Department Research:

Indirect Search for Dark Matter

John A.J. Matthews

johnm@phys.unm.edu

University of New Mexico

Albuquerque, NM 87131

Search for dark matter ... **Who/what at UNM?**

- *Using the virial theorem to analyze the Coma galaxy cluster in 1933, Fritz Zwicky inferred the existence of* Dark Matter, DM.
- *During the 1970s, Vera Rubin obtained the strongest evidence (to that time) for the existence of* DM.
- Yet today many DM details are still unknown ... sort of embarrassing!

- Several PANDA faculty's research focuses on Dark Matter; my (experimental physics) research group includes:
  - Faculty: John Matthews
  - Post Doc: Robert Lauer
  - Student: Zhixiang Ren

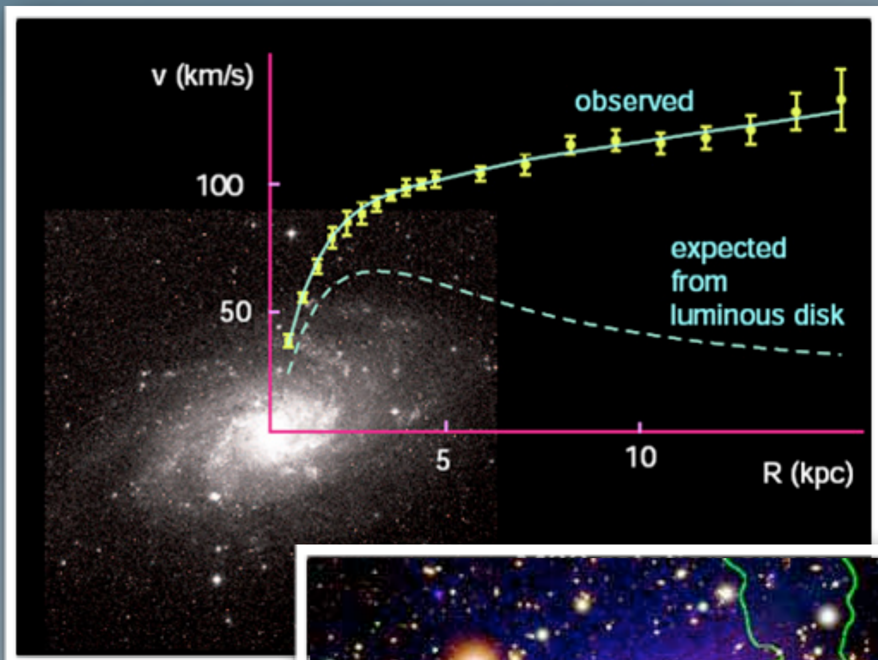
- Which of my experiments focus on Dark Matter:
  - High Altitude Water Cherenkov [HAWC] in Mexico with Professor Gold.
  - Small program of *laboratory* dark matter R&D with Professor Loomba's (directional dark matter) DRIFT experiment group.

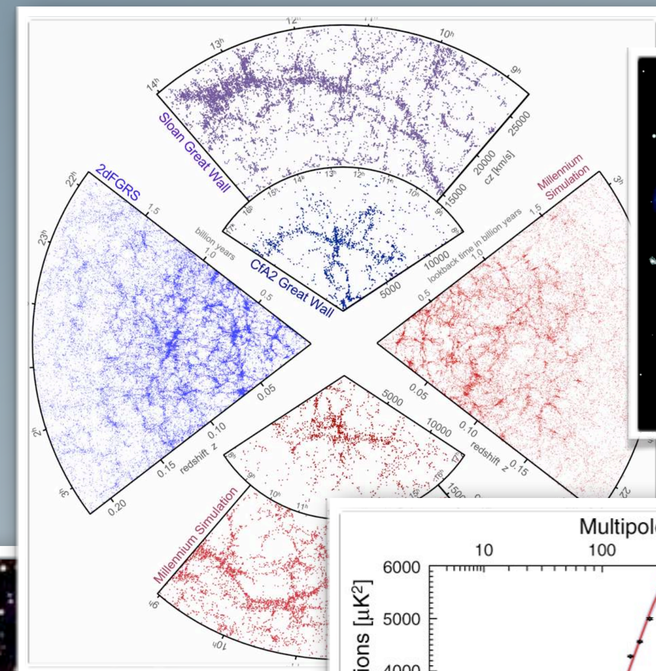
DM overview ... **Particle Physics Focus**

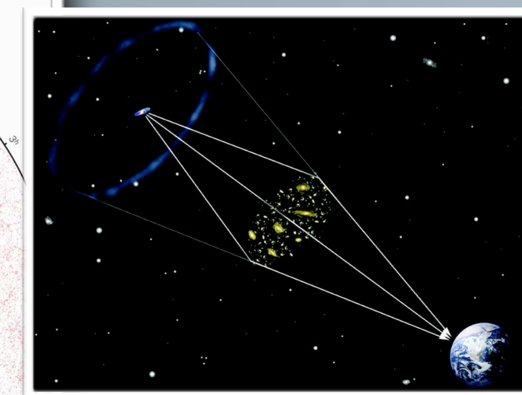
Our DM tour for today includes:

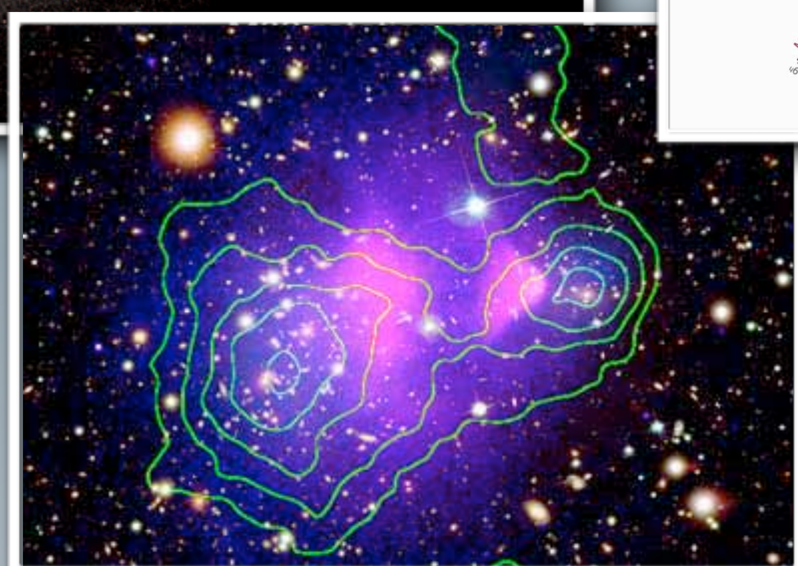
- brief overview of what we know about DM
- particle physics view of DM
- particle physics experimental plan:
  1. direct detection of DM through scattering of DM particles on target nuclei in the laboratory, *e.g.* DRIFT experiment
  2. indirect detection of DM through observation of DM annihilation (or decay) to *e.g.* gamma-rays by the HAWC experiment
  3. direct production of DM particles, *e.g.* at the LHC collider at CERN.
- overview of HAWC experiment
- some details of our HAWC program looking for DM annihilation/decays in nearby astronomical objects

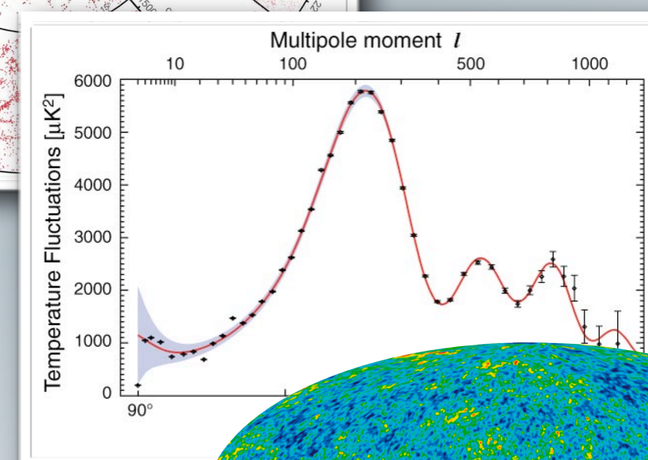
Dark matter all around

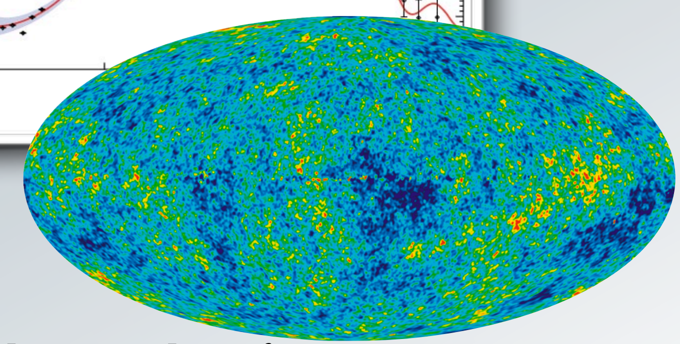






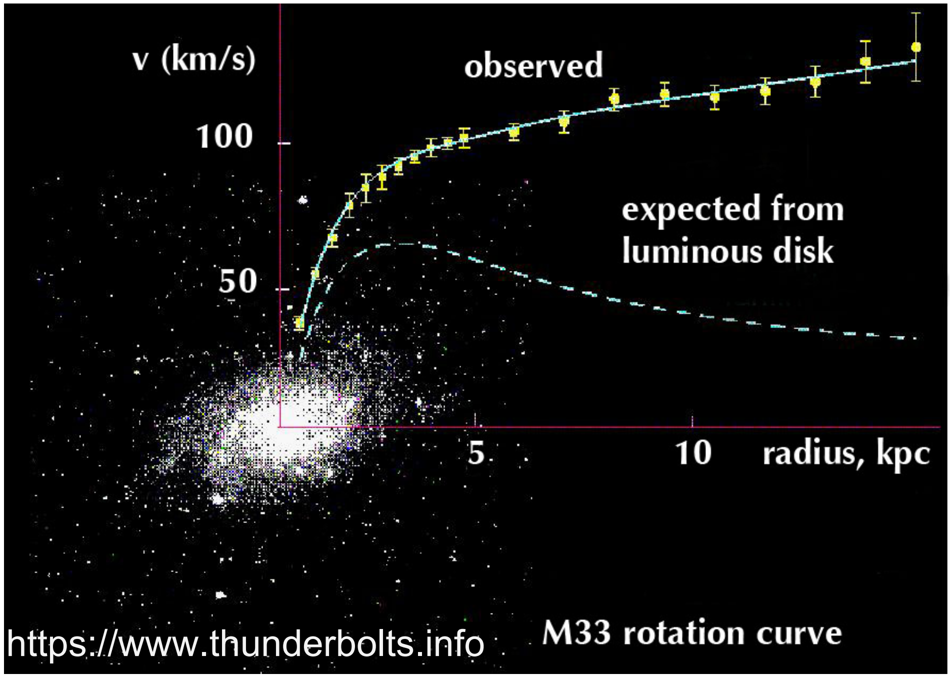






→ *overwhelming evidence on all scales!*

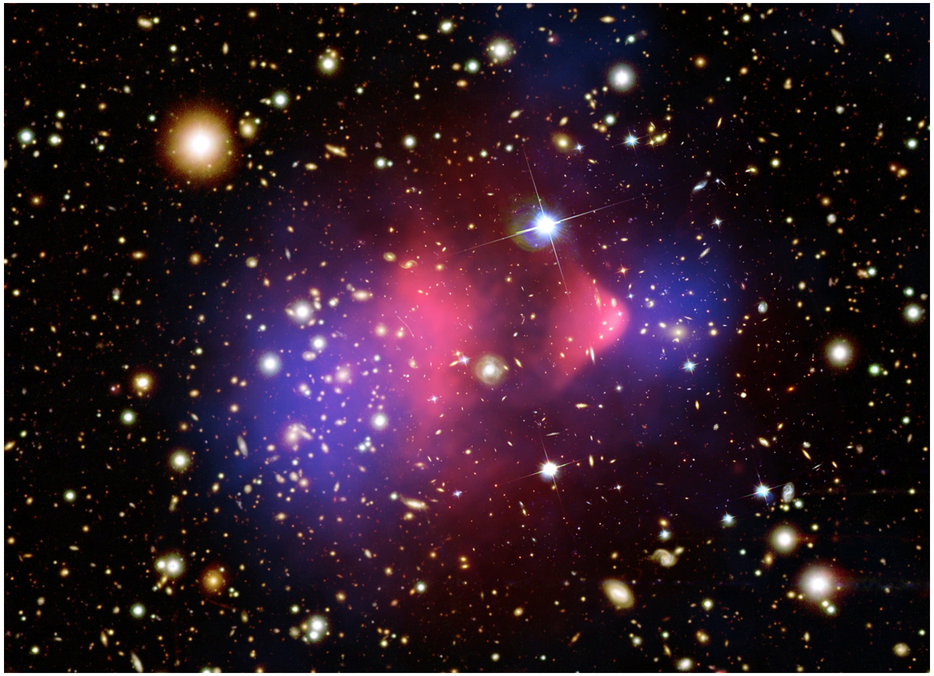
Cosmic Dark Matter Evidence



- **Galaxies reside in large dark matter halos that make up most of their mass**
  - **Coma Cluster + Virial Theorem, F. Zwicky (1937)**
  - **Galactic rotation curves, V. Rubin et al. (1980)**

All observational evidence for dark matter comes from space

Cosmic Dark Matter Evidence

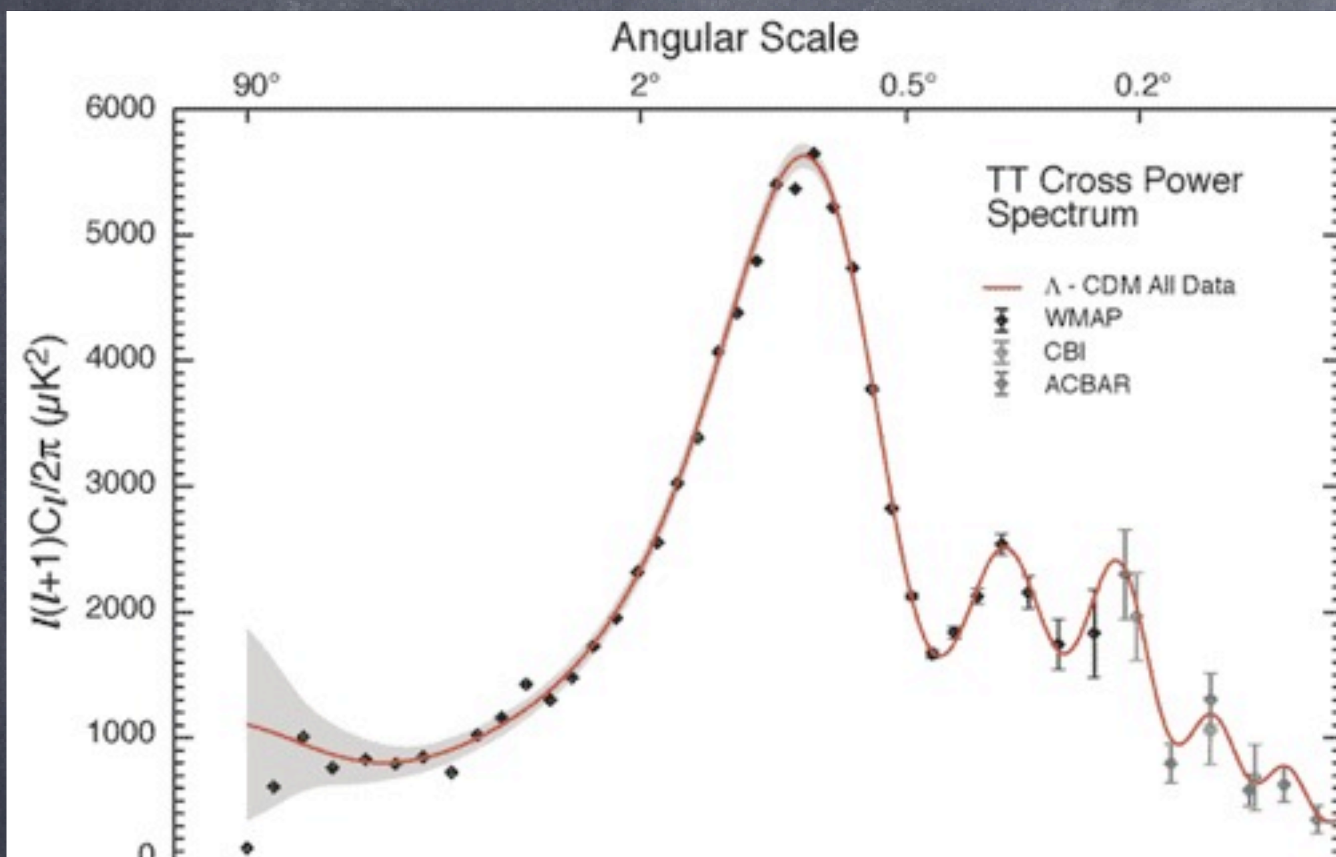


- Dark Matter is virtually **collisionless**
  - The Bullet Cluster, D. Clowe et al. (2006)

All observational evidence for dark matter comes from space

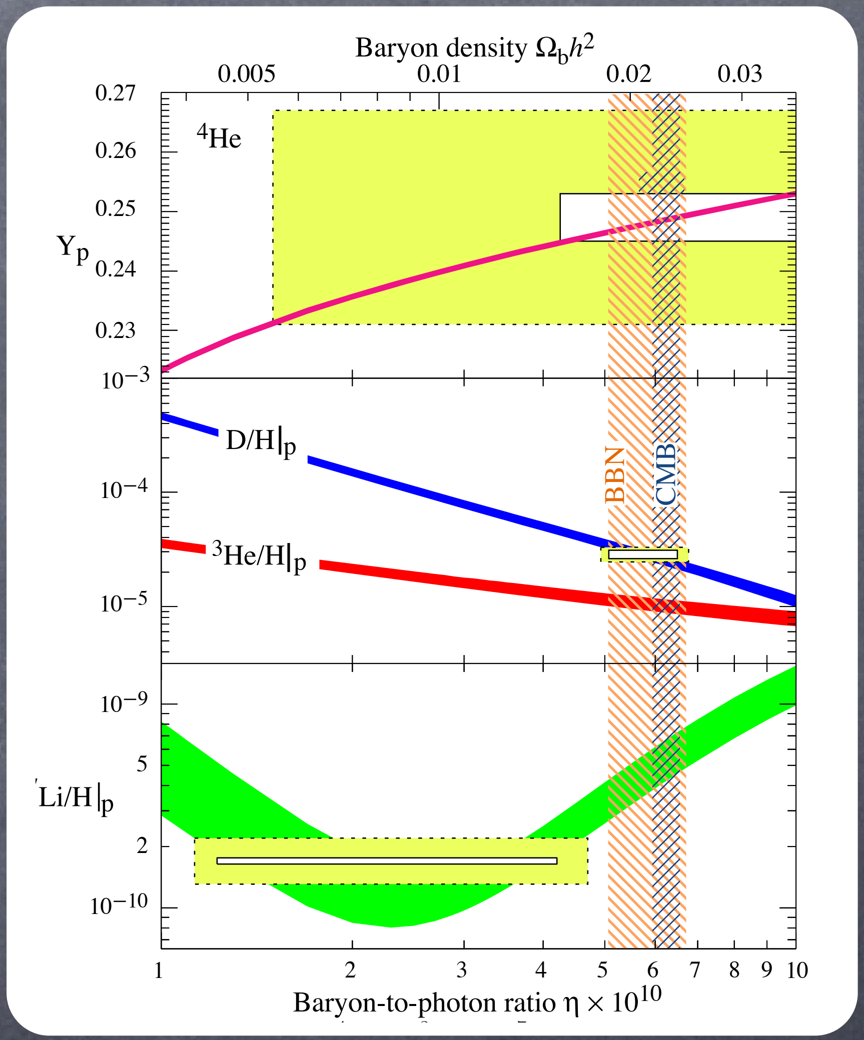
Why particle dark matter?

curvature, z_eq



Baryon density

sound speed = baryon to radiation ratio



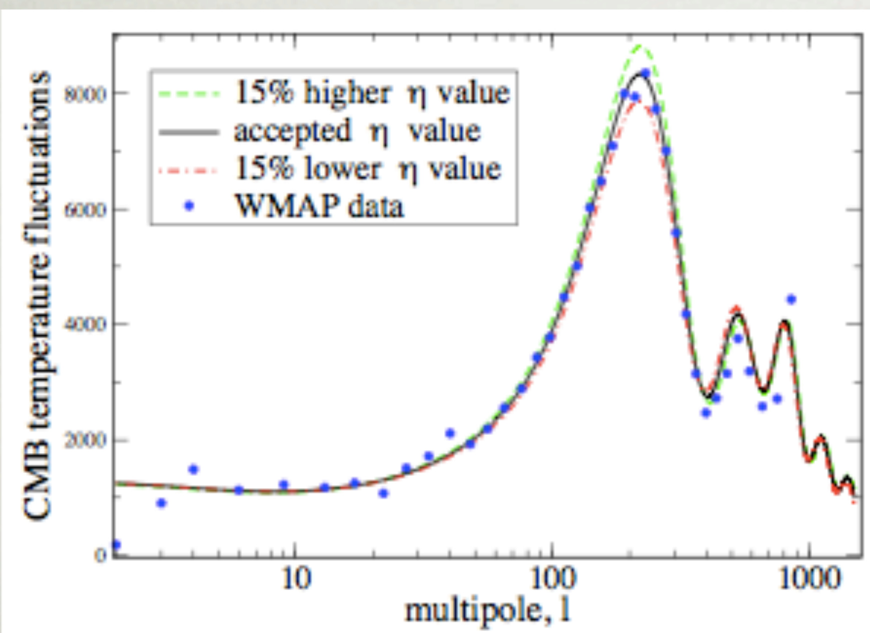
- Why not just ordinary (dark) baryons?
- A: BBN and CMB make independent measurements of the baryon fraction. Observations only accounted for with **non-interacting** matter

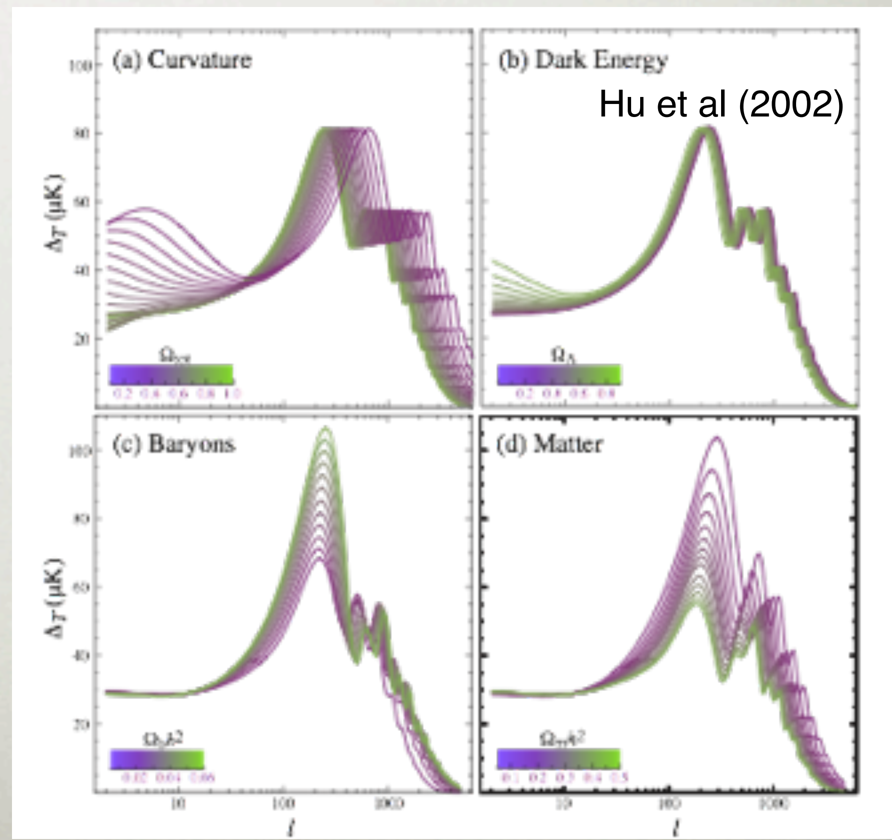
Cosmic Microwave Background

- The CMB angular power spectrum depends on several parameters, including Ω_{B}, Ω_{M}, Ω_{Λ} (Ω_{Λ} is the vacuum density)
- Matching location and heights of the peaks constrains these parameters and geometry of the Universe (flat, Ω_{total}=1)

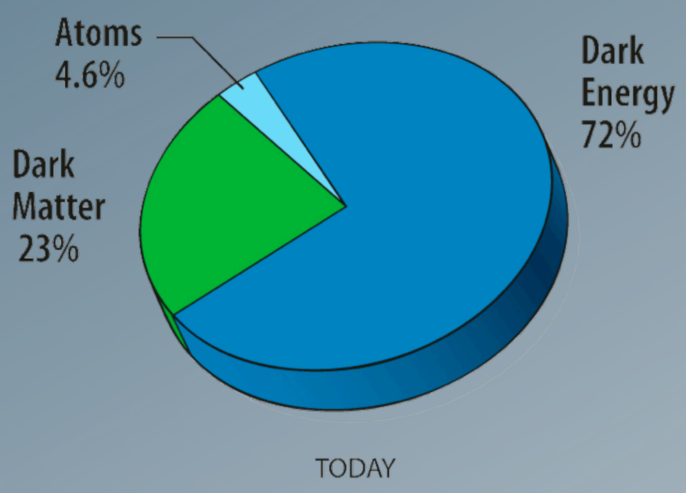
Jarosik et al. 2011

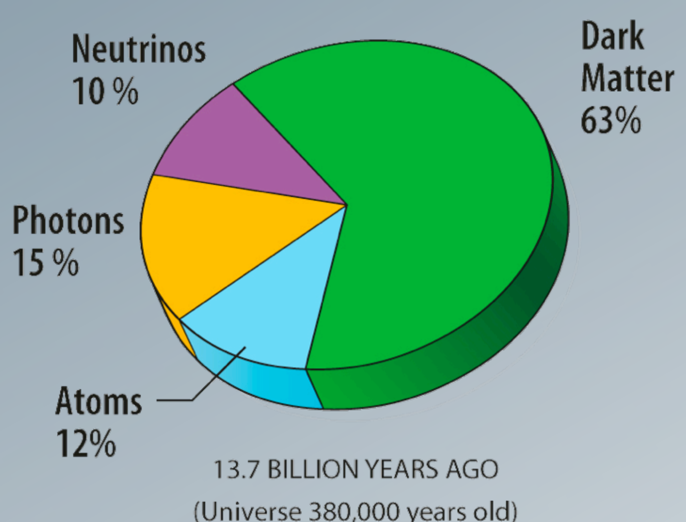
Ω_B 0.0449 ± 0.0028
DM density 0.222 ± 0.026
Ω_Λ 0.734 ± 0.029





Dark matter





credit: WMAP

- *Existence* by now essentially impossible to challenge!
  - $\boxed{\Omega_{\mathrm{CDM}} = 0.233 \pm 0.013}$ (WMAP)
  - electrically neutral (dark!)
  - non-baryonic (BBN)
  - cold – dissipationless and negligible free-streaming effects (structure formation)
  - collisionless (bullet cluster)

- *WIMPS* are particularly good candidates:
  - ✓ well-motivated from particle physics [SUSY, EDs, little Higgs, ...]
  - ✓ thermal production “automatically” leads to the right relic abundance

The WIMP "miracle"

- The number density of Weakly Interacting Massive Particles in the early universe:

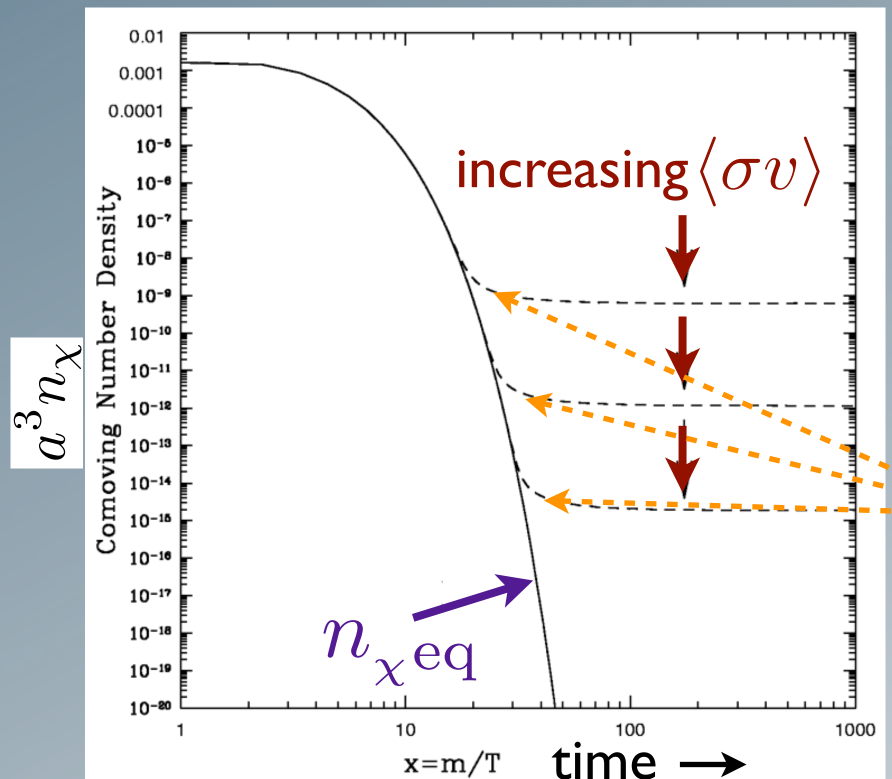


Fig.: Jungman, Kamionkowski & Griest, PR'96

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi\mathrm{eq}}^2\right)$$

$\langle\sigma v\rangle$: $\chi\chi \to \mathrm{SM\ SM}$ **(thermal average)**

"Freeze-out" when annihilation rate falls behind expansion rate ($\to a^3 n_\chi \sim \mathrm{const.}$)

for weak-scale interactions!

- Relic density **(today):** $\Omega_\chi h^2 \sim \dfrac{3\cdot 10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle} \sim \mathcal{O}(0.1)$

The Dark Matter Questionnaire

- ☐ Mass
- ☐ Spin
- ☐ Stable?
  - ☐ Yes ☐ No

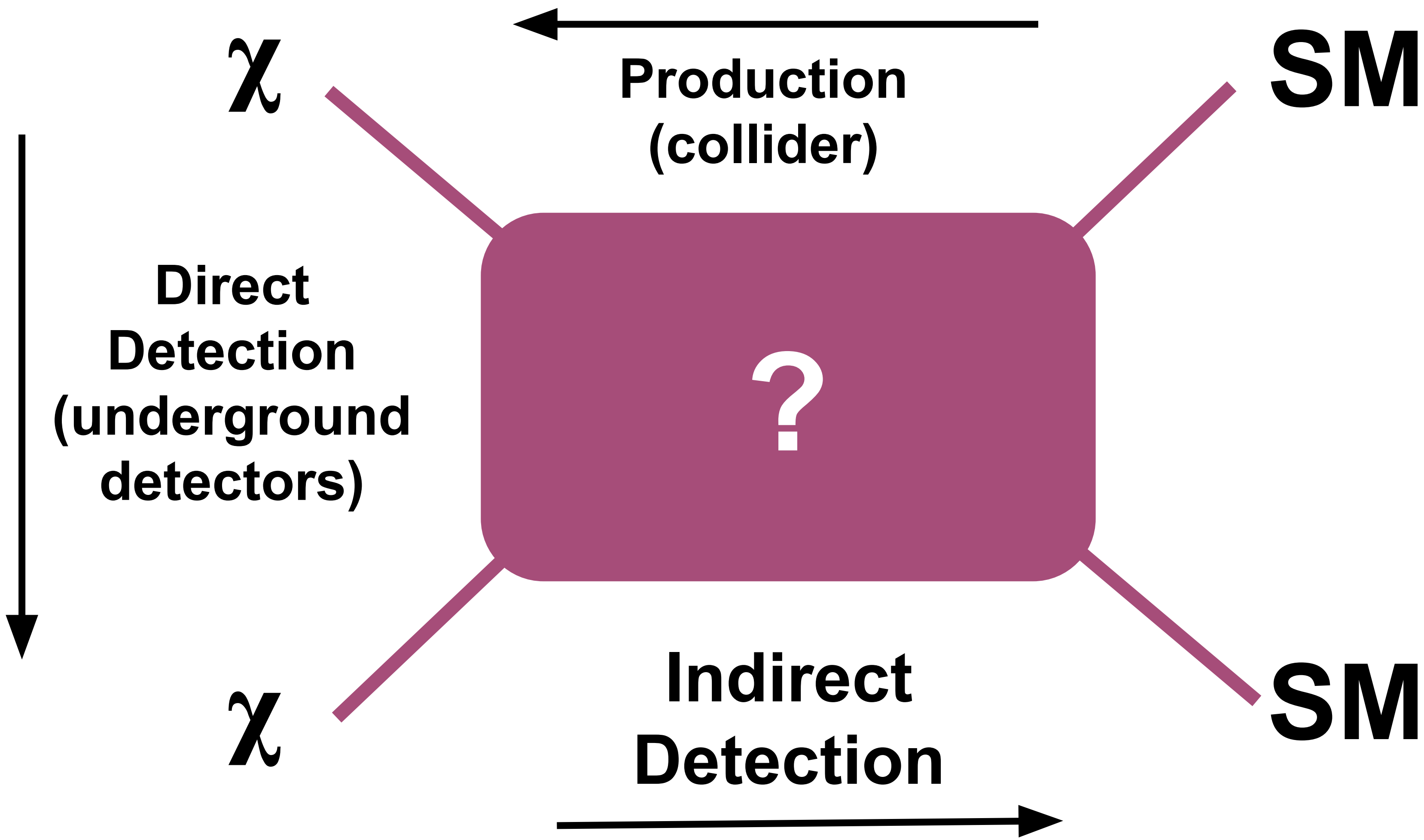
Couplings:

- ☑ Gravity
- ☐ Weak Interaction?
- ☐ Higgs?
- ☐ Quarks / Gluons?
- ☐ Leptons?

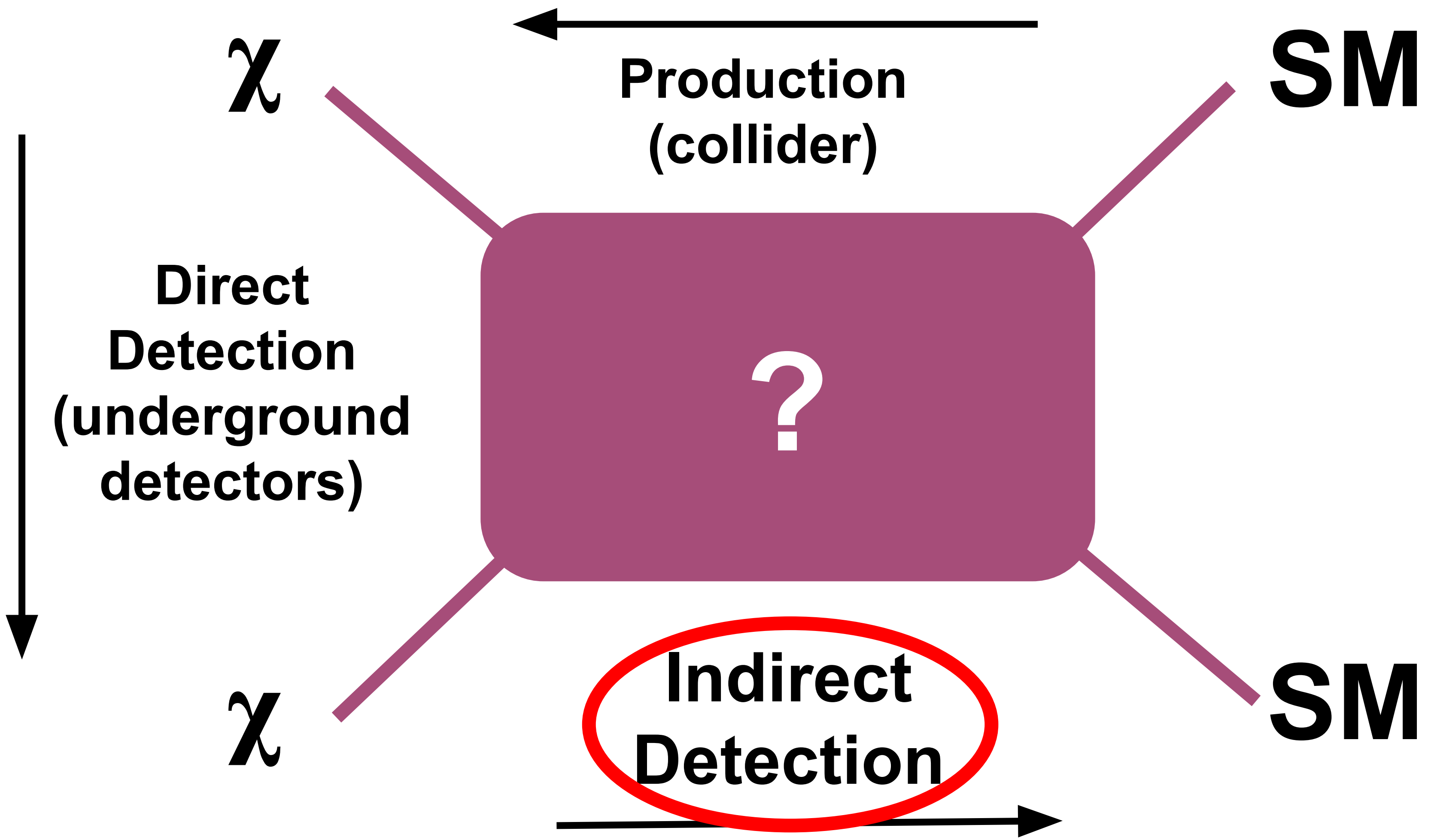
Thermal Relic?

- ☐ Yes ☐ No

How to Investigate Dark Matter



How to Investigate Dark Matter

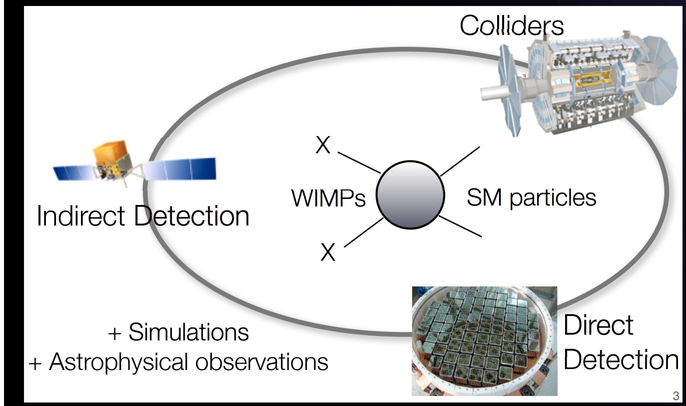


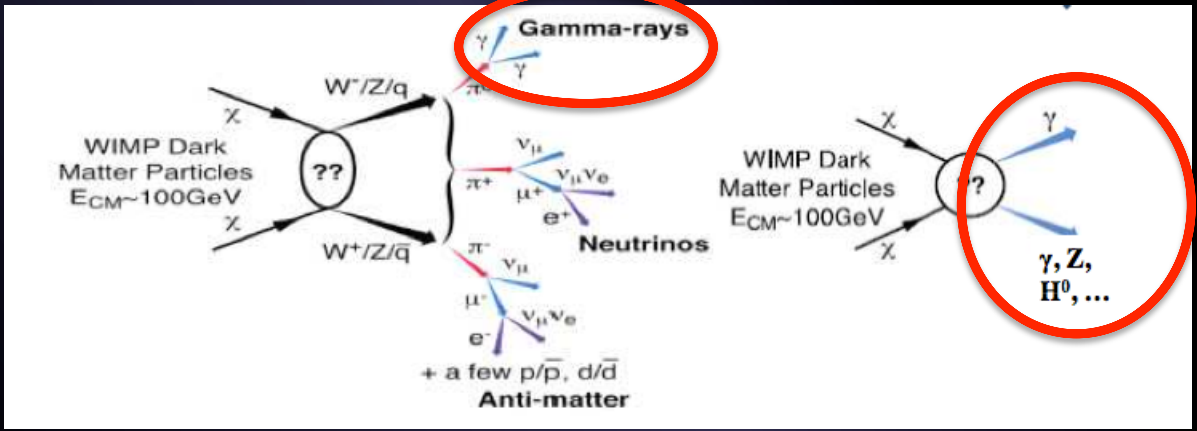
Gamma-rays from dark matter annihilations

A. **Direct detection:** scattering of DM particles on target nuclei (nuclei recoil expected).

B. **Indirect detection:** DM annihilation products (neutrinos, positrons, gammas…)

C. **Direct production** of DM particles at the lab.





Why gammas?

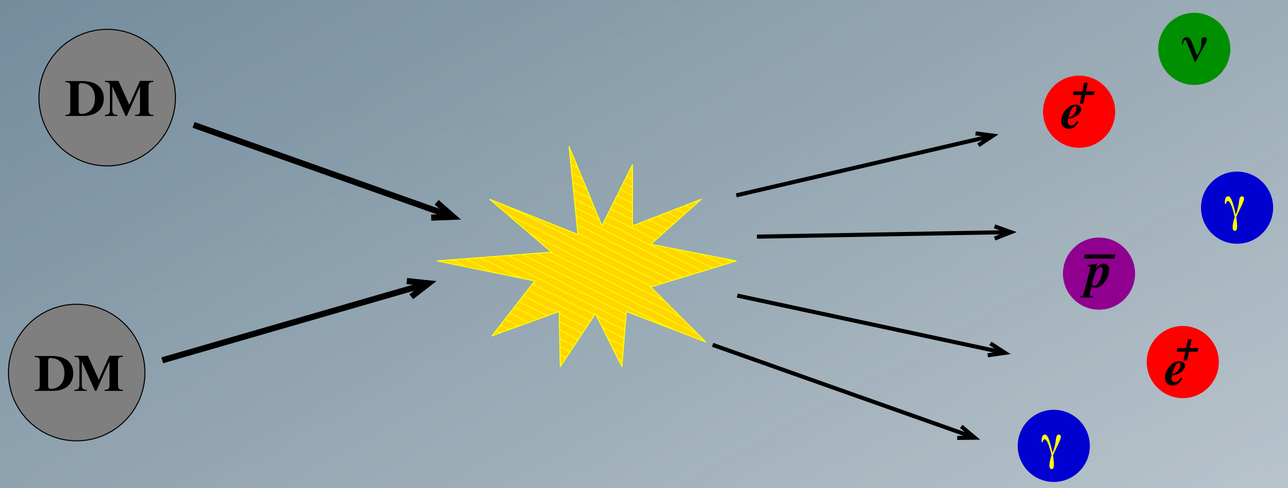
✓Energy scale of annihilation products set by DM particle mass
→ favored models ~GeV-TeV

✓Gamma-rays travel following straight lines
→ source can be known

✓[In the local Universe] Gamma-rays do not suffer from attenuation
→ spectral information retained.

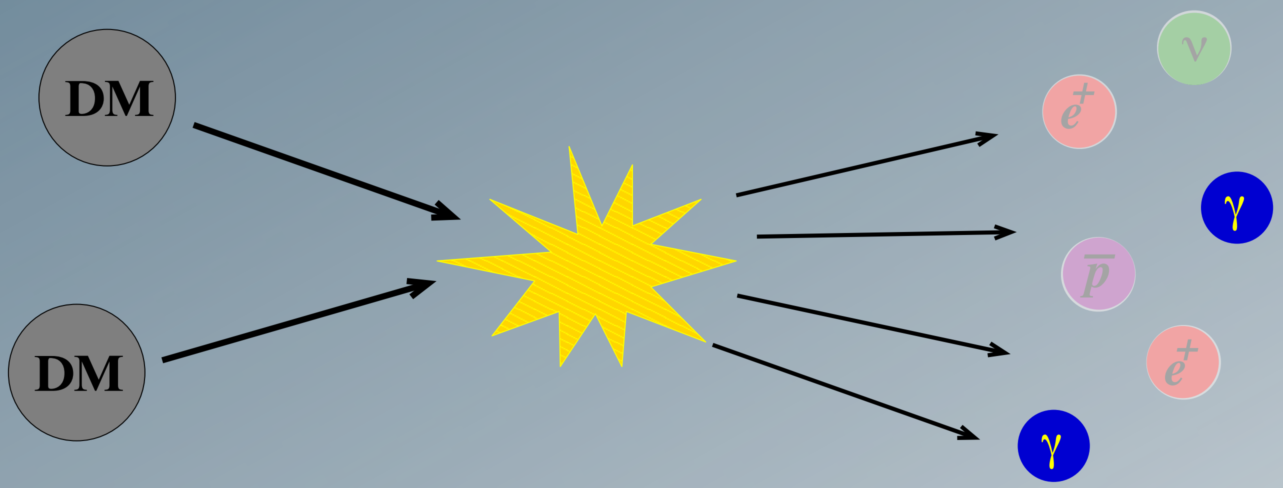
Siegal-Gaskins' talks

Indirect DM searches



- DM has to be (quasi-)stable against decay...
- … but can usually pair-annihilate into SM particles
- Try to spot those in cosmic rays of various kinds
- The challenge: i) absolute rates
  $\rightsquigarrow$ regions of high DM density
  ii) discrimination against other sources
  $\rightsquigarrow$ low background; clear signatures

Indirect DM searches



Gamma rays:

- Rather high rates
- No attenuation when propagating through halo
- No assumptions about diffuse halo necessary
- Point directly to the sources: clear spatial signatures
- Clear spectral signatures to look for

Complementarity of Gamma-Ray Detectors

- Space-based detectors - continuous full-sky coverage in GeV
- Ground-based detectors have TeV sensitivity
  - IACTs (pointed) excellent energy and angle resolution
  - HAWC has 24-hour >1/2 sky coverage

Wide-field/Continuous Operation   TeV Sensitivity

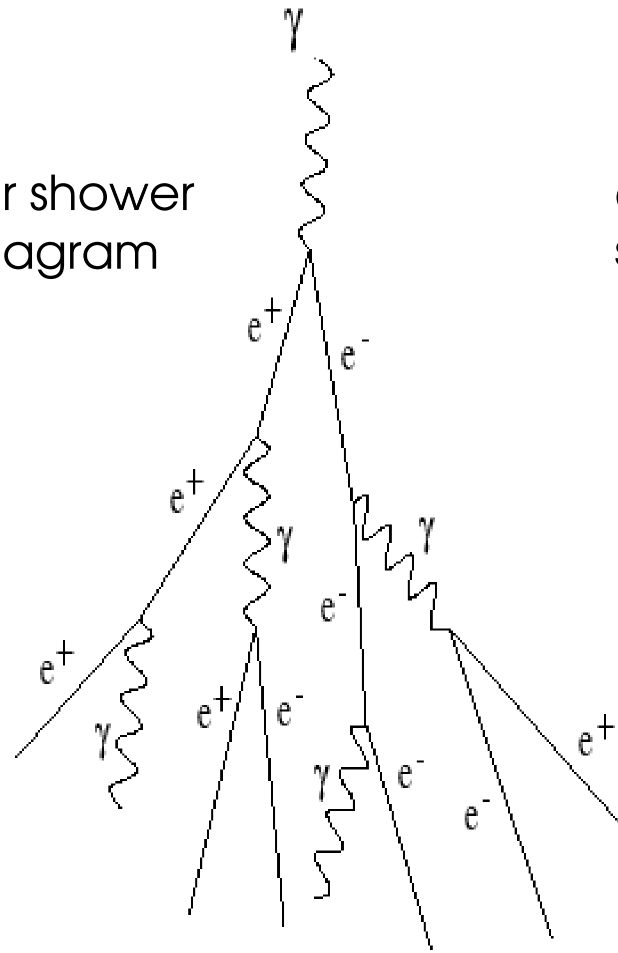
Fermi
AGILE
EGRET

HAWC
ARGO
Milagro

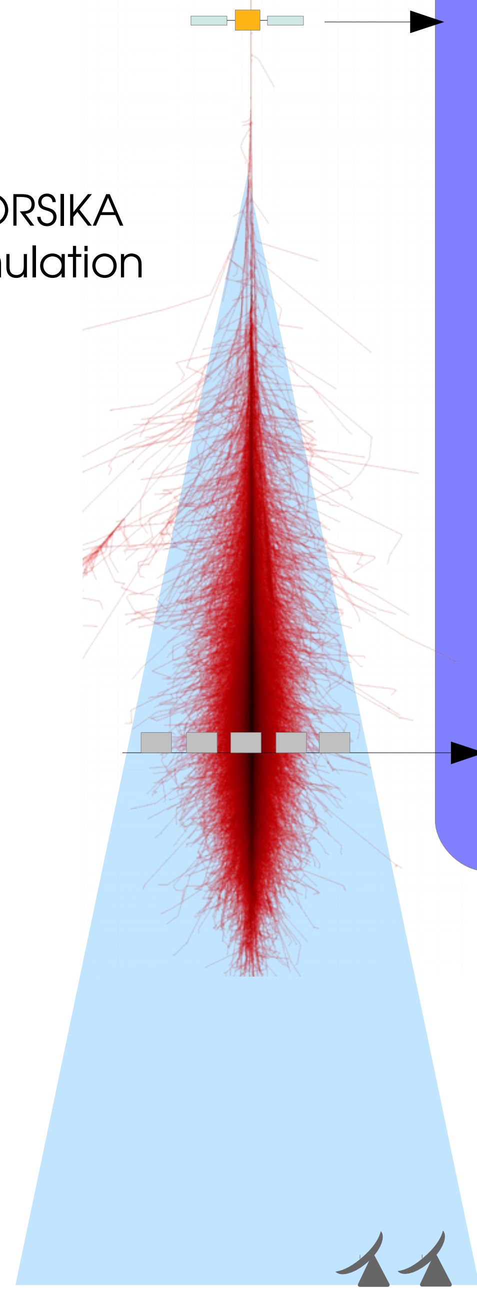
VERITAS
HESS
MAGIC

Gamma-ray air showers

air shower diagram



CORSIKA simulation



Direct γ-detection

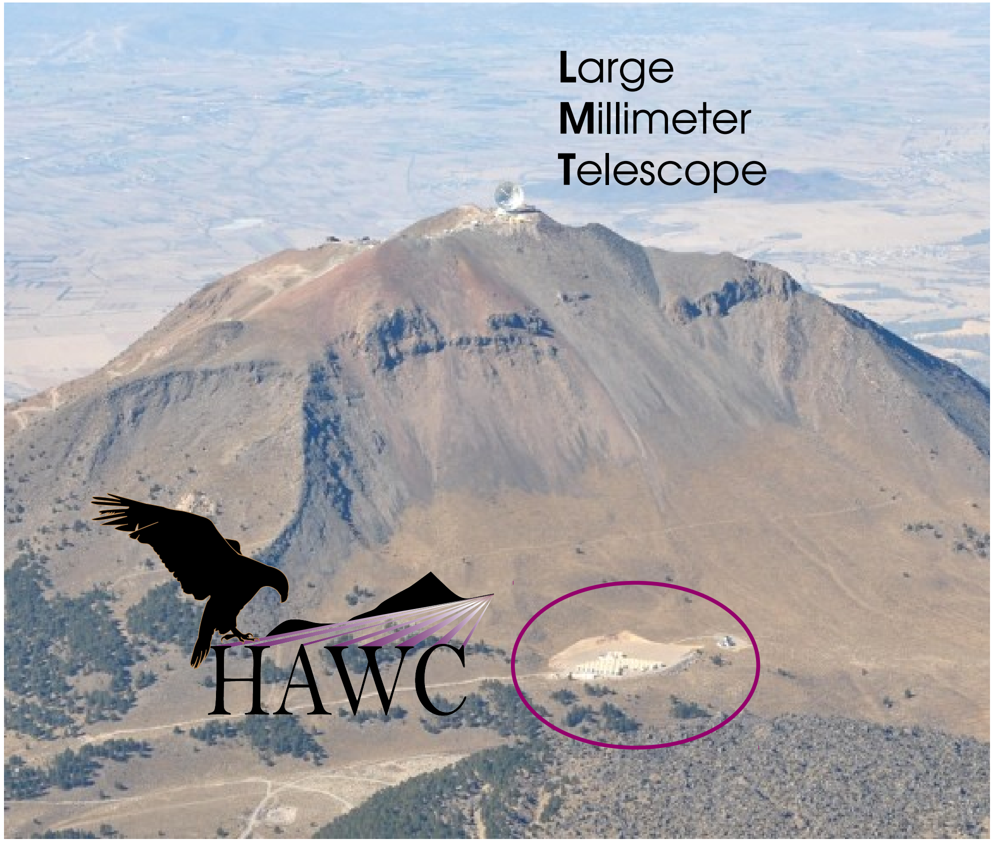
Wide Field of View, Continuous Operations

Shower particle interception

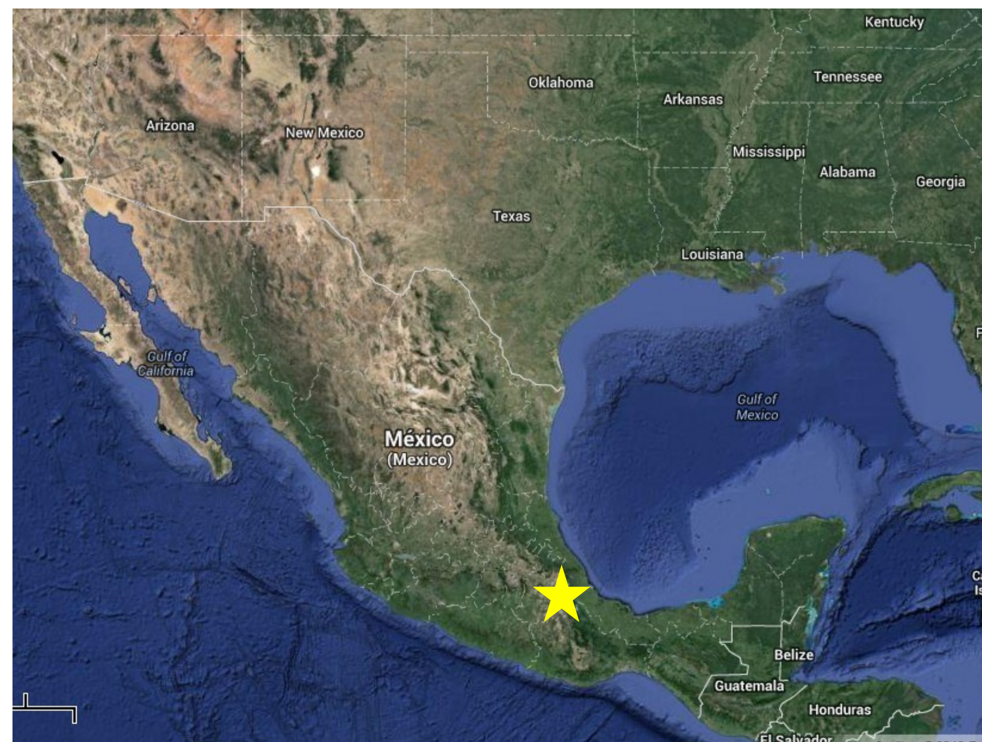
TeV Sensitivity

Shower imaging

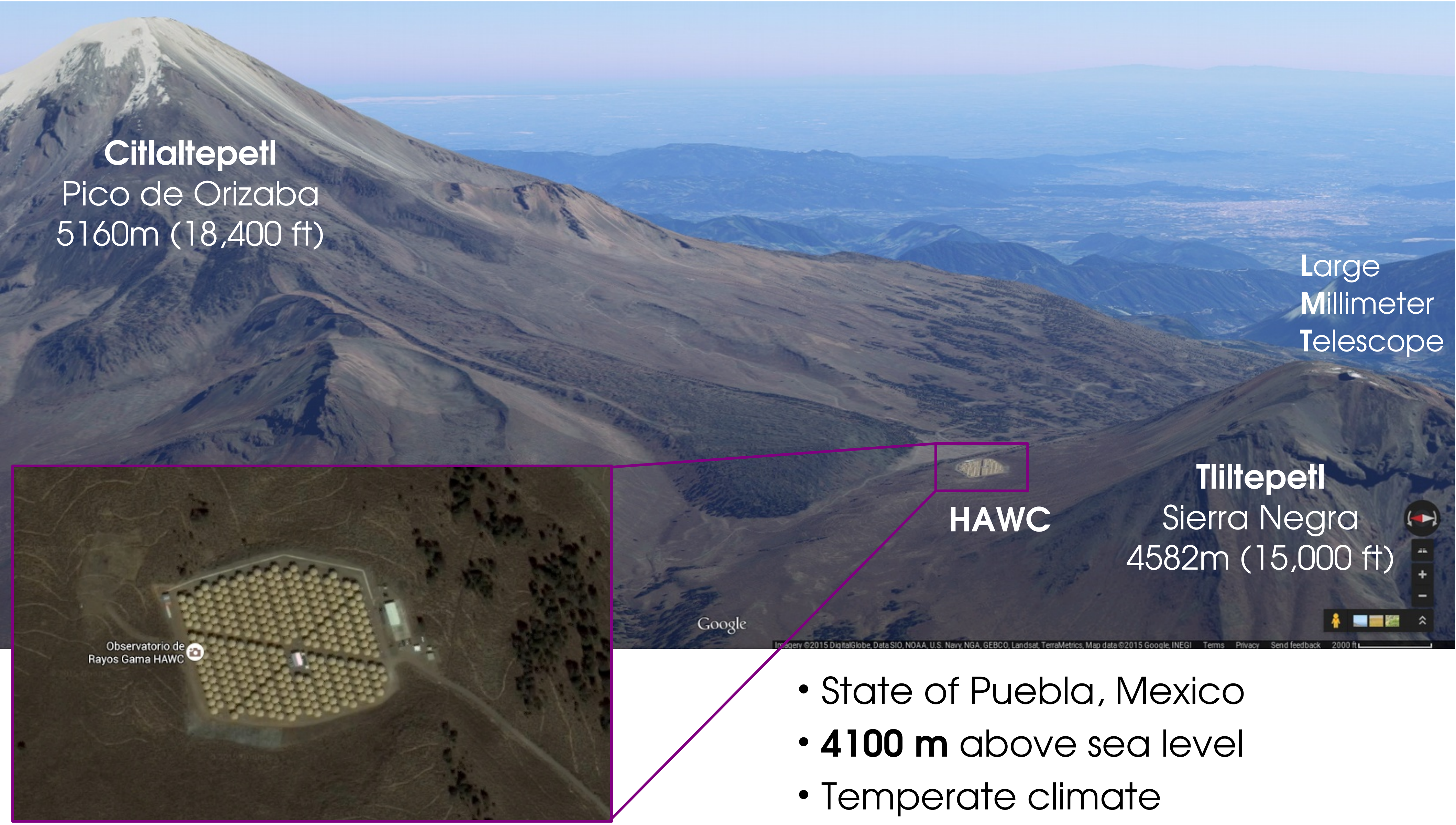
2^{nd} Generation Water Cherenkov: HAWC



- Sierra Negra volcano near Puebla, Mexico
- High altitude site at 4100 m
- Temperate climate
- Existing infrastructure from LMT
- 17 radiation lengths of atm. Overburden (vs. 27 at sea level)



HAWC Site



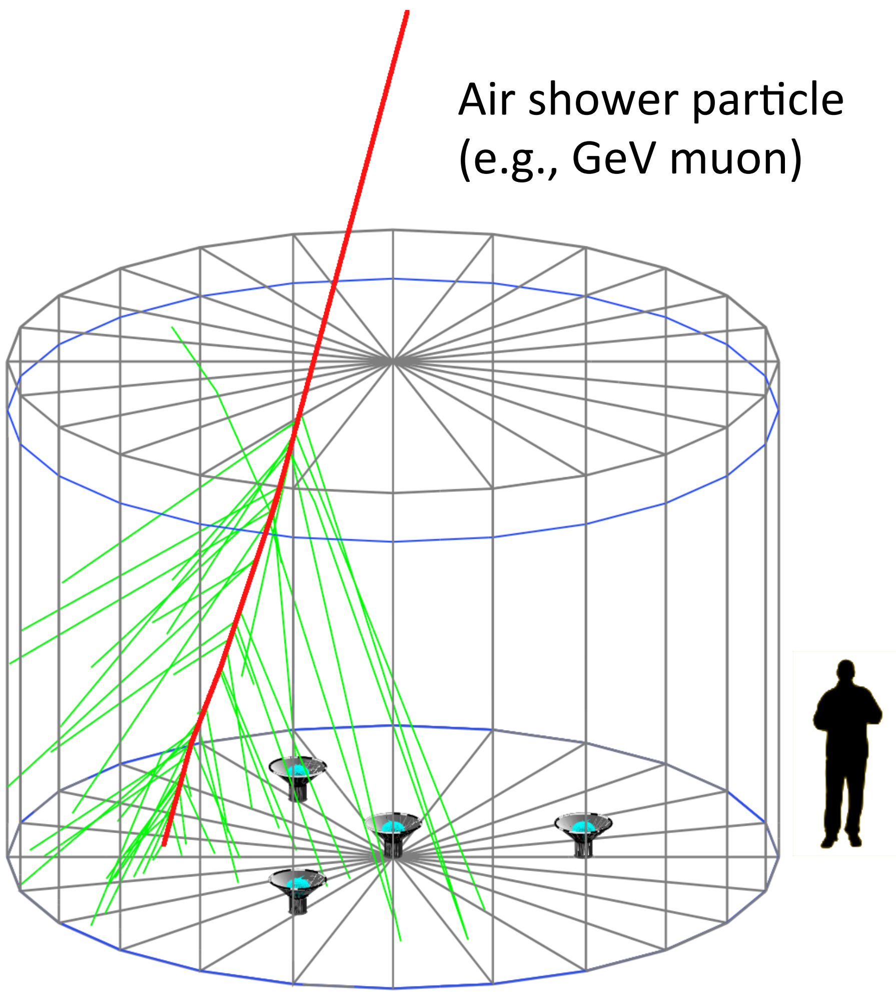
- State of Puebla, Mexico
- **4100 m** above sea level
- Temperate climate
- Existing infrastructure from LMT

HAWC Construction

- Project funding began Feb 2011
- Operations with 111 water Cherenkov detectors in Aug 2013
- 250 WCD array completed in Nov 2014
- 300 WCD array complete in March 2015, inauguration

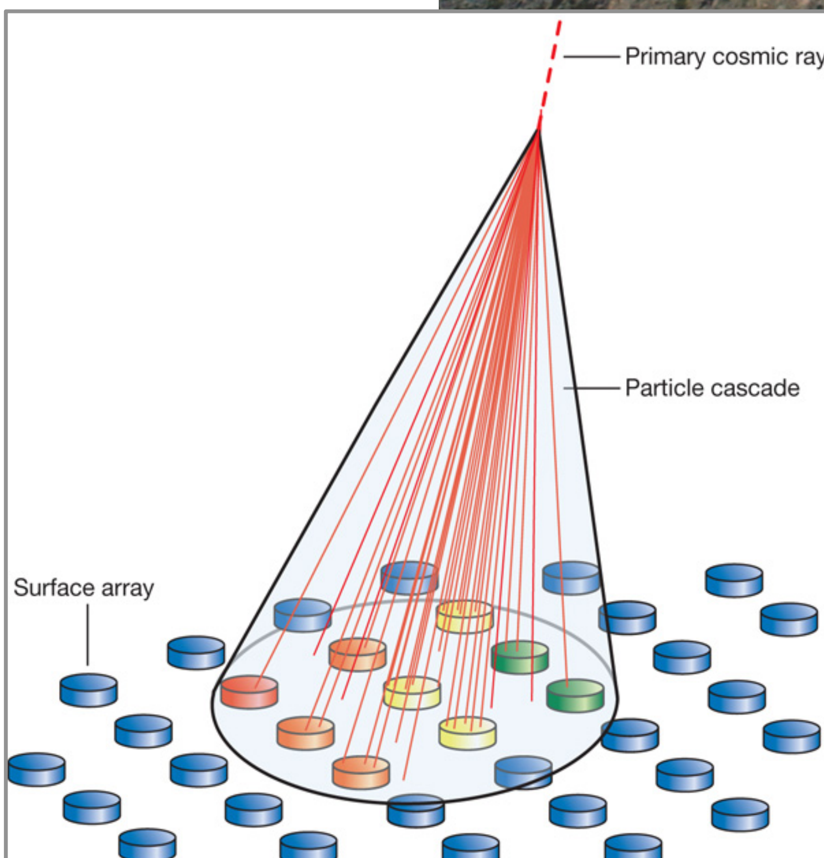
Water Cherenkov Method

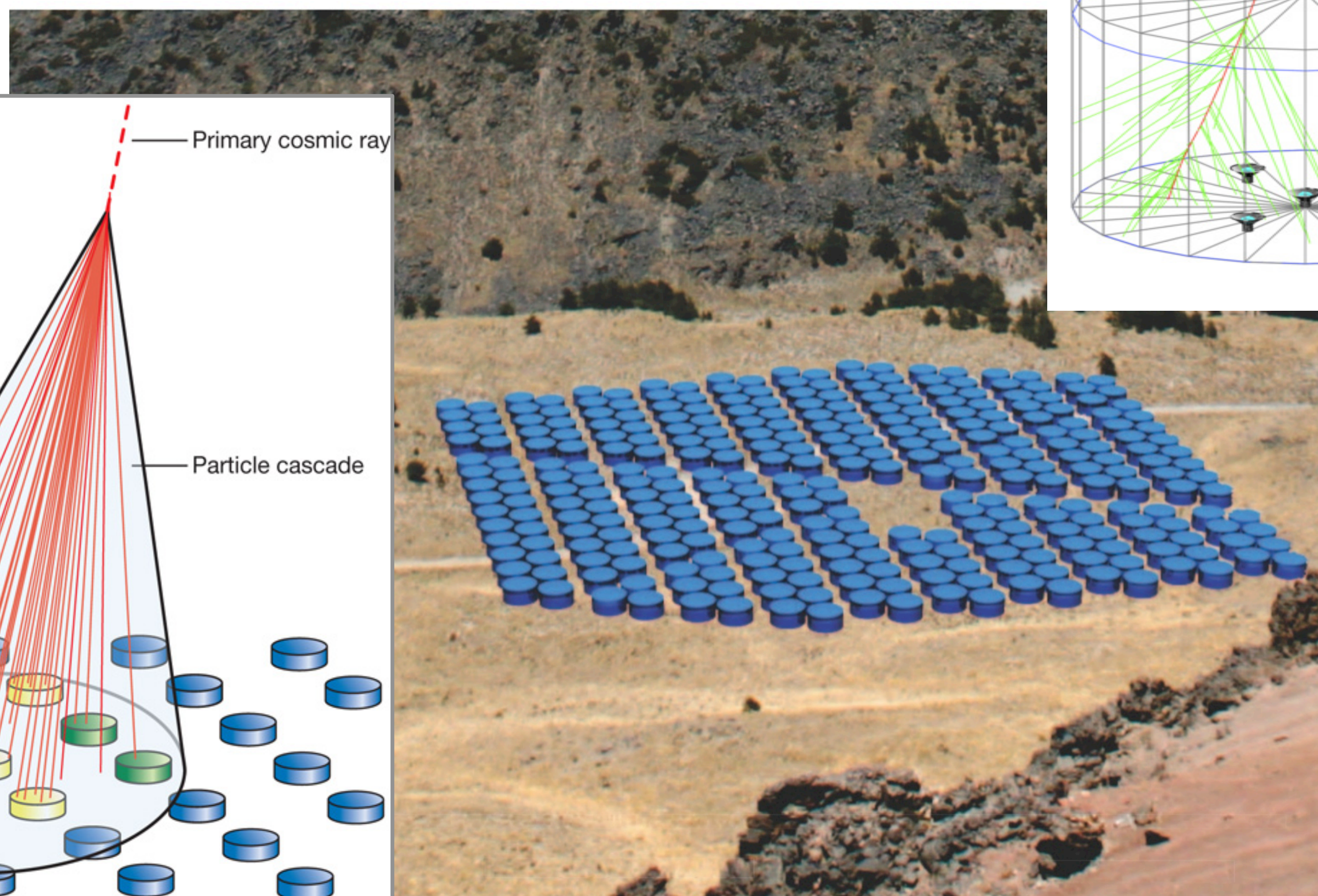
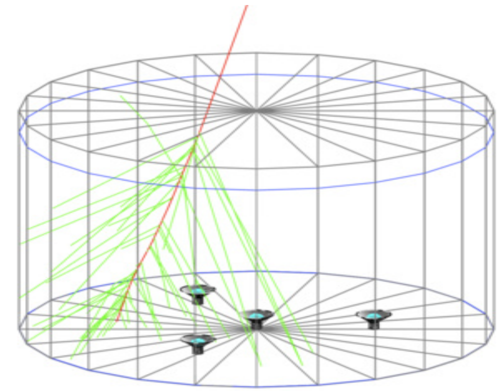
- Robust and cost-effective surface detection technique
- Water tanks: 7.3 m radius, 5 m height, 185 kL purified water
- Tanks contain three 8” R5912 PMTs and one 10” R7081-HQE PMT looking up to capture Cherenkov light from shower front



How Does HAWC Work?

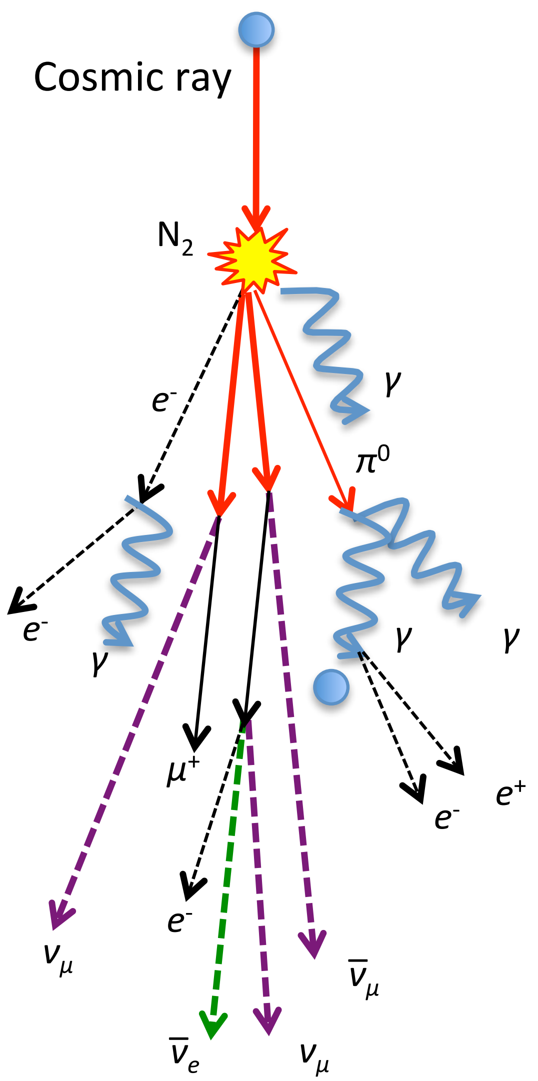
- Close-packed array of water-Cherenkov detectors, 20000 m^2

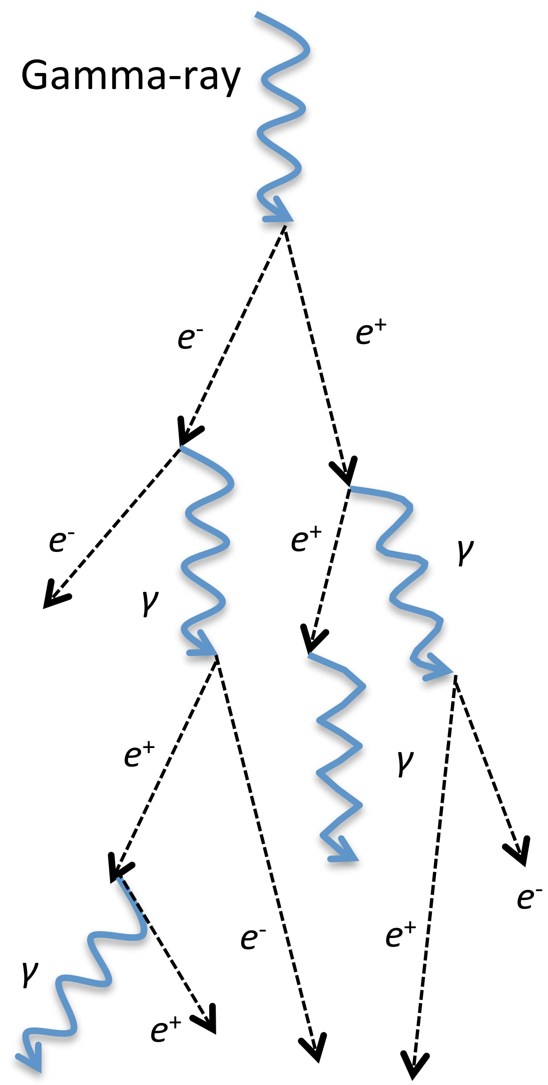


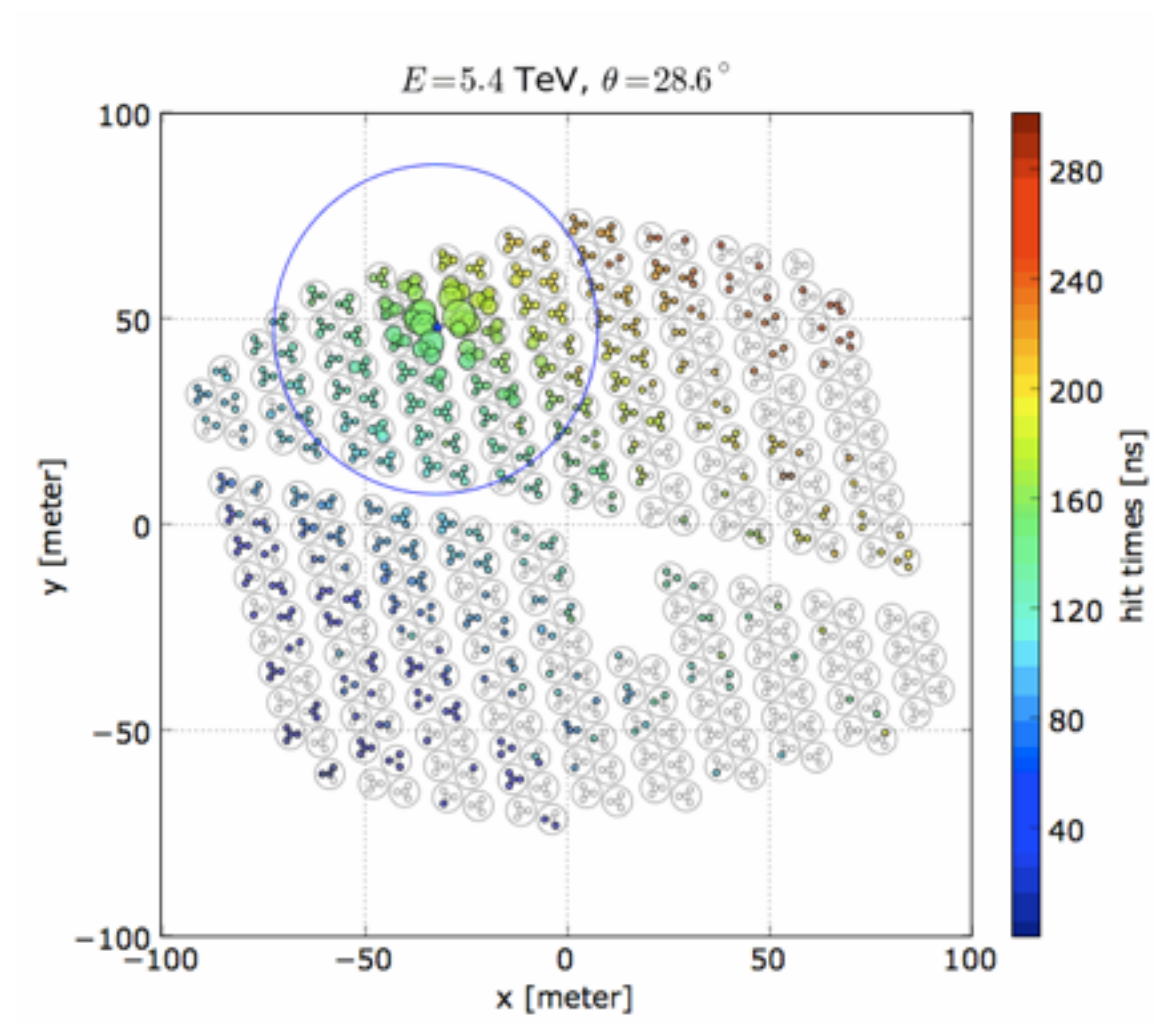



Background Rejection

- CR rejection using topological cut in hit pattern



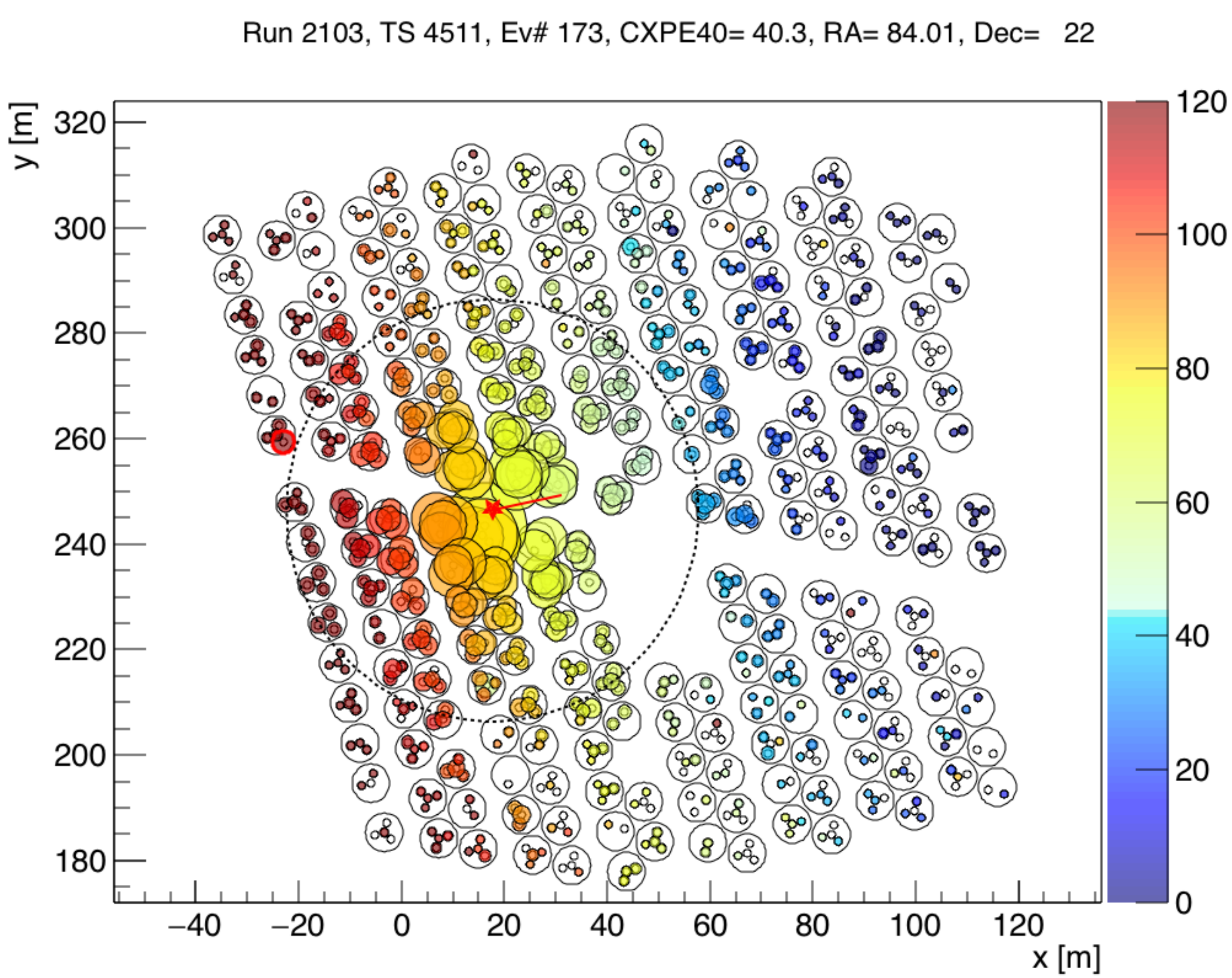




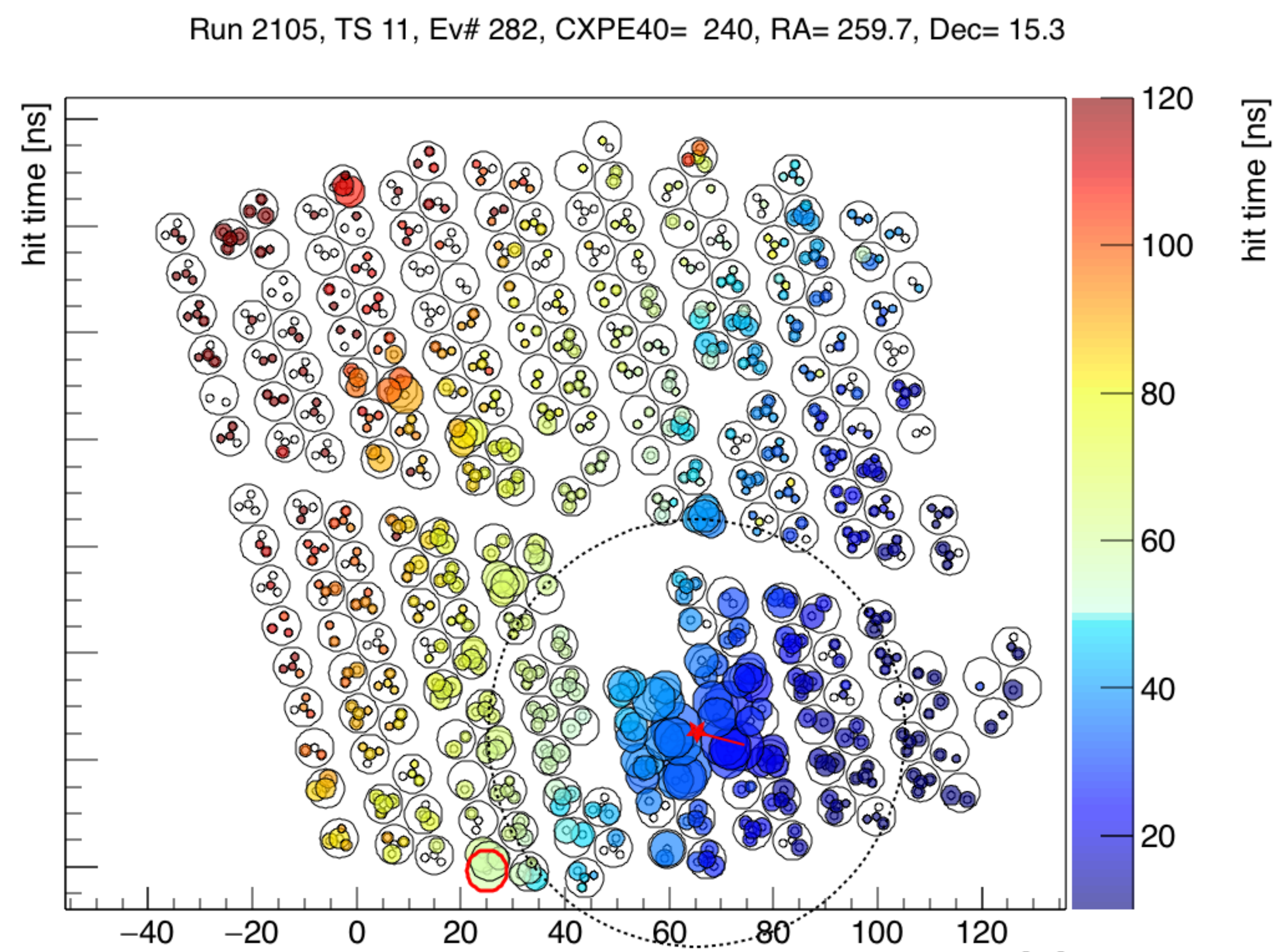
- Requires sufficient number of triggered channels (>70) to work well. Q-value ($\epsilon_\gamma/\sqrt{\epsilon_{CR}}$) is ~5 for point sources

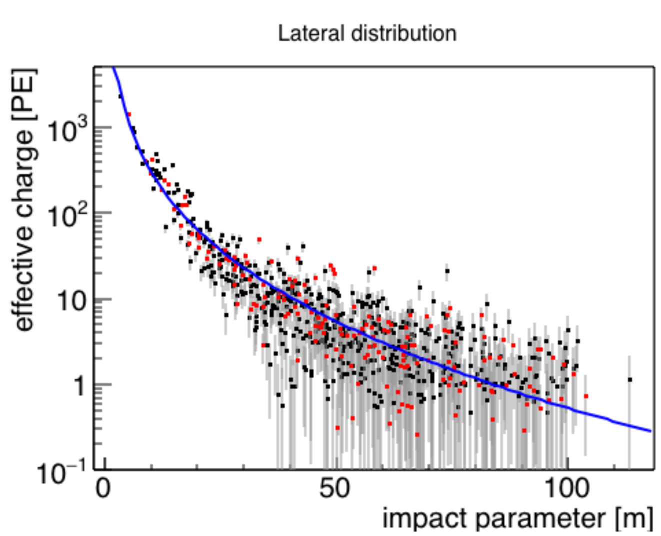
HAWC Events

Gamma



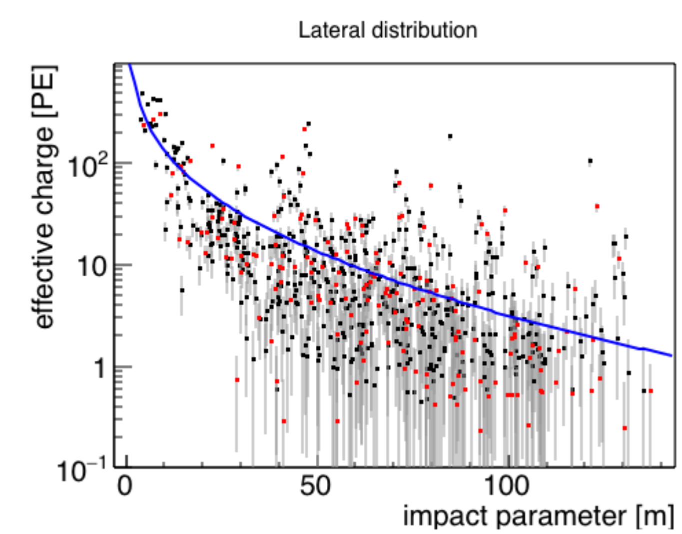
Hadron



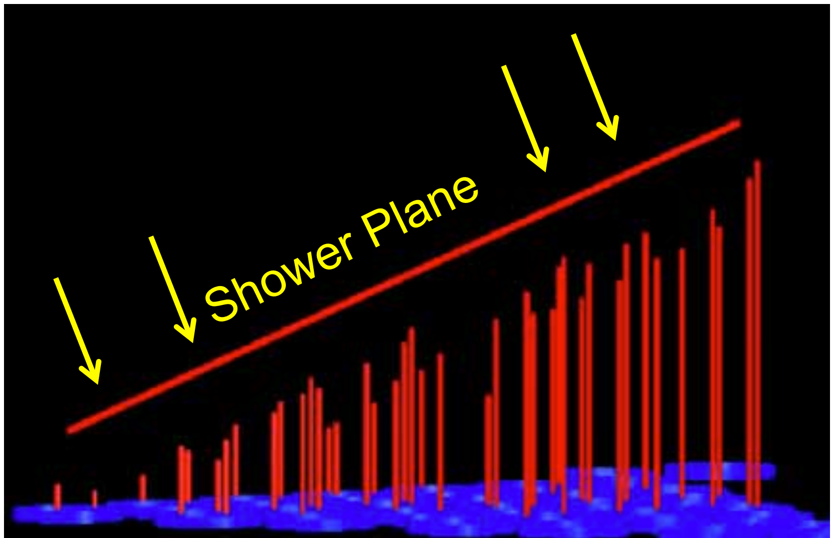


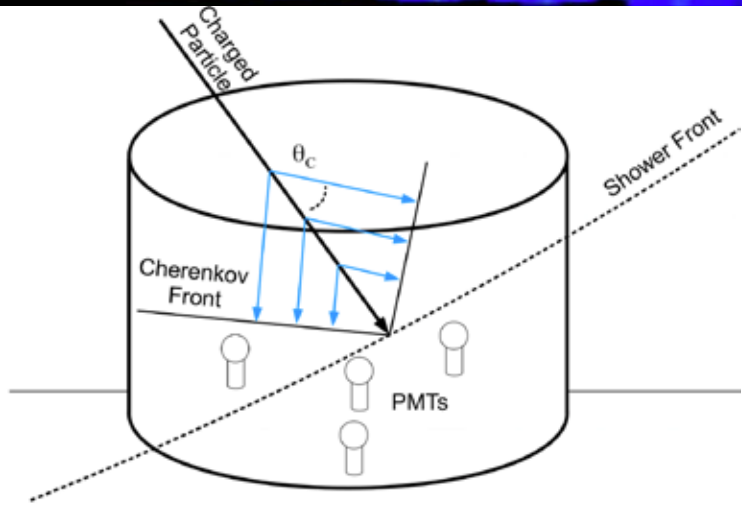
- Gamma: smooth lateral distribution
- Hadrons: irregular pattern, sub-showers, muons

=> Gamma/Hadron discrimination



Angle Reconstruction





Photons convert to e+e- in the water

The HAWC collaboration

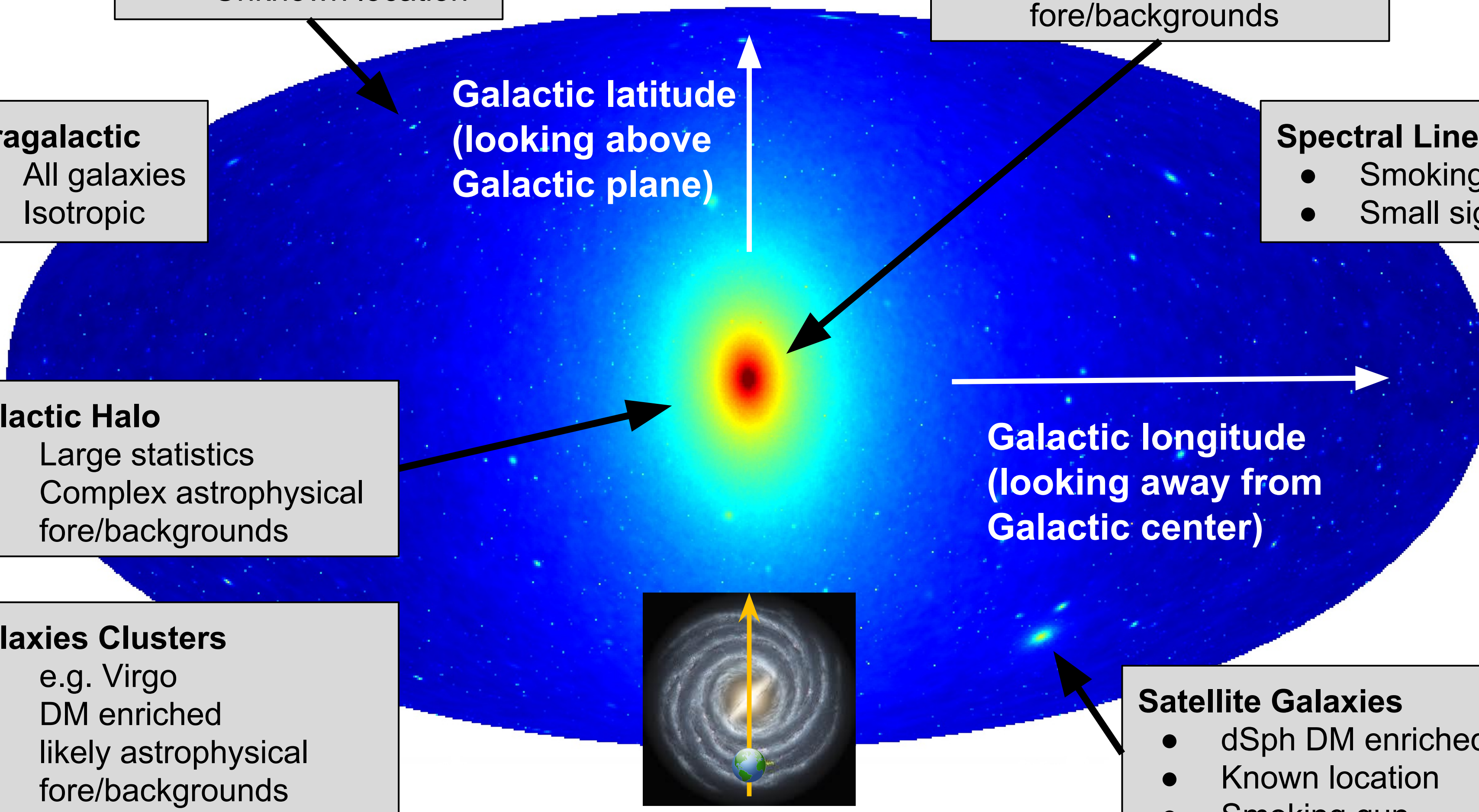
Galactic Distribution of Dark Matter

DM clumps in Halo
- Few backgrounds
- Unknown location

Galactic Center
- Large statistics
- Complex astrophysical fore/backgrounds

Extragalactic
- All galaxies
- Isotropic

Spectral Lines
- Smoking gun
- Small signal



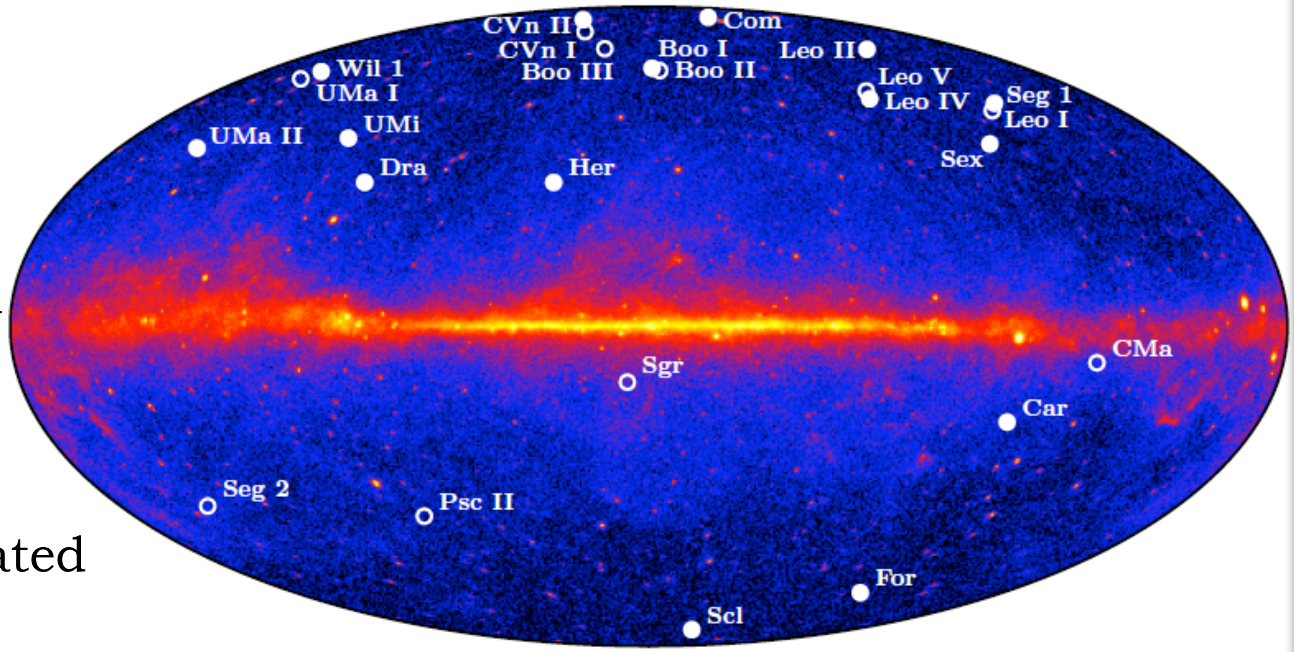
Galactic Halo
- Large statistics
- Complex astrophysical fore/backgrounds

Galaxies Clusters
- e.g. Virgo
- DM enriched
- likely astrophysical fore/backgrounds

Satellite Galaxies
- dSph DM enriched
- Known location
- Smoking gun

Aquarius (A1) simulation

Milky Way satellite galaxies (dwarf spheroidals)



- Interesting astrophysical systems!
- Dark matter masses from motions of individual stars
- Most dark matter-dominated galaxies known
- Luminosities from hundreds to millions Solar luminosities
- No high energy gamma-rays from astrophysical sources

WIMP Annihilation(or Decay) Signal

- E.g. photons from DM annihilation:

particle physics

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

DM distribution

For DM decay:

- $<\sigma_{ann}v>/2m^2_{WIMP} \rightarrow 1/\tau m_{WIMP}$
- $\rho^2 \rightarrow \rho$

➡ Charged particles are more complicated (need to include propagation, energy losses)

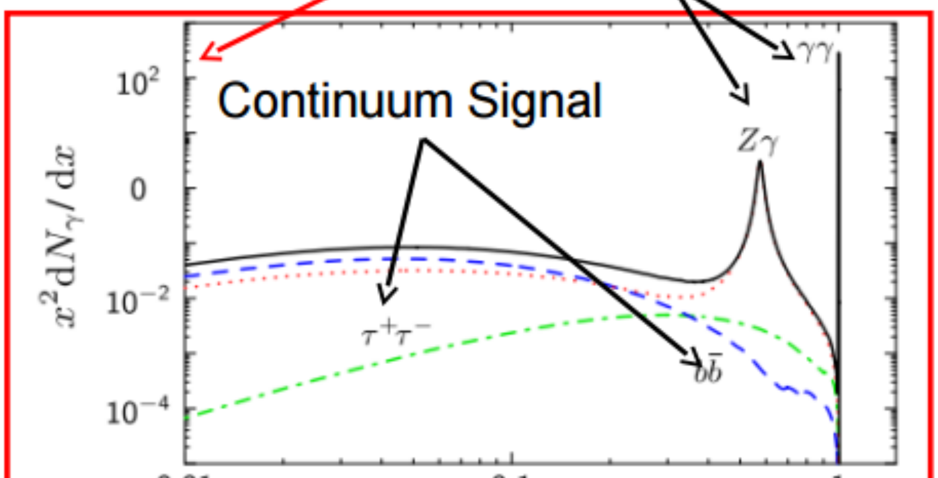
Gamma rays from DM Annihilation

What we observe	Intrinsic Particle Properties	Astrophysics

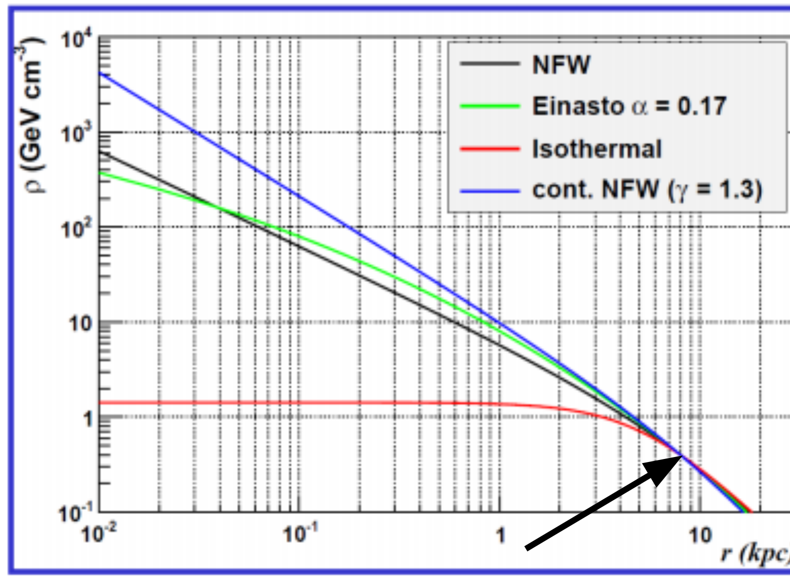
$$\Phi_\chi(E,\Psi)=\frac{\langle\sigma_\chi v\rangle}{2}\sum\frac{dN_f}{dE}B_f\int_{LOS}dl(\Psi)\frac{1}{4\pi}\frac{\rho(l)^2}{m_\chi^2}$$

J-factor – Line of sight integral over a ROI

Monochromatic Signal



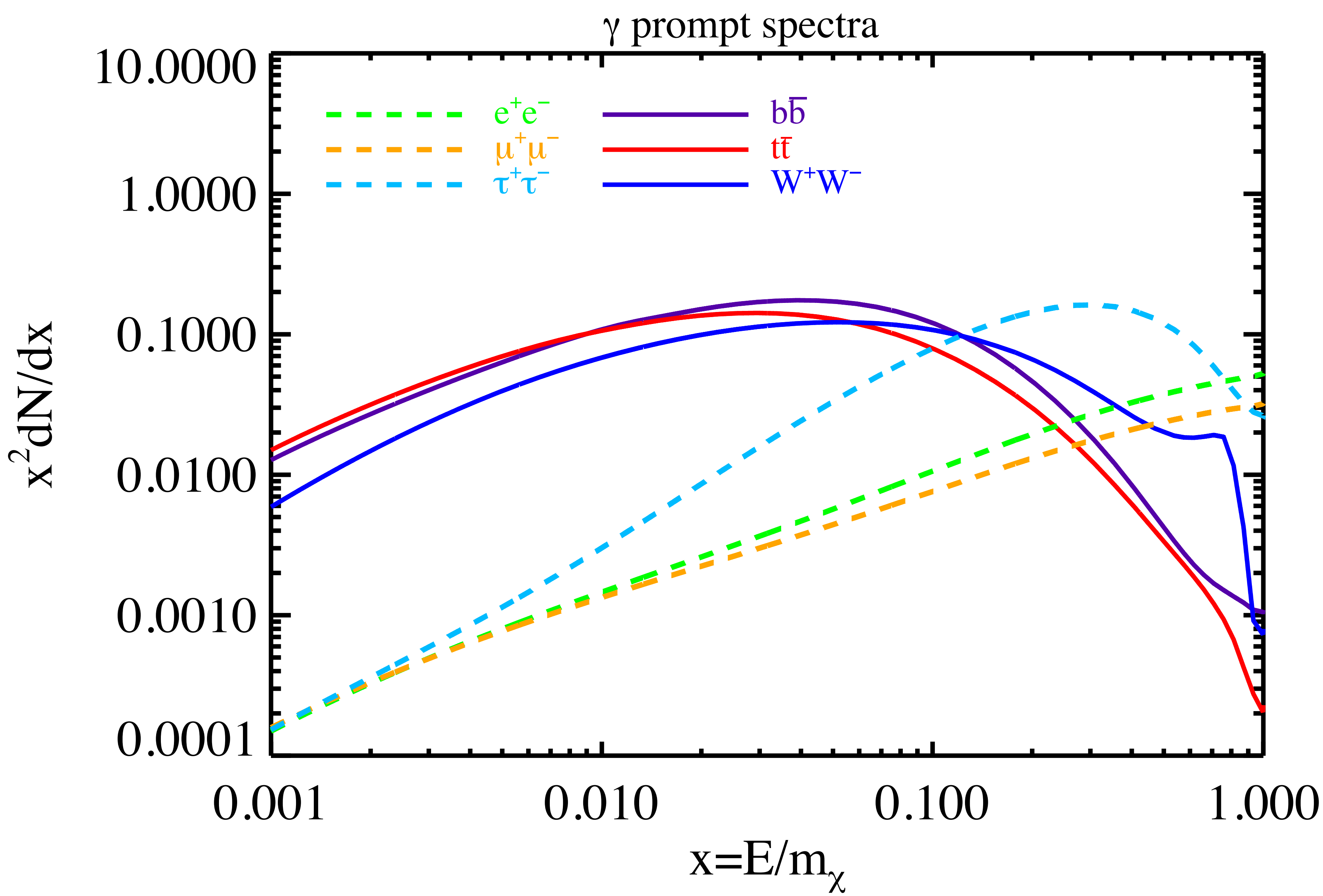
Gustafsson et al.
PRL 99.041301



r_{sun} = 8.5 kpc

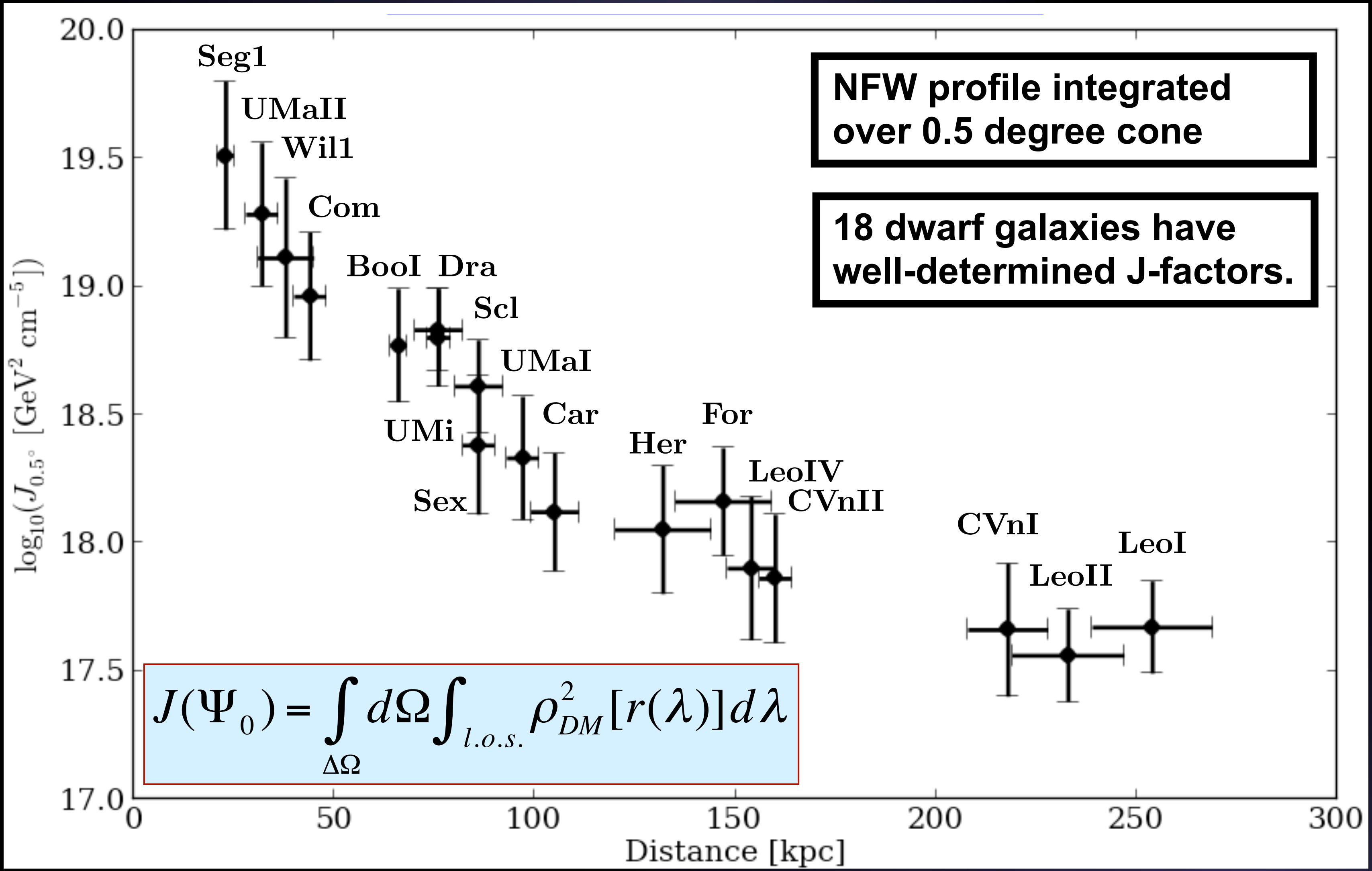
Dark matter photon spectra

- "soft" channels: produce a continuum gamma-ray spectrum primarily from decay of neutral pions
- "hard channels": include final state radiation (FSR) associated with charged leptons in the final states
- line emission: γγ, Zγ, hγ (not shown), loop-suppressed



Spectra calculated with PPPC 4 DM ID [Cirelli et al. 2010]

Dwarf Galaxies' J-Factors

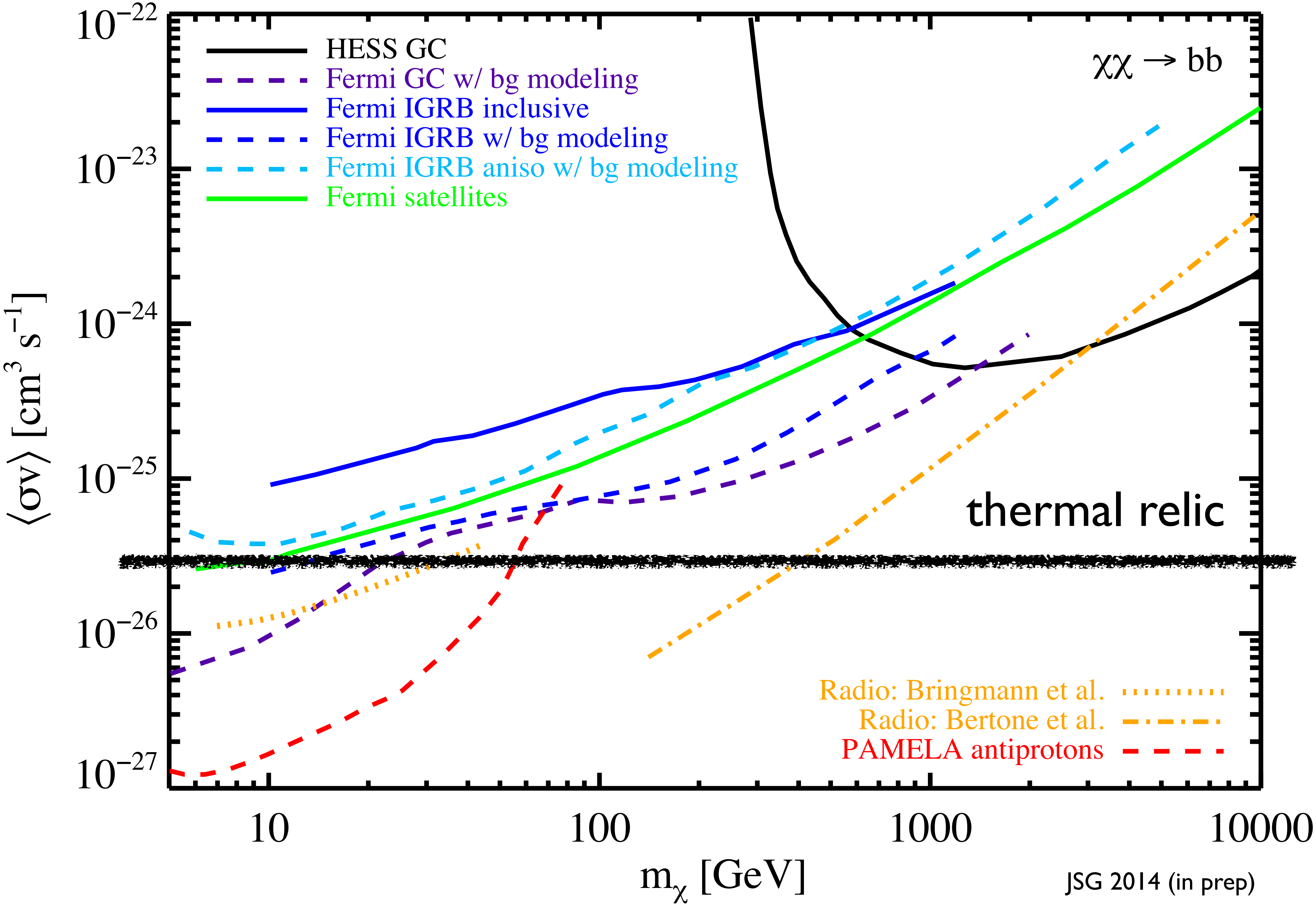


A.Drlica-Wagner DPF 2013

RECAP

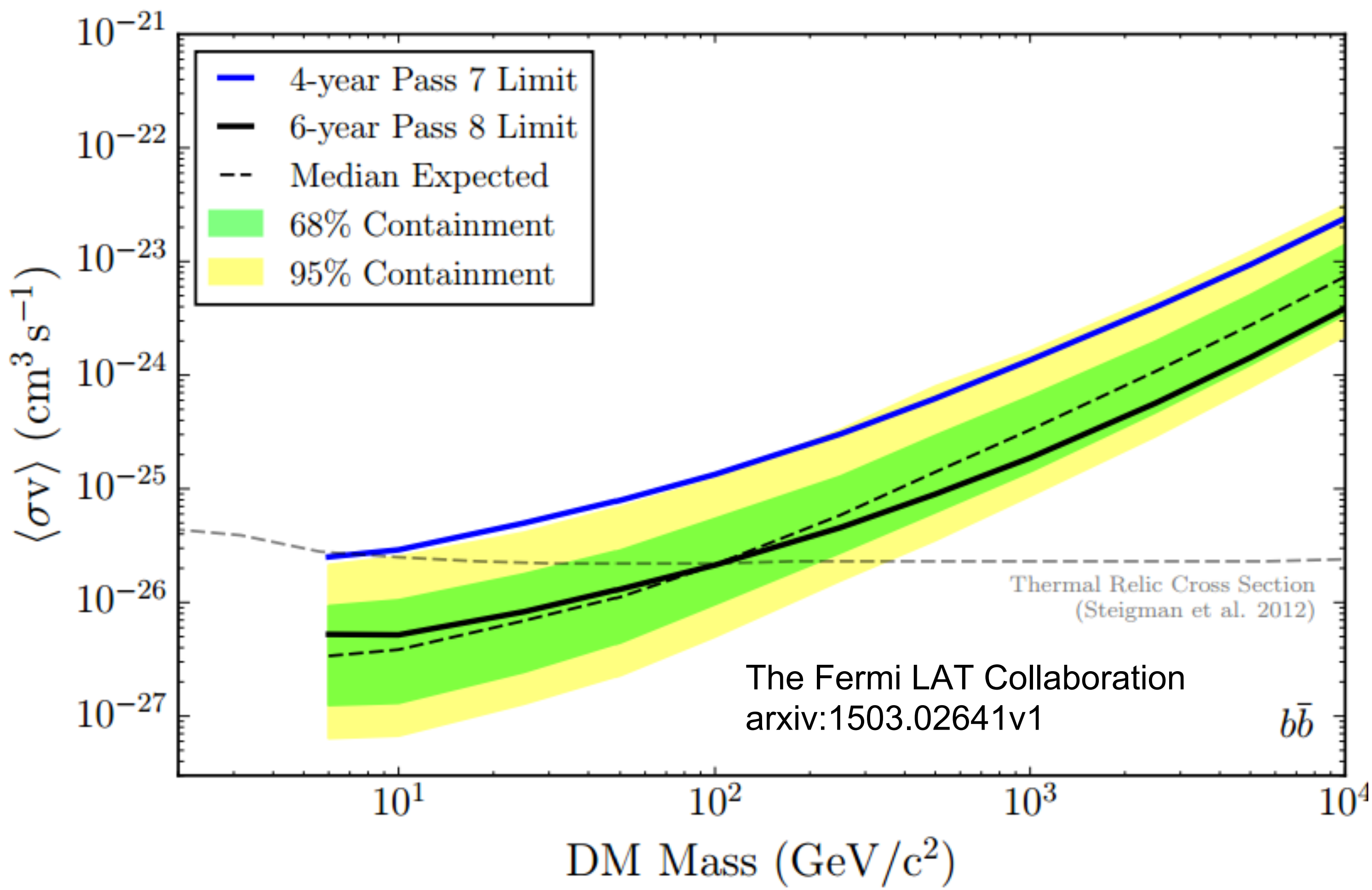
Current constraints

95% CL upper limits on annihilation cross section to bb



JSG 2014 (in prep)

Fermi LAT dSphs Results

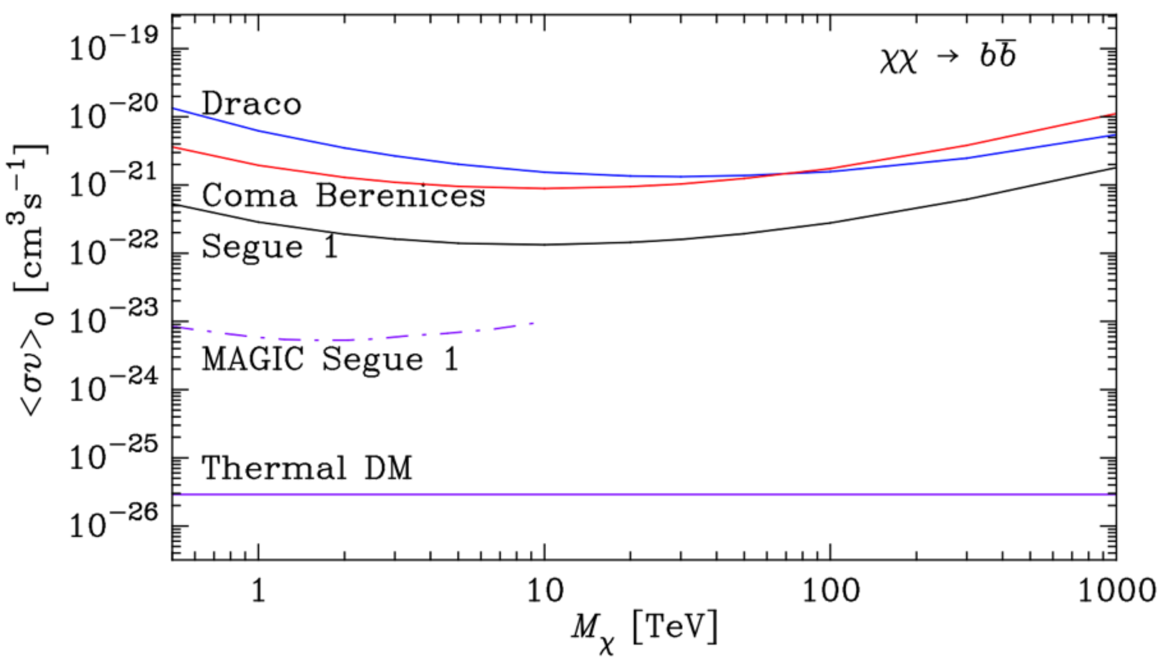


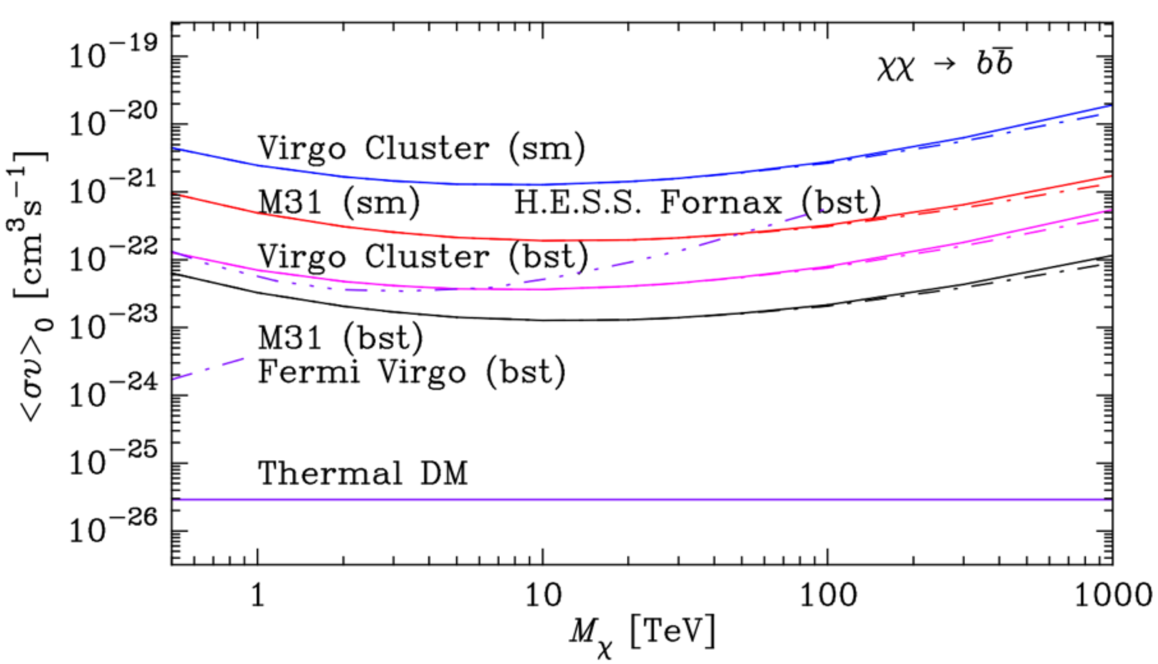
- **Joint likelihood analysis of 15 dwarf galaxies**
- **Limits exclude thermal relic $\langle\sigma v\rangle_{ann}$ in $b\bar{b}$ channel for 5 GeV $< m_\chi <$ 100 GeV**

Dark Matter Sensitivity (5 years)

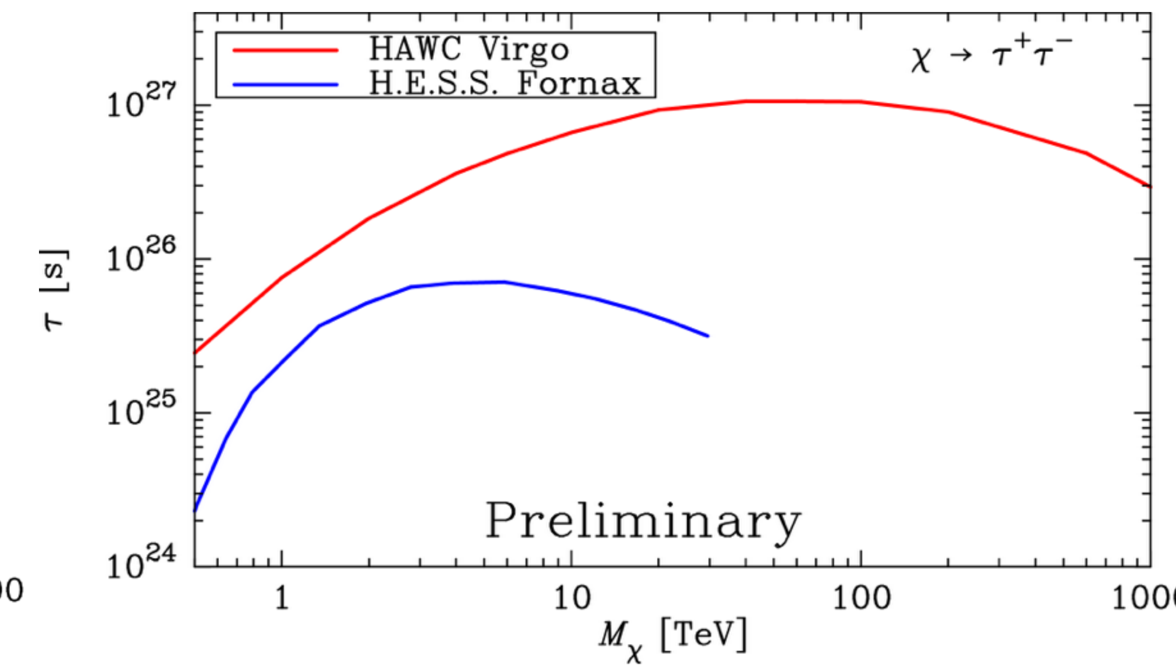
Annihilation

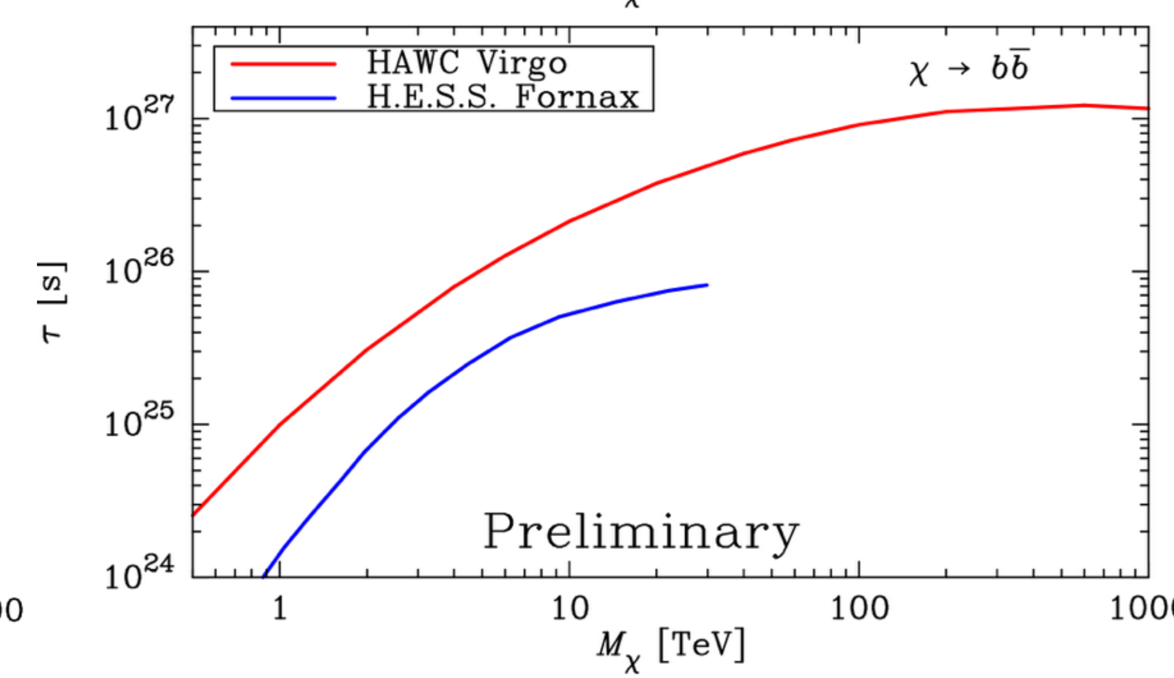
[Phys. Rev. D 90 (2014), arxiv:1405.1730]





Decay





Most competitive for extended sources

Summary

- The recently completed HAWC TeV gamma-ray observatory provides a unique instrument for studying several particle physics topics: most significantly the indirect-detection search for dark matter annihilation/decay.
- Indirect detection searches for dark matter are an important complement to other dark matter searches. Recall that all observational evidence for dark matter comes (so far) from space!
- HAWC is not the only experiment but is closest in its' survey operation to the Fermi GeV gamma-ray satellite. The Fermi-LAT measurements have reached the *thermal relic* limit over some of their mass-sensitivity range.
- Sadly no definitive gamma-ray signal has been seen ...
- Thus the embarrassement continues ...