The standard model of cosmology: $\Lambda$CDM

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Slides available from

www.physics.mcgill.ca/~patscott
Cosmological Models

2 CDM – Background
- Evidence and models
- Dark matter detection

3 CDM – Selected results
- Indirect detection
- Multimessenger particle physics: global fits
- Effects of dark matter on stars
Outline

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The Friedmann Equation

Take the Einstein Equation from General Relativity:

\[ G_{\mu\nu} = 8\pi T_{\mu\nu} + \Lambda g_{\mu\nu}. \]  \hspace{1cm} (1)
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Assume the Universe to be isotropic and homogeneous
\[ \implies \text{Friedmann-Robertson Walker (FRW) metric:} \]

\[ g_{\mu\nu} x^\mu x^\nu = dt^2 + R(t)^2 \left( \frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right). \] (2)
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Solve \( \mu = 0, \nu = 0 \) of (1) \( \Rightarrow \) Friedmann Equation:

\[ H(t) \equiv \frac{\dot{R}(t)}{R(t)} = \frac{8\pi G}{3} \rho(t) - \frac{k}{R(t)^2}. \]  
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Solving this gives Hubble parameter $H(t)$ for some
- energy density-scalefactor relation $R(t) = f(\rho(t))$
- curvature $k \in \{+1, 0, -1\}$
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**Critical density:**
For a flat Universe $k = 0$. This defines

- *critical density:* $\rho_c \equiv \frac{3H(t)}{8\pi G}$
- *cosmological density:* $\Omega_x \equiv \frac{\rho_x}{\rho_c}$
Equations of state:

1st law of thermodynamics ($\mu = 0$ in conservation of $T_{\mu \nu}$) is

$$d(\rho R^3) = -p d(R^3), \quad \text{i.e. } \Delta E = -p \Delta V$$

with a constant equation of state $\rho = wp$, we get energy density-scalefactor relations

$$\rho \propto R^{-3(1+w)}$$

For different types of energy:

- **Matter:** $w = 0 \quad \implies \quad \rho \propto R^{-3}$
- **Radiation:** $w = 1/3 \quad \implies \quad \rho \propto R^{-4}$
- **Vacuum ($\Lambda$):** $w = -1 \quad \implies \quad \rho \propto \text{constant}$

This is basically enough to solve the Friedmann Equation.
### Ingredients of $\Lambda$CDM

#### Ingredients required for a cosmological model

- **A theory of gravity**
- **+ associated assumptions**
- **Types of energy**
- **their equations of state**
- **their (self-)interactions**
- **An initial spectrum of perturbations**

#### Choices in $\Lambda$CDM

- **GR**
- **+ isotropy, homogeneity**
- **radiation, matter, vacuum/dark energy**
- **$w = 1/3, 0, −1$/other**
- **photons, baryonic (SM) matter**
- **+ cold dark matter (CDM), ??**
- **approximately scale invariant on large scales**
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Question

Isn’t inflation part of the ΛCDM model?

Answer

Not really, no. Approximately scale-invariant spectrum of perturbations to start with, on CMB scales (small $k$)? Yes. Due to inflation by definition? No. $P_δ(k) \propto P_R(k) \propto k^{n_s-1} + \alpha \log \frac{k}{k_0}$ (7)

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...
An aside: inflation

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Cosmological probes & ‘concordance cosmology’

Joint fit to multiple cosmological observables gives a consistent set of parameter values:

\[ \Omega_\Lambda \approx 0.73 \]
\[ \Omega_{\text{matter}} \approx 0.27 \]
\[ \Omega_{\text{CDM}} \approx 0.23 + \Omega_{\text{baryons}} \approx 0.04 \]
\[ \rightarrow \Lambda CDM \]
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(I follow a similar global fit strategy to hunt for DM and particle theories beyond the SM)
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How we know dark matter exists

The only way to consistently explain:

1. rotation curves + vel. dispersions
2. gravitational lensing
3. cosmological data

- Large-scale structure (2dF/Chandra/SDSS-BAO) says $\Omega_{\text{matter}} \approx 0.27$
- BBN says that $\Omega_{\text{baryonic}} \approx 0.04$
- $\Rightarrow \Omega_{\text{non–baryonic}} \approx 5 \times \Omega_{\text{baryons}}$
- CMB (WMAP) and SN1a agree; also indicate that $\Omega_{\text{total}} \approx 1$
- $\Rightarrow$ universe is 23% dark matter, 4% baryonic (visible) matter, 73% something else
What we know about it

**Must be:**
- massive (gravitationally-interacting)
- unable to interact via the electromagnetic force (dark)
- non-baryonic
- “cold(ish)” (in order to allow structure formation)
- stable on cosmological timescales
- produced with the right relic abundance in the early Universe.

**Good options:**
- Weakly Interacting Massive Particles (WIMPs)
- sterile neutrinos
- gravitinos
- axions
- hidden sector dark matter (e.g. WIMPless dark matter)
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- MAssive Compact Halo Objects (MACHOs)
- standard model neutrinos
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The standard model of cosmology: $\Lambda$CDM
WIMPs at a glance

- Dark because no electromagnetic interactions
- Cold because very massive ($\sim 10$ GeV to $\sim 10$ TeV)
- Non-baryonic and stable - no problems with BBN or CMB
- Weak-scale annihilation cross-sections *naturally* lead to a relic abundance of the right order of magnitude

(Kolb & Turner 1990)
WIMPs at a glance

- Many theoretically well-motivated particle candidates
  - Supersymmetric (SUSY) neutralinos $\chi$ if $R$-parity is conserved - lightest mixture of neutral higgsinos and gauginos
  - Inert Higgses - extra Higgs in the Standard Model
  - Kaluza-Klein particles - extra dimensions
  - Right-handed neutrinos, sneutrinos, other exotic things...

- Weak interaction means scattering with nuclei $\rightarrow$ detection channel
- Many WIMPs are Majorana particles (own antiparticles) $\implies$ self-annihilation cross-section
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The standard model of cosmology: ΛCDM
Ways to detect WIMPs

- Direct detection – nuclear collisions and recoils – CDMS, XENON, DAMA, CRESST, CoGeNT
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Your favourite photodetector

something very reflective
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![Diagram showing direct detection of WIMPs]
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- Indirect detection – annihilations producing
  - gamma-rays – Fermi, HESS, CTA
  - anti-protons – PAMELA, AMS
  - anti-deuterons – GAPS
  - neutrinos – IceCube, ANTARES
  - $e^+ e^−$ – PAMELA, Fermi, ATIC, AMS
    → secondary radiation: Compton$^{-1}$, synchrotron, bremsstrahlung
  - secondary impacts on the CMB
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Finding dark matter with neutrino telescopes

The cartoon version:

1. Halo WIMPs crash into the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core
4. Annihilate with each other, producing neutrinos
5. Propagate+oscillate their way to the Earth, convert into muons in ice/water
6. Look for Čerenkov radiation from the muons in IceCube, ANTARES, etc
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The IceCube Neutrino Observatory

- 86 strings
- 1.5–2.5 km deep in Antarctic ice sheet
- \( \sim 125 \) m spacing between strings
- \( \sim 70 \) m in DeepCore (10\( \times \) higher optical detector density)
- 1 km\(^3\) instrumented volume (1 Gton)
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Graphs showing predicted signal events and log\(10(\sigma_{SD,p}/\text{cm}^2)\) with IC22 × 100, flat priors, CMSSM \( \mu > 0 \), and marginalized posterior.

PS, Savage, Edsjö & The IceCube Collaboration, arxiv:1207.0810
Gamma-rays from dark matter

- 3 main gamma-ray channels:
Gamma-rays from dark matter

- 2 photons (or Z+photon): monochromatic lines
- Internal bremsstrahlung (FSR + VIB)
- Continuum from secondary decay

3 main gamma-ray channels:
- Monochromatic lines

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The standard model of cosmology: $\Lambda$CDM
Gamma-rays from dark matter

- 2 photons (or Z+photon): monochromatic lines
- Internal bremsstrahlung: hard gamma-ray spectrum

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\[ \Phi \propto \text{annihilation rate} \propto \rho_{\text{DM}}^2 \]

Likely targets:

- Galactic centre - large signal, large BG
- Galactic halo - moderate signal, moderate BG
- Dwarf galaxies - low statistics, low BG
- Clusters/extragalactic diffuse - large modelling uncertainties, low signal, low BG
- Dark clumps - low statistics, low BG
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Hooper & Linden, arXiv:1110.0006
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Scott et al. 2009
PS, Conrad, Edsjö et al, *JCAP* 2010
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An example of dark clumps: Ultracompact minihalos

Question
What is an *ultracompact* minihalo (UCMH)?

Answer
A DM halo that collapses shortly after matter-radiation equality. ‘Shortly’ means $z_{\text{collapse}}$ is $O(100)$ or more (vs $z_{\text{eq}} \sim 3000$) $\Rightarrow$ isolated collapse $\Rightarrow$ formation by radial infall $\Rightarrow$ very steep density profile $\rightarrow \rho \propto r^{-9/4}$ $\Rightarrow$ excellent indirect detection targets. Also good lensing prospects.


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Scott & Sivertsson *Phys. Rev. Lett.* 2009

Lacki & Beacom *ApJL* 2010
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How would UCMHs be created?

Answer

- Large amplitude density perturbations in the early Universe (e.g. on small scales)
- Small-scale power in primordial perturbation spectrum (e.g. features in the potential associated with inflation)
- Phase transitions
- Other seeds (e.g. cosmic strings)
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Limits on $\mathcal{P}_R$ from gamma-ray searches for UCMHs $\sim$5 orders better than from PBHs
$\implies$ strong limits on inflationary models
Implications for cosmology

Impacts on inflation:

Limits on non-Gaussianities:

- Hierarchical Scaling
  \[ k = 2 \times 10^3 \text{ Mpc}^{-1} \]

- Excluded by UCMHs
- Excluded by PBHs

\[ M_3 (k) \]

\[ \log_{10} [P_{\delta, \text{Gaussian}} (k)] \]

- \( z_c = 200 \)
- \( z_c = 1000 \)

\[ \alpha \equiv \frac{d \ln n_s}{d \ln k} \]

- Not visible
- Visible in \( \gamma \) rays

- Slow roll
- WMAP5
- WMAP7+SPT

- Scale-free spectrum

\[ n_s \]

- \( m_\chi = 10 \text{ GeV} \)
- \( m_\chi = 1 \text{ TeV} \)
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Putting it all together

Base Observables
(relic density, $B$-physics, LEP, etc.)

Contours indicate $1\sigma$ and $2\sigma$ credible regions
Shading + contours indicate relative probability only, not overall goodness of fit
Putting it all together

Base Observables + XENON-100

Grey contours correspond to Base Observables only

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Base Observables + XENON-100 + CMS 5 fb$^{-1}$

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Base Observables + XENON-100 + CMS 5 fb⁻¹ + IC22 × 100

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IceCube-22 with 100× boosted effective area (kinda like final IceCube)
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6. Look for Čerenkov radiation from the muons in IceCube, ANTARES, etc
The cartoon version:

1. Halo WIMPs crash into the Sun stars
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core
4. Annihilate with each other, producing neutrinos

The standard model of cosmology: \( \Lambda \)CDM
Reminder:

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4. Annihilate with each other, producing neutrinos + other energetic particles
5. Particles dump their energy in the stellar core
6. Stellar structure responds, star evolves accordingly
Stellar evolution with dark matter annihilation

log_{10}(\rho_x/\text{GeV cm}^{-3}) = -5
log_{10}(\rho_x/\text{GeV cm}^{-3}) = 9
log_{10}(\rho_x/\text{GeV cm}^{-3}) = 10
ZAMS

Luminosity, log_{10}(L/L_{\odot})

Effective (surface) temperature, log_{10}\left(\frac{T_{\text{eff}}}{K}\right)

Z = 0.01
Finding ‘dark stars’

- Best candidates have low masses, near Galactic Centre
- First stars also good targets
- Maybe visible with JWST (if lensed), or by impacts on reionisation

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PS, Fairbairn, Edsjö, *MNRAS* 2009

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The standard model of cosmology: $\Lambda$CDM
Summary

- $\Lambda$CDM currently rests on CDM being some new particle – but what??
- There are many complementary ways to find out!
- Indirect detection generally probes masses and annihilation channels
- Stellar evolution can test both annihilation and interactions with quarks
- Ultracompact minihalos present an exciting way to also probe cosmology at the same time
- The different probes can (and should) be put together into global fits to gain a consistent picture. This will be required for a credible detection to be claimed!
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Extras 1: DarkStars code

- Lots of options and switches: different velocity distributions, widths, stellar orbits, WIMP conductive transport / internal distribution schemes, particle data, stellar masses and metallicities, numerical options...

- Save and restart - good for evolving part-way then trying different late-stage scenarios

- DarkStars 2.0 coming soon: conversion to full $Z = 0$ (new opacities, equation of state) – DarkStars 1.03 can only do $Z = 0$ on pre-MS

- Future options for expansion to include alternative form factors and/or WIMP evaporation

- DarkStars 1.03 publicly available from http://www.physics.mcgill.ca/~patscott/darkstars

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The standard model of cosmology: $\Lambda$CDM
Model: focus has mostly been on the Constrained MSSM (CMSSM)

- GUT boundary conditions on soft SUSY breaking parameters such that only 4 free parameters and 1 sign remain
- includes the simplest implementation of mSUGRA

\[ m_0 \quad \text{scalar mass parameter} \]
\[ m_1^2 \quad \text{gaugino mass parameter} \]
\[ \tan \beta \quad \text{ratio of Higgs VEVs} \]
\[ A_0 \quad \text{trilinear coupling} \]
\[ \text{sgn } \mu \quad \text{Higgs mass parameter} \]
(\(+ve \text{ in our scans}\))

Just a testbed framework – all techniques are applicable to any MSSM parameterisation