Five lectures on

INTRODUCTION TO COSMOLOGY

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Lecture 1: The large picture

observations, cosmological principle, Friedmann model, Hubble diagram, thermal history

Lecture 2: From quantum to classical

cosmological inflation, isotropy & homogeneity, causality, flatness, metric & matter fluctuations

Lecture 3: Hot big bang

radiation domination, hot phase transitions, relics, nucleosythesis, cosmic microwave radiation

Lecture 4: Cosmic structure

primary and secondary cmb fluctuations, large scale structure, gravitational instability

Lecture 5: Cosmic substratum

evidence and candidates for dark matter and dark energy, direct and indirect dm searches

Minimal model: Where do we stand?

globular cluster age	✓
SN 1a Hubble diagram	✓
CMB spectrum	✓
light element abundance	✓
CMB temperature & polarisation anisotropies	✓
galaxy redshift surveys	✓
...	

BUT we don't understand what we are fitting

Conceptional problems of the minimal model

- no theory for vacuum energy density, i.e. cosmological constant;
(cosmological constant problem)

- why is $\Omega_\Lambda(t_0) \sim \Omega_{\rm m}(t_0)$?
(coincidence problem)

- why is $\Omega_{\rm b}(t_0) \sim \Omega_{\rm cdm}(t_0)$?
(another coincidence problem)

Cosmological constant problem

$\Lambda_{\rm gr}$ free parameter of gr

$\Lambda_{\rm qft} \equiv 8\pi G\epsilon_{\rm V}$ to be calculated from quantum field theory
flat space-time: normal ordering puts $\epsilon_{\rm V} = 0$ in true vacuum
qft in curved space-time not sufficiently understood to predict a value

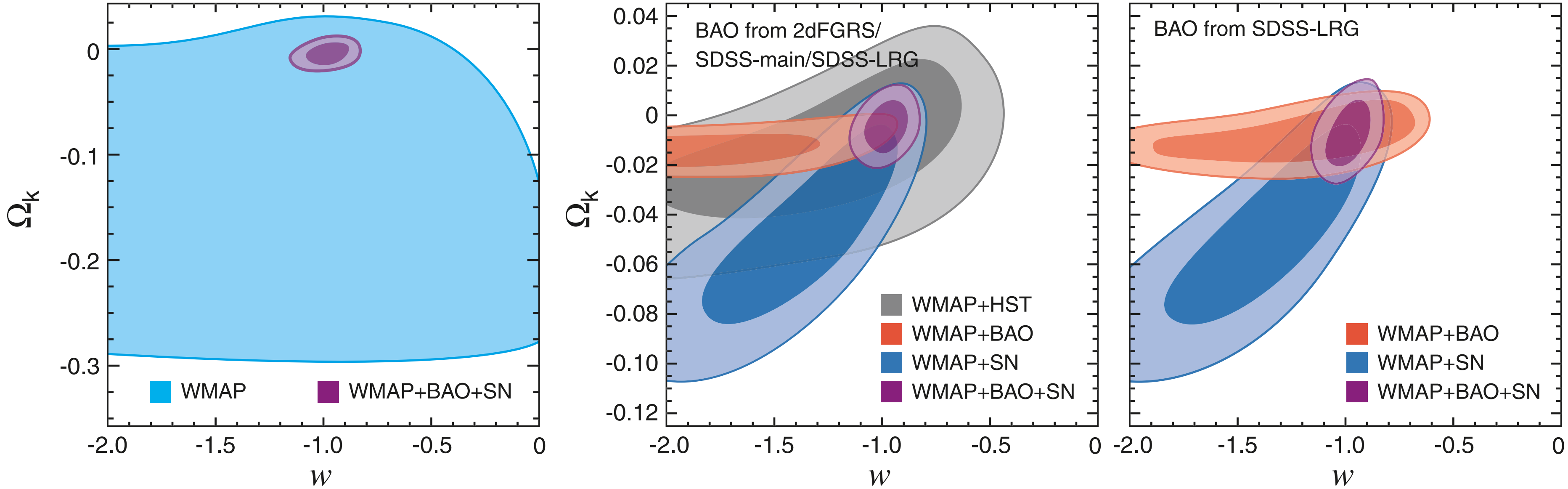
$$\Lambda_{\rm obs} \equiv \Lambda_{\rm gr} + \Lambda_{\rm qft} \sim H_0^2 \approx 10^{-122} M_{\rm P}^2$$

is that natural?
important physics is missing

Cosmological constant vs. more general dark energy

for flat cosmology and constant $w_{\rm de} = p_{\rm de}/\epsilon_{\rm de}$: $w = -0.972^{+0.061}_{-0.060}$

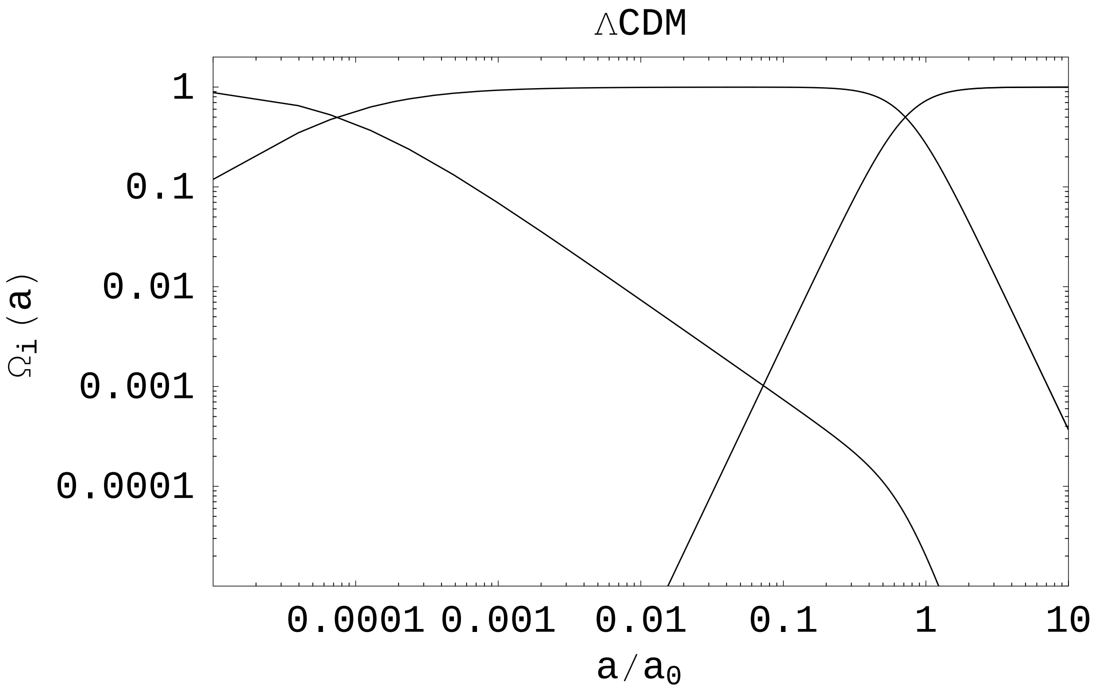
curved cosmology:



CMB, H_0, SN, BAO

Komatsu et al. 2008

Coincidence problem



We seem to observe the universe at a very special moment. Why?

Ideas to solve the coincidence problem

dynamic de: quintessence/k-essence − another scalar field
make the dynamics trace dominant component (tracker solutions)
acceleration, weakens coincidence, $w \neq -1$

unified de/dm: e.g. generalised Chaplygin gas
no compelling physics, acceleration, may solve the coincidence

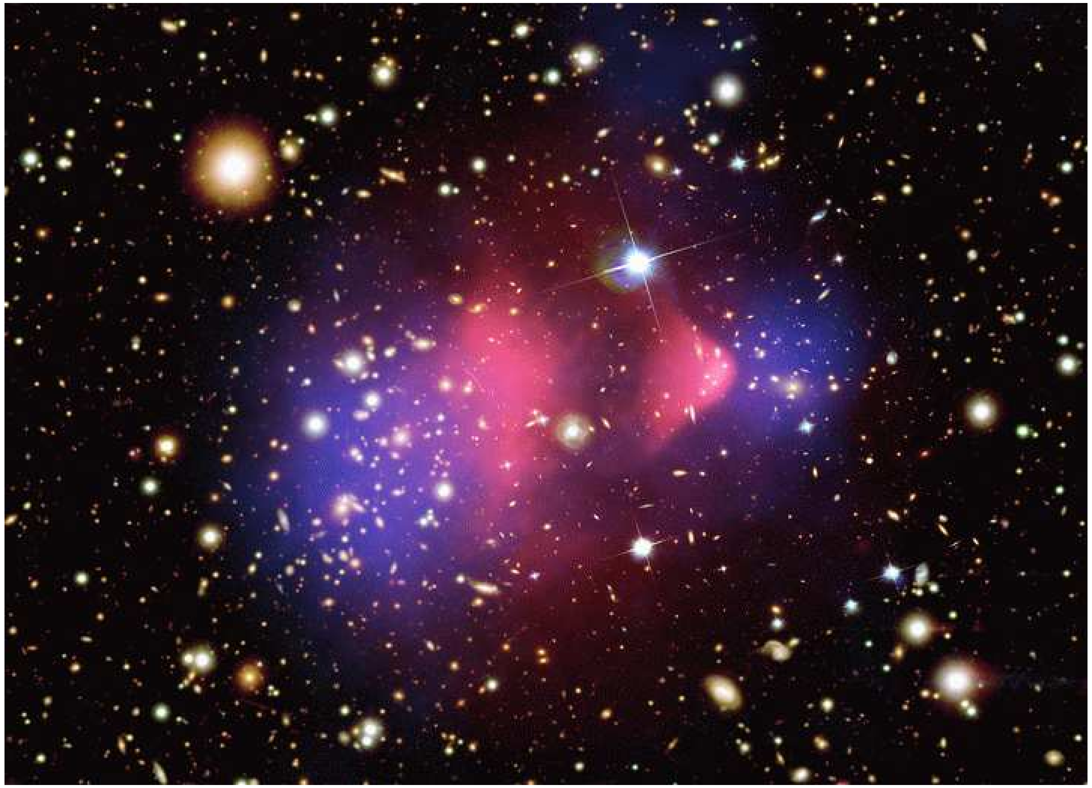
modify gravity: change the large scale properties of gr
some extra dimension models provide interesting ideas
acceleration, does not solve coincidence, Solar system tests of gravity?

cosmological backreaction: no new physics, non-linear effect of gr
evolution of averaged metric $\neq$ averaged evolution of real metric
nonlinear effect, hard to quantify
acceleration possible but not inevitable, would solve coincidence

abandon Copernican principle: inhomogeneous dust models high price

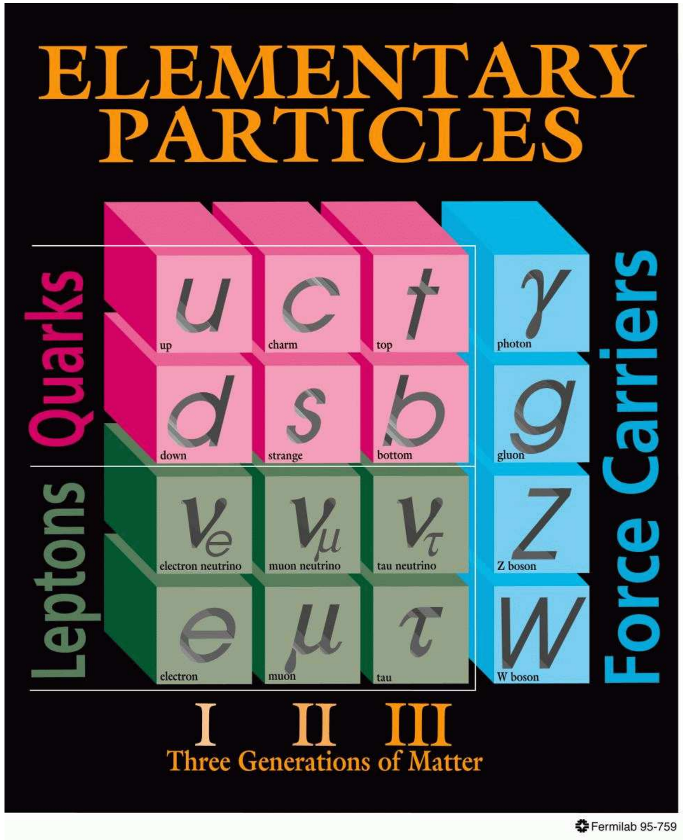
antropic principle: give up

Dark matter



“bullet cluster” Markevitch et al. 2006

Requirements for a dark matter candidate



1. white (no coulor charge)
2. neutral (no electric charge)
3. stable (or $\tau \geq t_0$)

SM candidates:
neutrinos,
atoms (dark baryonic matter)
n.b.: photons are not dark

Classification of dm candidates

two criteria: pressure gradients (Jeans mass) and thermalisation

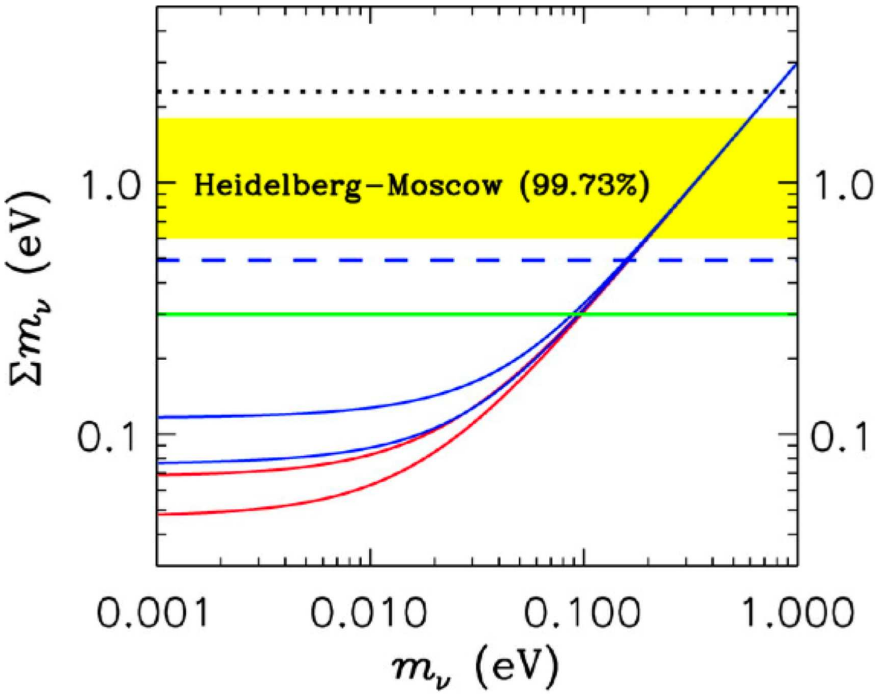
HOT: $p \sim \epsilon$ at onset of structure formation (= matter-radiation equality)
COLD: $p \ll \epsilon$ at onset of structure formation

THERMAL: was in local thermal equilibrium with radiation (after inflation)

NON-THERMAL: was never in local thermal equilibrium with radiation

	HOT (relativistic)	COLD (non-relativistic)
THERMAL	light ν, ...	WIMP(heavy ν, LSP, ...), ...
NON-THERMAL	string gas, ...	misalignment axion, primordial black holes, ...

Light neutrinos



Hannestad S. 2006.
Annu. Rev. Nucl. Part. Sci. 56:137–61

$m_{\nu_e} < 2.3$ eV tritium decay

$\Delta m^2_{12} \simeq 8 \times 10^{-5}$ eV^2 solar

$|\Delta m^2_{23}| \simeq 2 \times 10^{-3}$ eV^2 atmospheric

$$\omega_\nu = \frac{\sum_\nu m_\nu}{93.8 \text{ eV}}$$

range of ν energy density from particle physics:

$0.0006 \leq \omega_\nu \leq 0.08$

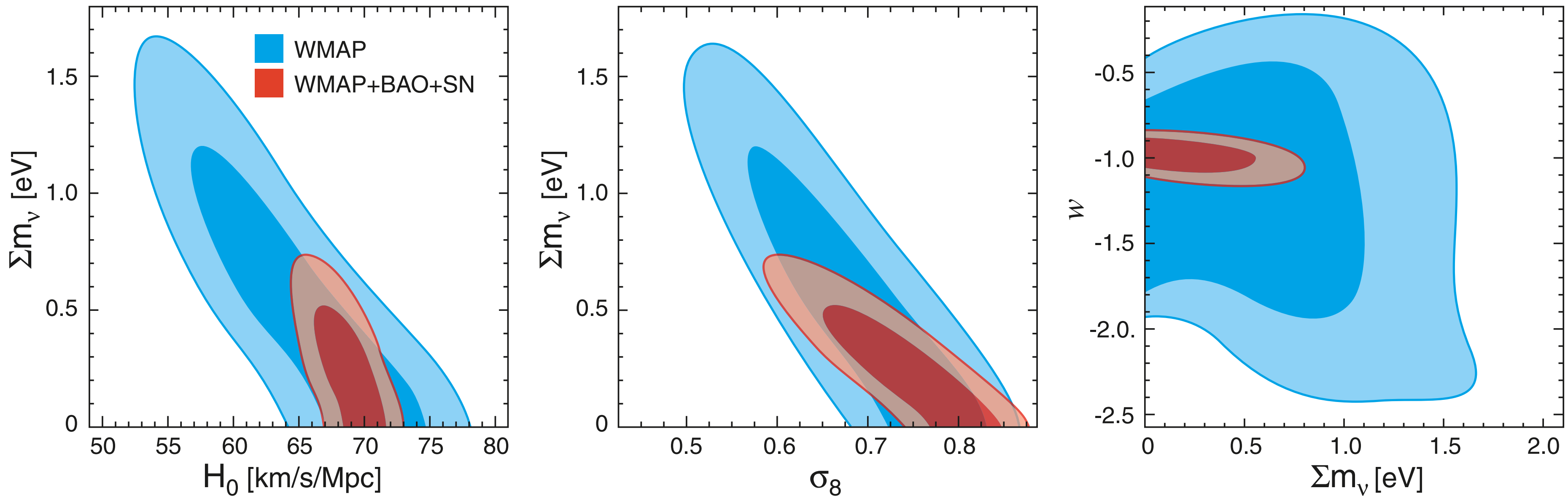
$(0.001 < \Omega_\nu < 0.2)$

but, $\omega_{\rm m} \sim 0.15$ from CMB

need something else besides ν

Limits on neutrino masses from cosmology

massive neutrinos lead to extra damping of small structures



CMB $\sum m_v < 1.3$ eV; +SN+BAO: < 0.61 eV (95% CL) Komatsu et al. 2008

A strong argument for cold dark matter

Can we make $\Omega_\mathrm{m} = \Omega_\mathrm{b}$? No!

baryon density continues to oscillate after photon decoupling
Coulomb interactions due to residual ionisation, Van der Waals forces
baryon decoupling happens at $z_{\mathrm{b-dec}} \sim 150$, no growth before

initial density contrast at $k_\mathrm{ph} \sim H$: $\Delta_m \sim 10^{-4}$ (from CMB)

ΛBDM: maximal density contrast of baryons (any scale): $\sim 10^{-2} \ll 1$
non-linear structures (e.g. galaxies) do not form

ΛCDM: cdm structure starts to grow at $z_\mathrm{eq} \sim 3500$
density contrast of 100 Mpc (10 Mpc) scale ~ 0.3 (~ 1)
after baryon decoupling: baryons fall into gravitational potential wells of cdm

Baryonic dark matter

most baryons are in gas

mass in stars only $\Omega_* \sim 0.001$

massive cold halo objects (MACHOs)

limits from microlensing

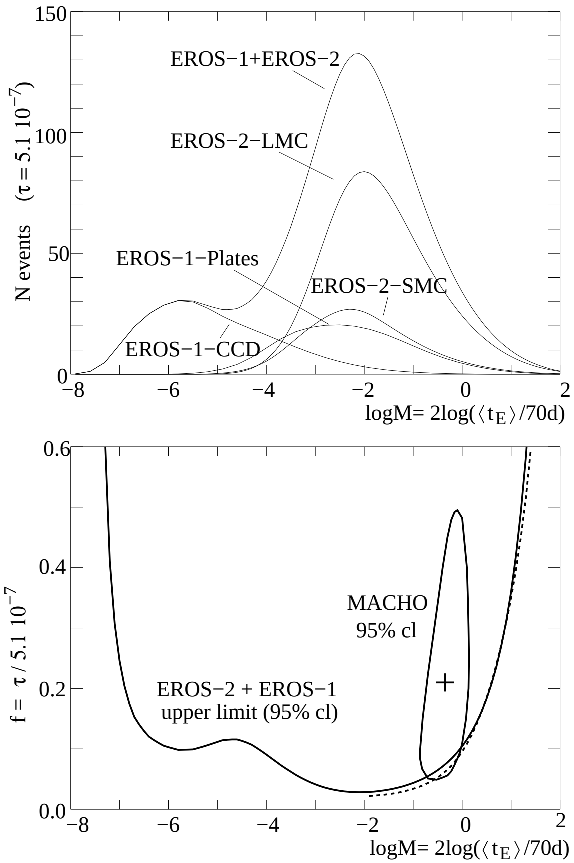
baryonic dm in non-nuclear form might naturally explain $\Omega_{cdm} \sim \Omega_b$, e.g. strangelets

no compelling scenario to from them

primordial black holes:

$10^{-17} M_\odot < M < 10^{-7} M_\odot$

no compelling scenario to from them



Tisserand et al. 2006

Non-baryonic cold dark matter

thermal cdm candidates from particle physics:
weakly interacting massive particles (WIMPs)
heavy ν ($m > 80.5$ GeV from LEP)
lightest neutralino $\tilde{\chi}_1^0$ ($m > 46$ GeV from LEP)

non-thermal cdm candidates:
very heavy WIMPs WIMPzillas ($m > 25T_{\text{rh}}$)
superweakly coupled particles primordial black holes

coherently oscillating fields: $\langle p \rangle = 0$
axion
(10^{-6} eV $< m_a < 10^{-3}$ eV; lower limit from cosmology; upper limit form SN1987a)

Dark matter decoupling: chemical vs. kinetic

thermal dm candidates:
time of chemical decoupling (freeze-out) $\neq$ time of kinetic decoupling
hdm: $T_{\text{cd}} \sim T_{\text{kd}}$, e.g. light νs

before kinetic decoupling, dm and radiation are a single fluid

after kinetic decoupling, dm and radiation are two fluids

$\Rightarrow$
at t_{cd} the amount of dm Ω_{dm} is fixed (for stable dm)
at t_{kd} the initial conditions for structure formation are set

non-thermal dm candidates: not an issue

Direct & indirect dm search

both methods involve astrophysical uncertainties

direct search (laboratory)

$$\Gamma_{\text{scatter}} = n\langle\sigma v\rangle, \qquad n = n(\mathbf{x}, t), \mathbf{v} = \mathbf{v}(\mathbf{x}, t)$$

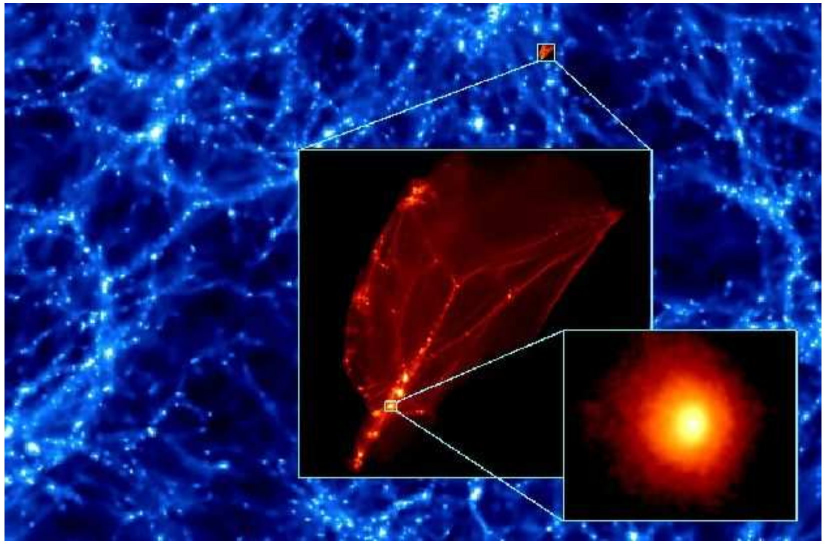
astrophysics on Solar system scales

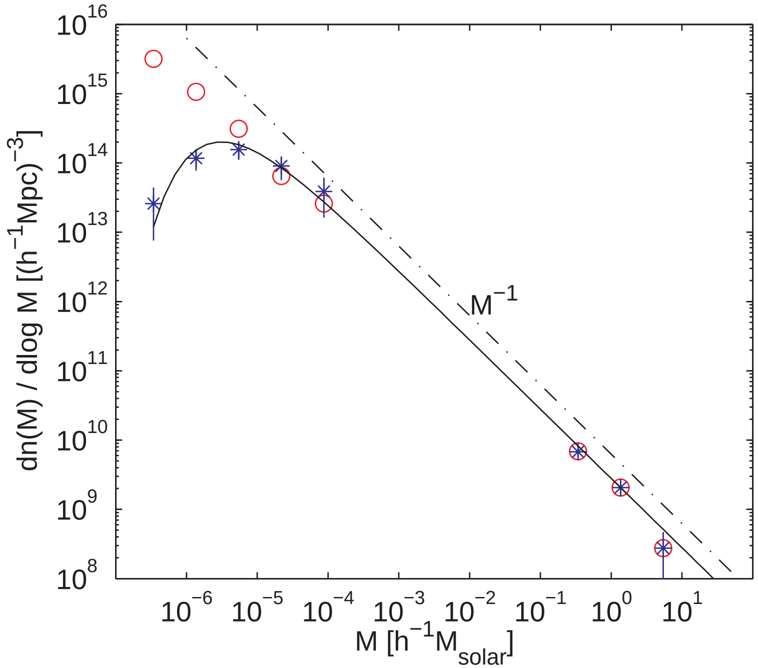
indirect search (observation of sky in γ, ν or cosmic rays)

$$\Gamma_{\text{annihilation}} = \int n^2\langle\sigma v\rangle \mathrm{d}V, \qquad n = n(\mathbf{x}, t)$$

astrophysics on subgalactic scales

Nonlinear evolution of structure: snapshot at $z = 25$





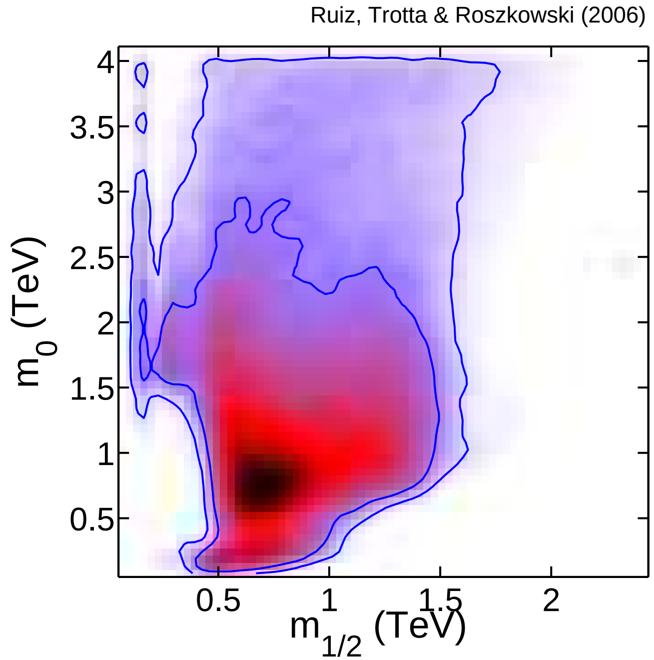
Diemand, Moore & Stadel 2005

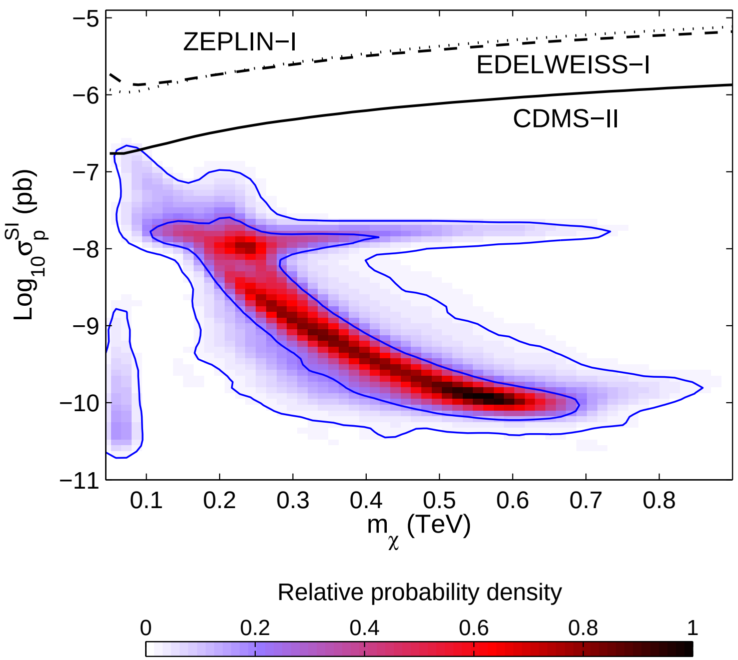
linear evolution: cut-off at smallest scales Green, Hofmann & Schwarz 2004

WIMPs

natural candidates: $\Omega_{\text{wimp}} \sim 0.2 \frac{(m/T_{\text{cd}})/25}{\langle \sigma_{\text{ann}} v \rangle / 1 \text{ pb}}$

best studied candidate: neutralino (lightest SUSY particle)





Ruiz, Trotta & Roszkowski 2006

Summary of 5th lecture

minimal model: We do not understand 96% of the Universe!

cosmological constant problem

coincidence problems

How to make progress: Rule out the wrong possibilities!

need laboratory experiments (LHC, . . .), direct search (underground), indirect search (GLAST, . . .)

The last slide of the lecture

we arrived at a very successful model based on
standard model of particle physics & general relativity
idea of cosmological inflation
introduction of cosmological constant and dark matter

minimal set of well motivated physical parameters (9):
$T_0, m_\nu, \omega_\mathrm{b}, \omega_m, h, H_\mathrm{inf}, \varepsilon_1, \varepsilon_2, T_\mathrm{rh}$

minimal used set (6):
$T_0, \omega_\mathrm{b}, \omega_m, h, A, n-1$

astrophysical parameters

(follow from physical parameters, but cannot be calculated):

$\tau, b_s, Q_\mathrm{nl}, \sigma_v, \ldots$

Copernican principle?
What is the dark energy? What is the dark matter?