Cosmology review/intro

- We live in an expanding universe described approximately by Friedman-Lemaitre-Robertson-Walker metric, (FLRW) $ds^2 = -dt^2 + \underset{\substack{\downarrow \\ \text{scale factor, describes expansion}}}{(a(t))^2} \left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2 \right)$ $k = 0, \pm 1$ in principle In practice $k=0$ as far as we can tell

Scale factor evolution controlled by Friedmann equation,

$$H \equiv \frac{1}{a}\frac{da}{dt}, \quad H^2 = \frac{8\pi G}{3}\overset{\nearrow \text{energy density}}{\rho} - \underbrace{\frac{k}{a^2}}_{\text{vanishes in } k=0 \text{ universe}}$$

Matter/energy content in FLRW metric corresponds to a perfect fluid, $\overset{\text{energy density}}{\rho} = \overset{\text{pressure}}{P}/w$

From energy conservation can show $\rho \propto a^{-3(1+w)}$

Radiation: $w = \frac{1}{3}$, $\rho = 3P$, $\rho \propto a^{-4}$ – dilutes w/ volume + wavelength expands, as space expands

Matter: $w = 0$, $P = 0$, $\rho \propto a^{-3}$ – dilutes w/ volume as space expands

Dark energy: $w = -1$, $P = -\rho$, $\rho \propto a^0$ (current constraint: $w = -1.01 \pm 0.04$, Alam et al '17)

Define $\rho_c \equiv \frac{3H^2}{8\pi G}$ ($= \rho$ for $k=0$), write $\rho = \rho_{m,0}\left(\frac{a(t)}{a_0}\right)^{-3} + \rho_{rad,0}\left(\frac{a(t)}{a_0}\right)^{-4} + \rho_{\Lambda,0}$

$$\Omega_x \equiv \frac{\rho_{x,0}}{\rho_{c,0}}, \quad \Omega_k \equiv \frac{-k}{a_0^2 H_0^2}$$

Then $$\frac{H^2}{H_0^2} = \Omega_{rad}\left(\frac{a}{a_0}\right)^{-4} + \Omega_m\left(\frac{a}{a_0}\right)^{-3} + \Omega_k\left(\frac{a}{a_0}\right)^{-2} + \Omega_\Lambda$$

Current values: $\Omega_{rad} = 9 \times 10^{-5}$, $\Omega_m \approx$ ~~0.308 ± 0.012~~ 0.3153 ± 0.0073, $\Omega_\Lambda =$ ~~0.692 ± 0.012~~ 0.6847 ± 0.0073
(Planck 2018) ($\Omega_b \approx 0.049$) $\Omega_k = -0.0007 \pm^{0.0019}_{0.0019}$ (95%)

Wavelength of light scales as $\lambda_{rec} = \lambda_{emit} \times \frac{a(t_{rec})}{a(t_{emit})}$ – wavelength stretched, energy decreases, cosmological redshift

Define $1+z \equiv \frac{a_0}{a(t)}$, z referred to as "redshift"

"Comoving volume" – volume that expands w/ expansion of universe, physical volume scales as $(1+z)^{-3}$ $(\propto a^3)$

As $\frac{H^2}{H_0^2} = \Omega_{rad}(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\Lambda$

Ω_{rad} ↓ dominates at early times / high z

Ω_m ↓ dominates at intermediate times

Ω_Λ ↳ dominates today

Temperature of photon bath redshifts as $T \propto E \propto (1+z)$ in absence of energy injection

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- Cosmological constraints (1) – limits on light degrees of freedom
  - Earliest observations come from epochs of Big Bang nucleosynthesis (aka BBN) (T ~ MeV) and recombination (T ~ eV), ~~for~~ hydrogen atoms form from free p+, e−
    - nucleosynthesis ↓ helium, other light elements formed
  - Both constrain $\rho_{radiation} = \rho_\gamma + \underbrace{(3 + \Delta N_\nu)}\rho_\nu$
    - n_{eff} = number of "effective neutrino species"
    - Effectively counts contribution of exotic* degrees of freedom to energy density of radiation
    - Note energy density of radiation $\propto T^4$ – depends on both # & temperature of new dof

Full SM calculation:

$(n_{eff})_{SM} = 3.046$

BBN: Δn_{eff} (T ~ 1MeV) ≤ 1 (arXiv: 1103.1261)

Recombination: $n_{eff} = 3.15 \pm 0.23$ (T ~ 1eV) (Planck 2015)

These limits constrain any new degrees of freedom lighter than ~MeV, if temperature is comparable to SM (hotter = more constrained, colder = less constrained)

If new d.o.f decay/annihilate/etc to produce photons, neutrinos, other relativistic species in this epoch, can also be constrained. (See Berlin & Blinov '17 for a caveat.)

How are we actually observing this? / setting these limits?

BBN: present-day element abundances

Recombination: cosmic microwave background radiation (CMB)

For $T \gtrsim 1$ eV, universe is ~100% ionized. Then ionization level drops rapidly at $z \sim 1000$, $T \sim 0.4$ eV. Photons scatter poorly off neutral atoms → universe becomes transparent, photons in bath free-stream to present day. This is the CMB - a snapshot of the cosmos at $z \sim 1000$.

Prior to release of photons, universe is plasma of ions, electrons, photons, neutrinos, + dark matter (?). Small perturbations in density/temperature oscillate over time; gravity drives density ↑, radiation pressure drives density ↓

Resulting temperature fluctuations imprinted on CMB - temperature & polarization anisotropies measured exquisitely today by Planck, ACT, SPT, etc

To explain data, need a component that feels gravity but not radiation pressure (or has equivalent effects), roughly 5x more abundant than ordinary matter. Call this "dark matter", hypothesize it is the same stuff surrounding galaxies/clusters (Note: also gives measurement of baryonic matter that agrees well with BBN)

- Tells us DM must be present by $z \sim 1000$, $t \sim$ few 100,000 years - long before stars, galaxies, etc. Eliminates many collapsed objects as candidates - primordial black holes sourced by inflation could work in principle, but hard to reconcile w/ constraints (at least as 100% of DM - see Carr et al 1705.05567, Zumalacarregui & Seljak '1~~8~~7, Bringmann et al '18).
- Modern CMB measurements also test "darkness" of dark matter - can test small interactions between DM + baryons or DM + radiation (e.g. Dvorkin et al '13, Boddy et al 1808.00001)

After the CMB - Structure Formation

- Density fluctuations present at CMB epoch continue to grow under gravity, once photons decouple - eventually collapse into virialized structures
- Can simulate nonlinear collapse, formation of DM filaments & halos, using large N-body simulations
- Baryons fall ~~out~~ into DM-sourced potential wells, forming galaxies
- As discussed last time, small dwarf galaxies & colliding clusters can probe DM self-interactions - structure formation also gives a handle on how fast DM is moving, & its allowed mass range

Limiting cases:

COLD DM: very non-relativistic during relevant epoch, small clumps form first, accrete to form large structures, "cosmic web"

HOT DM: DM relativistic, large free-streaming length erases small-scale structure, large structures form first then fragment - clusters older than galaxies - observationally excluded (can be ~1%, e.g Archidiacono et al '13)

WARM DM: structures are erased below some critical scale - look for cutoff in matter power spectrum

Strongest constraints on WDM come from the Lyman-α forest - distant quasars emit radiation that is absorbed by intervening clouds of hydrogen gas - maps overdensities of matter at $z \sim 2-6$. Limit depends on DM velocity in early universe* as a function of z; for DM that was once at same temperature as SM & then decoupled while relativistic, its velocity is controlled by its mass.

* More precisely, limit set by free-streaming length $\int_0^t \frac{v(t')}{a(t')} dt' = \lambda_{fs}^{com}$

In this scenario $m_{DM} \gtrsim 5.3$ keV (Viel et al 1702.01764) – faster-moving DM can be ruled out at higher masses, slower-moving DM can survive at lower masses.

→ DM must be slow/cold in this sense.

By bounding size of smallest DM structures, Ly-α forest also sets a bound on DM wavelength – structure is also suppressed on scales smaller than 1 wavelength

$\Rightarrow$ wavelength $\ll 1$ kpc. Detailed constraint: $m_{DM} \gtrsim 2\text{-}3 \times 10^{-21}$ eV (Irsic et al, Armengaud et al '17)

For fermions, we can do better, as Pauli exclusion limits how many fermions we can pack into a DM halo.

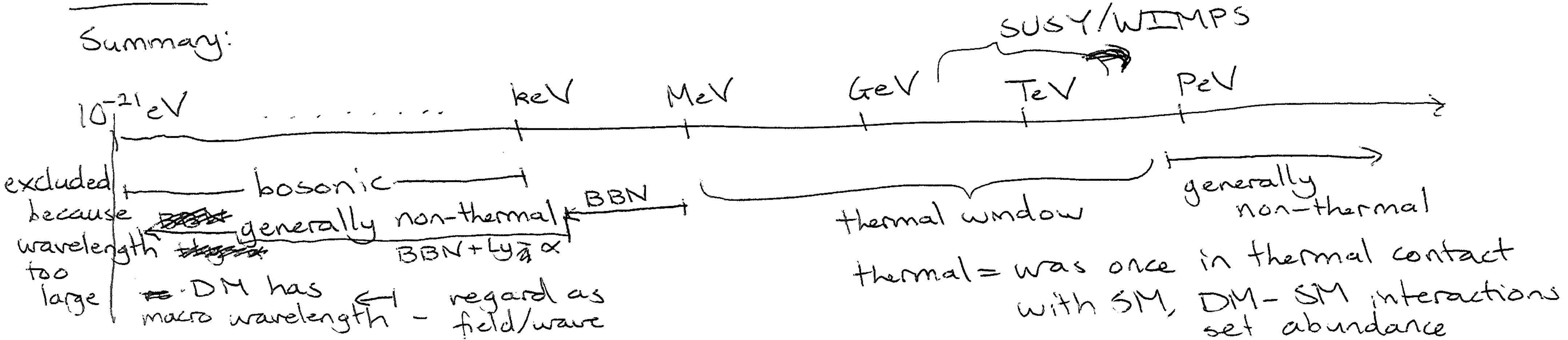
Tremaine-Gunn bound: phase space density $\sim \frac{n}{p^3} \sim \frac{\rho}{m_{DM}(m_{DM}v)^3} \leq 2$ for fermions

$$\Rightarrow m_{DM} \gtrsim \left(\frac{\rho}{v^3}\right)^{1/4} \sim \left(\frac{1\text{ GeV/cm}^3}{(10^{-5})^3}\right)^{1/4} \sim 10^{-6.5}\text{ GeV} \sim \text{few hundred eV}$$

using $1\text{ cm} \sim 5 \times 10^{13}\text{ GeV}^{-1}$

Particle DM below this scale must be bosonic.

Summary:



thermal = was once in thermal contact with SM, DM-SM interactions set abundance