Connection to Observation: Overview

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Kuver Sinha (University of Oklahoma)

PITT PACC Workshop: Non-standard cosmological epochs and expansion histories

Cosmological expansion

cosmological principle

$$(\mathrm{d}s)^2 = (\mathrm{d}t)^2 - a(t)^2\,|\mathrm{d}\boldsymbol{x}|^2$$

spacetime is homogenous & isotropic on the largest length scales

Einstein gravity

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

perfect fluid

$$T_{\mu\nu} = \left(\rho + p\right) u_\mu u_\nu - p\, g_{\mu\nu}$$

Friedmann equations

$$\frac{1}{a}\frac{\mathrm{d}a}{\mathrm{d}t} = \sqrt{\frac{8\pi G}{3}\,\rho(t)}$$

$$\frac{1}{a}\frac{\mathrm{d}^2 a}{\mathrm{d}t^2} = -\frac{8\pi G}{6}\left[\rho(t) + 3p(t)\right]$$

cosmological expansion is induced by the matter/radiation content of the Universe

What's the Universe made out of?

Standard Model particles + radiation

electroweak plasma (T > TeV)
quark-gluon plasma (T > GeV)
electron-ion plasma (T > eV)
stars & stuff
CMB radiation
neutrinos

Standard model condensates

Higgs condensate
QCD condensates

Gravitational energy

gravitational wave radiation

stellar remnant black holes

Inflaton sector

inflaton condensate (during inflation)

inflaton matter/radiation (during reheating)

Dark matter

nonrelativistic matter

maybe relativistic @ early times?

Dark energy

cosmo. const.?

dynamical?

Extra stuff

more matter!
more radiation!
more GWs!
primordial BHs!
topological defects!
phase transitions!

[more?]

The standard story

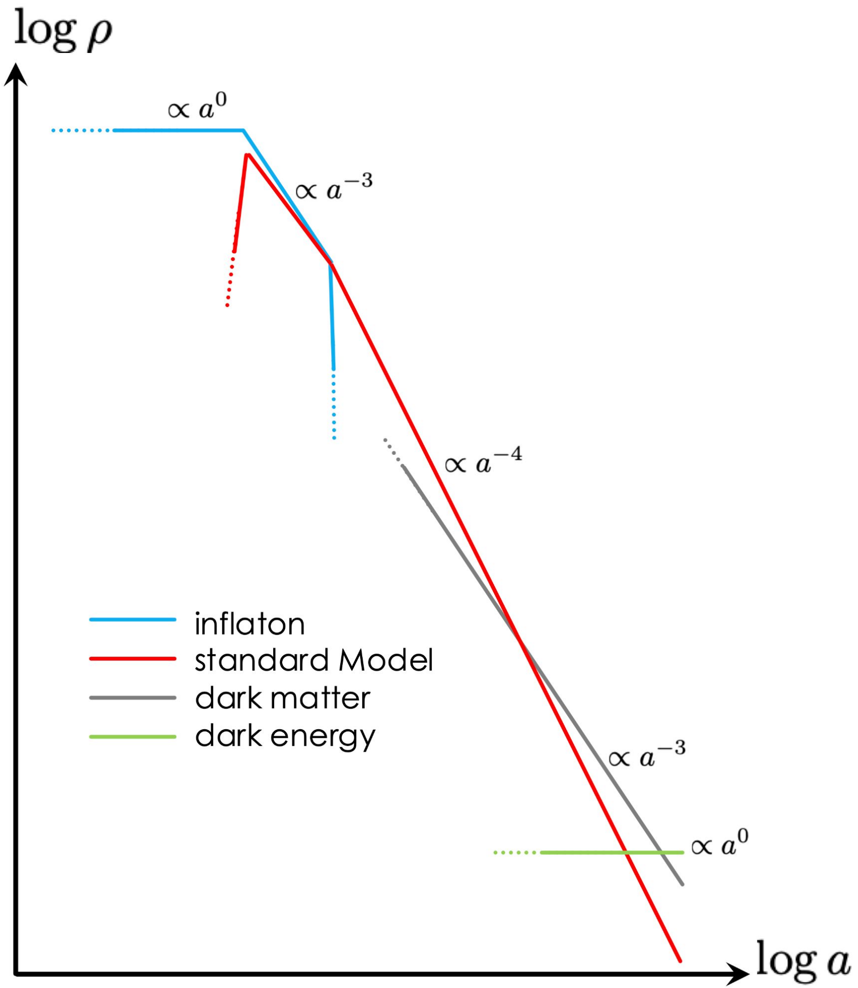
⇒ inflaton domination drives a (quasi-dS) phase of accelerated expansion

⇒ the inflaton transfers its energy to Standard Model particles + radiation

⇒ SM plasma passes through a sequence of phase transitions, which redistribute the energy

⇒ dark matter overtakes electron-ion plasma & neutrinos to become the dominant component

⇒ dark energy overtakes dark matter as dominant



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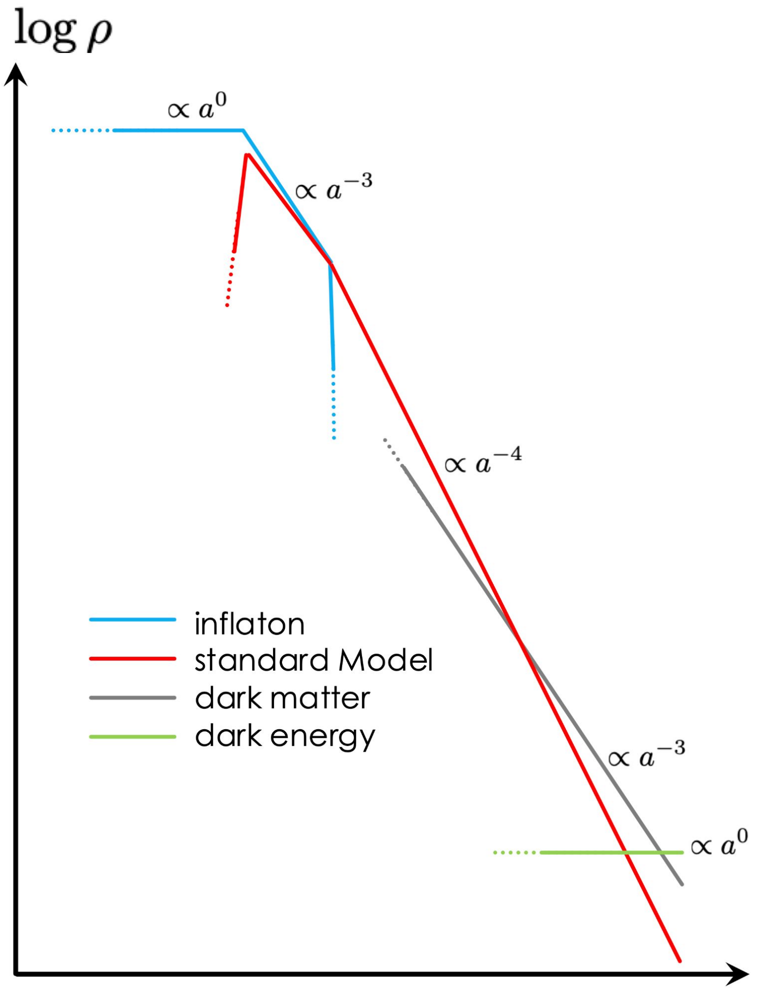


Some open questions

How much energy was stored in the inflaton (Hinf)?

How long did it take to transfer to the SM (Nrh)?

How efficient was the energy transfer (Trh)?

Was energy shared with other sectors (e.g., SUSY)?

Did BSM physics dominate at some point (e.g., moduli)?

Does dark matter evolve (e.g., rel->nonrel, stasis, etc)?

Does dark energy evolve (e.g., Hub tension, DESI)?

What do we know about the expansion history from past observations?

What kinds of new physics would modify the expansion history - and how can we tell?

What can we learn with future observations?

Inflation

Quantum fluctuations of the metric during inflation correspond to gravitational waves when these modes later re-enter the horizon.

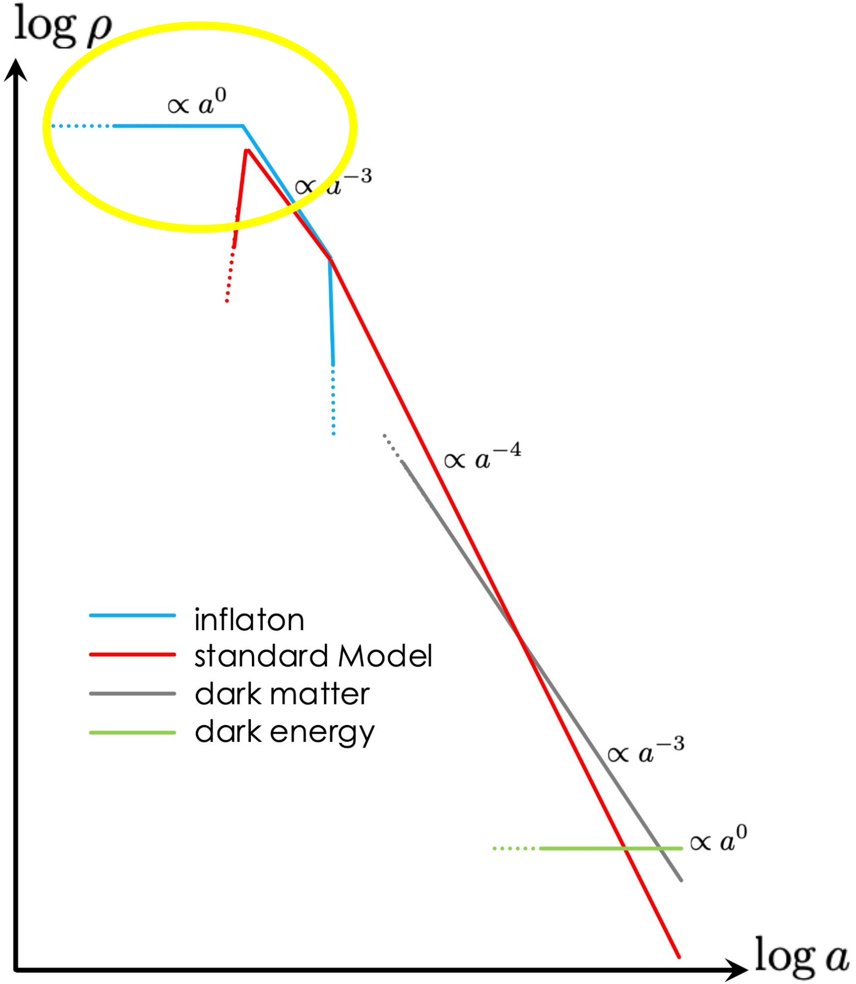
$$\delta g_{\mu\nu} \sim H_{\rm inf}/2\pi M_{\rm pl}$$

We don't observe the imprint of these GWs in CMB polarization (B-mode patterns).

$$r < 0.036$$ BICEP2/Keck/BICEP3 (95% CL)

This implies an upper limit on the cosmological expansion rate during inflation.

$$H_{\rm inf} < 0.5 \times 10^{14}\ {\rm GeV}$$

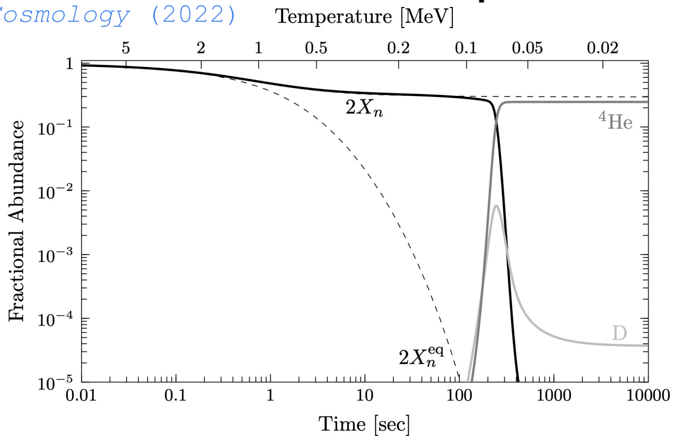


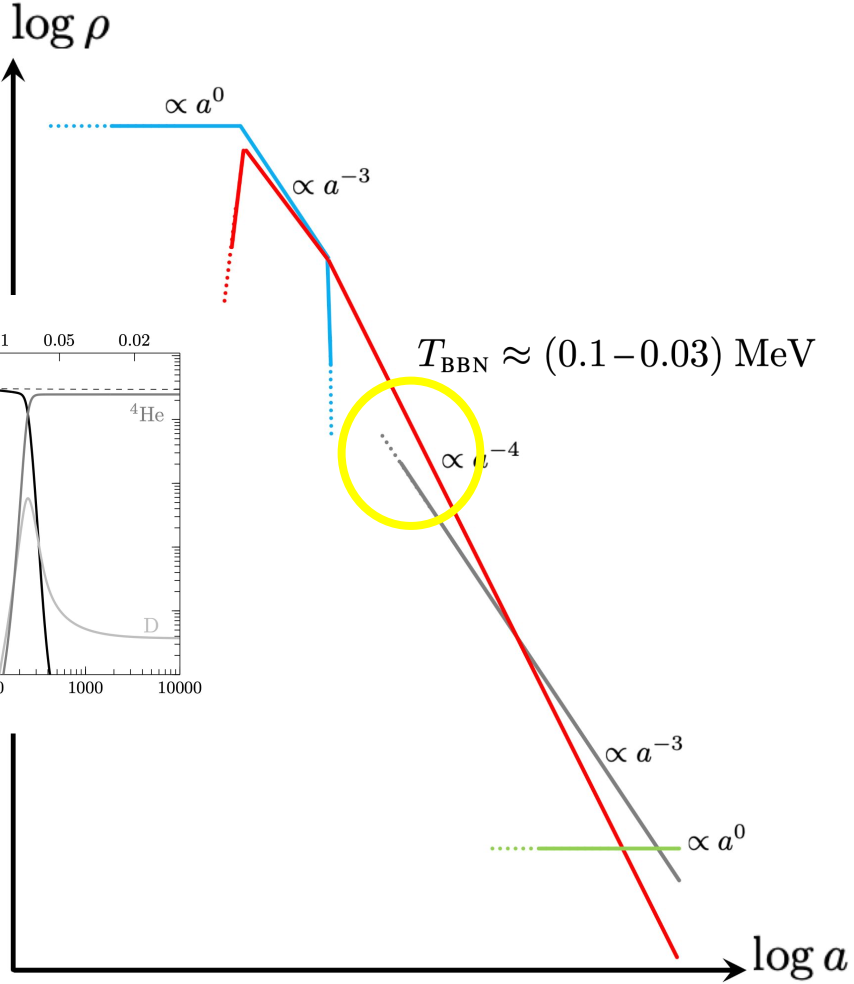
Nucleosynthesis

The light nuclei (He, D, Li, ...) are formed when the nuclear reaction rates are comparable to the Hubble expansion rate.

$$
\begin{aligned}
n + p^+ &\leftrightarrow \mathrm{D} + \gamma\,. \\
\mathrm{D} + p^+ &\leftrightarrow {}^3\mathrm{He} + \gamma\,, \\
\mathrm{D} + \mathrm{D} &\leftrightarrow {}^3\mathrm{H} + p^+\,, \\
\mathrm{D} + \mathrm{D} &\leftrightarrow {}^3\mathrm{He} + n\,. \\
{}^3\mathrm{H} + p^+ &\leftrightarrow {}^3\mathrm{He} + n\,, \\
{}^3\mathrm{H} + \mathrm{D} &\leftrightarrow {}^4\mathrm{He} + n\,, \\
{}^3\mathrm{He} + \mathrm{D} &\leftrightarrow {}^4\mathrm{He} + p^+\,.
\end{aligned}
$$

Baumann's Cosmology (2022)





Agreement between the observed light-element abundances & BBN predictions impose two conditions:

- SM radiation-domination at T ~ MeV
- no entropy injection during/after BBN

Late-time cosmology

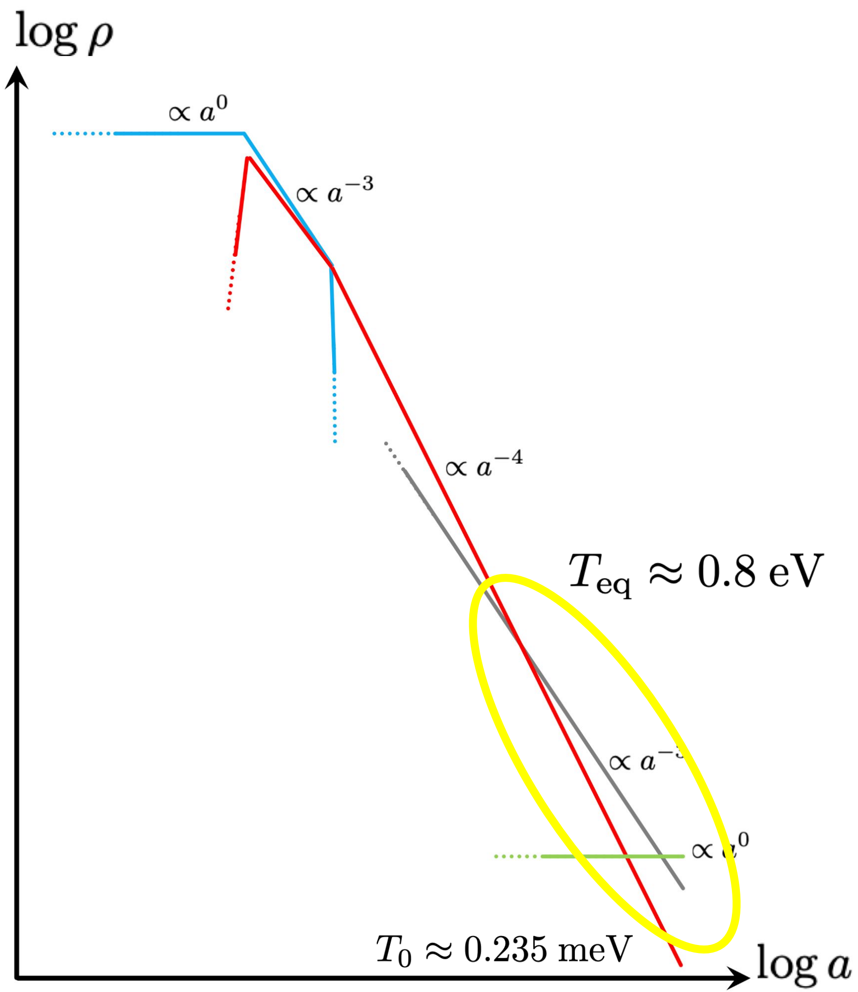
There are several observational handles on cosmological expansion at late times.

⇒ Acoustic oscillations of the baryon photon fluid around radiation-matter equality and recombination create plasma inhomogeneities that are probed by CMB & LSS observations.

⇒ Distance ladders (e.g., parallax + cepheid + Type-Ia SNe) probe Hubble through the redshift-distance relationship.

⇒ … also standard sirens, reionization history, probes of matter power spectrum, …

[a good topic for discussion time]



Linear matter power spectrum

We quantify the amplitude of dark matter inhomogeneities (energy density contrast) using the linear matter power spectrum.

$$\delta(\boldsymbol{x}, t) = \frac{\rho_{\mathrm{m}}(\boldsymbol{x}, t) - \bar{\rho}_{\mathrm{m}}(t)}{\bar{\rho}_{\mathrm{m}}(t)}$$

assume: statistically homogenous & isotropic

$$\langle \delta(\boldsymbol{x}, t)\, \delta(\boldsymbol{y}, t) \rangle = \int \frac{\mathrm{d}^3\boldsymbol{k}}{(2\pi)^3} \boxed{P_{\mathrm{m}}(k)} \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot(\boldsymbol{x}-\boldsymbol{y})}$$

$$\Delta^2_{\mathrm{m}}(k) = \frac{k^3}{2\pi^2} P_{\mathrm{m}}(k)$$

power per log-spaced k-intervals

Various observations probe dark matter inhomogeneity on many scales, and translate into precise measurements of the LMPS.

These measurements are compatible with LCDM Cosmology (std. expansion history) after roughly radiation-matter equality.

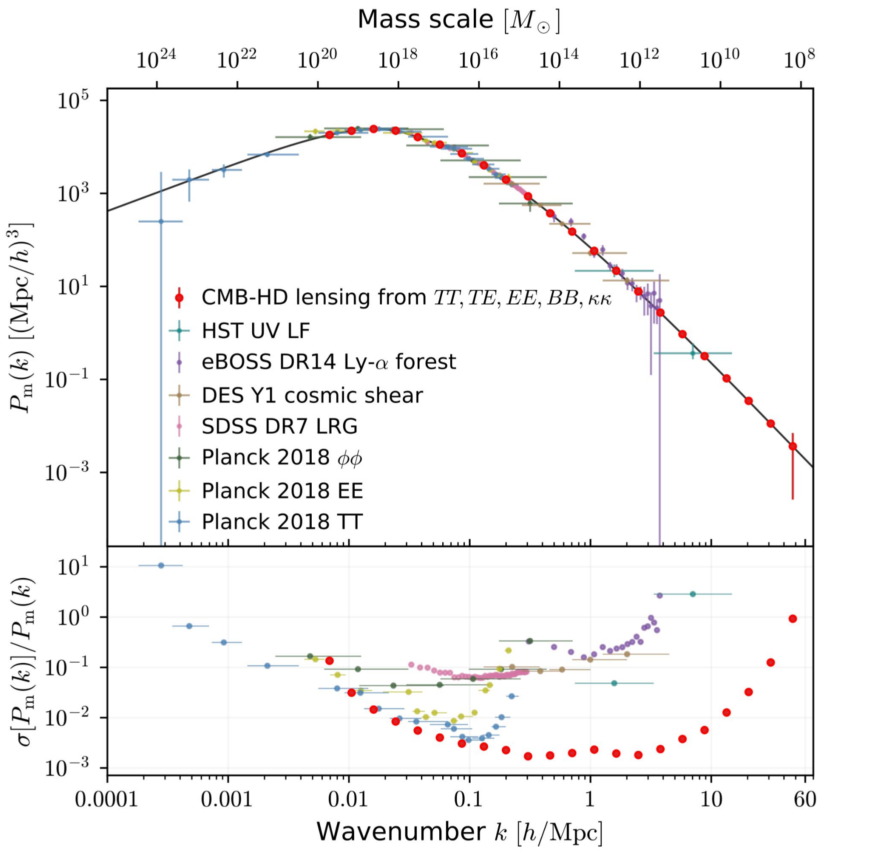
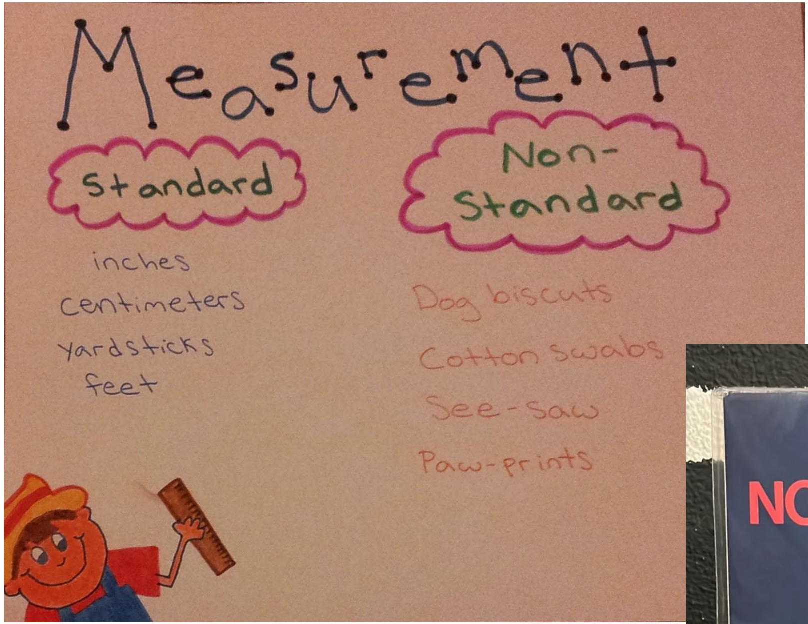


figure: 2405.12220

going non-standard



What kinds of new physics would modify the expansion history - and how can we tell?

Where is there room for nonstandard?

During inflation or reheating
⇒ multi-field inflation
⇒ not inflation at all (e.g., bounce)
⇒ nonlinear preheating
⇒ inflation self-interaction & fragmentation
⇒ gravitational waves

Before nucleosynthesis
⇒ lots of freedom here … early matter-dominated era (EMDE) … early dark energy … kination … multi-component stasis … topological defect domination … etc

After radiation-matter equality
⇒ very constrained
⇒ cannot be an O(1) departure from LCDM
⇒ early dark energy for Hubble tension
⇒ evolving dark energy (today)
⇒ additional subdominant matter or rad.

Tracers of the nonstandard expansion:

Dark matter
⇒ relic abundance
⇒ inhomogeneities (power spectrum)
⇒ measurements: CMB, LSS, Ly-alpha, …

Gravitational wave radiation
⇒ spectrum
⇒ polarization(?)
⇒ anisotropies(?)
⇒ observatories: LVK, NANOGrav, LISA, …

Photons
⇒ CMB spectrum (distortion)
⇒ CMB anisotropies

Neutrinos & UHECRs
⇒ relic neutrino bkg.
⇒ ultra-high energy

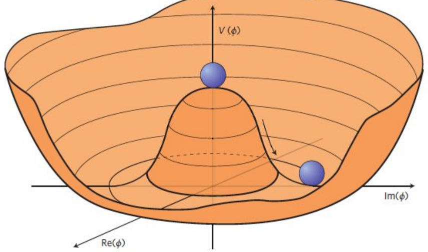
[more from Kuver shortly + room for discussion]

(1) DM freeze out @ EW phase transition

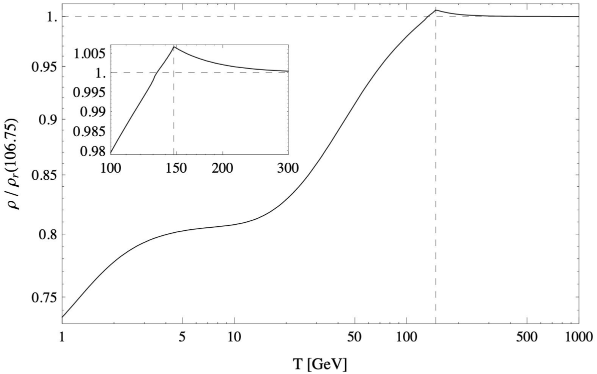
Chung, AL, & Wang [1104.5034]; Chung & AL [1108.5193]

electroweak phase transition

$T_{\rm EWPT} \approx 160~\mathrm{GeV}$

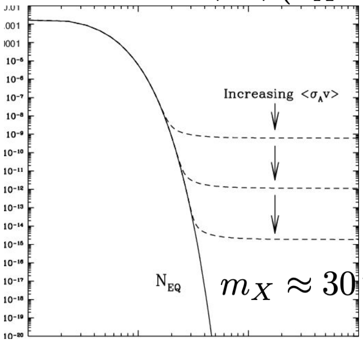


total energy from plasma + Higgs:



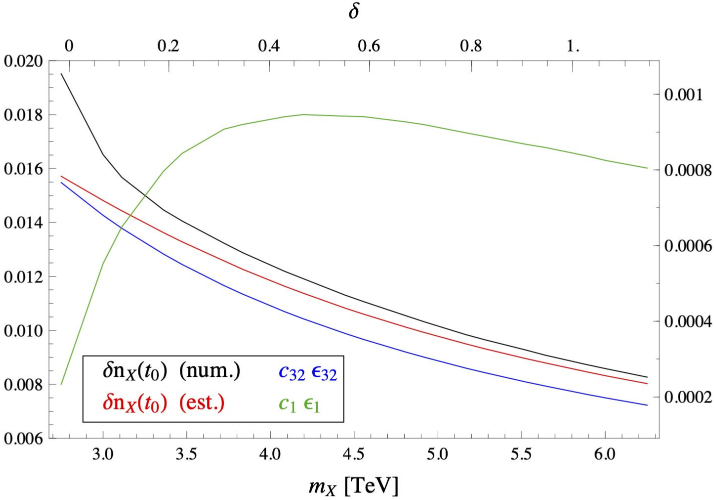
thermal relic dark matter

$$\frac{\mathrm{d}}{\mathrm{d}t} n_X + 3 H n_X = -\langle \sigma v \rangle \left(n_X^2 - n_{X,\mathrm{eq}}^2 \right)$$



$m_X \approx 30\, T_{\rm EWPT} \approx 5~\mathrm{TeV}$

change in predicted relic abundance:



if you could measure the DM relic abundance with %-level precision, you could probe Higgs condensate during EWPT

(1) DM freeze out @ EW phase transition

extension of Higgs sector

⇒ new scalar singlet allows for 1st order PT

$$U(\{h,s\}) = \frac{m_h^2}{8v^2}\left(h^2 - v^2\right)^2 + \frac{b_4}{4}s^4 + \frac{1}{2}m_s^2 s^2 + \frac{b_3}{3}s^3 + \frac{1}{2}s\left(h^2 - v^2\right)(a_1 + a_2 s)$$

significant supercooling

⇒ vacuum energy has a bigger effect

$$\{a_1, b_3, m_h, m_s, m_X\} = \{-25, -20, 128, 91.1, 2000\}\ \mathrm{GeV}, \qquad \{a_2, b_4\} = \{0.2, 0.2\},$$

$$M^2 = -47.7\ \mathrm{GeV}^2 \qquad \{T_f, T_c, T_{PT}^+, T_{PT}^-, T_0\} = \{107, 70.7, 30.0, 13.7, 12.7\}\ \mathrm{GeV},$$

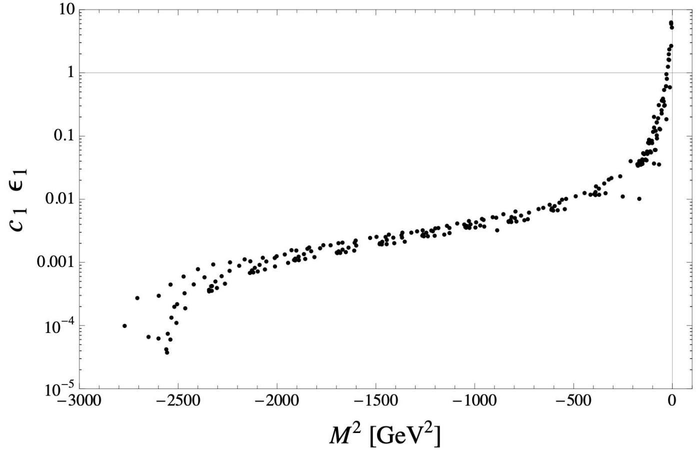
$$c_1\epsilon_1 = 0.390, \qquad \rho_{\mathrm{ex}} = (69.7\ \mathrm{GeV})^4\ .$$

$$M_H = 141\ \mathrm{GeV} \qquad \{0.78, 0.22\}$$

$$M_S = 70.7\ \mathrm{GeV} \qquad \{0.22, 0.78\}$$

fractional change in dark matter relic abundance

(due to additional vacuum energy)

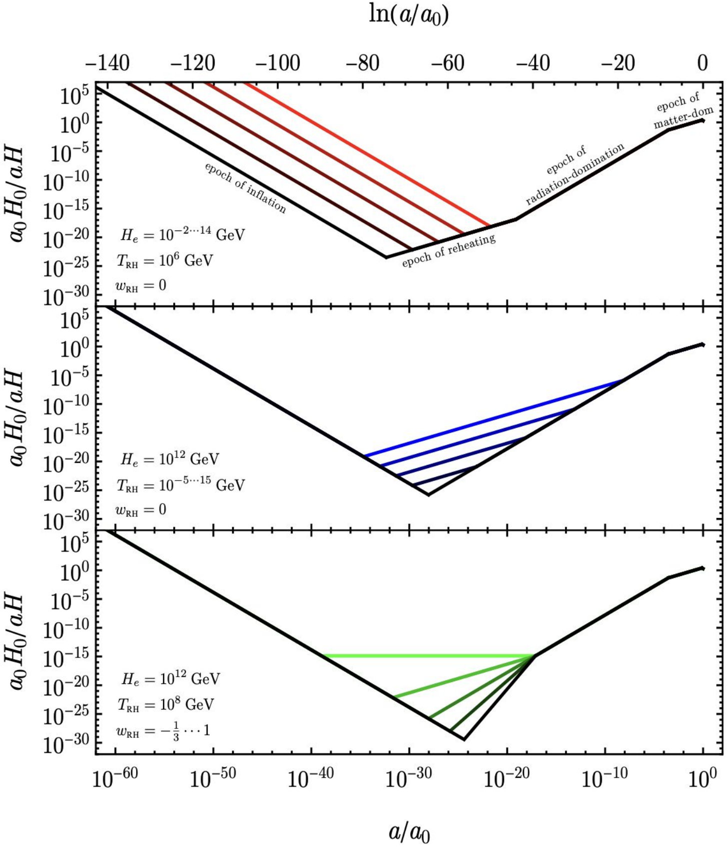


dark matter freezeout at the electroweak phase transition can probe a nonstandard expansion & cooling history

Kolb & AL (2023)

(2) Inflationary quantum fluctuations

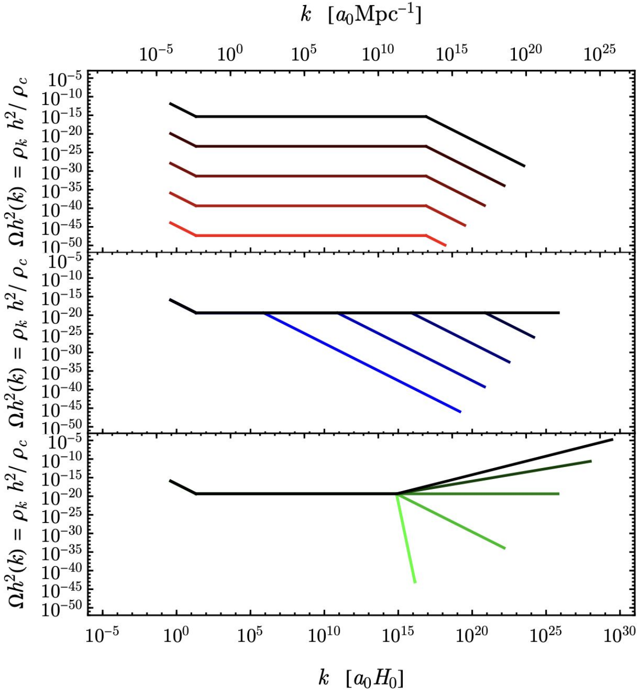
inflation/reheating scenarios



$$\delta\phi_k \sim H_{\rm inf}/2\pi$$

$$h_k \sim H_{\rm inf}/2\pi$$

energy spectrum at late time



modes that re-enter the horizon during reheating develop a scale-dependent spectrum (toward high k)

Amin, AL, & Venegas (in prep)

(3) Warm wave DM in modified expansion histories

free streaming

if dark matter starts out relativistic, it can travel (free stream) a significant distance over the cosmic history and suppress the growth of structure on scales k > 1/l_fs

$$\boldsymbol{l}_{\mathrm{fs}} = \int_0^\tau \mathrm{d}\tau' \, \boldsymbol{v}(\tau') = \int_0^a \frac{\mathrm{d}a'}{a'} \frac{1}{a' \, H(a')} \frac{\boldsymbol{p}}{\sqrt{\boldsymbol{p}^2 + (a')^2 m^2}}$$

white noise

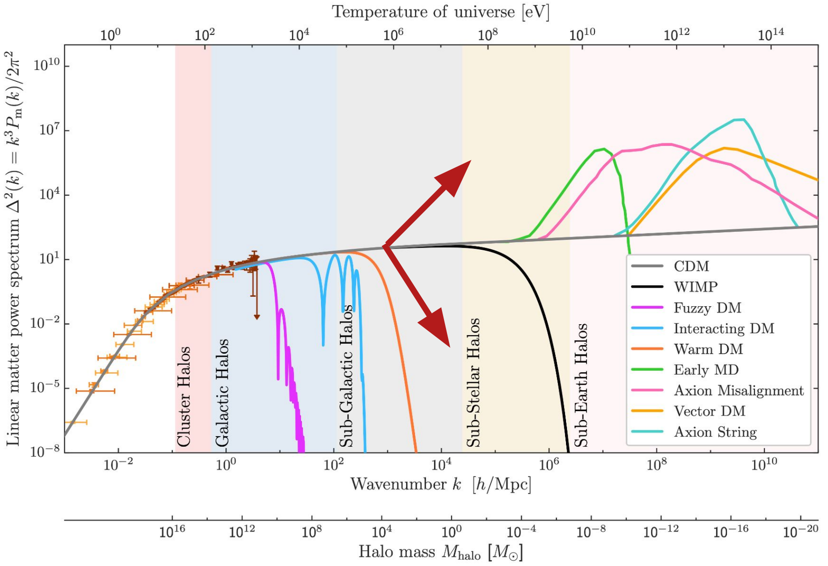
if dark matter is created with a finite correlation length l_corr then causality implies power falling like k^3

$$\Delta^2(k) \propto k^3 \quad \text{for } k \ll 1/l_{\mathrm{corr}}$$

effects on small-scale power

⇒ free streaming - suppression

⇒ white noise - enhancement



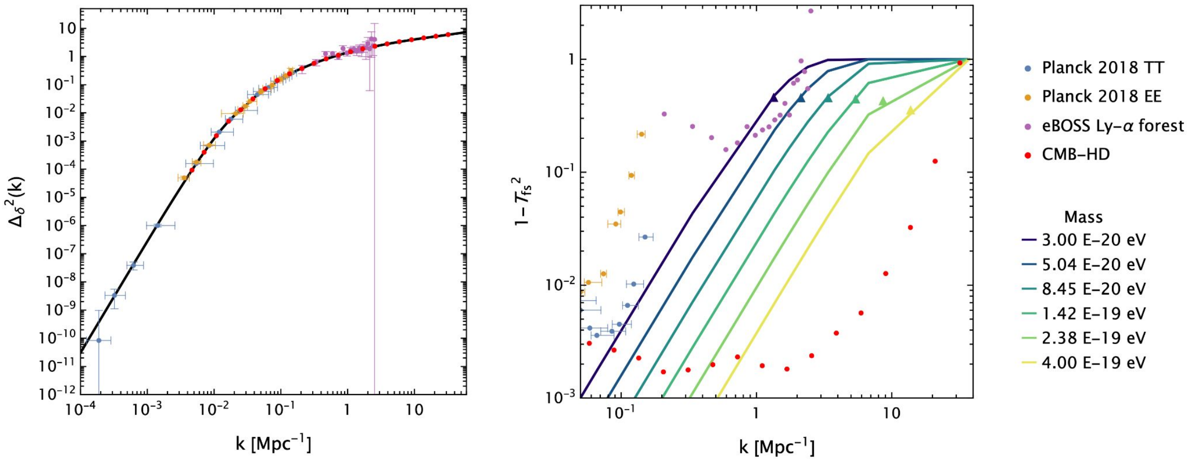
Snowmass (2209.08215)

Amin, AL, & Venegas (in prep)

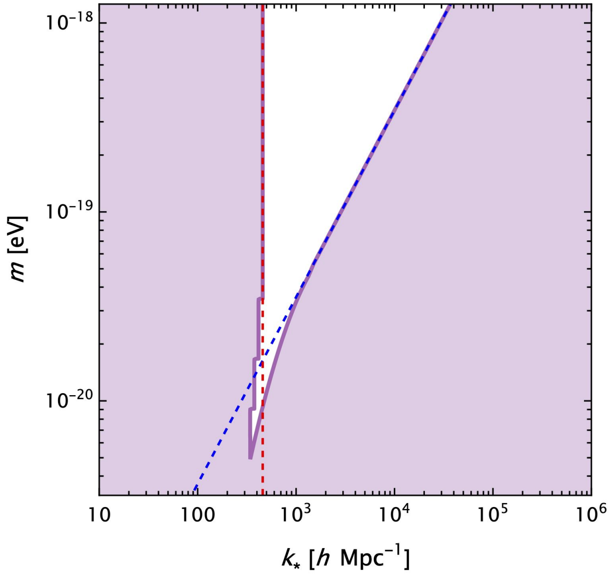
PRELIMINARY

(3) Warm wave DM in modified expansion histories

limits driven by Ly-alpha



constraints



Ly-alpha observations probe dark matter inhomogeneities on Mpc-scales … we use the corresponding measurement of the linear matter power spectrum to constrain warm wave dark matter

- free-streaming suppression prohibits small m
- white-noise enhancement prohibits small k*
- here we assumed LCDM Cosmology … we're exploring how the limits change in several modified cosmic expansion histories.

What are Non-standard Cosmological Epochs?

Let’s say:

Standard = high-scale single-field inflation → perturbative reheating → high-scale baryogenesis mechanism (AD, lepto, etc.) → thermal freezeout of GeV-scale dark matter → radiation domination throughout after reheating till BBN

Non-standard = ?

high-scale single-field inflation → low-scale, multifield, and multiple stages of inflation

perturbative reheating → non-perturbative decays, soliton-like phenomena

high-scale (pre-sphaleron) baryogenesis mechanism (AD, lepto, etc.) → low-scale baryogenesis

thermal freezeout of GeV-scale dark matter → freeze-in, non-thermal production from decays, etc.

radiation domination throughout until BBN → changing equation of state (EMDE, kination, stasis)

A lot of us are here…

THE FIRST THREE SECONDS:
A REVIEW OF POSSIBLE EXPANSION HISTORIES OF THE EARLY UNIVERSE

ROUZBEH ALLAHVERDI[1], MUSTAFA A. AMIN[2], ASHER BERLIN[3], NICOLÁS BERNAL[4], CHRISTIAN T. BYRNES[5], M. STEN DELOS[6], ADRIENNE L. ERICKCEK[6], MIGUEL ESCUDERO[7], DANIEL G. FIGUEROA[8], KATHERINE FREESE[9,10], TOMOHIRO HARADA[11], DAN HOOPER[12,13,14], DAVID I. KAISER[15], TANVI KARWAL[16], KAZUNORI KOHRI[17,18], GORDAN KRNJAIC[12], MAREK LEWICKI[7,19], KALOIAN D. LOZANOV[20], VIVIAN POULIN[21], KUVER SINHA[22], TRISTAN L. SMITH[23], TOMO TAKAHASHI[24], TOMMI TENKANEN[25,a], JAMES UNWIN[26], VILLE VASKONEN[7,27,a], AND SCOTT WATSON[28]

Post-inflation reheating (Authors: M. A. Amin, D. I. Kaiser & K. D. Lozanov)
Moduli fields (Authors: K. Sinha & S. Watson)
Phase transitions and baryon asymmetry (Authors: R. Allahverdi & M. Lewicki)
Formation of microhalos (Author: A. Erickcek)
Observational probes of microhalos (Authors: M. S. Delos & A. L. Erickcek)
Primordial black holes (Authors: *T. Harada & K. Kohri*)

Stasis

Observational prospects of non-standard cosmologies are extremely challenging (thanks organizers!)

Very Challenging

compatibility with BBN necessitates that they leave the Universe in a state of thermal equilibrium by the time they vanish, obscuring their very existence, which must then be inferred indirectly.

Gehrman, Shams Es Haghi, Sinha, Xu, arXiv:2304.09194

Broad Observational Signatures

-bumps and dips in GW spectra

-enhanced matter substructure

-dilution of previously existing DM/baryon population

-effect on PBHs (make them spin more, etc.)

-creation of new DM/DR/baryons from decays of the agent dominating the universe

-dark sector physics

-post-BBN Universe?

Directions explored by the community

(1) EMDE affects matter power spectrum, but we don't necessarily link the EMDE field to other stuff

Adrienne's program for over ten years

(2) EMDE affects axion dark matter (but doesn't source axions or WIMPs)

Gondolo, Visinelli (2009), Hertzberg, Temark, Wilczek (2010), Grin, Smith, Kamionkowski (2007)

(3) EMDE affects axion dark matter + properties of axion miniclusters

Nelson, Xiao (2018), papers by Patrick Draper, Adrienne's papers

(4) EMDE field = modulus → let it source dark matter

"Non-thermal DM" - many of us here, over ten + years

(5) EMDE field = modulus → let it source dark matter + dark radiation (axions) →DR constraints, miniclusters

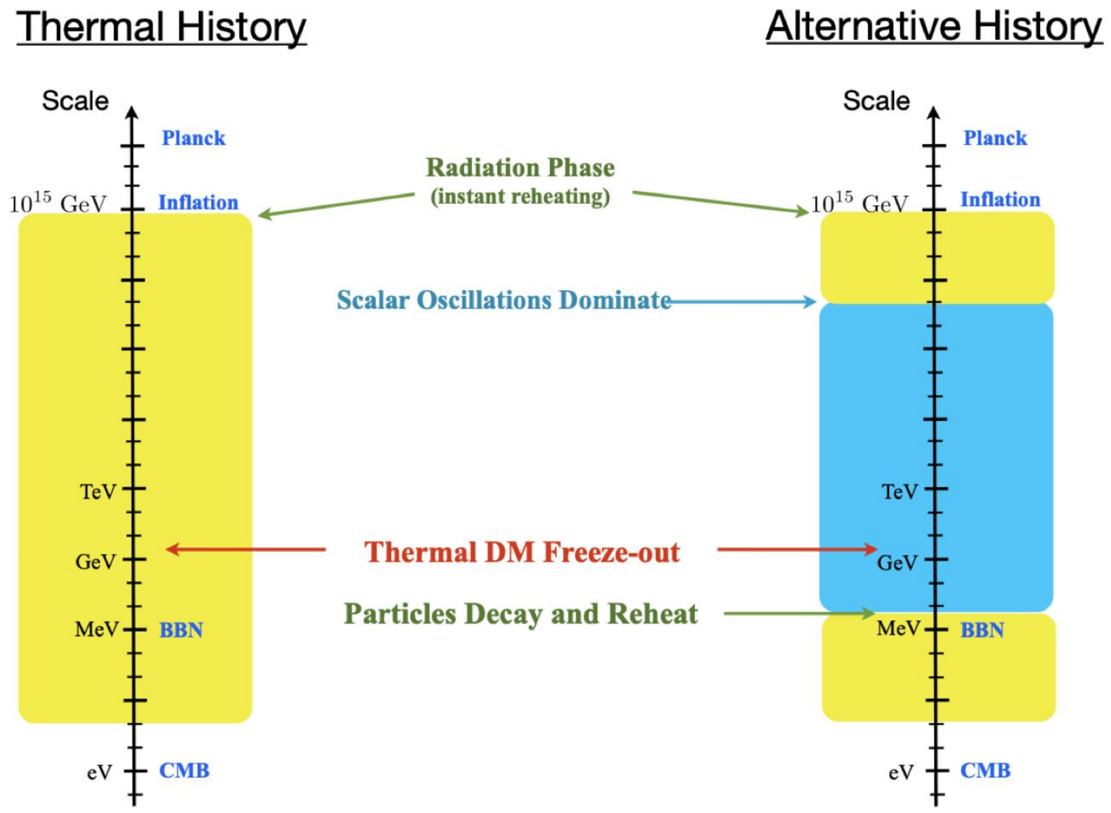
Allahverdi, Cicoli, Dutta, Sinha (2016), Sinha, Watson, Wiley (2023)

(6) EMDE field = modulus → let it decay non-perturbatively

Giblin, Watson et. al. (2016), Adams, Barrows, Giblin, Sinha, Watson, Wiley (ongoing)

Moduli and Alternative Histories

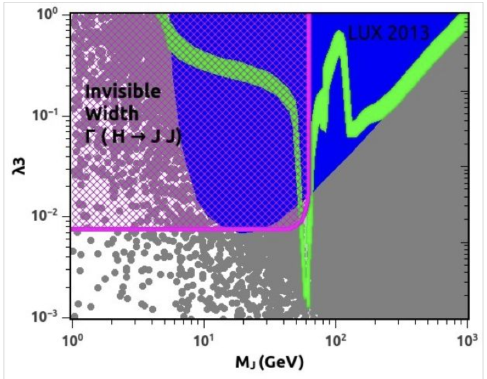
Alternative Histories (Scott’s famous diagram)



Why DM theorists got into the game

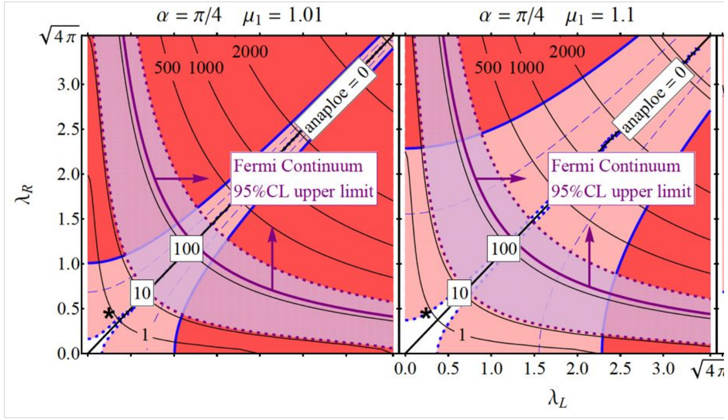
Thermal DM is great: predictive, minimal, agnostic to pre-BBN cosmology

But it really needs a miracle in parameter space. Moreover, increasingly constrained



$$V \supset \lambda_3 J^2 \Phi^\dagger \Phi \Rightarrow \lambda_3 v J^2 H + \frac{1}{2}\lambda_3 J^2 H^2$$

Quieroz, KS (2013)



$$\mathcal{L}_{\rm int} = \lambda_L \widetilde{f}_L^* \overline{\chi} P_L f + \lambda_R \widetilde{f}_R^* \overline{\chi} P_R f + \text{c.c.}$$

Sandick, KS, Teng (2016)

Non-thermal histories open up a lot of parameter space and come with novel signatures. Enhanced annihilation, DM substructure, GWs, etc.

X

Boltzmann Equations

Boltzmann equations for modulus, WIMP, axion, and radiation

Sankharva, Sinha, Watson, Wiley (2023)

Fan, Ozsoy, Watson (2015)

$$\begin{aligned}
\frac{d\rho_\phi}{dN} &= -3(1+w_\phi)\rho_\phi - \frac{\Gamma_\phi}{H}\rho_\phi, \\
\frac{d\rho_\chi}{dN} &= -3(1+w_\chi)\rho_\chi - \frac{\langle\sigma v\rangle_\chi}{m_\chi H}\left(\rho_\chi^2 - \bar{\rho_\chi}^2\right) + B_{\phi\to\chi}\left(\frac{\Gamma_\phi}{H}\right)\rho_\phi, \\
\frac{dn_a}{dN} &= -3\left(1+w_a\right)n_a, \\
\frac{d\rho_r}{dN} &= -4\rho_r + \frac{\langle\sigma v\rangle_\chi}{m_\chi H}\left(\rho_\chi^2 - \bar{\rho_\chi}^2\right) + (1-B_{\phi\to\chi})\frac{\Gamma_\phi}{H}\rho_\phi,
\end{aligned}$$

Modulus only branches to WIMPs.

Work with e-folds $H\,dt = dN = d(\ln a)$

Cicoli, Sinha, Wiley (2022)

X

Modulus

Modulus

$$\frac{d\rho_\phi}{dN} = -3(1+w_\phi)\rho_\phi - \frac{\Gamma_\phi}{H}\rho_\phi,$$

$$\Gamma_\phi \simeq \frac{c}{48\pi}\frac{m_\phi^3}{m_P^2}.$$

Decay term sizable when $\Gamma_\phi \sim H$ with decay temperature

$$T_D^\phi \simeq \sqrt{m_P \Gamma_\phi}\left(\frac{90}{\pi^2 g_*(T_D^\phi)}\right)^{1/4} = c^{1/2}\left(\frac{10.75}{g_*}\right)^{1/4}\left(\frac{m_\phi}{50\ \mathrm{TeV}}\right)^{3/2} T_{\mathrm{BBN}}$$

Interesting non-thermal physics for light moduli (cosmological moduli problem becomes a virtue)

BBN limits give $\Gamma_\phi \gtrsim 5 \times 10^{-25}\ \mathrm{GeV}$

Dark Matter

WIMP (*annihilation scenario*)

$$\frac{d\rho_\chi}{dN} = -3(1+w_\chi)\rho_\chi - \frac{\langle\sigma v\rangle_\chi}{m_\chi H}\left(\rho_\chi^2 - \bar{\rho_\chi}^2\right) + B_{\phi\to\chi}\left(\frac{\Gamma_\phi}{H}\right)\rho_\phi,$$

Dominant annihilations, close to freeze-out, cold dark matter. $w_\chi = 0 \text{ and } \rho_\chi \simeq m_\chi n_\chi$

Define $Y_\chi \equiv n_\chi/s$ $\Rightarrow$ $\frac{dY_\chi}{dN} \simeq -\frac{\langle\sigma v\rangle_\chi}{H} Y_\chi^2 s.$

Constant $\langle\sigma v\rangle_\chi$, integrate from T_D^ϕ to the present $\Rightarrow$ $Y_\chi \simeq \frac{H(T_D^\phi)}{\langle\sigma v\rangle_\chi\, s(T_D^\phi)}.$

Relic density $\Omega_\chi h^2 \simeq \frac{m_\chi Y_\chi h^2}{\rho_c/s_0}$ $\Rightarrow$ Relic density in non-thermal history is

$$\Omega_\chi h^2 = \Omega_\chi^{\rm th} h^2 \times \max\{T_f/T_D^\phi, 1\}$$

X

Dark Matter

WIMP (*branching scenario*)

$$\frac{d\rho_\chi}{dN} = -3(1+w_\chi)\rho_\chi - \frac{\langle\sigma v\rangle_\chi}{m_\chi H}\left(\rho_\chi^2 - \bar{\rho_\chi}^2\right) + B_{\phi\to\chi}\left(\frac{\Gamma_\phi}{H}\right)\rho_\phi,$$

$$Y_\chi \equiv n_\chi/s \quad \Rightarrow \quad \frac{dY_\chi}{dN} = \mathcal{B}_{\phi\to\chi}\frac{\Gamma_\phi}{H}Y_\phi$$

The yield of particle abundance from modulus decay is $Y_\phi \equiv \frac{3T_{\rm rh}}{4m_\phi} = \frac{0.9}{\pi}\sqrt{\frac{c\, m_\phi}{M_{\rm P}}}.$

Integrate from T_D^ϕ to the present $\Rightarrow$ $Y_\chi \simeq \mathcal{B}_{\phi\to\chi}Y_\phi(T_D^\phi).$

Dark Matter

WIMP (*summary*)

$$\boxed{\frac{n_{\rm DM}}{s} = \min\left[\left(\frac{n_{\rm DM}}{s}\right)_{\rm obs} \frac{\langle\sigma_{\rm ann}v\rangle_{\rm f}^{\rm th}}{\langle\sigma_{\rm ann}v\rangle_{\rm f}}\left(\frac{T_{\rm f}}{T_{\rm rh}}\right), Y_\phi\, {\rm Br}_{\rm DM}\right]}$$

annihilation branching

Annihilation: constrained by indirect detection unless reheat temperature is high

1. Annihilation scenario for $T_{\rm f}/30 \lesssim T_{\rm rh} < T_{\rm f}$;
2. Branching scenario for $T_{\rm BBN} \lesssim T_{\rm rh} \lesssim 70$ MeV.

Fermi-LAT Limits on DM Annihilation

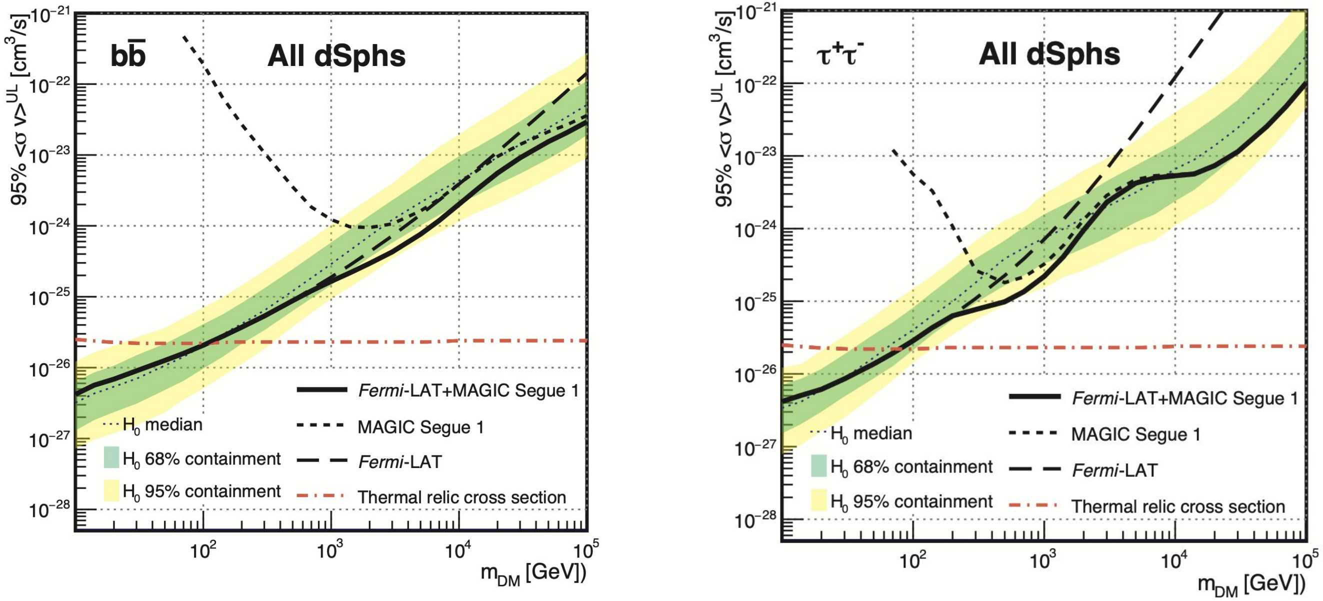


Figure 2: 95% CL upper limits on the thermally-averaged cross-section for DM particles annihilating into $b\bar{b}$ (upper-left), W^+W^- (upper-right), $\tau^+\tau^-$ (bottom-left) and $\mu^+\mu^-$ (bottom-right) pairs. Thick solid lines show the limits obtained by combining *Fermi*-LAT observations of 15 dSphs with MAGIC observations of Segue 1. Dashed lines show the observed individual MAGIC (short dashes) and *Fermi*-LAT (long dashes) limits. J-factor statistical uncertainties (Table 1) are considered as described in Section 3.2. The thin-dotted line, green and yellow bands show, respectively, the median and the symmetrical, two-sided 68% and 95% containment bands for the distribution of limits under the null hypothesis (see main text for more details). The red-dashed-dotted line shows the thermal relic cross-section from Ref. [54].

Modulus Decays to Dark Matter + Axions

Allahverdi, Cicoli, Dutta, Sinha (2014 -)
Kane, Sinha, Watson (2017)

$$\Gamma_{\rm vis} = c_{\rm vis}\Gamma_0 \text{ and } \Gamma_{\rm hid} = c_{\rm hid}\Gamma_0 \qquad \Gamma_0 = \frac{1}{48\pi}\frac{m_\phi^3}{M_P^2}$$

$$\rho_{\rm vis} = \frac{c_{\rm vis}}{c_{\rm tot}}\rho_{\rm tot} = \frac{3c_{\rm vis}}{c_{\rm tot}}H^2 M_P^2 \,.$$

Using the fact that at ϕ decay $3H^2 \simeq 4\Gamma_{\rm tot}^2/3$, one finds:

$$T_{\rm rh} \simeq \frac{1}{\pi}\left(\frac{5\,c_{\rm vis}c_{\rm tot}}{288 g_*}\right)^{1/4} m_\phi\sqrt{\frac{m_\phi}{M_P}}\,. \qquad (1)$$

$$\Delta N_{\rm eff} = \frac{43}{7}\frac{c_{\rm hid}}{c_{\rm vis}}\,.$$

$$T_{\rm rh} \simeq \kappa\sqrt{\frac{c_{\rm hid}}{\Delta N_{\rm eff}}}\left(\frac{68.5}{g_*}\right)^{1/4}\left(\frac{m_\phi}{5\cdot 10^6\,{\rm GeV}}\right)^{3/2} 0.72\,{\rm GeV}$$

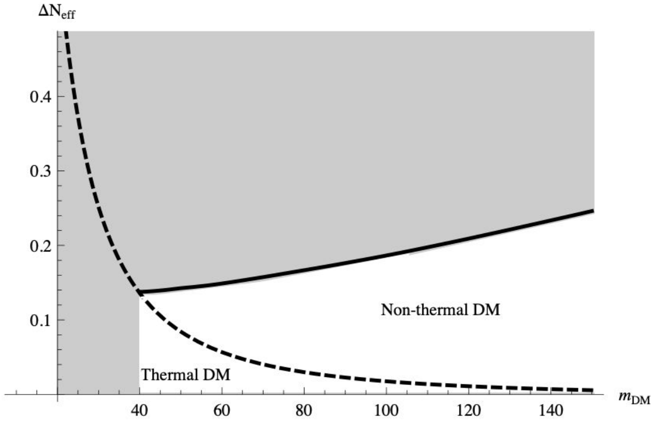


FIG. 2: Constraints on the $(\Delta N_{\rm eff}, m_{\rm DM})$-plane for $c_{\rm hid} = 1$, $g_* = 68.5$ and $m_\phi = 5\cdot 10^6$ GeV: the solid line is based on Fermi data whereas the dashed line represents the freeze-out temperature. The shaded region is ruled out due to DM overproduction both in the thermal case (for $m_{\rm DM} \lesssim 40$ GeV and below the dashed line) and in the non-thermal branching scenario (above the solid and dashed lines).

DR Constraints on LVS Scenarios

Cicoli, Sinha, Wiley (2022)

$$\frac{K}{m_P^2} = -n_1 \ln(T_1 + \overline{T}_1) - n_2 \ln(T_2 + \overline{T}_2).$$

$$\frac{K}{m_P^2} \supset \frac{H_u \overline{H}_u}{(T_1+\overline{T}_1)^{y_1}(T_2+\overline{T}_2)^{y_2}} + \frac{H_d \overline{H}_d}{(T_1+\overline{T}_1)^{w_1}(T_2+\overline{T}_2)^{w_2}} + \frac{Z H_u H_d + \text{h.c.}}{(T_1+\overline{T}_1)^{k_1}(T_2+\overline{T}_2)^{k_2}} \tag{42}$$

$$\begin{aligned}\Delta N_{\text{eff}} &= 3\frac{\rho_{\text{hid}}}{\rho_{\text{neutrinos}}} = \frac{43}{7}\frac{\rho_{\text{hid}}}{\rho_{\text{SM}}} \\ &= \frac{43}{7}\frac{f_{\text{hid}}}{1-f_{\text{hid}}}\left(\frac{g_*(T_{\text{dec}})}{g_*(T_{\text{rh}})}\right)^{1/3},\end{aligned}$$

$$f_{\text{hid}} \equiv \frac{\Gamma(\phi_u \to aa)}{\Gamma(\phi_u \to aa) + \Gamma(\phi_u \to H_u H_d)}.$$

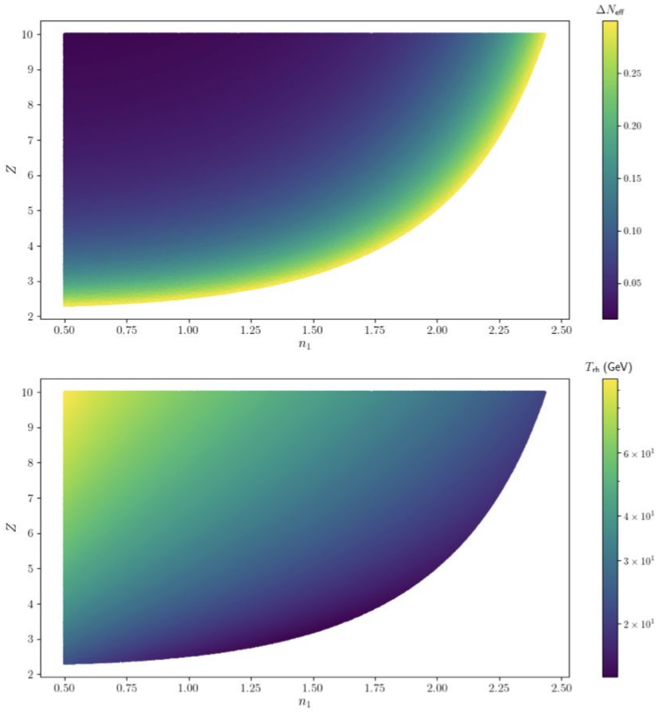


FIG. 2. The upper plot shows allowed ΔN_{eff} for the case $k_1 = 1$ and $k_2 = 0$ in the ultralocal limit. The lower plot again shows the corresponding reheat temperature in GeV for the benchmark mass in Table I. This plot also describes the case $k_1 = 0$ and $k_2 = 1$ under the interchange $n_1 \leftrightarrow n_2$.

Moduli and Pre-existing Axions

Sinha, Watson, Wiley (2023)

Axions

$$\ddot{\varphi} + 3\frac{\dot{a}}{a}\dot{\varphi} + m_a^2(T)\varphi = 0.$$

finite-temperature contributions to the mass from instantons

$$m_a(T) = (6.2 \times 10^{-3}\ \mathrm{GeV})\left(\frac{N_{\mathrm{DW}}}{f_a/(1\ \mathrm{GeV})}\right) \times \begin{cases} 1 & (T \lesssim \Lambda_{\mathrm{QCD}}) \\ b\left(\frac{\Lambda_{\mathrm{QCD}}}{T}\right)^4 & (T \gtrsim \Lambda_{\mathrm{QCD}}) \end{cases}$$

Visinelli, Gondolo (2009)

Becomes underdamped and starts oscillating when $3H(T^a_{\mathrm{osc}}) \sim m_a(T^a_{\mathrm{osc}})$

Frozen for $t < t_{\mathrm{osc}}$, and oscillates very rapidly for $t > t_{\mathrm{osc}}$.

Average equation of state: $\langle w_a \rangle = 0$

Behaves like a cosmological constant for $t < t_{\mathrm{osc}}$ with $\rho_a = \mathrm{constant}$

Behaves like dark matter for $t > t_{\mathrm{osc}}$ with $\rho_a \sim a^{-3}$. Energy density $\rho_a = m_a(T)n_a$

Moduli and Pre-existing Axions

Sinha, Watson, Wiley (2023)

Hubble scale at the onset of axion oscillations: $$H(T^a_{\rm osc}) \simeq \frac{g_*(T^a_{\rm osc})}{g_*(T^\phi_D)} \frac{(T^a_{\rm osc})^4}{(T^\phi_D)^2} \sqrt{\frac{\pi^2 g_*(T^\phi_D)}{90 m_P^2}}$$

Solve $T^a_{\rm osc} \sim \mathcal{O}(0.1 - 1\ \mathrm{GeV})$

Grin, Smith, Kamionkowski (2007)

Axion number density $n_a(T^a_{\rm osc}) \simeq \frac{1}{2} m_a(T^a_{\rm osc}) \mathcal{A}_0^2$, with $\mathcal{A}_0^2 = \frac{1.44 f_a^2 \theta_i^2}{N_{\rm DW}^2} \left[\log\left(\frac{e}{1-\theta_i^2/\pi^2}\right)\right]^{7/6}$

Visinelli, Gondolo (2009)

Accounting for the remaining matter-dominated period between $T^a_{\rm osc}$ and T^ϕ_D

$$n_a(T^\phi_D) = n_a(T^a_{\rm osc}) \frac{a^3(T^a_{\rm osc})}{a^3(T^\phi_D)} \simeq n_a(T^a_{\rm osc}) \left(\frac{g_*(T^\phi_D)(T^\phi_D)^4}{g_*(T^a_{\rm osc})(T^a_{\rm osc})^4}\right)^2$$

No further entropy production after T^ϕ_D

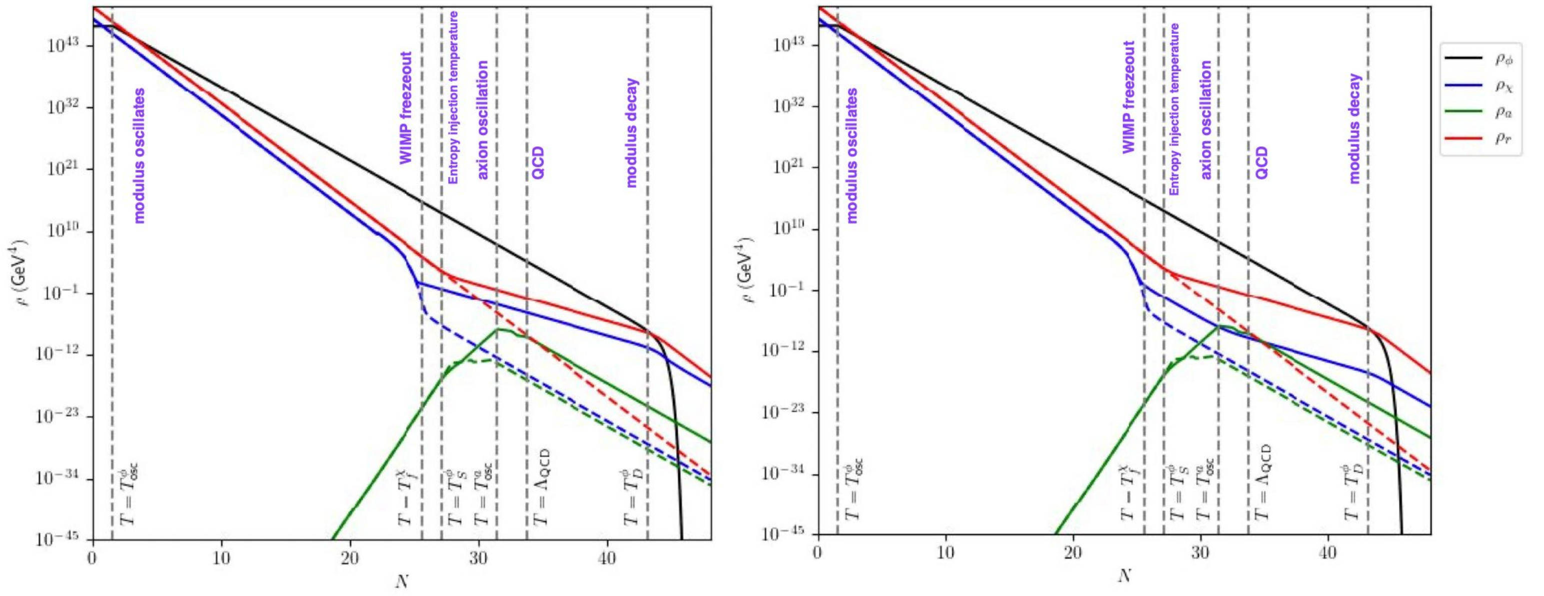
Hertzberg, Tegmark, Wilczek (2010)

$$\Omega_a h^2 \simeq \frac{45}{4\pi^2} \frac{m_a(T=0) m_a(T^a_{\rm osc}) \mathcal{A}_0^2}{\rho_c/(h^2 s_0)} \frac{g_*(T^\phi_D)}{g_*^2(T^a_{\rm osc})} \frac{(T^\phi_D)^5}{(T^a_{\rm osc})^8}.$$

X

Evolution of thermal history

Sinha, Watson, Wiley (2023)



Annihilation Scenario $B_{\phi\to\chi} = 0.01$

Branching Scenario $B_{\phi\to\chi} = 10^{-8}$

$m_\phi = 100$ TeV, $m_\chi = 200$ GeV, $\langle\sigma v\rangle_\chi = 1.05\times10^{-25}\ \mathrm{cm}^3\cdot\mathrm{s}^{-1}$.

$f_a = 10^{11}$ GeV, $\theta_i = 3.113$, and $T_R = 10^{12}$ GeV.

Axion Perturbation Condition

Axion perturbation growth

$$\delta_a(a,k) = 2\Phi_0 + \frac{2}{3}\left(\frac{k}{H(T^a_{\rm osc})}\right)^2 a\Phi_0$$

Sankharva, Sinha, Watson, Wiley (2023)

$\Phi_0 \sim 10^{-4}$ represents the primordial perturbation during inflation

Normalization $a(T^a_{\rm osc}) \equiv 1$.

Consider $k \sim H(T^a_{\rm osc})$. (For subhorizon modes at $T^a_{\rm osc}$ with $k > H(T_{\rm osc})$ only miniclusters with very small masses can form. For superhorizon modes at $T^a_{\rm osc}$ with $k < H(T_{\rm osc})$ sufficient growth of perturbations may be difficult.)

Condition 1: $\delta_a \sim 1$ at T^ϕ_D

Condition 2: $T^\phi_D < T^a_{\rm osc}$

Perturbation Condition + Relic Density

Perturbation condition

$$1 \simeq 2\Phi_0 + \frac{2}{3}\left(\frac{H(T^a_{\rm osc})}{H(T^\phi_D)}\right)^{2/3}\Phi_0$$

Sankharva, Sinha, Watson, Wiley (2023)

Moreover, $H(T^\phi_D) \sim \Gamma_\phi$ and $H(T^a_{\rm osc}) \sim$ $m_a(T^a_{\rm osc}) \propto f_a^{-1}$

$$\delta_a \propto \frac{1}{f_a^{2/3}(T^\phi_D)^{4/3}}$$

Relic density

$$\Omega_a h^2 \simeq \frac{45}{4\pi^2}\frac{m_a(T=0)m_a(T^a_{\rm osc})\mathcal{A}_0^2}{\rho_c/(h^2 s_0)}\frac{g_*(T^\phi_D)}{g_*^2(T^a_{\rm osc})}\frac{(T^\phi_D)^5}{(T^a_{\rm osc})^8}.$$

This can then be translated into a maximal value of f_a which can be expected to form miniclusters for a given decay temperature

Moduli and Pre-existing Axions + Miniclusters + WIMPs

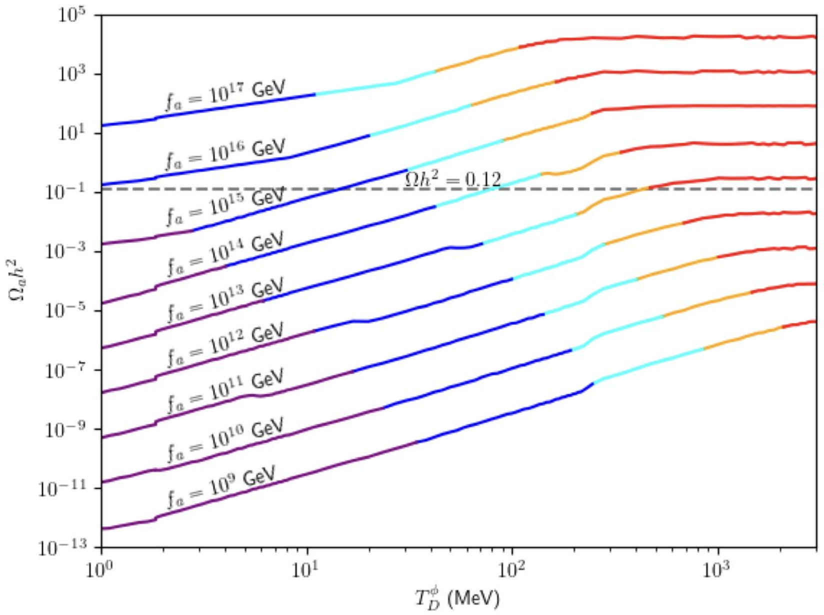


Figure 5: Axion relic density versus T_D^ϕ where $\theta_i = 2$. For our benchmark, these values of T_D^ϕ correspond to $m_\phi \in [2.4 \times 10^4,\ 5 \times 10^6]$ GeV. Purple regions are consistent with $\delta_a = 1$, dark blue with $\delta_a = 10^{-2}$, and light blue with $\delta_a = 10^{-3}$. Orange regions correspond to even lower values of δ_a but still have some overlap with an EMDE. Red regions have no overlap with an EMDE.

Moduli and Axions: Non-perturbative Decays

Adams, Barrows, Giblin, Sinha, Watson, Wiley (2024)

non-perturbative effects can be expected to be most pronounced within the first oscillation cycle of the modulus

In the case where the modulus decays entirely through this non-perturbative effect, the lower mass bound on modulus mass is effectively removed due the high scale of the decay, preventing any overlap with BBN.

No sizeable contribution to entropy, as the energy density transferred to decay products will not thermalize significantly. In this case, the radiation bath is simply set by the inflationary reheating process - leaving any inflationary relics present, despite the short-lived appearance of a modulus. The modulus does not “reheat” the universe.

Axions produced are relativistic if

$$\frac{k^2}{m_\phi^2} \gtrsim 4.4 \times 10^1 \left(\frac{10^{13}}{m_\phi/m_a}\right)^2 \left(\frac{m_\phi}{10\ \mathrm{TeV}}\right) \left(\frac{2.3 \times 10^{-24}\ \mathrm{GeV}}{H_{\mathrm{BBN}}}\right)$$

Discussions

Discussion Slides

What are the experimental facilities?

Gravitons: GW experiments - LIGO, LISA, PTAs, etc.

Photons: Radio, X-ray, Gamma-ray telescopes. CMB measurements

Neutrinos: Icecube, DUNE

Table-top experiments (many axion searches, maybe high frequency GWs)

How should we make connections to the experimental frontier?

Post-inflation reheating (Authors: M. A. Amin, D. I. Kaiser & K. D. Lozanov)
Moduli fields (Authors: K. Sinha & S. Watson)
Phase transitions and baryon asymmetry (Authors: R. Allahverdi & M. Lewicki)
Formation of microhalos (Author: A. Erickcek)
Observational probes of microhalos (Authors: M. S. Delos & A. L. Erickcek)

Discussion Slides

EMDEs: Microhalo Probes

Blinov, Dolan, Draper (2020)

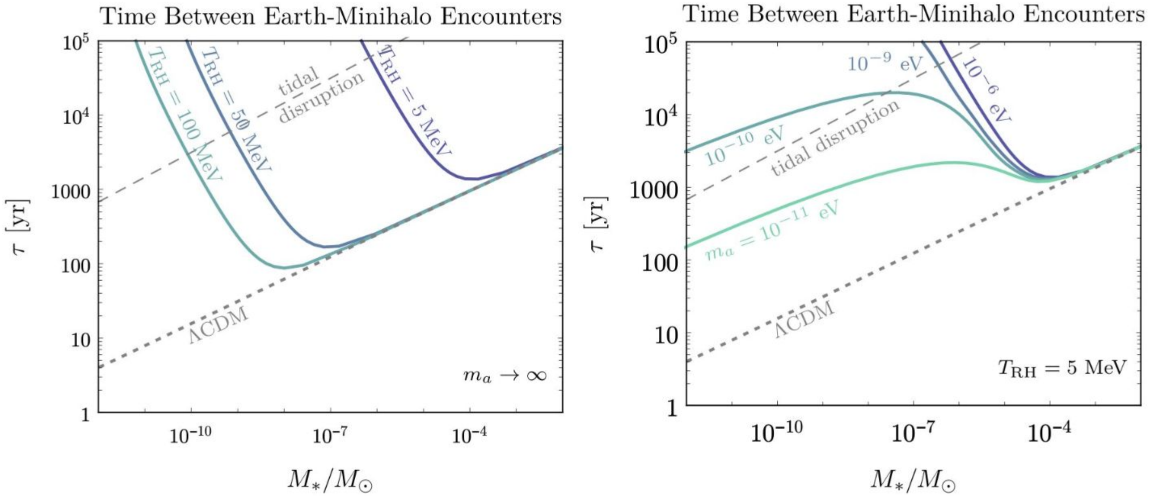


FIG. 12. Time between Earth-minihalo encounters assuming all of DM is inside minihalos of a single mass that survive tidal disruption until today. In the left panel we fix $m_a \gtrsim 10^{-6}$ eV so that the small-scale cut-off due to the ALP effective pressure is irrelevant; in right panel we take $T_{RH} = 5$ MeV and vary the ALP mass. Early matter domination produces minihalos at high redshift, leading to dense and therefore compact minihalos. The resulting reduced geometric cross-section increases the time between encounters for $M < M_{RH}$, despite the increasing number density for smaller M. Smaller ALP masses suppress growth of small scales, leading to the formation of more diffuse objects with larger cross-sections and encounter rates. Gray dotted lines correspond to encounter rates for ΛCDM minihalos. Above the thin gray dashed line, tidal disruption of minihalos due to stellar encounters is expected to be unimportant.

Discussion Slides

EMDEs: Microhalo Probes

Blinov, Dolan, Draper (2020)

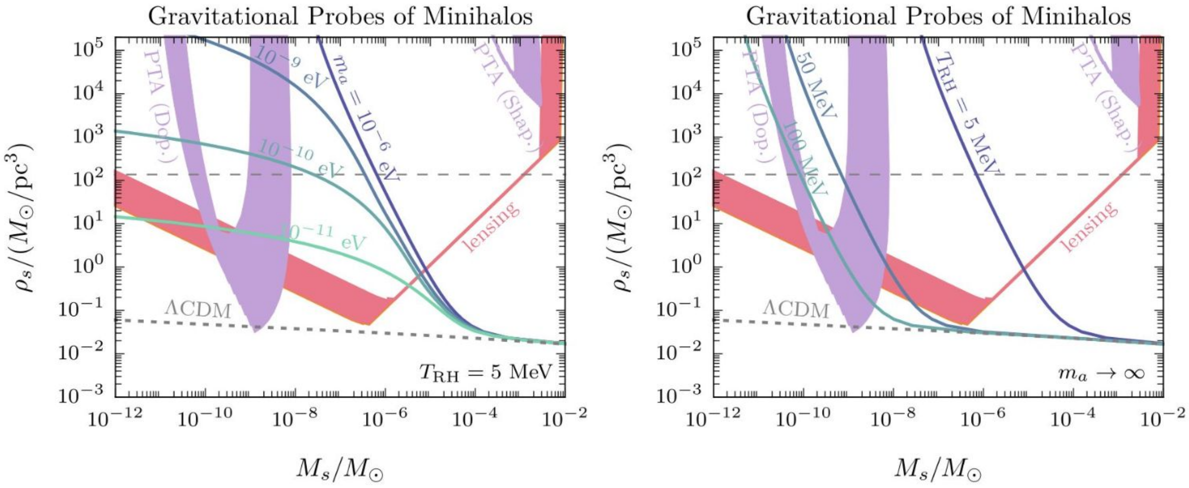
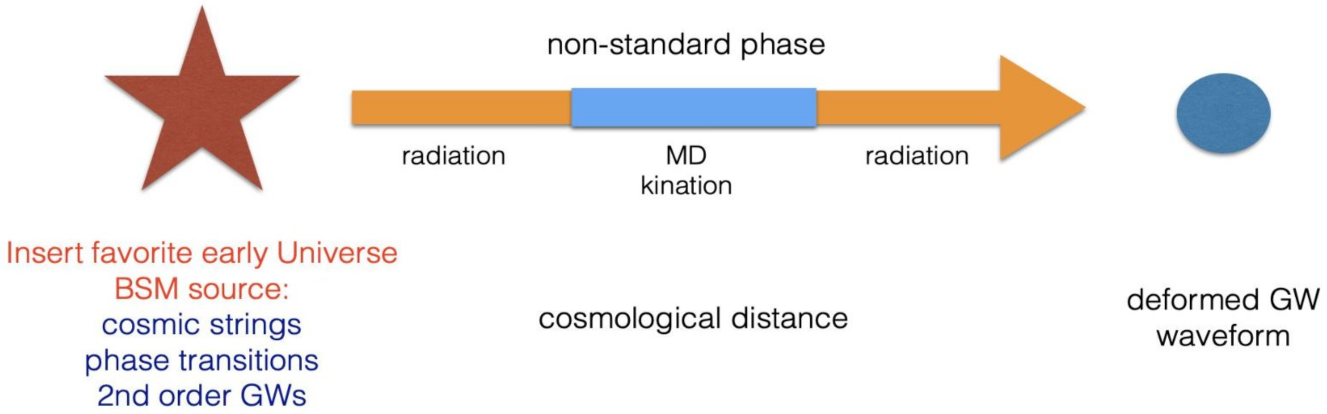


FIG. 13. The reach of future pulsar timing array (PTA) Doppler and Shapiro dynamic measurements (purple) and photometric microlensing (red) in the M_s–ρ_s plane. In each panel, the (upper) grey dashed line corresponds to a collapse redshift of 250: the region of the plane above this has $z_c > 250$ with minihalos that are likely to survive tidal disruption in stellar encounters. The (lower) grey dotted line shows the prediction from the standard ΛCDM scenario. The left-hand panel shows EMD predictions for $m_a = 10^{-6}$, 10^{-9}, 10^{-10} and 10^{-11} eV and fixed $T_{\rm RH} = 5$ MeV. The right-hand panel shows EMD predictions for $T_{\rm RH} = 10$, 50 and 100 MeV for fixed $m_a \to \infty$ (this limit is already reached for $m_a \gtrsim 10^{-6}$ eV). The thickness of the PTA and lensing projections corresponds to varying the DM fraction in minihalos of mass M_s between 0.3 and 1. The actual fraction of ALPs in minihalos can span a wide range and depends on model parameters (see Fig. 10) and tidal disruption history.

Discussion Slides

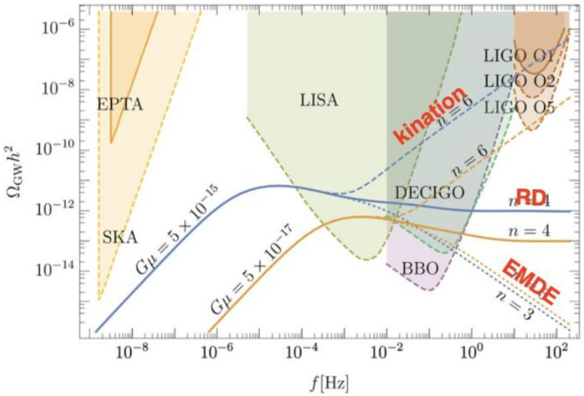
Non-standard Histories: Gravitational Probes



Discussion Slides

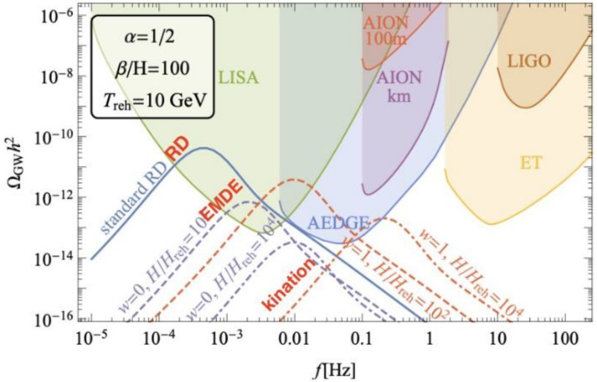
Non-standard Histories: Gravitational Probes

example: source = cosmic strings



Cui, Lewicki, Morrissey, Wells (2016)
Gouttenoire, Servant, Simakachorn (2020)

example: source = phase transition



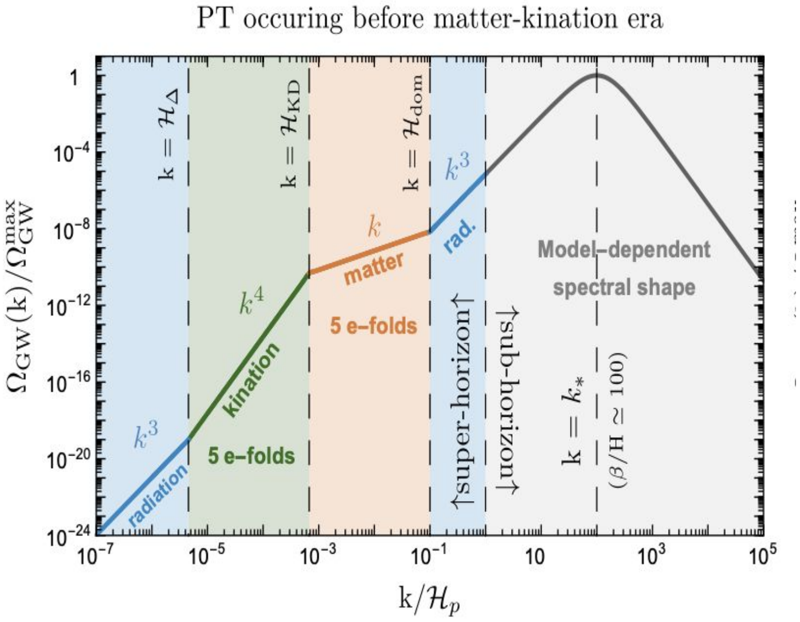
Figueroa et. al. (2020)

source = primordial GWs, induced GWs, etc.

Bernal, Hajkarim (2018)
Domenec et. al. (2020)

Discussion Slides

Causal tail behavior is universal



Gouttenoire, Servant, Simakachorn (2022)

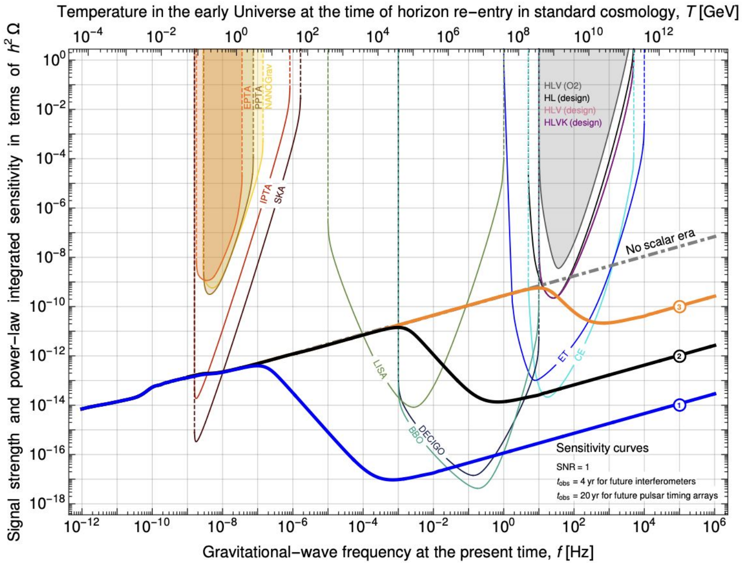


FIG. 2: Final GW spectrum for three parameter examples (see Fig. 3) alongside the power-law integrated sensitivity curves [95] of existing and upcoming GW experiments.

D'Eramo, Schmitz (2016)

Discussion Slides

Post-inflation reheating

Easther, Giblin, Lim (2007)

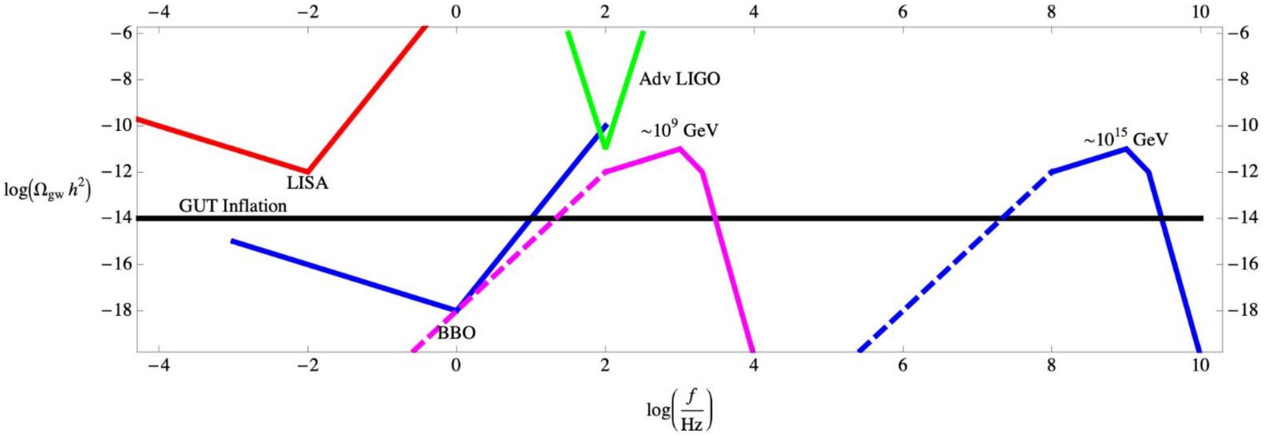
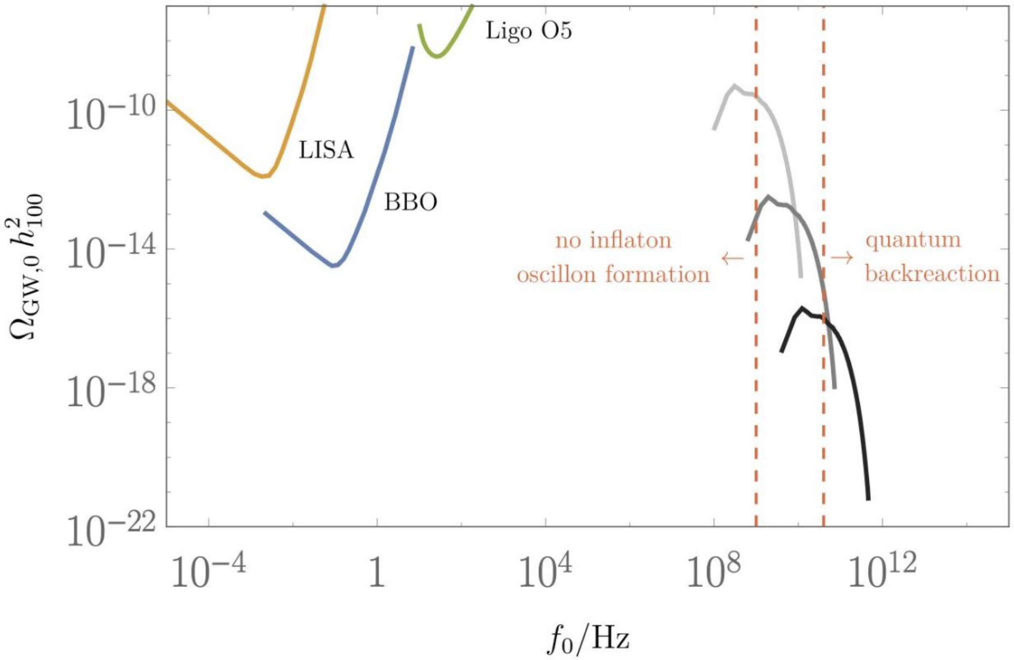


FIG. 2: We sketch the gravitational wave spectra obtained for the lowest and highest energy models computed here, relative to that of the Advanced LIGO goal, and the proposed LISA and BBO experiments. We see that inflationary models with lower energy scale may lead to a signal which is visible at LIGO scales if the sensitivity of LIGO is further improved, and with BBO. The tensor background generated by quantum fluctuations during GUT scale inflation is shown by the solid horizontal line. The dashed lines denote the inferred k^3 tails. The spectra generated by the inflationary scenarios considered in [5, 15] roughly overlap with the 10^{15} GeV spectrum depicted above.

Discussion Slides

GWs from Oscillons

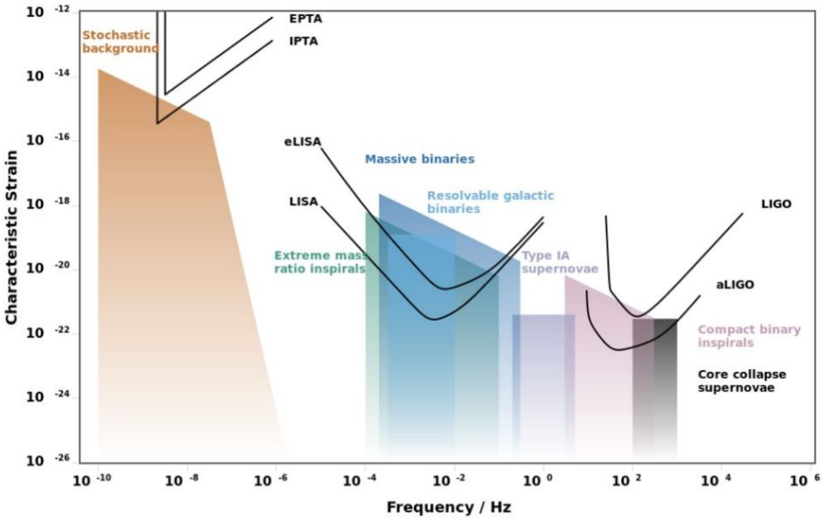
Lozanov, Amin (2019)



Discussion Slides

Non-standard Histories: Gravitational Probes

Low f GW



High f GW

N. Aggarwal et. al. (2020)

V. Domcke et. al. (2020-)

Non-standard Histories: Post-BBN Universe??

Changes to post-BBN history are pretty radical in my opinion.

Do we have enough of a physics motivation?

What agent would cause such a change?

The observational landscape is richer (we know a lot more about post-BBN)

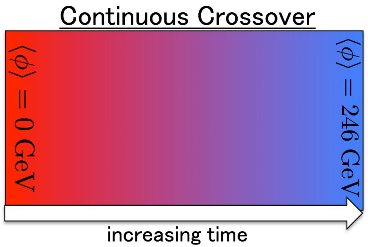
How does an EMDE impact the matter power spectrum, how is the matter power spectrum probed via Ly-alpha observations etc, what's the status of these measurements, what will the situation look like in coming years, and what are we hoping to learn about modified expansion histories?

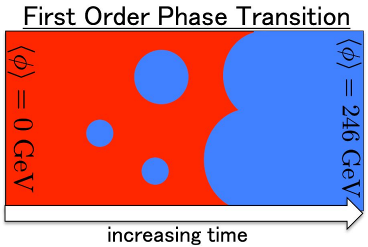
Non-standard Histories: Dark Sectors

Huang, AL, Wang (2016)

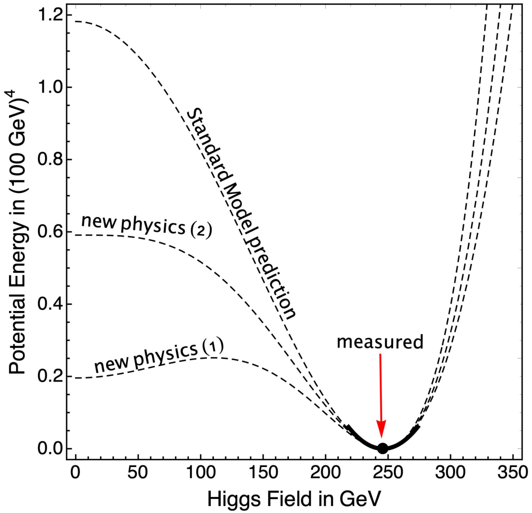
Collider / Cosmo complementarity

electroweak phase transition
⇒ SM predicts a crossover
⇒ BSM allows 1st order

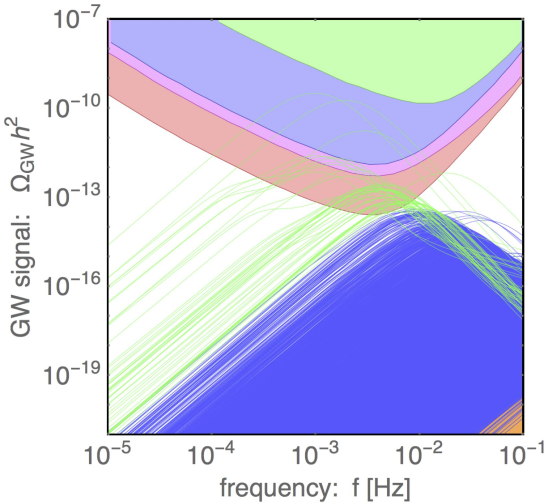




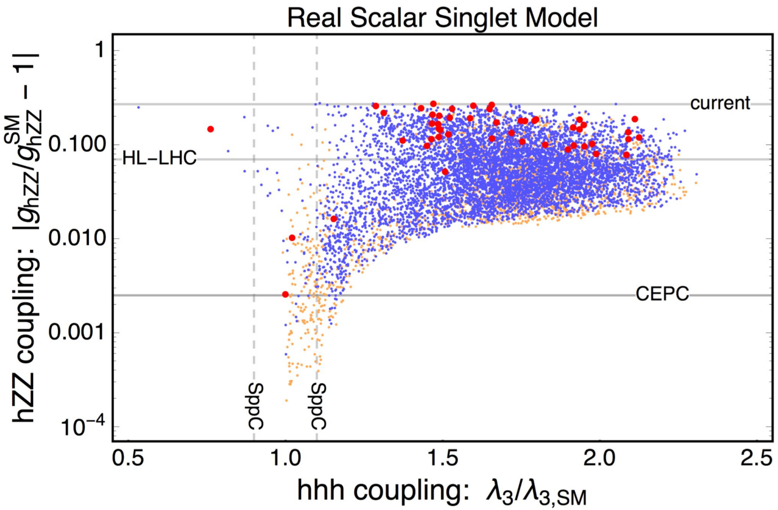
Higgs potential



grav waves



collider complementarity



Non-standard Histories: Stasis

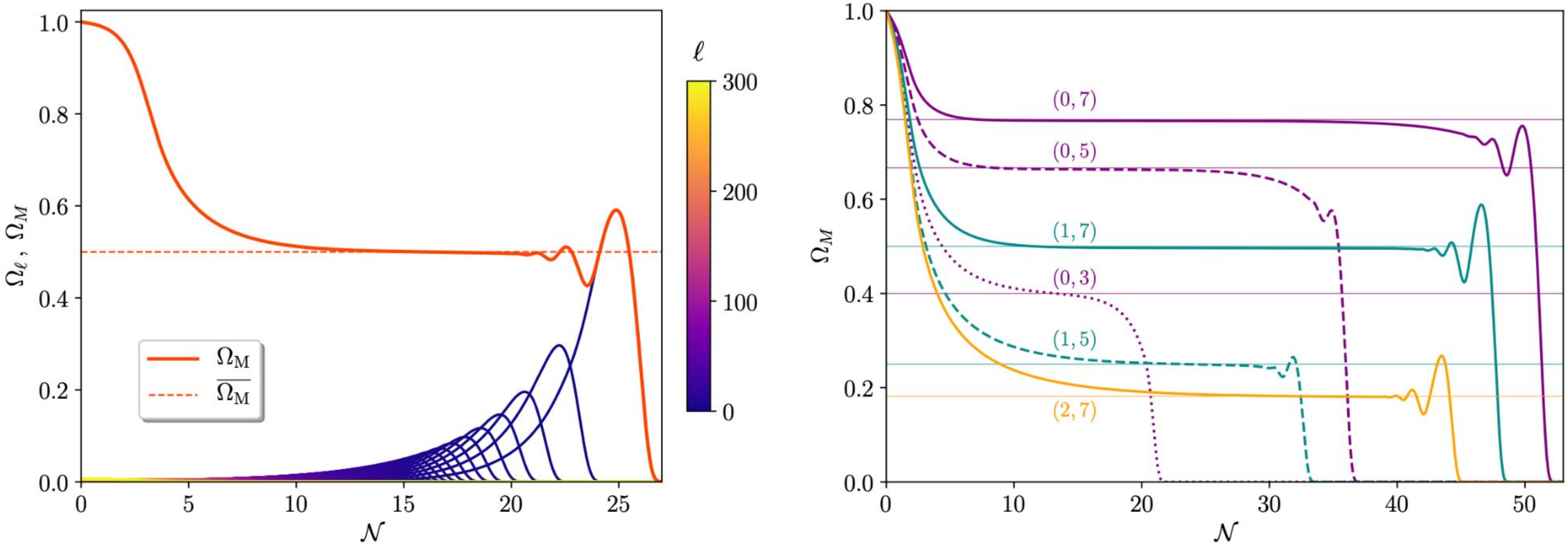


FIG. 1. Matter/radiation stasis. *Left panel*: The individual matter abundances Ω_ℓ (shown with colors ranging from orange to blue) and the corresponding total matter abundance Ω_M (red), plotted as functions of the number $\mathcal{N}$ of e-folds since the initial time of production. Even though the individual abundances Ω_ℓ exhibit complex behaviors which are affected by cosmological expansion as well as ϕ_ℓ decay, the system quickly evolves into a stasis state in which their sum Ω_M becomes constant. These

Non-standard Histories: PBHs

Kawasaki, Yanagida, et. al. (2020)