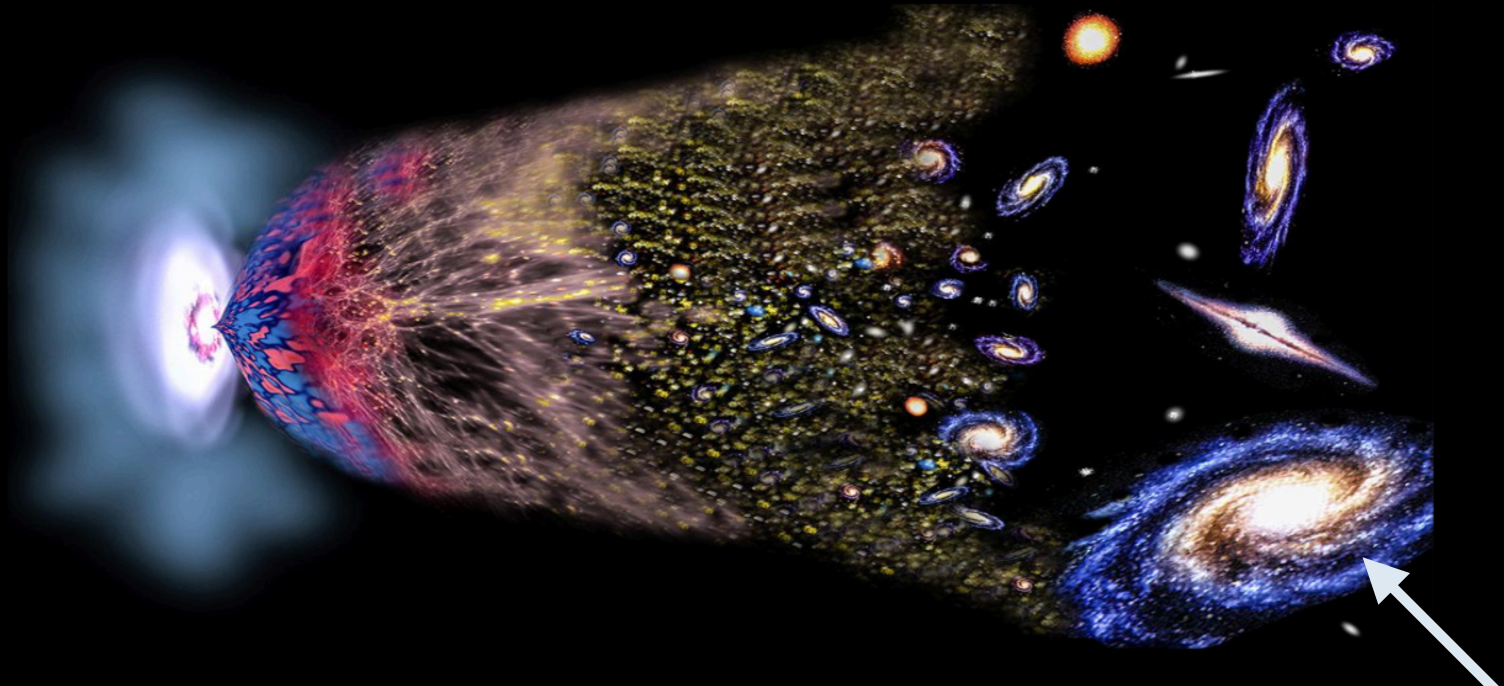
Cosmology and New Physics

Scott Watson (Syracuse University)



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PHENO 2020

FROM THE INFRARED TO THE ULTRAVIOLET

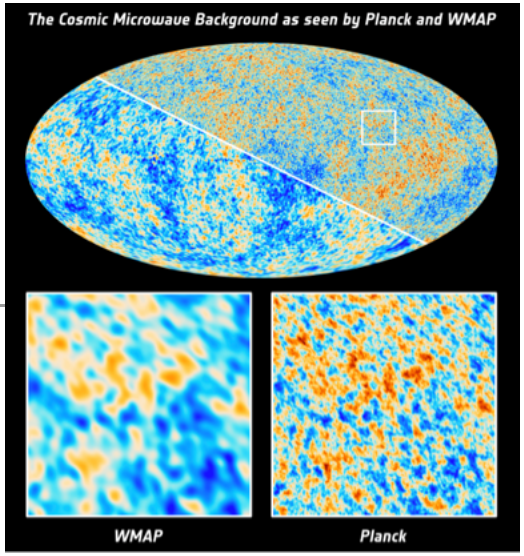
LATEST TOPICS IN PARTICLE PHYSICS
AND RELATED ISSUES IN
ASTROPHYSICS AND COSMOLOGY

MAY 4-6, 2020

photo by Jim Marino

indico.cern.ch/e/pheno20

Observations Agree with Theory



flat

homogeneous

Gaussian

adiabatic

scale-invariant

superhorizon

isotropic

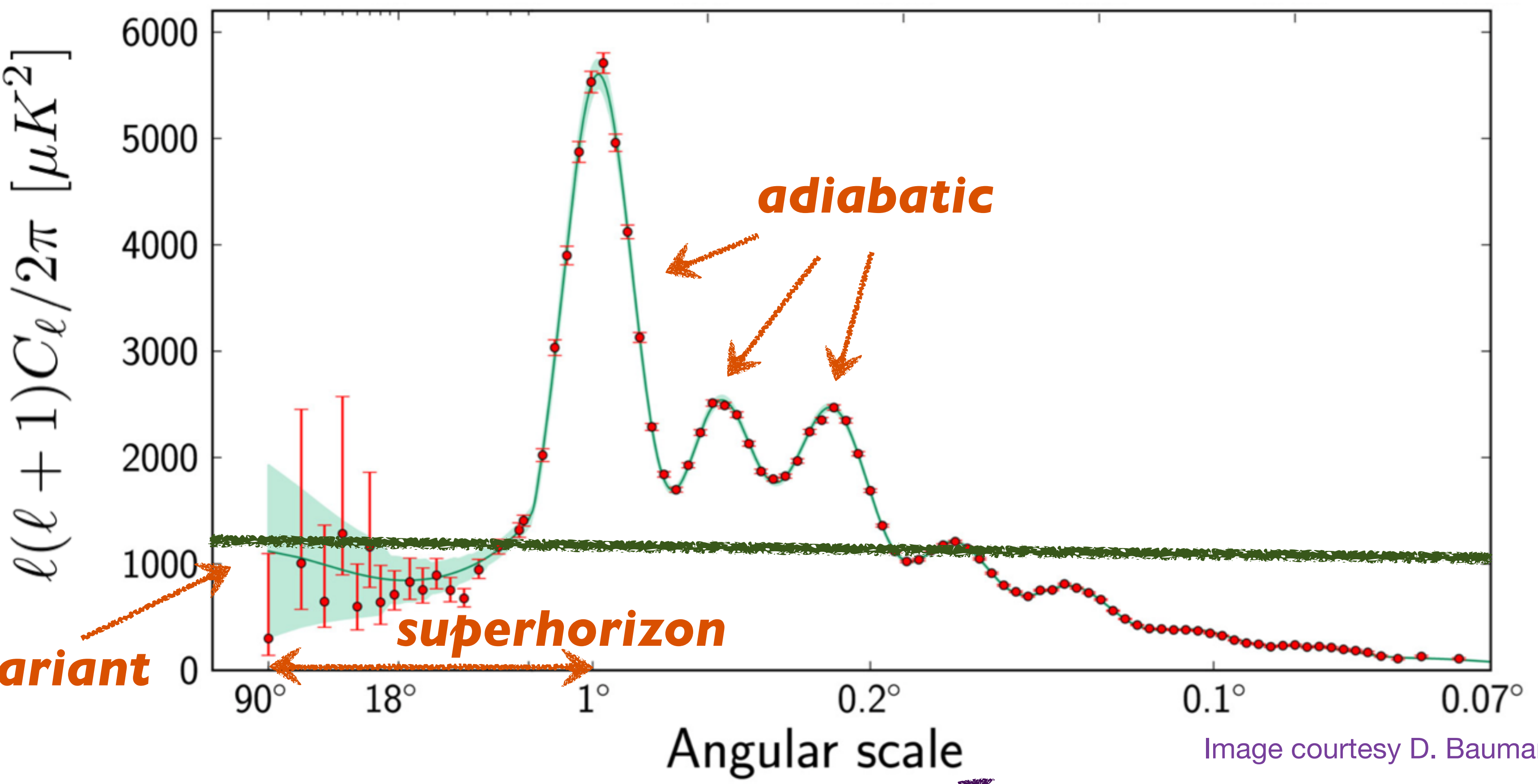
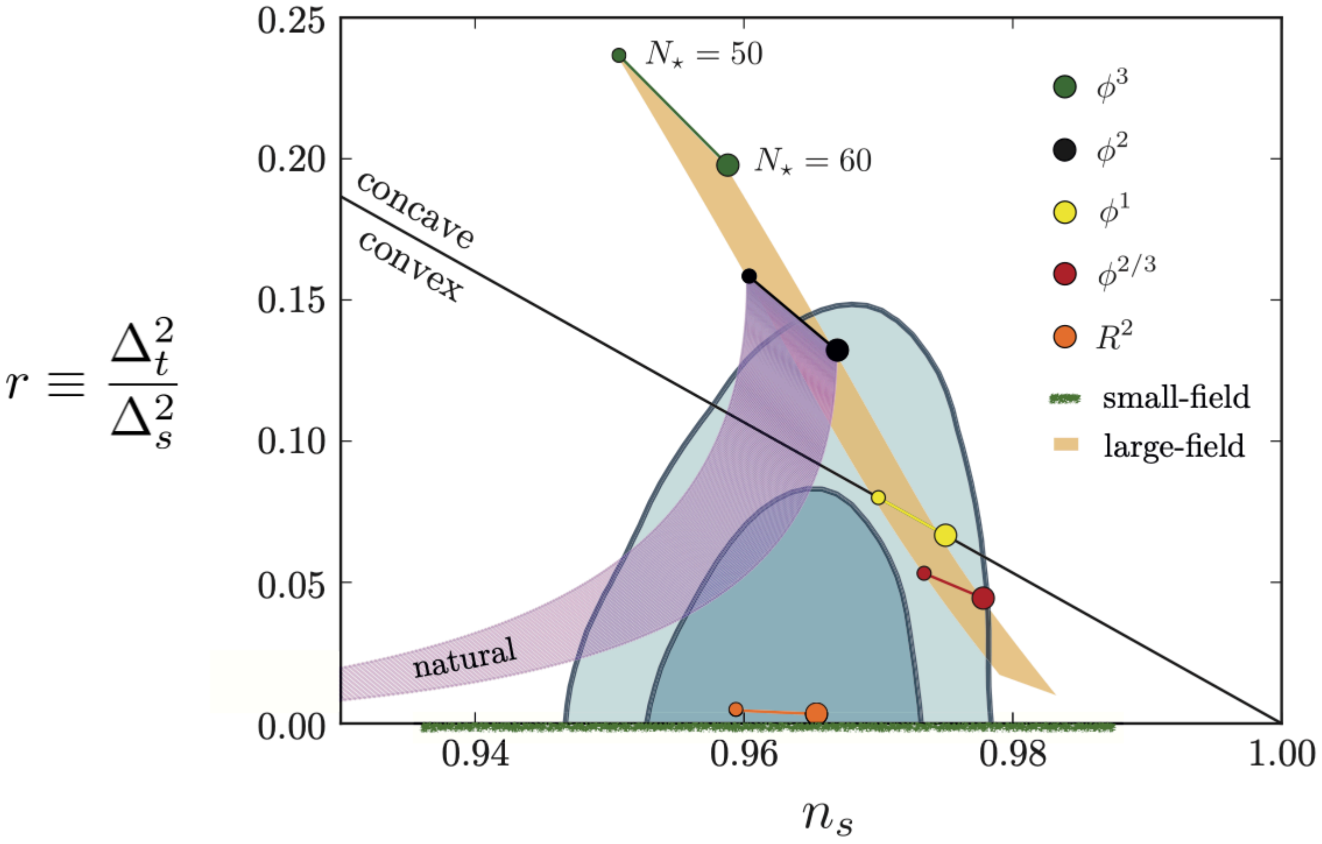
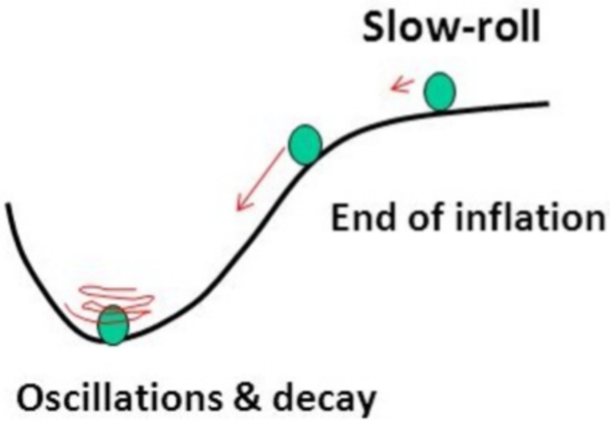


Image courtesy D. Baumann

We know a lot about inflation





Little or no interactions

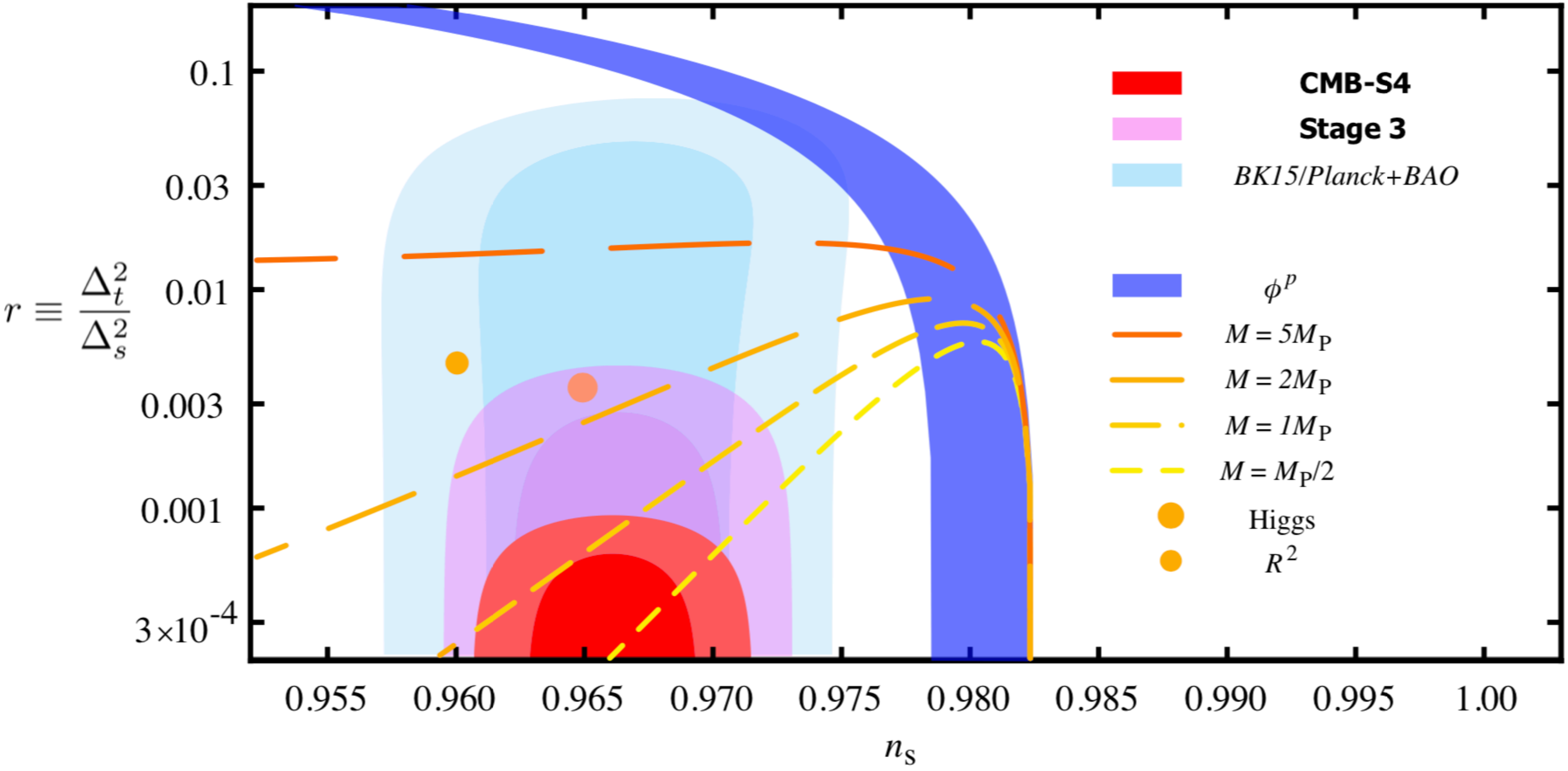
$$f_{\rm NL}^{\rm local} = -0.9 \pm 5.1$$

$$f_{\rm NL}^{\rm equil} = -26 \pm 47$$

$$f_{\rm NL}^{\rm ortho} = -38 \pm 24$$

Planck 2018
(68% CL)

And we will know more…

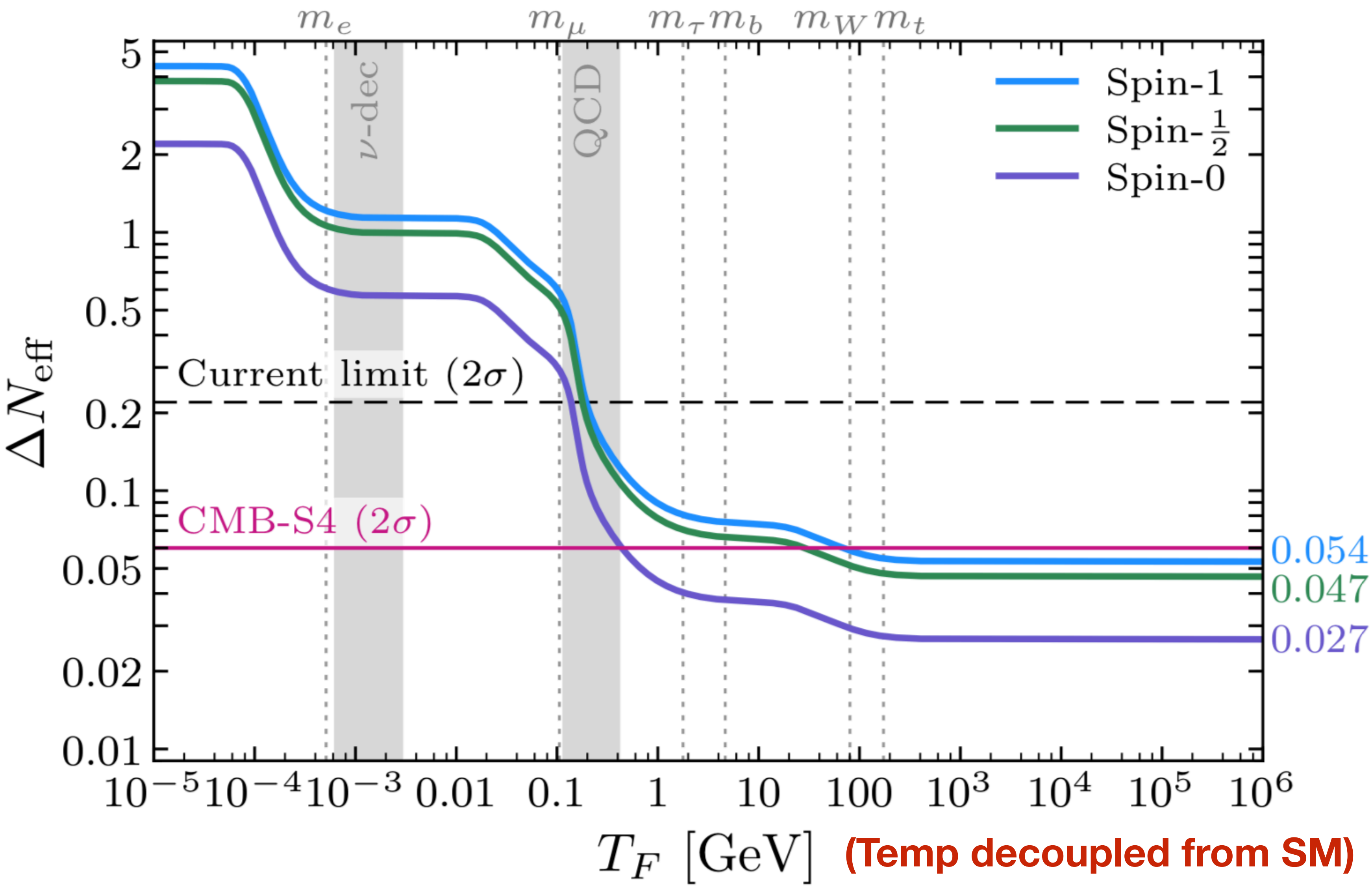


A detection of gravitational waves would tell us the scale of new physics

$$\frac{H_I}{m_p} \simeq 10^{-5} \left(\frac{r}{0.1}\right)^{1/2}$$

And we will know more…

Projected bounds on new light particles



(Temp decoupled from SM)

How did inflation end?

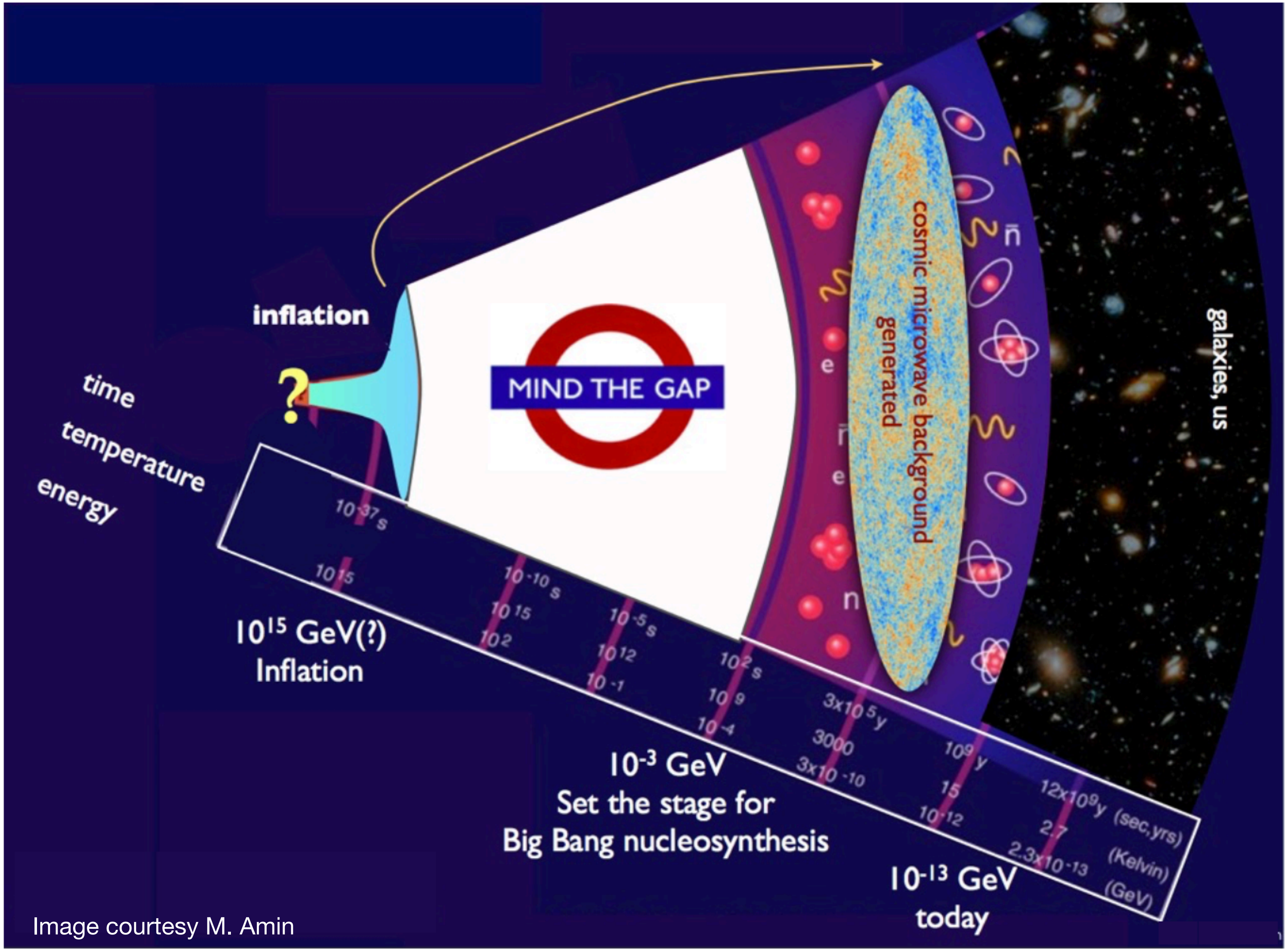
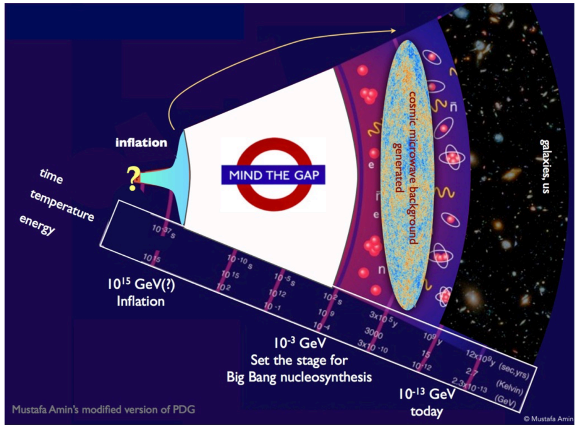


Image courtesy M. Amin

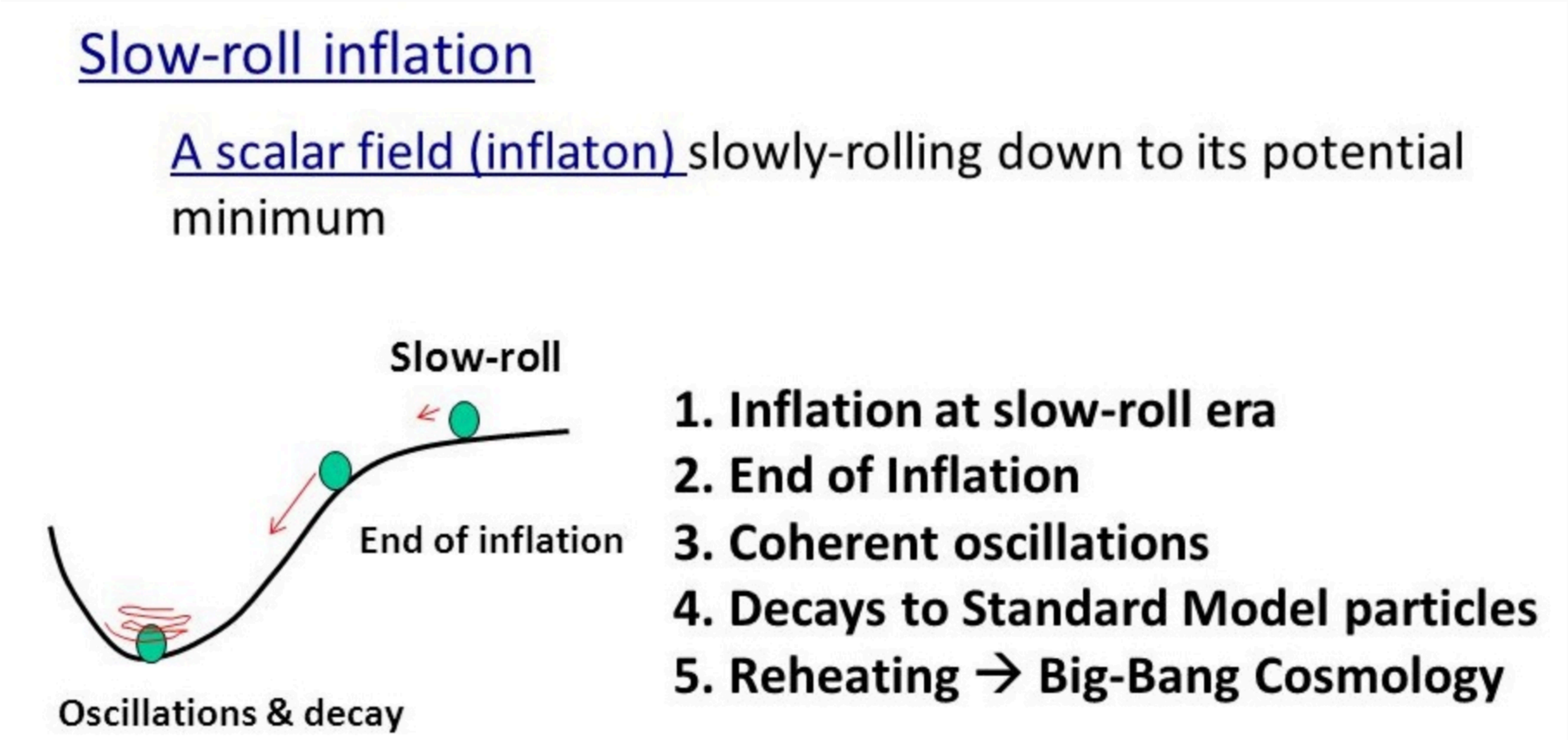
Does this require new physics?

How did inflation end?



Mustafa Amin's modified version of PDG

© Mustafa Amin



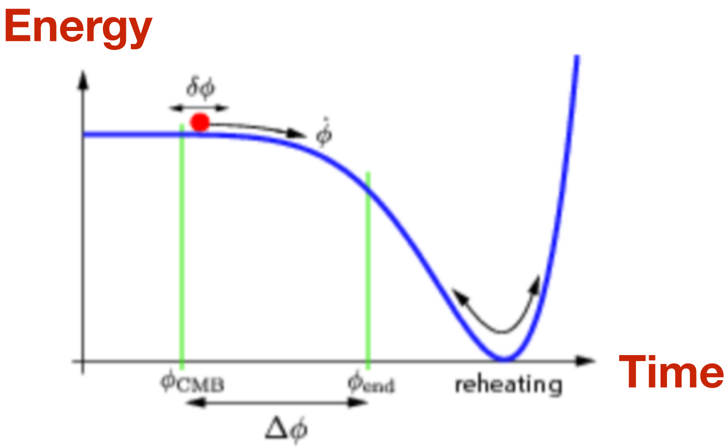
Slow-roll inflation

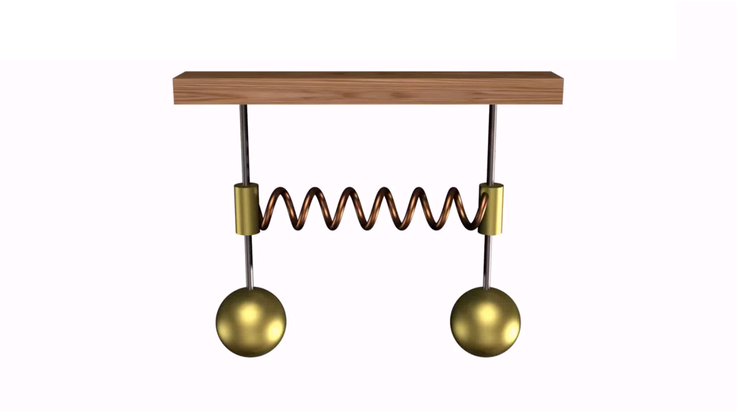
A scalar field (inflaton) slowly-rolling down to its potential minimum

1. Inflation at slow-roll era
2. End of Inflation
3. Coherent oscillations
4. Decays to Standard Model particles
5. Reheating → Big-Bang Cosmology

Lecture notes on Cosmology (UT Austin)

The process of reheating can be highly non-linear and NOT instantaneous

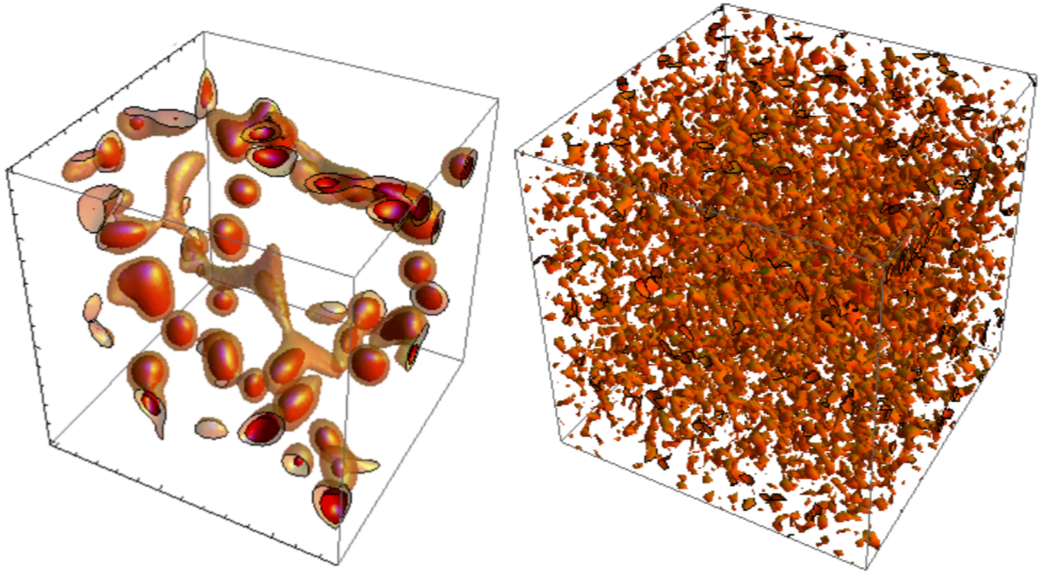




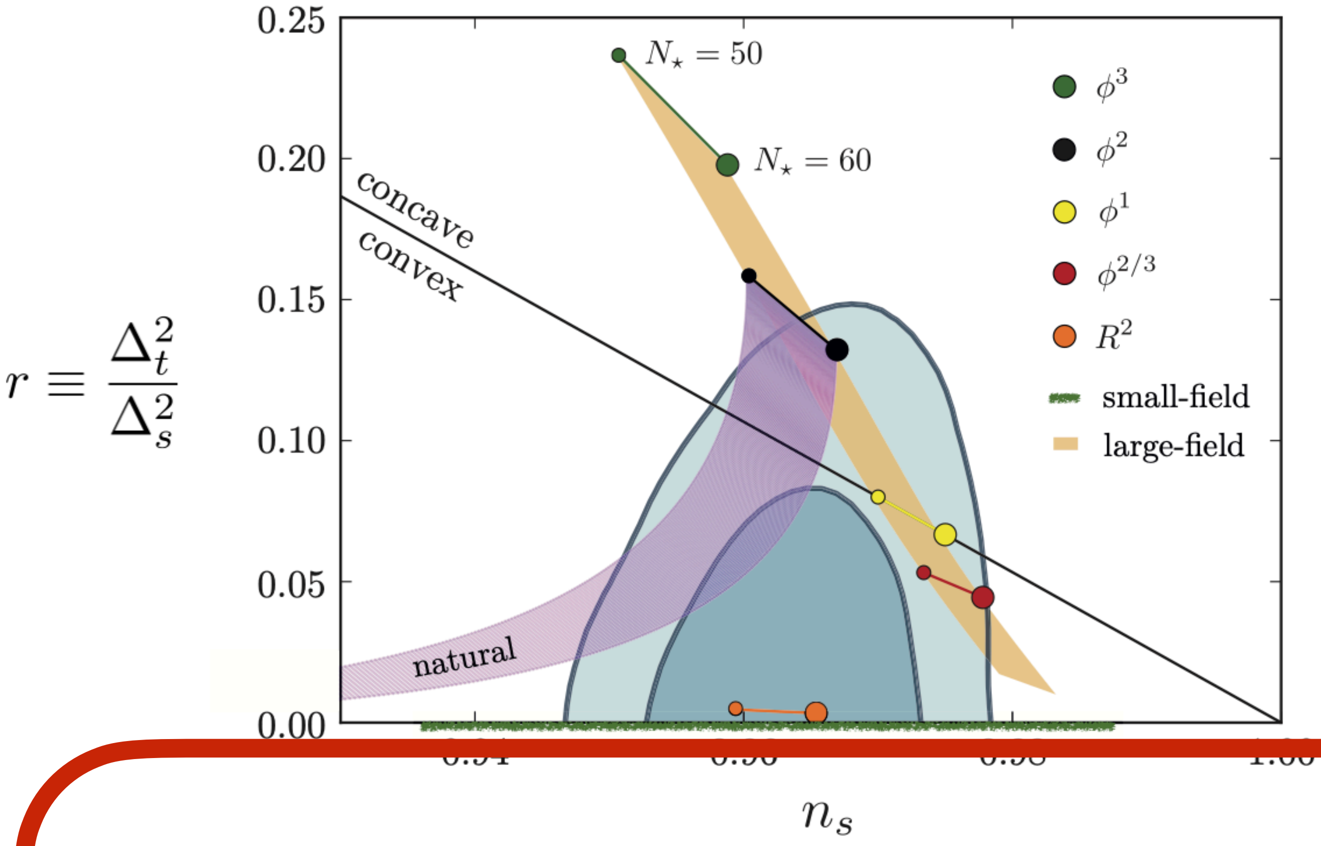
The transition from inflation to “reheating” can be complicated.

Stages of Reheating:

1. Non-perturbative (parametric resonance)
2. Non-linear Dynamics and Chaos
3. Turbulence
4. Thermalization



We know a lot about inflation



How long does reheating take?

Little or no interactions

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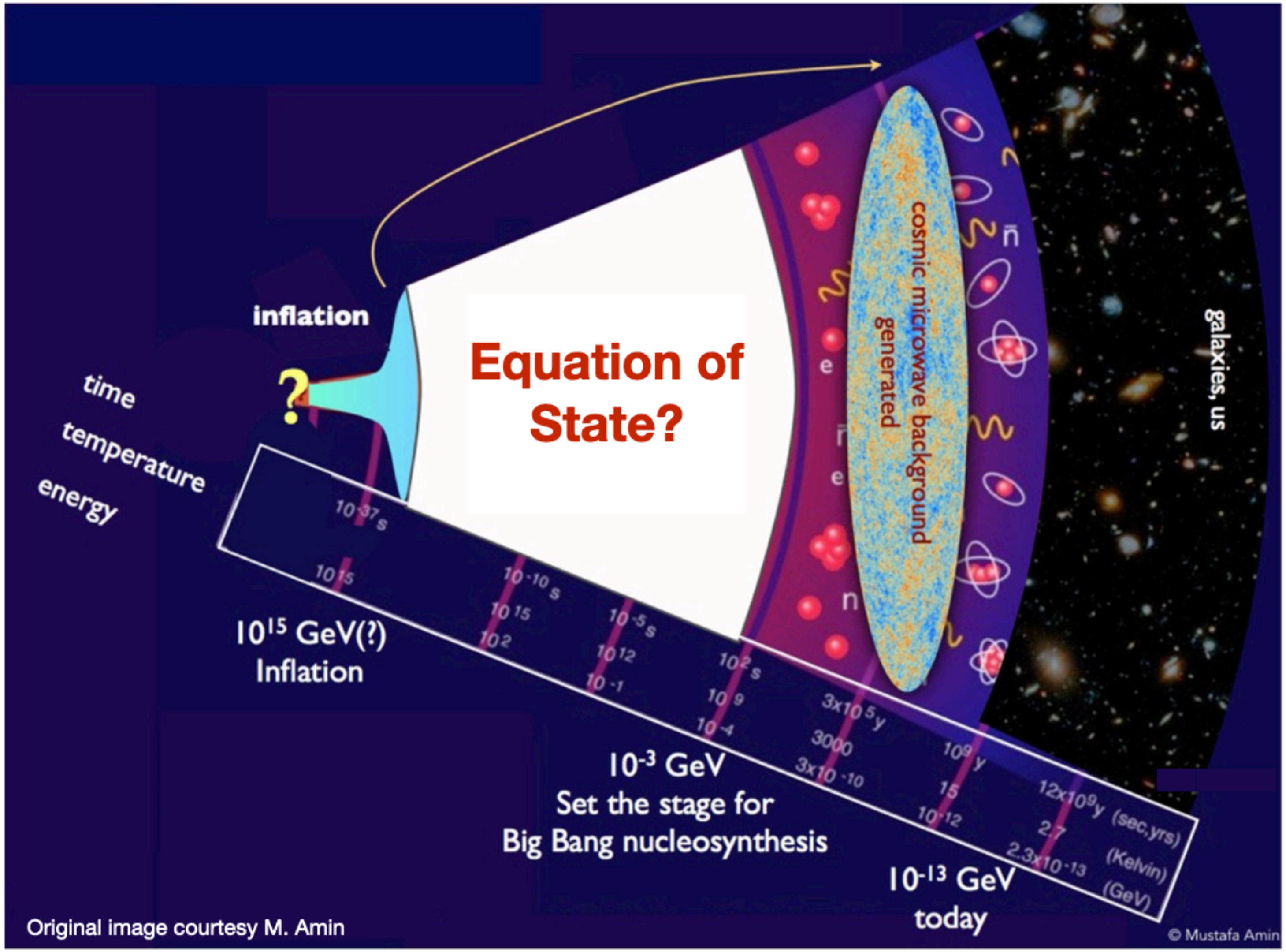
Planck 2018 (68% CL)

Weak couplings to other fields <u>during</u> inflation →

Prolonged reheating phase can alter the early expansion history implying a departure from a standard thermal history

(Observational consequences in a few minutes)



Equation of State?

Original image courtesy M. Amin

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When / how did the universe thermalize?

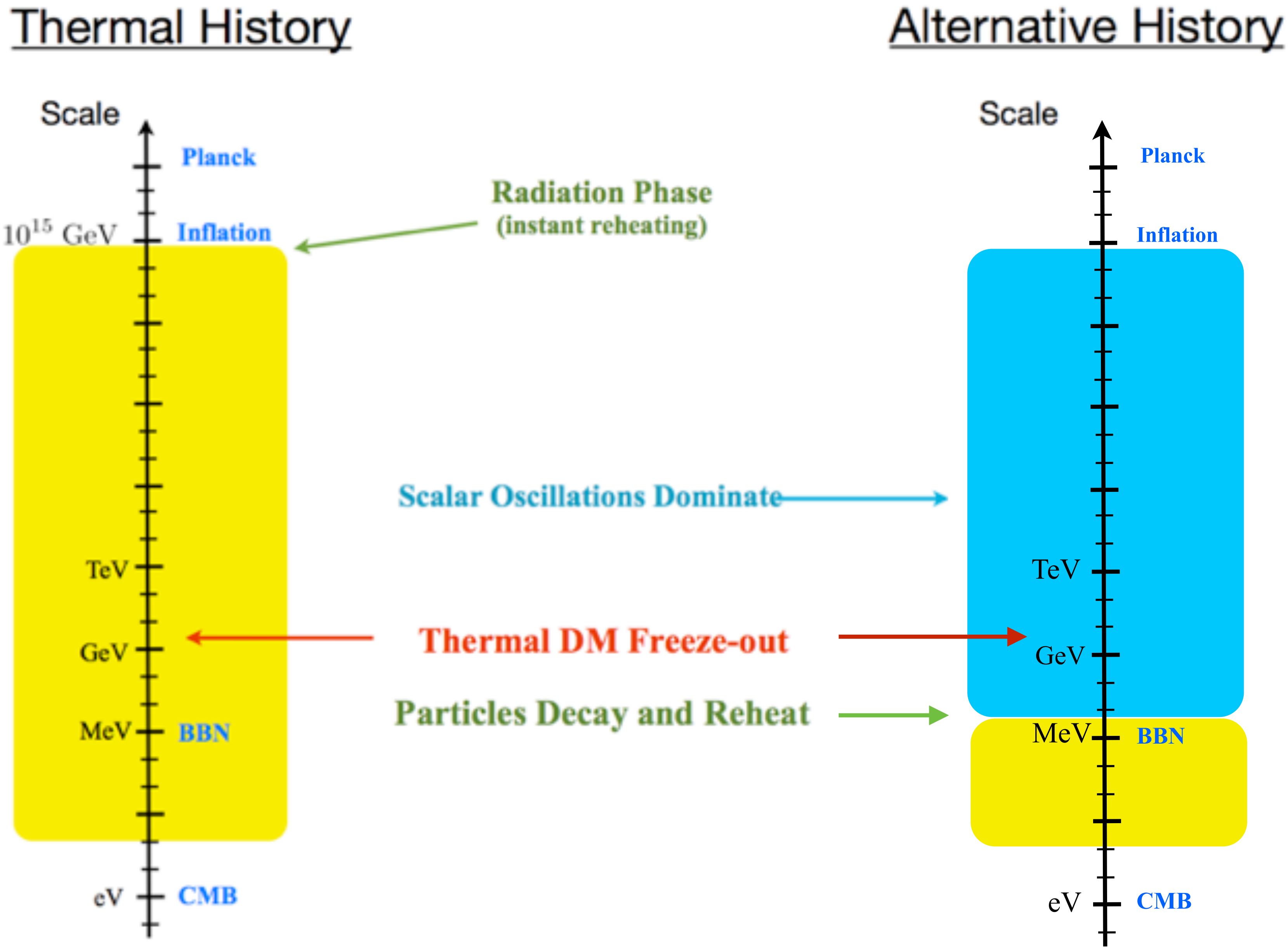


Image courtesy S. Watson

Observational Implications?

Constraints on Inflation and reheating

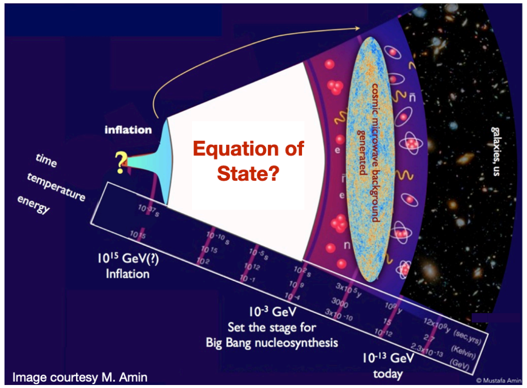
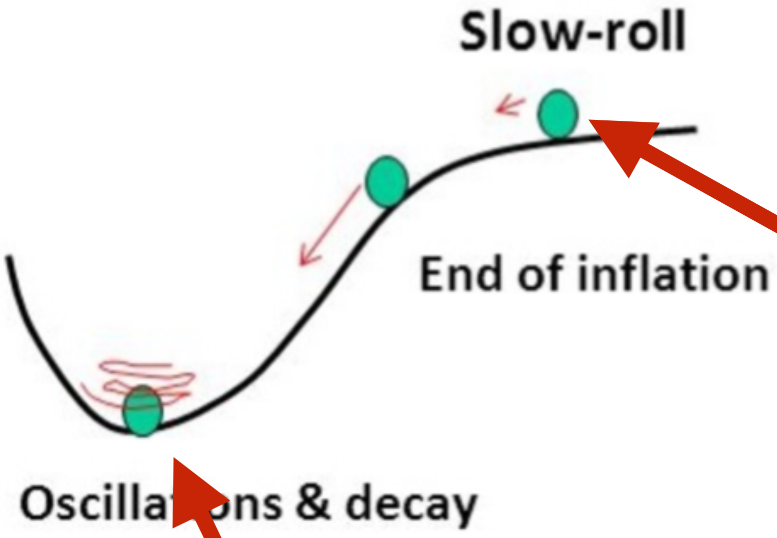
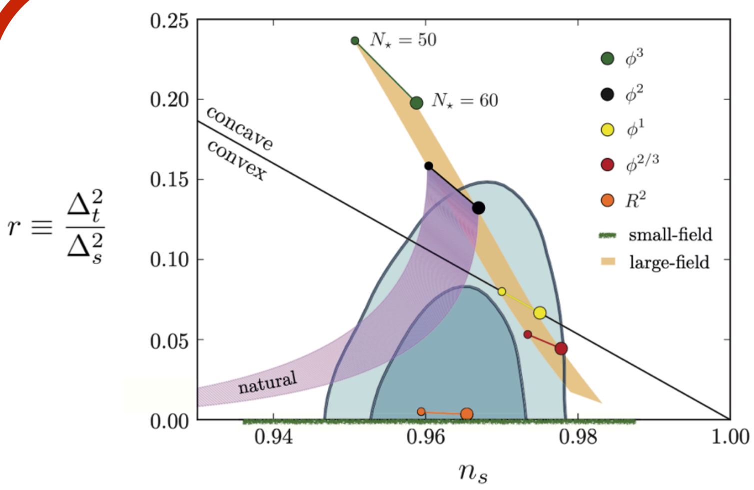


Image courtesy M. Amin



Anything goes?



Little or no interactions

Weak couplings to other fields during inflation →

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Planck 2018 (68% CL)

Can’t a dimension five or six operator provide reheating to the Standard Model?

Inflation is UV Sensitive (Eta problem)

Gravity is non-renormalizable

Graviton scattering is non-unitary near Planck scale, new degrees of freedom expected.

$$\mathcal{L}_{\rm eff}(\phi) = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{4}\lambda\phi^4 - \sum_{p=1}^{\infty}\Big[\lambda_p\phi^4 + \nu_p(\partial\phi)^2\Big]\Big(\frac{g\,\phi}{\Lambda}\Big)^{2p} + \dots\,,$$

Example: Dimension 6 operators present a challenge for inflation given proximity to the Planck scale

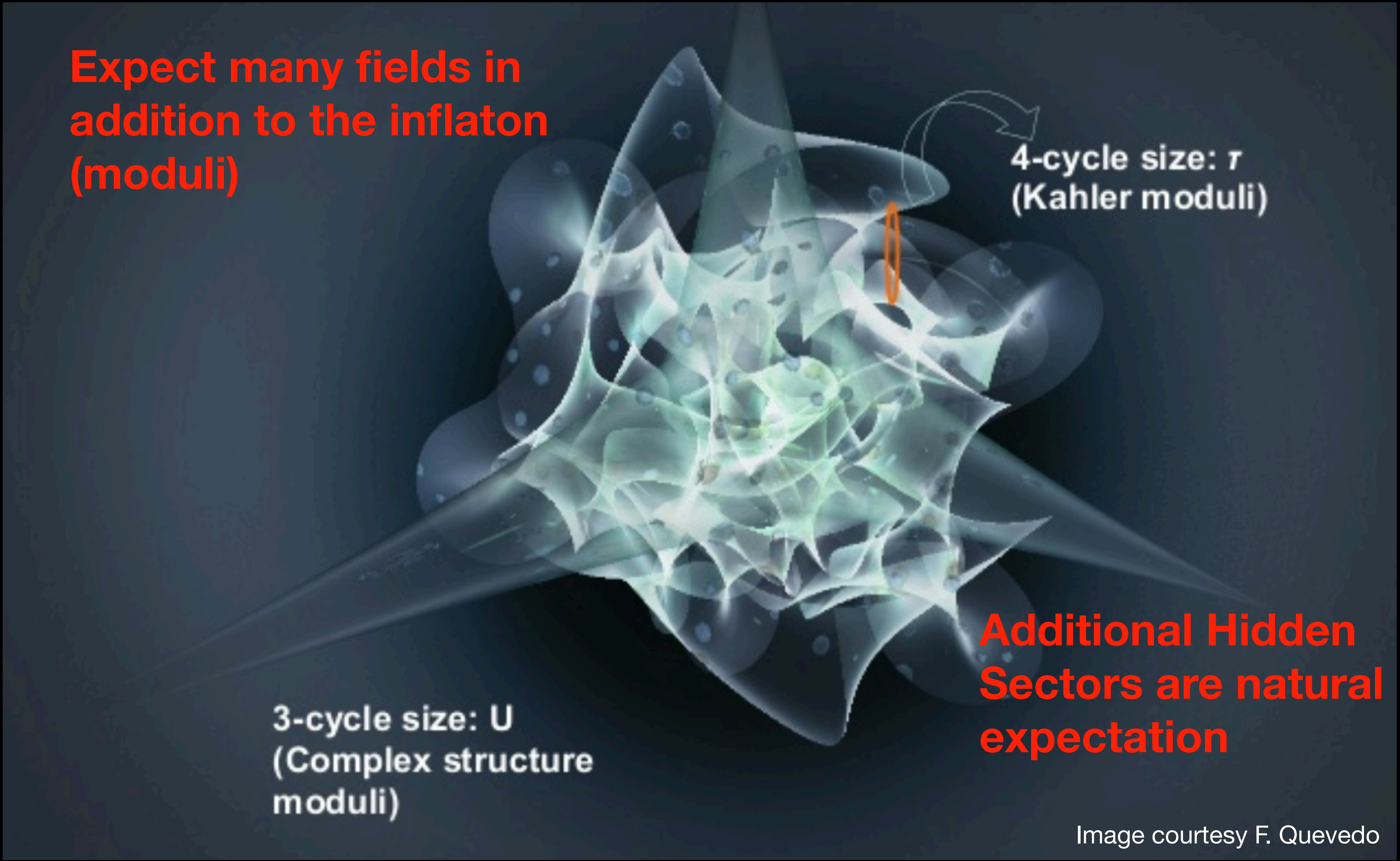
$$\hat{\mathcal{O}}_6 \sim \frac{\phi^6}{\Lambda^2} \subset \frac{\langle\phi^4\rangle}{\Lambda^2}\phi^2 \sim \frac{V_0}{m_p^2}\phi^2 = H^2\phi^2$$

Systematically and self consistently calculating these corrections are crucial and require UV theory (e.g. String Theory)

Lesson: You can’t just have an inflaton

The end of Inflation?

Gravitationally coupled hidden sectors are a natural consequence of inflationary model building.

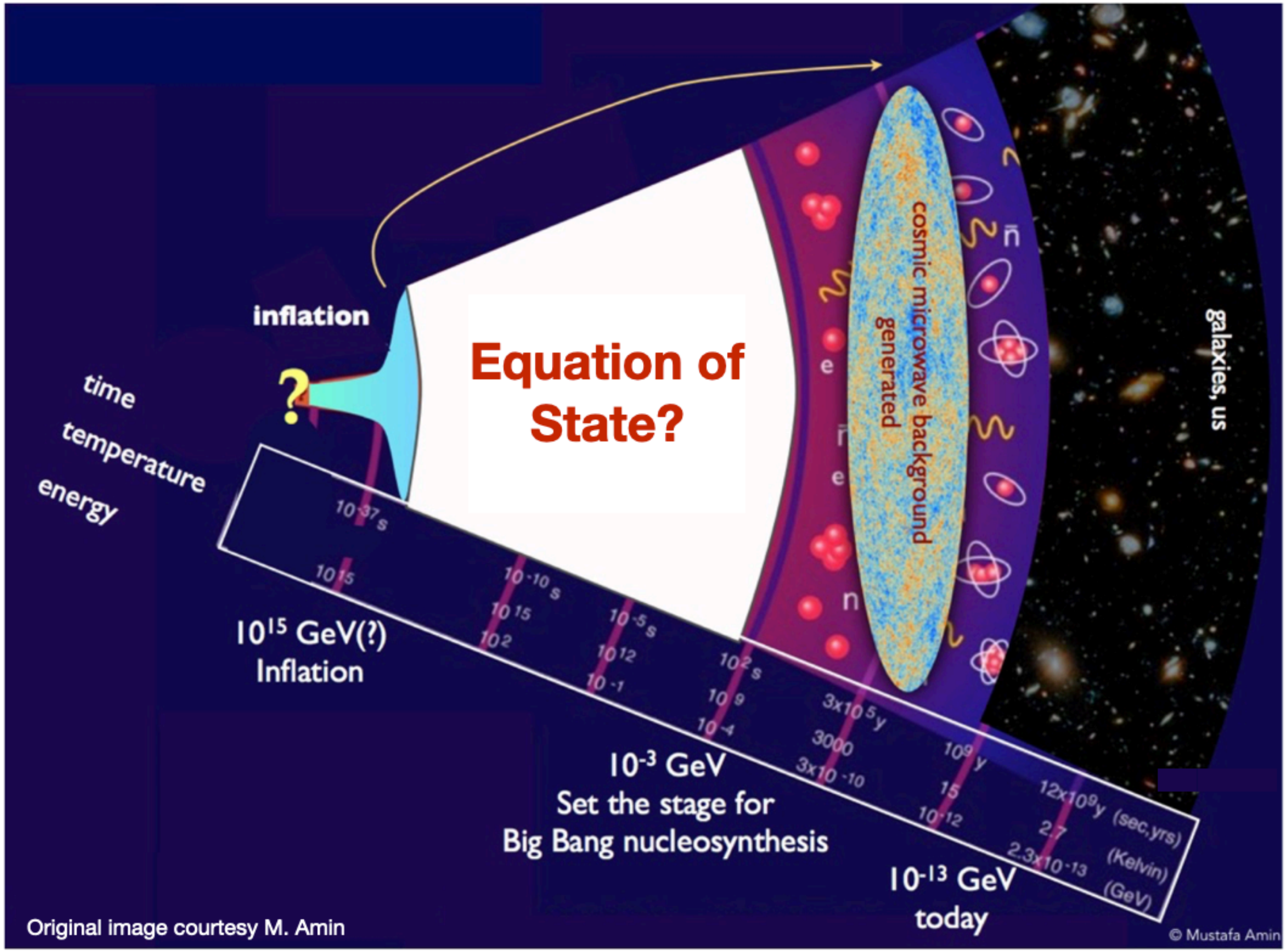


Expect many fields in addition to the inflaton (moduli)

Additional Hidden Sectors are natural expectation

Image courtesy F. Quevedo

The presence of additional fields (e.g. moduli) also alter the early expansion history — “Non-thermal Histories”.



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Non-Thermal Histories Are Well Motivated

“Cosmological Moduli and the Post-Inflationary Universe: A Critical Review ”

with Kuver Sinha and Gordon Kane [arXiv: 1502.07746]

Experimental:

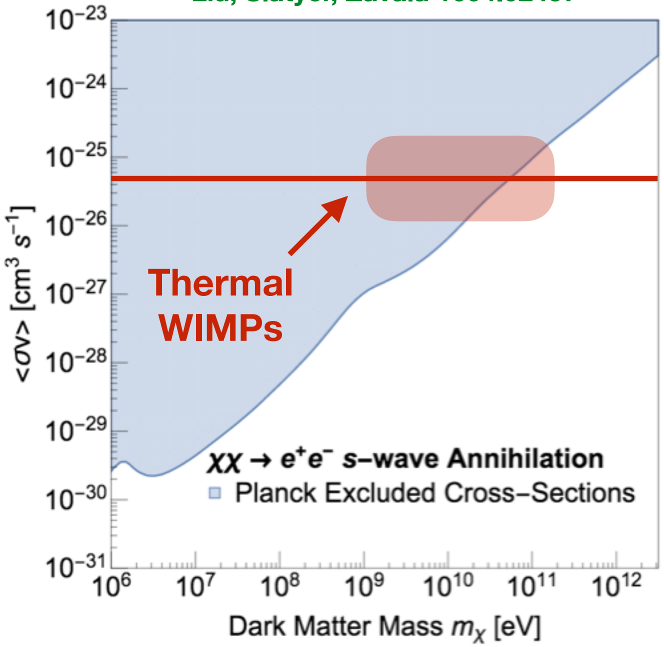
CMB and Inflation (Planck)
Many inflationary models favor non-thermal history.

Lack of thermal WIMP detection

Recombination Constraints (Planck)
Thermal WIMPs in tension

Non-Standard History —> New Phenomenology

Liu, Slatyer, Zavala 1604.02457

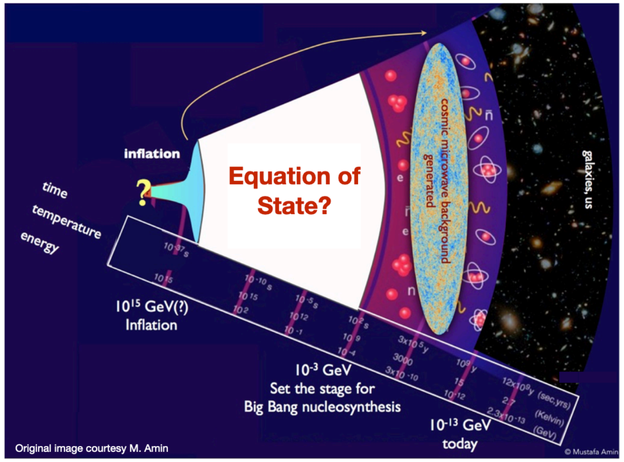


Theoretical:

Many **String Theory** models motivate non-thermal histories.
(Example: Moduli with low-scale masses (near TeV) form condensates.)

Inflationary Reheating:
Transfer of energy from inflationary sector to Standard Model and hidden sectors (BSM / dark matter) can lead to prolonged matter domination.

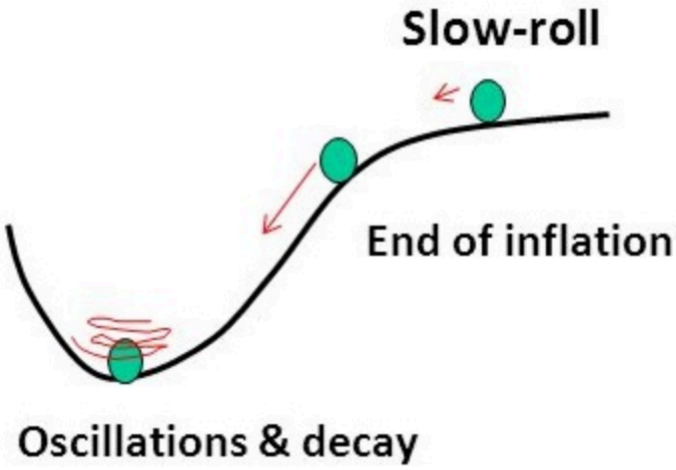
How did inflation end?



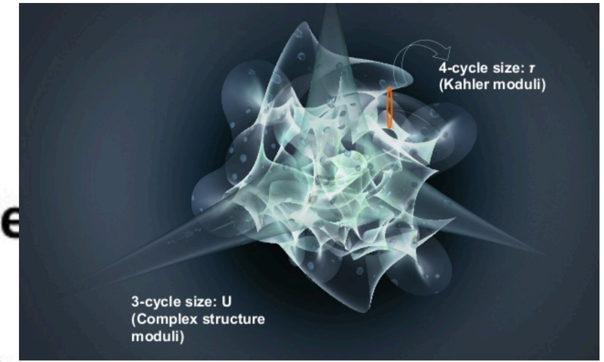
Original image courtesy M. Amin

Slow-roll inflation

A scalar field (inflaton) slowly-rolling down to its potential minimum



1. Inflation at slow-roll e
2. End of Inflation
3. Coherent oscillations
4. Decays to Standard Model particles ?
5. Reheating → Big-Bang Cosmology



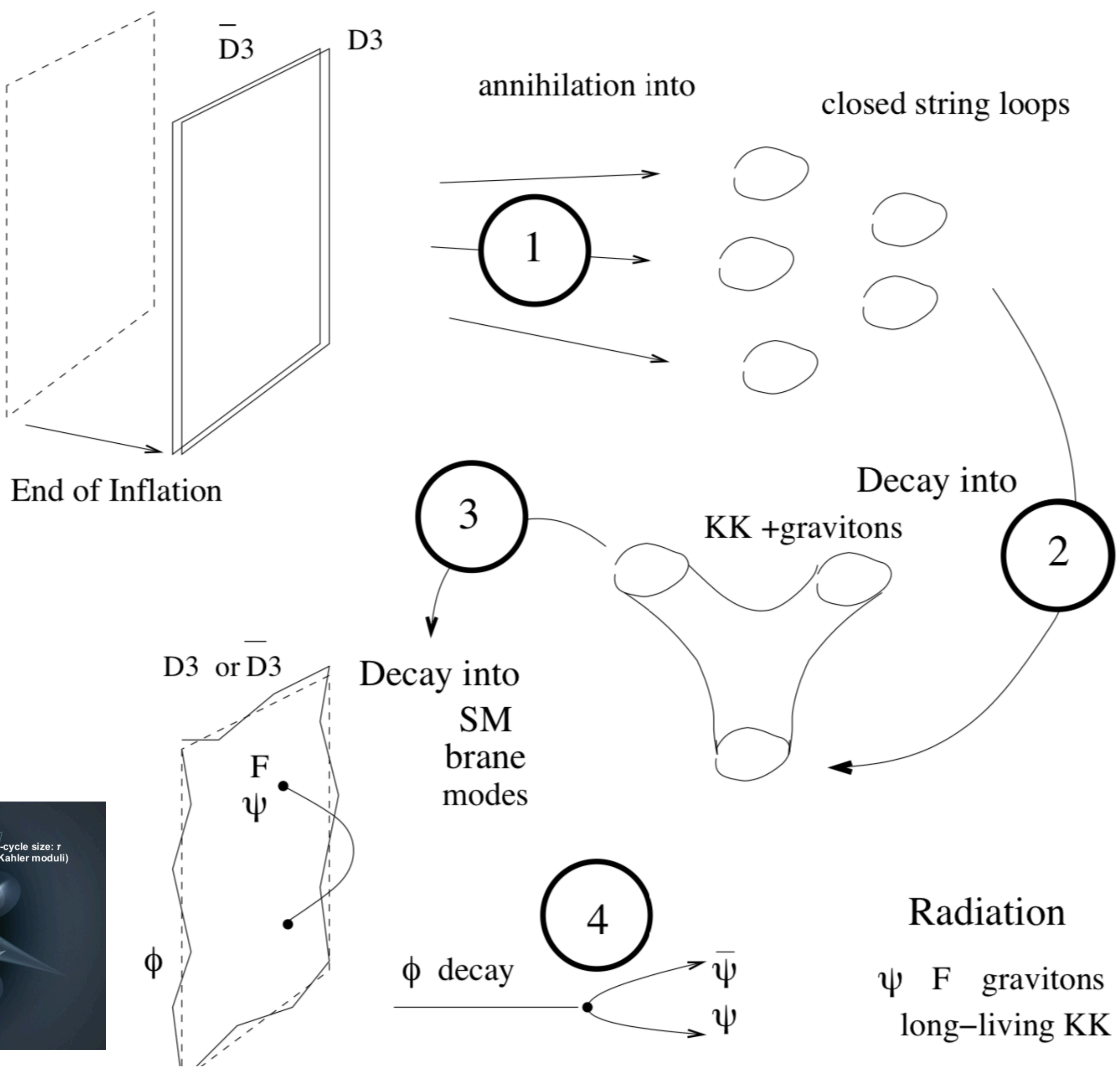
Lecture notes on Cosmology (UT Austin)

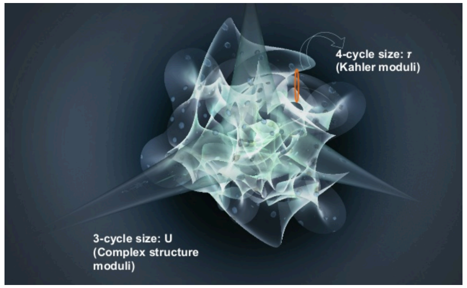
Reheating the universe after string theory inflation

Kofman and Yi   hep-th/0507257

Lev Kofman
1957 — 2009

Cascading Energy from Inflaton to Radiation





Very little work on UV complete theories of Inflationary reheating…

Perturbative reheating in Large Volume Inflation (closed string model)

Reheating and Dark Radiation after Fibre Inflation
Cicoli and Piovano arXiv:1809.01159

Reheating for Closed String Inflation
Cicoli and Mazumdar arXiv:1005.5076

Standard Model on D3 branes

$$\frac{\mathrm{Br}\left(\varphi \to \mathrm{SM}\right)}{\mathrm{Br}\left(\varphi \to \mathrm{Hidden}\right)} \simeq \frac{2}{5}\left(\alpha_{\mathrm{SM}}\right)^2 \ll 1$$

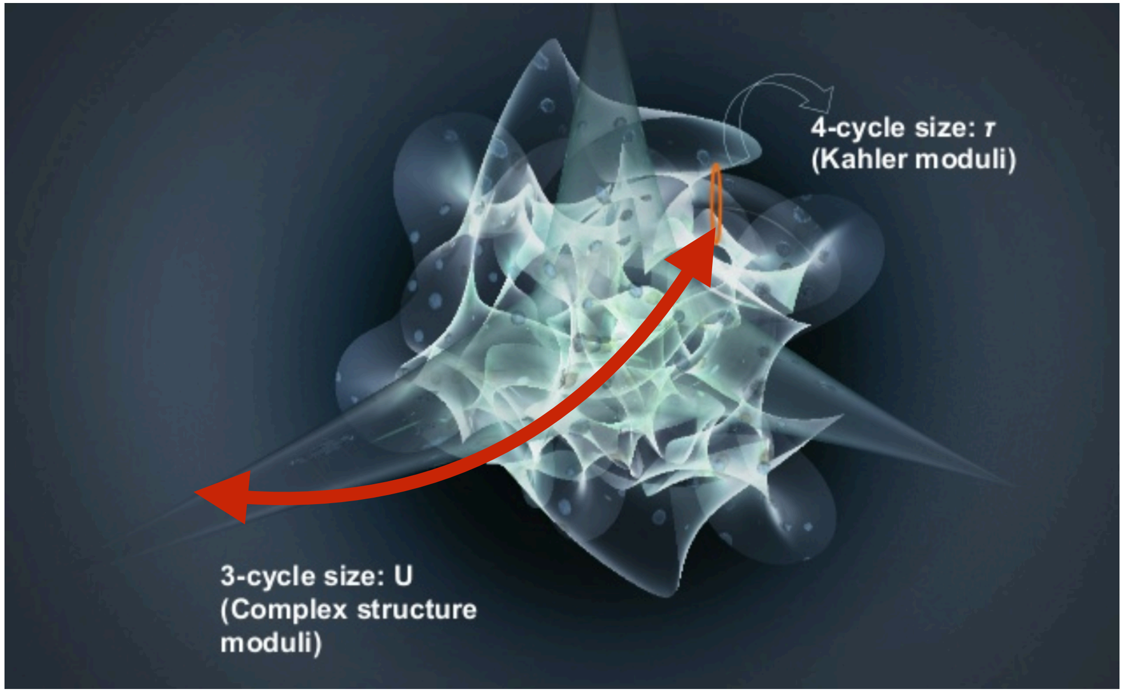
Standard Model on D7 branes (difficult to avoid hidden sector production)

$$\Gamma_{\varphi \to a_i a_i} = \frac{5}{96\pi}\left(\frac{m_\phi^3}{m_p^2}\right) \qquad \Gamma_{\varphi \to \mathrm{SM}} = \frac{\gamma^2 N_g}{48\pi}\left(\frac{m_\phi^3}{m_p^2}\right)$$

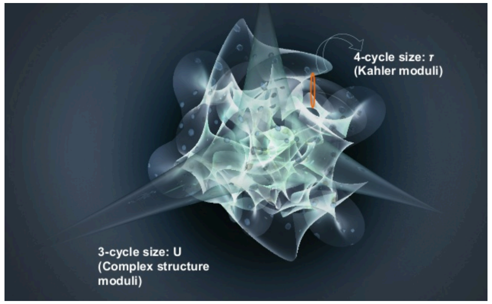
Sufficiently isolating the inflaton is problematic for reheating.

Hidden Sectors v.s. Standard Model

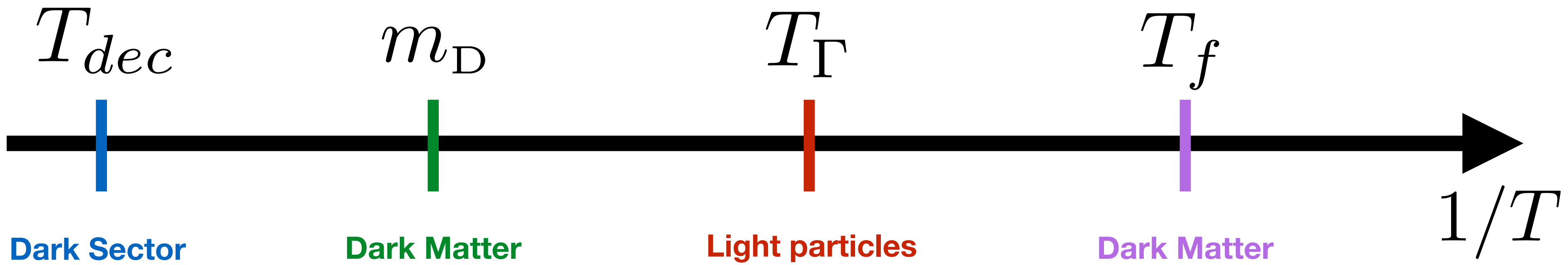
New ways to populate Dark Matter (Hidden Sector)



Co-decay Mechanism



"Co-Decaying Dark Matter" — PRL 117 (arXiv: 1607.03110)
by J. Dror (Berkeley), E. Kuflik (Hebrew University), and W. Ng (Cornell)

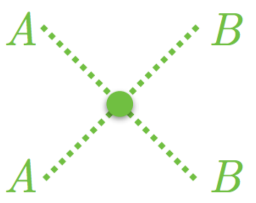


(time)

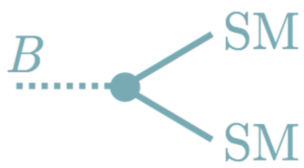
Dark Sector decouples from SM (while relativistic)

Dark Matter non-Relativistic

$AA \leftrightarrow BB$



Light particles Decay to SM



Dark Matter freezes out

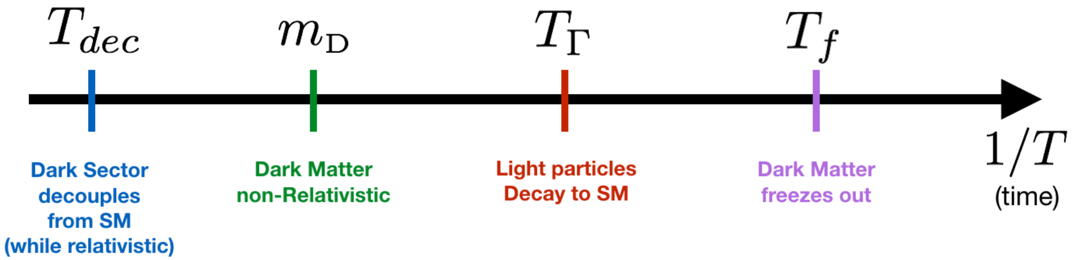
'A' particles are the DM

Dark Sector is not in thermal equilibrium with Standard Model (it decouples completely, very early, and while relativistic).

Dark sector temperature scales differently than Standard Model.

Dark Sector particles in equilibrium until decay. No Boltzmann suppression.

Co-decay Mechanism



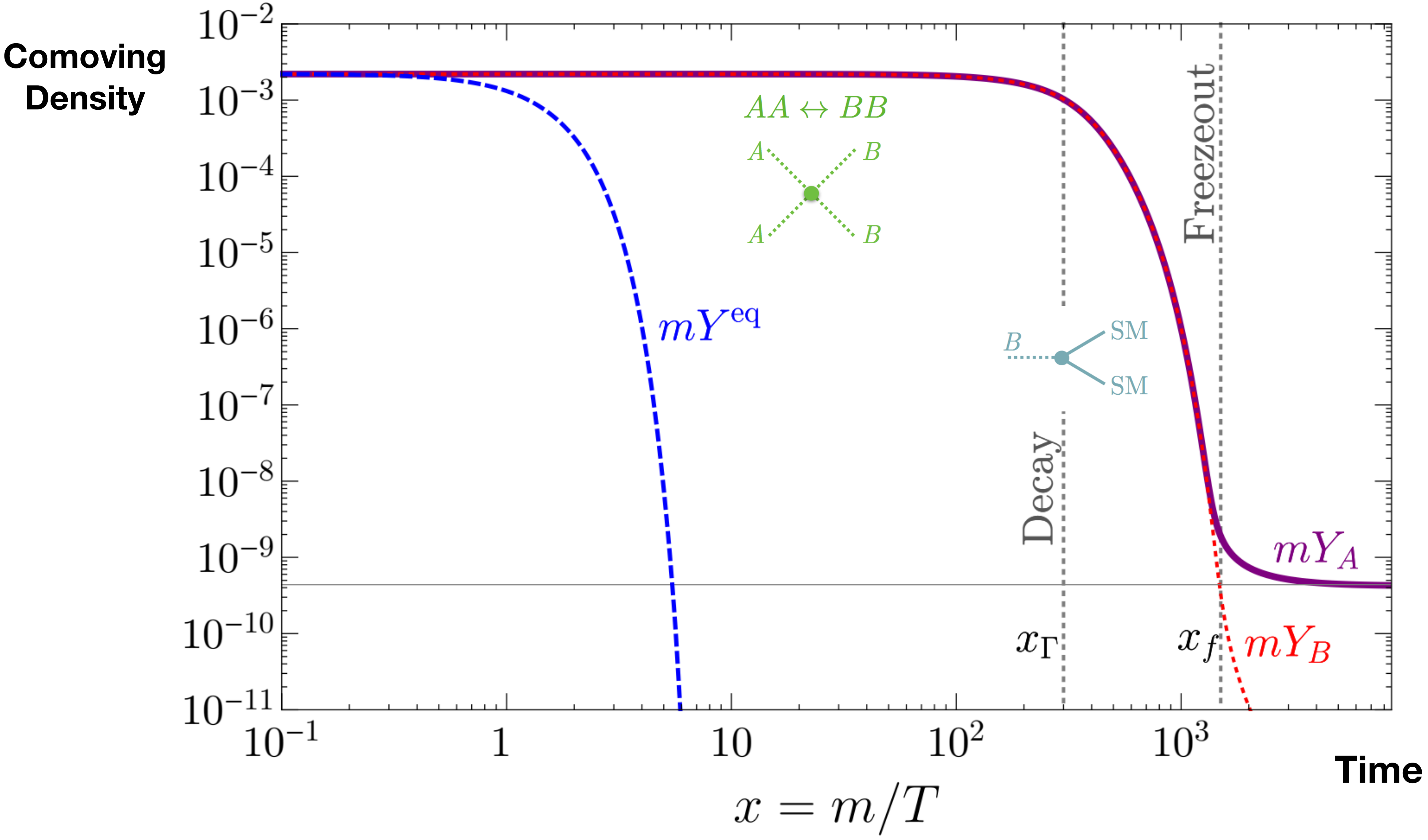
T_{dec} — Dark Sector decouples from SM (while relativistic)

m_D — Dark Matter non-Relativistic

T_Γ — Light particles Decay to SM

T_f — Dark Matter freezes out

$1/T$ (time)



Co-decaying Dark Matter: An Explicit Model

Dark SU(2) Gauge theory

$$D^\mu \Phi_D^\dagger D_\mu \Phi_D - \frac{1}{4} F_D^{a,\mu\nu} F^a_{D,\mu\nu} - \lambda_D \left(\Phi_D^\dagger \Phi_D - \frac{v_D^2}{2} \right)^2$$

Custodial symmetry implies nearly degenerate masses and stability of gauge bosons

Explicitly broken to U(1)

$$\mathcal{O}_6 = \frac{\left(\Phi_D^\dagger D^\mu \Phi_D\right)\left(\Phi^\dagger D^\mu \Phi\right)}{\Lambda^2}$$

(E.g. integrate out heavy fermions charged under both sectors)

Stable Dark Matter ("A" sector)

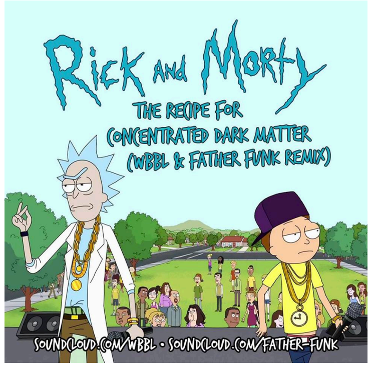
$$W_D^\pm = \left(W_D^1 \mp W_D^2\right)/\sqrt{2}$$

$$\boxed{m_{\mathrm{D}} \simeq m_{\mathrm{Z}}^{(\mathrm{D})} \simeq m_{\mathrm{W}}^{(\mathrm{D})}}$$

Decaying particle ("B" sector)

$$Z_D \equiv W_D^3$$

Decays to Standard model through mixing



Concentrated Dark Matter

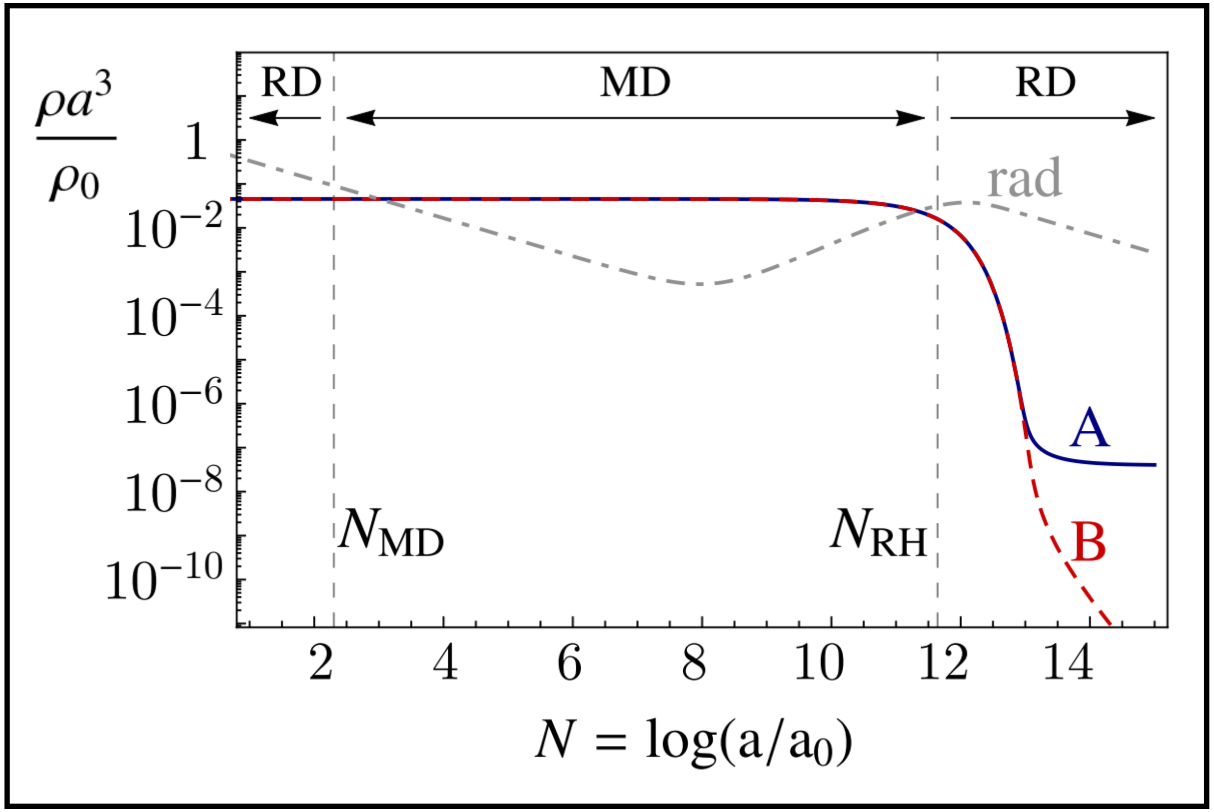
“Concentrated Dark Matter” — PRD 97 (arXiv: 1711.04773)
with J. Dror (Berkeley), E. Kuflik (Hebrew University), and B. Melcher (Syracuse)

Co-decay leads to interesting consequences for the early cosmic history and the structure of dark matter

$$\rho'_A + \rho'_B = -3(\rho_A + \rho_B) - \frac{\Gamma_B}{H}\rho_B,$$

$$\rho'_A = -3\rho_A - \frac{\langle \sigma v \rangle}{mH}\left[\rho_A^2 - \rho_B^2\right],$$

$$\rho'_r = -4\rho_r + \frac{\Gamma_B}{H}\rho_B,$$



The Dark Sector leads to an early matter dominated phase.

Concentrated Dark Matter

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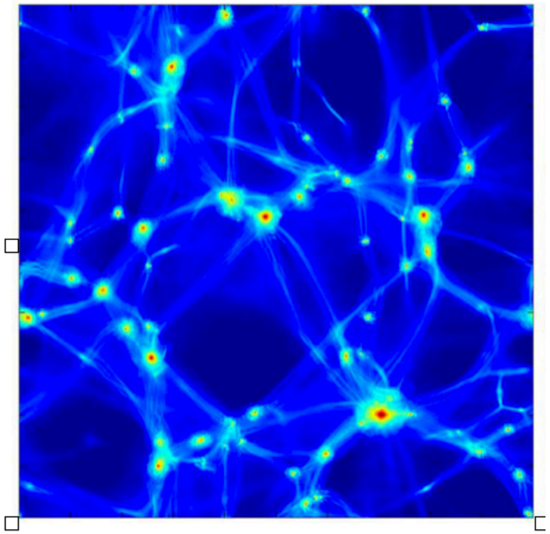
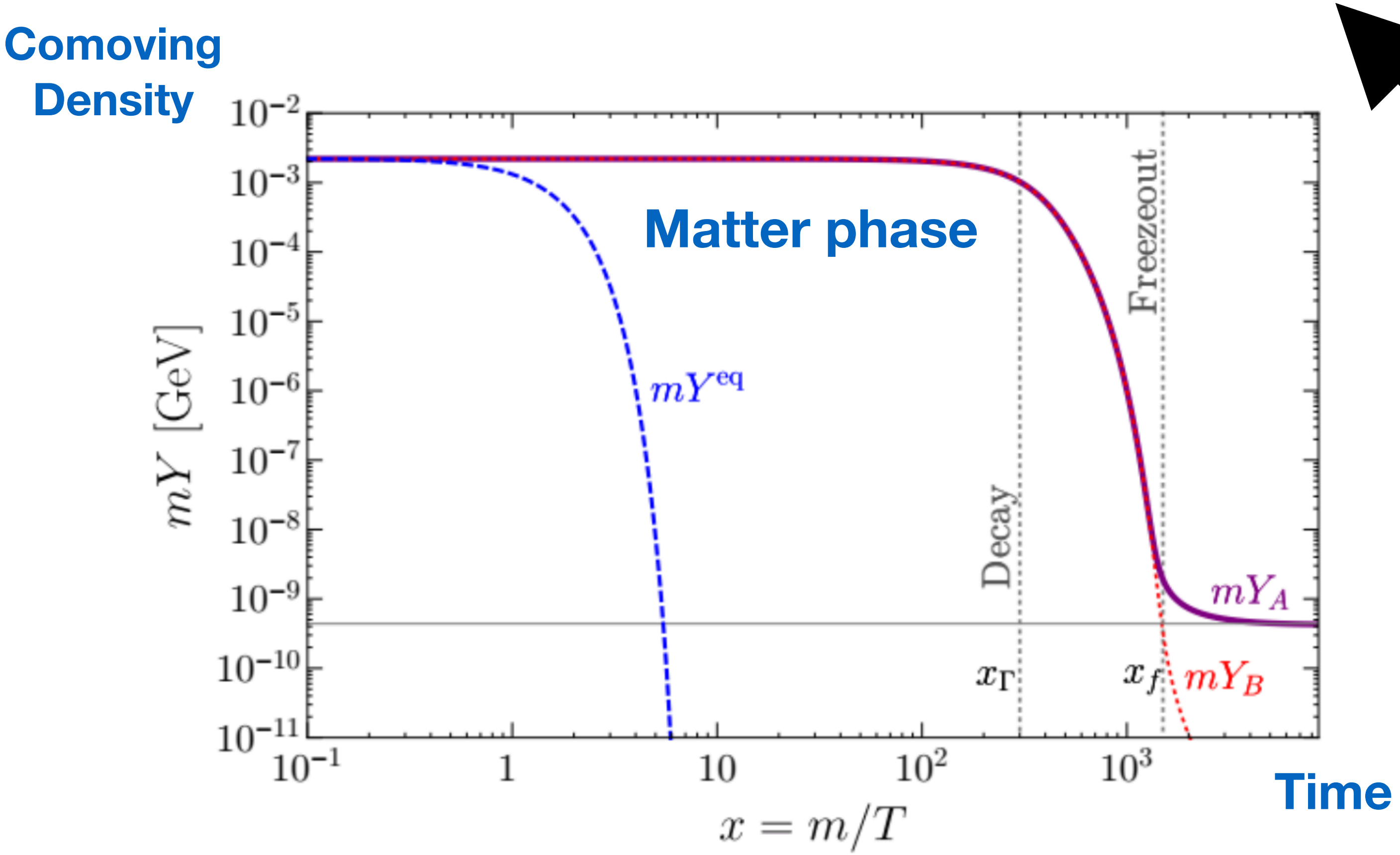


Unlike, Standard SUSY WIMPs,
Dark matter decouples from Standard Model early .



Compare to:

Fan, Ozsoy, and Watson (Phy. Rev. D90)

Erickcek and Sigurdson (Phy. Rev. D84)

Cosmological Dark matter results from decay of hidden sector particles.

Growth of substructure can lead to enhanced signals for indirect detection.

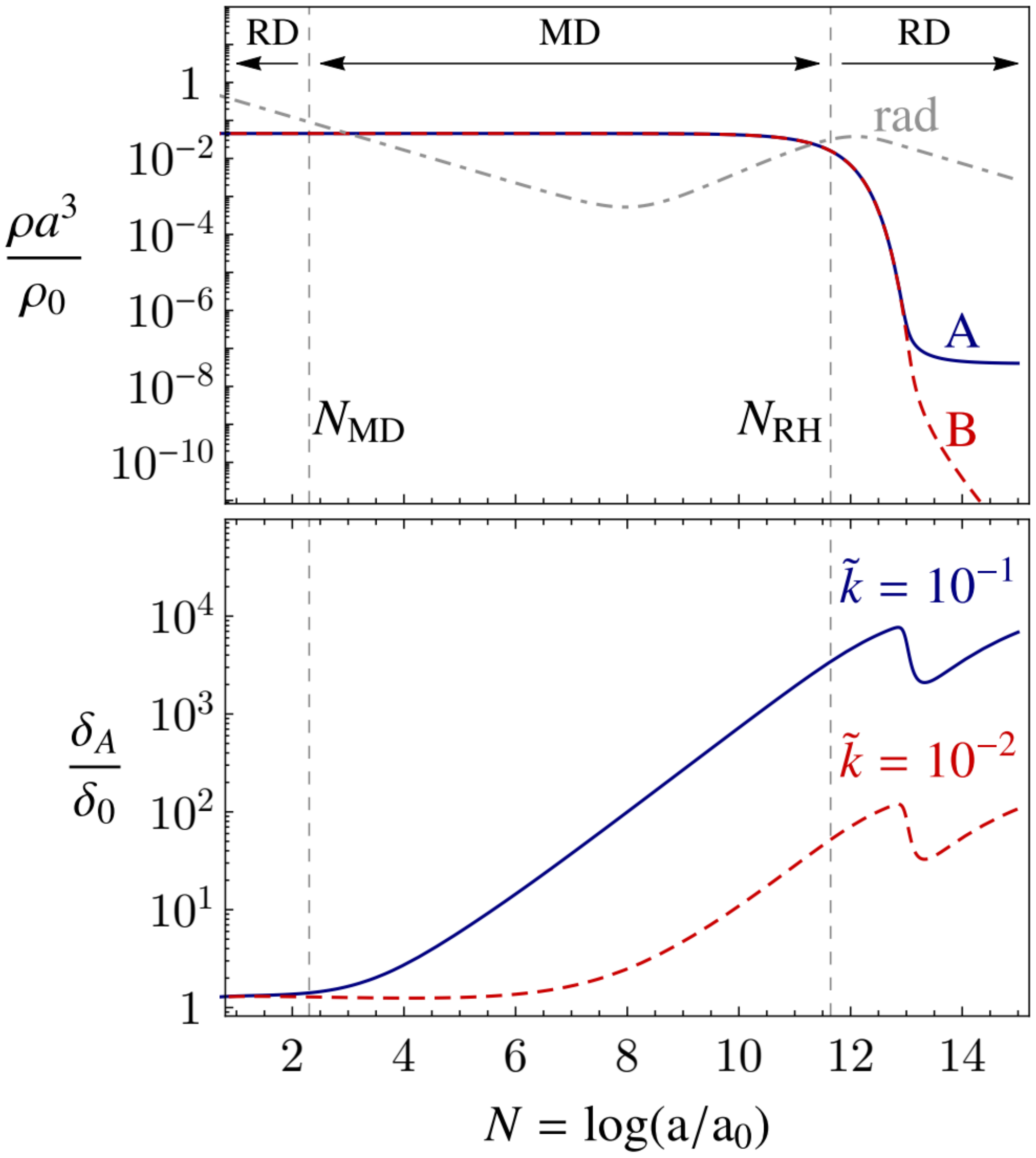
Concentrated Dark Matter

"Concentrated Dark Matter" — PRD 97 (arXiv: 1711.04773)
with J. Dror (Berkeley), E. Kuflik (Hebrew University), and B. Melcher (Syracuse)

DM decouples from Standard Model early in the universe.

Enhanced DM substructure will not suffer from free streaming and kinetic coupling.

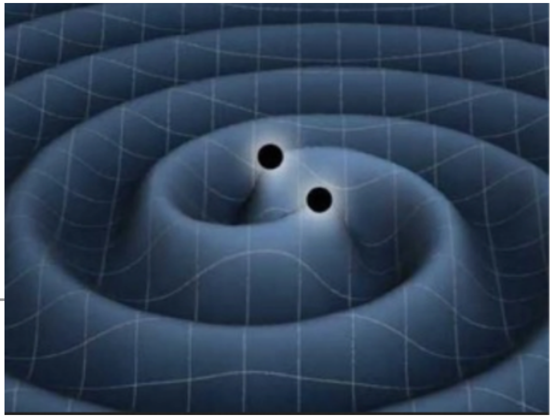
If these structures survive until today, they lead to enhanced indirect detection signals.



Could Black Holes be a significant fraction of the Dark Matter?

Did LIGO see PBH Dark Matter?

Bird, et. al.   PRL116   [arXiv: 1603.00464]



"GW150914"

LIGO detected a gravity wave signal
consistent with the merger of two $\sim 30\ M_\odot$
Black holes at around a 1.3 billion Lyr away

Dark Matter Interpretation

$$20\ M_\odot \lesssim M \lesssim 100\ M_\odot$$

Lensing (improved)

Disrupt Wide Binaries (perhaps CMB as well)

LIGO observation lies in the window where MACHOs are still viable to be all of the dark matter.

Constraints weaken if PBHs are not all of the dark matter.

1603.08338 Sasaki, et. al.;

Could primordial Black Holes be some of the dark matter?

with J. Georg JHEP 1709 (2017)

If structures can form in a matter phase, why can't black holes?

Mass Fraction in PBHs (Thermal History)

Equation of State ($w > 0$)

$$\beta_0(M) \simeq \delta_M(t_H)\exp\left(-\frac{w^2}{2\delta_M^2(t_H)}\right) \qquad \delta_M \equiv \frac{\delta M}{M}$$

Evolution of Density Perturbations

$$\ddot{\delta}_k + 2H\dot{\delta}_k + \left(c_s^2 k_p^2 - \frac{3}{2}H^2\right)\delta_k = 0$$

Hubble "friction" slows the instability

Pressure prevents collapse

Gravity drives collapse

ke PBH formation
thermal universe)

y in black holes

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with J. Georg JHEP 1709 (2017)

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$$\delta_M \equiv \frac{\delta M}{M}$$

Mass Fraction in PBHs (Early Matter Phase)

$$\boxed{\delta_k(t_H) \sim 10^{-4} \longrightarrow \delta_k(t > t_H) \sim \mathcal{O}(1)}$$

(unlike PBH formation in a thermal universe)

Non-linearity does not guarantee PBH formation!

$$\boxed{\beta(M) \simeq 2 \times 10^{-2}\, \delta_M^{13/2}}$$

(Fraction of density in black holes at Mass scale M)

PBH Mass Range from an Early Matter Phase

$$\boxed{M_{min} = 3\frac{m_p^2}{m_\sigma}}$$

$$\boxed{M_{max} \sim \left(\frac{M_{cmb}}{m_p}\right)^{\frac{n-1}{n+3}} \left(\frac{m_p}{m_\sigma}\right)^{\frac{12}{n+3}} m_p}$$

Duration of matter phase determines maximal mass

$$T_r^2 \sim \frac{m_\sigma^3}{m_p}$$

Mass range depends on two parameters.

~~m_σ **Moduli mass**~~

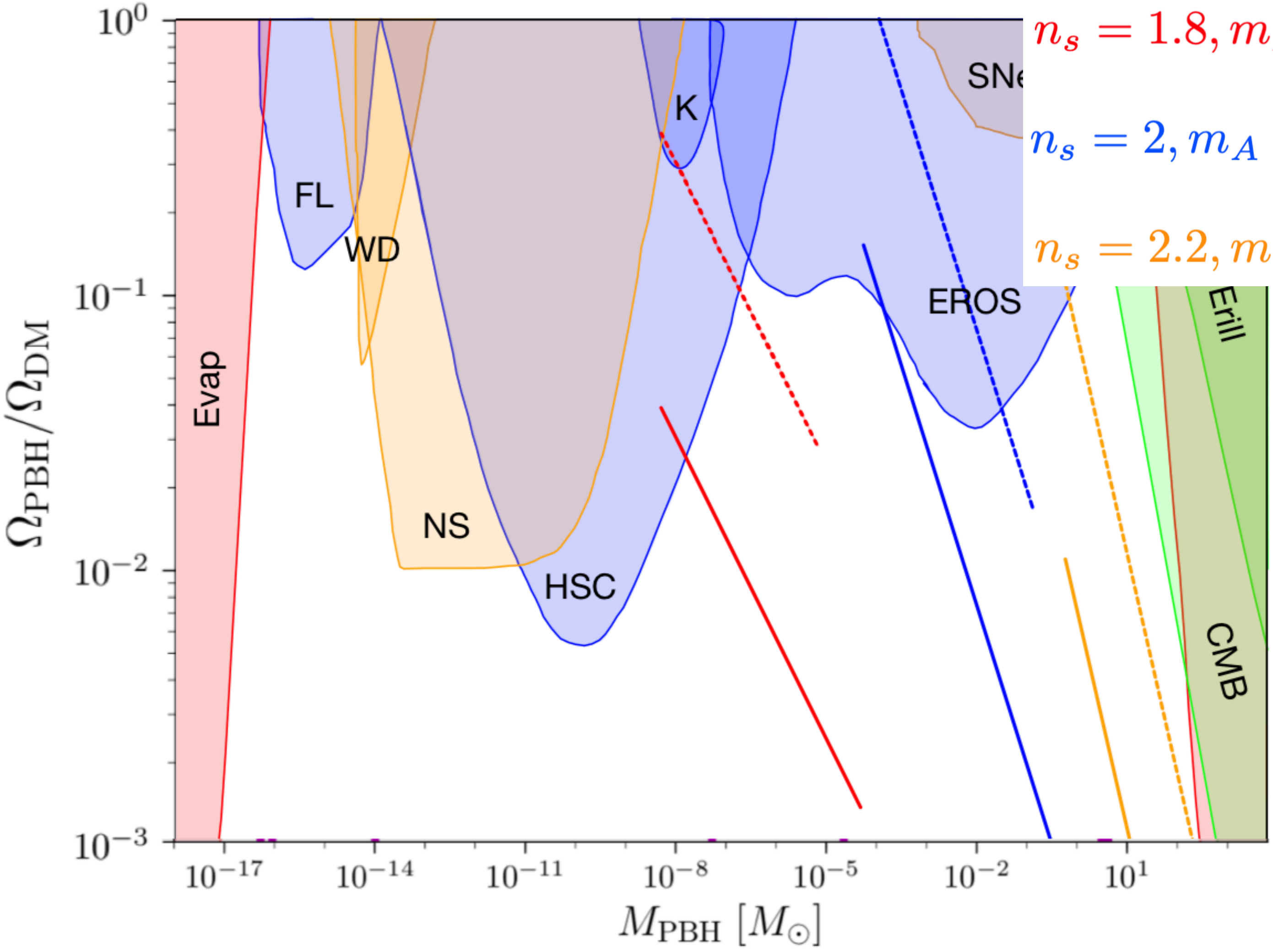
n **Tilt of primordial power spectrum**

$$m_\sigma \sim m_{3/2} \sim 10 - 100\ \mathrm{TeV}$$

Not a free parameter:
Connected to underlying theory

Allowed fraction of DM in PBHs Produced from Co-Decay

“Primordial Blackholes and Co-decaying Dark matter”
with J. Georg (RPI) and B. Melcher (Syracuse) — arXiv: 1902.04082



$n_s = 1.8, m_A = 10^4\ \mathrm{GeV}, \Gamma_{\rm B} = 10^{-16}\mathrm{GeV}$

$n_s = 2, m_A = 100\ \mathrm{GeV}, \Gamma_{\rm B} = 10^{-20}\mathrm{GeV}$

$n_s = 2.2, m_A = 1\ \mathrm{GeV}, \Gamma_{\rm B} = 10^{-24}\mathrm{GeV}$

(dashed lines are 10 times the decay rate)

See talk by Stefano

Data set courtesy of B. V. Lehmann,
S. Profumo, and J. Yant

Conclusions

Cosmology and New Physics

A positive B-mode detection would establish the scale of new physics associated with inflation.

These observations will also put constraints on the presence of new light particles.

Dark matter can be represented by many sources (WIMPs, axions, PBHs, etc…)

Uncertainties in the expansion history prior to BBN can have interesting and impactful implications.

Reheating to the Standard Model, compared to other sectors, could present a substantial challenge for complete models of inflation.

Backup Slides

Early Matter Domination and Structure Growth

Evolution of Density Perturbations

$$\delta_k \equiv \frac{\delta\rho(t,\vec{k})}{\bar{\rho}}$$

$$\ddot{\delta}_k + 2H\dot{\delta}_k + \left(c_s^2 k_p^2 - \frac{3}{2}H^2\right)\delta_k = 0$$

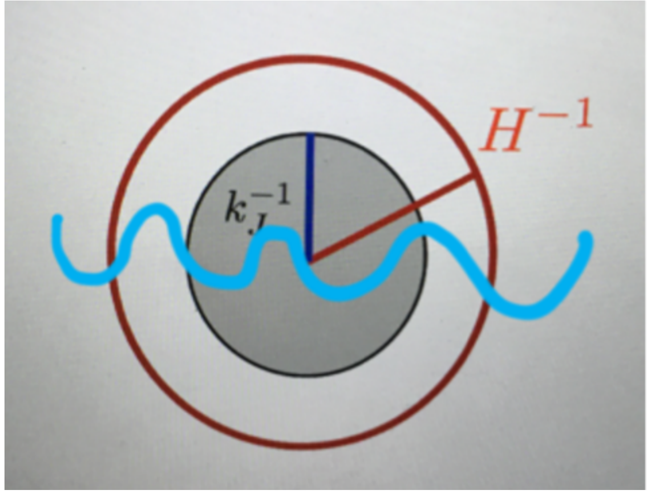
Hubble “friction” slows the instability

Pressure prevents collapse

Gravity drives collapse

Jean’s scale sets the growth scale

$$k_J^2 = \frac{3H^2}{2c_s^2}$$



Co-decaying Dark Matter: An Explicit Model

Self annihilation

$$\sigma \sim \frac{\alpha_{\rm D}^2}{m_{\rm D}^2}$$

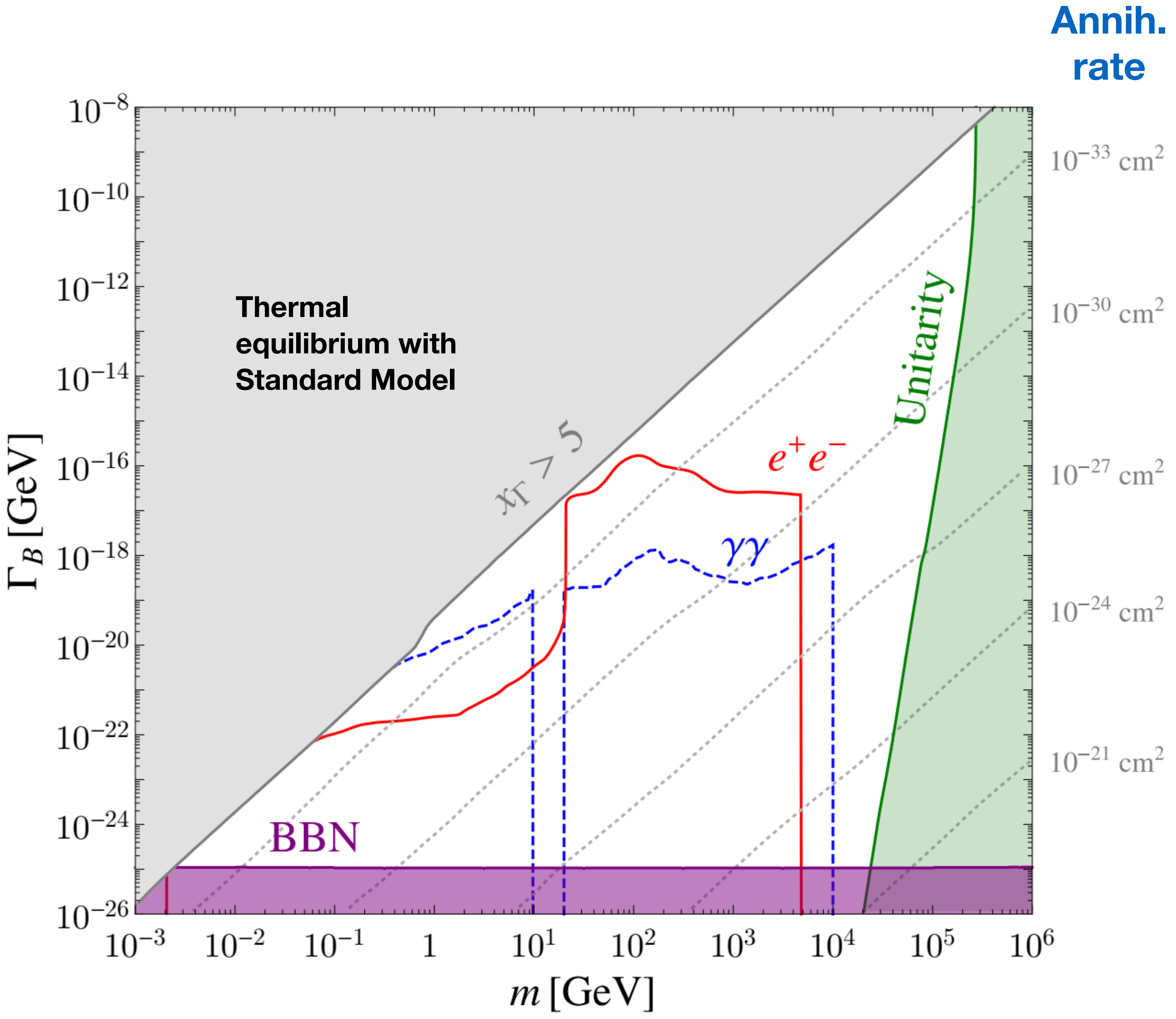
Decay Rate

$$\Gamma_{\rm B} \sim \frac{m_{\rm D}^5}{\alpha_{\rm D}^2 \Lambda^4} \, |g|^2$$

fermion axial/vector coupling to Z

Example:

$$\Lambda \simeq 10 \text{ TeV}$$
$$m_{\rm D} \simeq \text{GeV}$$



No direct detection, no collider signal,
but **meaningful constraints from indirect detection**

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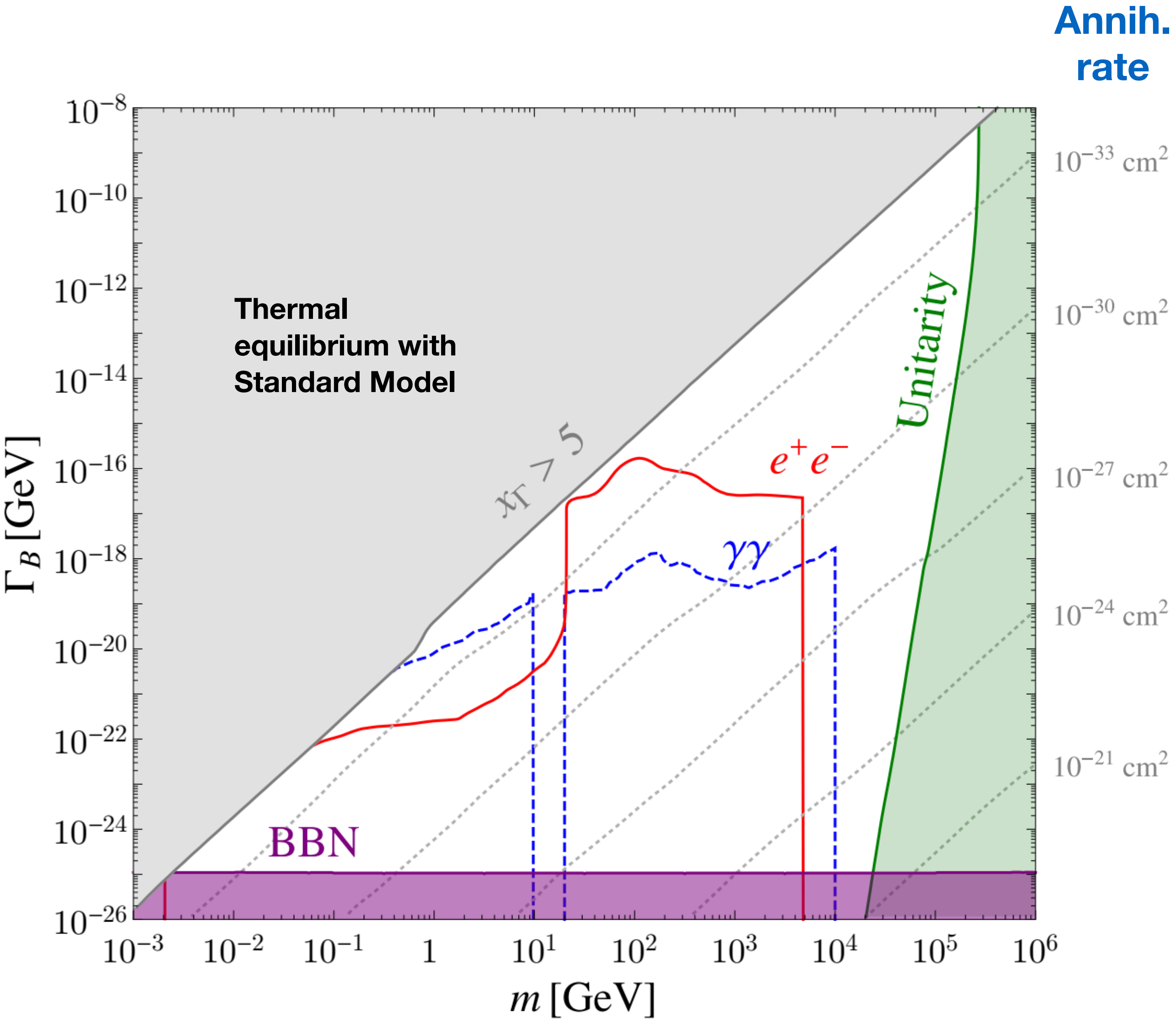
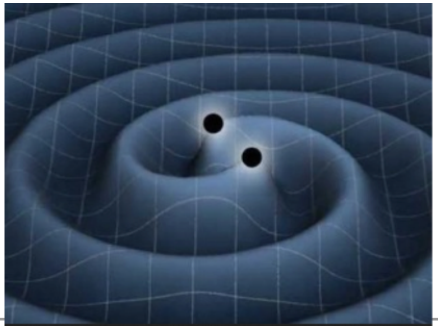


$$f_A \equiv \frac{\Omega_A}{\Omega_{DM}} = \left(\frac{1 \text{ pb}}{\sigma}\right)\left(\frac{m_{\rm A}}{1 \text{ GeV}}\right)^2\left(\frac{10^{-18} \text{ GeV}}{\Gamma_{\rm B}}\right)$$

Did LIGO see PBH Dark Matter?

Bird, et. al. PRL116 [arXiv: 1603.00464]



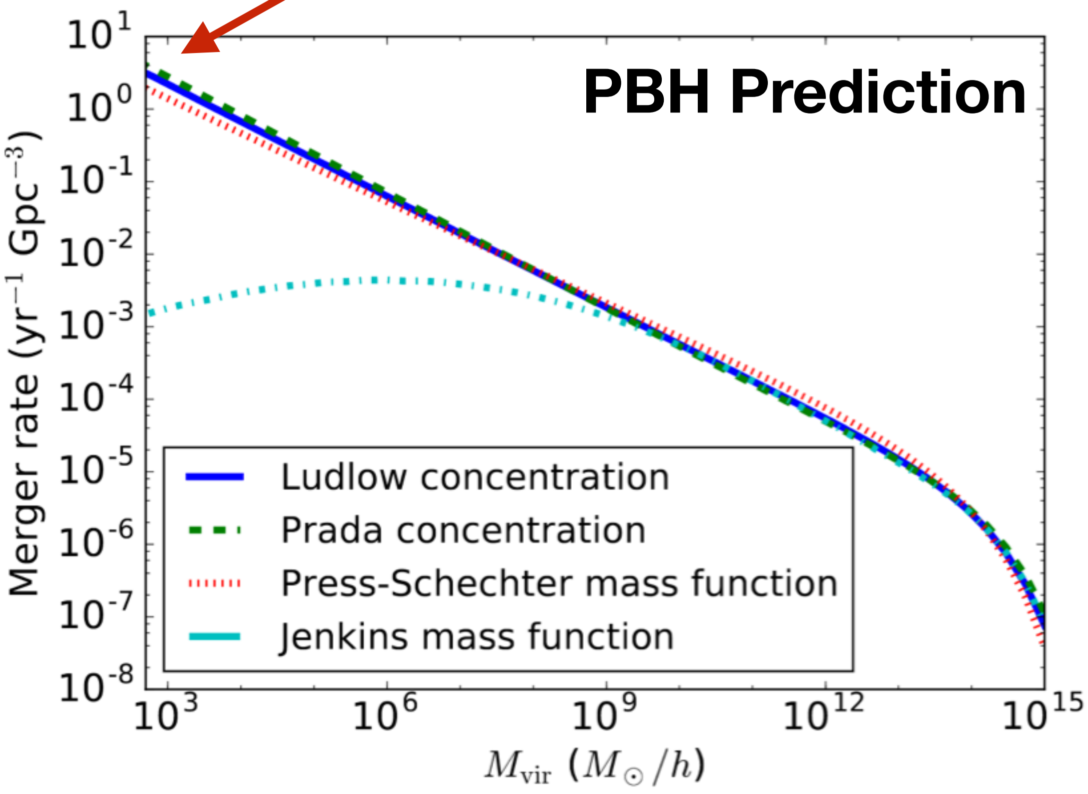
Dark Matter Interpretation

$$20\ M_\odot \lesssim M \lesssim 100\ M_\odot$$

LIGO Merger rate:

$$0.5 - 12\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

Majority reside in low mass halos



Halo Mass

5 years of advanced LIGO data (No PBH DM)

(Kovetz et al., arXiv:1611.01157)

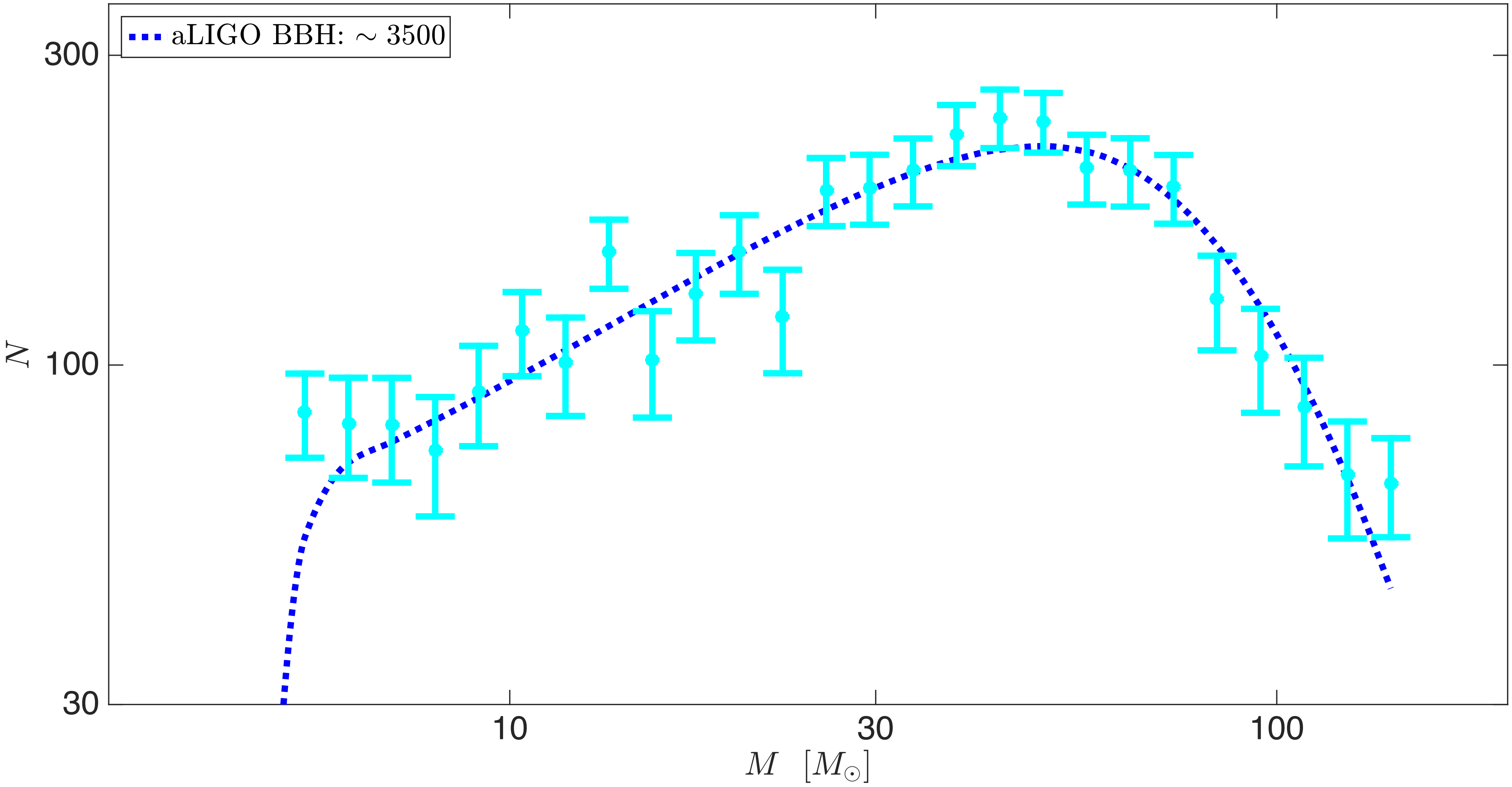


Figure Credit: Ely Kovetz

5 years of advanced LIGO data (with PBH DM)

(Kovetz et al., arXiv:1611.01157)

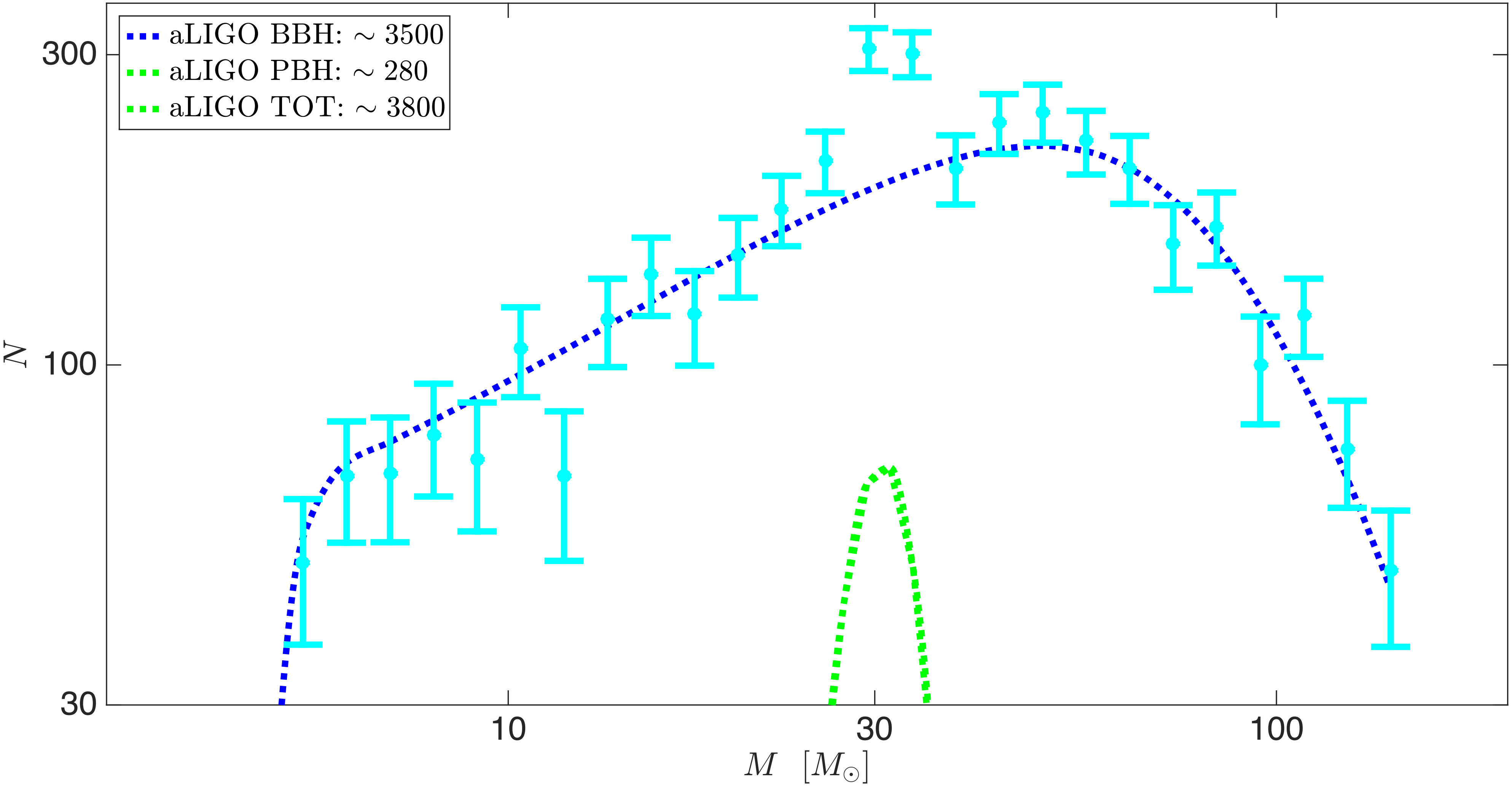


Figure Credit: Ely Kovetz

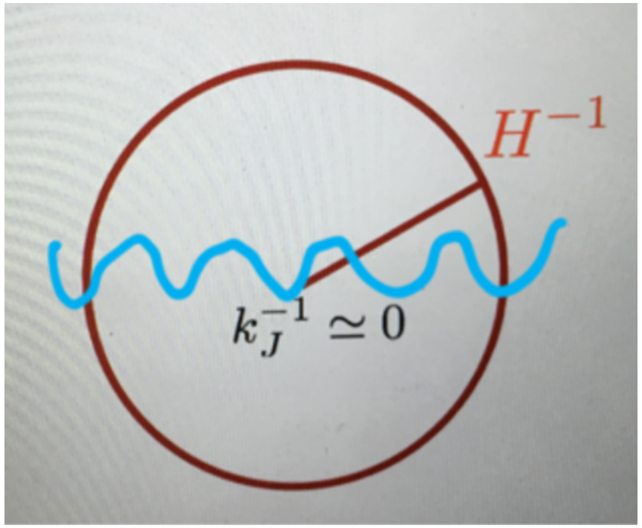
PBH Mass Range from an Early Matter Phase

Low Mass Region

Matter phase begins at $H_{osc} \simeq m_\sigma$

No sub-horizon growth yet, only possibility is collapse of entire Hubble patch into a PBH.

$$3H_{osc}^2 m_p^2 = \rho_{PBH} = M_{PBH} H_{osc}^{-3}$$



$$\boxed{M_{min} = 3\frac{m_p^2}{m_\sigma}}$$

Overly conservative!

PBH Mass Range from an Early Matter Phase

High Mass Region

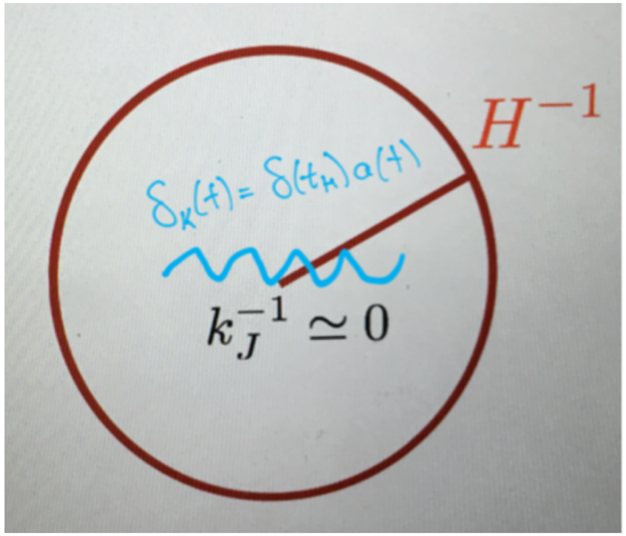
Sub-horizon growth is important.

Tilt of Primordial spectrum

$$\delta_M(t_r) = \delta_{cmb}\left(\frac{M_{max}}{M_{cmb}}\right)^{\frac{1-n}{6}}\left(\frac{t_r}{t_H}\right)^{2/3} \simeq \mathcal{O}(1)$$

Normalize to CMB scales

Sub-horizon growth



Solve this equation implicitly for mass

$$\boxed{M_{max} \sim \left(\frac{M_{cmb}}{m_p}\right)^{\frac{n-1}{n+3}}\left(\frac{m_p}{m_\sigma}\right)^{\frac{12}{n+3}} m_p}$$

Duration of matter phase determines maximal mass

$$T_r^2 \sim \frac{m_\sigma^3}{m_p}$$