Research Overview Seminar

Indirect Search for Dark Matter

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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.

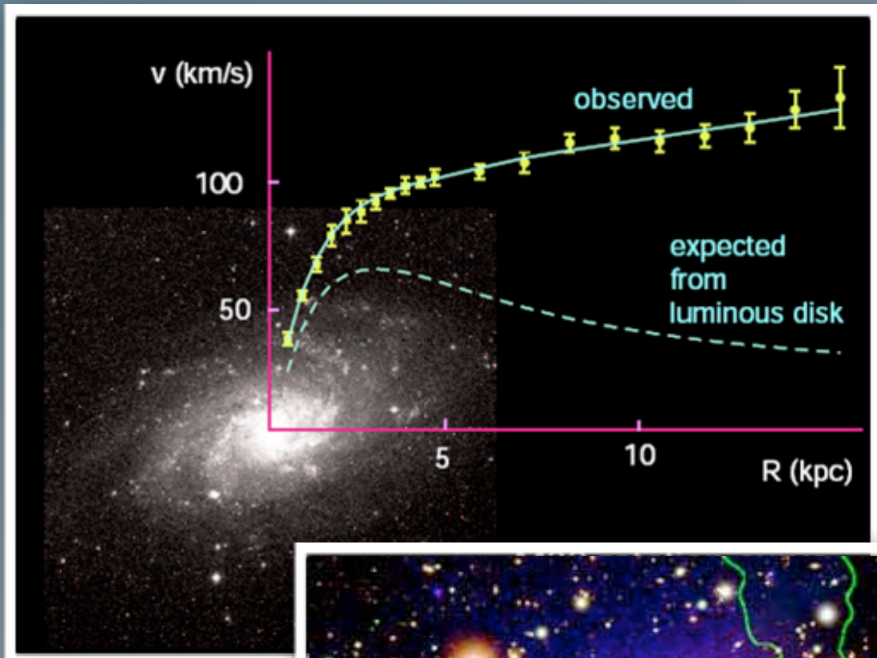
DM overview ... **Particle Physics Focus**

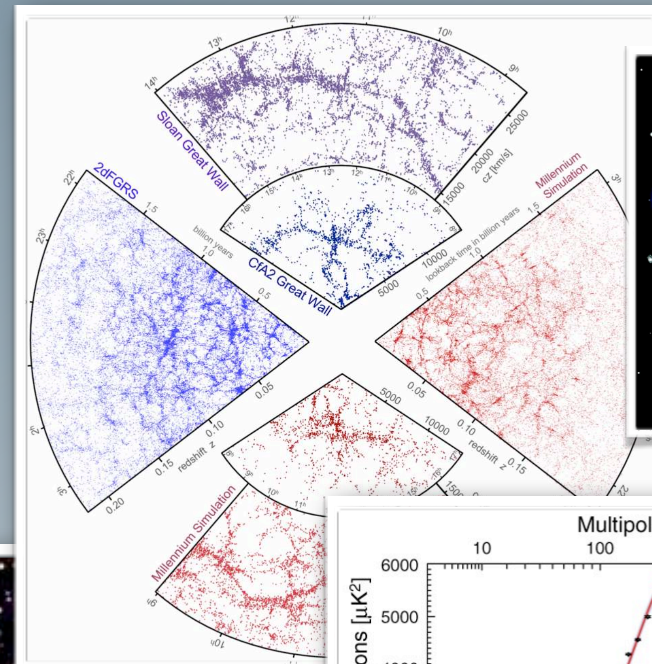
The University of New Mexico

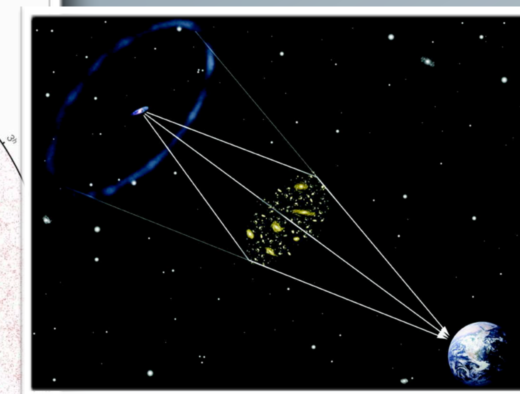
Our DM tour for today includes:

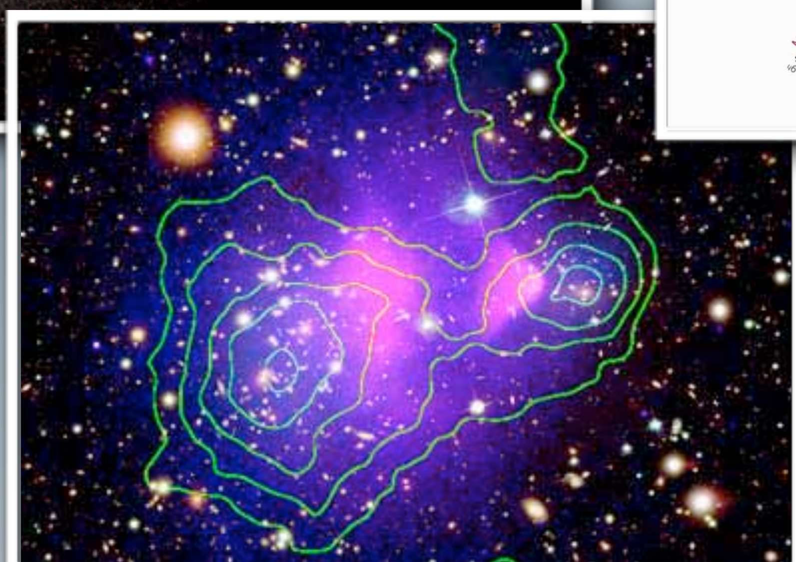
- brief overview of what we know about DM
- particle physics view of DM
- particle physics experimental plan:
  1. direct detection of DM through scattering of DM particles on target nuclei in the laboratory, *e.g.* DRIFT experiment
  2. indirect detection of DM through observation of DM annihilation (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

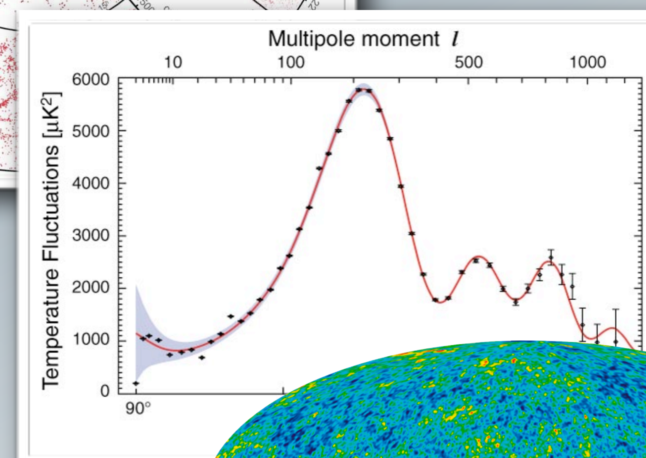
Dark matter all around

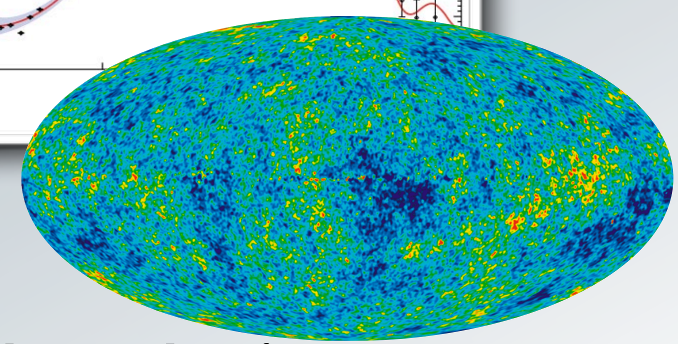








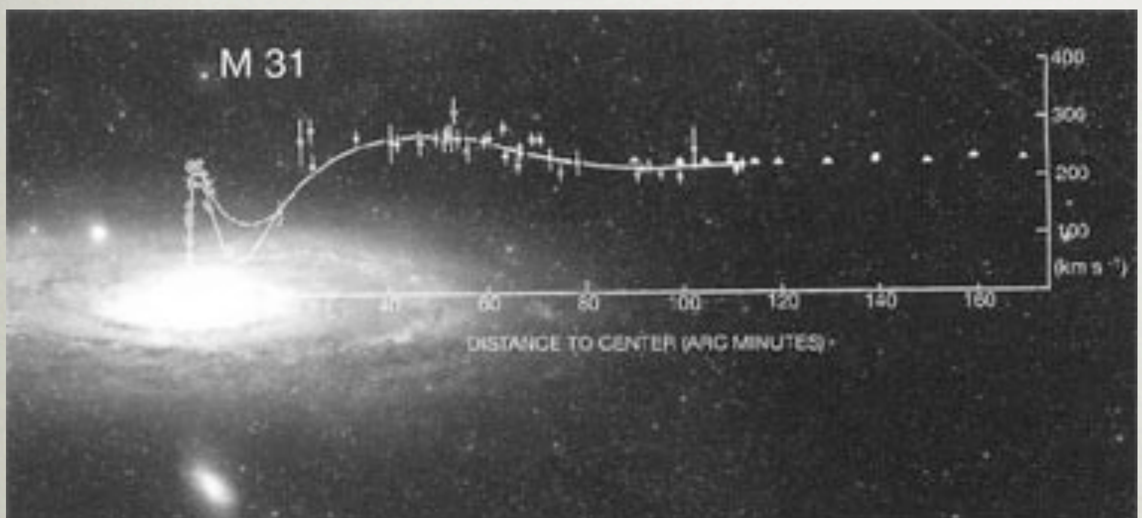


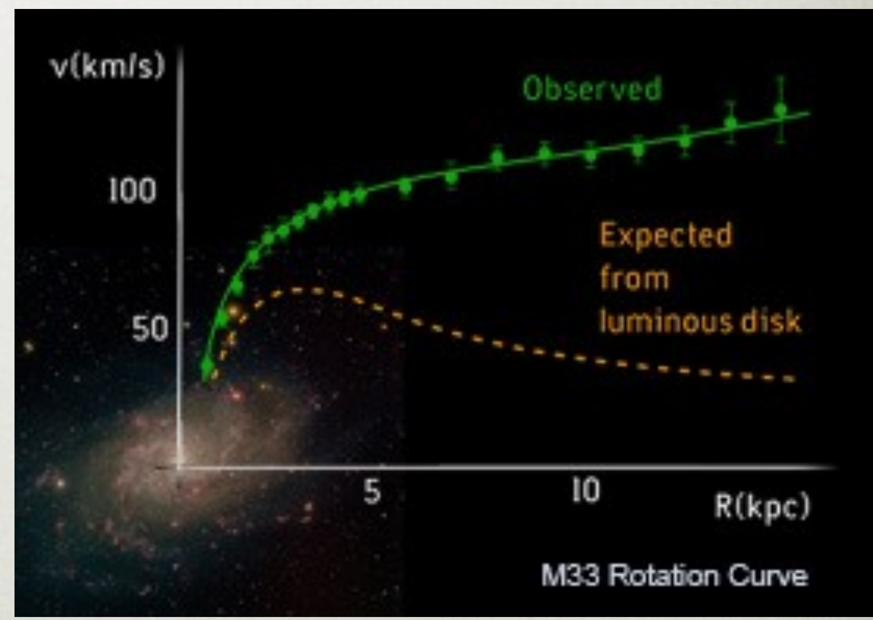


➩ *overwhelming evidence on all scales!*

Rotation Curves of Galaxies

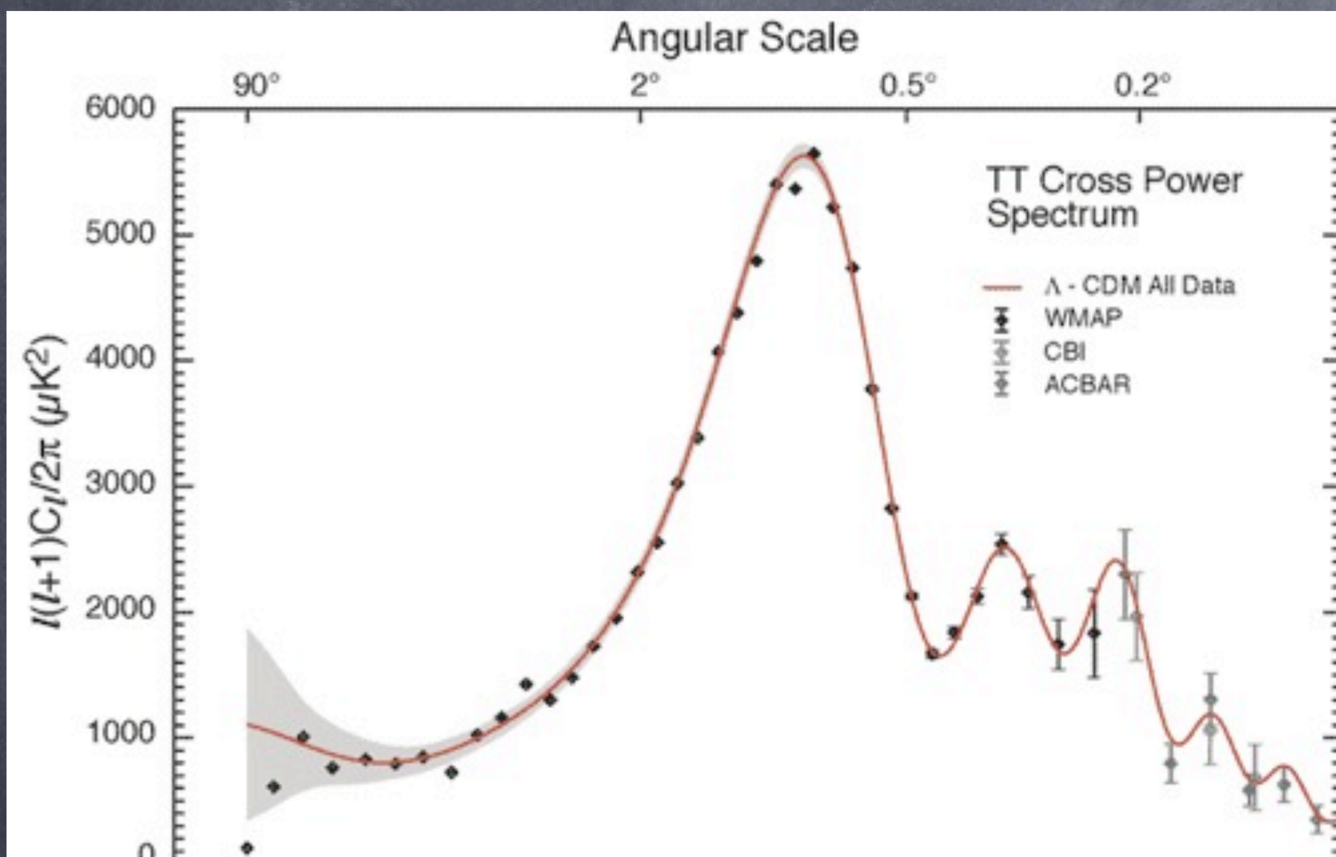
- Departures from the predictions of newtonian gravity became apparent also at galactic scales with the measurement of rotation curves of galaxies (Rubin et al, 1970)





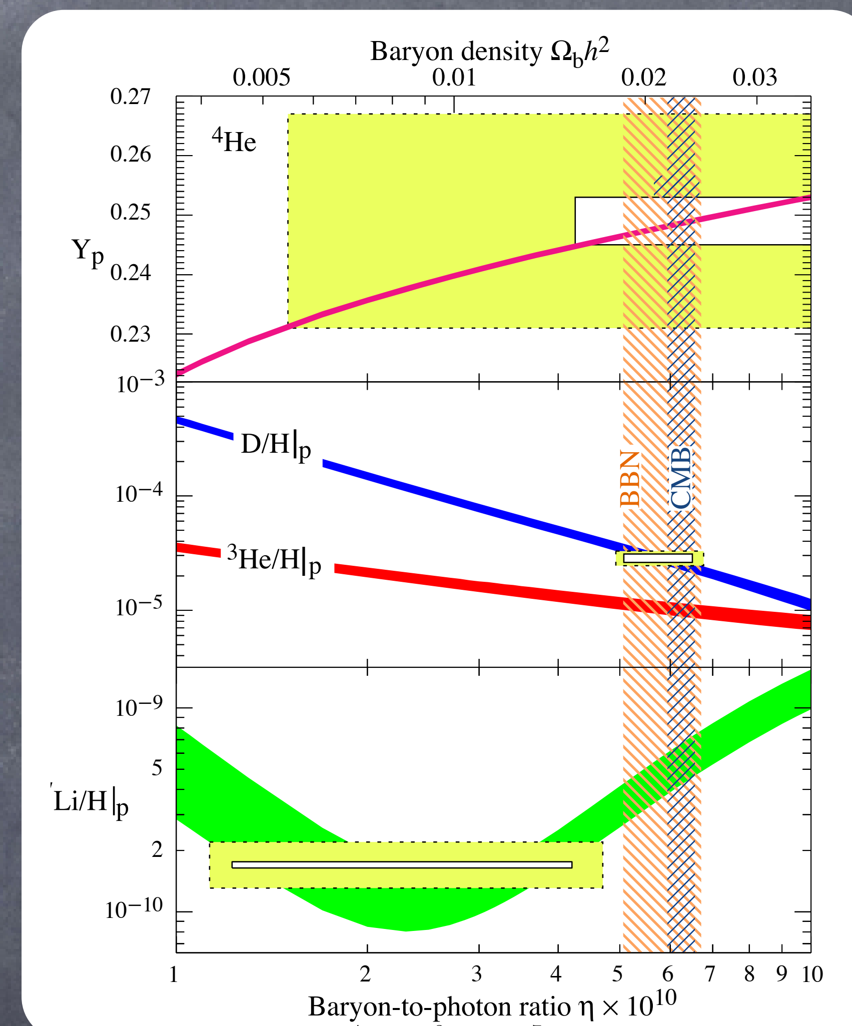
Why particle dark matter?

curvature, z_eq



Baryon density

sound speed = baryon to radiation ratio



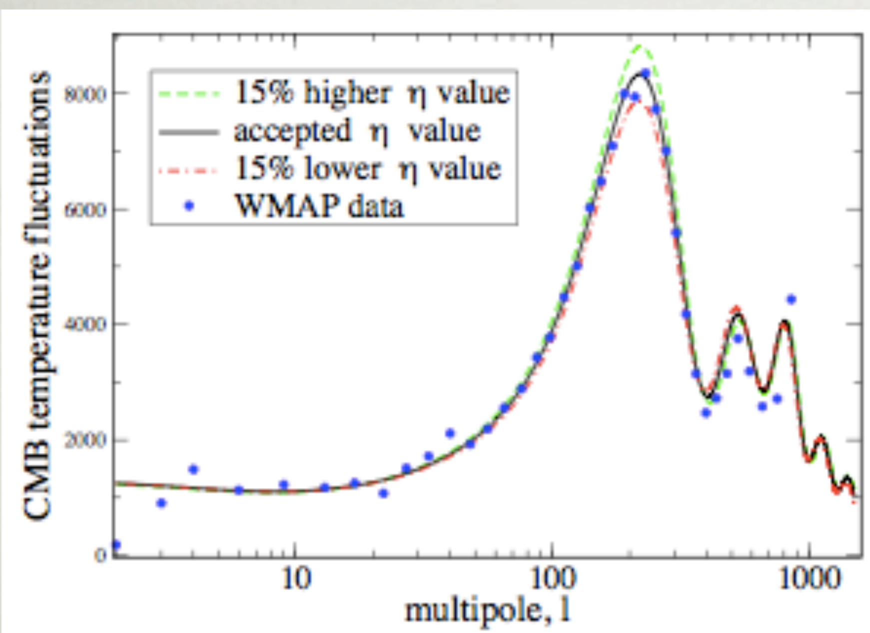
- Why not just ordinary (dark) baryons?
- A: BBN and CMB make independent measurements of the baryon fraction. Observations only accounted for with **non-interacting** matter

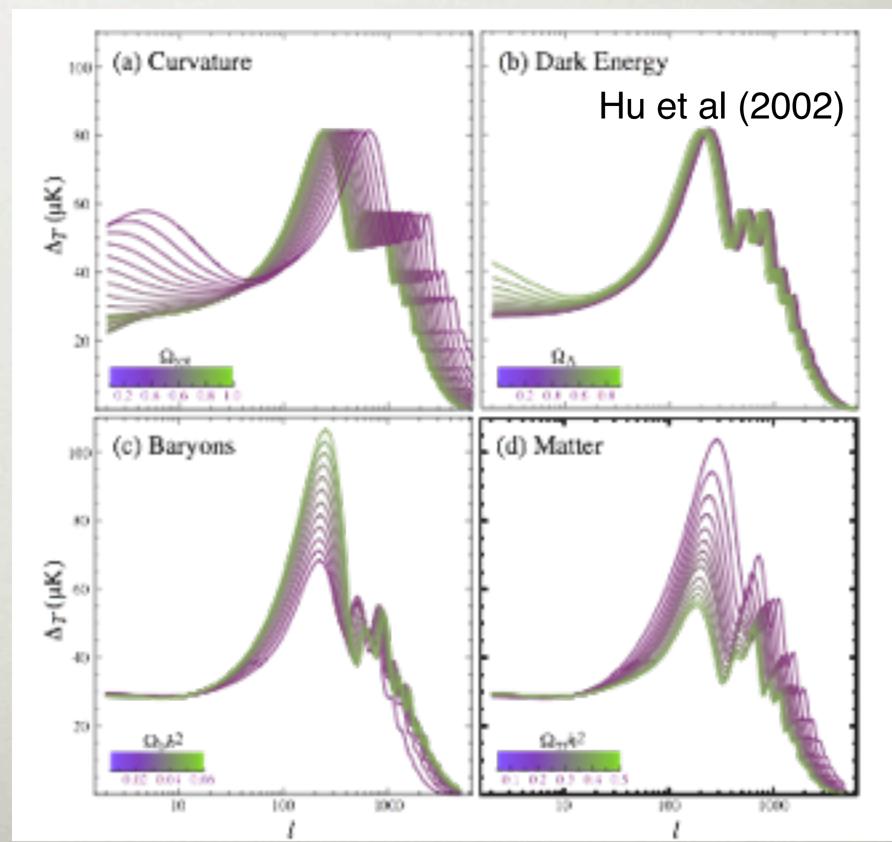
Cosmic Microwave Background

- 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, $\Omega_{total}=1$)

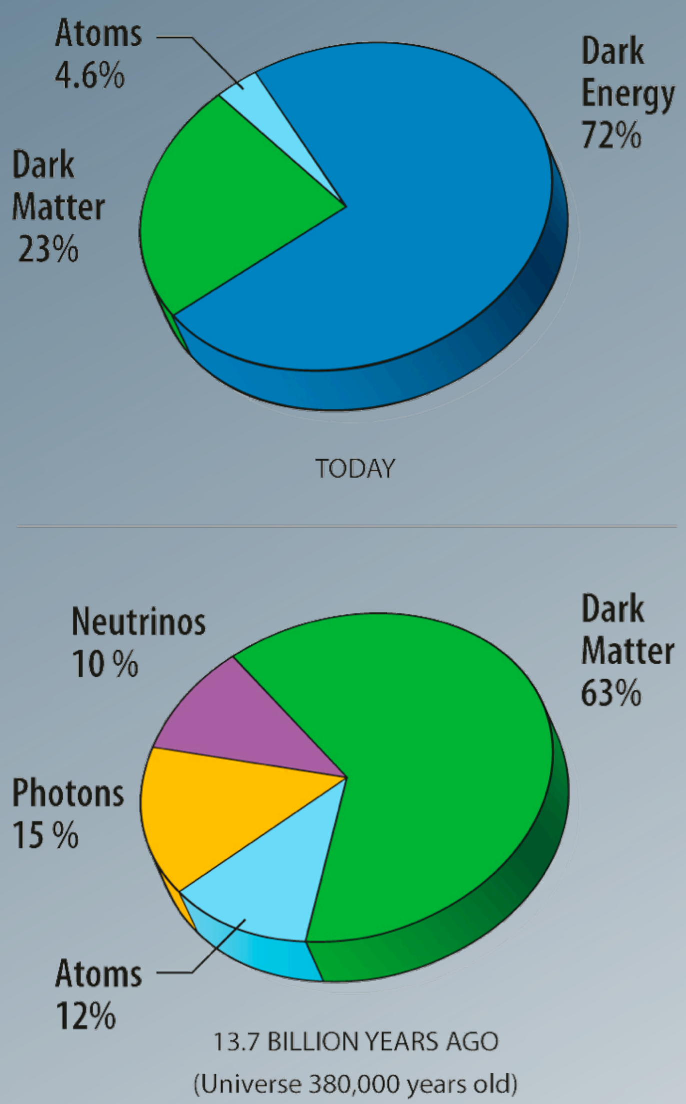
Jarosik et al. 2011

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!
  - $\Omega_{\mathrm{CDM}} = 0.233 \pm 0.013$ (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:

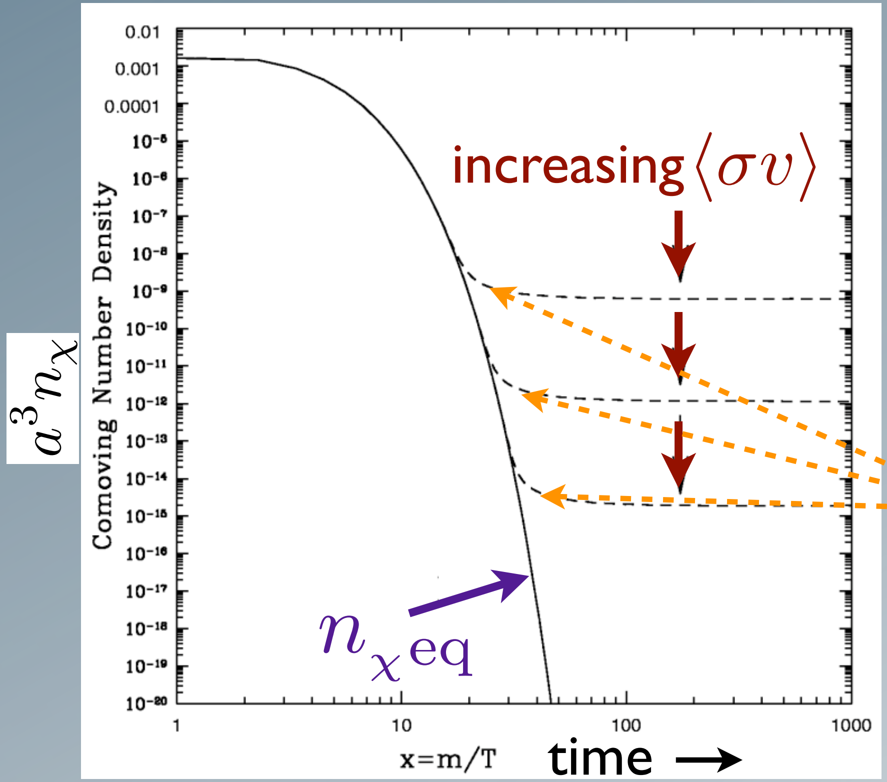


Fig.: Jungman, Kamionkowski & Griest, PR'96

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

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

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

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

for weak-scale interactions!

The Dark Matter Questionnaire

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

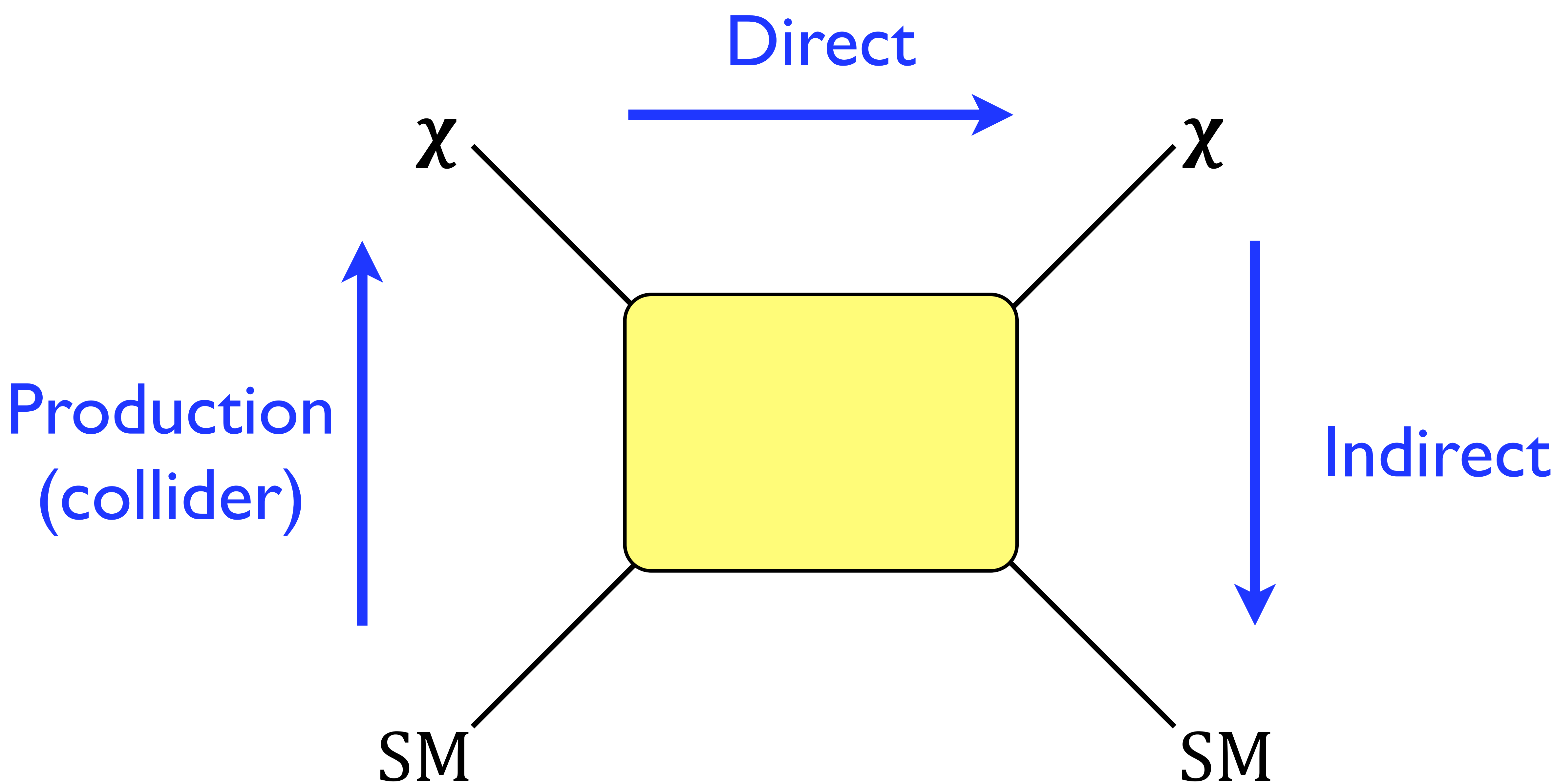
Couplings:

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

Thermal Relic?

- ☐ Yes ☐ No

How to detect particle dark matter?

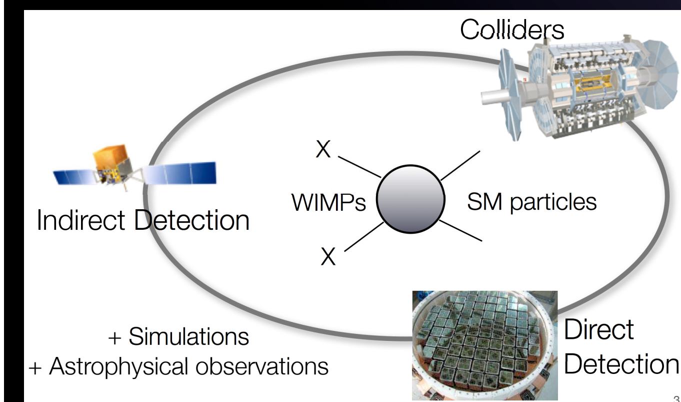


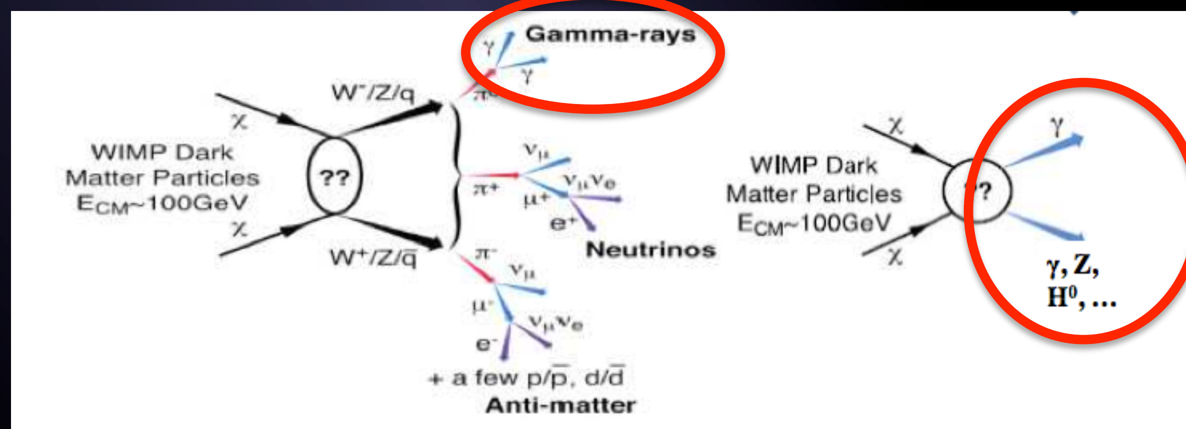
Gamma-rays from dark matter annihilations

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?

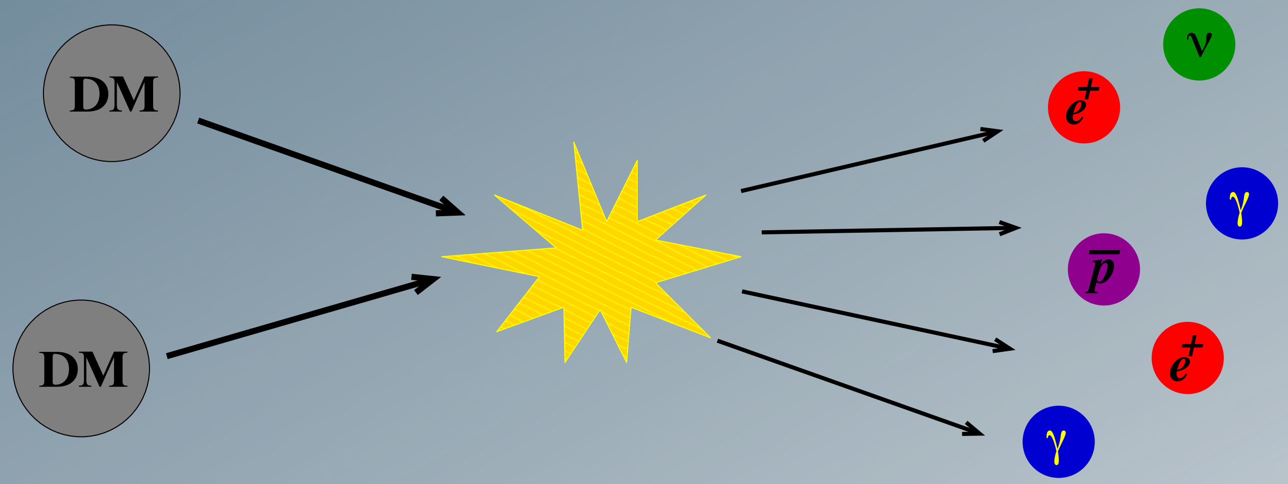
✓Energy scale of annihilation products set by DM particle mass
→ favored models ~GeV-TeV

✓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

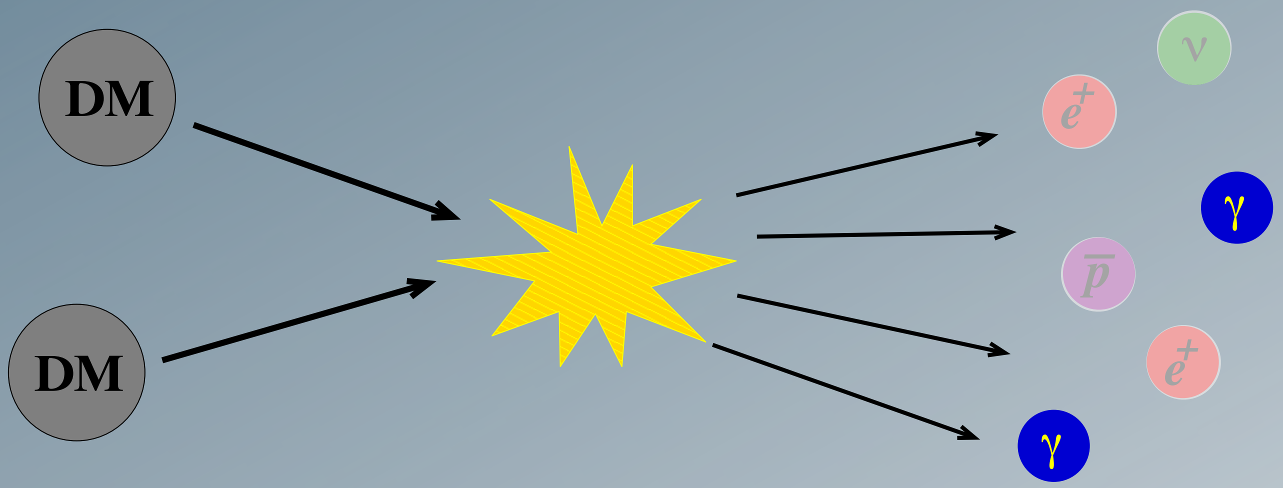
Indirect DM searches



- 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

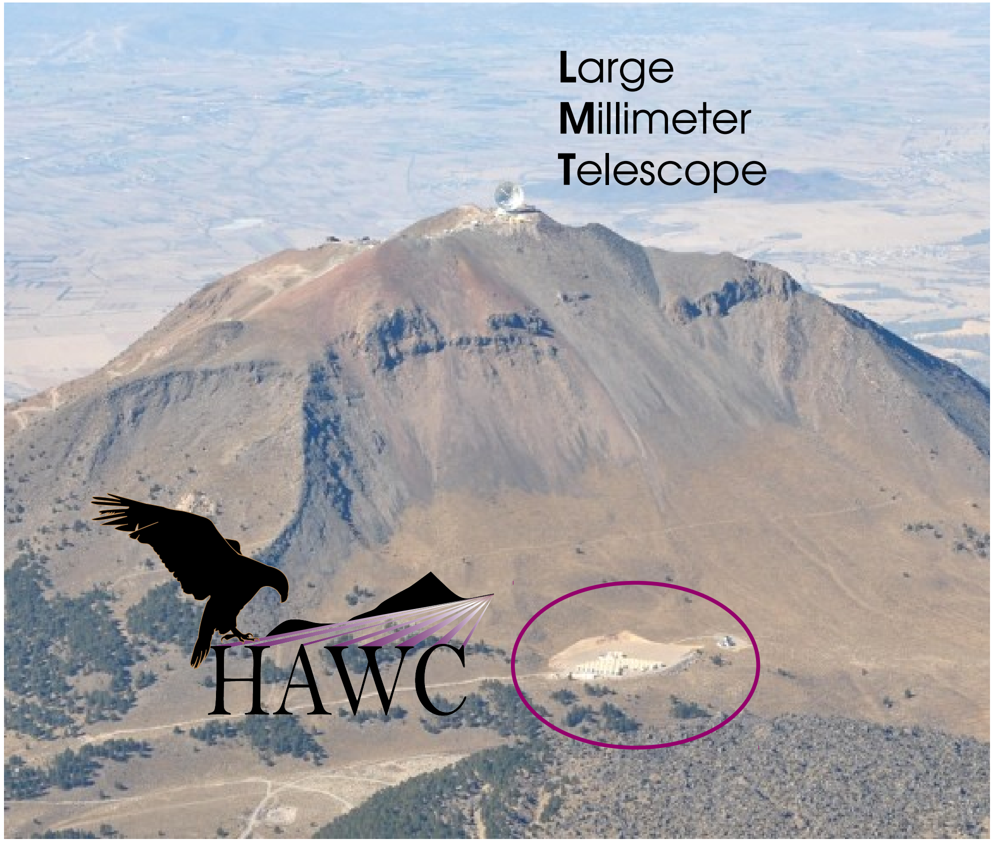
Indirect DM searches



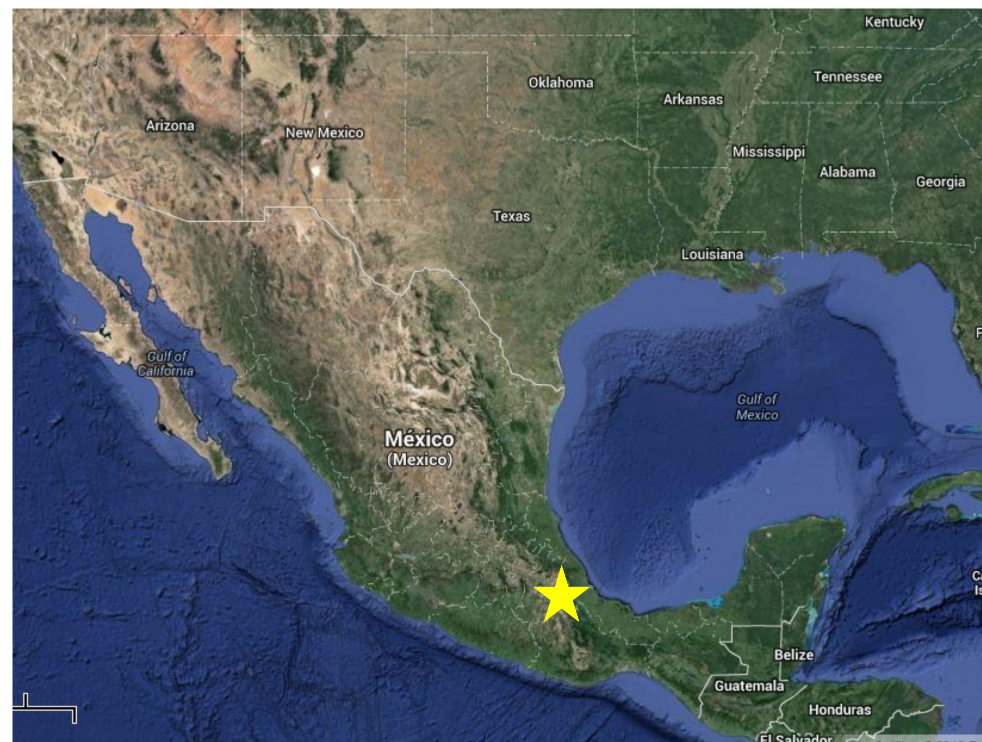
Gamma rays:

- 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

2nd Generation Water Cherenkov: HAWC

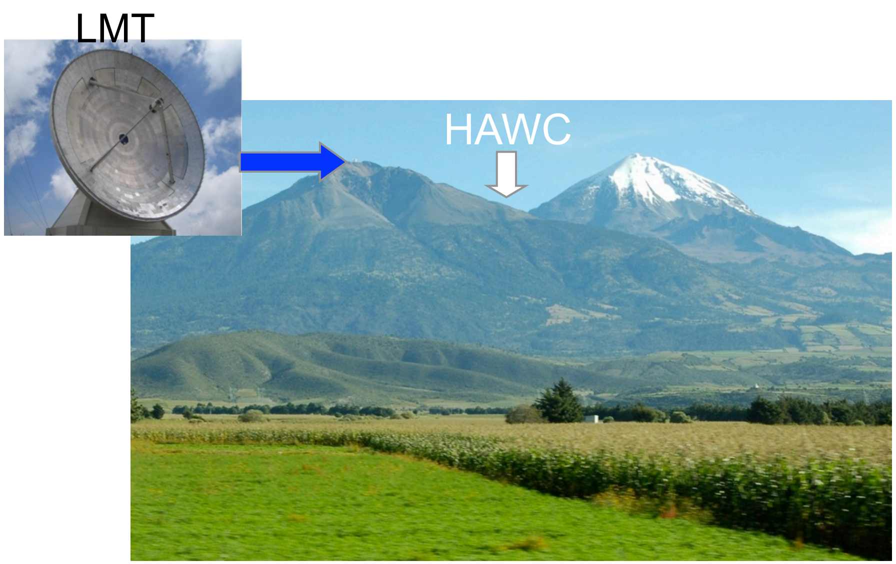


- Sierra Negra volcano near Puebla, Mexico
- High altitude site at 4100 m
- Temperate climate
- Existing infrastructure from LMT
- 17 radiation lengths of atm. Overburden (vs. 27 at sea level)



The HAWC Site

- Near ideal:
  - High elevation (4100m), but flat – Shoulder area between Mount Pico de Orizaba and Sierra Negra.
  - Just above tree line – not extreme climate.
  - Existing infrastructure from LMT.

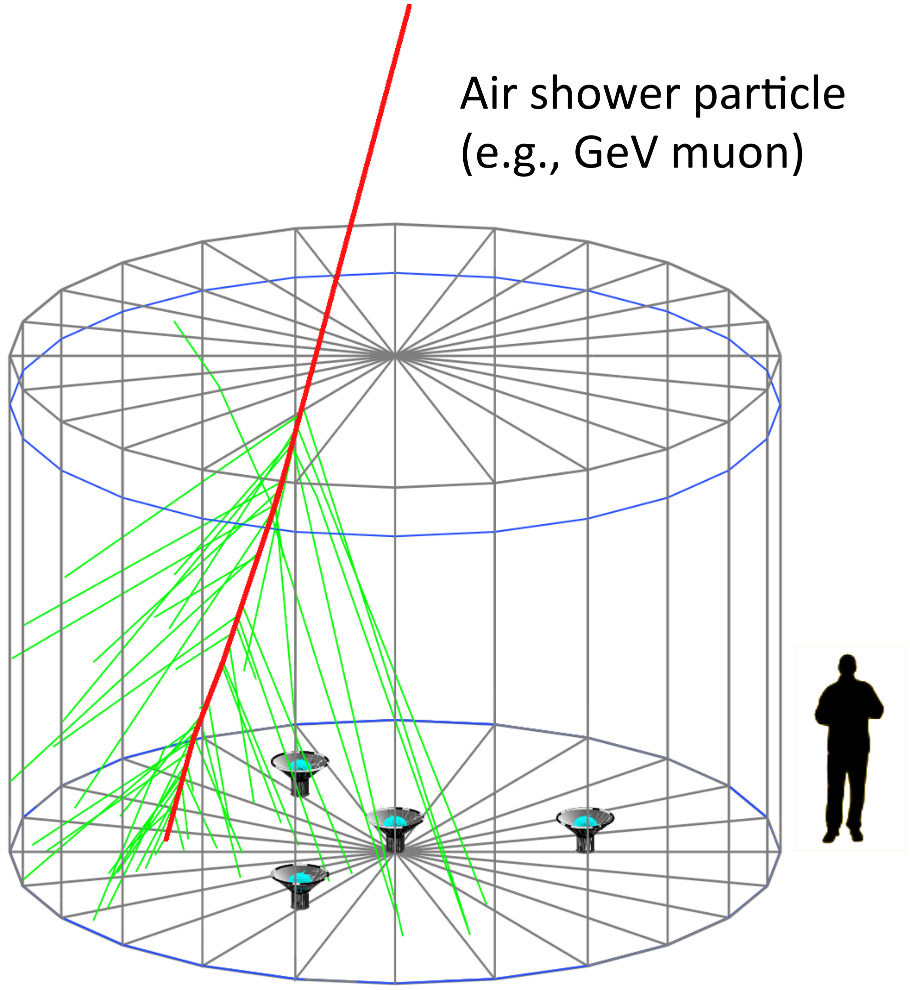


HAWC Construction

- 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

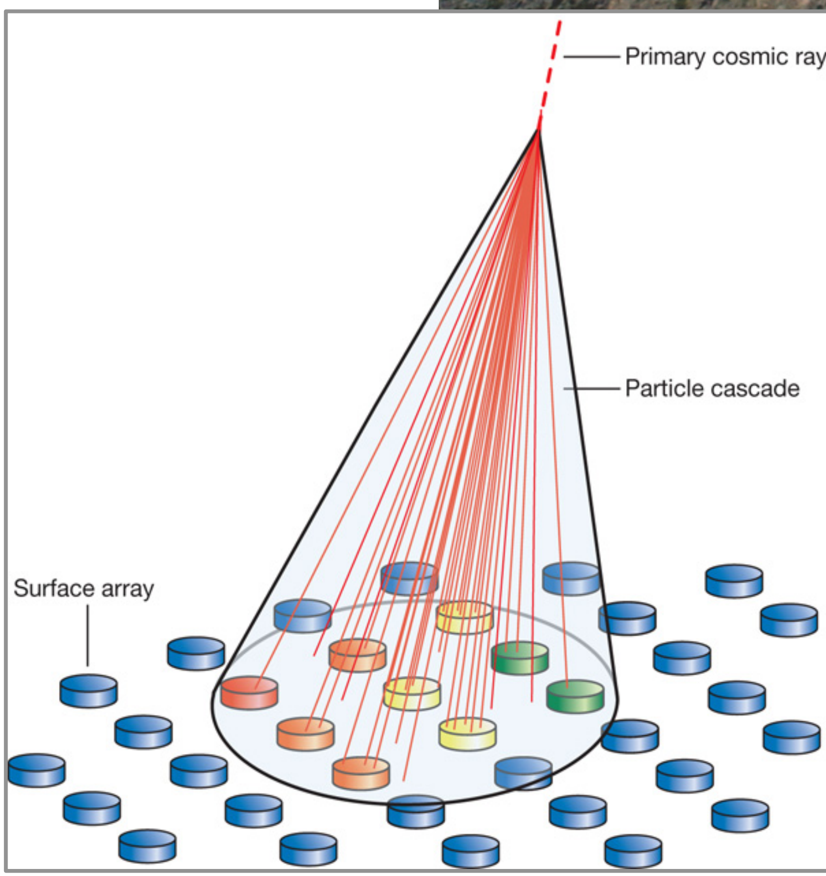
Water Cherenkov Method

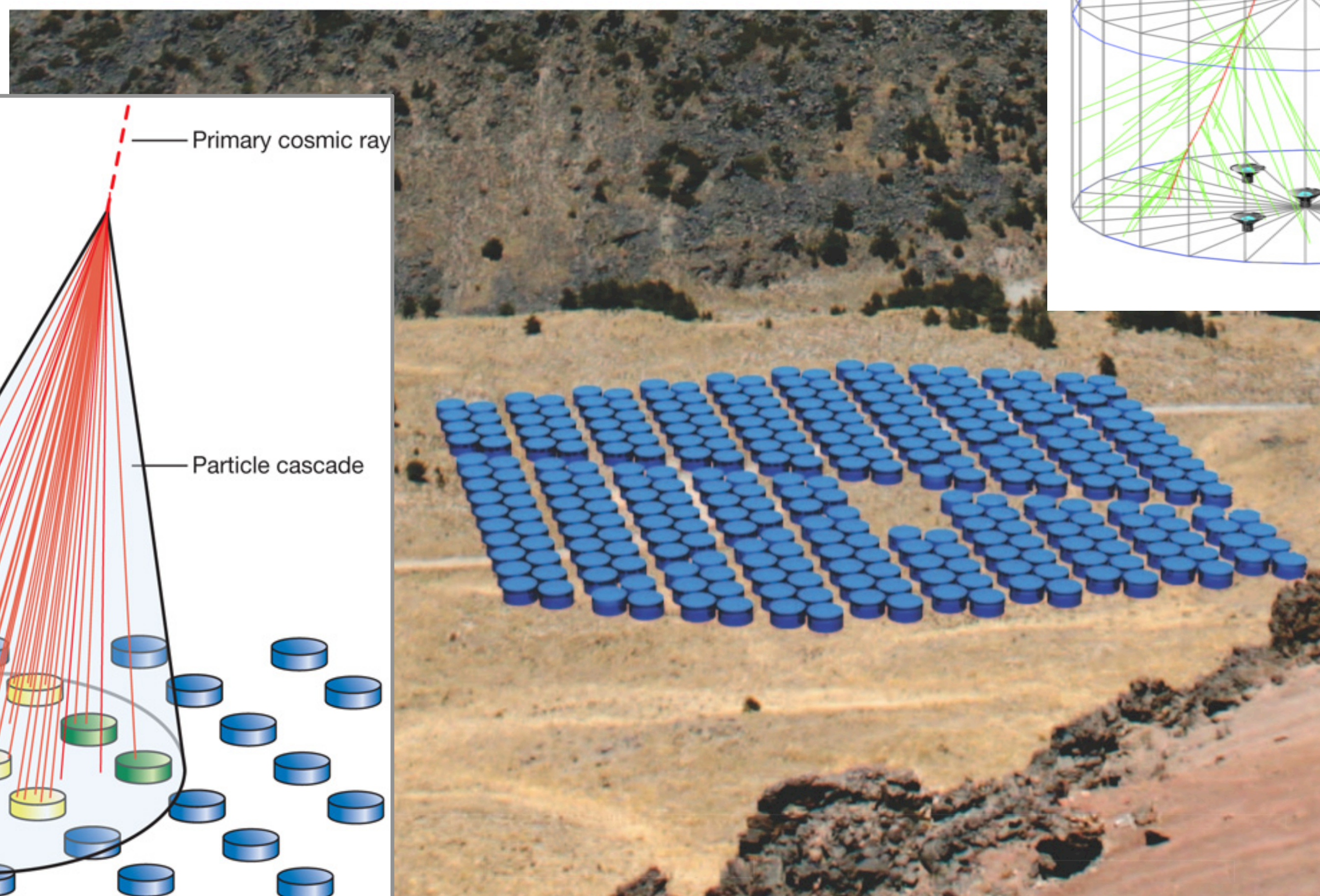
- Robust and cost-effective surface detection technique
- Water tanks: 7.3 m radius, 5 m height, 185 kL purified water
- Tanks contain three 8" R5912 PMTs and one 10" R7081-HQE PMT looking up to capture Cherenkov light from shower front

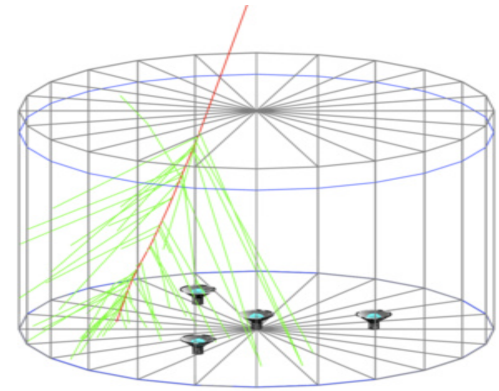


How Does HAWC Work?

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

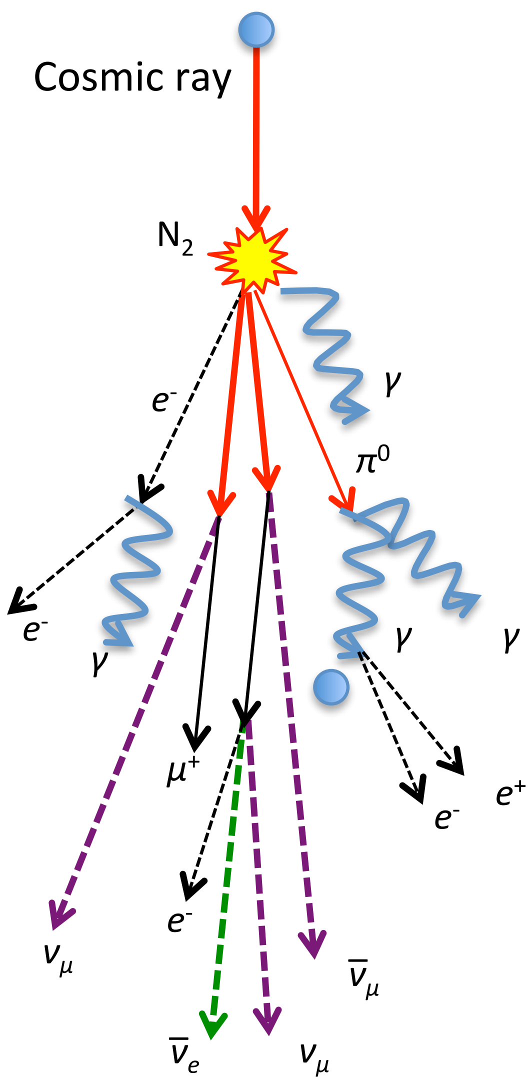


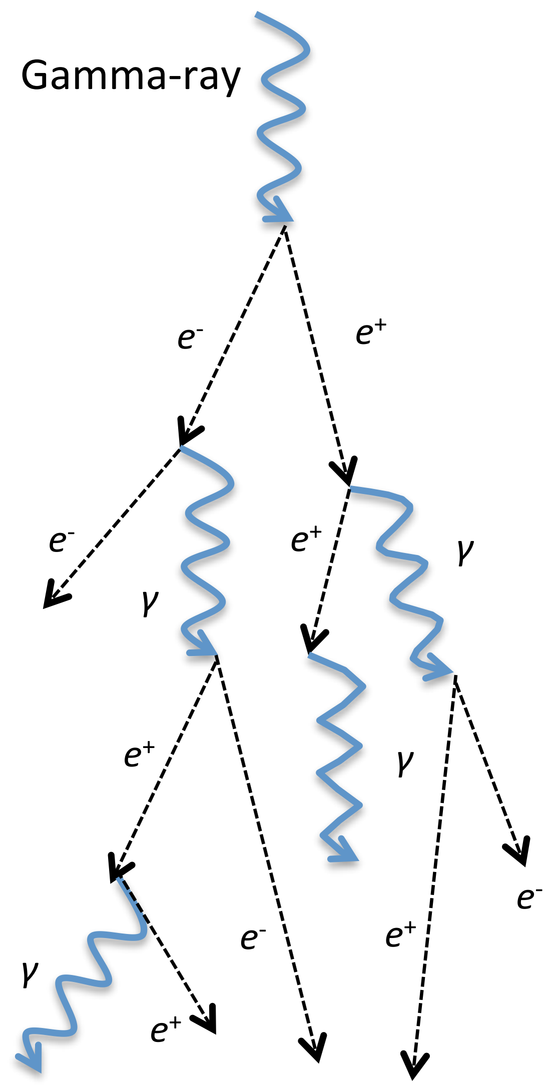


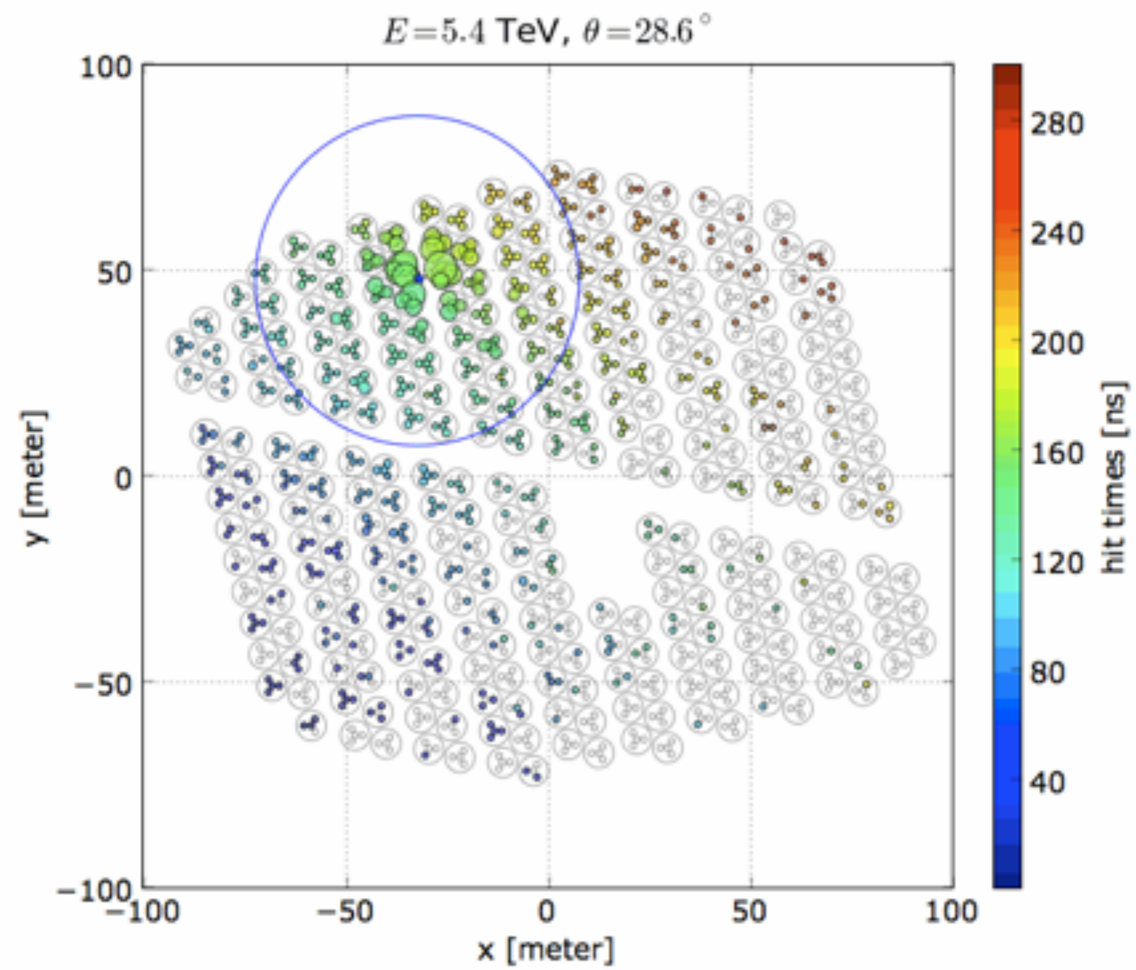


Background Rejection

- CR rejection using topological cut in hit pattern



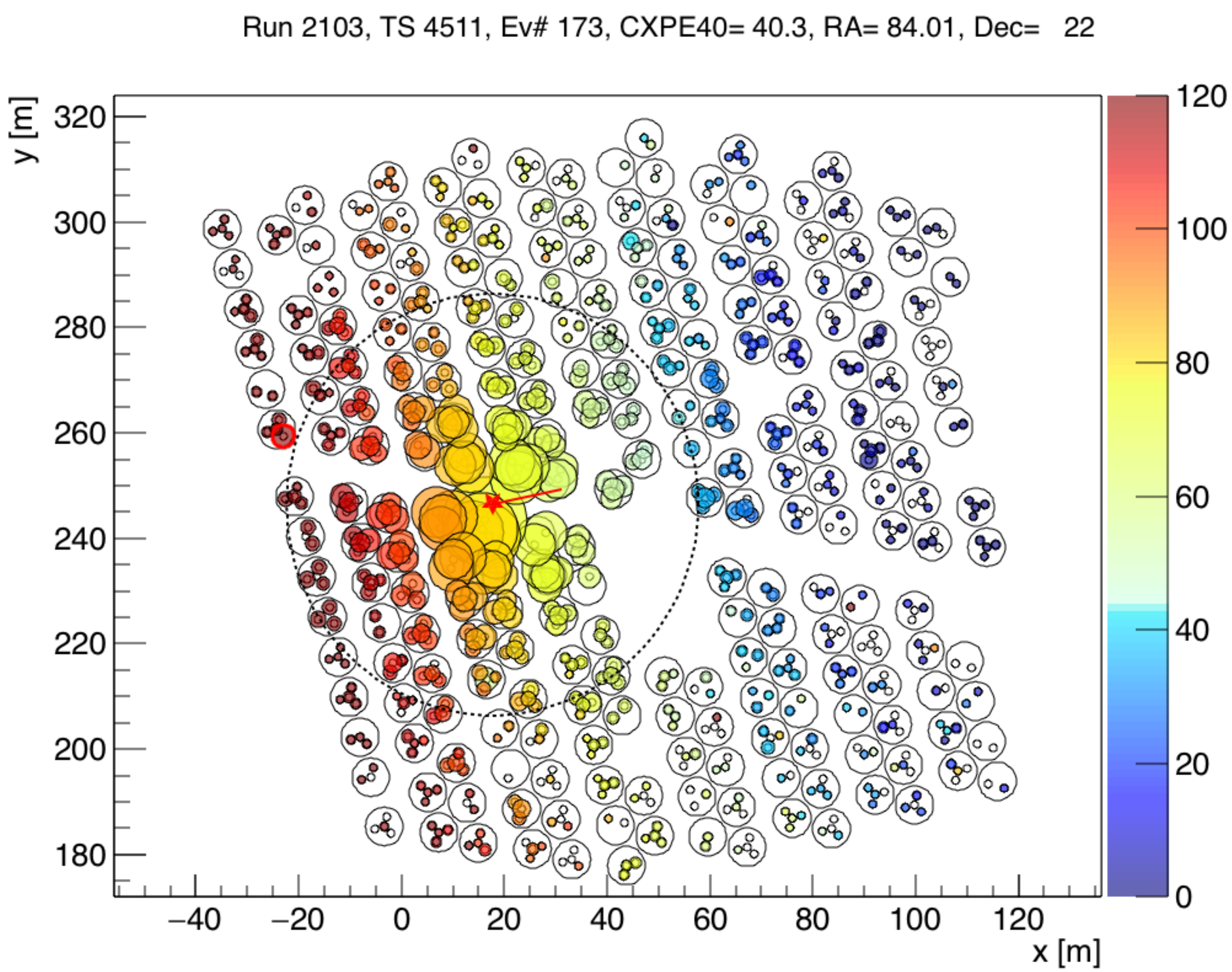


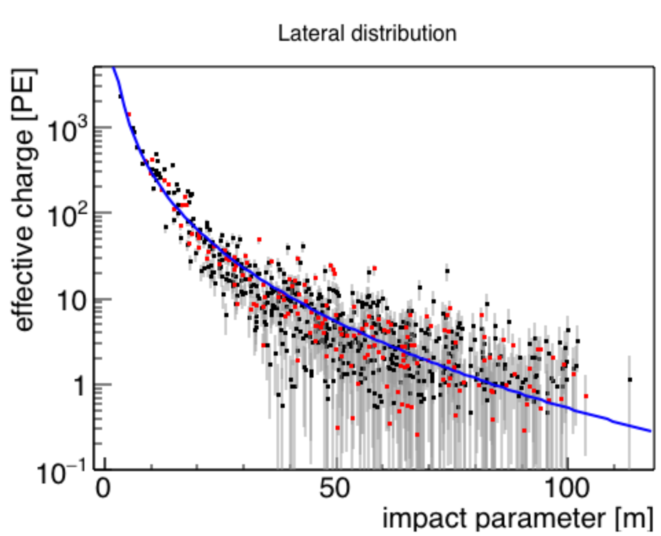


- Requires sufficient number of triggered channels (>70) to work well. Q-value ($\epsilon_\gamma/\sqrt{\epsilon_{CR}}$) is ~5 for point sources

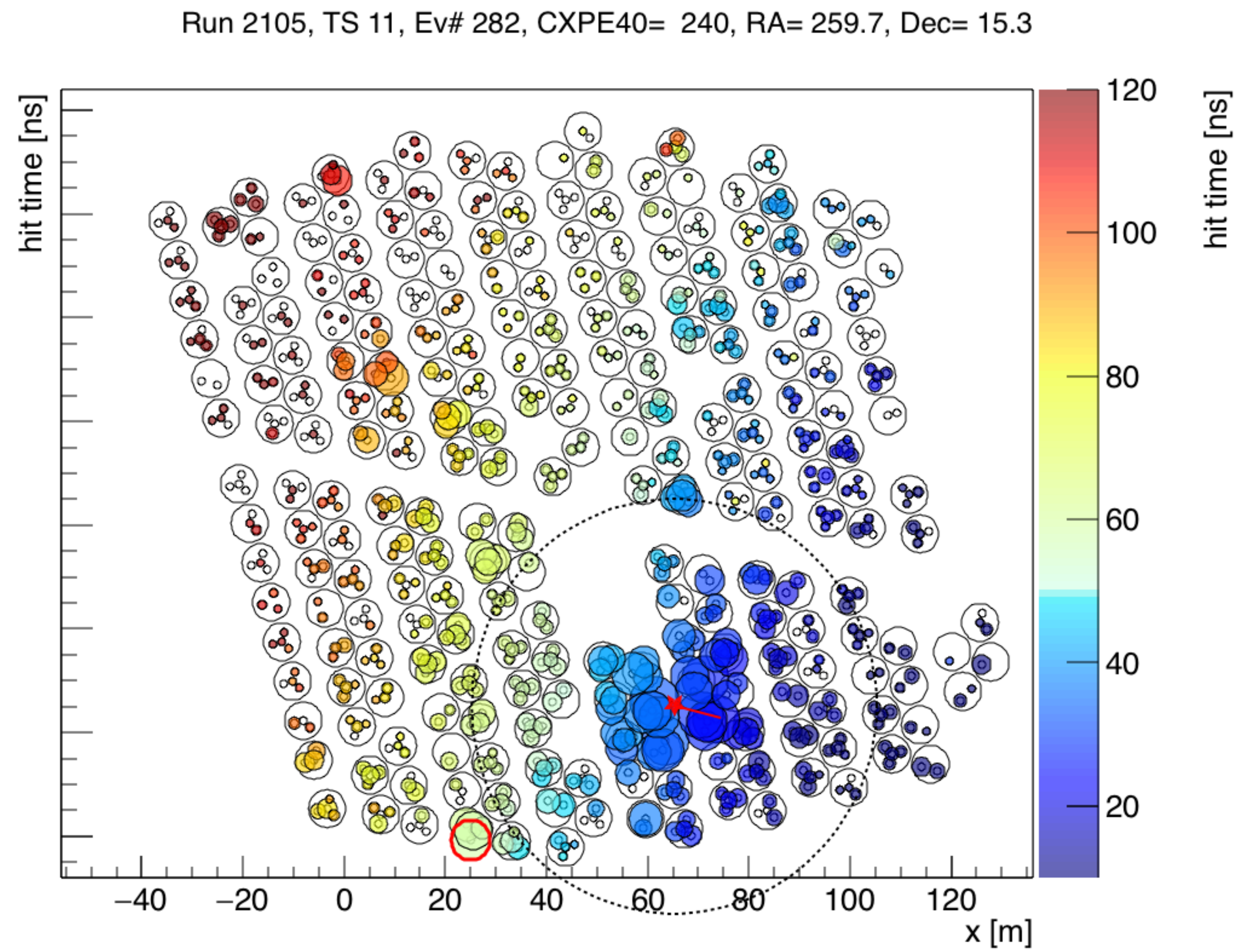
HAWC Events

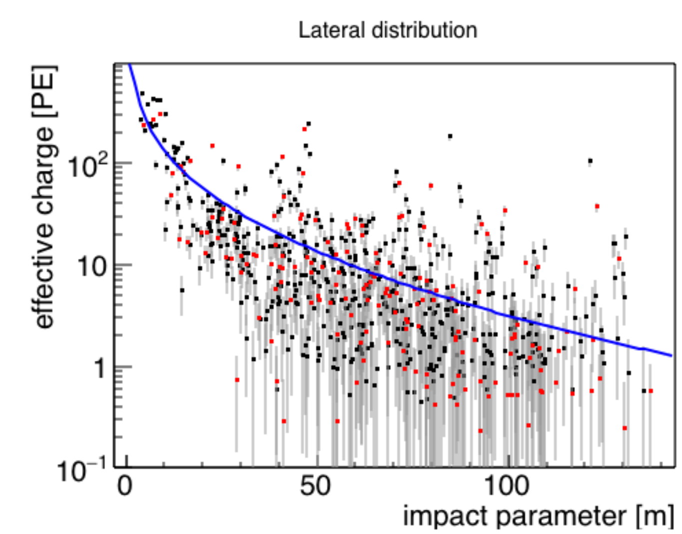
Gamma





Hadron

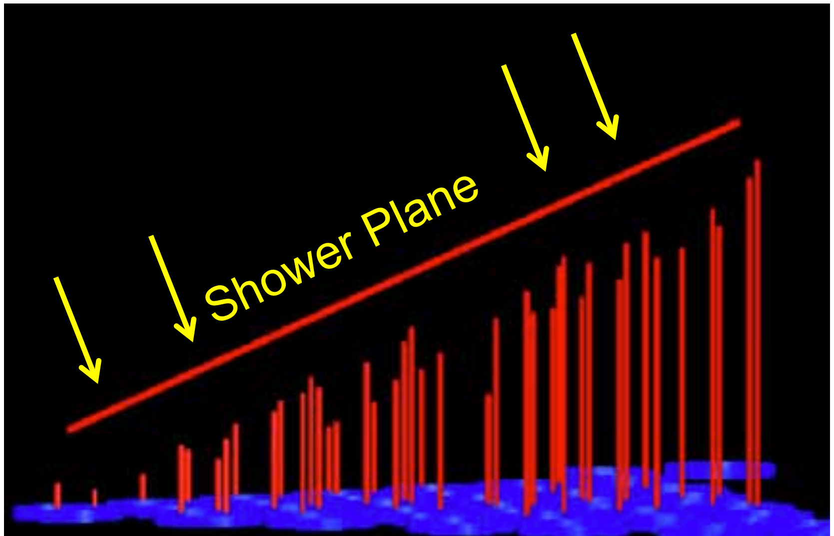


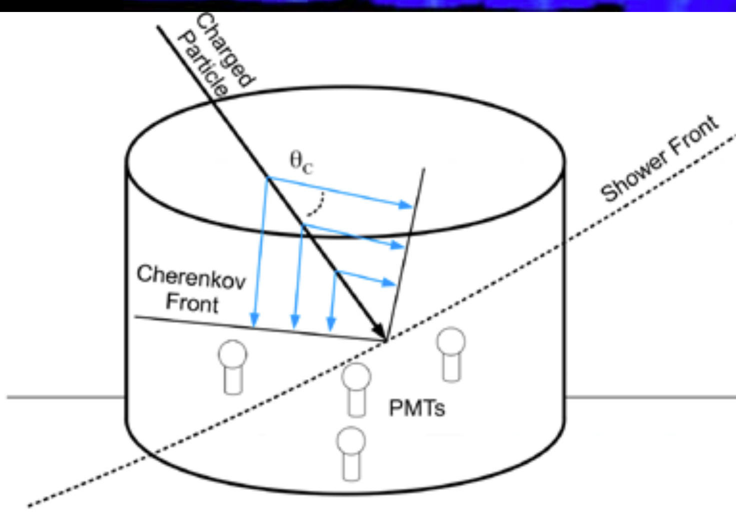


- Gamma: smooth lateral distribution
- Hadrons: irregular pattern, sub-showers, muons

=> Gamma/Hadron discrimination

Angle Reconstruction





Photons convert to e+e- in the water

México

Benemérita Universidad Autónoma de Puebla
Centro de Investigación y de Estudios Avanzados
Instituto Nacional de Astrofísica Óptica y Electrónica
Universidad Autónoma de Chiapas
Universidad de Guadalajara
Universidad de Guanajuato
Universidad Michoacana de San Nicolás de Hidalgo
Universidad Nacional Autónoma de México
- Instituto de Astronomía
- Instituto de Física
- Instituto de Ciencias Nucleares
- Instituto de Geofísica

USA

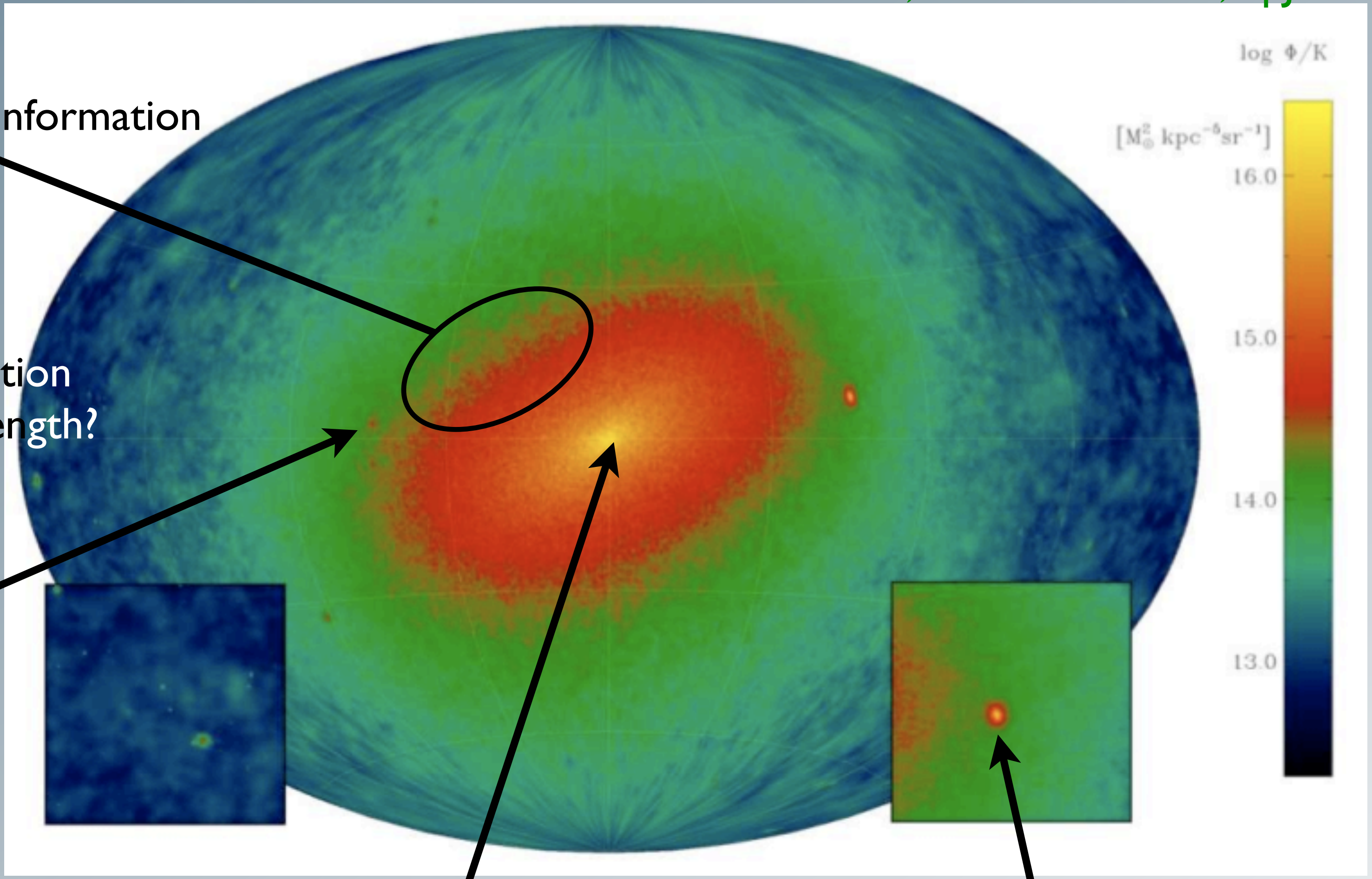
Colorado State University
George Mason University
Georgia Institute of Technology
Harvey Mudd College
Los Alamos National Laboratory
Michigan State University
Michigan Technological University
NASA/Goddard Space Flight Center
Ohio State University at Lima
Pennsylvania State University
University of California, Irvine
University of California, Santa Cruz
University of Maryland
University of New Hampshire
University of New Mexico
University of Utah
University of Wisconsin-Madison

http://www.hawc-observatory.org

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Possible targets

Diemand, Kuhlen & Madau, ApJ '07



Galactic halo

- good statistics, angular information
- galactic backgrounds?

Galaxy clusters

- cosmic ray contamination
- better in multi-wavelength?
- substructure boost?

Dwarf Galaxies

- DM dominated, M/L~1000
- fluxes soon in reach!

Extragalactic background

- DM contribution from all z
- background difficult to model
- substructure evolution?

Galactic center

- brightest DM source in sky
- large background contributions

DM clumps

- easy discrimination (once found)
- bright enough?

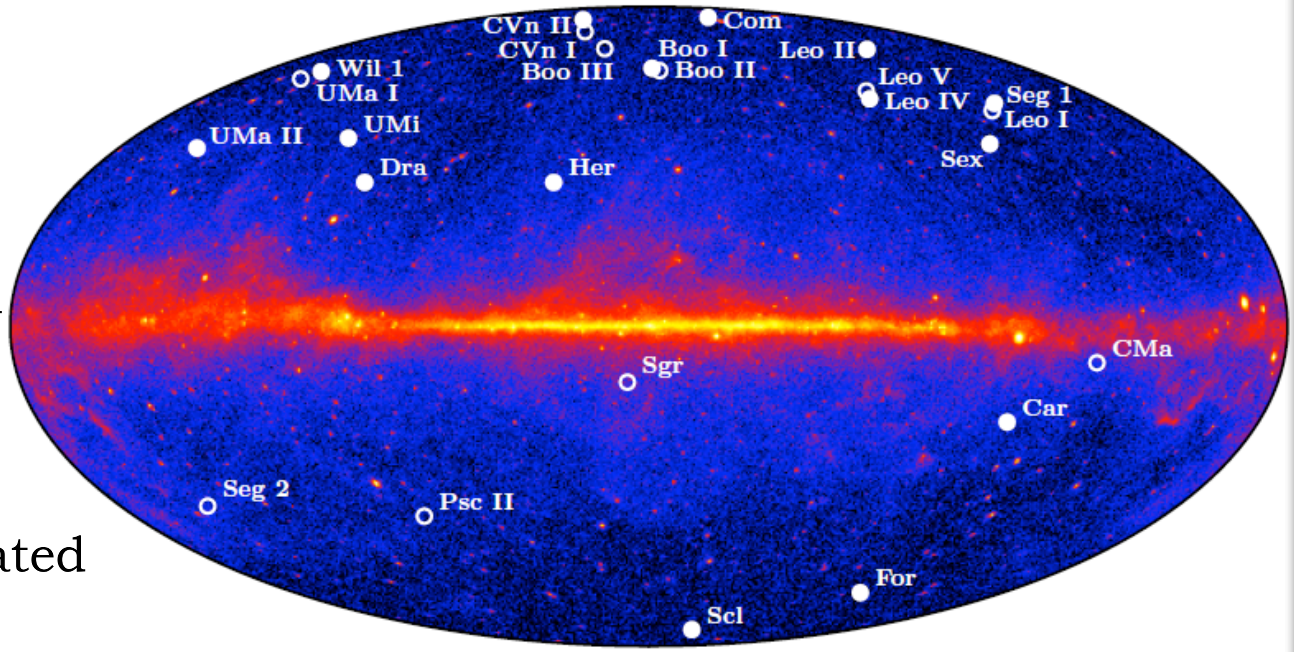
Dwarf Spheroidal satellite galaxies

- The most DM dominated systems in the Universe.
- Roughly two dozens dwarf spheroidal satellite galaxies of the Milky Way
- Several of them closer than 100 kpc from us
- Most of them expected to be free from any bright astrophysical gamma source.

  (Low content in gas and dust.)

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

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

DM distribution

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)

The DM annihilation γ-ray flux

$$F(E_\gamma > E_{th}, \Psi_0) = J(\Psi_0) \times f_{PP}\left(E_\gamma > E_{th}\right)$$

photons cm^{-2} s^{-1}

Astrophysics

Particle physics

Integration of the squared DM density

$$J(\Psi_0) = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{l.o.s.} \rho^2_{DM}[r(\lambda)]\, d\lambda$$

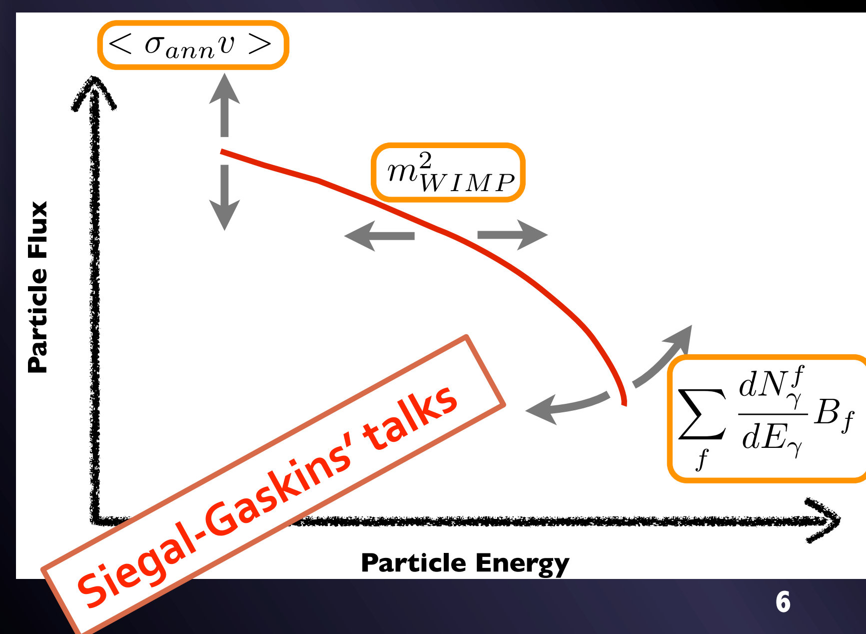
DM density squared

$$f_{PP} \propto \sum_f \frac{dN^f_\gamma}{dE_\gamma} B_f \frac{\langle \sigma \cdot v \rangle}{m_\chi{}^2}$$

N_g : number of photons per annihilation above E_{th}

<σ v>: cross section

m_χ: neutralino mass

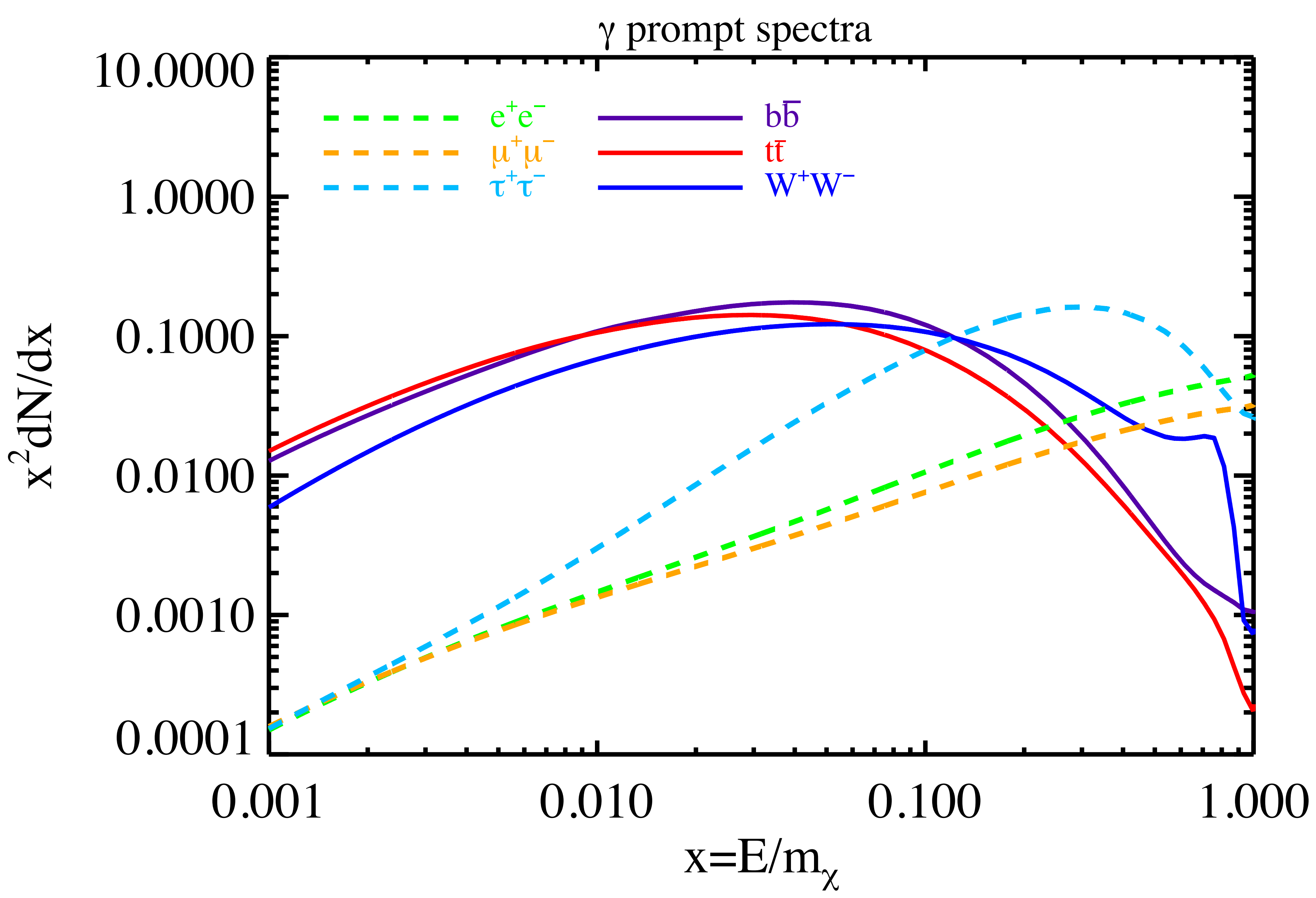


Where to search?

- Galactic Center
- Dwarf spheroidal galaxies
- Local galaxy clusters
- Nearby galaxies...

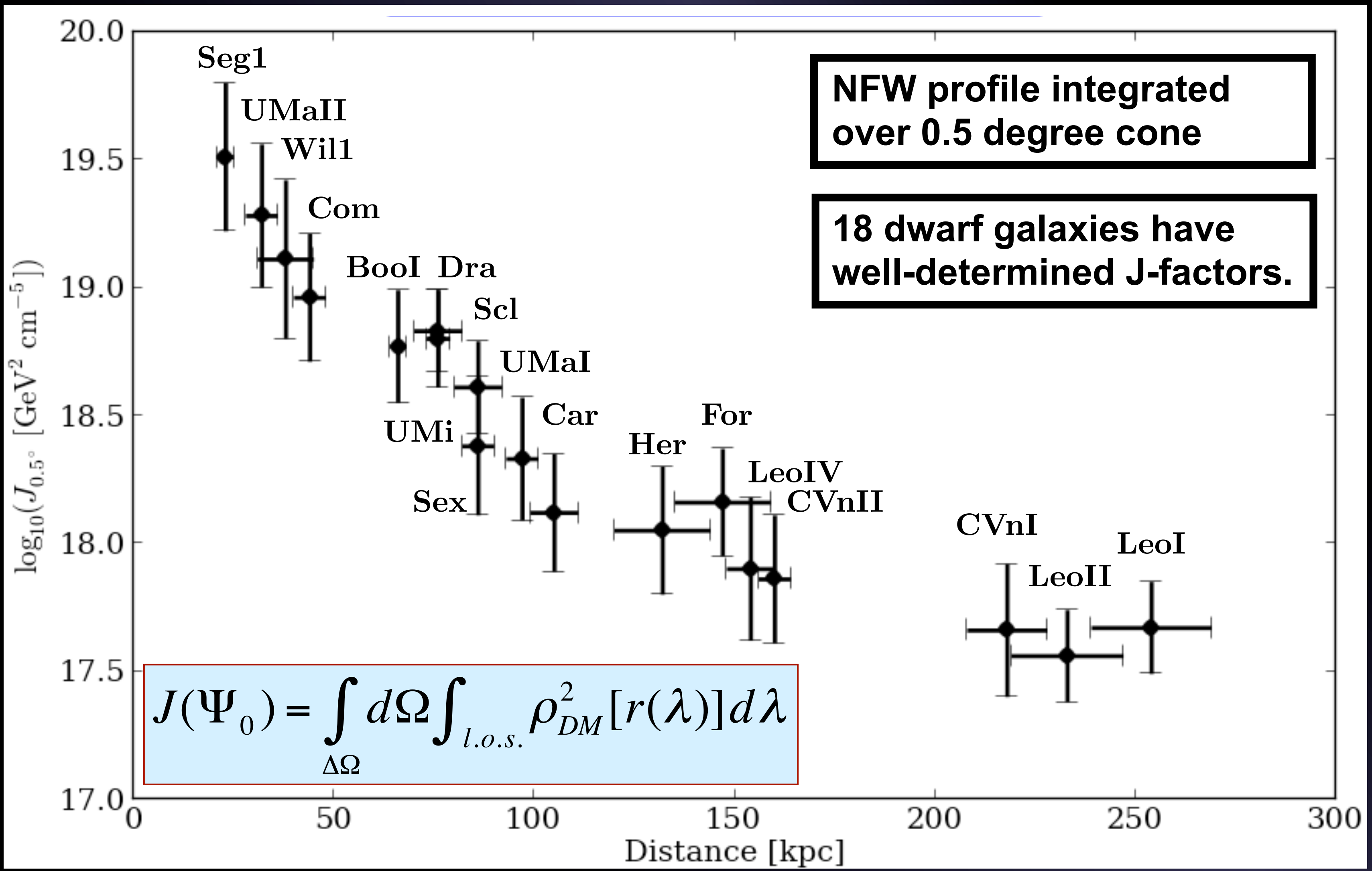
Dark matter photon spectra

- "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

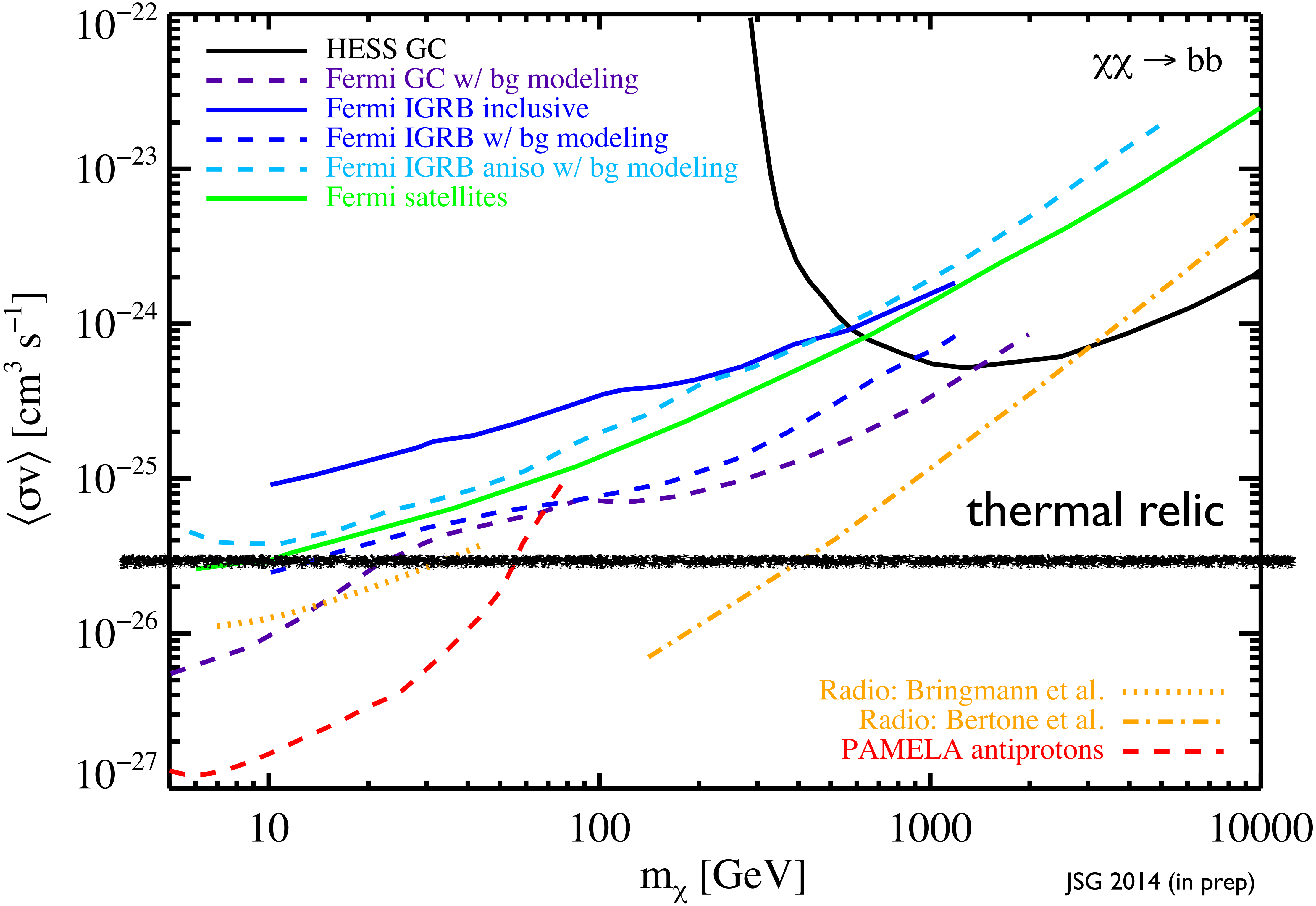


A.Drlica-Wagner DPF 2013

RECAP

Current constraints

95% CL upper limits on annihilation cross section to bb

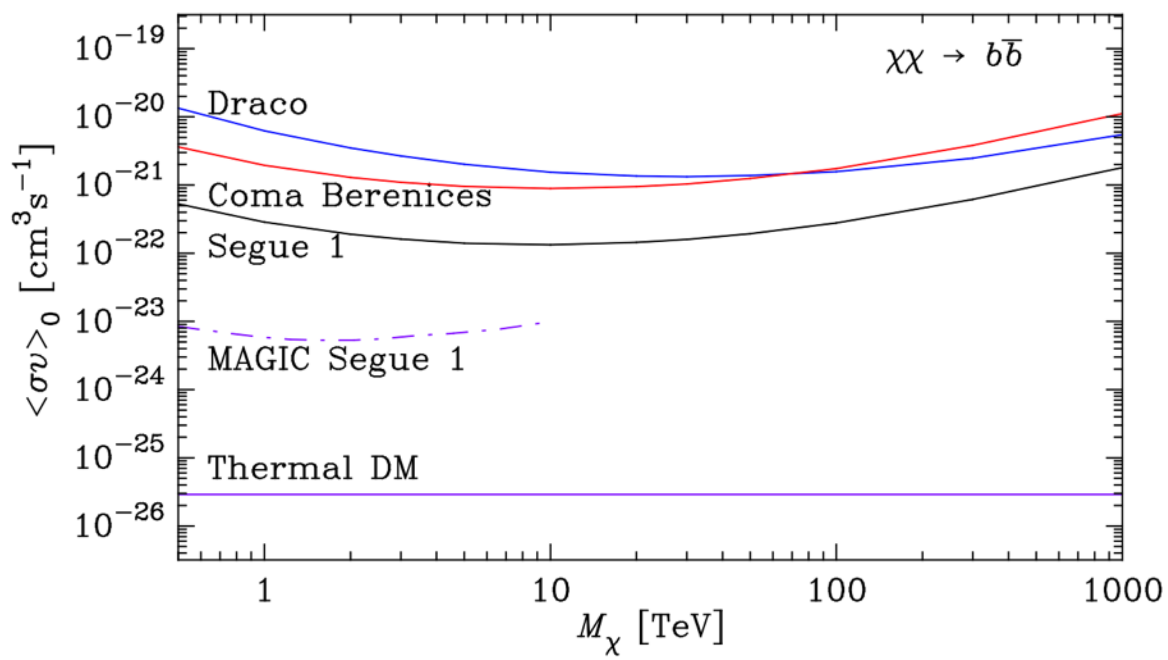


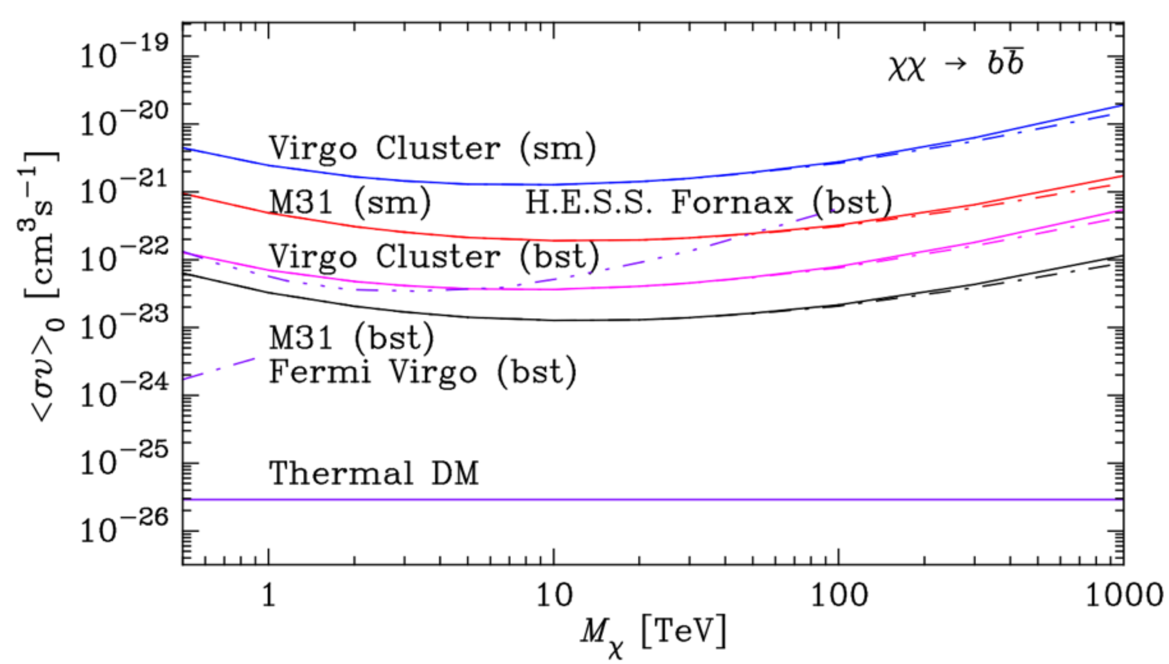
JSG 2014 (in prep)

Dark Matter Sensitivity (5 years)

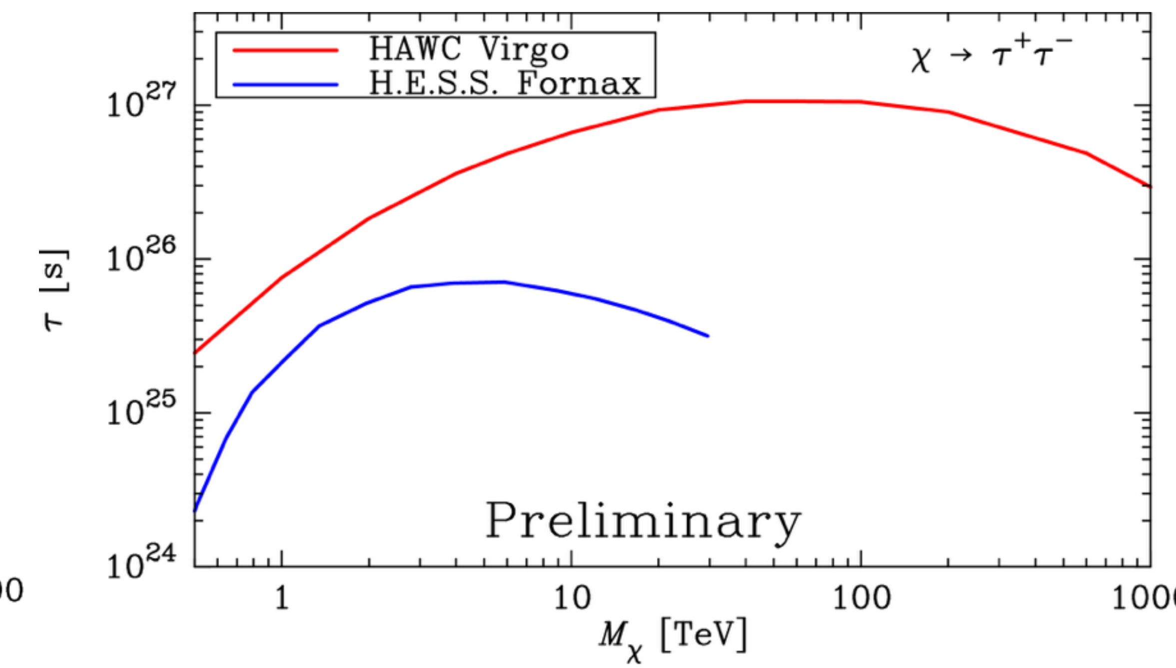
Annihilation

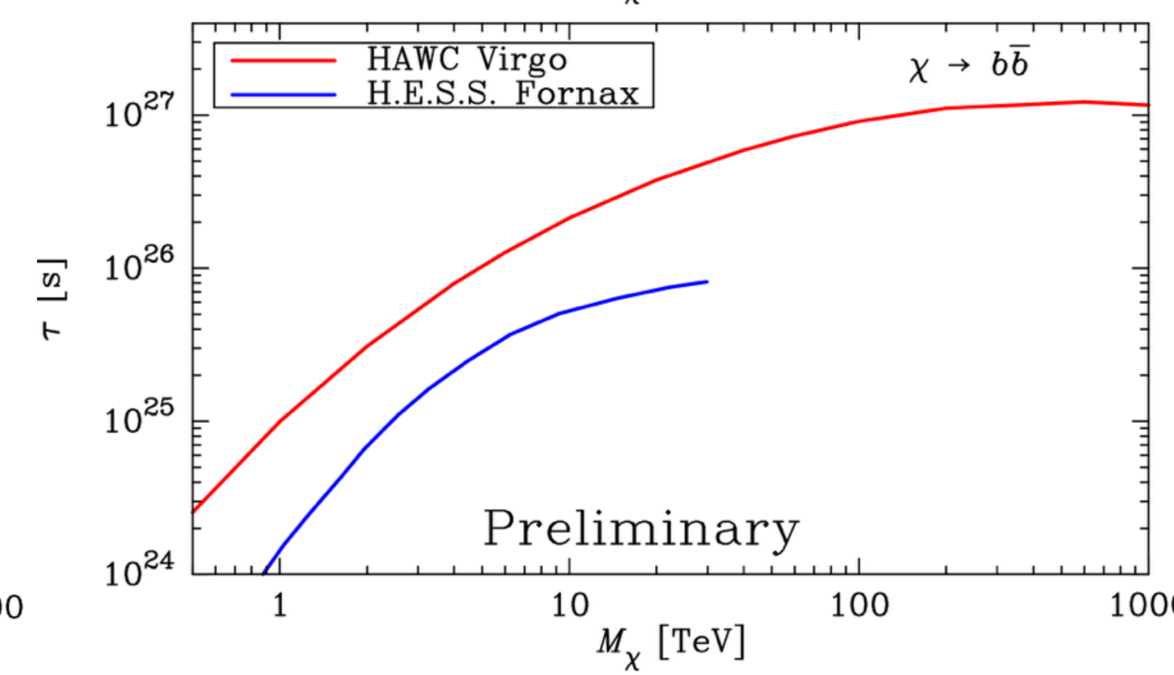
[Phys. Rev. D 90 (2014), arxiv:1405.1730]





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 DM annihilation/decay.
- The UNM group in HAWC is well positioned (as leader of the precision (timing) calibration system and one of the co-developers of the HAWC maximum likelihood analysis framework) to play a major role in HAWC physics.
- While HAWC has been taking data for approximately two years, (analysis) software is still maturing providing many opportunities for student involvement and leadership.
- The HAWC experiment also benefits from close collaboration with nearby LANL
- So: many opportunities and no lack of challenges!