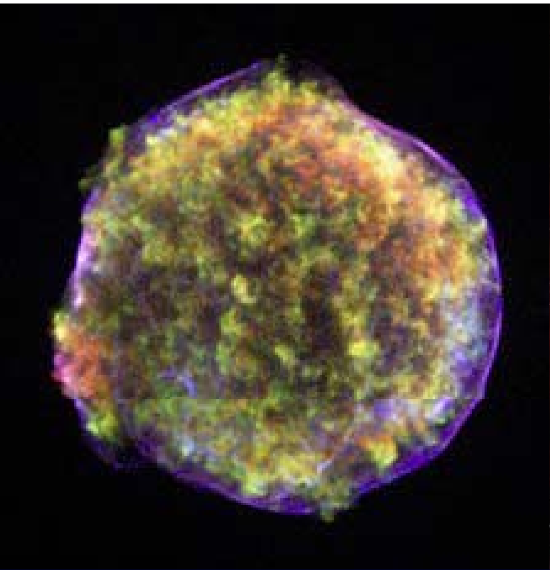
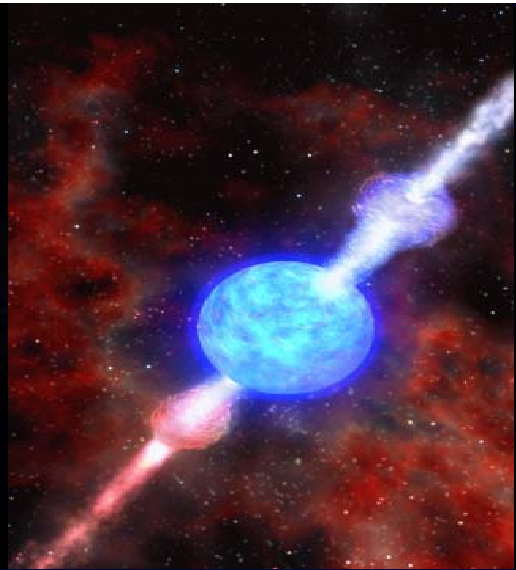
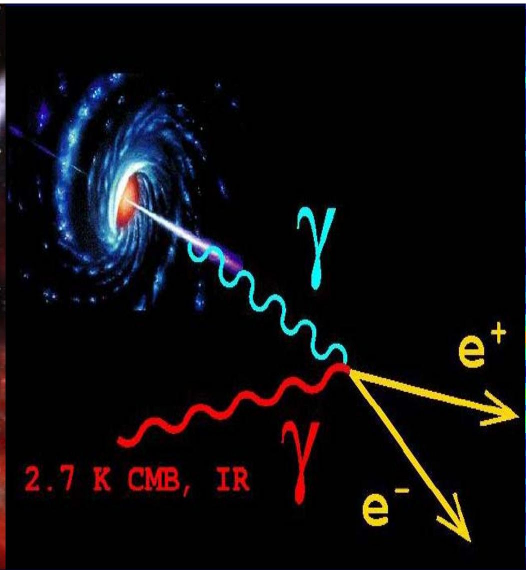
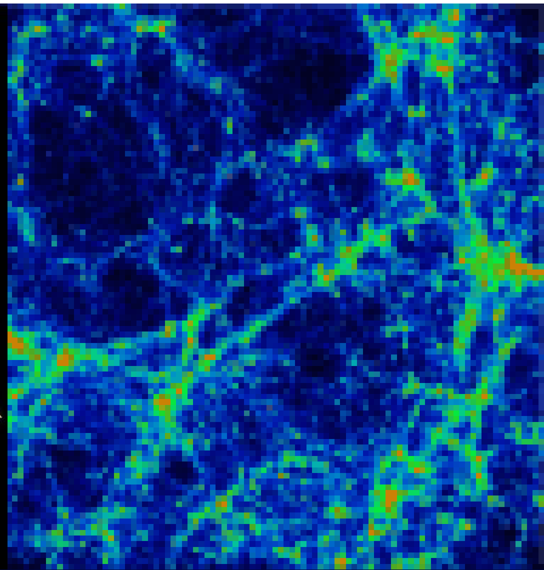
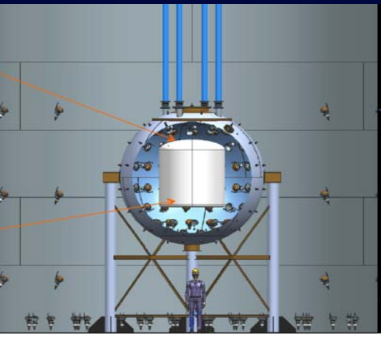
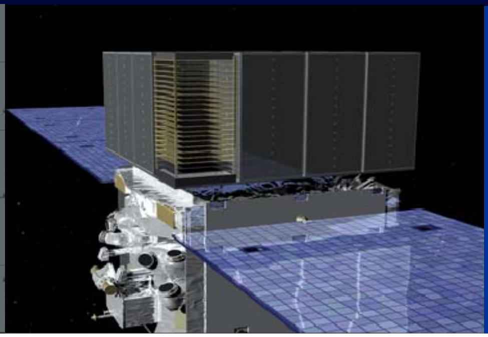
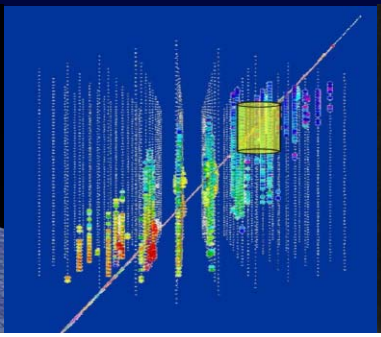






Astroparticle Physics

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

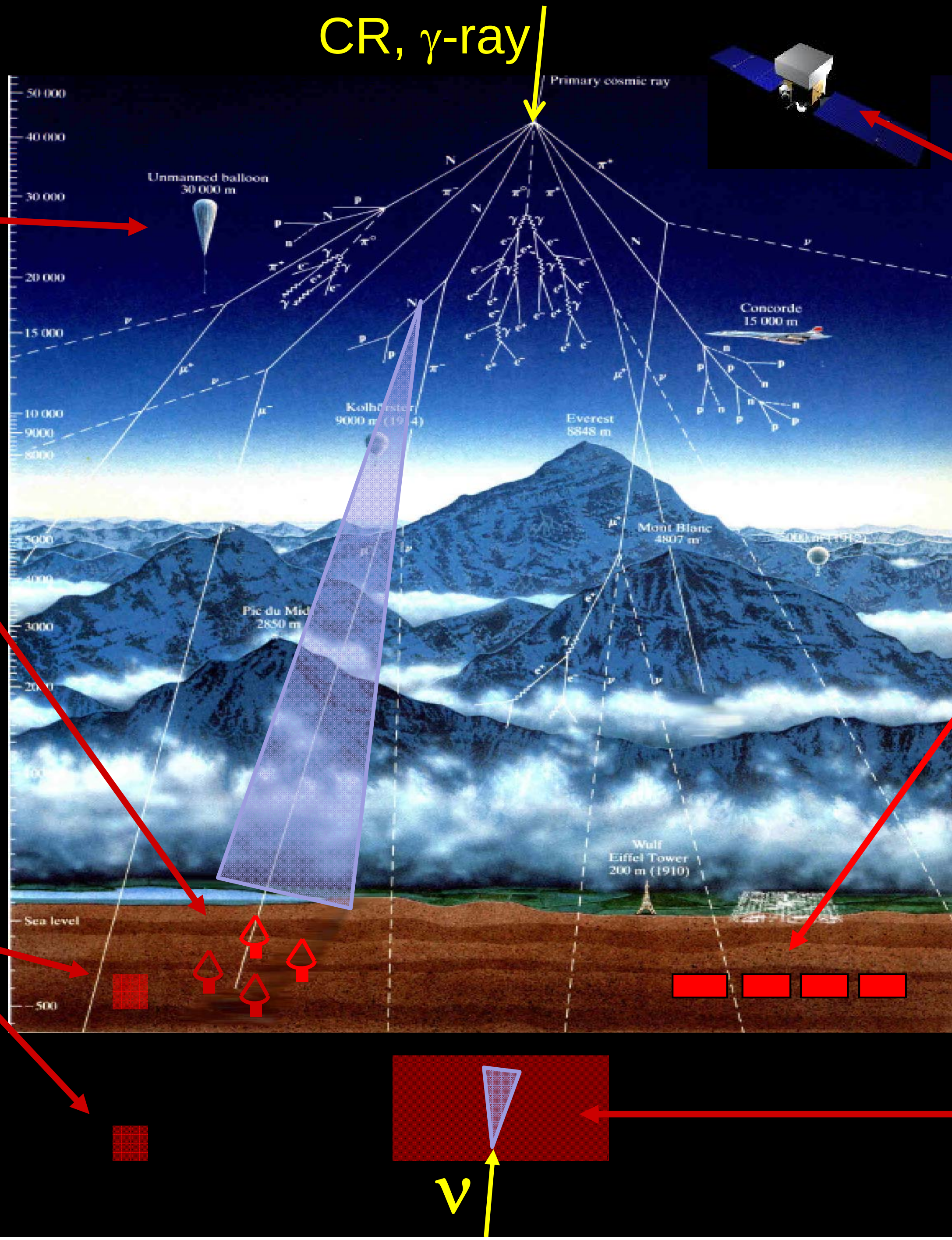
C. Other Topics (possibly connected to LHC)

- 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 …

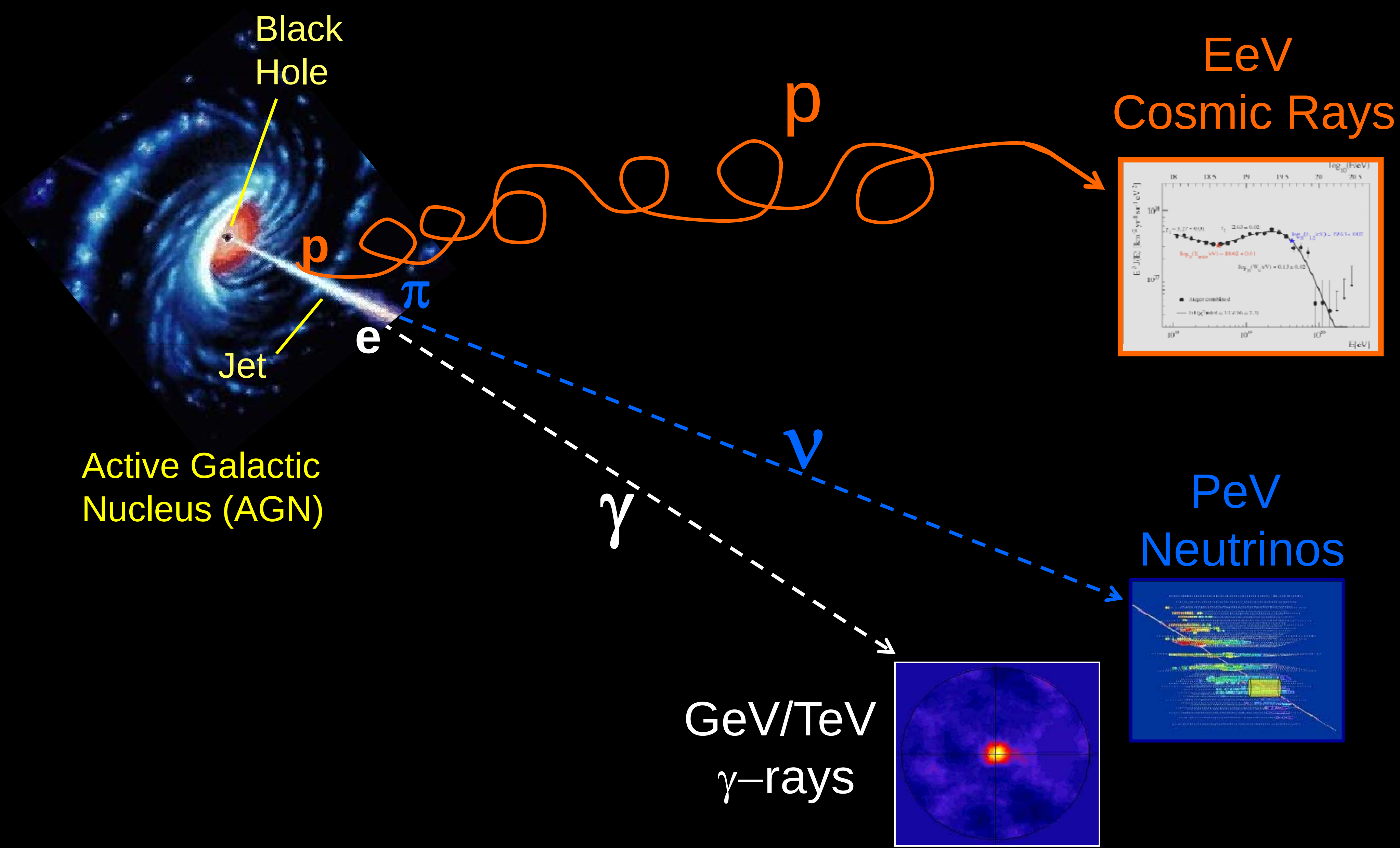
Ice/Water Cherenkov Detectors

Outline

A. Very High Energy (VHE) Astrophysics

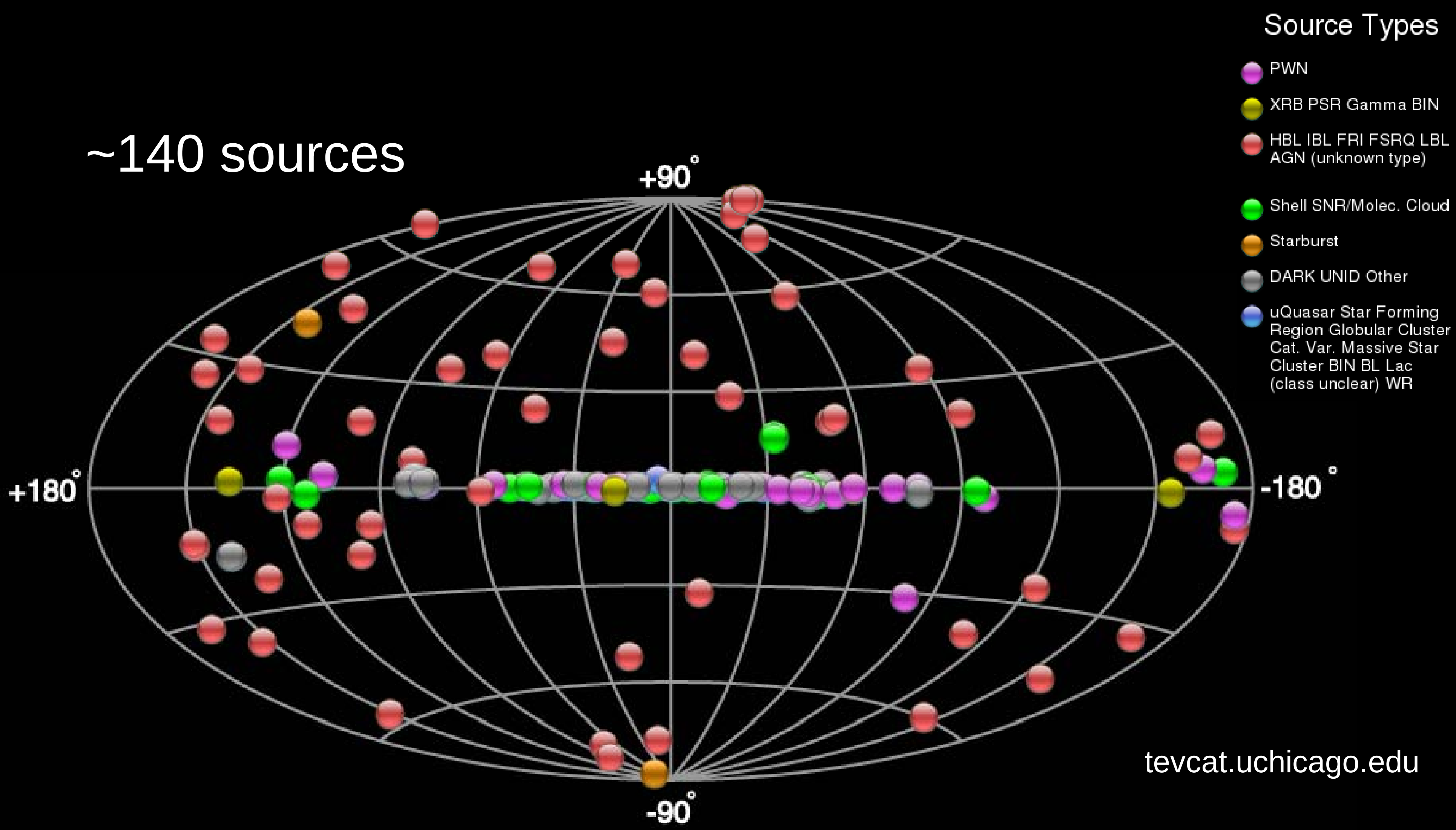
- VHE sources of γ-rays (and possibly neutrinos and CR's)

VHE Multi-Messenger Astrophysics



TeV γ-ray Sky c2013

~140 sources



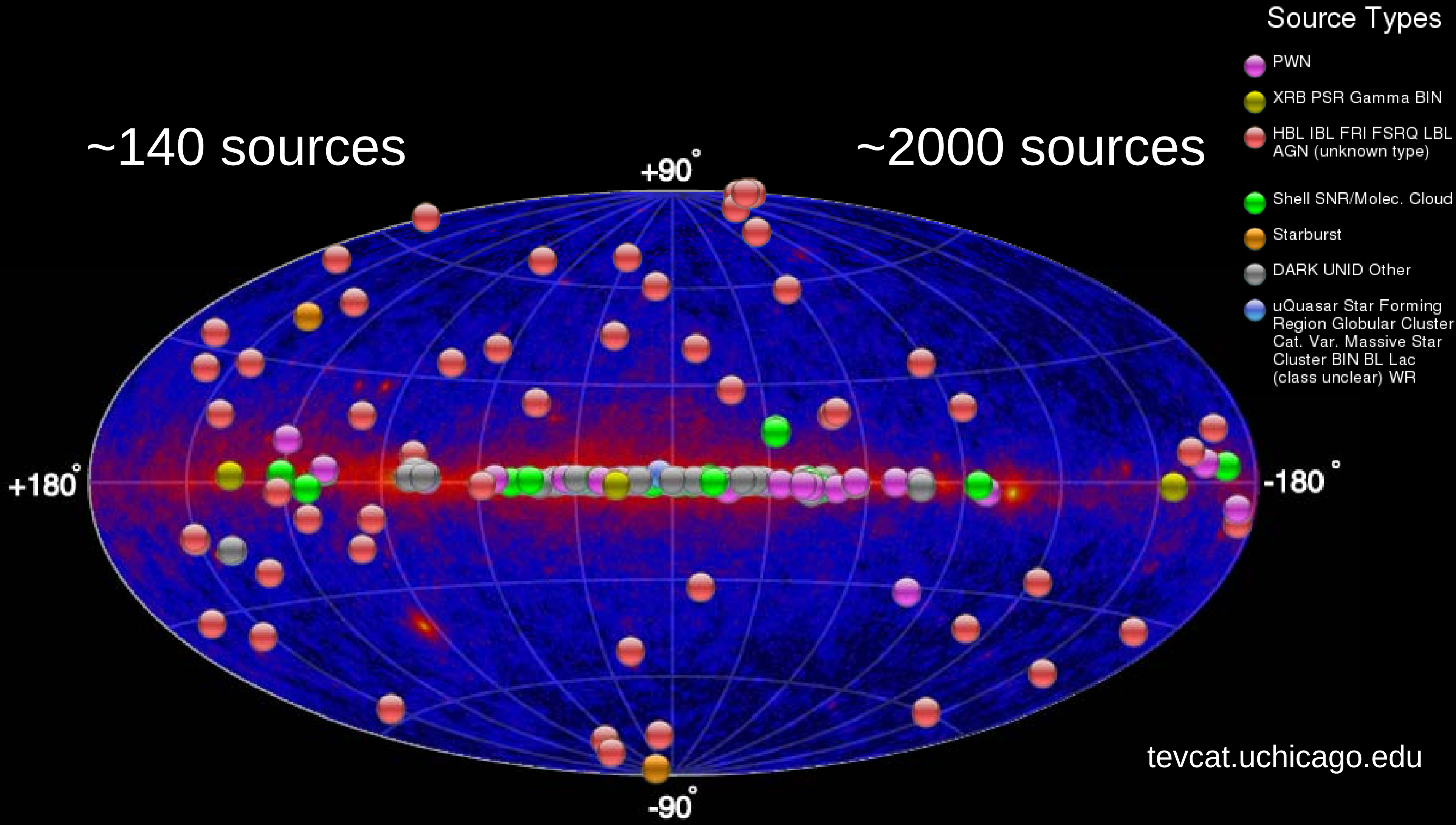
tevcat.uchicago.edu

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

VHE γ-ray Sky c2013 + HE γ-ray Sky

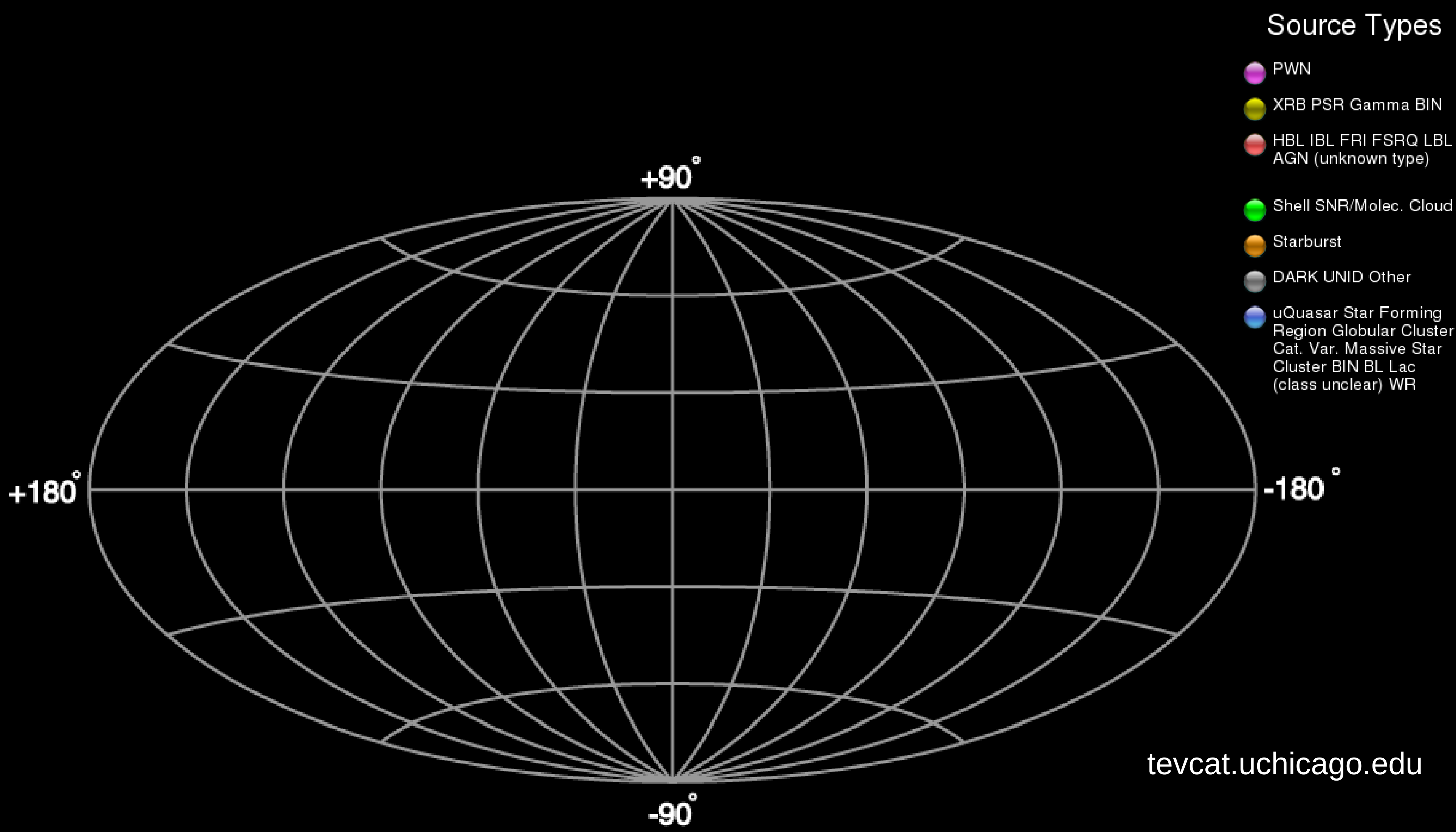
~140 sources

~2000 sources



tevcat.uchicago.edu

VHE/UHE ν Sky c2013

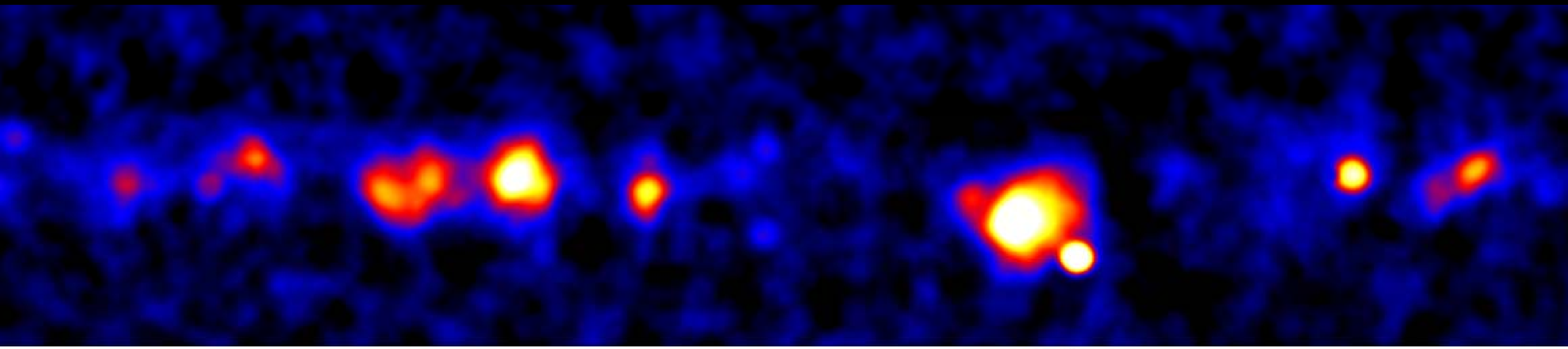


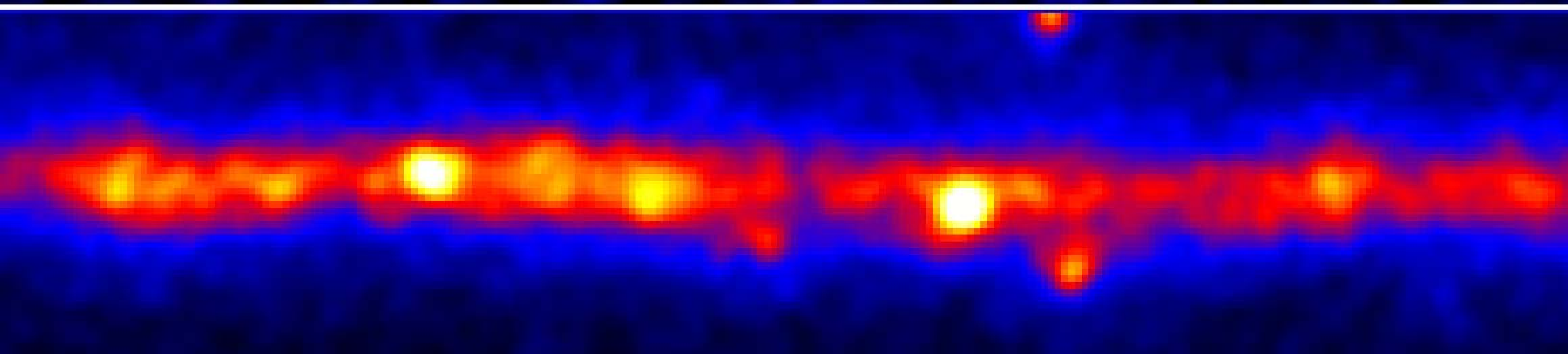
- Neutrino detections should be coming soon !

The High Energy Milky Way

Extended sources, size typically few 0.1^{o}
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

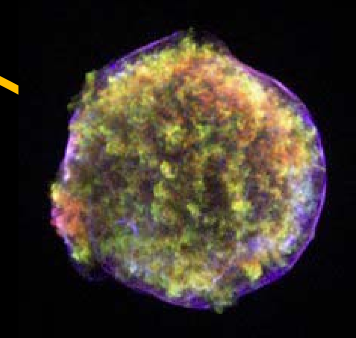
AGN

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

Star Forming Regions

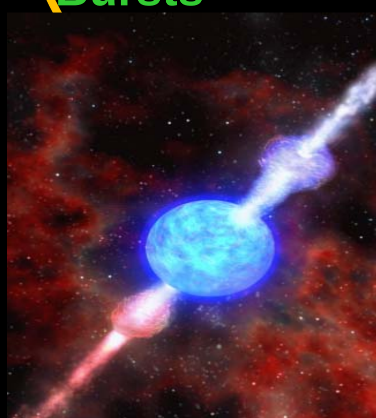
SNRs, cosmic rays, molecular clouds.

Supernova Remnants



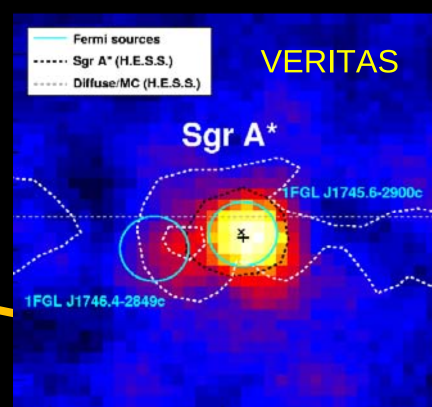
Fermi Acceleration

Gamma-Ray Bursts



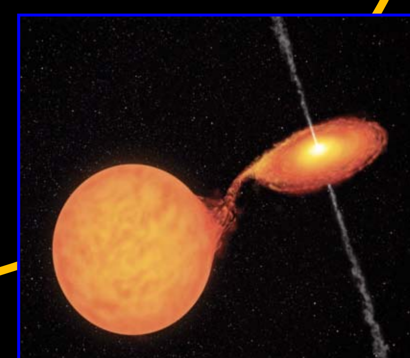
Star collapse→ relativistic jets

Unidentifieds



???

Binary Systems



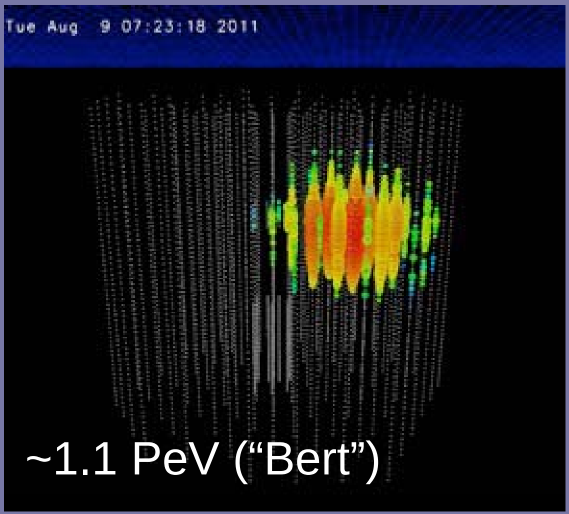
Accretion jets or stellar winds

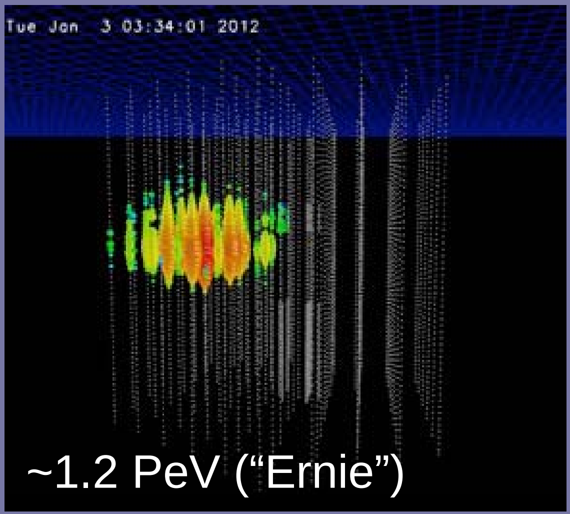
Latest IceCube Results

Simple Search for Diffuse ν's

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

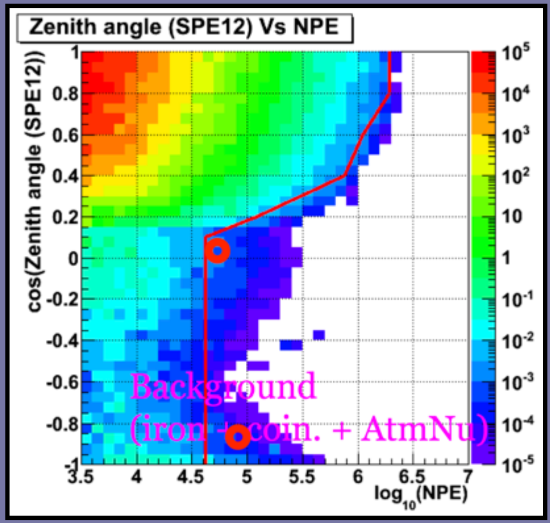
Find 2 events (0.08 exp. bkgnd)



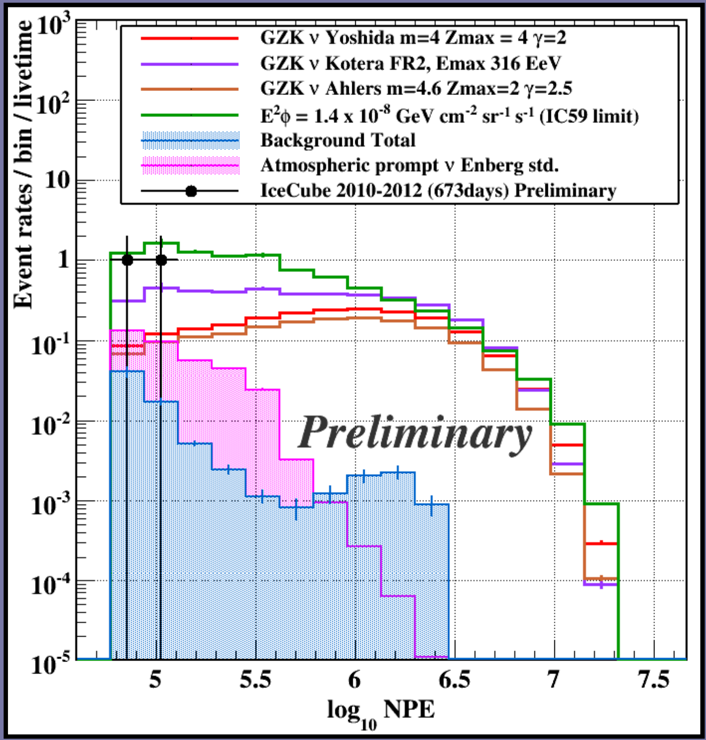


Not consistent with atm. background nor consistent with expected cosmogenic ν.

… perhaps the "tip of the iceberg" ?!



C. Kopper, LLWI 2013



Outline

B. AP Topics Connected to LHC

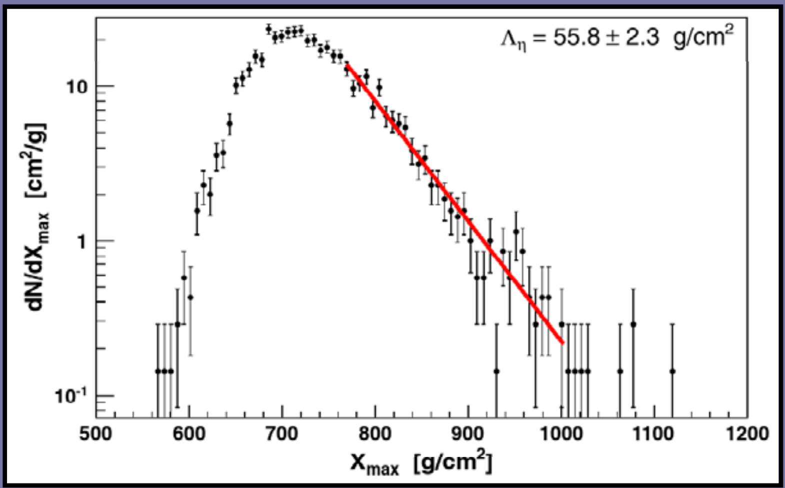
- Proton-Proton Cross Section at 70 TeV
- WIMP DM – Direct and Indirect Detection Results & LHC

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

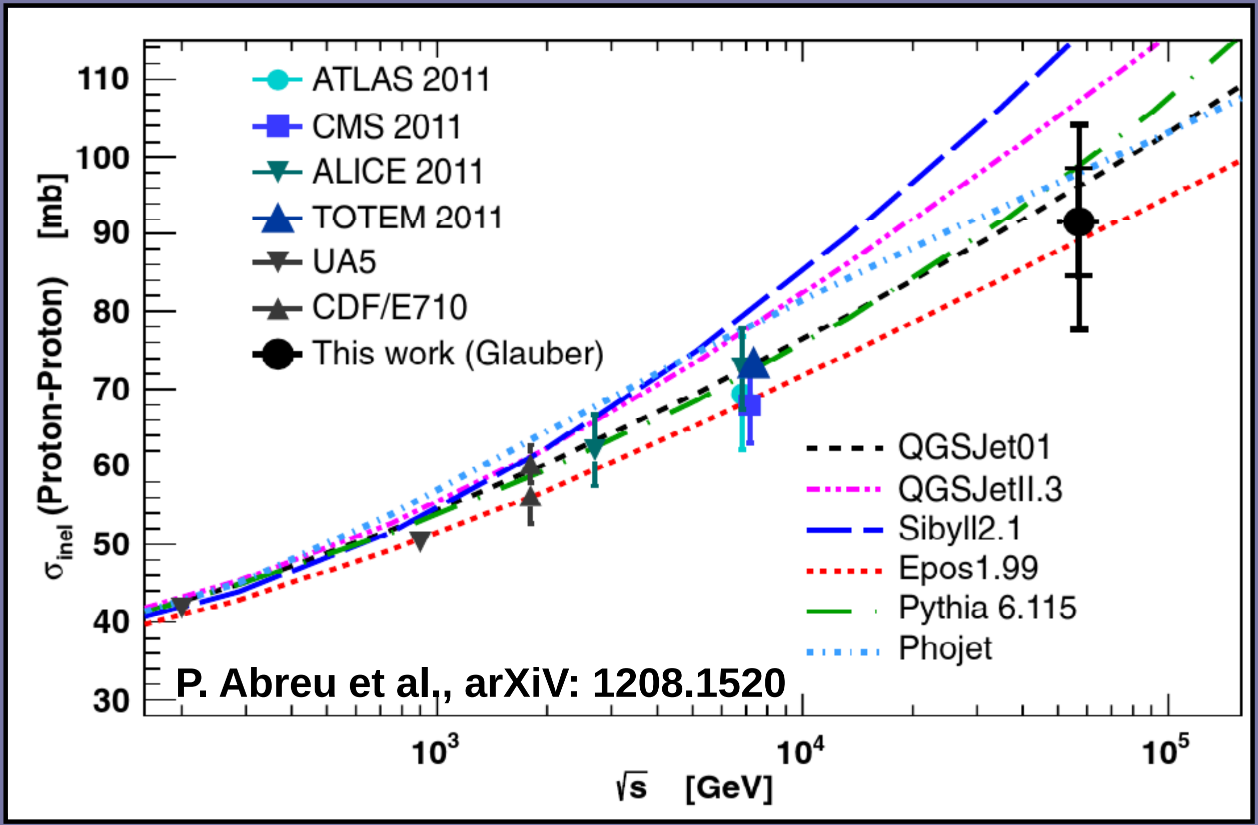
Auger measures p-air collisions at $E_{lab} \sim 10^{18}$-$10^{18.5}$eV

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

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



dn/dx_{max} distribution



Auger results consistent with smooth extrapolation from LHC.

Dark Matter

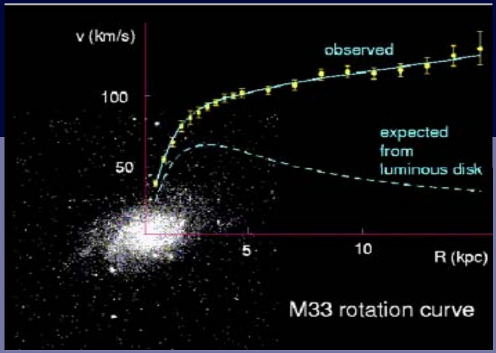
Postulated in the 1930’s, dark matter (DM) remains one of the deepest mysteries of science.

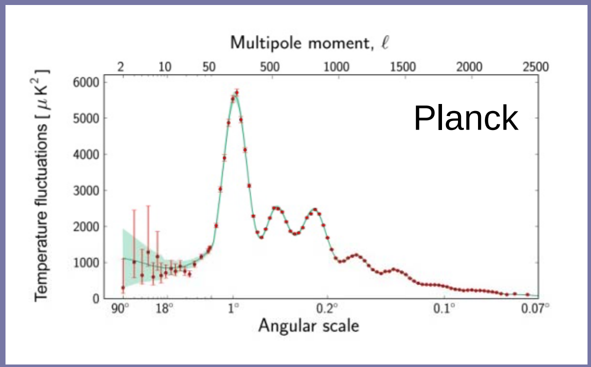
There is now <u>overwhelming evidence</u> for existence of DM.

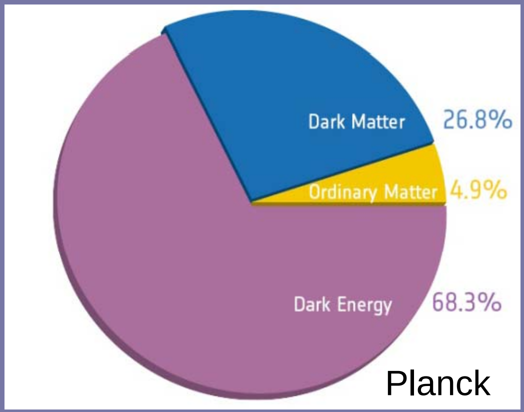
What we do know:
Dark matter:

- 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

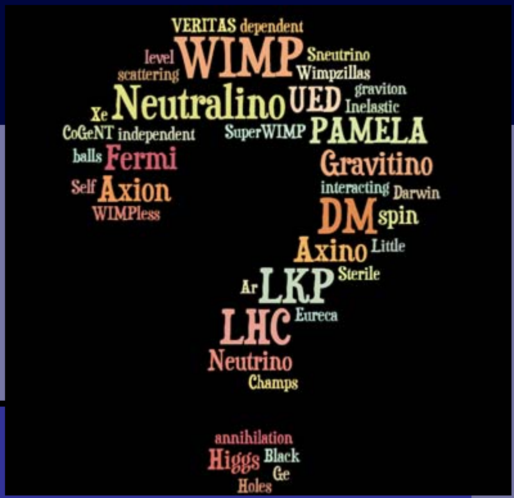
One of the clearest indications for physics beyond the standard model !



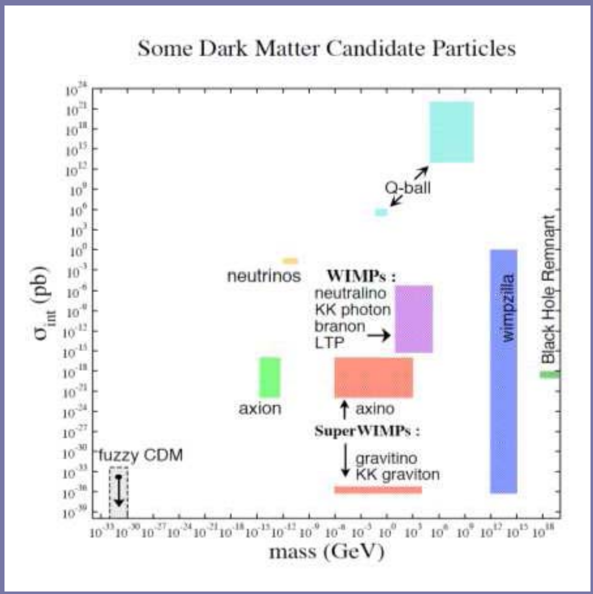




What is Dark Matter ?



We don't know … many candidates !

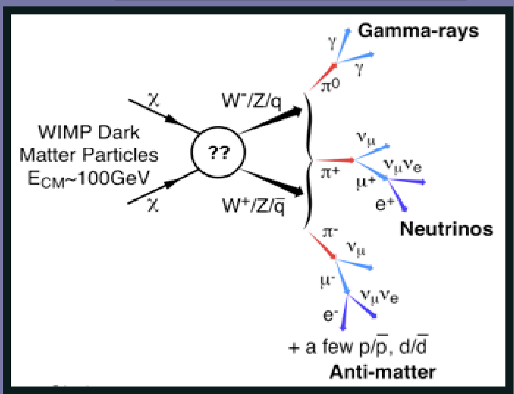


Candidate	Mass Range	"Bonus"
WIMP	1 – 10^4 GeV	"WIMP miracle" (new physics ~WI scale)
Axion	1 μeV – 1 meV	Strong CP problem (PQ symmetry)
Sterile ν	various	Accel./reactor ν experiments
Many others	various	

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

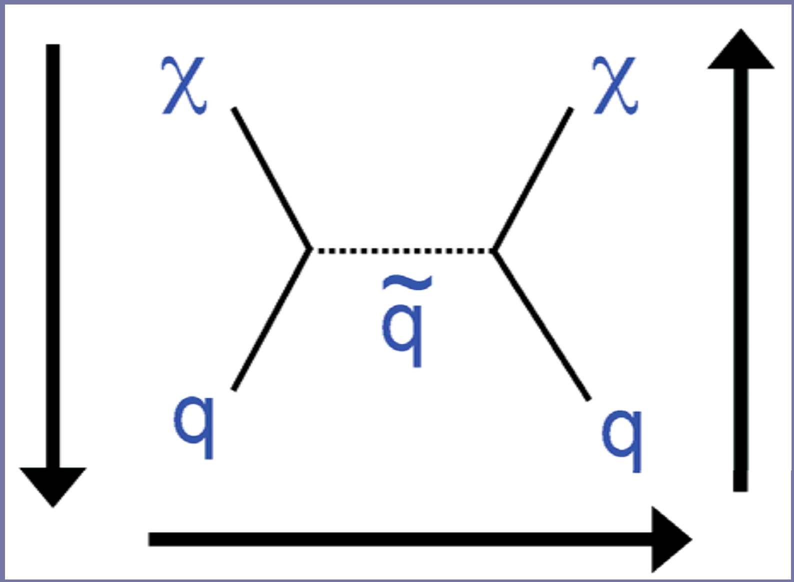
1. CDM has well-known problems (e.g. missing satellites, cusps …)
   → "warm" DM, "fuzzy" DM, self-interacting DM, …
2. DM might consist of multiple constituents, i.e.
   → "Dark Sector", such as asymmetric DM

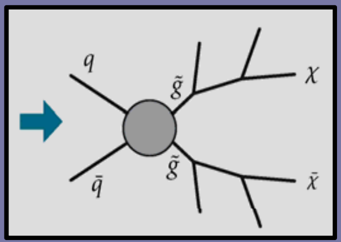
WIMP DM Complementary Approaches

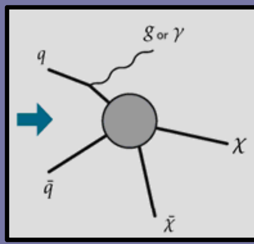


WIMP annihilation
In the cosmos

Indirect Detection

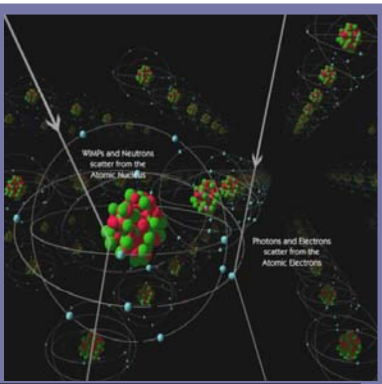






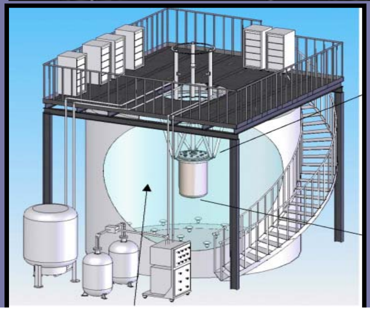
Heavy particle prod.
MET + jets
Weak pair prod.
MET + monojet

LHC Production



WIMP-Nucleon
Elastic scattering

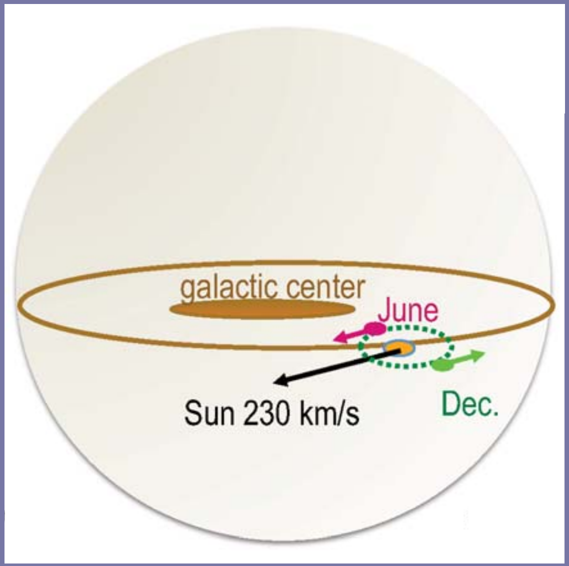
Direct Detection



WIMP Direct Detection

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

Particle Physics **Astrophysics**



D. Bauer, LLWI 2013

Particle Physics:

Elastic scattering of WIMPs off nuclei

a) Spin-independent (coherent) ~ A^2
b) Spin-dependent (target has net spin)

Astrophysics:

Isothermal, spherical halo with MB velocity dist, f(v)dv, for v_o ~ 230 km/s and ρ_χ ~ 0.3 GeV/cm^3

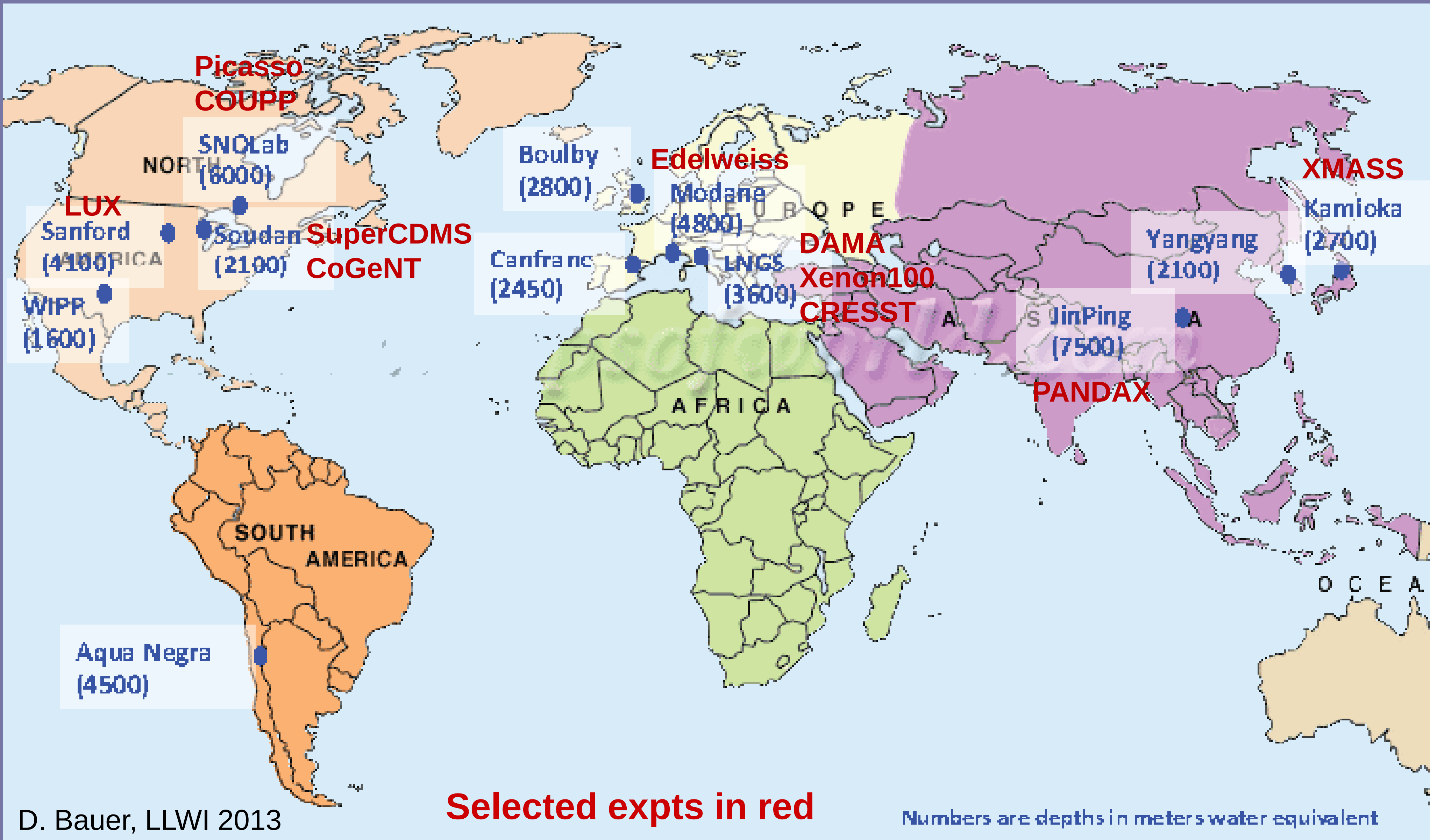
Signals:

1) Counting (eliminate SM interactions)
2) Annual modulation
3) Diurnal modulation

Challenges:

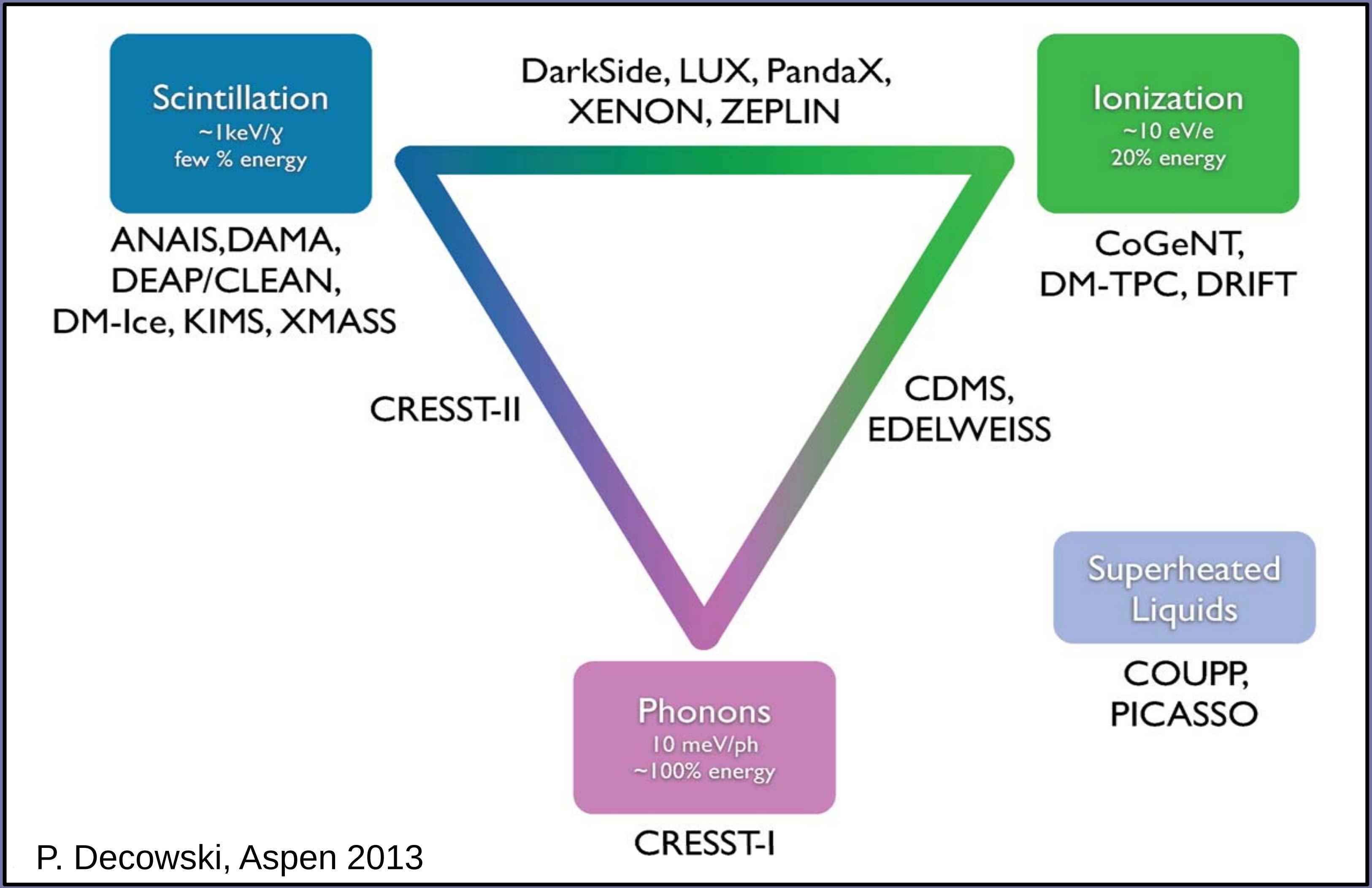
1) Very low bkgnd required
2) Low E threshold (<25 keV)
3) Stable, large mass detectors

Underground Labs & Some Expts



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

Detection Techniques by Experiment

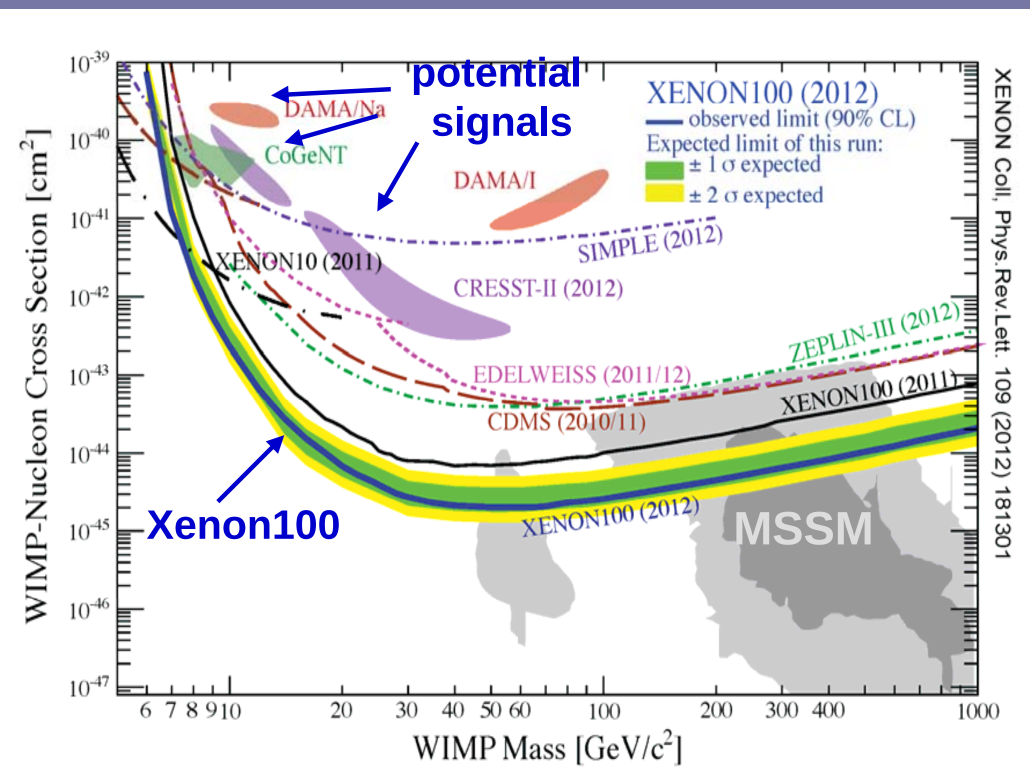


The use of <u>two detection techniques</u> allows for cleaner separation of nuclear recoils from background.

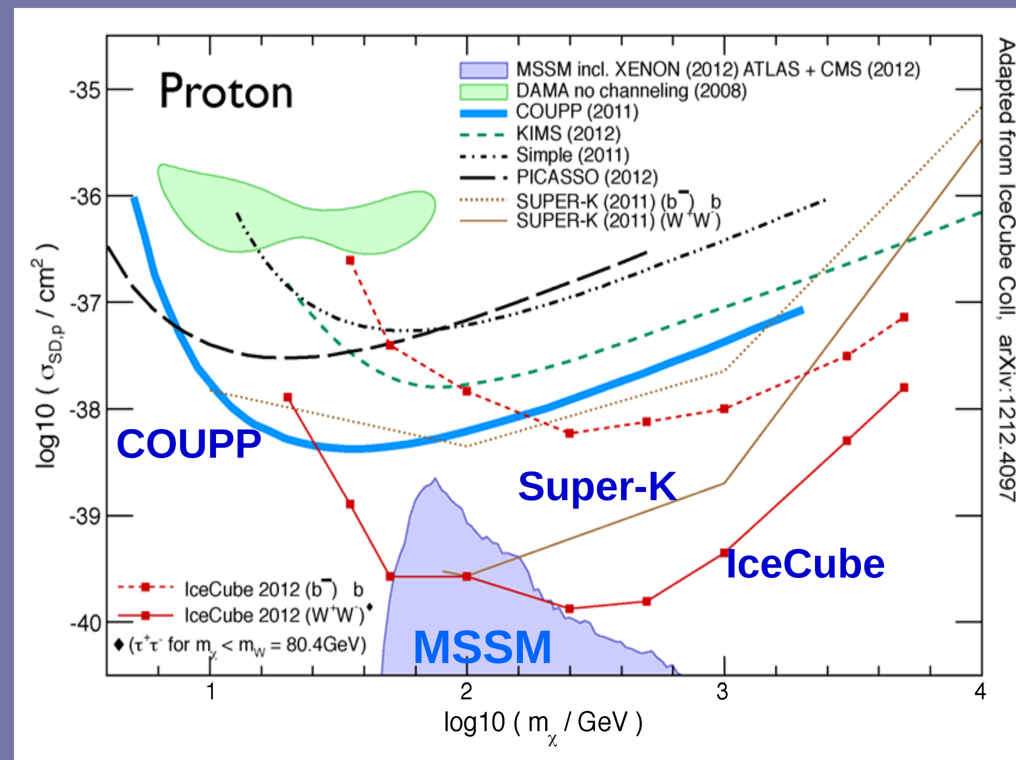
Also important is use of <u>different targets</u> – different A, properties.

WIMP Direct Detection Limits

Spin Independent



Spin Dependent



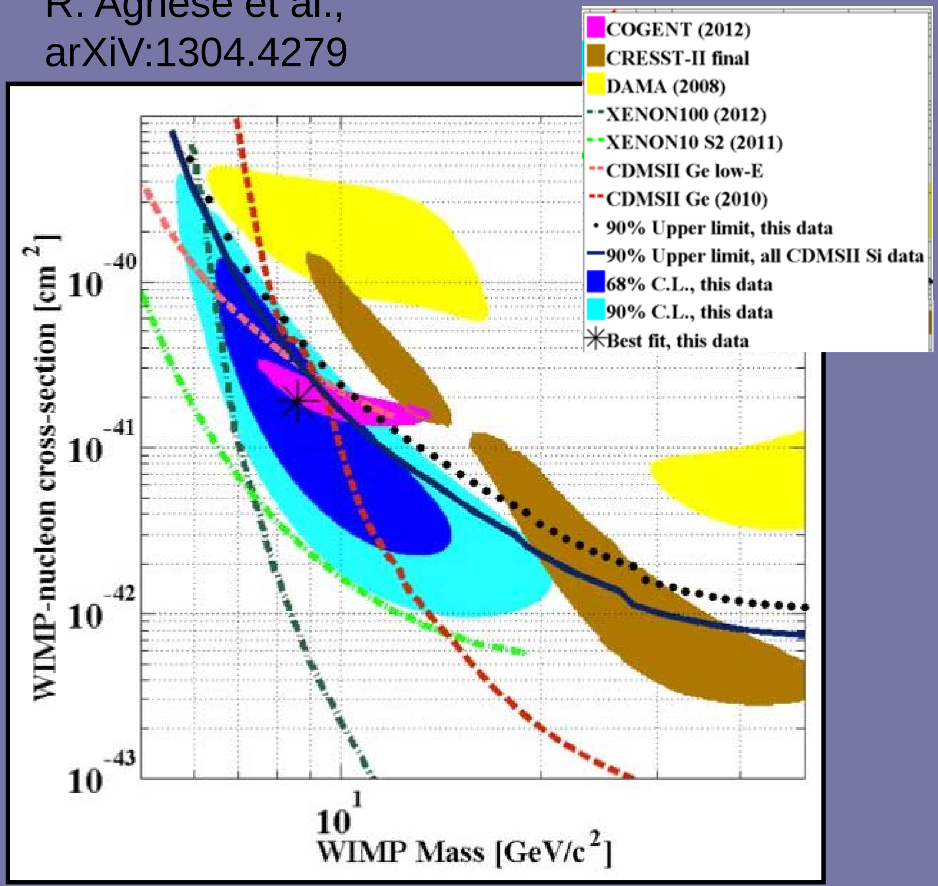
(Potential signals: DAMA/LIBRA, CRESST, CoGeNT – see backup slides)

SuperCDMS Results (2013)

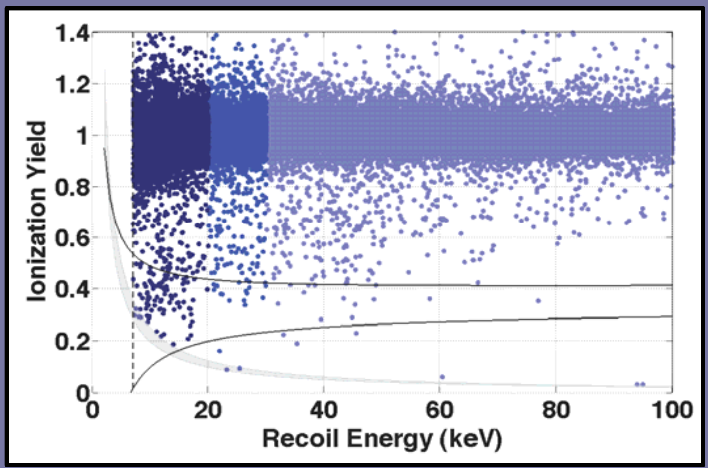
SuperCDMS
Si detectors, more sensitive below 15 GeV

Prob for 3 evts from bgnd ~ 5.4%, but
Prob for measured energies ~0.19%.

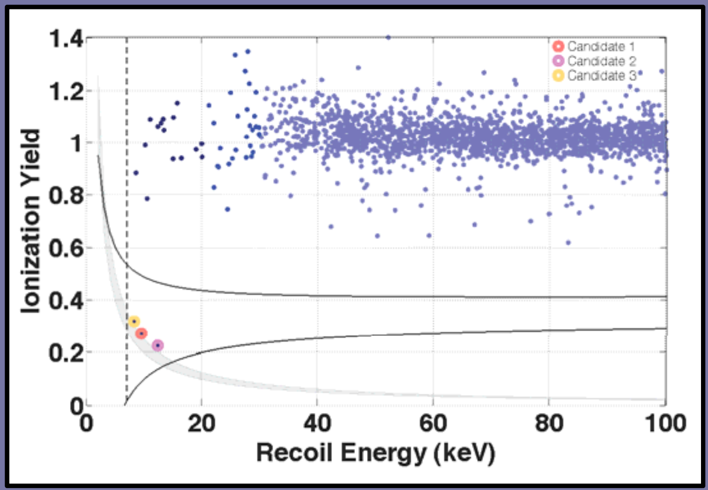
R. Agnese et al.,
arXiV:1304.4279



Before
timing cut



After
timing cut

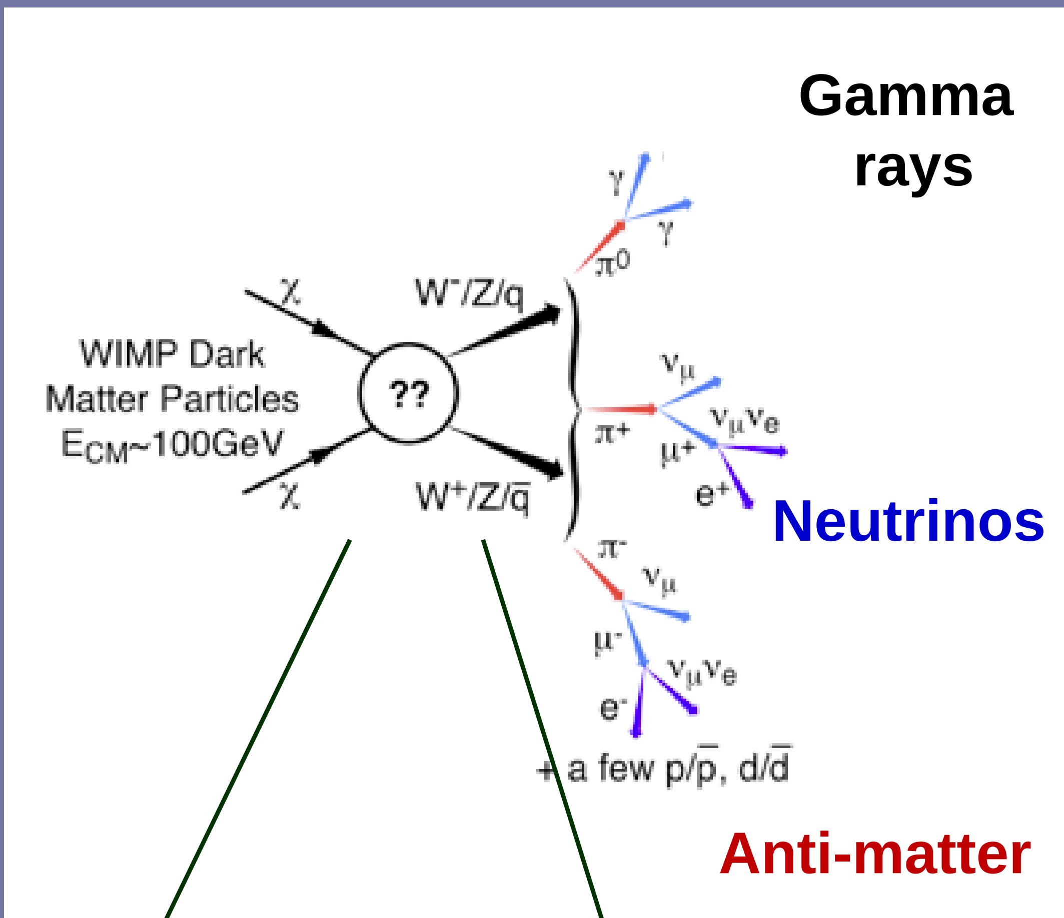


Max. likelihood @ m = 8.6 GeV,
σ = 1.9 x 10^{-41} cm²

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:

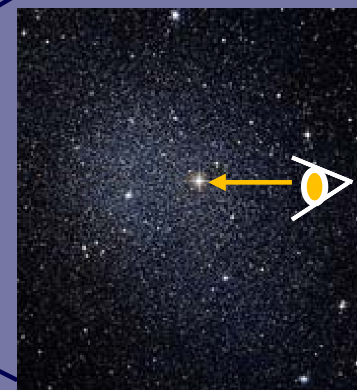
particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

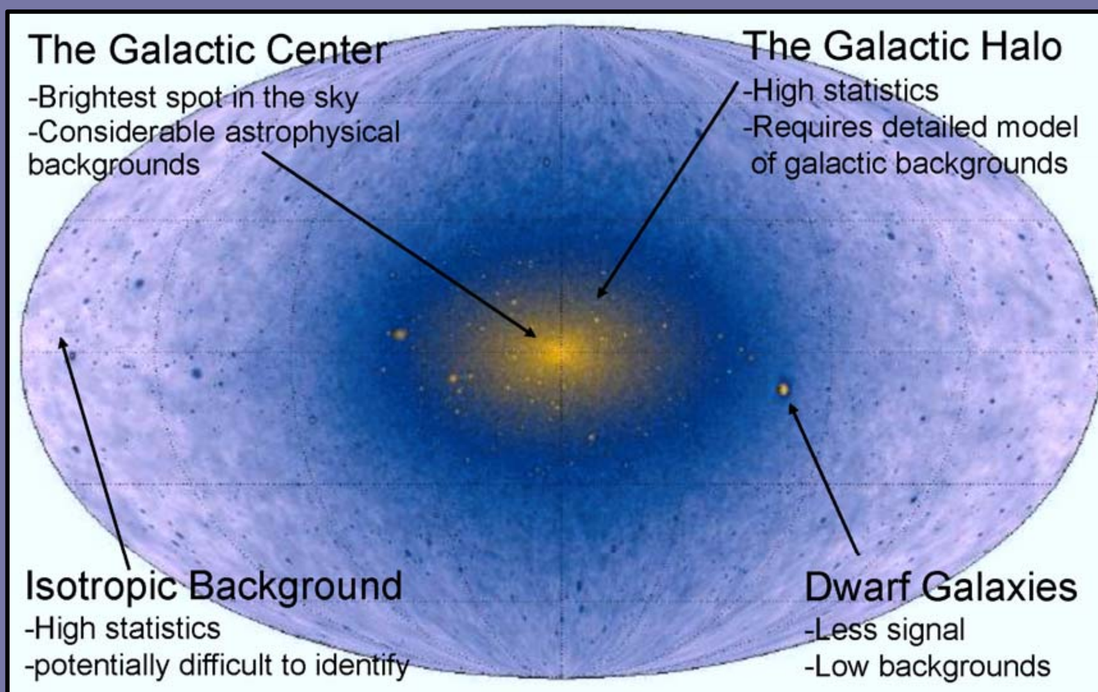
DM distribution

DM distribution

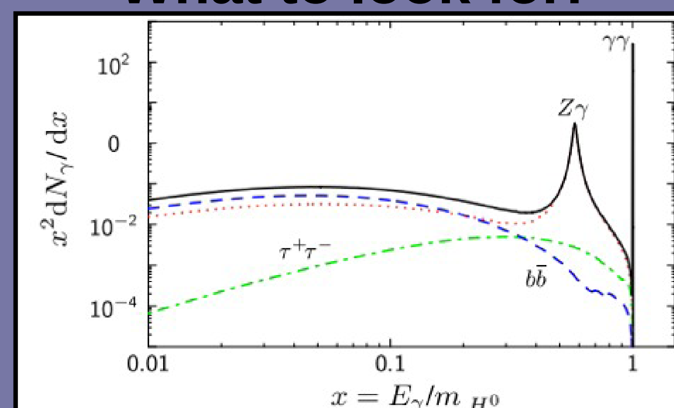
Line-of-sight Integral
(Uncertainty from unknown DM profile)



Where to look:



What to look for:

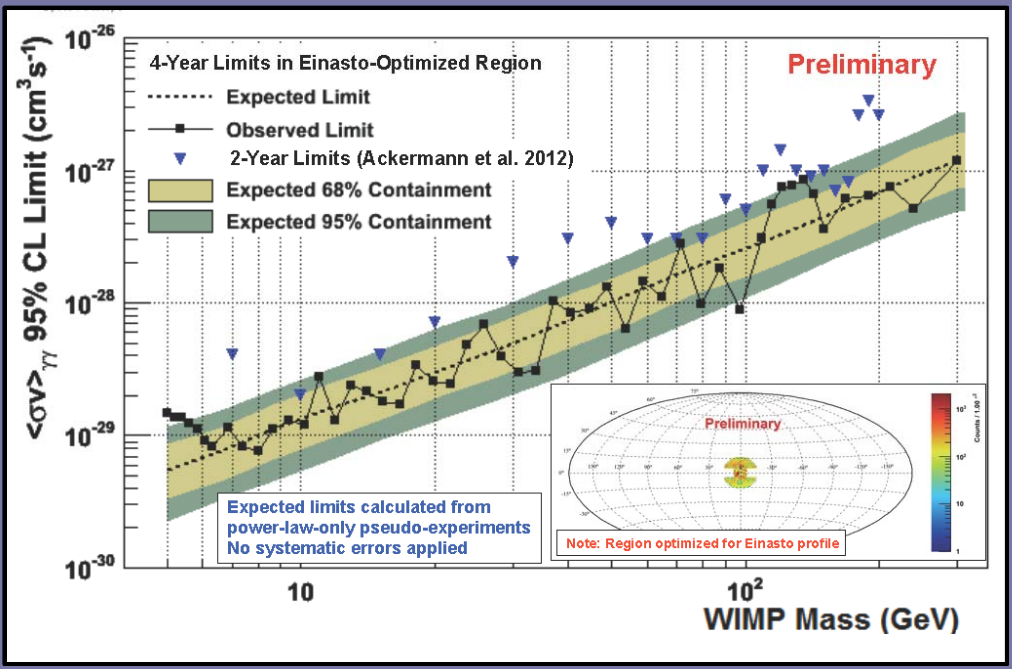


D. Hooper, Aspen 2013

WIMP Limits: γ-rays

Fermi

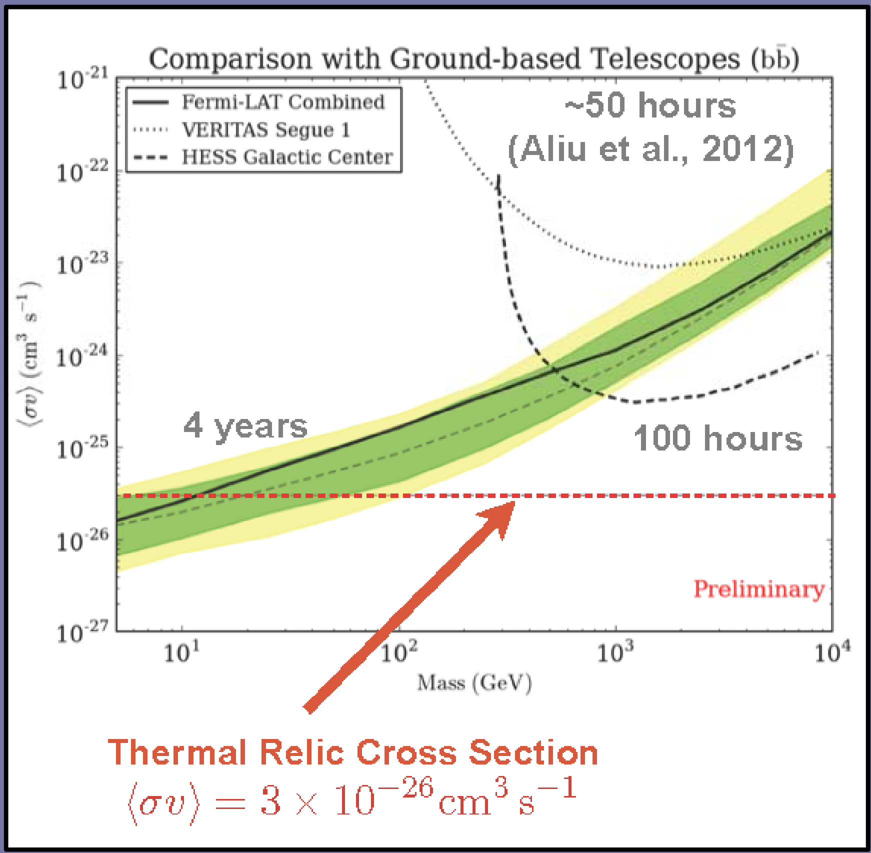
γγ line limits



A. Drlica-Wagner, APS 2013

Fermi, HESS, VERITAS

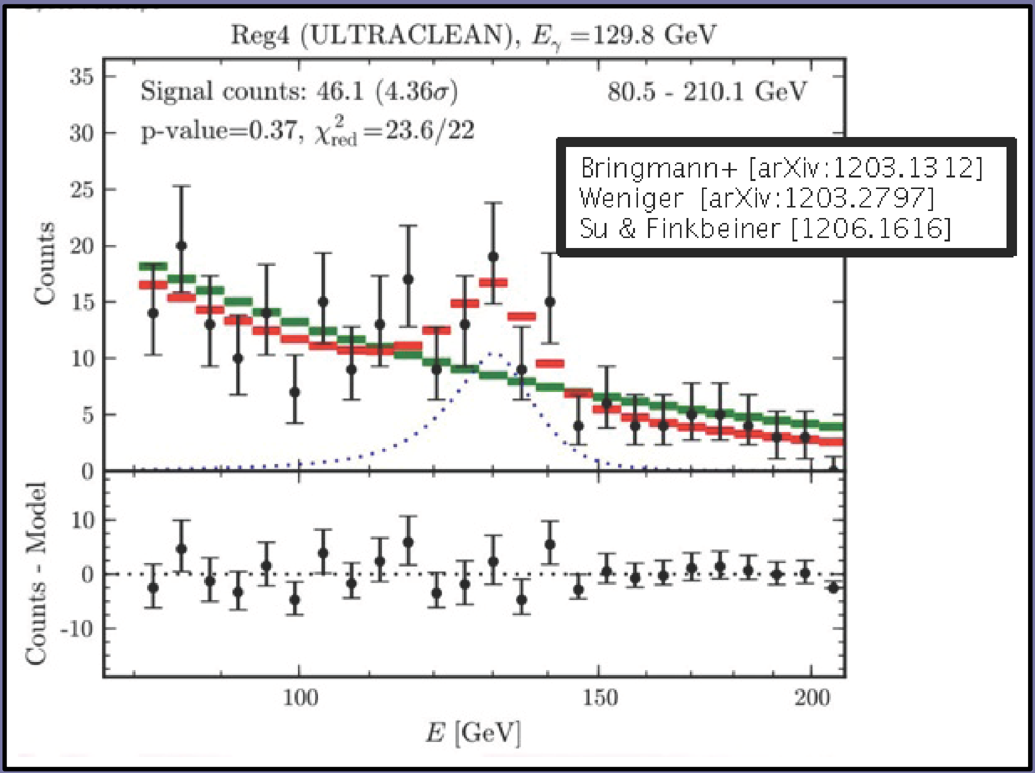
Gal. center, dwarf galaxies



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

130 GeV WIMP Line in Fermi Data ?

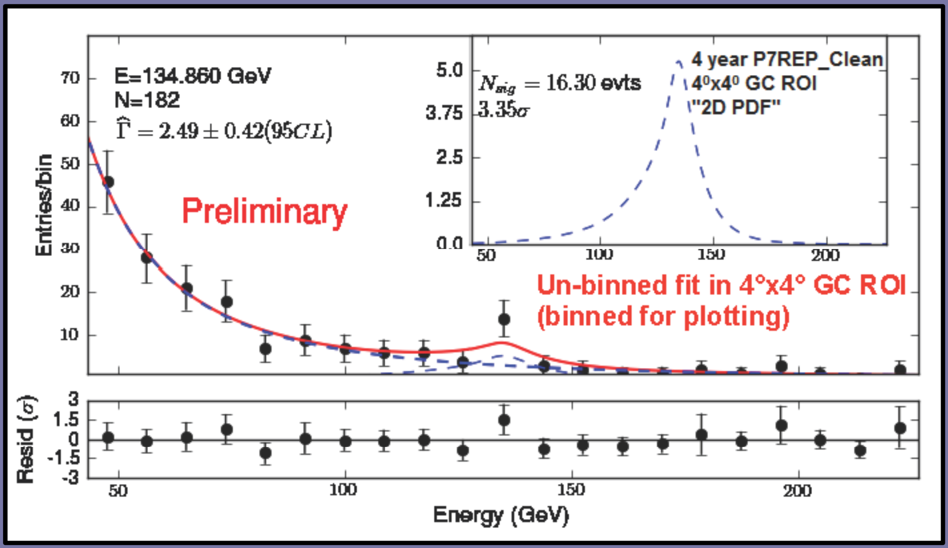
Line evidence:



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:



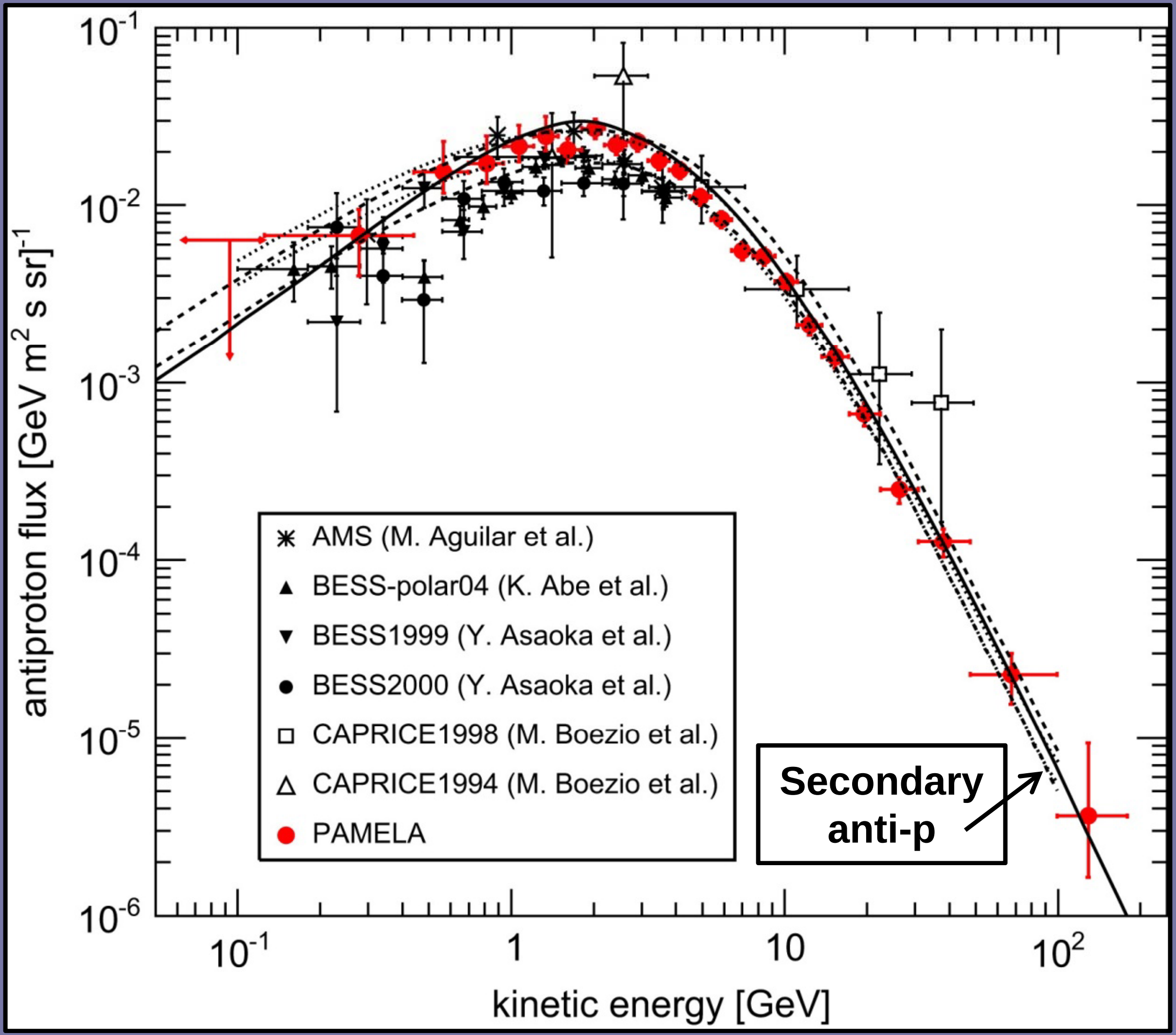
A. Drlica-Wagner, APS 2013

Analysis done by Fermi-LAT team:

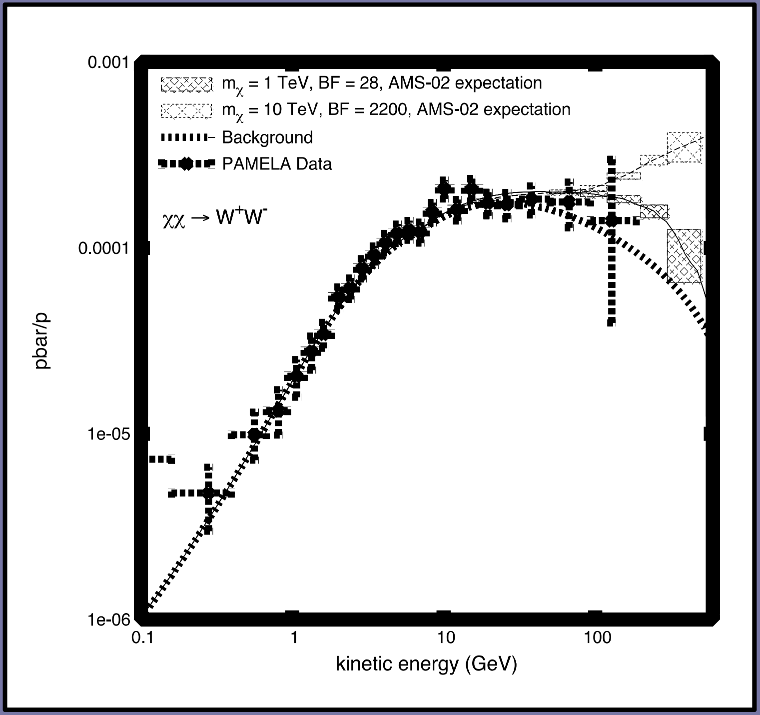
- Re-processed data, includes better calibration, reconstruction
- 3.4-3.7σ (local), ~2σ (global)
- “Peak” seen in Earth limb data, largely at incident cos(θ) ~ 0.7.

Systematic Effect ?

Anti-Protons



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

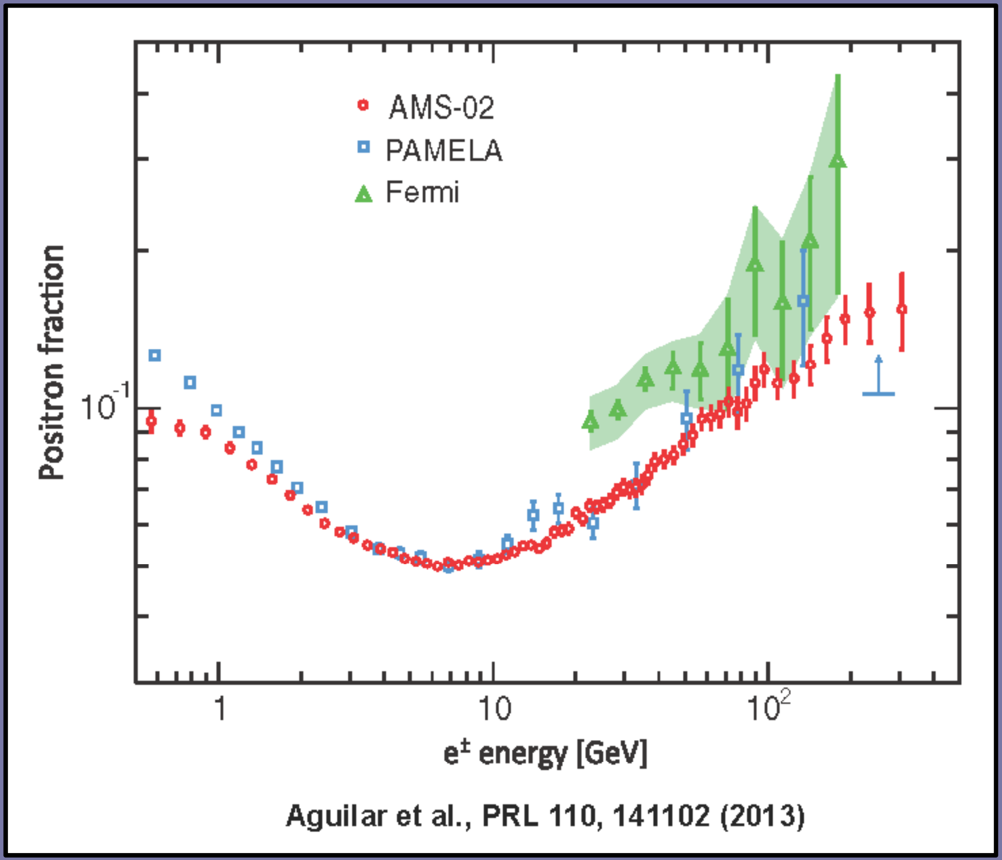


Future AMS-02 sensitivity
(note: p-bar/p is plotted)

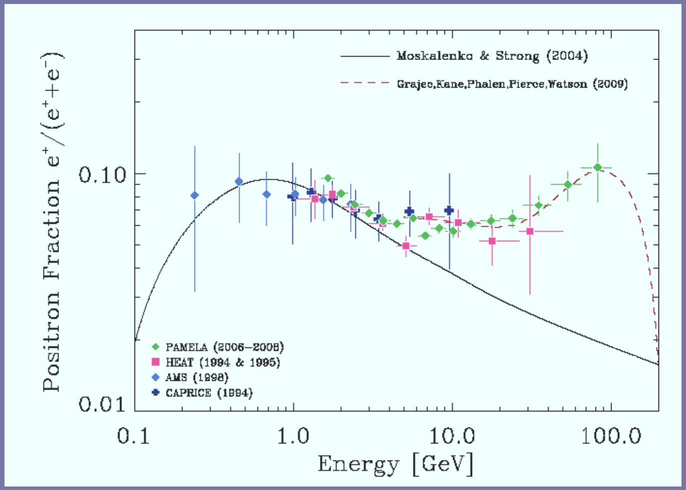
No evidence in anti-protons

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). <u>Anti-deuteron signal</u> 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

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Anti-Protons	N…		
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:

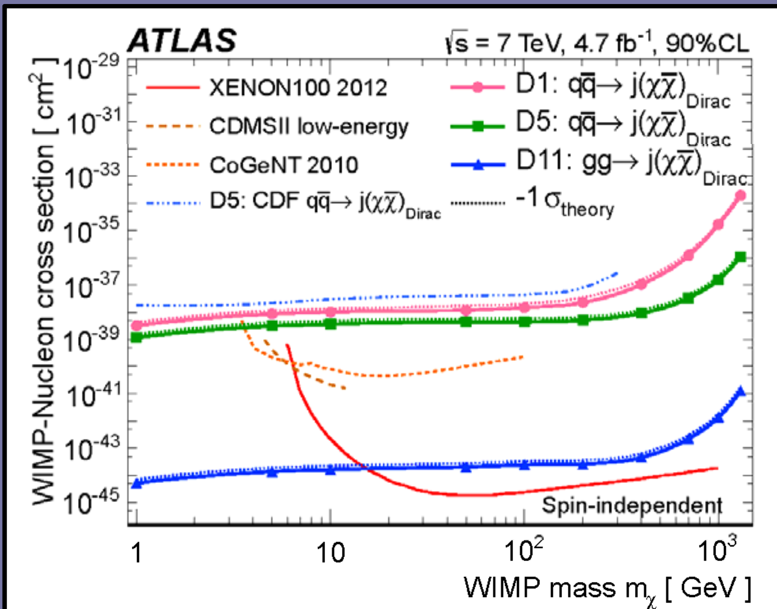
1. Compare in context of specific models (e.g. MSSM)
2. Compare using generalized models (e.g. effective field theory models)

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	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	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	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
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

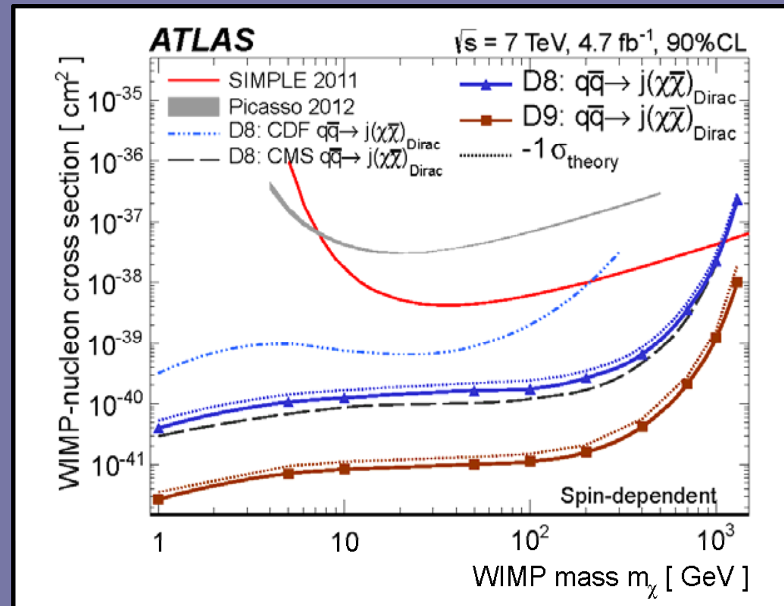
Operators for Dirac WIMP

Some LHC Results and Comparisons

σ_{scatt} spin-ind

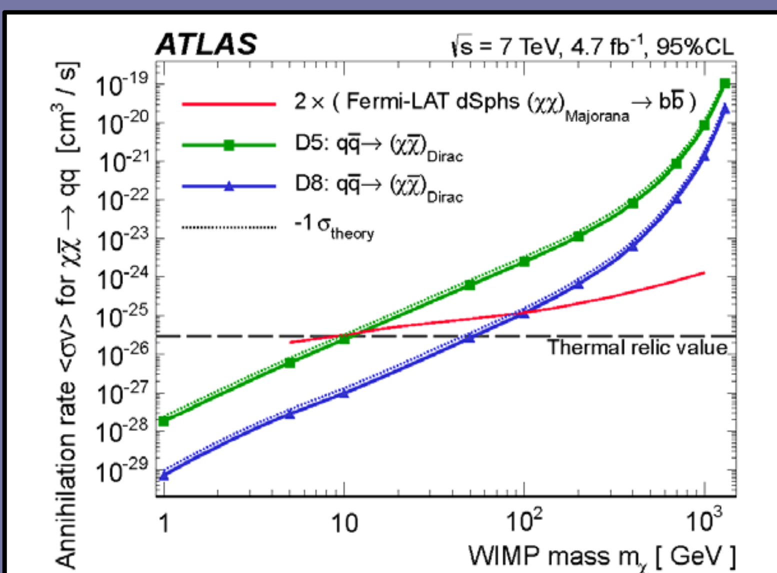


σ_{scatt} spin-dep



ATLAS Collab., arXiV: 1210:4491v2.

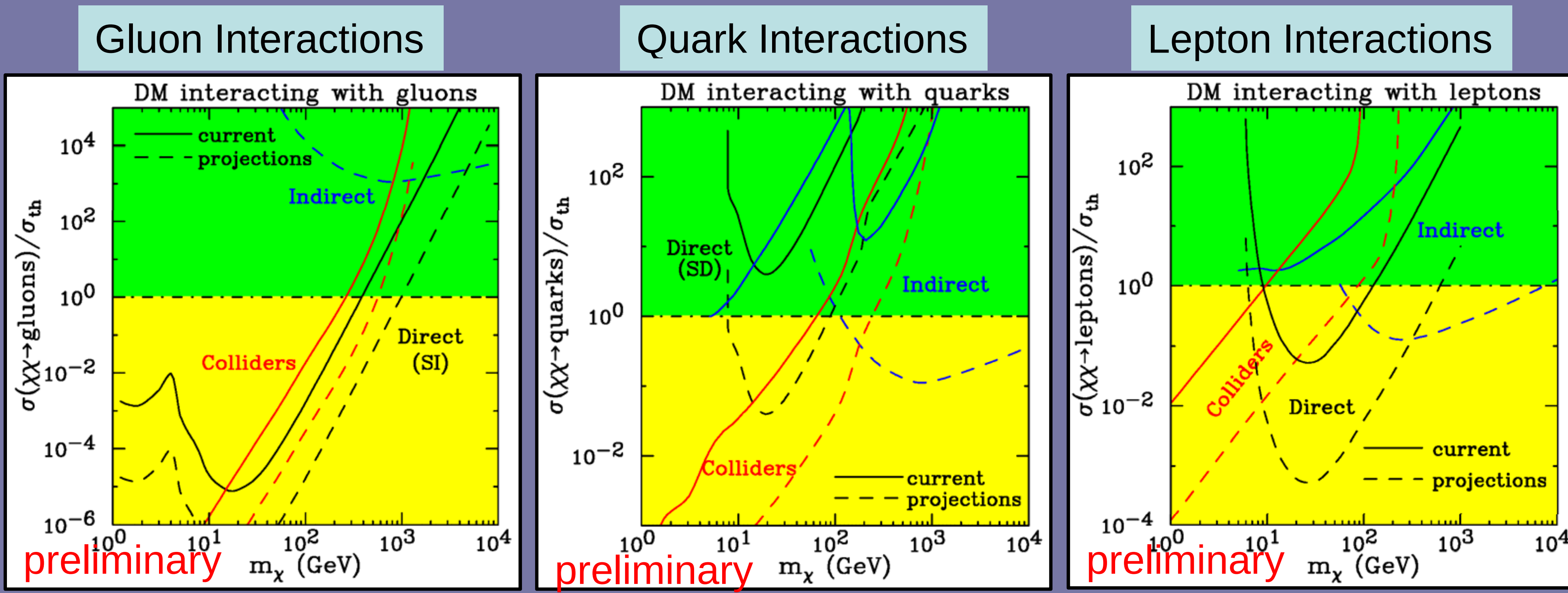
$<\sigma_{anh}\, v>$



- For some operators, LHC limits are quite constraining for m_χ < 100 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.



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

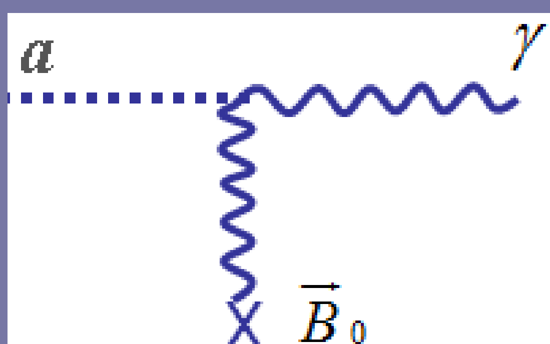
- Axion motivated by strong CP problem (PQ symmetry).
- Constraints (astrophysics, accelerators) on the axion coupling (and mass).
- For a stable relic axion, and a DM candidate:

  e.g. for $n_a \sim 2 \times 10^{13}$ /cm^3 and m_a = 20 μeV, $\Omega_a \sim 0.23$.

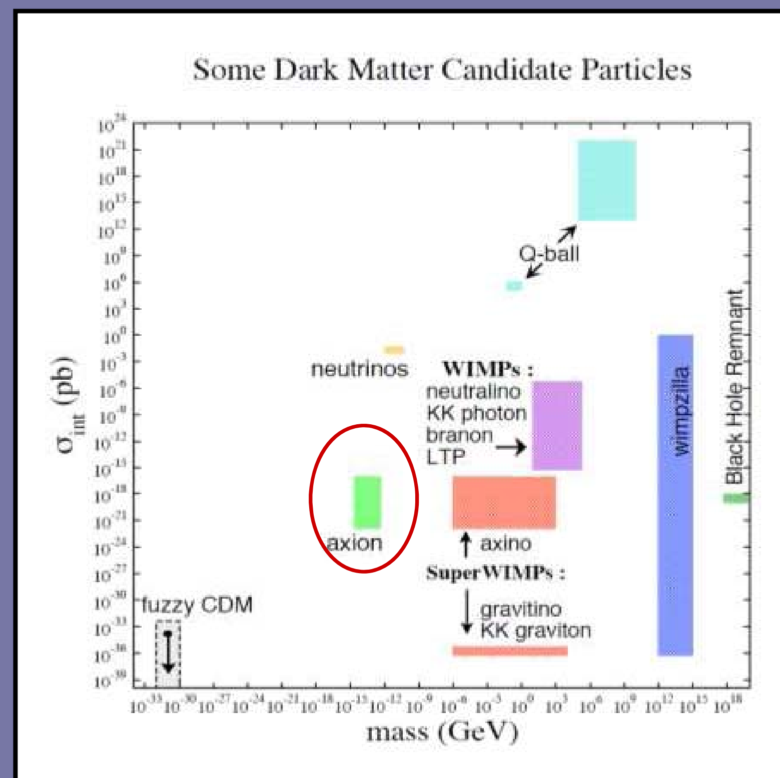
- Axion: neutral psuedoscalar boson

  (light cousin of π^o)

  Produced/detected via Primakoff effect (Sikivie):



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

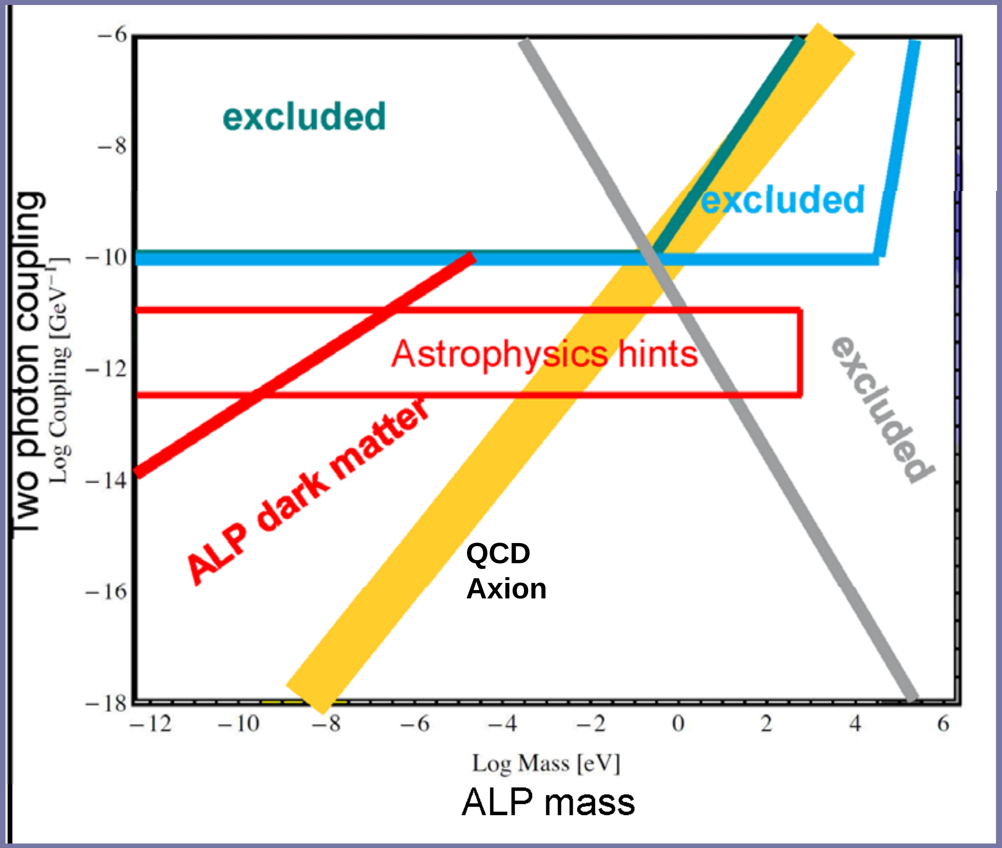


Extension to ALPs

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

Laboratory Axions

- "Light-shining-through -walls" (OSQAR,LIPSS,ALPS …)

Solar Axions

- Helioscopes (CAST, Tokyo …)

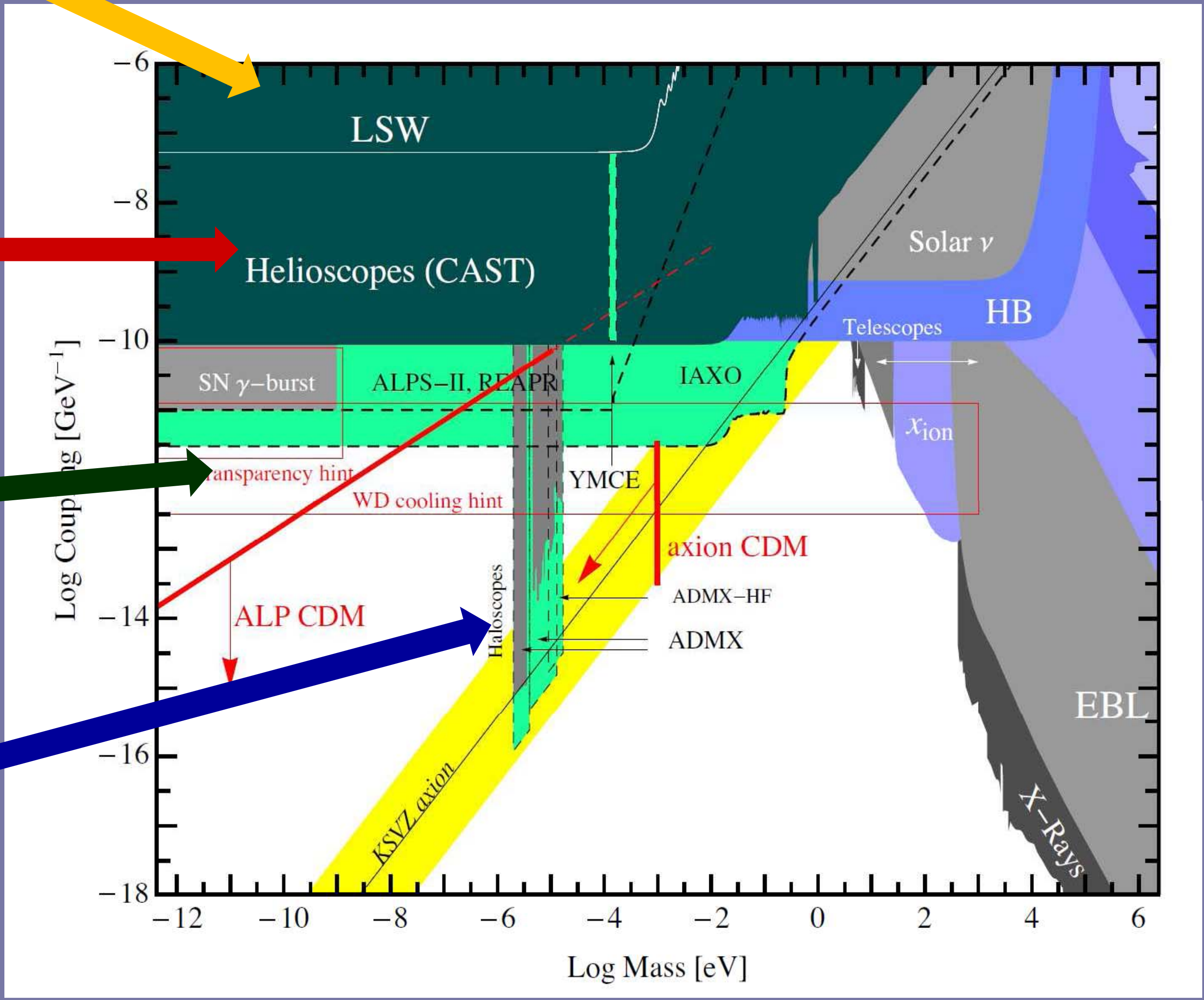
Cosmic ALPs

- γ-ray Telescopes (Fermi, VERITAS …)

DM Halo Axions

- Haloscopes (ADMX)

A. Lindner, DPG 2013

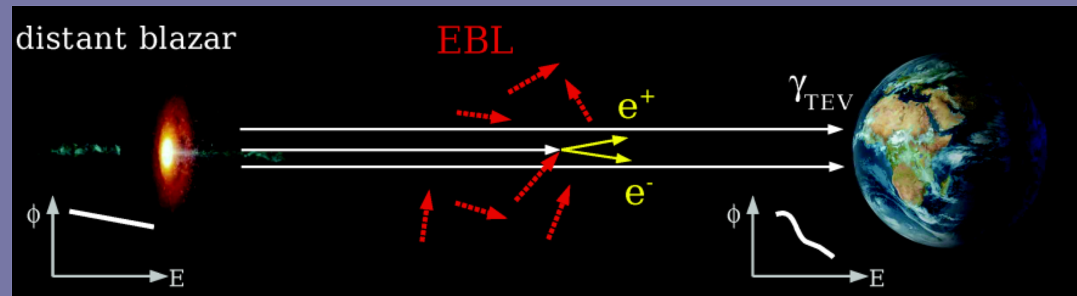


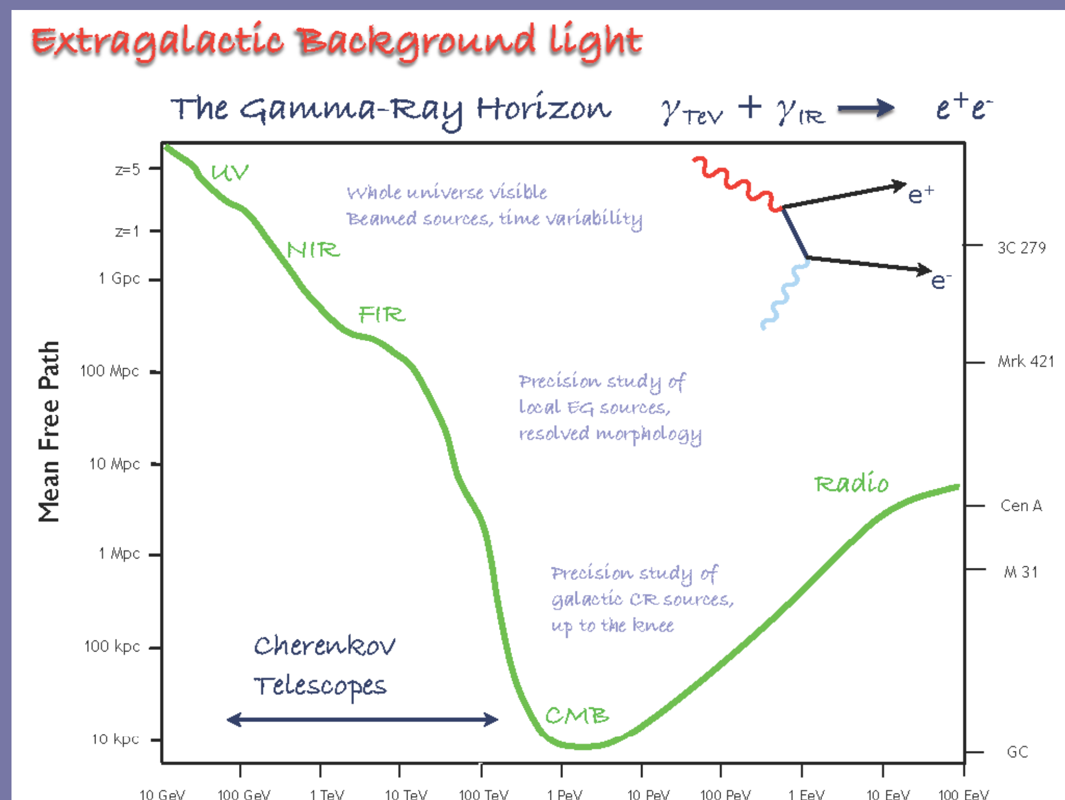
VHE γ-rays as Cosmological Probes

Extragalactic Background Light (EBL):

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

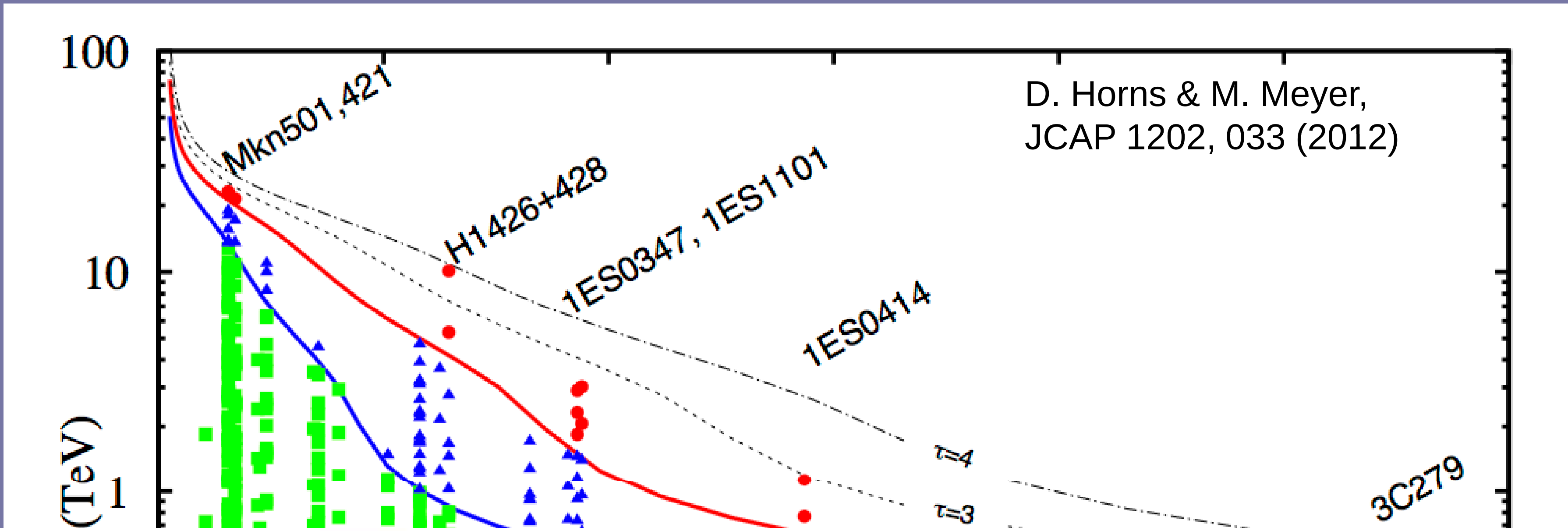
B ~ 10^{-9} - 10^{-18} G

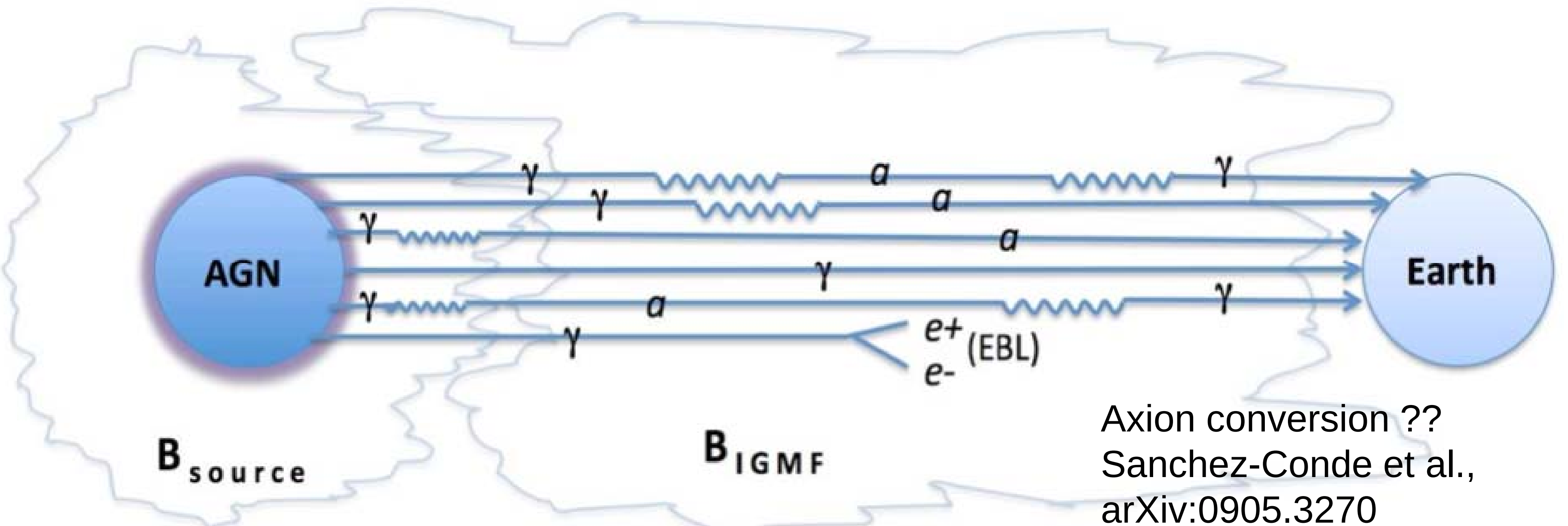




1 TeV **1 PeV** Energy

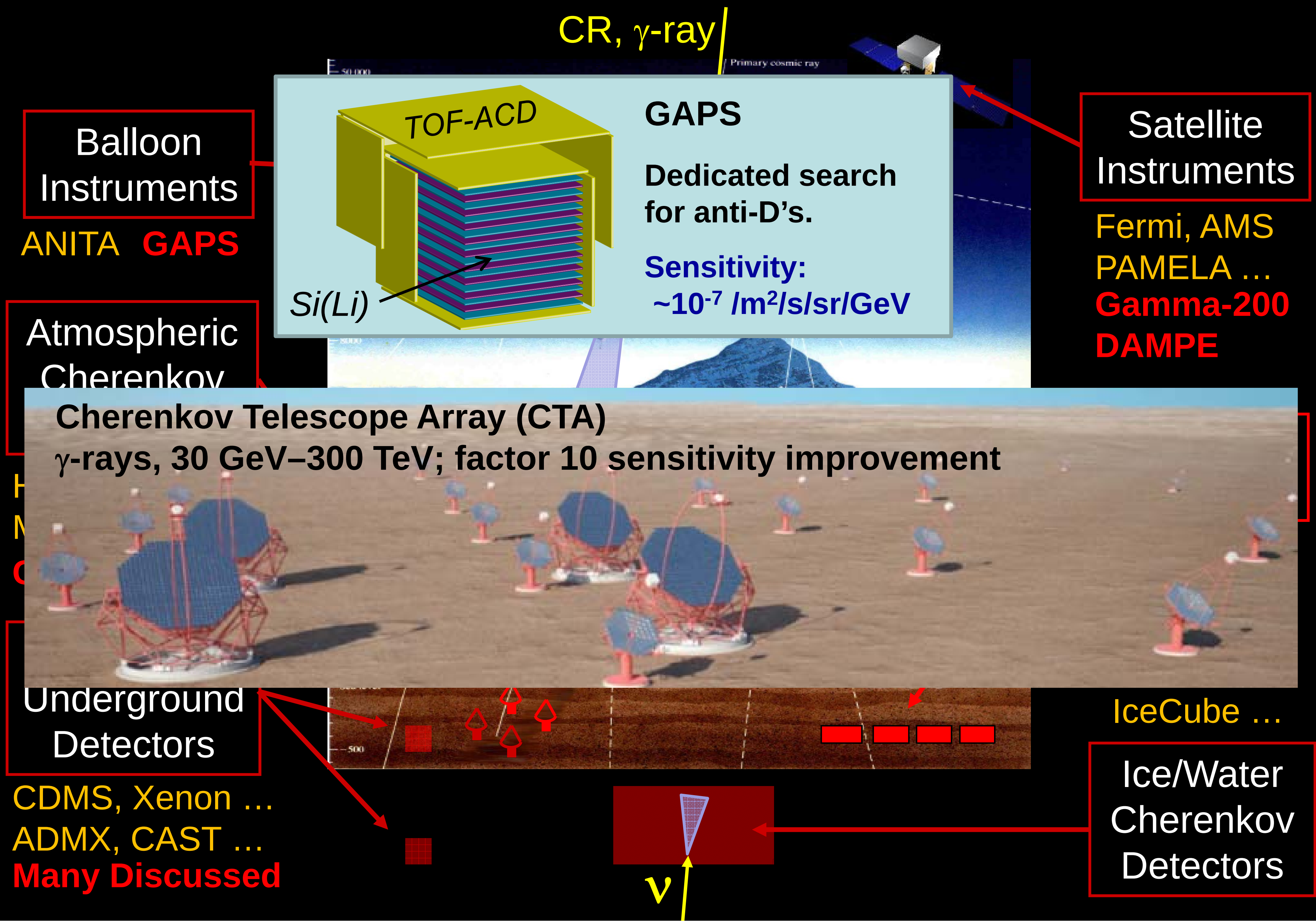
Is the Universe too Transparent ?





Axion conversion ??
Sanchez-Conde et al.,
arXiv:0905.3270

(Some) Future Experiments



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.

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/Plank “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 !)
- …

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 well?).

3) When can we say that we have determined the origin of cosmic rays? ("astro" part)

4) What is the appropriate balance of accelerator and non-accelerator projects in particle physics?