Frontiers in Astrophysics

Particle Astrophysics:

Cosmological Parameters, ΛCDM, extensions, particle cosmology

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Credit to Pat Scott for many of the slides

Introduction

- For those who don't know me:
- Ben Roberts – b.roberts@uq.edu.au
  - Room 6-427
  - Feel free to contact (email/blackboard) w/ Q's

- Work mostly in theoretical atomic physics
  - Particle astrophysics (using atomic sensors)
  - Searches for exotic physics
  - Dark matter direct detection

Overview

- **Today: Cosmological Parameters, ΛCDM, extensions, particle cosmology**
  - Brief overview, revision
- **Then: Astroparticle Physics, focusing on Dark Matter**
  - General properties, production
  - Direct detection
  - Indirect detection

Cosmological Parameters, ΛCDM

- **Cosmological Parameters, ΛCDM**
  - Brief overview, revision
  - How each are constrained, combined
- **Extensions**
  - General idea, brief look at a few examples
- **Particle Cosmology, Particle astrophysics**
  - Introduction, leading into next lectures
  - Extensions involve new particles: link cosmo. w/ particle

Particle cosmology

- phase transitions and topological defects
- baryogenesis and leptogenesis
- impacts of new particles on:
    - cosmological power spectra
    - the CMB and reionisation
    - Big Bang nucleosynthesis
    - stars and compact objects

Dark matter

- gravitational signatures
- cosmological production
- collider production
- direct detection
- indirect detection

Cosmic rays, compact objects and high-energy astrophysics

- Cosmic ray production (astrophysical particle acceleration)
- Cosmic ray propagation
- High-energy ν, γ-ray and proton/nuclear cosmic ray detection
- Neutron star equation of state

Particle cosmology

- phase transitions and topological defects
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Dark matter

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- indirect detection

Tomorrow

Next Week

Cosmic rays, compact objects and high-energy astrophysics

- Cosmic ray production (astrophysical particle acceleration)
- Cosmic ray propagation
- High-energy ν, γ-ray and proton/nuclear cosmic ray detection
- Neutron star equation of state

Wide field...

- Idea of these lectures:
- Very brief introduction to wide range
- Zoom in on a few aspects, particularly in later lectures
- Zoom in a little further in project/problems
- Please interrupt with Question/comments/discussion

Natural units

$$c = \hbar = k_B = 1$$
$$G = 1/M_{\mathrm{Planck}}^2$$

- Mass, energy: GeV
- Length, Time: GeV^{-1}
- Equations nicer
- Numerical: work with order ~1 quantities
  - (not always completely possible – example in project 3)
- Can be tricky to convert back to “observable” units
  - Be mindful of differing conventions etc.
- “Multiply by one” trick:
  - Multiply by any quantity that has value 1 in “from” units, and desired dimension in “to” units: combos of ħ, c, k

- Mass $m = \frac{E}{c^2} = E$ $[m] = \text{MeV}$
- Velocity $v \to \frac{v}{c}$ $[v] = 1$ (dimensionless)
- Momentum $p = mv$ $[p] = \text{MeV}$
- Distance $\Delta x = \frac{\hbar}{\Delta p}$ $[x] = \text{MeV}^{-1}$
- Time $\Delta t = \frac{\hbar}{\Delta E}$ $[t] = \text{MeV}^{-1}$
- $\frac{1}{1\,\text{fm}} = \frac{\hbar c}{1\,\text{fm}} = 197\ \text{MeV}$
- $\frac{1}{1\,\text{sec}} = \frac{\hbar}{1\,\text{sec}} = 0.658 \times 10^{-21}\ \text{MeV}$

$m_p \sim 1\,\text{GeV}$

Example: (Useful for Proj. 3)

$$\frac{\hbar c}{1\,\text{fm}} \approx 197.326\,\text{MeV}$$
$$\text{fm}^{-1} \approx 197.326\,\text{MeV}$$
$$\text{GeV} \approx 5.07 \times 10^{13}\,\text{cm}^{-1}$$

$$\boxed{\frac{\sigma v}{\text{GeV}^{-2}} = \frac{\sigma(v/c)}{\text{GeV}^{-2}} = \#}$$
$$= \frac{\sigma(v/c)}{\text{GeV}^{-2}} \times \frac{c}{3 \times 10^{10}\text{cm/s}} \times \frac{\text{GeV}^{-2}}{3.9 \times 10^{-28}\text{cm}^2}$$
$$= \frac{\sigma v}{\text{cm}^3\text{s}^{-1}} \times \frac{1}{1.17 \times 10^{-17}}$$

$$\sigma v = 1.17 \times 10^{-17} \boxed{\left[\frac{\sigma v}{\text{GeV}^{-2}}\right]} \text{cm}^3\text{s}^{-1}$$

Dimensionless number

Part 1:

ΛCDM & constraints

ΛCDM & constraints

ΛCDM

$\Omega_b h^2$	Baryon content of the Universe
$\Omega_{cdm} h^2$	Dark matter content of the Universe
H_0 $(100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}\,h)$	Hubble parameter (typically in $\mathrm{km\,s^{-1}\,Mpc^{-1}}$)
$\ln\left(10^{10} A_s\right)$	Amplitude of primordial scalar perturbations
n_s	Tilt of primordial scalar perturbations $\mathcal{P}(k) = A_s (k/k_\star)^{n_s - 1}$
τ_{reion}	Optical depth to $z_{\mathrm{reionisation}}$ (and thus to z_{CMB})

- **Covered P(k) with Holger, will cover reionisation next few weeks**
- **Many other combinations (m = b + c)**

ΛCDM & constraints

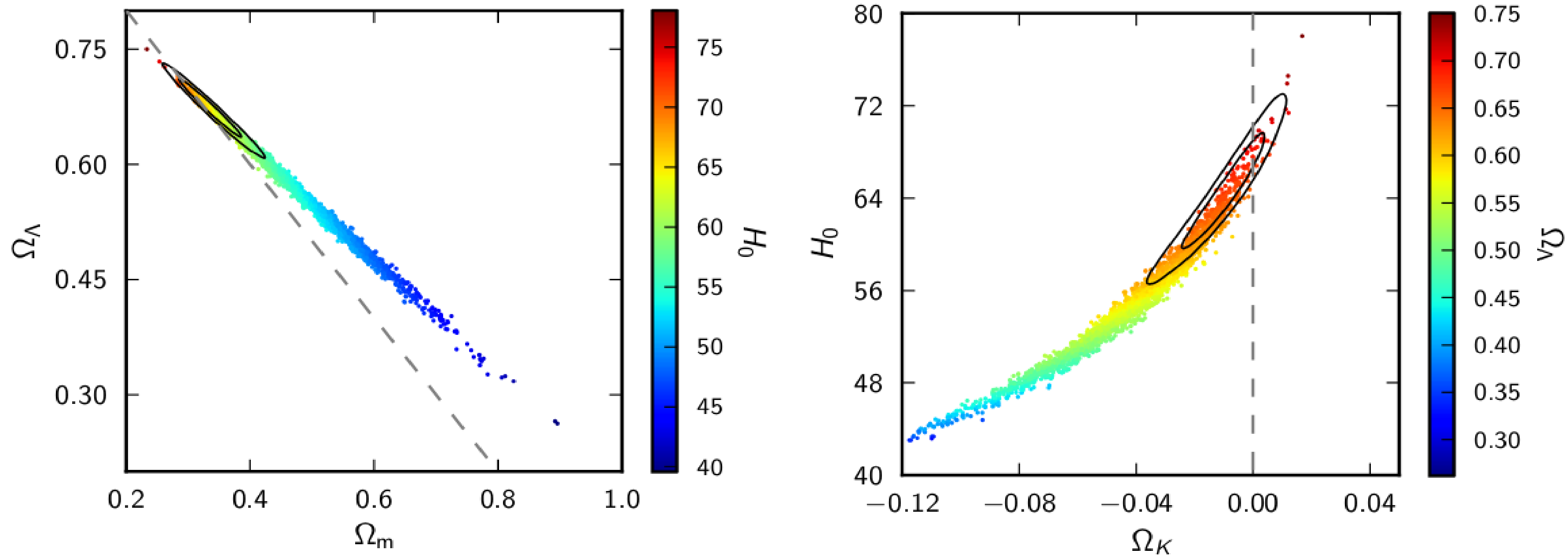
- What about Λ?
  - Simplest "flat" ΛCDM: makes assumption of flatness
  - $\Omega_k = 0; \Rightarrow \Omega_m + \Omega_\Lambda = 1$
  - Derived parameter
- Inflation?
  - Not intrinsic part of ΛCDM

ΛCDM does not *demand* inflation, just as it does not *demand* any particular CDM

– inflation is just an idea for getting the required spectrum on CMB scales
– any particular DM model is just an idea for getting CDM

ΛCDM constraints: CMB
Most important

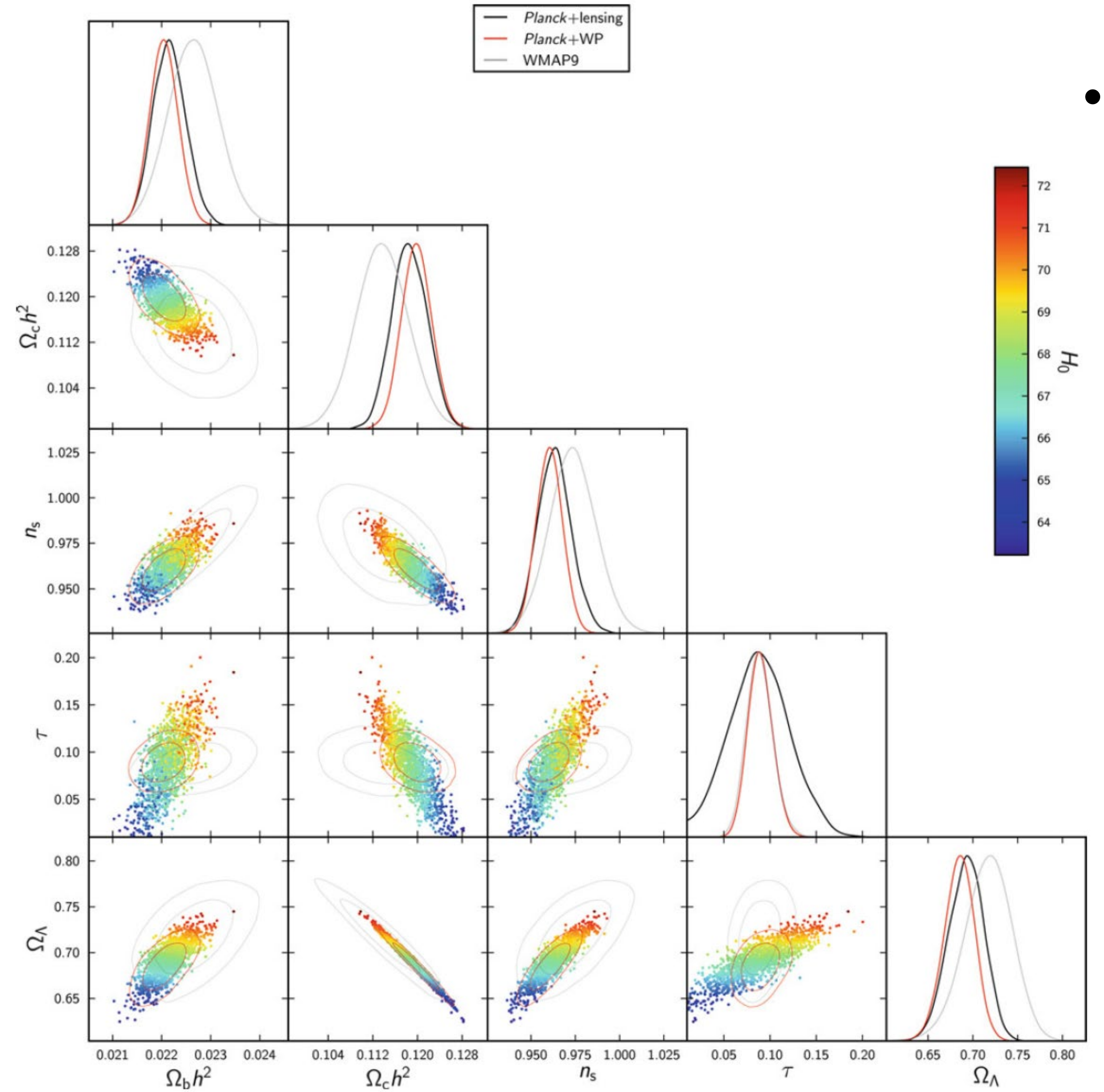
- Primarily sensitive to geometry of the Universe (flat/closed/open $\rightarrow \Omega_m + \Omega_\Lambda$)



- Plots from textbook: contours show CMB preferred region
- Dotted line: Flat universe ($\Omega_m + \Omega_\Lambda = 1$)
- Aligns very well: show universe is flat (better than each Ω_m, Ω_Λ)

Lecture with Cullan => Your current project

ΛCDM constraints: CMB



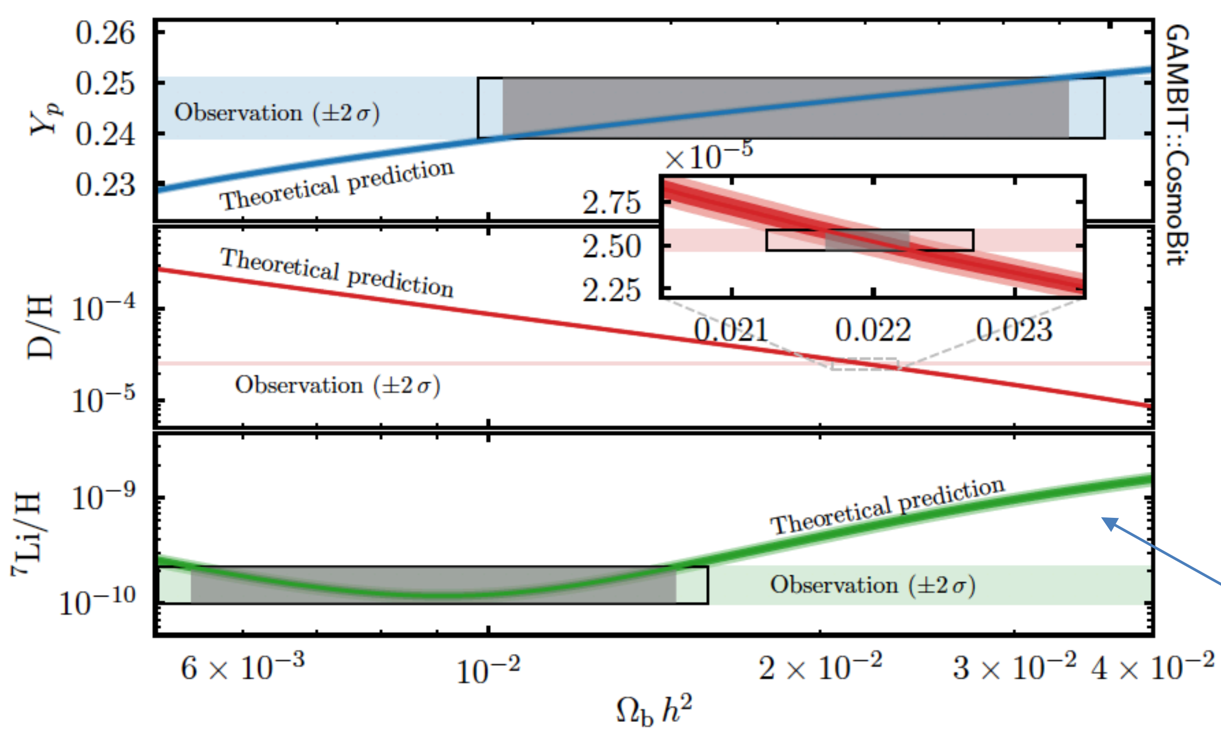
- CMB also allows measurement of many other parameters
  - τ: How much scattering between CMB and now
  - P(k), A, n: temperature anisotropy power spectrum + polarisation
  - (Data little out-of-data)

Lecture with Cullan => Your current project

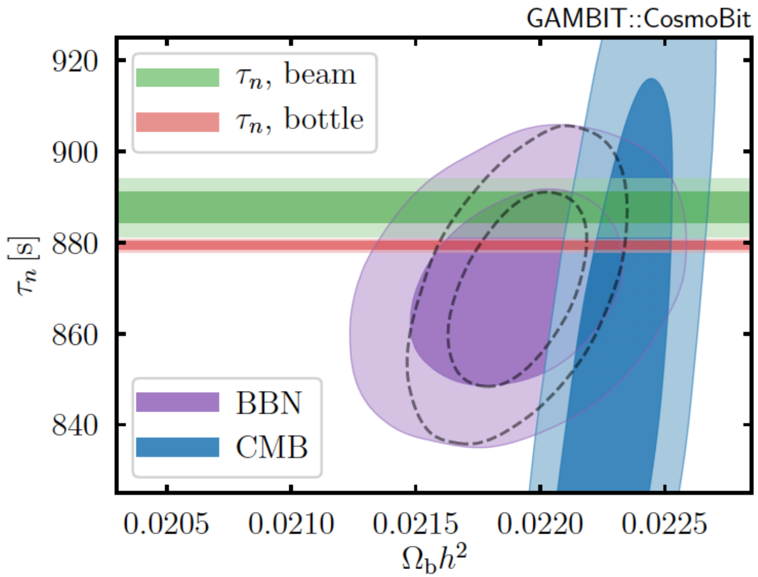
ΛCDM constraints: BBN
(Big-Bang Nucleosynthesis)

Abundances of light elements are very sensitive to number of baryons $\rightarrow \Omega_b$

- Yp: Helium abundance, D: deuterium (2-H)



Neutron lifetime



- Lithium problem
- (but more difficult)

More: Ch. 4 of Kolb & Turner (details well beyond scope of course)

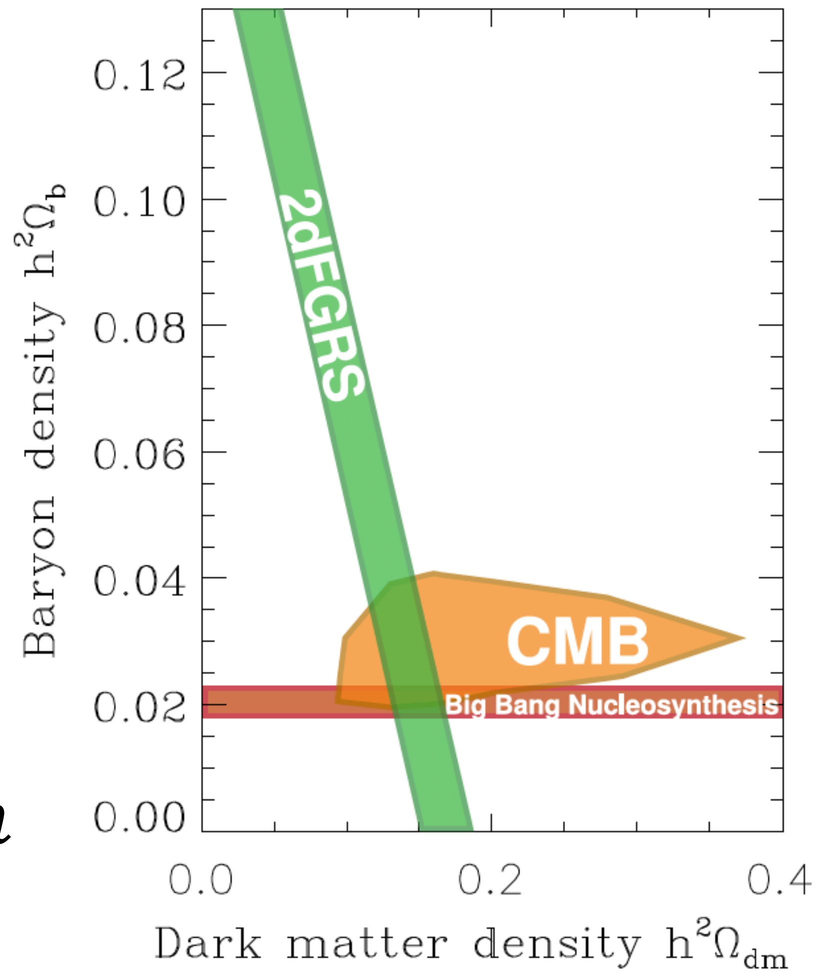
ΛCDM constraints: Galaxy/cluster counts

Counting galaxies essentially tells us how much matter there is
$\rightarrow$ constrains $\Omega_m h^2$

- See more in next few weeks

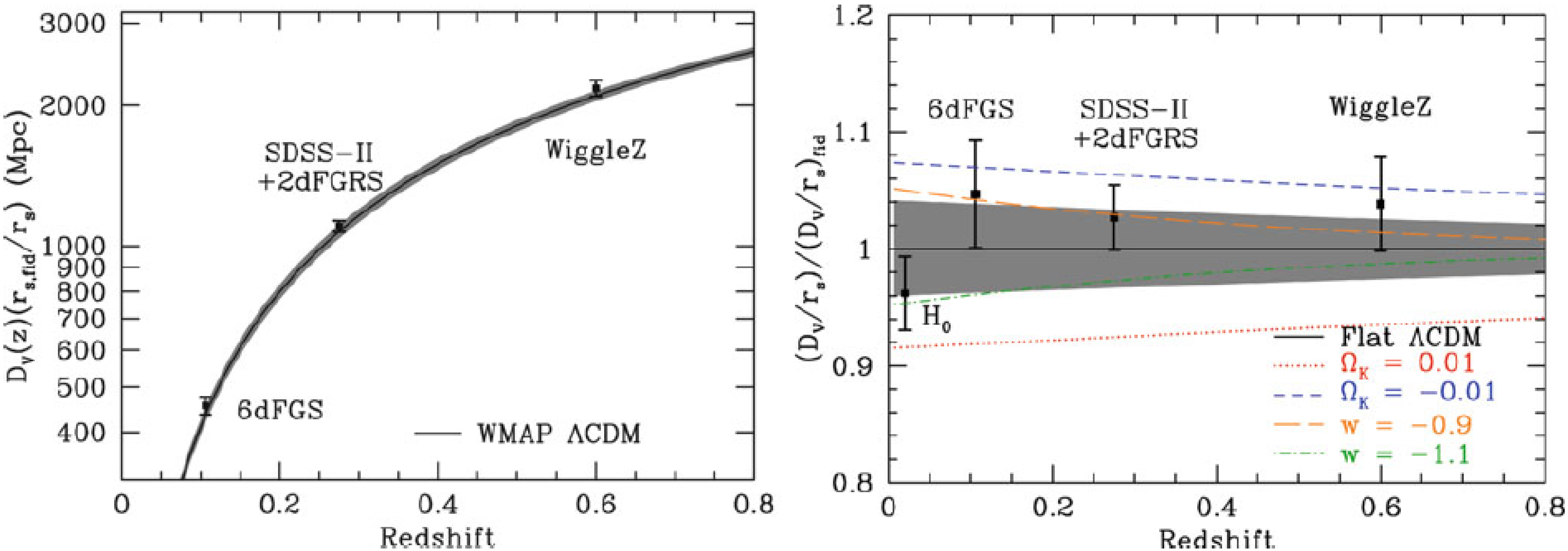
$$\Omega_{matter} = \Omega_{CDM} + \Omega_{baryon}$$

- Implies existence of dark matter



ΛCDM constraints: BAO

- BAO scale: standard rulers vs sound horizon at baryon drag epoch r_d
- Sensitive to everything that impacts expansion history, i.e. Ω_m, H_0.

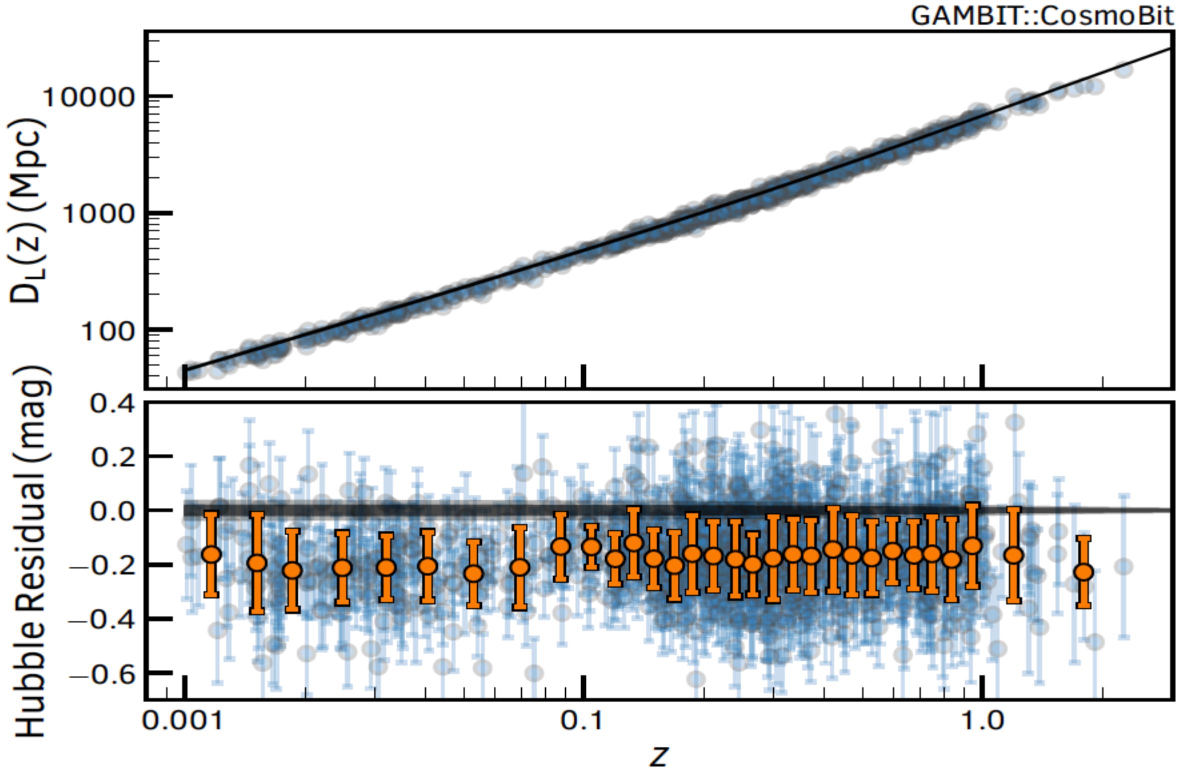


- Lecture with Khaled

Fig. 8.8 (Schneider)

ΛCDM constraints: Supernovae

Constrains expansion history → H_0, Ω parameters



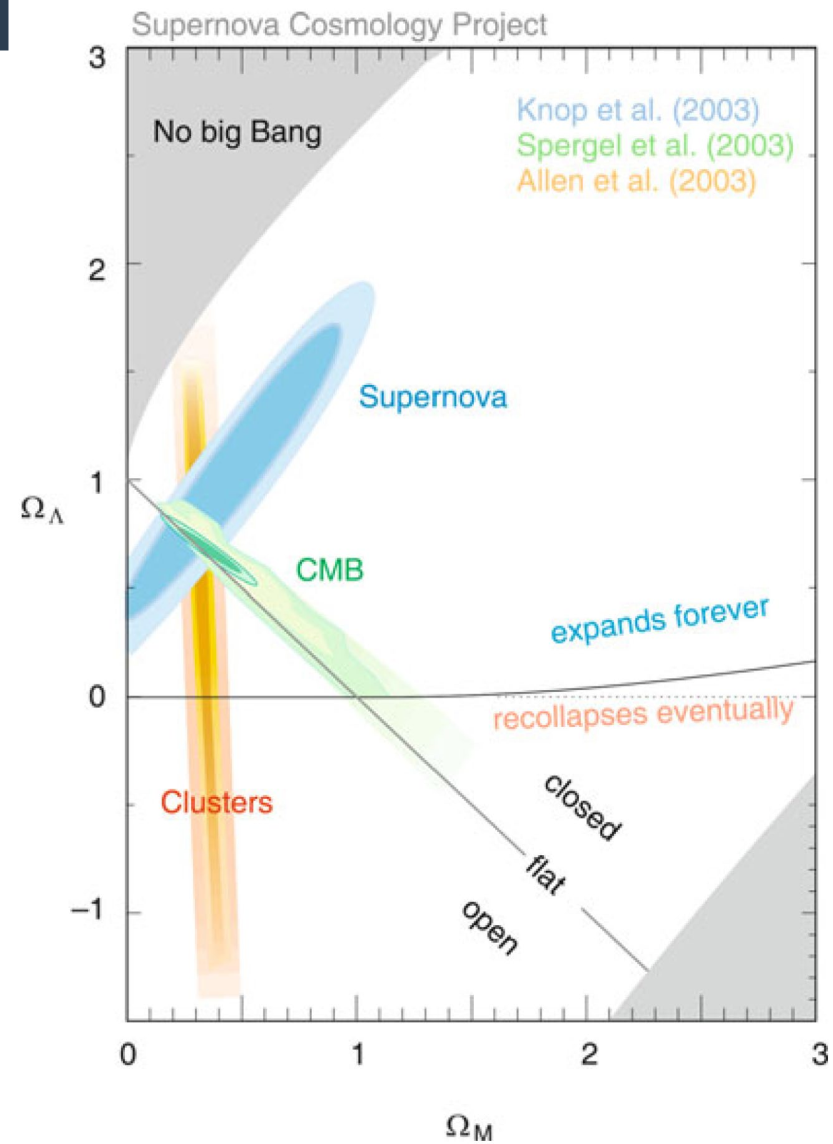
- Lectures with Tamara
- CMB (Planck) vs supernovae
  ← Hubble tension!

ΛCDM constraints: Combination

- Ω_b/Ω_m
  - Cluster counts, red-shift surveys, CMB fluctuations: ~0.015
- Ω_b
  - BBN, deuterium/helium abundance, CMB
- Ω_m
  - Galaxy distributions, CMB, + combination of above
- Curvature: k
  - CMB power spectrum peaks
- Ω_λ
  - K, with Ω_m

ΛCDM constraints: Combination

- Different observations depend on different combos
- Combined give current cosmology
- Essentially great agreement with standard ΛCDM
  - … except Hubble tension



	Description	Symbol	Value
Independent parameters	Physical baryon density parameter[a]	$\Omega_b h^2$	0.022 30 ±0.000 14
	Physical dark matter density parameter[a]	$\Omega_c h^2$	0.1188 ±0.0010
	Age of the universe	t_0	$13.799 \pm 0.021 \times 10^9$ years
	Scalar spectral index	n_s	0.9667 ±0.0040
	Curvature fluctuation amplitude, $k_0 = 0.002\ \mathrm{Mpc}^{-1}$	Δ^2_R	$2.441^{+0.088}_{-0.092} \times 10^{-9}$[22]
	Reionization optical depth	τ	0.066 ±0.012
Calculated values	Hubble constant	H_0	67.74 ± 0.46 km s^{-1} Mpc^{-1}
	Baryon density parameter[b]	Ω_b	0.0486 ±0.0010[e]
	Dark matter density parameter[b]	Ω_c	0.2589 ±0.0057[f]
	Matter density parameter[b]	Ω_m	0.3089 ±0.0062
	Dark energy density parameter[b]	Ω_Λ	0.6911 ±0.0062
	Critical density	ρ_{crit}	$(8.62 \pm 0.12) \times 10^{-27}$ kg/m^3[g]
	The present root-mean-square matter fluctuation averaged over a sphere of radius $8h^{-1}$ Mpc	σ_8	0.8159 ±0.0086
	Redshift at decoupling	z_*	1 089.90 ±0.23
	Age at decoupling	t_*	377 700 ±3200 years[22]
	Redshift of reionization (with uniform prior)	z_{re}	$8.5^{+1.0}_{-1.1}$[23]

Part 2:

Extensions

Extensions

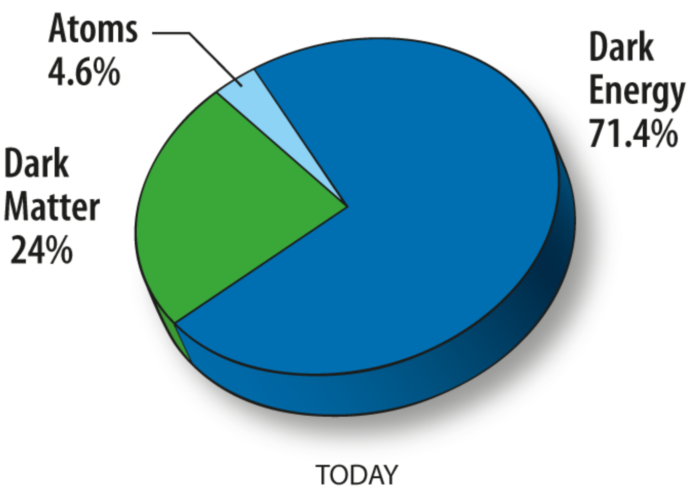
- Many (infinite) possible extensions
  - Each could constitute entire lecture/course
- Many are tightly constrained by observation
- Careful in analysis: often analysis done assuming ΛCDM (sometimes have to make assumptions)
- But when trying to constrain beyond-ΛCDM parameters, this can clearly lead to errors
  - Your project 2

Extensions: DE + curvature

- You can allow non-zero curvature $\Omega_k \neq 0$
- Can also postulate dark energy is not cosmological constant

$\Longrightarrow$ $w \neq -1$ in $\rho_{\mathrm{DE}} = \rho_{\mathrm{DE},0} a^{-3(1+w)}$

$\Longrightarrow$ "wCDM" with w a free parameter

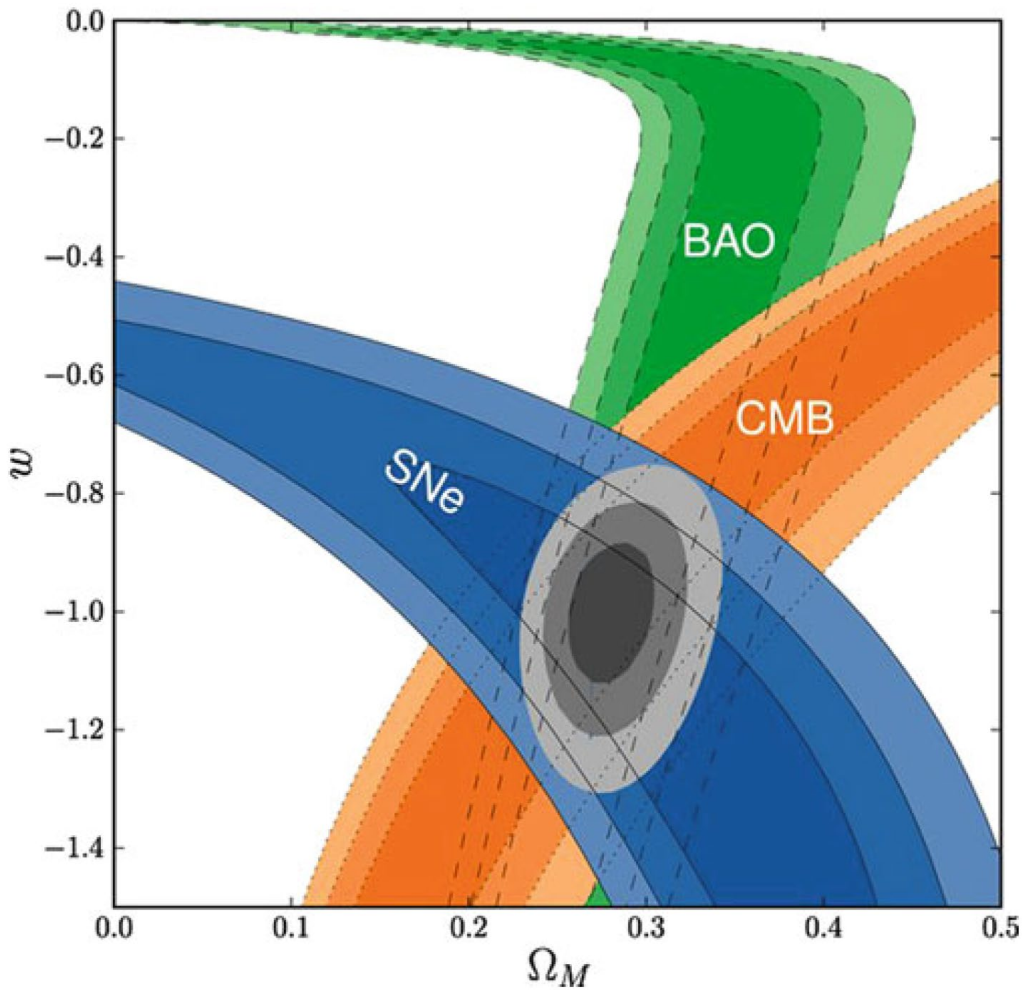


$$Why\ \rho_b \sim \rho_\Lambda \sim \rho_c\ ?$$

$$P_{\mathrm{DE}} = w \rho_{\mathrm{DE}} c^2$$

DE density
changes with time

Extensions: DE



$$P_{\rm DE} = w\rho_{\rm DE}c^2$$

Tightly constrained by observations

Equation of state of dark energy	w	–0.980 ±0.053

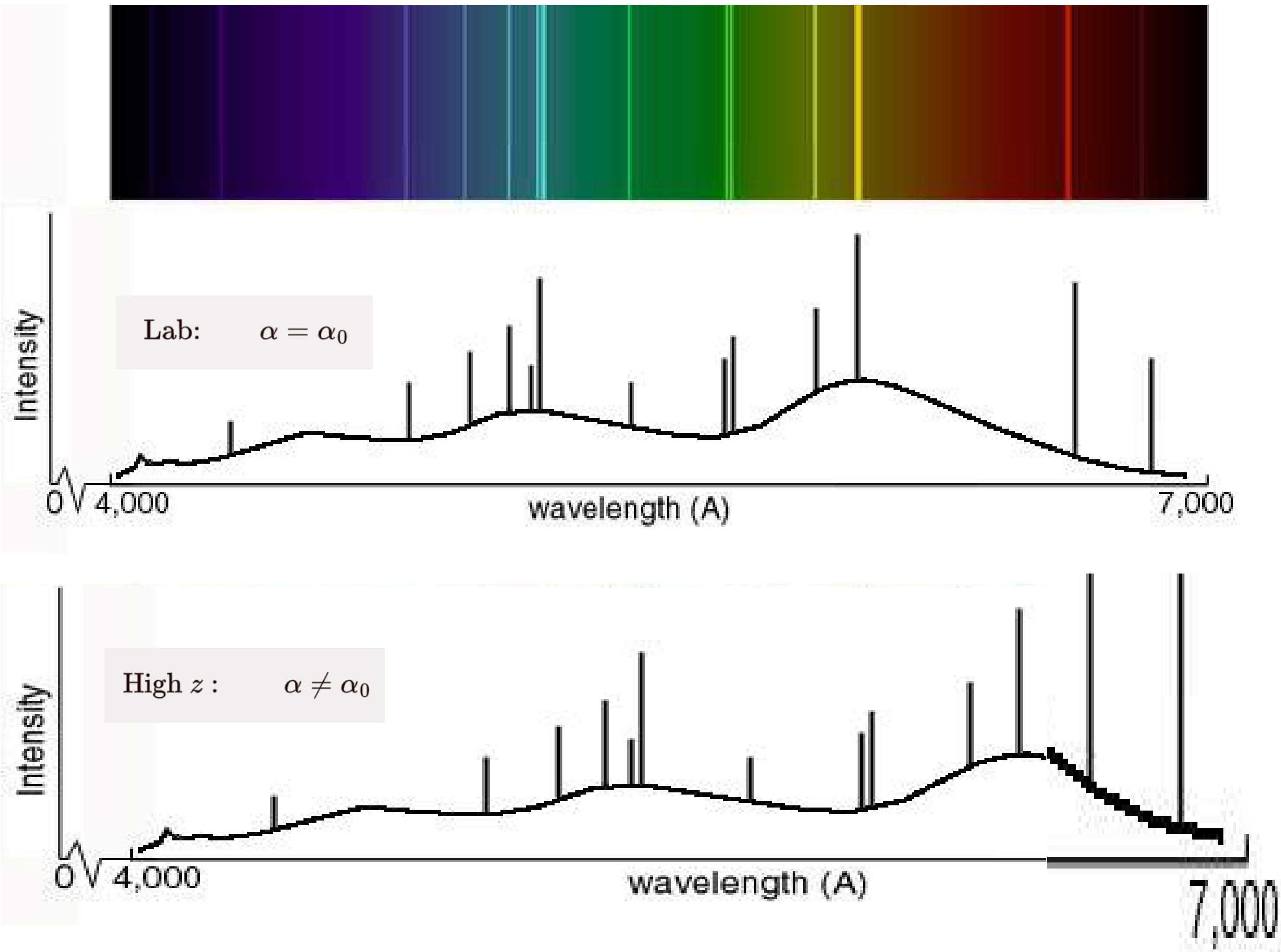
eg: Variation of fundamental constants

- If certain constants were even slightly different: no atoms, no planets, no life..
- (No researchers to ask the question)
- Fine tuning problem
- Perhaps take different values long ago, or far away

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \approx \frac{1}{137}$$

- How to test?

Atomic Absorption Lines, large z

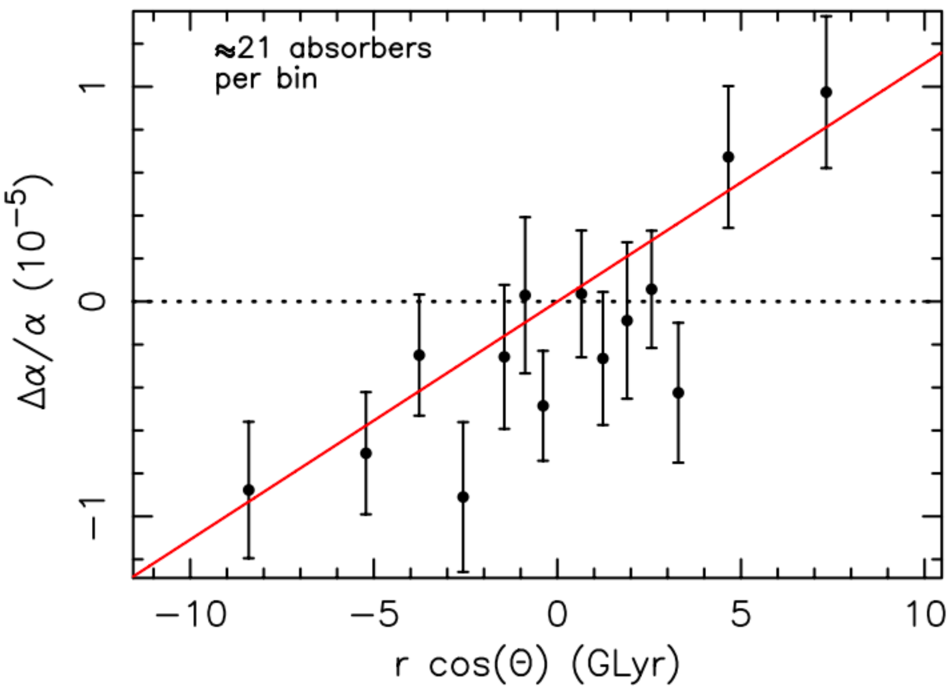


- Compare lab to high-z
- Fit for z and shift
- Requires atomic calculations

Variation of fine structure constant

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \approx \frac{1}{137}$$

- Atomic energy levels: absorption spectra
- Quasar absorption: measure α at large z
- Hint for variation (hard to rule out systematics)



J. K. Webb, J. A. King, M. T. Murphy, V. V. Flambaum, R. F. Carswell, and M. B. Bainbridge, Phys. Rev. Lett. **107**, 191101 (2011).

- In theory: Can measure in lab!
- Earth revolves around sun: large ΔR
- Need clocks good to $\sim 10^{-21}$

e.g.: Deviation from GR

- Many models for non-GR gravity
  - E.g., scalar-tensor theories
  - Some quantum, some classical (effective)

- Motivation: Quantum theory of Gravitation
- Motivation: Dark matter + dark energy

- Very tightly constrained in some circumstances
  - But hard to do on very weak scales

New particles

- New models often imply new particles

  - impacts of new particles on:
    - cosmological power spectra
    - the CMB and reionisation
    - Big Bang nucleosynthesis
    - stars and compact objects

- Constrain new-physics models
  - Require calculations of particle interactions

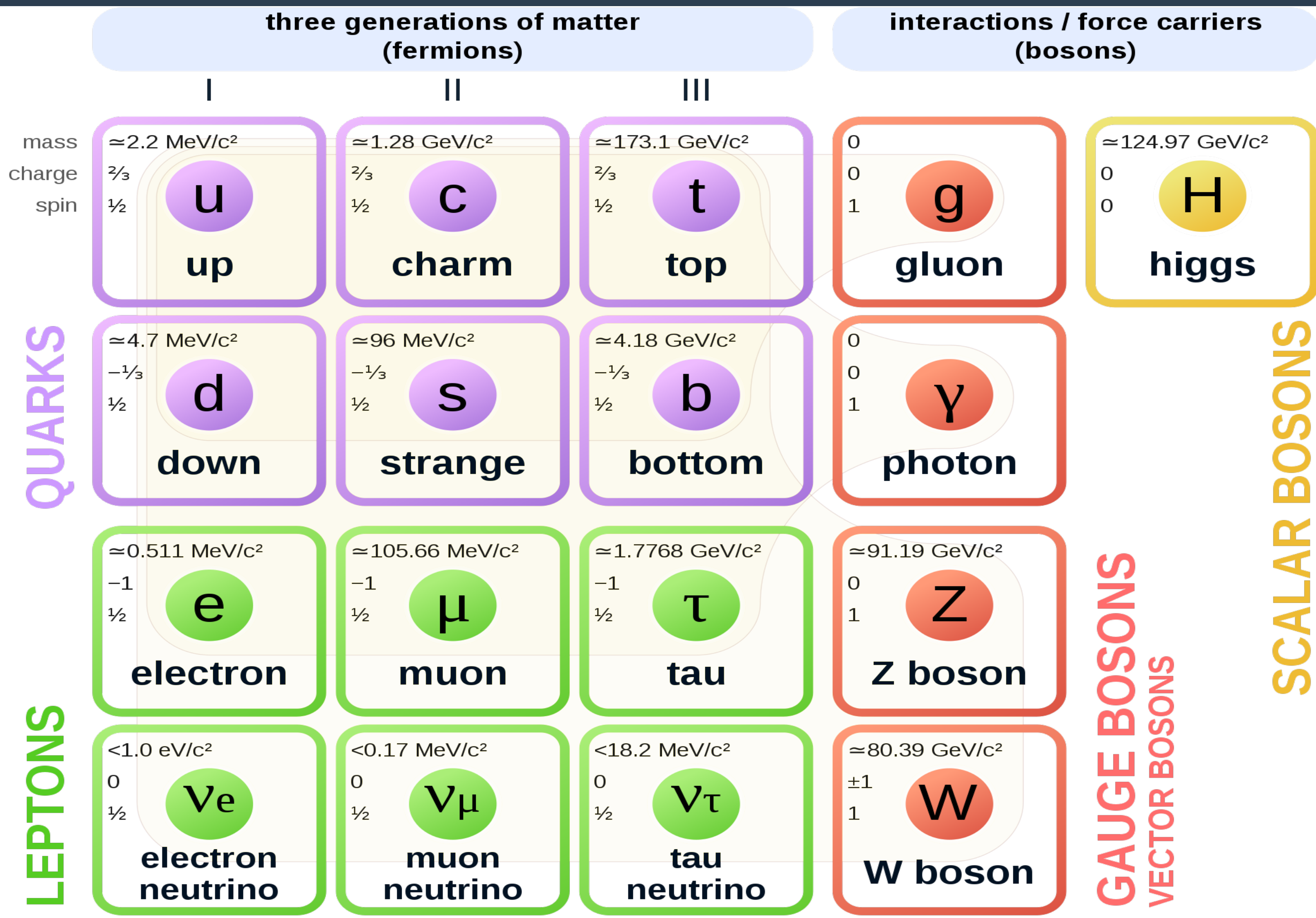
Extensions

- Covered just a few of simplest extensions
  - Possibilities are essentially infinite..

- However, combination of observables (CMB, BBN, LHC etc.) place tight constraints

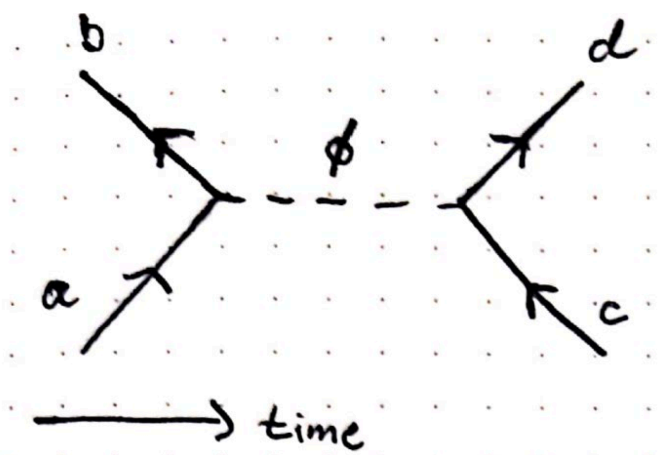
- Many ways to hunt for and constrain them!

Particle Physics 101:

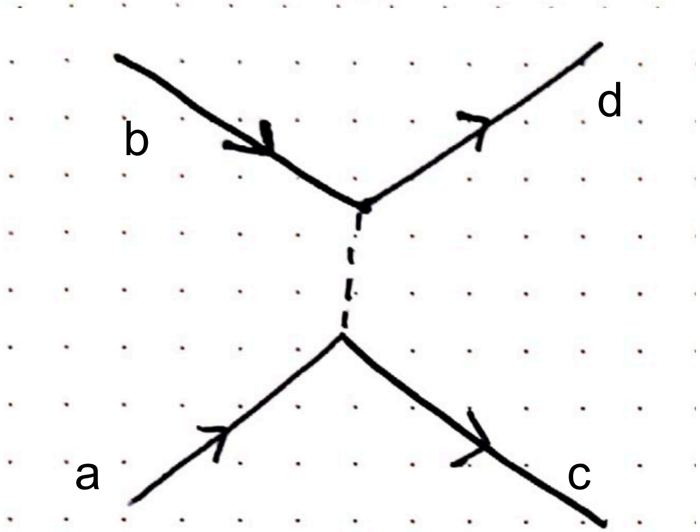


Particle Interactions

- Interactions mediated by particle exchange



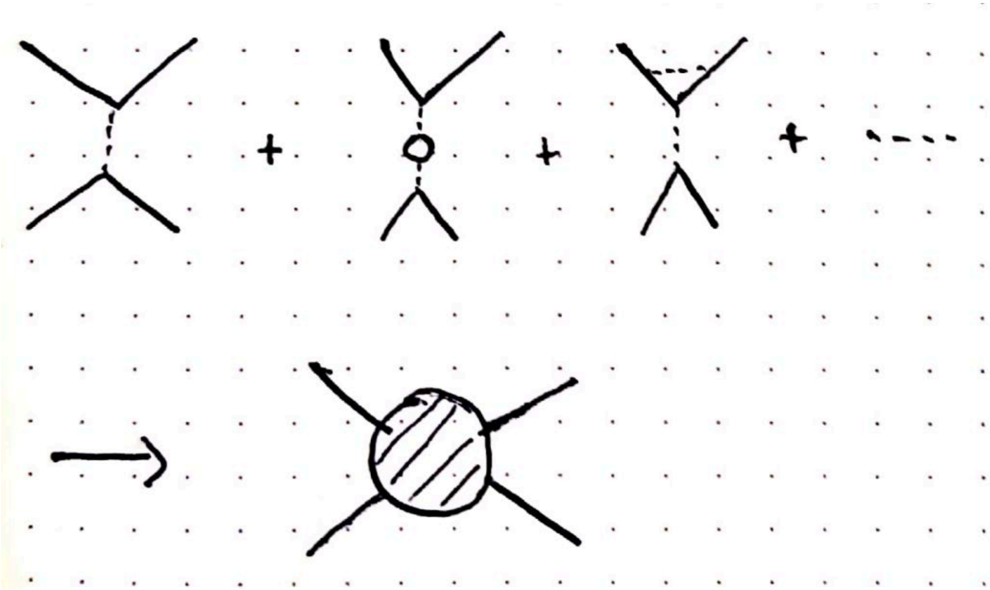
- a,b annihilate, producing c,d
- Mediated by ϕ particle



- Initial state (a,b) scatter
- Form final state (c,d)

- Calculate:
  - Vertex factor (interactions)
  - Propagator (exchange particle)

Particle Interactions: simplified



- In general: consider all possible interactions
- Often: can simplify
  - Effective interaction

- Effective interaction:
  - Can be calculated (e.g., non-rel limit)
  - Can be simply observed (treat as unknown observable)

Interaction rates, cross-sections

$$R = n\, v\, \sigma \times N_{\text{target}}$$

- Rate parameterised via cross-section, σ
- n is volume density of projectiles
- Can think of this as definition of σ
- σ Calculated using QM, QFT

$$\frac{d\sigma}{d\Omega} \qquad \frac{d\sigma}{d(q^2)} \qquad \frac{d\sigma}{dE}$$

- Next lecture: Dark Matter