Primordial Black Holes Dark Matter from Axion Inflation

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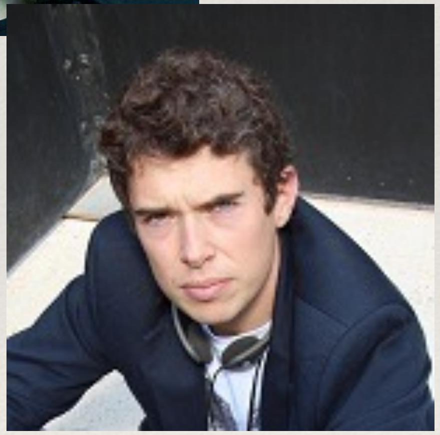


Based on:

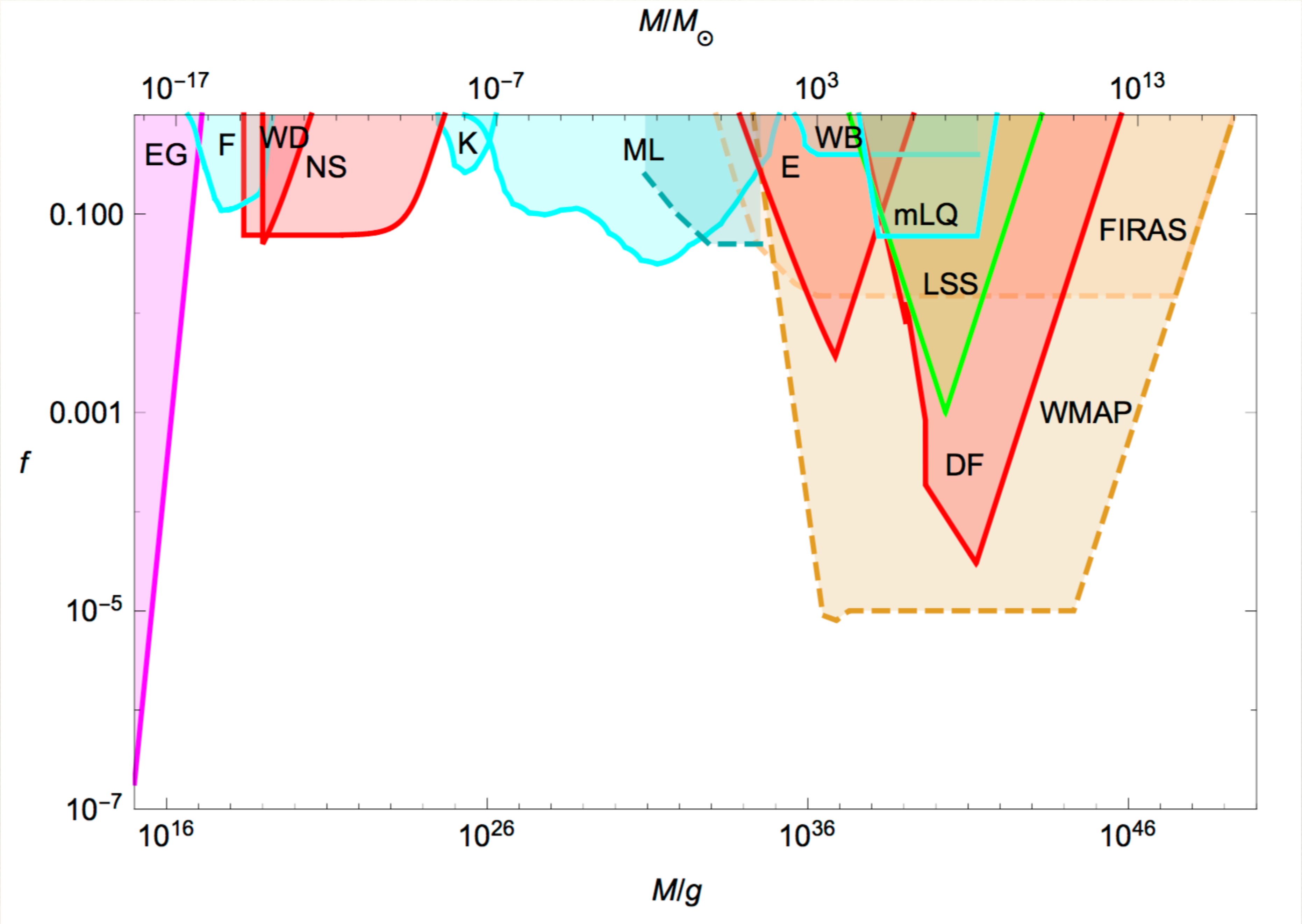
"PBH Dark Matter from Axion Inflation"
V. Domcke, FM, M. Pieroni & L. T. Witkowski
arXiv: 1704.03464 [astro-ph.CO].

PASCOS 2017

IFT Madrid, 20/06/2017

[Carr et al., ’10, ’17]

the abundance of PBHs is subject to many strong constraints



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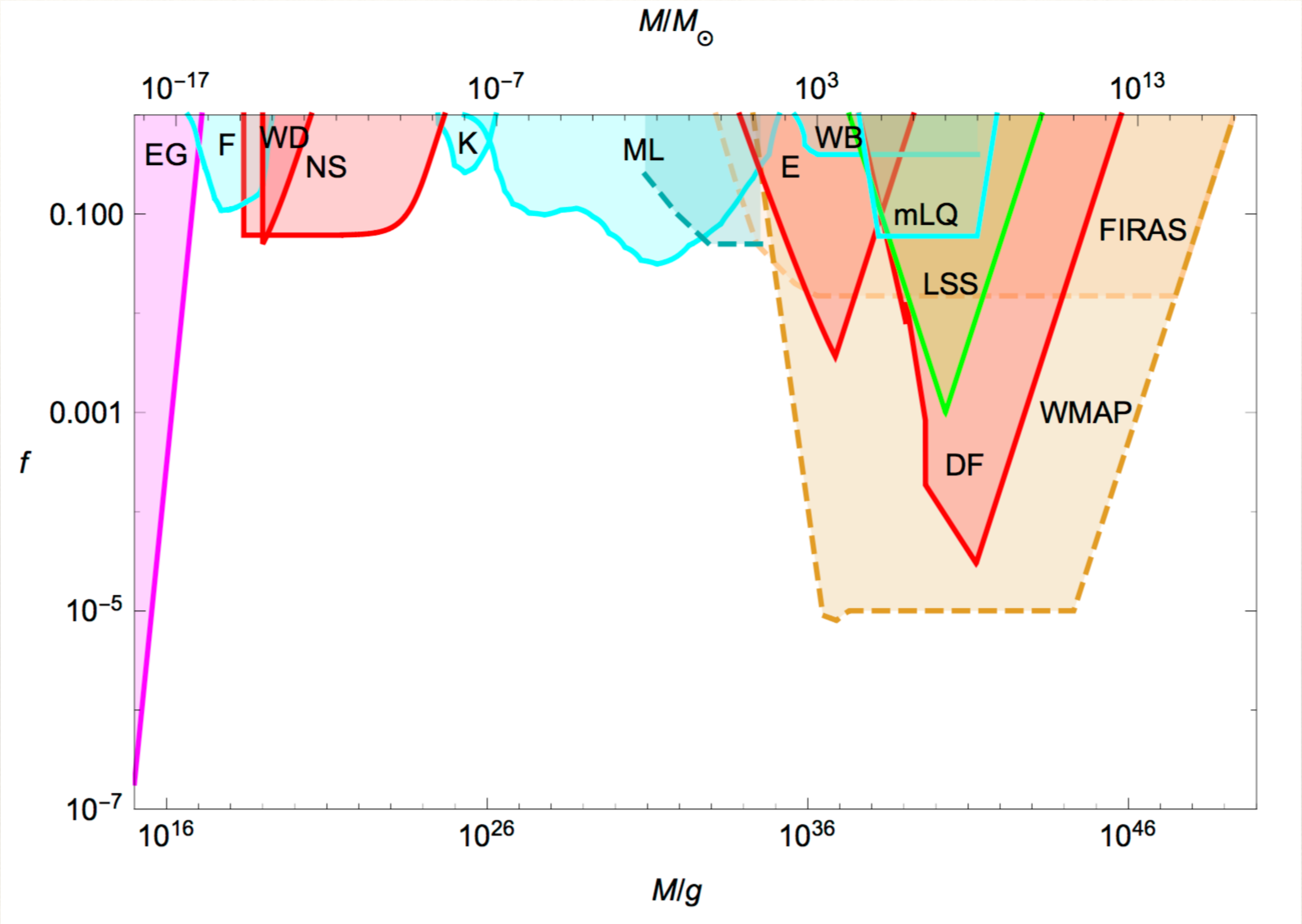

$\underline{M < M_*}$ **Completely evaporated.**

[Carr et al., '10, '17]

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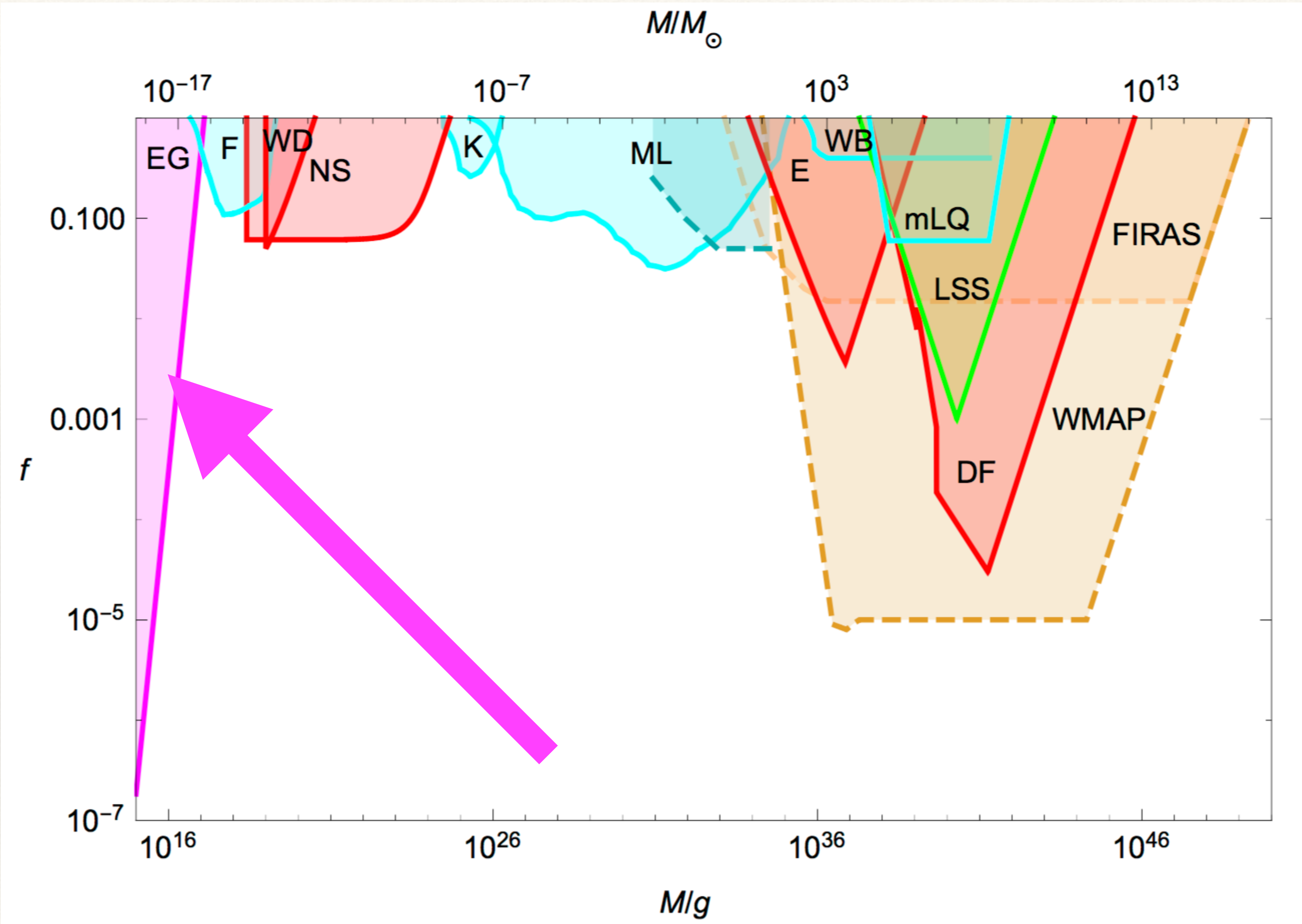


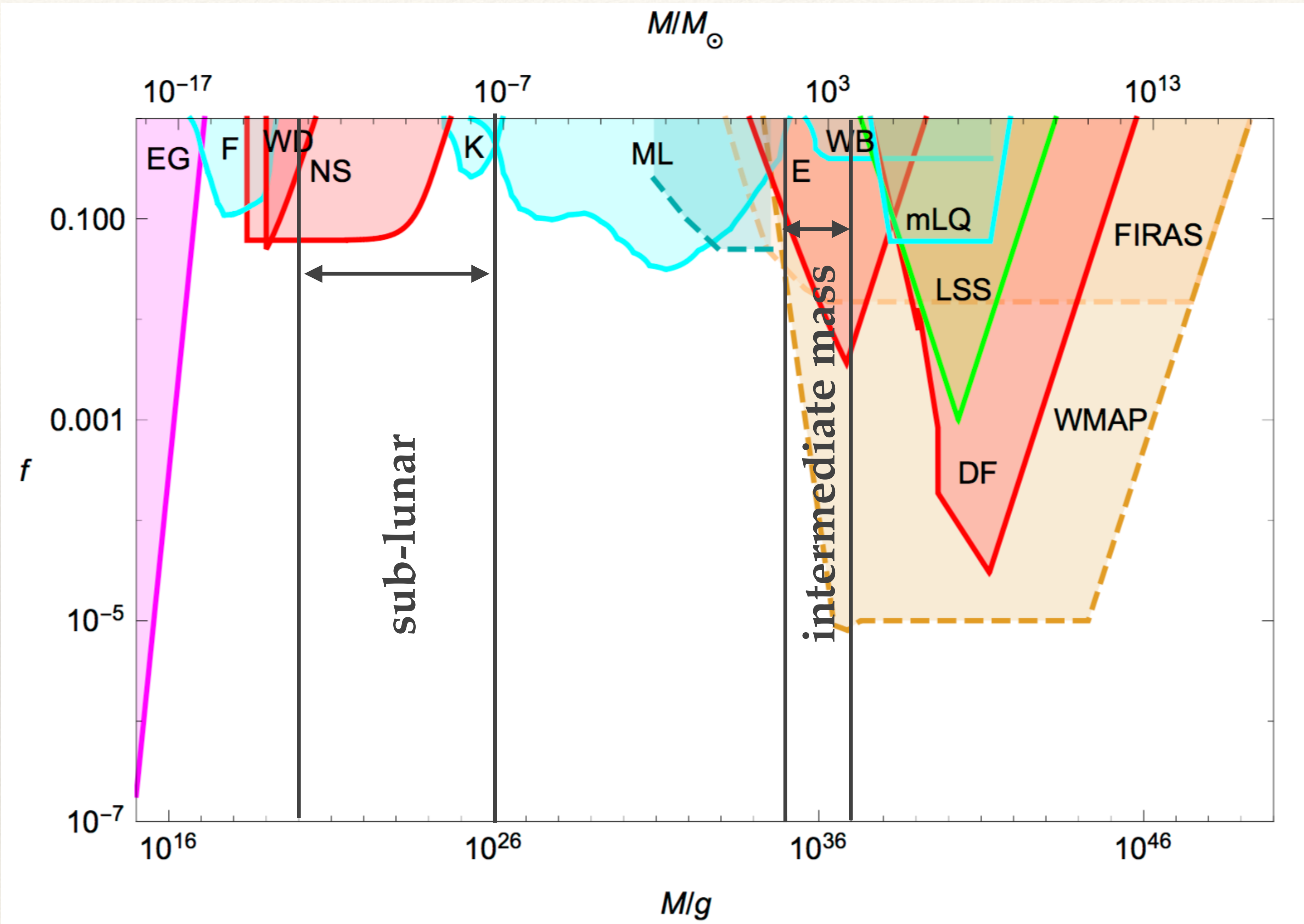
Evaporating now

$$\underline{M \sim M_*}$$

Contribute to the extra-galactic gamma-ray background.
They are subject to the most stringent constraints (EG).

[Carr et al., ’10, ’17]

the abundance of PBHs is subject to many strong constraints



SUB-LUNAR

$$10^{20}\,\mathrm{g} < M < 10^{26}\,\mathrm{g}$$

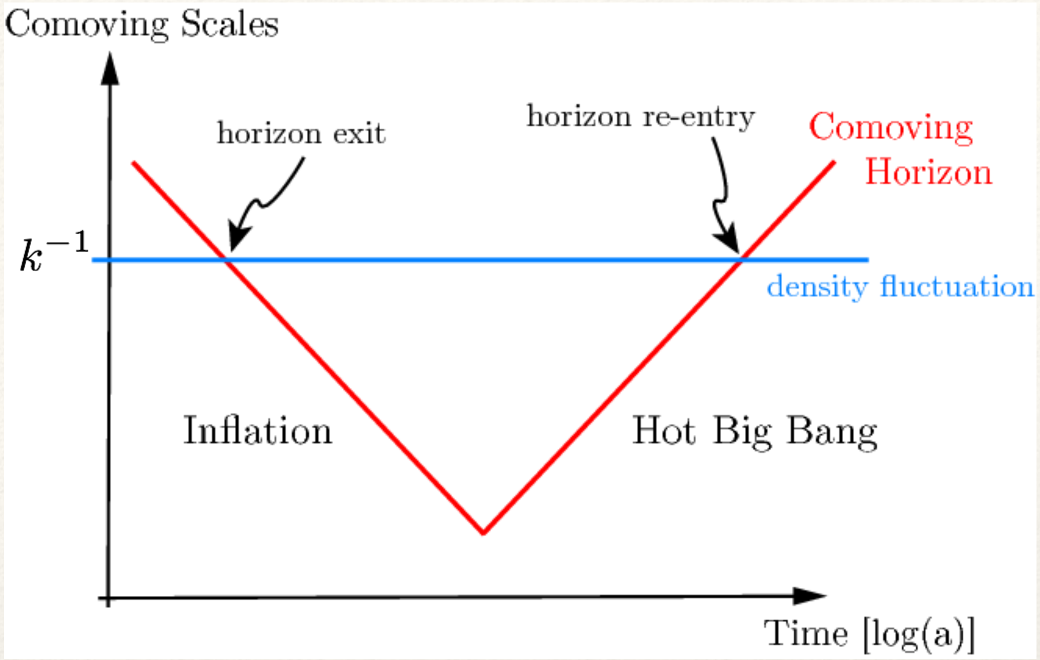
INTERMEDIATE

$$10^{2}\,M_\odot < M < 10^{4}\,M_\odot$$

$M > M_*$ They survive today and can contribute to dark matter.

PBH production

[Garcia-Bellido et al., '96]



<u>IDEA</u>

a PBH is formed when a mode re-enter the horizon if the related density perturbation is above a certain threshold

↓

1-1 map between N and M

$$M_N \simeq 4\pi\gamma M_p^2 \frac{e^{2N}}{H_{\rm inf}}$$

N = number of e-foldings
(before the end of inflation)
at which the mode k left the horizon

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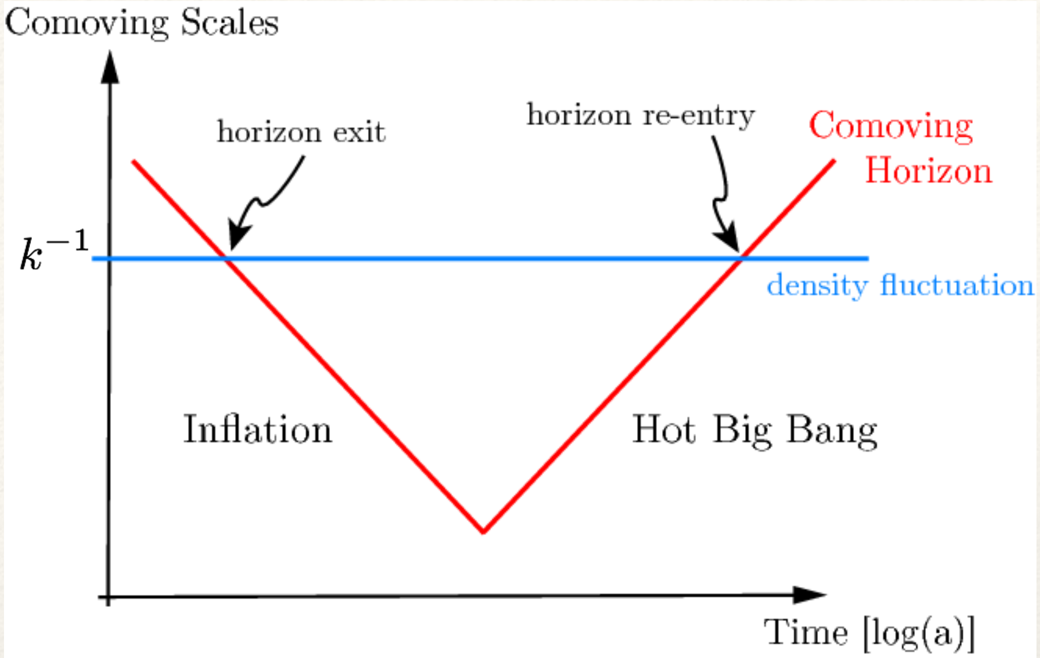

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THRESHOLD

[Carr and Hawking, '74]

A mode collapses if the over-density is large enough at horizon re-entry

Hydrodynamical simulations give

$$0.3 \lesssim \frac{\delta\rho_c}{\rho} \lesssim 0.7$$

[Nadezhin et al., '74]
[Niemeyer et al., '99]
[Shibata et al., '99]
[Musco et al., '05]

PBH production

[Peloso et al., '11]

We consider the curvature perturbation on uniform-density hypersurfaces

$$\zeta = -\frac{H}{\dot{\rho}}\delta\rho \approx -\frac{H}{\dot{\phi}}\delta\phi$$

(spatially flat gauge)

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The probability of forming PBHs with mass M_k upon re-entry of the corresponding mode k is

$$\beta(M_{k_N}) = \int_{\zeta_c}^{\infty} \mathcal{P}(\zeta_{k_N}) d\zeta_{k_N}$$

$\mathcal{P}(\zeta_{k_N})$ **probability distribution**

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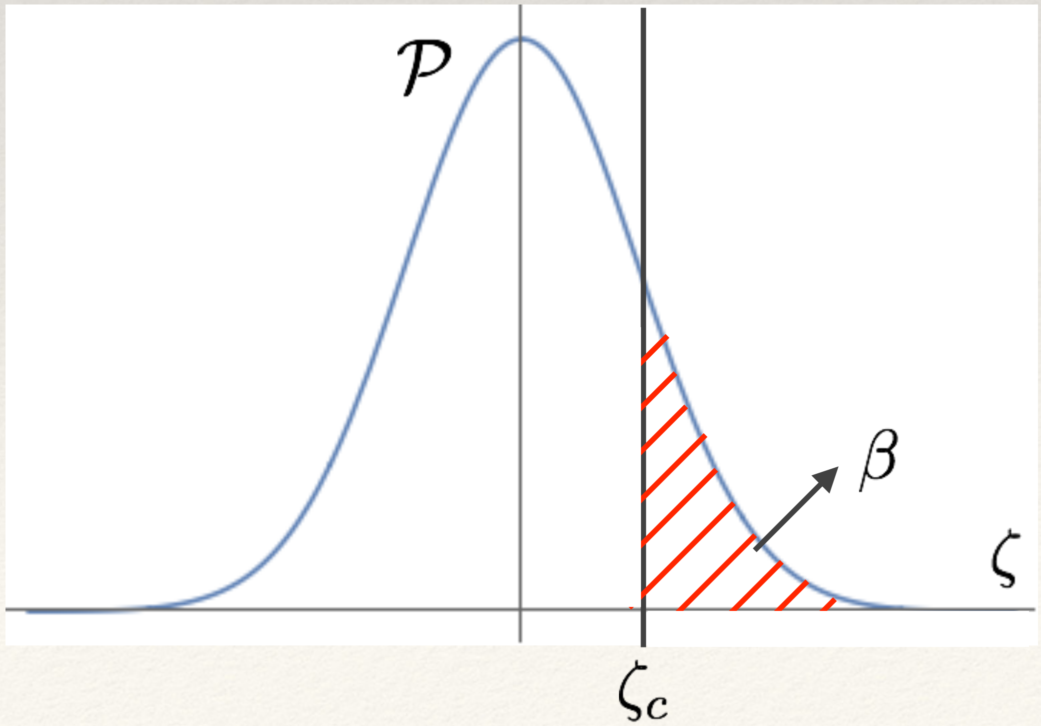
E.g.

$$\mathcal{P}(\zeta_{k_N}) = \frac{e^{-\frac{\zeta_{k_N}^2}{2\sigma_N^2}}}{\sqrt{2\pi}\sigma_N}$$

$$\sigma_N^2 = \Delta_s^2(k_N)$$



PBH density

[Carr et al., ’10, ’17]

The fraction of the universe in PBHs of mass M at the formation epoch t_N is

$$\beta(M) \equiv \frac{\rho_{\rm PBH}(t_N)}{\rho(t_N)} \approx$$

$$\approx 8 \times 10^{-29} \gamma^{-1/2} \left(\frac{g_{*i}}{106.75}\right)^{1/4} \left(\frac{M}{M_\odot}\right)^{3/2} \left(\frac{n_{\rm PBH}(t_0)}{1\,{\rm Gpc}^{-3}}\right)$$

neglecting accretion

TODAY

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TODAY

Fraction of PBH dark matter today is

$$f(M) = \frac{M n_{\rm PBH}(t_0)}{\Omega_{\rm CDM}\rho_c} \simeq 4{\times}10^8 \gamma^{1/2} \left(\frac{g_*(t_N)}{106.75}\right)^{-1/4} \left(\frac{h}{0.68}\right)^{-2} \left(\frac{M}{M_\odot}\right)^{-1/2} \beta(M)$$

Need large inhomogeneities…

at the CMB scales $\Delta_s^2\big|_{\mathrm{CMB}} \simeq 10^{-9}$

COBE normalisation

the spectrum is *locally* almost flat

$$\Delta_s^2(k) \propto k^{n_s-1} \qquad n_s \simeq 0.96$$

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We consider axion inflation coupled with abelian gauge fields

Axion inflation coupled to gauge fields

Generic model

[Sorbo et al., '09]

inflationary potential

$$\frac{\Lambda}{\alpha} \ll M_p$$

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - V(\phi) - \frac{\alpha}{4\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

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Gauge fields

$$\left(\frac{d^2}{d\tau^2} - \nabla^2 - \frac{\alpha}{\Lambda}\frac{d\phi}{d\tau}\nabla\times\right)\mathbf{A} = 0$$

$$\frac{d^2 A_\pm(\tau,k)}{d\tau^2} + \left[k^2 \pm 2k\frac{\xi}{\tau}\right]A_\pm(\tau,k) = 0$$

$$\xi = \frac{\alpha|\dot{\phi}|}{2\Lambda H} \propto \sqrt{\epsilon}$$

increases towards the end of inflation

assuming inflating background $a(\tau) = -\dfrac{1}{H\tau}$

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tachyonic instability

for modes

$$A_+(k,\tau) \propto \left(\frac{k}{aH}\right)^{1/4} e^{\pi\xi - 2\sqrt{2\xi\frac{k}{aH}}}$$

$$(8\xi)^{-1} \lesssim \frac{k}{aH} \lesssim 2\xi$$

$$\downarrow$$

$$\xi \gtrsim 1$$

gauge fields production

exponential amplification of gauge field modes towards the end of inflation

Equations of motion

<u>Inflaton</u> $$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = \boxed{\frac{\alpha}{\Lambda}\langle \mathbf{E}\cdot\mathbf{B}\rangle}$$

new friction term

$$\langle \mathbf{E}\cdot\mathbf{B}\rangle \simeq 2.4\times 10^{-4}\frac{H^4}{\xi^4}e^{2\pi\xi}$$

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Hubble friction dominates at CMB scales (around N=60).

As ξ increases, the new friction term becomes important.

The inflaton speed increase slows down $\longrightarrow$ Additional e-foldings

$$dN = H dt \simeq \frac{H}{\dot{\phi}} d\phi$$

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Friedmann $$3H^2 = \frac{\dot{\phi}^2}{2} + V(\phi) + \underbrace{\frac{1}{2}\langle \mathbf{E}^2 + \mathbf{B}^2\rangle}_{\text{always negligible}}$$

$$\frac{1}{2}\langle \mathbf{E}^2 + \mathbf{B}^2\rangle \simeq 1.4\times 10^{-4}\frac{H^4}{\xi^3}e^{2\pi\xi}$$

Perturbations

Inflaton $\phi(\tau, \mathbf{x}) = \phi(\tau) + \delta\phi(\tau, \mathbf{x})$

$$\delta\phi'' + 2aH\delta\phi' + \left(-\nabla^2 + a^2 V''\right)\delta\phi = -\frac{\alpha}{\Lambda}\delta\left[\mathbf{E}\cdot\mathbf{B}\right] \longrightarrow$$

source for the scalar power spectrum

[Sorbo et al., ‘09]
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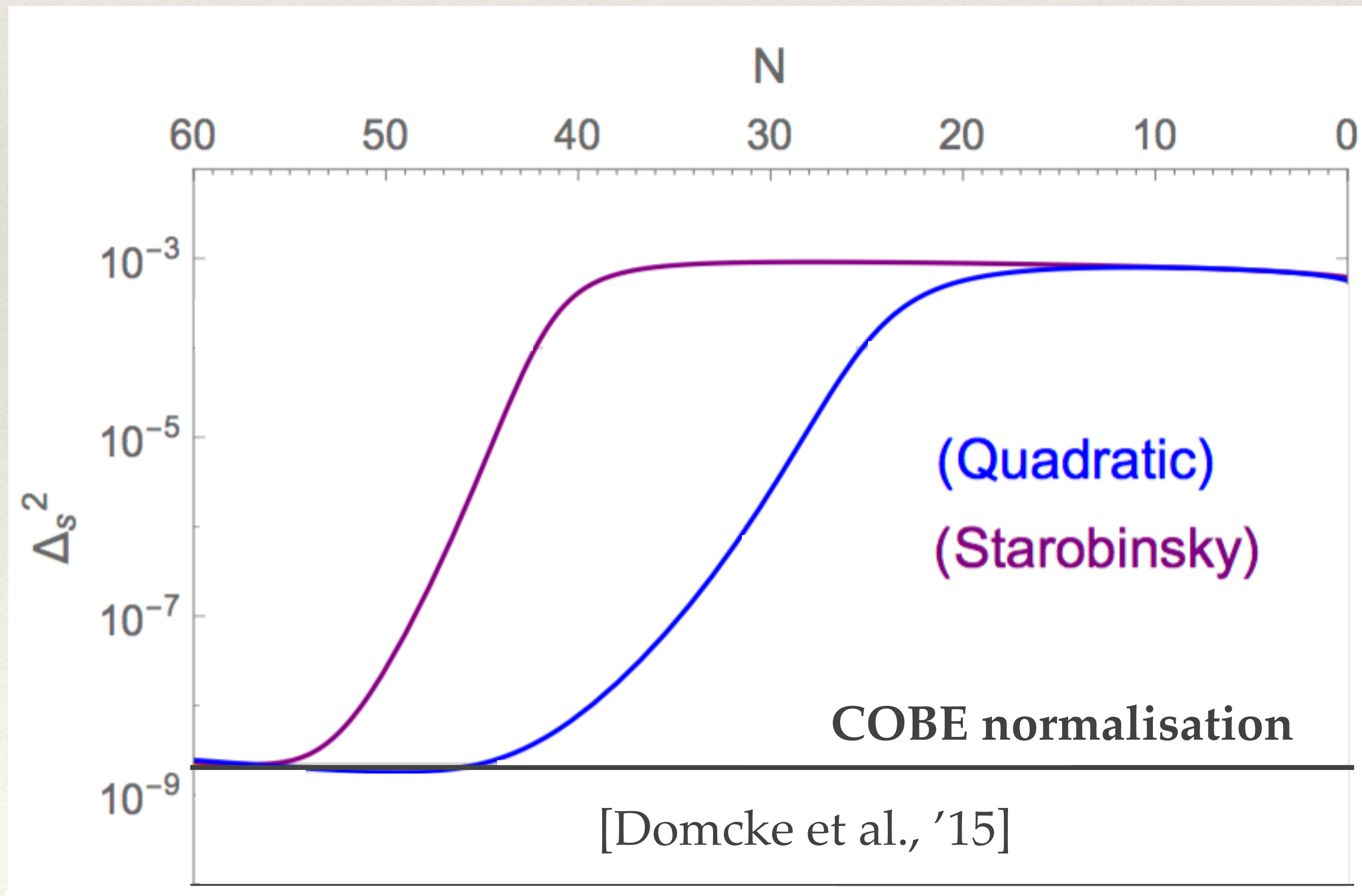
Power spectrum

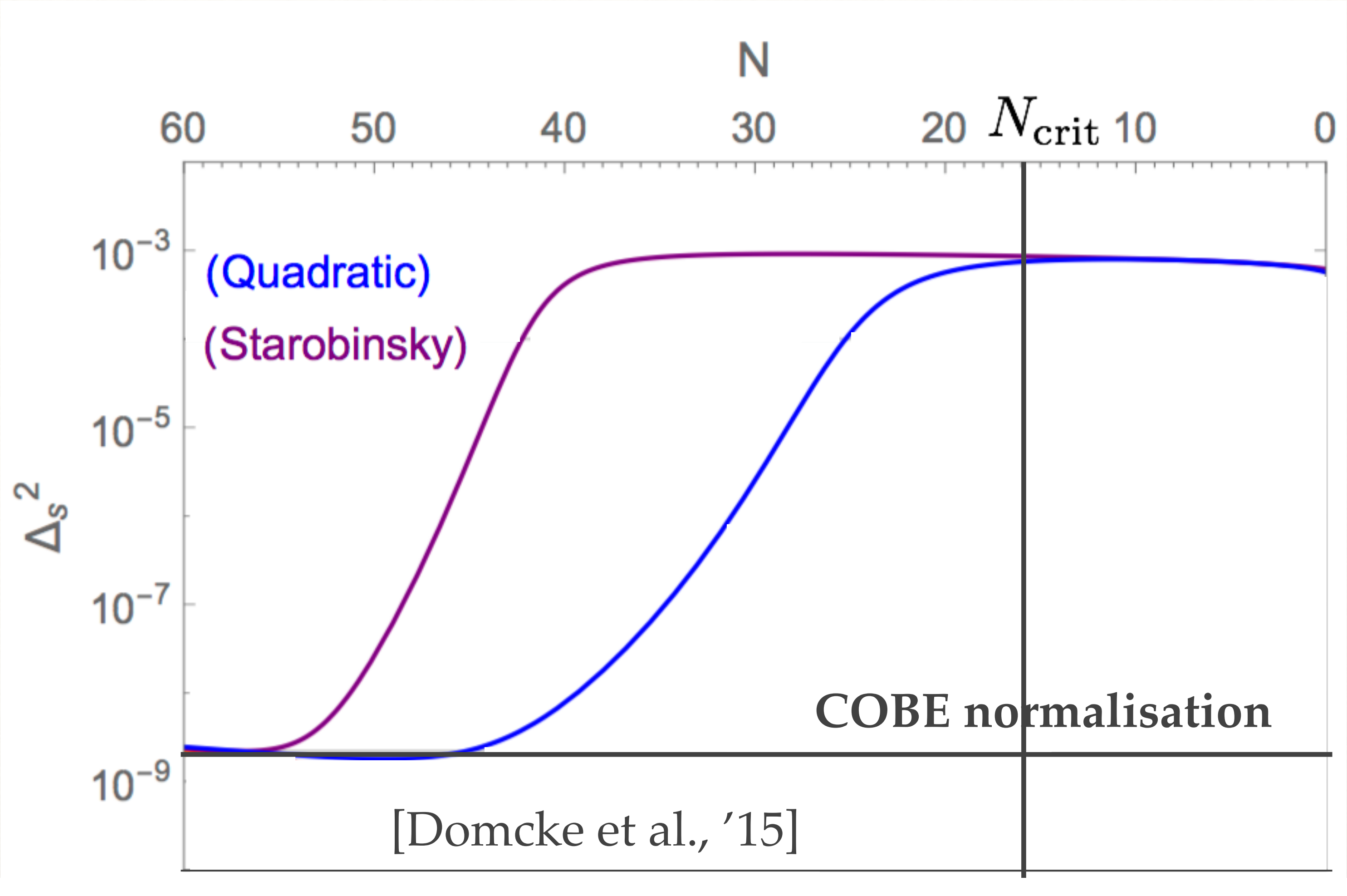
$$\Delta_s^2(k) = \left(\frac{H^2}{2\pi|\dot{\phi}|}\right)^2 + \left(\frac{\alpha\langle\mathbf{E}\cdot\mathbf{B}\rangle}{3\Lambda b H\dot{\phi}}\right)^2$$

$$b \equiv 1 - 2\pi\xi\frac{\alpha\langle\mathbf{E}\cdot\mathbf{B}\rangle}{3\Lambda H\dot{\phi}}$$

$$\boxed{\textbf{Blue spectrum}}$$



plateau in the scalar power spectrum



plateau in the scalar power spectrum

↓

at small N, PBHs of critical mass are produced

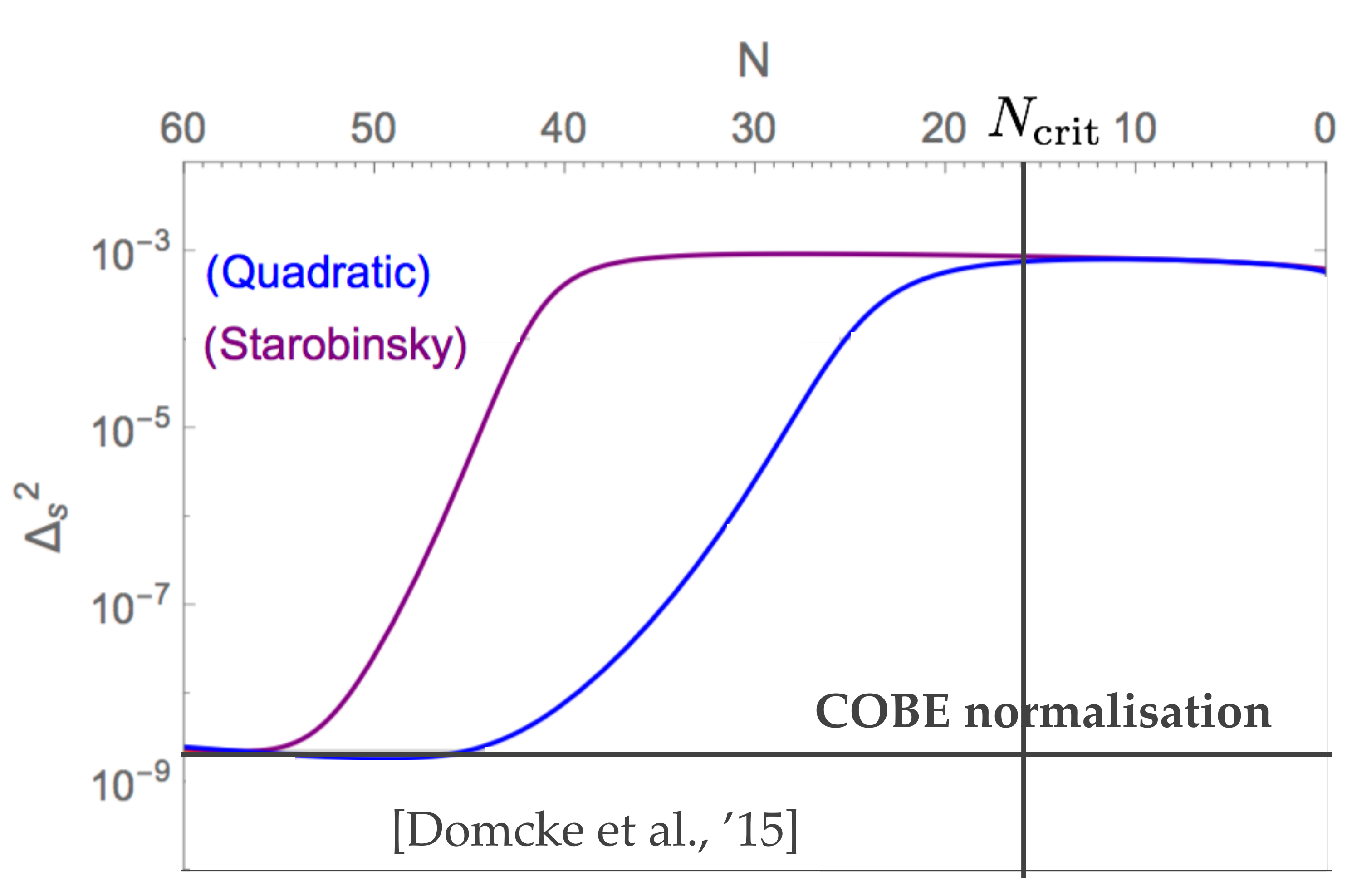
E.g. for $H_{\rm inf} \simeq 10^{-5}\, M_p$

$$N_{\rm crit} \simeq 16$$

↓

$$f_{\rm tot} \lesssim 10^{-11}$$

totally negligible



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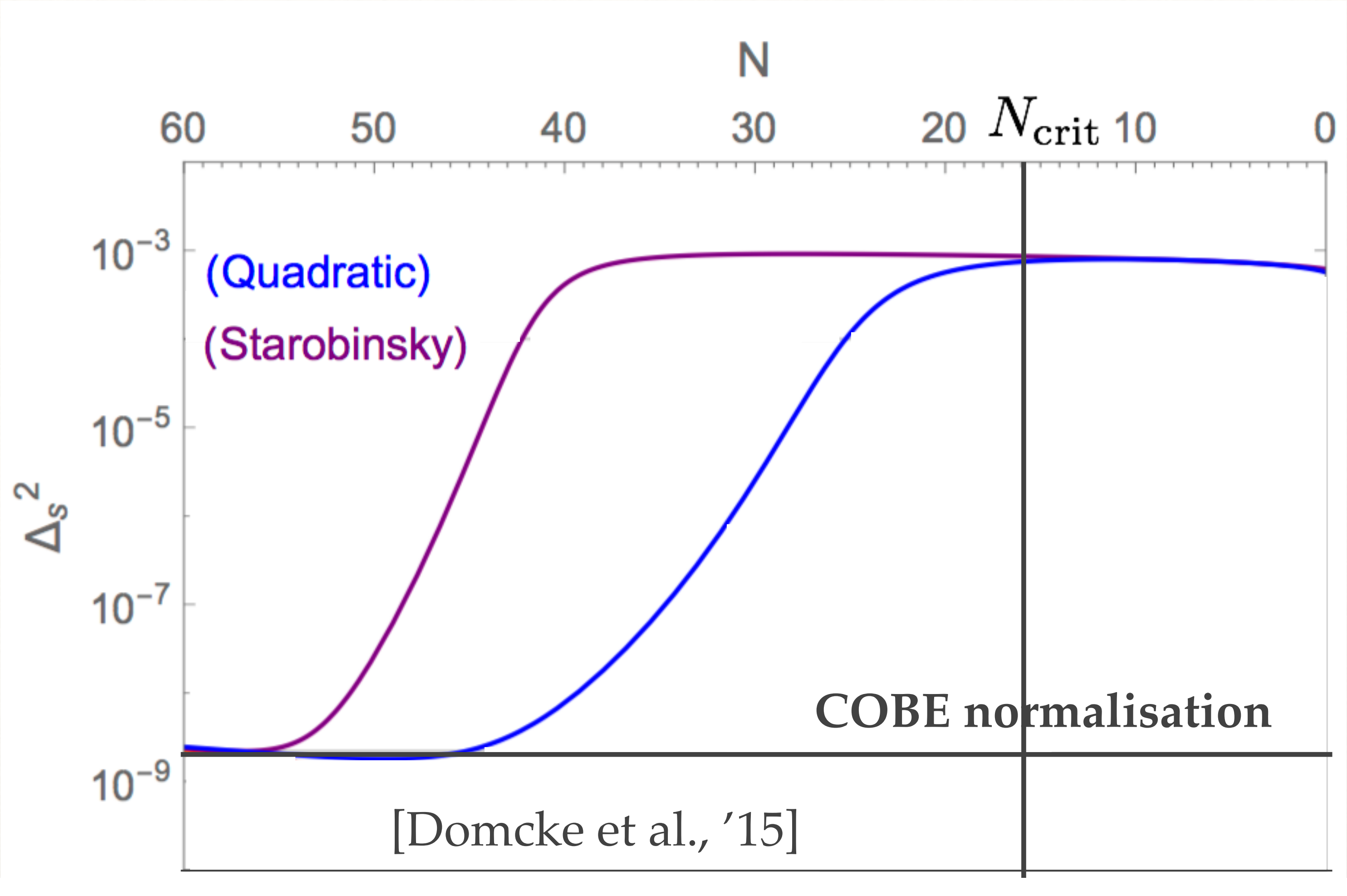

coupling to gauge fields is useful to rise the spectrum, but we need a mechanism to suppress it at small scales

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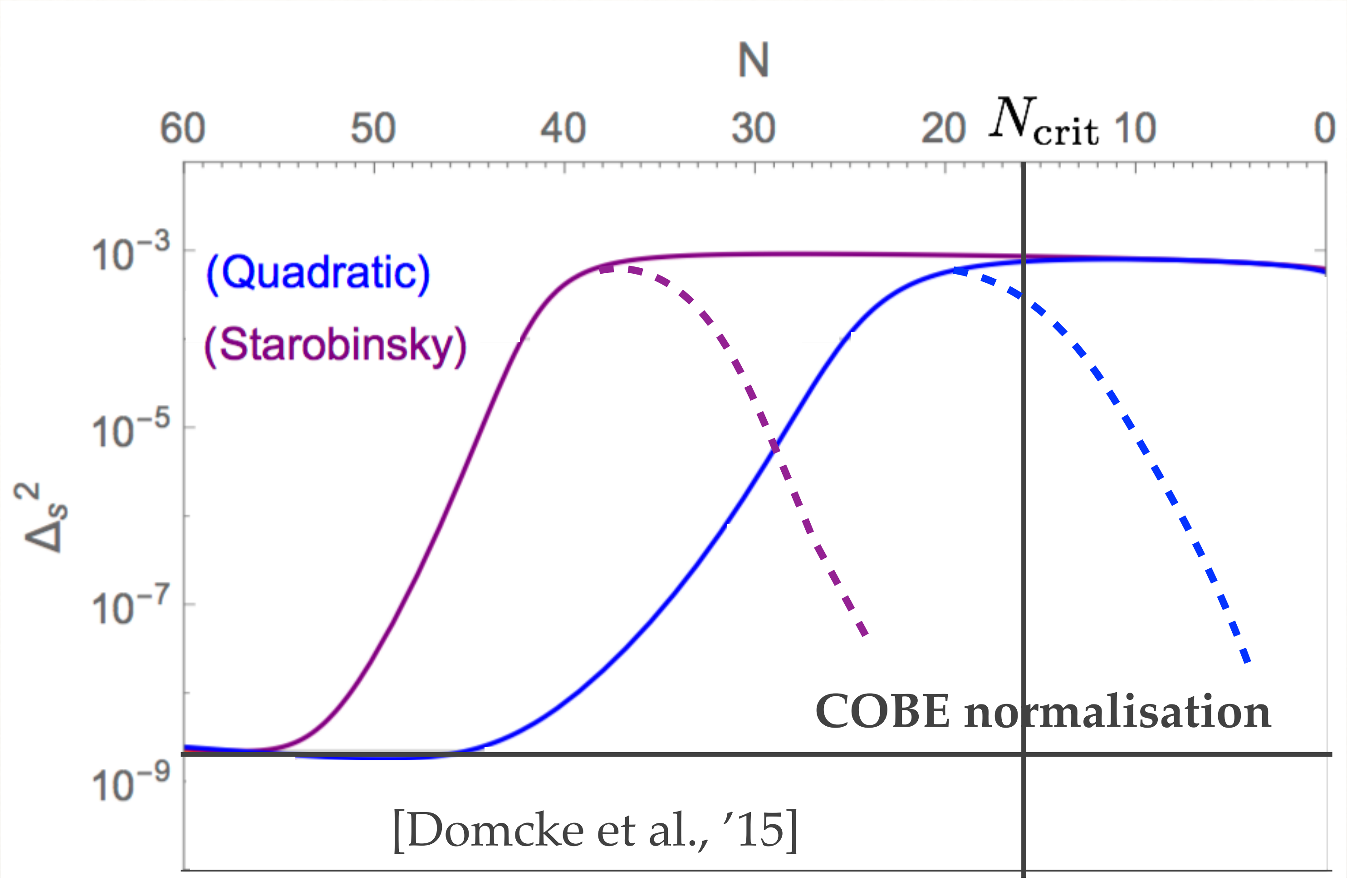

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Simplest extension

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{2} - K(\phi)\partial_\mu\phi\partial^\mu\phi - V - \frac{g^{\mu\rho}g^{\nu\sigma}}{4}F_{\mu\nu}F_{\rho\sigma} - \frac{\alpha}{4\Lambda}\frac{\epsilon^{\mu\nu\rho\sigma}}{2\sqrt{-g}}\phi F_{\mu\nu}F_{\rho\sigma}\right]$$

non-canonical kinetic term

The presence of K implies that the tachyonic instability is governed by

$$\xi = \sqrt{\frac{\epsilon}{K}} \longrightarrow$$ **results depend on the behaviour of K**

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<u>Attractors at strong coupling</u> [Linde et al., '13]

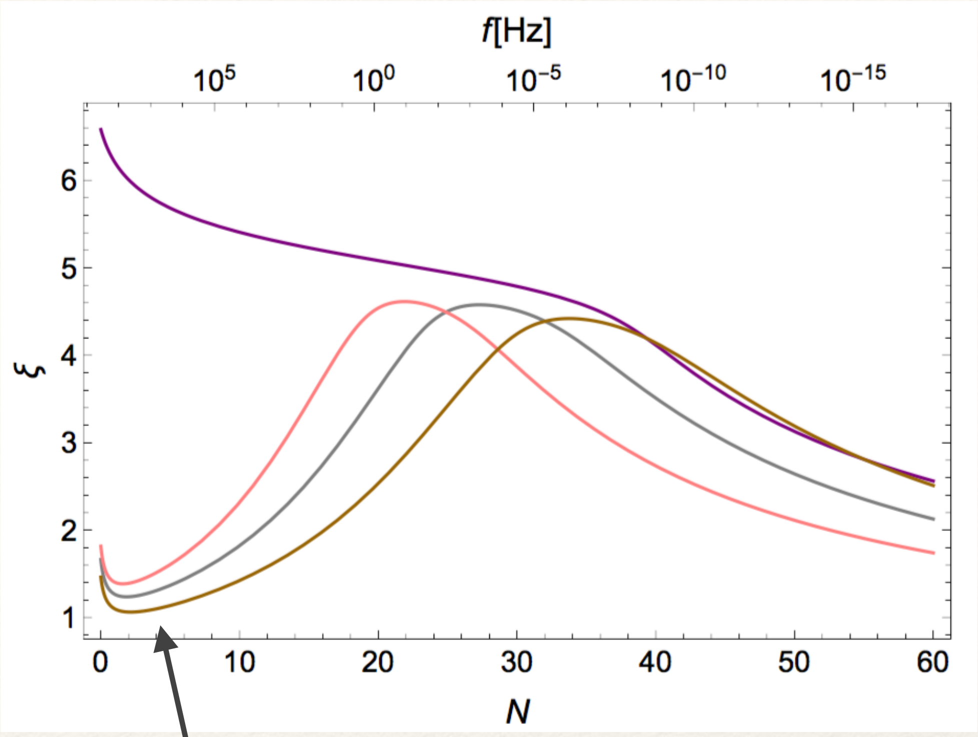
$$K(\phi) = \frac{1 + \varsigma h(\phi) + 3/2\,\varsigma^2 h_{,\phi}^2(\phi)}{(1+\varsigma h(\phi))^2} \qquad V(\phi) = \lambda^4 \frac{h^2(\phi)}{(1+\varsigma h(\phi))^2}$$

$\varsigma \to 0$ **canonical kinetic terms**

$$h = 1 - \frac{1}{\phi}$$

$$\epsilon \sim N^{-4/3}$$

$$K \sim e^{-N}$$



the instability is turned off towards the end of inflation

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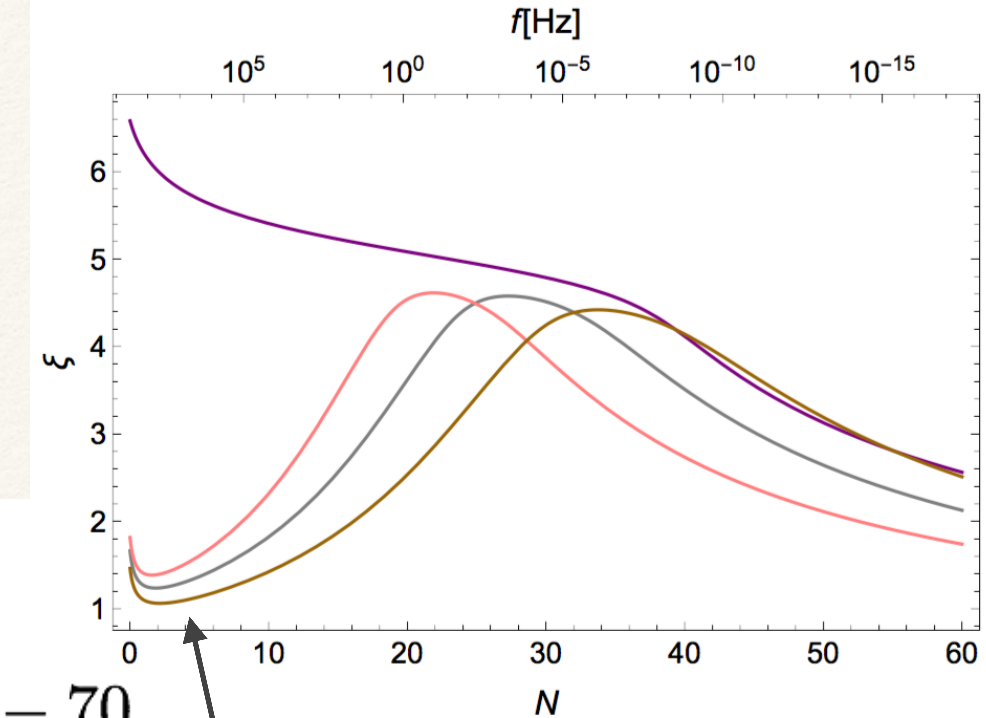

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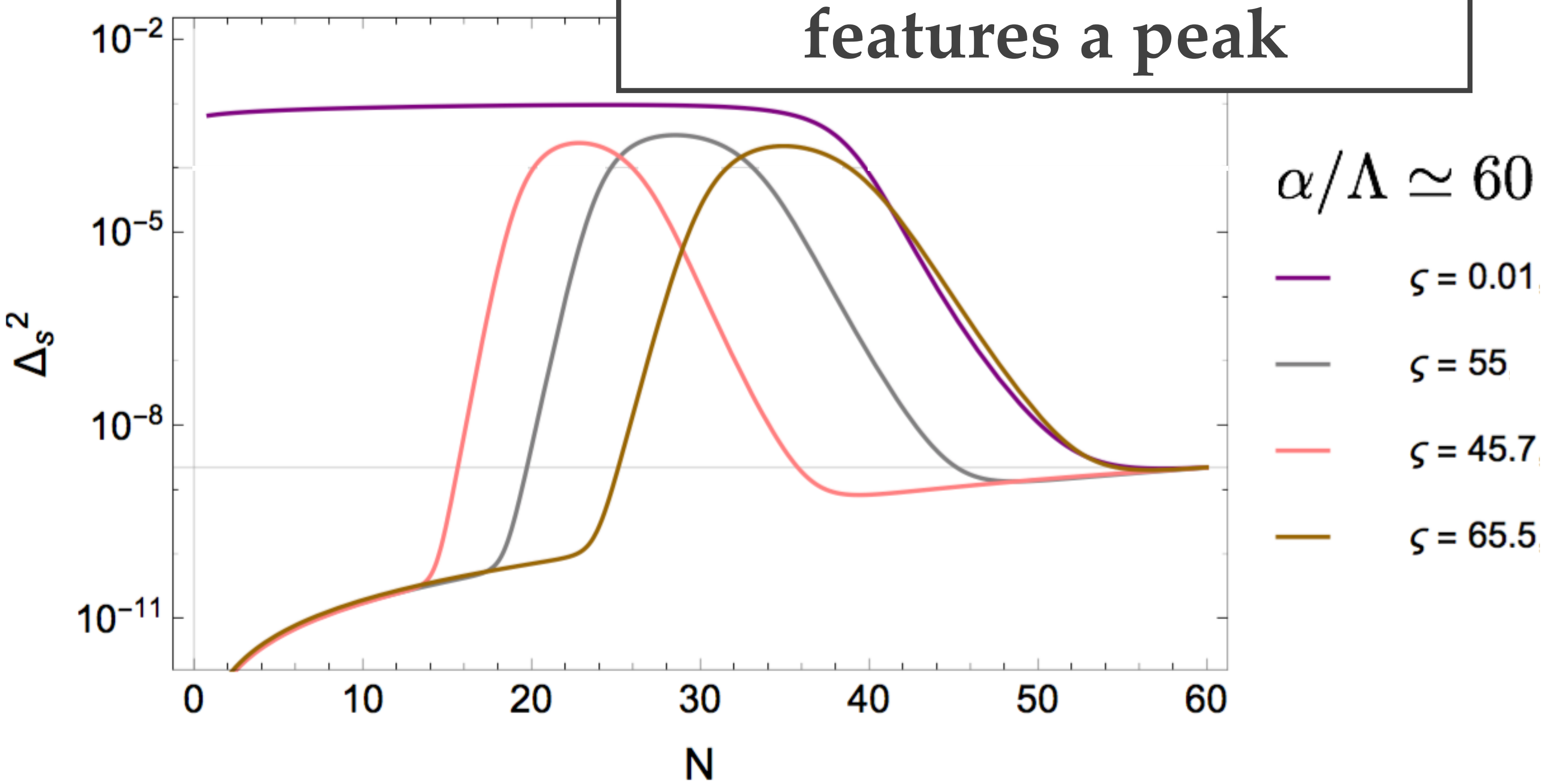
the power spectrum features a peak



$\alpha/\Lambda \simeq 60 - 70$

i) Increasing α/Λ the instability starts earlier.

ii) Increasing ς the instability is turned off earlier.

iii) GW production always negligible in the case interesting for PBHs.

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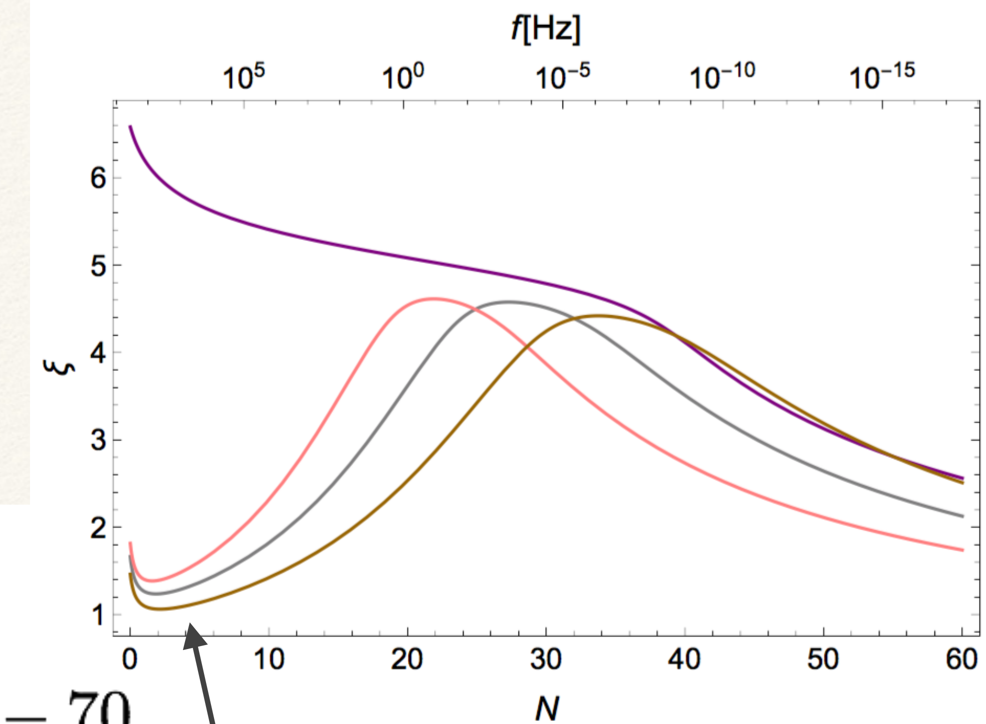

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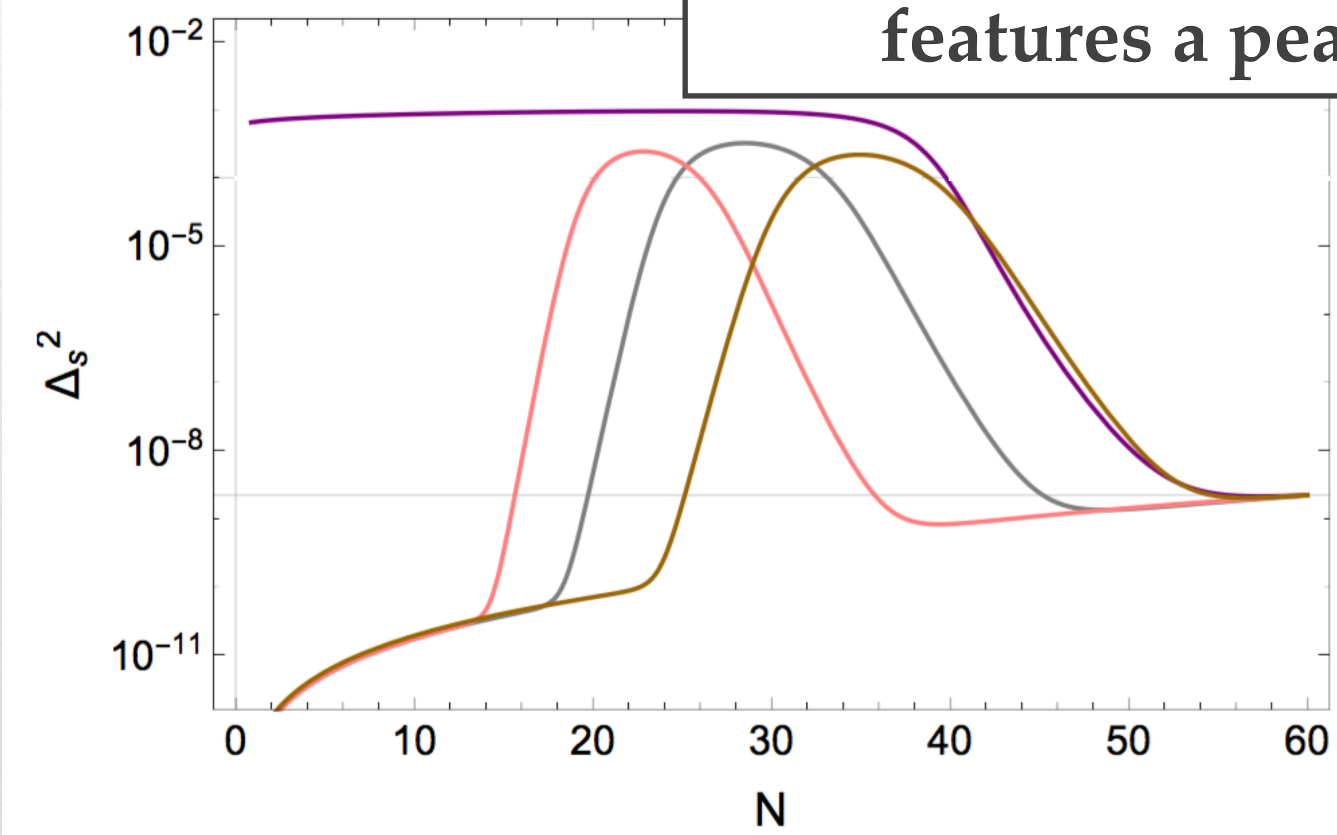
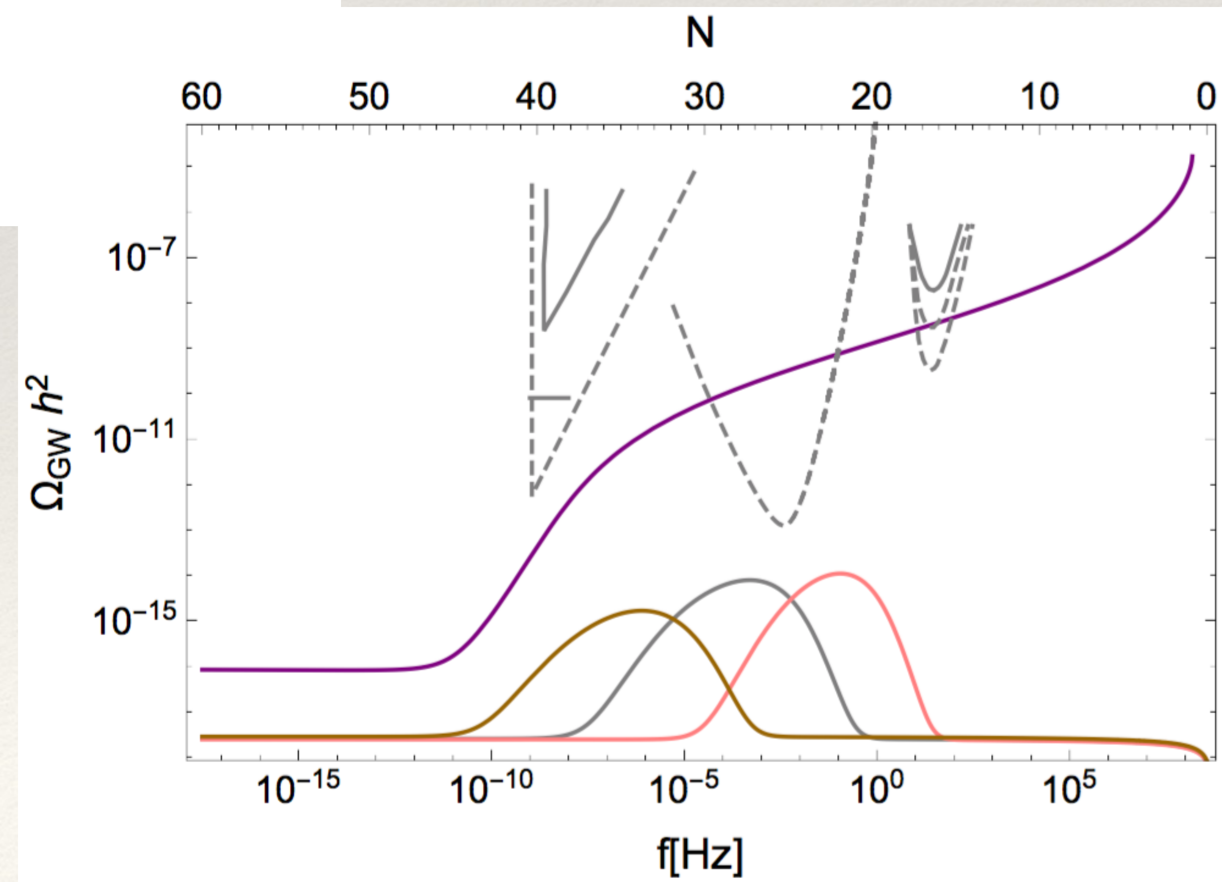


$\alpha/\Lambda \simeq 60 - 70$

- $\varsigma = 0.01$
- $\varsigma = 55$
- $\varsigma = 45.7$
- $\varsigma = 65.5$

the instability is turned off towards the end of inflation



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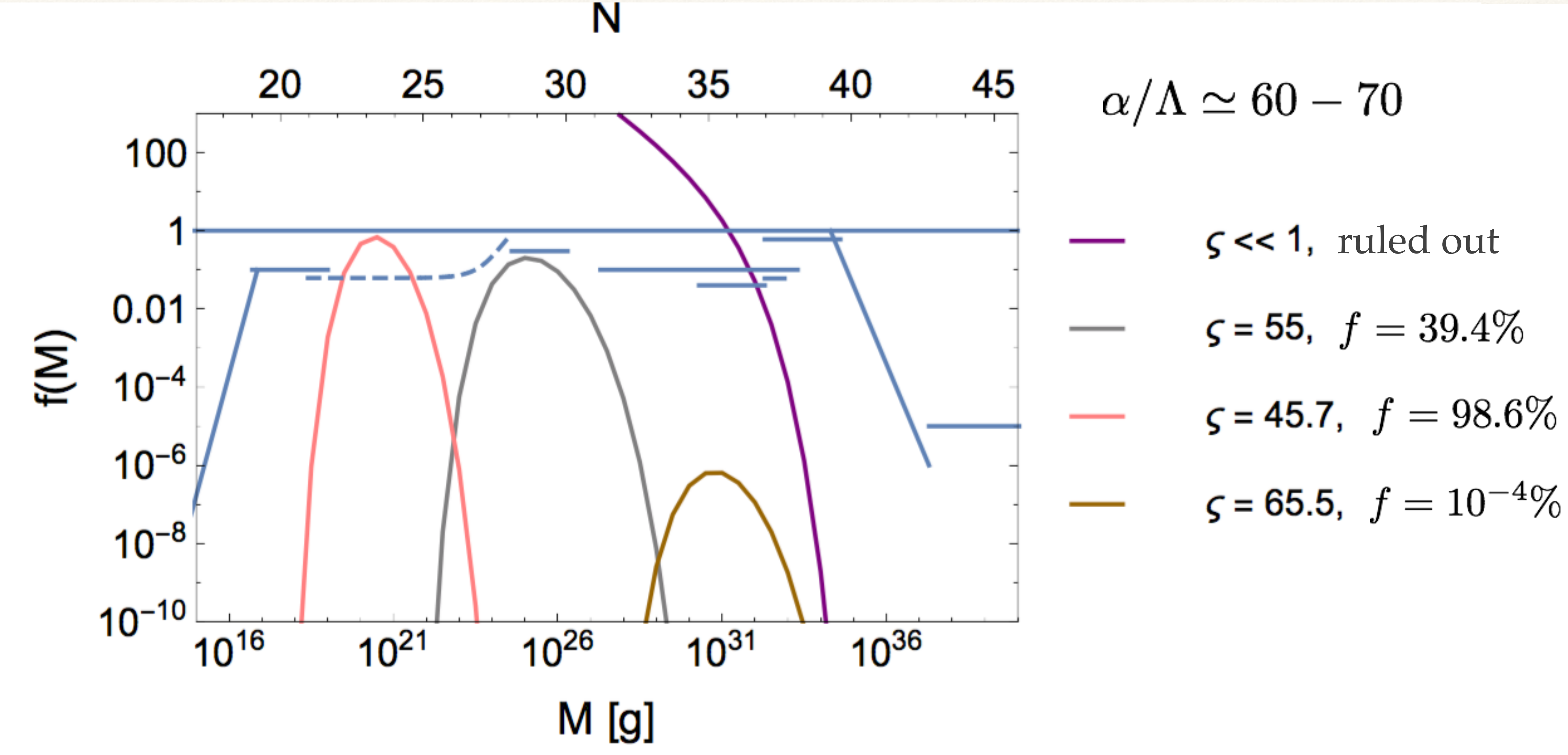
PBH production



i) Increasing α/Λ and ς shifts the peak towards larger mass values.

ii) We neglected NS capture constraints.

iii) The amplitude of the brown curve is constrained by CMB: cannot be larger than this.

iv) The case with canonical kinetic terms is ruled out by PBH overproduction.

Conclusions and outlook

Models of axion inflation with coupling to gauge fields are extremely interesting from a phenomenological point of view

potentially observable chiral GWs, non-gaussianities

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- **Systematic scan of K's that allow for a bump in the scalar power spectrum.**
- **Reheating (generic tension with dark radiation?).**
- **String theory embedding.**
- **Extension to non-abelian gauge fields.**

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$\boxed{\text{A simple extension allows for PBH dark matter}}$

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- Reheating (generic tension with dark radiation?).
- String theory embedding.
- Extension to non-abelian gauge fields.

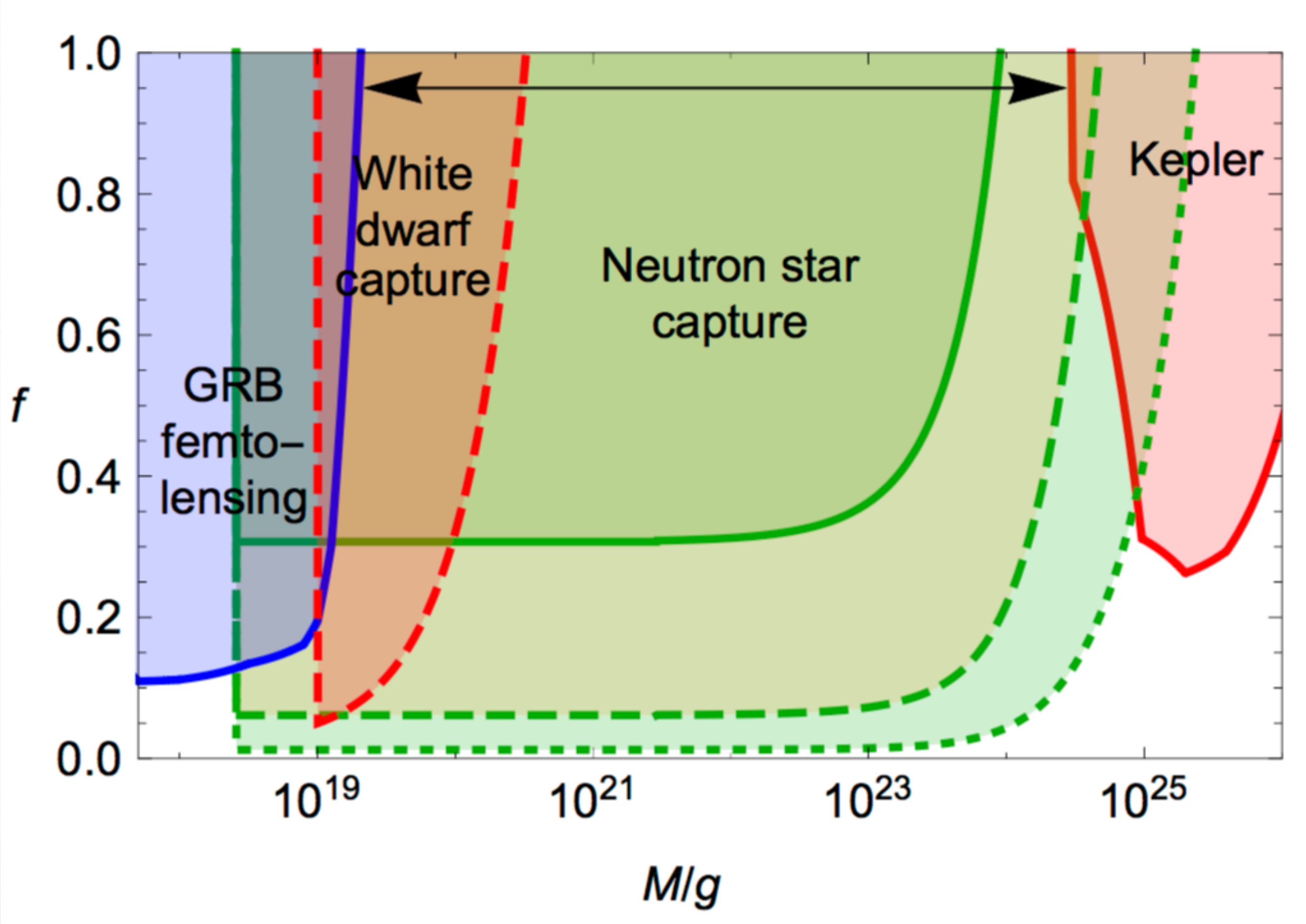
Thank you!

Neutron stars capture

Neutron stars:

$$M_{\rm NS} \simeq M_{\odot}$$

$$R_{\rm NS} \simeq 10\,{\rm Km}$$



The presence of a PBH inside a NS leads to its rapid destruction by the accretion of the star matter onto the PBH

[Kouvaris et al., '04, '11, '12]

Capture rate depends on the DM density

"Assuming that cores of globular clusters possess the DM densities exceeding several hundred ${\rm GeV/cm^3}$ would imply that PBHs are excluded as comprising all of the dark matter in the mass range $3\times10^{18}\,{\rm g} \lesssim M \lesssim 10^{24}\,{\rm g}$"

[Capela et al., '13]

HOWEVER

Observations of globular clusters show no evidence of significant dark matter content in such systems

[Ibata et al., '12]

[Bradford et al., '11]

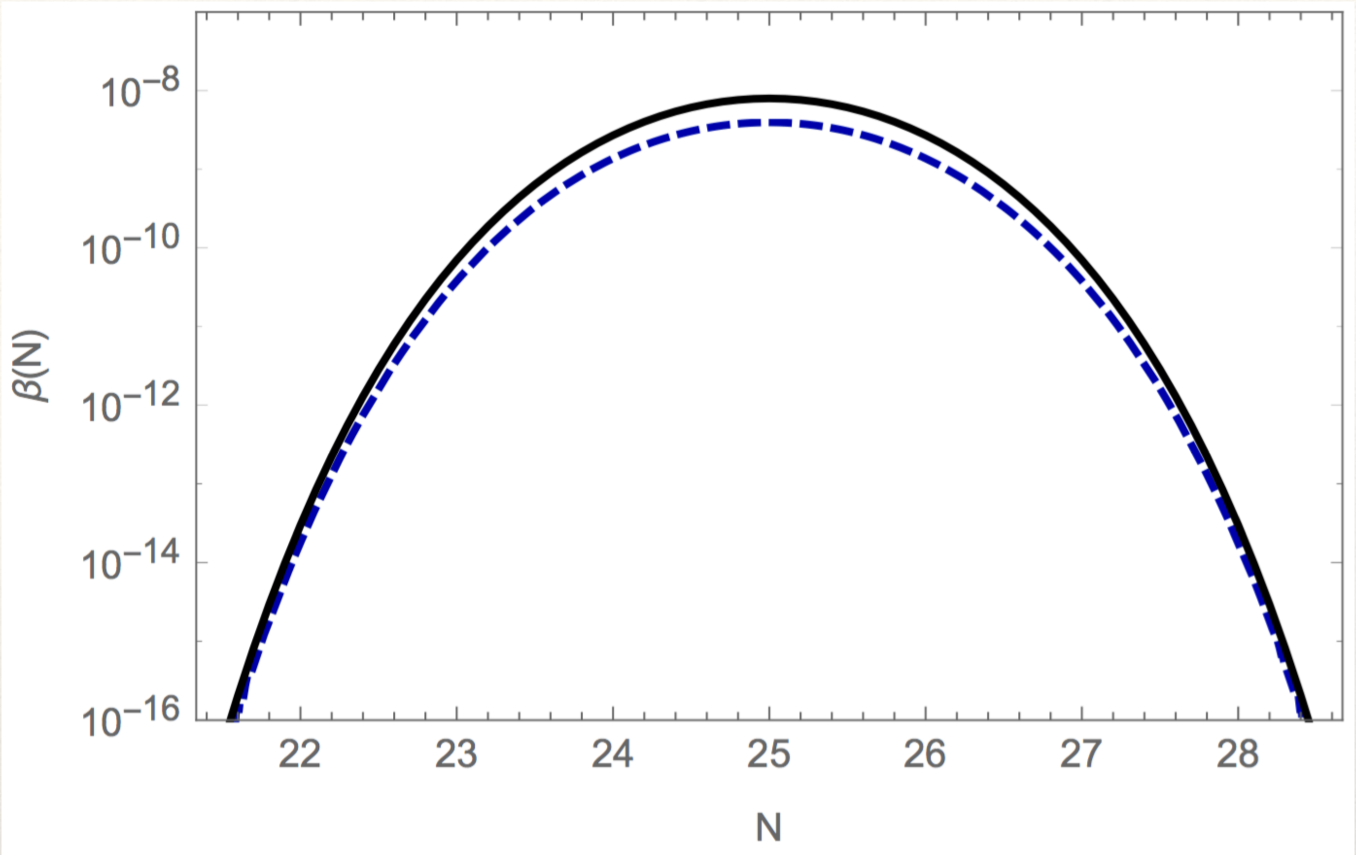
Are we neglecting something?

Yes, several things…

- Critical collapse.

$$M(\zeta, N) = \lambda M_H(N)(\zeta - \zeta_c)^y$$

$\longrightarrow$ typically O(1) corrections



- Accretion and mergers.

critical mass at equality $M_*^{\rm eq} \simeq 3 \times 10^{12}\,{\rm g}$

During matter domination PBHs of mass M_* merge and become stable.

All PBHs become heavier.

- Non sphericity. $\longrightarrow$ generically increases the threshold ζ_c

$$\boxed{\text{Proof-of-principle that these models can give rise to a sizeable amount of PBH dark matter}}$$

Perturbations

Metric

$$\langle h_+(\mathbf{k})h_+(\mathbf{k}')\rangle \simeq 8.6\times10^{-7}\frac{H^4}{M_P^4}\frac{e^{4\pi\xi}}{\xi^6}\frac{\delta(\mathbf{k}+\mathbf{k}')}{k^3}$$

$$\langle h_-(\mathbf{k})h_-(\mathbf{k}')\rangle \simeq 1.8\times10^{-9}\frac{H^4}{M_P^4}\frac{e^{4\pi\xi}}{\xi^6}\frac{\delta(\mathbf{k}+\mathbf{k}')}{k^3}$$

[Sorbo, ’11]
[Sorbo et al., ’12]

Chiral spectrum

kind of smoking gun

GW energy density

$$\Omega_{\rm GW} = \frac{\Omega_{\rm R,0}}{24}\Delta_t^2 \simeq \frac{1}{12}\Omega_{\rm R,0}\left(\frac{H}{\pi M_p}\right)^2\left(1+4.3\times10^{-7}\frac{H^2}{M_p^2\xi^6}e^{4\pi\xi}\right)$$

$$\Omega_{\rm R,0}\simeq 8.6\times10^{-5}$$

ALSO

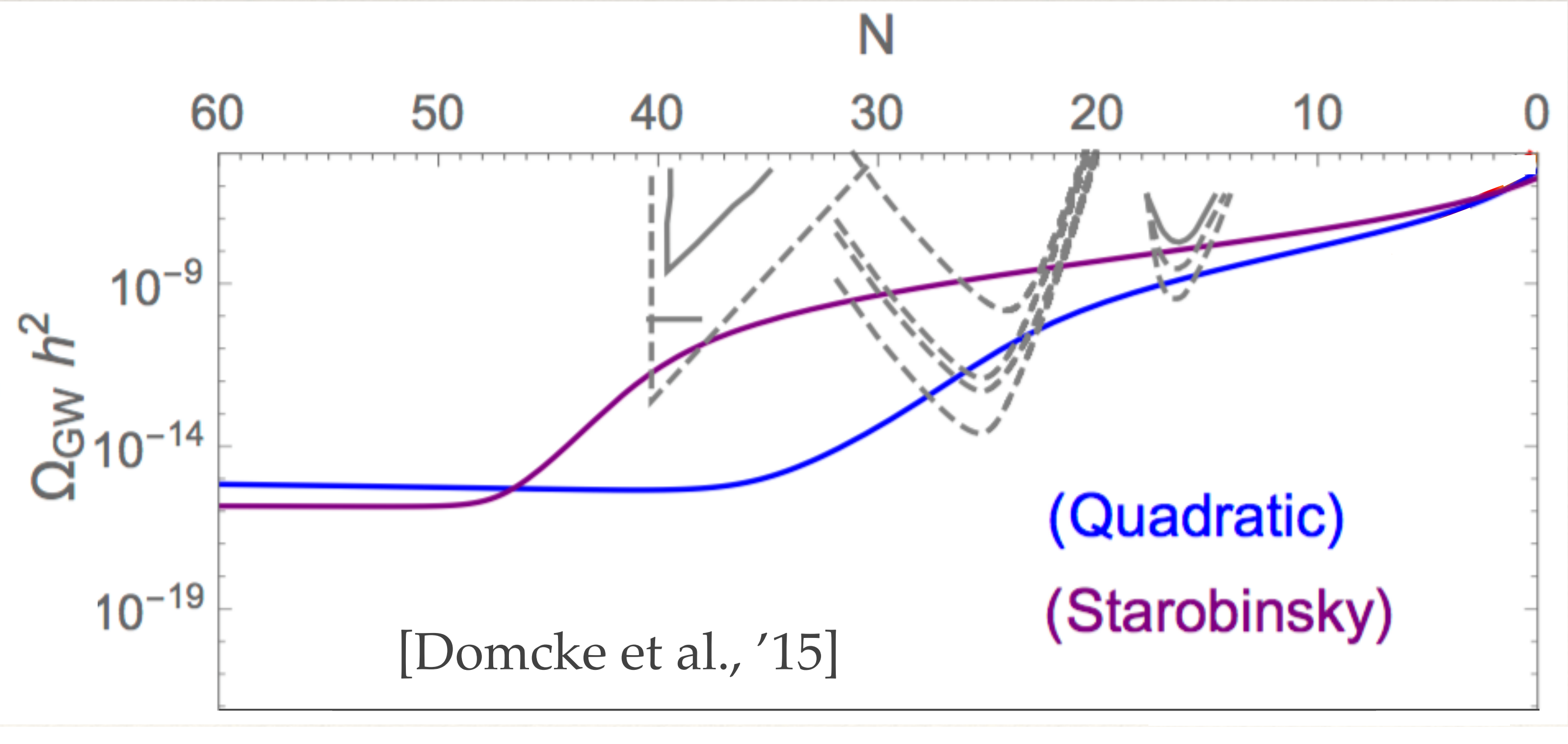
Large non-gaussianities

$$f_{\rm NL}^{\rm equil} \simeq 8.9\times10^4\frac{H^6}{\epsilon^3 M_p^6}\frac{e^{6\pi\xi}}{\xi^9}$$

$$\downarrow$$

$$\xi|_{\rm CMB} \lesssim 2.6$$

[Sorbo et al., ’12]



[Domcke et al., ’15]

Perturbations revisited

[Peloso et al., '11]
[Linde and Pajer, '13]

Inflaton

$$\cancel{\ddot{\delta\phi}} + 3bH\dot{\delta\phi} + \left(-\cancel{\frac{\nabla^2}{a^2}} \boxed{+V''}\right)\delta\phi = -\frac{\alpha}{\Lambda}\left[\mathbf{E}\cdot\mathbf{B} - \langle\mathbf{E}\cdot\mathbf{B}\rangle\right]_{\phi=0}$$

small correction (slow-roll)

$$b \equiv 1 - 2\pi\xi\frac{\alpha\langle\mathbf{E}\cdot\mathbf{B}\rangle}{3\Lambda H\dot{\phi}}$$

At horizon crossing

$$\partial \sim H$$
$$aH = k$$

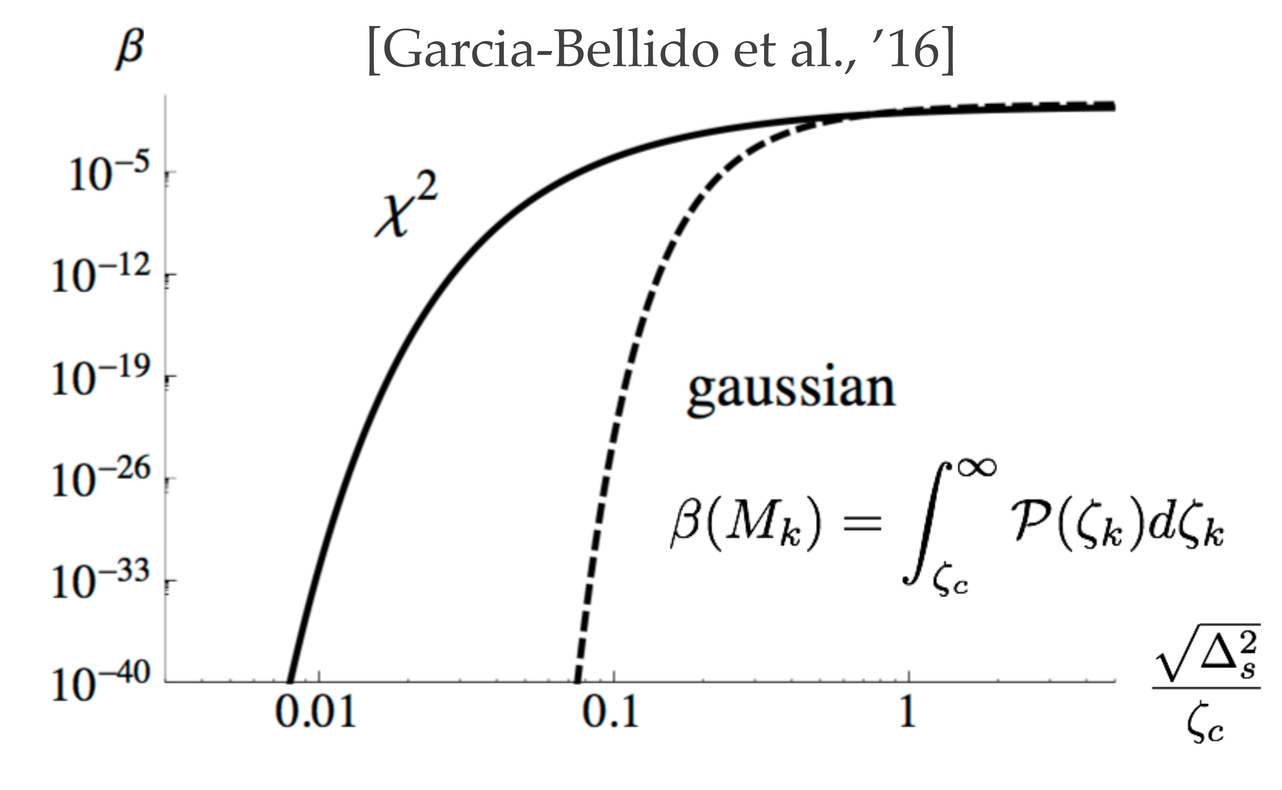
$b \gg 1$ in the gauge field regime

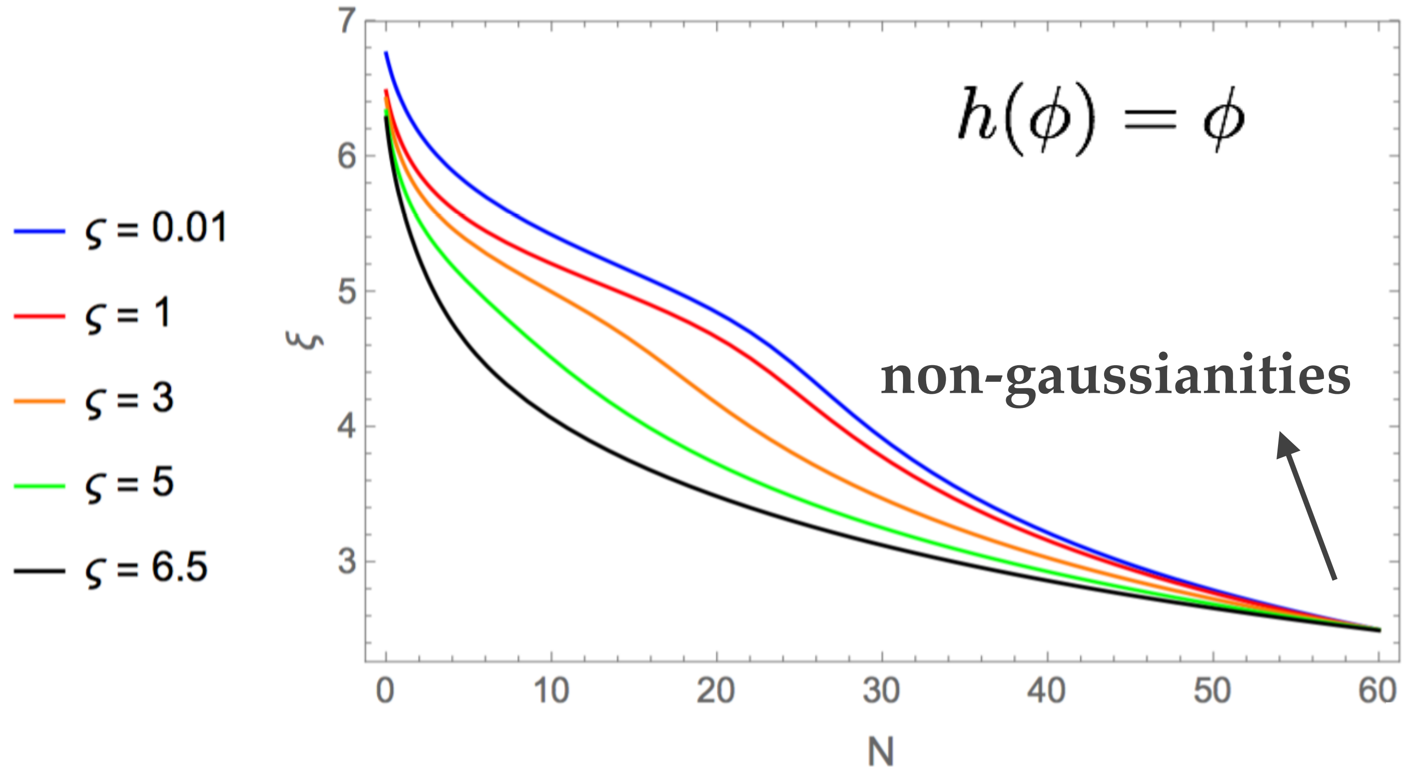
$$\delta\phi \approx \frac{\alpha\left(\mathbf{E}\cdot\mathbf{B} - \langle\mathbf{E}\cdot\mathbf{B}\rangle\right)}{3bH^2} \longrightarrow \zeta \sim \frac{H}{\dot{\phi}}\delta\phi$$

Not a gaussian! $P(\zeta)d\zeta = P(g)dg$

$$P(\zeta_N) = \frac{e^{-\frac{\zeta_N+\sigma_N^2}{2\sigma_N^2}}}{\sqrt{2\pi\sigma_N^2(\zeta_N+\sigma_N^2)}}$$

$$\sigma_N^2 = \left(\Delta_s^2(k_N)\right)^{1/2}$$





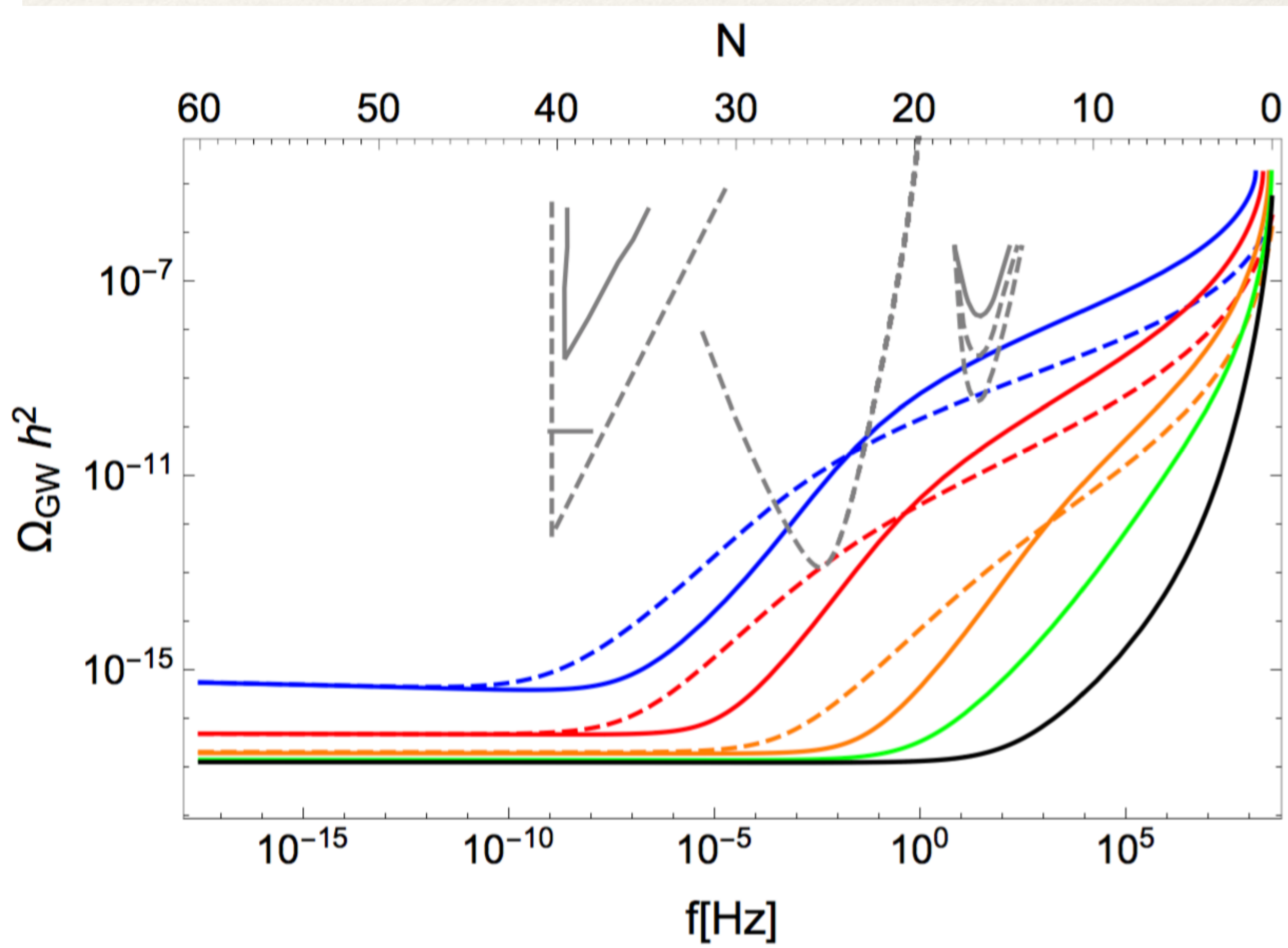
larger ς

↓

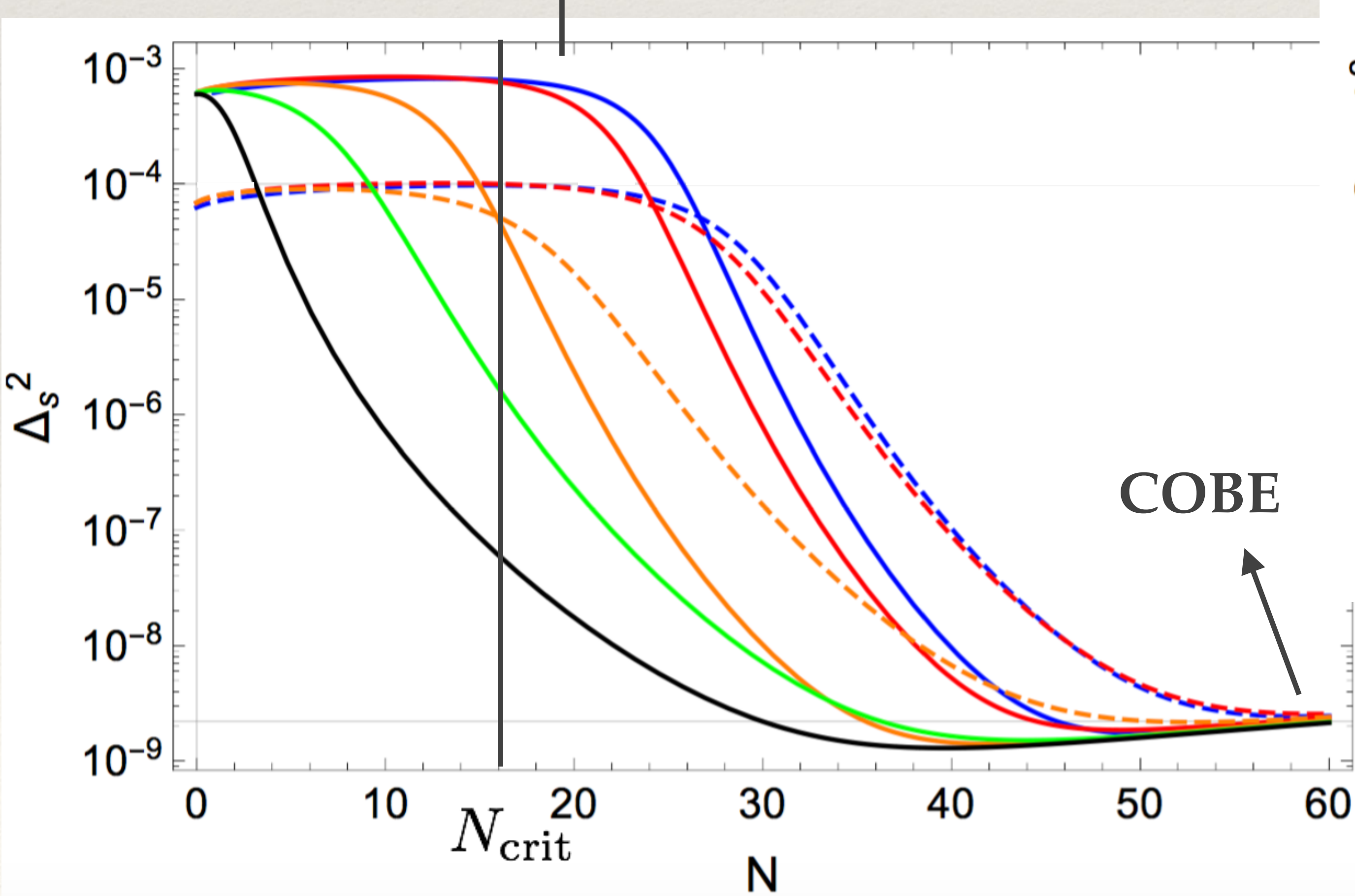
more suppressed ξ

↓

suppressed tensor and scalar spectra

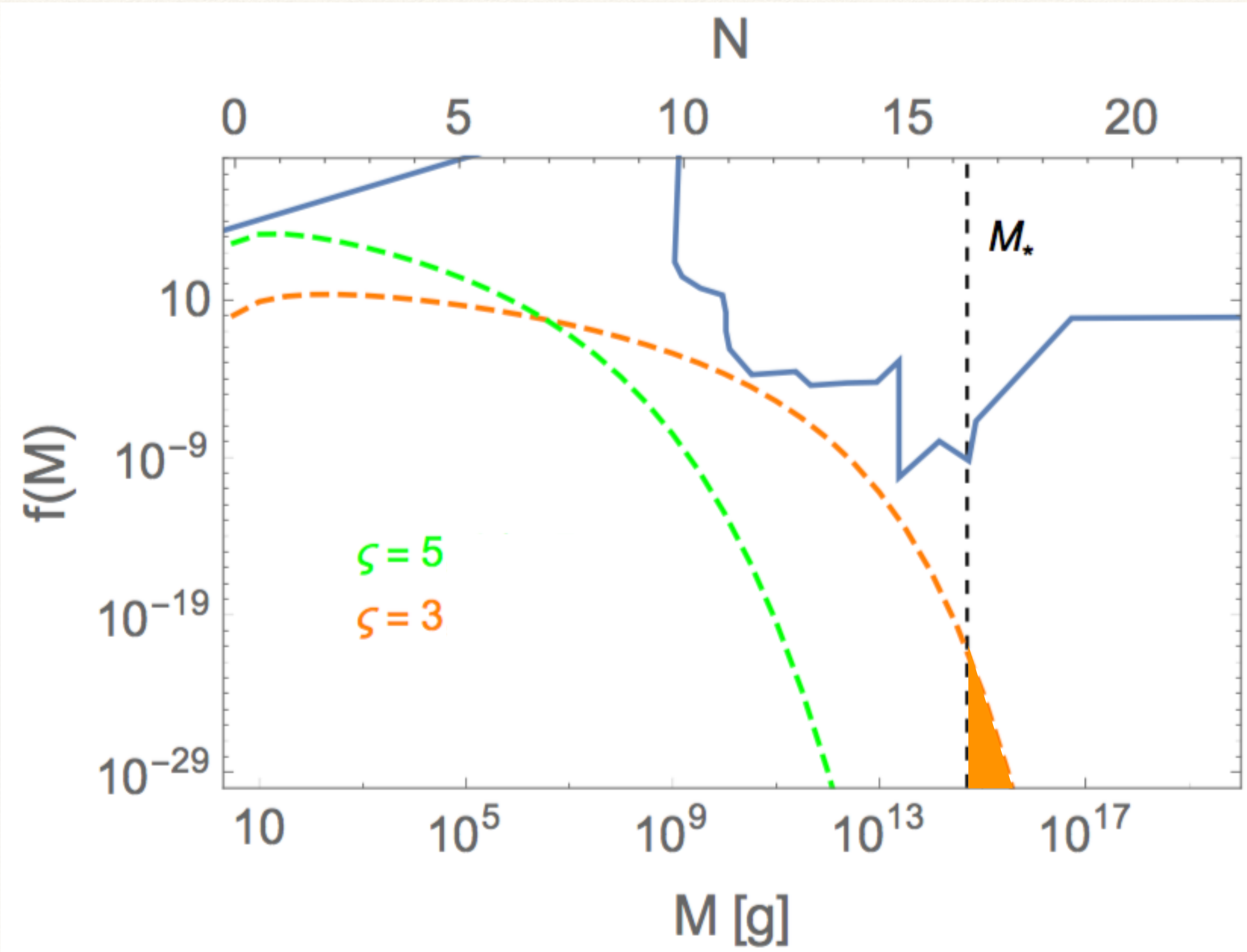


plateau-like if not suppressed



PBH production

$$\boxed{h(\phi) = \phi}$$



$H_{\rm inf} \simeq 10^{-5} M_p$

$\boxed{\varsigma = 3}$

$\frac{\alpha}{\Lambda} = 37 \quad f_{\rm tot} \approx 3 \times 10^{-23}$

$\boxed{\varsigma = 5}$

$\frac{\alpha}{\Lambda} = 43 \quad f_{\rm tot} \approx 0$

Only PBHs with mass $M > M_*$ **contribute to dark matter**