Cosmology To Come:
Vacuum Energy and Dark Matter

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Cosmology Finished?

After 3/4 century, 3 basic cosm. parameters known:

\[ H_0 \approx 70 \text{ km/s/Mpc} \]
\[ \Omega_m \approx 0.3 \]
\[ \Omega_v \approx 0.7 \]

Total atoms in observable U. known:

\[ \Omega_b \approx 0.04 \]

Basic structure from Ly \( \alpha \) forest to clusters explained by model:

Structure by gravity from acausal, adiabatic, inflation-like perturbations created during big bang.

"Standard Model" in place?

Is cosmology today like stellar physics in past?
Yes: Search for $H_0$, etc. winding up. New basic models tough.

No: Values of numbers
  $\Rightarrow$ remarkable and little understood $U$.
  $\Rightarrow$ new questions as fundamental as old quest.

1) What is negative equation-of-state energy that dominates $U$? Where does it come from and how does it evolve?
   $\Rightarrow$ theory/exp.
   [Dark energy? Vacuum energy? Neos energy?]

IF $U$, accelerating and $p < -\frac{1}{2}$, we are in midst of inflationary period controlled by perhaps dynamic vacuum field we don't understand.

Values of $H_0, \Omega, \Lambda \Rightarrow$ theory incomplete.
Aside on nomenclature

Term "Dark Energy" unfortunate: neither descriptive nor accurate!
massless \( \gamma \) are "dark energy"; even black holes, WIMPs & axions!

Key is \underline{Negative equation of state} \( (\text{Neos}) \)
\( \Rightarrow \) Drives acceleration.

Better Neos energy or \underline{Vacuum Energy}.

True vacuum \( \Rightarrow \) Cosmological constant \( w = -1 \)
False Vacuum \( \Rightarrow \) Quintessence, dynamic field energy, etc.

\underline{Long tradition} of dynamic vacuum energy...

Also public confused by Dark Matter, black holes - Dark Energy makes it worse.
Vacuum Energy sounds really different - that's good.
Negative pressure is hard to understand
vacuum energy has Neos property.
particle - astro and theory - exp.
connections are crucial
- strings, extra dimensions, inflation phenomenology may give theory
- observations can see transition from matter domination to vacuum domination.
  ⇒ moderate redshift observation crucial

\[ P_{\text{mat}} \propto (1+z)^3 \]
\[ P_{\text{rad}} \propto (1+z)^4 \]
\[ E_V \propto (1+z)^3(1+w) \quad w = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)} \]

-1 < w < 1 for vacuum energy.
  w = -1 for \( E_V \) = const = cosmological constant.

If \( w \approx -\frac{1}{2} \) as observed ⇒ Neos Energy

Today \( \Omega_V \approx 1 \) ⇒ \( E_V \approx E_{\text{mat}} \).
so at \( z = 10 \)
  \( E_V < 0.1\% \) \( E_{\text{m}} \) for \( w = -1 \)
  \( E_V < 3\% \) \( E_{\text{m}} \) for \( w = -\frac{1}{2} \)

At \( z = 1100 \) (CMB) \( E_V \) basically negligible
⇒ CMB and Early U. not very helpful

Need \( z \approx 2 \) observations to see transition
Observables? Same for last 50 years! (in principle)

Luminosity distance of standard candles (SN Ia)

\[ d_L = r (1 + z) \]
\[ r = \int_0^z \frac{dz}{H(z)} \]
\[ H(z) = H_0 \left[ \frac{\rho_m + \rho_m}{\rho_\gamma} \right]^{1/2} \]
\[ + \frac{\dot{\phi}^2 + V(\phi)}{2\rho_\gamma} \]
\[ - \left( \frac{\Omega_{\text{tot}} - 1}{a^2} \right) \]

Info contained in integrals over \( H(z) \).

\( H(z) \) driven by vacuum energy potential \( V(\phi) \)
and change in \( \phi \), \( d\phi/dt \), characterized by equation of state:

\[ w(z) = \frac{p}{\rho} = \frac{\dot{\phi}^2 + V}{\dot{\phi}^2 + V} \]

Would like to measure \( w(z) \).

as Universe goes from matter domination to Neos energy domination.

Is \( w \) changing? Is \( w = -1 \) \( \Rightarrow \) cosmological constant?
Current ground-based data compared with binned simulated SNAP data.

Dark Energy Models:

Claim: measure $\Omega_m$ and $w$ to 5%
FIG. 1.  (a) The luminosity distance $H_0d_L(z)$ for nine choices of equation-of-state $w_Q(z)$ for the dark energy shown.
CMB

→ Boomerang/Maxima clearly demonstrated first acoustic peak and set us on road to "standard model" $\Omega_{\Lambda} = 0.7$, $\Omega_m = 0.3$, $H_0 = 70$

→ still could have surprises.
  - 2nd and 3rd peaks:
    - $\Omega M^2 = 0.03$ rather than 0.02 Tytler & Burbidge?
    - But poor stats and early day.

→ No polarization measurements yet.
  Indicator of tensor/gravity modes, one of very few observational handles on inflation era vacuum energy and its potential
Other huge problem whose solution will make fundamental change in physics is **Nature of Dark Matter**.

Now know how much DM, but nature, distribution and history now very confused and very important for cosmology.

- new fundamental particles?
- masses for neutrinos?
- DM different on different scales?
- clustering and formation history?
- distribution in galaxies and clusters?
- several components?

Galaxies and large scale structure are dark matter. Can't understand these w/o understanding DM. Now have mostly assumptions.
Super K atmospheric $\nu \Rightarrow \Omega_{\nu} > 10^{-3}$ (as much)

Could be more, but not all of DM.

$\text{BBN} \Rightarrow$ Most DM non-baryonic on large scales

Microlensing rules out objects in $10^{7} - 30 \, M_\odot$ range from being bulk of DM in Milky Way. (30 Mo limit is new result (preliminary))

But detections may indicate important population of MW (20%), MACHO DM $\Rightarrow$ more than stars

So DM in MW and on large scales non-baryonic. But what?

Axions and WIMPs are most popular. Major searches underway.
Cosmic axion exclusion plot

- Phase I Upgrade: SQUIDs at 1.3 K will allow us to run at KSVZ 4 times faster than with HEMTS.
- Phase II Upgrade: SQUIDs at 200 mK will give us sensitivity to DFSZ axions even if they only constitute 50% of the halo.


Could be looking at a definitive exp!
WIMP Search Projections

Interactive web plotter
http://dmtools.berkeley.edu/limitplots/
WIMP neutrinos from Sun

\[ \phi_\mu \text{ [muons/km}^2\text{yr]} \]

\[ m_\chi \text{ [GeV]} \]

Paolo Gondolo, "Neutrino 2002," Sudbury
WIMP neutrinos from Earth

$\Phi_\mu$ [muons/km$^2$yr]

$m_x$ [GeV]

Pablo Gondolo, "Neutrino 2000," Sudbury
Potential Problems for CDM (I):

- Cold Dark Matter halos are "cuspy": i.e. the density increases monotonically towards the center. (At odds with rotation curves of low surface brightness galaxies?)

McGaugh & de Block 1998
Navarro, Frenk & White 1996
see also Moore 1994
Flores & Primack 1994
Potential Problems for CDM (II):

- CDM galaxy halos possess large amounts of "substructure"; several hundred satellites with circular velocities > 10 km/s. (At odds with the relatively few known satellite companions of the Milky Way?)
Potential Problems for CDM (III):

- Cold Dark Matter halos are assembled through a sequence of merger events. (At odds with the angular momentum and thinness of stellar disks?)

Steinmetz & Navarro 1999
New axion expt. may be nearly definitive, and new direct and indirect SUSY particle searches get much of parameter space.

But DM particle could have only gravitational interaction - e.g. shadow matter. \Rightarrow undetectable. \Rightarrow problem for cosmology.

Any other clues possible?

Yes

Structure of halos reflects DM properties. Currently there are problems with non-interacting, cold DM hypothesis.

\Rightarrow Halos too cuspy?
\Rightarrow too much halo substructure?
\Rightarrow angular momentum of disks wrong?
What does it mean?

- Problems with measurements? (beam smearing, Hα)
- Problems with current calculations?
- Missing astrophysics?
- CDM particles have properties different than assumed (self-interacting? warm eff.?)
- DM particles not there! (non-Newtonian grav.)

DM picture is very confused and we have little data on DM itself:

★ Distrib of stars, formation history, kinematics, density of stars not clear; get DM by subtraction.

★ What are microlensing events? 20% of DM? New property of LMC?

★ Shapes, extent and kinematics of dark halos not understood. Simulations not helping!

★ Possible γ component

★ Large black holes at centers of galaxies - not understood how and when they form

★ If DM not weakly interacting particle, => major surprises in store
DM is large, central problem
⇒ must be approached from several angles.
⇒ searches in accelerators, direct, indirect.
⇒ large scale simulations — agreement with observation must be found
⇒ push to earlier redshifts. Structural properties as a function of z are crucial tests of models and may expose problems.
⇒ hard observations: IR, submillimeter, DEEP
⇒ Galactic structure. We need detailed models of stars in current day galaxies
⇒ astrometry, SIM
DM found by subtraction.
Conclusions

Recent results greatly increased importance of the particle/nuclear/astro/cosmology connection.

The really fundamental questions now lie on this interface.

Need gritty galactic & extragalactic observations plus accelerator & non-accelerator searches plus more theory.

Problems may be too hard. It took ~70 years to measure the 3 key numbers, but it is the best game in town at present.