Dark Matter and Cosmology

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Standard Model + GR : Major Problems

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

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

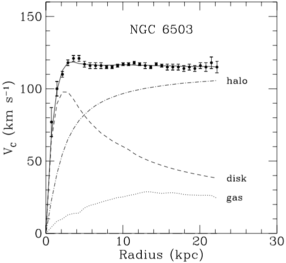
- Describes all experiments dealing with
  - electroweak and strong interactions (anomalies: $g-2$, B-physics, . . .)
- Does not describe (PHENO)
  - Neutrino oscillations (and anomalies. . .)
  - Dark matter (Ω_{DM})
  - Baryon asymmetry (Ω_B)
  - Why the Universe is flat and homogeneous?
  - Where did the matter perturbations come from?

(THEORY)

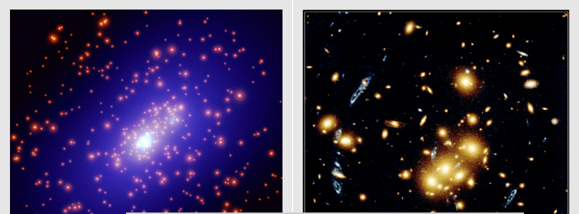
- Dark energy (Ω_Λ)
- Strong CP-problem
- Gauge hierarchy
- Quantum gravity
- Quantization of electric charge
- Why 3 generations?
- Why $Y_e \ll Y_\mu \ll .. \ll Y_t$

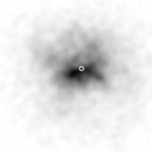
Universe content from astrophysics

Rotational curves



Gravitational lensing



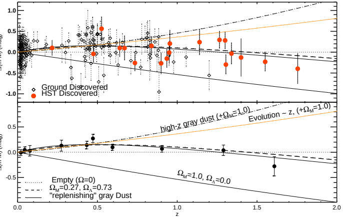


X-rays from centers of galaxy clusters

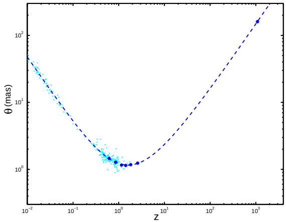
“Bullet” cluster

Universe content from cosmology

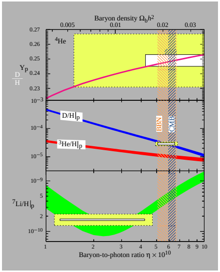
Standard candles

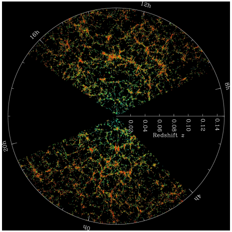


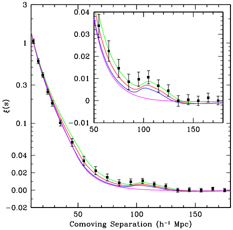
Angular distance

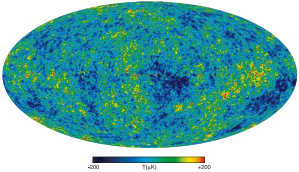


Nucleosynthesis







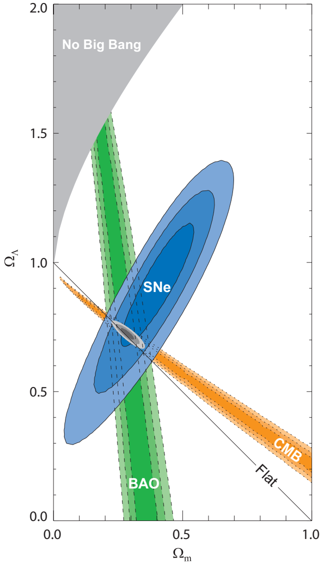


Large Scale Structures

Baryon acoustic oscillations

CMB anisotropy

Cosmological data suggest . . . DM, DE, flatness, etc



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

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

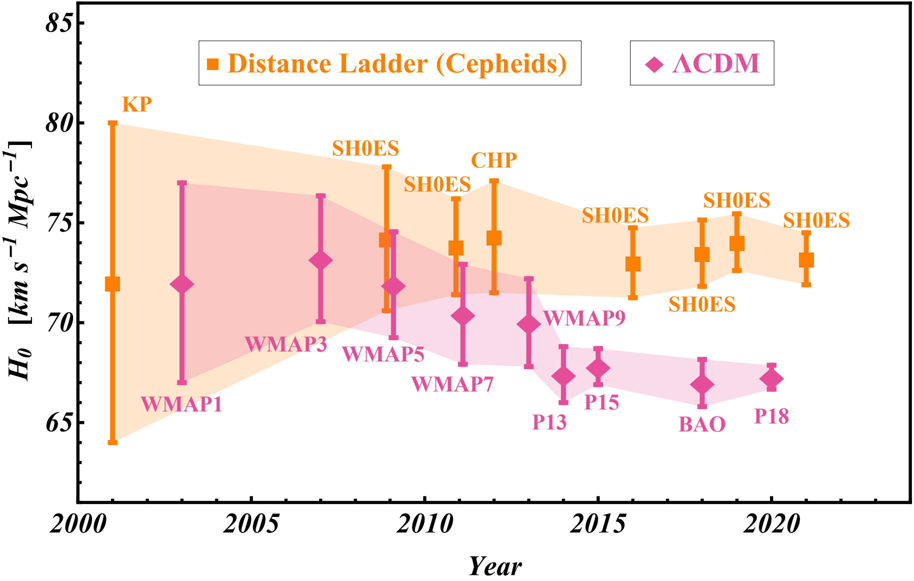
$$\rho_{\text{radiation}} \propto 1/a^4(t) \propto T^4(t)\,, \quad \rho_{\text{matter}} \propto 1/a^3(t)$$

$$\rho_\Lambda = \text{const}, \quad 1/a^2(t) \propto \rho_{\text{curvature}} = 0$$

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

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

Dark matter:	$\Omega_{DM} \equiv \frac{\rho_{DM}}{\rho_c} = 0.28\ (0.24...0.20\ ?)$
Dark energy:	$\Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} = 0.67\ (0.71...0.75\ ?)$


■ Distance Ladder (Cepheids)
◆ ΛCDM
H_0 [$km\ s^{-1}\ Mpc^{-1}$]
85
80
75
70
65
2000
2005
2010
2015
2020
Year
KP
SH0ES
SH0ES
CHP
SH0ES
SH0ES
SH0ES
SH0ES
SH0ES
WMAP1
WMAP3
WMAP5
WMAP7
WMAP9
P13
P15
BAO
P18

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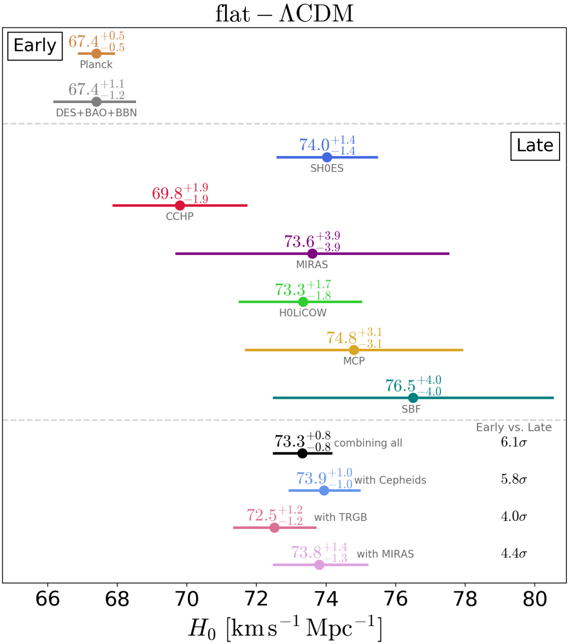

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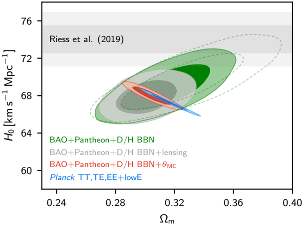

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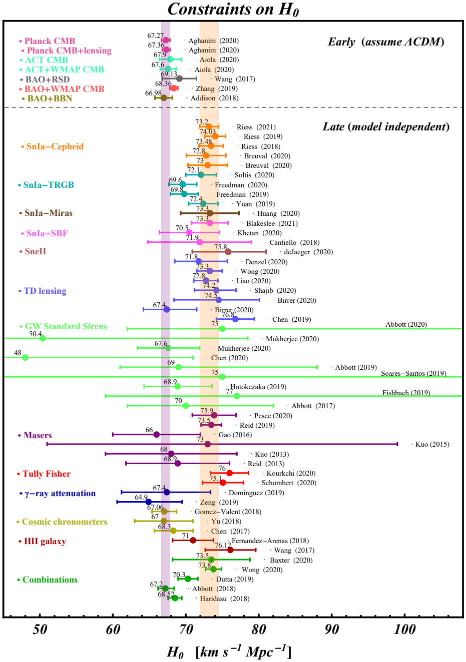

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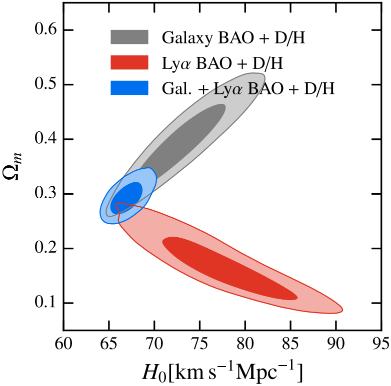

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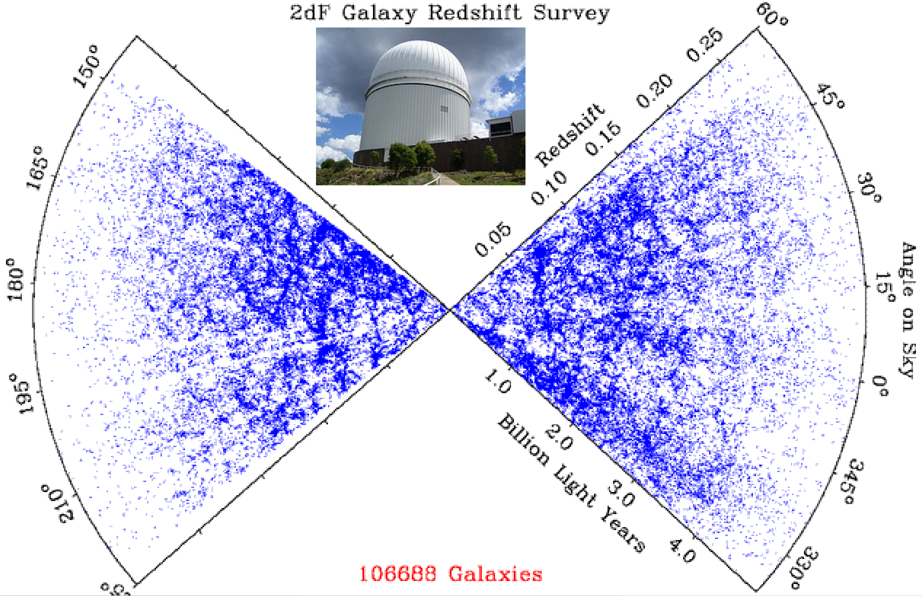
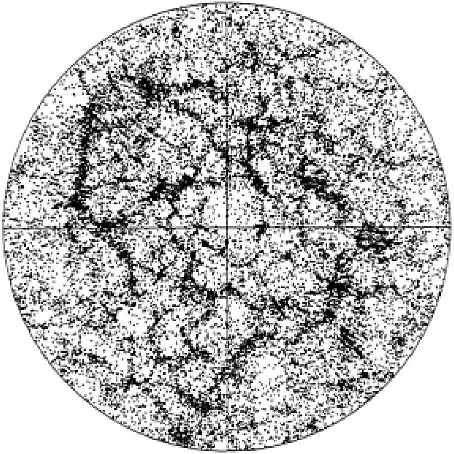
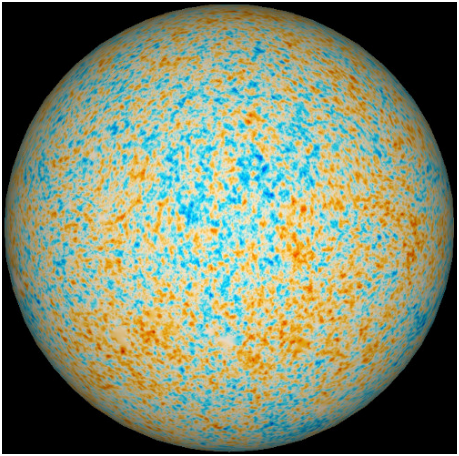
Very large scales: homogeneity and isotropy



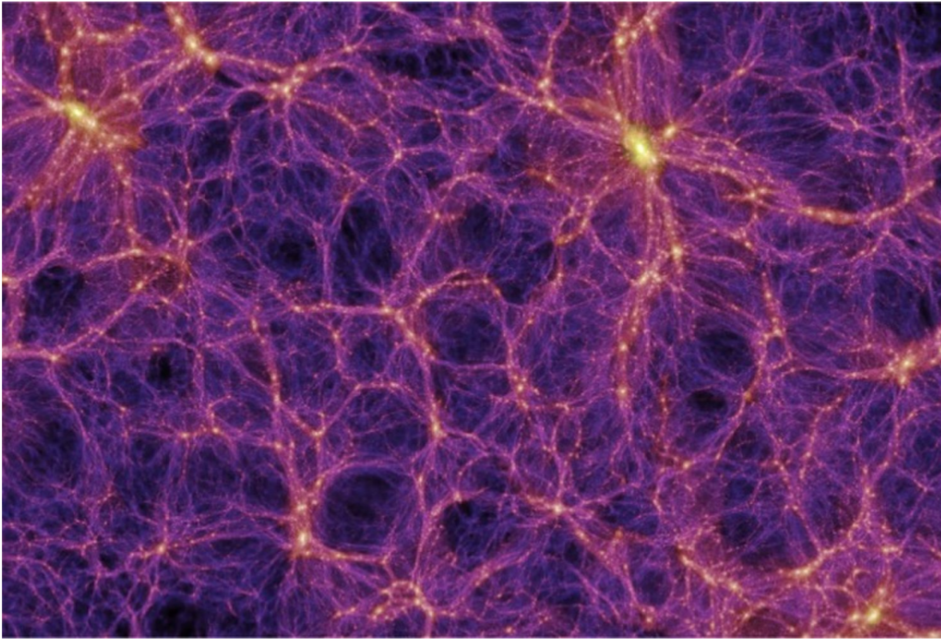
Inhomogeneous Universe

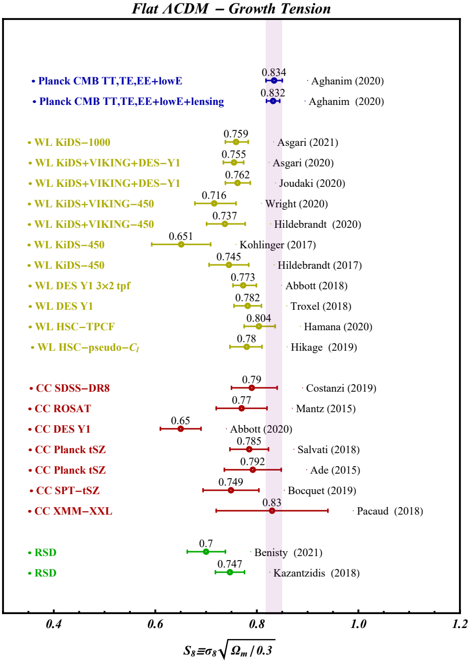




Large Scale Structure

CMB anisotropy





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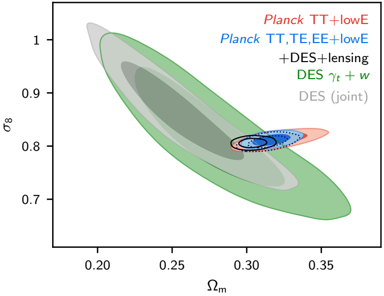

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Dark Matter properties from astrophysics

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: $\lambda = 2\pi/(M_X v_X) < l_{\text{galaxy}}$, 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

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

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 ($T = 0.8\,\mathrm{eV}$)

3. nonrelativistic particles long before RD/MD-transition ($T = 0.8\,\mathrm{eV}$)
   (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$)
   Otherwise no small-size structures, like dwarf galaxies: $l_{fs} = a\int v(t)dt/a(t)$
   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
6. all matter inhomogeneities (perturbations) are adiabatic:

$$\delta\left(\frac{n_B}{n_{DM}}\right) = \delta\left(\frac{n_B}{n_\gamma}\right) = \delta\left(\frac{n_\nu}{n_\gamma}\right) = 0$$

Suggested solutions except particles

- Modified gravity…
  - massive gravitons
  - Weyl Gravity
  - MOND (modified but not gravity !... TeVeS, etc) only galaxies
- Macroscopic objects
  - Massive Astrophysical Compact Halo Objects: only galaxies

    searches via microlensing

    Compact stars: white, brown dwarfs, black holes
  - Q-balls may be related to BAU
  - boson stars, scalar field clumps, etc

    searches for bursts, pulsar timing, GW destrortion etc
  - Primordial Black holes:

    searches for BH evaporation

Each needs New Physics...

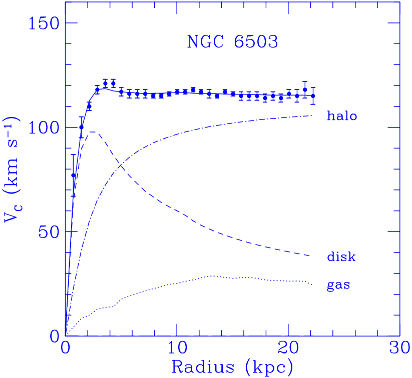
Galactic dark halos: flat rotation curves

Newtonian dynamics

$$\frac{V^2(R)}{R}m = G\frac{mM(R)}{R^2}$$

$$v(R) = \sqrt{G\frac{M(R)}{R}}$$

$$M(R) = 4\pi\int_0^R \rho(r)r^2dr$$



observations: $v(R) \simeq \text{const}$

visible matter:

internal regions $v(R) \propto \sqrt{R}$

external (“empty”) regions $v(R) \propto 1/\sqrt{R}$

Flat rotation curves: suggested solutions

compact non-relativistic 'dark' objects: e.g. Dark Matter particles

N-body simulations within GR show

Navarro, Frank, White

$$\rho_{DM}(r) = \frac{\rho_c}{r\,(r+r_c)^2}\,, \qquad M(R) = 4\pi\int_0^R \rho_{DM}(r)r^2dr \propto \log(R) \simeq \text{const}\,,$$

Other selected solutions to this particular problem

- MOdified Newtonian Dynamcs (MOND)

  M.Milgrom

$$F_N = ma \;\; \to \;\; F_N = m\frac{a^2}{a_0}\,, \;\; \text{for} \;\; a < a_0 \simeq 10^{-8}\text{cm}^2\text{s}^{-1}$$

- Weyl Gravity

  Ph.Mannheim

$$\nabla^2\phi(R) = 4\pi G\rho(R)\,, \;\; \to \nabla^4\phi(R) \propto G\rho(R)$$

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Each needs New Physics...

Intermediate solution: black hole remnants

Speculations within the minimalistic popular extension: Higgs inflation

$$\mathscr{L} = \xi R\Phi^\dagger\Phi\,, \qquad \xi \sim (\delta\rho/\rho)^{-1} \sim 10^4$$

Two possible options to resolve the strong coupling:

- Non-renormalizable operators at $\Lambda = M_{Planck}/\xi$

  if their dynamics allow for BH production...

  they evaporate, and the remnants give at present

  1 BH in 10^{14} horizons is enough $\rho_{BHR} \simeq 10^{14}\rho_{DM}$

- healthy variant with added $\mu^2 R^2$:

  no problems with strong coupling

  instant violent preheating... not always under control

  if their dynamics allow for small BH production... e.g. in transplackian particle scattering

  1 pair in 10^{20} horizons is enough $\rho_{BHR} \simeq 10^{20}\rho_{DM}$

They could be what we need for Dark Matter

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
  Usually stability at cosmological time scales implies a new (almost) conserved charge
  Make your choice or suggest one more candidate!
- Need a Guiding Principle to set priorities

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:

  antibaryonic DM

  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

Dark Matter: many well-motivated candidates

WIMPs	related to EW scale, SUSY
sterile neutrinos	active neutrino oscillations
light scalar field	string theory
axion	strong CP-problem
gravitino	local SUSY
Heavy relics	GUTs
(Topological) defects	GUTs
Massive Astrophysical Compact Heavy Objects	
Primordial black hole (remnants)	Phase transitions exotic inflation, reheating

Multicomponent Dark Matter ?

γ, ν, H, He

Illustration with a simple example of scalar DM

most general renormalizable coupled to SM:

Z_2-invariant Higgs (Φ) portal

$$\Delta\mathscr{L} = \frac{1}{2}g^{\mu\nu}\partial_\mu S\partial_\nu S - \frac{1}{2}m^2S^2 + g^2S^2\Phi^\dagger\Phi - \frac{\lambda}{4}S^4$$

Options:

- freeze-out: sufficiently large g^2

$$\sigma_{hh\to SS}\times n_h \gtrsim H \;\;\rightarrow\;\; \sigma_{SS\to\ldots} = \sigma_0, \;\; \text{e.g.} \;\; \frac{g^4}{(4\pi\ldots)^2m_S^2} = \sigma_0$$

- freeze-in: intermediate g^2

$$\dot{n}_S + 3Hn_S = \sigma_{hh\to SS}n_h^2 \;\;\rightarrow\;\; \frac{n_S}{s} = \#\int dT\frac{n_h^2}{sHT}\times\frac{g^4}{T^2} \sim g^4\frac{M_{Pl}}{m_S} \;\;\rightarrow$$

$\Omega_S \propto g^4 \;\;\rightarrow\;\; g^2 \approx 10^{-11}$ still natural...

WIMPs: discussion

$$\Omega_X = 0.1 \cdot \left(\frac{(10\ \text{TeV})^{-2}}{\sigma_0} \right) \frac{10}{\sqrt{g_*(T_f)}} \ln \left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}} \right) \cdot \frac{1}{2h^2}$$

- natural DM: subweak-scale cross section $\sigma_0 \sim 0.01 \times \sigma_W$
  say, $M_X \sim 1$ TeV or X is not a weak gauge eigenstate
- naturaly "light" unitarity $\sigma_0 \lesssim \frac{4\pi}{M_X^2} \longrightarrow M_X \lesssim 100$ TeV
- all stable particles with smaller σ_0 are forbidden !!
- WIMPs remain in kinetic equilibrium with plasma till $T \sim 10$ MeV

  this is Cold Dark Matter, $v_{RD/MD} \ll 10^{-3}$

  WIMPs may form dark halos (clumps) much lighter than dwarf galaxies

Weakly IMPs are mostly welcome (e.g. LSP in SUSY)

We can fully explore the model !!

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

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

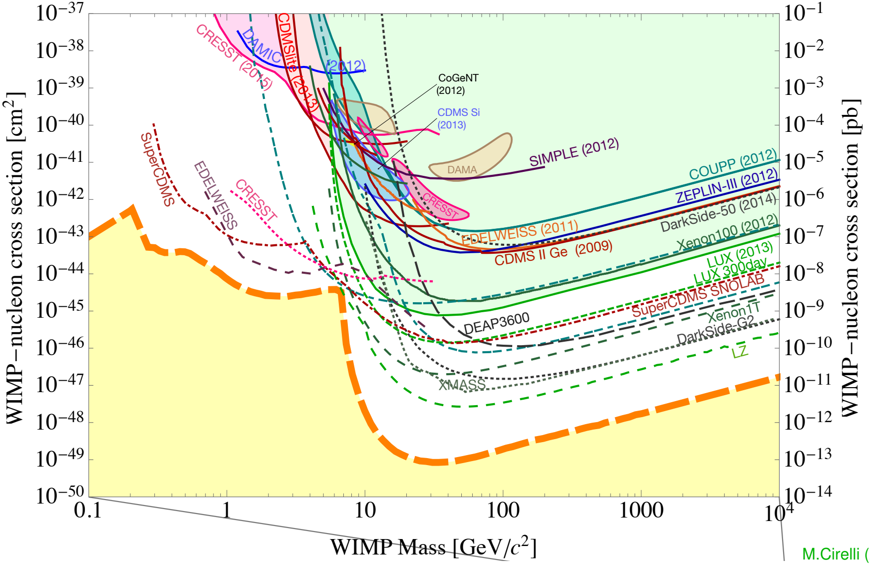
- Can search for WIMPs in cosmic rays: products of WIMPs annihilation (in Galactic center, dwarf galaxies, Sun) $\propto n^2$

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

- Can search for WIMPs in collision experiments (LHC): missing

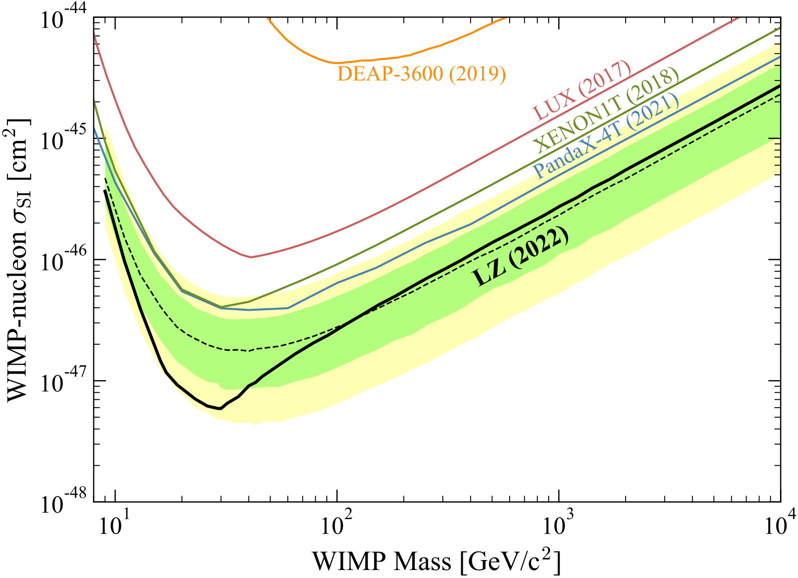
$$X + \bar{X} \leftrightarrow \text{SM} + \text{SM'} + \dots$$

Prospects in WIMP searches



M.Cirelli (2015)

First results of next-gen experiments: LUX-ZEPLIN



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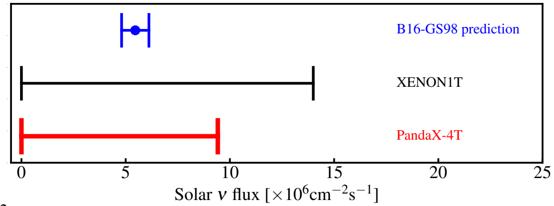
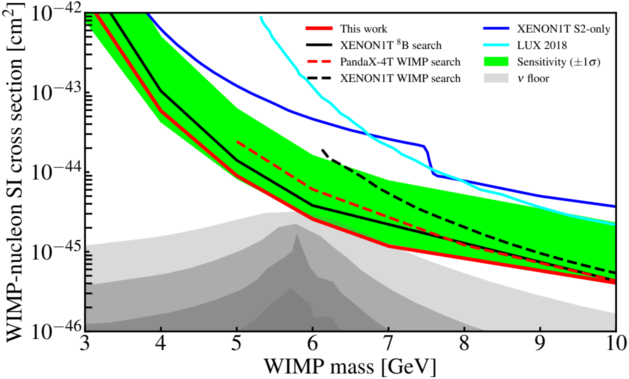
Testing neutrino floor with PandaX-4T

2207.04883





Other by-product results:

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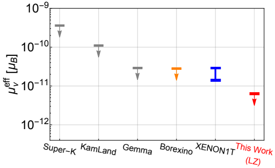
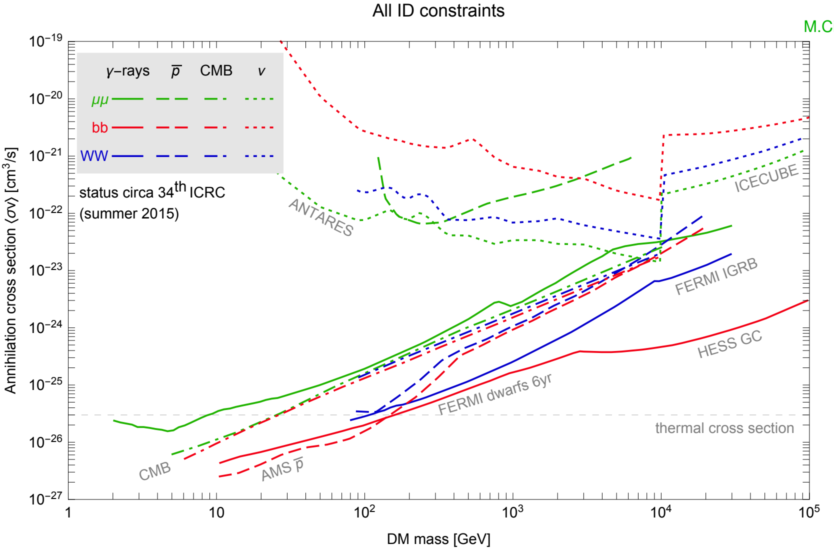
the strongest limit on μ_ν from LZ:



Indirect limits on DM annihilation (clumps..)

M.Cirelli (2015)



Next generation: CTA

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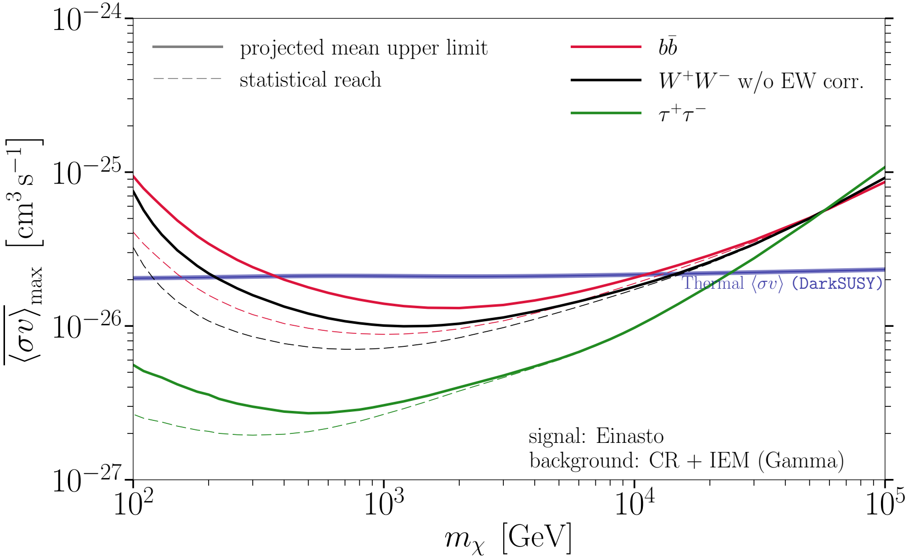
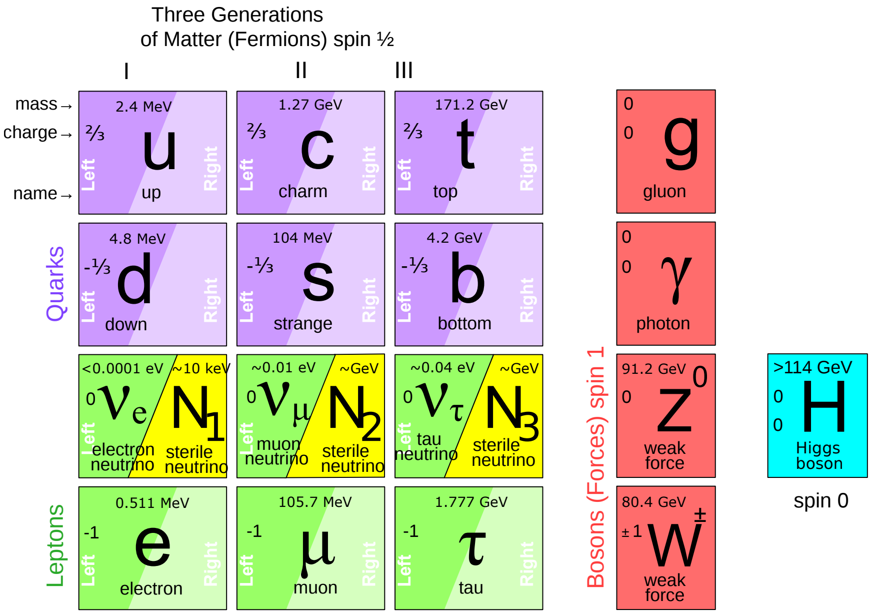




Three Generations of Matter (Fermions) spin ½

	I	II	III	Bosons (Forces) spin 1	spin 0
mass → charge → name → Quarks	2.4 MeV ⅔ u up Left Right	1.27 GeV ⅔ c charm Left Right	171.2 GeV ⅔ t top Left Right	0 0 g gluon	
	4.8 MeV -⅓ d down Left Right	104 MeV -⅓ s strange Left Right	4.2 GeV -⅓ b bottom Left Right	0 0 γ photon	
Leptons	<0.0001 eV 0 ν_e Left electron neutrino ~10 keV N_1 sterile neutrino	~0.01 eV 0 ν_μ Left muon neutrino ~GeV N_2 sterile neutrino	~0.04 eV 0 ν_τ Left tau neutrino ~GeV N_3 sterile neutrino	91.2 GeV 0 Z^0 weak force	>114 GeV 0 0 H Higgs boson
	0.511 MeV -1 e electron Left Right	105.7 MeV -1 μ muon Left Right	1.777 GeV -1 τ tau Left Right	80.4 GeV ±1 $W^\pm$ weak force	

Seesaw mechanism: $M_N \gg 1$ eV

With $m_{active} \lesssim 1$ eV we work in the seesaw (type I) regime:

$$\mathscr{L}_N = \overline{N} i\partial\!\!\!/ N - f\overline{L}_e^c \tilde{H} N - \frac{M_N}{2}\overline{N}^c N + \text{h.c.}$$

Higgs gains $\langle H\rangle = v/\sqrt{2}$ and then

$$\mathscr{V}_N = \frac{1}{2}\left(\overline{\nu}_e\,,\overline{N}^c\right)\begin{pmatrix} 0 & v\,\frac{f}{\sqrt{2}} \\ v\,\frac{f}{\sqrt{2}} & M_N \end{pmatrix}\begin{pmatrix} \nu_e \\ N \end{pmatrix} + \text{h.c.}$$

For a hierarchy $M_N \gg M^D = v\,\frac{f}{\sqrt{2}}$ we have

flavor state $\nu_e = U\,\nu_1 + \theta\,N$ with $U \approx 1$ and

active-sterile mixing: $$\theta = \frac{M^D}{M_N} = \frac{v\,f}{2M_N} \ll 1$$

and mass eigenvalues

$$\approx M_N \quad \text{and} \quad -m_{active} = \theta^2 M_N \lll M_N$$

Sterile neutrino: well-motivated keV-mass Dark Matter

- massive fermions giving mass to active neutrino through mixing (seesaw)

$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- unstable, $N \to \nu\nu\nu$ is always open
  but exceeding the age of the Universe if

(applicable for $M_N < M_W$)

$$\theta^2 < 1.5 \times 10^{-7} \left(\frac{50\,\text{keV}}{M_N}\right)^5$$

- with seesaw constraint $m_a \sim \theta^2 M_N$

$$\tau_{N\to 3\nu} \sim 1/\left(G_F^2 M_N^5 \theta_{\alpha N}^2\right) \sim 1/\left(G_F^2 M_N^4 m_\nu\right) \sim 10^{11}\,\text{yr}\,(10\,\text{keV}/M_N)^4$$

Sterile neutrino: indirect searches

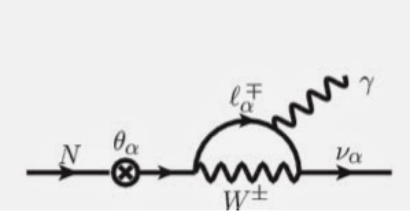
$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- unstable, but exceeding the age of the Universe if

$$\frac{\theta^2}{3\times10^{-3}} < \left(\frac{10\,\mathrm{keV}}{M_N}\right)^5$$

- DM sterile neutrinos can be searched at X-ray telescopes because of two-body radiative decay

give limits in absence of the feature

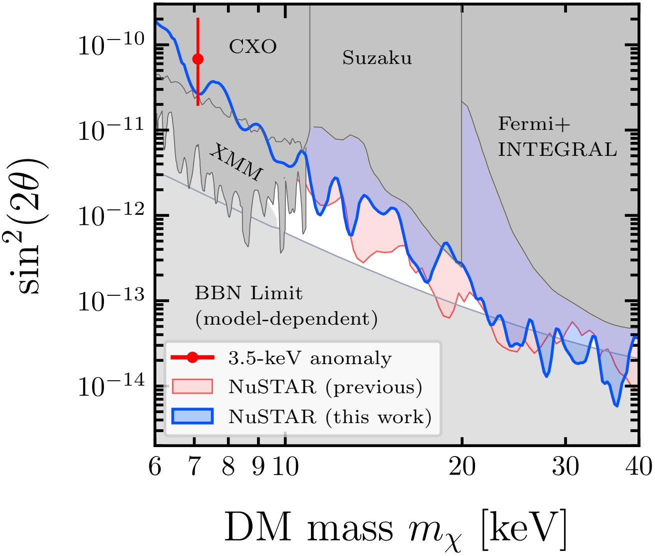


a narrow line $(\delta E_\gamma/E_\gamma \sim v \sim 10^{-3})$
at photon frequency $E_\gamma = M_N/2$

$$\frac{\theta^2}{10^{-11}} \lesssim \left(\frac{10\ \mathrm{keV}}{M_N}\right)^4$$

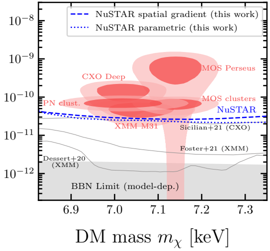
. . . present searches: NuSTAR

2207.04572

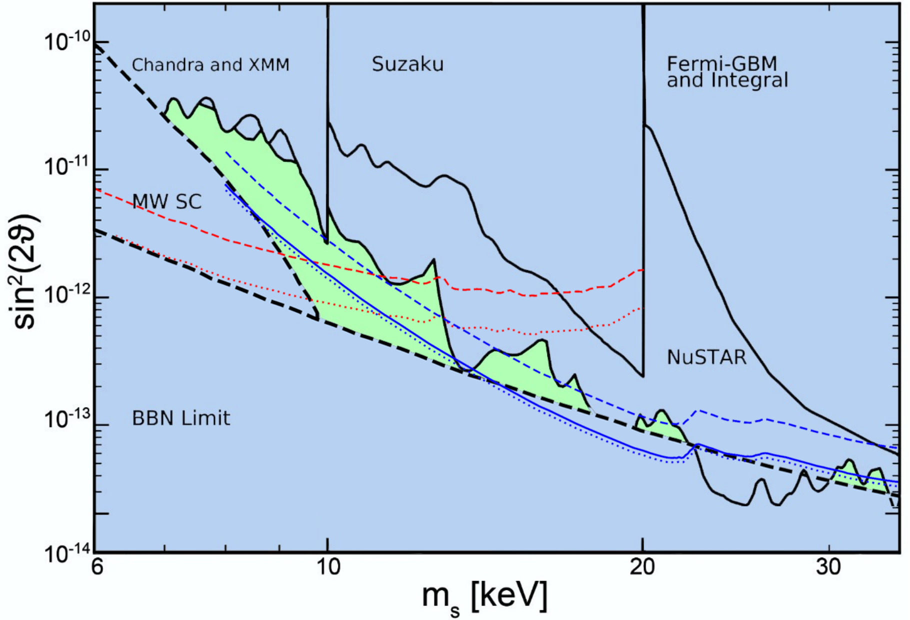


- upper limits on mixing: from *X*-ray searches
- lower limits on mass: from structure formation

  and BBN predictions



eROSITA (0.2-10 keV), ART-XC (4-30 keV)



1908.09037

2007.07969 (V. Barinov, R. Burenin, D.G., R. Krivonos)

Anomalies with matter structures at small scales

- Core-cusp problem

  Dark Matter density profiles in the centers of simulated halos are cusped

  while in observed dwarf galaxies are cored

- Lack of dwarf galaxies

  Matter perturbations of almost flat spectrum produce flat halo mass spectrum

  low abundance of small galaxies

- Too-big-To-fail problem

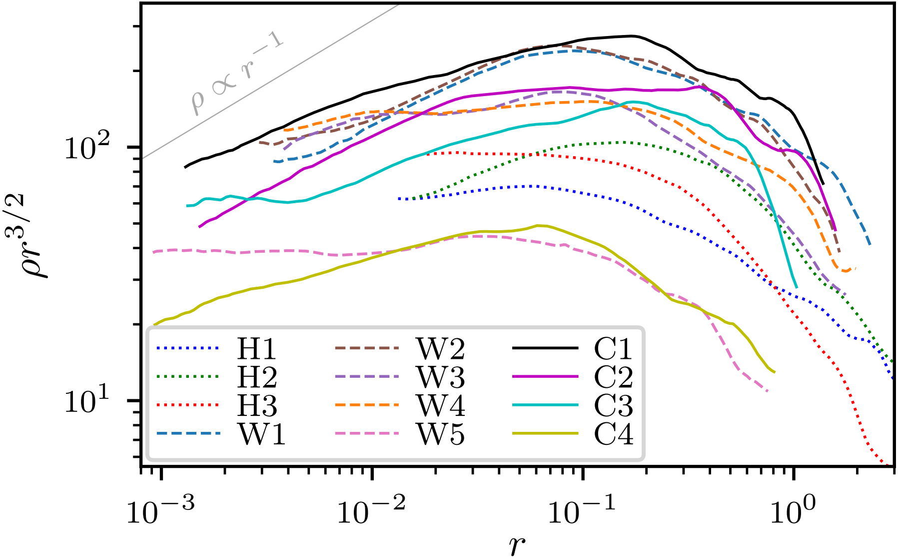
  There must be galaxies heavy enough to keep baryons inside

  Milky Way hosts only two such galaxies

WDM, SIDM, Fuzzy DM etc: to suppress structures at small scales

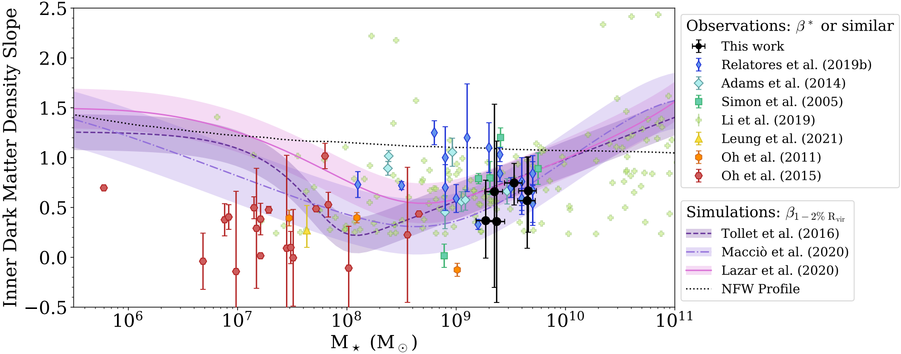
Cusps in simulations

2207.05082



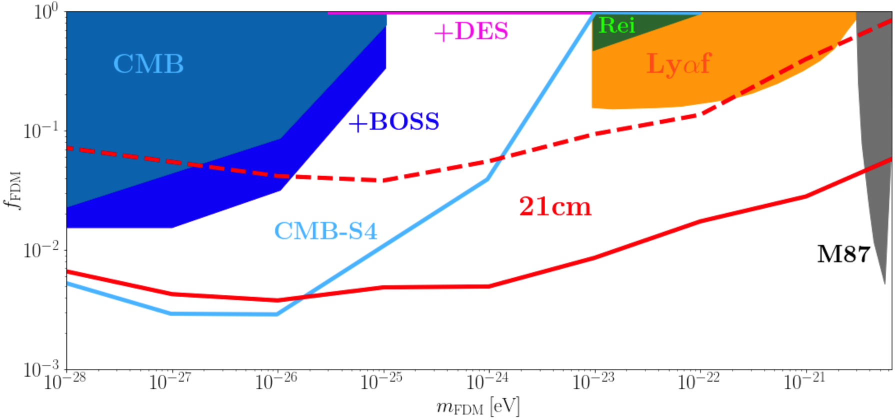
Core vs cusp in a galaxy...

2203.00694



$$\rho(r) \propto \frac{1}{r^{\beta^*}}$$

HERA sensitivity to Fuzzy DM (quantum pressure)



new observable to test the model...

2207.05083

Gravity works admirably

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)

DM particles may be produced
in scattering
of SM particles in plasma
of inflaton particles
in inflaton field oscillations
via virtual gravitons
just fine-tune the mass...

see e.g. many works by Y.Mambrini

Generically untestable

Summary

- So far only gravitational evidences for Dark Matter
- It would be nice to have something else...
- But nobody guarantees it...

On this way we face problems with

- Hubble crisis and S_8 discrepancy
- Various issues with small scale structures
- Excluding (seemingly) most natural models...

We are looking forward to

- New data and observables
- New models and simulations
- New interesting by-product results...

Never give up !

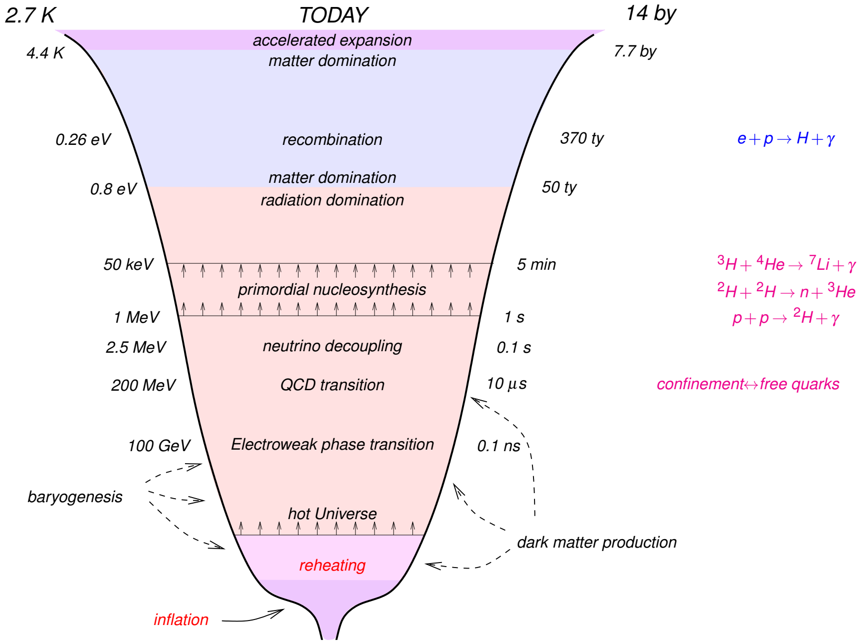
Standard cosmological model $ds^2 = dt^2 - a^2(t)dx^2$

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = H_0^2 \left[\Omega_\Lambda + (\Omega_{DM} + \Omega_B + \Omega_{\nu,m\neq 0})\left(\frac{a_0}{a}\right)^3 + (\Omega_\gamma + \Omega_{\nu,m=0})\left(\frac{a_0}{a}\right)^4\right]$$

- $T_\gamma = 2.735\,\mathrm{K}, \quad \Longrightarrow \quad \Omega_\gamma \sim 10^{-5}$
- $N_\nu \approx 3, \quad \sum m_\nu < 0.2\,\mathrm{eV} \quad \Longrightarrow \quad \Omega_{\nu,\neq 0}, \Omega_{\nu,0} \sim 10^{-5}$?
- $\Omega_B = 4.5\% \quad \Longrightarrow \quad \eta_B \equiv n_B/n_\gamma = 6 \times 10^{-10}$
- $\Omega_{DM} = 27.5\%$
- $l_{s,rec} \sim l_{H,rec}/\sqrt{3} \to \quad H_0 = 67\,\mathrm{km/s/Mpc} \quad \Longrightarrow \quad \rho_0 = 5\,\mathrm{GeV/m^3}$
- $\Omega_\Lambda = 68\% \quad \Longrightarrow$ flat space
- adiabatic, gaussian matter perturbations

  $$\langle\left(\frac{\delta\rho}{\rho}\right)^2\rangle \sim A_S \int \frac{dk}{k}\left(\frac{k}{k_*}\right)^{n_S - 1}$$

  with $A_S = 3 \times 10^{-9}$ and $n_S = 0.97$
- no tensor perturbations, $r \equiv A_T/A_S < 0.05$
- reionization at $z_{rei} \equiv a_0/a = 8$



2.7 K *TODAY* *14 by*

accelerated expansion

4.4 K *matter domination* *7.7 by*

0.26 eV *recombination* *370 ty* $e+p\to H+\gamma$

matter domination

0.8 eV *radiation domination* *50 ty*

50 keV *5 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 transition* *10 μs* *confinement↔free quarks*

100 GeV *Electroweak phase transition* *0.1 ns*

baryogenesis

hot Universe

dark matter production

reheating

inflation

Microscopic processes in the expanding Universe

A competition between scattering, decays, etc and expansion

for general processes one should solve kinetic equations

$$\frac{dn_{X_i}}{dt} + 3Hn_{X_i} = \sum(production - destruction)$$

Boltzmann equation in a comoving volume: $\frac{d}{dt}\left(n\,a^3\right) = a^3 \int \dots$

production:

$$\sigma(A+B \to X+C)n_A n_B, \quad \Gamma(D \to E+X)n_D \cdot M_D/E_D, \quad \text{etc}$$

destruction:

$$\sigma(A+X \to C+B)n_A n_X, \quad \Gamma(X \to F+G)n_X \cdot M_X/E_X, \quad \text{etc}$$

Fast processes, $\Gamma \gtrsim H$, are in equilibrium, $\sum(\ ) = 0$

and thermalize particles
no history-dependence

Core vs cusp in a galaxy...

2203.00694