Super-Heavy Dark Matter From Coleman-Weinberg Inflation

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K.K., A. Racioppi, M. Raidal [arXiv:1605.09378]

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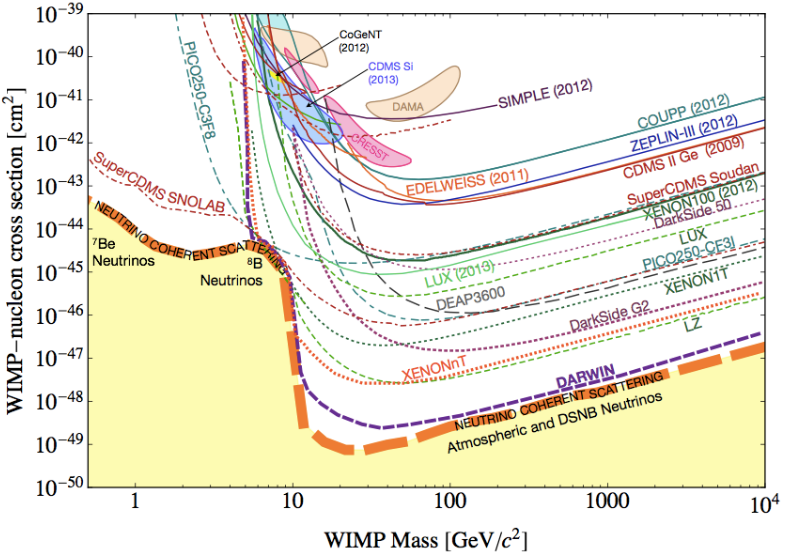
2 Direct Detection of WIMPs



Adapted from Snowmass [1310.8327]

3 Dark Matter: WIMPy, Light or Heavy?

- No dark matter has been seen yet
- Direct detection experiments are closing in on the 'WIMP miracle' parameter space
- New experiments will probe the light dark matter frontier
- *Another* frontier: super-heavy dark matter

3 Dark Matter: WIMPy, Light or Heavy?

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4 Super-Heavy Dark Matter

- Super-heavy dark matter a.k.a. WIMPzilla produced gravitationally in inflation
- Mass range about 10^{12} GeV to 10^{16} GeV

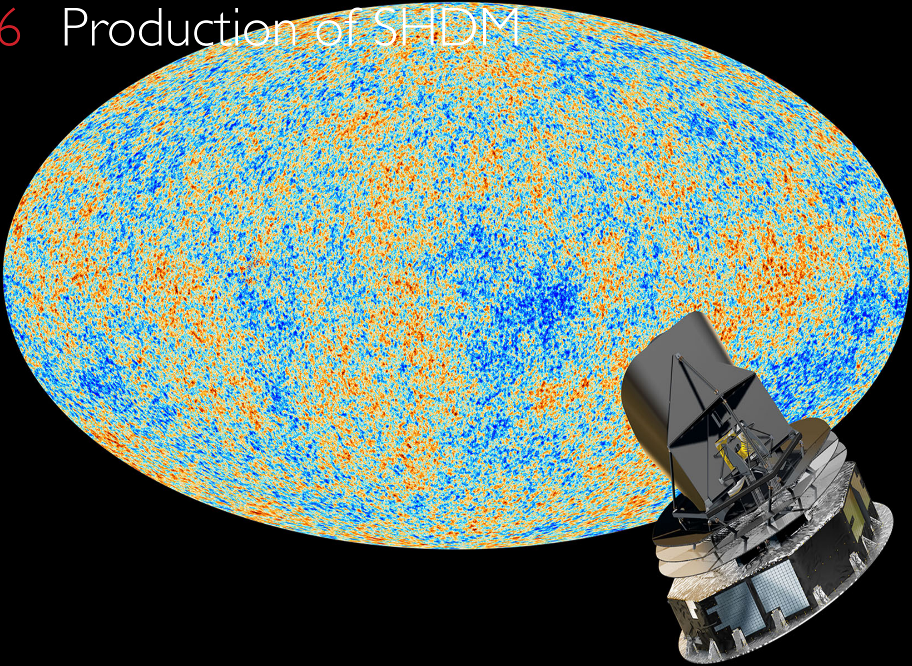
Chung, Kolb & Riotto, *Phys.Rev.* **D59** (1999) 023501, [hep-ph/9802238];

Kuzmin & Tkachev, *JETP Lett.* **68** (1998) 271–275, [hep-ph/9802304]; etc.

5 Production of SHDM

- Preheating (requires large portal couplings)
- Gravitational production in inflation

6 Production of SHDM



Planck

7 Production of SHDM

Relic density of gravitationally produced SHDM is

$$\Omega_X(t_0) \simeq 10^{-3}\Omega_R \frac{8\pi}{3}\left(\frac{T_{\rm RH}}{T_0}\right)\left(\frac{m_\phi}{M_P}\right)^2\left(\frac{m_X}{m_\phi}\right)^{5/2} e^{-2m_X/m_\phi}$$

- $\Omega_R \simeq 4 \times 10^{-5}$ is the radiation density today
- $T_0 \simeq 2.3 \times 10^{-13}$ GeV is the CMB temperature today

8 Production of SHDM

- Dark matter is at least coupled to gravity
- Gravitationally produced dark matter must be super-heavy to be relevant today
- Inflation scale is about 10^{13} GeV for simple models
- Super-heavy dark matter is as natural as the WIMP

9 Problems with SHDM

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- Coleman-Weinberg inflation offers concrete models & signals

10 Coleman-Weinberg inflation

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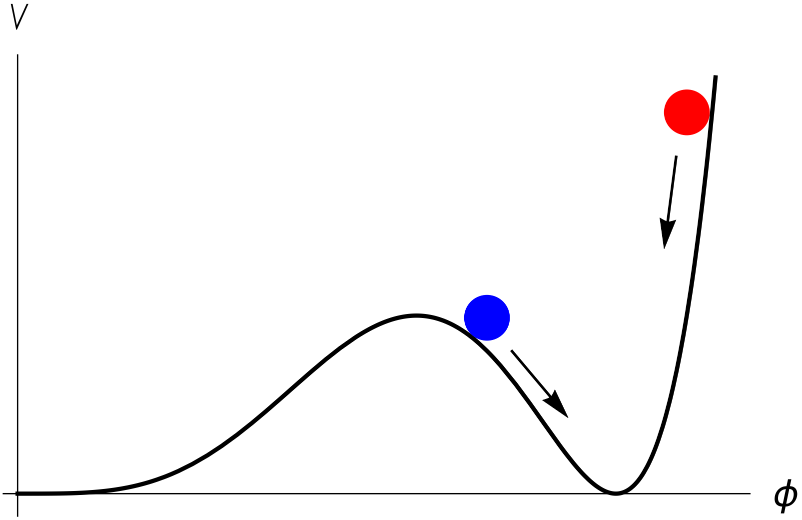
- Coleman-Weinberg inflation involves new super-heavy particles to make $\lambda_\phi(\phi)$ run
- Inflaton is the pseudo-Goldstone boson of classical scale invariance
- Inflaton gets its mass at loop level, other particles at tree level
- A nonminimal coupling $\xi_\phi \phi^2 R$ to gravity can induce general relativity

11 Coleman-Weinberg inflation



12 Coleman-Weinberg inflation

- Super-heavy scalar mass

$$m_X^2 = \lambda_{\phi X} v_\phi^2$$

- The running of λ_ϕ depends on

$$\frac{\mathrm{d}\lambda_\phi}{\mathrm{d}(\ln\mu)} = \beta_{\lambda_\phi} \propto \lambda_{\phi X}^2$$

- In minimal setup

$$\frac{m_X}{m_\phi} \approx 10^{3-4}$$

- Generations of X_i are necessary

13 Generalised CW Inflation

$$\sqrt{-g^J}\mathcal{L}^J = \sqrt{-g^J}\left[\mathcal{L}_R + \mathcal{L}_\phi + \mathcal{L}^J_{\sigma,\psi,A_\mu} + \Lambda^4\right],$$

where

$$\mathcal{L}_R = -\frac{M_{EH}^2 + \xi_\phi \phi^2}{2} R,$$

and

$$\mathcal{L}_\phi = \frac{(\partial\phi)^2}{2} - V^J(\phi),$$

where due to classical scale invariance,

$$V^J = \frac{1}{4}\lambda_\phi(\phi)\phi^4$$

14 Requirements on the Potential

- Reproduce the Planck mass:

$$M_{EH}^2 + \xi_\phi v_\phi^2 = \bar{M}_P^2$$

- Fix the cosmological constant:

$$\frac{1}{4}\lambda_\phi(v_\phi)v_\phi^4 + \Lambda^4 \simeq 0$$

15 Minimum via the CW Mechanism

$$\left.\frac{dV^J}{d\phi}\right|_{\phi=v_\phi} = \frac{1}{4}\beta_{\lambda_\phi}(v_\phi) + \lambda_\phi(v_\phi) = 0,$$

Two types of solutions:

$$\beta_{\lambda_\phi}(v_\phi) > 0,\ \lambda_\phi(v_\phi) < 0 \tag{1}$$

and

$$\beta_{\lambda_\phi}(v_\phi) = \lambda_\phi(v_\phi) = 0 \tag{2}$$

16 Coleman-Weinberg Inflation

A Coleman-Weinberg inflation with a new scalar

Kannike, Racioppi & Raidal, JHEP 1406 (2014) 154, [1405.3987]

B Type (1) Coleman-Weinberg induced gravity inflation

Kannike, Racioppi, Raidal JHEP 01 (2016) 035 [1509.05423]

C Type (2) Coleman-Weinberg induced gravity inflation

Kannike, Hütsi, Pizza, Racioppi, Raidal, Strumia, JHEP 1505 (2015) 065, [1502.01334]

17 Inflationary Observables

- Spectral tilt

$$n_s = 0.968 \pm 0.006$$

- Tensor-to-scalar ratio

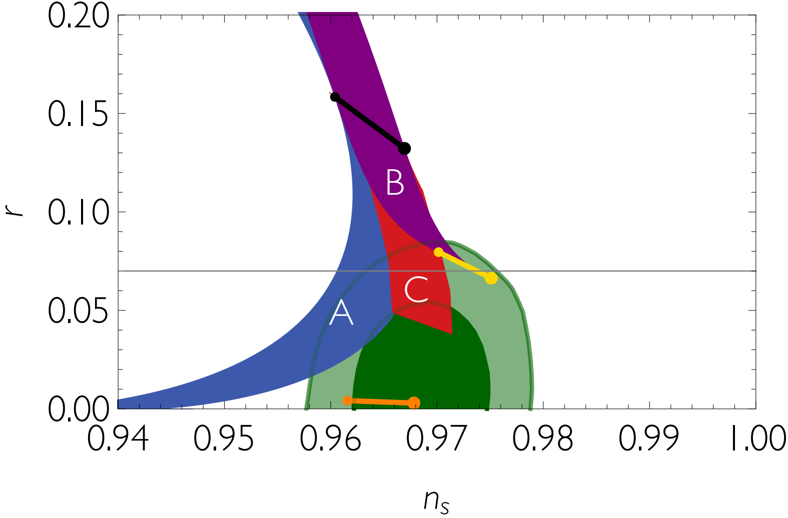
$$r < 0.07$$

- Amplitude of the spectrum

$$A_s = (2.14 \pm 0.05) \times 10^{-9}$$

Planck [1502.02114]; BICEP2/Keck and Planck, Phys. Rev. Lett. 114, 101301, 2015; Keck Array and BICEP2, Phys. Rev. Lett. 116, 031302, 2015

18 Inflationary Predictions



19 SHDM Isocurvature Constraints

Local non-Gaussianities

$$f_{NL}^{\text{local}} \approx 30 \left(\frac{a}{0.07}\right)^{3/2},$$

where the isocurvature parameter

$$a = \frac{A_{\delta X}}{A_s + A_{\delta X}}$$

and

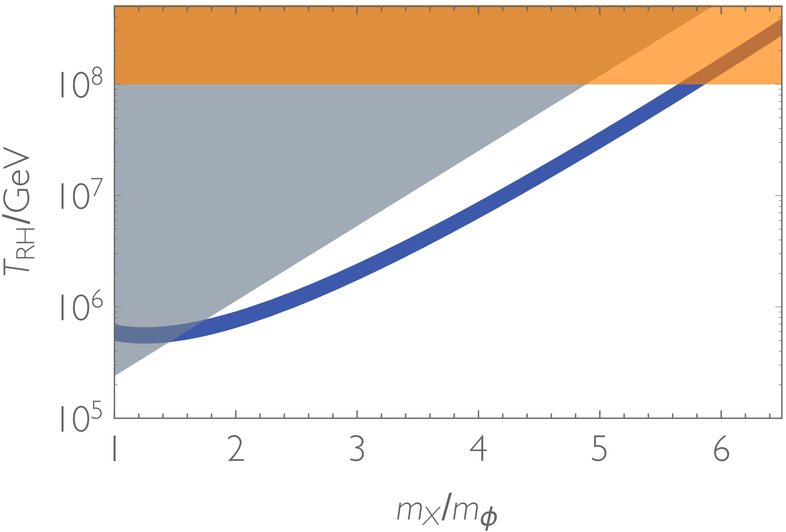
$$A_{\delta X} \simeq \frac{25\pi^2}{96} \frac{M_P^4}{m_X m_\phi^3} (A_s r)^2 \exp\left(4\frac{m_X}{m_\phi} - \frac{5280Q}{\pi A_s r} \frac{m_X^2}{M_P^2}\right)$$

20 SHDM Isocurvature Constraints

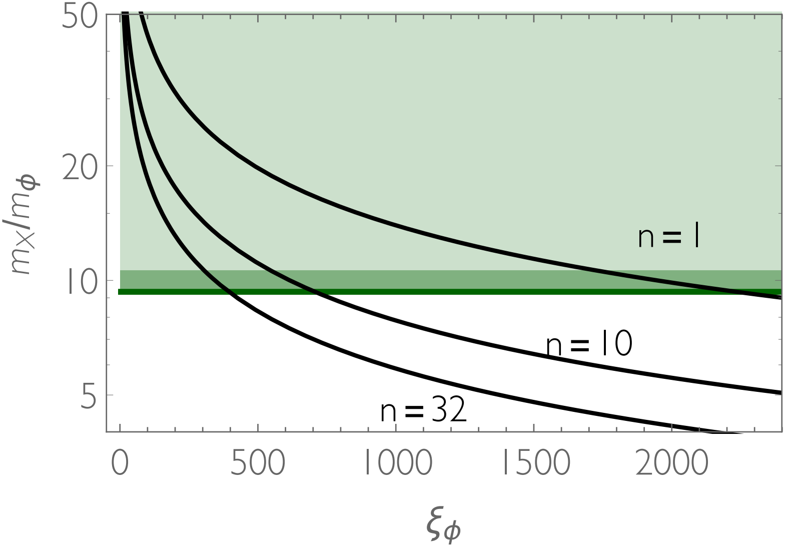
- Local non-Gaussianities $f_{NL}^{\text{local}} = 0.8 \pm 5.0$ (future measurements constrain $f_{NL}^{\text{local}} \sim \mathcal{O}(1)$)
- Isocurvature parameter $a < 0.0019$
- Related as

$$f_{NL}^{\text{local}} \approx 30 \left(\frac{a}{0.07} \right)^{3/2}$$

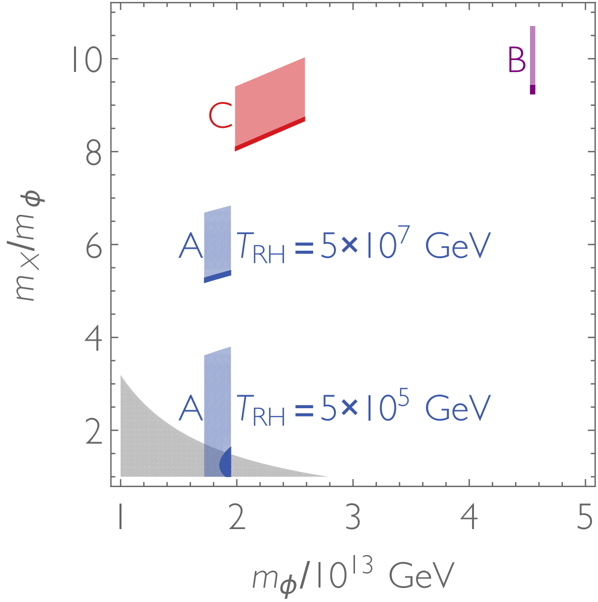
Reheating Temperature in (A)



Number of Generations in (B)



Isocurvature Constraints ($r = 0.07$)



Conclusions

- Gravitationally produced SHDM is as natural as WIMP
- SHDM can arise from new particles necessary in Coleman-Weinberg inflation
- SHDM mass about 1 to 10 inflaton masses
- Can be observed in isocurvature if below 4 inflaton masses