GRASPA

Cosmology and Dark Matter

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Annecy-le-Vieux, 25 July 2016

Outline

ΛCDM cosmology

- Cosmic microwave background
- Big Bang nucleosynthesis
- Cosmological structure formation

Evidences at the scale of galaxies and clusters of galaxies

What is the “Dark Matter”

How to obtain the correct relic abundance

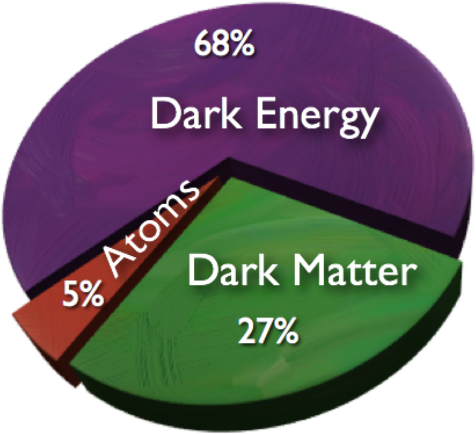
- Thermal freeze-out

WIMP dark matter

Selection of non-WIMP DM candidates

- Asymmetric DM
- keV sterile neutrino DM
- Axions

What is the Universe made of?



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Big Bang cosmology

the cosmological principle: universe is homogeneous and isotropic

+ general relativity
+ standard model of particle physics

observational pilars:

- Hubble diagram shows expansion
- Big Bang Nucleosynthesis (BBN)
- Cosmic microwave background (CMB)
- Distribution of structure at the largest scales

more ingredients:

- composition of the universe (radiation/neutrinos/baryons/DM/DE)
- evolution of density perturbations → structure formation
- generation of initial fluctuations → Inflation

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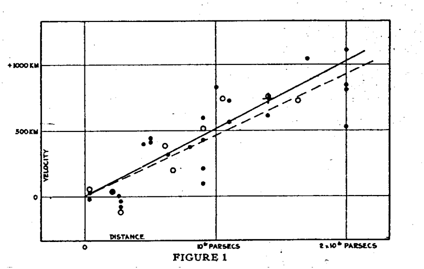
Cosmic expansion

space-time configuration consistent with cosmological principle (homogeneous and isotropic): Friedman-Lemaitre-Robertson-Walker

$$ds^2 = dt^2 - a(t)^2 (dV)^2$$

- 3-dim space dV can have positive, negative or zero curvature (observations: very close to flat)
- $a(t)$... cosmic scale factor
- Hubble parameter $H(t) = \dot{a}(t)/a(t)$
- Hubble constant $H_0 = H(t_0)$, where t_0 denotes "today"

Cosmic expansion



E. Hubble 1929

Cosmic expansion

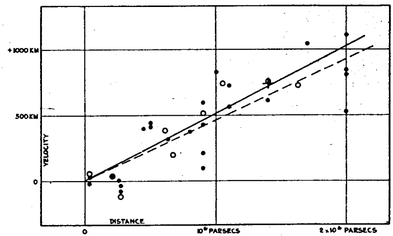
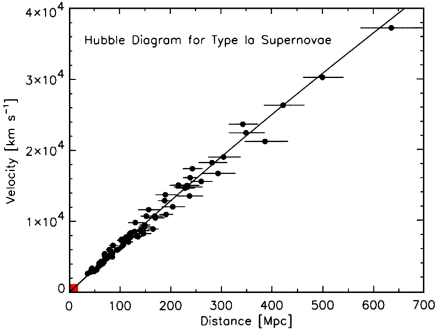


FIGURE 1

E. Hubble 1929

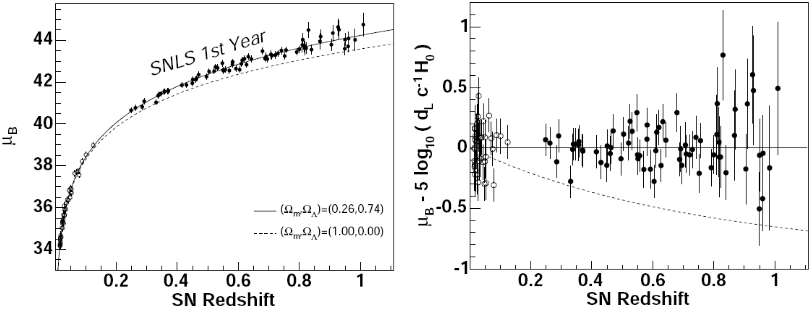


$$H_0 = 100\, h\, \mathrm{km/s/Mpc}\,, \qquad h = 0.679 \pm 0.006$$

$$1\,\mathrm{Mpc} = 10^6\,\mathrm{pc}\,, \quad 1\,\mathrm{pc} \approx 3.08 \times 10^{16}\,\mathrm{m} \approx 3.26\,\mathrm{ly}$$

Evidence for accelerated expansion

Extending the Hubble diagram to very large distances



Supernova Legacy Survey, astro-ph/0510447

red-shift:

$$1 + z = \frac{\lambda_{\text{obs}}}{\lambda_{\text{source}}} = \frac{a_0}{a(t)} \qquad z \approx 1 \leftrightarrow \quad \sim 10^4\,\text{Mpc}$$

Energy density in the expanding Universe

energy density $\rho = E/V$

cold matter (non-rel. particles)	$E = N\,mc^2$	$\Rightarrow \rho \propto a^{-3}$
radiation (relativistic particles)	$E = N\,\hbar\omega = N\,\hbar/\lambda$	$\Rightarrow \rho \propto a^{-4}$
cosmological constant Λ		$\rho = const$

$$\Rightarrow \quad \rho_{tot} = \rho_R(t_0)\left(\frac{a_0}{a}\right)^4 + \rho_M(t_0)\left(\frac{a_0}{a}\right)^3 + \rho_\Lambda$$

dynamics for $a(t)$ follow from Einstein equations:

R: $a(t) \propto \sqrt{t}$, M: $a(t) \propto t^{2/3}$, Λ: $a(t) \propto \exp(H_0\sqrt{\Omega_\Lambda}\,t)$

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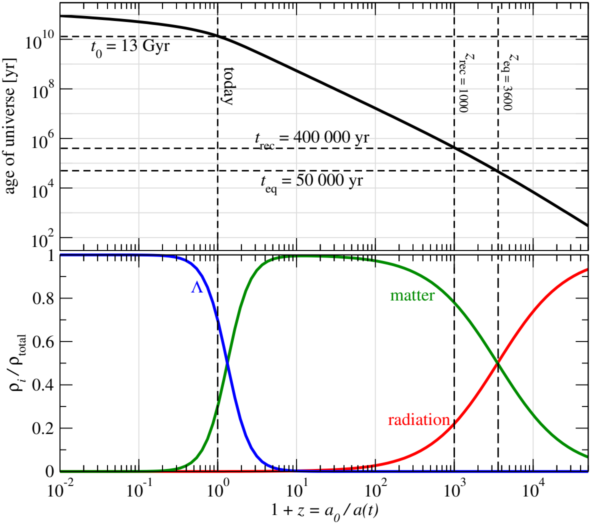
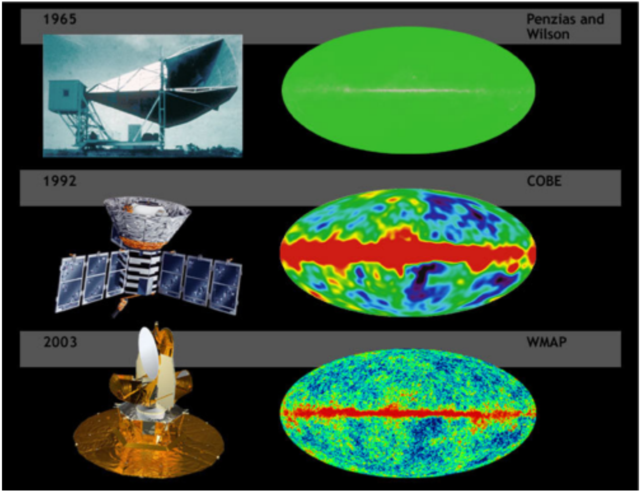
Evolution of the components



Cosmic microwave background (CMB)

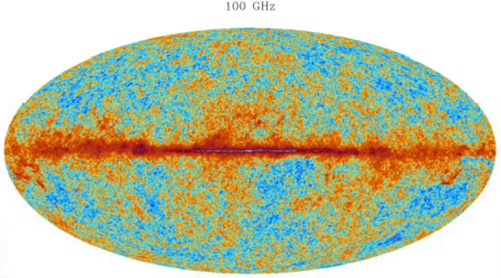
- When electrons get bound to the protons the universe becomes neutral and photons can travel freely ("decoupling")
- binding energy of H: 13.6 eV
  but: 10^{10} times more photons than baryons:
  $T_{dec} \approx 0.3\,\mathrm{eV} \approx 3000\,\mathrm{K} \quad \to \quad z_{dec} \approx 1000, \quad t_{dec} \approx 400000\,\mathrm{yr}$
- CMB predicted by Gamov, Alpher, Herman in 1948

CMB observations



Temperature fluctuations in the CMB

Planck satelite:



$$\bar{T} = 2.7260 \pm 0.0013\,\mathrm{K}$$

$$\delta(\hat{n}) = \frac{T(\hat{n}) - \bar{T}}{\bar{T}} \sim 10^{-5}$$

Density perturbations in the early universe

- Inflation introduces tiny density fluctuations in the primordial plasma
- gravity vs pressure (baryonic gas) $\rightarrow$ oscillations
- components in the plasma:
  - photons (relativistic, EM interactions)
  - neutrinos (relativistic, only weak int. + gravity)
  - baryonic matter
  - dark matter (only gravity)

important events:

- matter-radiation equality $z \approx 1000, t \approx 50000 yr$:
  - before: gravity dominated by photon gas (pressure vs gravity)
  - after: gravity dominated by DM (non-rel) structure grows on all scales
- photon decoupling $z \approx 3600, t \approx 400000 yr$:
  universe becomes neutral and photons decouple from matter (CMB)
  - before: baryons coupled to photons (feel pressure, conteracts gravity)
  - after: baryons decouple, fall into potential wells from DM overdensities

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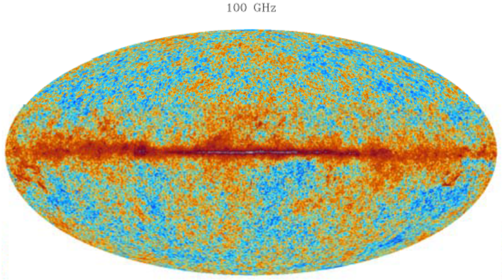


$$\bar{T} = 2.7260 \pm 0.0013\,\mathrm{K}$$

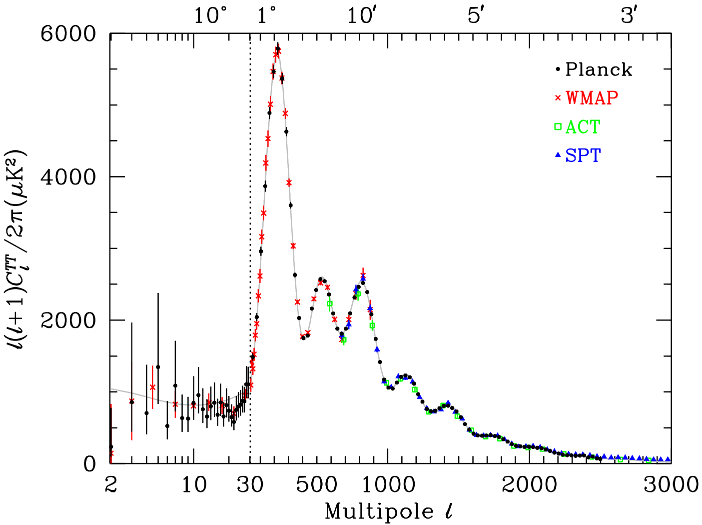
$$\delta(\hat{n}) = \frac{T(\hat{n}) - \bar{T}}{\bar{T}} \sim 10^{-5}$$

consider $\hat{n}$ and $\hat{n}'$: two unit-vectors pointing to the sky

$\langle\delta(\hat{n})\delta(\hat{n}')\rangle$ depends only on $\hat{n}\cdot\hat{n}' = \cos\theta$

$\langle\delta(\hat{n})\delta(\hat{n}')\rangle \rightarrow$ CMB temperature power spectrum:
"size" of fluctuations as a function of angular separation

CMB power spectrum



PDG 2016

Temperature fluctuations in the CMB

- primordial density fluctuations (Inflation) lead to acoustic oscillations of the baryon-photon plasma
- CMB: imprint of density fluctuations at decoupling
- position of first peak fixed by sound horizon @ decoupling (largest scale for which oscillations can build up)
- position and relative height of peaks depends on $\Omega_M, \Omega_\Lambda, \Omega_B, \ldots$

Ω_M : increasing DM:

- matter-radiation-equality earlier $\rightarrow$ photons (pressure) less important $\rightarrow$ height of peaks reduced
- gravity stronger $\rightarrow$ frequency increases $\rightarrow$ peaks shift to smaller ℓ

Ω_B : increase Baryons: more "mass" has to oscillate

- frequency lower $\rightarrow$ peaks shift to larger ℓ
- odd peaks enhanced over even peaks

Ω_Λ : indirect effect of curvature: changes angular size @ last scattering surface $\rightarrow$ different wave length at given ℓ $\rightarrow$ position of peaks shift

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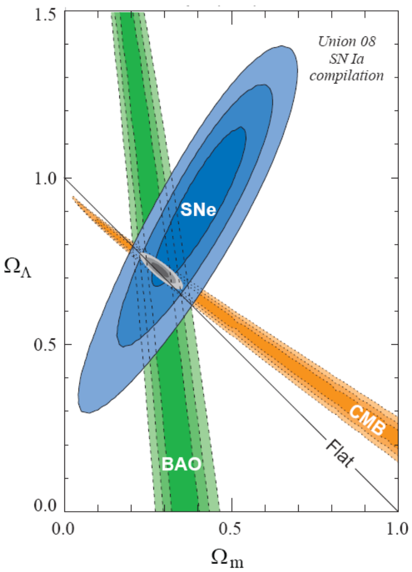
CMB + LSS + ...

$$\Omega_M + \Omega_R + \Omega_\Lambda = 1.0002 \pm 0.0026$$

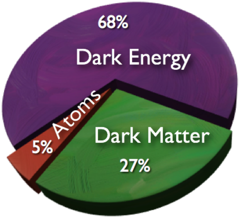
Planck 2015

$\Omega_i \equiv \rho_i / \rho_{\text{crit}}$

ρ_{crit}... density for which Univ. is flat



ΛCDM fit using CMB+BAO+... Planck, 1502.01589



baryons: $\Omega_b h^2 = 0.02227 \pm 0.00020$

CDM: $\Omega_c h^2 = 0.1184 \pm 0.0012$

DE: $\Omega_\Lambda = 0.694 \pm 0.007$

H_0 $h = 0.679 \pm 0.006$

$$\Rightarrow \qquad \frac{\Omega_B}{\Omega_M} = 0.188 \pm 0.0025$$

"normal" matter (baryons) can provide only about 19% of the total matter in the universe!

Big Bang nucleosynthesis (BBN)

- protons and neutrons in thermal equilibrium till around 1 MeV via

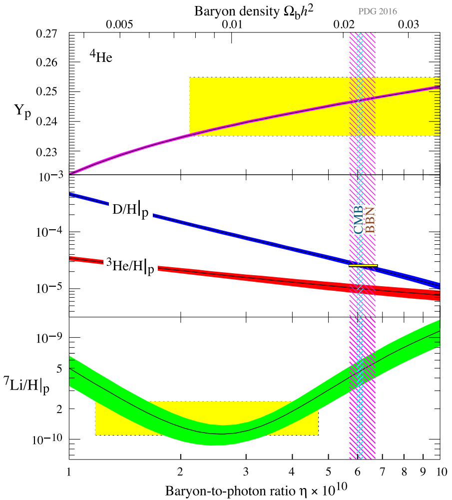
$$n + \nu_e \leftrightarrow p + e^-$$
$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$
$$n \leftrightarrow p + \bar{\nu}_e + e^-$$

- when temperature falls further nucleii start to form:

binding energies [MeV]:	D	^{3}H	^{3}He	^{4}He
	2.22	8.5	7.7	28.3

- formation of heavier nucleii is suppressed by low D binding energy
- $\sim 10^{10}$ more photons than baryons
  $\rightarrow$ D starts to form only around 0.07 MeV
- final out come of relative abundances sensitively depends on the photon-baryon ratio $\eta \propto \Omega_B h^2$

Big Bang nucleosynthesis (BBN)



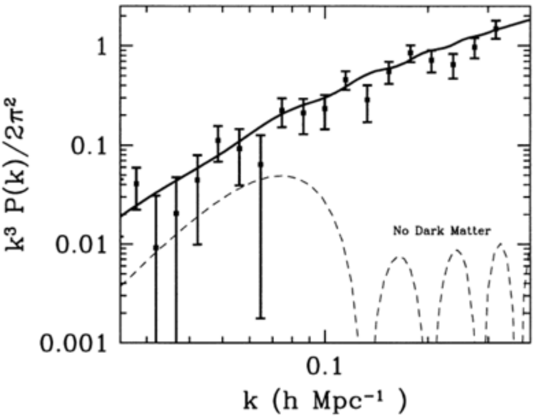
determinations of the baryon density from Big Bang Nucleosynthesis and CMB are in perfect agreement:

$$\Omega_b h^2 = 0.0214 \pm 0.0020 \quad \text{(BBN)}$$
$$\Omega_b h^2 = 0.0223 \pm 0.0002 \quad \text{(CMB)}$$

Structure formation

- initial density fluctuations from inflation
- after matter-radiation equality over-densities in non-relativistic DM start to grow
- after decoupling baryons fall into potential wells of DM over-densities
- structure forms “hierarchical” (small scales first)

Need DM to form enough structure at scales $\lesssim$ 10 Mpc



S. Dodelson

DM N-body simulations

Millennium simulation V. Springel et al., MPIA, 2005

- around 10^{10} particles
- start from initial conditions motivated by CMB temperature fluctuations
- trace the evolution of the matter distribution in a cubic region (periodic boundaries) of the Universe over 500 Mpc/h (2 billion light-years) on a side
- particle mass: $8.6 \times 10^8 / h\, M_\odot \to$ dwarf galaxies about a hundred particles, galaxies like the Milky Way about a thousand, and the richest clusters of galaxies several million

- projected density field for a 15 Mpc/h thick slice at redshift $z = 0$

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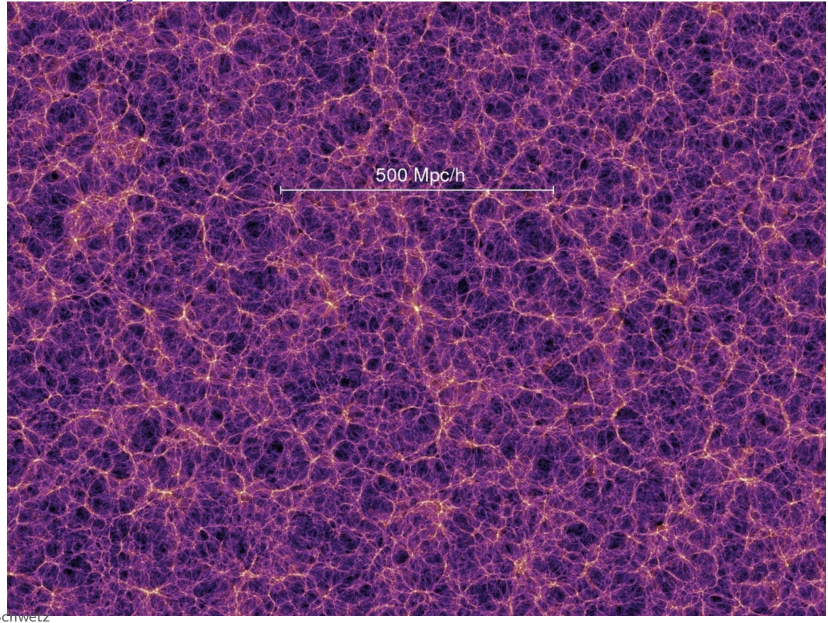

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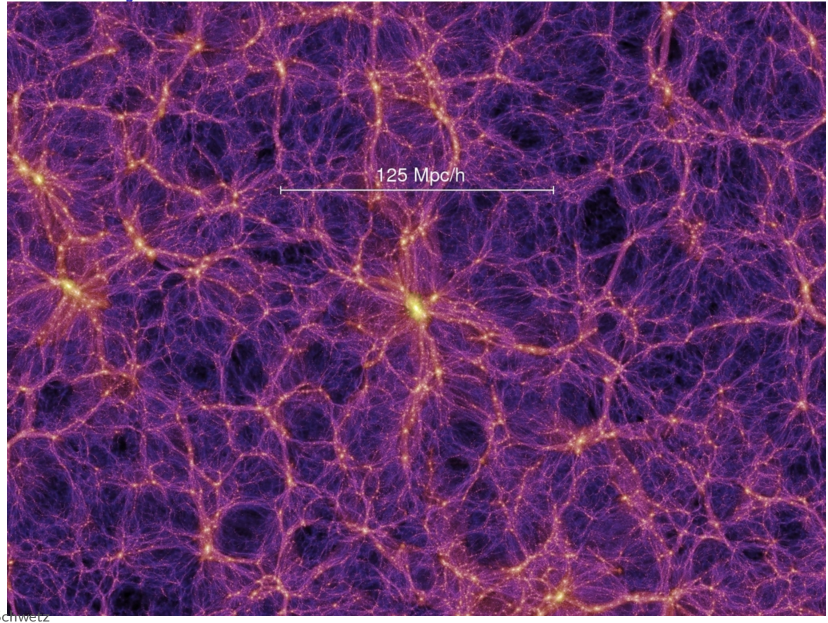

DM N-body simulations
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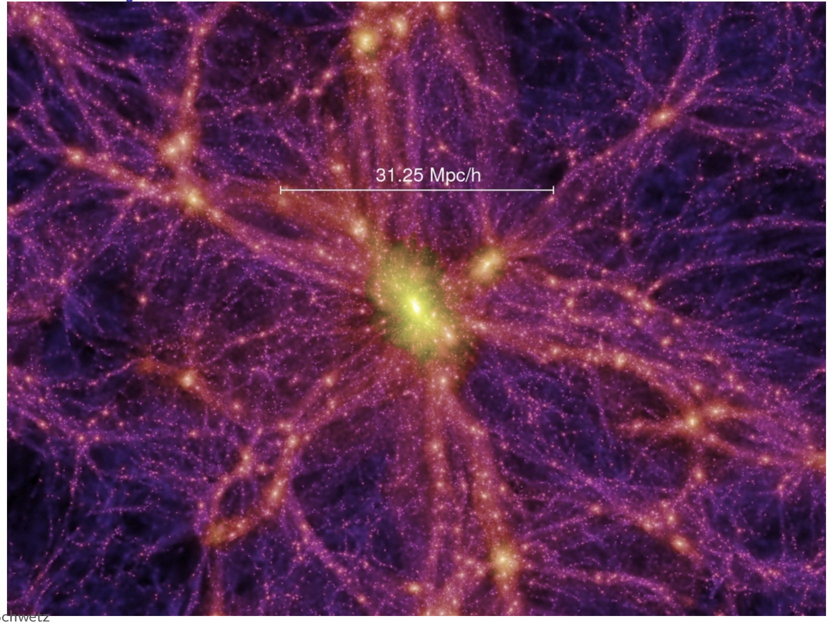
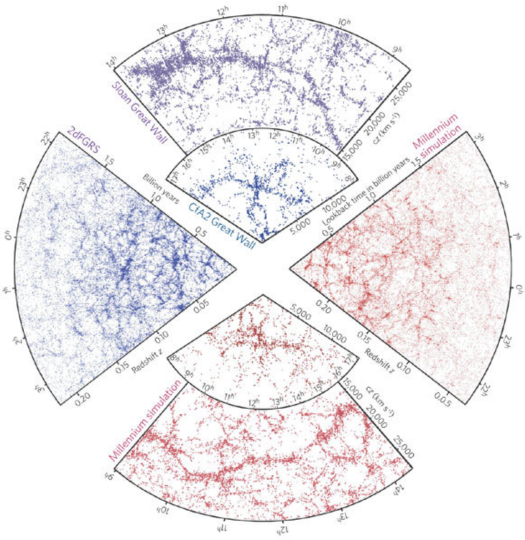


Comparison of CDM simulations and observations

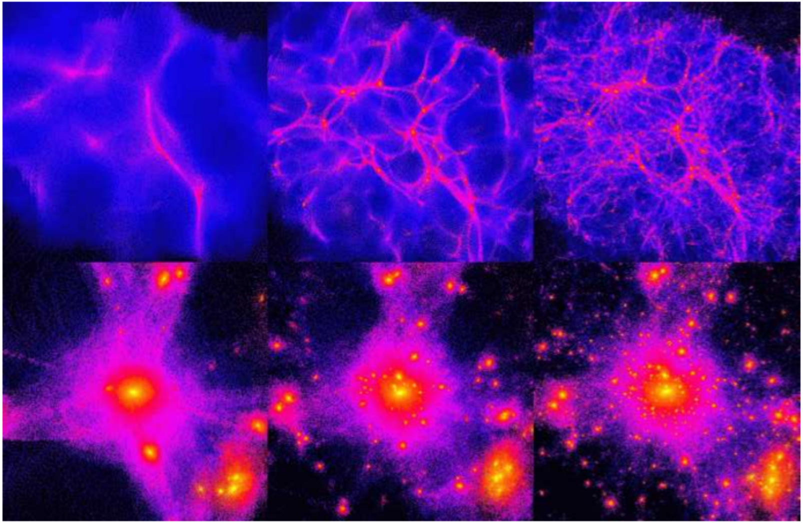


Springel, Frenk, White, Nature 440, 1137 (2006)

Dark Matter in a Milkyway-like Galaxy

Aquarius simulation

(impact of baryons?)

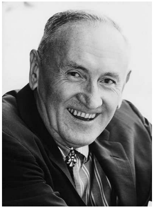


Ben Moore simulations

Outline

Virial theorem applied to galaxies and clusters

F. Zwicky 1933



assume that a galaxy (or cluster of galaxies) is a "gas" of gravitationally bound objects in equilibrium

$$m_i \ddot{\vec{x}}_i = -\vec{\nabla} V(\vec{x}_i) \,, \qquad V = -\frac{G_N}{2} \sum_{j \neq i} \frac{m_i m_j}{|\vec{x}_i - \vec{x}_j|}$$

multiply with $\vec{x}_i$ and sum over i:

$$\underbrace{-\sum_i \vec{x}_i \cdot \vec{\nabla} V(\vec{x}_i)}_{\approx V} = \sum_i m_m \vec{x}_i \ddot{\vec{x}}_i = \frac{1}{2} \underbrace{\frac{d^2}{dt^2} \left(\sum_i m_i \vec{x}_i^2 \right)}_{=0} - \underbrace{\sum_i m_i \dot{\vec{x}}_i^2}_{2T}$$

$$\Rightarrow \quad 2T + V \approx 0$$

Virial theorem applied to galaxies and clusters

$$T = \frac{1}{2} M \langle v^2 \rangle \,, \qquad V = -\frac{1}{2} G_N M^2 \langle \frac{1}{r} \rangle$$

- assume that $\langle v^2 \rangle$ of galaxies is equal to $\langle v^2 \rangle$ of total matter
- $\langle v^2 \rangle$ from spread of Doppler shifts
- $\langle v^2 \rangle$ from X-ray of intergalactic gas
- $\langle \frac{1}{r} \rangle$ from angular separations + redshift

$$2T + V \approx 0 \quad \Rightarrow \quad M \approx \frac{2\langle v^2 \rangle}{G_N \langle 1/r \rangle}$$

mass-to-light ratios:

$$\frac{M_{\rm cluster}}{L_{\rm cluster}} \sim 200 \frac{M_\odot}{L_\odot} \,, \qquad \frac{M_{\rm gal}}{L_{\rm gal}} \sim 10 \frac{M_\odot}{L_\odot}$$

Rotation curves of galaxies

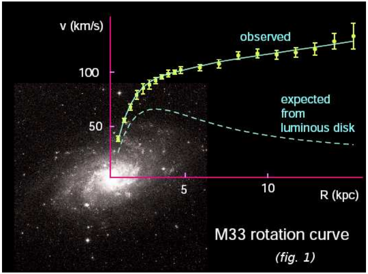
- measure rotation velocity around center of galaxy as a function of radius
- doppler shift from stars
- beyond the disc use 21.1 cm line of hydrogen gas

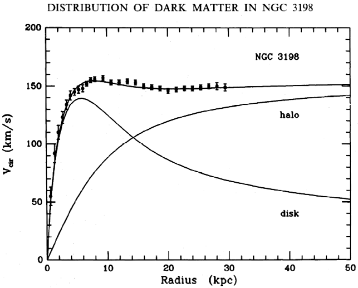
$$\frac{mv^2}{r} = G_N \frac{mM}{r^2} \quad \Rightarrow \quad v(r) = \sqrt{\frac{G_N M(r)}{r}}$$

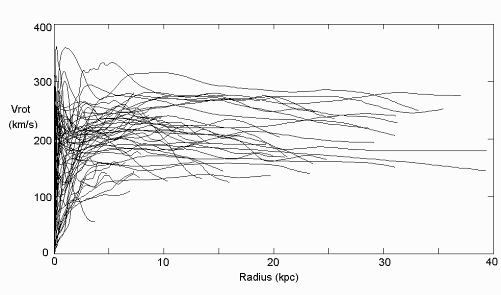
$$M(r) = 4\pi \int_0^r dr' \, r'^2 \rho(r') \qquad \text{(spherical distribution)}$$

- beyond visible matter expect $v(r) \propto 1/\sqrt{r}$
- flat rotation curve for $\rho \propto r^{-2}$

Rotation curves of galaxies







Sofue, Rubin, astro-ph/0010594

Gravitational lensing

distortion of images of distant objects by gravity of intervening gravitational lense (multiple images, giant arcs, Einstein rings)

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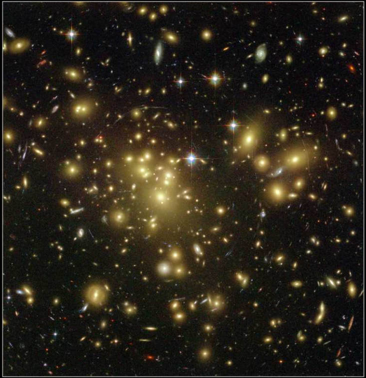
$$\frac{M_{\text{cluster}}}{L_{\text{cluster}}} \sim 200 \frac{M_\odot}{L_\odot}$$

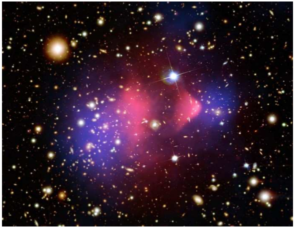
$$\frac{M_{\text{gal}}}{L_{\text{gal}}} \sim 10 \frac{M_\odot}{L_\odot}$$



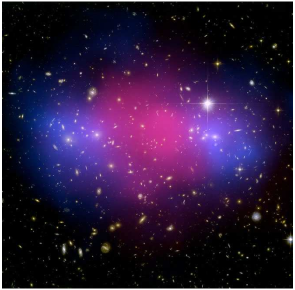
Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin (STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScI-PRC03-01a

Mergers of galaxy clusters



"Bullet Cluster"
1E0657-56 (2006)



"Baby Bullet"
MACS J0025.4-1222 (2008)

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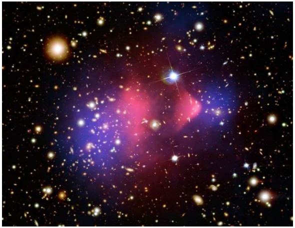

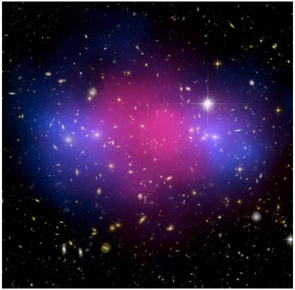

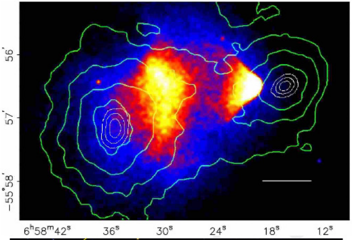

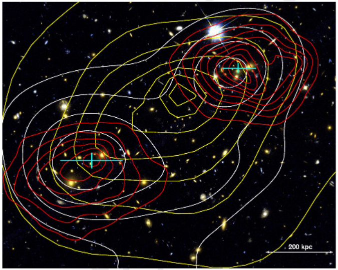

X-ray emissivity from Chandra overlayed with the convergence map

from strong and weak lensing data (arXiv:0704.0261, 0806.2320)

The scale of galaxies and clusters of galaxies

- Virial theorem applied to galaxies and clusters
- Rotation curves of galaxies
- X-rays from clusters of galaxies
- Gravitational lensing
- Mergers of galaxy clusters

Many independent observations are consistent with the hypothesis that the dominating gravitating component of the Universe cannot be the matter we know.

Outline

Dark Matter or Modified Gravity?

We observe “anomalies” in motion of gravitational systems:

Anomalies in the orbits of

- Uranus
  lead to the discovery of a “dark object” (Neptun),
- Mercury
  lead to a modification of gravity.

Dark Matter or Modified Gravity?

Modified Gravity Theories (e.g., Bekenstein)

- successful on scales of galaxies and galaxy clusters
- can reproduce General Relativity + cosmology
  (require Dark Energy and neutrino mass)
- gravitational lensing data and bullet clusters require an invisible component of gravitating matter $\rightarrow$ “large” neutrino masses (m_ν of few eV)

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crucial tests:

- gravitational lensing
- absolute neutrino mass measurements

Particle Dark Matter

We need a particle which has

- the correct abundance to give $\Omega_{\mathrm{CDM}} \approx 0.27$
  - production mechanism in the early Universe
  - has to be stable on the scale of the age of the Universe
- to be neutral (electrically, strong interaction)
- to fulfill constraints on
  - interactions with matter (direct detection)
  - self-interactions
  - searches for annihilation/decay products (gamma rays)
- to be consistent with structure formation $\rightarrow$ "cold DM", "warm DM"

Particle Dark Matter

The Standard Model has one potential candidate:

the neutrino

Particle Dark Matter

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the neutrino

which, however, does not work!

- the relic density of neutrinos is

$$\Omega_\nu \approx \frac{\sum m_\nu}{93h^2\,\mathrm{eV}} < 0.02$$

  $\rightarrow$ bounds on m_ν imply that neutrino density is too low

- neutrinos are "hot DM", inconsistent with structure formation

Particle Dark Matter

The Standard Model has one potential candidate:

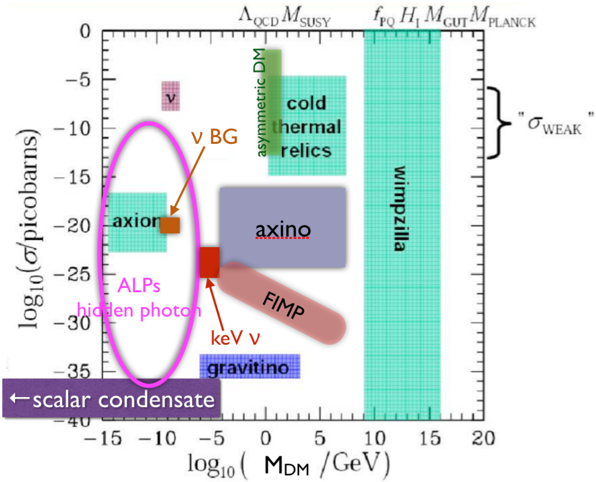
the neutrino

which, however, does not work!

$\Rightarrow$ **Dark Matter implies**

physics beyond the Standard Model

Particle DM candidates



Outline

Thermodynamics in the early Universe

number of particles per co-moving volume for a species in thermal equilibrium:

- $T \gg m \qquad n/a^3 = const \qquad (n \propto T^3,\, a \propto T^3)$
- $T \ll m \qquad n/a^3 \propto e^{-m/T}$

when is a species X in equilibrium?

$$\Gamma_{XX\leftrightarrow yy} \gg H(t) \qquad \text{species in chem. equilibrium}$$

$$\Gamma_{XX\leftrightarrow yy} \sim H(t) \qquad \text{freeze-out}$$

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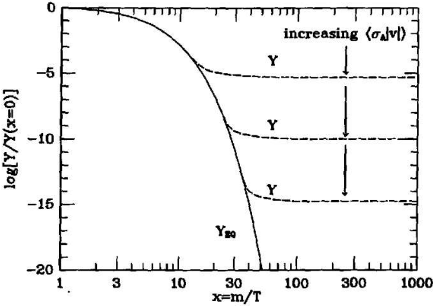
Thermal freeze-out



$$\boxed{\Omega h^2 \simeq \frac{10^{-37}\,\mathrm{cm}^2}{\langle \sigma_{\mathrm{ann}} v \rangle} \approx 0.118 \text{ [Planck]}}$$

- need $\sigma_{\mathrm{ann}} v \sim 10^{-36}\,\mathrm{cm}^2 = 1\,\mathrm{pb}$ to obtain correct relic abundance
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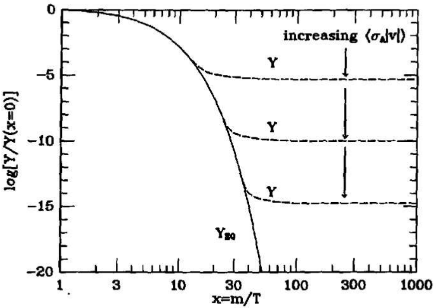

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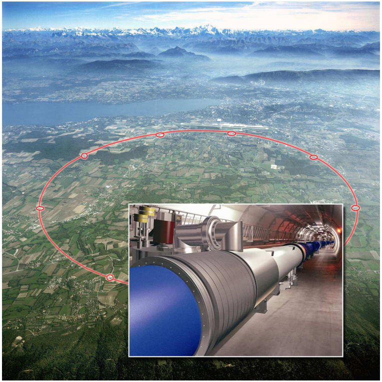

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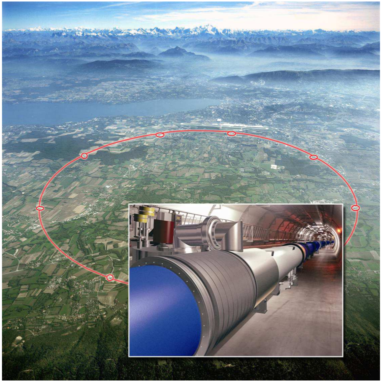
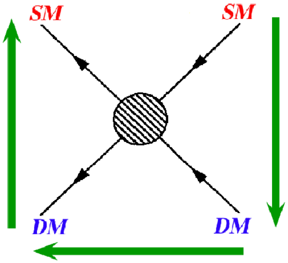


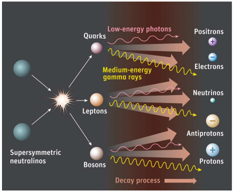
maybe DM is related to the new physics expected at the weak scale?

Testing the WIMP hypothesis

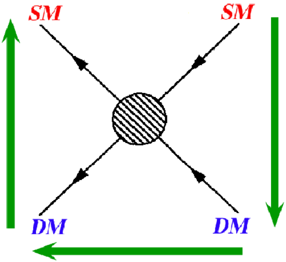


Testing the WIMP hypothesis

indirect detection



PAMELA, FERMI, AMS-II, IceCube, HESS, CTA,...



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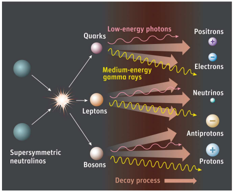

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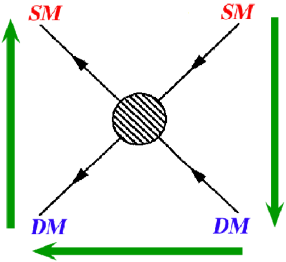
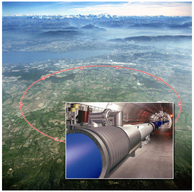


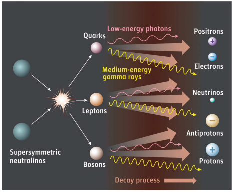
colliders



LHC at CERN

Testing the WIMP hypothesis

indirect detection



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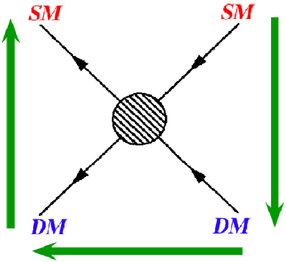

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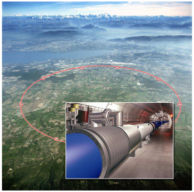
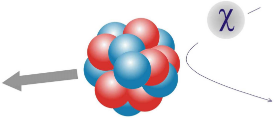


LHC at CERN

direct detection



XENON, LUX, CDMS, CRESST, DEAP, COUPP, PICASSO, ...

Testing the WIMP hypothesis

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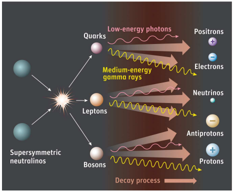

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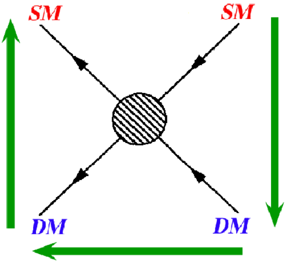

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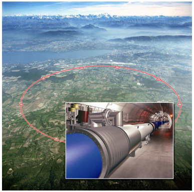

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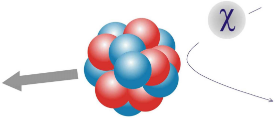

XENON, LUX, CDMS, CRESST, DEAP, COUPP, PICASSO, ...

WARNING: in real life things may be more complicated - lots of work has been devoted to break those links (avoid limits or accomodate “too large” signals)

Dark Matter at LHC

Missing energy signature:

- DM particle escapes detection
- Invisible particle with life time $\gtrsim 10^{-7}$ s
- No direct proof that we are seeing the DM particle

Dark Matter at LHC

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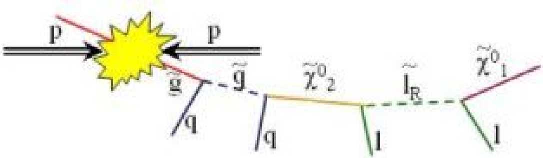
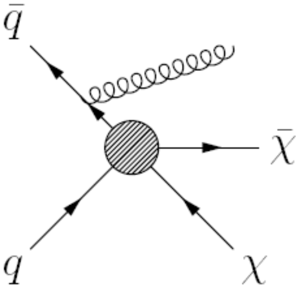
Hope for additional signatures of new physics and relate missing-energy to DM in a model-dependent way

Example: SUSY decay chain



Effective interaction and mono-jet signals

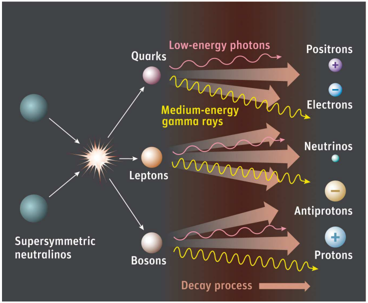


Consider effective vertex of DM with quarks/gluons

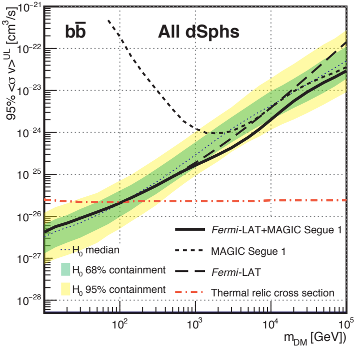
$$\frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}, \quad \frac{(\bar{\chi}\gamma_5\gamma_\mu\chi)(\bar{q}\gamma_5\gamma^\mu q)}{\Lambda^2}, \quad \frac{(\bar{\chi}\chi)(G_{\mu\nu}G^{\mu\nu})}{\Lambda^3}, \ldots$$

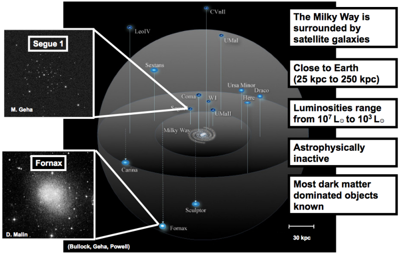
Dark Matter indirect detection

the WIMP hypothesis implies DM annihilations into SM particles in order to obtain the correct relic abundance $\Rightarrow$ look into regions of high DM concentration and search for high-energy DM annihilation products today



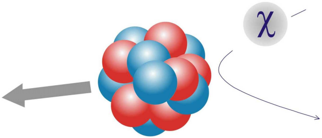
Gamma ray limits from spherical dwarf galaxies





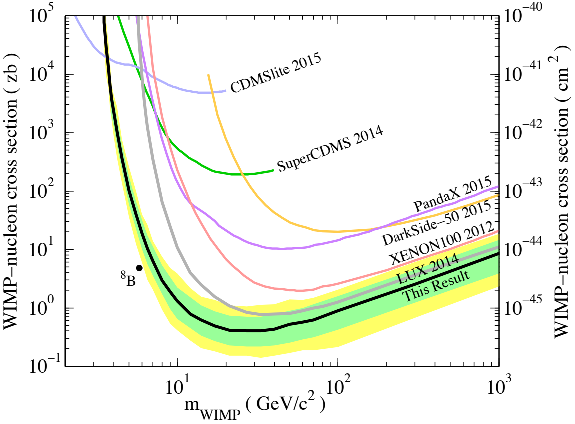
- "thermal" cross section excluded for DM mass < 100 GeV assuming a velocity-independent annihilation cross section
- BUT: in many models $\langle \sigma v \rangle \propto v^2$:
  at freeze-out: $v \sim 0.2c$, today: $v \sim 10^{-3}c$

Dark Matter direct detection



- Search for nuclear recoil events in underground detectors
- scattering cross section linked to annihilation cross section by crossing symmetry (may have different v-dependence)
- other channels may contribute to annihilations (e.g., gauge bosons)

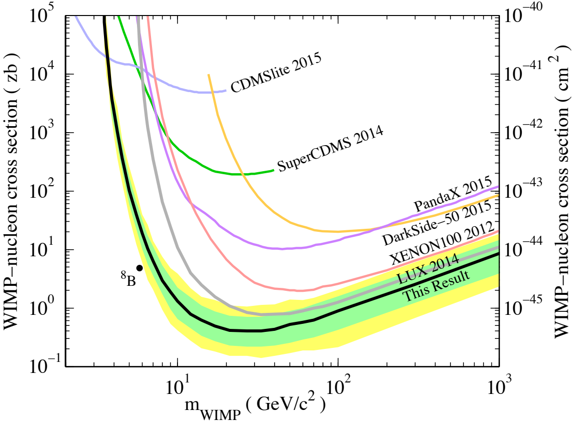
Dark Matter direct detection limits



LUX 1512.03506

$$\sigma_{\text{scat}} \sim 10^{-45}\,\text{cm}^2 \qquad \leftrightarrow \qquad \sigma_{\text{annih}} \sim 10^{-36}\,\text{cm}^2$$

Dark Matter direct detection limits



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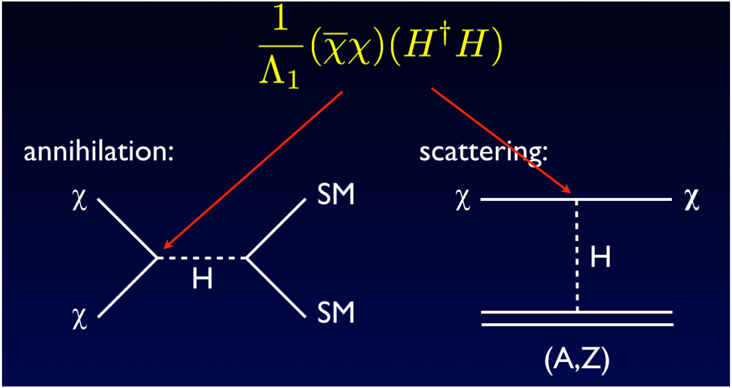
Direct detection limits and the WIMP hypothesis

Ex.: postulate that DM interacts with the SM via the Higgs boson



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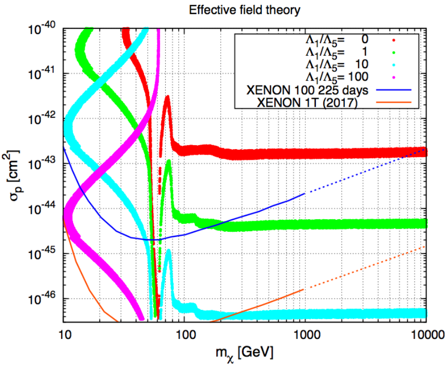

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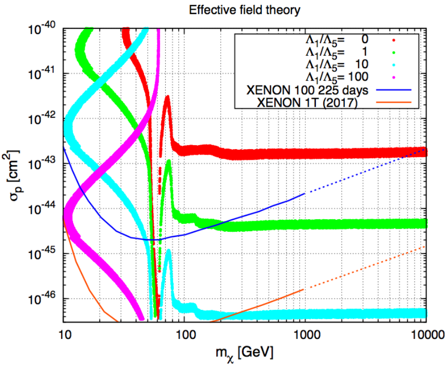
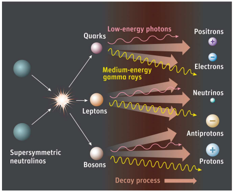
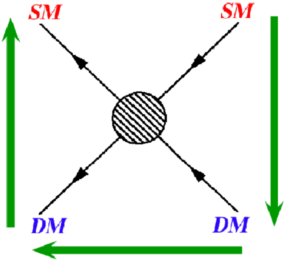


- "simplest version" excluded
- ways out: modify type of interaction or use resonance for $m_{DM} \approx m_H/2$

Exciting times for WIMP DM

indirect detection





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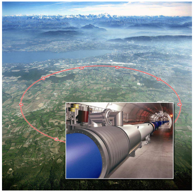

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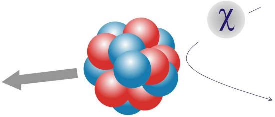

Exciting times for WIMP DM

Many examples for WIMP DM

- SUSY neutralino
- extra dimensions
- Higgs-portal DM
- inert Higgs-doublet models
- TeV-scale neutrino mass models
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Outline

ΛCDM cosmology
- Cosmic microwave background
- Big Bang nucleosynthesis
- Cosmological structure formation

Evidences at the scale of galaxies and clusters of galaxies

What is the "Dark Matter"

How to obtain the correct relic abundance
- Thermal freeze-out

WIMP dark matter

Selection of non-WIMP DM candidates
- Asymmetric DM
- keV sterile neutrino DM
- Axions

Asymmetric DM

Why are DM and baryon abundances similar?

$$\Omega_{DM}/\Omega_B \approx 5$$

This is a coincidence in the WIMP (freeze-out) scenario

Baryon abundance is set by an asymmetry:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$

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For a baryon-symmetric universe the baryon relic abundance (by freeze-out) would be 9 orders of magnitude lower, since strong interactions keep them in thermal equilibrium until very late:

$$\langle \sigma_{ann} v \rangle \sim \frac{1}{m_\pi^2} \approx 2 \times 10^{-26}\,\mathrm{cm}^2 \qquad (m_\pi = 135\,\mathrm{MeV})$$

$$\Omega h^2 \simeq \frac{10^{-37}\,\mathrm{cm}^2}{\langle \sigma_{ann} v \rangle} \sim \frac{1}{2} \times 10^{-11} \quad \Rightarrow \quad \eta_{sym} \simeq 2 \times 10^{-8} \Omega h^2 \sim 10^{-19}$$

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- the origin of the baryon asymmetry is unknown
- mechanism to generate it dynamically in the early universe (EW baryogenesis, Leptogenesis)

Asymmetric DM Nussinov 85; Barr, Chivukula, Farhi, 90; Barr, 91; Kaplan 92

- assume DM is charged under some quantum number $\rightarrow X, \bar{X}$
- assume some mechanism which generates an $X - \bar{X}$ asymmetry together with the baryon asymmetry
- have a large enough $X - \bar{X}$ annihilation cross section to get rid of thermal component
- under the assumption $n_X - n_{\bar{X}} \sim n_B - n_{\bar{B}}$ one expects:

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- the "prediction" $m_X \sim 5\,\text{GeV}$ does not hold in some models
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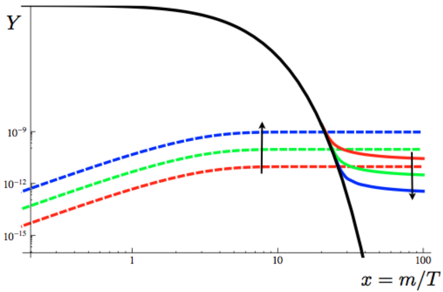
Sterile neutrino DM

- postulate existence of additional neutrinos species
- approx 10 000 times heavier than "normal" neutrinos (keV-scale masses)
- cannot participate in weak interactions (LEP)
- have extreemly small interactions ("sterile")
- non-thermal production mechanism $\rightarrow$ "freeze-in"

Freeze-in: feably interacting DM ("FIMP")



- particles with very feably interactions never reach thermal equilibrium
- they are produces as long as the interaction with the plasma is faster than the expansion rate
- once $\Gamma \lesssim H$, production stops and the species freezes in

Sterile neutrino DM

via mixing, the heavy neutrino can decay $N \to \nu\nu\bar{\nu}$

$$\Gamma_{3\nu} = \frac{G_F^2 M^5 \theta^2}{96\pi^3} \qquad \tau \approx 10^{14}\,\mathrm{yr} \left(\frac{10\,\mathrm{keV}}{M}\right)^5 \left(\frac{10^{-8}}{\theta^2}\right)$$

lives long enough for DM candidate for suitable M, θ
mass in the the keV range $\to$ warm DM

can also decay radiatively via a loop process: $N \to \nu\gamma$

$$\Gamma_{\nu\gamma} = \frac{9\alpha_{em} G_F^2 M^5 \theta^2}{256\pi^4}$$

narrow photon line with $E_\gamma = M/2 \to$ signal in X-ray searches

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Axion DM

- Axion is a very light scalar particle
  $m_a \lesssim 10^{-3}$ eV (can be lighter as neutrinos)
- Motivated by a fine-tuning problem of strong interactions (electric dipole moment of the neutron)
- Interactions with rest of the world are tiny $\rightarrow$ never in thermal equilibrum
- energy density is stored in oscillations of classical field
- despite the tiny mass it behaves as non-relativistic matter (CDM)
- interesting experiments searching for DM axions via interactions with photons