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Models of Dark Matter

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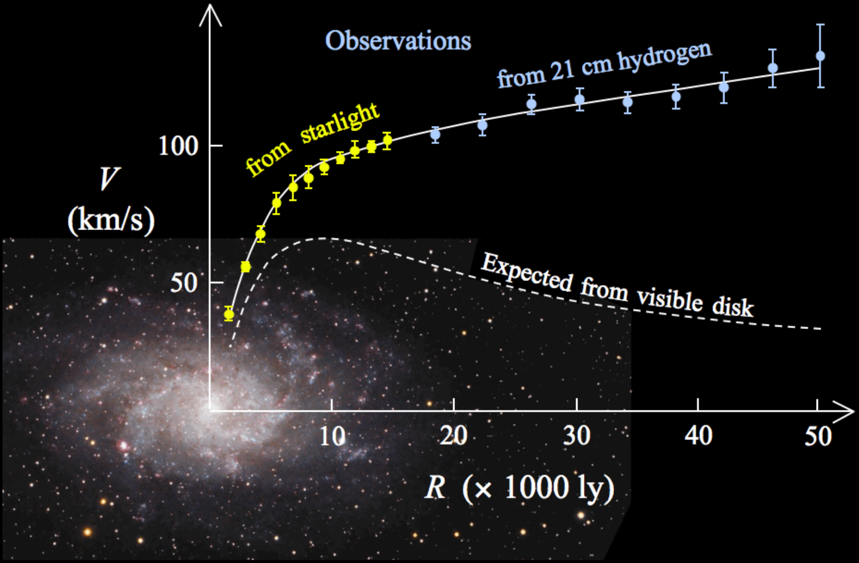
CERN Baltic Conference 2024 ✧ Tallinn

2 Dark matter

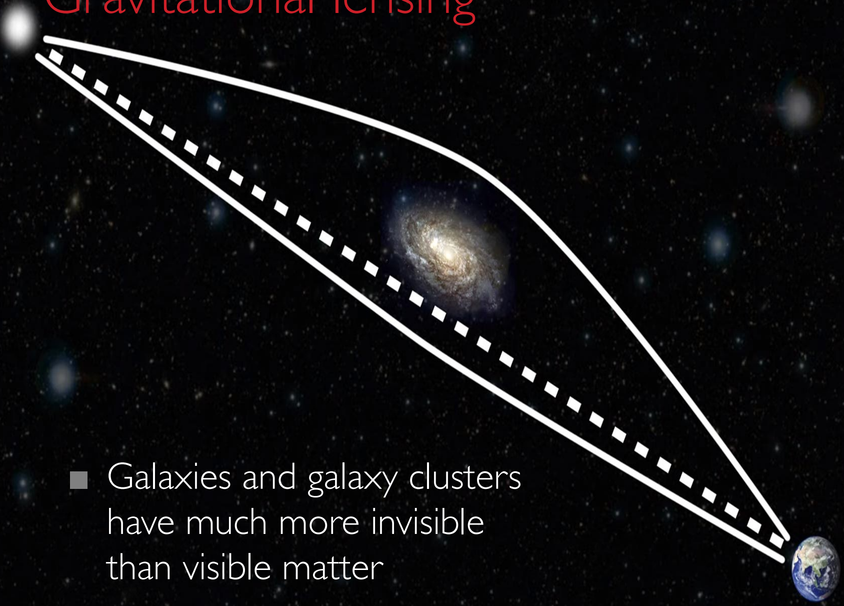
- Dark matter amounts to 26.4% of the matter-energy content of the Universe
- Dark matter is cold (velocity 300 km/s)
- Lifetime longer than the age of the Universe
- Many candidates from ultralight axions (10^{-22} eV) … to WIMPs (10 GeV to a few TeV) … to primordial black holes
- Interactions unknown – aside from gravitational
- Possibly rich dark sector: multi-component dark matter, dark photon &c.

3 Dark matter: galactic rotation curves



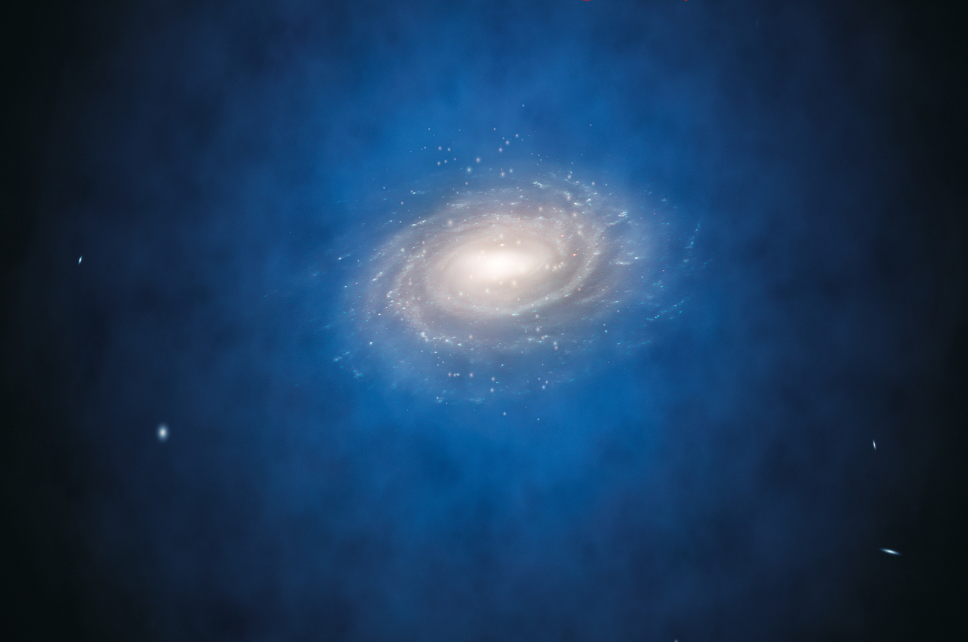
- Vera Rubin and others in 1970s

Gravitational lensing

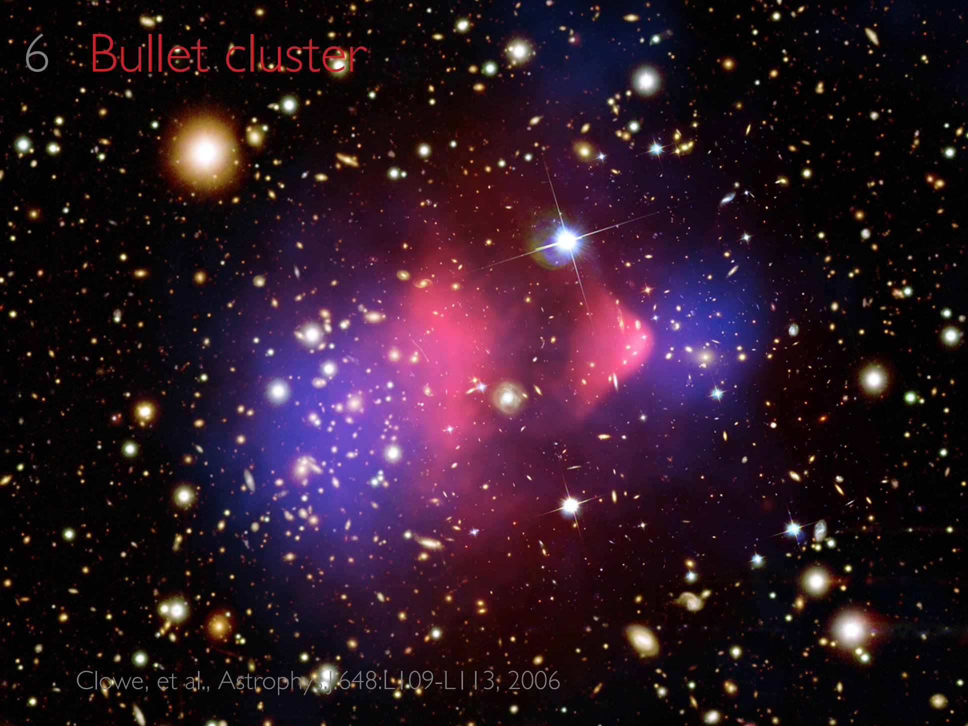


- Galaxies and galaxy clusters have much more invisible than visible matter

5 Dark matter halo of a galaxy

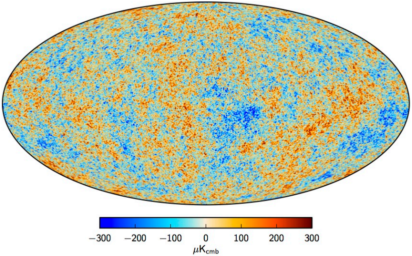


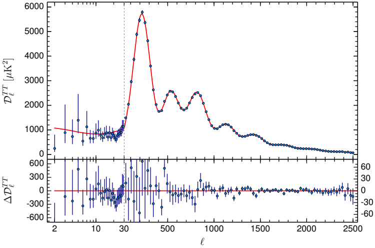
6 Bullet cluster



Clowe, et al., Astrophys.J.648:L109-L113, 2006

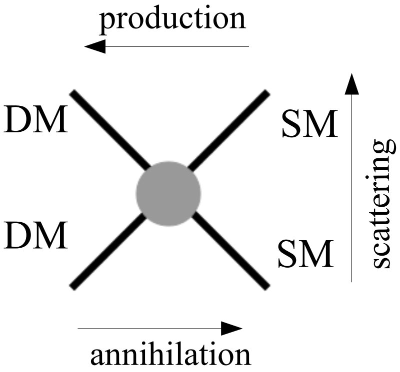
7 Cosmic Microwave Background





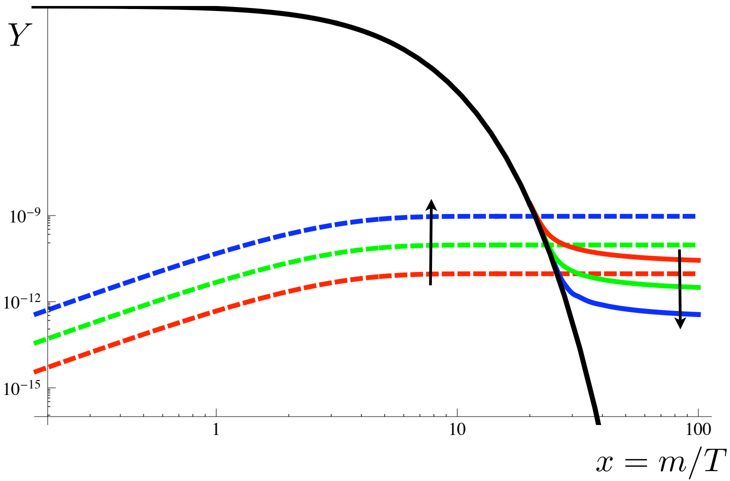
- Height and placement of peaks changes when we vary dark matter and dark energy content
- ΛCDM model is the cosmological Standard Model

8 Dark matter freeze-out and freeze-in



- Annihilation stops because of dilution of particles due to the expansion of the Universe
- Correct relic density if $\sigma \sim 1$ pb; $m_{DM} \sim 10$ GeV to 1 TeV

9 Dark matter freeze-out and freeze-in

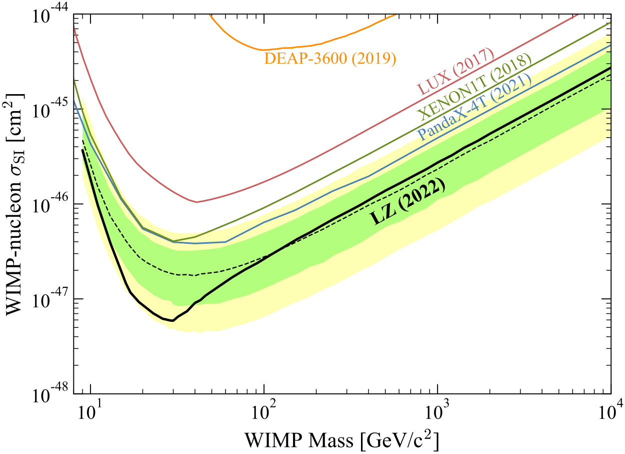


10 Dark matter detection

- Direct detection
- Indirect detection
- Collider searches

LUX-ZEPLIN dark matter detector

Exclusion curves



Model with scalar dark matter

Tree-level scalar potential given by

$$V = \frac{1}{4}\lambda_H h^4 + \frac{1}{4}\lambda_S s^4 + \frac{1}{4}\lambda_{HS} h^2 s^2 + \frac{1}{4}\lambda_{HS'} h^2 s'^2 + \frac{1}{4}\lambda_{SS'} s^2 s'^2 + \frac{1}{4}\lambda_{S'} s'^4$$

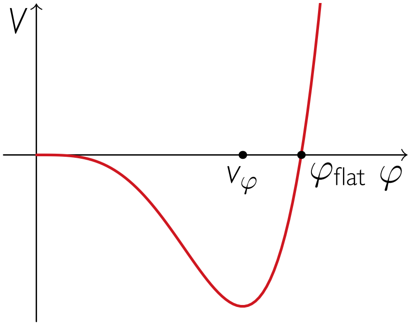
- In addition to the Higgs boson h, dilaton s, and dark matter s'
- Invariant under a $\mathbb{Z}_2 \otimes \mathbb{Z}_2'$ with $s \to -s$ and $s' \to -s'$
- VEVs $\langle h \rangle \equiv v$ and $\langle s \rangle \equiv w$

K.K., Koivunen, Kubarski, Marzola, Raidal, Strumia, Vipp

Phys.Lett.B 832 (2022) 137214 [arXiv:2204.01744]

Dynamical symmetry breaking

- No dimensionful terms in the scalar potential
- Symmetry broken by quantum corrections via the Coleman-Weinberg mechanism
- Minimum near the flat direction $V(\mu_{\text{flat}}) = 0$



S. R. Coleman, E. J. Weinberg, Phys. Rev. D 7 (1973) 1888–1910

E. Gildener, S. Weinberg, Phys. Rev. D 13 (1976) 3333

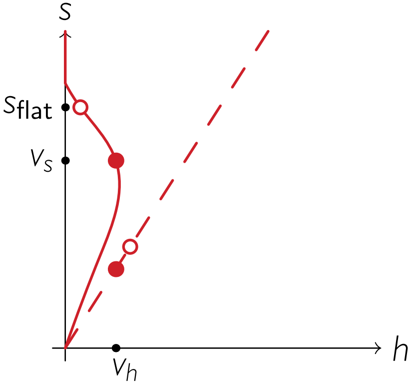
Two regimes

- In the Gildener-Weinberg regime, $\lambda_{HS}(w) \approx \lambda_{HS}(s_{\text{flat}})$ and

$$\frac{v}{w} \approx \sqrt{\frac{-\lambda_{HS}(s_{\text{flat}})}{2\lambda_H}}$$

- In the multi-phase critical regime, $\lambda_S(s_{\text{flat}}) \approx 0$, $\lambda_{HS}(w) \ll \lambda_{HS}(s_{\text{flat}}) \approx 0$, s and sh phases coincide and the Gildener-Weinberg approximation breaks down

Two regimes



Parameters

- Higgs mass $m_h \approx \sqrt{2\lambda_H} v \approx 125.1$ GeV
- Higgs VEV $v = 246.2$ GeV
- Free parameters: m_s, $m_{s'}$, $\ln R$
- Dark matter self-coupling $\lambda_{S'}$ largely irrelevant (not too large)
- Loop-level $m_s^2 \propto \beta_{\lambda_S}$, $m_h^2 \propto \beta_{\lambda_{HS}}$, tree-level $m_{s'}^2 \propto \lambda_{SS'}$

Parameters

$$\lambda_{SS'} \approx \frac{(4\pi)^2 m_s^2}{m_{s'}^2},$$

$$\lambda_{HS'} \approx -\frac{(4\pi)^2 m_h^2}{m_{s'}^2 \ln R},$$

$$w \approx \frac{\sqrt{2} m_{s'}^2}{4\pi\, m_s}$$

and

$$\theta \approx \frac{2\sqrt{2}\pi m_s m_h^2 v(1 + \ln R)}{(m_h^2 - m_s^2) m_{s'}^2 \ln R}$$

Dark matter abundance

- $\Omega_{\mathrm{DM}} h^2 = 0.120 \pm 0.001$

  N. Aghanim, et al., Astron. Astrophys. 641 (2020) A6

- Heavy-DM limit $m_{s'} \gg m_s, m_h$, where the non-relativistic DM annihilation cross section is simply given by

$$\sigma_{\mathrm{ann}} v_{\mathrm{rel}} \approx \frac{\lambda_{SS'}^2 + 4\lambda_{HS'}^2}{64\pi m_{s'}^2} \approx 4\pi^3 \frac{m_s^4 + 4m_h^4/\ln^2 R}{m_{s'}^6}$$

- Higgs-dominated for $m_s \ll m_h$, dilaton-dominated for $m_s \gg m_h$

Direct detection

Effective coupling to nucleons

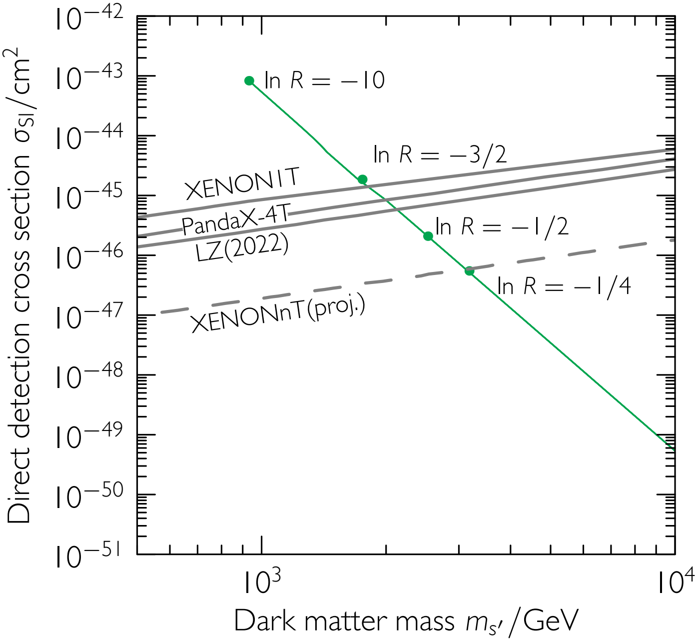
$$\frac{f_N m_N}{v} h\bar{N}N,$$

gives

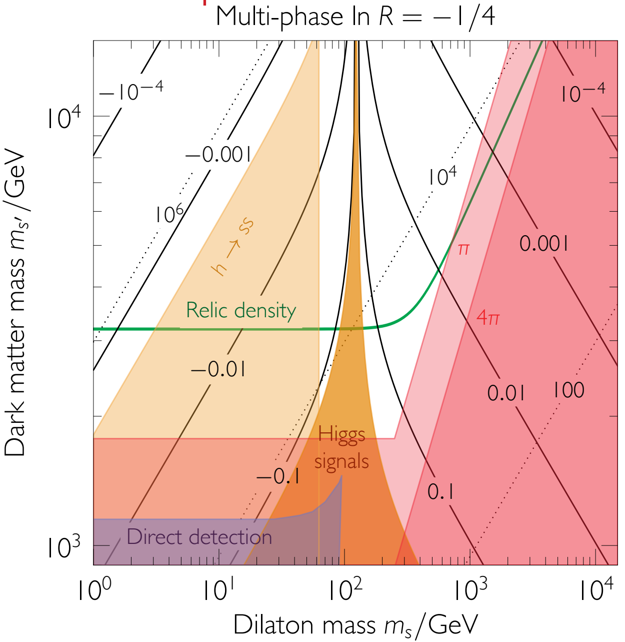
$$\sigma_{\rm SI} \approx \frac{64\pi^3 f_N^2 m_N^4}{m_{s'}^6},$$

where $m_N = 0.946$ GeV
is the nucleon mass and $f_N \approx 0.3$

Direct detection



Parameter space



Conclusions

- Wide range of possible dark matter candidates from ultralight to superheavy: axions, WIMPs, …, primordial black holes
- We consider dynamical Higgs symmetry breaking driven by dark matter
- Both dilaton and Higgs mass loop-suppressed
- Clear prediction for direct detection