DARK MATTERS

Jonathan Feng
University of California, Irvine

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WHAT IS THE UNIVERSE MADE OF?

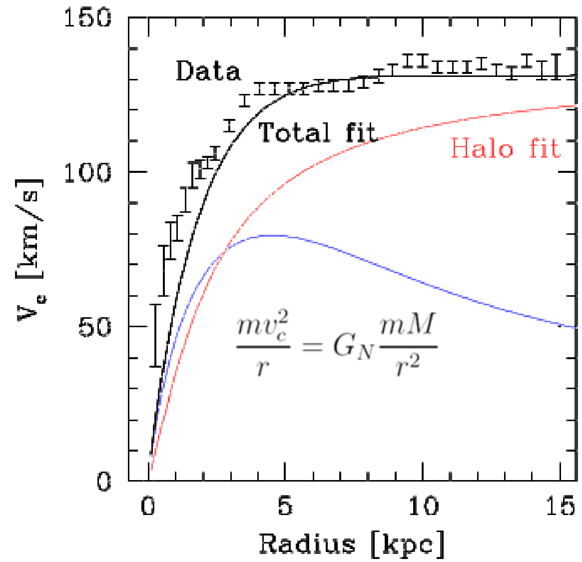
An age old question, but…

Recently there have been remarkable advances in our understanding of the Universe on the largest scales

We live in interesting times: for the first time in history, we have a complete census of the Universe

The Evidence

Rotation curves of galaxies and galactic clusters

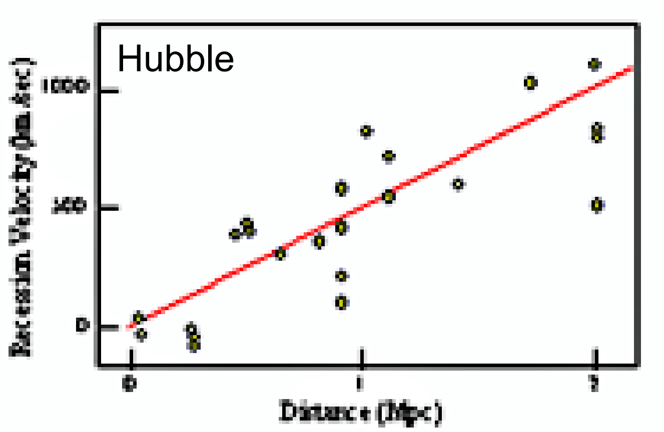


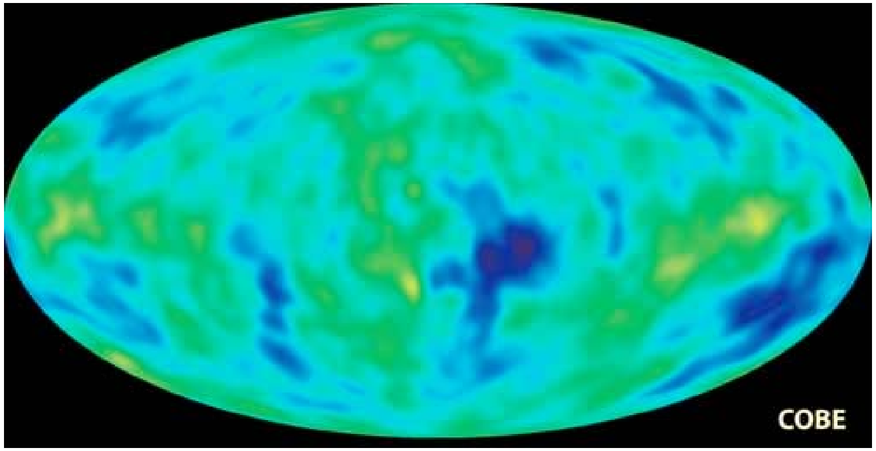
- Expect $v_c \sim r^{-1/2}$ beyond luminous region
- Instead find $v_c \sim$ constant
- Discrepancy resolved by postulating dark matter

Supernovae

Cosmic Microwave Background

Then

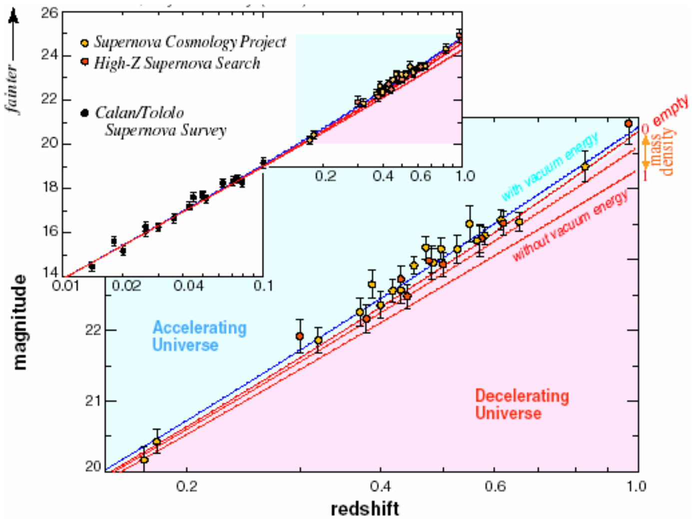


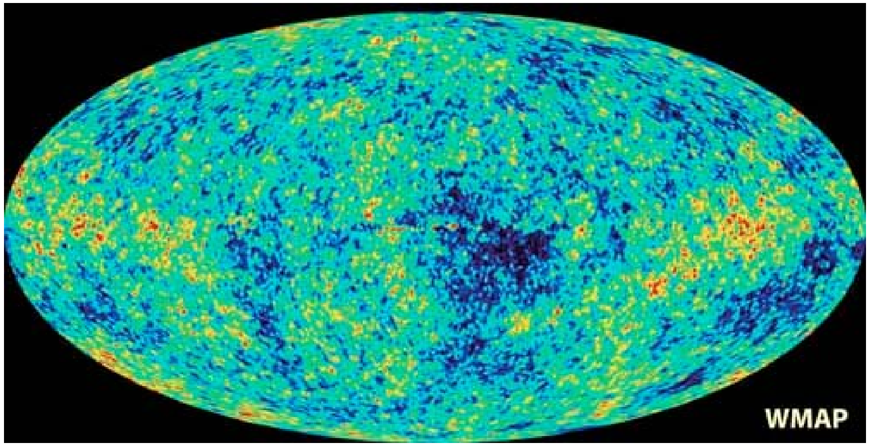


Constrains $\Omega_\Lambda - \Omega_M$

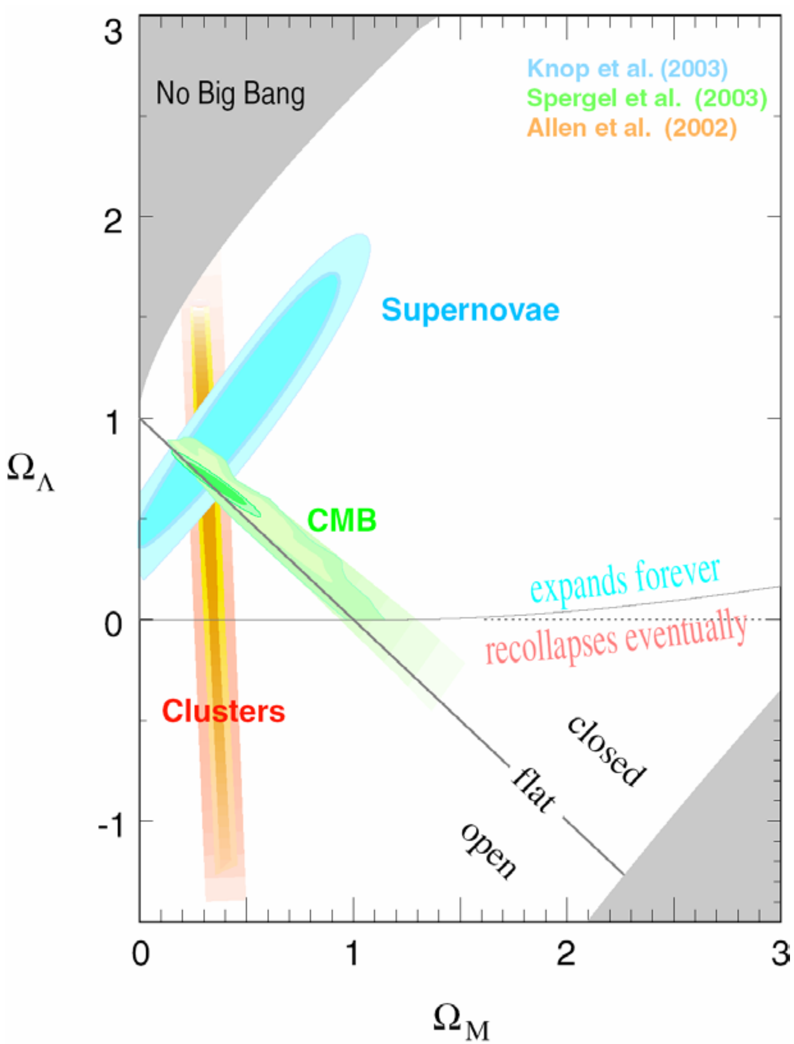
Constrains $\Omega_\Lambda + \Omega_M$

Now





Synthesis



- Remarkable agreement

  Dark Matter: 23% ± 4%
  Dark Energy: 73% ± 4%
  [Baryons: 4% ± 0.4%
  Neutrinos: ~0.5%]

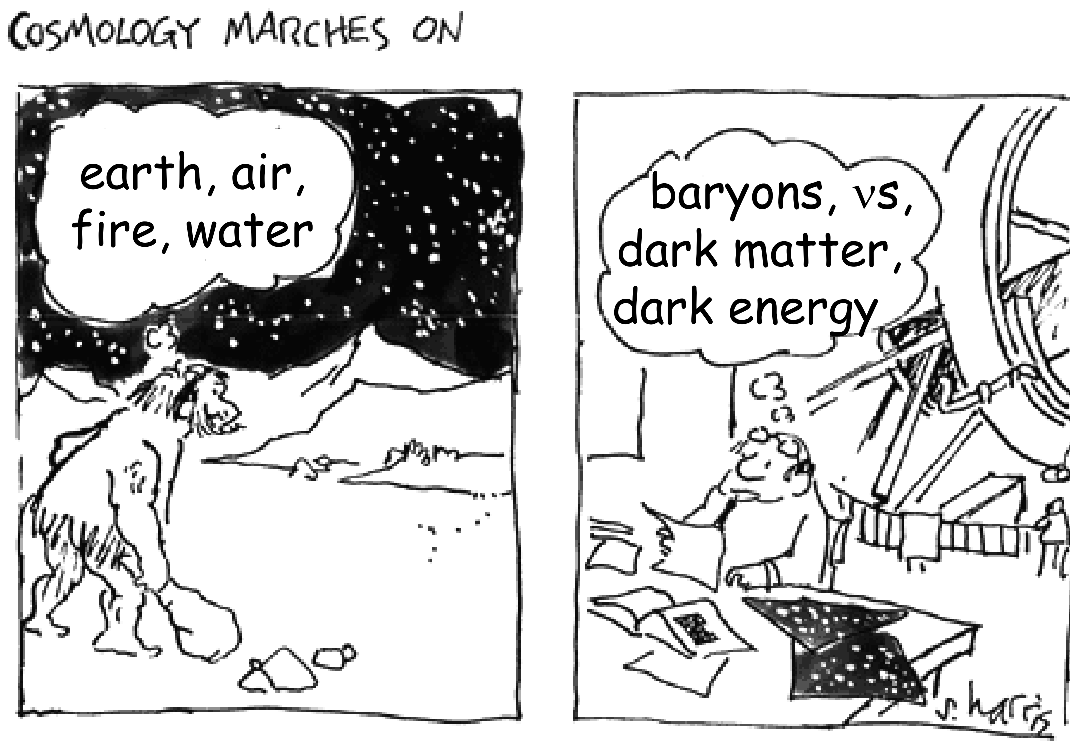
- Remarkable precision (~10%)

- Remarkable results

Historical Precedent

Eratosthenes measured the size of the Earth in 200 B.C.

- Remarkable precision (~10%)
- Remarkable result
- But just the first step in centuries of exploration


COSMOLOGY MARCHES ON
earth, air, fire, water
baryons, νs, dark matter, dark energy
S. Harris

What is the Dark Stuff Made Of?

We have no idea. But so far, these problems appear to be completely different.

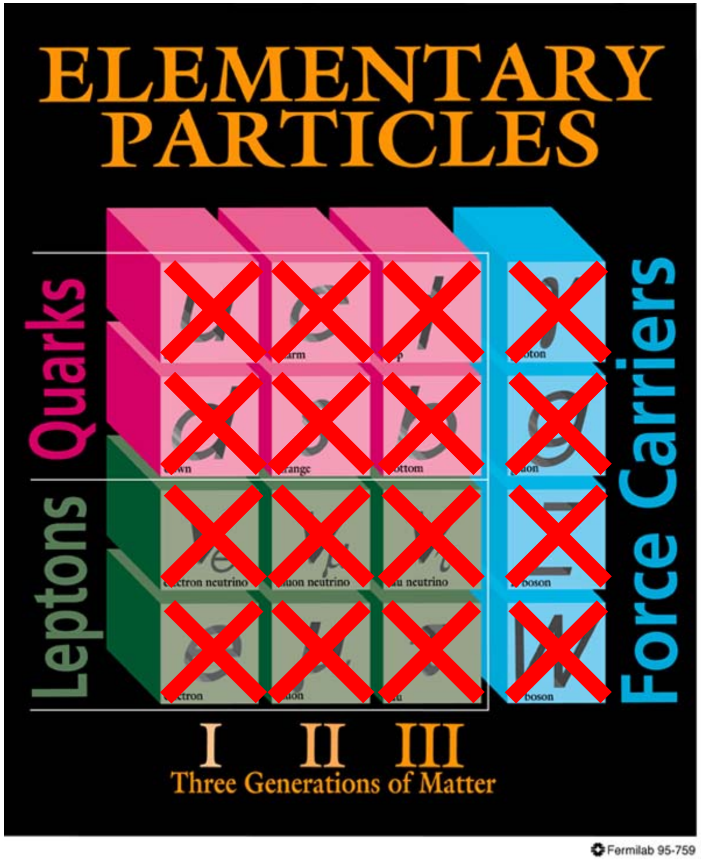
Dark Matter

- No known particles contribute
- Probably tied to $M_{\text{weak}} \sim 100$ GeV
- Several compelling solutions

Dark Energy

- All known particles contribute
- Probably tied to $M_{\text{Planck}} \sim 10^{19}$ GeV
- No compelling solutions

DARK MATTER



Known DM properties

- Stable
- Non-baryonic
- Cold

DM: precise, unambiguous evidence for physics beyond the standard model

Dark Matter Candidates

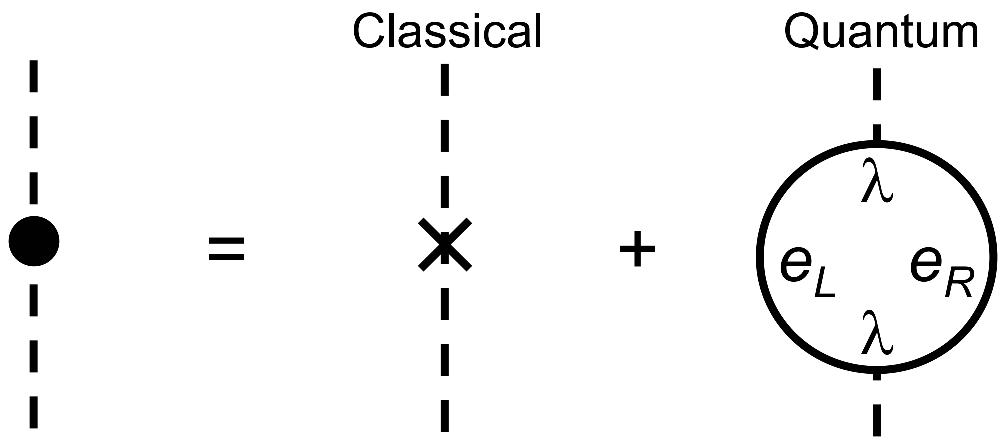
- The Wild, Wild West of particle physics: primodial black holes, axions, warm gravitinos, neutralinos, Kaluza-Klein particles, Q balls, wimpzillas, superWIMPs, self-interacting particles, self-annihilating particles, fuzzy dark matter,…

- Masses and interaction strengths span many, many orders of magnitude

- But independent of cosmology, we expect new particles:

  electroweak symmetry breaking

Electroweak Symmetry Breaking



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

$m_h \sim 100$ GeV, $\Lambda \sim 10^{19}$ GeV → cancellation of 1 part in 10^{34}

At $M_{\text{weak}} \sim 100$ GeV we expect new physics:
supersymmetry, extra dimensions, something!

Thermal Relic DM Particles

(1) Initially, DM is in thermal equilibrium:

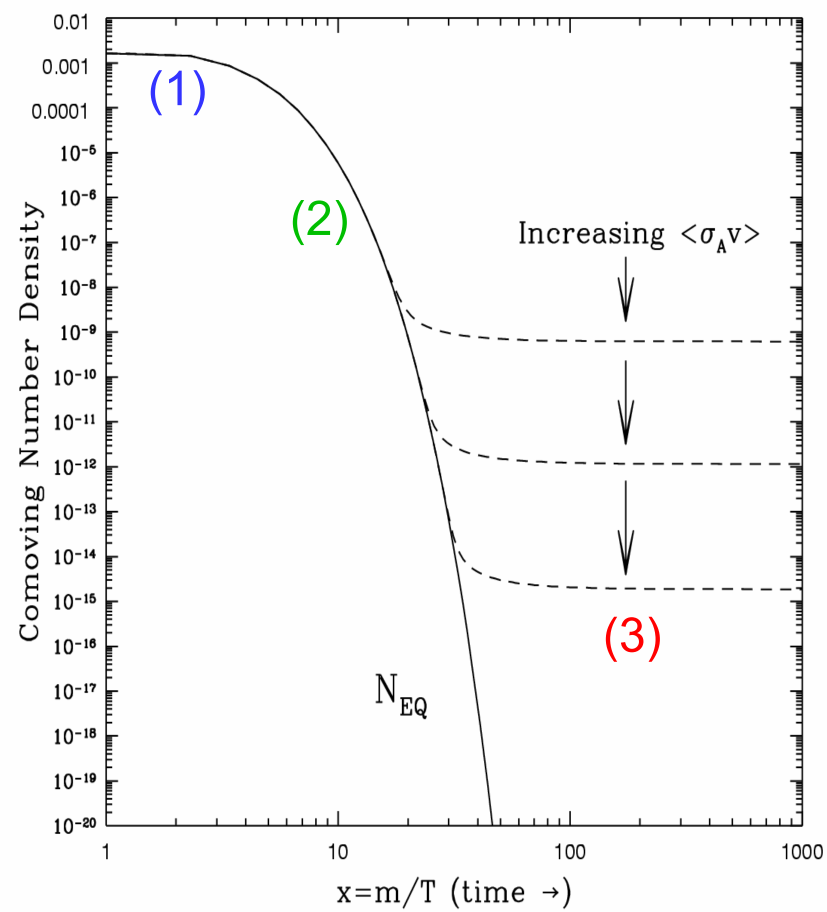
$$\chi\chi \leftrightarrow \bar{f}f$$

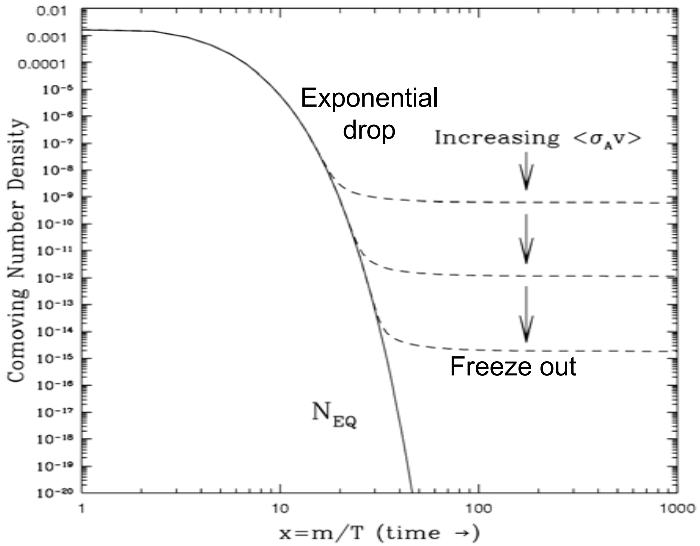
(2) Universe cools:

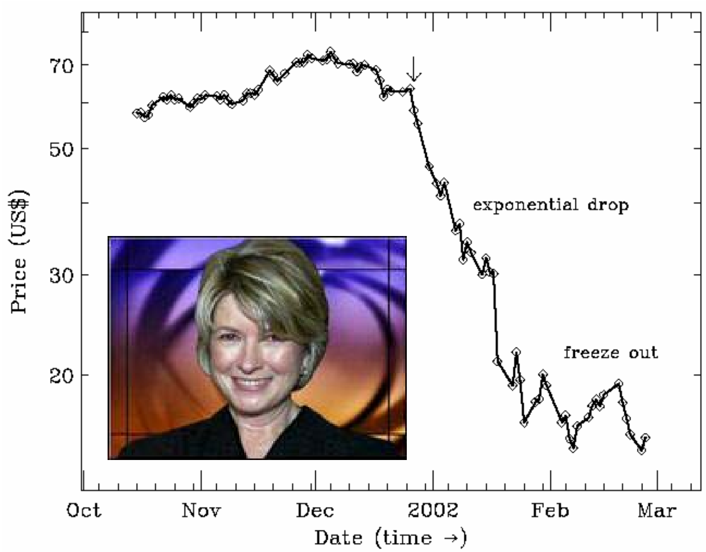
$$N = N_{EQ} \sim e^{-m/T}$$

(3) χs "freeze out":

$$N \sim \text{const}$$







- Final *N* fixed by annihilation cross section:

  $\Omega_{DM} \sim 0.1\ (\sigma_{weak}/\sigma_A)$

  Remarkable!

- 14 Gyr later, Martha Stewart sells ImClone stock – the next day, stock plummets

Coincidences? Maybe, but worth serious investigation!

NOTE

- I've assumed the lightest new particle is stable
- Problems (p decay, extra particles, …)

$\updownarrow$

Discrete symmetry

$\updownarrow$

Stability

- In many theories, dark matter is easier to explain than no dark matter

DARK MATTER CANDIDATES

Candidates that pass the Martha Stewart test

Ones you could bring home to mother – V. Trimble

WIMP Dark Matter

WIMPs: weakly-interacting massive particles

Many examples, some even qualitatively different.

Supersymmetry: electroweak symmetry breaking, string theory, unification of forces, … Predicts a partner particle for each known particle.

The prototypical WIMP: neutralino $\chi \in (\tilde{\gamma}, \tilde{Z}, \tilde{H}_u, \tilde{H}_d)$

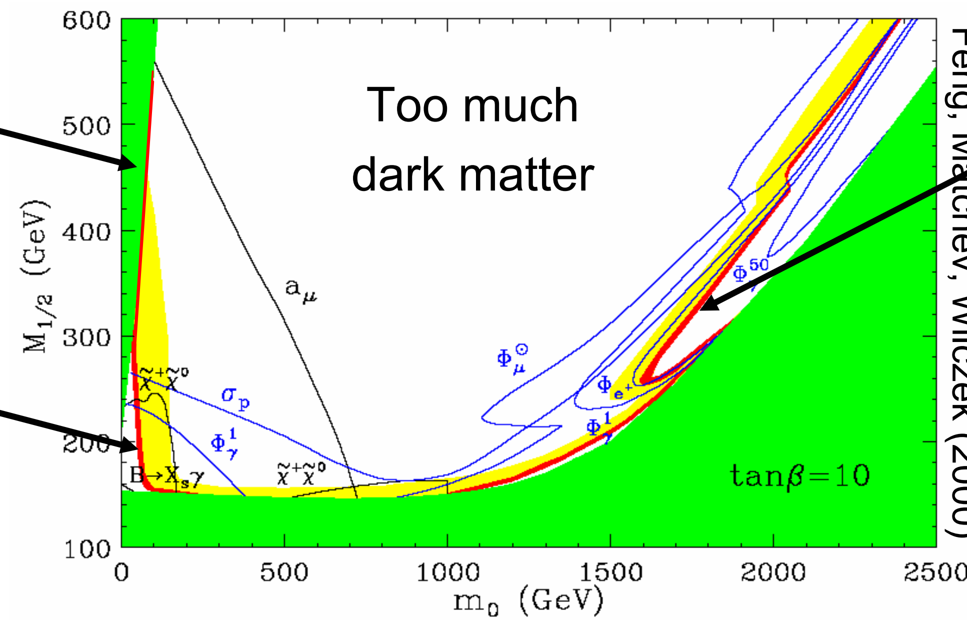
Particle physics alone → all the right properties: lightest superpartner, stable, mass ~ 100 GeV

Goldberg (1983)

The thermal relic density stringently constrains models

Co-annihilation region

Bulk region



Feng, Matchev, Wilczek (2000)

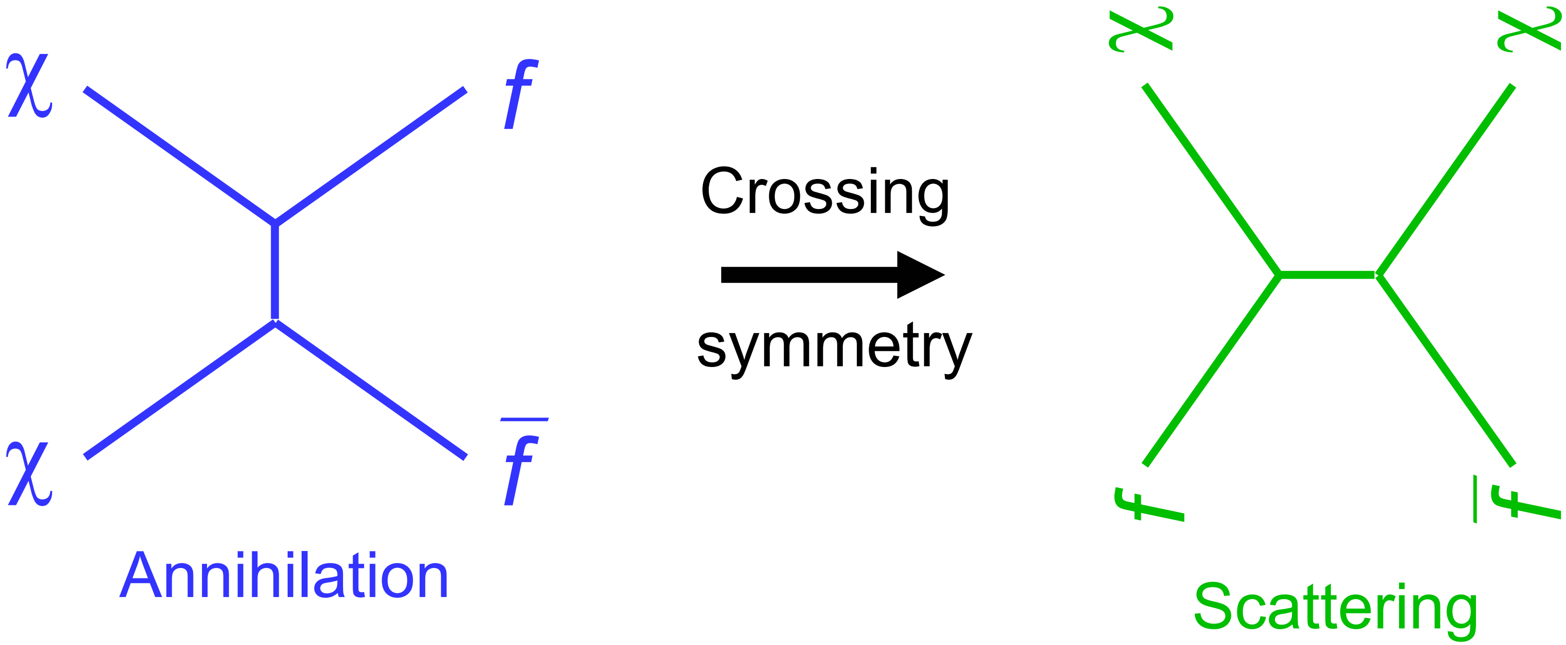
Focus point region

Yellow: pre-WMAP

Red: post-WMAP

Cosmology highlights certain regions, detection strategies

WIMP Detection: No-Lose Theorem

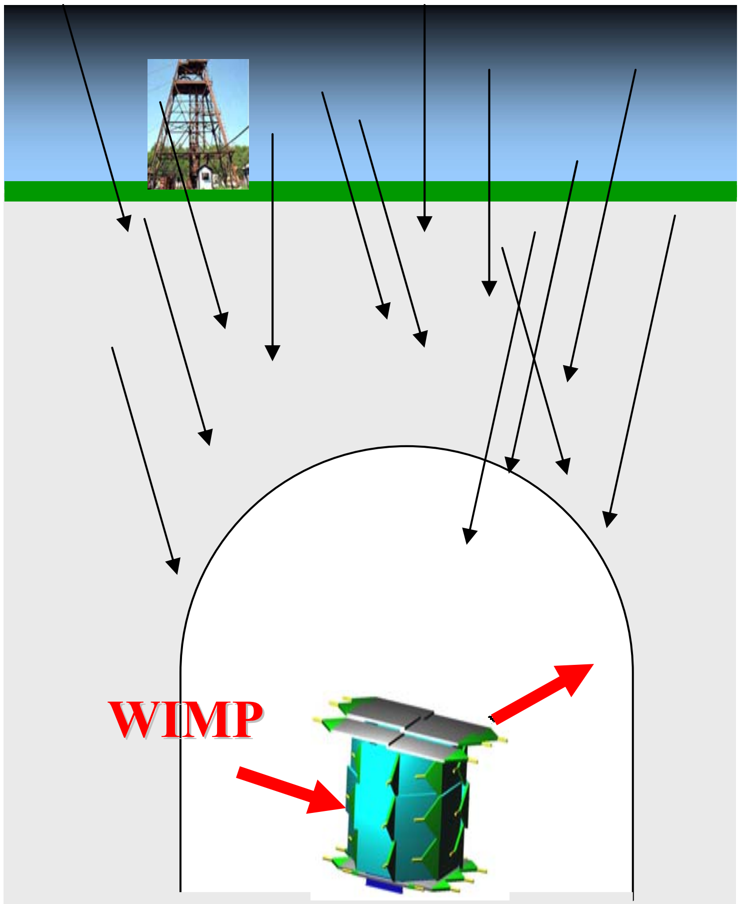


Correct relic density → Efficient annihilation then

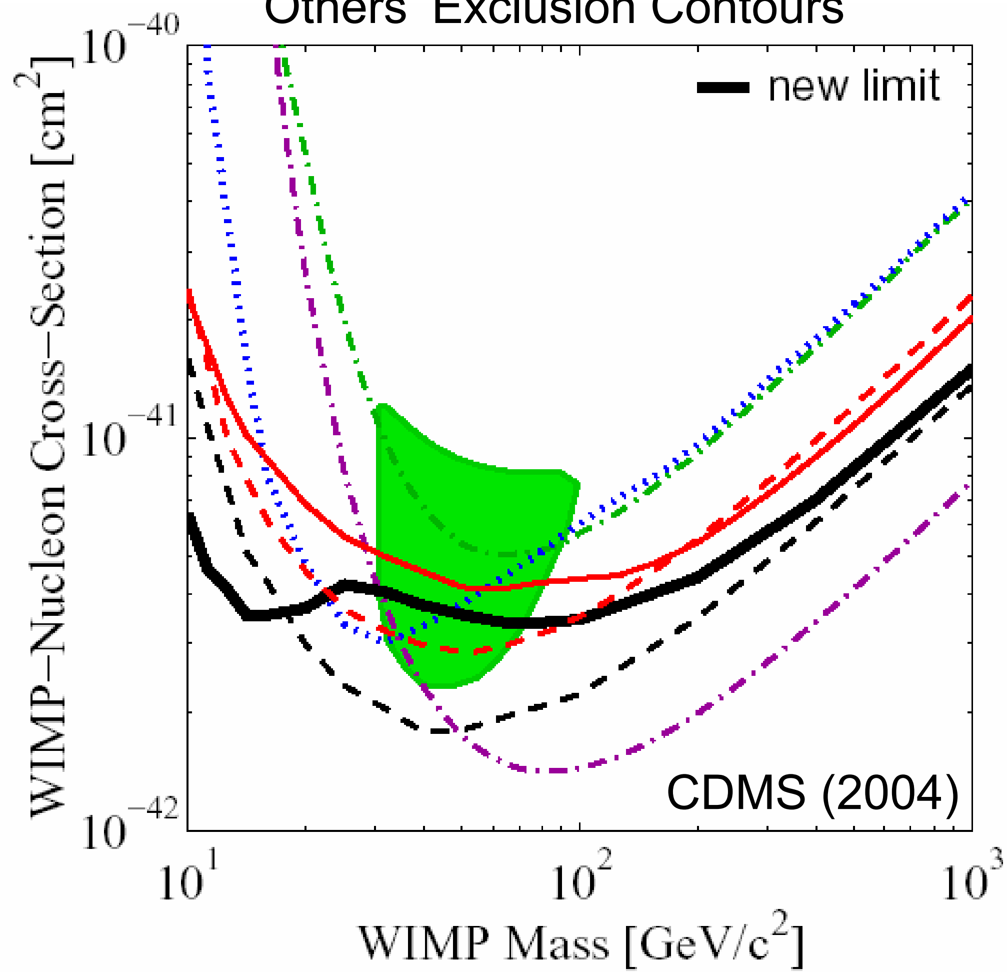
→ Efficient scattering now

→ Efficient annihilation now

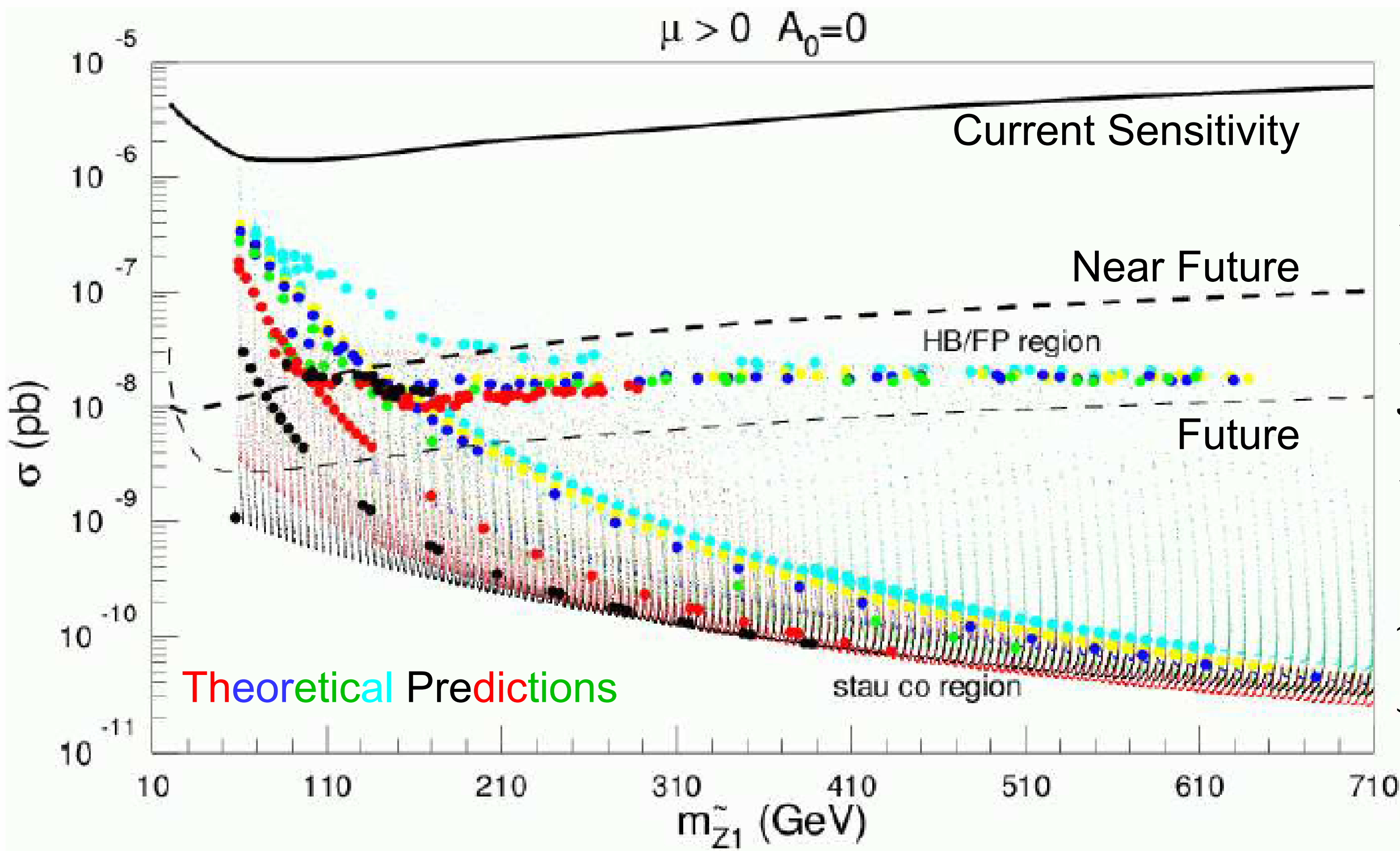
Direct Detection



DAMA Signal and
Others' Exclusion Contours



Direct Detection: Future



Baer, Balazs, Belyaev, O'Farrill (2003)

Indirect Detection

Dark Matter Madlibs!

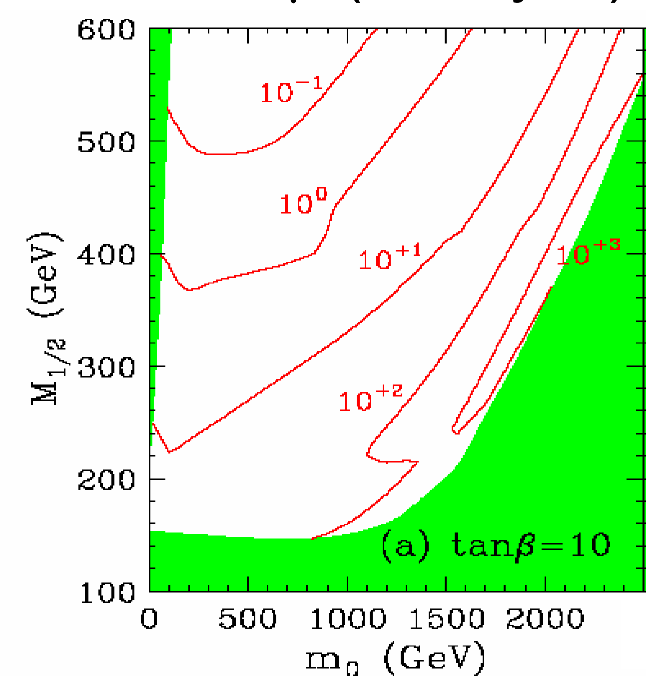
Dark matter annihilates in ____________________ to
a place

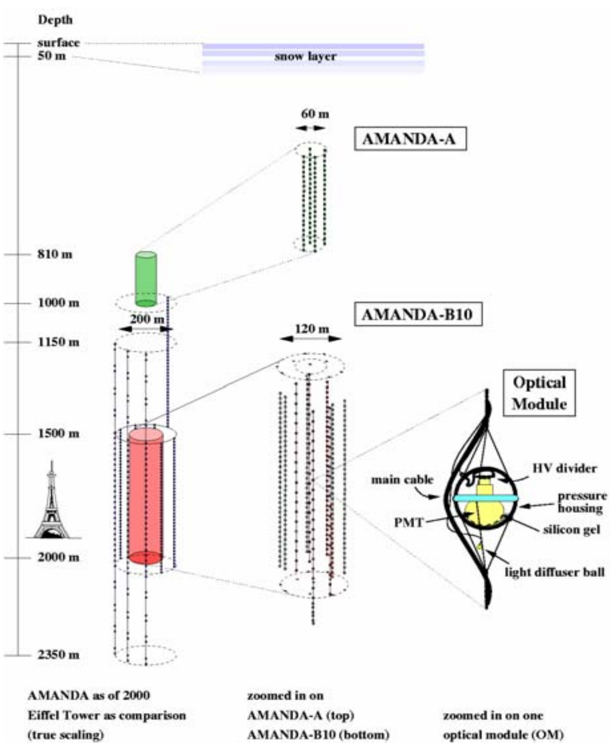
_____________ , which are detected by _________________ .
some particles an experiment

Dark Matter annihilates in ___center of the Sun___ to
a place

___neutrinos___ , which are detected by ___AMANDA, IceCube___ .
a particle an experiment

$\nu \rightarrow \mu$ (km^{-2} yr^{-1})

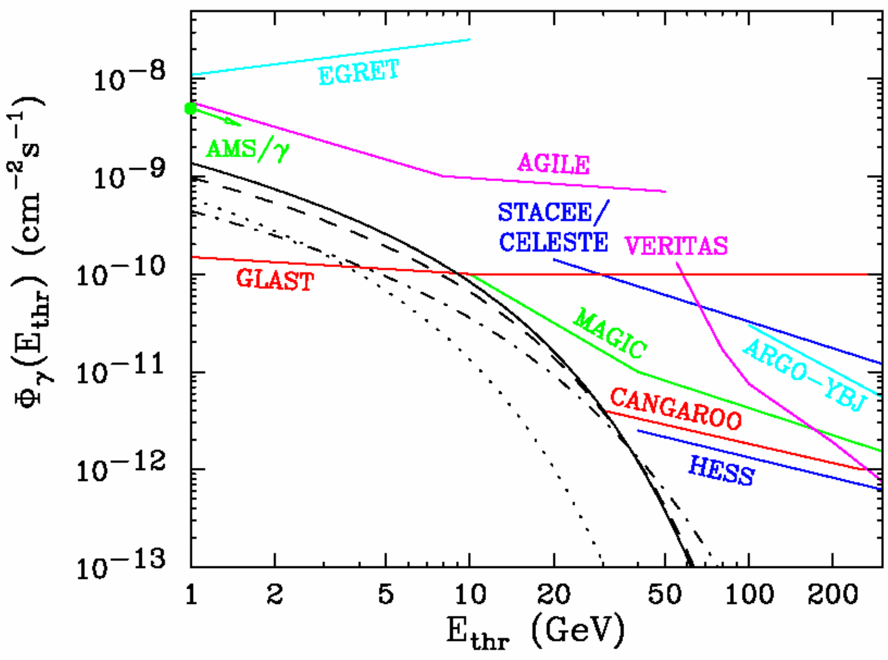




AMANDA in the Antarctic Ice

Dark Matter annihilates in __the galactic center__ to
a place

__photons__ , which are detected by __Cerenkov telescopes__ .
some particles an experiment



Typically

$$\chi\chi \not\to \gamma\gamma\ ,$$

so $\chi\chi \to f\bar{f} \to \gamma$

HESS: ~ 1 TeV signal

If DM, m_χ ~ 12 TeV

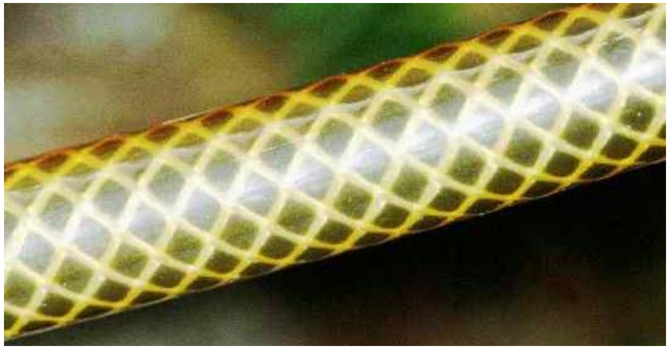
Horns (2004)

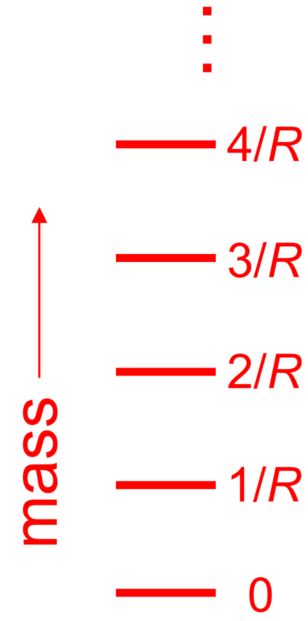
Extra Dimensional Dark Matter

Servant, Tait (2002)

- Extra spatial dimensions could be curled up into small circles.

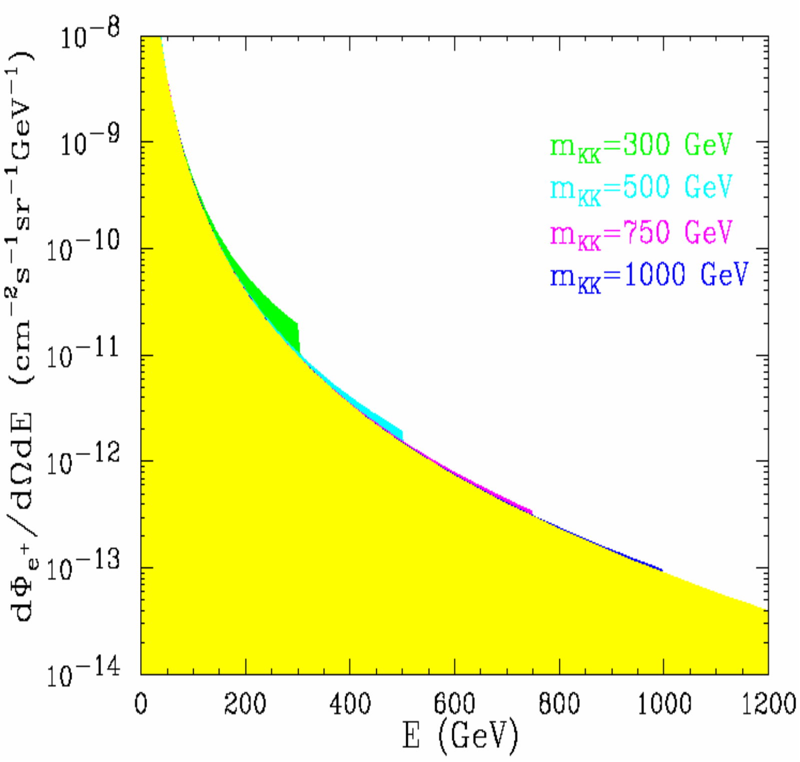
- Particles moving in extra dimensions appear as a set of copies of normal particles.

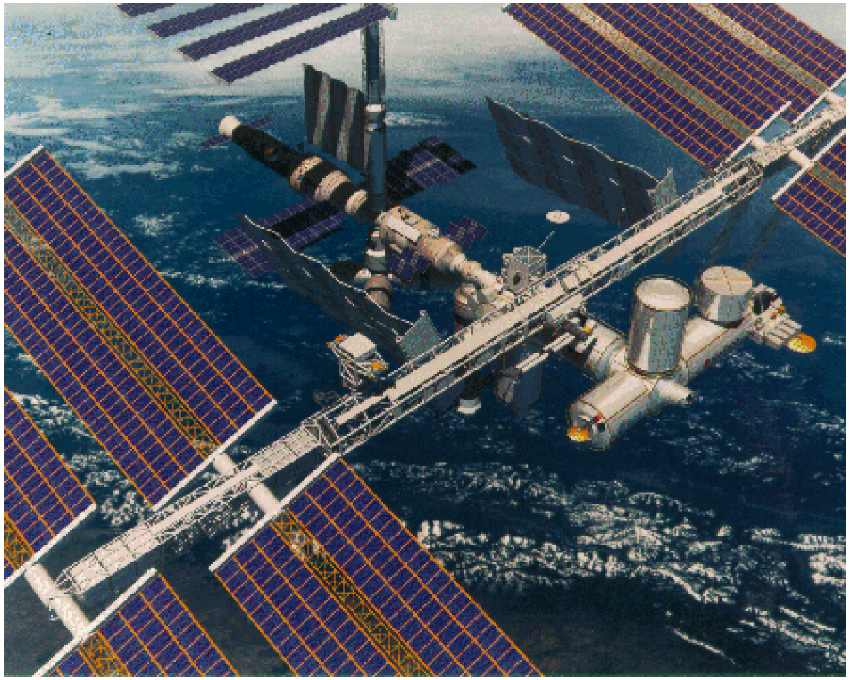




Dark Matter annihilates in ______the halo______ to
a place

__positrons__ , which are detected by _AMS on the ISS_ .
some particles — an experiment





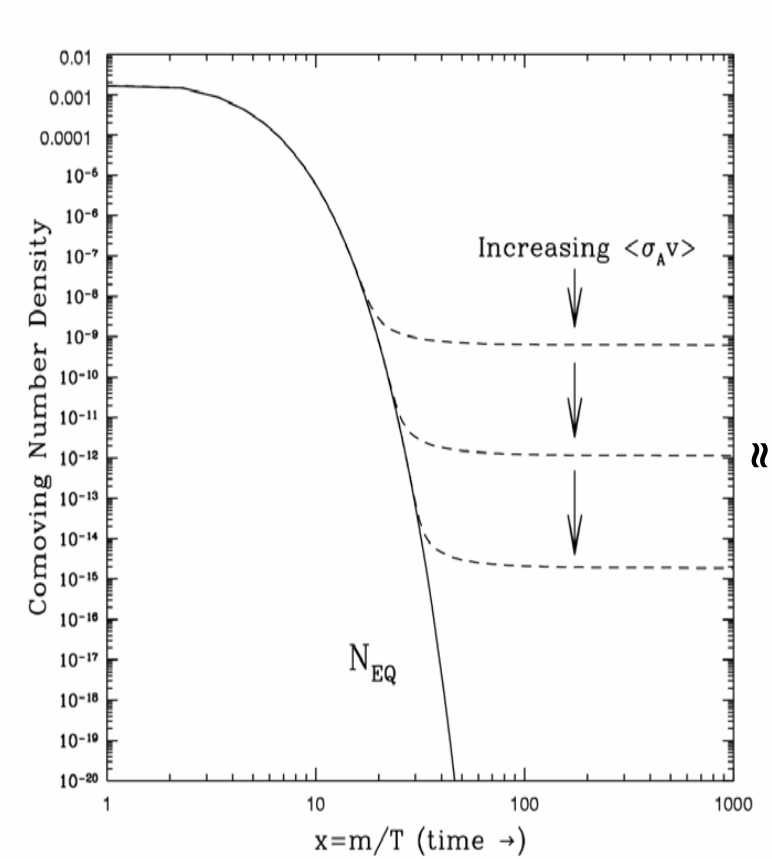
SuperWIMP Dark Matter

Feng, Rajaraman, Takayama (2003)

- All of these signals rely on DM having electroweak interactions. Is this required?
- No – the only required DM interactions are gravitational (much weaker than electroweak).
- But the relic density argument strongly prefers weak interactions.

Is there an exception to this rule?

No-Lose Theorem: Loophole



- Consider SUSY again:
  Gravitons → gravitinos $\tilde{G}$
- What if the $\tilde{G}$ is the lightest superpartner?

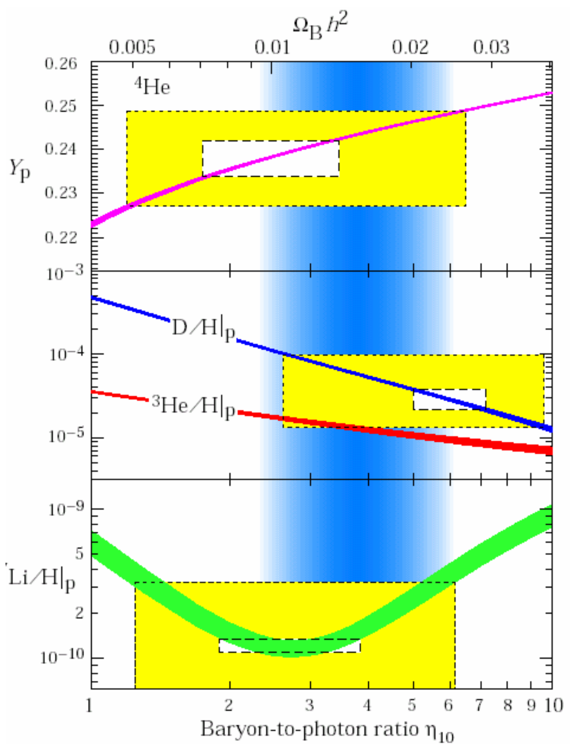
WIMP → $\tilde{G}$ $\approx$ M_{Pl}^2/M_W^3 ~ month

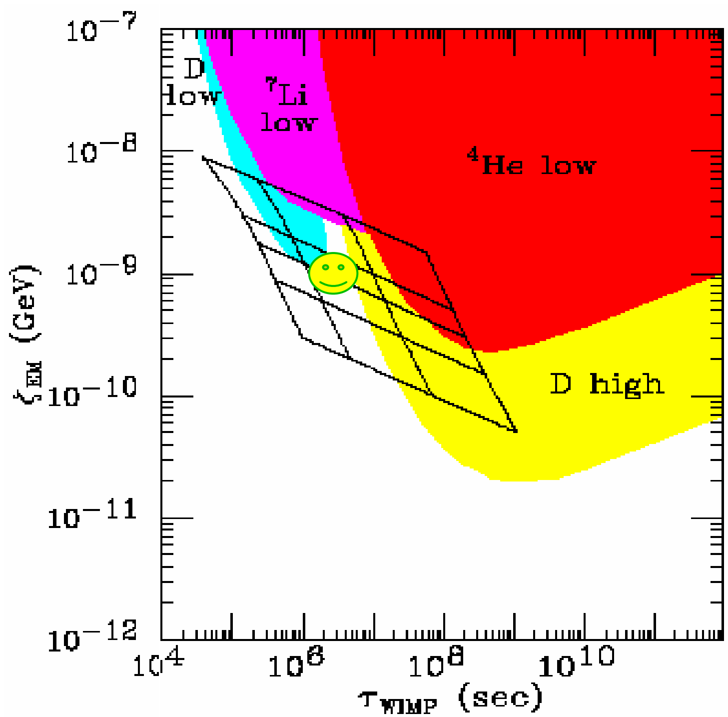
- A month passes…then all WIMPs decay to gravitinos

Gravitinos naturally inherit the right density, but they interact only gravitationally – they are "superWIMPs"

SuperWIMP Detection

- SuperWIMPs evade all conventional dark matter searches. But superweak interactions → very late decays $\tilde{l} \rightarrow \tilde{G}\, l$ → cosmological signals. For example: BBN, CMB.





Feng, Rajaraman, Takayama (2003)

PROSPECTS

If the relic density “coincidence” is no coincidence and DM is either WIMPs or superWIMPs, the new physics behind DM will very likely be discovered this decade:

Direct dark matter searches

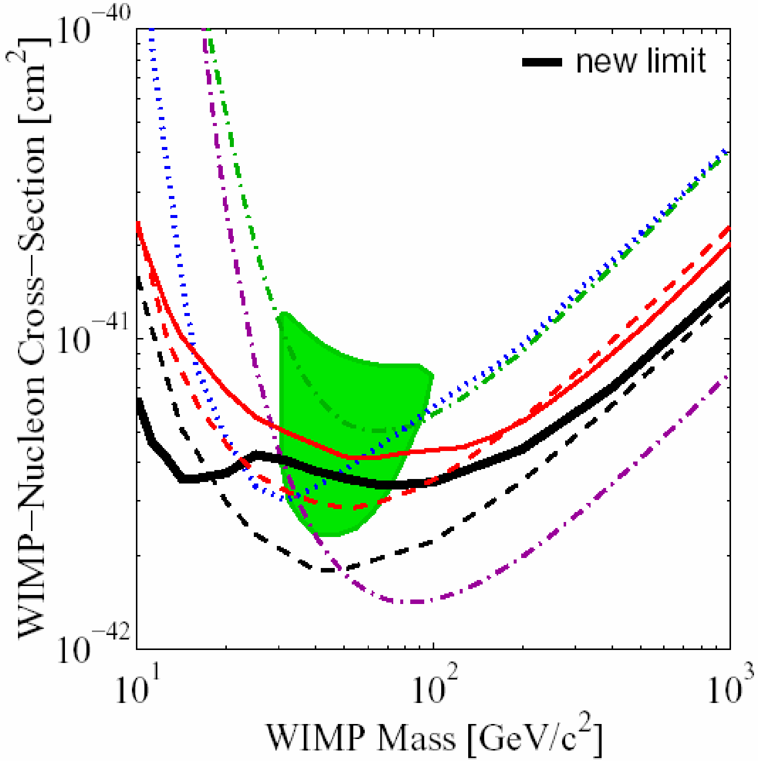
Indirect dark matter searches

The Tevatron at Fermilab

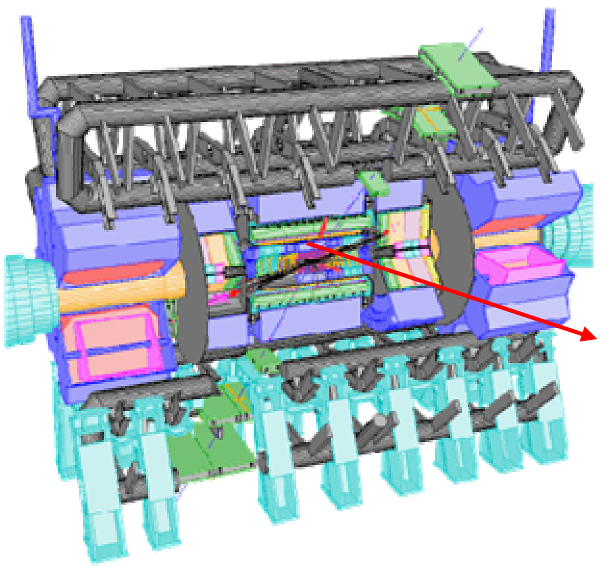
The Large Hadron Collider at CERN

What then?

- Cosmology can't discover SUSY

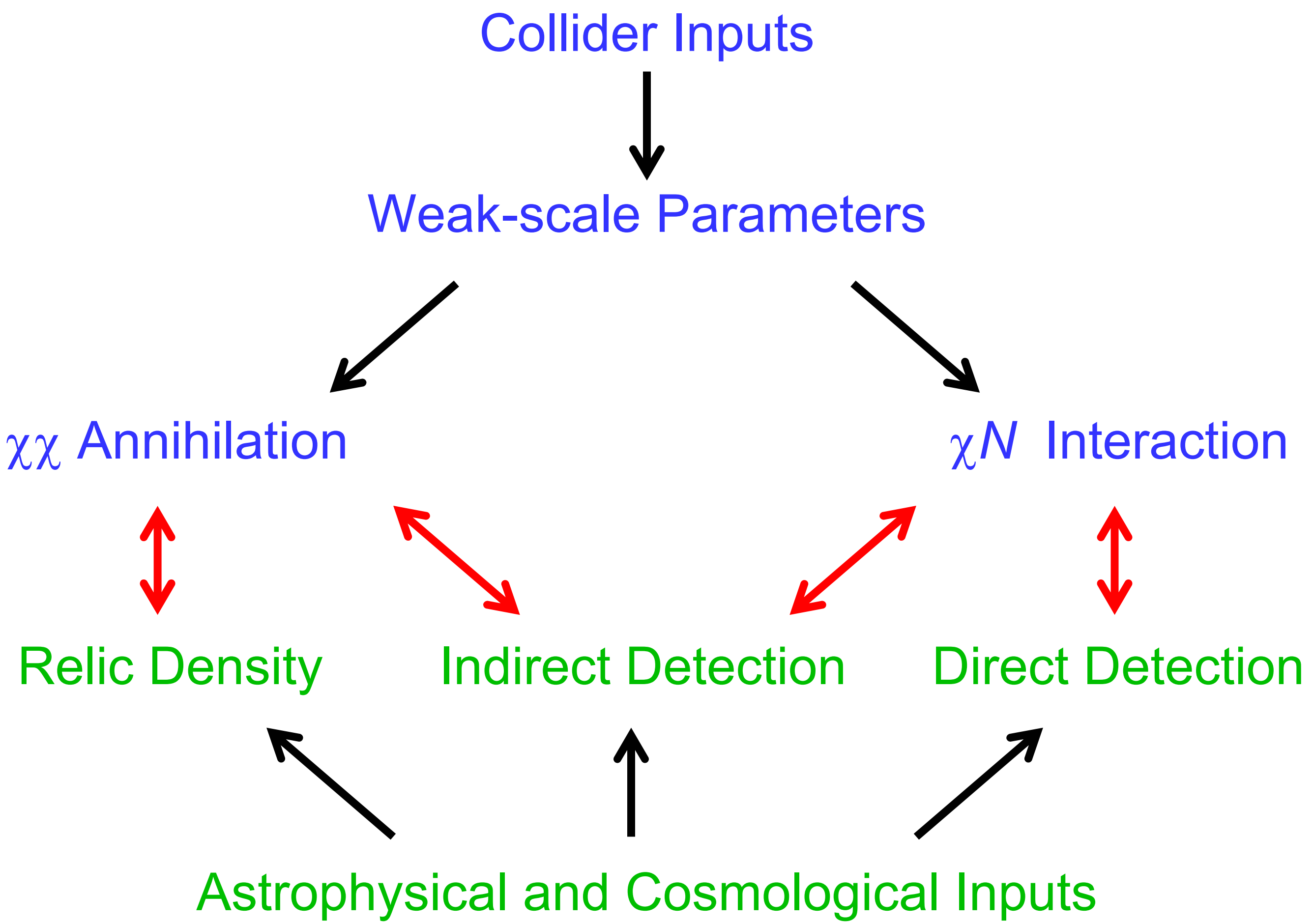


- Particle colliders can't discover DM



Lifetime > 10^{-7} s → 10^{17} s ?

Synergy


Collider Inputs
Weak-scale Parameters
$\chi\chi$ Annihilation
χN Interaction
Relic Density
Indirect Detection
Direct Detection
Astrophysical and Cosmological Inputs

Colliders as Dark Matter Labs

WIMP Dark Matter

- The Tevatron, LHC and International Linear Collider will discover WIMPs and determine their properties at the % level.

- Consistency of

  WIMP properties (particle physics)
  WIMP abundance (cosmology)

  will extend our understanding of the Universe back to

  T = 10 GeV, t = 10 $^{-8}$ s

  (Cf. BBN at T = 1 MeV, t = 1 s)

Colliders as Dark Matter Labs

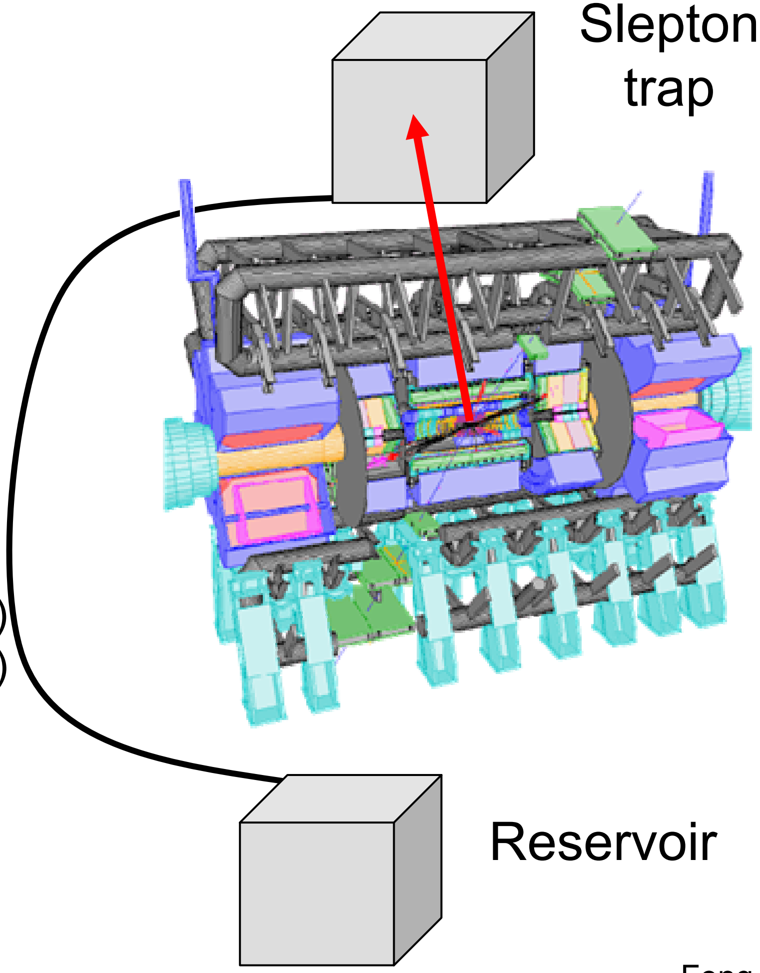
SuperWIMP Dark Matter

Sleptons are heavy, charged, live ~ a month – can be trapped, then moved to a quiet environment to observe decays.

At LHC, ILC can trap about ~1000/yr in 10 kton trap.

Hamaguchi, Kuno, Nakaya, Nojiri (2004)
Feng, Smith (2004)

Lifetime → test gravity at colliders, measure G_N for fundamental particles.



CONCLUSIONS

Extraordinary progress, but a long way from complete understanding

Cosmology + Particle Physics → New particles at the weak scale ~ 100 GeV – 1 TeV

Bright prospects