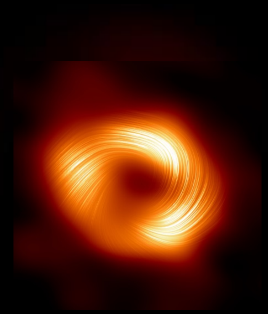
Supermassive Black Holes of a Primordial Origin



Aurora Ireland, *University of Chicago*

Based on [2308.00756]

Overview

- Motivations
- PBH Formation
- Spectral Distortions
- Departures from Gaussianity
- Non-Minimal Self-Interacting Curvaton
- Conclusions

Motivations

Supermassive black holes (SMBHs)

- *Massive:* $M_{\mathrm{SMBH}} \geq 10^5 M_{\odot}$
- *Ubiquitous:*
  - Reside at the center of nearly all massive galaxies
  - Power quasars and other active galactic nuclei
- *Poorly understood:*
  - Origin and evolution remain active areas of research
  - New observations from JWST challenge the traditional paradigm of SMBH growth

Motivations

early times, far away

- A surprising number of quasars have been observed in the high-z universe

Quasar/Galaxy	Redshift	Mass	Ref
GN-z11	10.6034 ± 0.0013	$1.6^{+1.6}_{-0.8} \times 10^6 M_\odot$	[2305.12492]
UHZ1	$\simeq 10.1$	$\simeq 4 \times 10^7 M_\odot$	[2308.03837]
J0313-1806	7.6423 ± 0.0013	$(1.6 \pm 0.4) \times 10^9 M_\odot$	[2101.03179]
J1342+0928	7.5413 ± 0.0007	$7.8^{+3.3}_{-1.9} \times 10^8 M_\odot$	[1712.01860]

- Plus ~300 more at $z > 6$, including 9 at $z > 7$ [2212.06907]
- Only a small fraction of SMBHs are observable as quasars
  ⇒ actual number likely much larger!

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- Traditional picture: SMBHs grow from **low-mass seeds** over a long period of time through **accretion, mergers**

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  - $M_{\mathrm{BH}} \sim 10^2 \mathrm{M}_\odot \rightarrow 10^{10} \mathrm{M}_\odot \;\Rightarrow\; \Delta t \sim 0.8$ Gyr
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  - $z = 6 - 7$ corresponds to $\sim 0.7 - 0.9$ Gyr after the Big Bang
- SMBHs must have grown **continuously** at high rates throughout the first Gyr
  - Contrasts with **intermittent** accretion observed of SMBHs at lower z

Motivations

Possible explanations:

- **Super-Eddington accretion**?
  - Pop III SMBH seeds are born in low density environments
    ⇒ prevents rapid initial growth
  - Super-Eddington periods are transient
    ⇒ feedback effects (powerful jets and outflows) can impede growth

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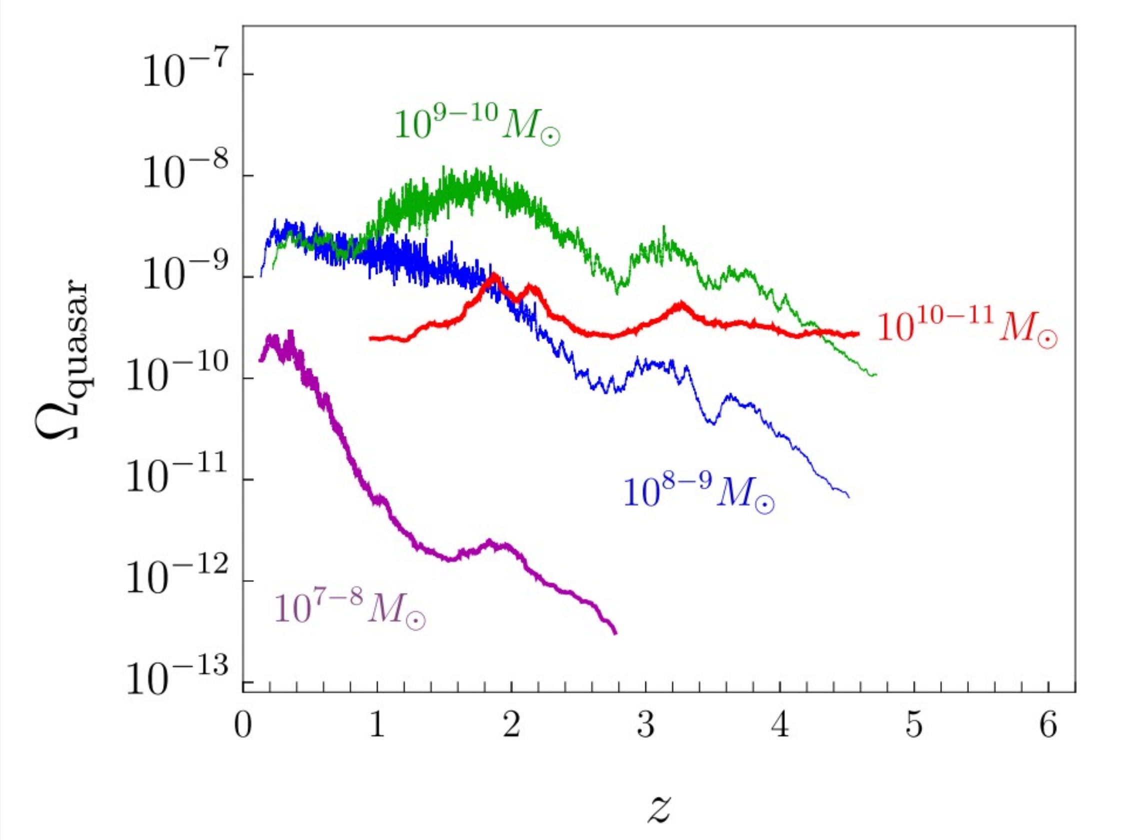
- **Enhanced role of mergers**?
  - Requires heavily clustered populations in the early universe
  - Can eject SMBHs out of material-rich galactic centers

Motivations

- Also surprising: Growth rate has **slowed** dramatically since ~1 Gyr
- For the most massive SMBHs, the comoving mass density has remained approximately **constant** since $z{\sim}5$



Estimates of quasar comoving mass density as a function of redshift; data from DR7 SDSS

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- Also surprising: Growth rate has **slowed** dramatically since ~1 Gyr
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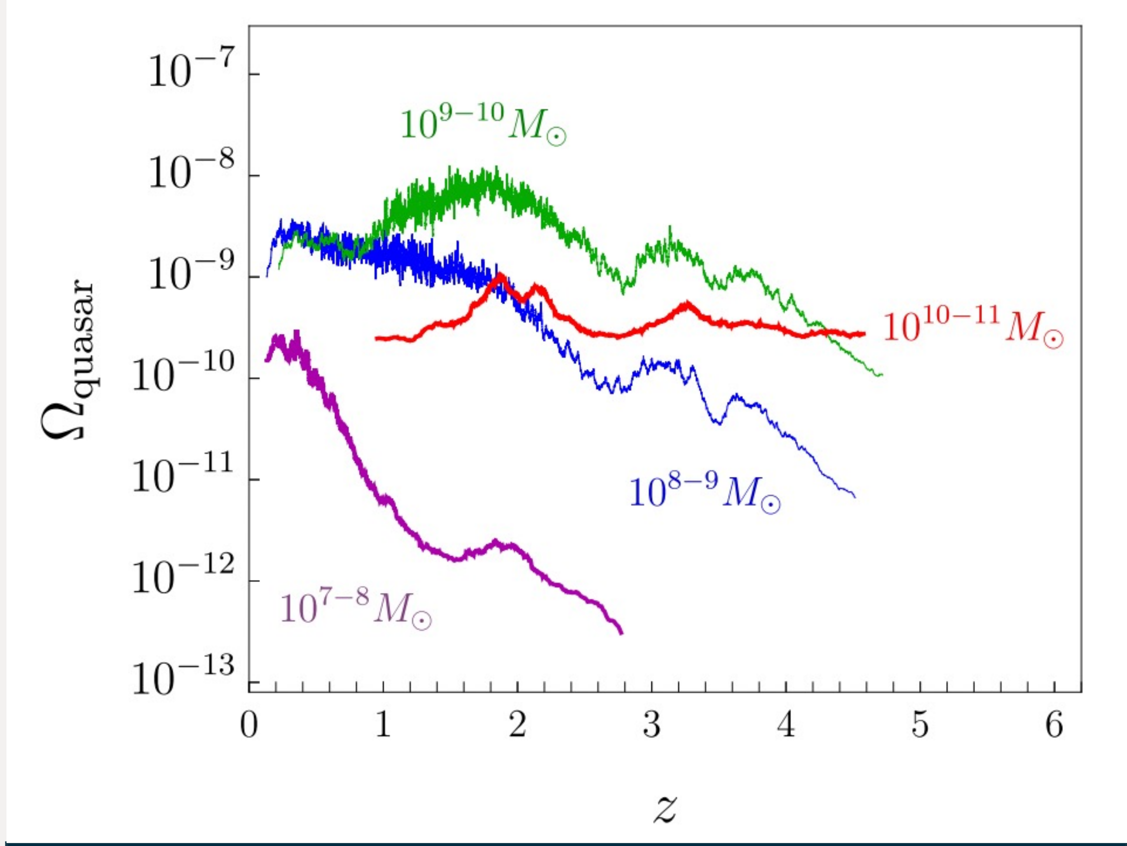
- Possible explanations:
  - Galactic scale feedback effects?
  - Maximum mass after which accretion disks fragments?



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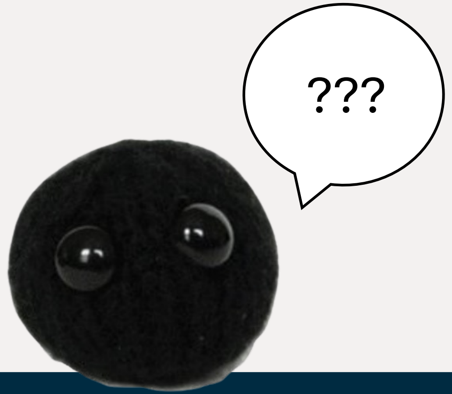
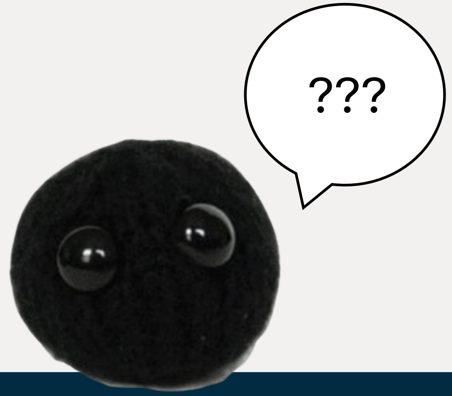


1) How did these SMBHs come to be so massive on such a short time scale?

2) Why did their growth rate dramatically slow in the subsequent ~ 13 Gyr?

Motivations



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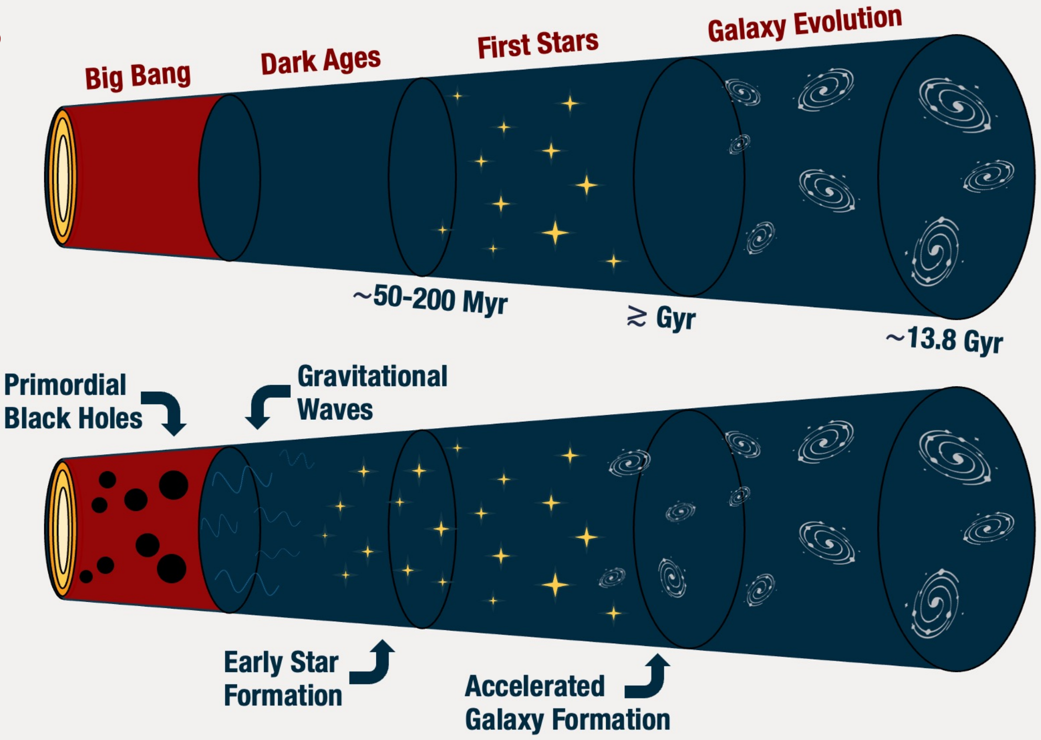
Possibility: Primordial origin?

Motivations

Many exciting implications of a primordial origin in light of recent observations!

- **JWST high-redshift galaxy candidates**
  - SMBHs could accelerate early galaxy formation
- **Gravitational waves**
  - Stochastic GW background in the nHz regime recently reported by NANOGrav and other PTAs
  - Leading astrophysical interpretation: SMBH binary mergers
  - Some aspects of fit are poor; better fit for primordial SMBHs?



Motivations

- Previous works: **Primordial SMBH seeds**
  - Form much earlier than $z \sim 30 \Rightarrow$ timing problem allayed [1202.3848]
  - Light seeds $M_{\rm BH} \geq 10^2\ M_\odot$ sufficient to seed present day SMBHs [1712.01311]
- This work: **SMBHs directly from inflation**
  - Massive seeds $M_{\rm BH} \geq 10^5\ M_\odot$

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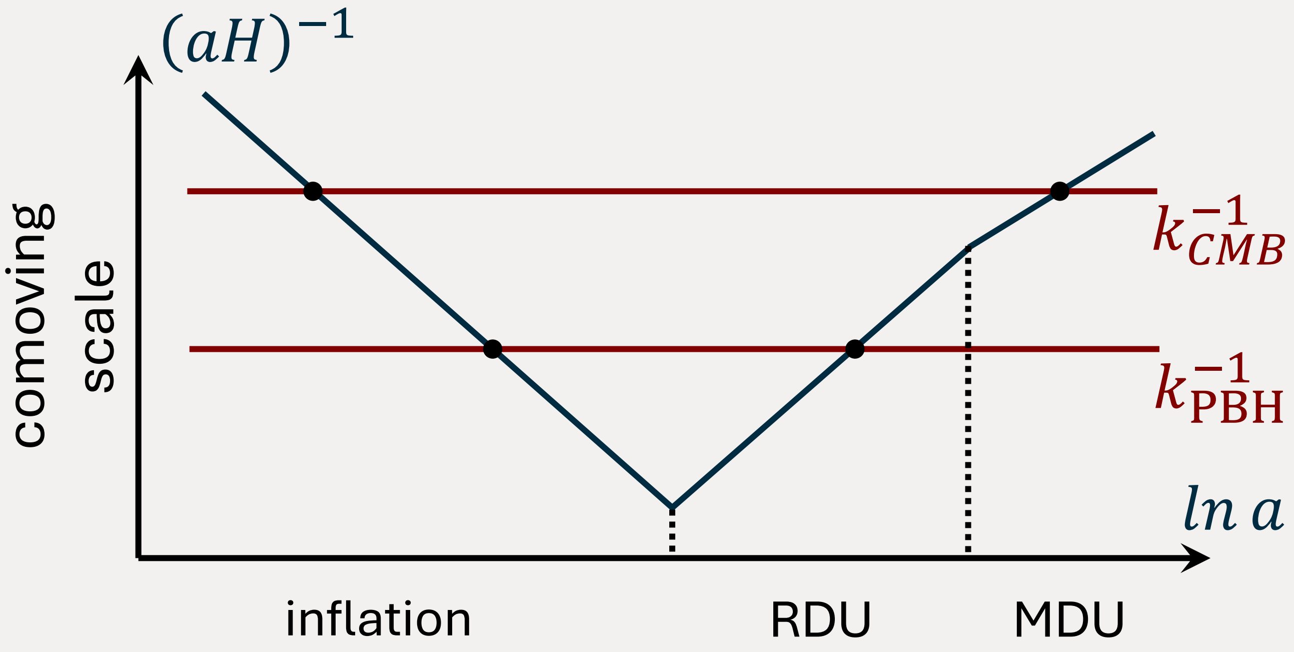
- This work: **SMBHs directly from inflation**
  - Massive seeds $M_{\rm BH} \geq 10^5\ M_\odot$
- Future data will help us to determine the nature of SMBH seeds
  - With JWST, can now observe smaller SMBHs in dimmer galaxies farther away
  - Opportunity to study how these early BHs and their host galaxies evolved together

PBH Formation

- **Primordial black holes** (PBHs):
  ⇒ Form in the early universe from the collapse of large density perturbations $\delta \equiv \delta\rho/\bar{\rho}$ exceeding the collapse threshold $\delta > \delta_{\text{th}}$
- One source of overdensities:
  ⇒ Quantum fluctuations stretched to superhorizon scales during **inflation**
- PBH formation is a causal process; compare
  - Comoving length scale of perturbation mode, $\lambda = k^{-1}$
  - Comoving Hubble horizon, $R_H = (aH)^{-1}$

PBH Formation

- $R_H = (aH)^{-1} \sim a^{(1+3w)/2}$
  - Inflation ($w = -1$): $R_H \sim a^{-1}$
  - Rad dom ($w = 1/3$): $R_H \sim a$
- Mode can be
  - Subhorizon: $k > aH$
  - At horizon crossing: $k = aH$
  - Superhorizon: $k < aH$
- Small scale modes (large k) exit later and re-enter earlier



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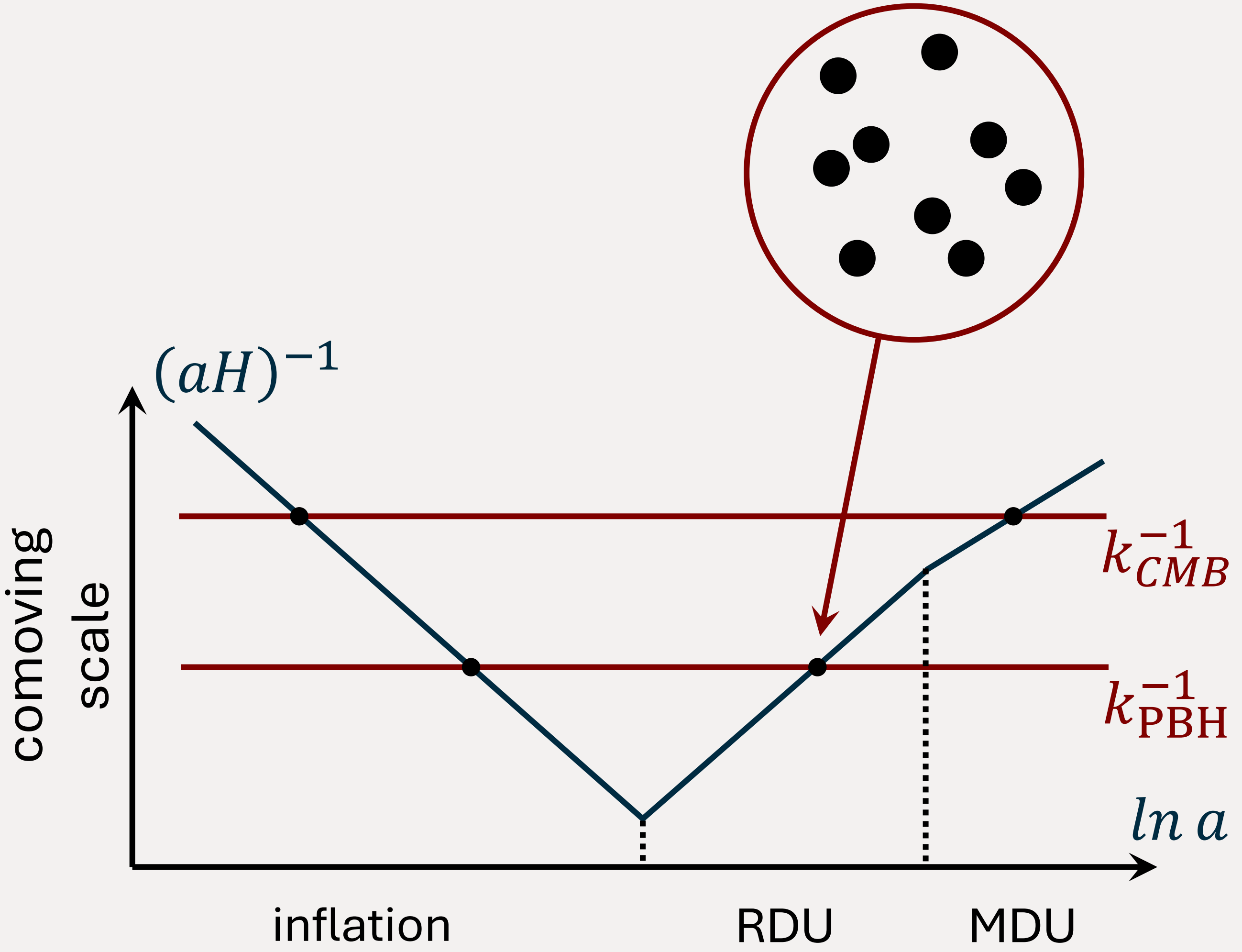
If $\delta > \delta_{\mathrm{th}}$, entire horizon collapses upon re-entry ⇒ PBHs!



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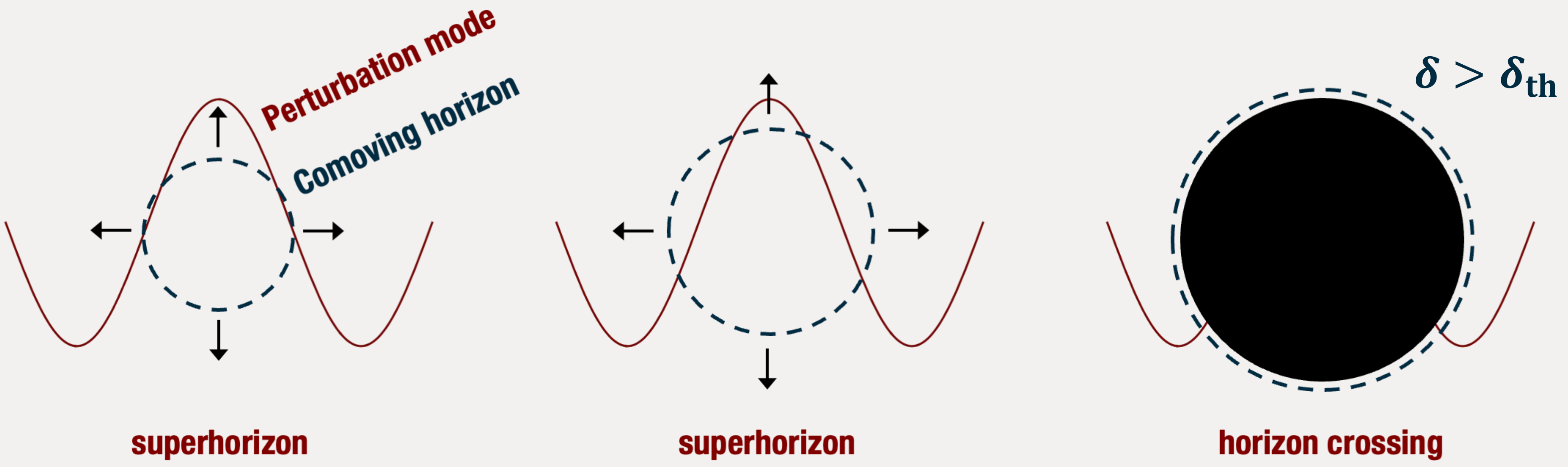

- Initial mass of PBH $\simeq$ mass of cosmological horizon

$$M_{\rm PBH} = \left(5\times10^{8}\, M_\odot\right)\left(\frac{\gamma}{0.2}\right)\left(\frac{92\ {\rm Mpc}^{-1}}{k_{\rm PBH}}\right)^{2}\left(\frac{g_\star(T)}{3.36}\right)^{1/2}\left(\frac{3.91}{g_{\star,s}(T)}\right)^{2/3}$$

PBH Formation

- Initial abundance ⇒ mass fraction at formation, $\beta = \rho_{PBH}/\rho_{tot}$
- In the Press Schechter formalism:

$$\beta \simeq 2 \int_{\delta_{\rm th}}^{\infty} d\delta \, P[\delta]$$

- Usual assumption: **Gaussian** probability distribution function (pdf)

$$P_G[\delta] = \frac{1}{\sqrt{2\pi}\sigma_\delta} \exp\left(-\frac{\delta^2}{2\sigma_\delta^2}\right)$$

- Variance computed from **primordial power spectrum** $\mathcal{P}_\delta(k)$

$$\sigma_\delta^2 = \int_0^{\infty} \frac{dk}{k} W^2(k,R)\, \mathcal{P}_\delta(k)$$

PBH Formation

- Value for collapse threshold $\delta_{\rm th}$?
- Intuition: Perturbation will collapse if overdensity exceeds radiation pressure

$$\Rightarrow \delta_{\rm th} \simeq c_s^2 = 1/3$$

- Numerical simulations: $\delta_{\rm th} \simeq 0.4 - 0.66$ [1309.4201]
- Precise value depends on overdensity profile
- PBH abundance is **extremely sensitive** to $\delta_{\rm th}$ $\longleftarrow$ $\beta \simeq \sqrt{\frac{2}{\pi}} \frac{\sigma_\delta}{\delta_{\rm th}} \exp\left(-\frac{\delta_{\rm th}^2}{2\sigma_\delta^2}\right)$
- We take: $\delta_{\rm th} = 0.414$

PBH Formation

- A non-vanishing abundance requires a large variance $\sigma_\delta^2 \sim \mathcal{P}_\delta(k)|_{\max}$
  $\Rightarrow$ need **significant enhancement** of power spectrum
- For Gaussian pdf, need peak $\mathcal{P}_\delta(k)|_{\max} \sim \mathcal{O}(10^{-2})$

PBH Formation

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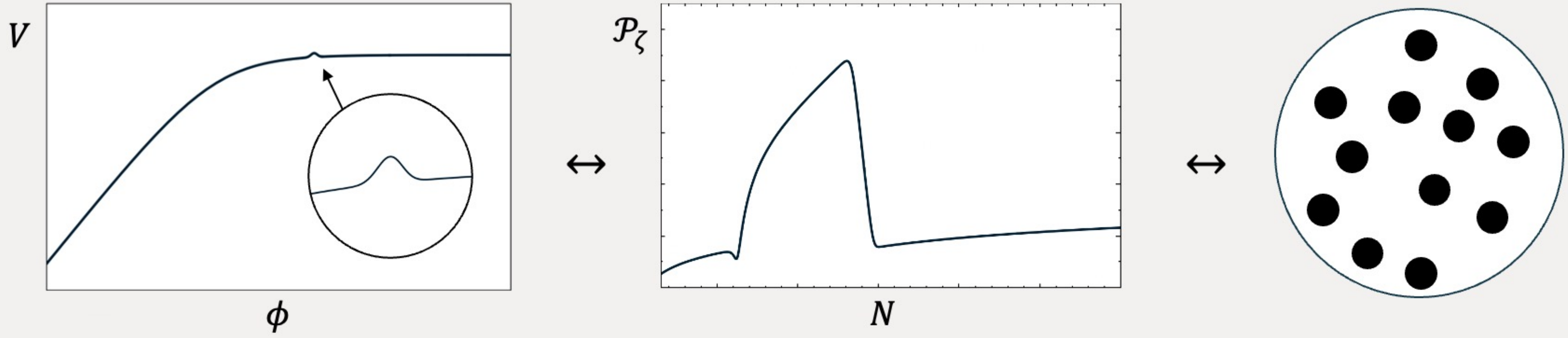
- For Gaussian pdf, need peak $\mathcal{P}_\delta(k)|_{\max} \sim \mathcal{O}(10^{-2})$
- Relatively **easy** to engineer amplified power
  - Single field: Inflection point, ultra-slow-roll plateau, localized features, etc.
  - Multifield: Scalar sector instabilities, non-canonical kinetic terms, non-minimal coupling to R, etc.
- More generically, any deviation from slow-roll $\Rightarrow$ amplified $\mathcal{P}_\delta(k)$

PBH Formation

- Shape of the inflaton potential determines
  - Shape of primordial power spectrum
  - Distribution of PBH masses and abundances



Spectral Distortions

- Issue: SMBH form **late**!
    - $T \sim$ MeV $\Rightarrow M_{\mathrm{H}} \sim 1.7 \times 10^5 \mathrm{M}_{\odot}$
    - $T \sim$ keV $\Rightarrow M_{\mathrm{H}} \sim 3 \times 10^{11} \mathrm{M}_{\odot}$

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- Corresponding modes: $10\ {\rm Mpc}^{-1} \lesssim k_{\rm SMBH} \lesssim 10^4\ {\rm Mpc}^{-1}$
  - Unconstrained by CMB anisotropy measurements
  - However, probed by CMB spectral distortions
- Enhanced power on these scales inevitably leads to **spectral distortions** of the CMB

Spectral Distortions

- Spectral distortions = isotropic deviations from the CMB blackbody distribution
- **μ-type distortions**
  - $2\times10^5 < z < 2\times10^6$
  - Photon number changing processes become ineffective
  - Departure from chemical equilibrium
    ⇒ Bose-Einstein distribution with effective chemical potential μ
- **y-type distortions**
  - $z < 2\times10^5$
  - Compton scattering becomes ineffective
  - Complete departure from equilibrium distribution

Spectral Distortions

- Quantify in terms of parameters μ, $y \sim \Delta\rho_\gamma/\bar{\rho}_\gamma$
- Constraints from COBE/FIRAS:

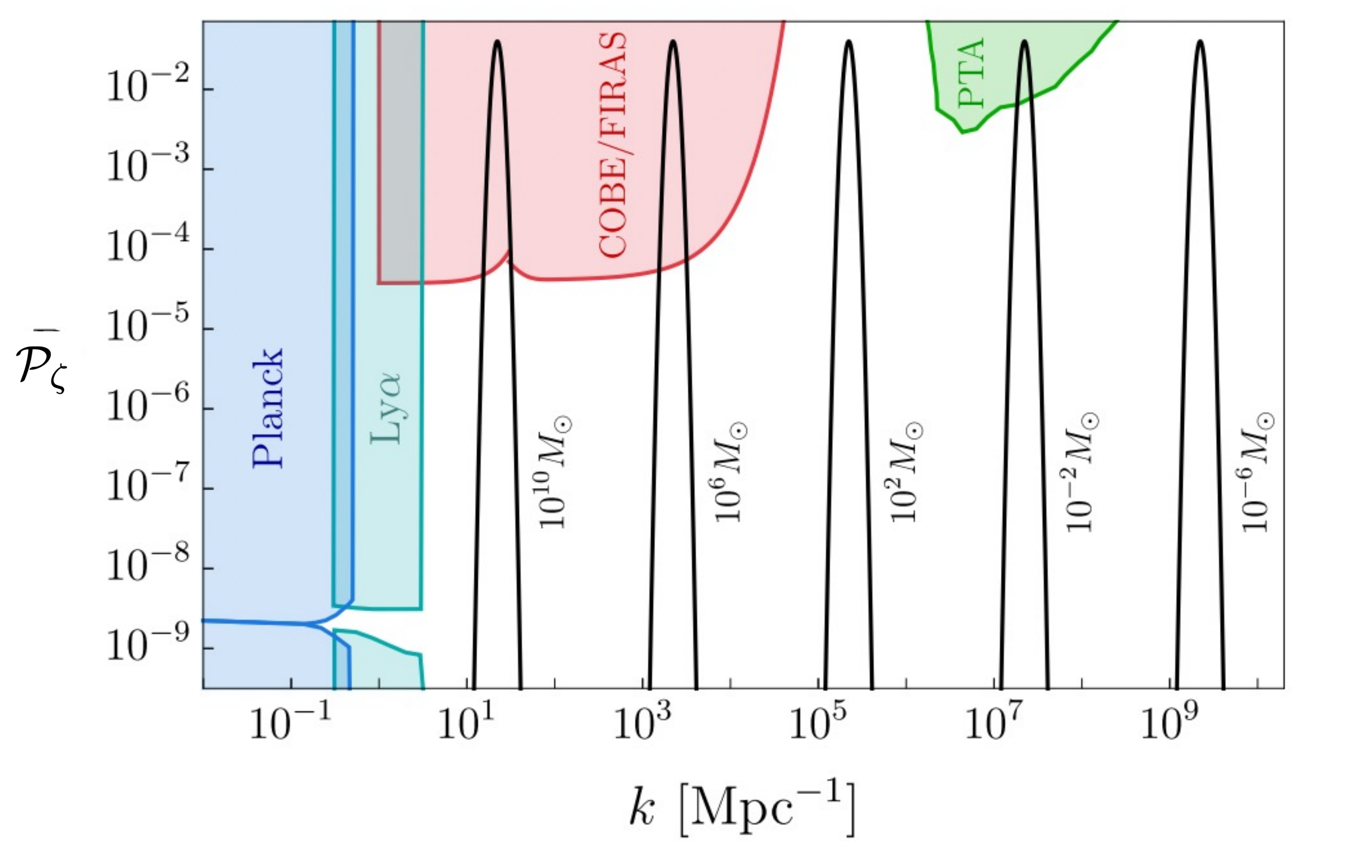
$$|\mu| \lesssim 9.0\times10^{-5}\ ,\ \ |y| \lesssim 1.5\times10^{-5}$$

- For sharply peaked $\mathcal{P}_\zeta(k)$

$$\mu \simeq 2.2\,\sigma_\zeta^2\left(\exp\left[-\left(\frac{1.5\times10^5 M_\odot}{M_{PBH}}\right)^{1/2}\right] - \exp\left[-\left(\frac{4.5\times10^9 M_\odot}{M_{PBH}}\right)\right]\right)$$

$$y \simeq 0.4\,\sigma_\zeta^2\exp\left[-\left(\frac{4.5\times10^9 M_\odot}{M_{PBH}}\right)\right]$$

Spectral Distortions



Lognormal peaked power spectra with amplitude required for $\beta \simeq 10^{-20}$ overlaid against various constraints

Departures from Gaussianity

- Fundamental tension
  - Compatibility with spectral distortions ⇒ Small $\sigma_\zeta^2 \sim \mathcal{P}_\zeta(k)|_{\max}$
  - Non-vanishing PBH abundance ⇒ Large $\sigma_\zeta^2 \sim \mathcal{P}_\zeta(k)|_{\max}$

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- Recall: We compute PBH abundance by integrating over the tail of the distribution, $\delta > \delta_{\rm th}$
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- Incidentally, the Gaussian assumption is **generically false**

Departures from Gaussianity

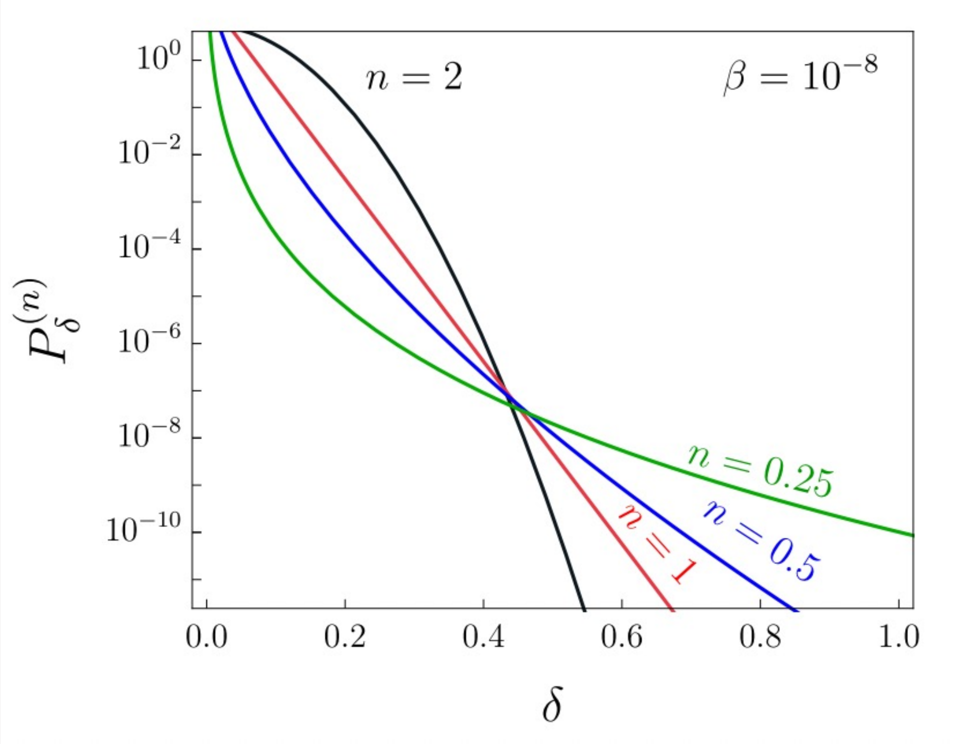
- To quantify required degree of non-Gaussianity, introduce

$$P_\delta^{(n)} = \frac{1}{2\sqrt{2}\,\Gamma(1+1/n)\sigma_0} \exp\left[-\left(\frac{|\delta|}{\sqrt{2}\sigma_0}\right)^n\right]$$

- Variance

$$\sigma_\delta^2(\sigma_0) = \int d\delta\, \delta^2\, P_\delta^{(n)} = \frac{\Gamma(1+3/n)}{3\,\Gamma(1+1/n)} \sigma_0^2$$

- Cases
  - $n = 2 \Rightarrow$ Gaussian
  - $n = 1 \Rightarrow$ Exponential
  - $n < 1 \Rightarrow$ **Heavy**



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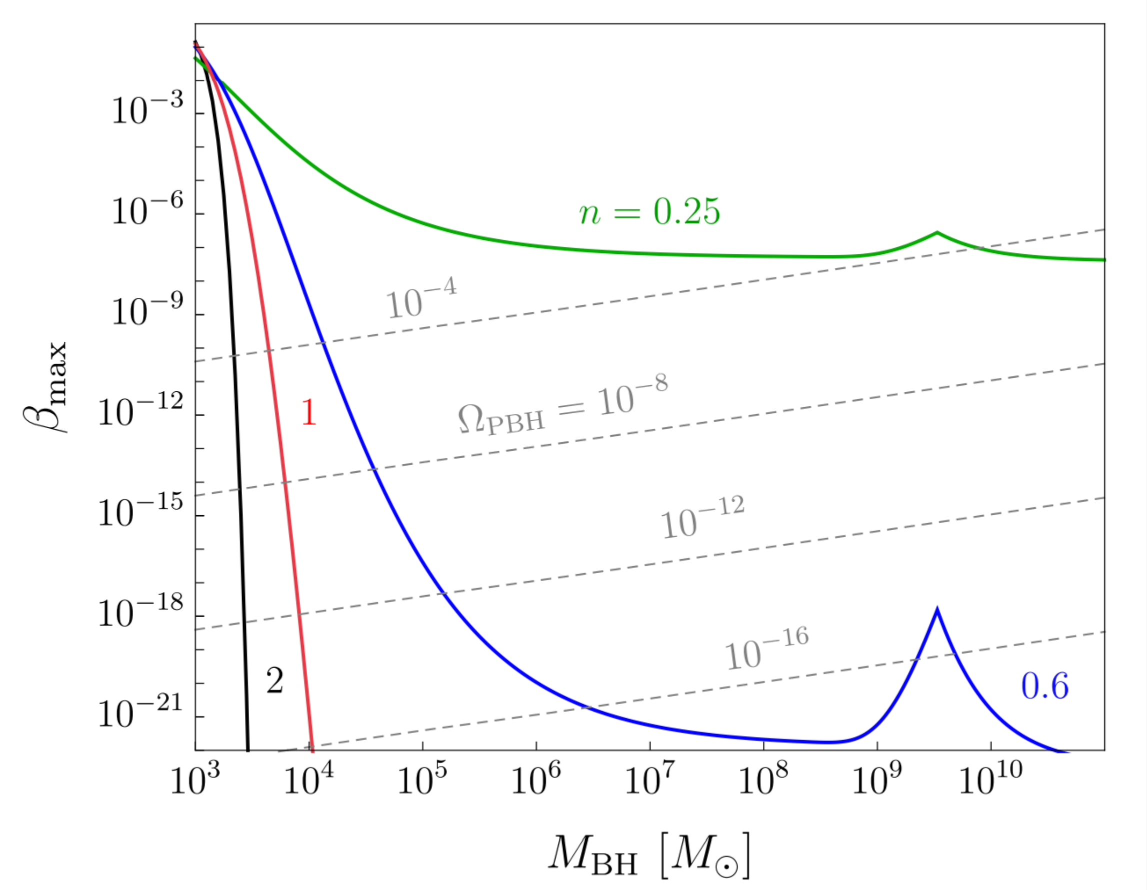

Maximum PBH abundance β for variance σ_δ^2 saturating CMB spectral distortion constraints

Departures from Gaussianity

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  ⇒ Ultra-slow-roll regime ⇒ quantum diffusion

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- Possibility: **Non-minimal self-interacting curvaton model**?

~~Non-Minimal Self-Interacting~~ Curvaton

- Curvaton χ
  - Light $(m_\chi^2 \ll H)$ spectator field
  - Subdominant during inflation
  - Responsible for generating the dominant contribution ζ_χ to the curvature perturbation
- Curvature perturbation ζ_χ
  - Initially an **isocurvature** mode
  - Converted to **adiabatic** upon curvaton decay
- Non-Gaussianity arises due to **inefficient** conversion of isocurvature to adiabatic perturbations

~~Non-Minimal Self-Interacting~~ Curvaton

- Curvaton cosmology
  - During inflation
    - Background value "frozen-in" at χ_*
    - Receives (**Gaussian**) perturbations $\delta\chi_* \simeq H_*/2\pi$
  - After inflation
    - Starts to oscillate about minimum when $H \simeq m_\chi$
    - Decays when $H \sim \Gamma_\chi$
- Non-linear mapping between ζ and $\zeta_\chi \Rightarrow$ non-Gaussian pdf
- Goal: Want to compute pdf for ζ

~~Non-Minimal Self-Interacting~~ Curvaton

- **δN formalism** [astro-ph/0411220], [astro-ph/0504045]
  - Compute non-linear evolution of cosmological perturbations on super-horizon scales
  - Curvature perturbation = difference between perturbed vs unperturbed amount of expansion: $\zeta = N(\bar{\chi} + \delta\chi) - N(\bar{\chi})$
- Curvaton curvature perturbation ζ_χ and total ζ related as [astro-ph/0607627]

$$e^{4\zeta} - \frac{4r}{3+r}\left(e^{3\zeta_\chi}\right)e^{\zeta} + \frac{3r-3}{3+r} = 0$$

- Solve for $\zeta = \ln X\left(\zeta_\chi\right)$

$$r = \left.\frac{3\Omega_\chi}{4-\Omega_\chi}\right|_{\mathrm{decay}}$$

~~Non-Minimal Self-Interacting~~ Curvaton

- Curvaton curvature perturbation ζ_χ related to field perturbation $\delta\chi$ as

$$e^{3\zeta_\chi} = \left(1 + \frac{\delta\chi}{\bar{\chi}}\right)^2$$

- Quadratic potential $\Rightarrow$ $\delta\chi$ and $\bar{\chi}$ obey **same** e.o.m. on superhorizon scales

$$\Rightarrow \delta\chi/\bar{\chi} = \delta\chi_*/\bar{\chi}_* \equiv \delta_\chi$$

- Result: Mapping between ζ and the **Gaussian reference variable** δ_χ
- Can now obtain pdf of ζ using conservation of probability

~~Non-Minimal Self-Interacting~~ Curvaton

- By conservation of probability

$$P_\zeta[\zeta] = P_G\left[\delta_\chi^+(\zeta)\right]\left|\frac{d\delta_\chi^+}{d\zeta}\right| + P_G\left[\delta_\chi^-(\zeta)\right]\left|\frac{d\delta_\chi^-}{d\zeta}\right|$$

with

$$\delta_\chi^\pm = -1 \pm \sqrt{\frac{3+r}{4r}e^{3\zeta} + \frac{3r-3}{4r}e^{-\zeta}}$$

and

$$P_G[\delta_\chi] = \frac{1}{\sqrt{2\pi}\sigma_0}\exp\left(-\frac{\delta_\chi^2}{2\sigma_0^2}\right)$$

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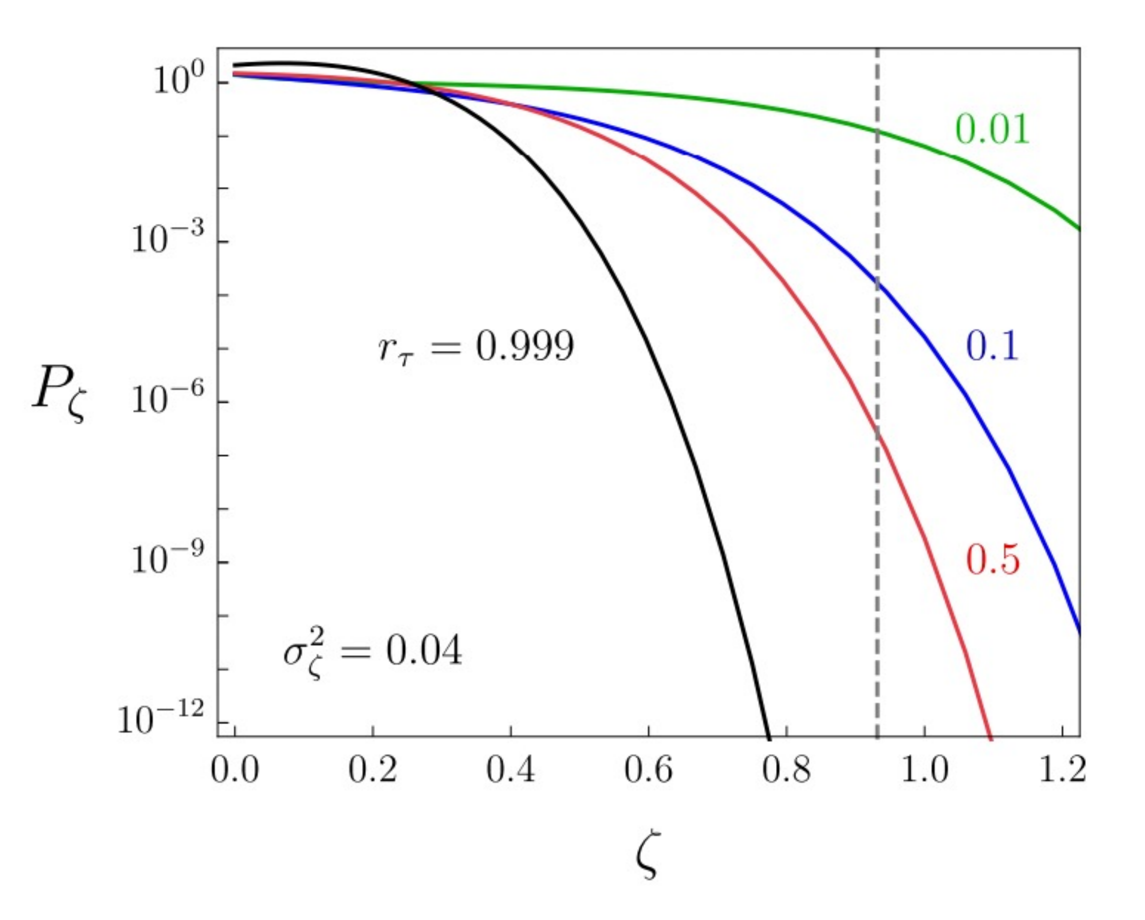


Probability distribution function for the curvature perturbation as a function of r

Non-Minimal ~~Self-Interacting~~ Curvaton

- Curvaton model yields ζ with non-Gaussian statistics
- Still need local amplification of $\mathcal{P}_\zeta(k)$
- Simple option: **Non-minimal kinetic term** [2112.12680]

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi) + \frac{1}{2}f(\phi)^2(\partial\chi)^2 - \frac{1}{2}m_\chi^2\chi^2$$

- Choose $f(\phi)$ s.t. kinetic term is suppressed on scale $k_{\rm PBH} \Rightarrow$ **peak**!

$$\mathcal{P}_{\delta_\chi}(k) = \frac{k^3}{2\pi^2}\left|\frac{\delta\chi_k}{\chi}\right|^2 = \frac{1}{\chi(t_k)^2}\left(\frac{H(t_k)}{2\pi f(\phi_k)}\right)^2$$

Non-Minimal ~~Self-Interacting~~ Curvaton

- PBH mass fraction at formation

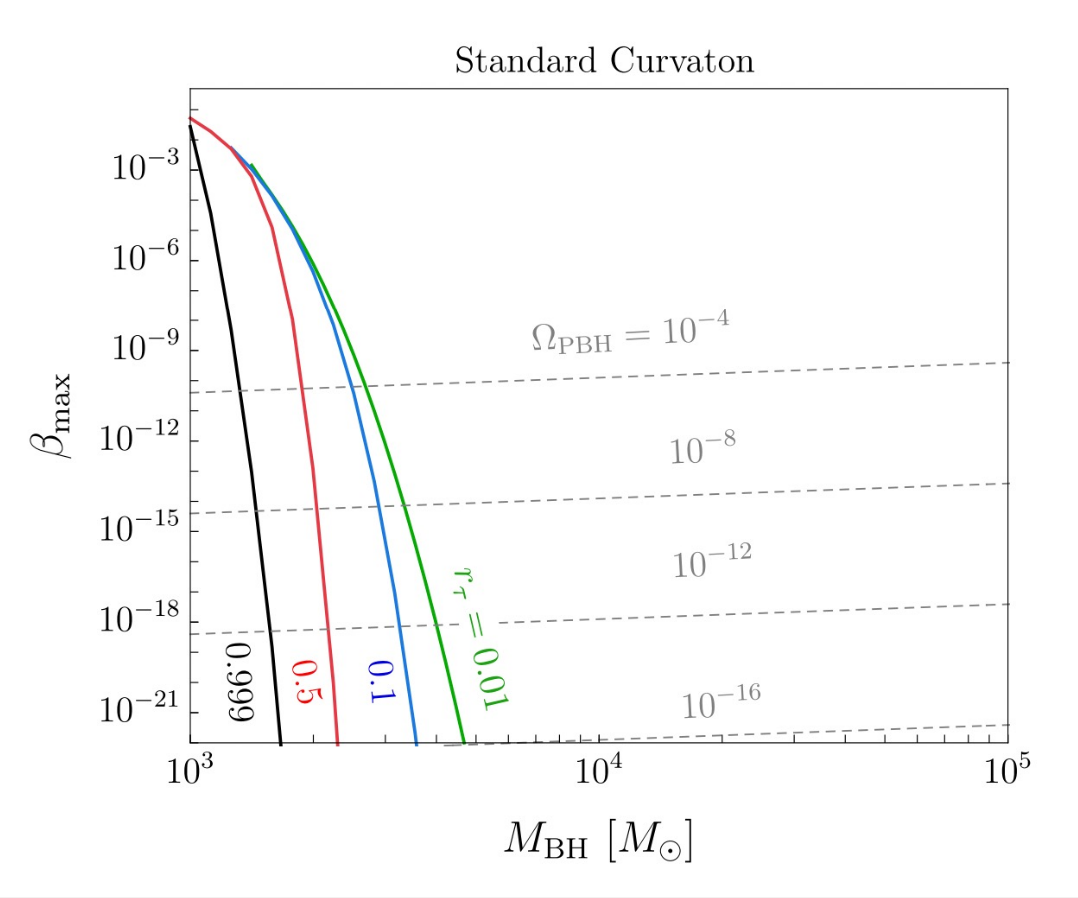
$$\beta = 2\int_{\delta_{\chi,\mathrm{th}}^{+}}^{\infty} d\delta_\chi\, P_G[\delta_\chi] + 2\int_{-\infty}^{\delta_{\chi,\mathrm{th}}^{-}} d\delta_\chi\, P_G[\delta_\chi]$$

$$= \mathrm{erfc}\left(\frac{\delta_{\chi,\mathrm{th}}^{+}}{\sqrt{2}\,\sigma_0}\right) + \mathrm{erfc}\left(\frac{|\delta_{\chi,\mathrm{th}}^{-}|}{\sqrt{2}\,\sigma_0}\right)$$

- Variance

$$\sigma_\zeta^2 = \int d\delta_\chi\, \zeta^2\, P_G[\delta_\chi] - \left(\int d\delta_\chi\, \zeta\, P_G[\delta_\chi]\right)^2$$

Non-Minimal ~~Self-Interacting~~ Curvaton



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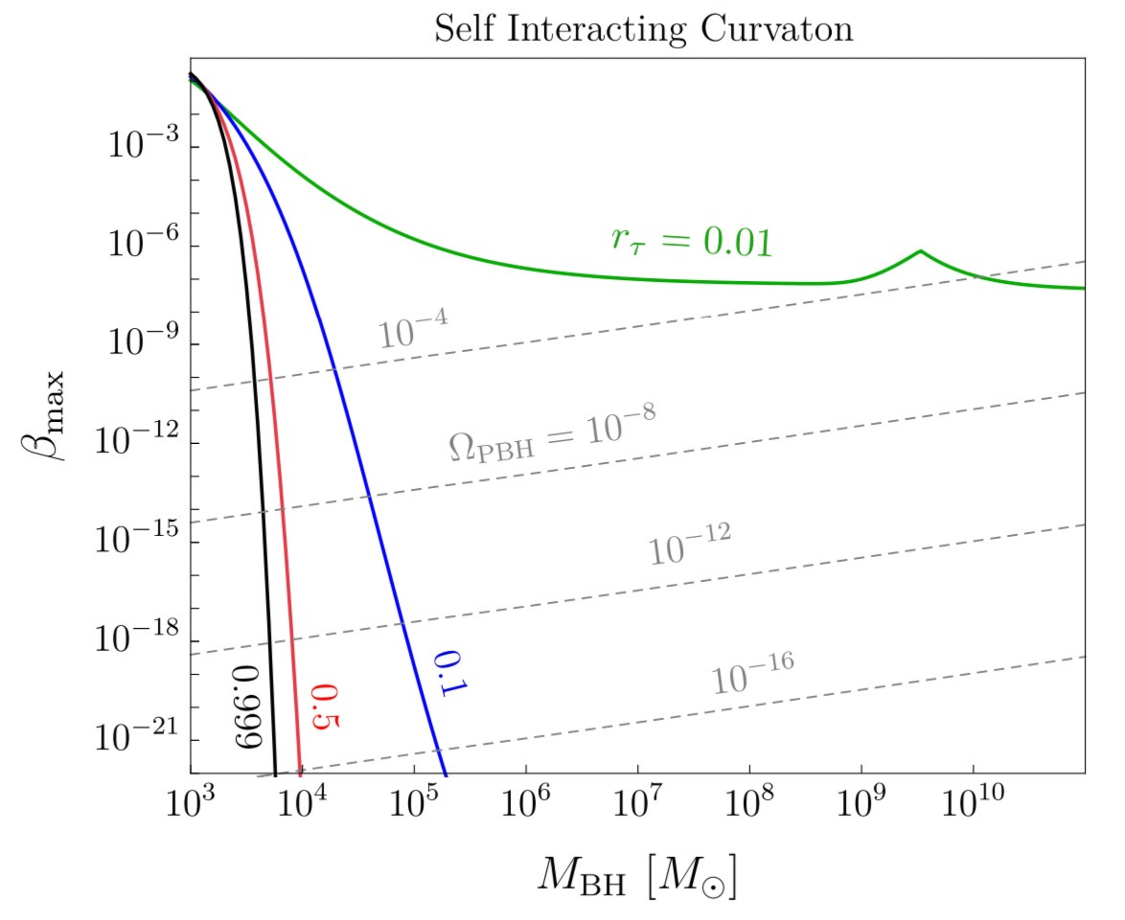
- One option: Curvaton **self-interactions**
- Quadratic potential
  - $\bar{\chi} \sim \delta\chi \;\Rightarrow\; \delta\chi/\bar{\chi} = \delta\chi_*/\bar{\chi}_* \equiv \delta_\chi$
  - No **non-linear evolution** for δ_χ between horizon exit and onset of oscillations
  - Exact relation $e^{3\zeta_\chi} = \left(1 + \delta_\chi\right)^2$
- With self-interactions, mapping between ζ_χ and initial Gaussian perturbations $\delta\chi_*$ can be made even **more dramatically** non-linear!

Non-Minimal Self-Interacting Curvaton

- Curvaton cosmology
  - $t_* \lesssim t \lesssim t_{\mathrm{int}}$ $\Rightarrow$ $\bar{\chi} \simeq \bar{\chi}_*$
  - $t_{\mathrm{int}} \lesssim t \lesssim t_{\mathrm{osc}}$ $\Rightarrow$ non-quadratic interaction regime
  - $t_{\mathrm{osc}} \lesssim t \lesssim t_{\mathrm{dec}}$ $\Rightarrow$ quadratic field oscillations
- Gaussian reference variable $\delta\chi_*$
- Same mapping between ζ and ζ_χ: $\zeta = \ln X(\zeta_\chi)$
- Need mapping between ζ_χ and $\delta\chi_*$: $\delta\chi_*^j = g_j(\zeta_\chi)$
- By conservation of probability: $P_\zeta = \sum_j \left|\frac{g_j(\zeta)}{d\zeta}\right| P_G[g_j(\zeta)]$

Non-Minimal Self-Interacting Curvaton



Maximum PBH abundance β for variance σ_δ^2 saturating CMB spectral distortion constraints

Conclusions

- Inferred SMBH population in the high-redshift universe is **surprising**
- Possibility: **Primordial origin**?
- Issue: Required amplification of $\mathcal{P}_\zeta$ naively violates CMB **spectral distortions**
- Resolution: ζ with **non-Gaussian, heavy-tailed** probability distribution
- Physical realization: Non-minimal self-interacting curvaton model?
- Future directions:
    - Curvaton numerics, model building
    - Gravitational wave signal