Five lectures on

PARTICLE 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; naive guess from quantum field theory is 122 order of magnitudes off (cosmological constant problem)

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

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

Cosmological constant problem

Λ_{gr} free parameter of gr

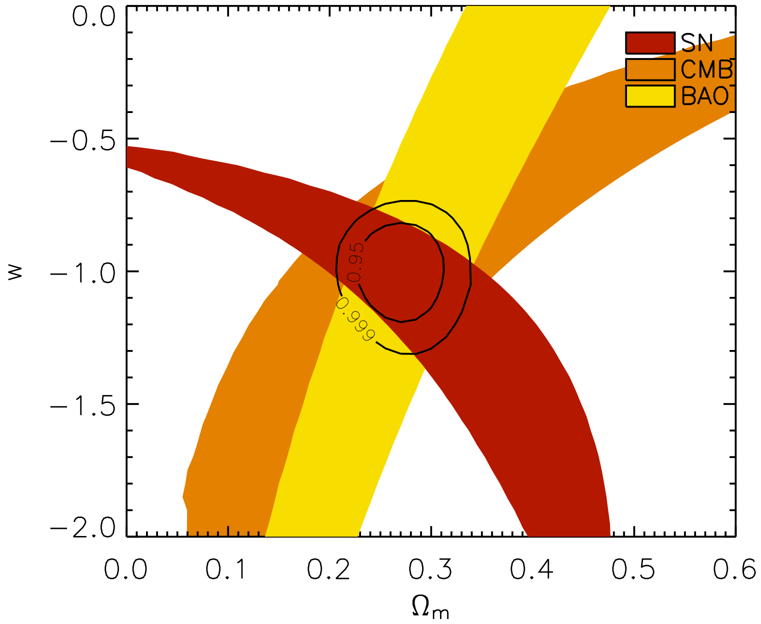
$\Lambda_{\mathrm{qft}} \equiv 8\pi G\epsilon_{\mathrm{V}}$ to be calculated from quantum field theory
flat space-time: normal ordering puts $\epsilon_{\mathrm{V}} = 0$ in true vacuum
qft in curved space-time not sufficiently understood to predict a value
naive guess: (natural cut-off) $\Lambda_{\mathrm{qft}} \sim M_{\mathrm{Pl}}^2$

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

seems to require cancelation of 122 digits:
important physics is missing

Cosmological constant vs. more general dark energy

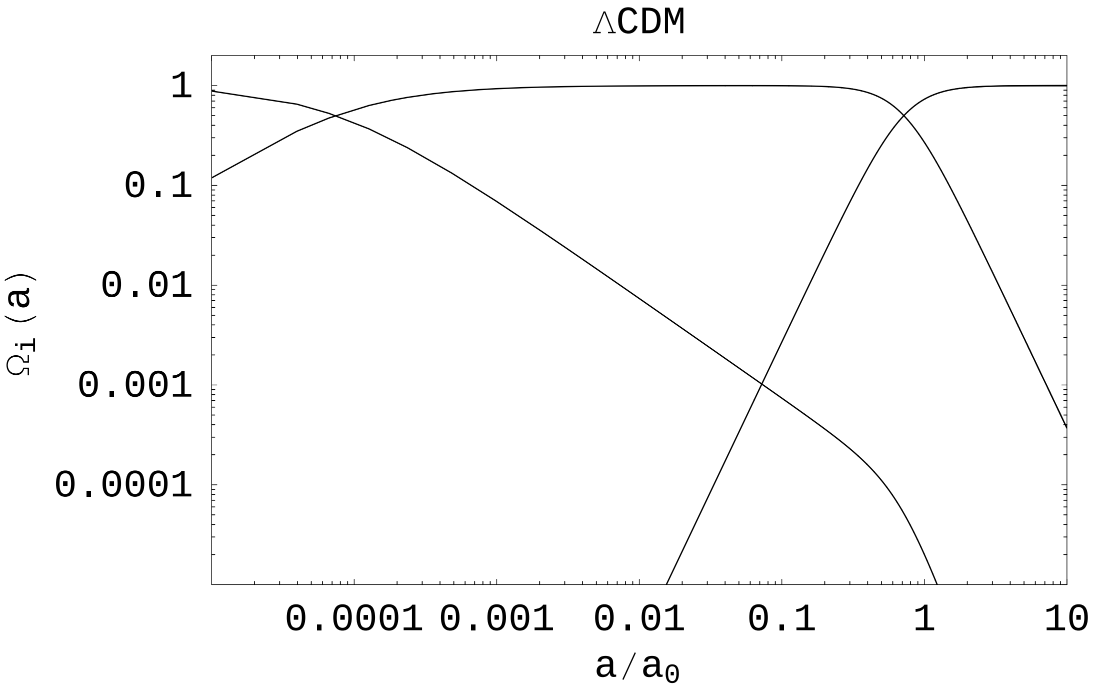
flat cosmology, constant $w_{\mathrm{de}} = p_{\mathrm{de}}/\epsilon_{\mathrm{de}}$: $w = -1.01 \pm 0.15$



SN 1a, CMB, BAO

Davis et al. 2007

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)
leads to accelerated, but weaker coincidence problem

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

modify gravity: change the large scale properties of gr
some extra dimension models provide interesting ideas
leads to acceleration, but does not solve the coincidence problem

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
unclear if it leads to acceleration, but would solve the coincidence problem

antropic principle: give up

Questions to particle physics wrt dark energy

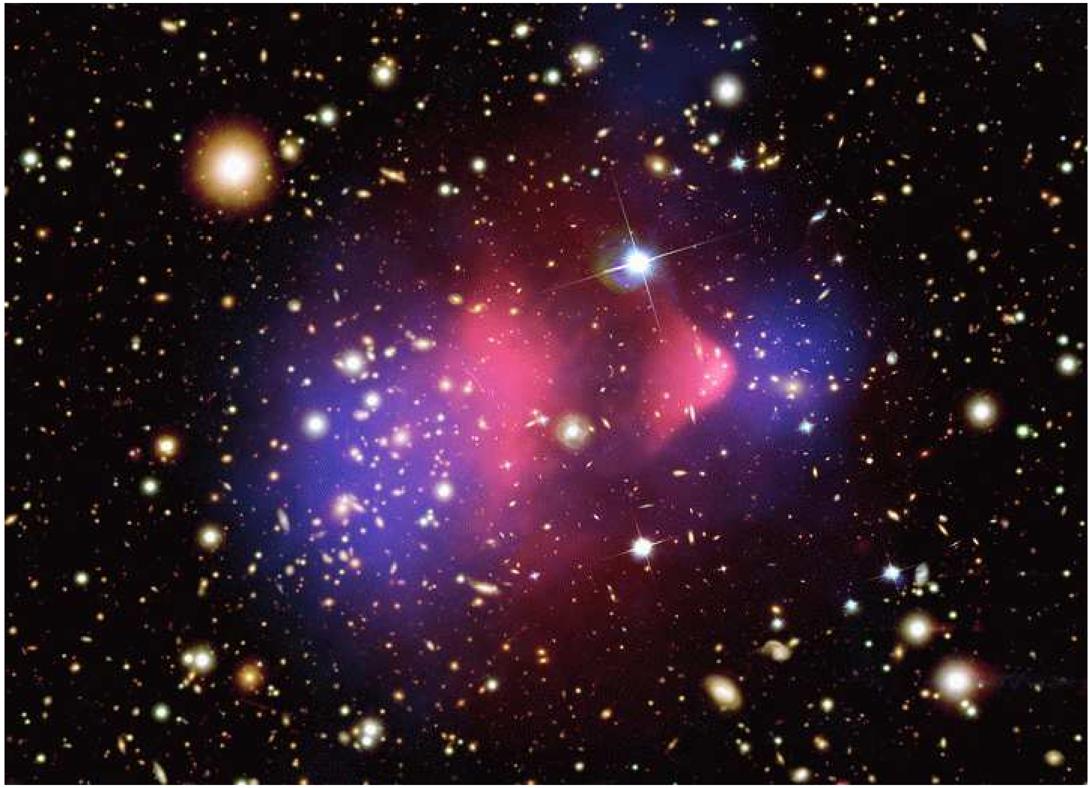
- Do fundamental scalar fields exist in Nature?
find or rule out the Higgs at LHC
affects how we have to think about dark energy and cosmological inflation

- Do extra dimensions exist?
e.g. detect Kaluza-Klein particles or produce mini-black holes at LHC
if yes, it is much easier to think about modifications to gr

- If dark matter particles are found, what are their couplings?
relevant for unified scenarios

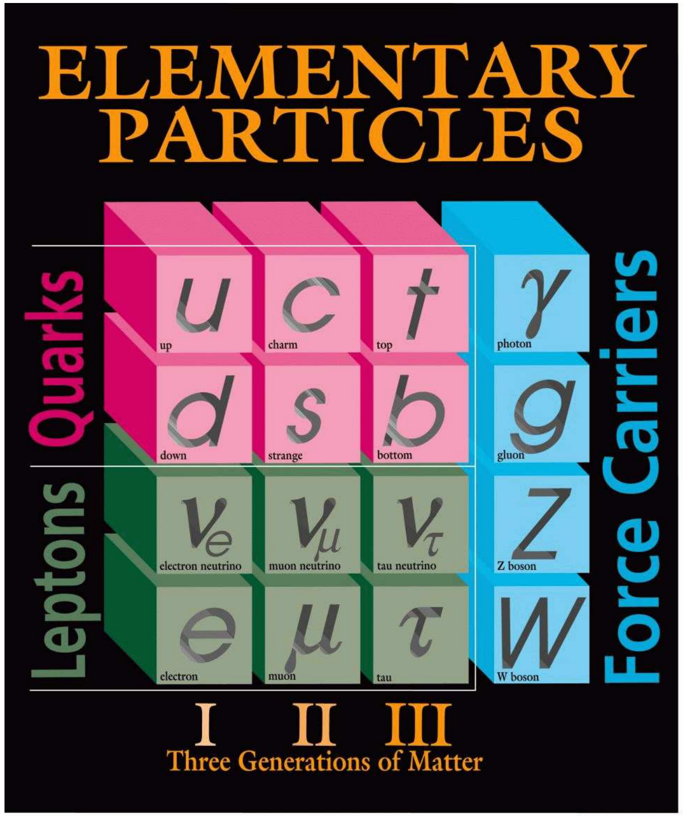
- Measure the value of vacuum energy in a laboratory experiment!
(Sorry, but I don't know how)

Dark matter



"bullet cluster" Markevitch et al. 2006

Requirements for a dark matter candidate



Fermilab 95-759

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, ...

Thermal vs. non-thermal: initial conditions

all thermal dm candidates (hot or cold) are subject to isentropic i.c.

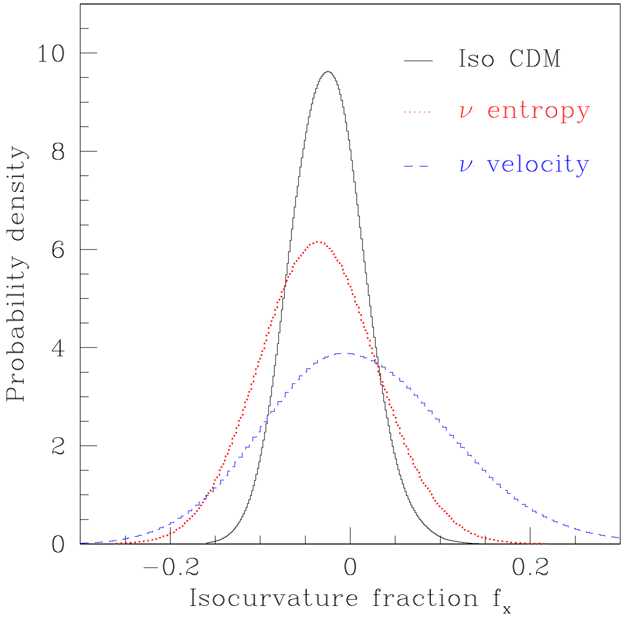
non-thermal dm candidates may have more general i.c.

definitions

$$\Delta_{\mathrm{a}} = \frac{\delta\epsilon_{\mathrm{a}}}{(\epsilon + p)_{\mathrm{a}}}, \quad v_{\mathrm{a}}, \quad \mathrm{a} = \mathrm{r},\ \mathrm{b},\ \mathrm{dm}$$

isentropic i.c.: $\Delta_{\mathrm{dm}} = \Delta_{\mathrm{b}} = \Delta_{\mathrm{r}}$ and $v_{\mathrm{dm}} = v_{\mathrm{b}} = v_{\mathrm{r}}$

Thermal vs. non-thermal: hints from CMB & LSS

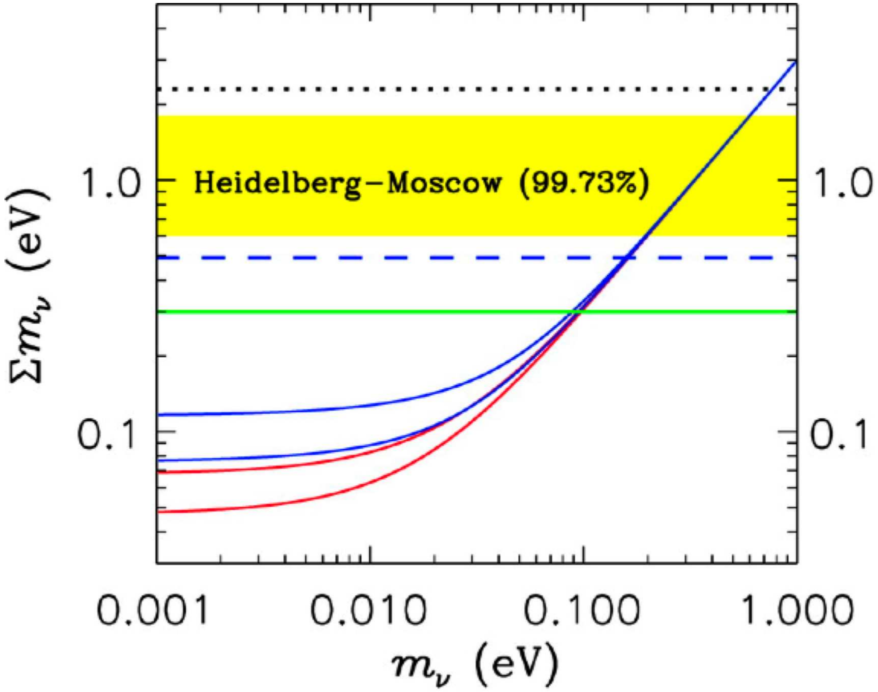


WMAP: isentropic i.c. are preferred

Trotta 2006

a discovery of isocurvature modes would point to non-thermal dm

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:

$0.0006 \le \omega_\nu \le 0.08$

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

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

need something else besides ν

Limits on neutrino masses from cosmology

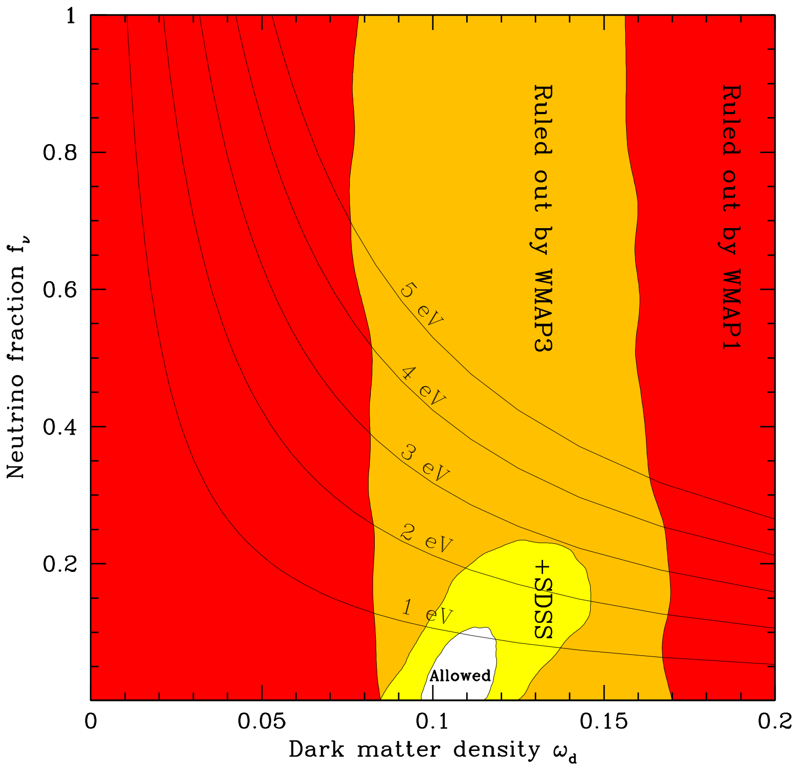
massive neutrinos lead to extra damping of small structures

upper limits (95% CL):
CMB: 2 eV
+ LSS: 1.8 eV
+ SN1a + BAO: 0.44 eV
(8 parameters) Hannestad 2007

cosmological limits cannot replace laboratory limits!

KATRIN (2008), GERDA (2008)

fraction of hot dm < 0.1



WMAP+SDSS Tegmark et al. 2006

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 $\Omega_{\mathrm{cdm}} \sim \Omega_{\mathrm{b}}$, e.g.

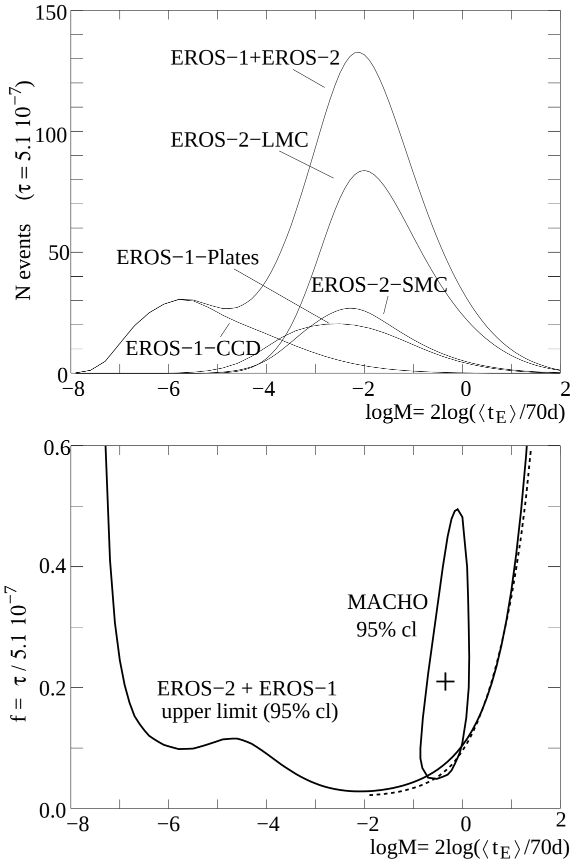
strangelets

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 ($m > 25T_{\mathrm{rh}}$)
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: $T_{\mathrm{cd}} \sim T_{\mathrm{kd}}$, 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)

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

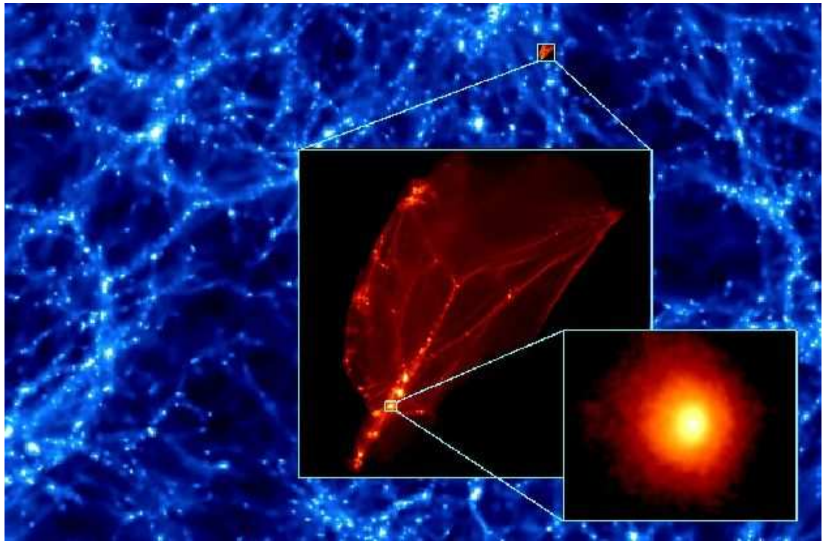
astrophysics on Solar system scales

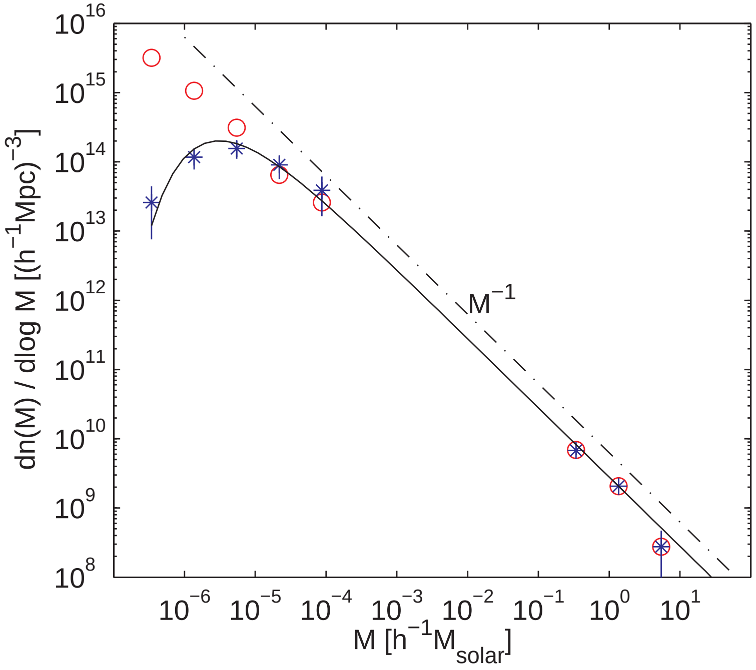
indirect search (observation of sky in γ, ν or cosmic rays)

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

astrophysics on subgalactic scales

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





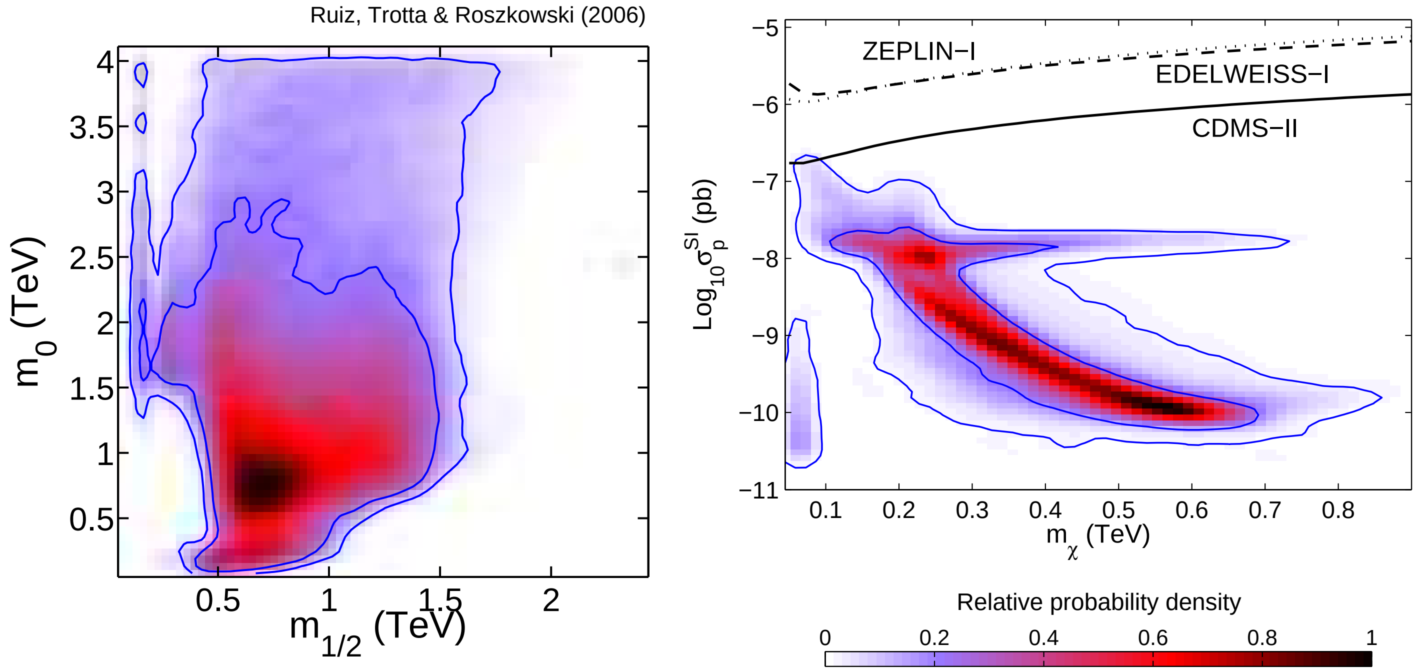
Diemand, Moore & Stadel 2005

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

WIMPs

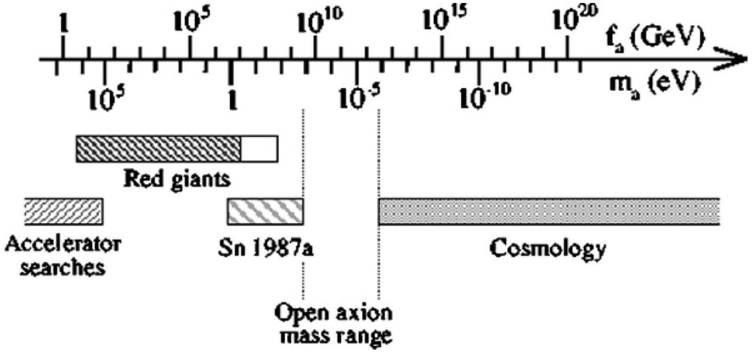
natural candidates: $\Omega_{\rm wimp} \sim 0.2 \frac{(m/T_{\rm cd})/25}{\langle \sigma_{\rm ann} v \rangle / 1 \ {\rm pb}}$

best studied candidate: neutralino (lightest SUSY particle)

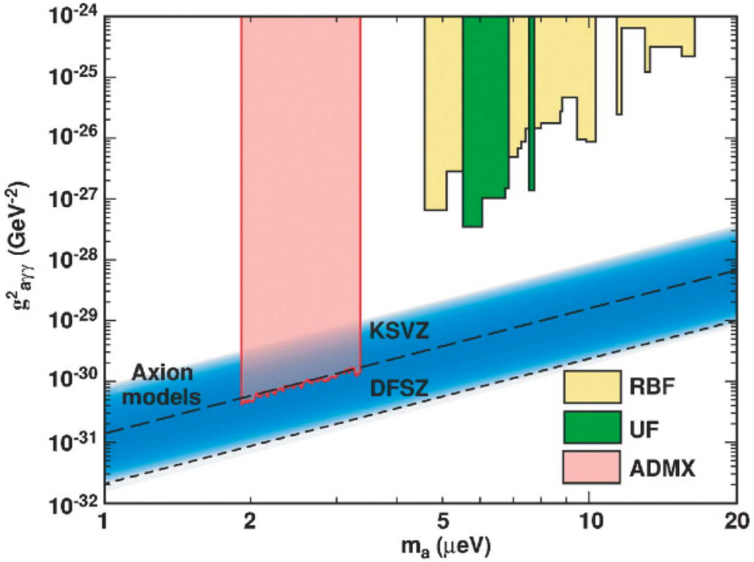


Ruiz, Trotta & Roszkowski 2006

Axions



Asztalos SJ, et al. 2006.
Annu. Rev. Nucl. Part. Sci. 56:293–326



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How can LHC probe dark matter?

- Is there a new conserved quantum number,
such that a stable WIMP must exist?
e.g. R-parity from SUSY or a winding number for compact extra dimensions

- detection of dm particles only via missing energy,
but some excited states or partner particles might exist
e.g. charginos would herold neutralinos

- put constraints on and rule out existing models
new exclusion limits are important for the design of direct and indirect search experiments

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 2007, . . .), direct search (underground), indirect search (GLAST 2007, . . .)

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):

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

What is the dark energy? What is the dark matter?