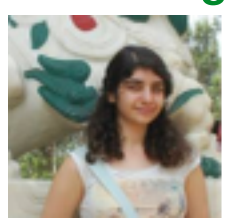
Primordial Black Holes, Dark Matter, and the Post-Inflationary Universe

Scott Watson
Syracuse University

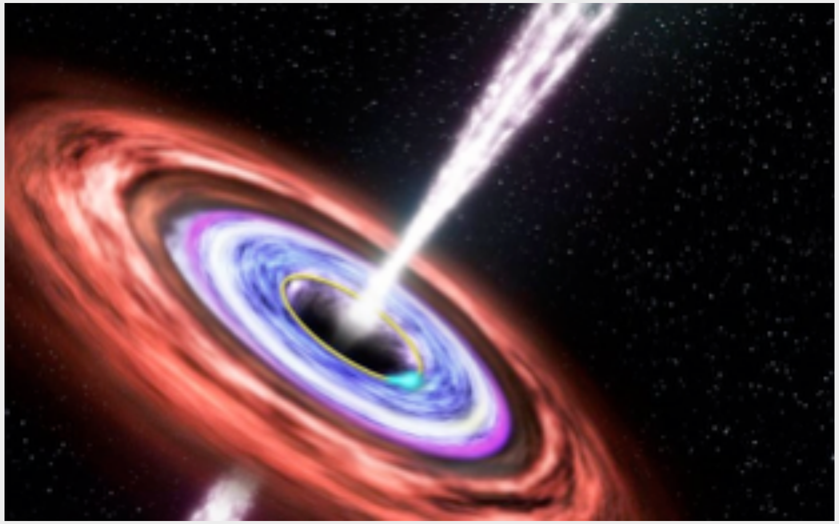
"Non-thermal WIMPs and Primordial Black Holes"
with Julian Georg and Gizem Sengor [arXiv: 1603.00023]



Also based on work in progress with Julian, Bhaskar, and Louis.

See also talk <u>tomorrow</u> by Yu Gao.

Astrophysical Black Holes

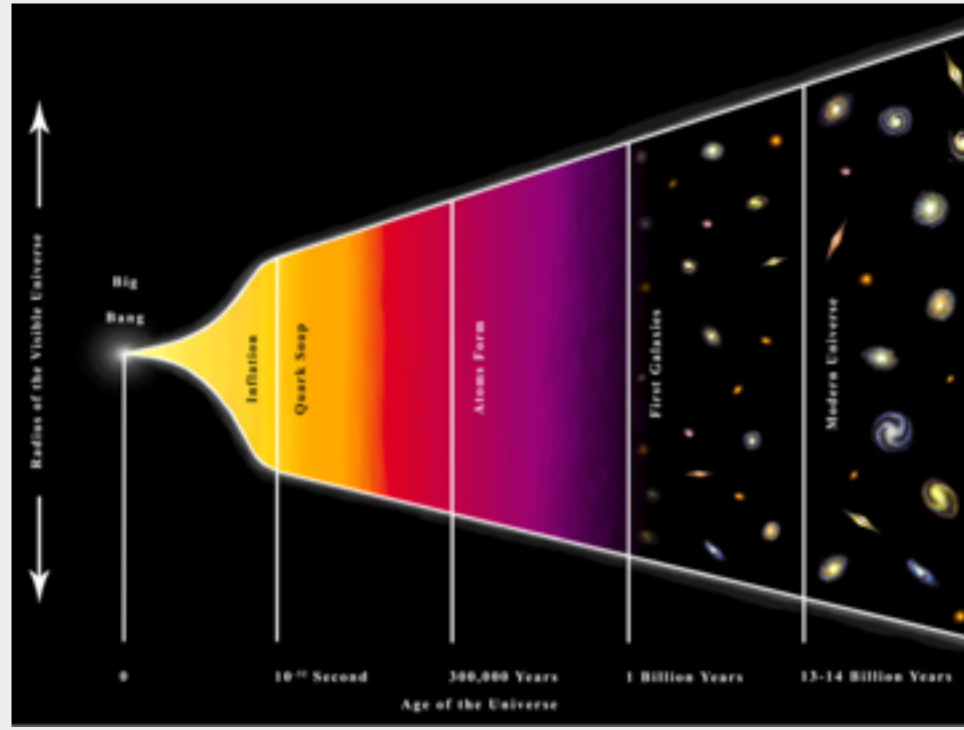


Astrophysical Black Holes can form from collapsed stars. They can be detected by their jets, gamma-ray bursts, and effect on stellar orbits.

$$M_\odot \lesssim M_{BH} \lesssim 10^{10} M_\odot$$

$$M_\odot \simeq 10^{33}\ \mathrm{g}$$

Primordial Black Holes



PBHs formed in the early universe from collapse of density perturbations. They can lead to relics, providing all or part of the dark matter.

$$m_p \simeq 10^{-6}\ \mathrm{g} \lesssim M_{PBH}$$

PBHs can (Hawking) evaporate before today.

$$t_{\mathrm{evap}} \simeq 6.7 \times 10^{17} \left(\frac{M_{\mathrm{PBH}}}{10^{15}\ \mathrm{g}} \right)^3 \mathrm{s}$$

Conclusions

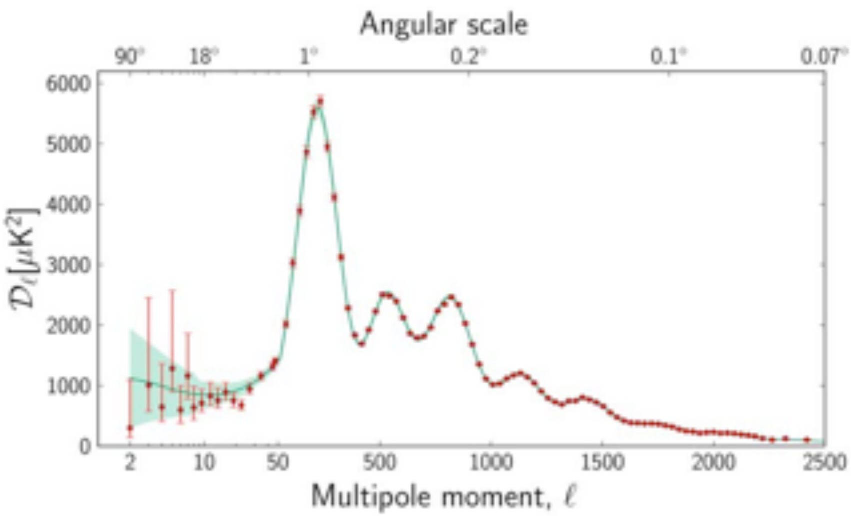
Primordial Black Holes (PBHs) can provide rigid constraints on the post-inflationary / pre-BBN cosmic history.

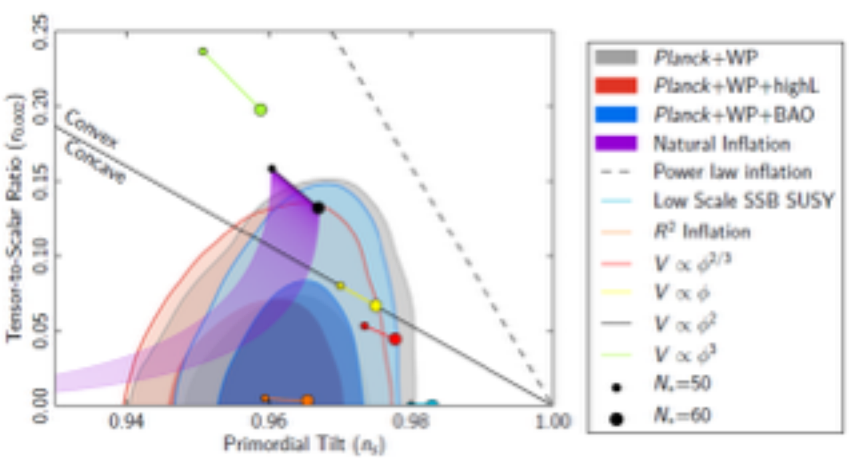
PBHs restrict the primordial power spectrum on a wide range of scales (beyond CMB and Structure formation (LSS) probes).

Provocative Conclusion:

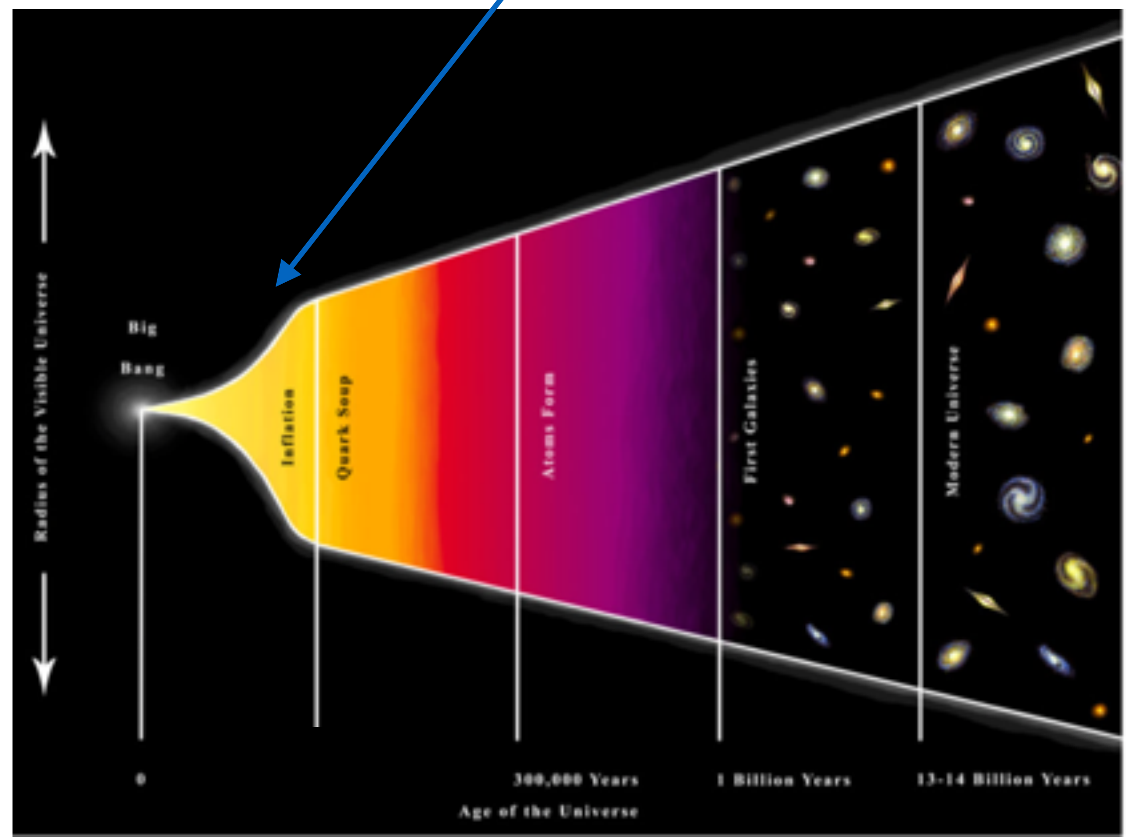
PBHs could be all or part of the dark matter and LIGO may have detected the first "self-annihilation" signal!

Planck provides high precision data to probe the early universe



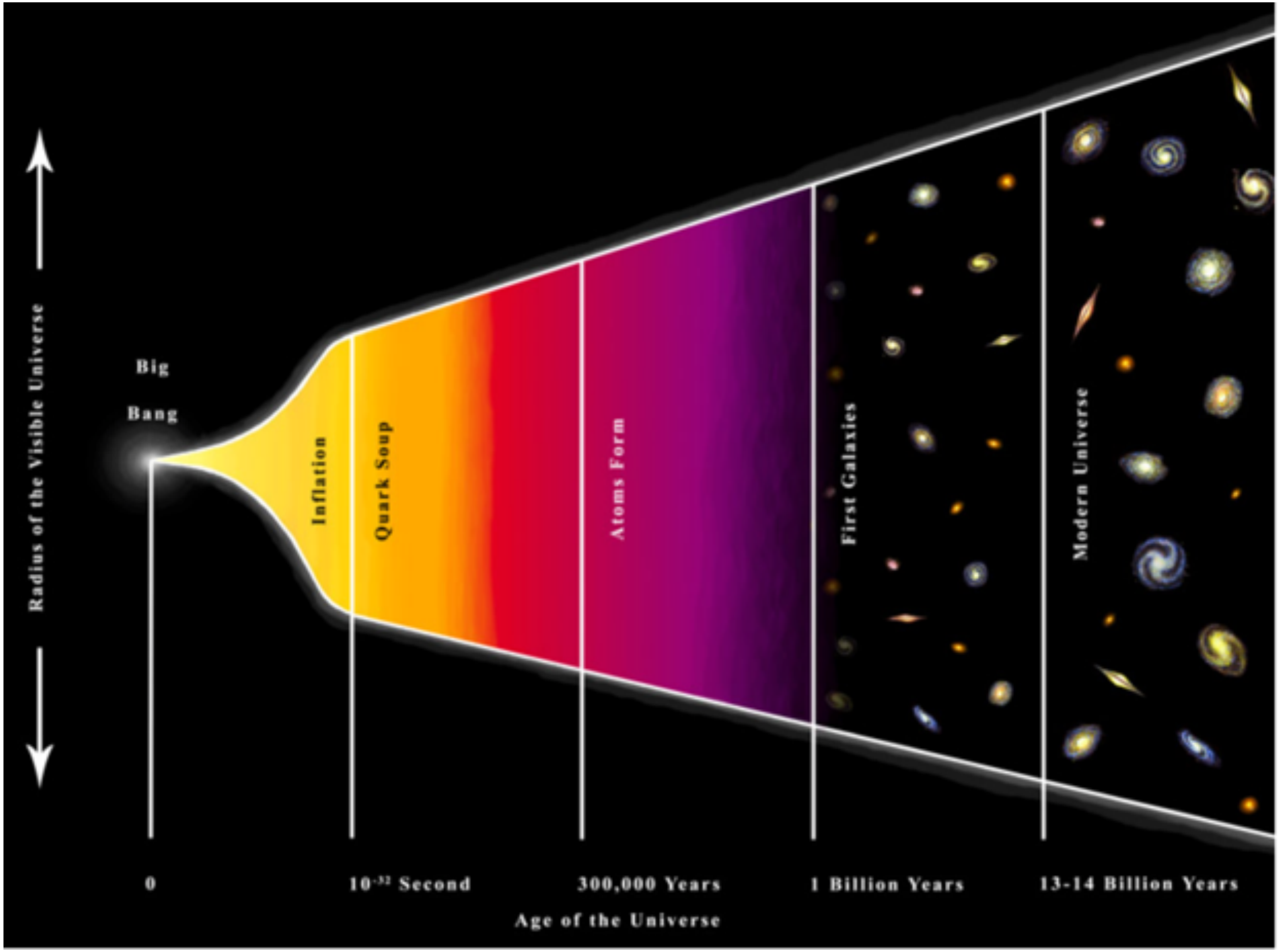


Departure from hot, thermal "Big Bang" picture (i.e. Inflation)



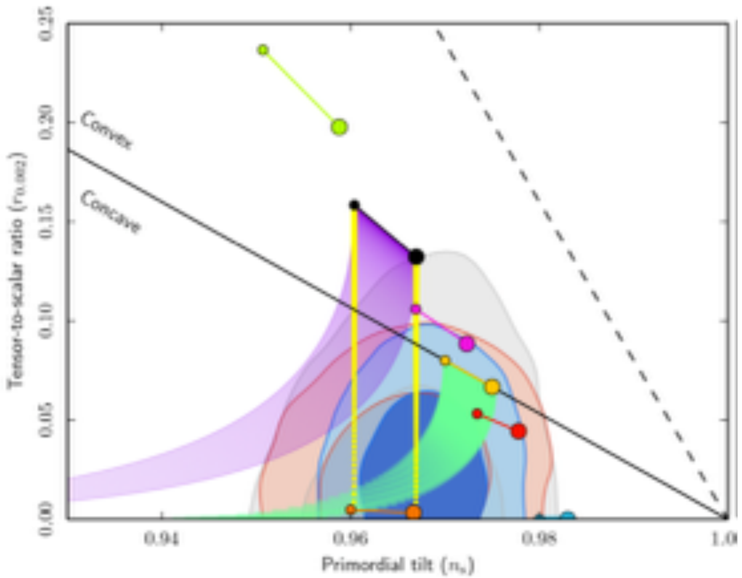
A strictly thermal history can not account for the data!

When did the universe thermalize?

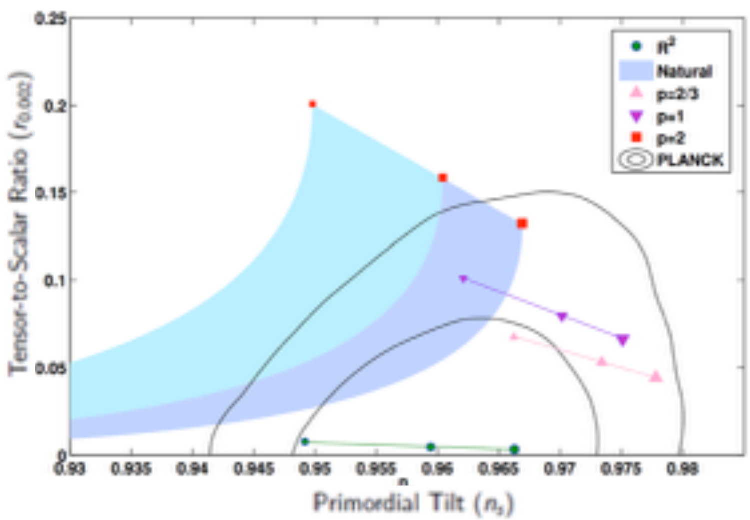


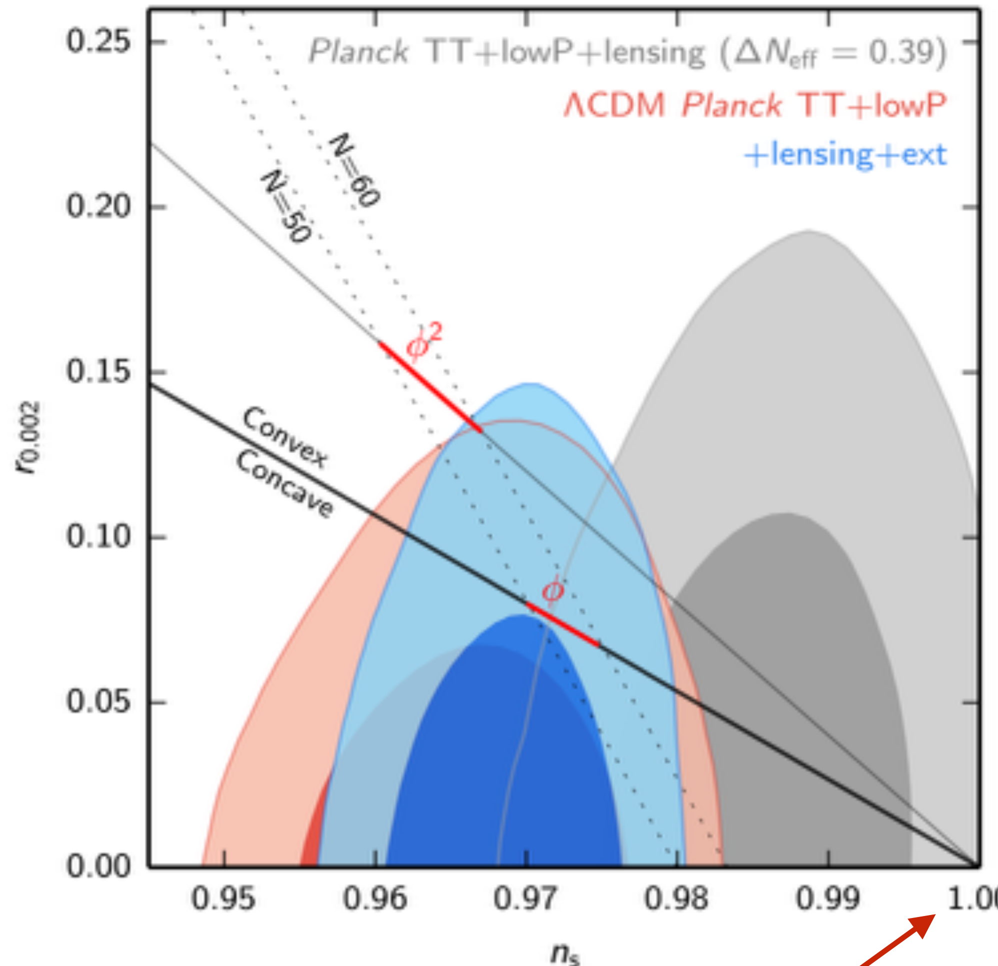
Planck constraints are prior dependent (Bayesian Approach)

Immediate Thermalization



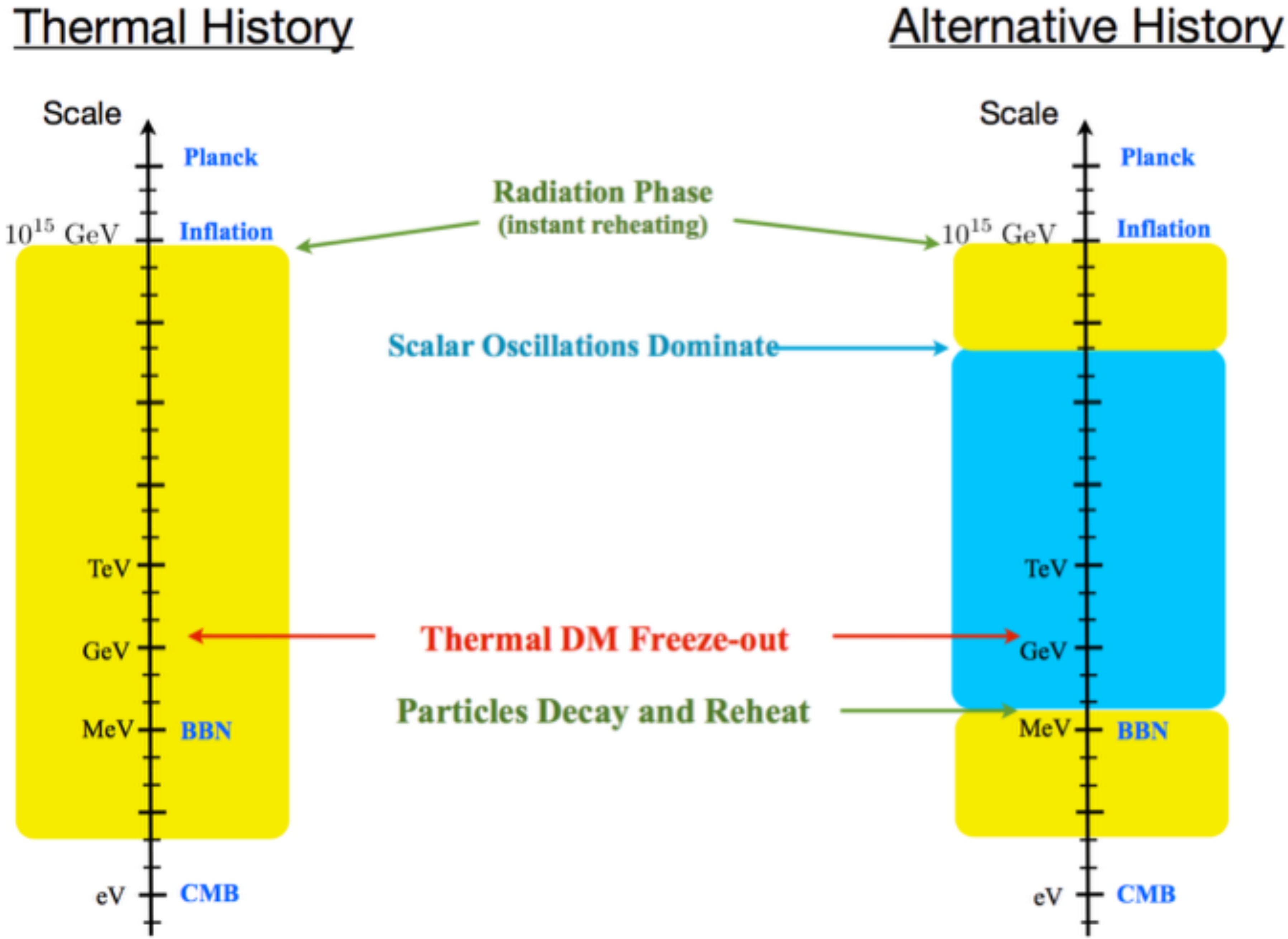
Delayed Thermalization (non-thermal history)





Scale Invariance

Alternative Histories are Possible



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:

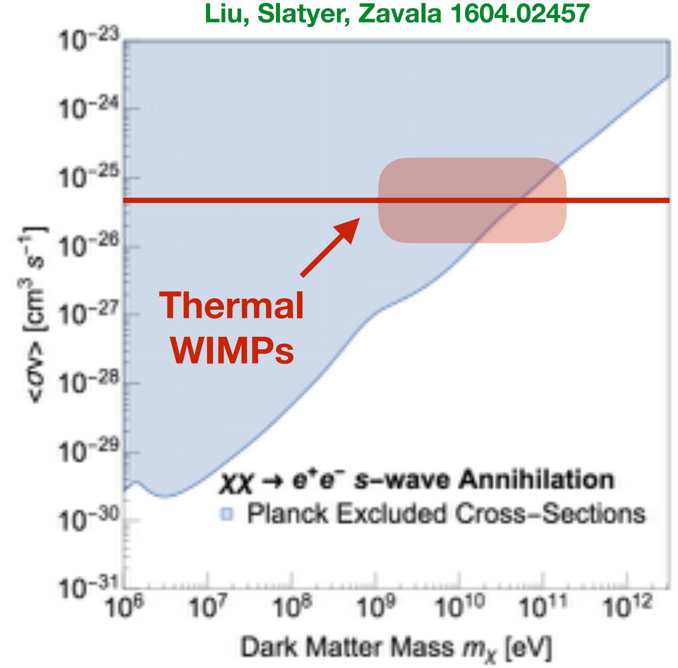
CMB and Inflation (Planck)
Many inflationary models favor non-thermal history.

Lack of thermal WIMP detection

Recombination Constraints (Planck)
Thermal WIMPs in tension

Non-Standard History —> New Phenomenology

Liu, Slatyer, Zavala 1604.02457



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]

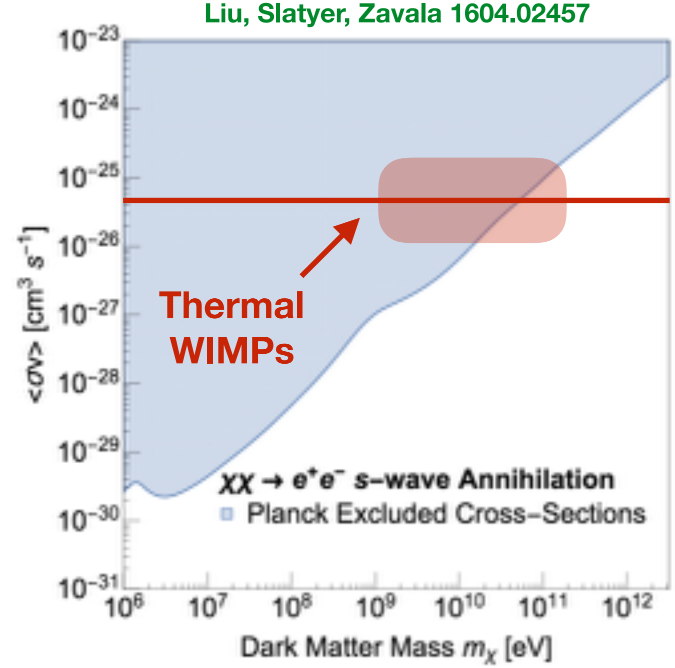
Experimental:

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



Theoretical:

Beyond Standard Model (BSM) Physics often favors non-thermal histories.
(Example: Efforts to address the EW hierarchy problem lead to shift symmetric scalars leading to a matter phase prior to BBN)

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

Early Matter Domination and Structure Growth

1106.0536 A. Erickcek and K Sigurdson
1405.7373 with JiJi Fan and Ogan Ozsoy

Evolution of Density Perturbations

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

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

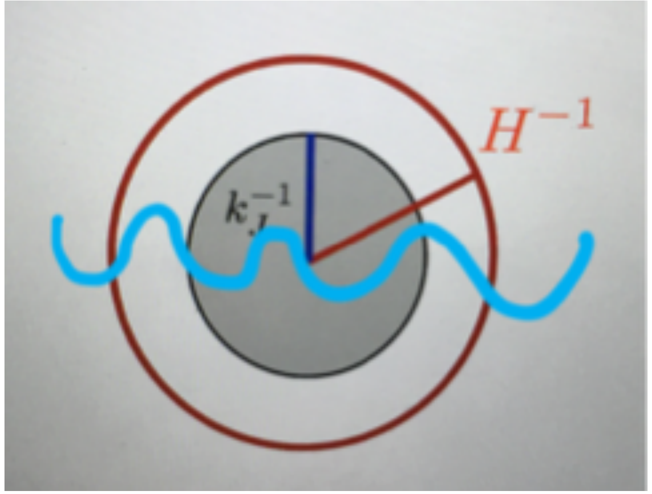
Hubble "friction" slows the instability

Pressure prevents collapse

Gravity drives collapse

Jean's scale sets the growth scale

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



Early Matter Domination and Structure Growth

1106.0536 A. Erickcek and K Sigurdson
1405.7373 with JiJi Fan and Ogan Ozsoy

Evolution of Density Perturbations

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

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

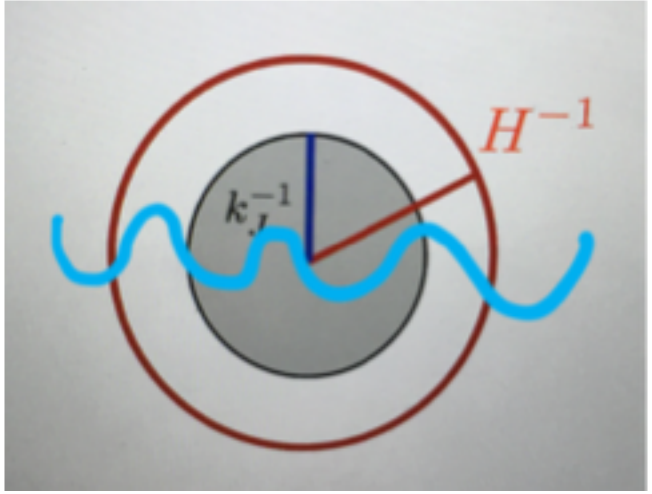
Hubble "friction" slows the instability

Pressure prevents collapse

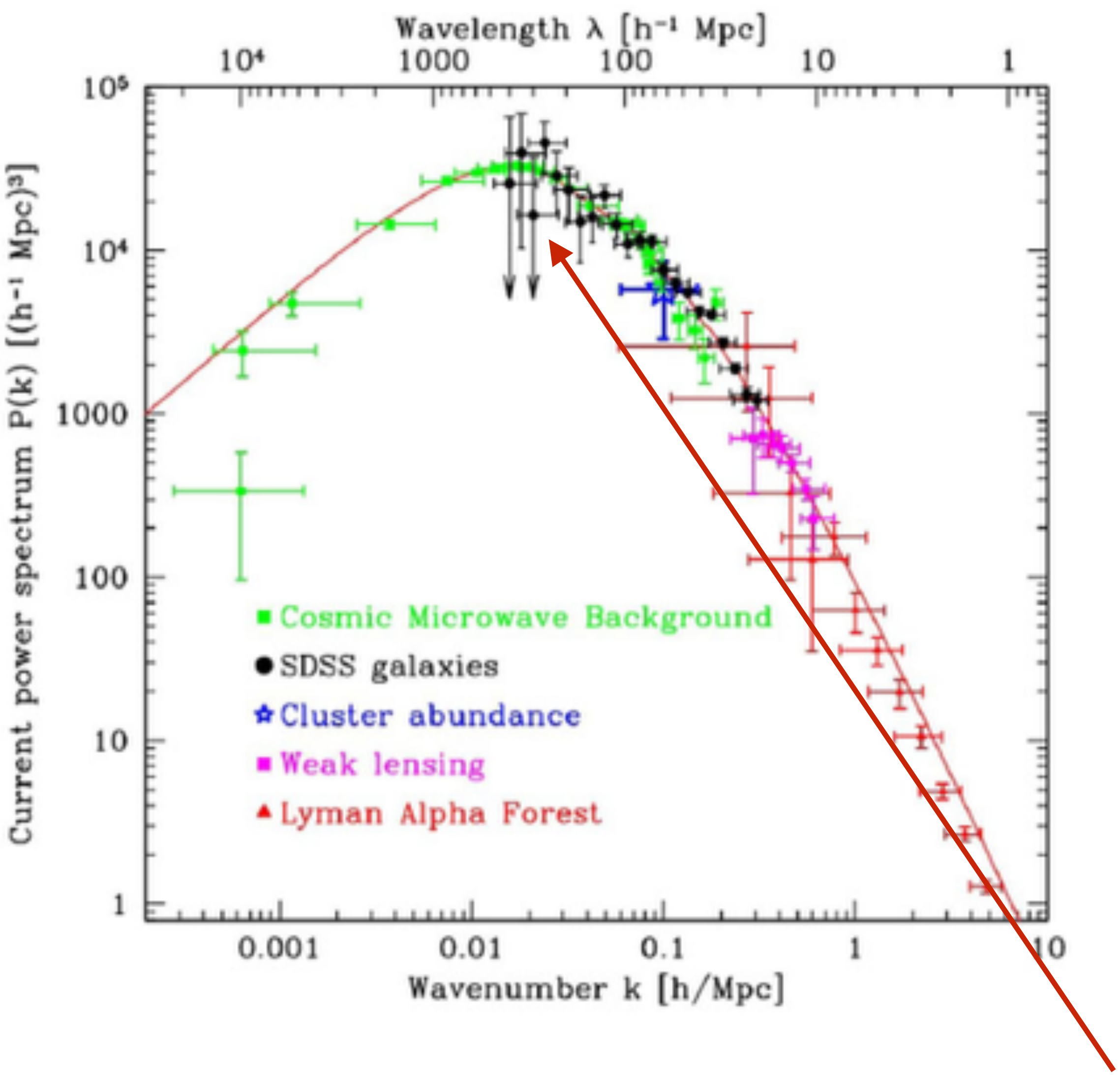
Gravity drives collapse

Structures grow in a Matter Dominated Universe

$$c_s^2 = 0$$



Perturbations Grow in a Matter Dominated Universe



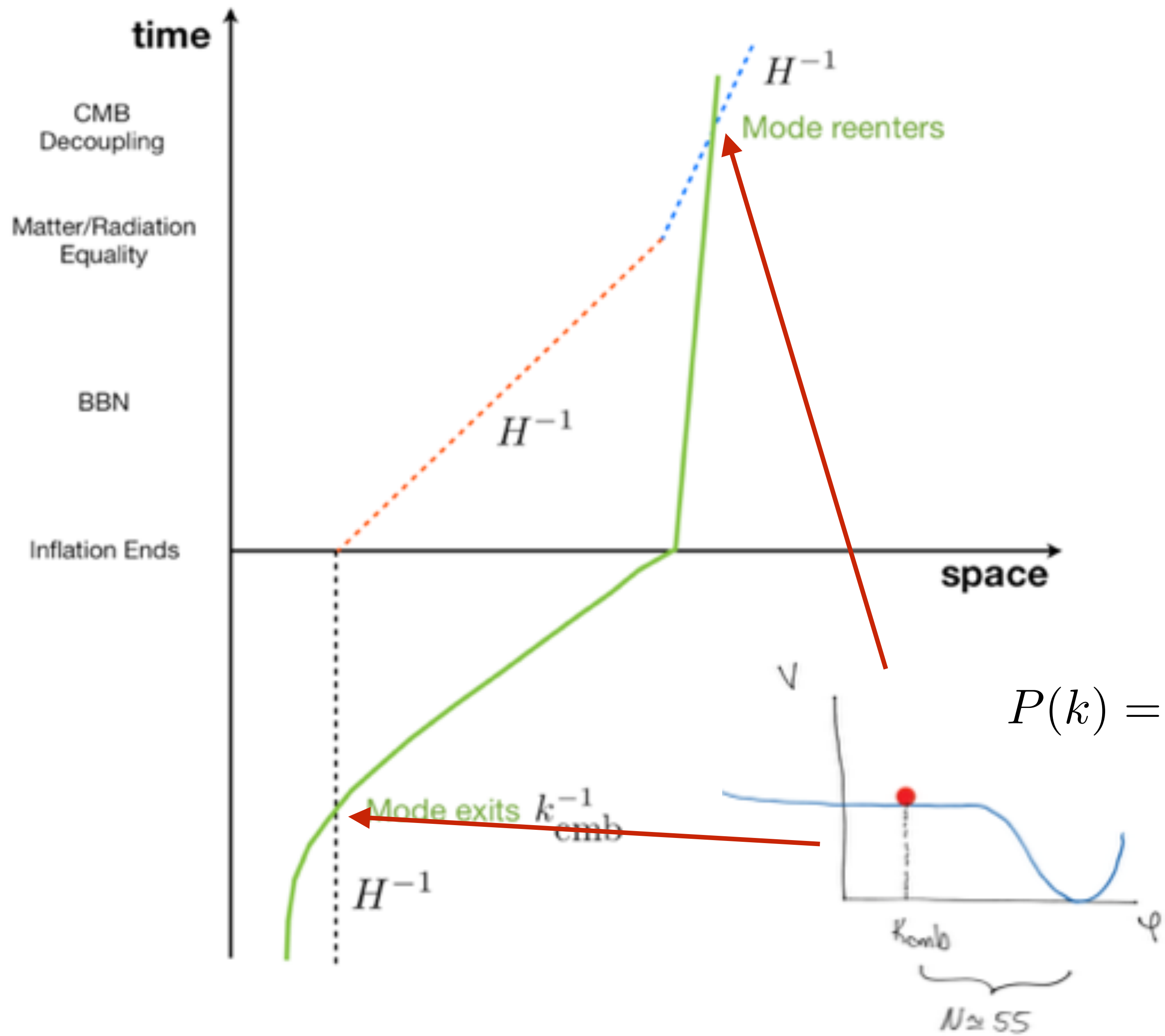
Scalar Power Spectrum

$$P(k) = \mathcal{A}_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

The Power Spectrum is probed by observations over about 4 decades

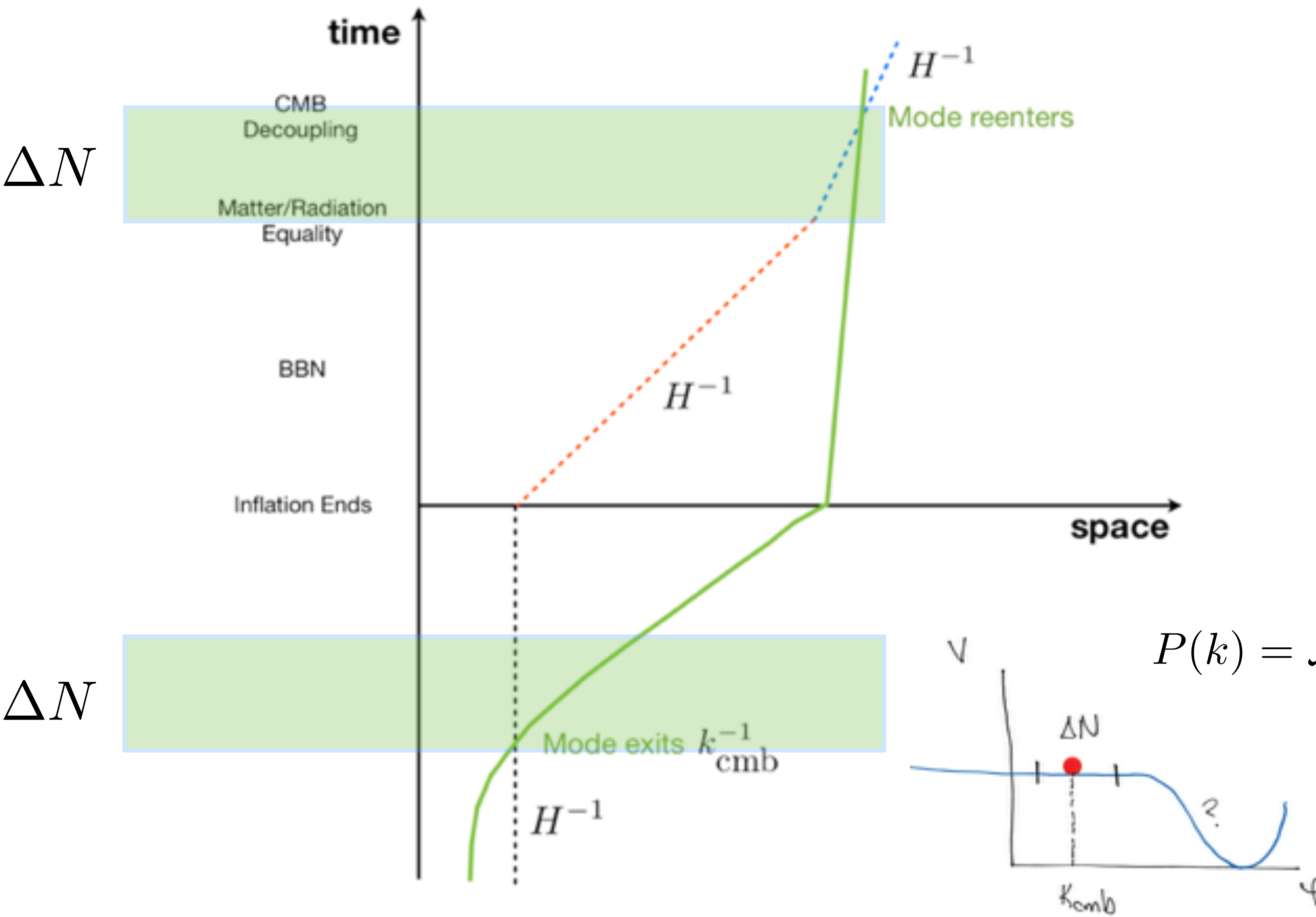
Most Structures grow after radiation / matter equality

Primordial Origin of the Power Spectrum



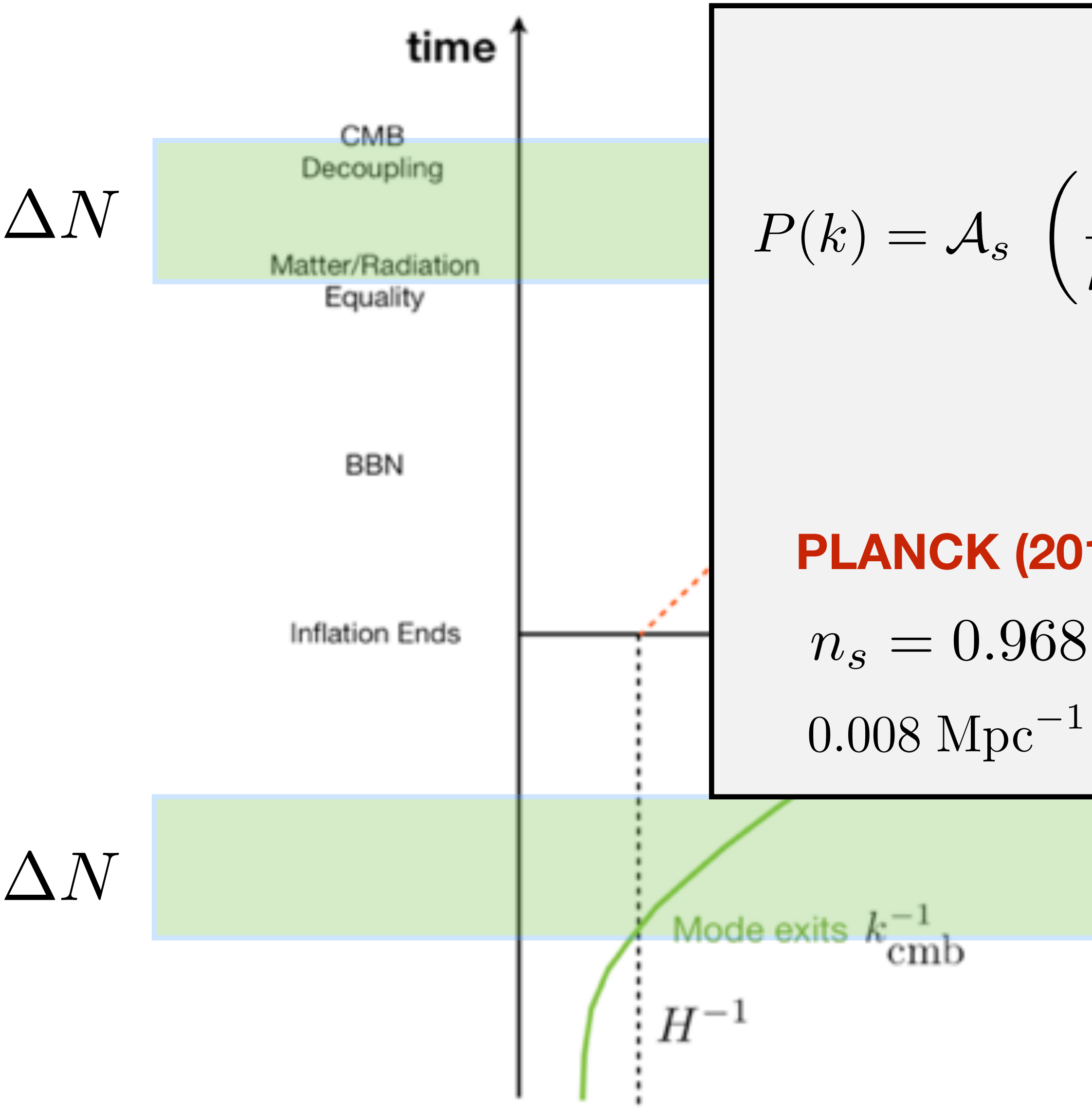
$$P(k) = \mathcal{A}_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

Primordial Origin of the Power Spectrum

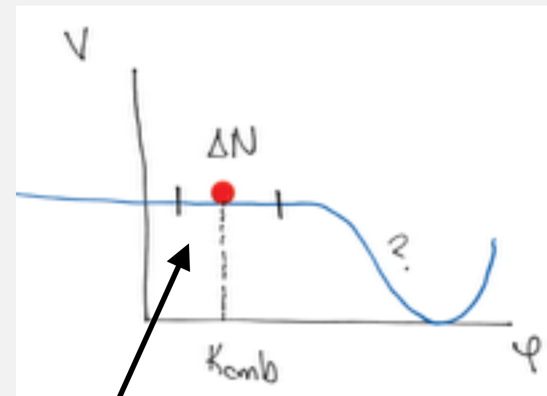


$$P(k) = \mathcal{A}_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

Primordial Origin of the Power Spectrum



$$P(k) = \mathcal{A}_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$



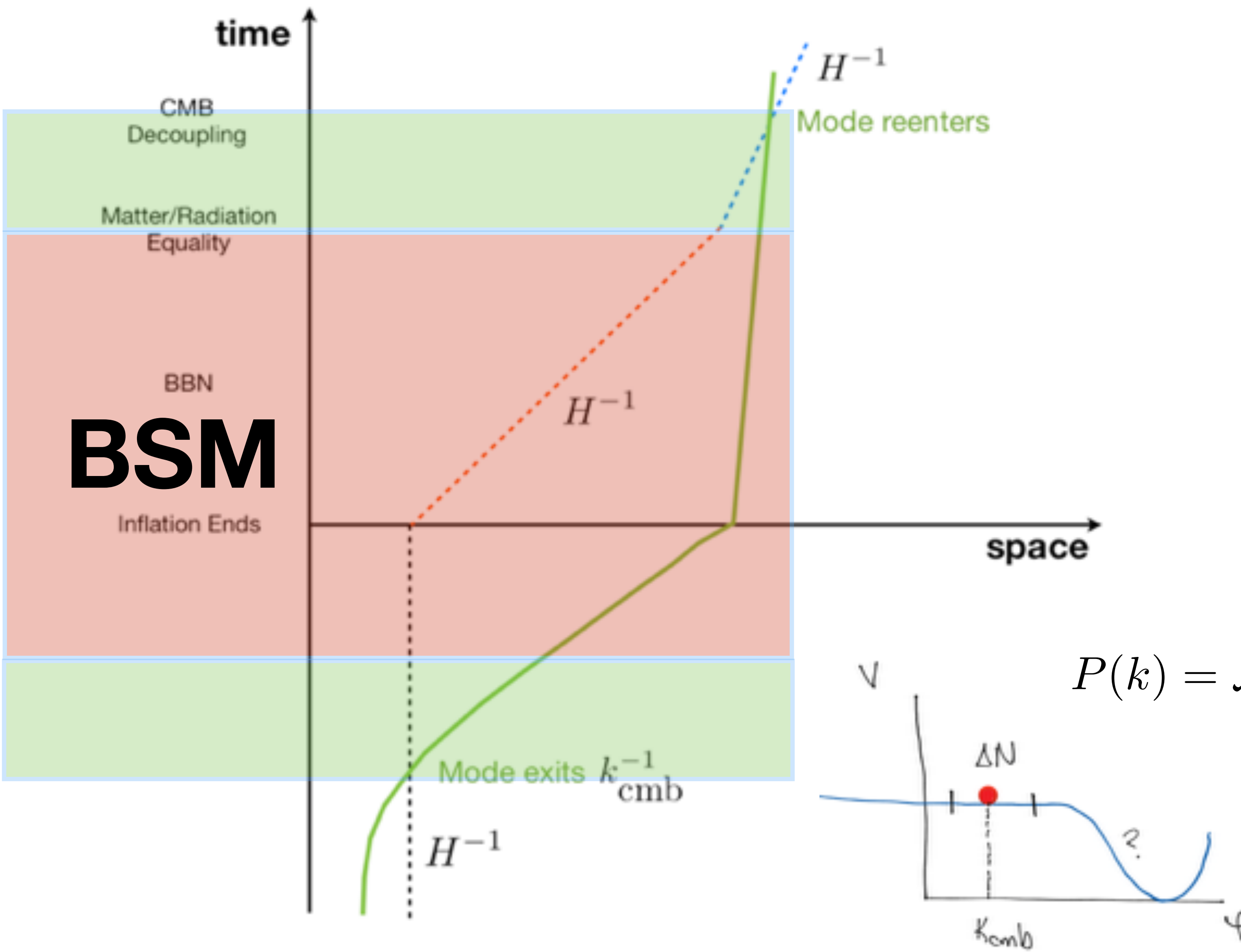
PLANCK (2015)

$$n_s = 0.968 \pm 0.006$$

$$0.008\ \mathrm{Mpc}^{-1} \lesssim k \lesssim 0.1\ \mathrm{Mpc}^{-1}$$

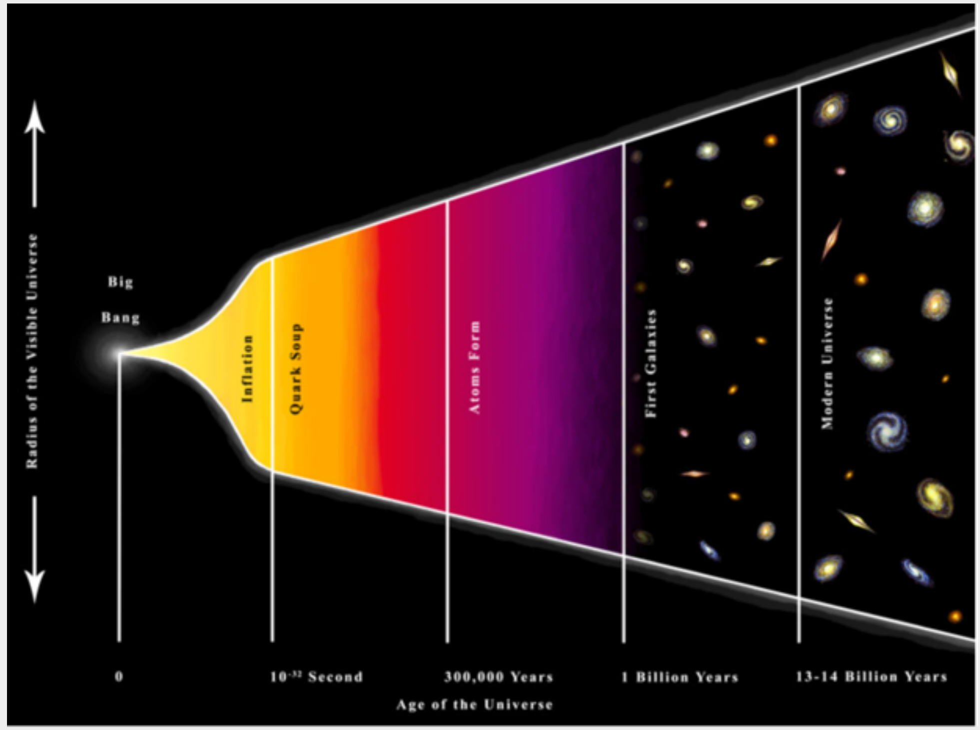
What is the Power Spectrum on other scales?

?



$$P(k) = \mathcal{A}_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

Primordial Black Holes (PBHs)



PBHs formed in the early universe
from **collapse of density perturbations**.
They can lead to relics, providing all or part of the dark matter.

$$m_p \simeq 10^{-6}\ \mathrm{g} \lesssim M_{PBH}$$

PBH Formation in a Thermal Universe

Original work by Carr and Hawking (many refinements since that time).

Mass Fraction in PBHs (Thermal History)

Equation of State ($w > 0$)

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

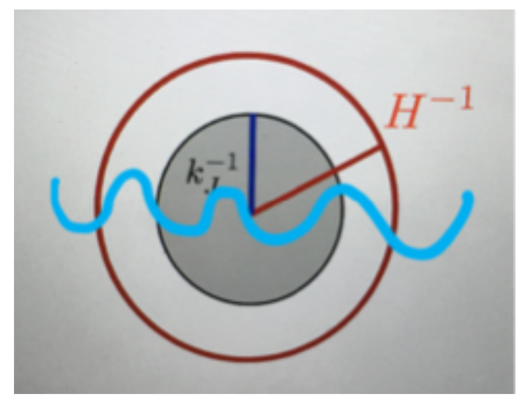
$$\delta_M \equiv \frac{\delta M}{M}$$

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

Hubble "friction" slows the instability

Pressure prevents collapse

Gravity drives collapse



$$H \sim M_H \rightarrow M_{PBH}$$

PBH's would form from large density perturbations in tail of Gaussian distribution

$$\delta_M \sim \mathcal{O}(1)$$

After non-linearity reached, mass breaks away from expansion, PBHs can form.

PBH Formation in an Early Matter Phase

Work of Zeldovich, Peebles, Doroshkevich, Khlopov, Polnarev, and others.

Matter Domination

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

Hubble "friction" slows the instability

Pressure prevents collapse

Gravity drives collapse

Sub-horizon Modes grow

$$\delta_k(t) = \delta_k(t_H)a(t)$$

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

Non-linearity does not guarantee PBH formation!

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

Key Points:
Spherical collapse (no angular momentum), Density and velocity perturbations initially Gaussian.

PBH Mass Range from an Early Matter Phase

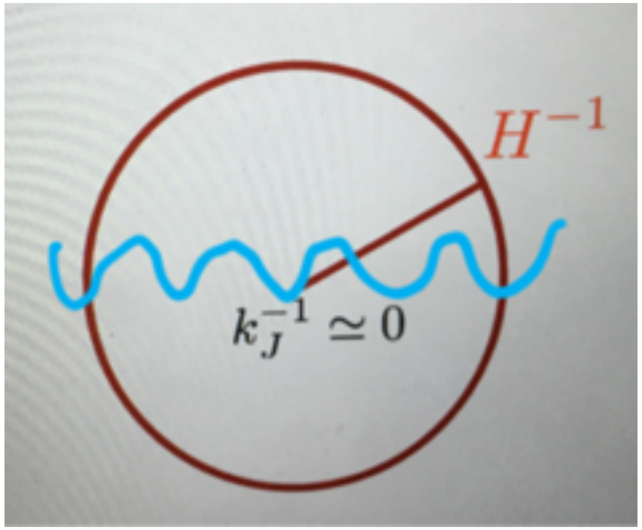
Low Mass Region

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.

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

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



PBH Mass Range from an Early Matter Phase

High Mass Region

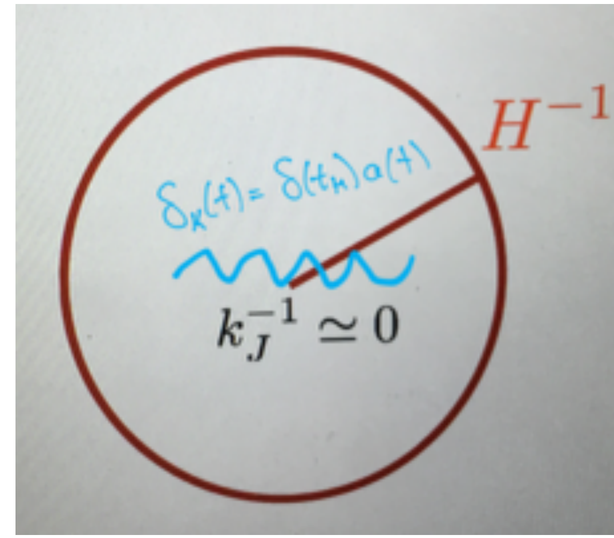
Sub-horizon growth is important.

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

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

Duration of matter phase determines maximal mass

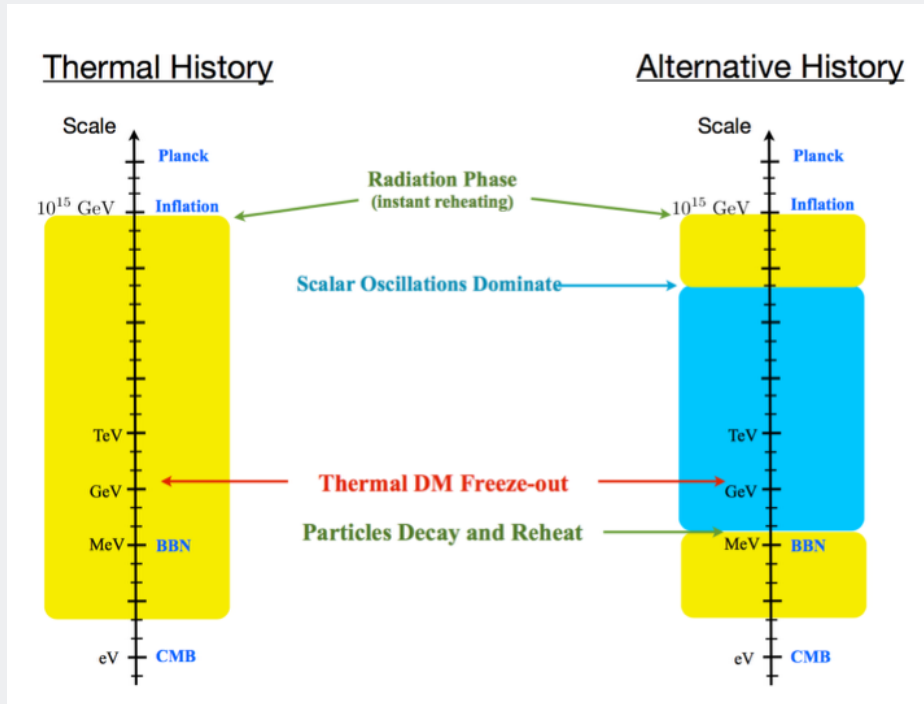
$$T_r^2 \sim \frac{m_\sigma^3}{m_p}$$

PB

High

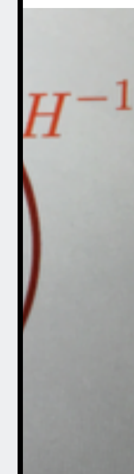
Su

Example: Matter phase from oscillating scalar



$$m_\sigma = 50 \text{ TeV} \qquad T_r \simeq 5 \text{ MeV}$$

$$10^9 \text{ g} \lesssim M_{PBH} \lesssim 10\, M_\odot$$



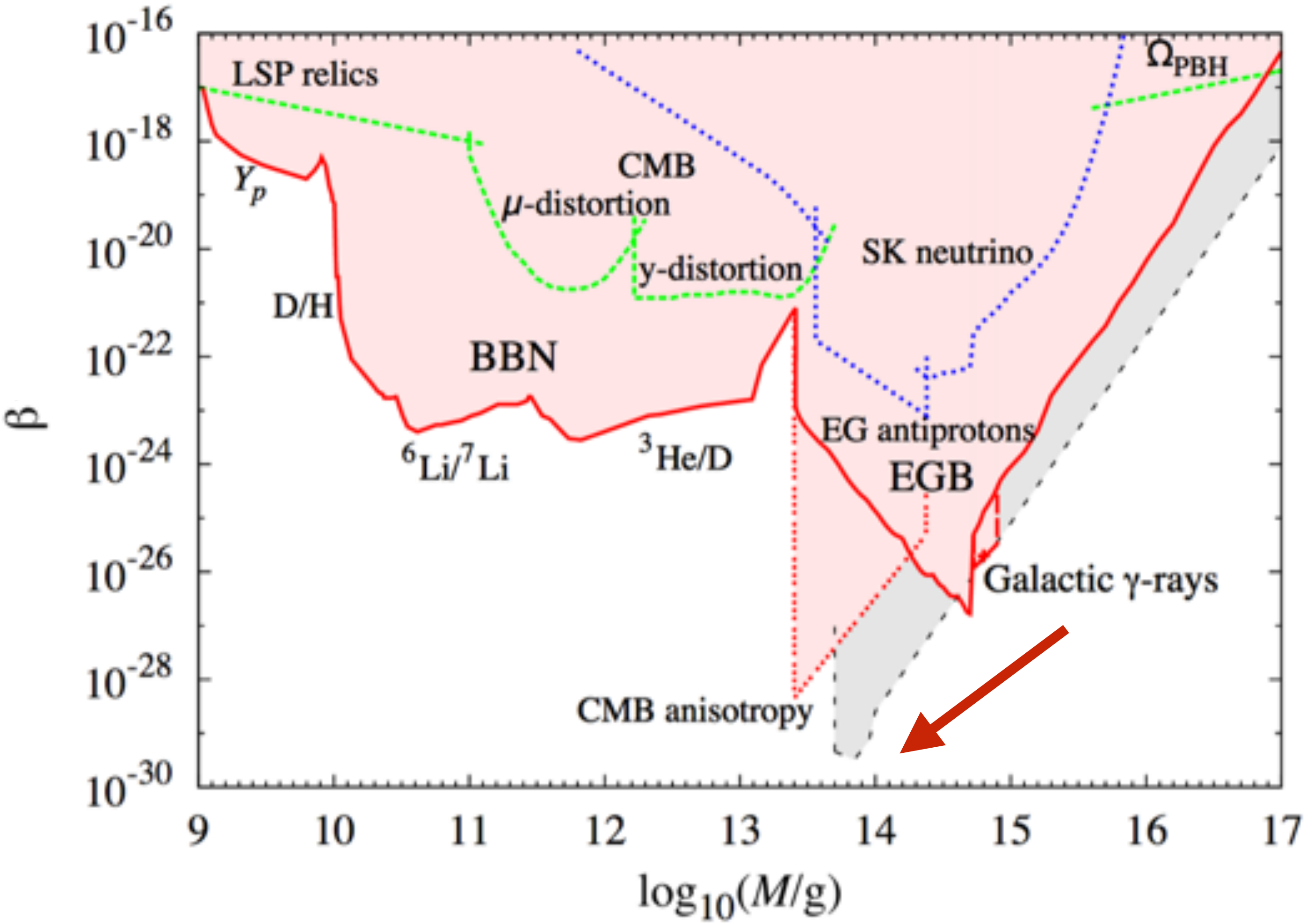
M_{max} … m_p … m_σ … m_p

maximal mass

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

Observational Constraints

0912.5297 Carr, et. al.

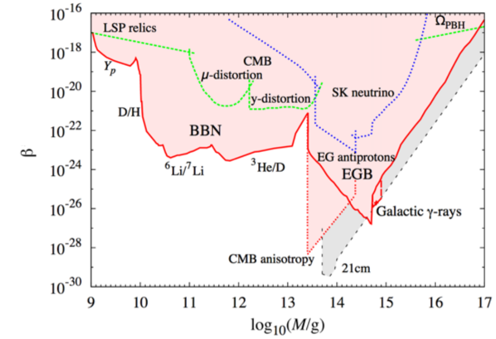


These constraints need updated! (work in progress with Julian, Bhaskar and Louis)

For CMB update (thermal PBHs) **see Yu's talk tomorrow.**

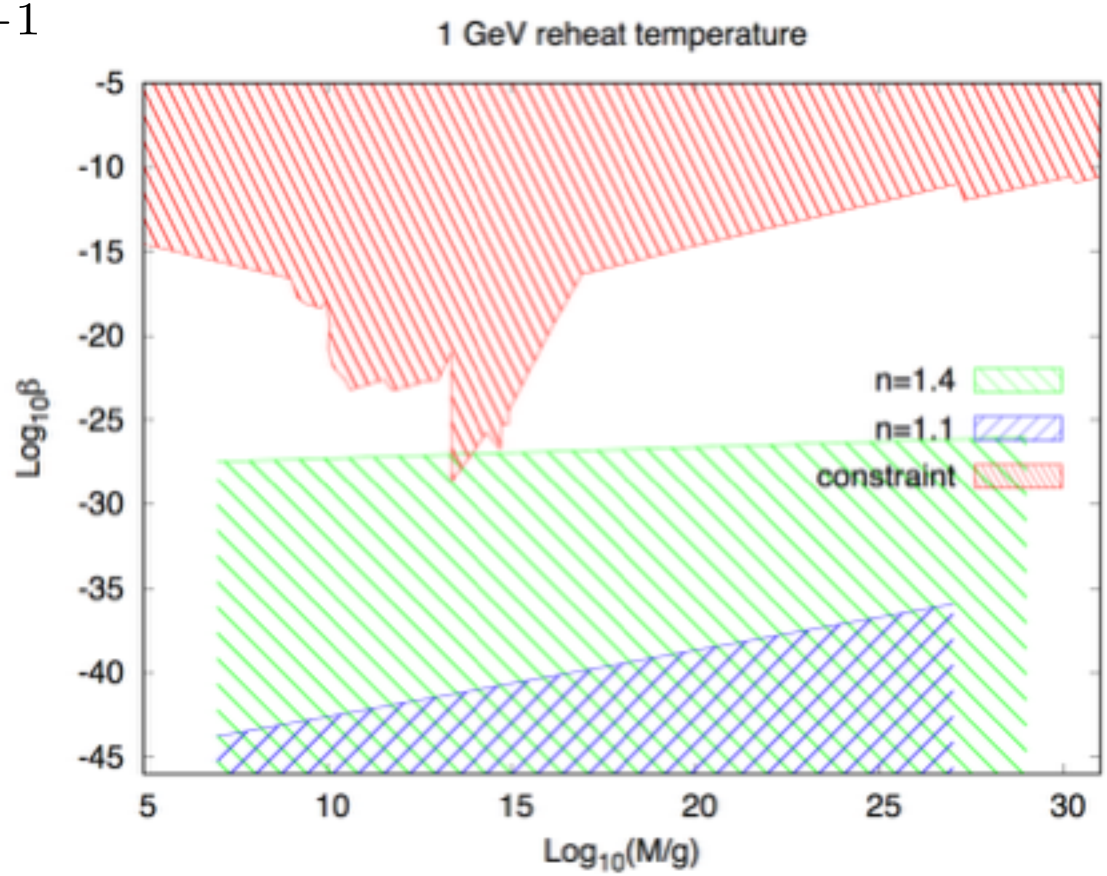
Observational Constraints

"Non-thermal WIMPs and Primordial Black Holes"
1603.00023 with Julian Georg, Gizem Sengor



0912.5297 Carr, et. al.

$$P(k) = \mathcal{A}_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$



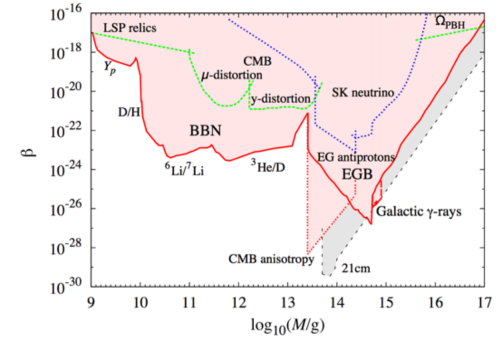
Motivation:
Non-thermal WIMPs
(e.g. SUSY Winos)

Strongest constraints on 10^{14-15} g PBHs

Blue tilt for the primordial power spectrum disfavored.

Observational Constraints

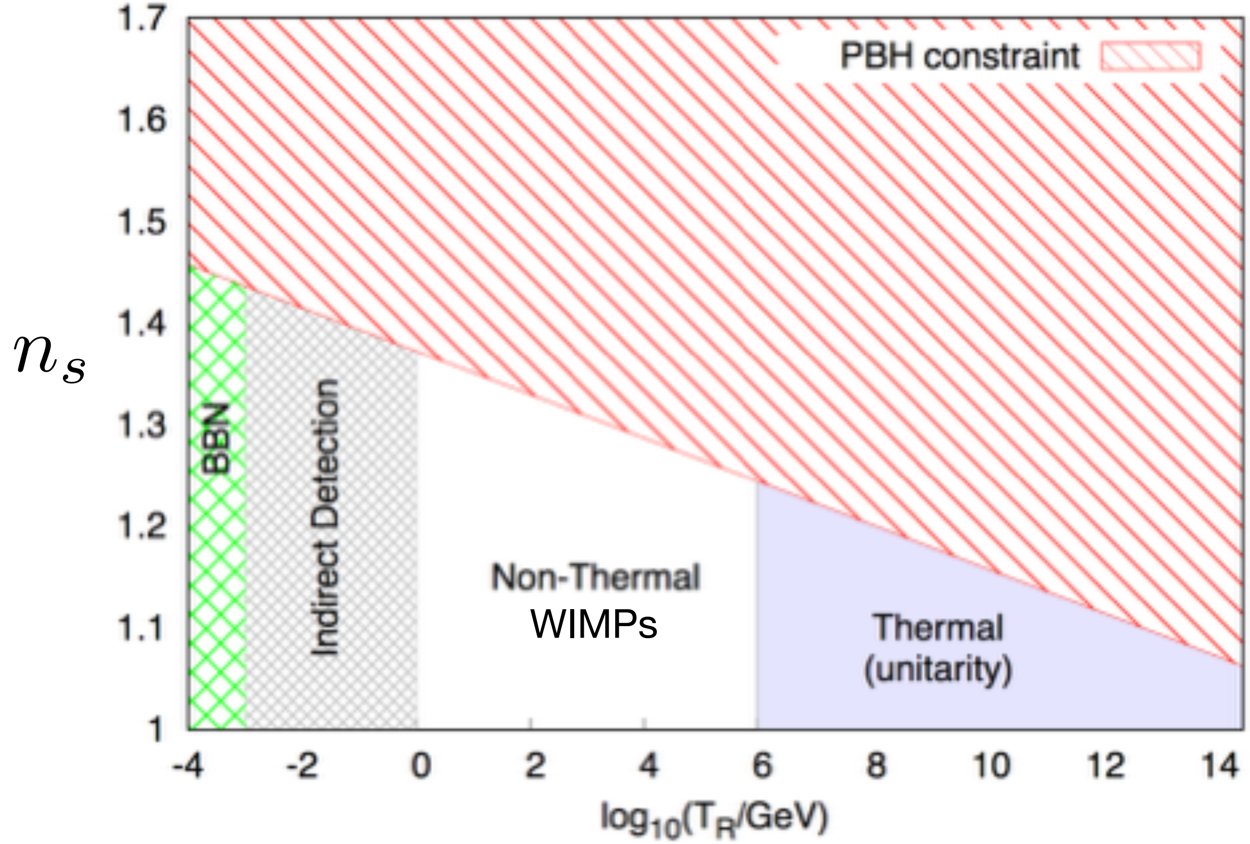
"Non-thermal WIMPs and Primordial Black Holes"
1603.00023 with Julian Georg, Gizem Sengor



0912.5297 Carr, et. al.

$$P(k) = \mathcal{A}_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

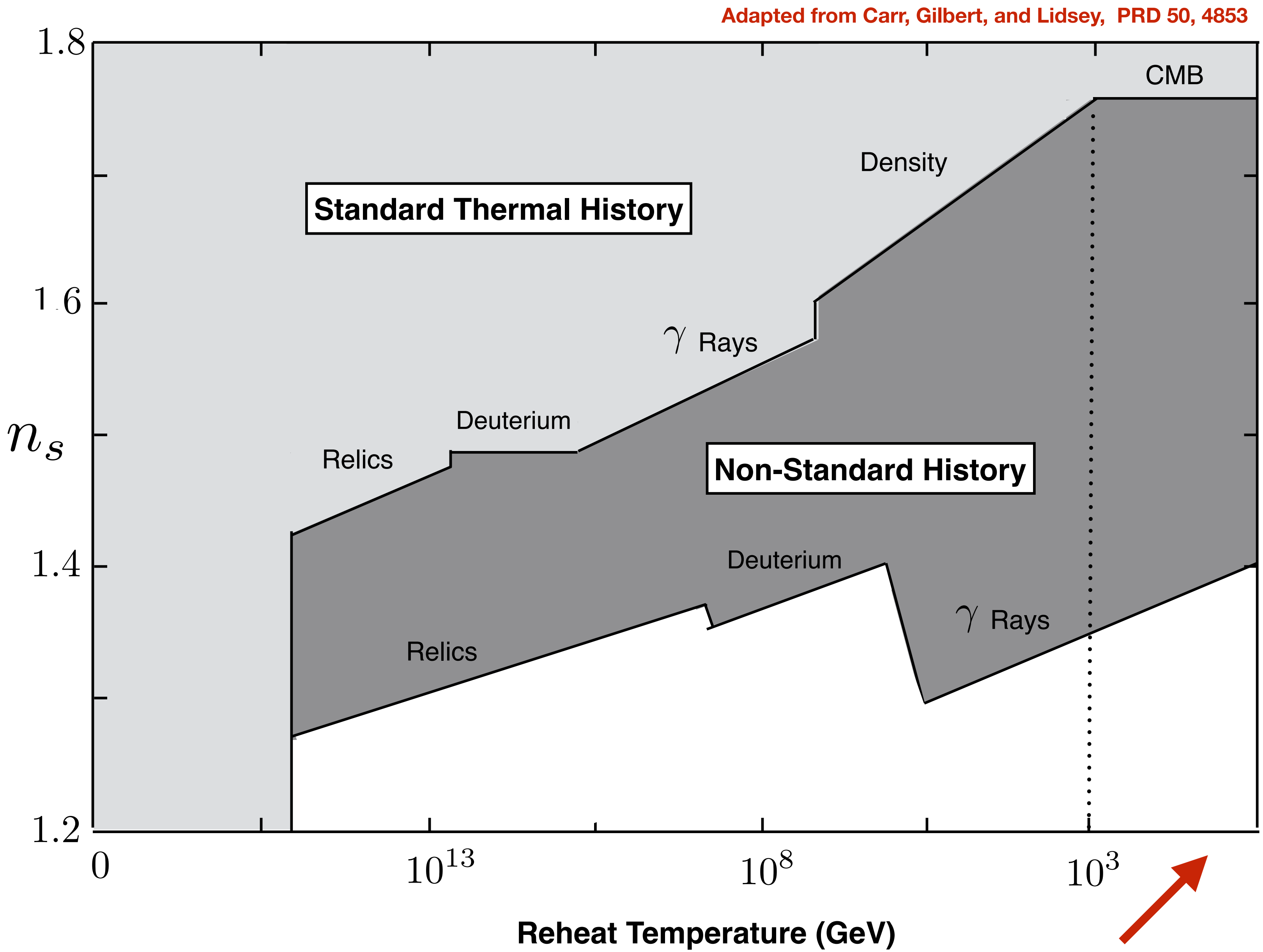
Motivation:
Non-thermal WIMPs
(e.g. SUSY Winos)



Strongest constraints on 10^{15} g PBHs

<u>Blue tilt for the primordial power spectrum disfavored.</u>

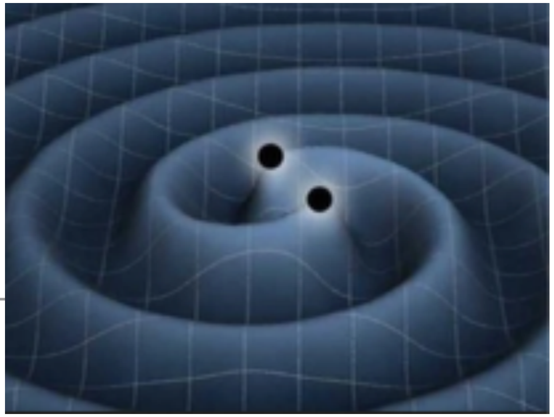
“Non-thermal WIMPs and Primordial Black Holes”
1603.00023 with Julian Georg, Gizem Sengor
and work in progress with Julian, Bhaskar, and Louis



Low reheat models.

Did LIGO see PBH Dark Matter?

1603.00464 Bird, et. al.; 1603.08338 Sasaki, et. al.; 1605.01405 Raccanelli, et. al.



"GW150914"

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

Dark Matter Interpretation

$$10\, M_\odot \lesssim M \lesssim 100\, M_\odot$$

Lensing (lower bound)

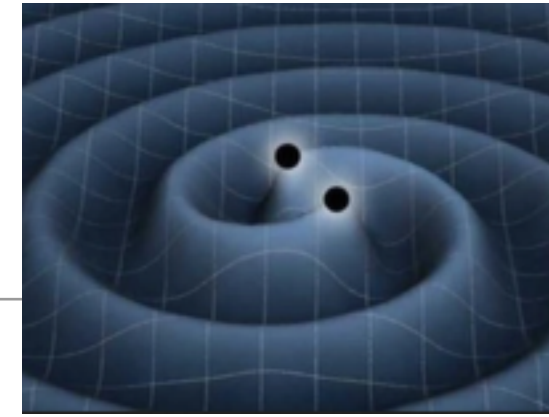
Disrupt Wide Binaries (perhaps CMB as well) (upper bound)

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

1603.08338 Sasaki, et. al.;

Did LIGO see PBH Dark Matter?

1603.00464 Bird, et. al.; 1603.08338 Sasaki, et. al.; 1605.01405 Raccanelli, et. al.



Dark Matter Interpretation

$$10\, M_\odot \lesssim M \lesssim 100\, M_\odot$$

Key is BH Merger rate:

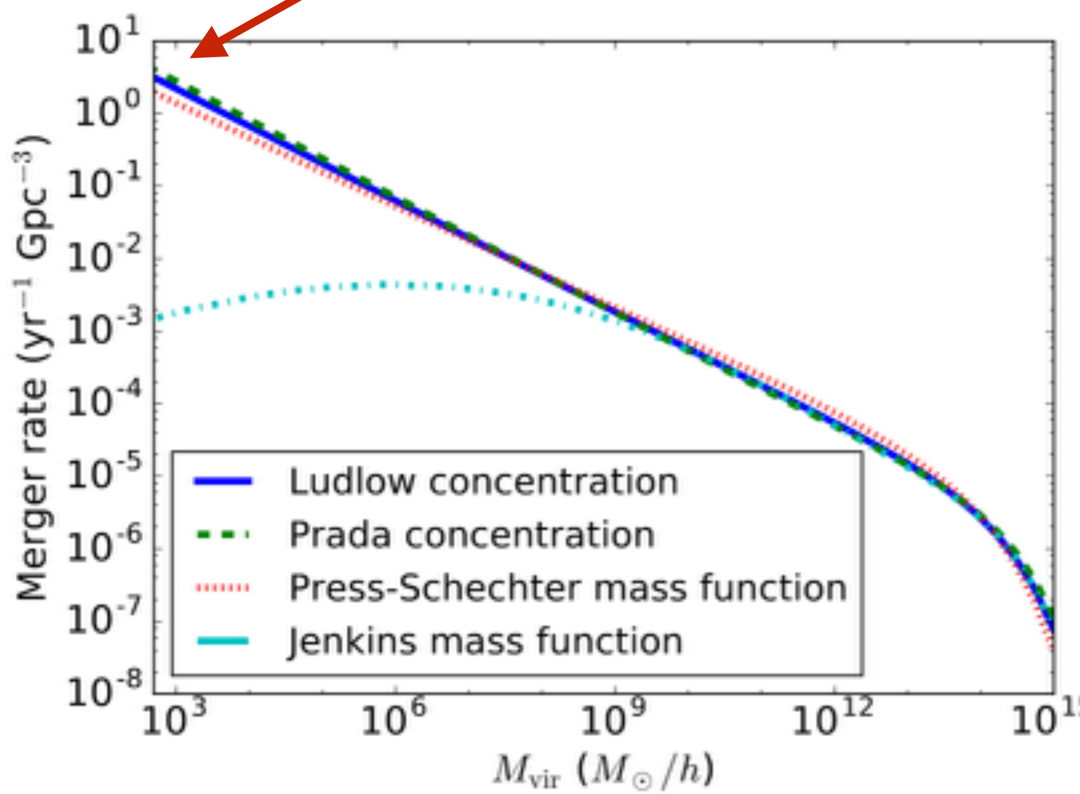
$$2 - 53\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}\ \text{(LIGO)}$$

Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

Would reside in the lightest mass halos
(these calculations are challenging)



Halo Mass

BH Formation?
BH Origin?

1605.01405 Raccanelli, et. al.

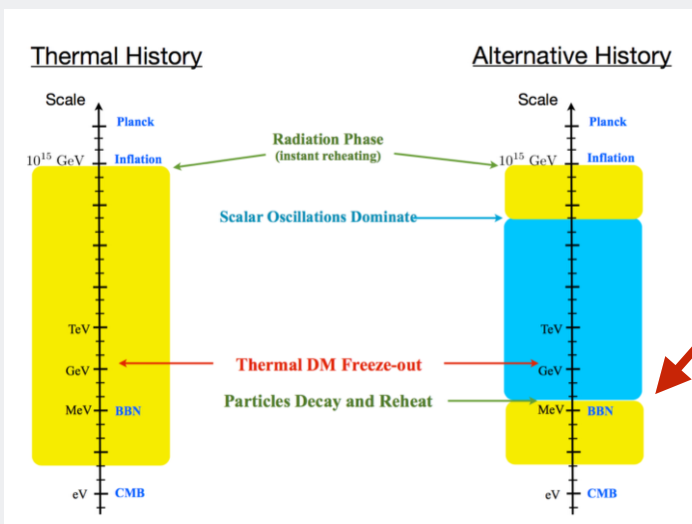
Non-Standard Histories and an Interesting Coincidence

Work in progress with Julian, Bhaskar, and Louis

Dark Matter Interpretation

$$10\,M_\odot \lesssim M \lesssim 100\,M_\odot$$

Example: Matter phase from oscillating scalar



$$m_\sigma = 50\ \text{TeV} \qquad T_r \simeq 5\ \text{MeV}$$

$$10^9\ \text{g} \lesssim M_{PBH} \lesssim 10\ M_\odot$$

Large entropy production at time of reheating.

Previous abundances of dark matter, baryons, and PBHs diluted.

Only last PBH's survive?

All or part of the DM?

Conclusions

Primordial Black Holes (PBHs) can provide rigid constraints on the post-inflationary / pre-BBN cosmic history.

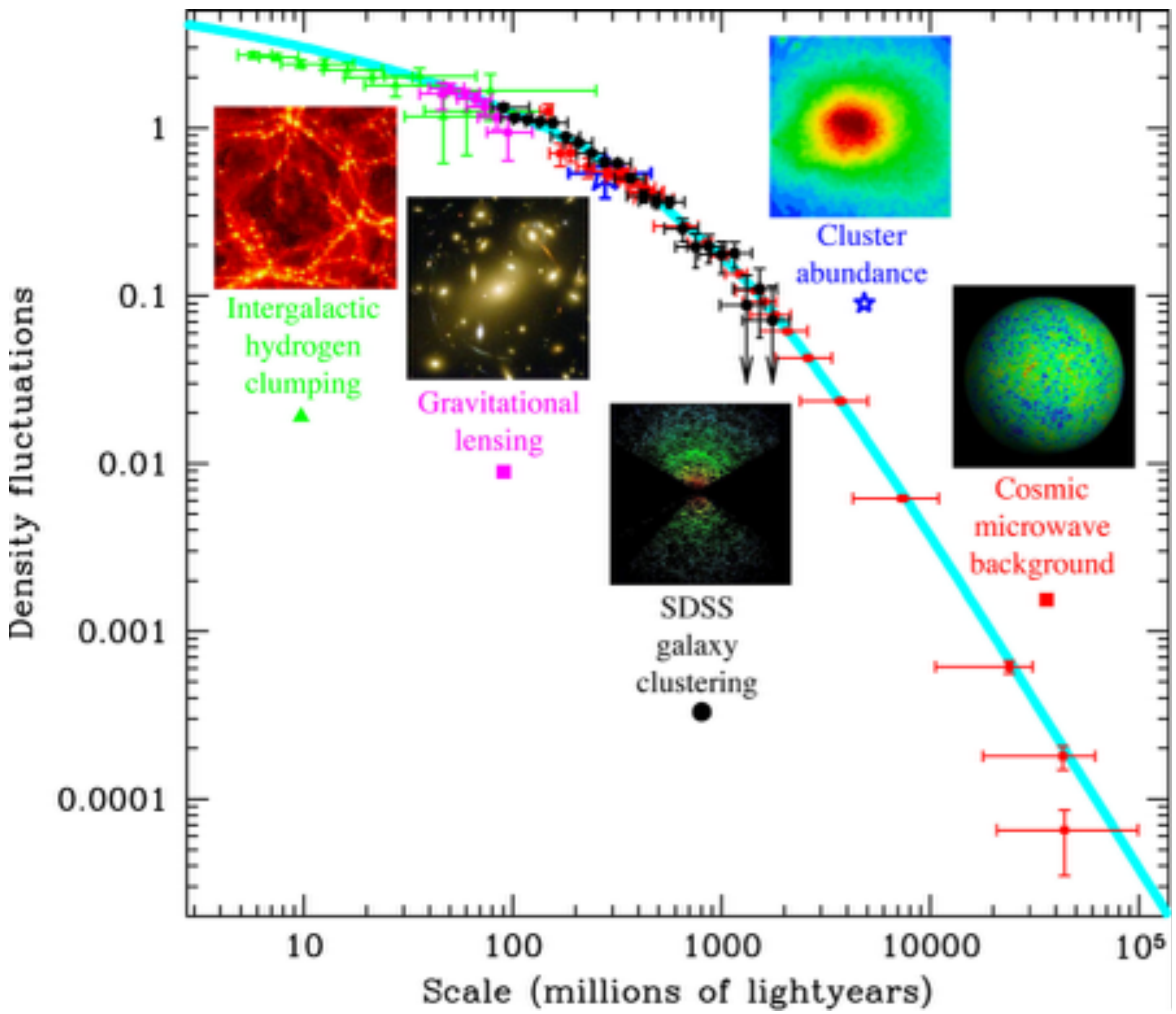
PBHs restrict the primordial power spectrum on a wide range of scales (beyond CMB and Structure formation (LSS) probes).

Provocative Conclusion:

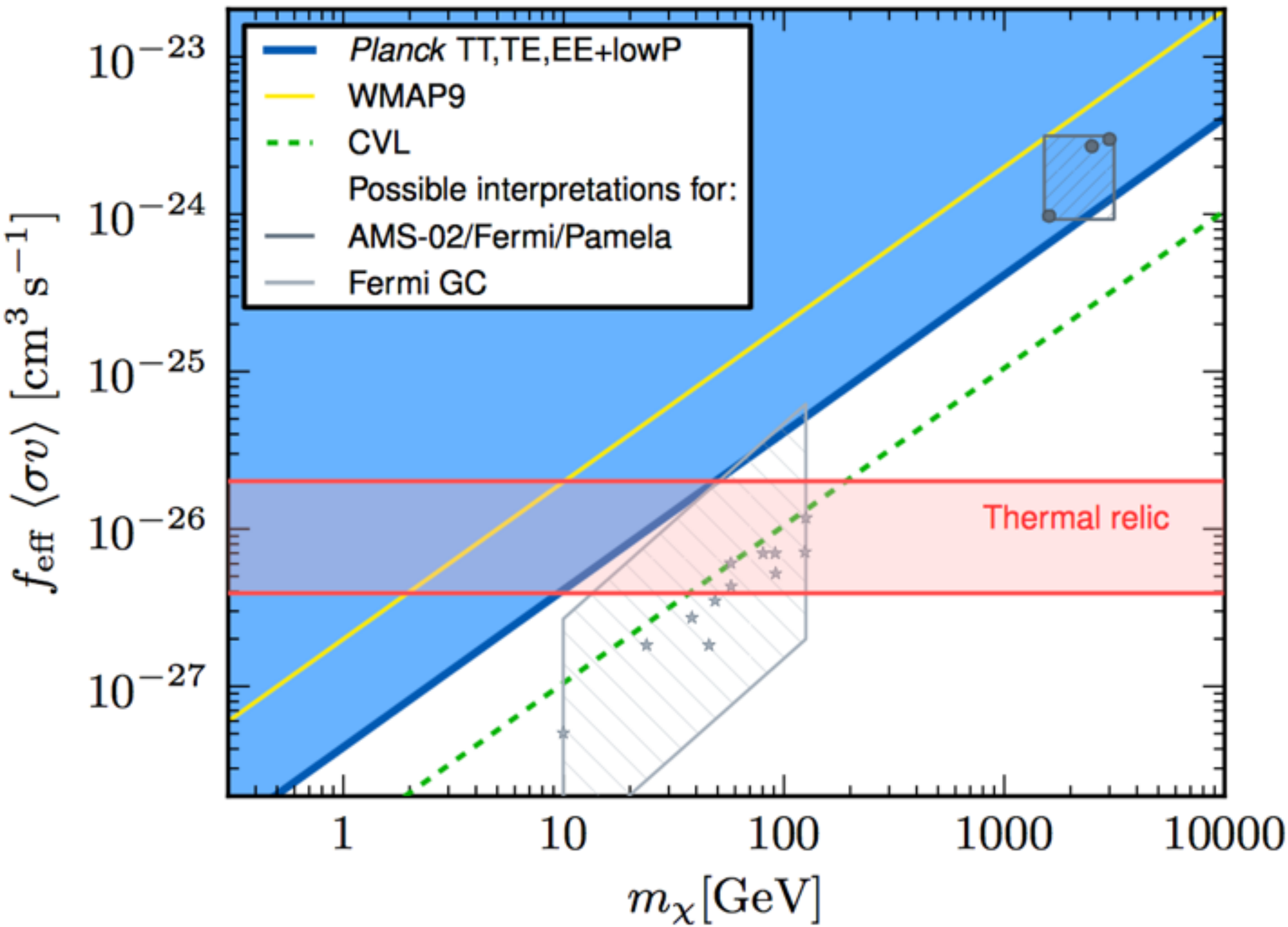
PBHs could be all or part of the dark matter and LIGO may have detected the first "self-annihilation" signal!

Backup Slides

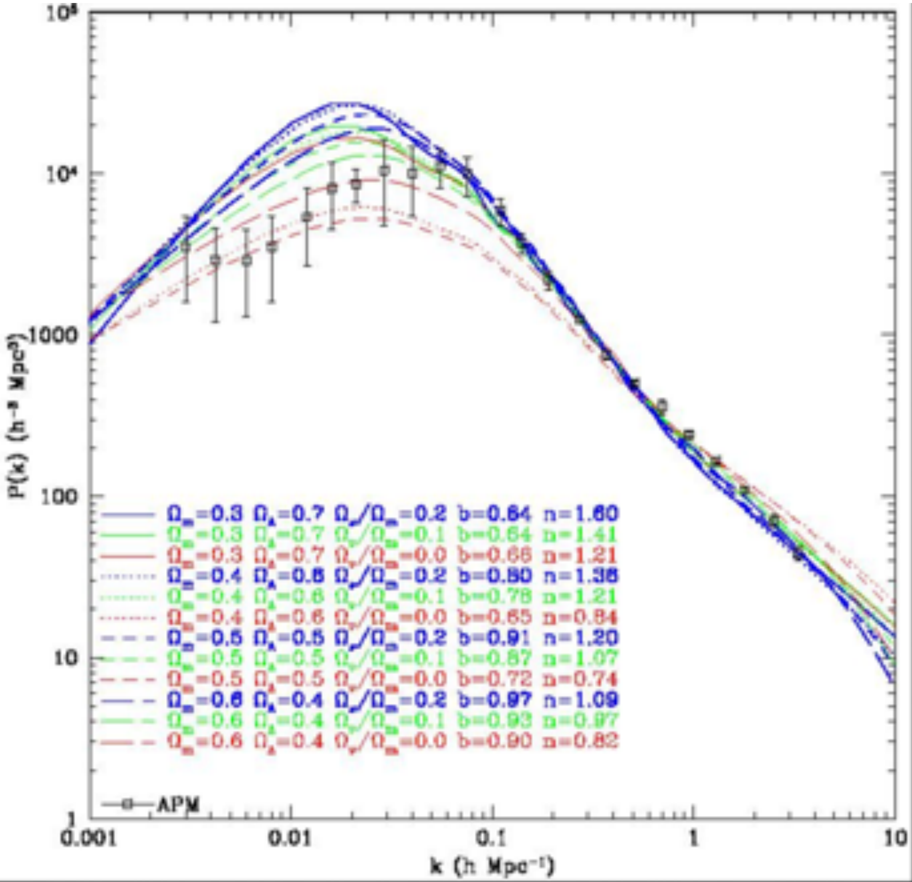
Perturbations Grow in a Matter Dominated Universe



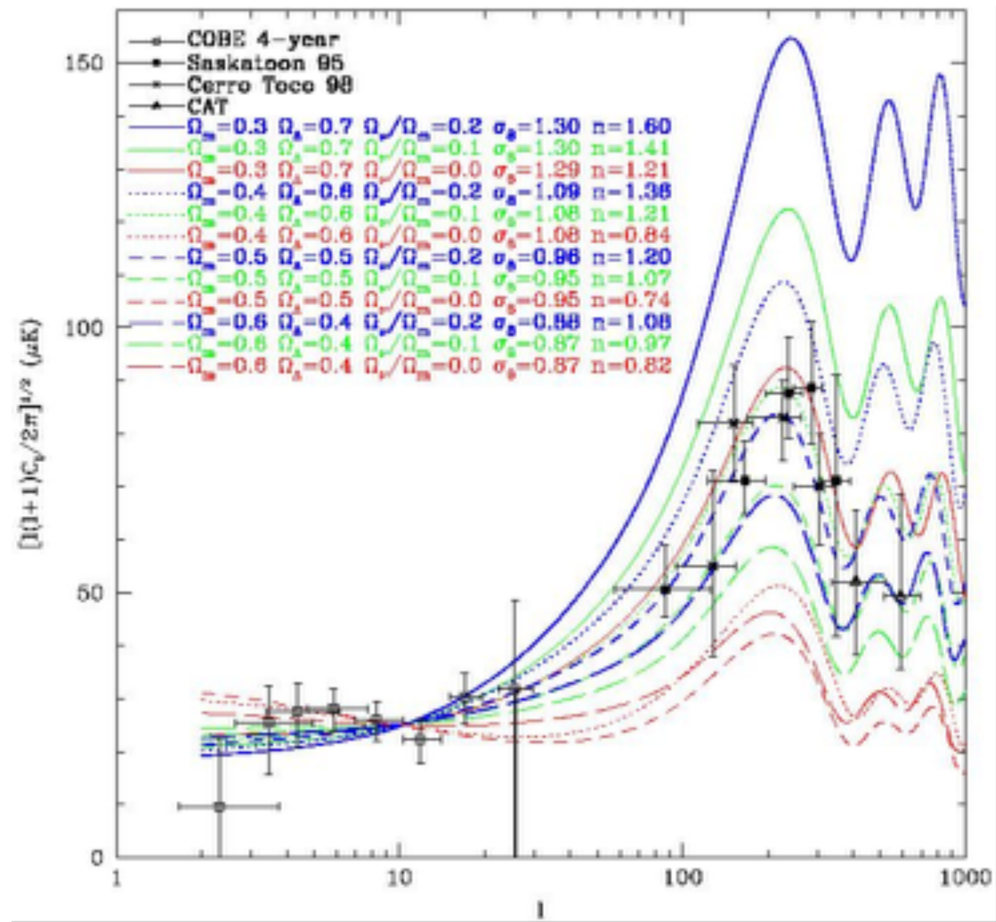
Planck (2015)



Planck TT,TE,EE+lowP
WMAP9
CVL
Possible interpretations for:
AMS-02/Fermi/Pamela
Fermi GC
Thermal relic
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
$f_{\rm eff}\ \langle\sigma v\rangle\ [\rm cm^3\, s^{-1}]$
1
10
100
1000
10000
$m_\chi\,[\rm GeV]$



P(k) (h⁻³ Mpc³)
k (h Mpc⁻¹)
Ωm=0.3 ΩΛ=0.7 Ων/Ωm=0.2 b=0.64 n=1.60
Ωm=0.3 ΩΛ=0.7 Ων/Ωm=0.1 b=0.64 n=1.41
Ωm=0.3 ΩΛ=0.7 Ων/Ωm=0.0 b=0.66 n=1.21
Ωm=0.4 ΩΛ=0.6 Ων/Ωm=0.2 b=0.80 n=1.38
Ωm=0.4 ΩΛ=0.6 Ων/Ωm=0.1 b=0.78 n=1.21
Ωm=0.4 ΩΛ=0.6 Ων/Ωm=0.0 b=0.65 n=0.84
Ωm=0.5 ΩΛ=0.5 Ων/Ωm=0.2 b=0.91 n=1.20
Ωm=0.5 ΩΛ=0.5 Ων/Ωm=0.1 b=0.87 n=1.07
Ωm=0.5 ΩΛ=0.5 Ων/Ωm=0.0 b=0.72 n=0.74
Ωm=0.6 ΩΛ=0.4 Ων/Ωm=0.2 b=0.97 n=1.09
Ωm=0.6 ΩΛ=0.4 Ων/Ωm=0.1 b=0.93 n=0.97
Ωm=0.6 ΩΛ=0.4 Ων/Ωm=0.0 b=0.90 n=0.82
APM



COBE 4-year
Saskatoon 95
Cerro Toco 98
CAT
Ωm=0.3 ΩΛ=0.7 Ων/Ωm=0.2 σ8=1.30 n=1.60
Ωm=0.3 ΩΛ=0.7 Ων/Ωm=0.1 σ8=1.30 n=1.41
Ωm=0.3 ΩΛ=0.7 Ων/Ωm=0.0 σ8=1.29 n=1.21
Ωm=0.4 ΩΛ=0.6 Ων/Ωm=0.2 σ8=1.09 n=1.38
Ωm=0.4 ΩΛ=0.6 Ων/Ωm=0.1 σ8=1.08 n=1.21
Ωm=0.4 ΩΛ=0.6 Ων/Ωm=0.0 σ8=1.08 n=0.84
Ωm=0.5 ΩΛ=0.5 Ων/Ωm=0.2 σ8=0.96 n=1.20
Ωm=0.5 ΩΛ=0.5 Ων/Ωm=0.1 σ8=0.95 n=1.07
Ωm=0.5 ΩΛ=0.5 Ων/Ωm=0.0 σ8=0.95 n=0.74
Ωm=0.6 ΩΛ=0.4 Ων/Ωm=0.2 σ8=0.88 n=1.08
Ωm=0.6 ΩΛ=0.4 Ων/Ωm=0.1 σ8=0.87 n=0.97
Ωm=0.6 ΩΛ=0.4 Ων/Ωm=0.0 σ8=0.87 n=0.82
[l(l+1)Cl/2π]^1/2 (μK)
l

Planck Favors Different Histories for Different Inflationary Models

Model	Instant Reheating		History 1		History 2	
	$\ln[\mathcal{E}/\mathcal{E}_0]$	$\Delta\chi^2_{\rm eff}$	$\ln[\mathcal{E}/\mathcal{E}_0]$	$\Delta\chi^2_{\rm eff}$	$\ln[\mathcal{E}/\mathcal{E}_0]$	$\Delta\chi^2_{\rm eff}$
$n = 4$	−14.9	25.9	−18.8	27.2	−13.2	17.4
$n = 2$	−4.7	5.4	−7.3	6.3	−6.2	5.0
$n = 1$	−4.1	3.3	−5.4	2.8	−4.9	2.1
$n = 2/3$	−4.7	5.1	−5.2	3.1	−5.2	2.3
Natural	−6.6	5.2	−8.9	5.5	−8.2	5.0
Hilltop	−7.1	6.1	−9.1	7.1	−6.6	2.4
ΛCDM	−4940.7	9808.4	...	...	...	...

History 1 (Blue)

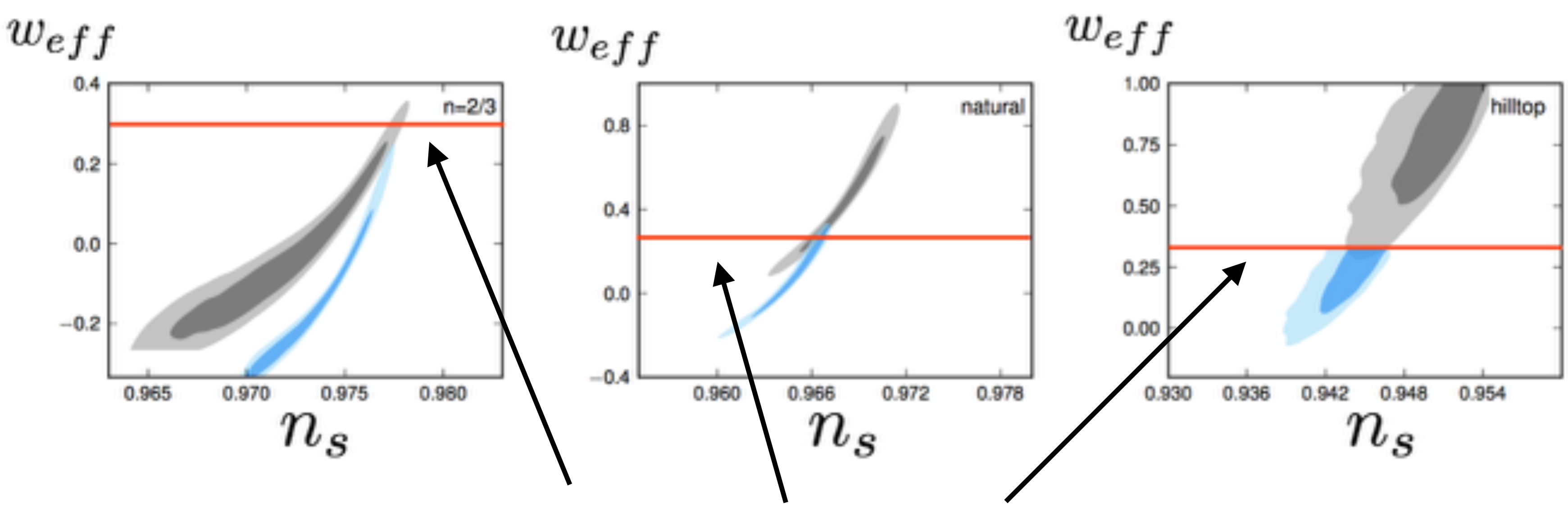
$$T_r = 10^8 \text{ GeV}$$

$$w_{eff} = -1/3 \ldots 1/3$$

History 2 (Grey)

$$T_r = 700 \text{ GeV}$$

$$w_{eff} = -1/3 \ldots 1$$



Radiation dominated universe (Thermal history)