Particle Astrophysics – Dark Energy
Dark Matter
Early Universe

Eric Linder
supernova.lbl.gov/∼evlinder

1 WHY PARTICLE ASTROPHYSICS

- Constraints on Particle Physics (*e.g. the saga of* N_ν)
- Dark Matter (*baryon chauvinism: light = pollution from baryons*)
- Dark Energy (*Hamlet's philosophy*)
- Structure Formation (*growth rate, seeing neutrinos*)
- Nucleosynthesis (*degrees of freedom*)
- Early Universe (*matter-antimatter, phase transitions*)
- Inflation (*particle creation, tensor modes*)
- Cosmological Constant (*is it? how much? why?*)
- Fate of Universe (*energy density, equation of state*)
- Origin of Universe (*quantum fluctuations, baby universes*)
- Origin of Physics (*symmetries, values of constants*)

. . . And recall need EOS to complete Friedmann equations.

2 INTERACTIONS, EQUILIBRIUM, AND FREEZEOUT

Early universe was ferment of particle interactions.

Was in **thermal equilibrium** – reaction rates equal forward and backward.

Expansion of universe gave **Hubble dilution**

- diluted particle density: $n \sim a^{-3}$
- reduced particle energies: $T \sim a^{-1}$

Freezeout

Competing time scales: if interaction rate Γ rapid then quick transition from equilibrium to *no* reactions – **freezeout**

$$\begin{aligned} N_{int}(>t) &= \int_t^\infty dt'\,\Gamma(t') \\ &= (n-2)^{-1}(\Gamma/H)_t \end{aligned}$$

$$\Gamma \sim T^n \qquad T \sim a^{-1} \sim t^{-1/2} \qquad H = (1/2)t^{-1}$$

Freezeout condition is $\Gamma < H$.
Excellent description since after freezeout time t_f: $N_{int}(> t_f) < 1$

Interaction rate $\Gamma = n \langle \sigma v \rangle$

- Cross section generically goes as

$$\sigma \sim \frac{\alpha^2 (\hbar c)^2}{(Mc^2)^\beta}$$

coupling constant α,
interaction strength $G = \alpha\,(\hbar c)$,
carrier mass M

Dimensionally, $\sigma \sim [\text{length}]^2$ so

$$\sigma = \sigma_0\,(E/E_0)^x \sim T^{\beta-2}$$

Only characteristic energy scale is temperature T of universe.

- Number density goes as $n \sim a^{-3} \sim T^3$

$\Rightarrow$ **Interaction rate** $\Gamma \sim T^{\beta+1}$

Examples

- Electromagnetism: carrier = photon (massless) ; $\sigma \sim \alpha^2 T^{-2}$

  $\Gamma \sim T \quad ; \quad H \sim T^2 \quad \Rightarrow \quad \Gamma/H \sim T^{-1}$

  $\Rightarrow$ Frozen in early universe, Equilibrium today

- Weak Force: carrier = W, Z bosons (massive) ; $\sigma \sim G_F^2 T^2$

  $\Gamma \sim T^5 \quad ; \quad H \sim T^2 \quad \Rightarrow \quad \Gamma/H \sim T^3$

  $\Rightarrow$ Equilibrium early, Frozen out today

- Generic Interaction:

  Weaker Interactions $\longrightarrow$ Earlier Decoupling ($\Gamma < H$ earlier)

  Earlier Decoupling $\longrightarrow$ Lower Abundance and Temperature

Particle Relics (= Nonbaryonic Dark Matter)

- Hot relic: relativistic, energy shared among degrees of freedom (favorite candidate – light neutrino)

  $n_X \approx n_\gamma$

  $\Omega_X h^2 = (M_X/92\,eV)$ (**Cowsik – McClelland bound**)

- Cold relic: decouples when nonrelativistic (favorite candidates – lsp (neutralino), axion)

$\Omega_X h^2 < 1 \quad \Rightarrow \quad M_X > 2\,GeV$ (**Lee – Weinberg bound**)

Aside: Neutrino Oscillations

- Vacuum Oscillations

If *flavor* (weak interaction) eigenstates not same as *mass* (free Hamiltonian) eigenstates then

Wave functions evolve by Heisenberg $\psi \sim e^{(i/\hbar)\Delta E\, t}$

Phase difference (oscillation) after time t or path length L

$$\Delta\phi = \Delta E \cdot L = L(\Delta m^2/2E)$$
$$L_{osc} = 4\pi E/\Delta m^2 = 800(E/GeV)(\Delta m^2/10^{-3}eV^2)^{-1}\text{km}$$

Atmospheric neutrinos: path length difference from near and far side of Earth (downward/upward). Different ratios of μ neutrinos from cosmic rays. SuperKamiokande: $\Delta m \approx 0.07\, eV$ for $\nu_\mu \to \nu_\tau$.

- Matter Resonant (MSW) Oscillations

Interactions of ν_e with electrons give *effective mass* $\to$ oscillations resonantly enhanced for certain ρ_e.

Solar neutrinos: SNO observation of oscillations. Solution of solar neutrino puzzle for $\Delta m \approx 0.005\, eV$.

Cosmic neutrinos: Don't know m, just Δm, but beta decay limits of $m_\nu < 2.8\, eV$ give

$$\Omega_\nu < (3 \times 2.8/92)h^{-2} = 0.18$$

Standard Model of Particle Physics

Bosons: force carriers – photons (em); $W^{\pm}$, Z^0 (weak); gluons (strong)

Fermions: hadrons (feel strong force), leptons (only feel weak force)

- hadrons – *baryons* (quark triplet "heavy ones": p,n, etc.),
  mesons (quark doublet: Π, K, etc.)
- leptons – elementary: quarks, electrons, mus, taus, neutrinos

Supersymmetry (SUSY)

Every boson (integer spin) has fermion partner (1/2 integral spin) and v.v.

boson $\to$ bosino ; fermion $\to$ sfermion

e.g. photon has photino, electron has selectron.

Astrophysical limits on charginos, so dark matter could be neutralino. Lightest supersymmetric particle (*lsp*) has no decay route so good stable candidate for dark matter. Weakly interacting, massive particle = **WIMP**.

And so on...

Axions: treats strong CP problem

String theory: 10 dimensional GUT, cool duality relations

Supergravity: SUGR/SUGRA, supersymmetry + gravitation

Higher dimensions: Kaluza-Klein, compactification (roll up)

M-theory: strings $\to$ branes, moduli

3 SCALAR FIELD PHYSICS

3.1 Lagrangian and Equation of State

Electromagnetism is vector field, gravitation is tensor field. Lagrangian of scalar field ϕ is extremely simple:

$$\begin{aligned}\mathcal{L} &= (1/2)\partial^\mu\phi\partial_\mu\phi - V(\phi) \\ &\approx (1/2)\dot{\phi}^2 - V\end{aligned}$$

Form energy-momentum tensor thru functional variation (Noether)

$$T^{ab} = \partial^a\phi\partial^b\phi - \mathcal{L}\, g^{ab}$$

and read off density and pressure in terms of kinetic and potential energies

$$\rho_\phi = (1/2)\dot{\phi}^2 + V \equiv K + V \qquad ; \qquad p_\phi = (1/2)\dot{\phi}^2 - V \equiv K - V$$

Equation of State

$$w \equiv \frac{p}{\rho} = \frac{K - V}{K + V}$$

$$\rho_w \sim a^{-3(1+w)} \qquad ; \qquad \ddot{a} \propto -(1 + 3w)$$

Special Cases

- Free Field V=0, $p = \rho$, $w = +1$
  Sometimes called *kination* in opposition to inflation.

- Slow Roll K=0, $p = -\rho$, $w = -1$
  Causes exponential inflation.
  One example is **cosmological constant**.

- Coherent Oscillations $\langle V \rangle = \langle K \rangle$, $p = 0$, $w = 0$
  Acts like nonrelativistic matter!
  One example is (pseudoscalar) **axion**.

NB the EOS w is generally not constant in time.

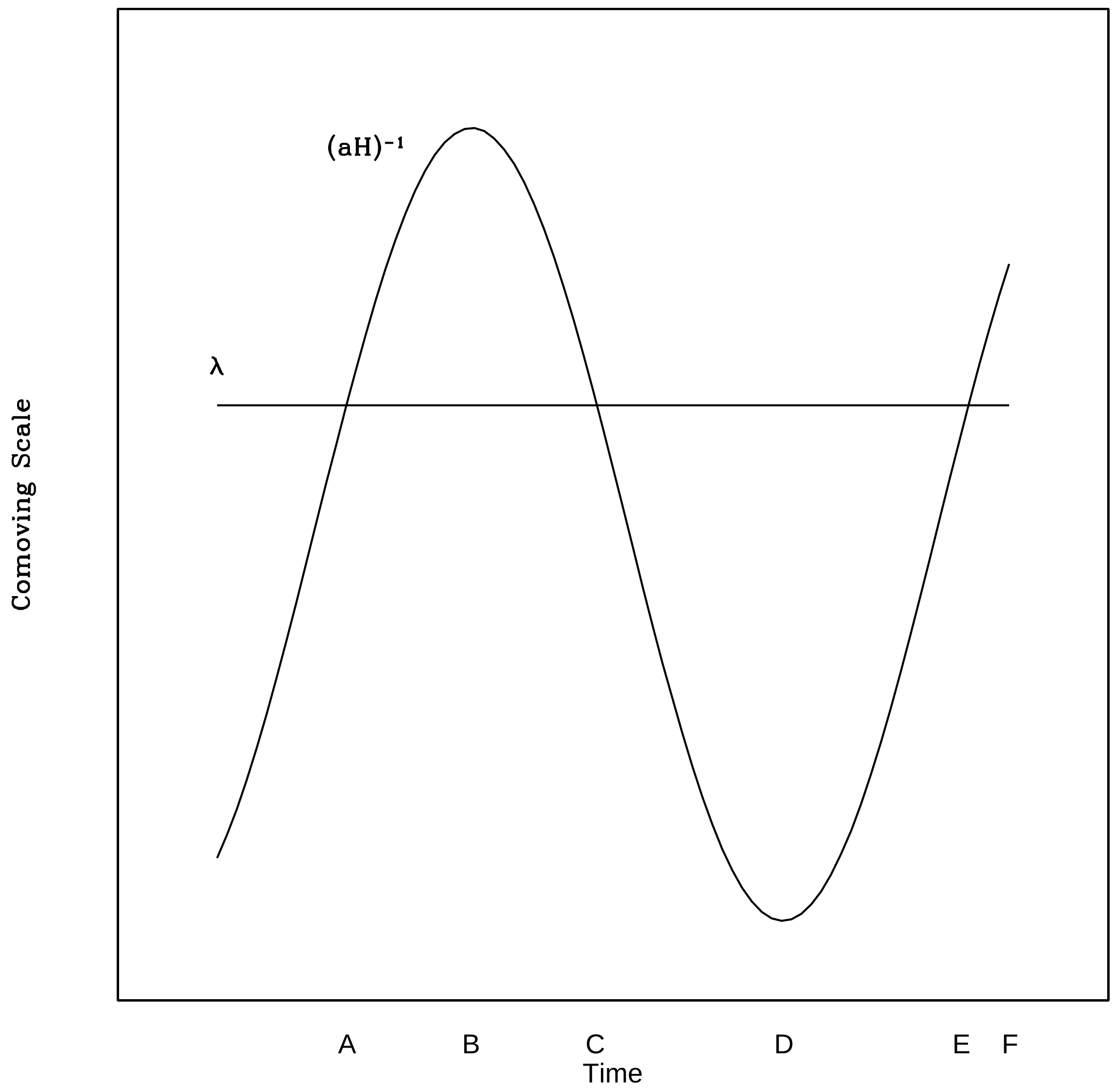
$$\rho_w(a) = \rho_w(0)\, e^{-3 \int d \ln a \,(1+w)}$$

NB depends on EOS from present back to observed epoch.

Inflation

$$\text{Inflation} = \text{Accelerated Expansion}$$

$$\ddot{a} > 0 \qquad \Rightarrow \qquad w < -1/3$$



3.2 Cosmological Constant

Equivalent to vacuum energy. Vacuum defined as the energy ground state and must be Lorentz invariant, since all observers must agree on the ground state.

Only Lorentz invariant tensor is Minkowski $\eta^{ab} = \mathrm{diag}(-1, 1, 1, 1)$. Thus the energy-momentum tensor of the vacuum must be

$$T^{ab} \sim \eta^{ab}$$

From this one can read off directly the EOS of this component:

$$T^{ab} = -\rho\{-1, 1, 1, 1\} \qquad \Rightarrow \qquad p = -\rho \quad (w = -1)$$

The conservation Friedmann equation

$$\dot{\rho} = -3(\dot{a}/a)(\rho + p)$$

tells us such a component has no time variation $\dot{\rho}$, so we call it the **cosmological constant** $\Lambda = \rho_{vac}$.

Natural value for such a constant is $\rho_{vac} \approx \rho(t_{Pl}) \approx 10^{92} g\, cm^{-3} \approx 10^{120} \rho_{crit}$. Oops! Is it incredibly small or is it exactly zero? Big debate.

3.3 Dynamical Fields

The constancy of the cosmological constant creates two problems:

- *Fine Tuning:* If Λ is small but nonzero, the only way to explain the 120 orders of magnitude deviation from ρ_{Pl} is to postulate a new energy scale around 1 meV or extreme fine tuning.

- *Coincidence:* $\Omega_\Lambda \approx \Omega_m$ only happens once in history of universe. Why are we now in this unique epoch?

Dynamical fields, that evolve with time, can alleviate these puzzles.

A particularly attractive subset are **tracking fields**. This name is sometimes given to *tracing* or *tuning* fields whose energy density evolves in a way to match the evolution of the dominant component, e.g. $\rho_\phi \sim a^{-4}$ in the radiation era.

These can generally solve the fine tuning but not the coincidence puzzle, and run into problems with the primordial nucleosynthesis epoch: Ω_ϕ/Ω_{dom} sufficient for observations today violate $\Omega_\phi/\Omega_{dom} < 0.1$ needed for nucleosynthesis abundances.

But often tracking means fields whose evolution leads them to an attractor solution: a common evolution despite a wide range of initial conditions. This can go a long way toward satisfying both puzzles. Fairly simple potentials $V(\phi)$ can give rise to either behavior.

4 QUINTESSENCE (The Fifth Element)

This is a tracking field (in the second sense) that can arise from, e.g., $V(\phi) \sim \phi^{-\alpha}$ or $V(\phi) \sim e^{M_{Pl}/\phi}$.

It solves the fine tuning puzzle for $\alpha > 2$: energy scale $\sim$ GeV.

The EOS w_ϕ(today) is determined by Ω_m, so it can explain why quintessence looks close to, but not exactly like, a cosmological constant today. Predicts that Ω_Q should not be too drastically different than Ω_m.

Easily calculated, observable consequences distinguishable from a cosmological constant. Since $w < 0$ and dominates only recently, best astrophysical probe is $z \approx 0.5 - 2$ supernovae distances.

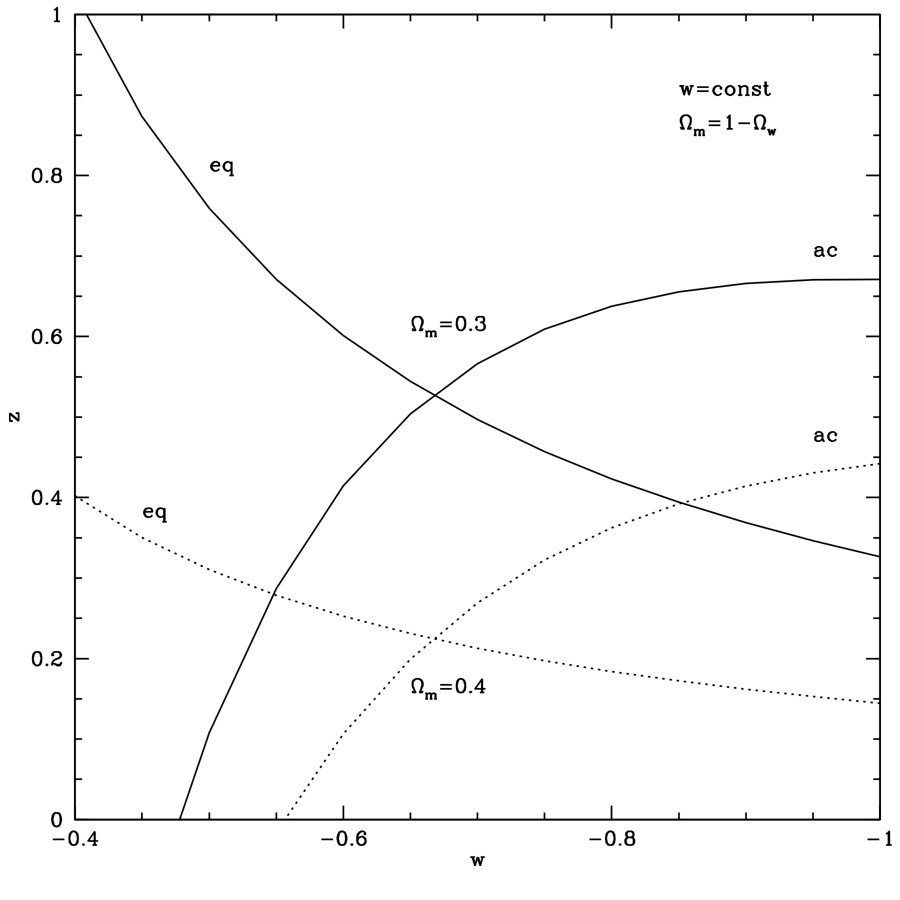
Seeing Dark Energy with SNAP

Redshift of Equality: $\Omega_m(z_{eq}) = \Omega_w(z_{eq})$

$$z_{eq} = \left(\frac{\Omega_w}{\Omega_m}\right)^{\frac{1}{-3w}} - 1$$

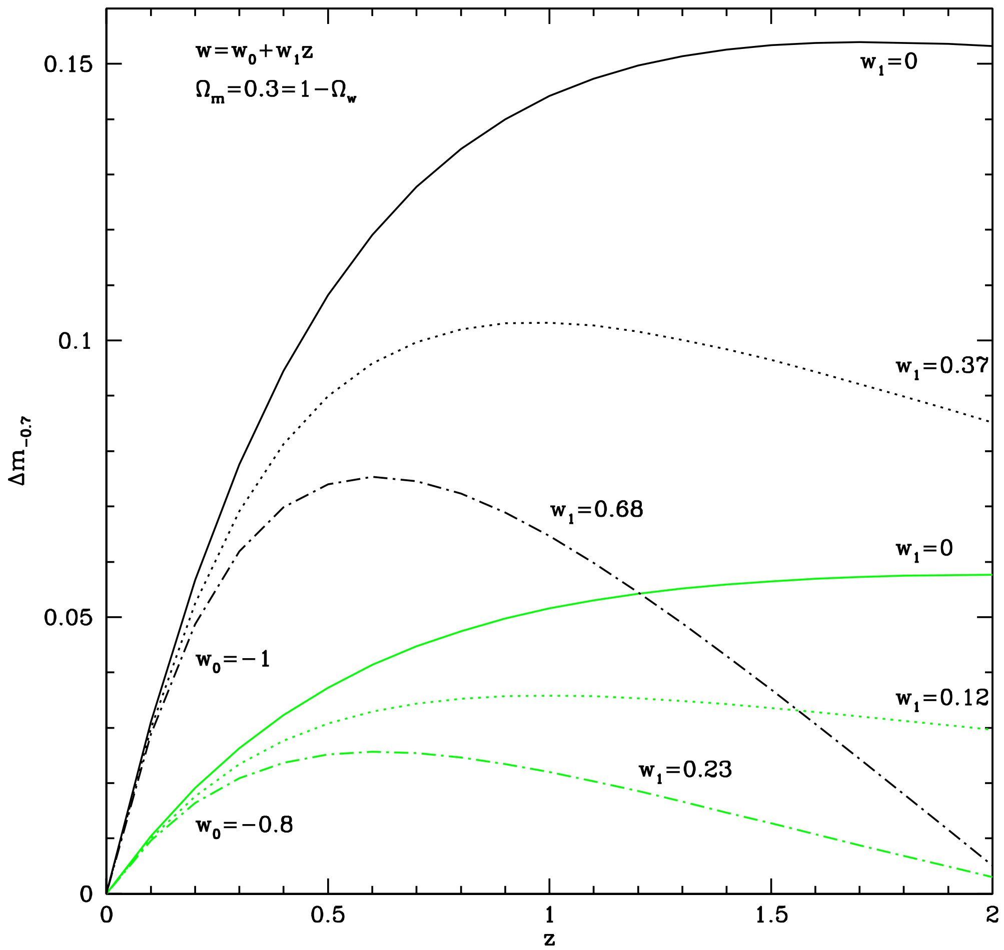
Redshift of Acceleration: $\ddot{a}$ changes from < 0 to > 0

$$z_{ac} = \left[-(1+3w)\frac{\Omega_w}{\Omega_m}\right]^{\frac{1}{-3w}} - 1$$



- Main action at $z \approx 0.5$ (unlike for Ω)
- Can have $z_{eq} <$ or $> z_{ac}$ depending on w

Seeing Dark Energy with SNAP



- Evolving w often reduces Δm
- Curves turnover from physics of *differential* acceleration: $w <,> w_c$
- Maximum Δm at z such that $w(z) \approx w_c$ (not exact due to "memory")
- Need $z > 0.5$ to distinguish evolving w from different w_c
  – turnover critical

FROM FIELD THEORY TO ASTROPHYSICS AND BACK

Field Theory: $V(\phi)$

From SUGRA, M-Theory (branes), Kaluza-Klein,...

Cosmological Evolution: $\phi(a)$

$$\ddot{\phi} + 3\frac{\dot{a}}{a}\dot{\phi} = -\frac{dV}{d\phi} \qquad \text{(Newton's 2nd Law)}$$

Kinetic energy $K \equiv \dot{\phi}^2/2, \dot{K} = \ddot{\phi}$ so

$$\frac{K}{V} \equiv \frac{1+w}{1-w}$$

or w is constant only for special $V(\phi)$.

Cosmological Model: $a(t)$

The Grail $V(\phi(a(t)))$**:**

$$r(z) \sim a(t) \quad \longrightarrow \quad w_\phi(z) \sim \phi(a) \quad \longrightarrow \quad V(\phi)$$

$$\text{Astrophysics} \quad \longrightarrow \quad \text{Cosmology} \quad \longrightarrow \quad \text{Field Theory}$$