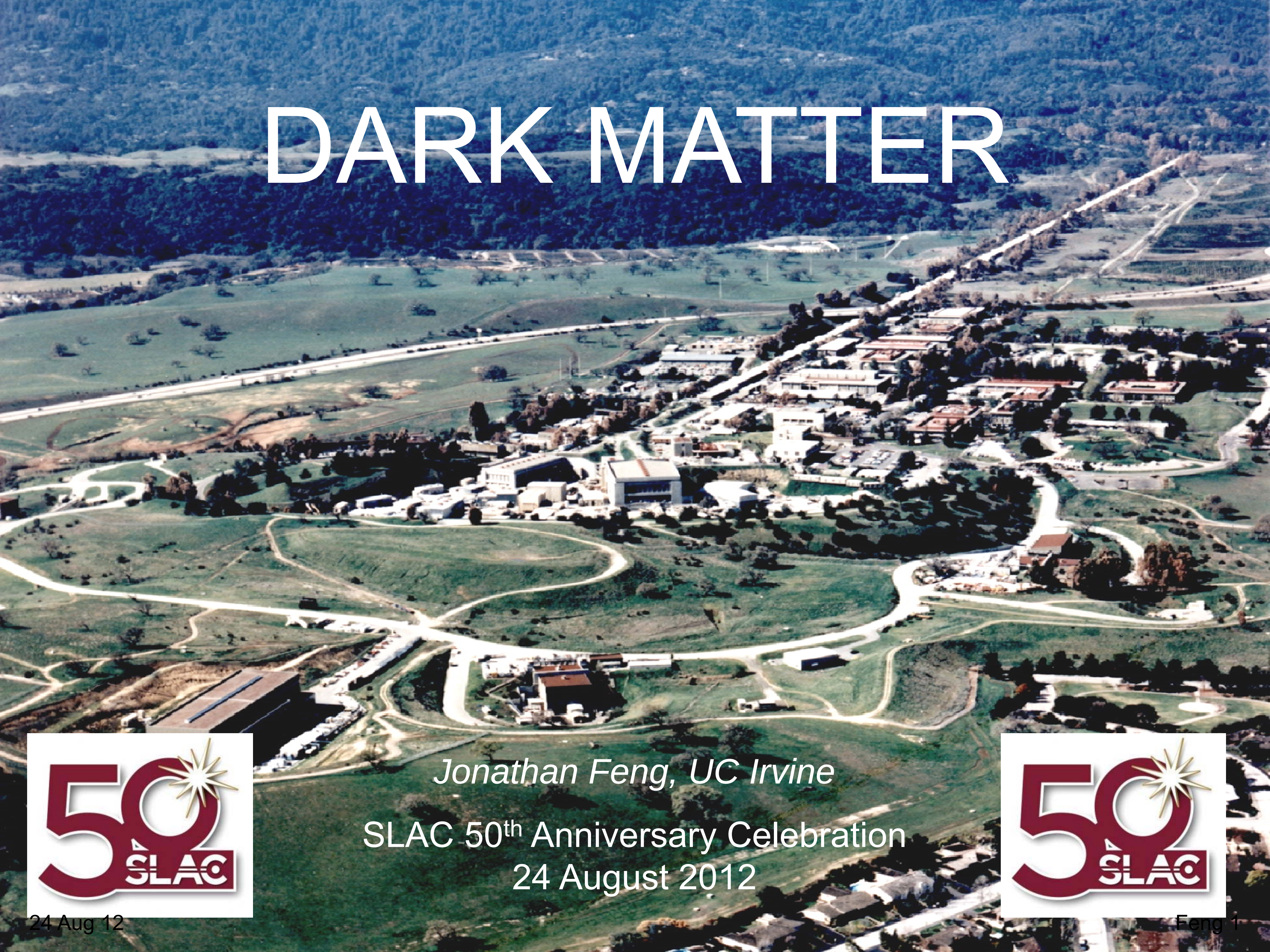


DARK MATTER

Jonathan Feng, UC Irvine

SLAC 50th Anniversary Celebration
24 August 2012

REMINISCENCES

On this happy occasion, it's a privilege to begin with some brief remarks about my connection to SLAC.

I was a particle theory graduate student at SLAC from 1990-95, roughly the middle of the era we are celebrating.

MY FIRST WEEK AT SLAC

1990 Nobel Prize in Physics: Friedman, Kendall and Taylor

MY LAST MONTH AT SLAC

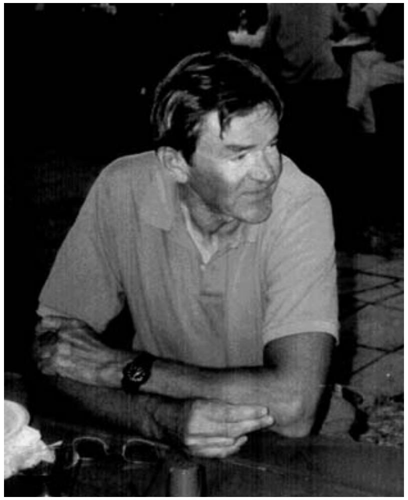
1995 Nobel Prize in Physics: Perl and Reines

SLAC THEORY 1992

HIGHLIGHTS

- SLAC fostered an atmosphere in which students were expected to learn something about everything. In fact, there was no escaping it! Everyone was housed on one floor, with students in an open public area near the mailboxes.

  Some personal highlights:



- Seminars and Talks
  - 1 hr elsewhere = 2 hrs at SLAC
  - The Bj Journal Club

- Meetings
  - SLAC Summer Institutes
  - Workshop on Physics and Experiments with Linear e^+e^- Colliders, Hawaii, 1993

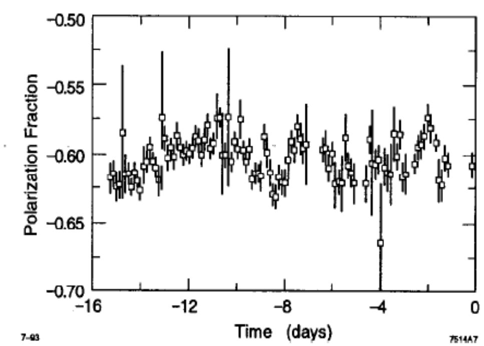
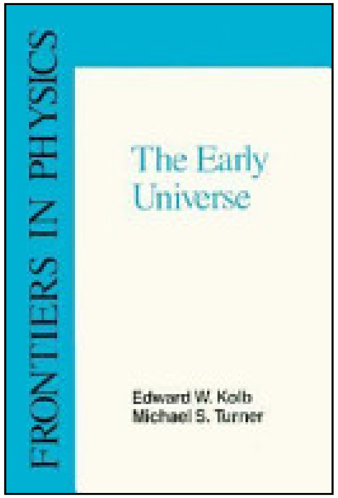
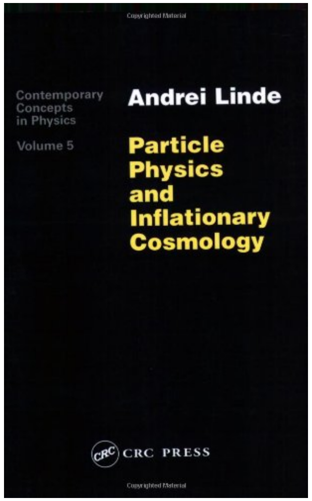


Figure 9. A time history of the polarization measured by the Compton Polarimeter at the IP during a representative two week period.

- Courses
  - 1 each quarter, covering a variety of advanced topics. E.g., cosmology hot off the presses!

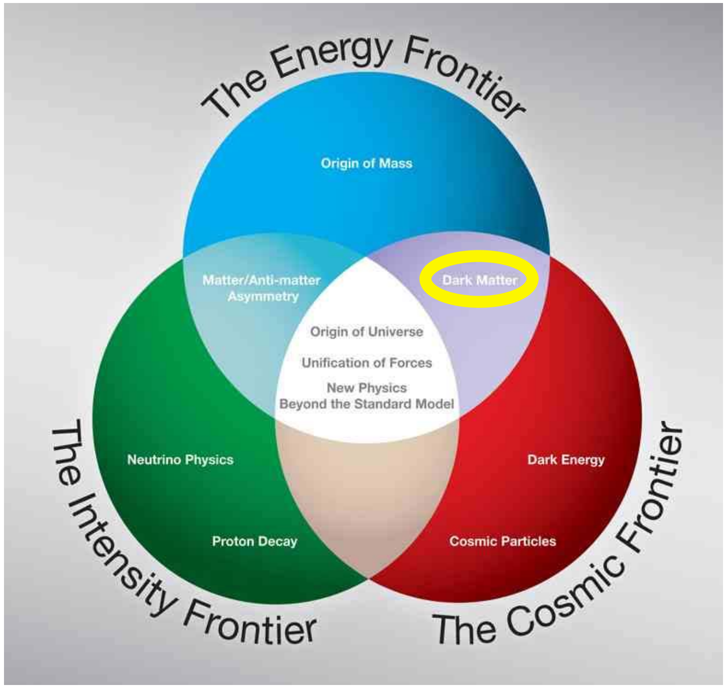




- SLAC's 50-year record of nurturing junior scientists is certainly an achievement worth celebrating today

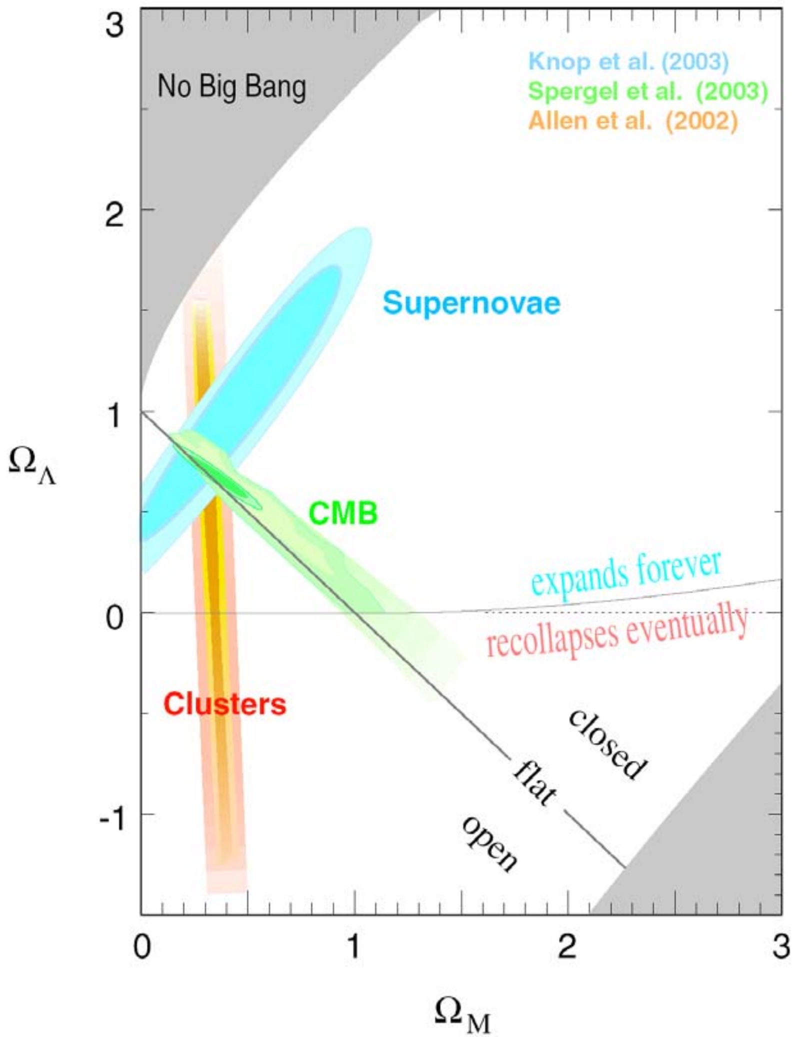
DARK MATTER

The topic of dark matter sits at the interface of astrophysics, cosmology, and particle physics and joins together the cosmic and energy frontiers



- Particle Dark Matter
- Experimental Probes
- Future Prospects

PARTICLE DARK MATTER



- We have learned a lot about the Universe in recent years
- There is now overwhelming evidence that normal (atomic) matter is not all the matter in the Universe:

  Dark Matter: 23% ± 4%

  Dark Energy: 73% ± 4%

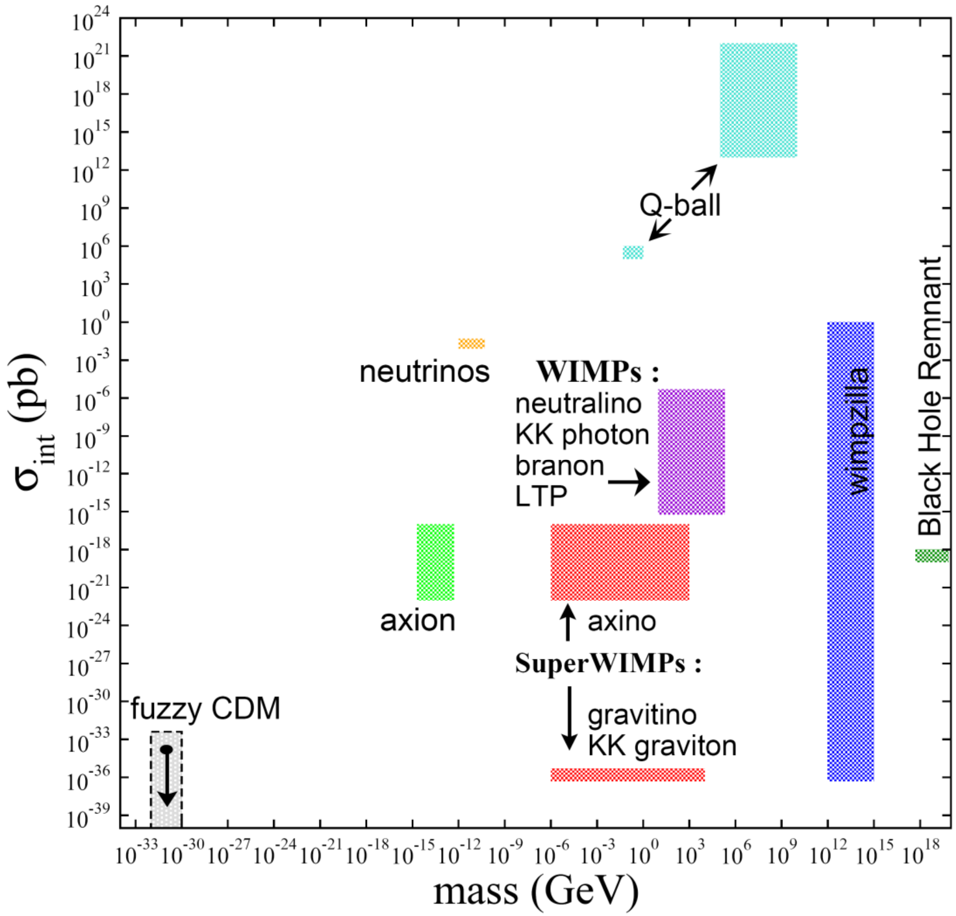
  Normal Matter: 4% ± 0.4%

  Neutrinos: 0.2% (Σm_ν/0.1eV)

- To date, all evidence is from dark matter's gravitational effects; to learn more, we'd like to see it in other ways

DARK MATTER CANDIDATES

- Unfortunately, we don't know what its other properties are, and there are many possibilities
- Masses and interaction strengths span many, many orders of magnitude. But some candidates are better motivated than others



HEPAP/AAAC DMSAG Subpanel (2007)

THE WEAK MASS SCALE

- Fermi's constant G_F introduced in 1930s to describe beta decay

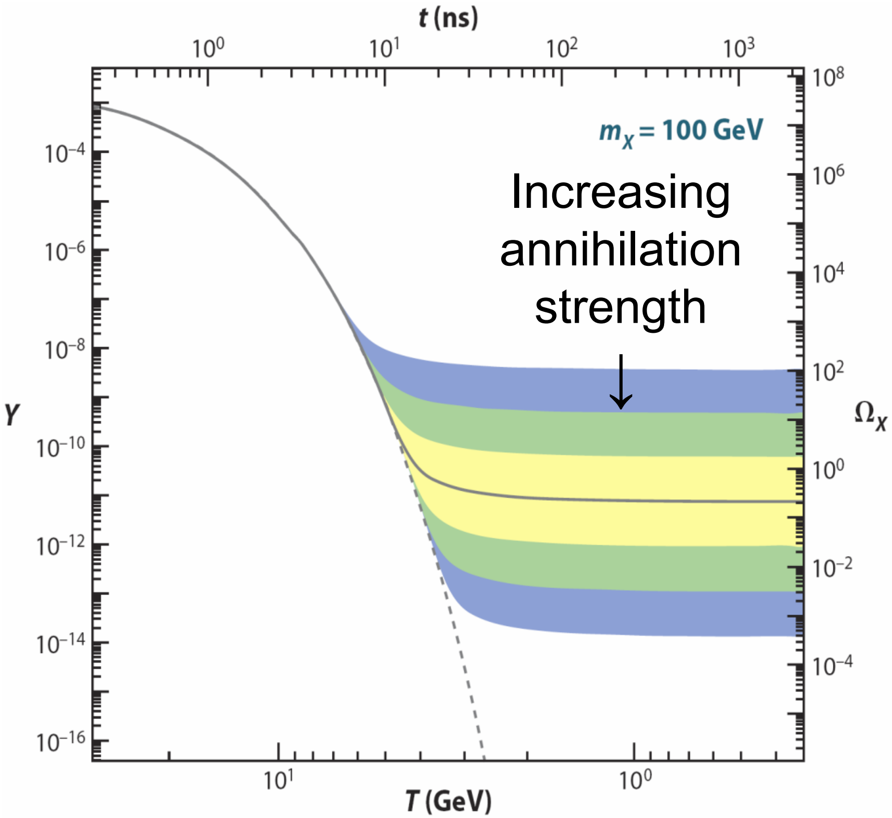
$$n \rightarrow p\, e^- \, \overline{\nu}$$

- $G_F \approx 1.1 \cdot 10^{-5}\ \mathrm{GeV}^{-2} \rightarrow$ a new mass scale in nature

$$m_{weak} \sim 100\ \mathrm{GeV}$$

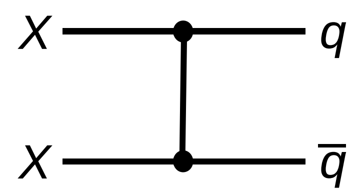
- We still don't understand the origin of this mass scale, but every attempt so far introduces new particles at the weak scale

THE WIMP MIRACLE



- If you add a new particle to the Universe, the amount of it left over now is related to its annihilation cross section:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

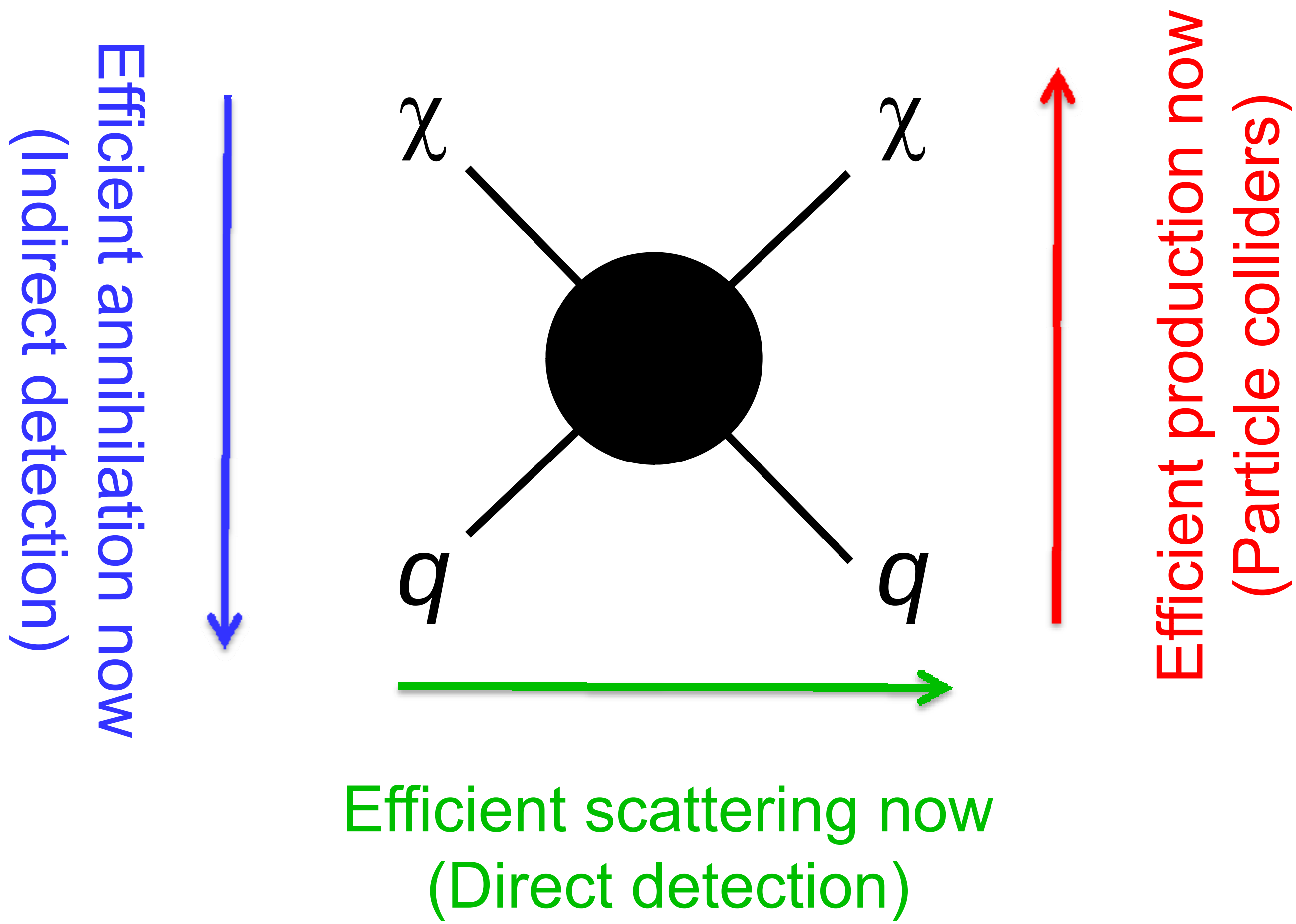


- m_X ~ 100 GeV, g_X ~ 0.6 → Ω_X ~ 0.1

- Remarkable coincidence: both particle physics and cosmology point to the 100 GeV scale for new particles

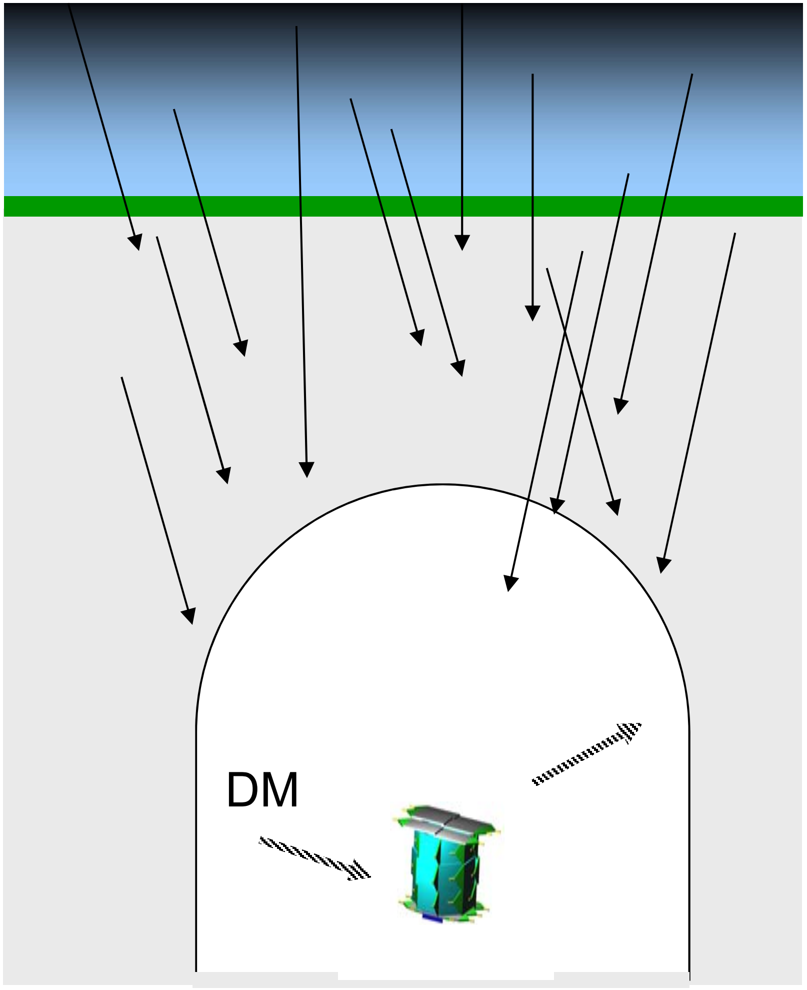
EXPERIMENTAL PROBES

Correct relic density → Efficient annihilation then



DIRECT DETECTION

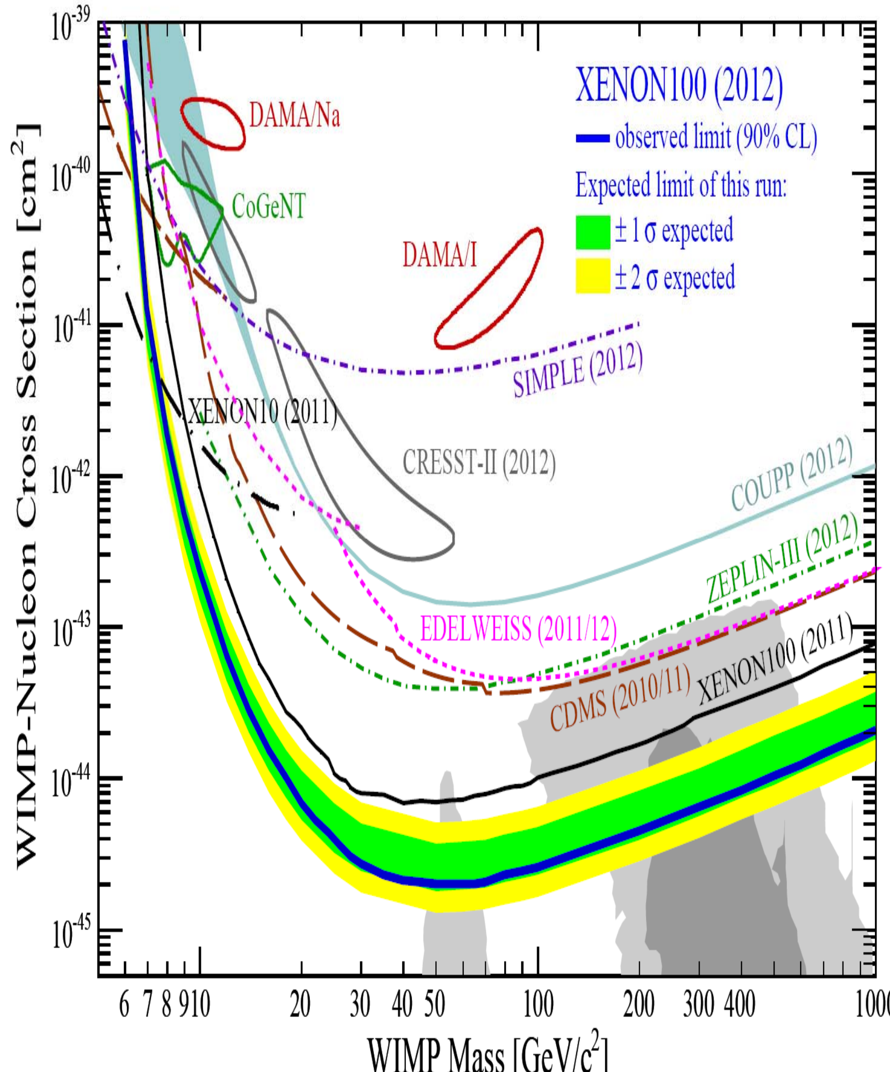
- WIMP properties
  - m ~ 100 GeV
  - local density ~ 1 per liter
  - velocity ~ 10^{-3} c
  - < 1 interaction per kg per year
- Can look for normal matter recoiling from WIMP collisions in ultra-sensitive detectors placed deep underground
- An area of rapid progress and great interest on two fronts



WEAK INTERACTION FRONTIER

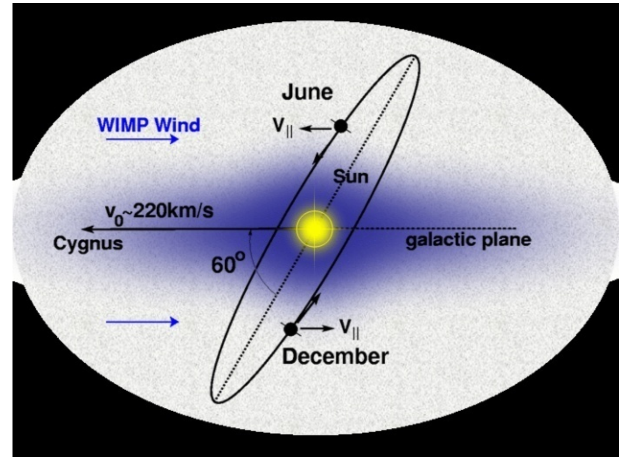
- Results typically normalized to DM-proton cross sections
- Many models with WIMP mass ~ 100 GeV are being probed NOW

CDMS in the Soudan mine (Minnesota)



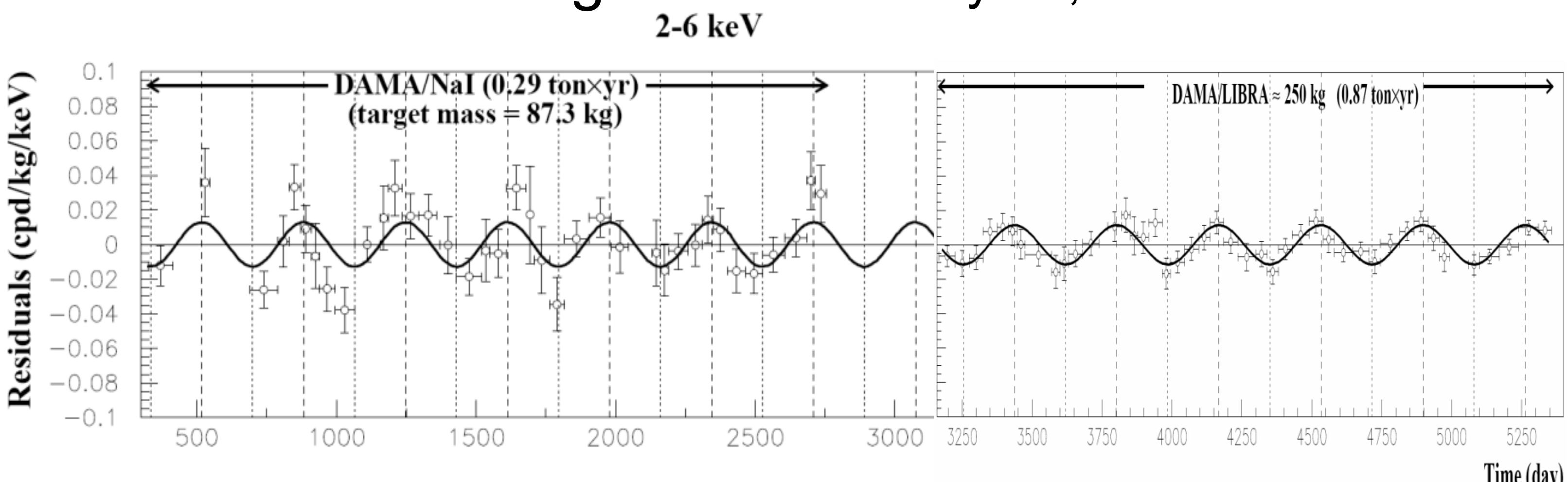
LOW MASS FRONTIER

Some experiments already claim a signal! E.g., collision rate should change as the Earth goes around the Sun → annual modulation



Drukier, Freese, Spergel (1986)

DAMA/LIBRA: 8.9σ signal with T ≈ 1 year, maximum ≈ June 2



DAMA/LIBRA (2010)

DAMA signal now supplemented by CoGeNT, CRESST

INDIRECT DETECTION

Dark Matter Madlibs!

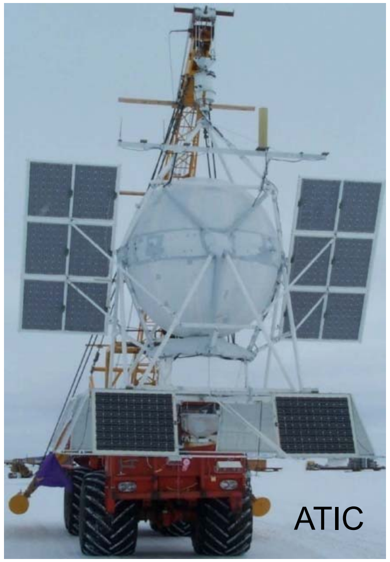
Dark matter annihilates in ____________________ to
a place

____________ , which are detected by ________________ .
particles an experiment

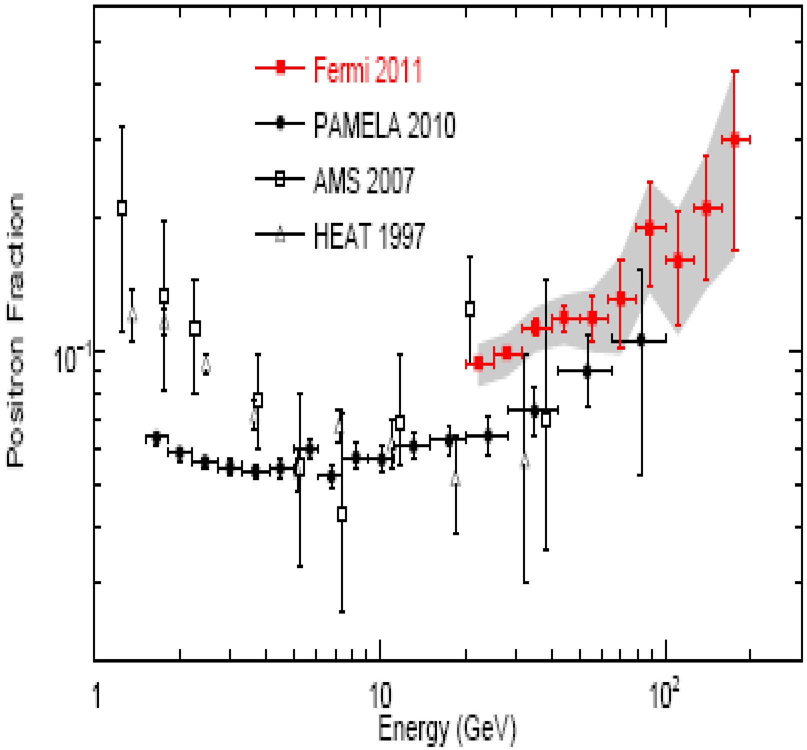
A small sample of the many possibilities…

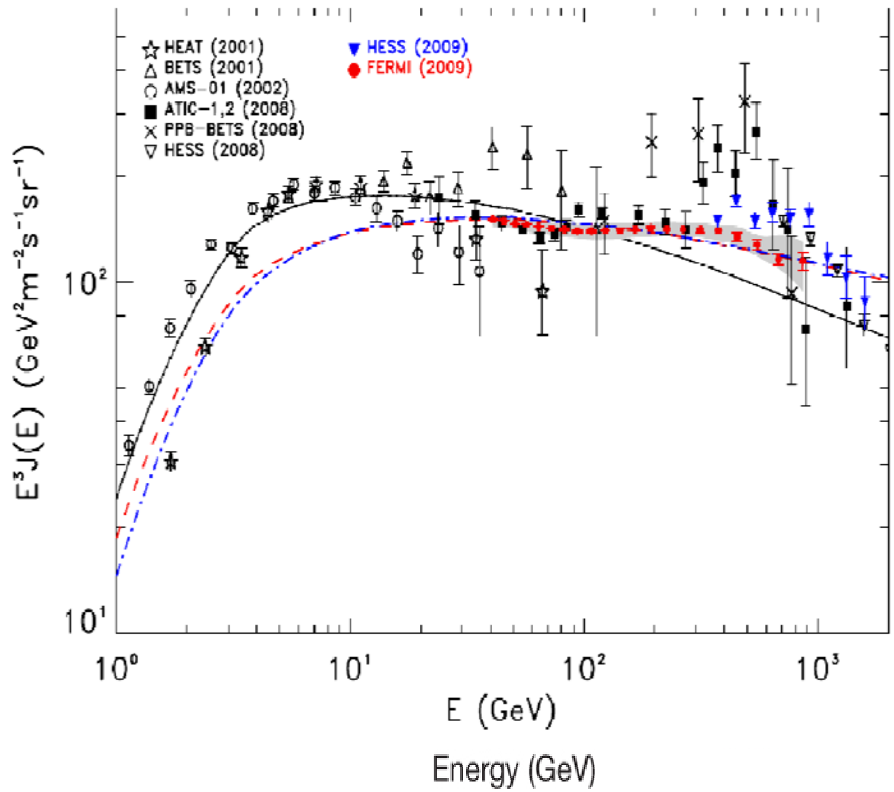
POSITRONS

Dark Matter annihilates in the galactic halo (a place) to positrons (some particles), which are detected by PAMELA/ATIC/Fermi… (an experiment).



POSITRON SIGNALS



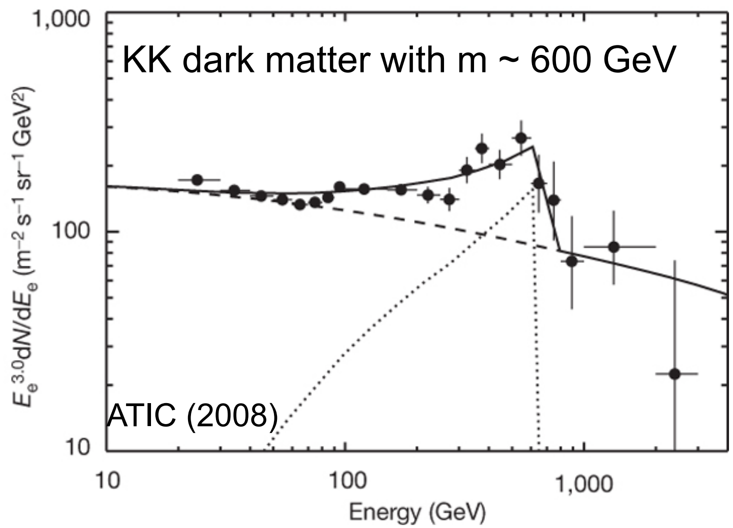


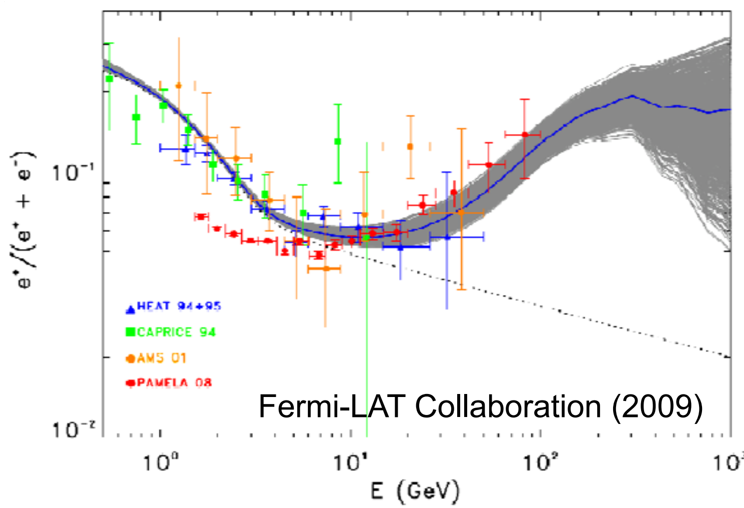
Solid lines are the astrophysical bkgd from GALPROP (Moskalenko, Strong)

ARE THESE DARK MATTER?

- The shape of the energy spectrum is consistent with WIMPs; e.g., Kaluza-Klein dark matter
- Unfortunately, the flux is a factor of 100-1000 too big for a thermal relic; requires
  - Enhancement from particle physics
  - Alternative production mechanism
- At this point, pulsars are a more likely explanation

Zhang, Cheng (2001); Hooper, Blasi, Serpico (2008)
Yuksel, Kistler, Stanev (2008); Profumo (2008)
Fermi-LAT Collaboration (2009)





PHOTONS

Dark Matter annihilates in <u>GC, dwarf galaxies</u> to
a place

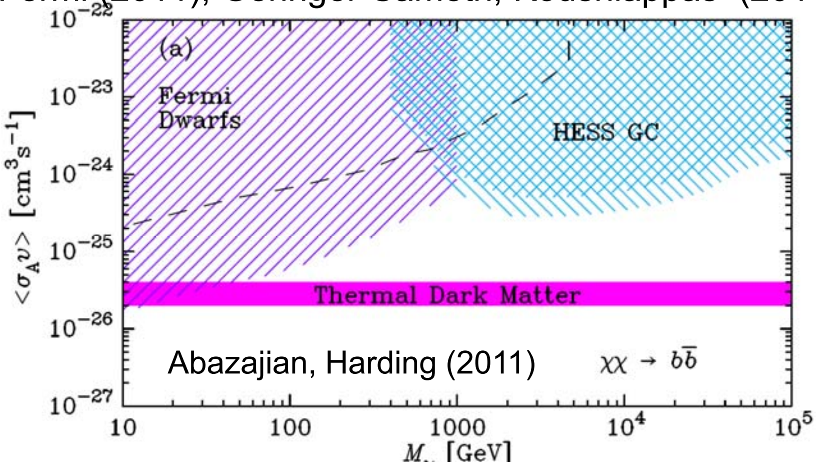
<u>photons</u> , which are detected by <u>Fermi, HESS, VERITAS, …</u>
some particles an experiment

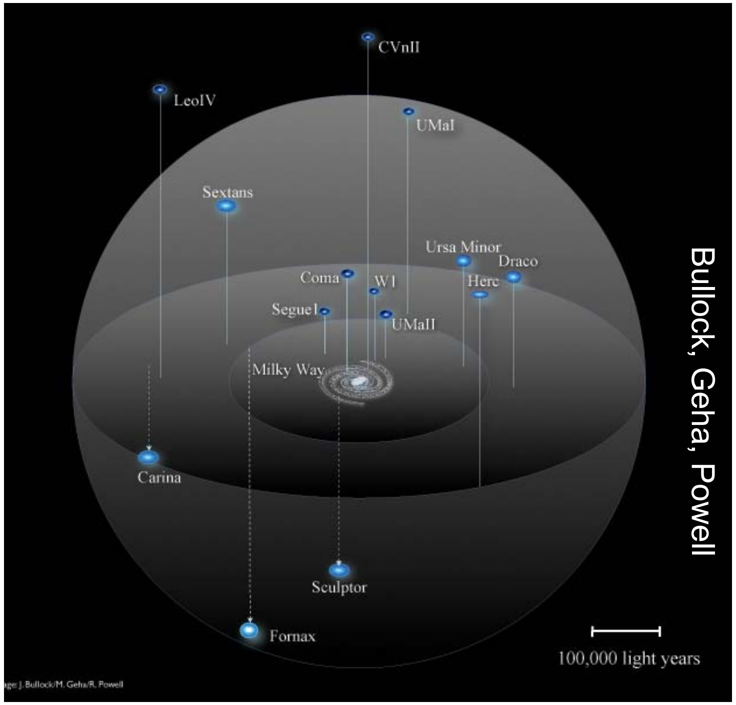
PHOTON SIGNALS

- Continuum: $X\, X \rightarrow f\, f \rightarrow \gamma$ (Monoenergetic lines also possible)
- For some annihilation channels, bounds exclude light thermal relics

$$\frac{d\Phi_\gamma}{d\Omega dE} = \sum_i \underbrace{\frac{dN_\gamma^i}{dE}\sigma_i v \frac{1}{4\pi m_\chi^2}}_{\text{Particle Physics}} \underbrace{\int_\psi \rho^2 dl}_{\text{Astro-Physics}}$$

Fermi (2011); Geringer-Sameth, Koushiappas (2011)



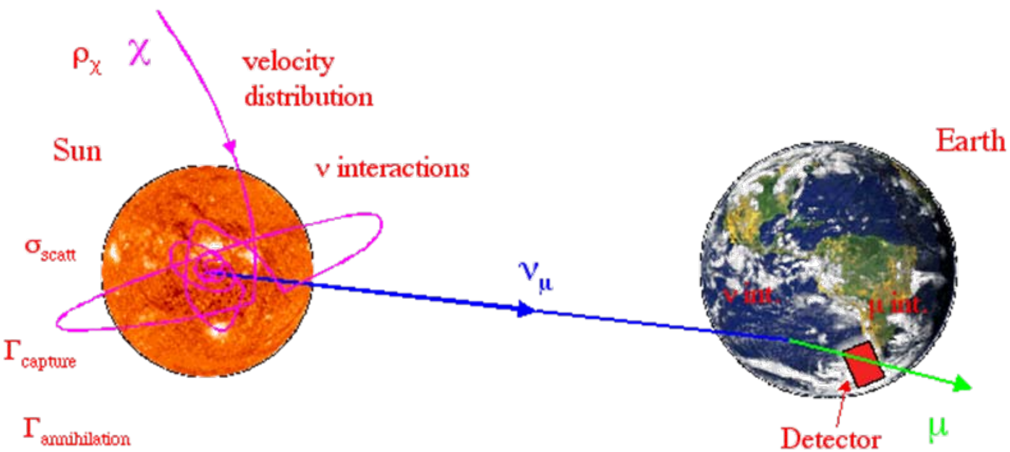


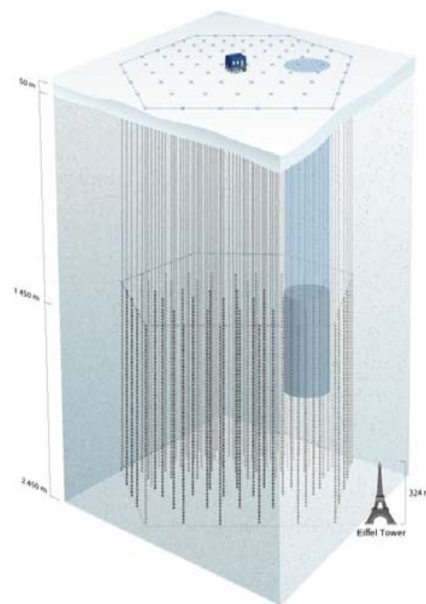
Bullock, Geha, Powell

NEUTRINOS

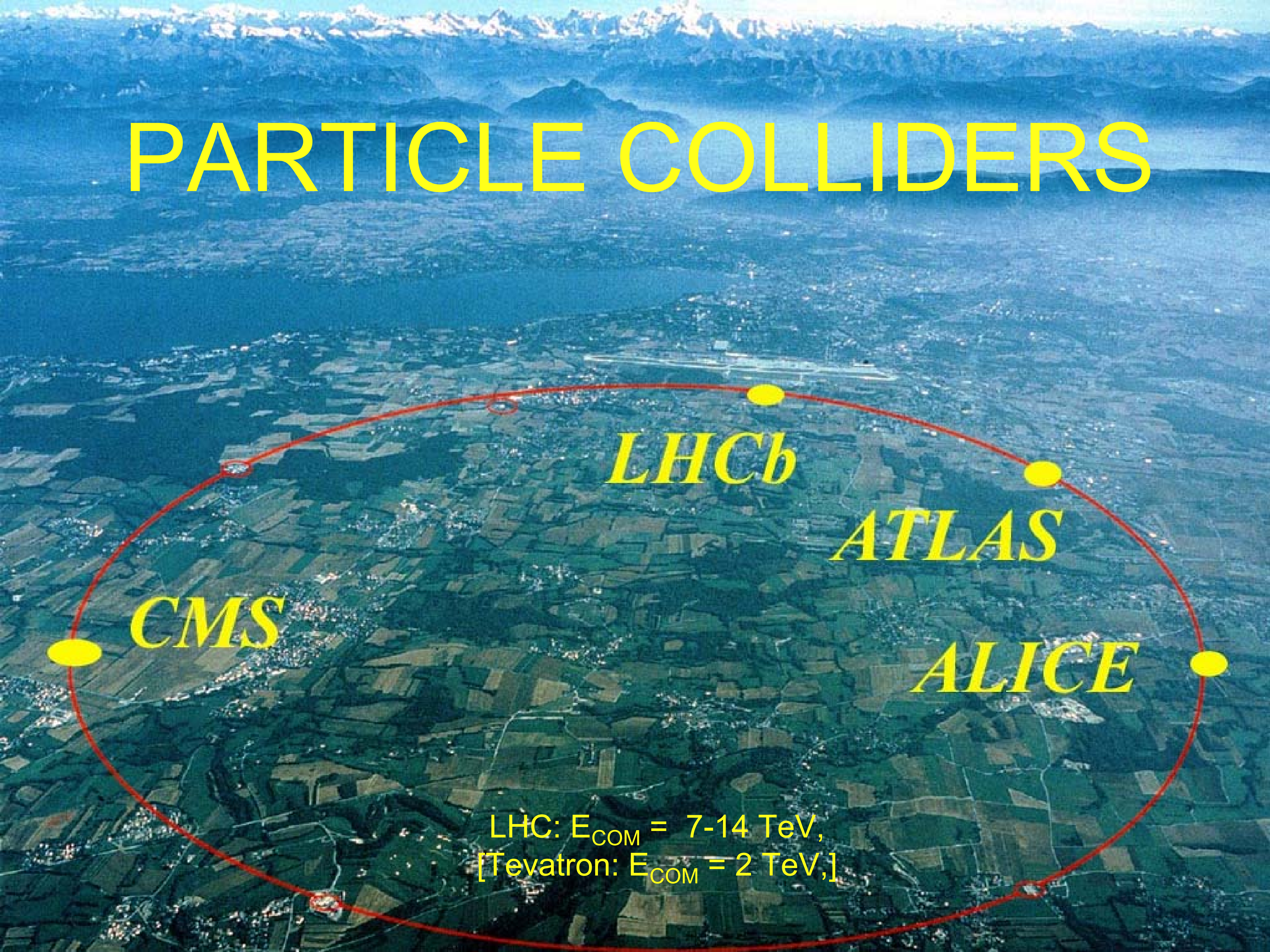
Dark Matter annihilates in __the center of the Sun__ to
a place

__neutrinos__ , which are detected by ______IceCube______ .
some particles
an experiment





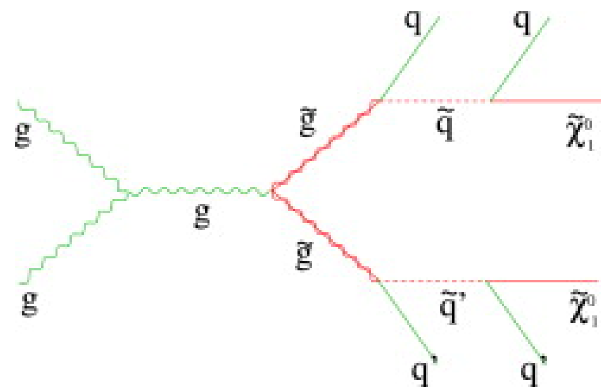
PARTICLE COLLIDERS

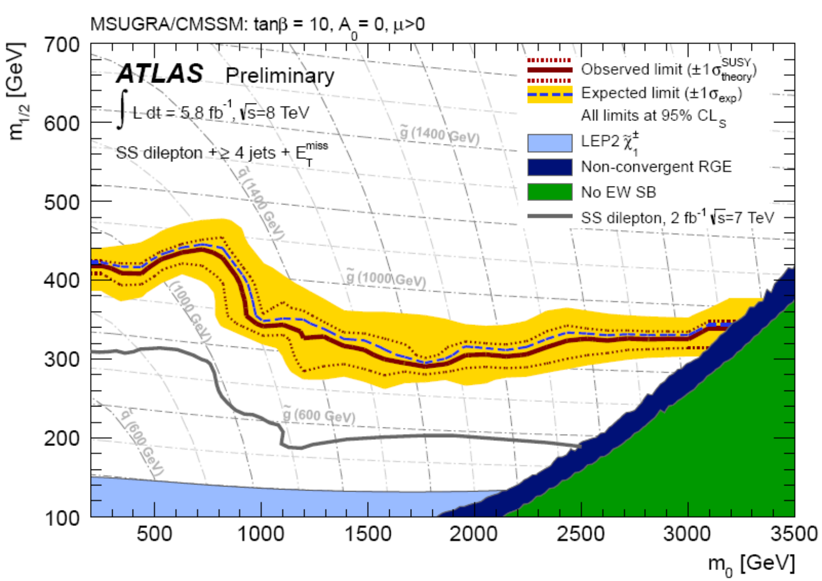


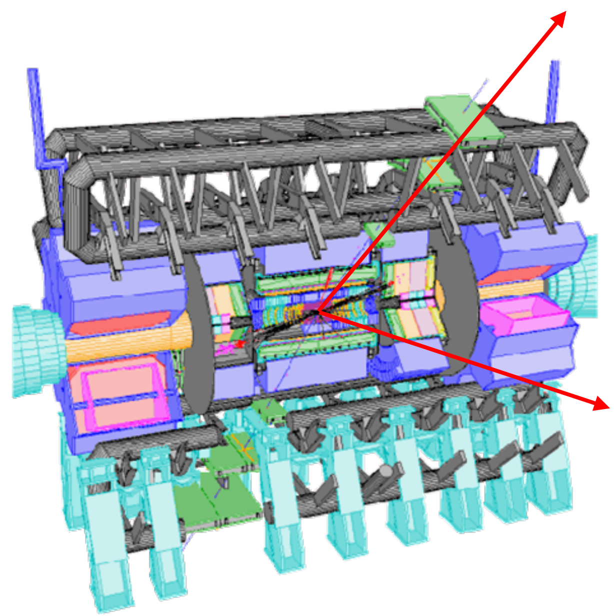
LHC: E_{COM} = 7-14 TeV,
[Tevatron: E_{COM} = 2 TeV,]

WHAT THE LHC ACTUALLY SEES

- E.g., $\tilde{g}\tilde{g}$ pair production
  - Each $\tilde{g}$ → dark matter χ
  - 2 dark matter particles escape detector
  - missing momentum







FUTURE PROSPECTS

- Question: Are we most likely to discover dark matter through direct detection, indirect detection, or at particle colliders?

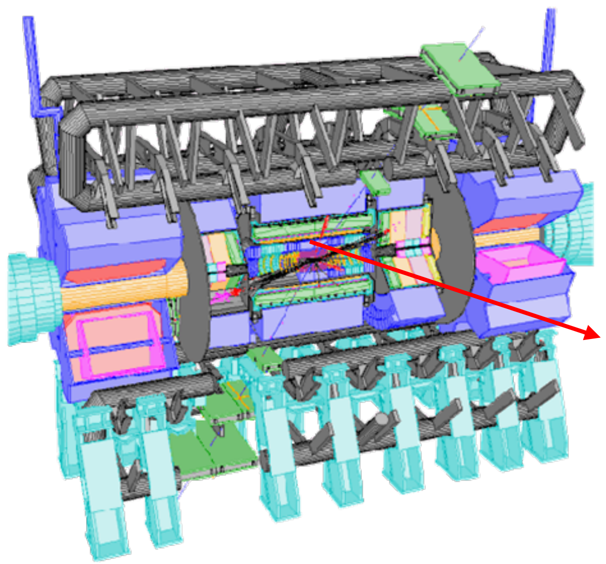
- Answer: Yes!

  We need all three (and also astrophysical probes). Why? Many answers: At one level, we have several signals already, but none is compelling. We need cross-checks: extraordinary claims require extraordinary evidence

DM COMPLEMENTARITY

- Direct and indirect detection: even future experiments with strong signals will be unable to determine the detailed properties of dark matter: is it SUSY? Is it extra dimensions?

- Particle colliders: can't discover DM



Lifetime > 10^{-7} s → 10^{17} s ?

FUTURE PROSPECTS: THE NEXT 50 YEARS

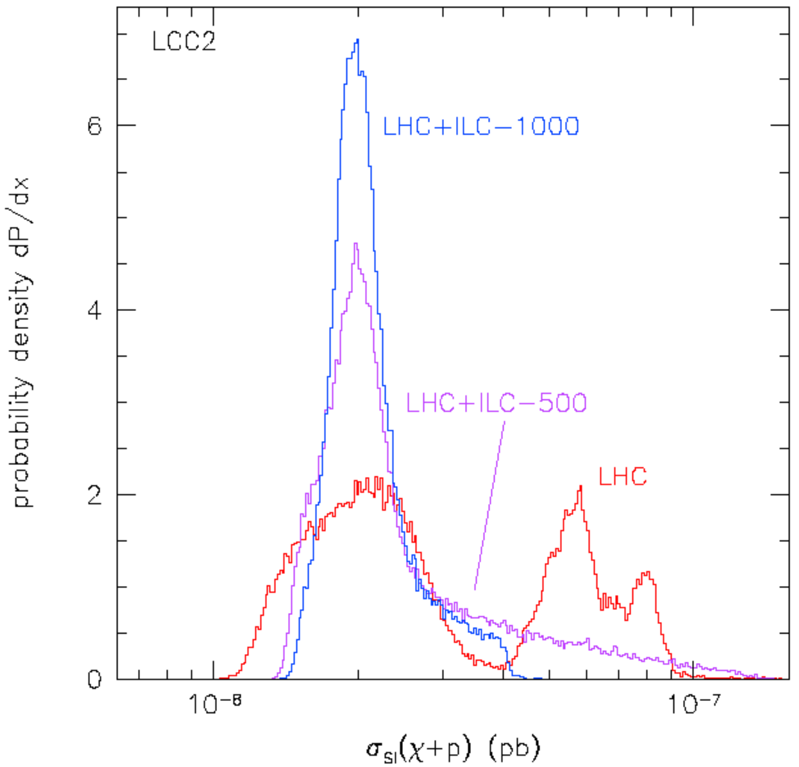
If WIMPs are a significant component of dark matter, progress will come in 3 stages:

I: Discovery: we will see signals by more than one method

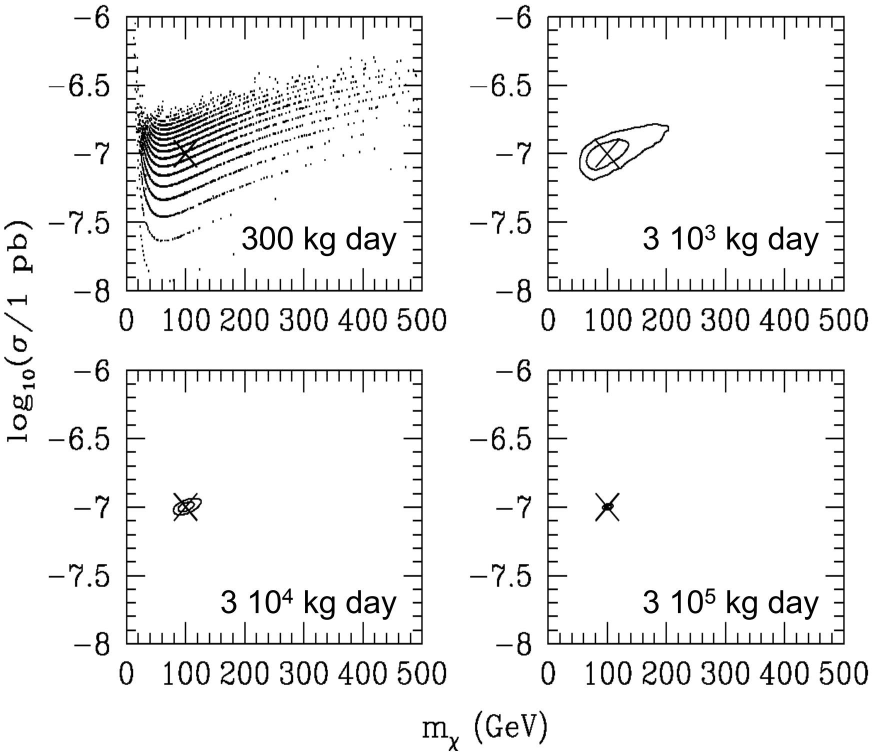
II: We will then enter an initial era of precision DM studies; this will strengthen the case for dark matter discovery, e.g., mass measurements should all agree, and provide information about particle properties

III: We will then enter an era of DM astronomy

COLLIDERS AND DIRECT DETECTION



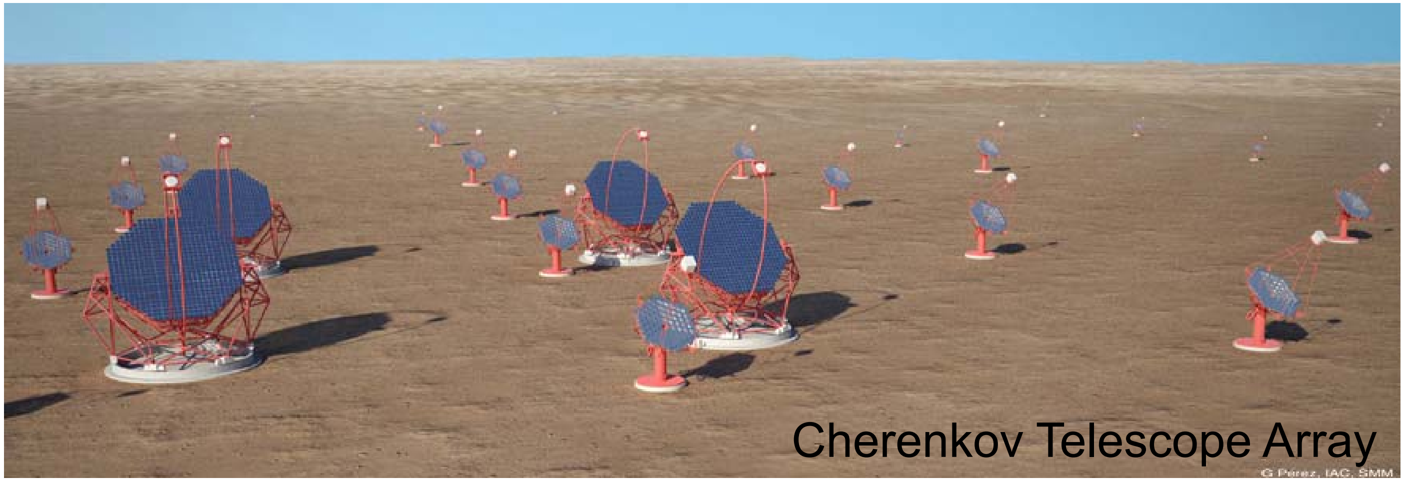
Baltz, Battaglia, Peskin, Wizansky (2006)



Green (2007)

COMPARISON TELLS US ABOUT LOCAL DARK MATTER DENSITY AND VELOCITY DISTRIBUTIONS

COLLIDERS AND INDIRECT DETECTION

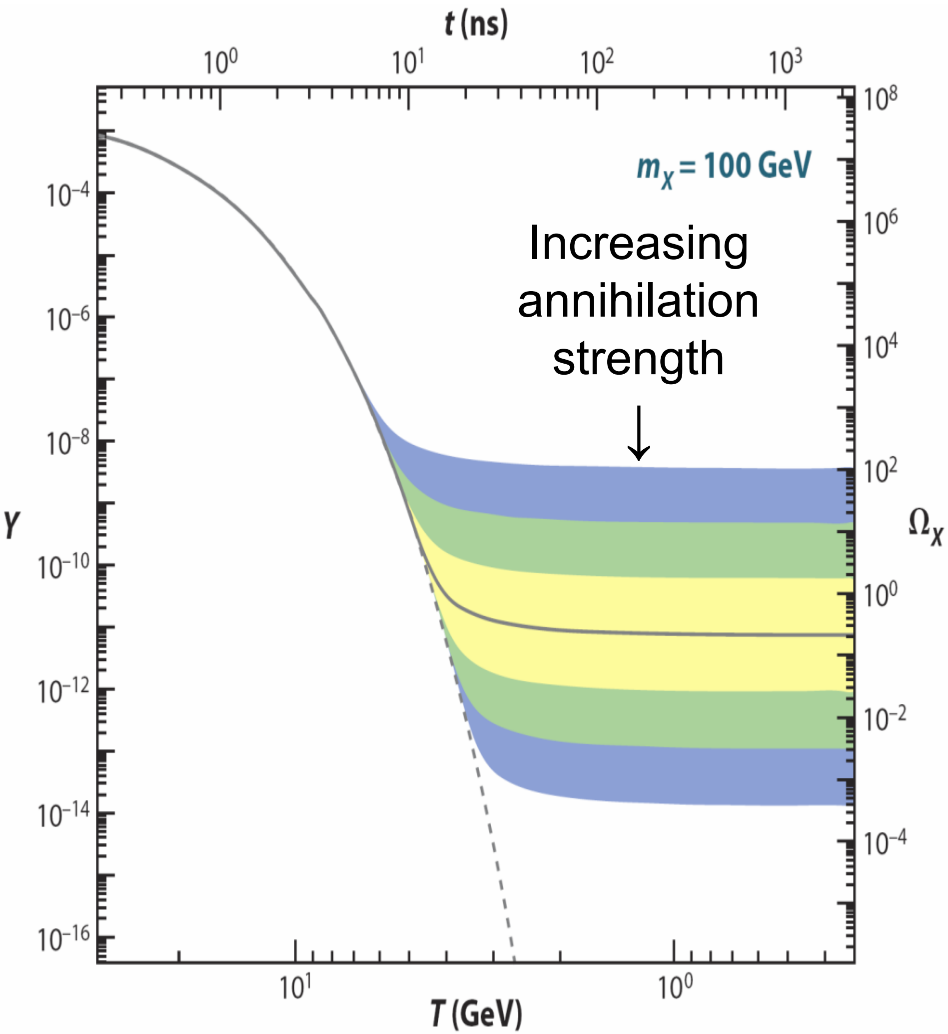


$$\frac{d\Phi_\gamma}{d\Omega dE} = \sum_i \underbrace{\frac{dN_\gamma^i}{dE}\sigma_i v \frac{1}{4\pi m_\chi^2}}_{\text{Particle Physics}} \underbrace{\int_\psi \rho^2 dl}_{\text{Astro-Physics}}$$

Gamma ray fluxes factorize

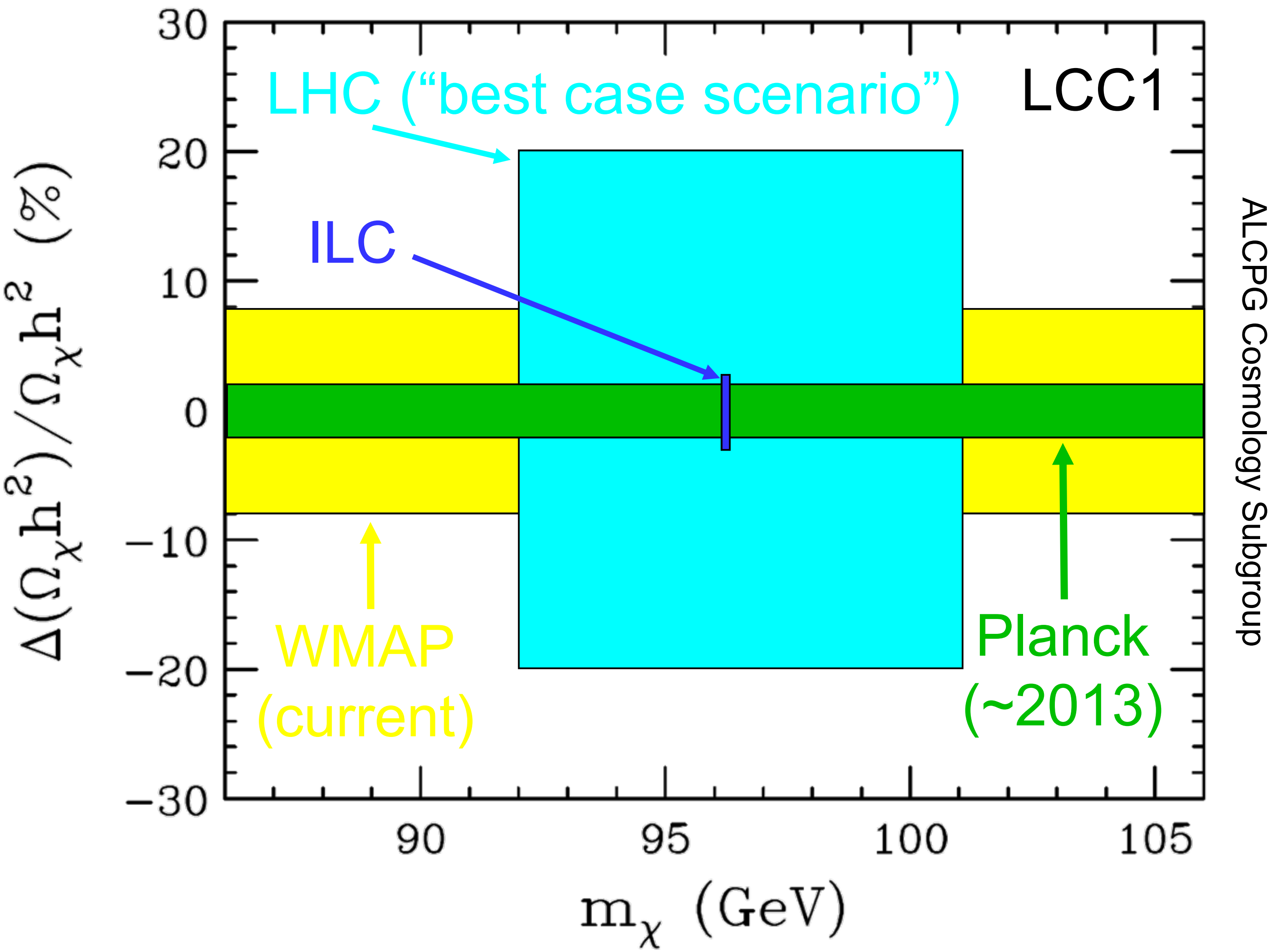
COLLIDERS WILL DETERMINE PARTICLE PROPERTIES, ALLOW ONE TO PROBE ASTROPHYSICAL DISTRIBUTIONS ON GALACTIC SCALES

DM PRODUCTION ON COSMOLOGICAL SCALES



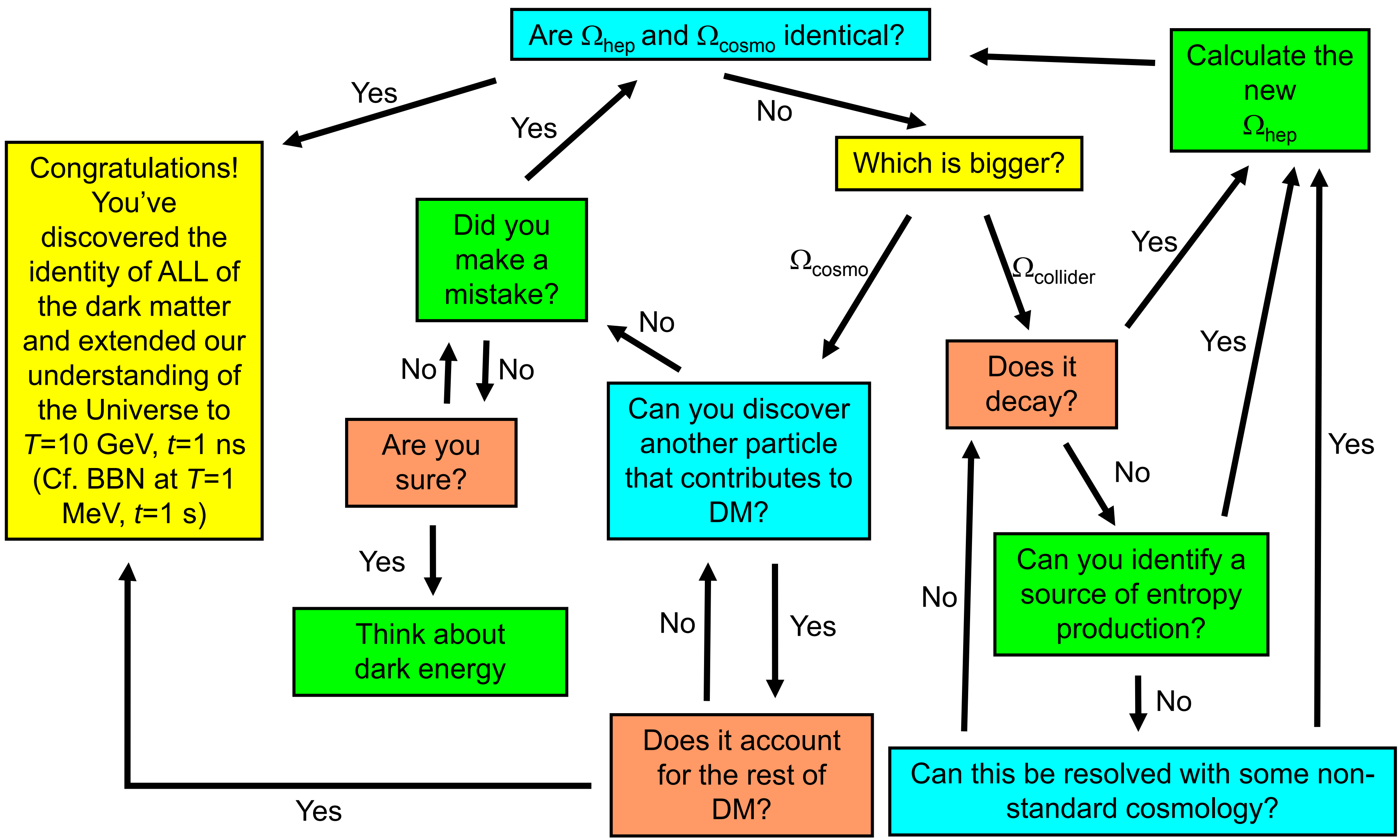
- Particle physics → dark matter abundance prediction
- Compare to dark matter abundance observation
- How well can we do?

RELIC DENSITY DETERMINATIONS



% level comparison of predicted Ω_{hep} with observed Ω_{cosmo}

IDENTIFYING DARK MATTER



CONCLUSIONS

- Dark Matter is central to both cosmology and particle physics
- LHC is running, direct detection, indirect detection, and astrophysical probes are improving rapidly – this field is being transformed now
- In the next 50 years, who knows what will happen, but SLAC will undoubtedly play a central role in the exciting era ahead