Dark Matter in cosmology and particle physics

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Standard Model: Success and Problems

Gauge fields (interactions): γ, $W^{\pm}$, Z, g

Three generations of matter: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \binom{u_L}{d_L}$, d_R, u_R

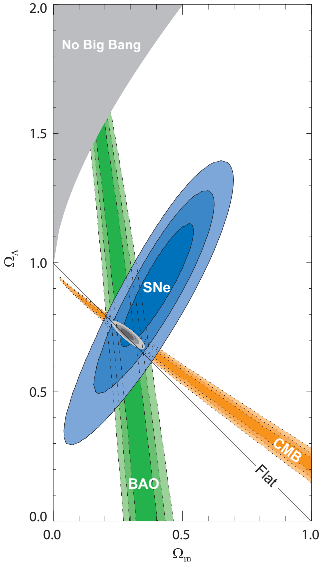
- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe
  - Neutrino oscillations
  - Dark matter (Ω_{DM})
  - Baryon asymmetry (Ω_B)
  - Inflationary stage
  - Dark energy (Ω_Λ)
  - Strong CP: ? (boundary terms, new topology, ...)
  - Gauge hierarchy: ? (No new scales!)
  - Quantum gravity

True extension must explain   Planck-scale physics saves the day

Outline

Outline

Astrophysical and cosmological data are in agreement



$$\left(\frac{\dot a}{a}\right)^2 = H^2(t) = \frac{8\pi}{3} G \rho^{\text{energy}}_{\text{density}}$$

$$\rho^{\text{energy}}_{\text{density}} = \rho_{\text{radiation}} + \rho^{\text{ordinary}}_{\text{matter}} + \rho^{\text{dark}}_{\text{matter}} + \rho_\Lambda$$

$$\rho_{\text{radiation}} \propto 1/a^4(t) \propto T^4(t)\,, \quad \rho_{\text{matter}} \propto 1/a^3(t)$$

$$\rho_\Lambda = \text{const}$$

$$\frac{3H_0^2}{8\pi G} = \rho^{\text{energy}}_{\text{density}}(t_0) \equiv \rho_c \approx 0.53 \times 10^{-5}\,\frac{\text{GeV}}{\text{cm}^3}$$

radiation: $\Omega_\gamma \equiv \frac{\rho_\gamma}{\rho_c} = 0.5 \times 10^{-4}$

Baryons (H, He): $\Omega_B \equiv \frac{\rho_B}{\rho_c} = 0.046$

Neutrino: $\Omega_\nu \equiv \frac{\sum \rho_{\nu_i}}{\rho_c} < 0.01$

Dark matter: $\Omega_{DM} \equiv \frac{\rho_{DM}}{\rho_c} = 0.23$

Dark energy: $\Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} = 0.73$

So far only gravitational evidence for DM

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2(t) = \frac{8\pi}{3} G \rho^{\text{energy}}_{\text{density}}$$

$$\rho^{\text{energy}}_{\text{density}} = \rho_{\text{radiation}} + \rho^{\text{ordinary}}_{\text{matter}} + \rho^{\text{dark}}_{\text{matter}} + \rho_{\Lambda}$$

$$\rho_{\text{radiation}} \propto 1/a^4(t) \propto T^4(t)\,, \quad \rho_{\text{matter}} \propto 1/a^3(t)$$

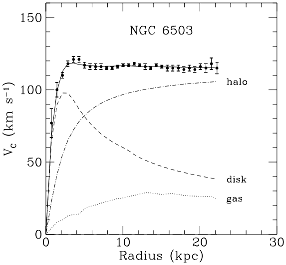
$$\rho_{\Lambda} = \text{const}$$

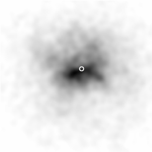
Why do we think it is most probably new particle physics (new gravity if any is not enough) ?

DM phenomena happen at various spatial and time scales

Universe content from astrophysics

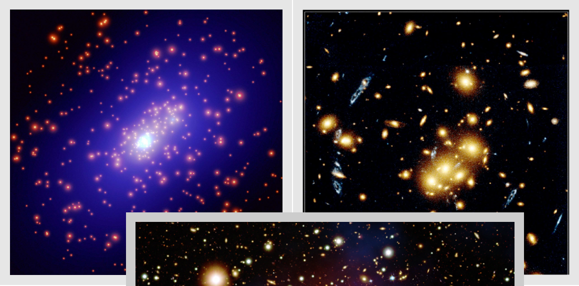
Rotational curves





X-rays from centers of galaxy clusters

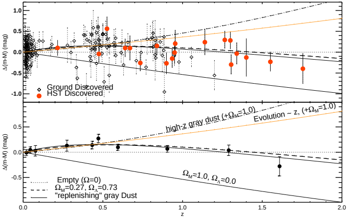
Gravitational lensing



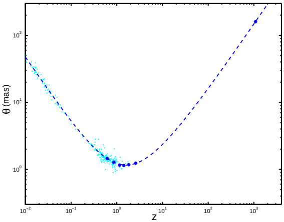
“Bullet” cluster

Universe content from cosmology

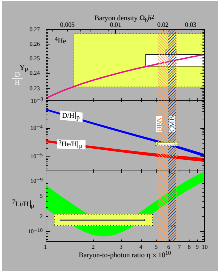
Standard candles

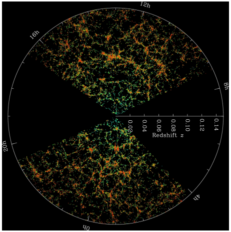


Angular distance

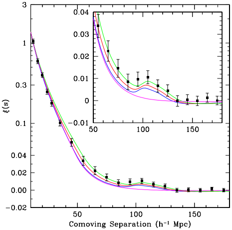


Nucleosynthesis

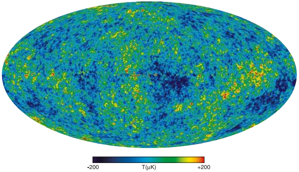




Large Scale Structures



Baryon acoustic oscillations

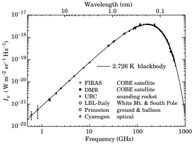


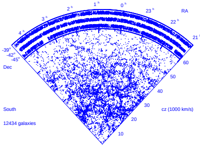
CMB anisotropy

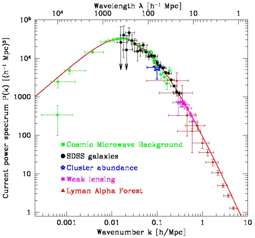
Key observable: matter perturbations

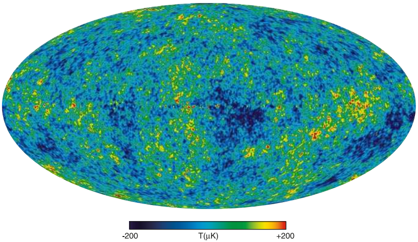
- CMB is isotropic, but "up to corrections, of course..."
  1. Earth movement with respect to CMB
     $$\frac{\Delta T_{\text{dipole}}}{T} \sim 10^{-3}$$
  2. More complex anisotropy: $\frac{\Delta T}{T} \sim 10^{-4}$
- There were matter inhomogenities $\Delta\rho/\rho \sim \Delta T/T$ at the stage of recombination ($e + p \to \gamma + H^*$) $\Longrightarrow$

  Jeans instability in the system of gravitating particles at rest $\Longrightarrow$ $\Delta\rho/\rho \nearrow$ galaxies (CDM halos)
- $\Delta\rho_{DM}/\rho_{DM} \propto a \propto 1/T$ from $T = 0.8\,\text{eV}$,
  while $\Delta\rho_B/\rho_B \propto a \propto 1/T$ only after recombination
  $T = 0.25\,\text{eV}$
  without DM total growth factor would be 1100
  not enough to explain structures!



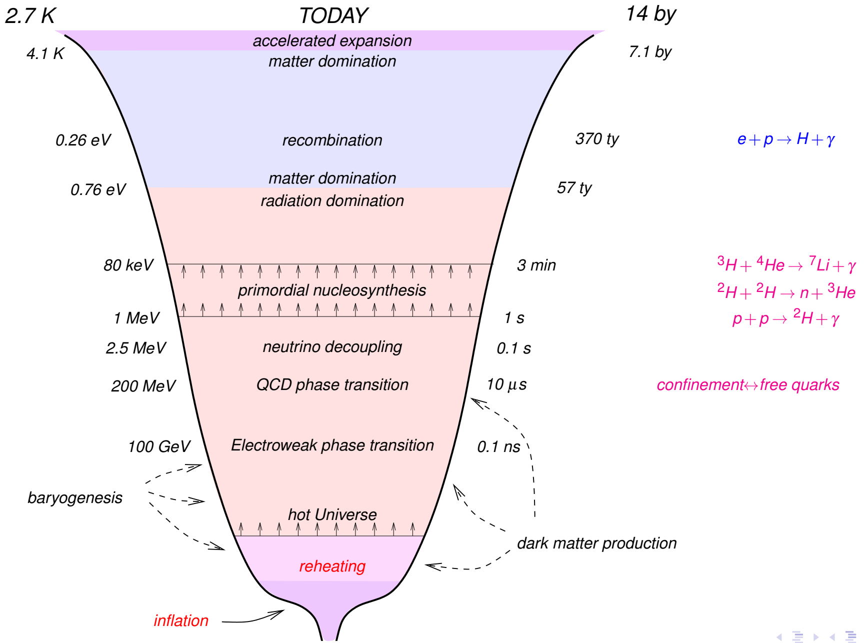






Why do we need Dark Matter component (within GR)?

- Astrophysical data favor Dark Matter
  - Observations in galaxies
  - Observations in galaxy clusters
- Cosmological data favor Dark Matter
  - Observation of objects at cosmological distances (far=early)
  - Baryonic Aciustic (Sakharov) Oscillations (BAO) in two-point galaxy correlation function
  - Anisotropy of Cosmic Microwave Background (CMB)
  - Evolution of Large Scale Structures in the Universe


2.7 K
TODAY
14 by
accelerated expansion
4.1 K
matter domination
7.1 by
0.26 eV
recombination
370 ty
$e+p\to H+\gamma$
0.76 eV
matter domination
57 ty
radiation domination
80 keV
3 min
$^3H+{}^4He\to {}^7Li+\gamma$
primordial nucleosynthesis
$^2H+{}^2H\to n+{}^3He$
1 MeV
1 s
$p+p\to {}^2H+\gamma$
2.5 MeV
neutrino decoupling
0.1 s
200 MeV
QCD phase transition
10 μs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
reheating
inflation

Outline

Dark Matter properties from cosmology: $p = 0$

(If) particles:

1. stable on cosmological time-scale
   requires new (almost) conserved quantum number
2. produced in the early Universe
   some time before RD/MD-transition ($T = 0.8\,\text{eV}$)
3. nonrelativistic particles long before RD/MD-transition ($T = 0.8\,\text{eV}$)
   (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$)
   Otherwise no small-size structures, like dwarf galaxies:
   smoothed out by free streaming
   If were in thermal equilibrium: $M_X \gtrsim 1$ keV
4. (almost) collisionless $p = 0$, $v_{\text{sound}} = 0$
5. (almost) electrically neutral CMB distortion

(almost) homogeneous free massive scalar field: at $m_\phi \gg H = \dot{a}/a$

$$\mathscr{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2\,, \qquad \ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi = 0\,, \implies p = \langle E_k\rangle - \langle E_p\rangle = 0$$

Dark Matter properties from astrophysics

1. stable on cosmological time-scale
2. (almost) collisionless — to form ellipsoidal halos
3. (almost) electrically neutral — to be Dark
4. stability of globular stellar clusters — $M_X \lesssim 10^3 M_\odot \approx 10^{61}$ GeV
   otherwise too strong tidal forces
5. confinement in a galaxy: — quantum physics!

   de Broglie wavelength: $\lambda = 2\pi/(M_X v_X) < l_{galaxy}$, — for bosons

   in a galaxy $v_X \sim 0.5 \cdot 10^{-3}$ $\longrightarrow$ $M_X \gtrsim 3 \cdot 10^{-22}$ eV

   for fermions

   Pauli blocking: $M_X \gtrsim 750$ eV

$$f(\mathbf{p},\mathbf{x}) = \frac{\rho_X(\mathbf{x})}{M_X} \cdot \frac{1}{\left(\sqrt{2\pi} M_X v_X\right)^3} \cdot e^{-\frac{\mathbf{p}^2}{2M_X^2 v_X^2}}\bigg|_{\mathbf{p}=0} \leq \frac{g_X}{(2\pi)^3}$$

Outline

Dark Matter: thermal production

1. freezing out while relativistic (e.g. neutrino)

   DM particle mass M_X fixes Ω_X: NO heavy particles!

$$\Omega_X = \frac{m_X \cdot n_{X,0}}{\rho_c} \approx 0.2 \times \frac{M_X}{100\ \text{eV}} \left(\frac{g_X}{2}\right) \cdot \left(\frac{100}{g_*(T_f)}\right)$$

   No realistic models:

   too energetic for the proper structure formation

   Pauli blocking prevents fermionic DM

2. freezing out while nonrelativistic (e.g. neutrons)

   DM annihilation cross section σ_0 fixes Ω_X: NO weaker coupled particles

$$\Omega_X \approx 0.1 \times \left(\frac{(10\ \text{TeV})^{-2}}{\sigma_0}\right) \frac{0.3}{\sqrt{g_*(T_f)}} \ln\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right)$$

   We need $\sigma_0 \simeq \sigma_W/100$ and any mass $M_X \lesssim 50\,\text{TeV}$ is OK

   There are realistic models: e.g. LSP as WIMP

Dark Matter: non-thermal production

1. in the primordial plasma of SM particles (via scatterings, oscillations):

   gravitino

   sterile neutrino of 1-50 keV

2. at phase transitions:

   axion of $10^{-4} - 10^{-7}$ eV

   Q-balls

   strangelets (?)

3. during reheating (after inflation?):

   any guy coupled (only) to inflaton

   - perturbatively:

     inflaton decays

     production by external (inflaton) field

   - non-perturbatively:

     Bose-enhancement of

     coherent production by external field

4. while the Universe expands:

   gravity produces any particles at $H \sim M_X$

General remarks on Dark Matter

- So far only gravitational evidences
  Hence, it may be a modification of GR . . . (no examples)
- A variety of SM extensions with Dark Matter candidates
  Make your choice or suggest one more candidate!
- Need a Guiding Principle to set priorities

Outline

Dark Matter: possible guiding principles

Naturality:

- exploit known interactions

  examples: WIMPs, free particles

- part of a well-motivated model

  examples: LSP, axion, sterile neutrinos

- Why $\Omega_B \sim \Omega_{DM}$?

  examples: baryonic dark matter Mirror World

Minimality:

Use as little new physics as possible

Motivation: No any hints of new physics in experiment

Usually the models are naturally untestable

example: gravitationally produced free massive fermion

Reality:

Deep insight into the gravitational properties of dark matter

what happen at small scales?

status of:
cusp/core in galactic centers
lack of dwarf galaxies
lack of small galaxies

examples:
cold dark matter
warm dark matter
selfinteracting dark matter

Outline

Examples: both Natural and Minimal

Natural source of dark matter production: gravity

Gravity produces any free massive particle when metric changes in the expanding Universe

most efficiently when $H \sim M$

say, at radiation domination stage

$$\Omega_X \sim \left(\frac{M_X}{10^9\,\text{GeV}}\right)^{5/2}$$

S.Mamaev, V.Mostepanenko, A.Starobinsky (1976)

Modified gravity $(R \to R - R^2/6\mu^2)$

may be responsible for inflation and subsequent reheating

A.Starobinsky (1980)

that is (universal) production of all particles, including those of dark matter

$$\Omega_X \simeq 0.15 \times \left(\frac{M_X}{10^7\,\text{GeV}}\right)^3$$

D.Gorbunov, A.Panin (2010)

Untestable

Examples: Minimal, but still testable

$$V_S = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hS} S^2 H^\dagger H$$

$$m_S = \sqrt{\mu_S^2 + \frac{1}{2}\lambda_{hS} v^2}$$

$$\Omega_S \propto n_S \propto \frac{1}{\sigma_{ann}} \propto \frac{1}{\lambda_{hS}^2}$$

indirect:

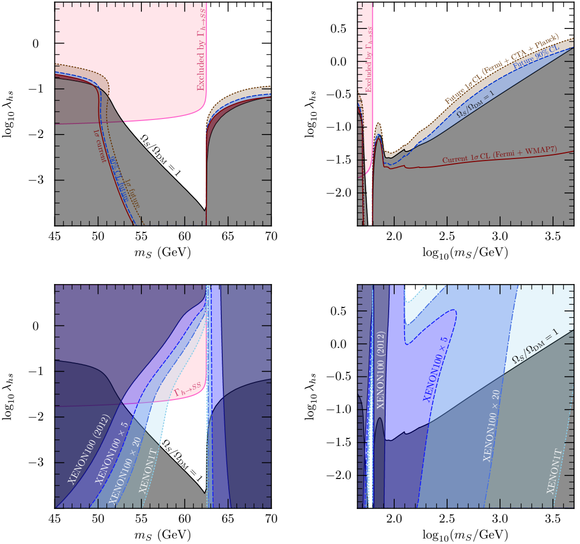
$$\text{flux}(SS \to SM) \propto n_S^2 \sigma_{ann} \propto \frac{1}{\lambda_{hS}^2}$$

direct:

$$\sigma(SA \to SA) \propto n_S \sigma_{ann} \propto \lambda_{hS}^0$$

- EW-phase transition of I-order ?
- EW-vacuum stability ?

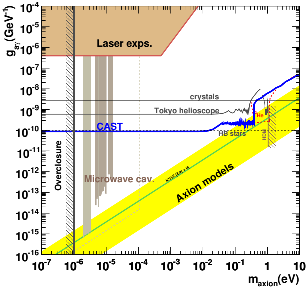
M.Gonderinger et al (2013)



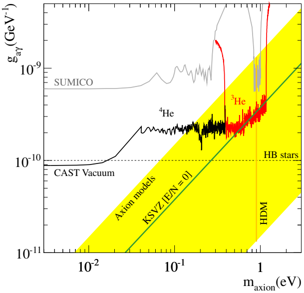
Natural: axion as Cold and Hot DM

Cold: at QCD(chiral) phase transition

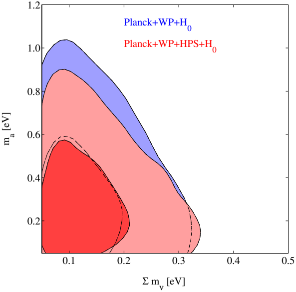
Hot: scatterings in plasma



E.Ribas et al (2009)



M.Arik et al (2013)



M.Archidiacono et al (2013)

$$\mathscr{L} \propto g_{a\gamma} \times a(x) F_{\mu\nu} F^{\mu\nu} \qquad g_{a\gamma} \propto \frac{m_a}{m_\pi f_\pi}$$

Natural: WIMPs are mostly welcome

- Do not need new physical scale (and interaction?)
- Can search for WIMPs in collision experiments (LHC):

$$X + \bar{X} \leftrightarrow \text{SM} + \text{SM'} + \ldots$$

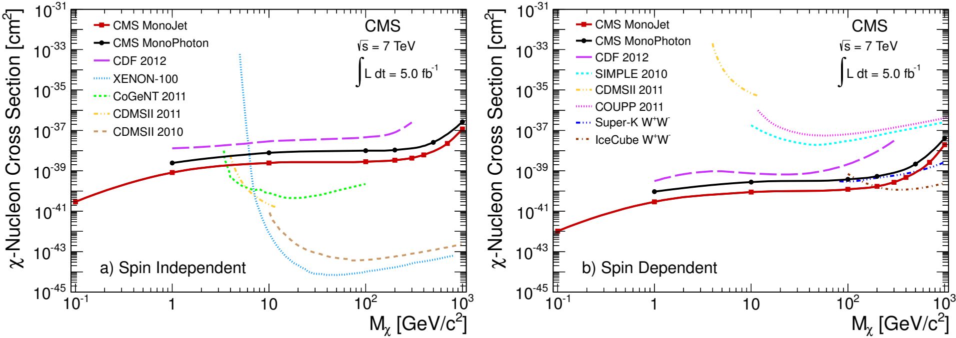
- Can search for WIMPs in cosmic rays: products of WIMPs annihilation (in Galactic center, dwarf galaxies, Sun)

$$X + \bar{X} \to p\bar{p}\,,\;\; e^+e^-\,,\;\; \nu, \gamma, \ldots$$

- Direct searches for Galactic Dark Matter ($v \sim 10^{-3}$)

$$X + \text{nuclei} \to X + \text{nuclei} + \Delta E$$

Recent results of (in)direct searches @ 7 TeV

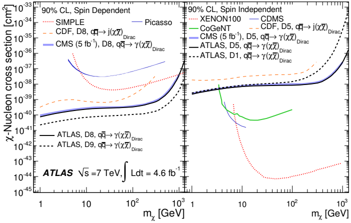


for WIMPs 1206.5663

Logic: no light superpartners, $M_{SUSY} > 500\,\text{GeV}$

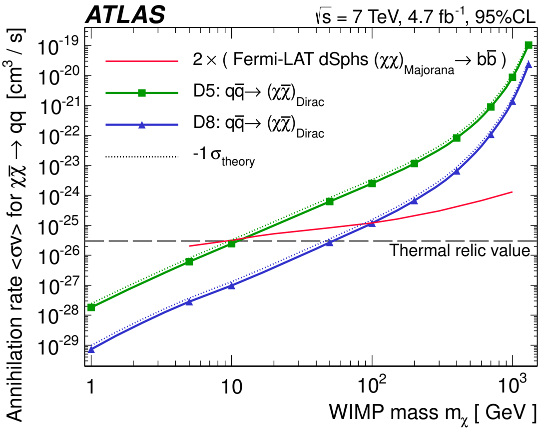
$$D1\ (scalar):\quad \frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q \qquad D8\ (axial):\quad \frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$$

$$D5\ (vector):\ \frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q \quad D9\ (tensor):\ \frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$$



1209.4625

Recent results of (in)direct searches @ 7 TeV



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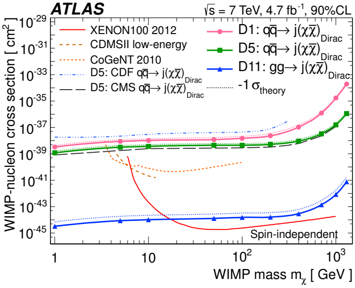
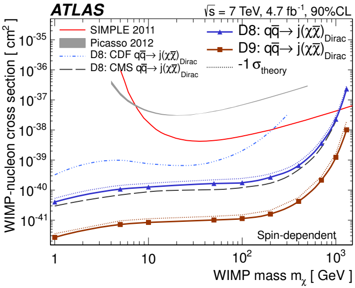




Conclusions

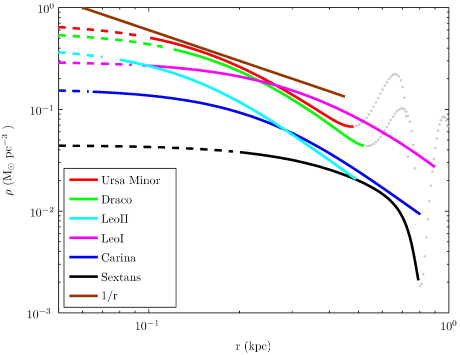
- We need clear evidences of DM in different experiments and channels (e.g., e^+ and $\bar{p}$)
- Studies at LHC are very competitive (small DM masses) with
  direct searches @ XENON, CDMS, etc
  and indirect searches @ IceCube, Baksan ...
- There are other candidates, not only WIMPs !
- DM-structure simulations:
  – Crucial question: CDM or WDM?
  – Should take into account: Central BH formation, baryon cooling,
  ... and finally arrive at present baryon structure in the GC!
  – If WIMPs are not found, the simulations is the only way to determine the correct DM to formulate the strategy of the direct search
- May be, modified gravity is responsible for DM phenomena, and we have to study GW, etc... ?

Backup slides

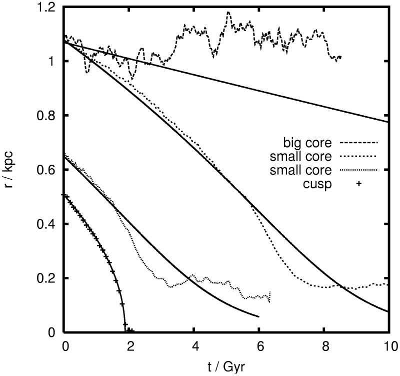
CDM Problems

- Missing satellites: $\frac{dN_{obj}}{d\ln M} \propto \frac{1}{M}$ no-scale 30 instead of 300
- Galactic density profiles: $\rho_M(r) \propto r^{-(0.5-1.5)}$ cusp

Cores observed (?)

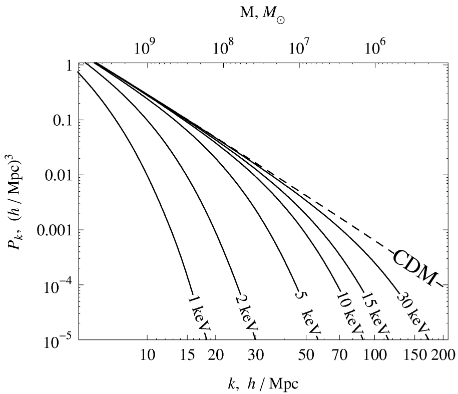


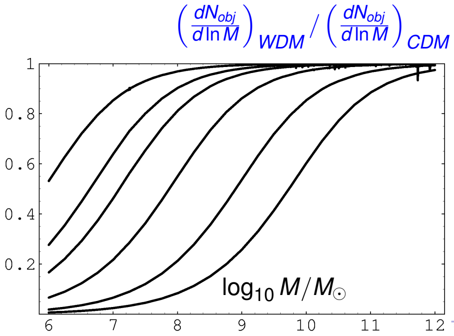
5 Clusters in the Fornax dSph



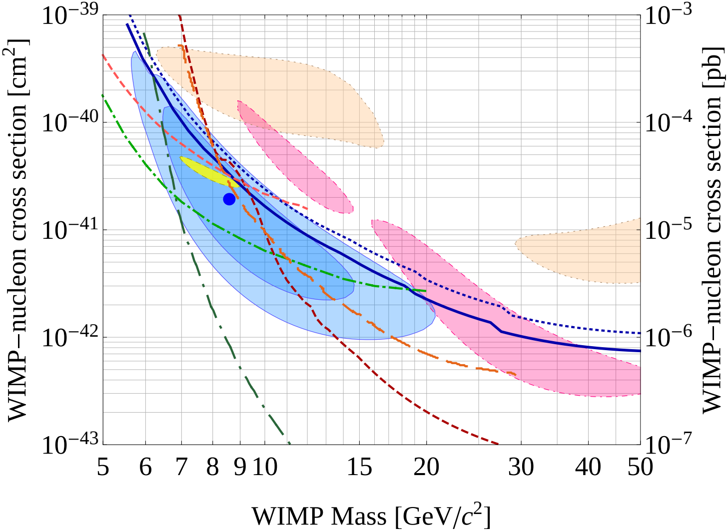
CDM Problems

- Missing satellites: $\frac{dN_{obj}}{d\ln M} \propto \frac{1}{M}$ no-scale 30 instead of 300
- Galactic density profiles: $\rho_M(r) \propto r^{-(0.5-1.5)}$ cusp
- Might be solved with Warm Dark Matter (sterile neutrino, gravitino)
  - Is non-relativistic ($v \sim 10^{-3}$) at $T \sim 1$ eV free-streaming scale $l \sim vt_H$
  - Nonthermal production is needed





Direct searches



R.Agnese et al (2013)