DARK MATTERS

Graphic: N. Graf

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UCSC Colloquium

WHAT IS THE UNIVERSE MADE OF?

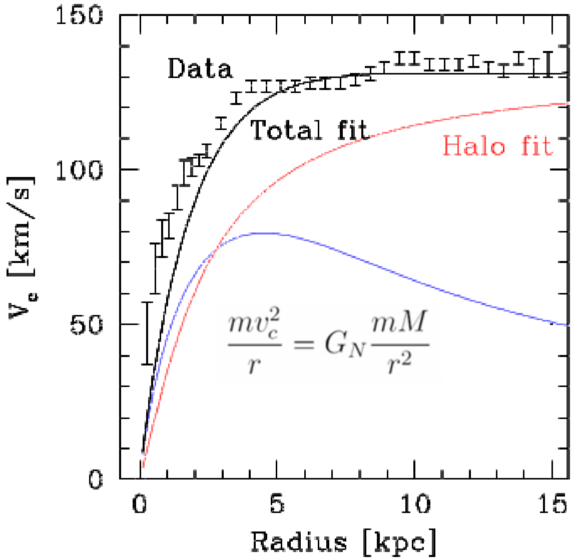
An age old question, but…

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 picture of the Universe

The Evidence

Rotation curves of galaxies and galactic clusters

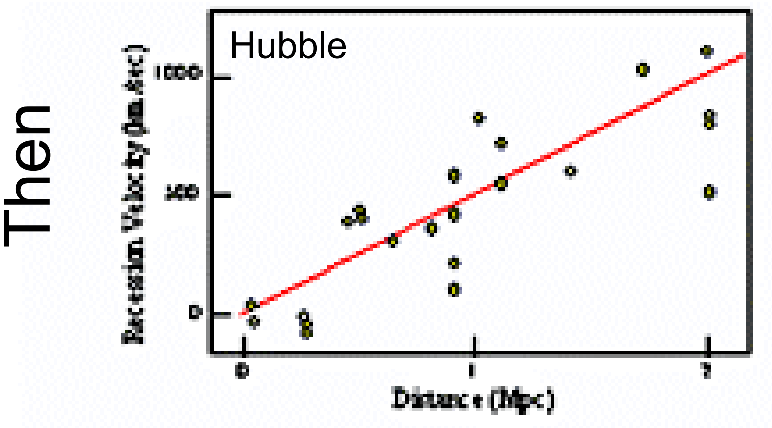


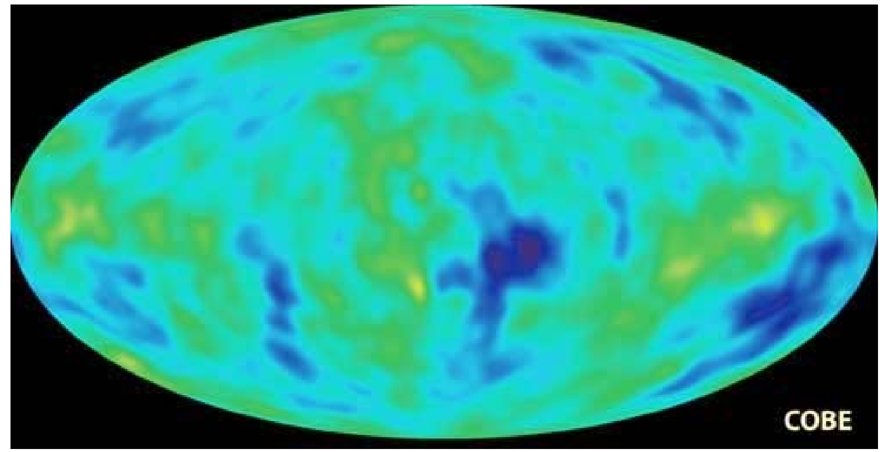
- Expect $v_c \sim r^{-1/2}$ beyond luminous region
- Instead find $v_c \sim$ constant
- Discrepancy resolved by postulating dark matter

Supernovae

Cosmic Microwave Background

Then

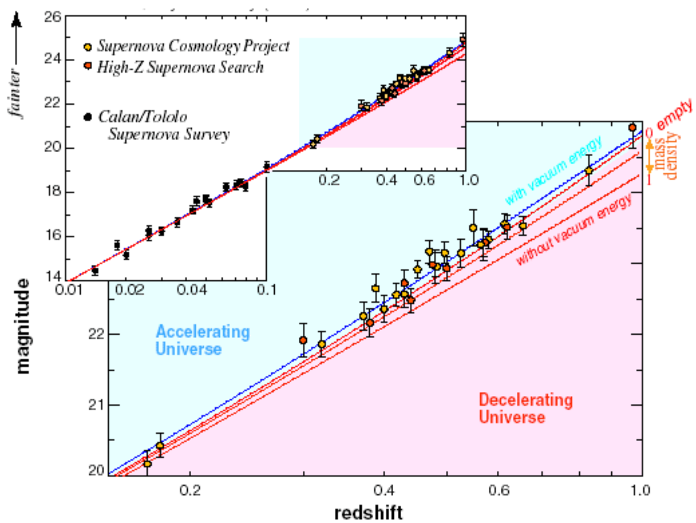


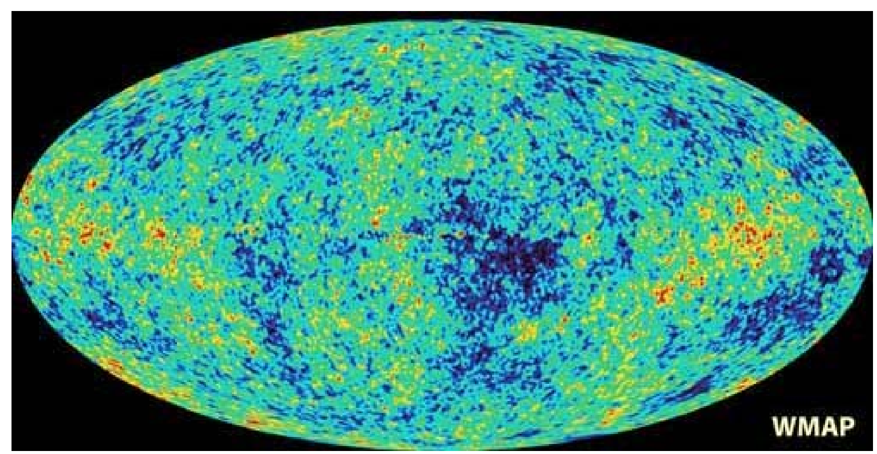


Constrains $\Omega_\Lambda - \Omega_M$

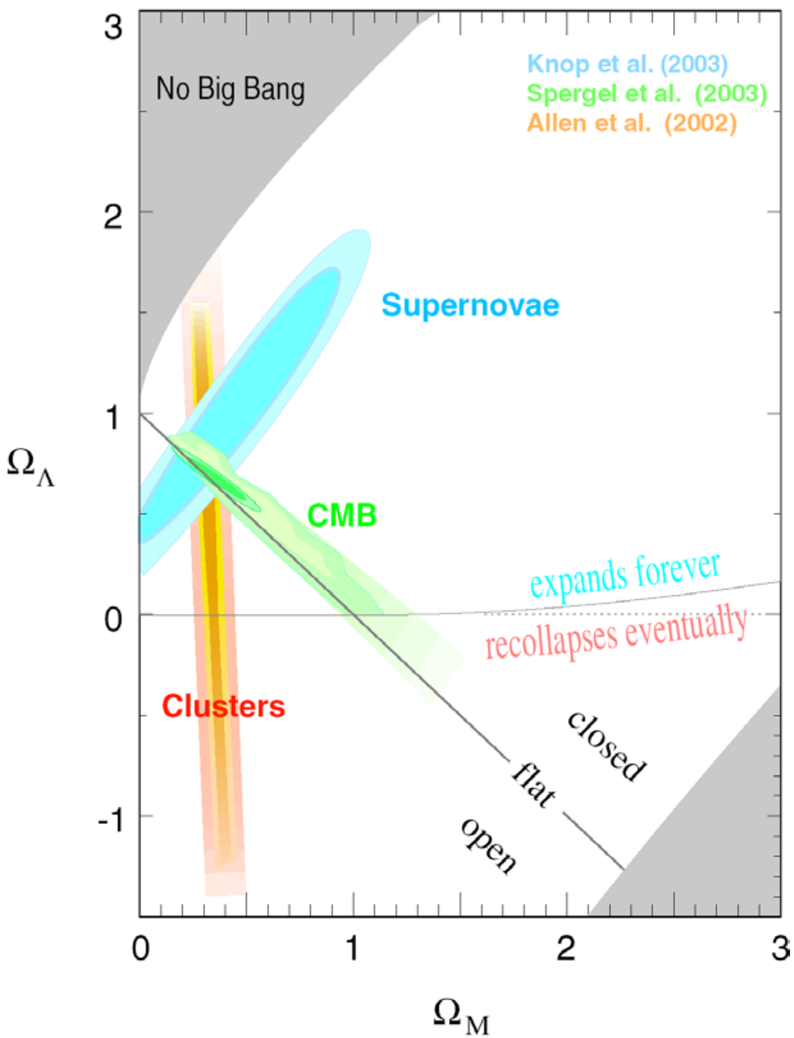
Constrains $\Omega_\Lambda + \Omega_M$

Now





Synthesis



- Remarkable agreement

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

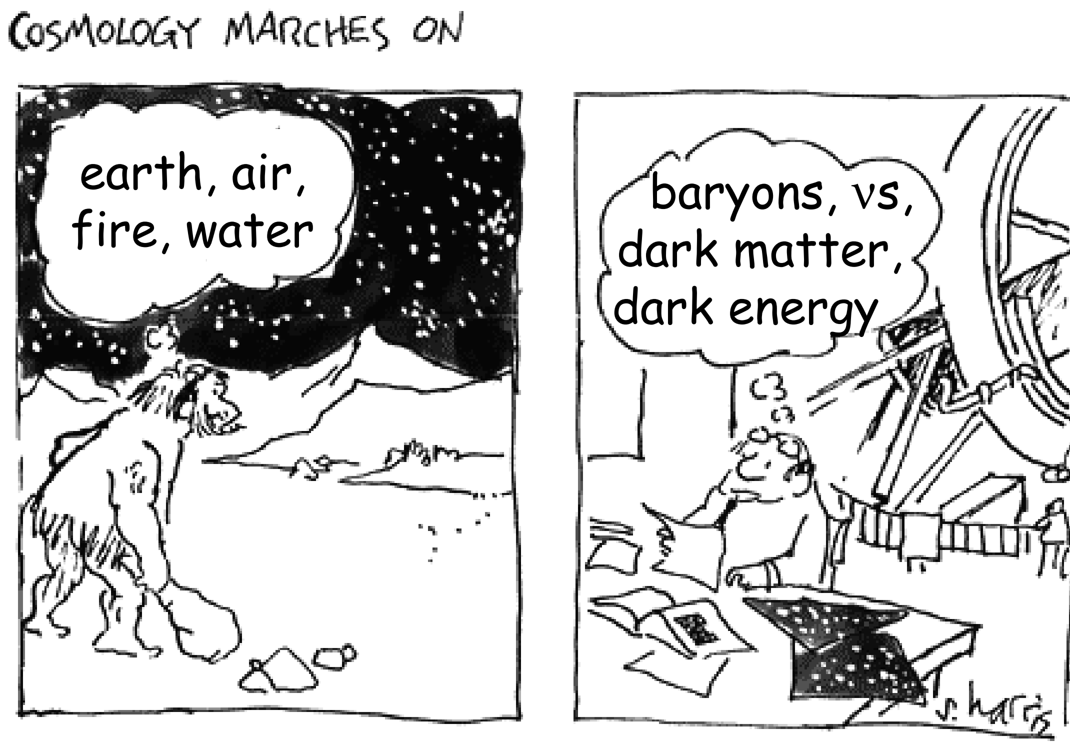
- Remarkable precision (~10%)

- 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 are Dark Matter and Dark Energy?

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

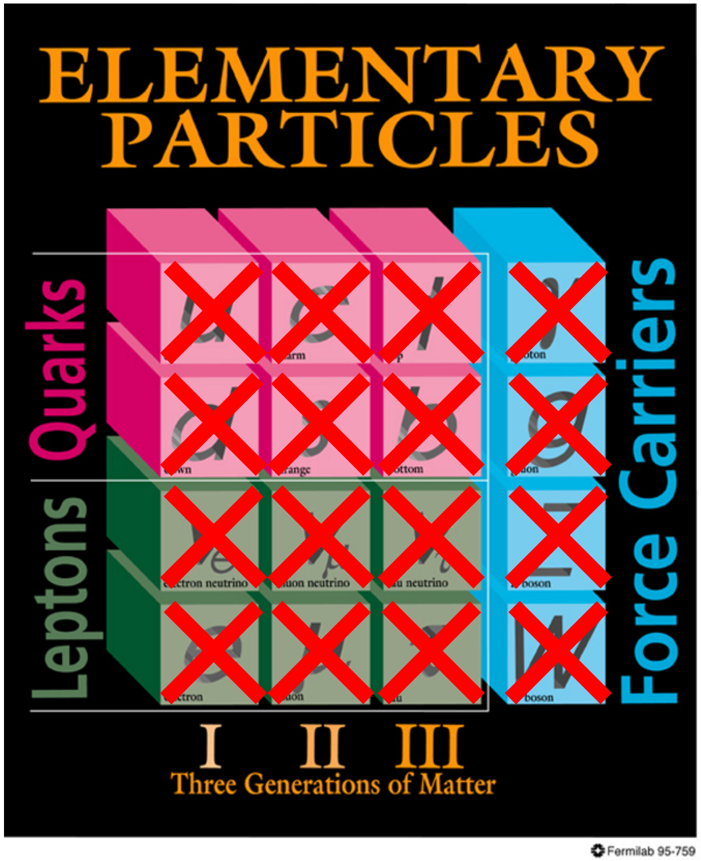
Dark Matter

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

Dark Energy

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

DARK MATTER



Known DM properties

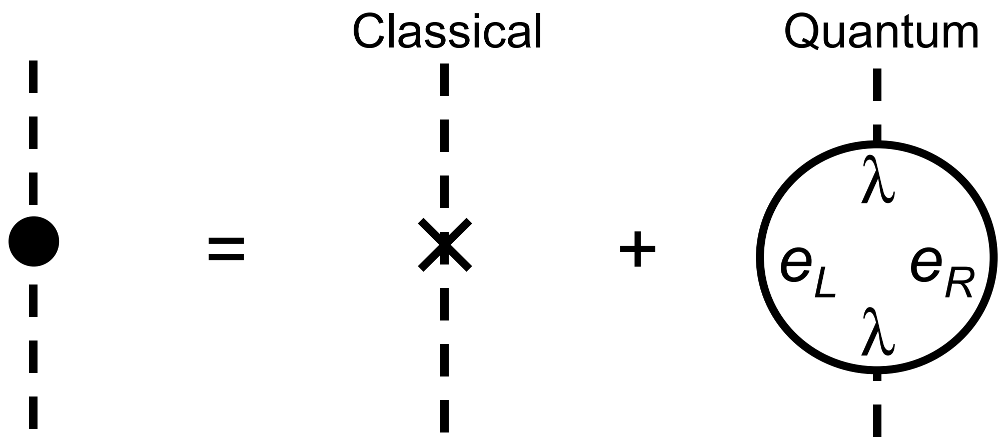
- Stable
- Non-baryonic
- Cold

DM: precise, unambiguous evidence
for new particles

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, new particles are required to understand the weak force

Weak Force and Higgs Boson



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

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

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

Cosmological Implications

(1) Initially, new particle is in thermal equilibrium:

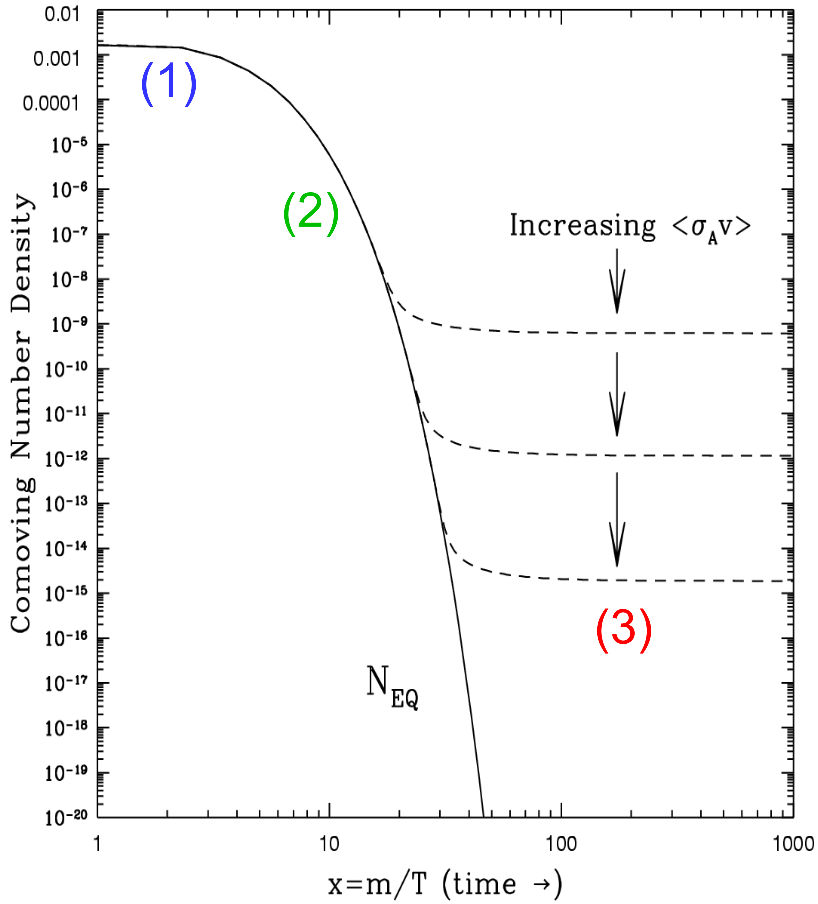
$$\chi\chi \leftrightarrow \bar{f} f$$

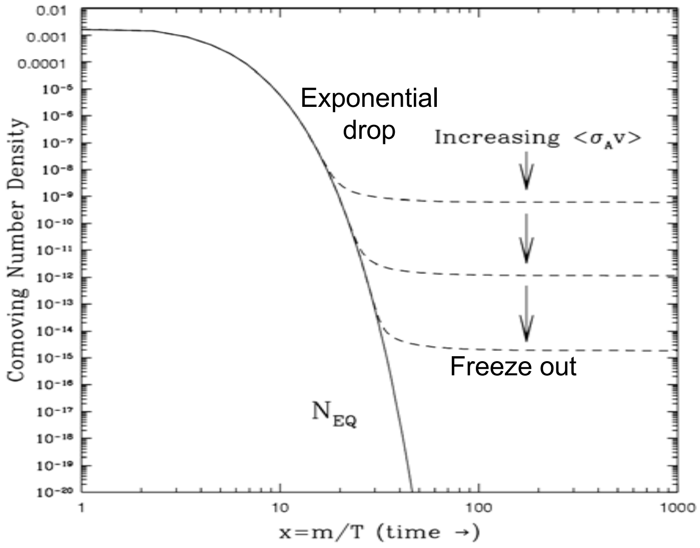
(2) Universe cools:

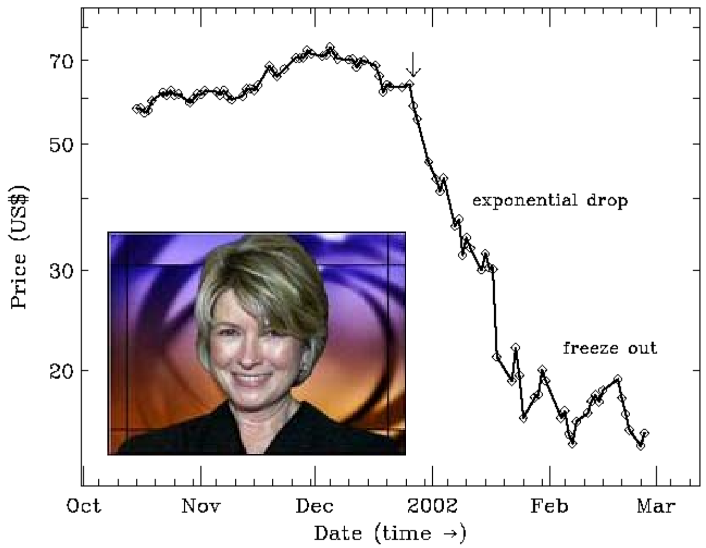
$$N = N_{EQ} \sim e^{-m/T}$$

(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!

- Domestic diva Martha Stewart sells ImClone stock – the next day, stock plummets

Coincidences? Maybe, but worth serious investigation!

NOTE

- I've assumed the new particle is stable

- Problems (proton decay, extra particles, …)

  ↕

  Discrete symmetry

  ↕

  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

Supersymmetry: extends rotations/boosts/translations, 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)

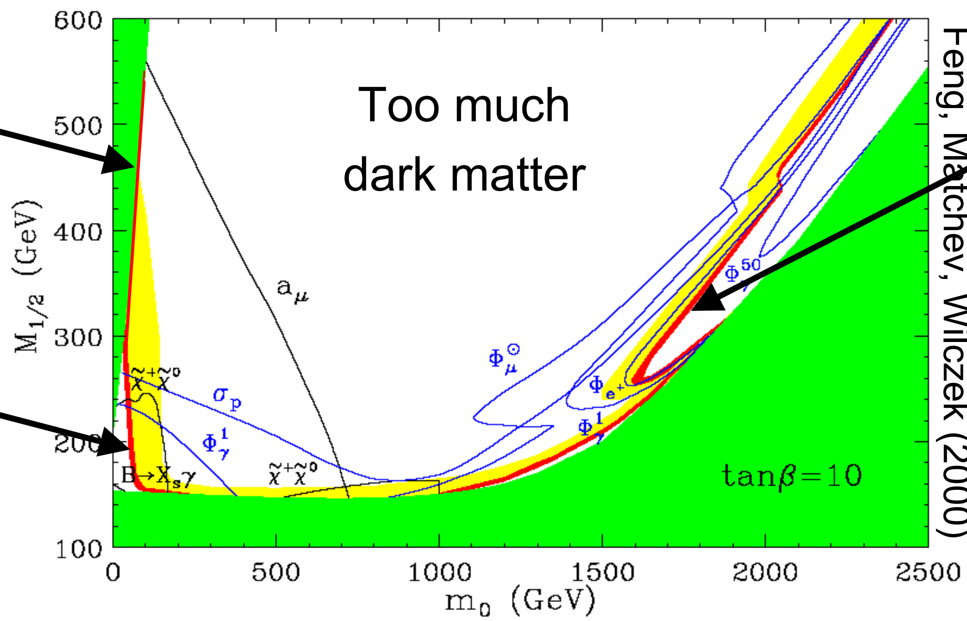
Ω_{DM} = 23% ± 4% stringently constrains models

Co-annihilation region

Bulk region

Too much dark matter

Focus point region



Feng, Matchev, Wilczek (2000)

Yellow: pre-WMAP

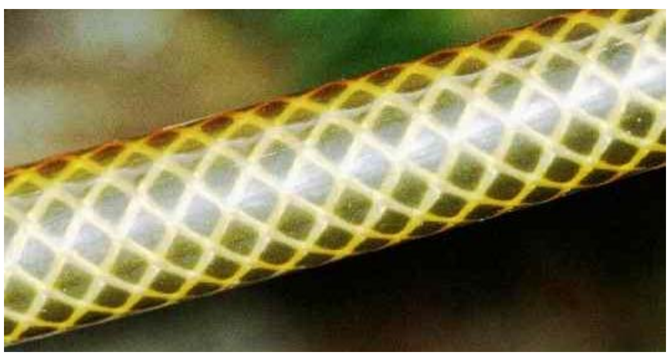
Red: post-WMAP

Cosmology highlights certain regions, detection strategies

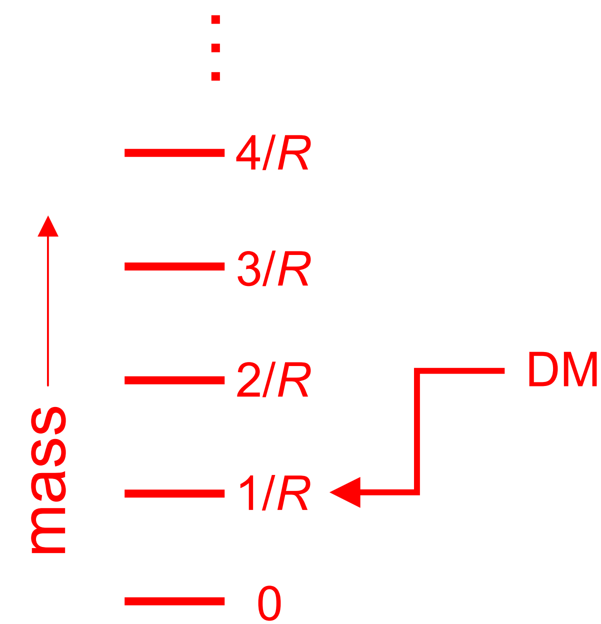
Extra Dimensional Dark Matter

Servant, Tait (2002)   Cheng, Feng, Matchev (2002)

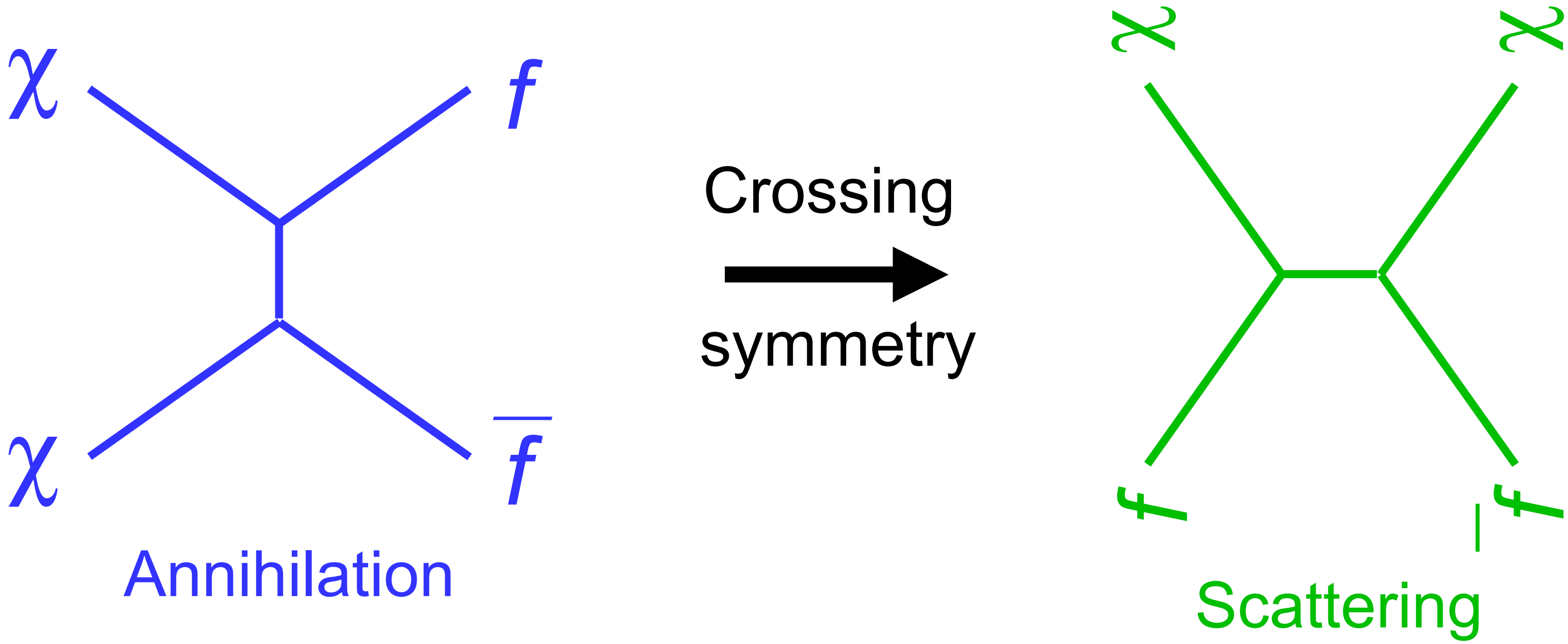
- Extra spatial dimensions could be curled up into small circles.



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



WIMP Detection: No-Lose Theorem

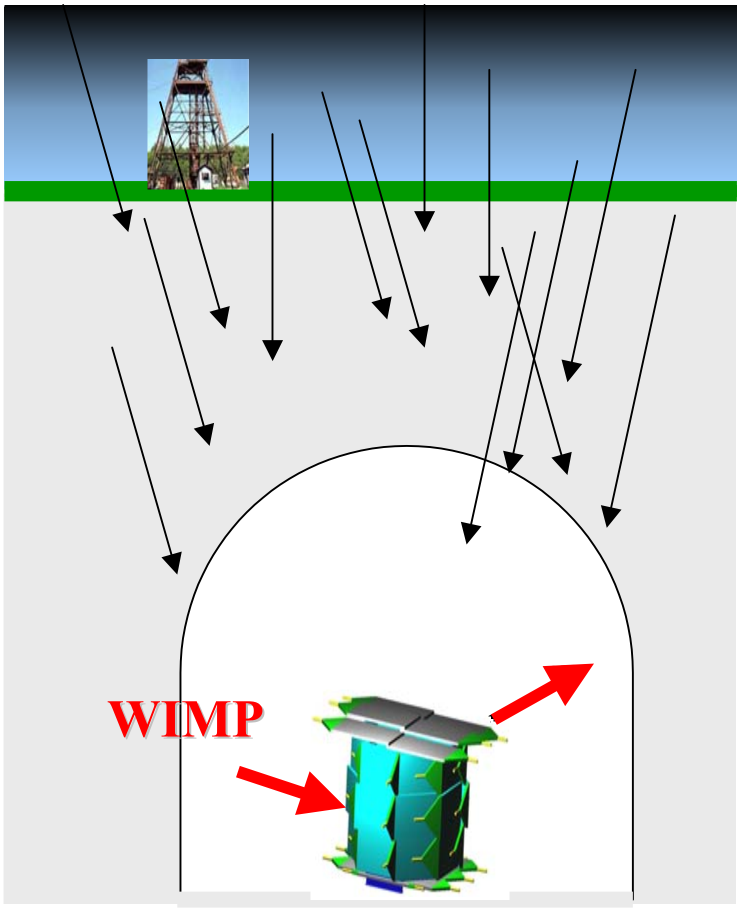


Correct relic density → Efficient annihilation then

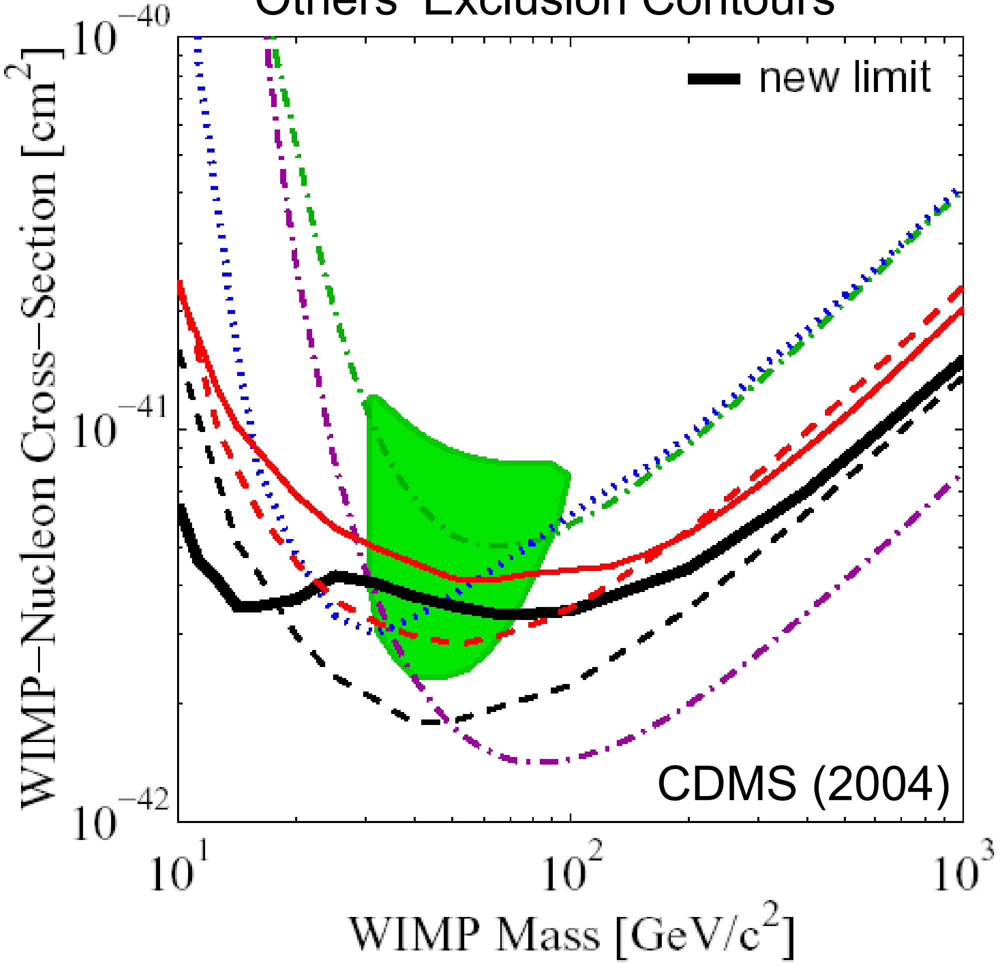
→ Efficient annihilation now

→ Efficient scattering now

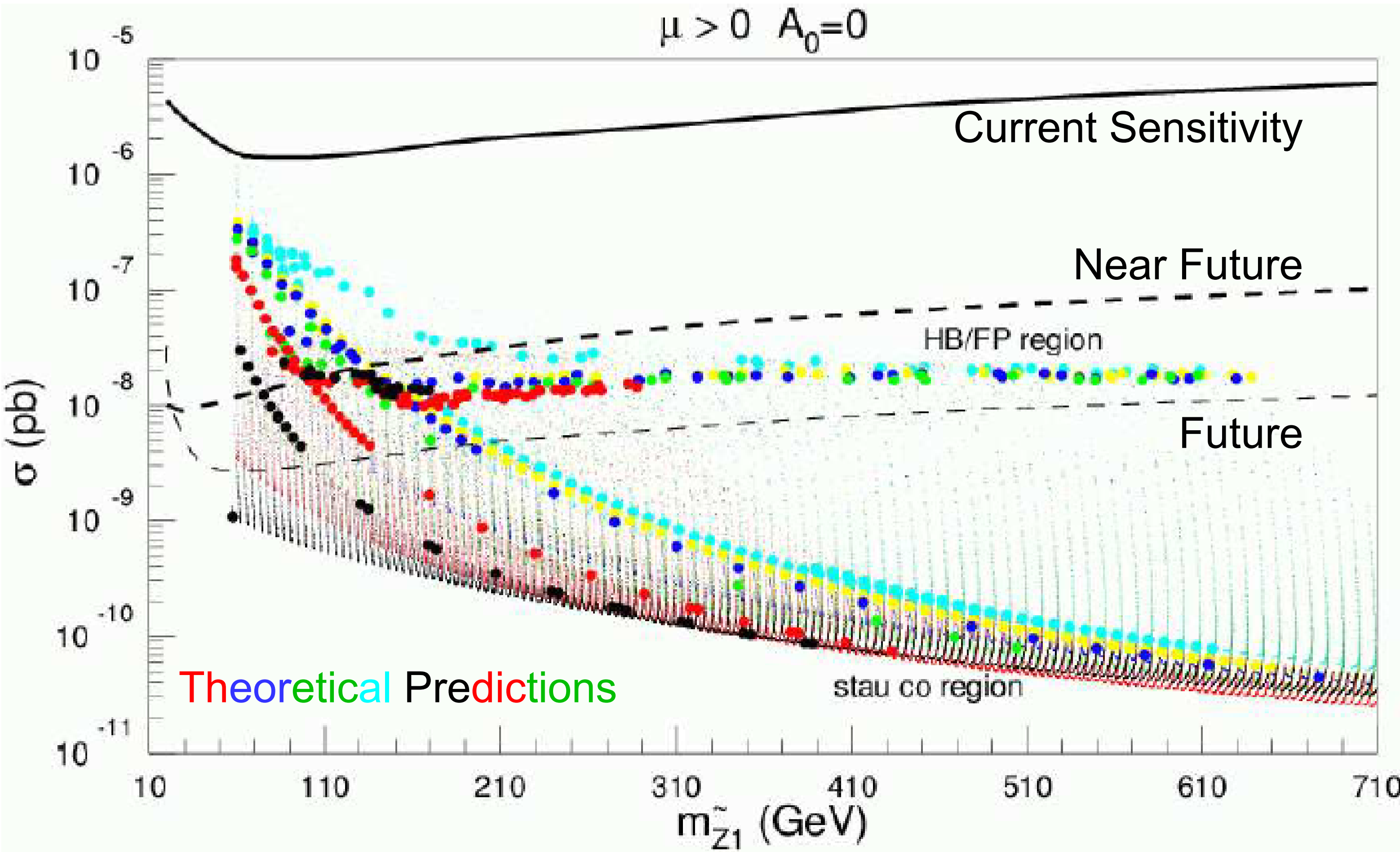
Direct Detection



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 ________________ .
particles an experiment

Dark Matter annihilates in __the galactic center__ to
a place

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

Typically

$$\chi\chi \not\rightarrow \gamma\gamma \,,$$

so $$\chi\chi \rightarrow \bar{ff} \rightarrow \gamma$$

HESS: ~ 1 TeV signal

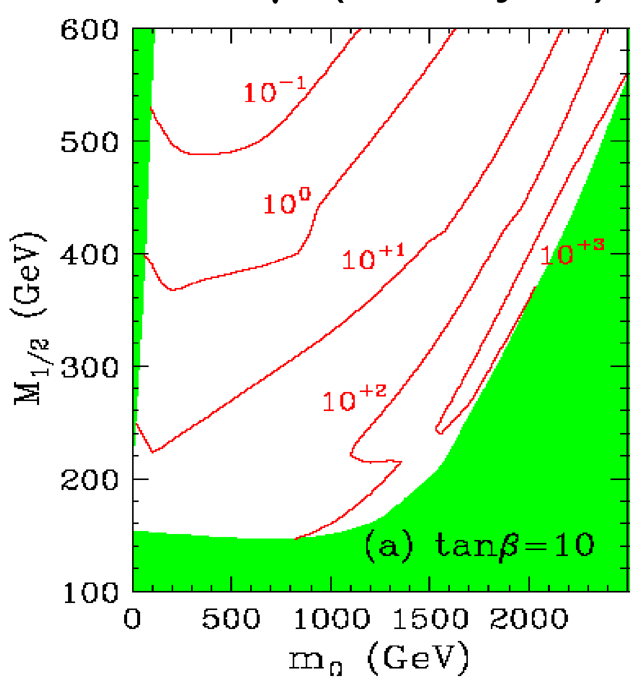
If DM, m_χ ~ 12 TeV

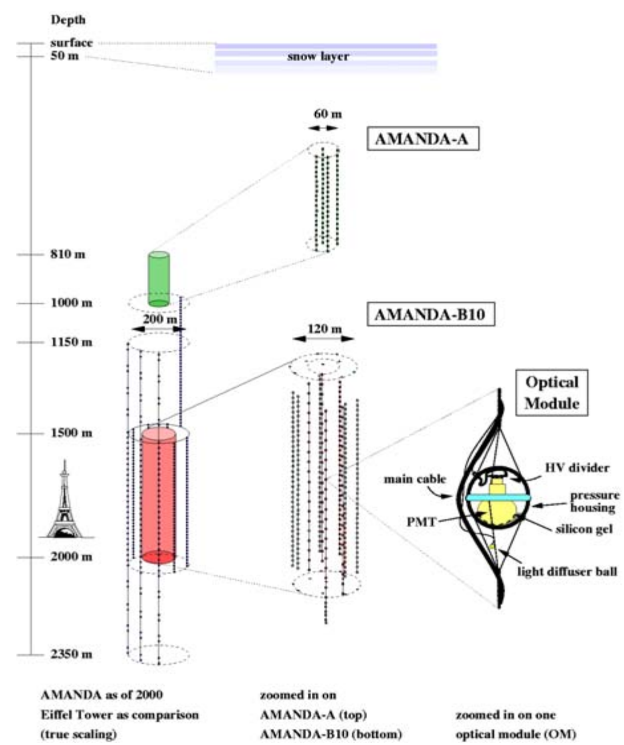
Horns (2004)

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

__neutrinos__ , which are detected by __AMANDA, IceCube__ .
some particles an experiment

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

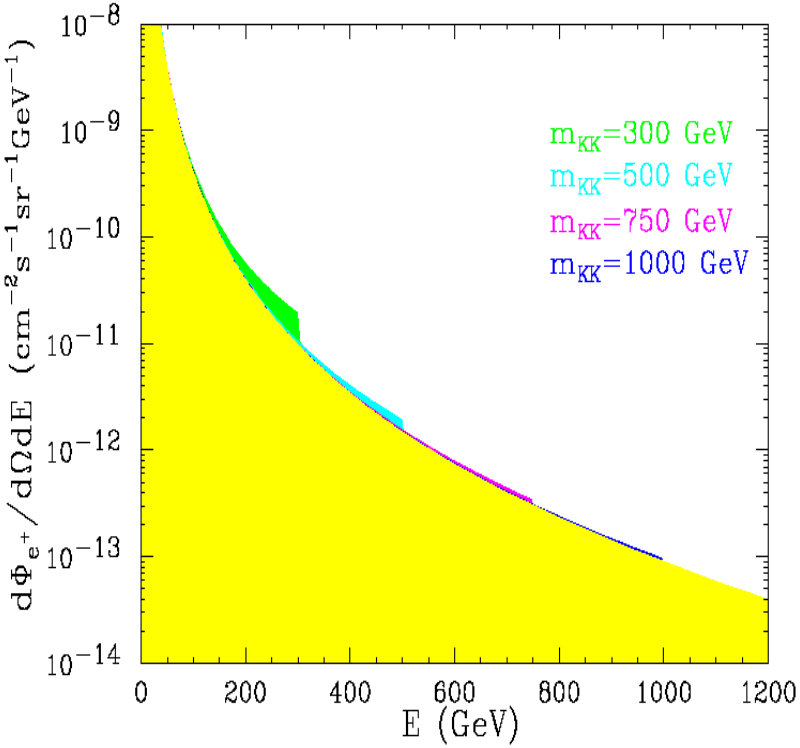


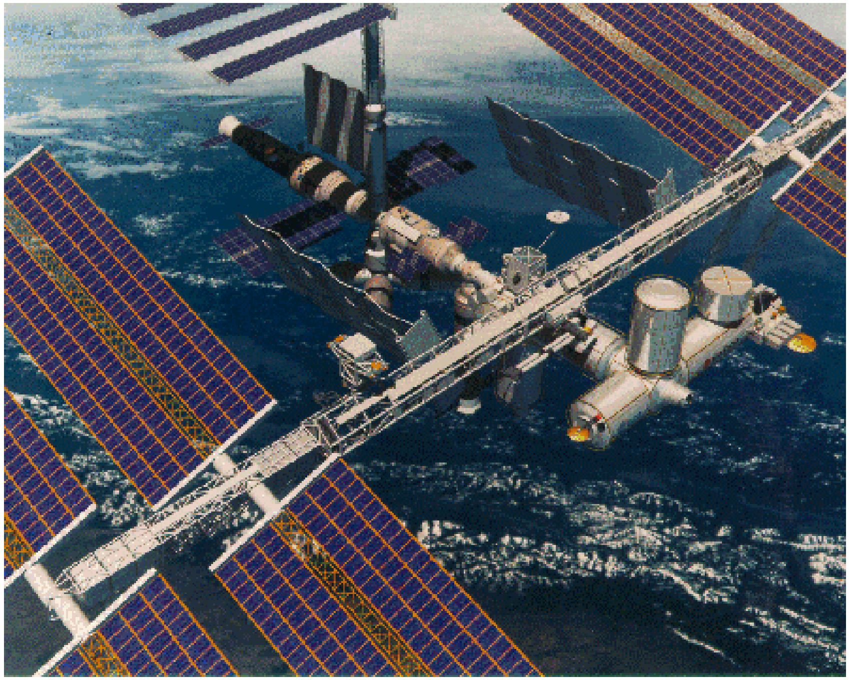


AMANDA in the Antarctic Ice

Dark Matter annihilates in ______the halo______ to
a place

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





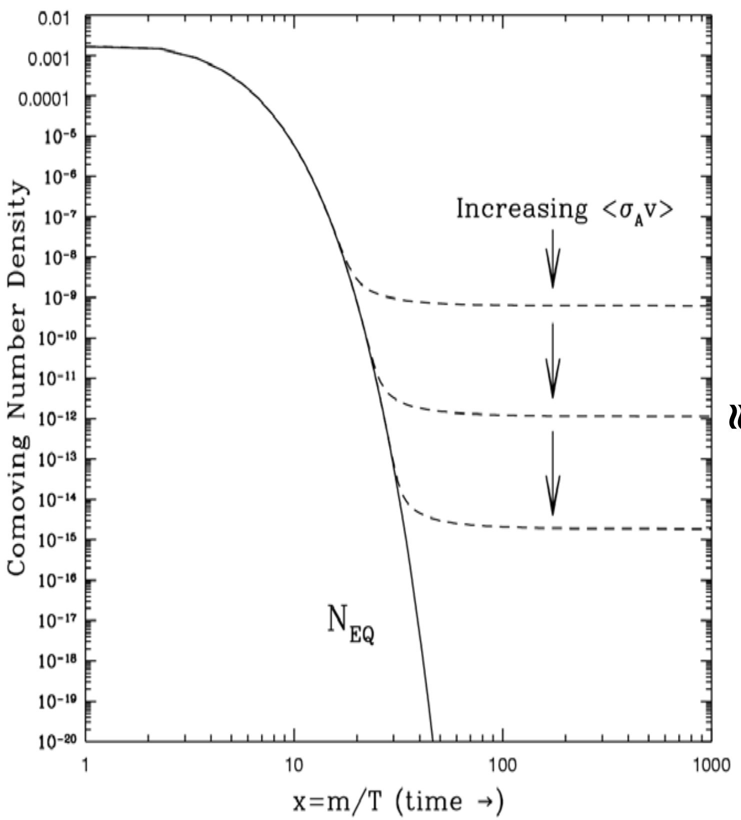
SuperWIMP Dark Matter

Feng, Rajaraman, Takayama (2003)

- All of these signals rely on DM having weak force interactions. Is this required?
- No – the only required DM interactions are gravitational (much weaker than weak).
- 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 $\tilde{G}$

  Pagels, Primack (1982)

- What if the $\tilde{G}$ is the lightest superpartner?

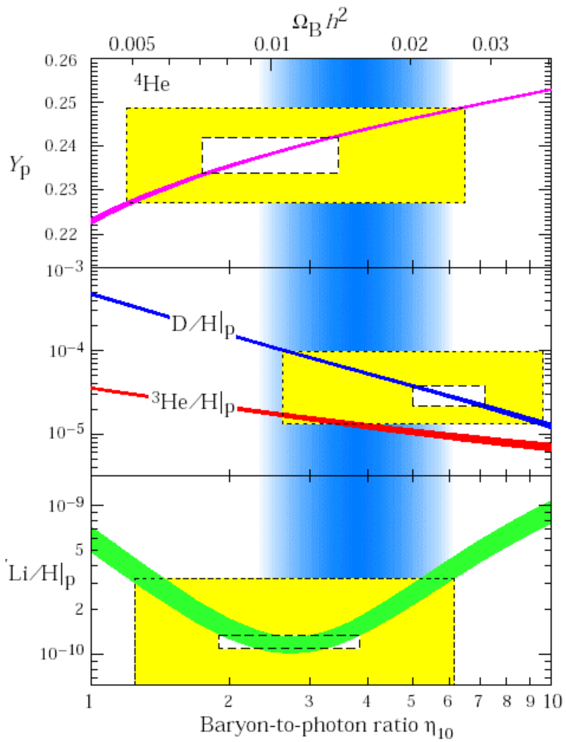
WIMP → $\tilde{G}$ $\qquad M_{Pl}^2/M_W^3$ ~ month

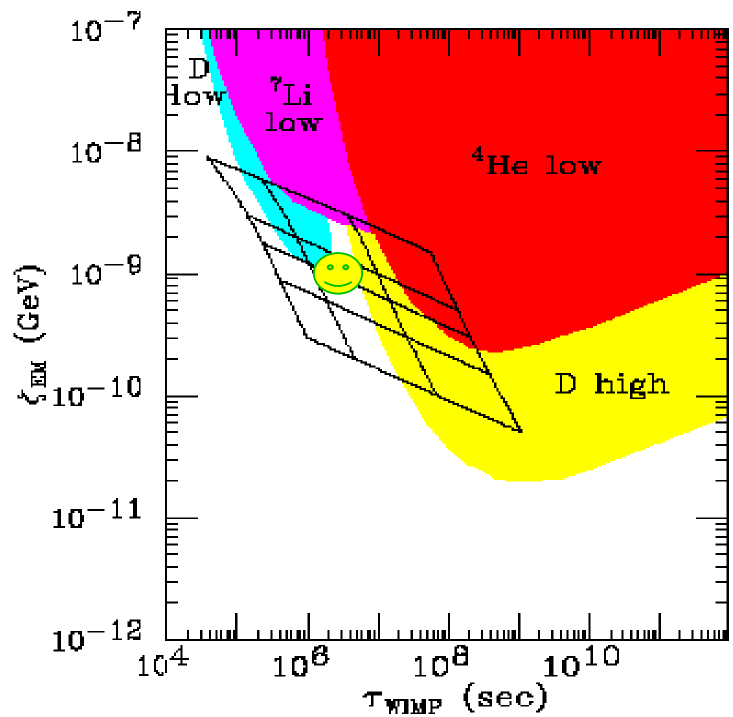
- A month passes…then all WIMPs decay to gravitinos

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 $\tilde{l} \to \tilde{G}\, l$ → 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 in this decade:

Direct dark matter searches

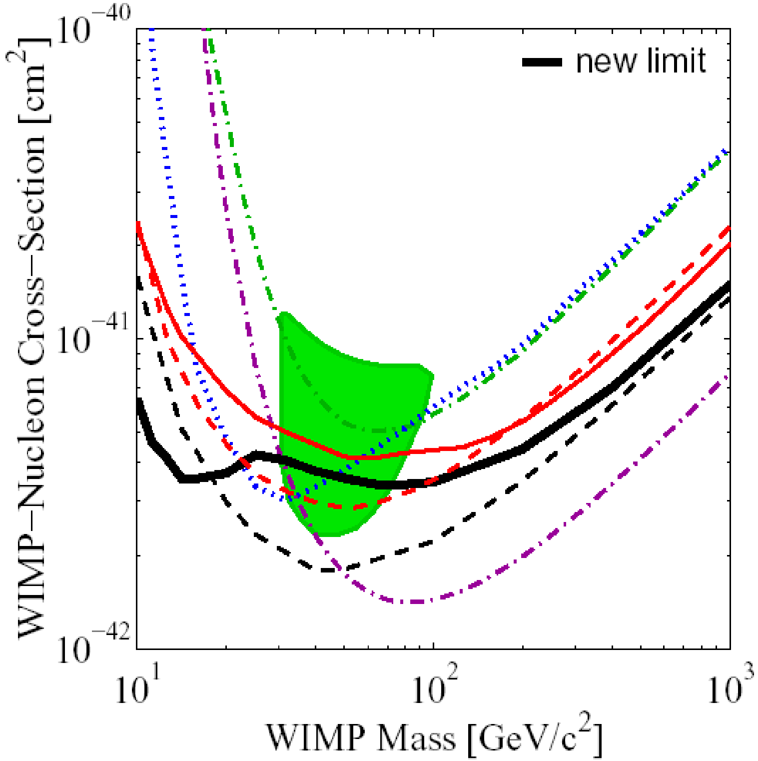
Indirect dark matter searches

The Tevatron at Fermilab

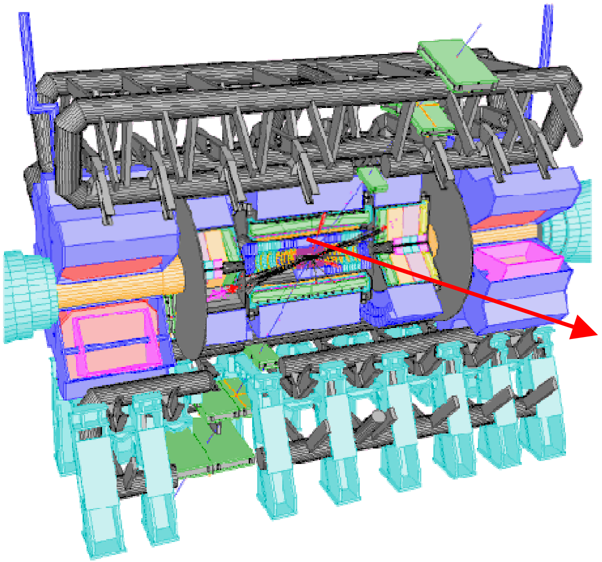
The Large Hadron Collider at CERN (2008)

What then?

- Cosmology can't discover SUSY

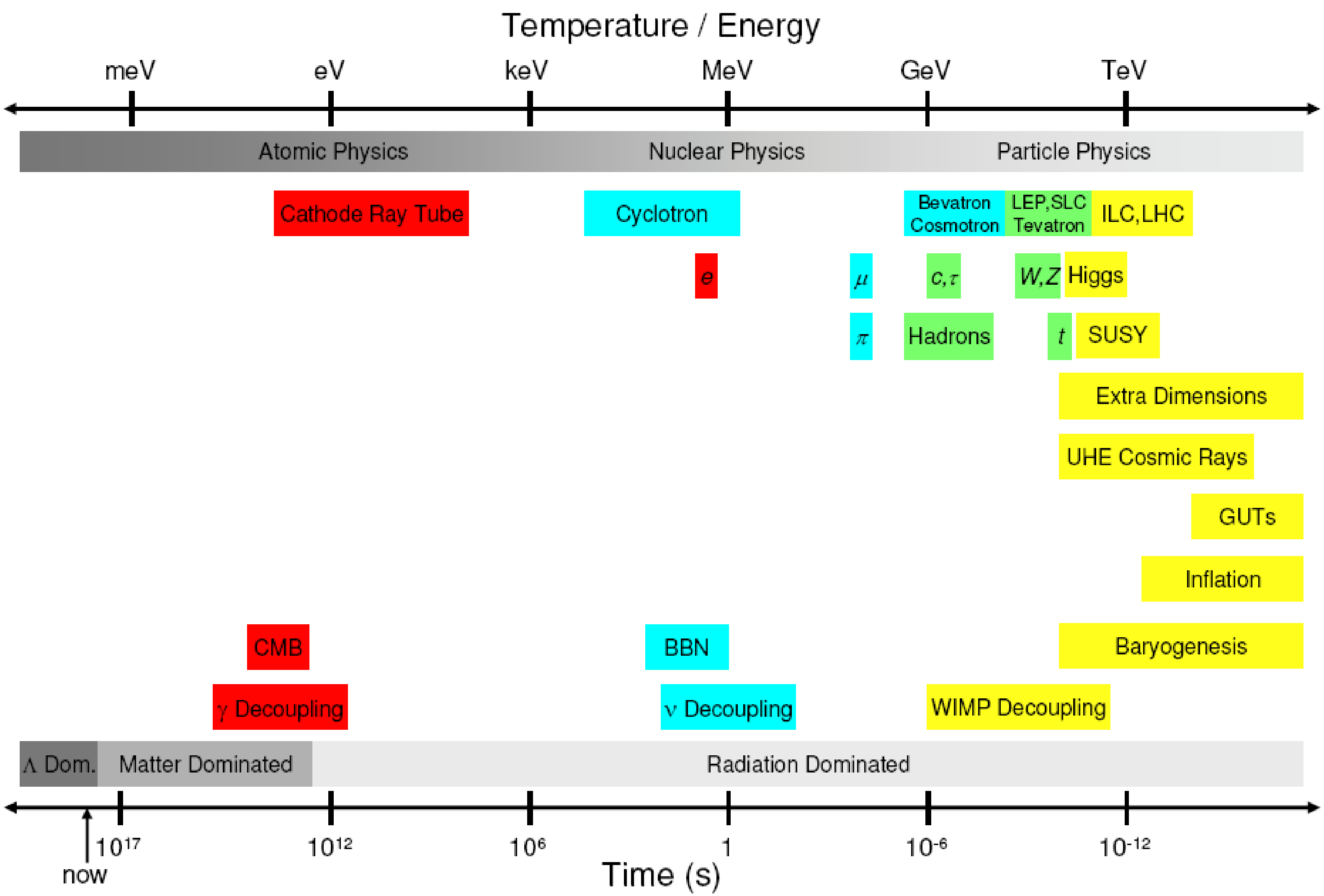


- Particle colliders can't discover DM



Lifetime > 10^{-7} s → 10^{17} s ?

SYNERGY


Temperature / Energy
meV
eV
keV
MeV
GeV
TeV
Atomic Physics
Nuclear Physics
Particle Physics
Cathode Ray Tube
Cyclotron
Bevatron Cosmotron
LEP,SLC Tevatron
ILC,LHC
e
μ
c,τ
W,Z
Higgs
π
Hadrons
t
SUSY
Extra Dimensions
UHE Cosmic Rays
GUTs
Inflation
CMB
BBN
Baryogenesis
γ Decoupling
ν Decoupling
WIMP Decoupling
Λ Dom.
Matter Dominated
Radiation Dominated
now
10^17
10^12
10^6
1
10^-6
10^-12
Time (s)

Colliders as WIMP Labs

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

- Consistency of

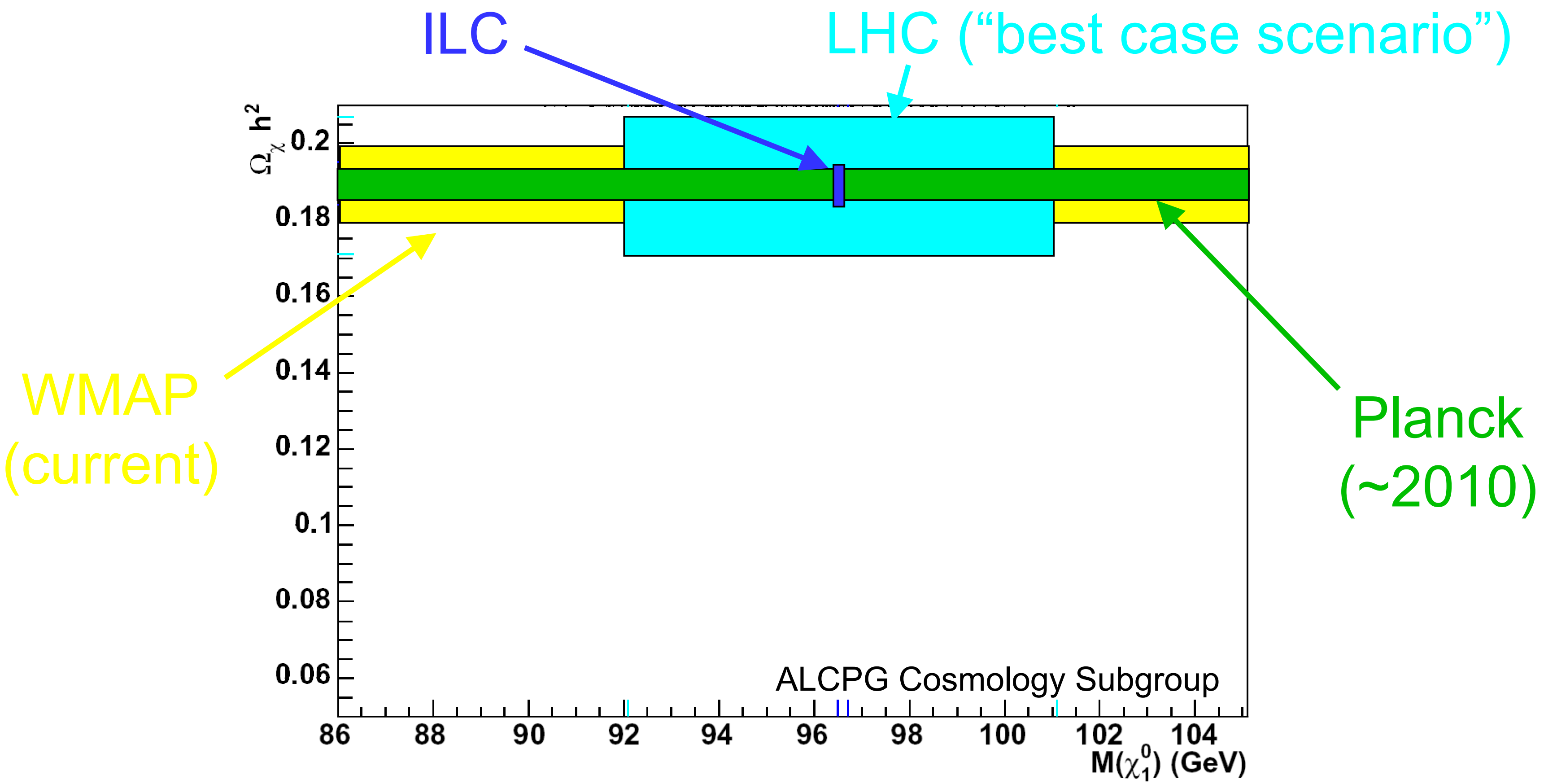
WIMP properties (particle physics)
WIMP abundance (cosmology)

will extend our understanding of the Universe back to

T = 10 GeV, t = 1 ns

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

RELIC DENSITY DETERMINATIONS



Parts per mille agreement for Ω_χ → discovery of dark matter

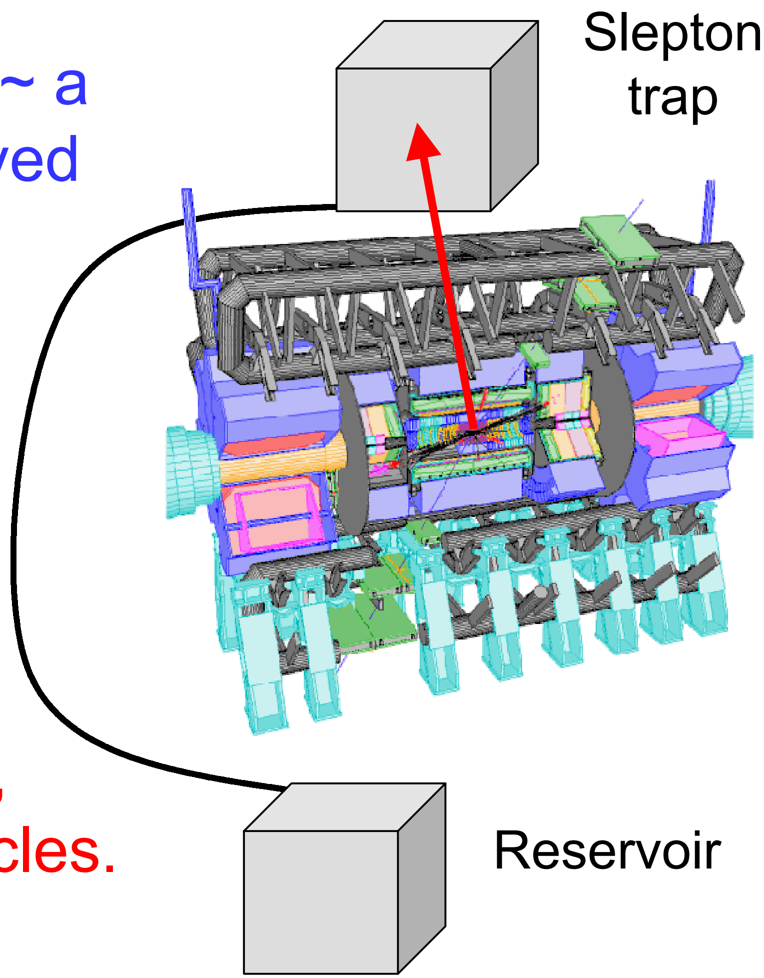
Colliders as SuperWIMP Labs

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

LHC, ILC can trap as many as ~10,000/yr in 10 kton trap.

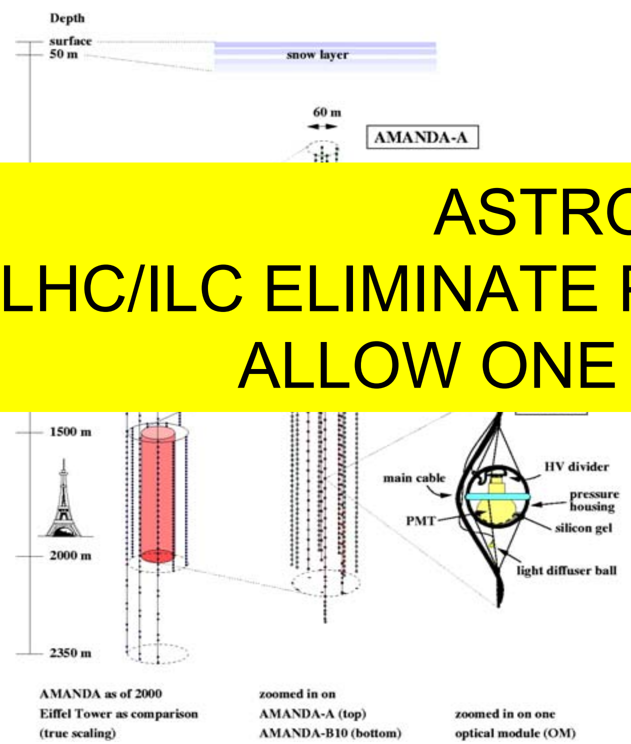
Hamaguchi, Kuno, Nakaya, Nojiri (2004)
Feng, Smith (2004)

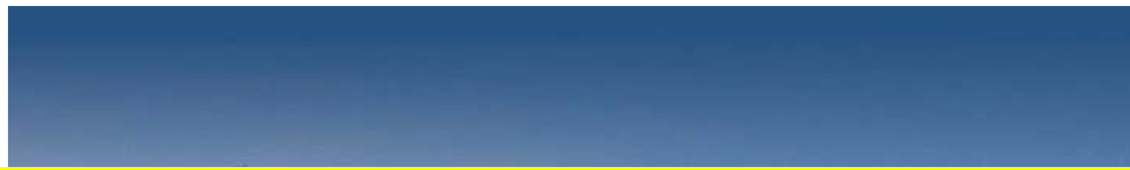
Lifetime → test gravity at colliders, measure G_N for fundamental particles.

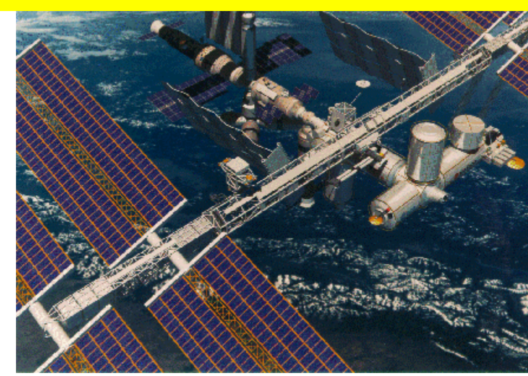


Mapping the Dark Universe

Once dark matter is identified, detection experiments tell us about dark matter distributions







ASTROPHYSICS VIEWPOINT:
LHC/ILC ELIMINATE PARTICLE PHYSICS UNCERTAINTIES,
ALLOW ONE TO DO REAL ASTROPHYSICS

CONCLUSIONS

Extraordinary progress, but a long way from complete understanding

Cosmology + Particle Physics →
New particles at 1 TeV: just around the corner

Bright prospects!