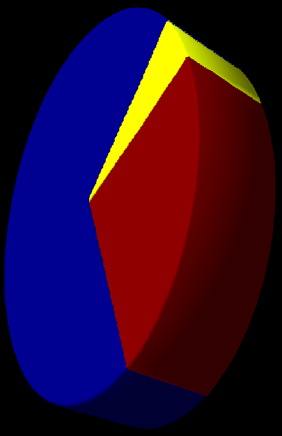
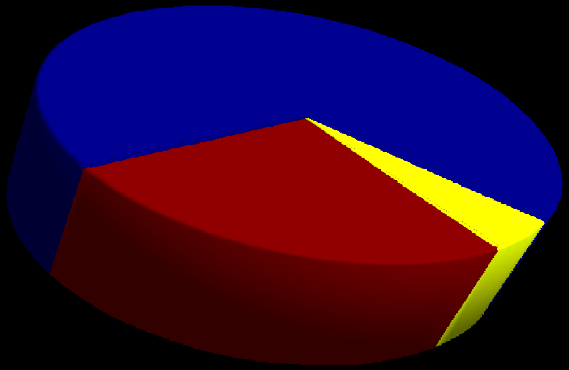


The Linear Collider and the Preposterous Universe

Sean Carroll, University of Chicago



5% Ordinary Matter
25% Dark Matter
70% Dark Energy

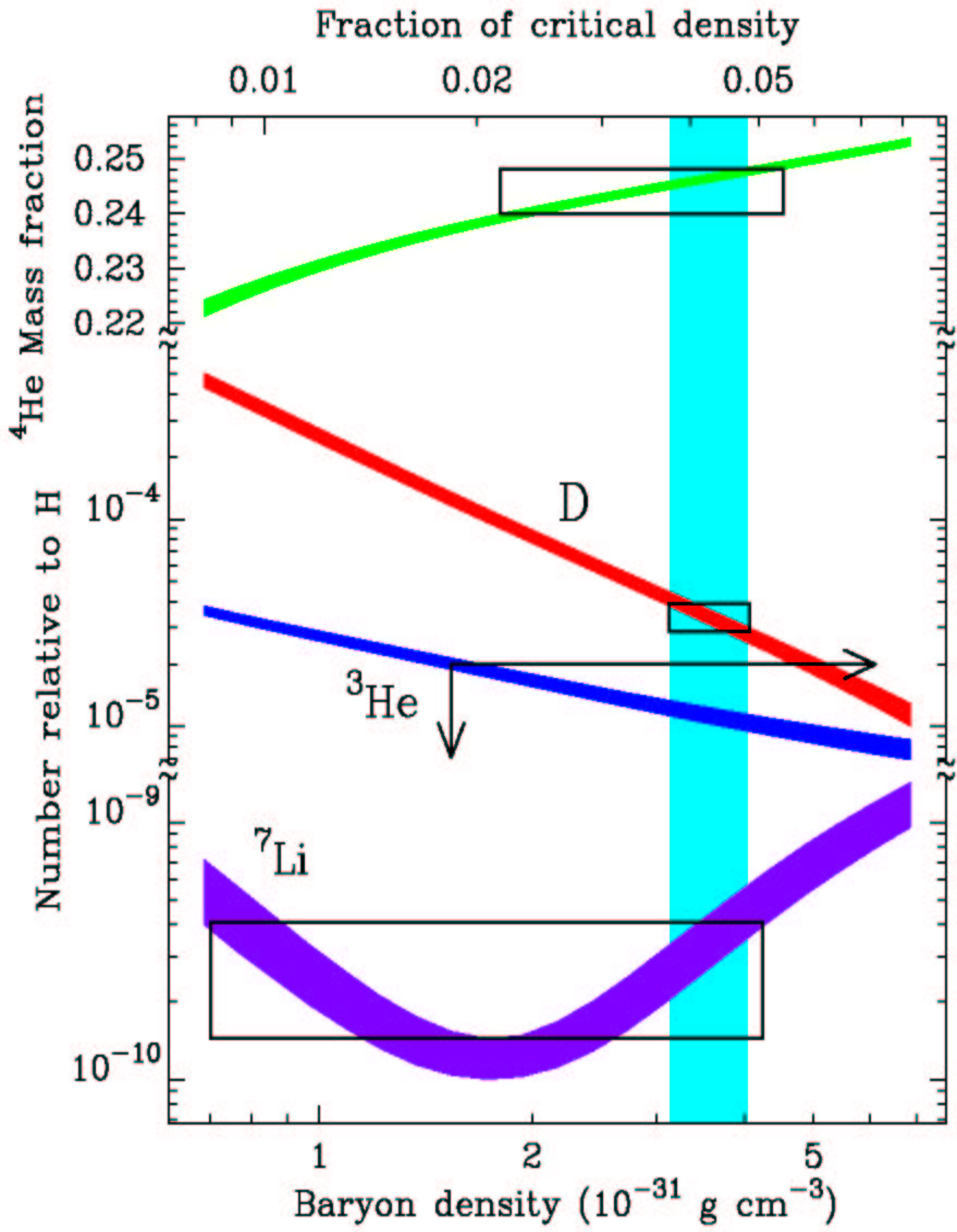
Why do these components dominate our universe? Would an Apollonian collider (linear $e^- e^+$) help us find out in a way that a Dyonisian (hadron) collider wouldn't?

Consider first ordinary matter (baryons).

Big−Bang Nucleosynthesis depends sensitively on the baryon/photon ratio, and we know how many photons there are, so we can constrain the baryon density.

Result:

$$\Omega_{\text{Baryon}} \approx 0.05$$

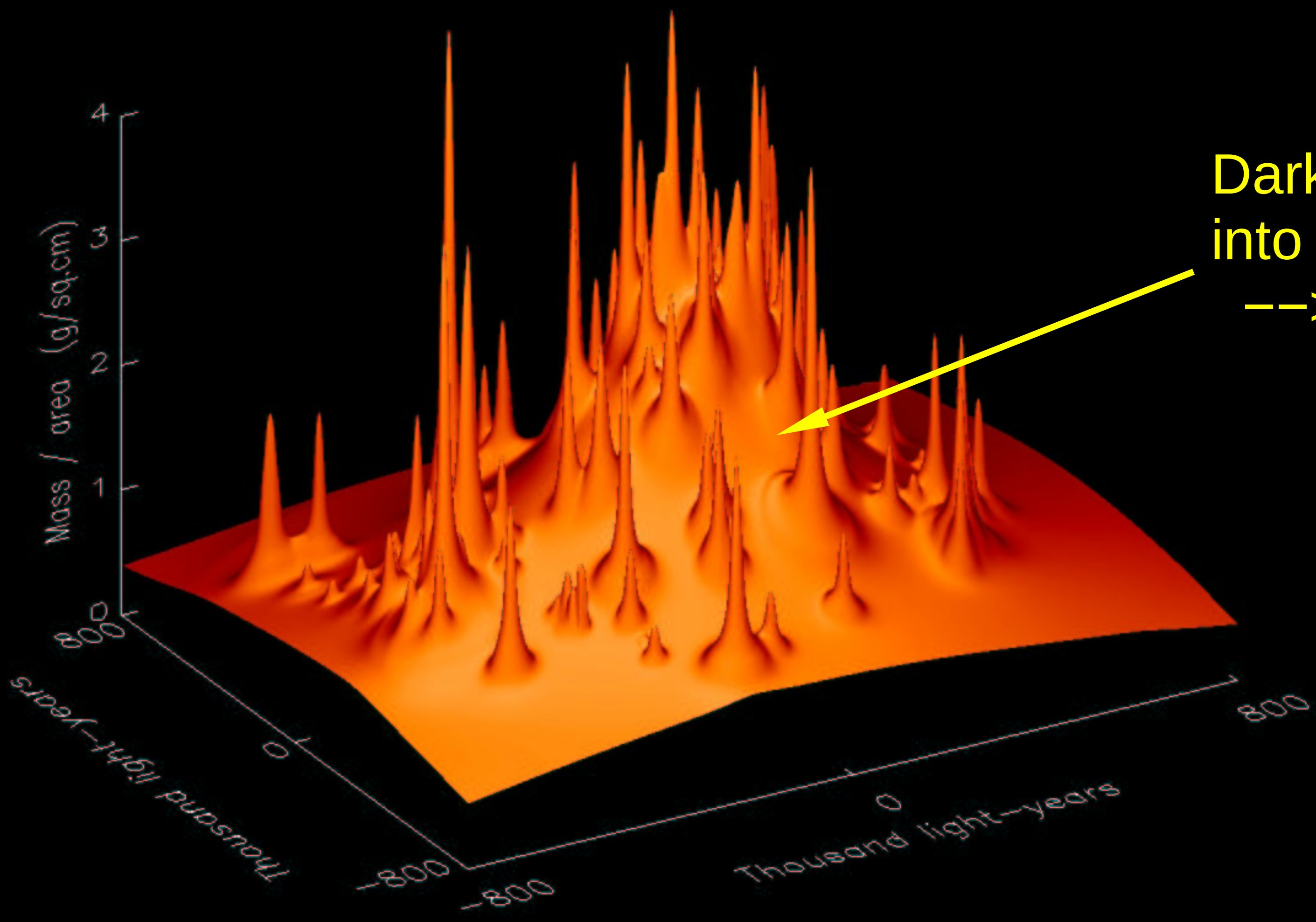


[Burles, Nollett & Turner]

Evidence for non−baryonic dark matter comes from many sources. One example: gravitational lensing.

Hubble Space Telescope image of a cluster of galaxies.

Mass reconstruction of the cluster.



Dark matter falls
into potential wells;
--> particles

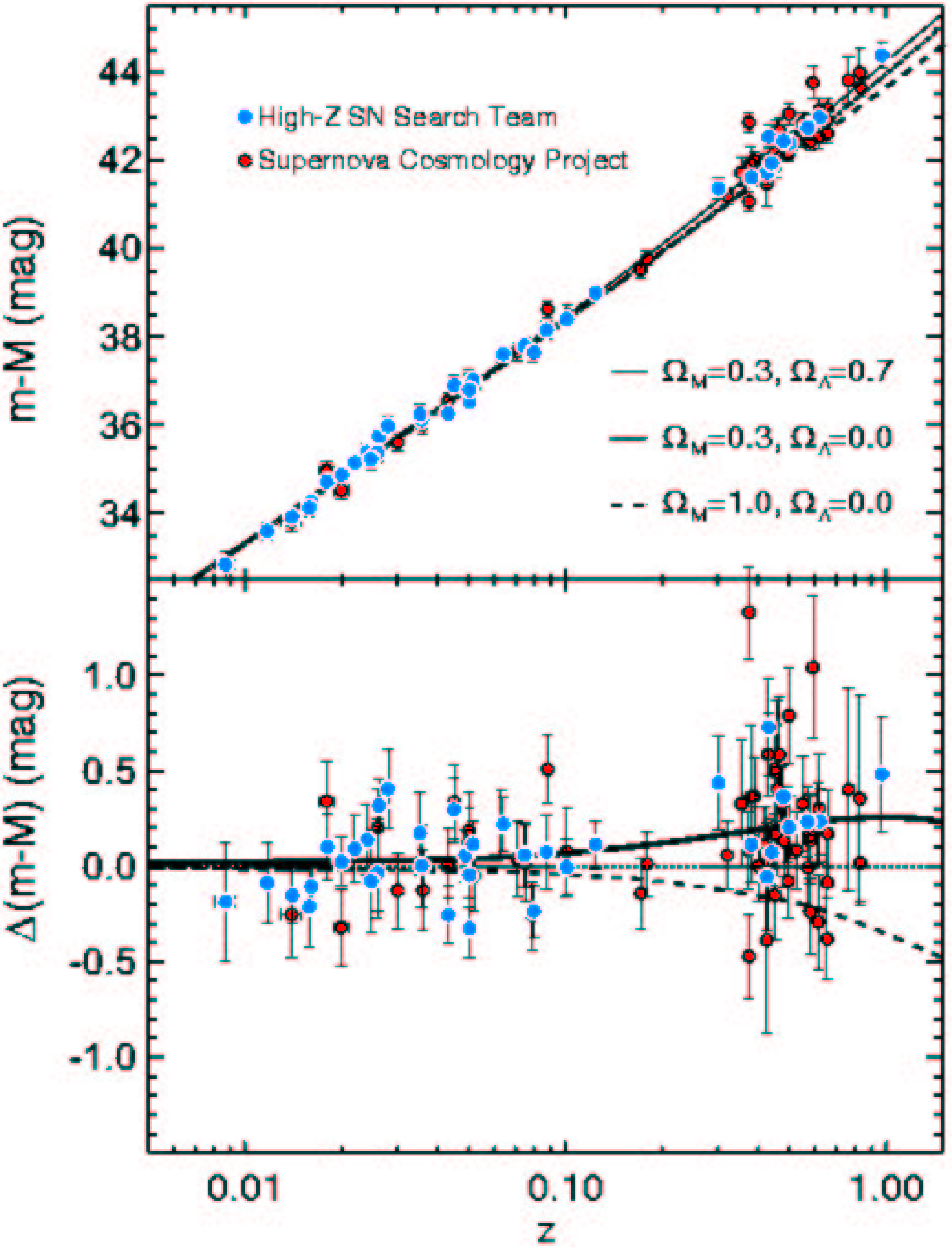
Result: $\Omega_{DM} \approx 0.25$

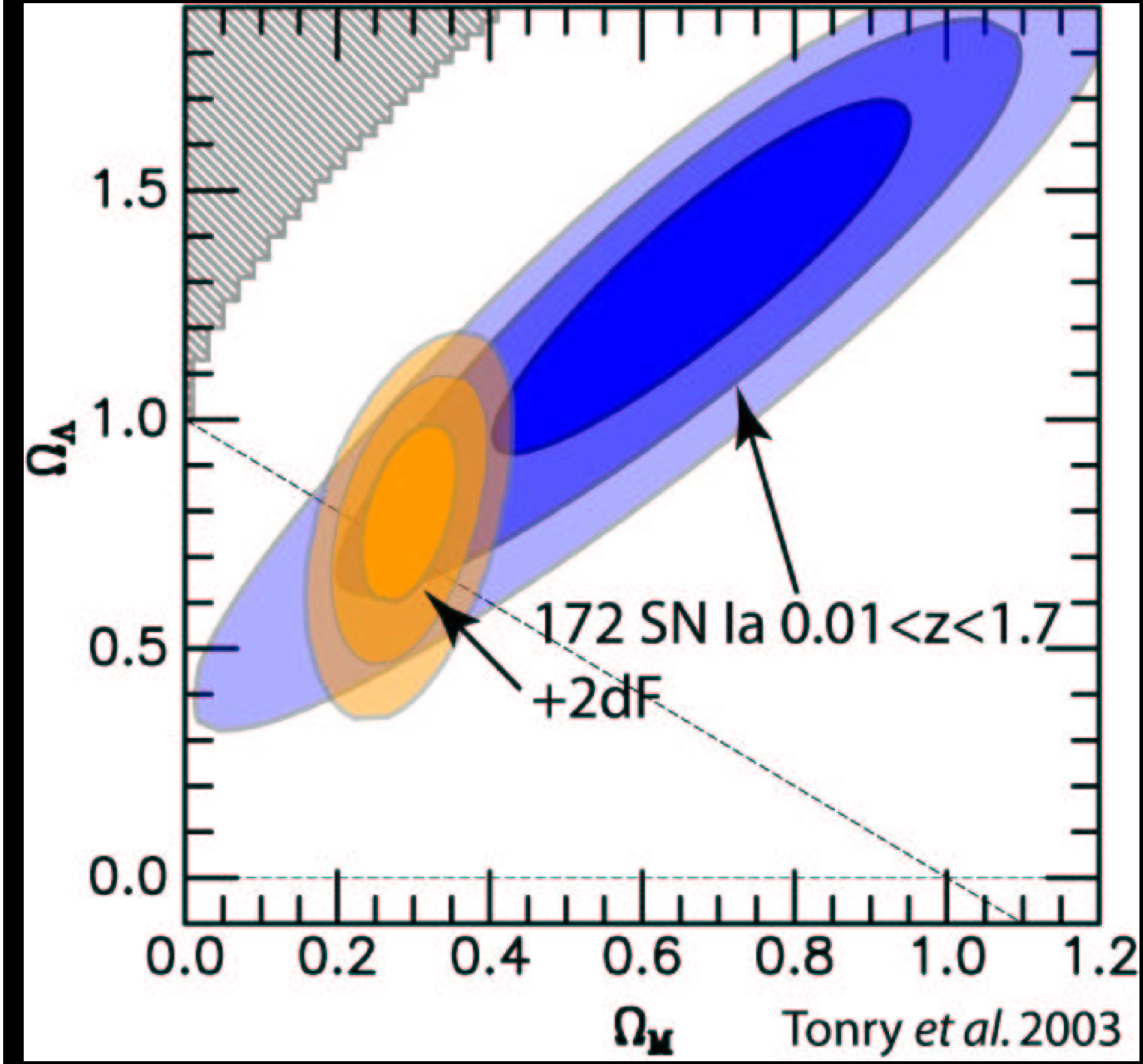
Type Ia supernovae are standardizable candles; observations of many at high redshift test the time evolution of the expansion rate.

Result: the universe is accelerating!

There must be some sort of dark energy which doesn't redshift away; maybe a cosmological constant Λ, maybe something dynamical.

[Riess et al.; Perlmutter et al.]





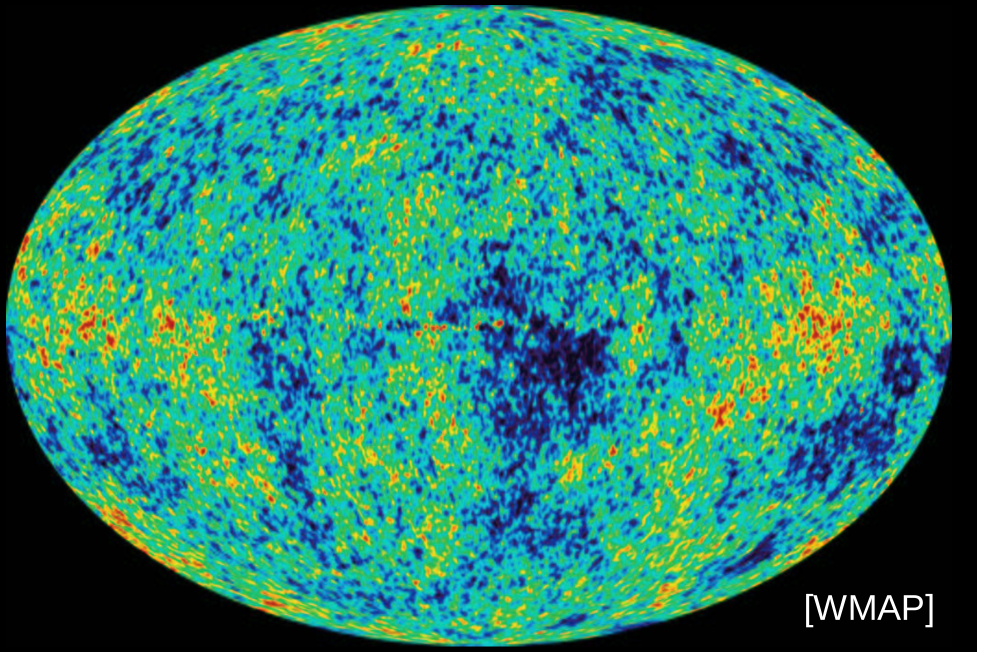
Combining supernovae with matter measurements (e.g. from 2dF redshift survey) and BBN gives a best−fit universe:

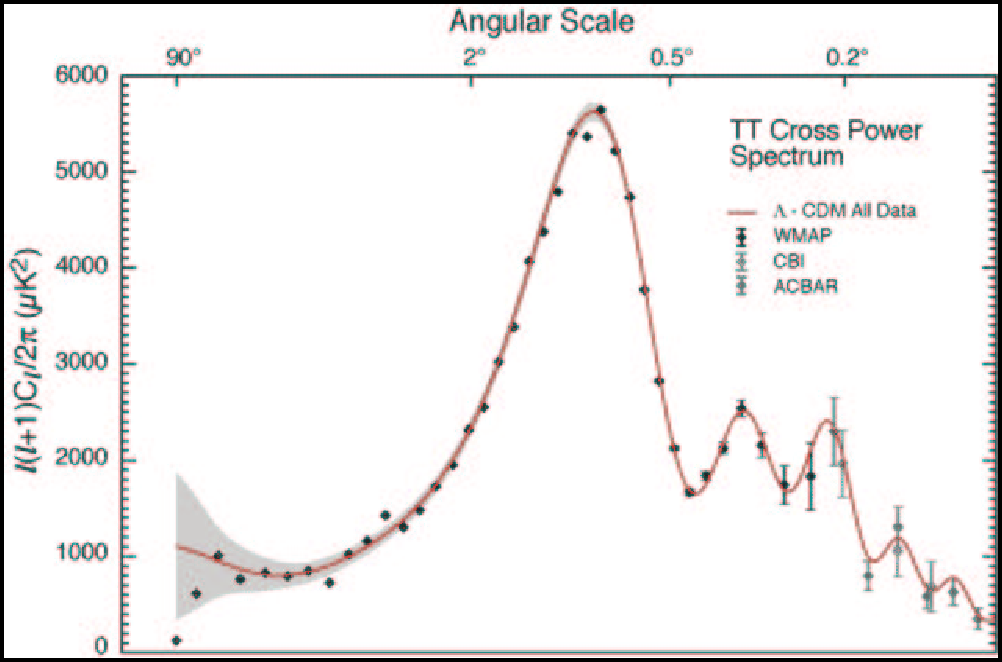
$\Omega_B \approx 0.05$

$\Omega_{DM} \approx 0.25$

$\Omega_{DE} \approx 0.7$

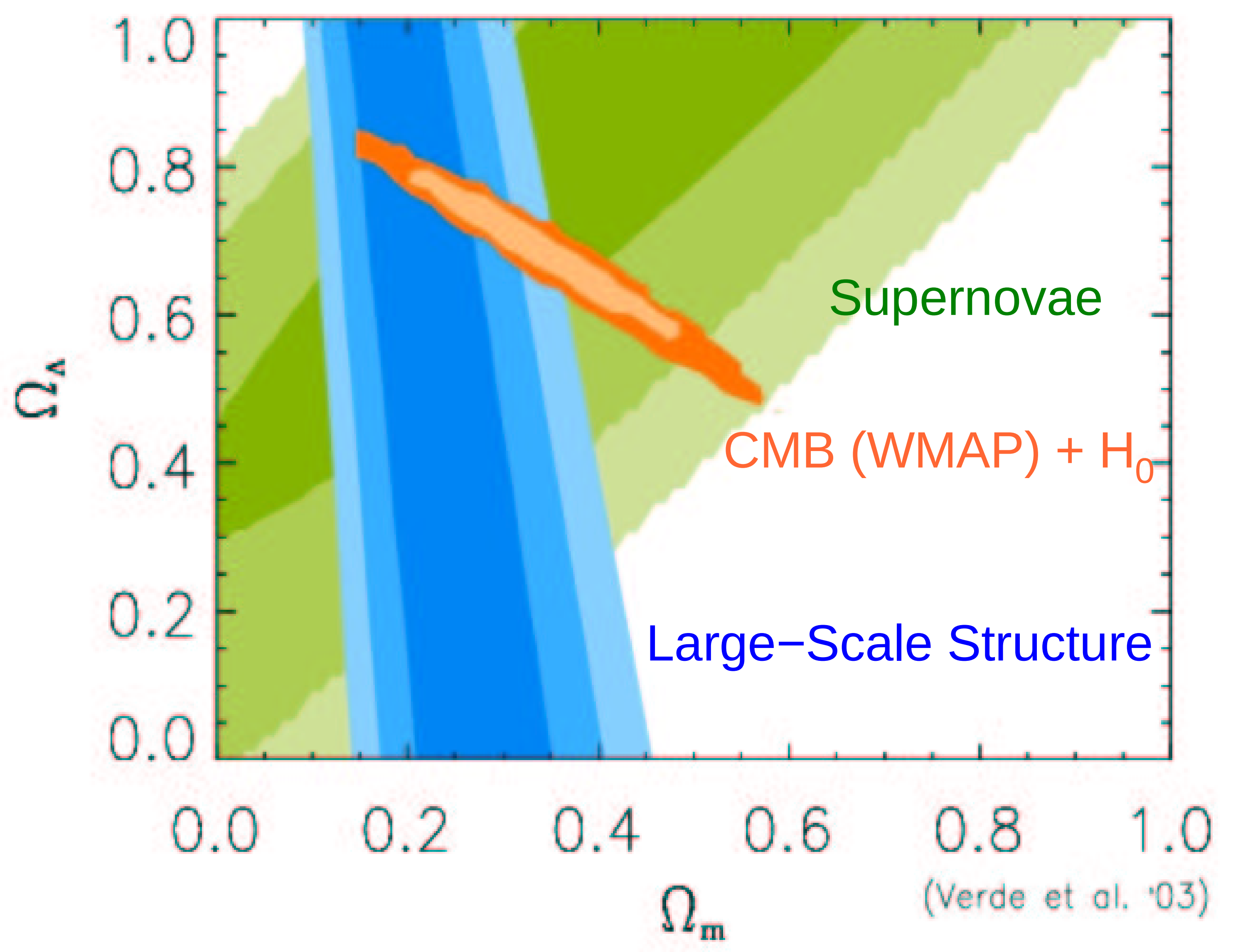
An independent probe: Cosmic Microwave Background temperature anisotropies.


[WMAP]



Primordial perturbations are nearly scale−free, but evolution leads to acoustic oscillations which imprint a predictable spectrum, depending on cosmological parameters.

Results: independent confirmation of best−fit model.

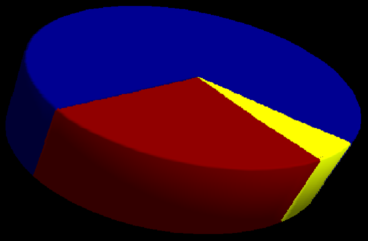


(Verde et al. '03)

$\Omega_B \approx 0.05$

$\Omega_{DM} \approx 0.25$

$\Omega_{DE} \approx 0.7$



There’s a lot we don’t understand.

Dark Energy:	clueless.
Dark Matter:	clueless.
Baryons:	clueless.

Perhaps a linear collider could help out with some of these mysteries.

Dark Matter: well−motivated candidates

- Weakly Interacting Massive Particles (WIMPs)
  - in equilibrium early; freeze−out after becoming nonrelativistic (cold)
  - must be neutral, color singlets
  - prime LC targets
- Axions
  - light pseudoscalars predicted by Peccei−Quinn solution to the strong−CP problem
  - produced out of equilibrium, by vacuum misalignment or topological−defect radiation
  - inaccessible at colliders
- anything else

The Early Universe

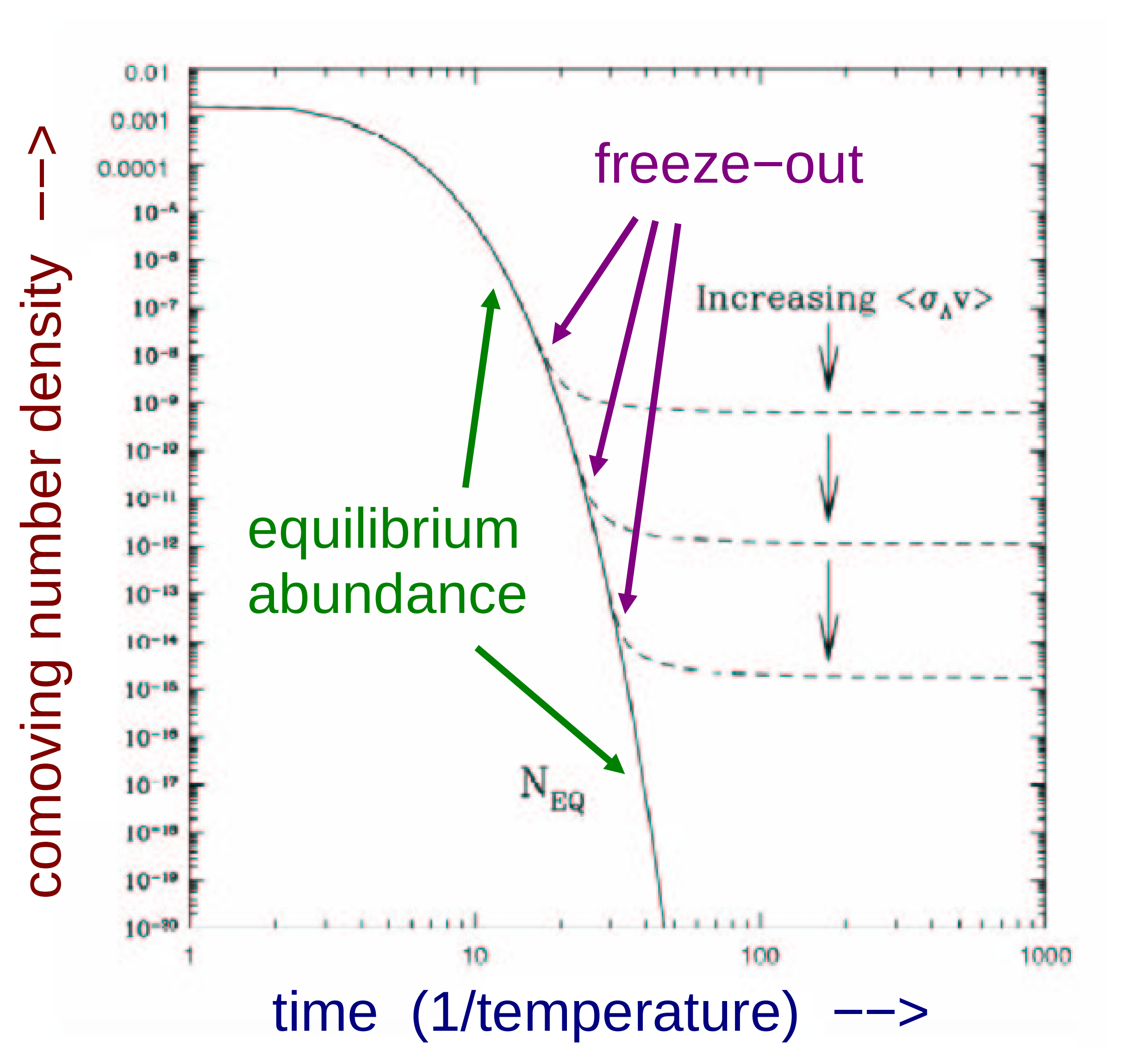
- It was hot, dense, nearly homogeneous.
- Expanding, but slowly (in a sense). At an energy density $\rho = E^4$, the expansion rate is

$$H = \left(\frac{E}{E_{Pl}}\right) E$$

- Thus, nearly in equilibrium.
- But reactions eventually freeze out (decouple); e.g. photons decouple at recombination.
- For a number density n and cross−section σ, a reaction rate $\Gamma = n\langle\sigma v\rangle$ freezes out when

$$\Gamma < H.$$

Cold relics: comoving equilibrium abundance plummets while non−relativistic, then stabilizes after freeze−out. (To do it right, solve Boltzmann equation.)



freeze−out

equilibrium abundance

comoving number density −−>

time (1/temperature) −−>

Predicted mass density is almost independent of m, but depends sensitively on annihilation cross−section $<\sigma v>$.

For σ at the weak scale, we naturally get $\Omega_{\text{wimp}} \sim 1$.

This compelling story can easily be upset by including additional particles.

[Griest and Seckel]

"Coannihilation." Imagine there is a particle χ_2, slightly heavier than the DM particle χ_1, with the same quantum number but a larger $<\sigma v>$. Then χ_1 can annihilate more quickly by first converting into χ_2.

"Forbidden annihilation." Imagine that χ_1 can annihilate into heavier particles that don't decay back into χ_1., but enhance $<\sigma v>$ for χ_1. Because freeze−out occurs at finite temperature, this channel becomes allowed.

For masses within 10%, abundances can change by $\mathcal{O}(1)$:
we need to understand an entire network of reactions.

(Not to mention angular−momentum dependence, resonances, etc.)

Actual models for WIMP dark matter:

- Supersymmetry.
  In MSSM with *R*−parity, the LSP is a perfect DM candidate if it is neutral and a color singlet. Some linear combination of bino, photino, higgsino.

- Universal extra dimensions.
  Forget branes, imagine Kaluza−Klein extra dimensions with size ~ $(\text{TeV})^{-1}$.
  Then "KK parity" is a conserved quantity, and the lightest KK mode (photon, maybe ν) can be dark matter.

[Servant and Tait;
Cheng, Matchev, Schmaltz]

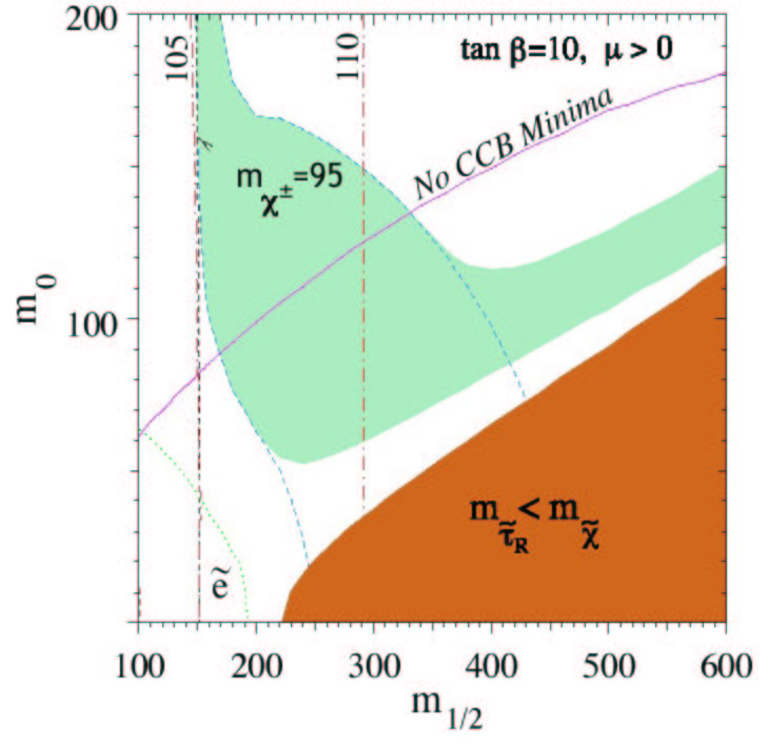
Both of these models feature the nearly−degenerate particle spectra that deform relic abundance calculations through coannihilation and forbidden annihilations. (E.g., a neutrino LSP can coannihilate with squarks or staus, or have a forbidden annihilation channel into Higgs bosons.)

Moral of the story:

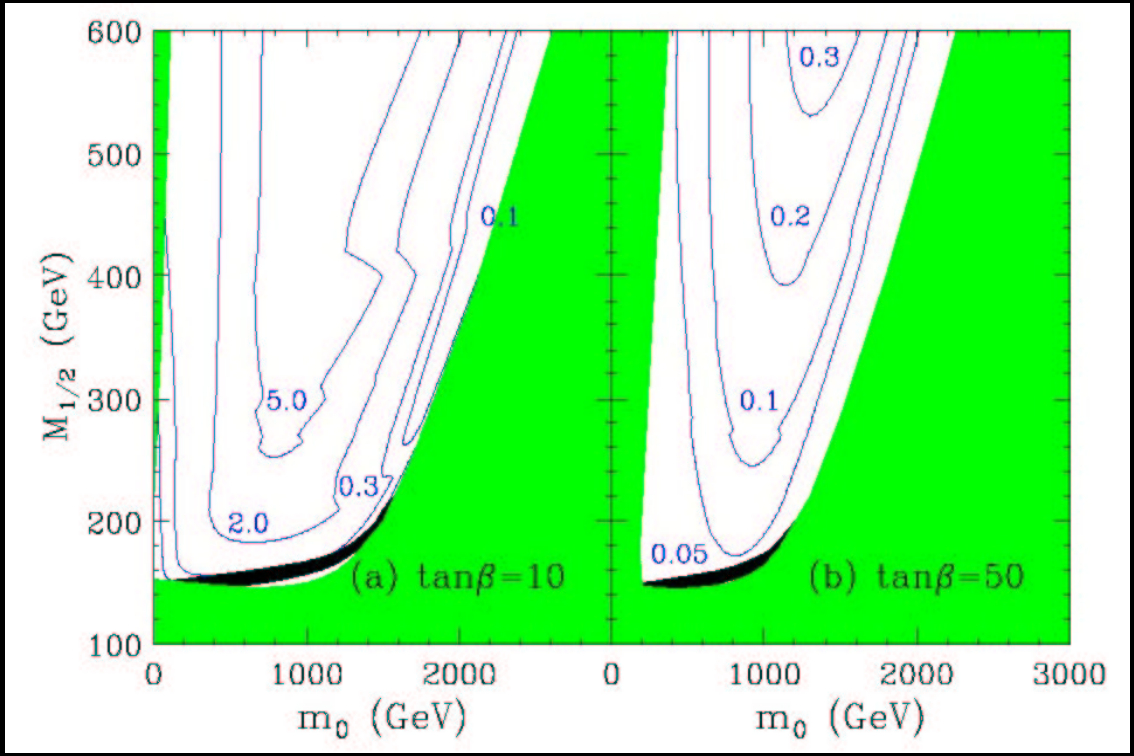
Understanding the dark matter abundance
to an order of magnitude may require measuring
model parameters at percent−level precision.

That is why cosmologists need a linear collider.

Constraints as a function of universal scalar mass m_0 and gaugino mass $m_{1/2}$.



[Ellis, Falk, Olive, Srednicki]



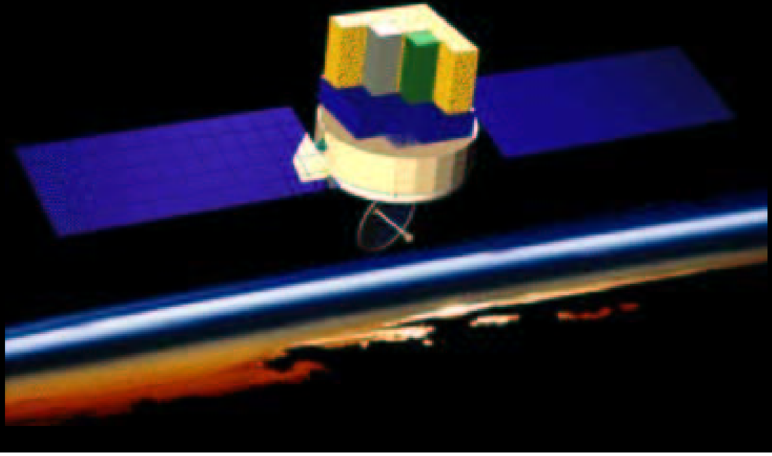
[Feng, Matchev, Wilczek]

Complementarity: try to detect ambient dark matter

- Directly:
  look for signs of WIMP scattering off of a cryogenic detector

[CDMS]

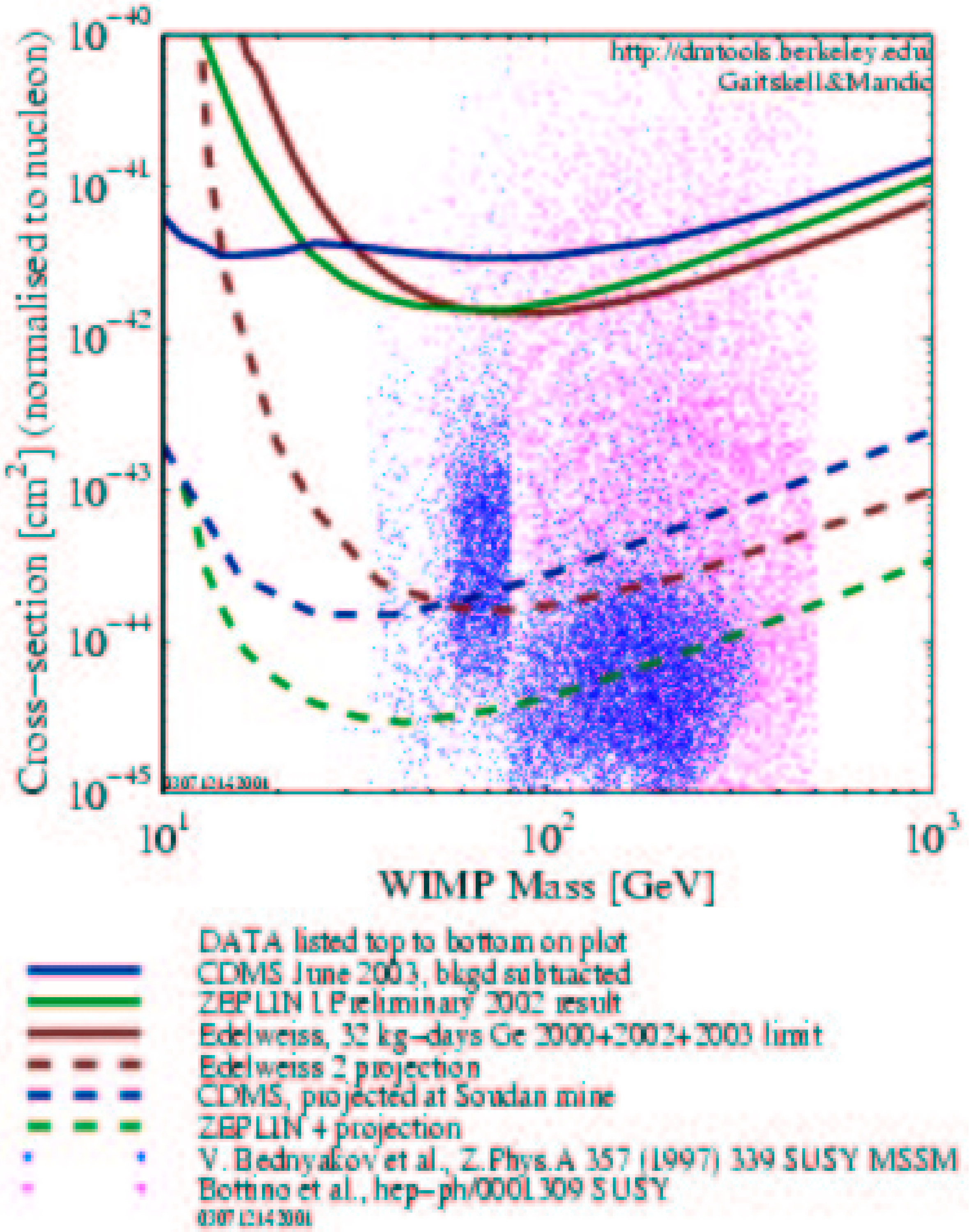
- Indirectly:
  look for annihilation products (e.g. γ–rays) of DM in galaxy



[GLAST]

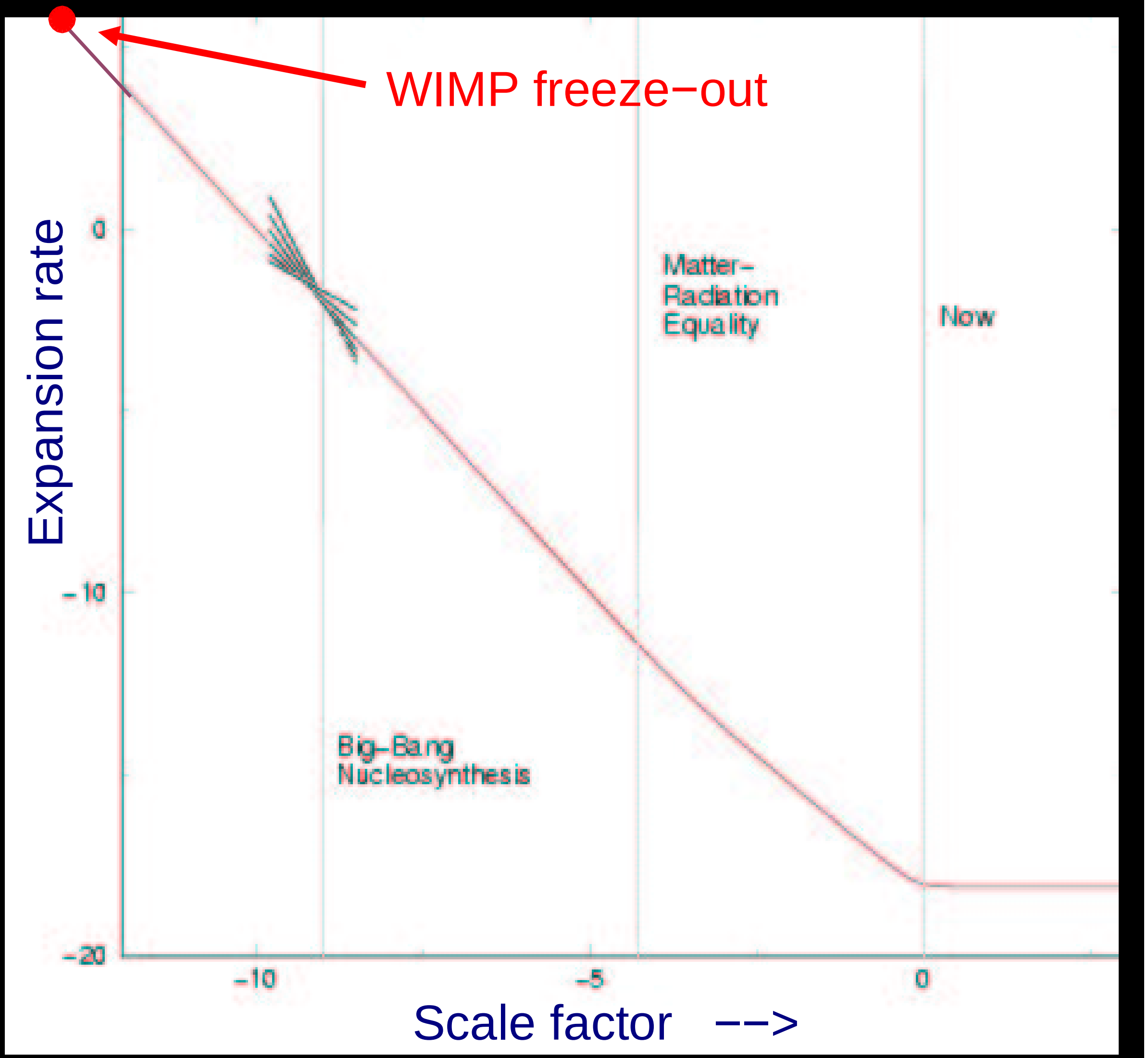
State of the art:

- beginning to cut into interesting parameter space
- will do much better
- won’t ever cover all of interesting parameter space



Crucial cosmological probe: testing general relativity (the Friedmann equation, $H^2 \sim \rho$) at T ~ 10 GeV.

Best current test
of Friedmann eq.
in the early
universe: Big Bang
Nucleosynthesis,
at 1 MeV – 50 keV.



[Carroll & Kaplinghat]

Baryogenesis: some popular scenarios

- Leptogenesis
  - out−of−equilibrium decay of a heavy lepton (e.g. right−handed Majorana neutrinos) create a lepton asymmetry, converted to baryons by electroweak processes

[Fukugita & Yanagida]

- Affleck−Dine baryogenesis
  - cosmological decay of a scalar "flat direction" carrying baryon number
- Electroweak baryogenesis
  - if the electroweak phase transition is suffiently violent (first−order), and extra CP violation is added somehow, bubble nucleation and evolution can produce the baryon asymmetry

Contemporary fashion disfavors electroweak baryogenesis.

In the minimal standard model, it’s hopeless:
not enough CP violation.

The MSSM has enough CP violation, but the phase transition will be first order only if $m_h < 120$ GeV.
(A tiny window indeed.)

[Carena, Quiros, Seco & Wagner]

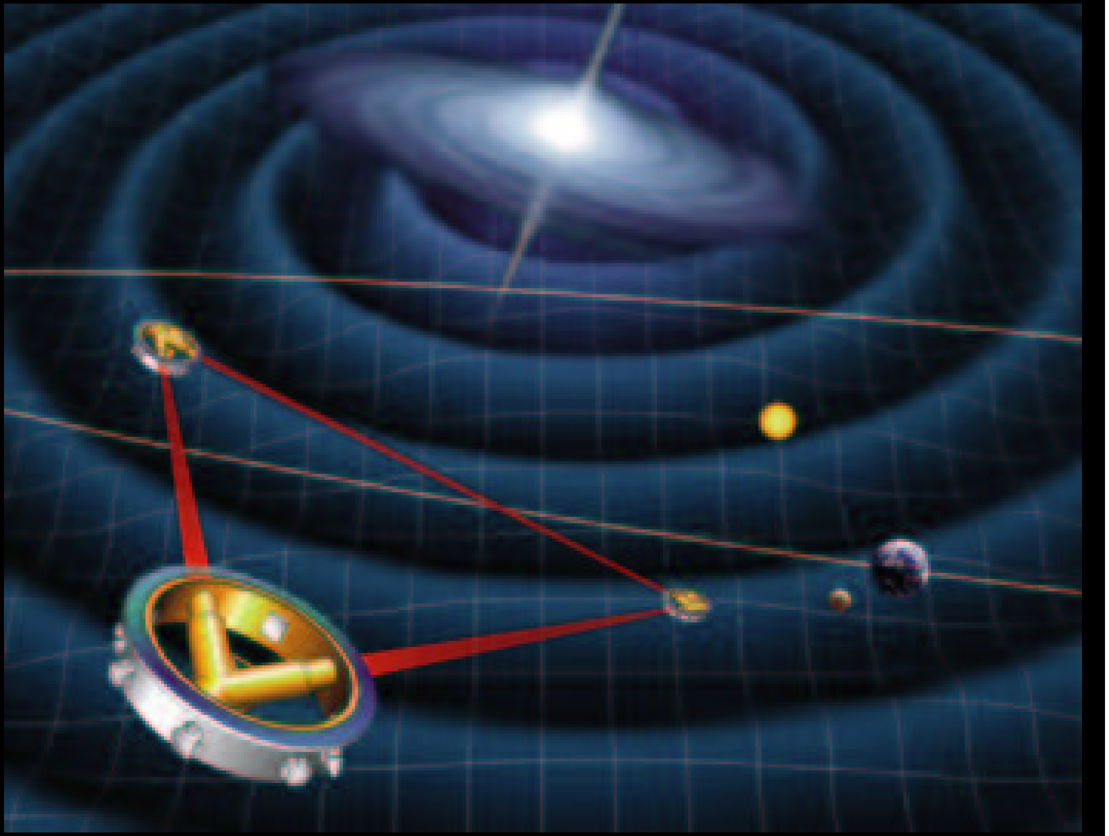
But: who knows? Pays to be open−minded.
It would be nice to map out the Higgs sector and related particles, to understand with confidence the order of the phase transition.

Complementarity again: a second−order EW phase transition produces gravitational waves, which can be detected by the LISA satellite observatory. (3 satellites, 5 million km separation; launch ~ 2010.)

Gravitational waves from a phase transition at temperature *T* redshift to a frequency

$$f \sim 10^{-3} \left(\frac{T}{TeV} \right) Hz$$

The electroweak scale is precisely in LISA’s sensitivity band.



Dark Energy: a complete mystery

- Naive guess: if $\rho_{vac} = E_{vac}{}^4$, we would estimate

$$E_{vac}^{(guess)} \sim E_{Pl} \sim 10^{18} GeV$$

but actually:

$$E_{vac}^{(obs)} \sim 10^{-3} eV \sim 10^{-30} E_{vac}^{(guess)}$$

- Supersymmetry:

$$E_{vac}^{(susy)} \sim E_{susy} \sim 10^{3} GeV$$

so that

$$E_{vac}^{(obs)} \sim 10^{-15} E_{vac}^{(susy)}$$

- But notice:

$$\boxed{E_{vac}^{(obs)} \sim \left(\frac{E_{susy}}{E_{Pl}}\right) E_{susy}}$$

- Is this just a coincidence?

  It would be nice to understand SUSY breaking.

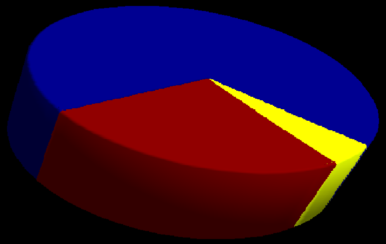
Unmentioned, but not unimportant.

- The "cusp problem" −− DM simulations don’t seem to match observations of cores of galaxies.
  Is DM physics more interesting?
- Do dark energy and dark matter interact?
- What explains ultra−high−energy cosmic rays?
- Neutrinos?
- Inflation?
- Extra dimensions?

Conclusions

Cosmology is blessed with knowing things but not understanding them. Investigations at a linear collider may be crucial to achieving understanding.

- Dark matter: we need to know the spectrum of particles that can influence relic abundances.
- Baryons: we need to map out the Higgs sector well enough to understand the EW phase transition.
- Dark energy: we need to search for any clues we can get, in supersymmetry breaking and elsewhere.



Apollo was,
after all, a
god of the sky.