

## ▷ Baryonic dark matter candidates

conventional

Brown dwarfs  $< 0.08 M_{\odot} \approx 80 M_J$   
 Jupiters  $\approx 12 M_J$   
 Cold ( $\approx 3K$ ) molecular gas  
 warm-hot ( $\approx 10^5 K$ ) gas

exotic

strange nuggets  $d \sim 10^{-15}$   
 white dwarfs  
 neutron stars  
 black holes

## ▷ Non-Baryonic dark matter candidates

neutrinos  $\nu$

• originally thought to have zero rest mass ("had" to be zero)

If there are 3  $\nu$  flavors (electron, muon, ~~tau~~ <sup>tau</sup>)  
 need each to weigh  $\sim 10 eV$  to add up to  $\Omega_{DM} \approx 0.3$

$$\sum_i m_{\nu,i} = 94 \Omega_{DM} h^2 eV$$

$$\Omega_{DM} = \rho / \rho_{crit}$$

known from equilibrium in early universe

$$h = H_0 / 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

But

• neutrinos free-stream, erasing structure  $< 3 \times 10^{15} \left(\frac{m_{\nu}}{30 eV}\right) M_{\odot}$   
 (destroy galaxies before they can form)

• neutrinos obey Pauli exclusion Principle  
 (can't pack them too closely)

Don't get up to observed DM density in dwarf galaxies  
 unless  $m_{\nu} > 30 eV$

neutrinos now known to have mass, but too small  
 to be solution:  $m_{\nu} < 2 eV$  (experimental)

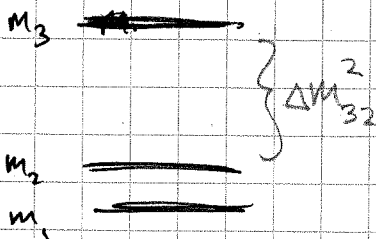
$m_{\nu} < 0.13 eV$  (arXiv: 1511.05983) probably  $\ll 1 eV$  (cosmology, assuming structure formation)  
 $\Sigma m_{\nu} < 0.17 eV$  (arXiv: 1703.10829)

## Neutrino mass states

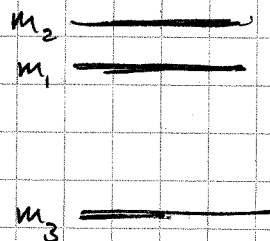
flavors: electron  $\nu_e$ , muon  $\nu_\mu$ , tau  $\nu_\tau$  neutrinos  
not identical to mass eigenstates (they're mixed)  
 $m_1, m_2, m_3$

Currently only difference in mass levels is known from  
solar and atmospheric oscillations.

### Normal hierarchy



### Inverted hierarchy



$$\Delta m_{32}^2 = 2.5 \times 10^{-3} \text{ eV}^2$$

$$\Delta m_{21}^2 = 7.6 \times 10^{-5} \text{ eV}^2$$

$$\text{minimum upper mass } m_3 \sim \sqrt{\Delta m_{32}^2} \gtrsim 0.05 \text{ eV}$$

$$\text{so } \Omega_\nu > 0.001$$

$$\Omega_\nu \approx \Omega_b \text{ if } \sum m_\nu \approx 2 \text{ eV}$$

$$(\Omega_b^2 \approx 0.022 \text{ from BBN and CMB})$$

## Cold dark matter

CDM leading candidate (popularity-wise)

Need entirely new particle outside the Standard Model of Particle Physics

### Motivations

- $\Omega_{DM} > \Omega_b$  something with mass that isn't baryons
- LSS growth factor  $10^5$  since  $z \approx 1000$  (CMB)  
baryons only give  $10^2$  or so

### CDM candidates

WIMP Weakly Interacting Massive Particle

presumed to be the lightest stable super symmetric partner particle  
i.e., the neutralino in minimal supersymmetry (MSSM)  
in SUSY

$m_x \sim 100 \text{ GeV}$  ( $\approx$  a heavy nucleus, like Xenon)  
 $\sigma_x \sim$  weak nuclear scale

"WIMP miracle" - cross-section about right to leave the right relic abundance ( $\Omega_{DM}$ ) to be the dark matter  
IF  $\sigma_x \sim$  weak force scale

other possibilities

SUSY/MSSM in bad shape  
after the LHC results

WIMPELLAS  $m_x > \text{TeV}$

Axions known to exist, but not necessarily in enough  
super-lightweight ( $\ll 1 \text{ eV}$ ), not produced thermally } numbers

Light Dark Matter ( $m_x \lesssim 10 \text{ GeV}$ )

Etc. (e.g. Q-balls)

## Other Ideas for Dark Matter

### △ Warm Dark Matter

WDM  $m \sim 1 - \text{a few keV}$

speed "just right" - not relativistic like  $\nu$   
but not zero like CDM

most commonly invoked to suppress  
structure formation on "small" scales (like  $\nu$ )  
without killing it on large scales

MIGHT help with small scale problems:

- missing satellites
- cusp/core
- too big to fail

### △ Self-Interacting Dark Matter

SIDM doesn't interact with baryons (like CDM)  
but has enhanced cross-section for self-interaction

Requires new force of nature that is only active  
in the dark sector.

"dark photons" transmit the interaction between  
SIDM particles

### △ Other - can always make up other DM candidates

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Modified gravity - change force law  
instead of invoking unseen mass