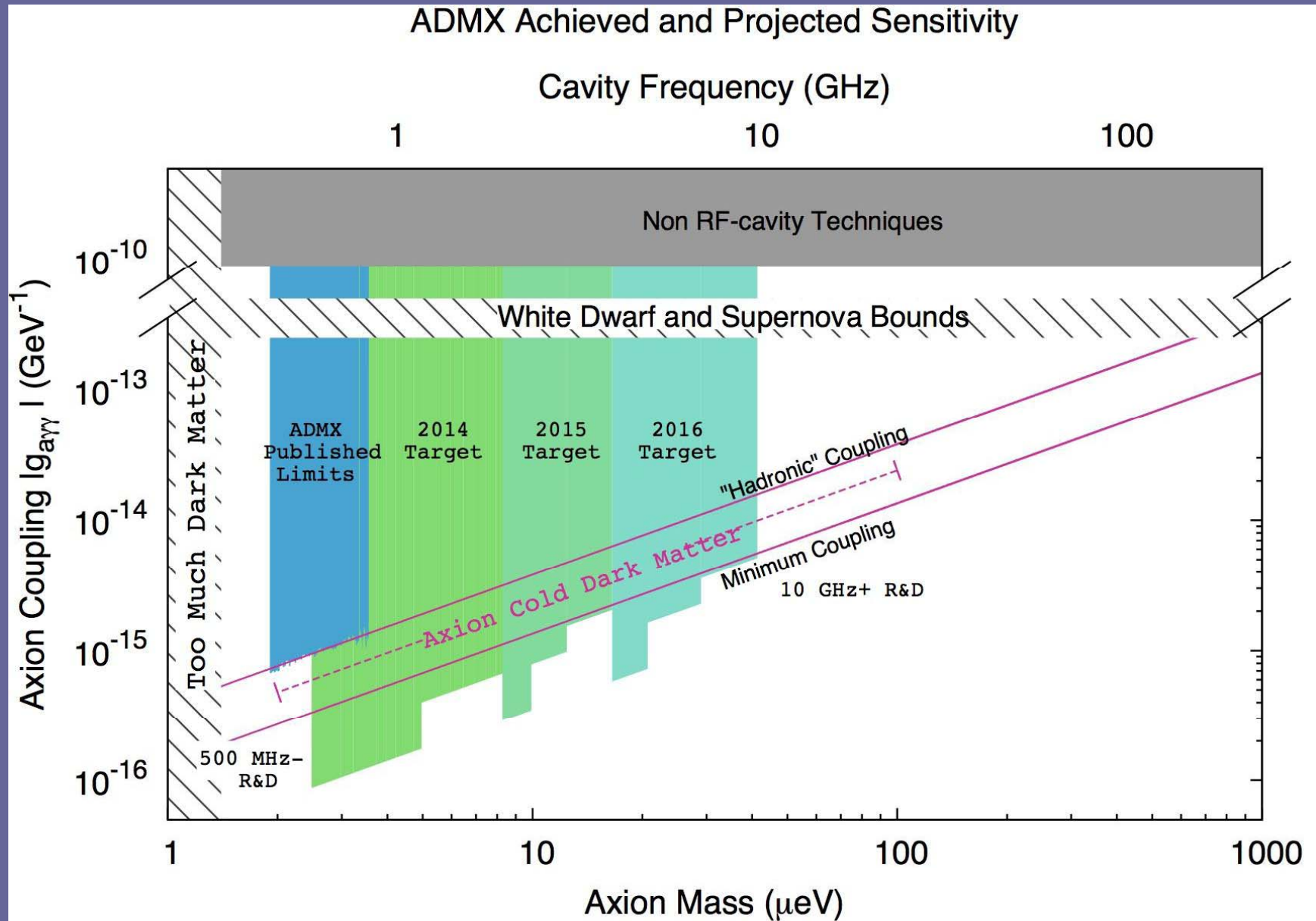
WIMP Comparisons to LHC

How about Simpler Theories?

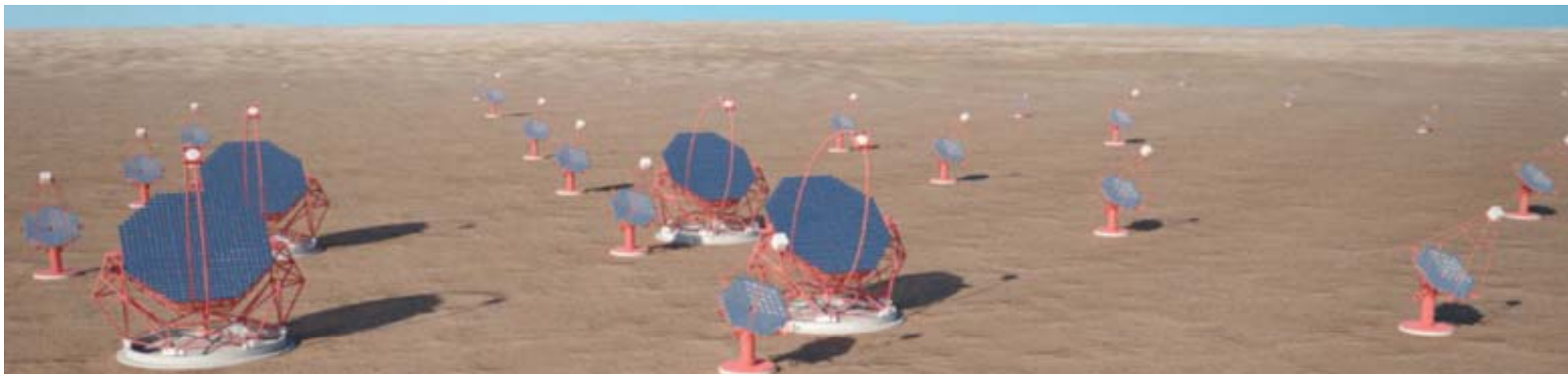


Future Experiments

ADMX Target Sensitivity



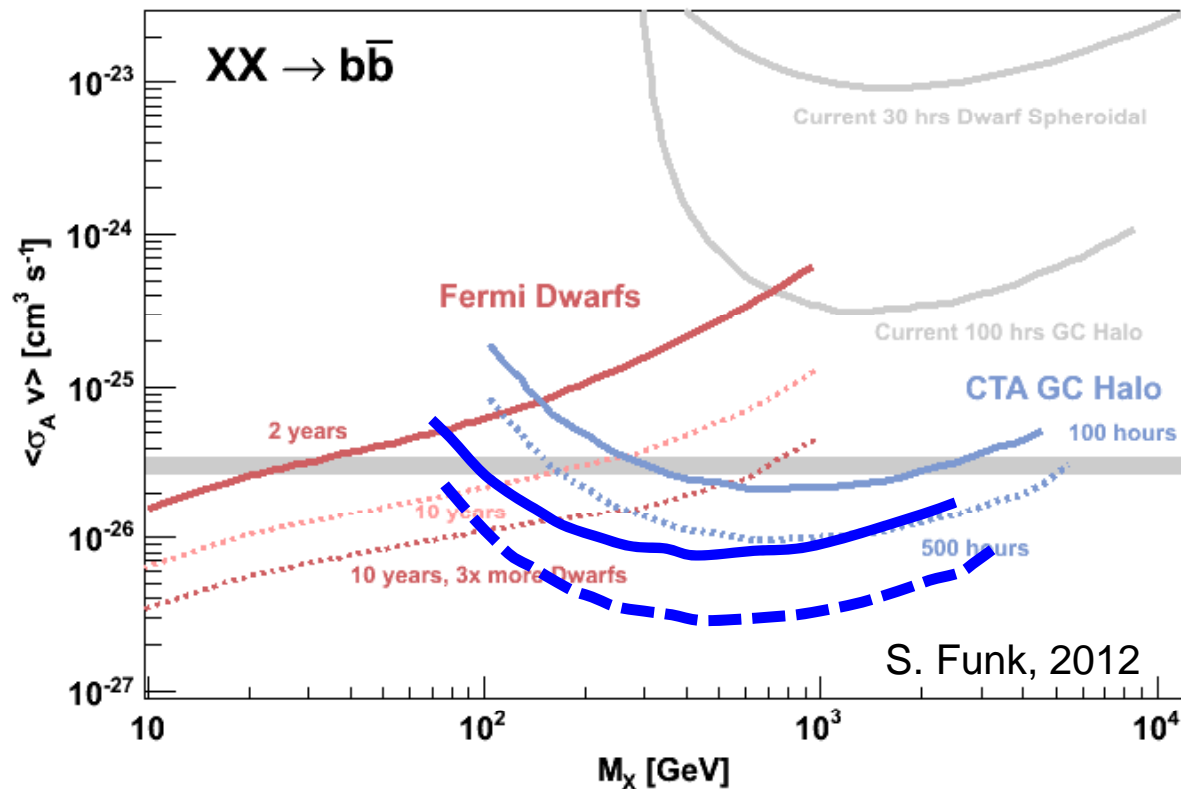
Cherenkov Telescope Array (CTA)



CTA: artist's conception

Key features of CTA:

- Factor of 10 more sensitive, better σ_{ang} and σ_E than HESS/VERITAS.
- Wide E range: 25 GeV – 100 TeV.
- Wide field-of-view ($>6^\circ$).
- Two sites: S (10 km²), N (1 km²)
- 40-80 Cherenkov telescopes/site.
- Open observatory.
- Complemented by HAWC (wide-field, high duty cycle) in N.

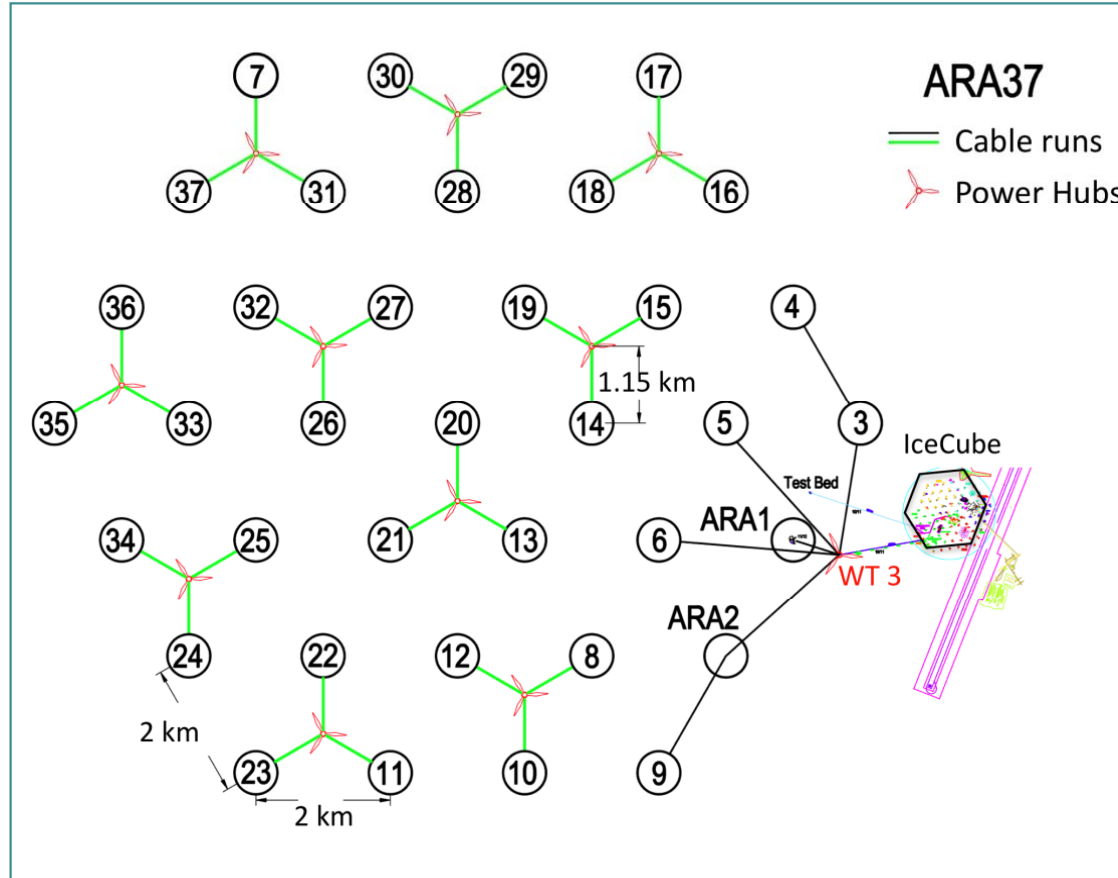


CTA and Fermi dark matter sensitivity

Askaryan Radio Array (ARA)

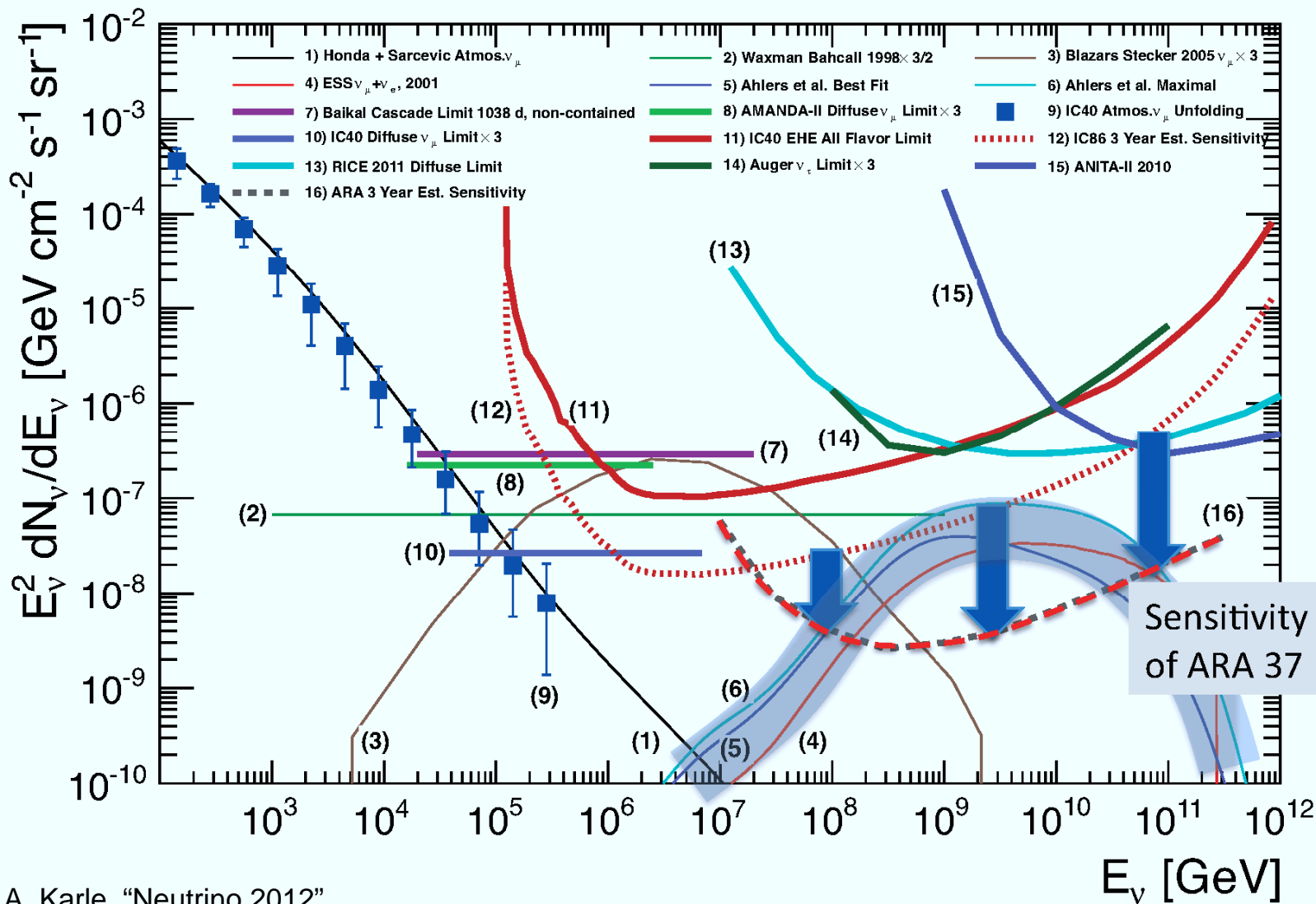
ARA:

- Very large (~150 km²) radio neutrino detector at South Pole.
- Uses Askaryan effect to detect radio Cherenkov signal.
- Main science goal: GZK neutrinos, $E > 10^{17}$ eV.



Possible layout for ARA at South Pole

ARA Projected Sensitivity



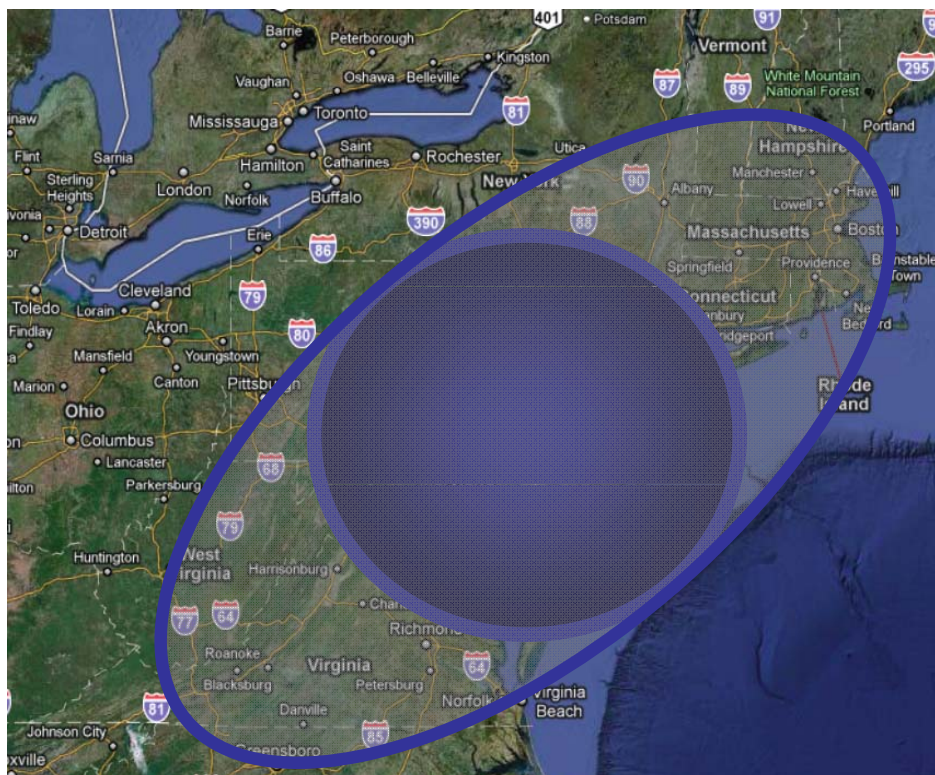
A. Karle, "Neutrino 2012"

ARA 3-year sensitivity to diffuse neutrino flux

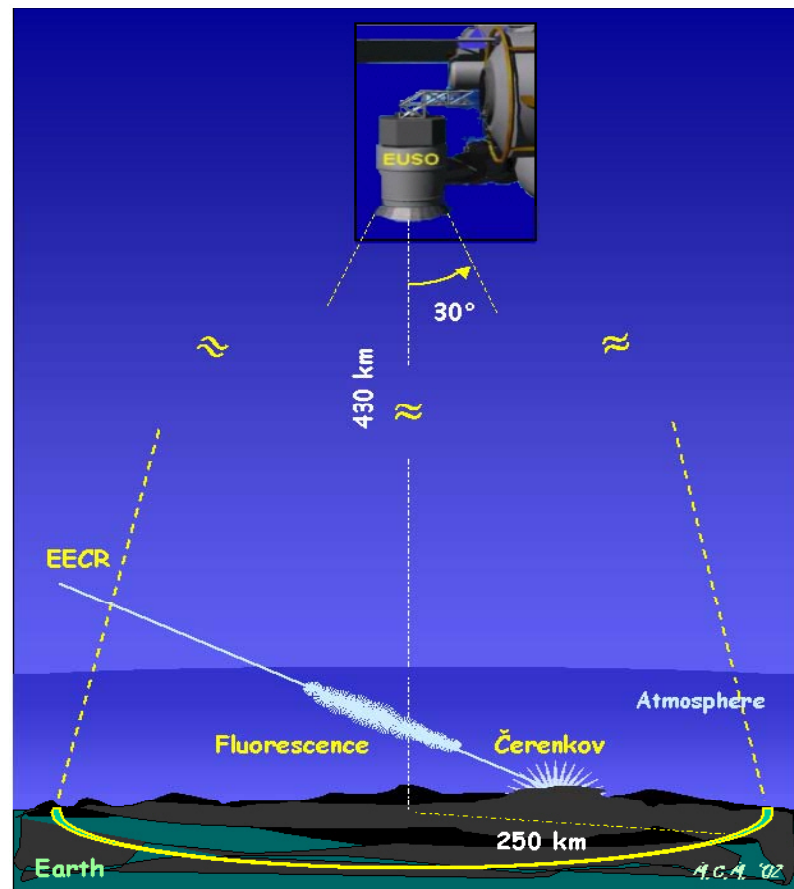
JEM-EUSO: UHECRs in Space

JEM-EUSO:

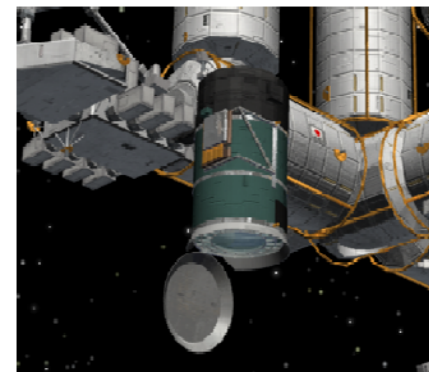
- N_2 fluorescence detector on ISS.
- Exposure/year is x10 Auger.
- Proposed launch in 2017.



JEM-EUSO effective area in nadir & tilt modes.

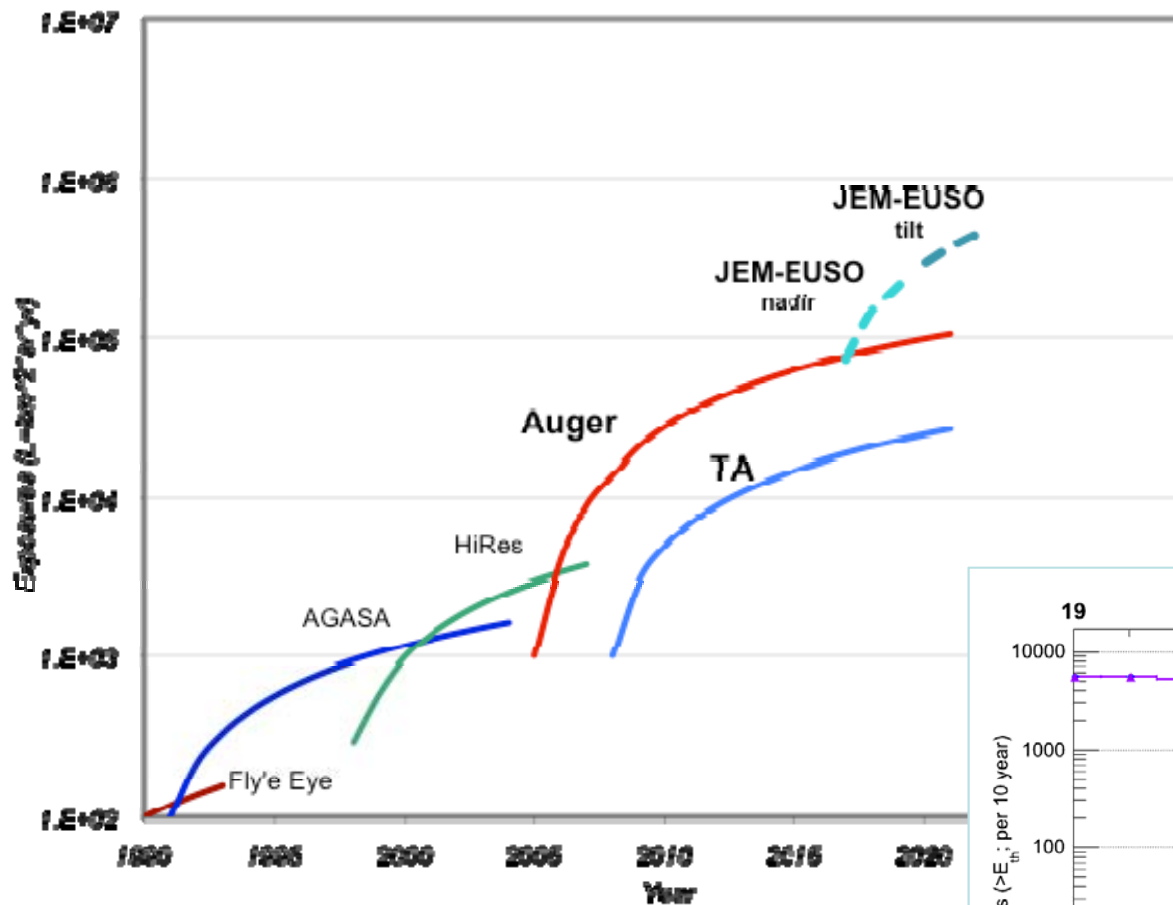


JEM-EUSO concept

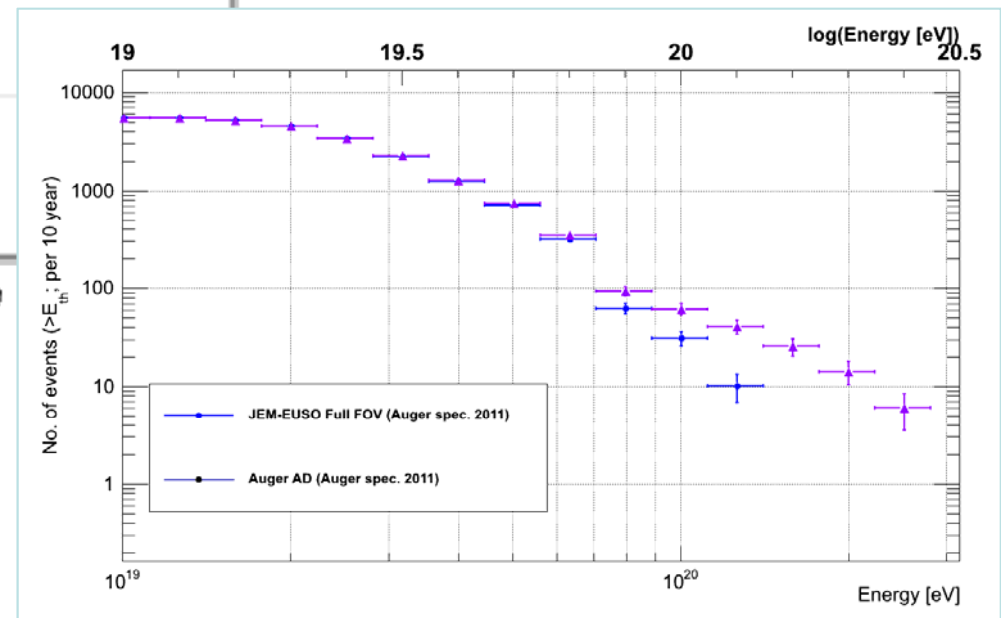


JEM-EUSO on ISS (nadir).

JEM-EUSO Energy Reach



UHECR exposure versus time.



JEM-EUSO expected event numbers (5 years).