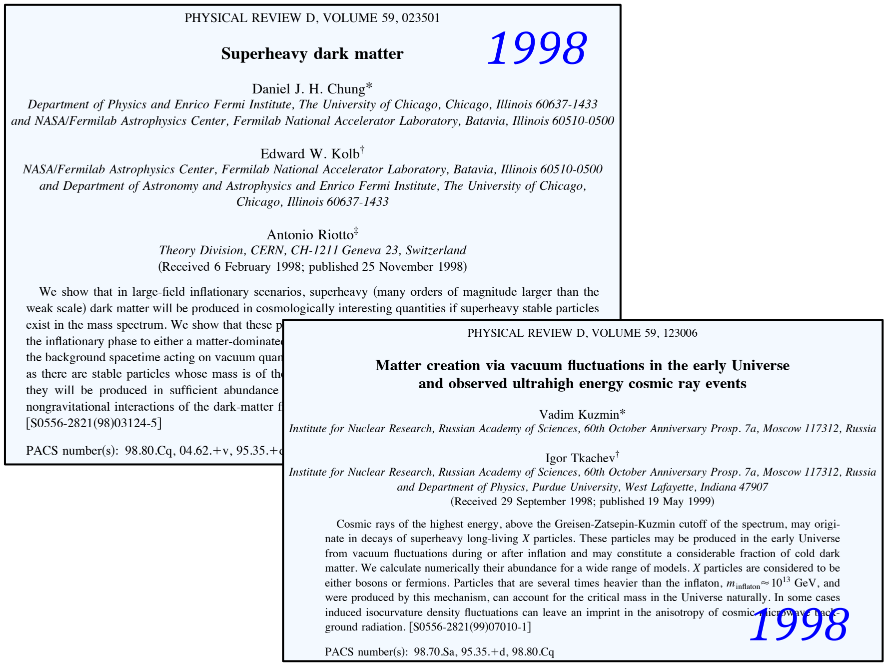
Gravitational production of dark matter at the end of inflation

Andrew Long
Rice University
@ KITP
Feb 4, 2020

RICE



PHYSICAL REVIEW D, VOLUME 59, 023501

Superheavy dark matter

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(Received 6 February 1998; published 25 November 1998)

We show that in large-field inflationary scenarios, superheavy (many orders of magnitude larger than the weak scale) dark matter will be produced in cosmologically interesting quantities if superheavy stable particles
exist in the mass spectrum. We show that these p
the inflationary phase to either a matter-dominated
the background spacetime acting on vacuum quan
as there are stable particles whose mass is of the
they will be produced in sufficient abundance
nongravitational interactions of the dark-matter f
[S0556-2821(98)03124-5]

PACS number(s): 98.80.Cq, 04.62.+v, 95.35.+d

1998

PHYSICAL REVIEW D, VOLUME 59, 123006

Matter creation via vacuum fluctuations in the early Universe and observed ultrahigh energy cosmic ray events

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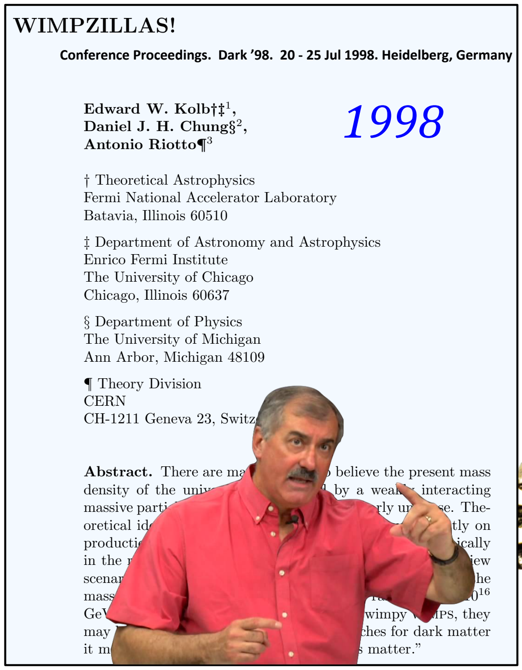
(Received 29 September 1998; published 19 May 1999)

Cosmic rays of the highest energy, above the Greisen-Zatsepin-Kuzmin cutoff of the spectrum, may originate in decays of superheavy long-living *X* particles. These particles may be produced in the early Universe from vacuum fluctuations during or after inflation and may constitute a considerable fraction of cold dark matter. We calculate numerically their abundance for a wide range of models. *X* particles are considered to be either bosons or fermions. Particles that are several times heavier than the inflaton, $m_{\text{inflaton}} \approx 10^{13}$ GeV, and were produced by this mechanism, can account for the critical mass in the Universe naturally. In some cases induced isocurvature density fluctuations can leave an imprint in the anisotropy of cosmic microwave background radiation. [S0556-2821(99)07010-1]

PACS number(s): 98.70.Sa, 95.35.+d, 98.80.Cq

1998



WIMPZILLAS!

Conference Proceedings. Dark '98. 20 - 25 Jul 1998. Heidelberg, Germany

Edward W. Kolb†‡[1],
Daniel J. H. Chung§[2],
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1998

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Abstract. There are ma
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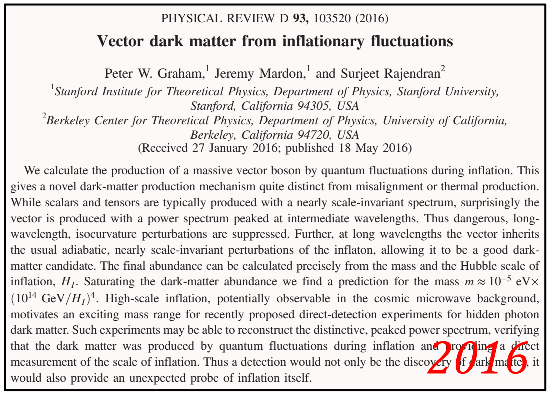

PHYSICAL REVIEW D **93,** 103520 (2016)

Vector dark matter from inflationary fluctuations

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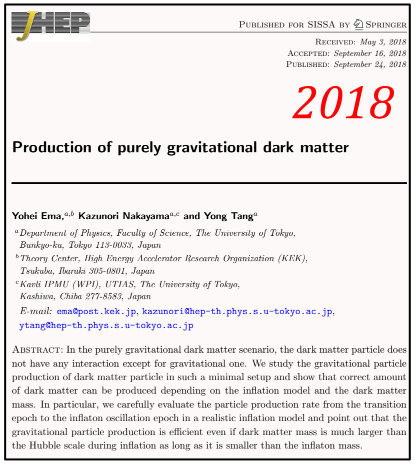
(Received 27 January 2016; published 18 May 2016)

We calculate the production of a massive vector boson by quantum fluctuations during inflation. This gives a novel dark-matter production mechanism quite distinct from misalignment or thermal production. While scalars and tensors are typically produced with a nearly scale-invariant spectrum, surprisingly the vector is produced with a power spectrum peaked at intermediate wavelengths. Thus dangerous, long-wavelength, isocurvature perturbations are suppressed. Further, at long wavelengths the vector inherits the usual adiabatic, nearly scale-invariant perturbations of the inflaton, allowing it to be a good dark-matter candidate. The final abundance can be calculated precisely from the mass and the Hubble scale of inflation, H_I. Saturating the dark-matter abundance we find a prediction for the mass $m \approx 10^{-5}$ eV$\times$ $(10^{14}\ \text{GeV}/H_I)^4$. High-scale inflation, potentially observable in the cosmic microwave background, motivates an exciting mass range for recently proposed direct-detection experiments for hidden photon dark matter. Such experiments may be able to reconstruct the distinctive, peaked power spectrum, verifying that the dark matter was produced by quantum fluctuations during inflation and providing a direct measurement of the scale of inflation. Thus a detection would not only be the discovery of dark matter, it would also provide an unexpected probe of inflation itself.

2016



JHEP

Published for SISSA by Springer

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2018

Production of purely gravitational dark matter

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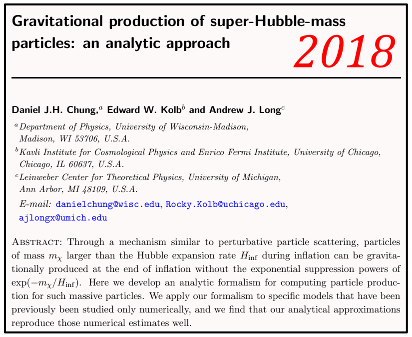
Abstract: In the purely gravitational dark matter scenario, the dark matter particle does not have any interaction except for gravitational one. We study the gravitational particle production of dark matter particle in such a minimal setup and show that correct amount of dark matter can be produced depending on the inflation model and the dark matter mass. In particular, we carefully evaluate the particle production rate from the transition epoch to the inflaton oscillation epoch in a realistic inflation model and point out that the gravitational particle production is efficient even if dark matter mass is much larger than the Hubble scale during inflation as long as it is smaller than the inflaton mass.



Gravitational production of super-Hubble-mass particles: an analytic approach

2018

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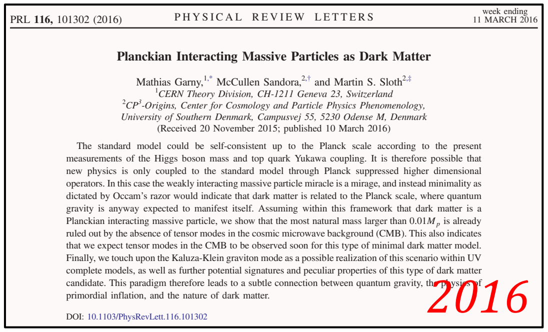
Abstract: Through a mechanism similar to perturbative particle scattering, particles of mass m_χ larger than the Hubble expansion rate H_{inf} during inflation can be gravitationally produced at the end of inflation without the exponential suppression powers of $\exp(-m_\chi/H_{\text{inf}})$. Here we develop an analytic formalism for computing particle production for such massive particles. We apply our formalism to specific models that have been previously been studied only numerically, and we find that our analytical approximations reproduce those numerical estimates well.



PRL **116,** 101302 (2016) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2016

Planckian Interacting Massive Particles as Dark Matter

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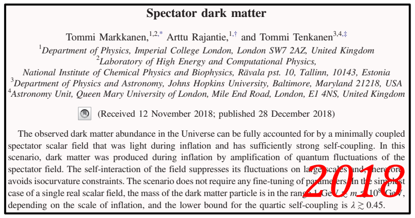
(Received 20 November 2015; published 10 March 2016)

The standard model could be self-consistent up to the Planck scale according to the present measurements of the Higgs boson mass and top quark Yukawa coupling. It is therefore possible that new physics is only coupled to the standard model through Planck suppressed higher dimensional operators. In this case the weakly interacting massive particle miracle is a mirage, and instead minimality as dictated by Occam's razor would indicate that dark matter is related to the Planck scale, where quantum gravity is anyway expected to manifest itself. Assuming within this framework that dark matter is a Planckian interacting massive particle, we show that the most natural mass larger than $0.01M_p$ is already ruled out by the absence of tensor modes in the cosmic microwave background (CMB). This also indicates that we expect tensor modes in the CMB to be observed soon for this type of minimal dark matter model. Finally, we touch upon the Kaluza-Klein graviton mode as a possible realization of this scenario within UV complete models, as well as further potential signatures and peculiar properties of this type of dark matter candidate. This paradigm therefore leads to a subtle connection between quantum gravity, the physics of primordial inflation, and the nature of dark matter.

DOI: 10.1103/PhysRevLett.116.101302

2016



Spectator dark matter

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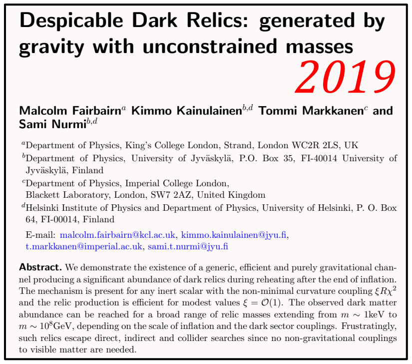
(Received 12 November 2018; published 28 December 2018)

The observed dark matter abundance in the Universe can be fully accounted for by a minimally coupled spectator scalar field that was light during inflation and has sufficiently strong self-coupling. In this scenario, dark matter was produced during inflation by amplification of quantum fluctuations of the spectator field. The self-interaction of the field suppresses its fluctuations on large scales and, therefore avoids isocurvature constraints. The scenario does not require any fine-tuning of parameters. In the simplest case of a single real scalar field, the mass of the dark matter particle is in the range 1 GeV $\lesssim m \lesssim 10^8$ GeV, depending on the scale of inflation, and the lower bound for the quartic self-coupling is $\lambda \gtrsim 0.45$.

2018



Despicable Dark Relics: generated by gravity with unconstrained masses

2019

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Abstract. We demonstrate the existence of a generic, efficient and purely gravitational channel producing a significant abundance of dark relics during reheating after the end of inflation. The mechanism is present for any inert scalar with the non-minimal curvature coupling $\xi R\chi^2$ and the relic production is efficient for modest values $\xi = \mathcal{O}(1)$. The observed dark matter abundance can be reached for a broad range of relic masses extending from $m \sim 1$keV to $m \sim 10^8$GeV, depending on the scale of inflation and the dark sector couplings. Frustratingly, such relics escape direct, indirect and collider searches since no non-gravitational couplings to visible matter are needed.

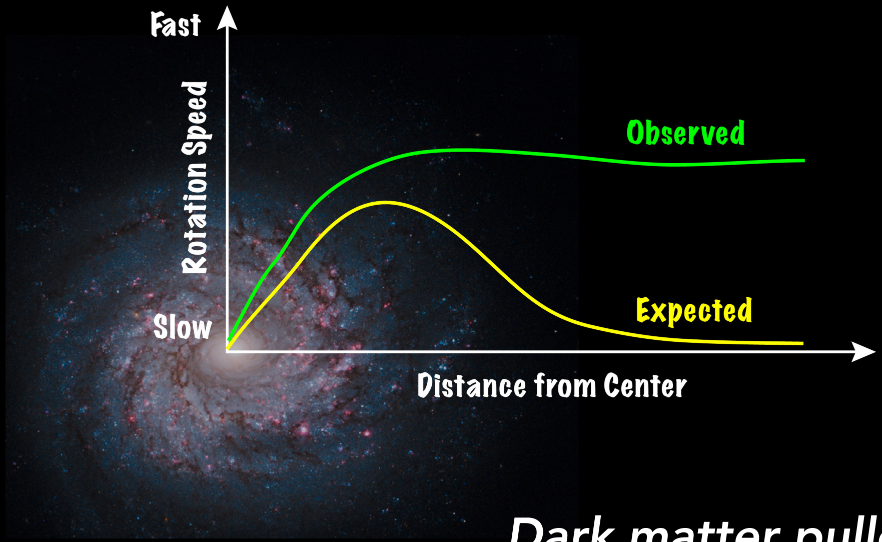
Matter Creation by Expansion of the Early Universe
(review article)
Rocky & Andrew
2020

Does dark matter interact with more than gravity?

Dark matter pulls on things

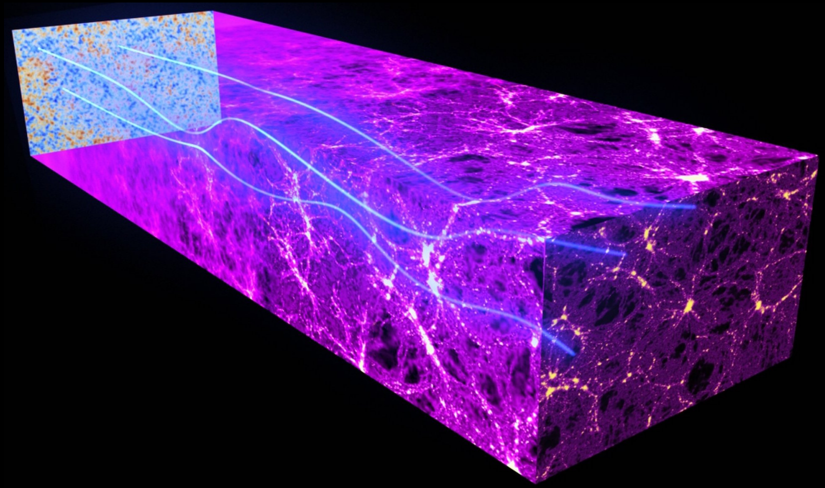
Dark matter pulls on stars in galaxies

(galactic rotation curves)



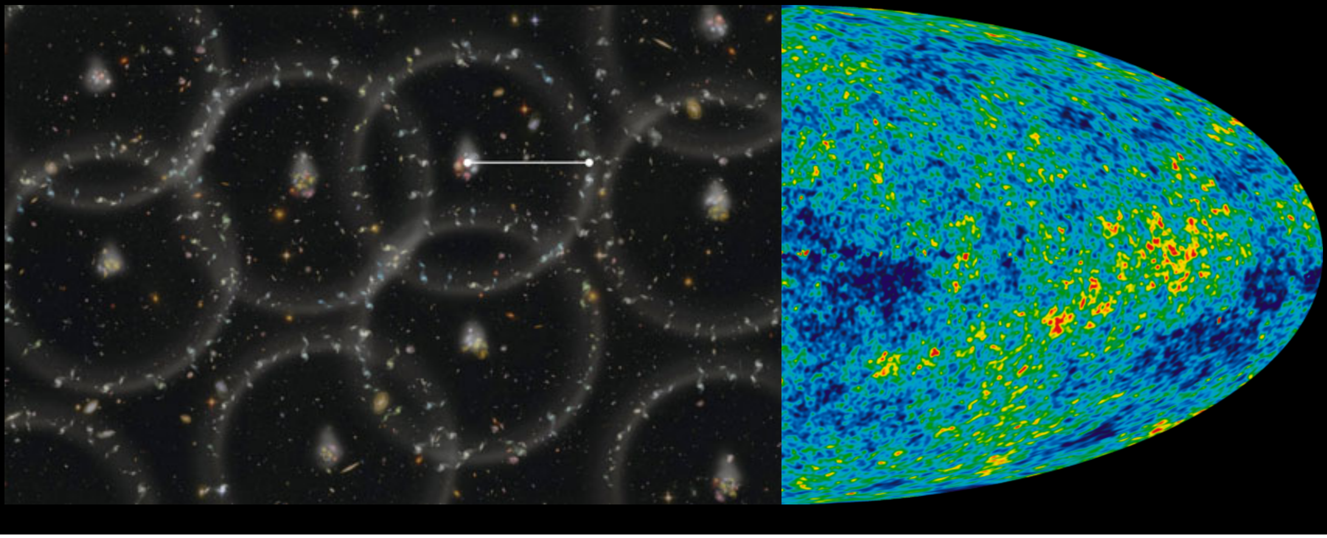
Dark matter pulls on light

(gravitational lensing)

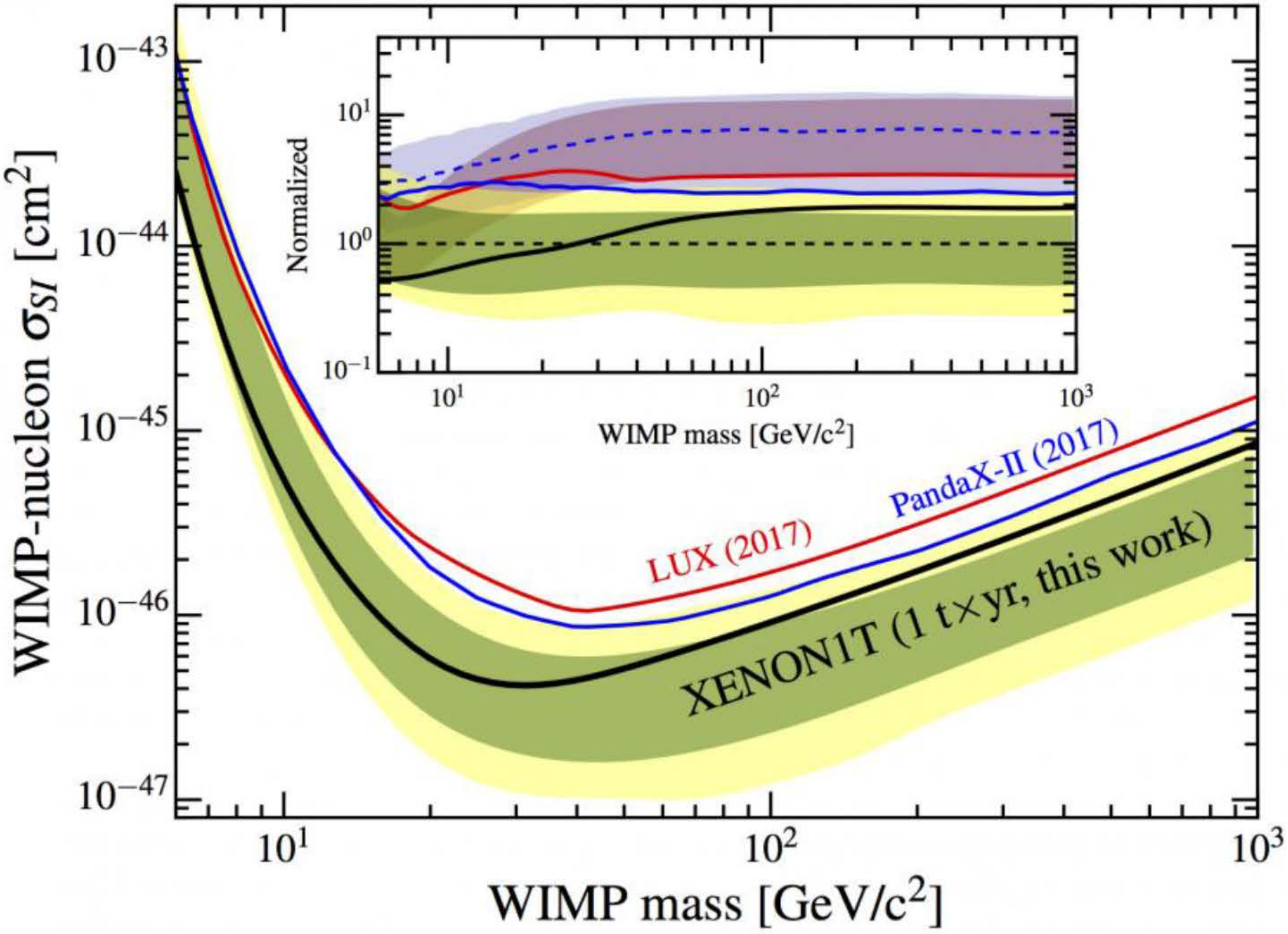


Dark matter pulled on e^-p^+ plasma

(CMB & large scale structure)



We haven’t yet seen dark matter bump into things



Does dark matter interact with more than gravity?

GRAVITON

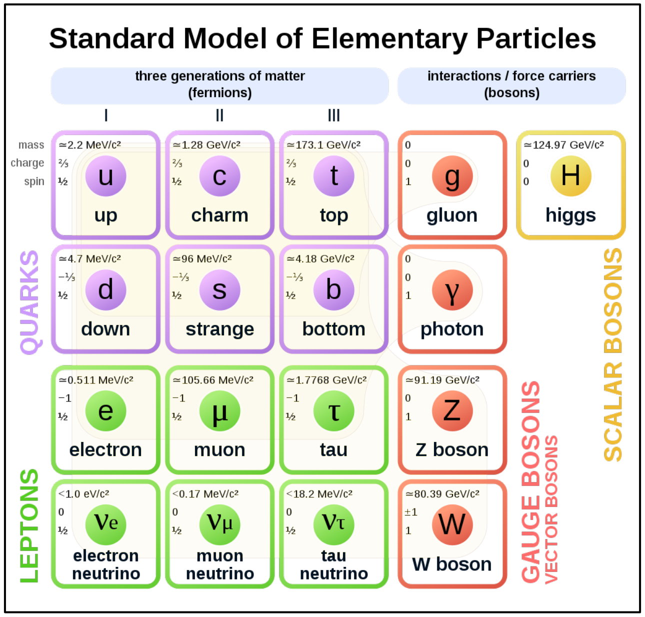
The **GRAVITON** is a particle not yet observed. It communicates the force of gravity and is the smallest bundle of the gravitational force field. Some theorists believe gravitons can travel between braneworlds. Lucky l'il fellas!

Acrylic felt with poly fill for minimum mass.

DARK MATTER

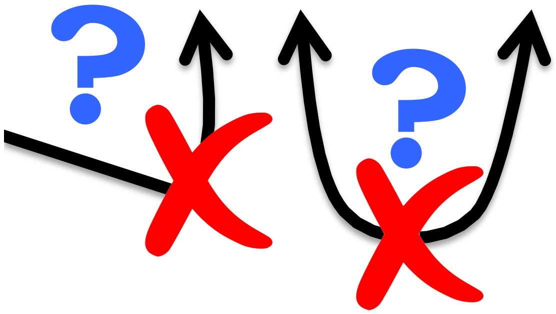
DARK MATTER is the name given to material in the Universe that does not emit or reflect light but is necessary to explain observed gravitational effects in galaxies and stars. Dark matter, along with dark energy, totals 96% of the Universe, yet it remains a mystery as to what exactly it is.

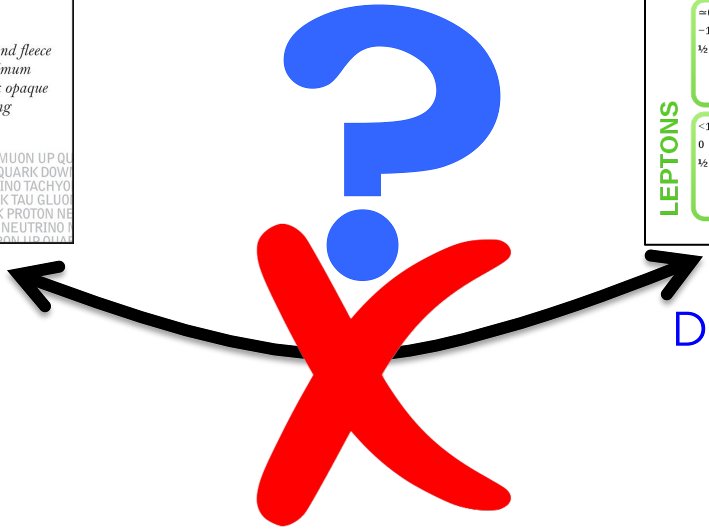
Acrylic felt, wool felt, and fleece with gravel fill for maximum mass. Packaged in a black opaque bag designed for concealing contents.



Standard Model of Elementary Particles

	three generations of matter (fermions) I	II	III	interactions / force carriers (bosons)	
mass charge spin	≃2.2 MeV/c² ⅔ ½ u up	≃1.28 GeV/c² ⅔ ½ c charm	≃173.1 GeV/c² ⅔ ½ t top	0 0 1 g gluon	≃124.97 GeV/c² 0 0 H higgs
QUARKS	≃4.7 MeV/c² −⅓ ½ d down	≃96 MeV/c² −⅓ ½ s strange	≃4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS
LEPTONS	≃0.511 MeV/c² −1 ½ e electron	≃105.66 MeV/c² −1 ½ μ muon	≃1.7768 GeV/c² −1 ½ τ tau	≃91.19 GeV/c² 0 1 Z Z boson	GAUGE BOSONS VECTOR BOSONS
	<1.0 eV/c² 0 ½ ν_e electron neutrino	<0.17 MeV/c² 0 ½ ν_μ muon neutrino	<18.2 MeV/c² 0 ½ ν_τ tau neutrino	≃80.39 GeV/c² ±1 1 W W boson	





Does dark matter interact…

… with the Standard Model?

… with itself?

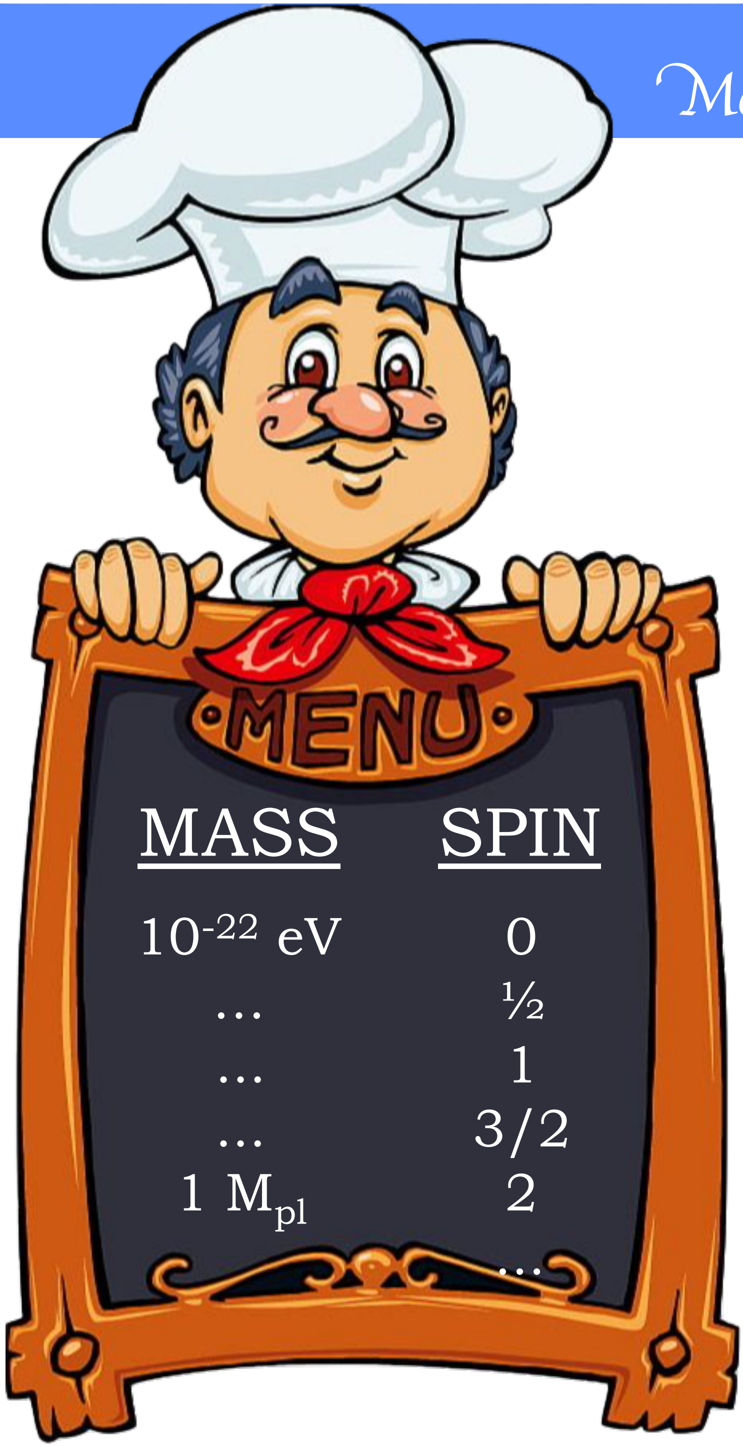
… with other dark particles?

For today: let's assume not.

Menu du models

(no PBH in this talk)
see: talks by Kusenko & Profumo

$$S = \int \mathrm{d}^4x \sqrt{-g}\, \mathscr{L}_{\text{dark matter}}$$



MASS	SPIN
10^{-22} eV	0
…	½
…	1
…	3/2
1 M_{pl}	2
	…

Dessert Menu

(“optional”)

$$\Delta\mathscr{L} = \phi^2 R\,,\ \bar{\psi}\psi R\,,$$

$$A_\mu A_\nu R^{\mu\nu}\,,\ A_\mu A_\nu g^{\mu\nu} R\,,$$

$$\ldots$$

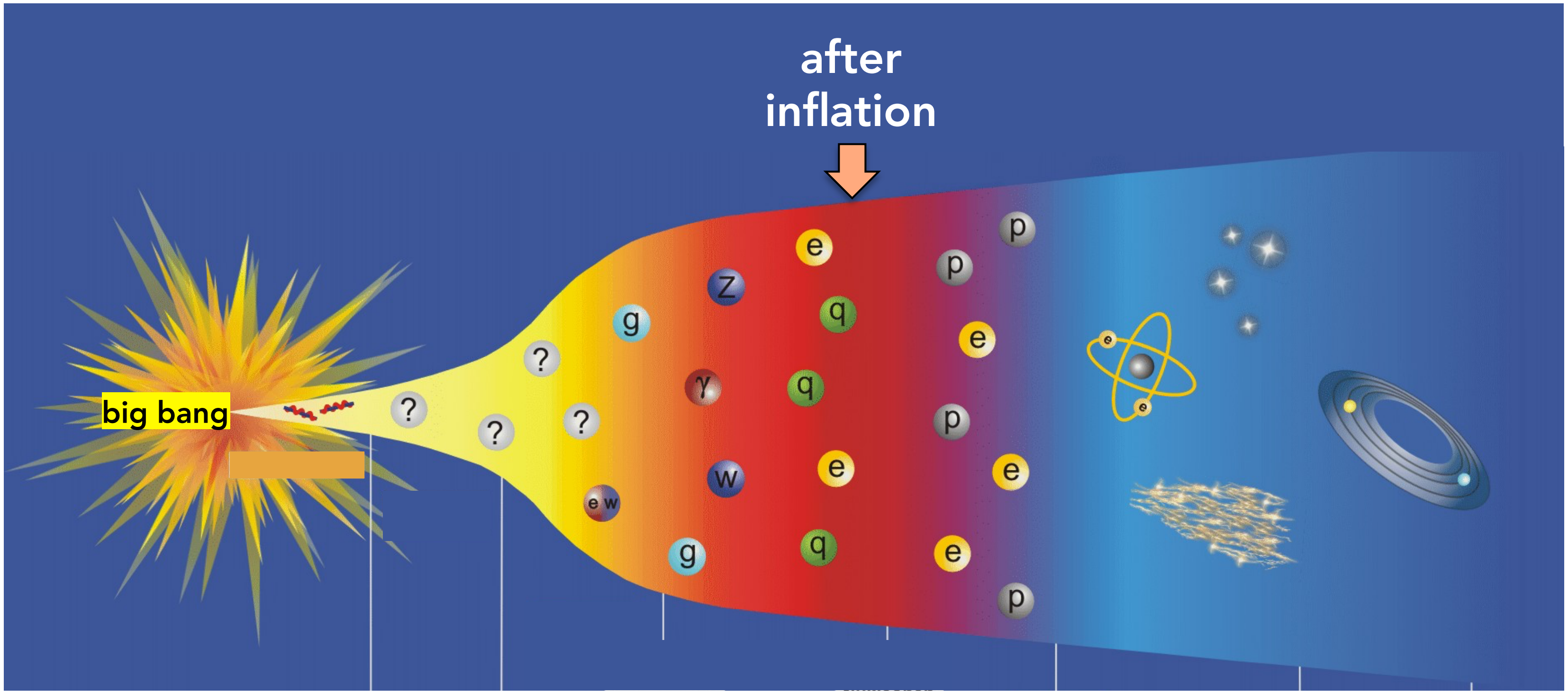
123RF

The problem:

Where did all the dark matter come from?

(how do we use gravity
to make dark matter?)

How do we *make* dark matter that only interacts with gravity?



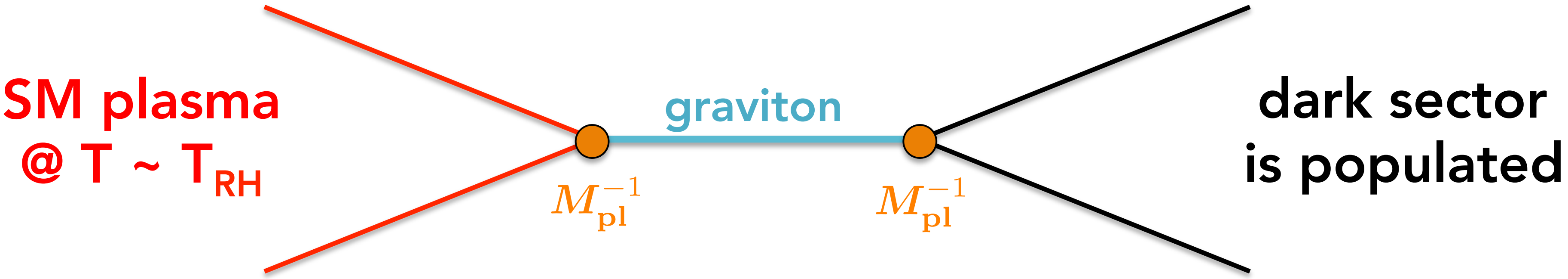
Graviton-mediated freeze in

PIDM: [Garny, Sandora, & Sloth (2015, 2018)]

see also [Tang & Wu (2017)]

see also [Adshead, Cui, & Shelton (2016)]

Gravity is a universal mediator: $\mathscr{L}_{\text{int}} = M_{\text{pl}}^{-1} h_{\mu\nu} T^{\mu\nu}$



This is an example of UV-dominated freeze-in (like the gravitino)

[Ellis, Kim, & Nanopoulos (1984); Hall, Jedamzik, March-Russell, & West (2010)]

$\Gamma \sim T^5 / M_{\text{pl}}^4$ VERSUS $H \sim T^2 / M_{\text{pl}}$

$$\boxed{\Omega_{\text{DM}} h^2 \simeq 0.1 \left(\frac{\langle \sigma v \rangle}{100 \frac{T^2}{64\pi M_{\text{pl}}^4}} \right) \left(\frac{m_{\text{DM}}}{10^{10}\ \text{GeV}} \right) \left(\frac{T_{\text{RH}}}{10^{14}\ \text{GeV}} \right)^3}$$

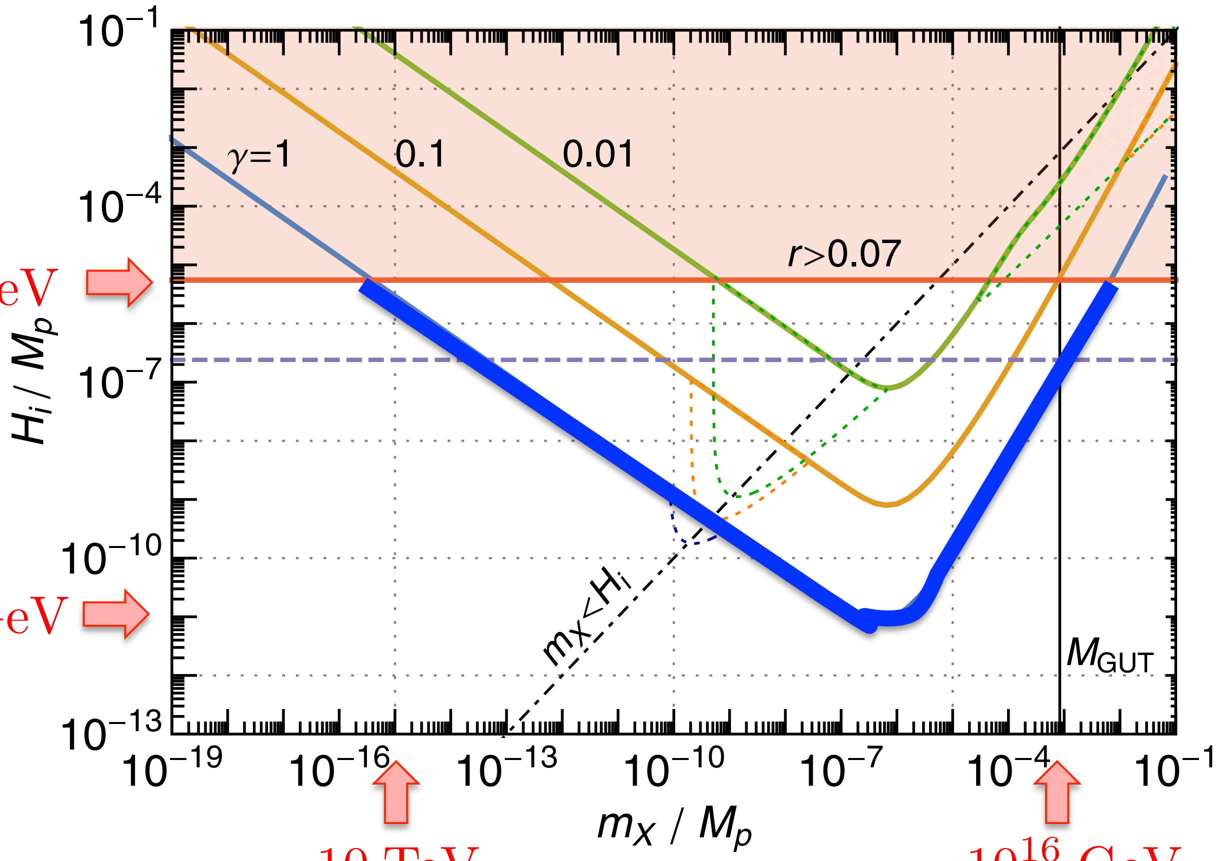
(assumes: instant reheating & $m_{\text{DM}} \ll T_{\text{RH}}$)

Graviton-mediated freeze in

PIDM: [Garny, Sandora, & Sloth (2015, 2018)]

$$\Omega_{\rm DM} h^2 \simeq 0.1 \left(\frac{\langle\sigma v\rangle}{100\frac{T^2}{64\pi M_{\rm pl}^4}}\right)\left(\frac{m_{\rm DM}}{10^{10}\ {\rm GeV}}\right)\left(\frac{T_{\rm RH}}{10^{14}\ {\rm GeV}}\right)^3$$

$M_p \simeq 1.2 \times 10^{19}$ GeV



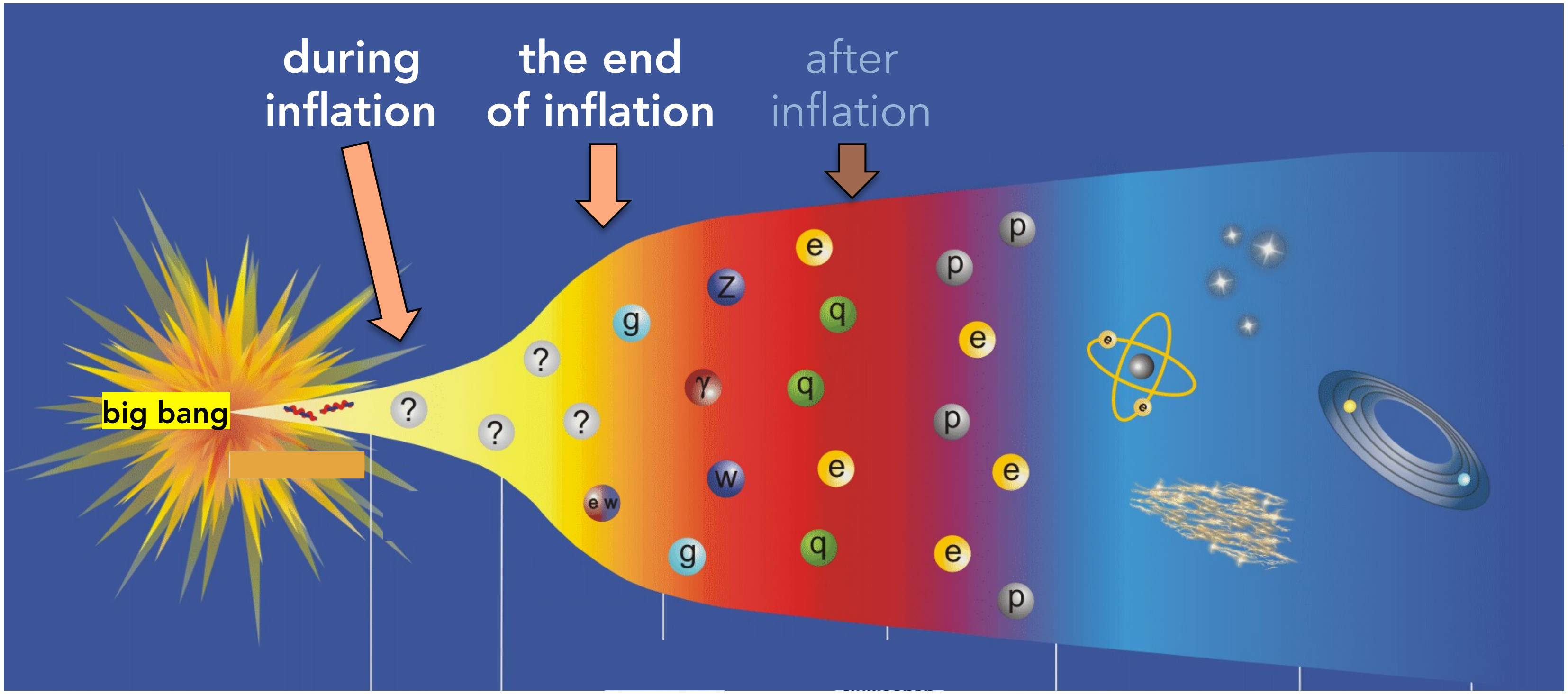
10^{14} GeV

10^{8} GeV

10 TeV

10^{16} GeV

How do we *make* dark matter that only interacts with gravity?



Gravitational particle production

[Schrodinger (1939); Parker (1965, 68); Fulling, Ford, & Hu; Zel'dovish; Starobinski; Grib, Frolov, Mamaev, & Mostepanenko; Mukhanov & Sasaki…]

particle creation results from
the non-adiabatic evolution
of the vacuum state of quantum fields
in a curved spacetime geometry
(e.g., expanding universe)

Example: scalar field in FRW background

$$\mathrm{d}s^2 = a(\eta)^2\left[\mathrm{d}\eta^2 - \mathrm{d}\boldsymbol{x}^2\right]$$

covariant action

$$S[\varphi(x), g_{\mu\nu}(x)] = \int \mathrm{d}^4x\,\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - \frac{1}{2}m^2\varphi^2 + \frac{1}{2}\xi\varphi^2 R\right]$$

action in an FRW background

$$S[\varphi(\eta, \boldsymbol{x})] = \int_{-\infty}^{\infty}\mathrm{d}\eta\int \mathrm{d}^3\boldsymbol{x}\left[\frac{1}{2}\underline{a^2\left(\partial_\eta\varphi\right)}^2 - \frac{1}{2}a^2\left(\boldsymbol{\nabla}\varphi\right)^2 - \frac{1}{2}a^4m^2\varphi^2 + \frac{1}{2}a^4\xi\varphi^2 R\right]$$

field rescaling

$$\phi(\eta, \boldsymbol{x}) = a(\eta)\,\varphi(\eta, \boldsymbol{x})$$

action for canonically-normalized field

$$S[\phi(\eta, \boldsymbol{x})] = \int_{-\infty}^{\infty}\mathrm{d}\eta\int \mathrm{d}^3\boldsymbol{x}\left[\frac{1}{2}\left(\partial_\eta\phi\right)^2 - \frac{1}{2}\left(\boldsymbol{\nabla}\phi\right)^2 - \frac{1}{2}m_{\text{eff}}^2\,\phi^2 - \frac{1}{2}\partial_\eta(aH\phi^2)\right]$$

time-dependent effective mass

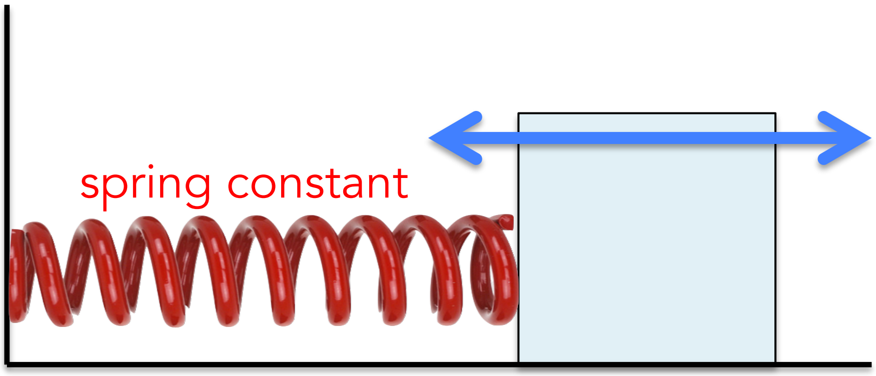
$$m_{\text{eff}}^2(\eta) = a(\eta)^2\left[m^2 + \left(\frac{1}{6} - \xi\right)R(\eta)\right]$$

time-dependent dispersion relation

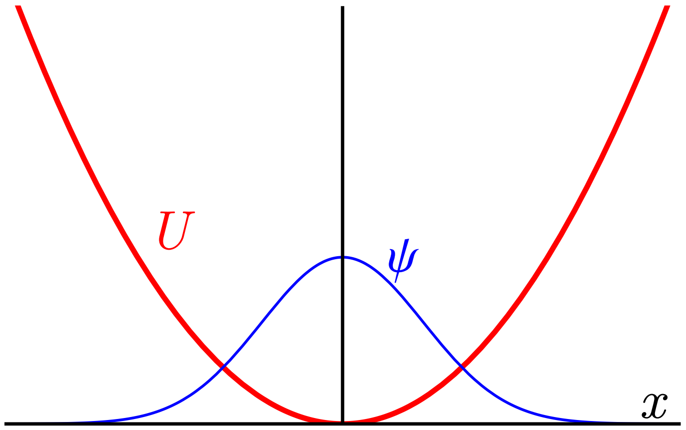
$$\omega_k^2(\eta) \;=\; |\boldsymbol{k}|^2 \;+\; m_{\text{eff}}^2(\eta)$$

the ground state
wavefunction must adjust
to the changing mass

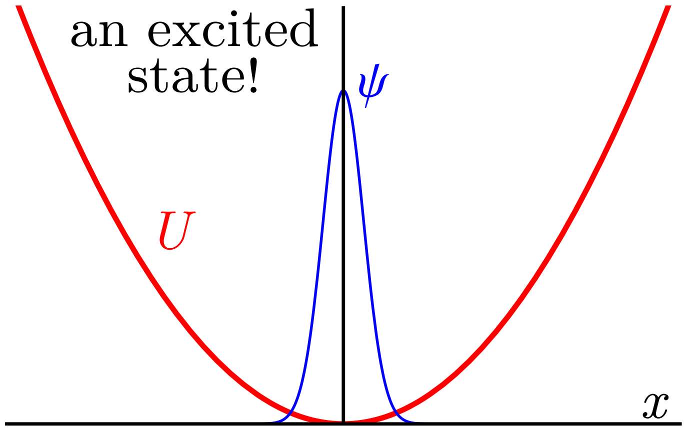
An analogy with 1D quantum mechanics



Spring constant is varied
slowly (adiabatically)



Spring constant is varied
abruptly (*non*-adiabatically)

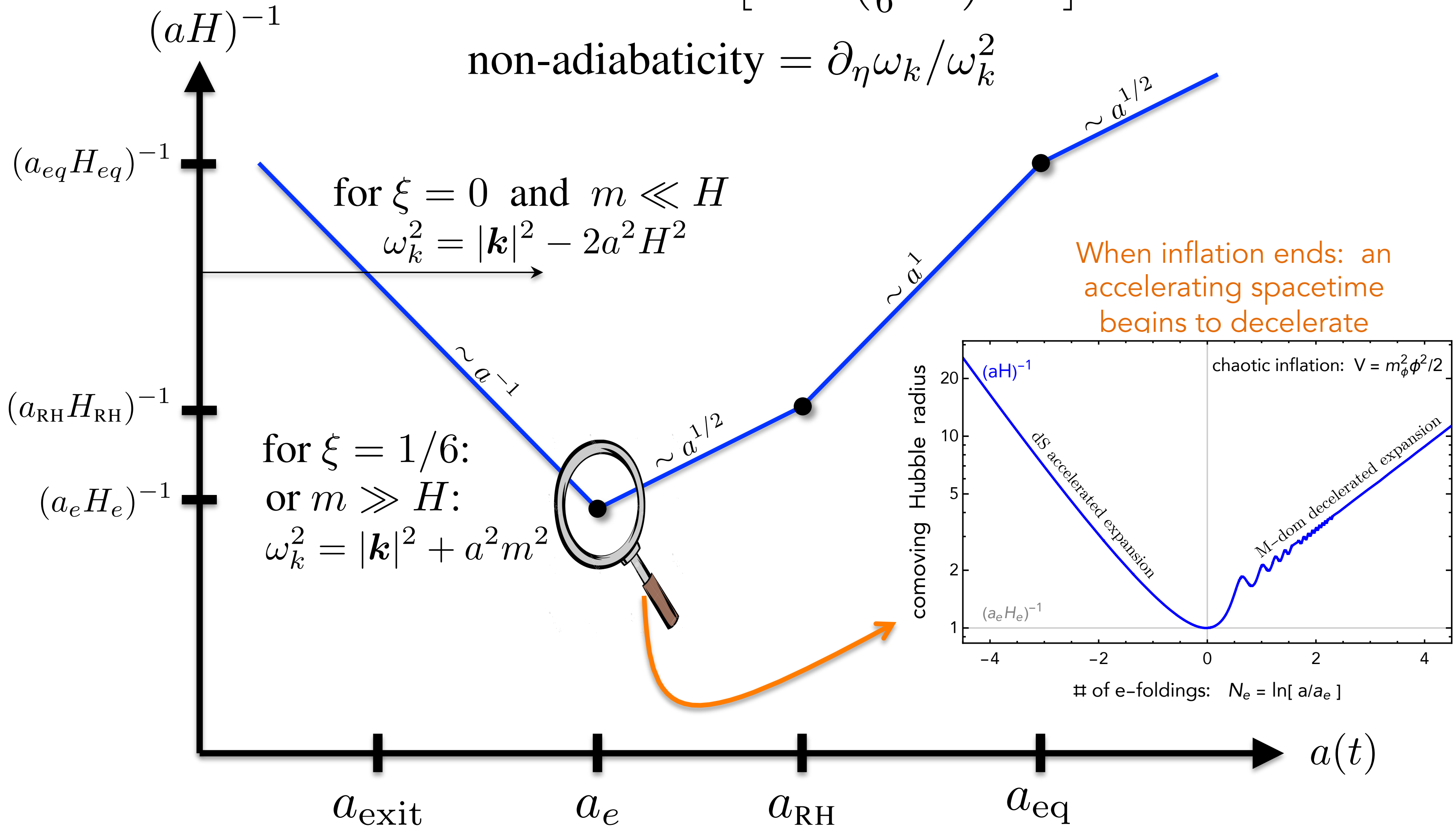


Non-adiabaticity during inflation

$$R_{\rm dS} = -12 H_{\rm dS}^2$$

$$\omega_k^2(\eta) = |\boldsymbol{k}|^2 + a(\eta)^2\left[m^2 + \left(\frac{1}{6} - \xi\right)R(\eta)\right]$$

$$\text{non-adiabaticity} = \partial_\eta \omega_k / \omega_k^2$$



for $\xi = 0$ and $m \ll H$

$$\omega_k^2 = |\boldsymbol{k}|^2 - 2a^2H^2$$

for $\xi = 1/6$:
or $m \gg H$:

$$\omega_k^2 = |\boldsymbol{k}|^2 + a^2 m^2$$

When inflation ends: an accelerating spacetime begins to decelerate

Example: scalar field in FRW background

mode decomposition

$$\hat{\phi}(\eta, \boldsymbol{x}) = \int \frac{\mathrm{d}^3\boldsymbol{k}}{(2\pi)^3} \left[\hat{a}_{\boldsymbol{k}}\, \chi_k(\eta)\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} + \hat{a}^\dagger_{\boldsymbol{k}}\, \chi^*_k(\eta)\, e^{-i\boldsymbol{k}\cdot\boldsymbol{x}}\right]$$

equations of motion

$$\partial^2_\eta\, \chi_k(\eta) \;+\; \omega^2_k(\eta)\, \chi_k(\eta) = 0$$

Bunch-Davies initial condition

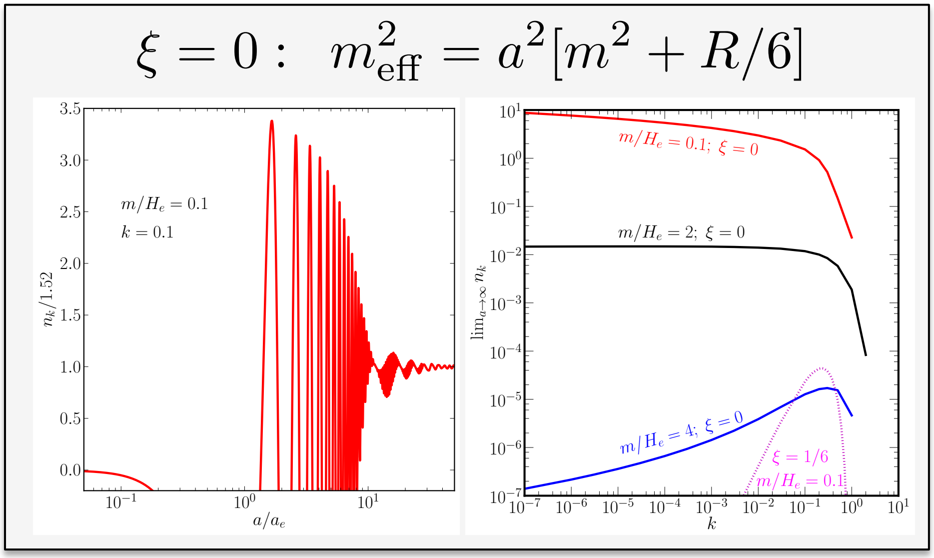
$$\chi_k(\eta) \xrightarrow{\eta\to-\infty} \chi^{\mathrm{BD}}_k(\eta) \equiv \frac{1}{\sqrt{2k}}\, e^{-ik\eta}$$

energy density

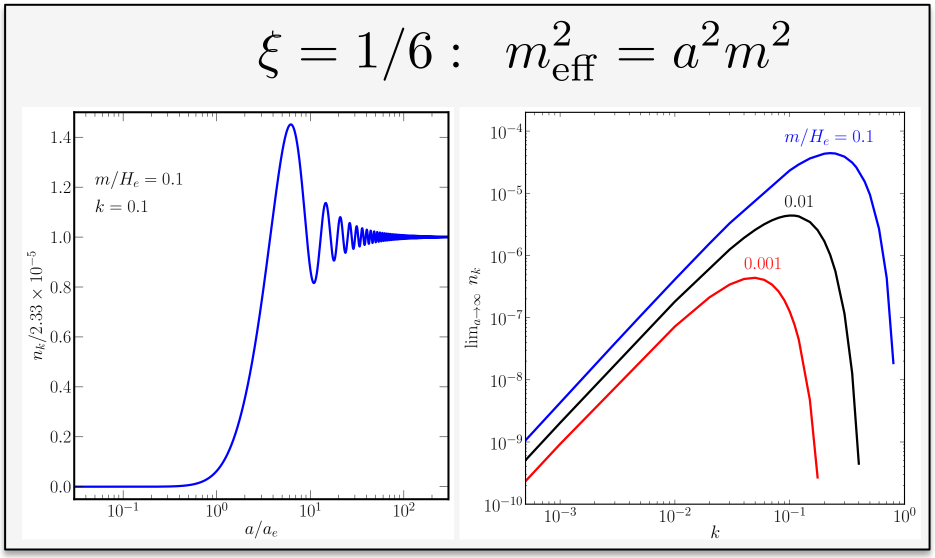
$$\bar{T}^{00}(\eta)\Big|_{\mathrm{ren}} = a^{-4} \int \frac{\mathrm{d}^3\boldsymbol{k}}{(2\pi)^3} \left[\frac{1}{2}|\partial_\eta \chi_k(\eta)|^2 + \frac{\omega^2_k(\eta)}{2}|\chi_k(\eta)|^2 - \frac{1}{2}\omega_k(\eta)\right]$$

$$\to a^{-3} m \int \frac{\mathrm{d}k}{k}\, n_k \qquad \text{at late times, } \omega_k \approx am$$

Example: scalar field in FRW background



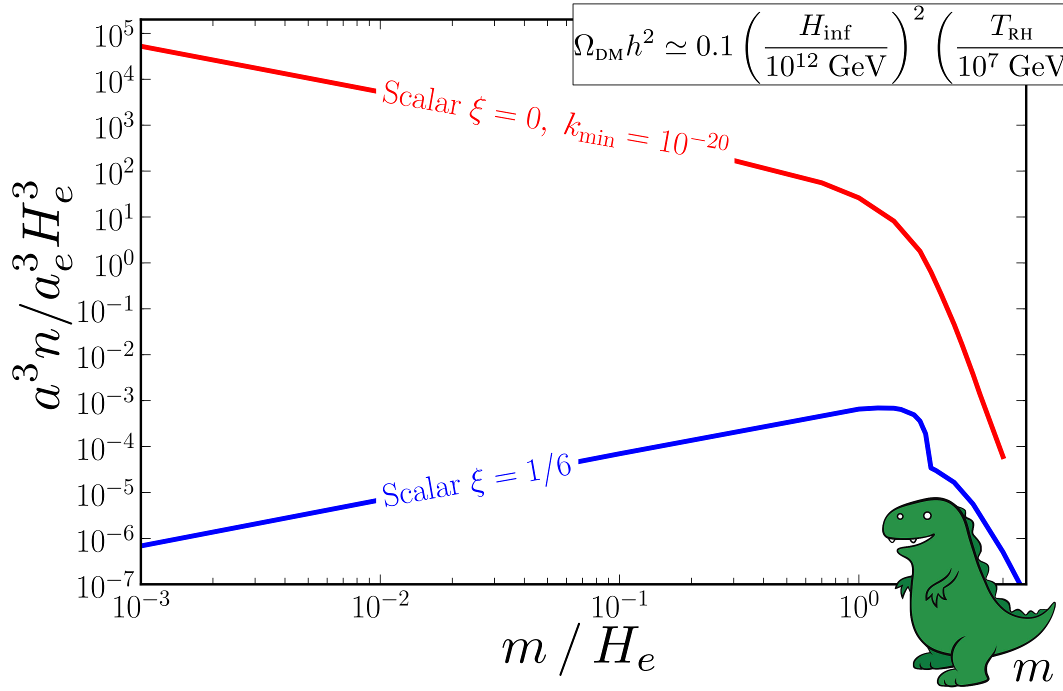
$\xi = 0: \quad m_{\text{eff}}^2 = a^2[m^2 + R/6]$



$\xi = 1/6: \quad m_{\text{eff}}^2 = a^2 m^2$

[Kolb & AL (in prep)]

$$\Omega_{\text{DM}} h^2 \simeq 0.1 \left(\frac{H_{\text{inf}}}{10^{12}\ \text{GeV}}\right)^2 \left(\frac{T_{\text{RH}}}{10^7\ \text{GeV}}\right) \left(\frac{m_{\text{DM}}}{H_{\text{inf}}}\right) \left(\frac{a^3 n / a_e^3 H_e^3}{10^{-3}}\right)$$



Take Aways

(1) light (m<<H) & min-coupled scalars are easily populated (a^3 n large)

(2) however, there is too much isocurvature to explain dark matter [see talk by Tommi Tenkanen]

(3) heavy & min-coupled scalars have a blue spectrum & avoid isocurvature ➔ WIMPzilla

Beyond scalar dark matter

Beyond $m^2\phi^2$ inflation

Beyond scalar fields …

$$S = \int \mathrm{d}^4x \, \sqrt{-g} \, \mathscr{L}$$

spin-0 (real scalar boson)

Chung, Kolb, & Riotto (1998)
Kuzmin & Tkachev (1998)

$$\mathscr{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi - \frac{1}{2} m^2 \varphi^2 + \frac{1}{2} \xi \varphi^2 R$$

spin-1/2 (Dirac fermion)

Kuzmin & Tkachev (1998)
Chung, Everett, Yoo, & Zhou (2011)

$$\mathscr{L} = \frac{i}{2} \bar{\Psi} \underline{\gamma}^\mu (\nabla_\mu \Psi) - \frac{1}{2} m \bar{\Psi} \Psi + \mathrm{h.c.}$$

spin-1 (real vector boson)

Graham, Mardon, & Rajendran (2016) … only for m<<H
earlier Dimopoulos (2006) did not consider dark matter

$$\mathscr{L} = -\frac{1}{4} g^{\mu\alpha} g^{\nu\beta} F_{\mu\nu} F_{\alpha\beta} + \frac{1}{2} m^2 g^{\mu\nu} A_\mu A_\nu - \frac{1}{2} \xi_1 R g^{\mu\nu} A_\mu A_\nu - \frac{1}{2} \xi_2 R^{\mu\nu} A_\mu A_\nu$$

spin-3/2 (Rarita-Schwinger fermion)

Kallosh, Kofman, Linde, & Van Proeyen (1999)
Giudice, Riotto, & Tkachev (1999); Lemoine (1999)

$$\mathscr{L} = \frac{i}{4} \bar{\Psi}_\mu \left(\underline{\gamma}^\mu \underline{\gamma}^\rho \underline{\gamma}^\sigma - \underline{\gamma}^\sigma \underline{\gamma}^\rho \underline{\gamma}^\mu \right) (\nabla_\rho \Psi_\sigma) + \frac{1}{2} m \bar{\Psi}_\mu \underline{\gamma}^\mu \underline{\gamma}^\sigma \Psi_\sigma + \mathrm{h.c.}$$

spin-2 (Fierz-Pauli boson)

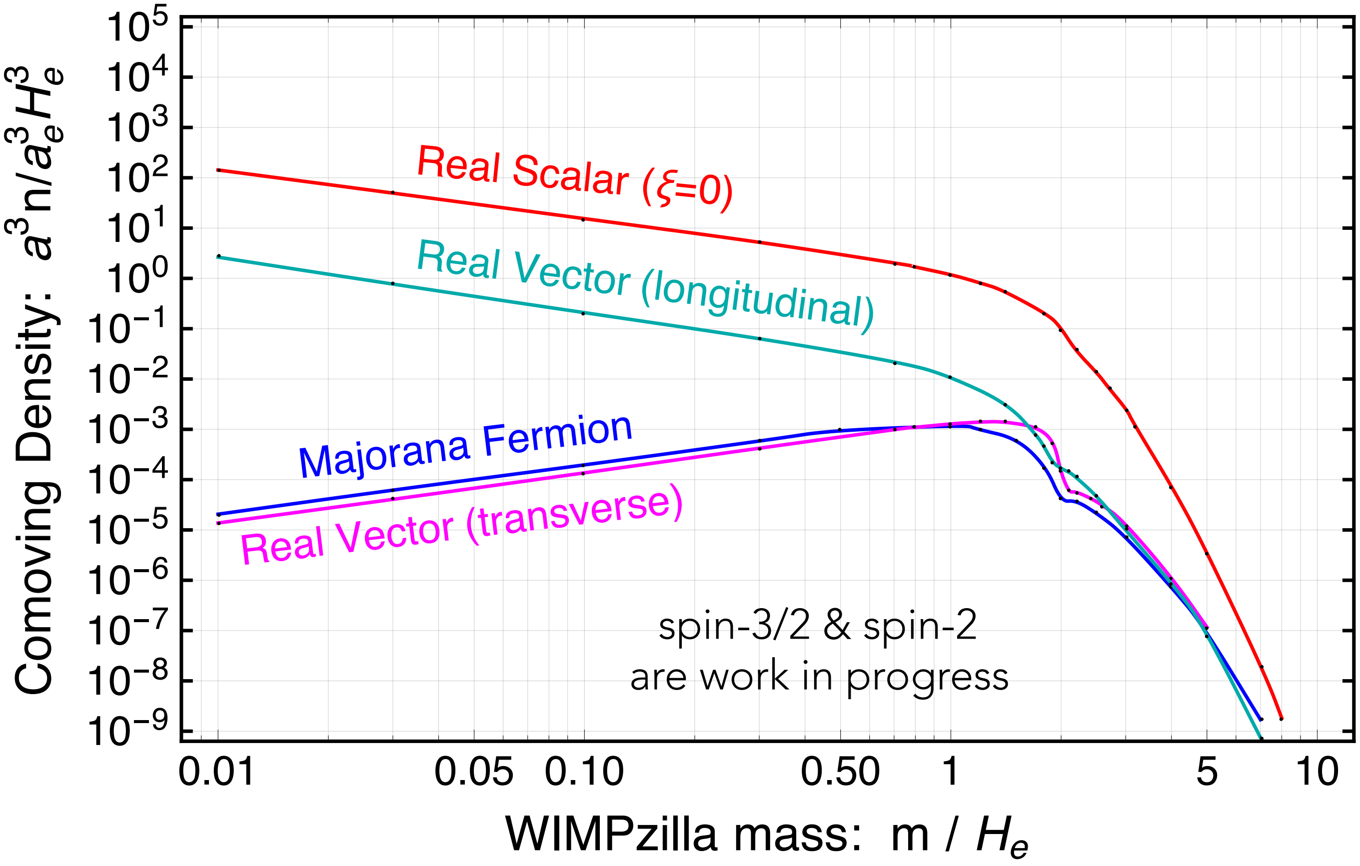
no studies of gravitational DM production ; see also Babichev, et al (2016)
see also Bernard, Deffayet, & von Strauss (2015); Mazuet & Volkov (2018)

$$\mathscr{L} = \frac{1}{2} M_g^2 h_{\mu\nu} \left(\tilde{\mathcal{E}}^{\mu\nu\rho\sigma} + m^2 \mathcal{M}^{\mu\nu\rho\sigma} \right) h_{\rho\sigma}$$

Summary of results for high-spin DM

assumes chaotic inflation

$V \propto \phi^2 \quad \& \quad m_{\rm inf} \approx H_{\rm inf}$



spin-3/2 & spin-2
are work in progress

$$\Omega_{\rm DM} h^2 \simeq 0.1 \left(\frac{H_{\rm inf}}{10^{12}\ {\rm GeV}} \right)^2 \left(\frac{T_{\rm RH}}{10^7\ {\rm GeV}} \right) \left(\frac{m_{\rm DM}}{H_{\rm inf}} \right) \left(\frac{a^3 n / a_e^3 H_e^3}{10^{-3}} \right)$$

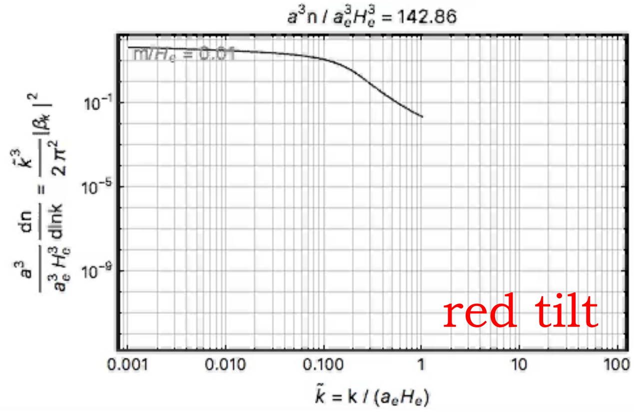
Summary of results for high-spin DM

assumes chaotic inflation

$V \propto \phi^2$ & $m_{\text{inf}} \approx H_{\text{inf}}$

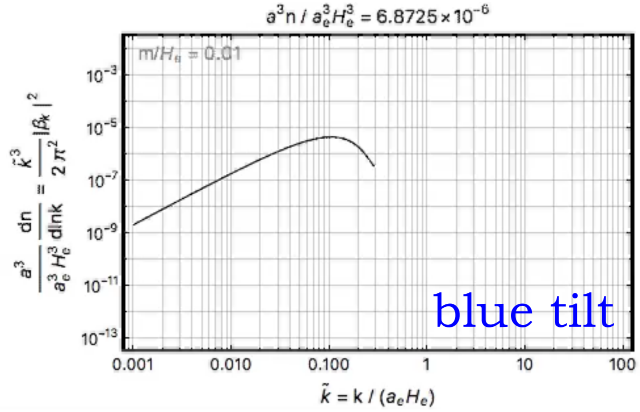
blue power spectrum:
s = 0 & ξ = 0 & m > H
or s = ½, 1

scalar (ξ=0)



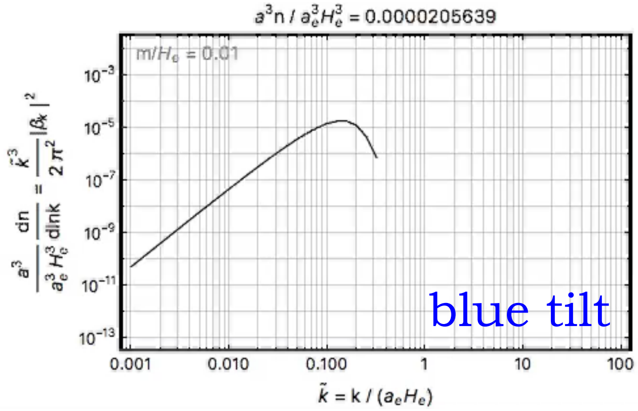
red tilt

vector (transverse)



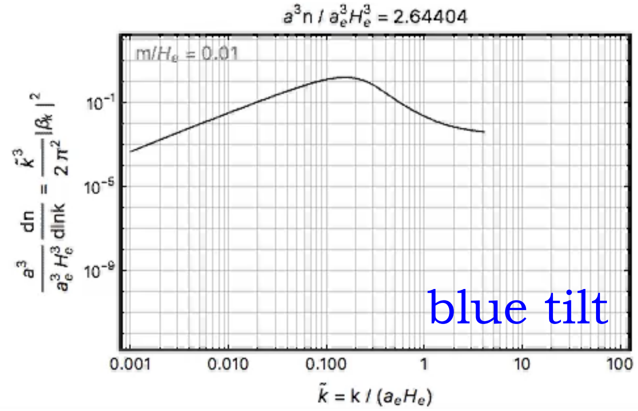
blue tilt

spin-1/2 fermion



blue tilt

vector (longitudinal)

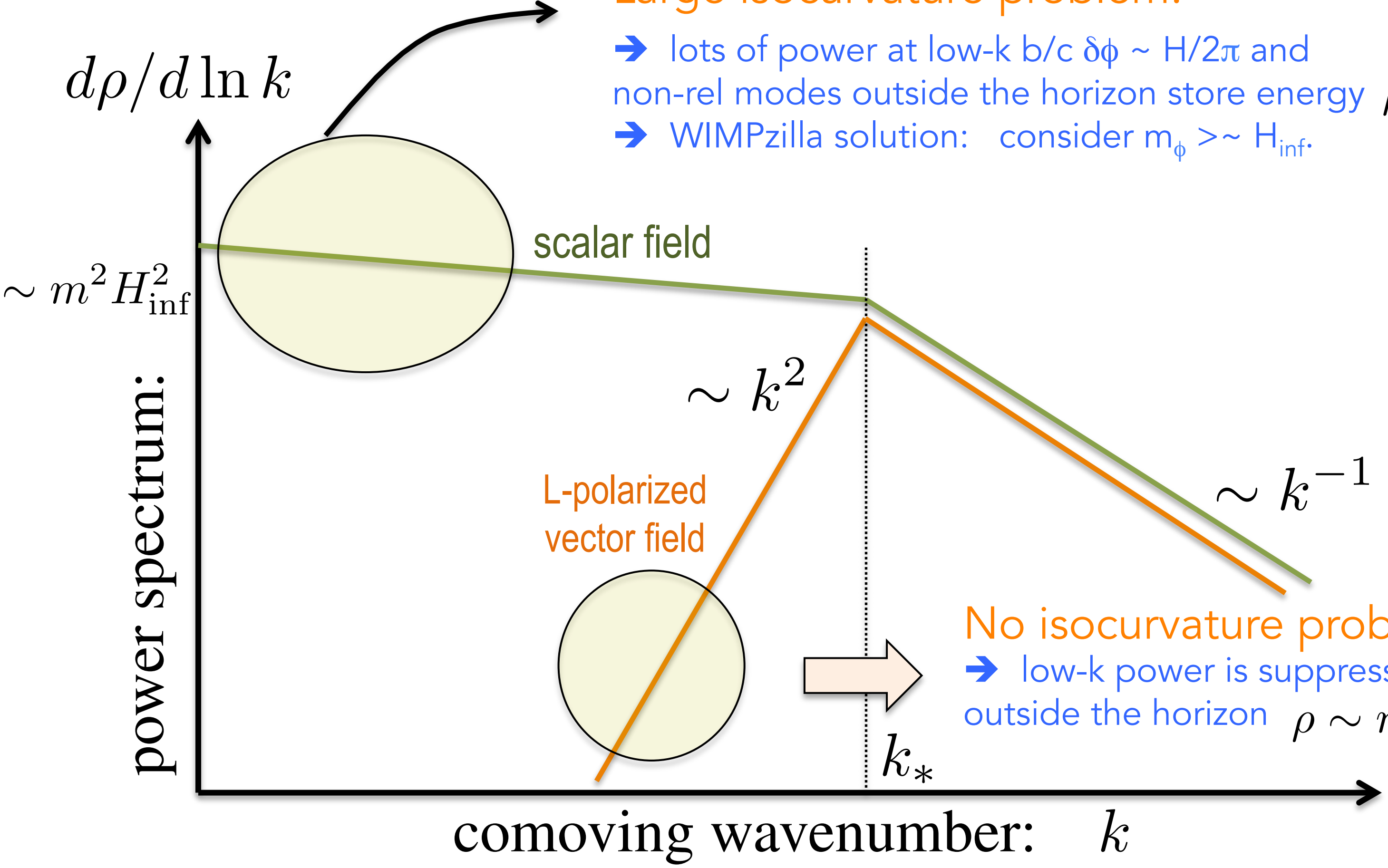


blue tilt

Comparing spin-0 and spin-1

for $m \ll H_{\rm inf}$

self-interaction saves scalar spectator: [Markkanen, Rajantie, & Tenkanen (2018); Tenkanen (2019)]
spin-1 spectator: [Dimopoulos (2006); Graham, Mardon, & Rajendran (2016)]
lightish-but-clumpy: [Alonso-Alvarez & Jaeckel (2018), + Hugel (2019)]



Large isocurvature problem!

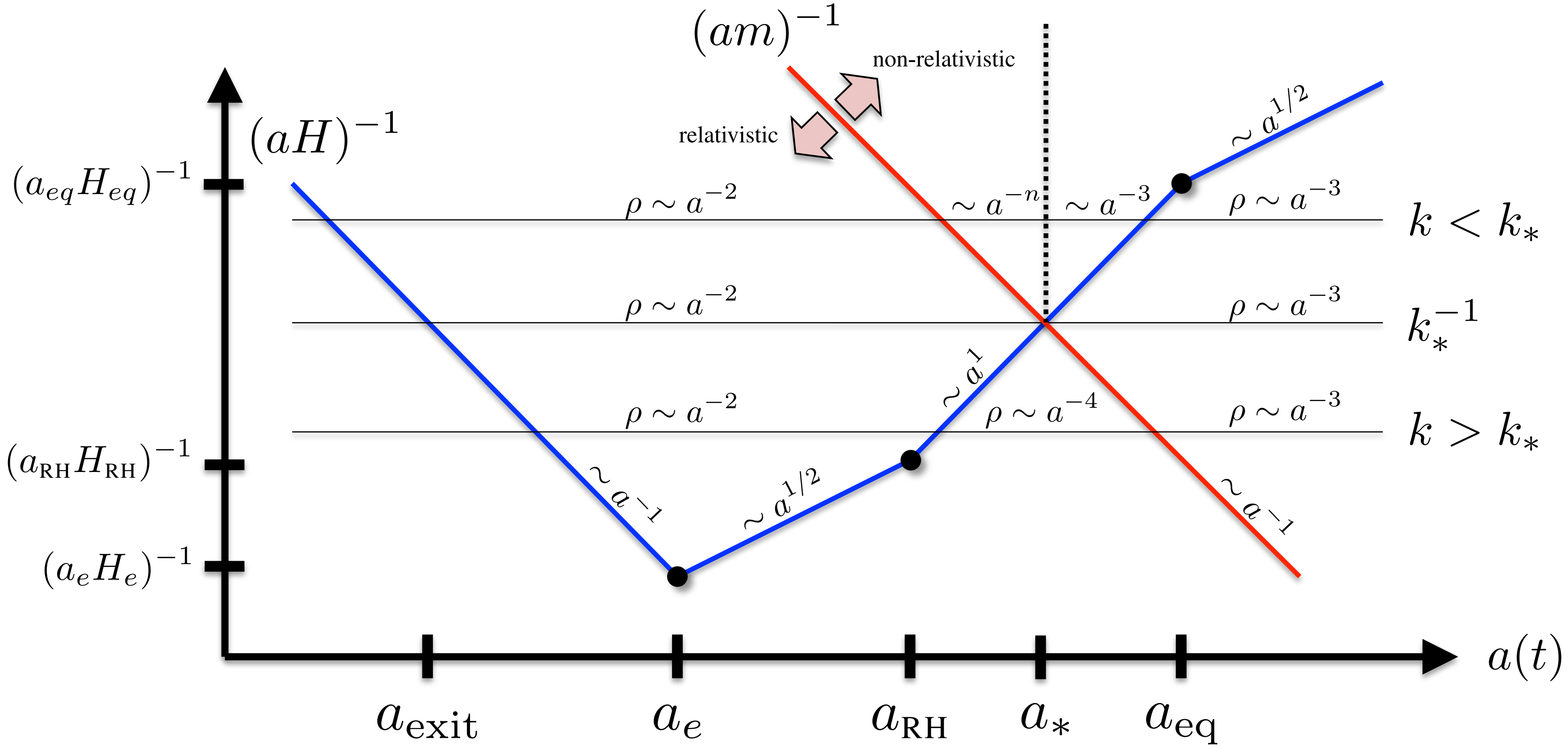
➔ lots of power at low-k b/c $\delta\phi \sim H/2\pi$ and non-rel modes outside the horizon store energy $\rho \sim m^2 \phi^2 \sim a^0$

➔ WIMPzilla solution: consider $m_\phi >\sim H_{\rm inf}$.

No isocurvature problem for spin-1

➔ low-k power is suppressed for non-rel modes outside the horizon $\rho \sim m^2 A_\mu A_\nu g^{\mu\nu} \sim a^{-2}$

Comparing spin-0 and spin-1



Non-minimally coupled vectors

[Golonev, Mukhanov, & Vanchurin (2008) only has ξ_1 term]

spin-1 (real vector boson)

$$\mathscr{L} = -\frac{1}{4} g^{\mu\alpha} g^{\nu\beta} F_{\mu\nu} F_{\alpha\beta} + \frac{1}{2} m^2 g^{\mu\nu} A_\mu A_\nu - \frac{1}{2} \underline{\xi_1 R g^{\mu\nu} A_\mu A_\nu} - \frac{1}{2} \underline{\xi_2 R^{\mu\nu} A_\mu A_\nu}$$

new work

time-dependent effective masses

$$m^2_{\mathrm{eff},t} \equiv a^2 \left[m^2 - \xi_1 R - \frac{1}{2} \xi_2 R - 3 \xi_2 H^2 \right]$$

$$m^2_{\mathrm{eff},s} \equiv a^2 \left[m^2 - \xi_1 R - \frac{1}{6} \xi_2 R + \xi_2 H^2 \right]$$

stress-energy tensor

$$\begin{aligned} T^{\mu\nu} = {} & \mathrm{s}\, \frac{1}{4} \left(g^{\mu\nu} g^{\alpha\gamma} g^{\beta\delta} - 4 g^{\mu\alpha} g^{\nu\gamma} g^{\beta\delta} \right) F_{\alpha\beta} F_{\gamma\delta} \\ & + \left[m^2 \left(g^{\mu\alpha} g^{\nu\beta} - \frac{1}{2} g^{\mu\nu} g^{\alpha\beta} \right) - \mathrm{s}\, \xi_1 \left(R g^{\mu\alpha} g^{\nu\beta} + G^{\mu\nu} g^{\alpha\beta} \right) - \mathrm{s}\, \xi_2 \left(g^{\mu\alpha} R^{\nu\beta} + g^{\mu\beta} R^{\nu\alpha} - \frac{1}{2} g^{\mu\nu} R^{\alpha\beta} \right) \right] A_\alpha A_\beta \\ & + \left[\mathrm{s}\, \xi_1 \left(g^{\mu\rho} g^{\nu\sigma} - g^{\mu\nu} g^{\rho\sigma} \right) g^{\alpha\beta} + \mathrm{s}\, \frac{1}{2} \xi_2 \left(g^{\alpha\nu} g^{\beta\rho} g^{\sigma\mu} + g^{\alpha\rho} g^{\beta\mu} g^{\sigma\nu} - g^{\alpha\nu} g^{\beta\mu} g^{\sigma\rho} - g^{\alpha\rho} g^{\beta\sigma} g^{\mu\nu} \right) \right] \nabla_\rho \nabla_\sigma \left(A_\alpha A_\beta \right) \end{aligned}$$

Beyond scalar dark matter

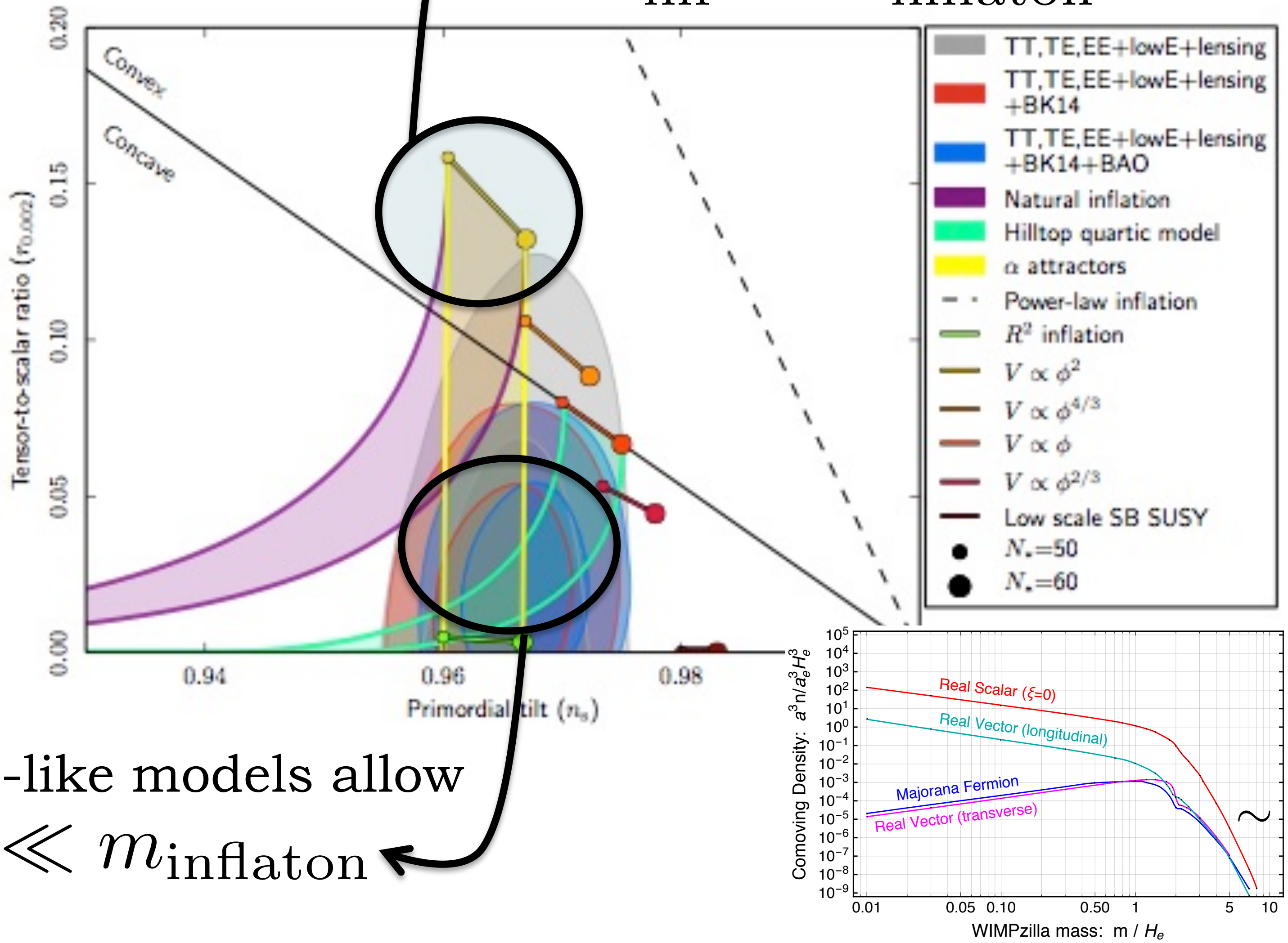
Beyond $m^2\phi^2$ inflation

Constraints on inflation

[Planck 2018]

$$V(\phi) \propto \phi^2$$

$$H_{\rm inf} \approx m_{\rm inflaton}$$



hilltop-like models allow

$$H_{\rm inf} \ll m_{\rm inflaton}$$

naïve:

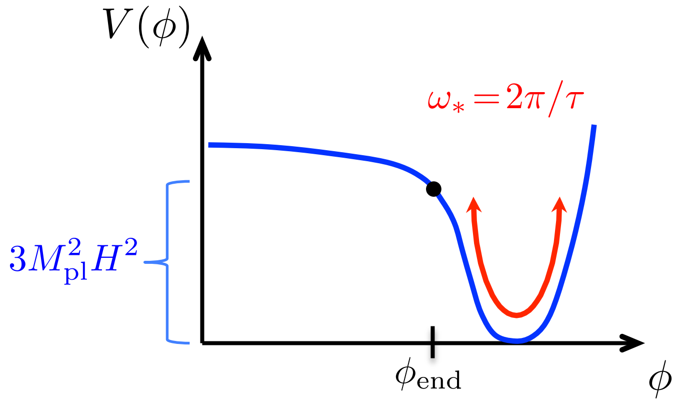
$$\sim e^{-m/H}$$

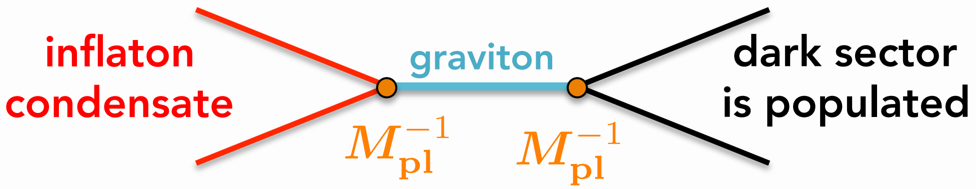
WIMPzilla production at the end of hilltop-like inflation

purely-gravitational DM: [Ema, Nakayama, & Tang (2018, 2019)]

Hilltop inflation breaks the relation beween H_{inf} and m_{inf}

$$H_{\text{inf}} \ll m_{\text{DM}} \ll m_{\text{inf}}$$





WIMPzilla production can be described by annihilations

High-mass exponential suppression is softened to a power law

Grav. particle production from rapid a(t) oscillations

[Chung, Kolb, & AL (2018)]

spectrum

$$dn_\chi = \frac{k^3\, \mathrm{d}\ln k}{2\pi^2} \lim_{t\to\infty} \frac{1}{a^3} |\beta_k|^2$$

dispersion relation

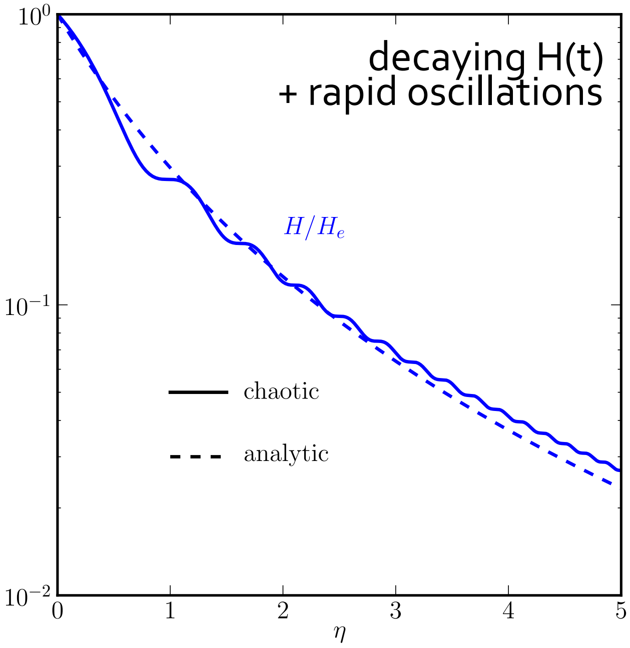
$$\omega_k = \sqrt{k^2 + a^2 m_\chi^2 + \frac{1}{6}(1-6\xi) a^2 R}$$

mode function

$$\beta_k = \int_{t_P}^{t} \mathrm{d}t' \, \frac{\dot{\omega}_k}{2\omega_k} \exp\left[-2i \int_{t_1}^{t'} \mathrm{d}t'' \, \frac{\omega_k}{a}\right]$$

for m >> H (acts like a Fourier transform)

$$\beta_k = \int_{t_P}^{t} \mathrm{d}t' \, \frac{\dot{\omega}_k}{2\omega_k} \exp\left[-2imt'\right]$$



if a(t) only varies on $\Delta t \sim H^{-1}$
then $\beta_k \sim \exp[-m/H]$

if a(t) includes rapid oscillations,
then the FT selects this out

Grav. particle production from rapid a(t) oscillations

[Chung, Kolb, & AL (2018)]

predicted abundance

$$\Omega_{\rm DM} h^2 \simeq 0.1 \left(\frac{H_{\rm inf}}{10^{12}\ {\rm GeV}} \right)^2 \left(\frac{T_{\rm RH}}{10^{7}\ {\rm GeV}} \right) \left(\frac{m_{\rm DM}}{H_{\rm inf}} \right) \left(\frac{a^3 n / a_e^3 H_e^3}{10^{-3}} \right)$$

$$a^3 n / a_e^3 H_e^3 = \begin{cases} \frac{9}{64} \frac{1}{16\pi^2} \frac{m_\chi^4}{m_\phi^4} \Theta(m_\phi - m_\chi) & \text{(conformally-coupled scalar)} \\ \frac{9}{16} \frac{1}{16\pi^2} \Theta(m_\phi - m_\chi) & \text{(minimally-coupled scalar)} \end{cases}$$

hilltop-like models of inflation

(incl. Higgs inflation, alpha attractor, …)

with dark matter mass in the window $H_{\rm inf} << m_\chi < m_{\rm inf}$

softens the standard exponential suppression to a power law

Closing comments

Summary & questions for discussion

Summary

- All of the evidence for dark matter arises from its gravitational influence.
- Even if dark matter *only* interacts through gravity, we can make it during inflation.
- For minimally-coupled scalars
  - light scalars ($m << H_{inf}$) can have a large abundance, but too much isocurvature
  - heavy scalars ($m >\sim H_{inf}$) have blue isocurvature ➔ WIMPzilla regime
- For minimally-coupled vectors & fermions … blue isocurvature avoids problems.
- We are extending these calculations to higher spin fields … s = 3/2 and 2 are WIP.
- For currently-favored hilltop-like models of inflation, gravitational production is efficient in the regime $H_{inf} << m_{DM} < m_{inf}$ where exponential suppression is avoided.

Questions (or: things I hope to learn from discussions with you at KITP)

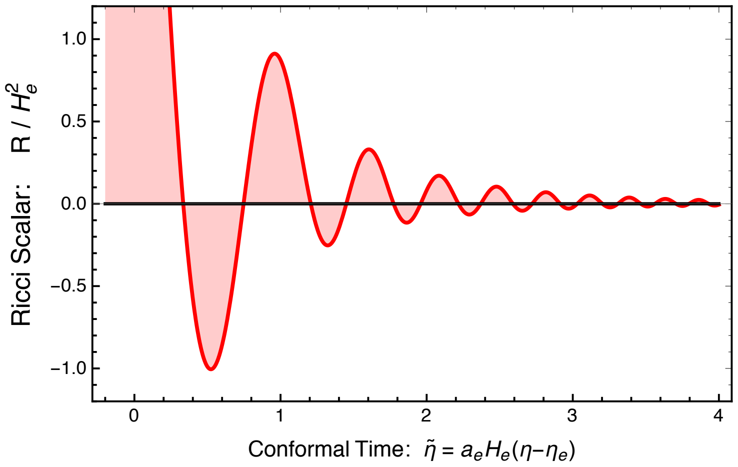
- If the inflaton fragments during preheating, how does this impact (shut off) gravitational dark matter production at the end of inflation?
- If the inflaton trajectory "turns a sharp corner," can this enhance gravitational particle production (since *a(t)* has rapid oscillations, similar to hilltop)?

BACKUP SLIDES

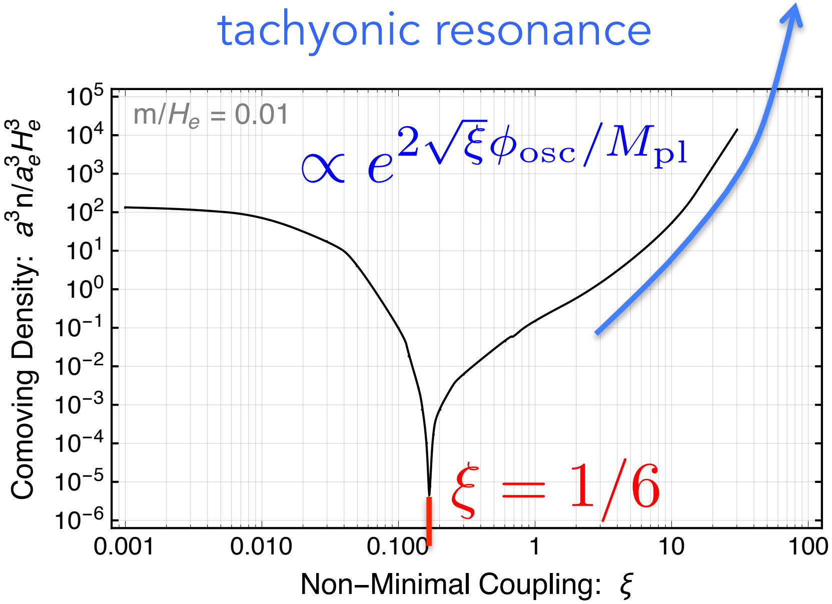
The effect of a large non-minimal coupling

despicable dark relics: [Markkanen & Nurmi (2016); Rairbairn, Kainulainen, Markkanen, & Nurmi (2019)]

Ricci scalar oscillates
+ & - during reheating



Efficient particle
production via
tachyonic resonance



Scalar WIMPzilla with large
non-minimal coupling to gravity

$$\mathscr{L}_{\rm non-minimal} = \frac{1}{2}\xi\varphi^2 R$$

[Kolb & AL (in prep)]

(caveat: raising ξ lowers the cutoff $M_{\rm pl} / \xi^{1/2}$)