PBH Dark Matter from Axion Inflation

Francesco Muia
University of Oxford
27/04/2017

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

dedicated to the memory of Pierre Binétruy

Progress on Old and New Themes in Cosmology 2017, Avignon

Primordial Black Holes

Zeldovich, Novikov, 1967
Hawking, 1971
Carr and Hawking, 1974

Can PBHs compose a sizeable fraction of dark matter?

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$$M_H \simeq \gamma \times \rho \times \frac{4}{3}\pi H^{-3}$$

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$$M \sim \frac{c^3 t}{G} \sim 10^{15}\left(\frac{t}{10^{-23}\,\mathrm{sec}}\right)\,\mathrm{g} \longrightarrow$$

Planck time

$t_P \sim 10^{-43}\,\mathrm{sec}$ → $M \sim 10^{-5}\,\mathrm{g} \equiv M_p$

pre-BBN

$t \sim 1\,\mathrm{sec}$ → $M \sim 10^{38}\,\mathrm{g} \equiv 10^5\,M_\odot$

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- (Meta-)Stable: BHs evaporate through Hawking radiation.

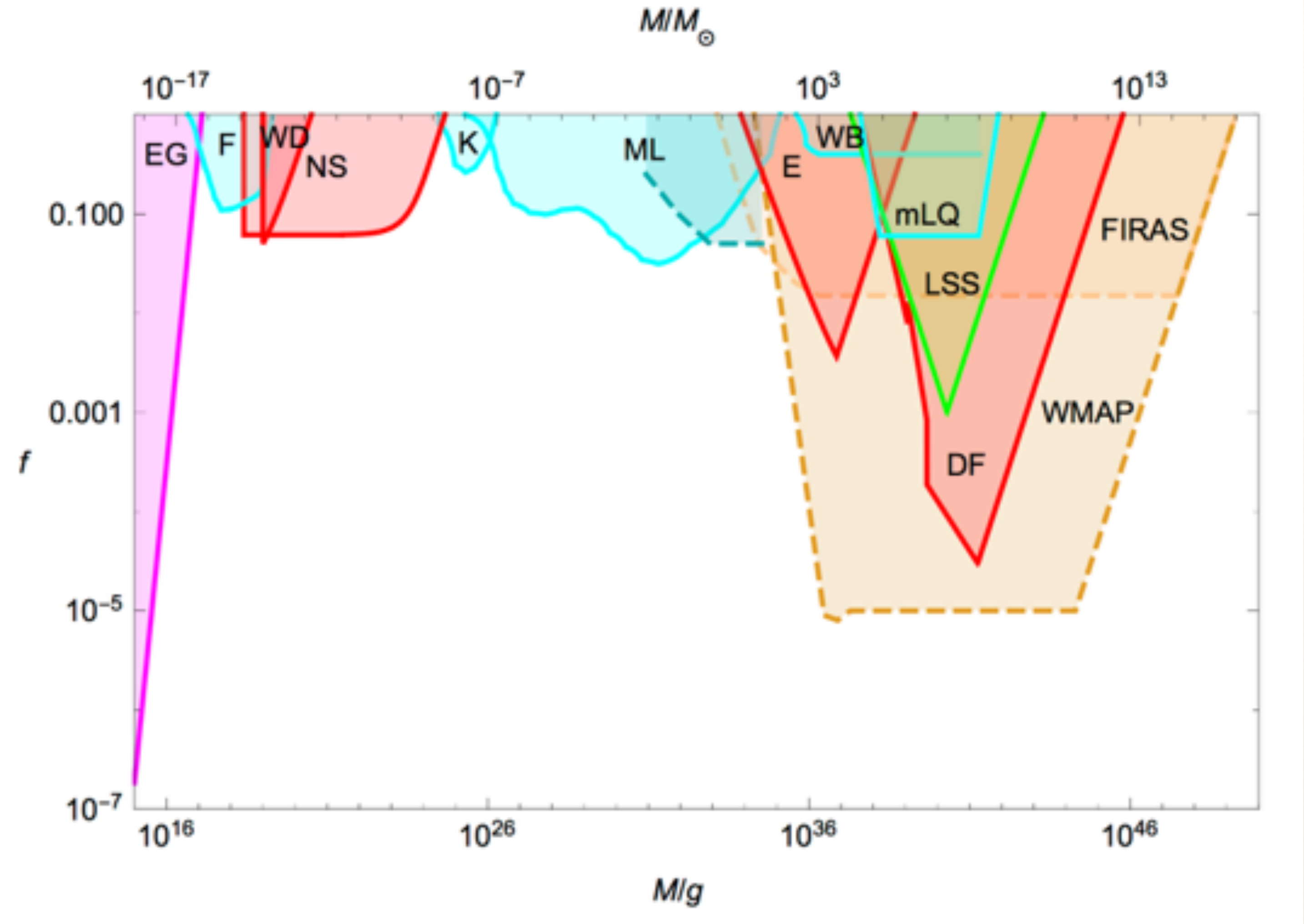
$$\tau(M) \sim \frac{G^2 M^3}{\hbar c^4} \sim 10^{64} \left(\frac{M}{M_\odot}\right)^3 \text{years} \longrightarrow \quad M > M_* \equiv 10^{15}\,\text{g}$$

such PBHs survive till today
and can compose dark matter

REQUIREMENTS & PROPERTIES:

Carr et al., 2010, 2017

the abundance of PBHs is subject to many strong constraints



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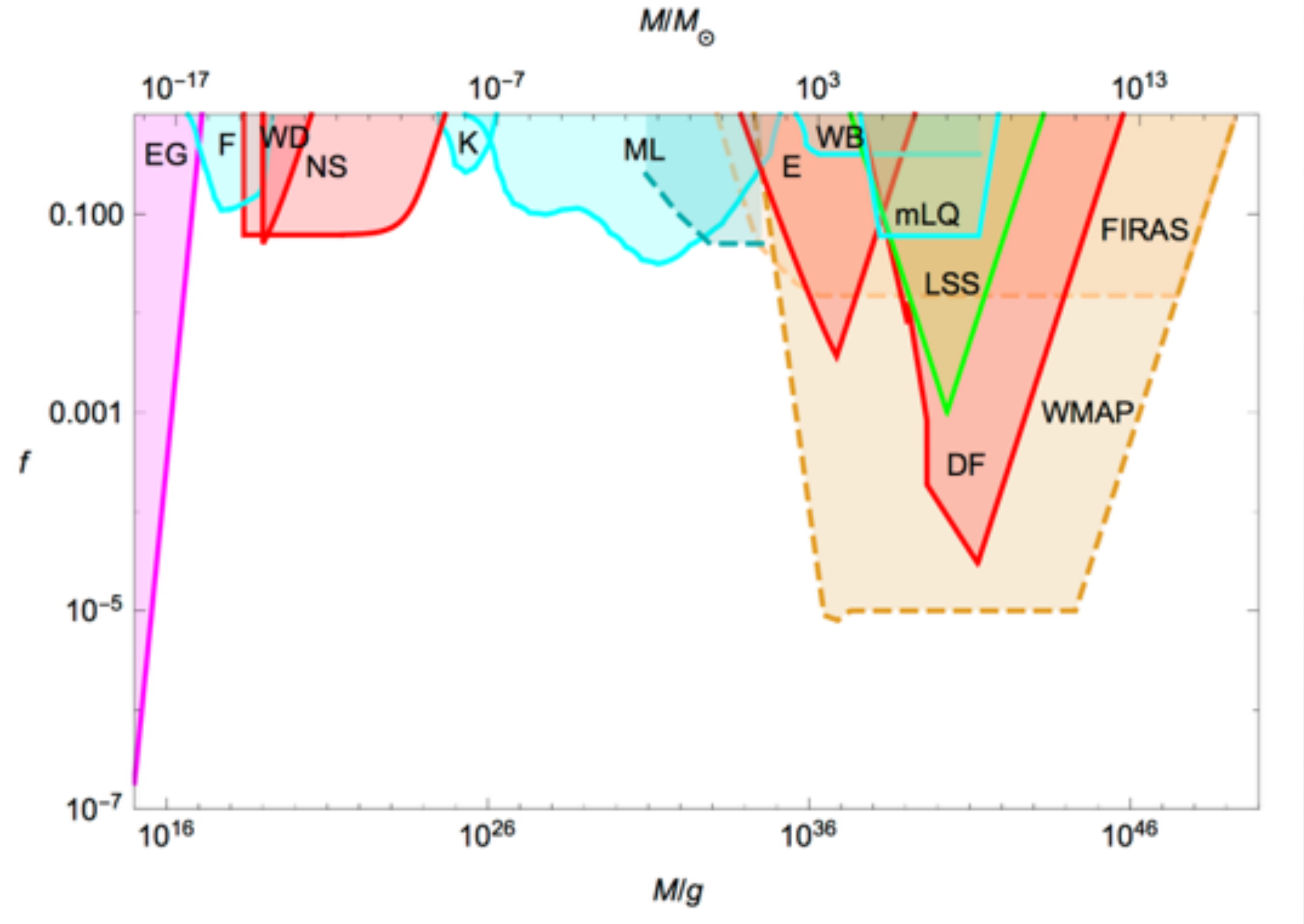

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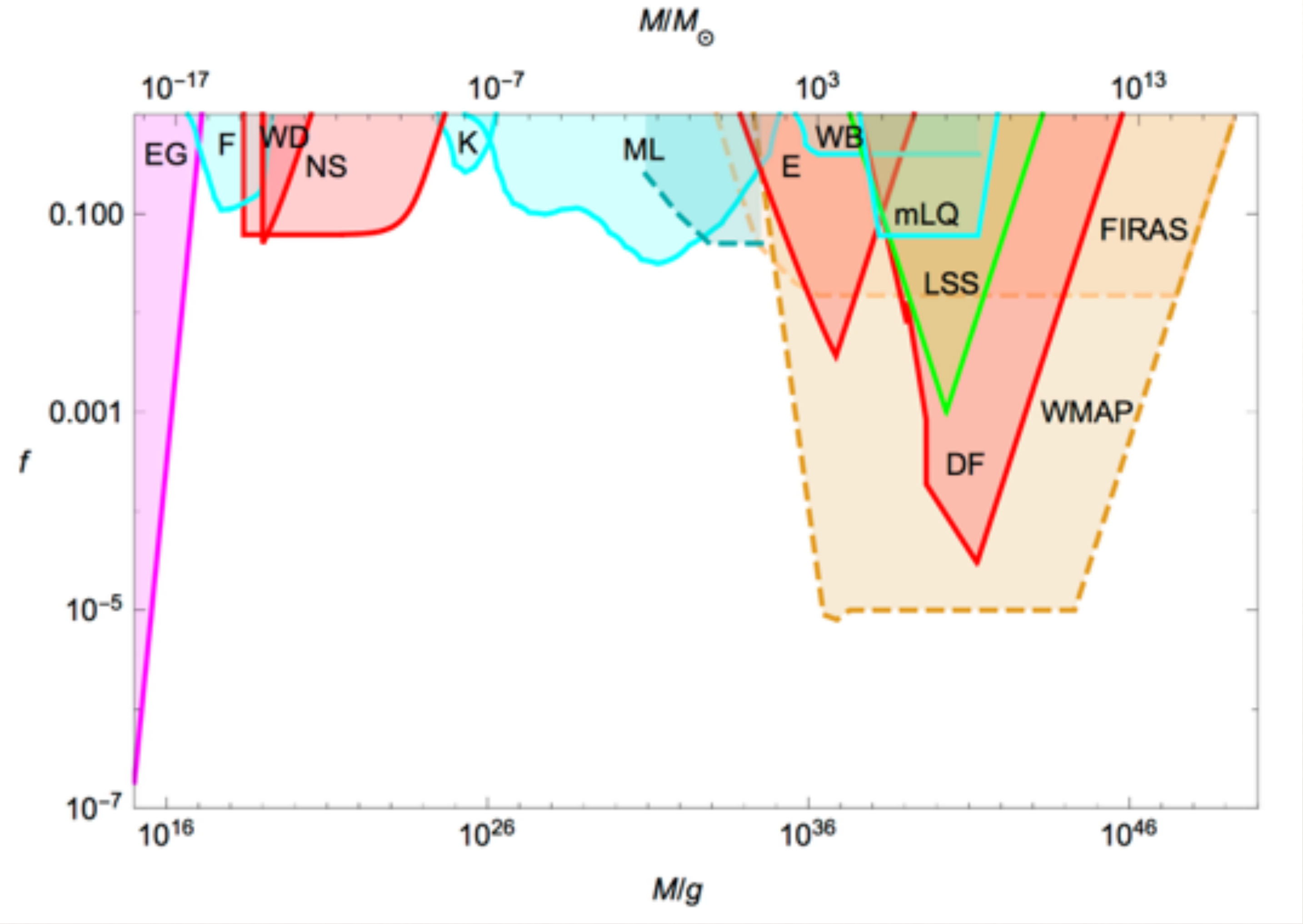

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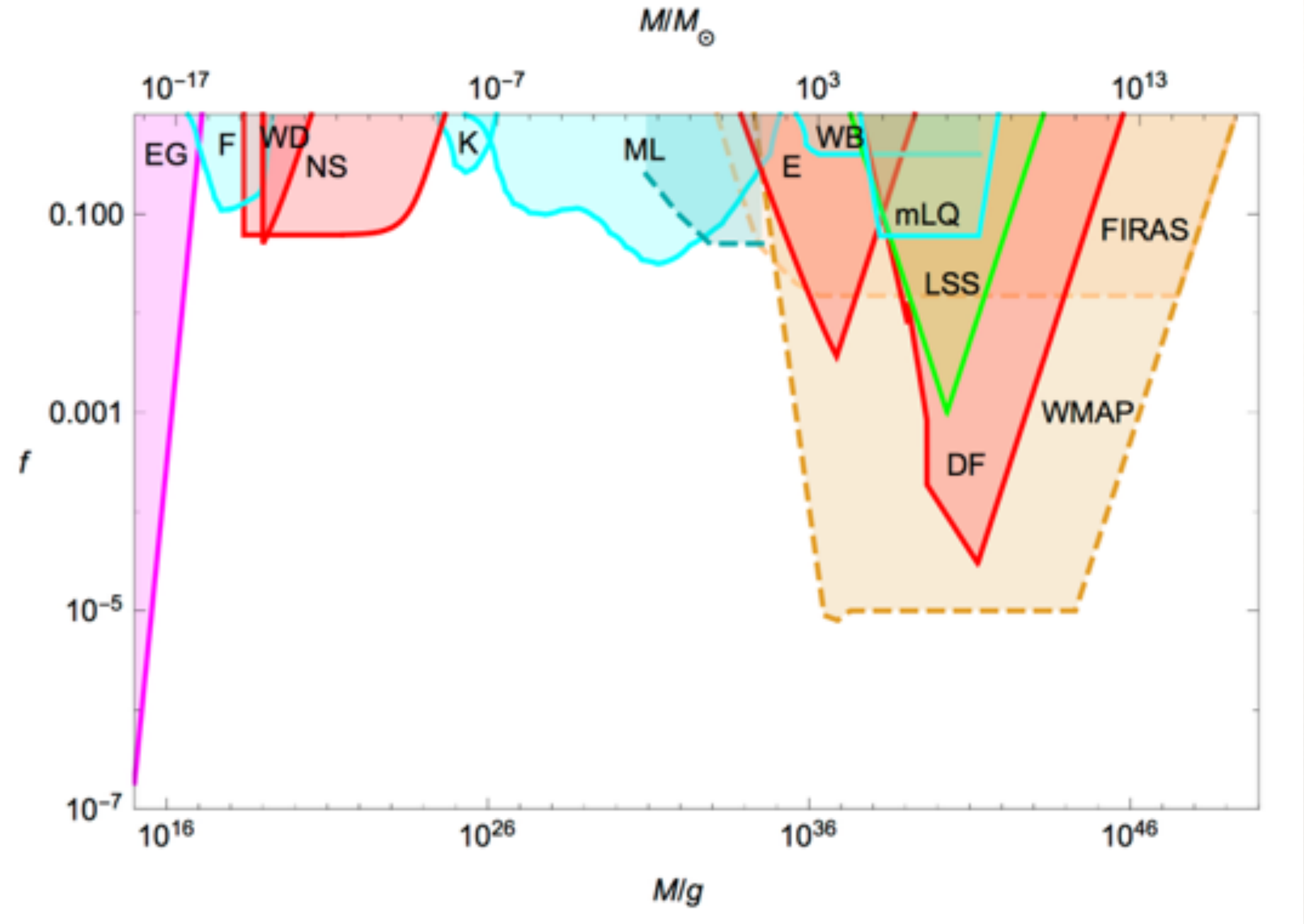

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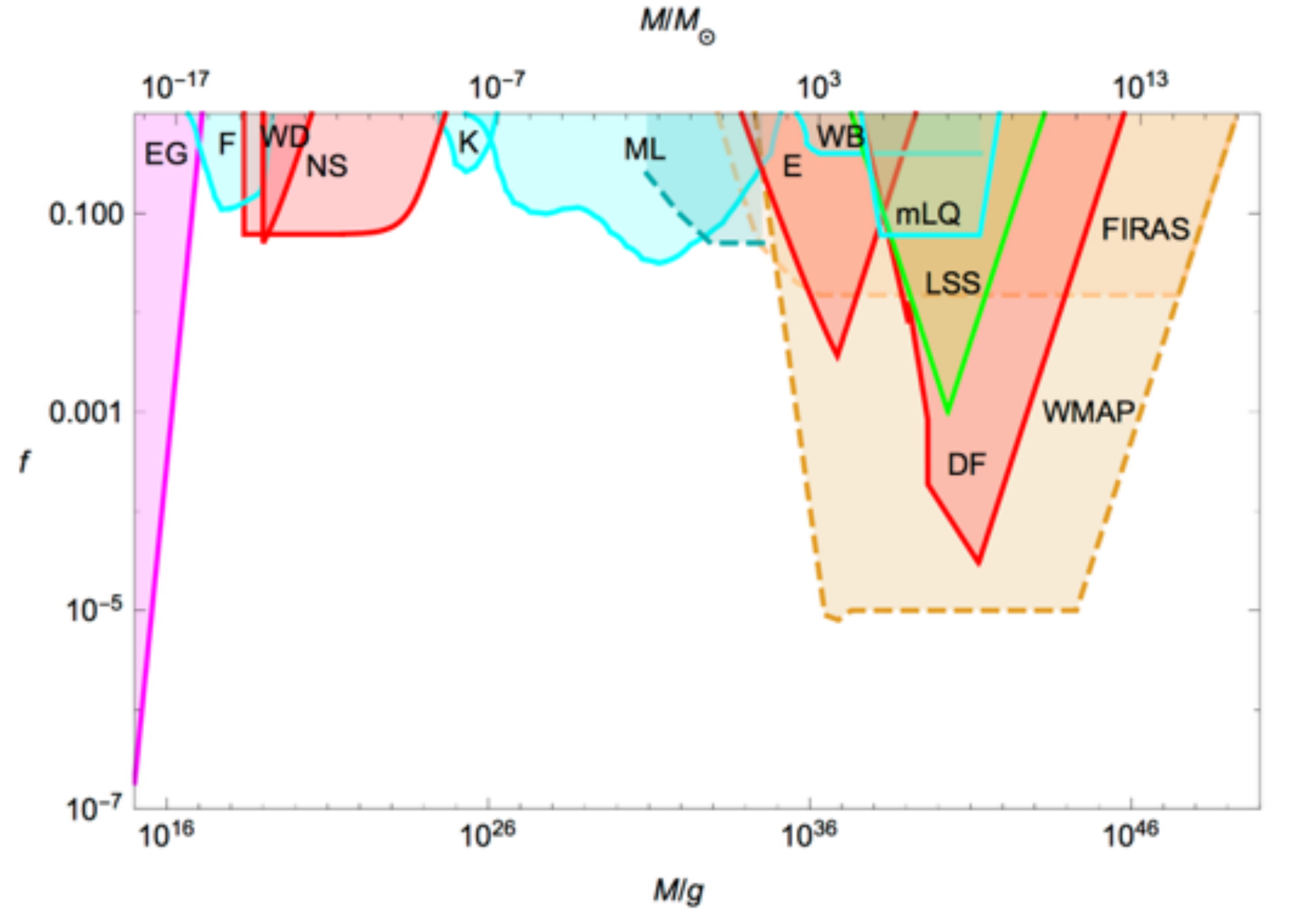

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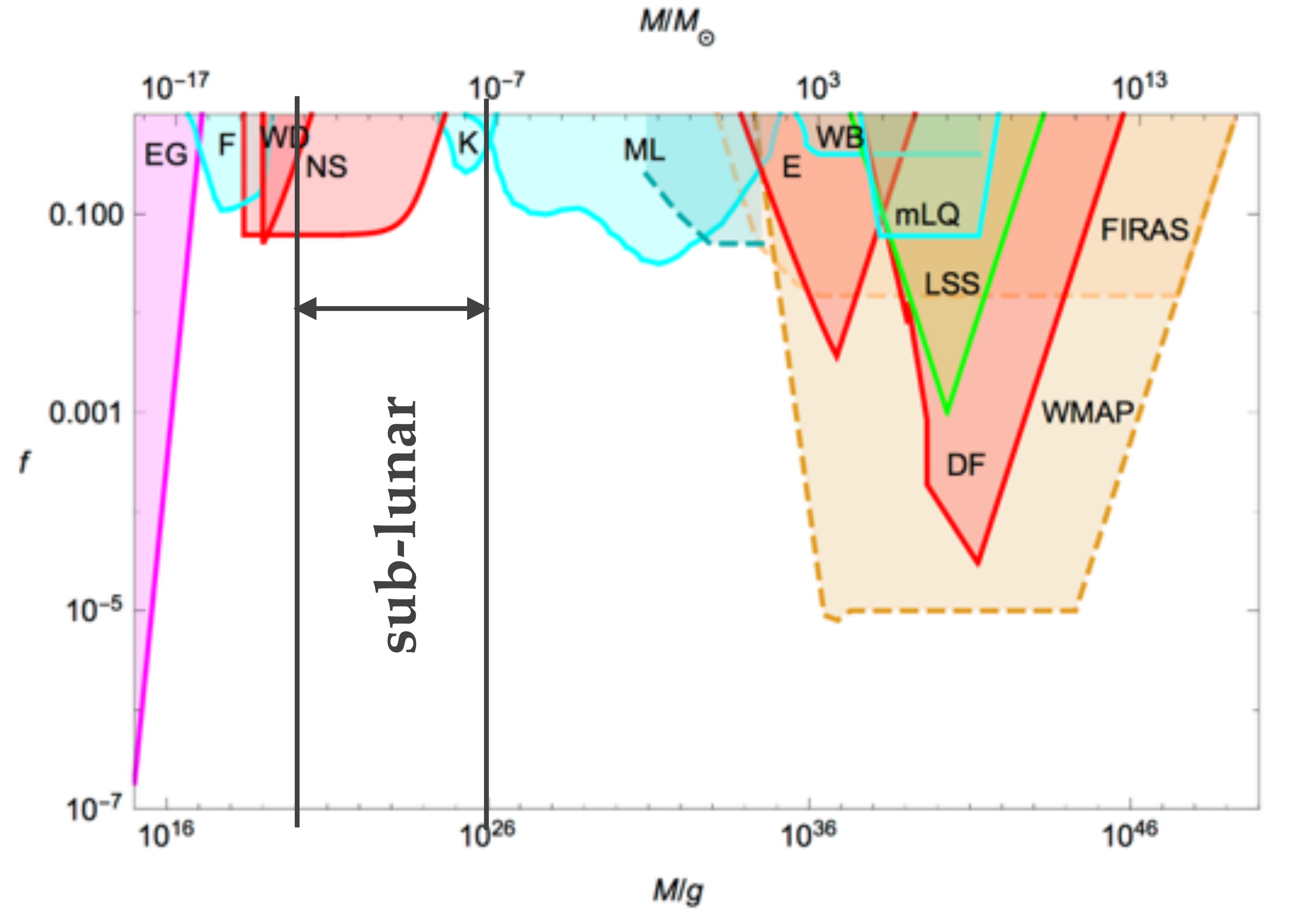

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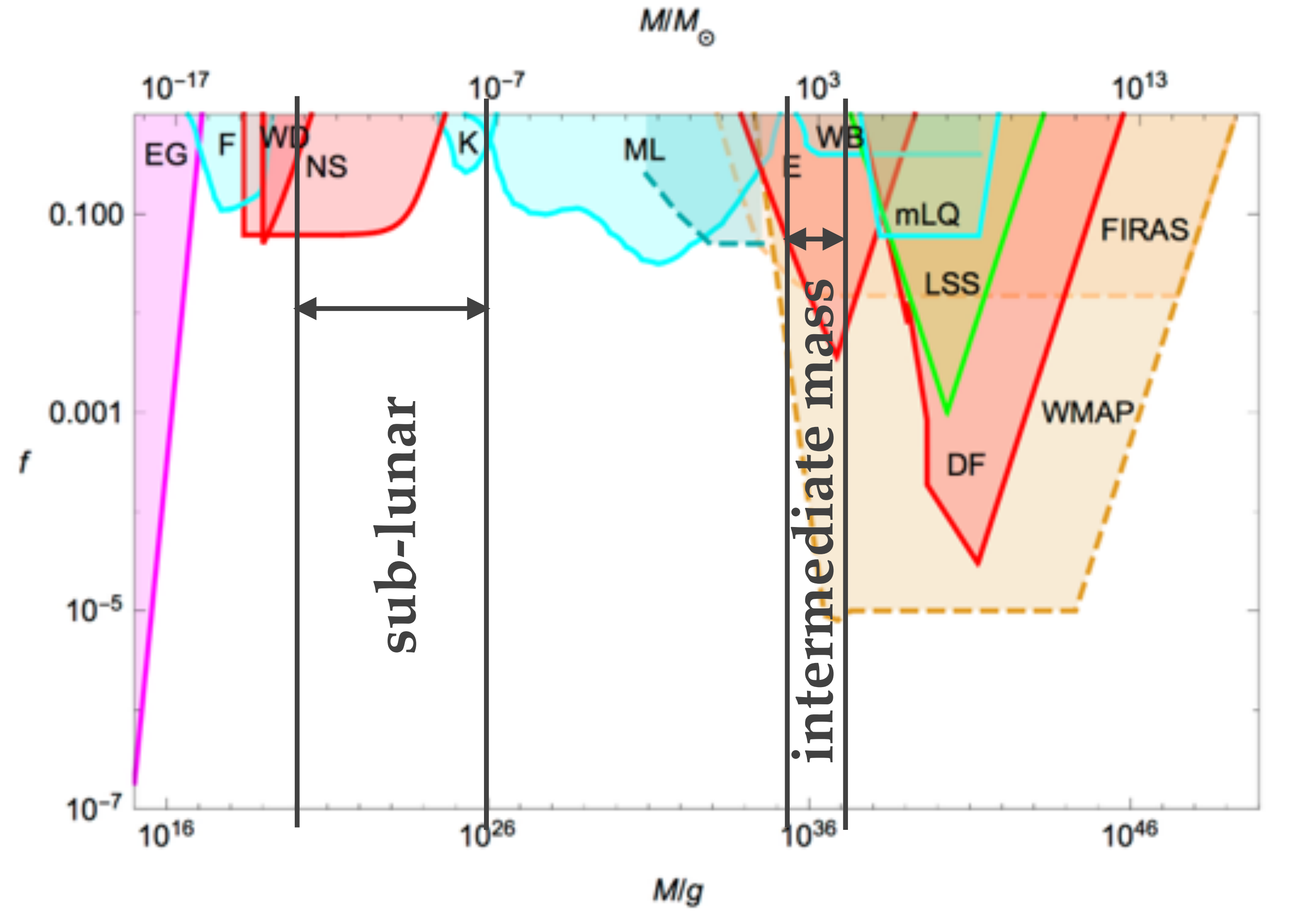

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intermediate mass $10^{2}\,M_\odot < M < 10^{4}\,M_\odot$

WMAP constraints depend upon uncertain astrophysical parameters.

REQUIREMENTS & PROPERTIES:

Schwarzschild radius

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high densities necessary but not sufficient condition

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PBH production depend on the development of inhomogeneities

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iii) collapse of cosmic strings.
iv) bubble collisions.
v) blue spectra of density fluctuations.
vi) etc.

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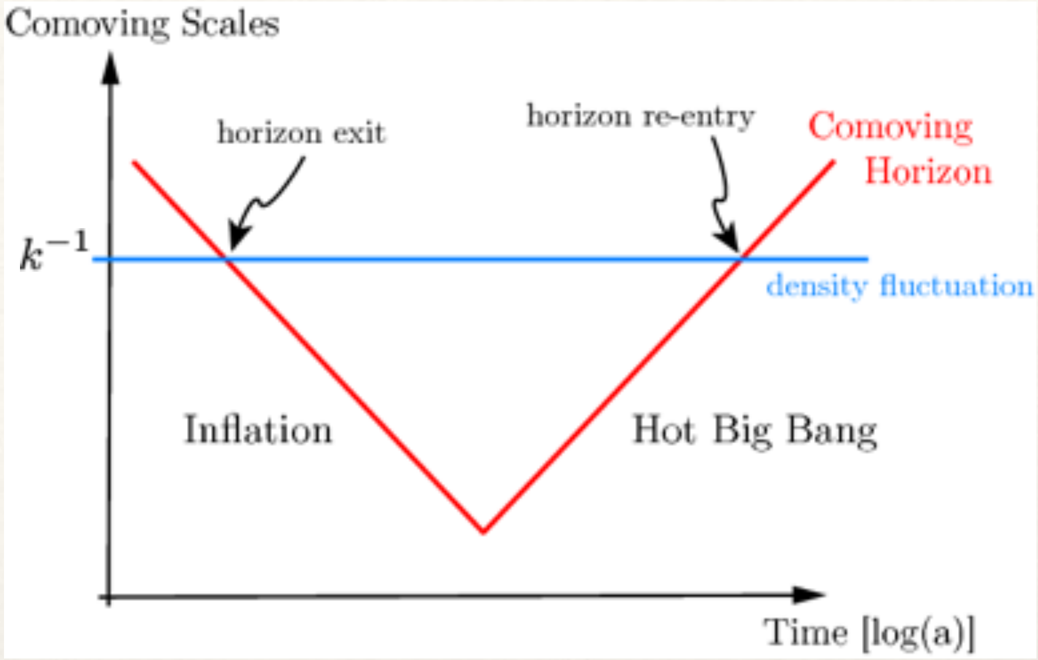
we focus on v):

large inhomogeneities created by some mechanism during inflation

PBH production

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

Garcia-Bellido et al., 1996



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1-1 map between N and M

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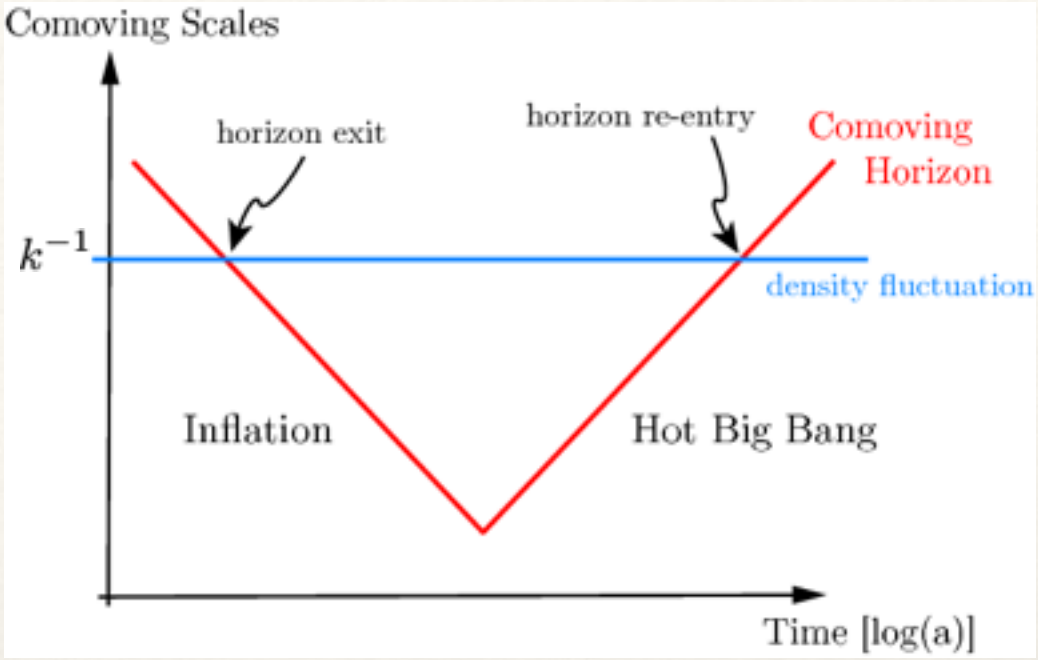

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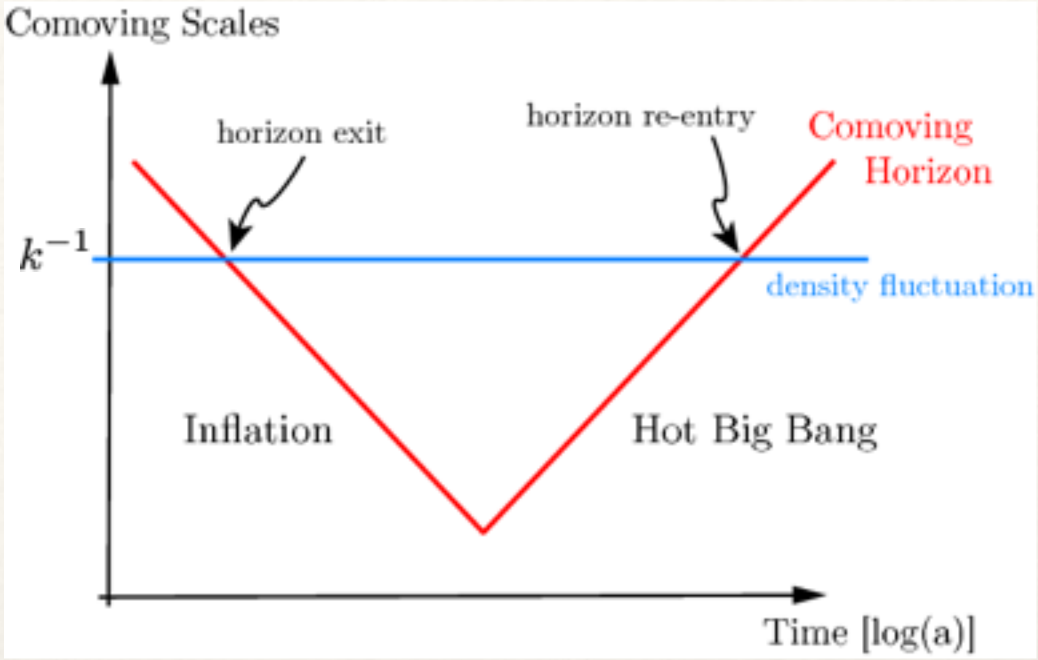

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the probability of forming a PBH with mass M is then

$$\beta(M) = \int_{\zeta_c}^{\infty} \mathcal{P}(\zeta_k) d\zeta_k$$

→ threshold for the collapse to occur

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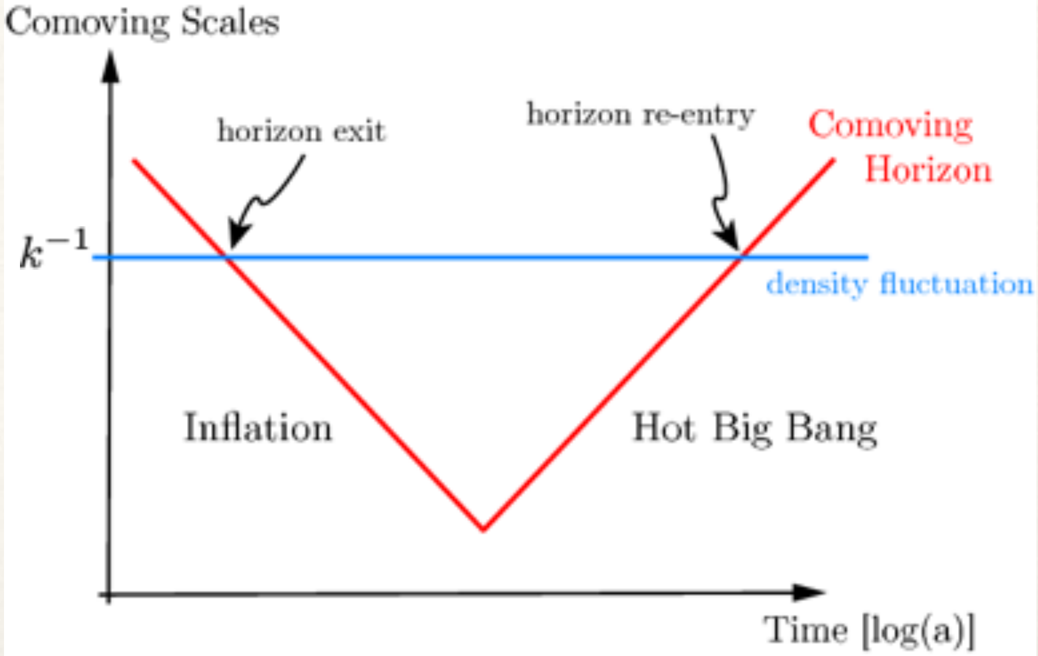

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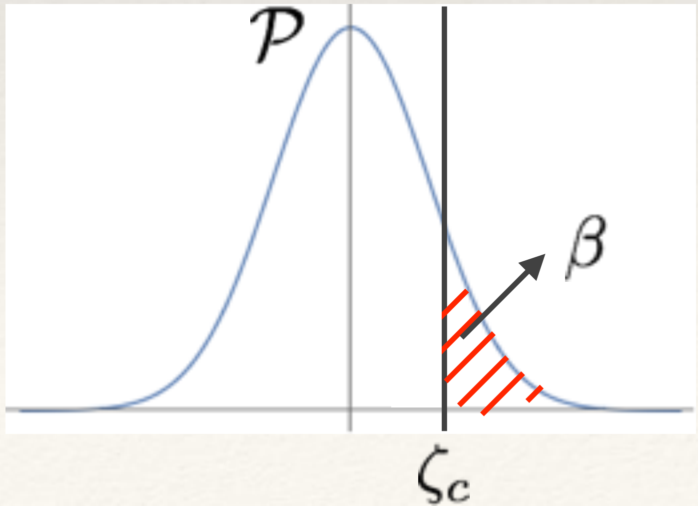

PBH density

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radiation domination $\rho \propto T^4$

adiabatic expansion $\frac{n_{\rm PBH}}{s} = {\rm const.}$

at the formation era t_N: $\beta(M) \equiv \frac{\rho_{\rm PBH}(t_N)}{\rho(t_N)} = \frac{M n_{\rm PBH}(t_N)}{\rho(t_N)} = \frac{4}{3}\frac{M}{T_N}\frac{n_{\rm PBH}(t)}{s(t)} \approx$

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

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in realistic cases the mass distribution won't be a delta-function

$$f_{\rm tot} = \int \frac{dM}{2M} f(M)$$

Carr et al., 2017

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

COBE normalisation

the spectrum is *locally* almost flat

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we consider axion inflation…

Interesting for many good reasons:

- **large tensor-to-scalar ratio,**
- **several phenomenological consequences,**
- **well motivated from the bottom-up perspective (arguably less motivated from the top down).**

Axion inflation coupled to gauge fields

Generic lagrangian

Sorbo et al., 2009

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

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new friction term

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tachyonic instability

for modes

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

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exponential amplification of gauge field modes towards the end of inflation

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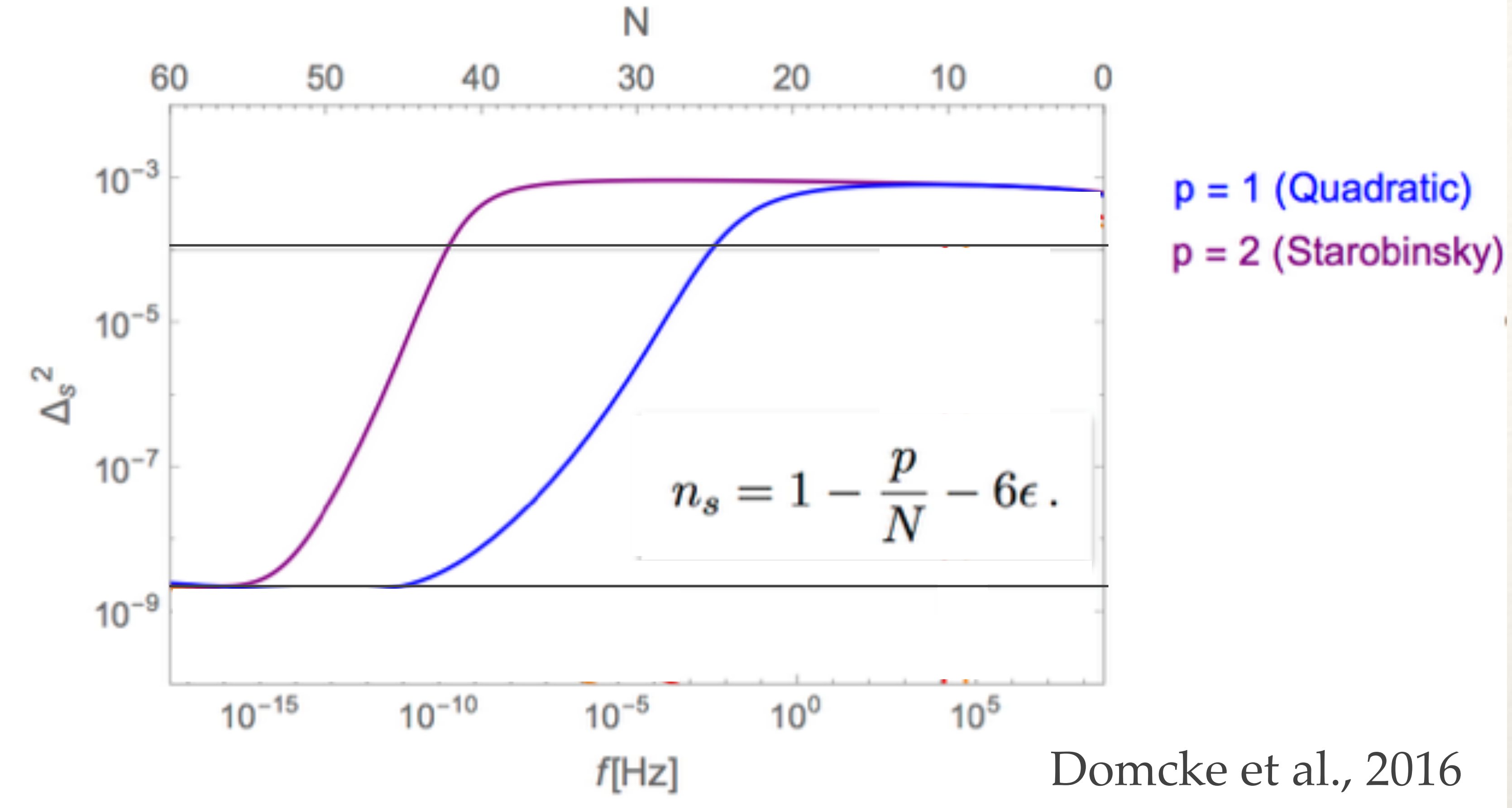
generic pheno features of the model

observable *chiral* GWs at interferometers, non-gaussianities



Domcke et al., 2016

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

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

$$\langle\mathbf{E}\cdot\mathbf{B}\rangle \simeq 2.4\times10^{-4}\frac{H^4}{\xi^4}e^{2\pi\xi}$$

plateau in the scalar power spectrum

↓

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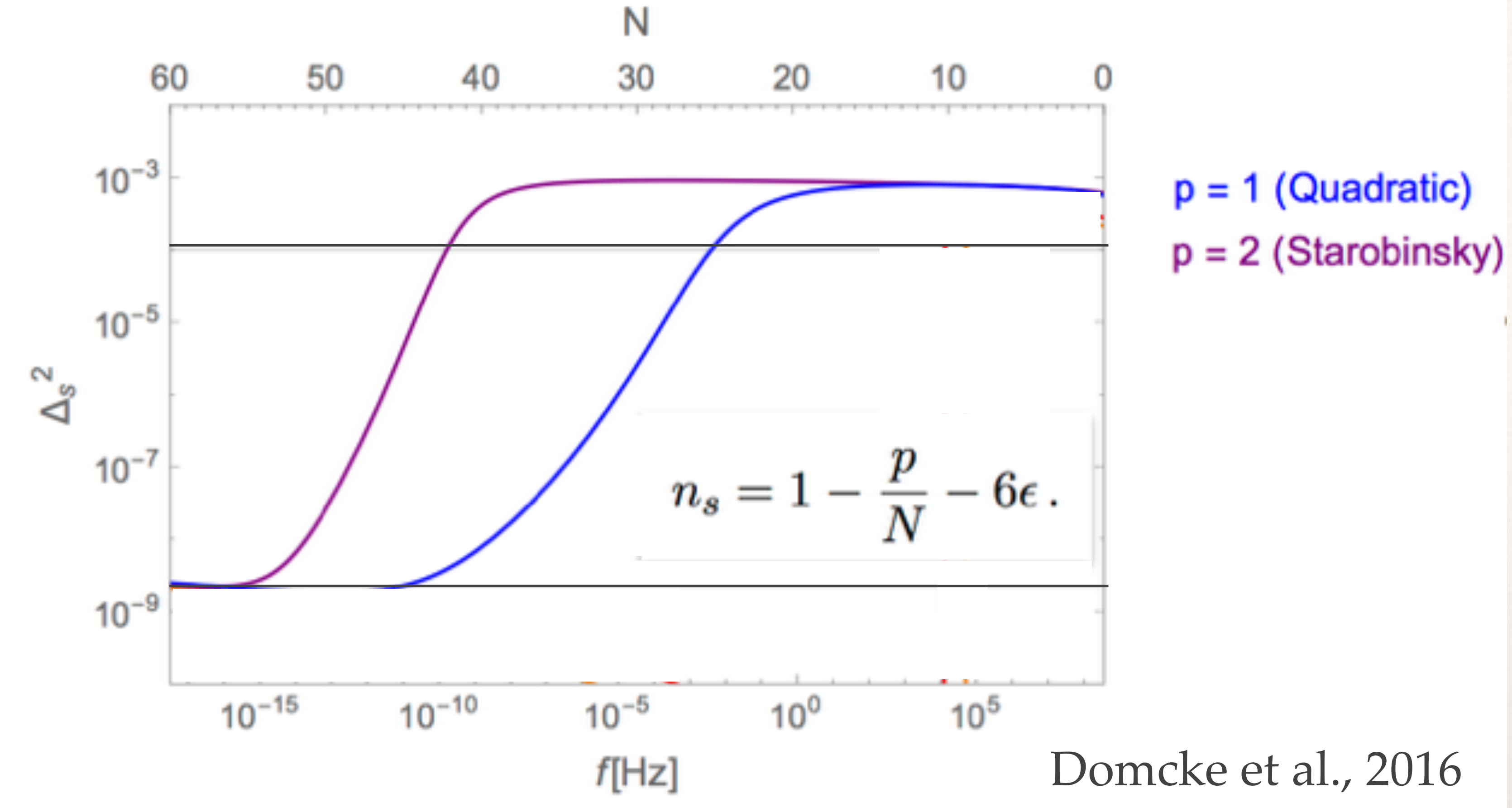

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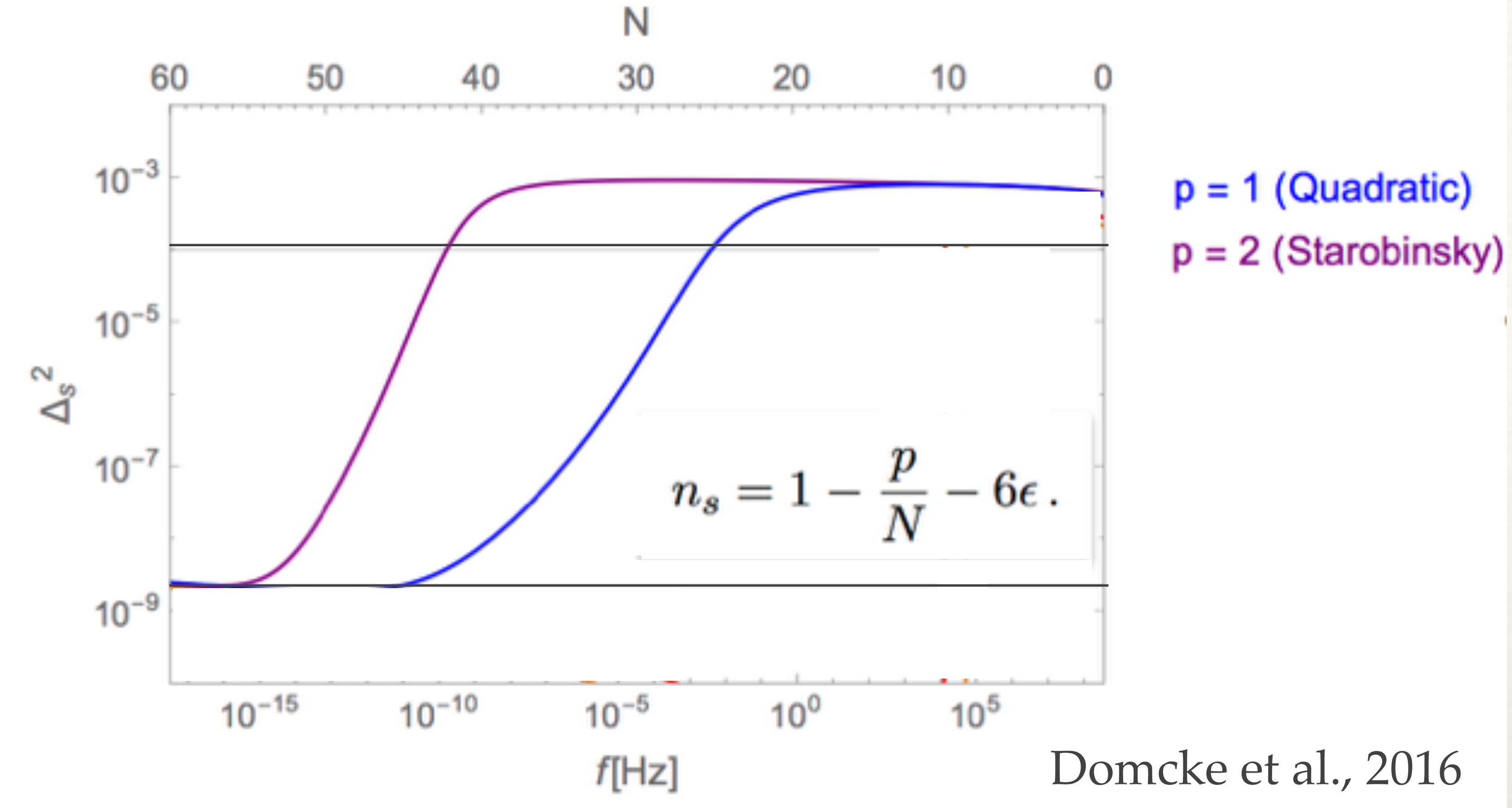

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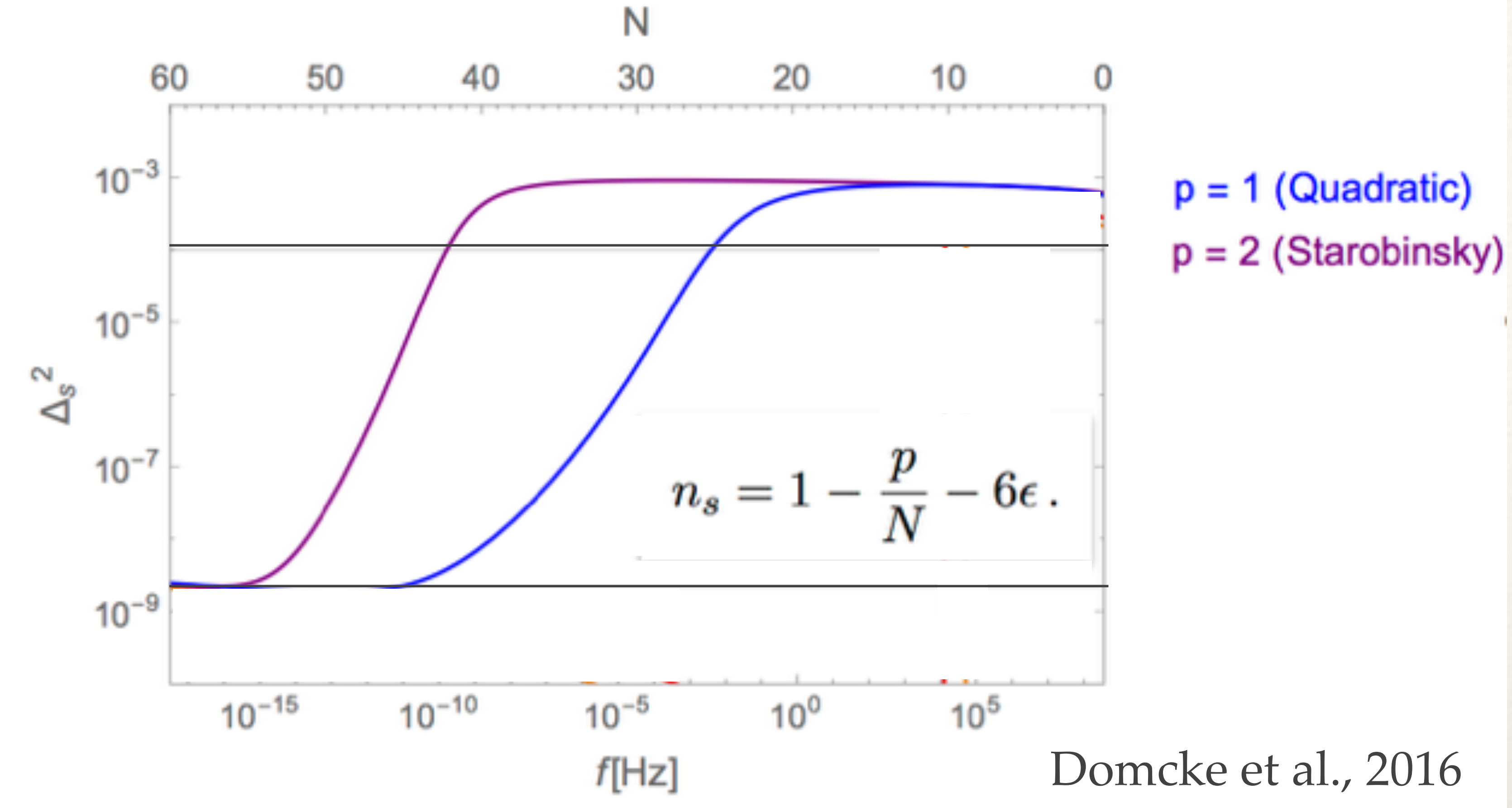

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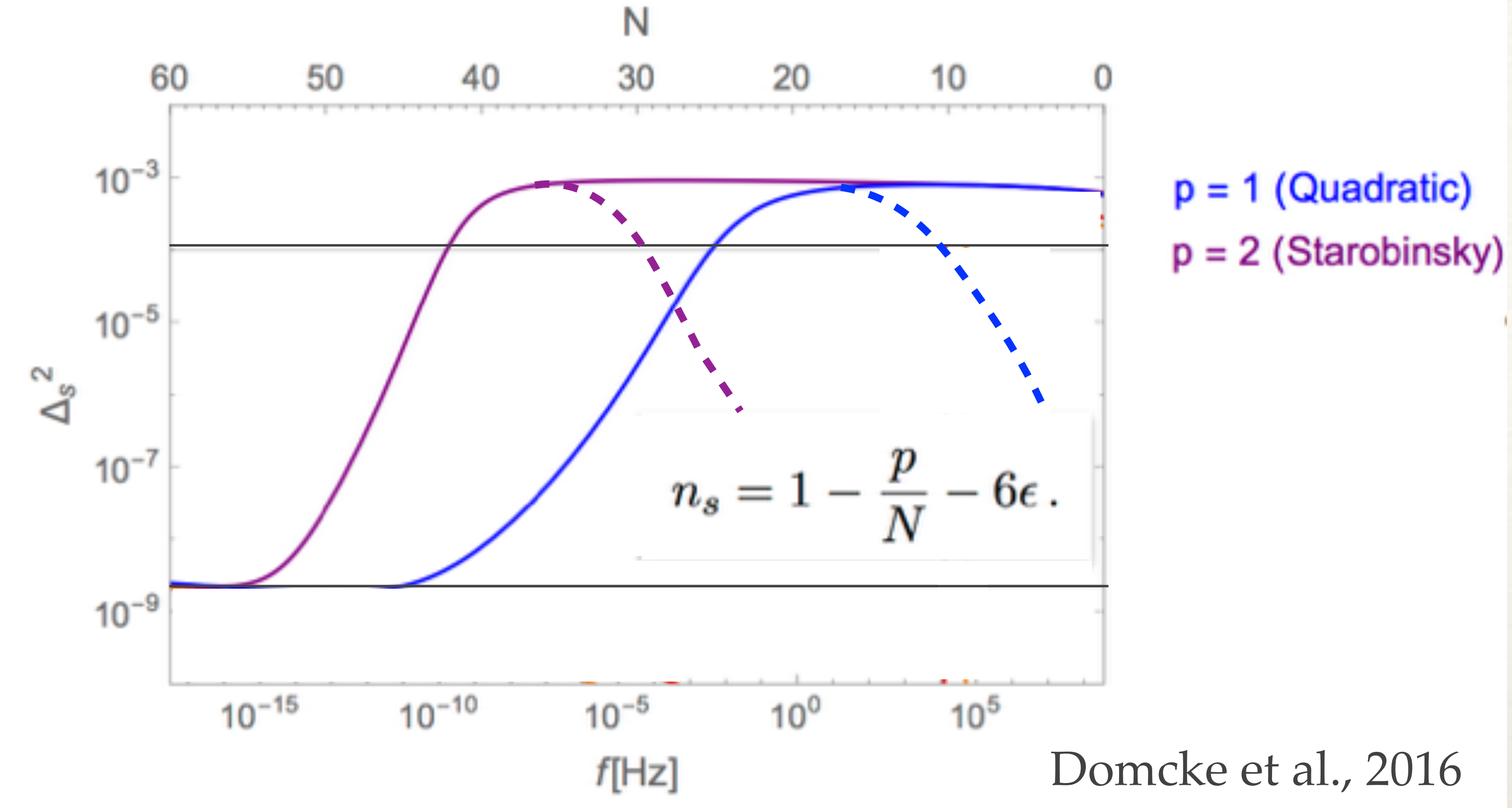

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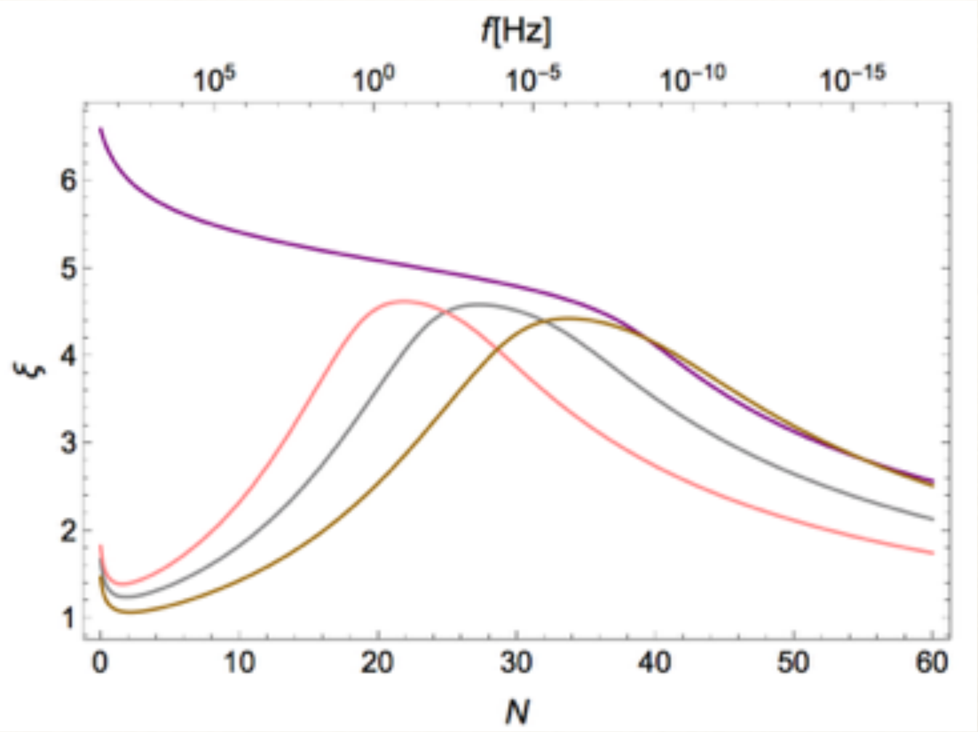
attractors at strong coupling

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

Linde et al., 2013

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

the instability is turned off $\longrightarrow$



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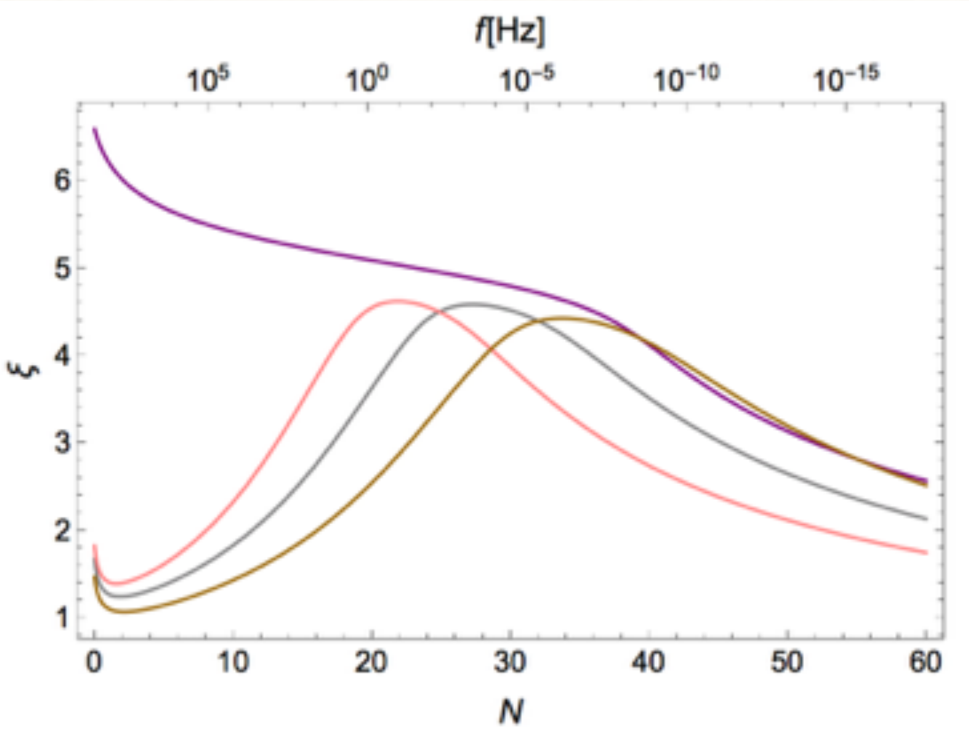
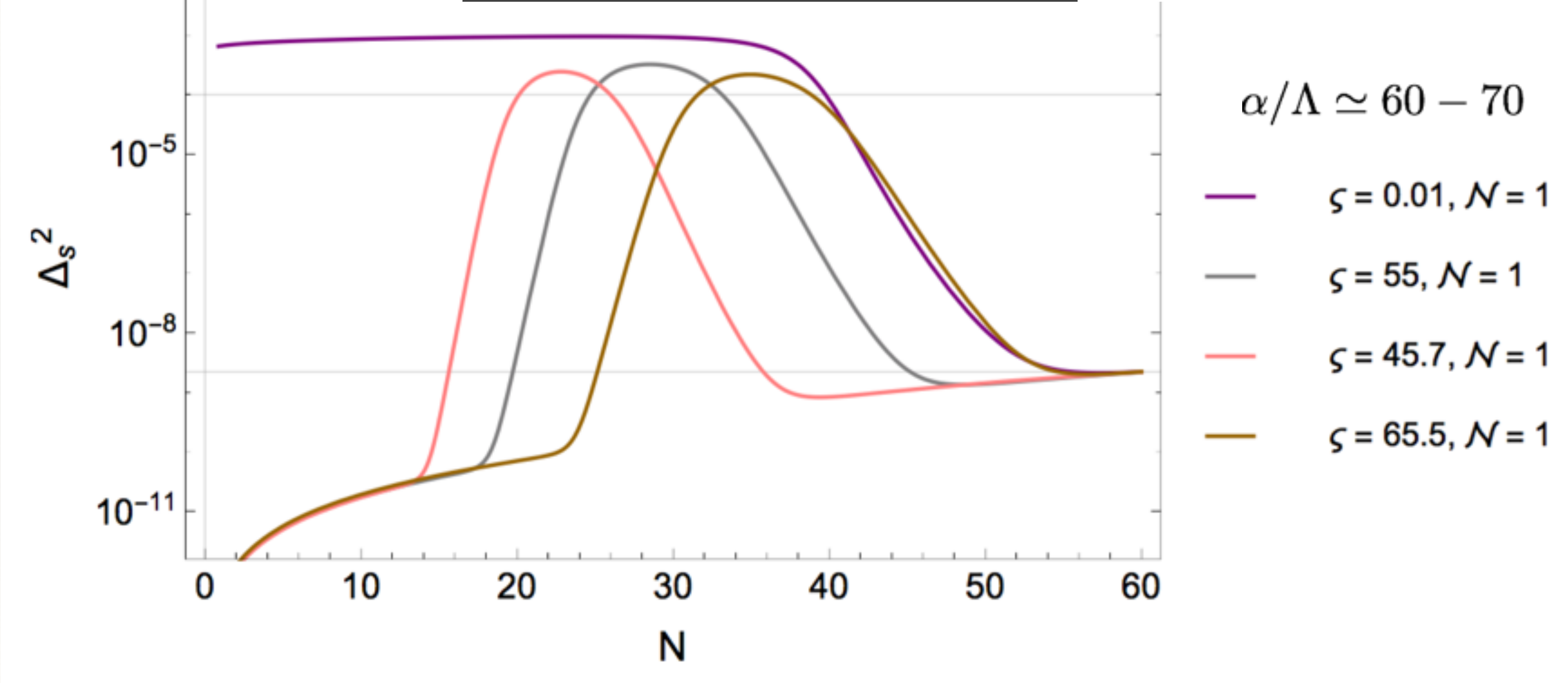


the power spectrum features a peak



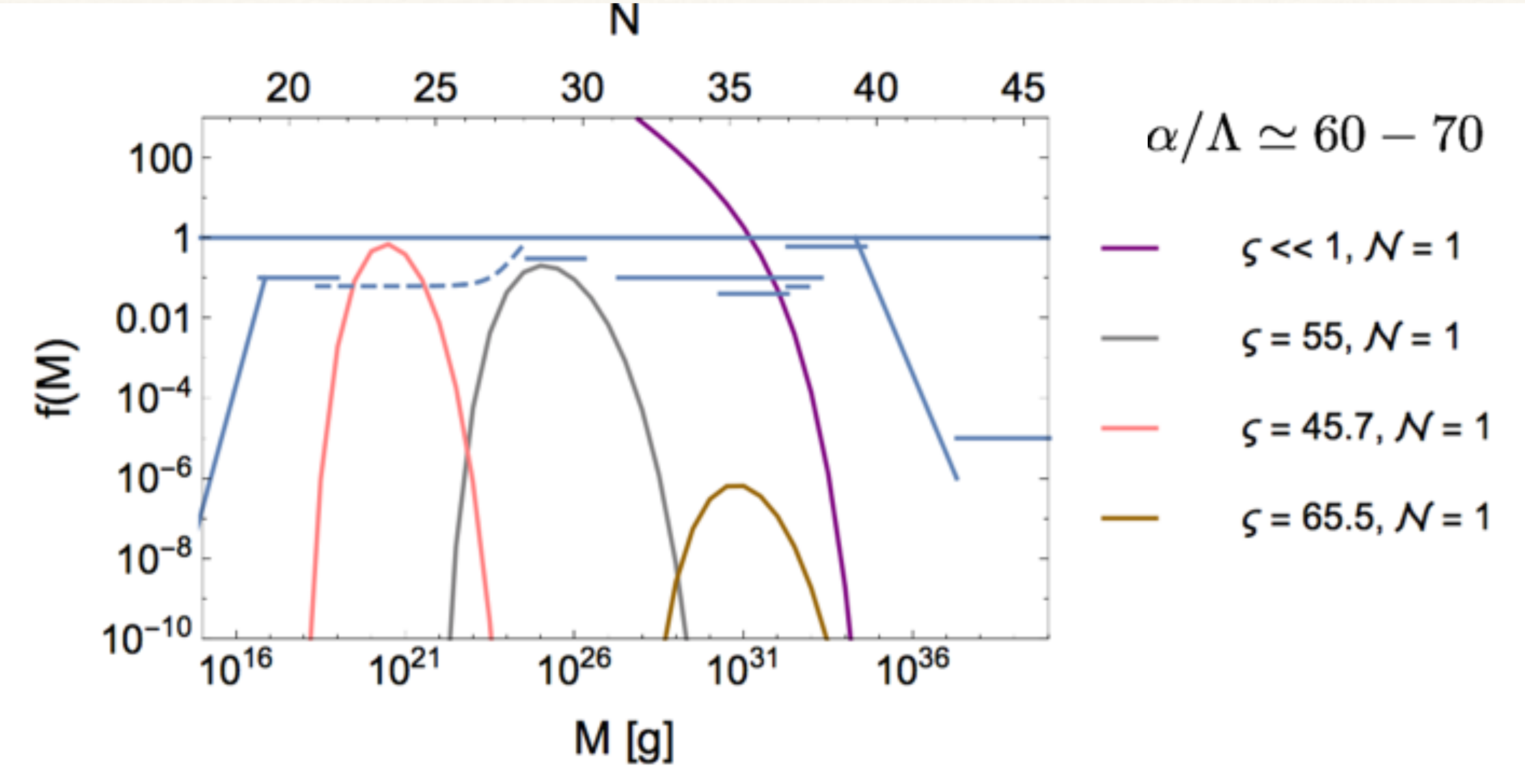
$\alpha/\Lambda \simeq 60 - 70$

i) All curves satisfy COBE normalization

ii) Increasing α/Λ the tachyonic instability starts earlier.

iii) Increasing ς the instability is turned off earlier.

Results



DM abundance

$f_{\rm tot}^{\varsigma=45.7} = 98.6\%$

$f_{\rm tot}^{\varsigma=55} = 39.4\%$

$f_{\rm tot}^{\varsigma=65.5} \simeq 10^{-4}\%$

i) Increasing α/Λ and ς shifts the peak towards larger mass values (modes involved exit the horizon earlier and re-enter later).

ii) In the pink case we neglected NS capture constraints, since they rely on assumptions about the amount of DM in globular clusters, that are disputed.

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.

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string moduli: $T = \tau + i\phi$

perturbative shift-symmetry: $\phi \to \phi + a$

Kaehler potential: $K \equiv K(T + \overline{T})$

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3. The Kaehler metric has to depend on the inflaton

typically K doesn't depend on the axion at leading order due to the shift-symmetry ⟶ **need to compute shift-symmetry violating corrections**

Conclusions

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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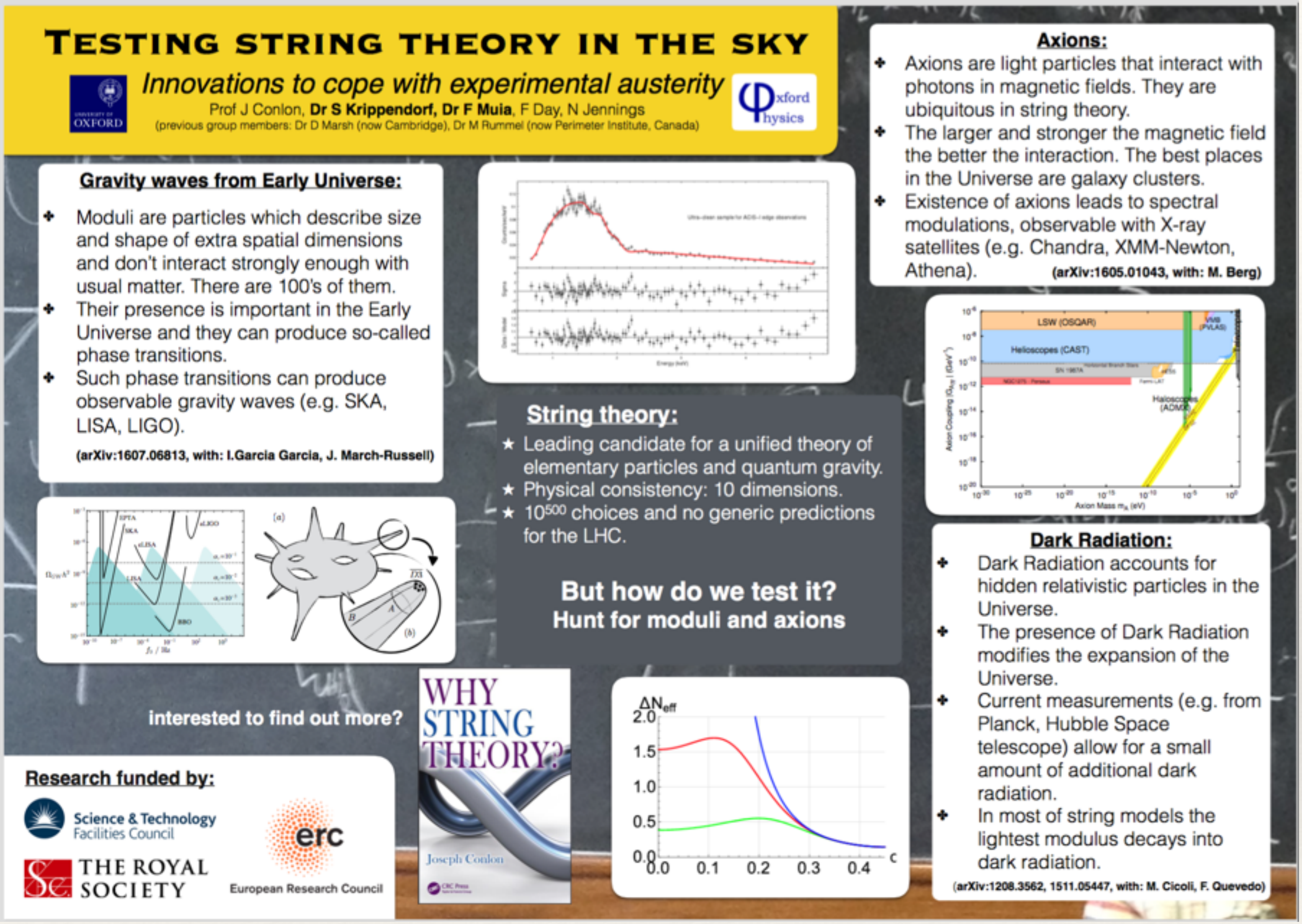
not an easy task…



TESTING STRING THEORY IN THE SKY

Innovations to cope with experimental austerity

Prof J Conlon, **Dr S Krippendorf, Dr F Muia**, F Day, N Jennings
(previous group members: Dr D Marsh (now Cambridge), Dr M Rummel (now Perimeter Institute, Canada)

Gravity waves from Early Universe:

- Moduli are particles which describe size and shape of extra spatial dimensions and don't interact strongly enough with usual matter. There are 100's of them.
- Their presence is important in the Early Universe and they can produce so-called phase transitions.
- Such phase transitions can produce observable gravity waves (e.g. SKA, LISA, LIGO).

(arXiv:1607.06813, with: I.Garcia Garcia, J. March-Russell)

String theory:

★ Leading candidate for a unified theory of elementary particles and quantum gravity.
★ Physical consistency: 10 dimensions.
★ 10^{500} choices and no generic predictions for the LHC.

But how do we test it?
Hunt for moduli and axions

Axions:

- Axions are light particles that interact with photons in magnetic fields. They are ubiquitous in string theory.
- The larger and stronger the magnetic field the better the interaction. The best places in the Universe are galaxy clusters.
- Existence of axions leads to spectral modulations, observable with X-ray satellites (e.g. Chandra, XMM-Newton, Athena). **(arXiv:1605.01043, with: M. Berg)**

Dark Radiation:

- Dark Radiation accounts for hidden relativistic particles in the Universe.
- The presence of Dark Radiation modifies the expansion of the Universe.
- Current measurements (e.g. from Planck, Hubble Space telescope) allow for a small amount of additional dark radiation.
- In most of string models the lightest modulus decays into dark radiation.

(arXiv:1208.3562, 1511.05447, with: M. Cicoli, F. Quevedo)

interested to find out more?

WHY STRING THEORY?
Joseph Conlon

Research funded by:

Science & Technology Facilities Council
THE ROYAL SOCIETY
erc European Research Council

Hope the collaboration between string theory and cosmology communities will strengthen in the next years!

Thank you!