Higgs stability + PBHs

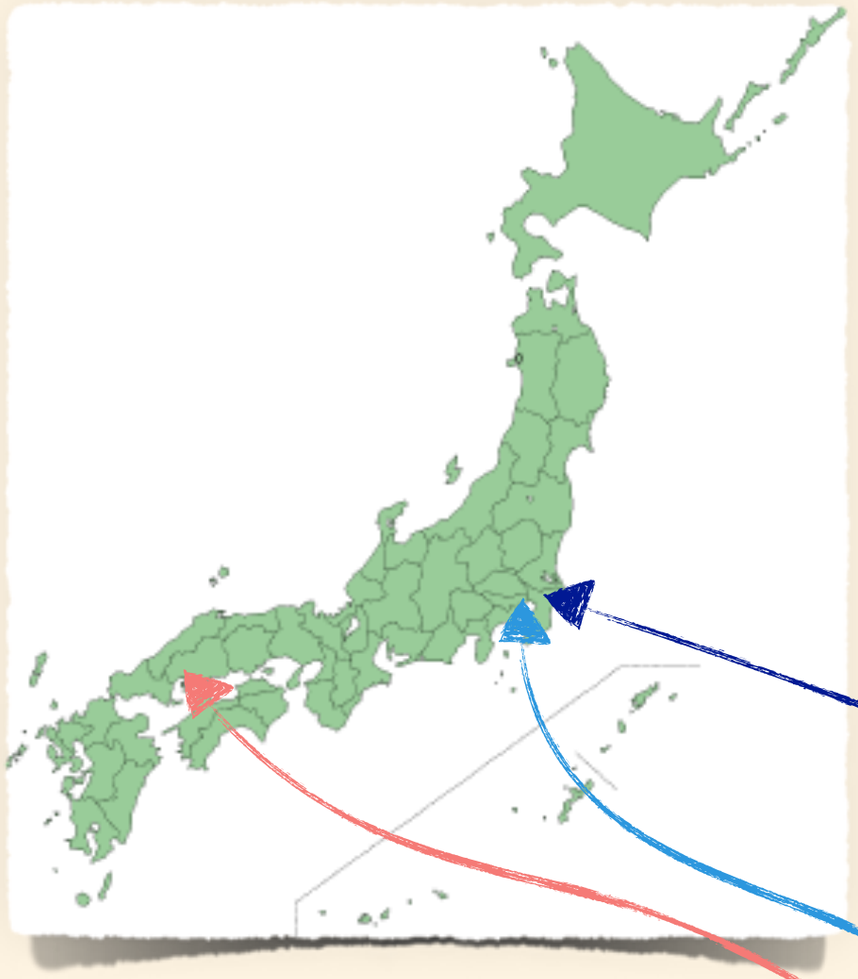
Kyohei Mukaida

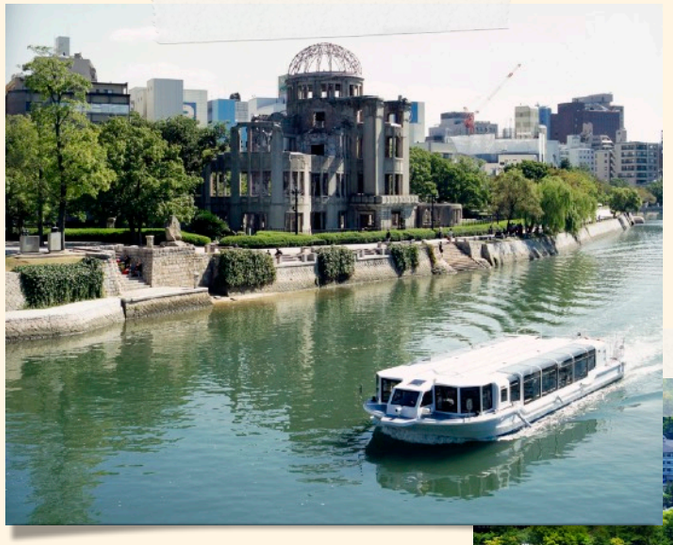
Room: 208a, Building 2a

DESY theory: Fellow's meeting 2017 @ Dec.12

About myself

Mukaida, Kyohei (向田 享平)





[Pictures in Hiroshima: www.hiroshima-kankou.com]

- Born on 27.4.1987 in Hiroshima
- Ph.D. Physics @ Univ. of Tokyo; 3.2015, supervised by **Koichi Hamaguchi**
- 1st Postdoc @ Kavli IPMU; 4.2015-9.2017
- **2nd Postdoc @ DESY; 10.2017**

My Interests

Interplay between **Particle Physics** & **Cosmology**

Mostly before BBN... t < 1s

- **Inflation, (P)Reheating, Thermalization**

  Finite T effects on (P)reheating: 1208.3399, 1212.4985; Thermalization during Reheating: 1212.4985, 1506.07661
  Violent preheating in inflation with non-minimal coupling: 1609.05209
  Dark Matter as Inflaton: 1308.4394, 1404.1880
  Oscillons: 1405.3233, 1612.07750

- **Particle (Dark Matter) Production**

  Finite T effects on DM production: 1111.4594; New DM production via Thermalization: 1402.2846, 1404.3138
  Gravitational Particle Production: 1502.02475, 1504.07119, 1604.08898
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- **Higgs stability**

  during Preheating: 1602.00483, 1706.08920, 1605.04974
  In the presence of BHs: 1706.04523

- **Primordial Black Holes**

  Constraints on inflationary PBHs for LIGO: 1611.06130; Constraints on extended mass function: 1701.02544
  PBHs from double inflation: 1605.04974, 1711.06129; PBHs from axion-like curvaton: 1711.08956

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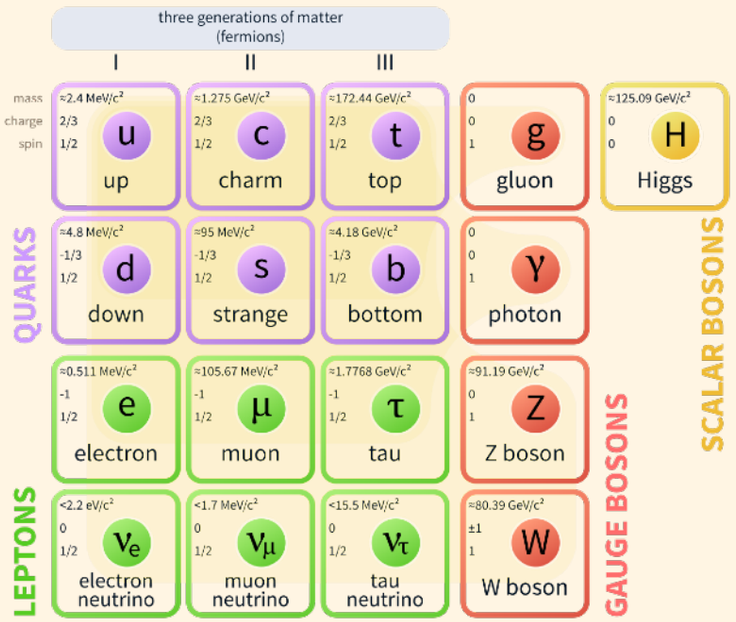
My attitude in this talk…

Suppose **new physics** is far away…

Standard Model



[wikipedia]

Poor communication

Dark Matter

Inflation

Baryon Asymmetry of Universe

Neutrino Masses

Can we **constrain** / **probe** such kind of scenarios?

Higgs stability

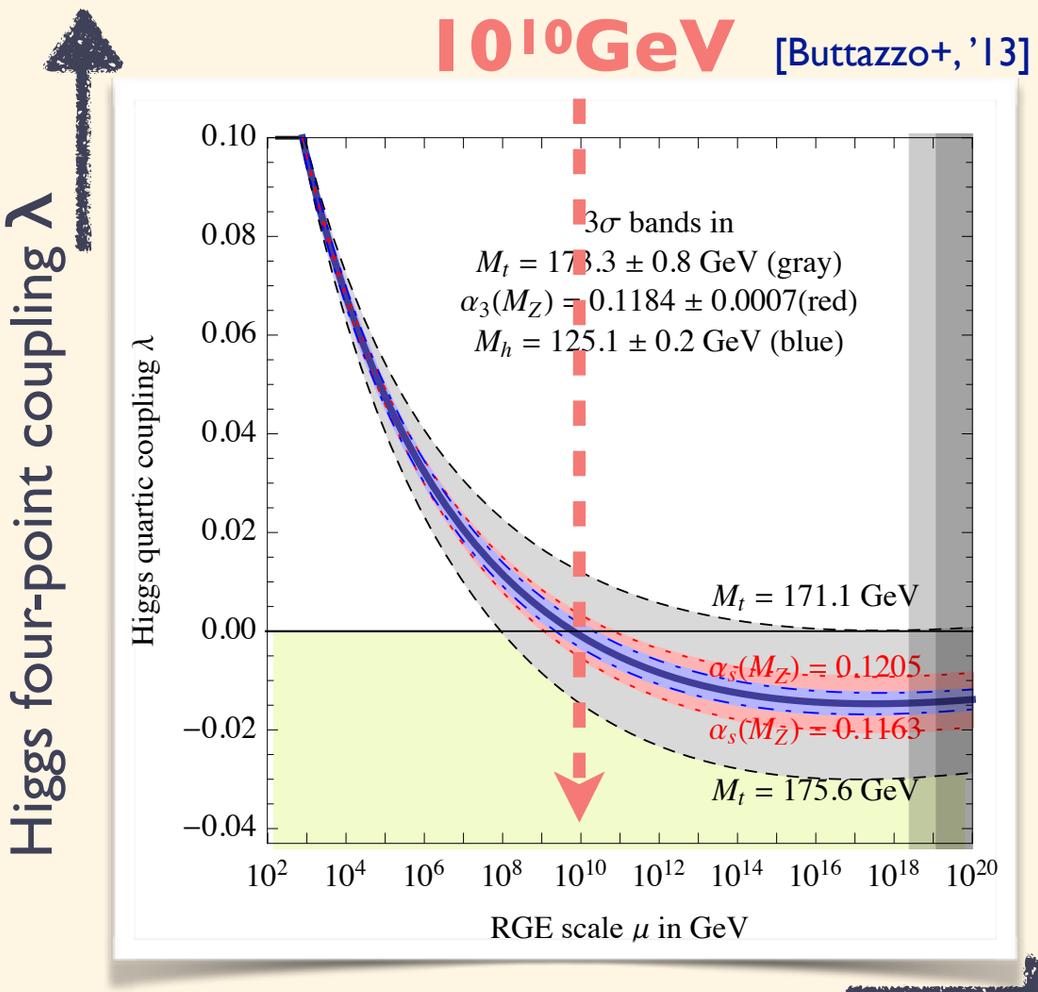
Kyohei Mukaida - DESY

Metastable EW Vacuum

Suppose **new physics** is far away…

- **Run** the Standard Model (SM) up to a high-energy scale, say $\mathbf{M_{Pl}}$.
- **Metastable Electroweak Vacuum**

10^{10}GeV [Buttazzo+, '13]



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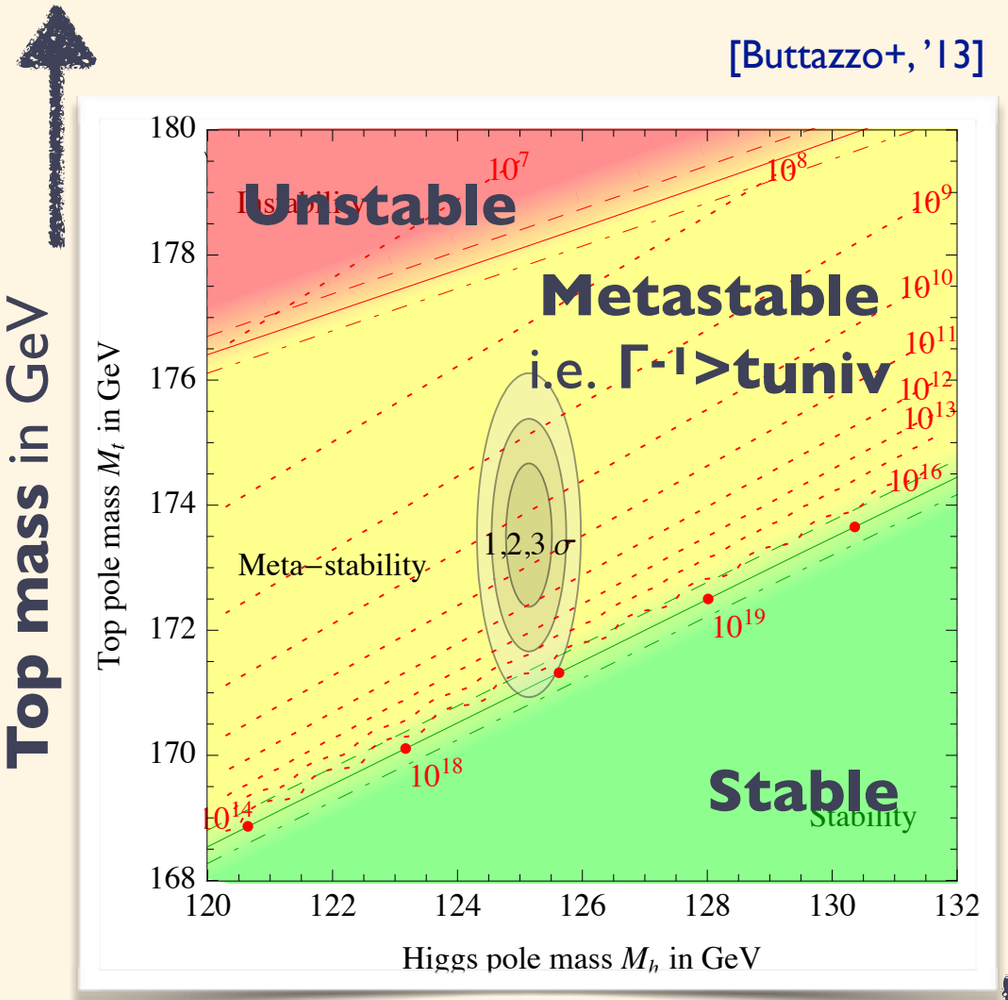


Metastable EW Vacuum

Suppose **new physics** is far away…

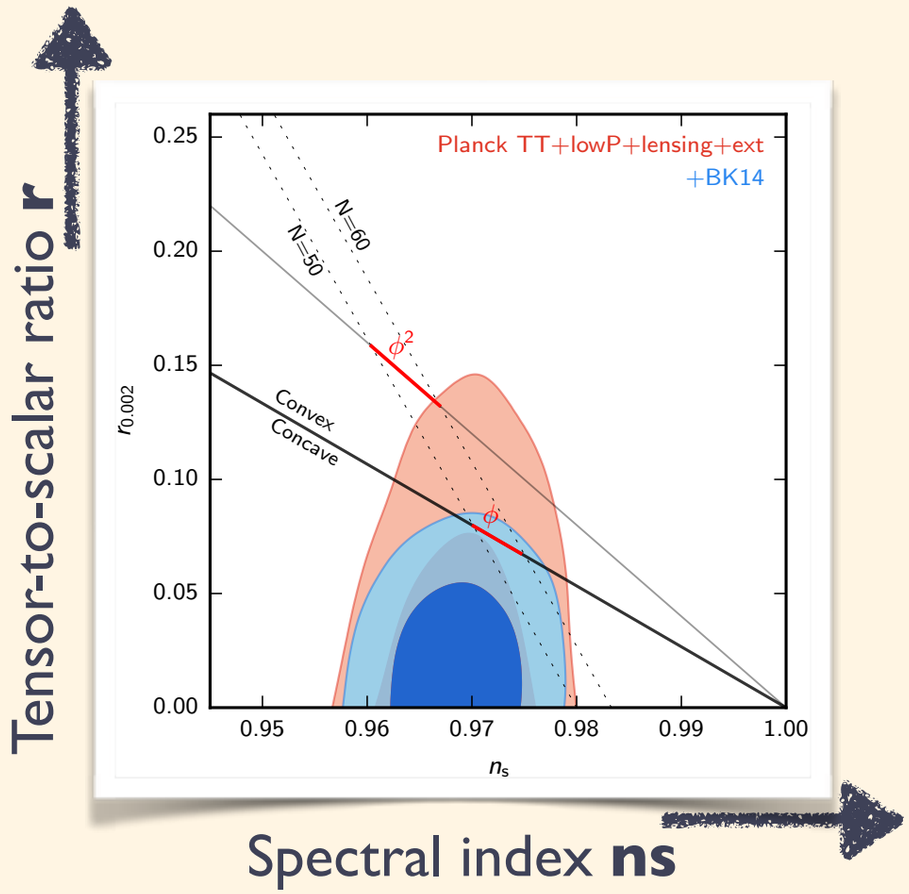
- **Run** the Standard Model (SM) up to a high-energy scale, say M_{Pl}.
- **Metastable Electroweak Vacuum**

$$\lambda < 0 \text{ for } h > h_{inst} \sim 10^{10}\ \text{GeV}$$

v.s.

- **High-scale Inflation**
  - r > 0.1: disfavored.
  - r ~ O(0.01): now being constrained.
  - r ~ 0.001: may be probed in future (e.g. LiteBIRD).

$$r \sim 0.1 \left(\frac{H_{\rm inf}}{10^{14}\,\text{GeV}} \right)^2$$

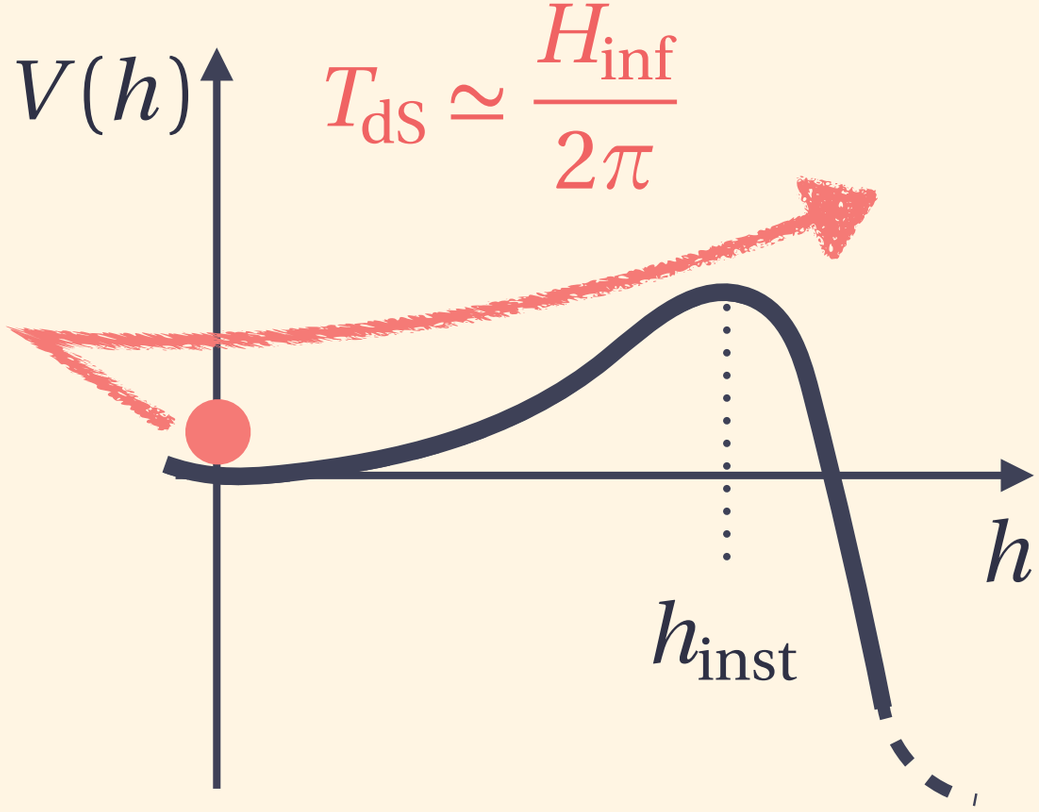


Can be tested within ~ 10 years?

Metastability v.s. Inflation

Higgs field **during** high-scale Inflation

✤ $\mathbf{m_\Phi} \gg \mathbf{h_{inst}}$: inflaton cannot change the running of λ below $\mathbf{m_\Phi}$.



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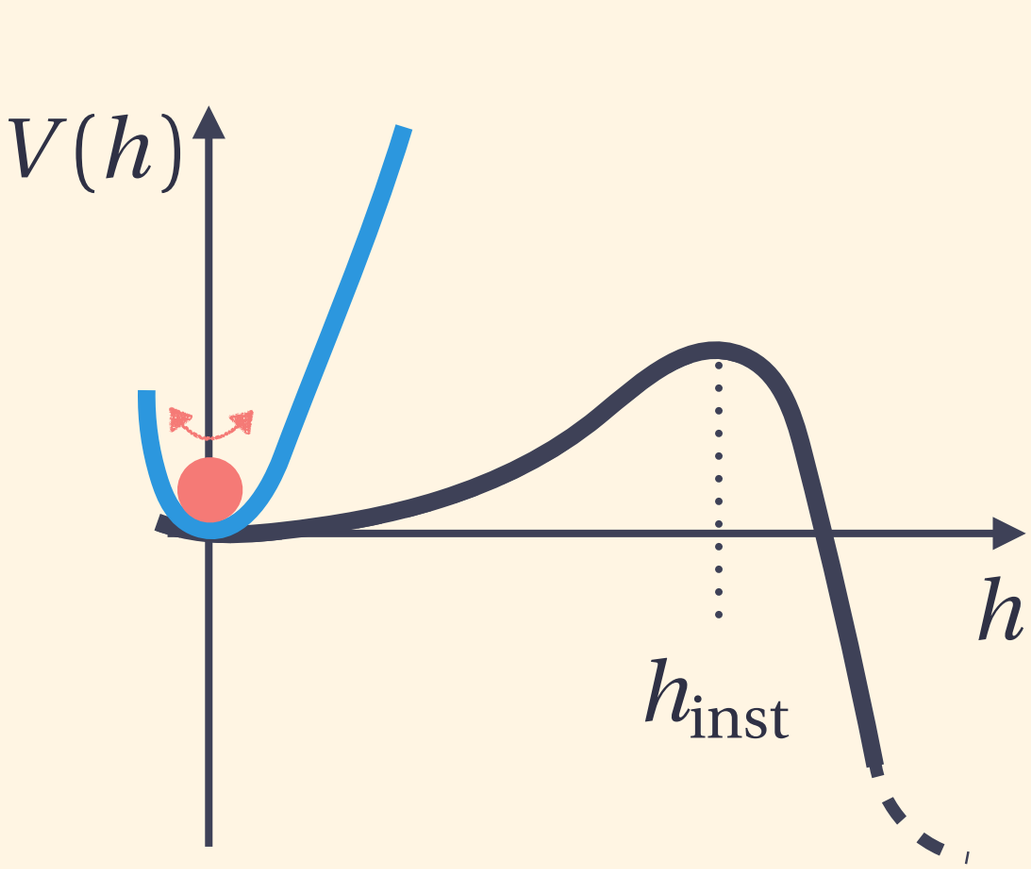
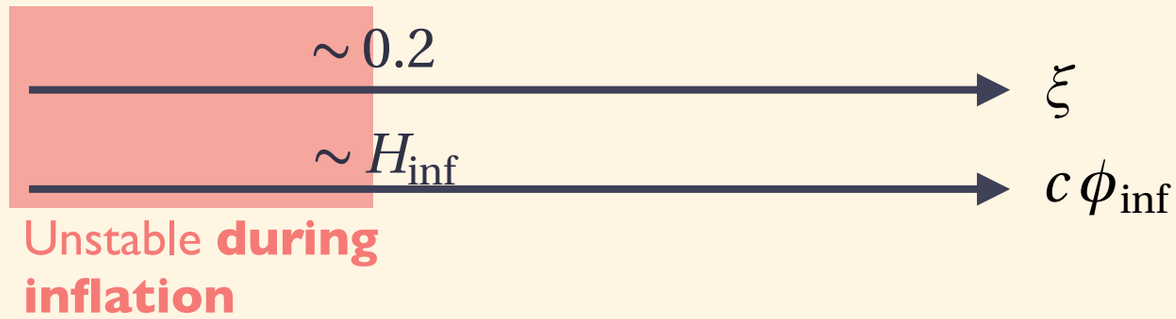
- ✤ $\mathbf{m_\Phi} \gg \mathbf{h_{inst}}$: inflaton cannot change the running of λ below $\mathbf{m_\Phi}$.
- ‣ "Tiny" Higgs-Inflaton coupling stabilizes it **during inflation.** [Westphal+; Espinosa+]



During inflation

- Curvature $\frac{1}{2}\xi R h^2 \;\Rightarrow\; 12\xi H_{\rm inf}^2$
- Portal $\frac{1}{2}c^2\phi^2 h^2 \;\Rightarrow\; c^2\phi_{\rm inf}^2$

$\gtrsim H_{\rm inf}^2$



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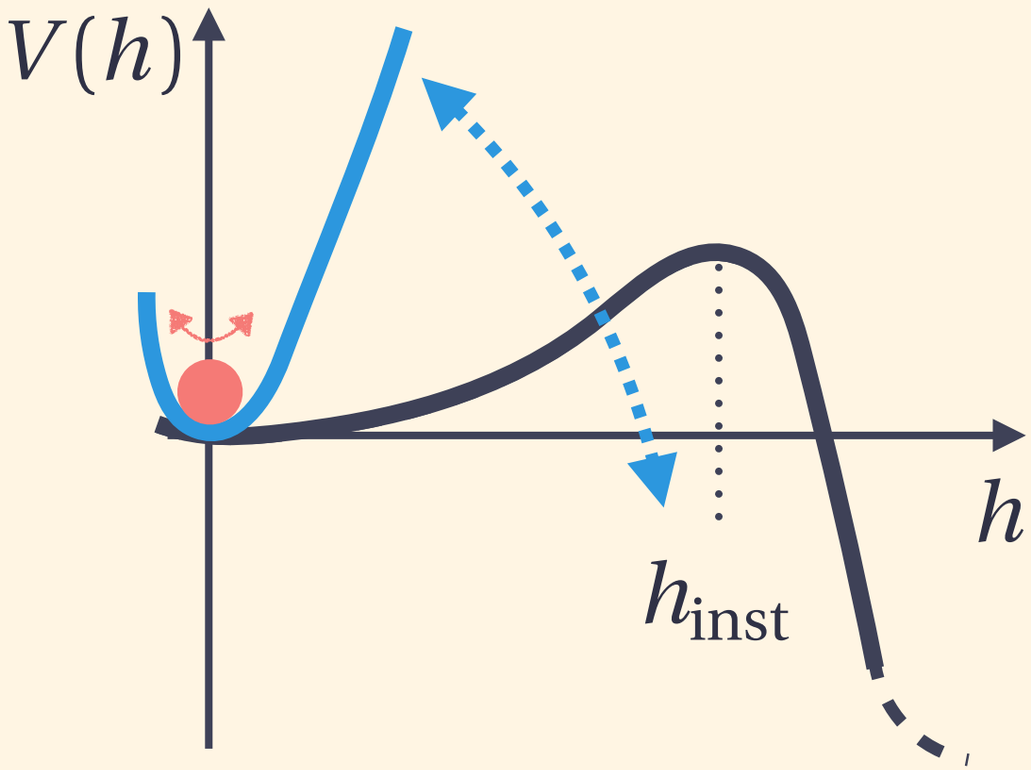
  - **After Inflation**, this coupling induces Higgs fluctuations, since inflaton oscillates. (i.e. preheating)



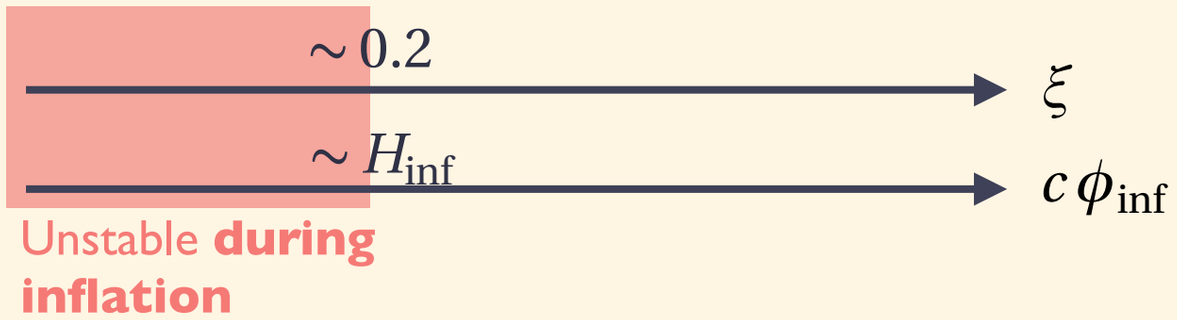
During inflation

- Curvature $\frac{1}{2}\xi R h^2$ → $12\xi H_{\rm inf}^2$
- Portal $\frac{1}{2}c^2\phi^2 h^2$ → $c^2\phi_{\rm inf}^2$

After inflation

$$\frac{\xi m_\phi^2 \Phi^2}{2M_{\rm Pl}^2}\left[3\cos(2m_\phi t)+1\right]$$

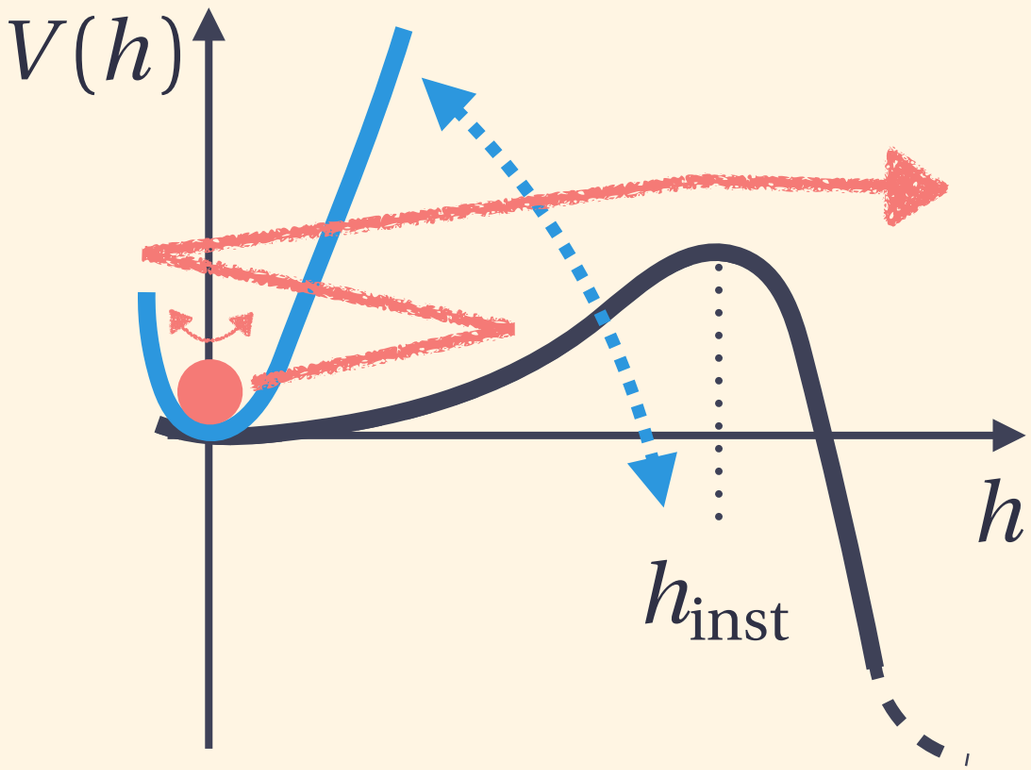
$$c^2\Phi^2\cos^2(m_\phi t)$$



Metastability v.s. Inflation

Higgs field **after** high-scale Inflation: $\mathbf{H_{inf} \gg h_{inst}}$

- $\mathbf{m_\Phi \gg h_{inst}}$: inflaton cannot change the running of λ below $\mathbf{m_\Phi}$.
  - "Tiny" Higgs-Inflaton coupling stabilizes it **during inflation.** [Westphal+; Espinosa+]
  - **After Inflation**, this coupling induces Higgs fluctuations, since inflaton oscillates. (i.e. preheating) Ema, **KM**, Nakayama; 1602.00483



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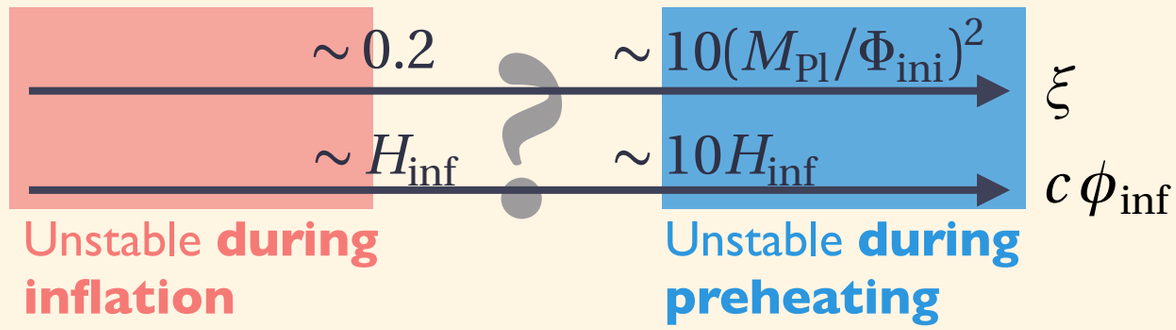
After inflation: $\frac{\xi m_\phi^2 \Phi^2}{2M_{\rm Pl}^2}\left[3\cos(2m_\phi t)+1\right]$, $c^2\Phi^2\cos^2(m_\phi t)$

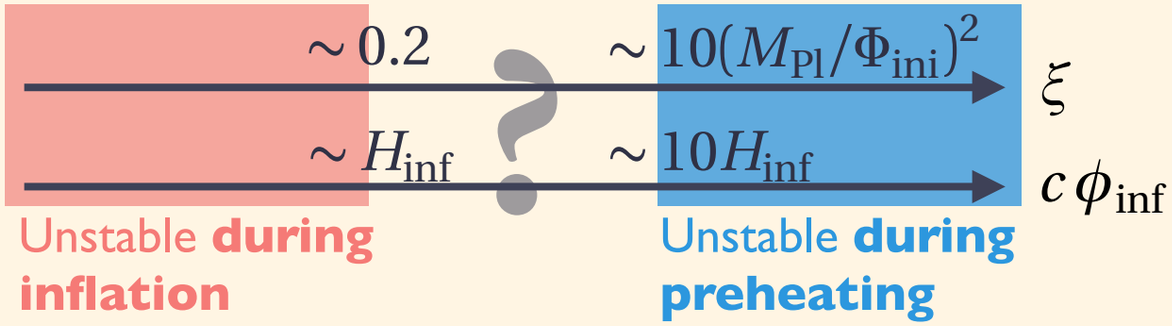


Summary & Questions

Metastability v.s. Inflation

for $\mathbf{H_{inf}} \gg \mathbf{h_{inst}}$

Ema, **KM**, Nakayama; 1602.00483
Kohri+; 1602.02100, Enqvist+; 1608.08848
Figueroa+; 1709.00398



Our bound is just a **necessary condition**.
Need to track thermalization to go one step further.

Constraints might be stronger because we have to impose stability on $\mathbf{e^{3N}}$ Hubble patches.

Manifestly gauge invariant treatment of vacuum decay in (non-)equilibrium environment…

EW vacuum decay in other cosmological environment is also interesting: e.g. **Black Holes**,…

KM, Yamada; 1706.04523

Primordial Black Holes

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Primordial Black Holes

Why Primordial Black Holes (PBHs)?

- **Non-particle** candidate of CDM
- Candidate of **gravitational wave events** observed by LIGO.
- Constrain **other** DM models; WIMP by UCMH, axion by super-radiance,…

How do you produce them?

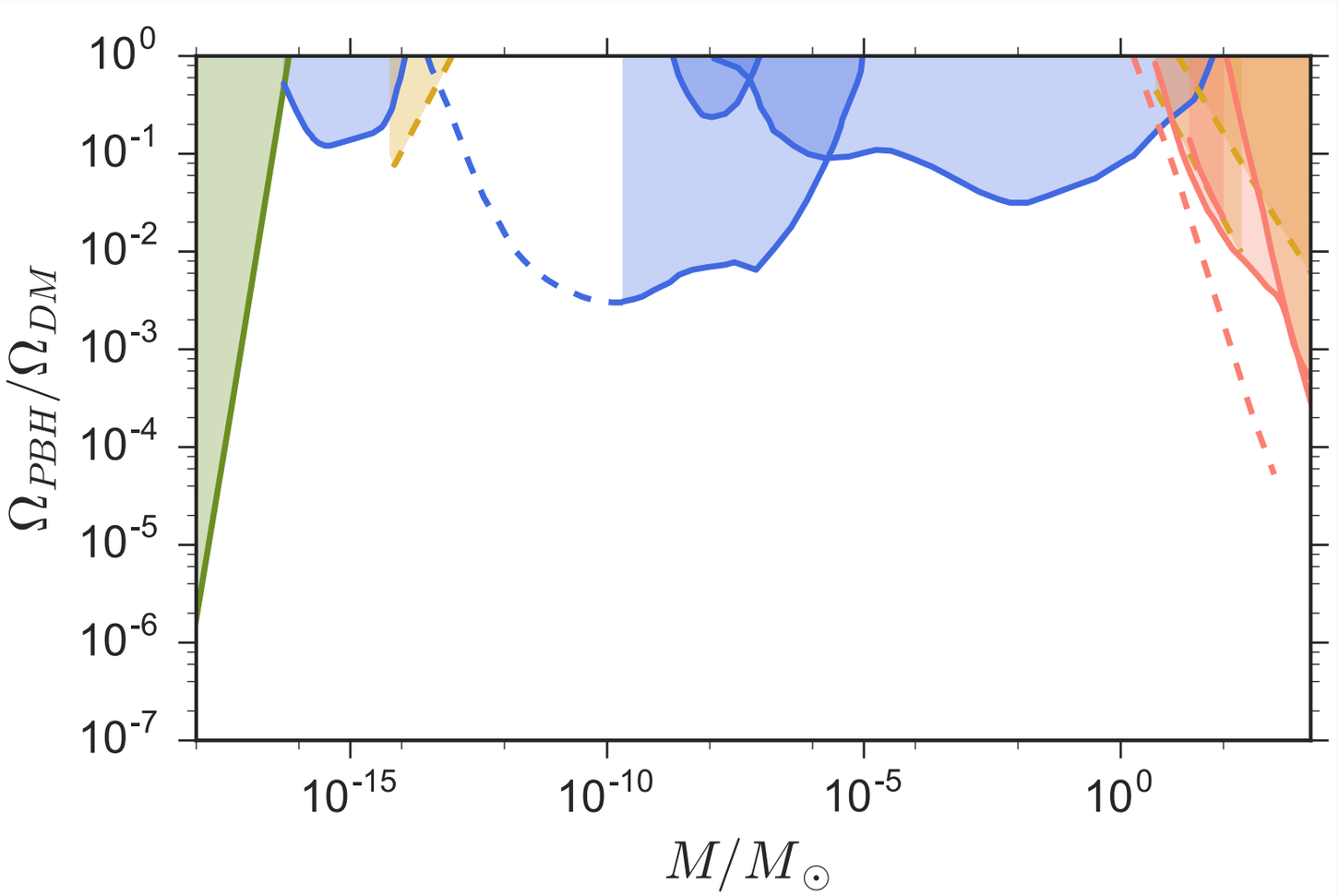
- Need **Large density perturbations** for **Gravity > Pressure**.
  - Collapse of localized configurations: bubble collision, cosmic string, Q-ball,…
  - Collapse of **primordial** density perturbations: **inflation**, curvaton,…

Leading candidate of PBH-production → **Inflation**

Current Constraints

Constraints **independent** of production mechanisms.

- PBH as **all DM**: marginal, but still viable.
- PBH for **LIGO events**: marginal, but still viable.



✤ Constraints from Neutron Star capture are evaded for a conservative value of DM inside the globular clusters. [See e.g. Kusenko+, 1310.8642; Carr+,1607.06077]

Hawking radiation

EGγ: 0912.5297

Gravitational lensing

Femto: 1204.2056

HSC: 1701.02151

Kepler: PhysRevLett.111.181302

EROS/MACHO/OGLE: 0011506, 0607207, 1106.2925

Dynamical

WD: 1505.04444

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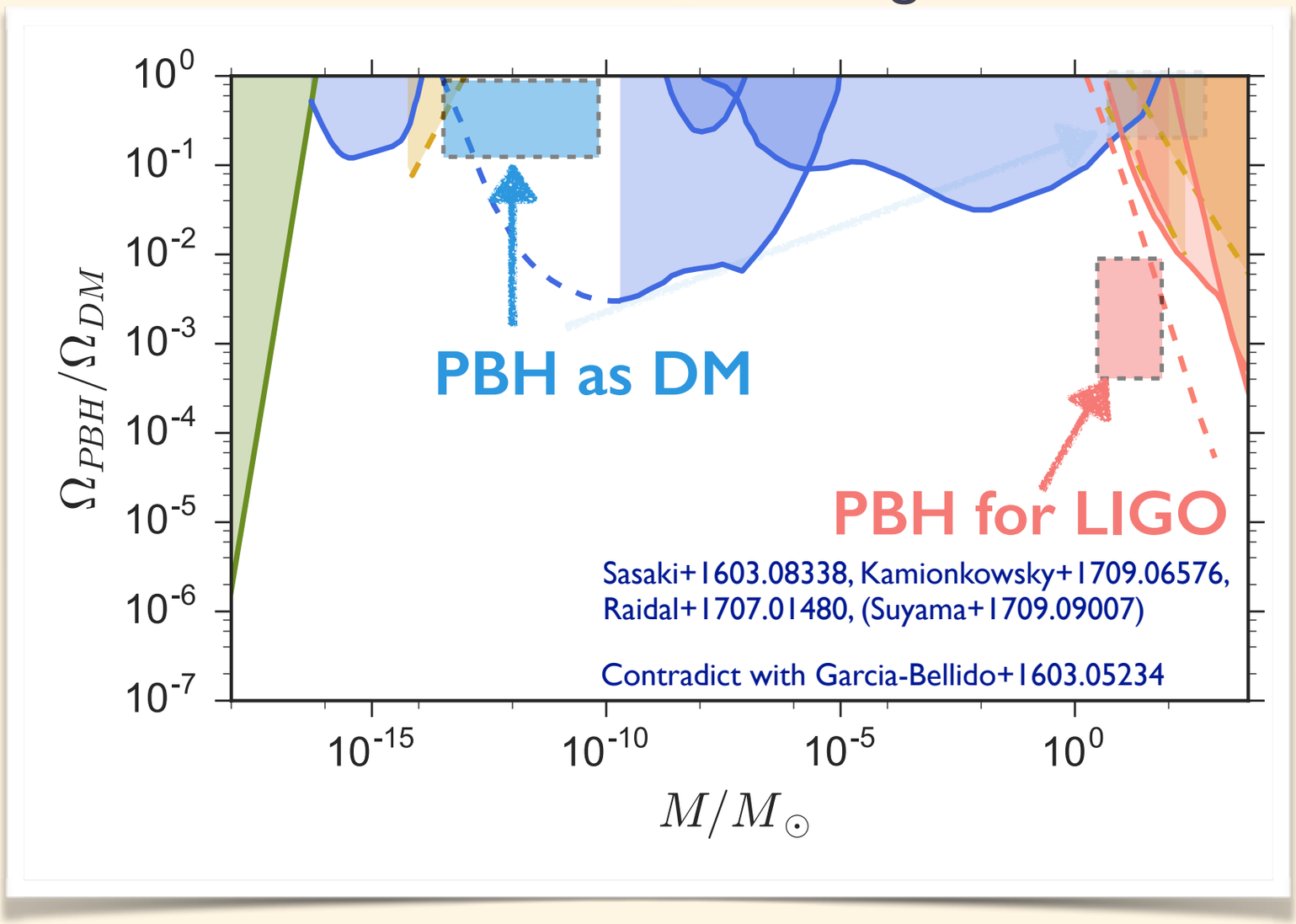

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- PBH as **all DM**: marginal, but still viable.
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Q.

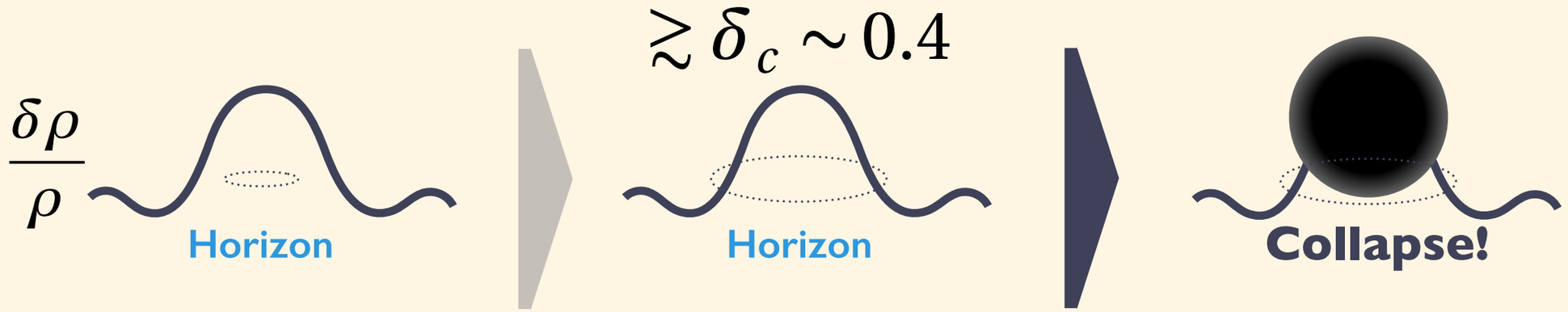
Assume a specific production mechanism (**inflation**).

Are there any other ways to probe them?

(Can we construct concrete inflation models? Yes.)

Formation of PBHs

Need **large δρ/ρ** for **Gravity > Pressure**

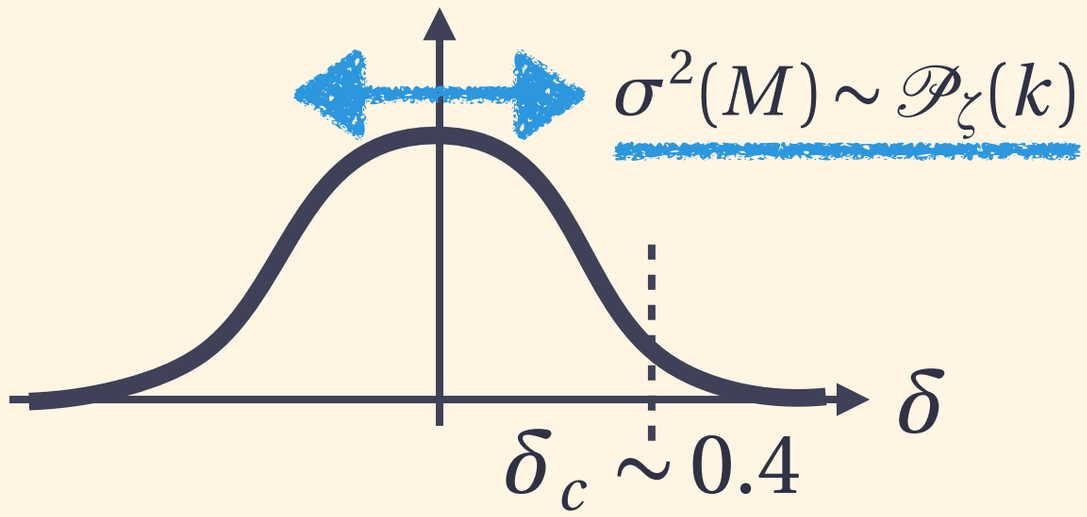


- PBH **mass** (**M**)
  ⇆ **scale** of perturbation (**k**)

$$M \simeq M_\odot \left(\frac{k}{2 \times 10^6\,\mathrm{Mpc}^{-1}} \right)^{-2}$$

- PBH **production rate** (**β**)
  ⇆ **amplitude** of perturbation (**Pζ**)

$$\beta(M) = \int_{\delta_c} \mathrm{d}\delta \frac{\mathrm{e}^{-\frac{\delta^2}{2\sigma^2(M)}}}{\sqrt{2\pi\sigma^2(M)}} \sim \sigma(M)\mathrm{e}^{-\frac{\delta_c^2}{2\sigma^2(M)}}$$



✤ Enhanced **non-Gaussianity** → same amount of PBHs w/ **smaller/larger** Pζ

Formation of PBHs

Typical probability we need

- 1% of DM w/ O(10) solarmass: $\beta \sim 10^{-10} \rightarrow P_\zeta \sim O(0.01) \gg P_{\zeta,\mathrm{CMB}}$

  $\beta \ll 1 \rightarrow$ PBHs

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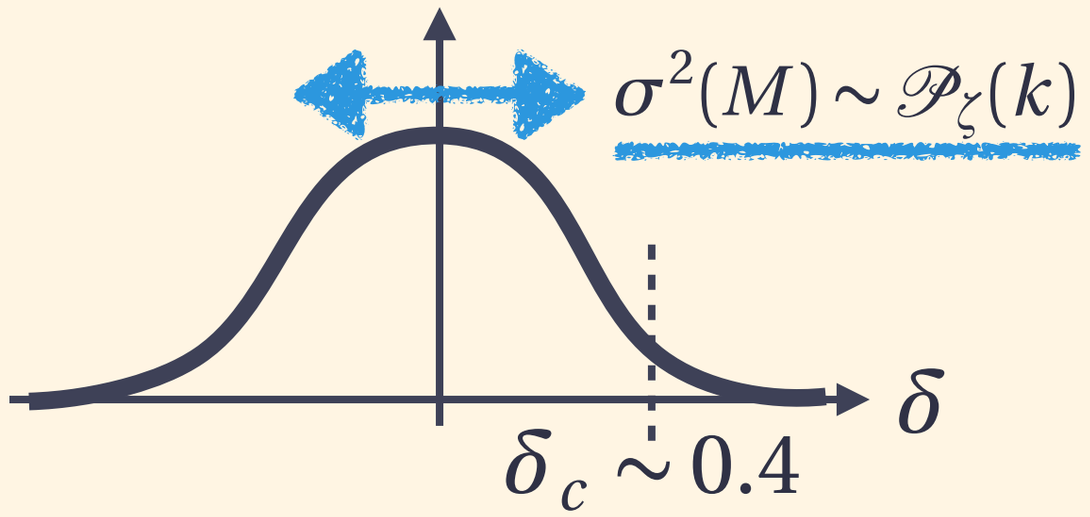

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  $1-\beta \rightarrow$ **plenty of** over-densities

  ➡ **explore** their footprints!

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⇆ **scale** of perturbation (**k**)

$$M \simeq M_\odot \left(\frac{k}{2 \times 10^6\,\mathrm{Mpc}^{-1}} \right)^{-2}$$

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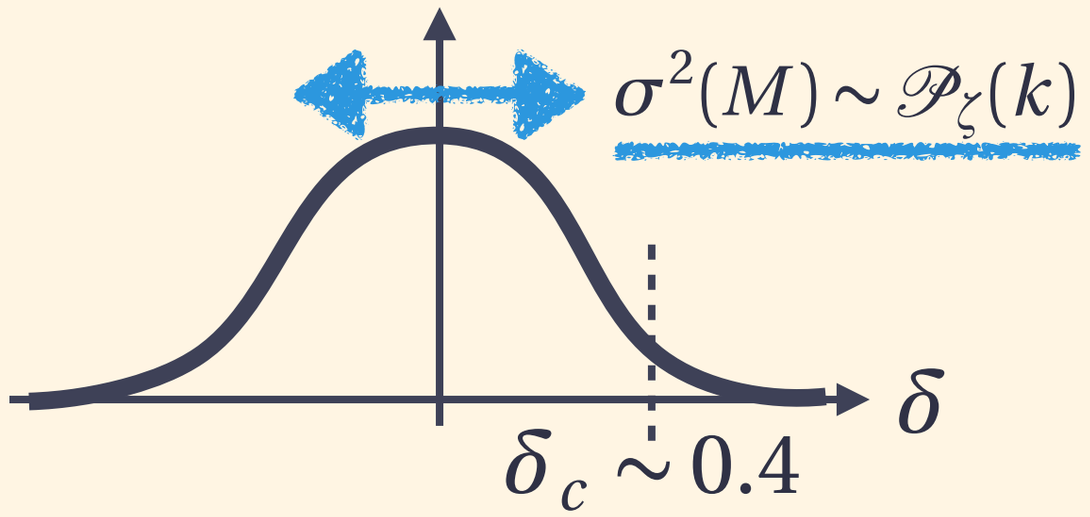


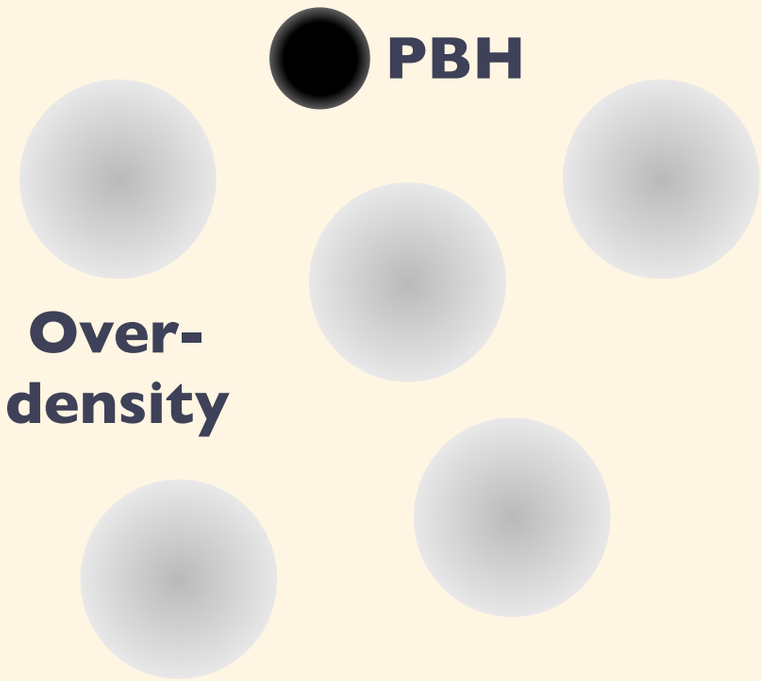
✤ Enhanced **non-Gaussianity** → same amount of PBHs w/ **smaller/larger** P_ζ

Probes of small-scale perturb.

Energy injection from over-densities.

- How do they affect? → **Depends on components and era.**

After reentry



Now

- via **GW** via 2nd order effects
- via **radiation**
  - ➡ CMB spectral distortion/ BBN
- via **CDM**
  - ➡ **UCMH**; depends on DM models

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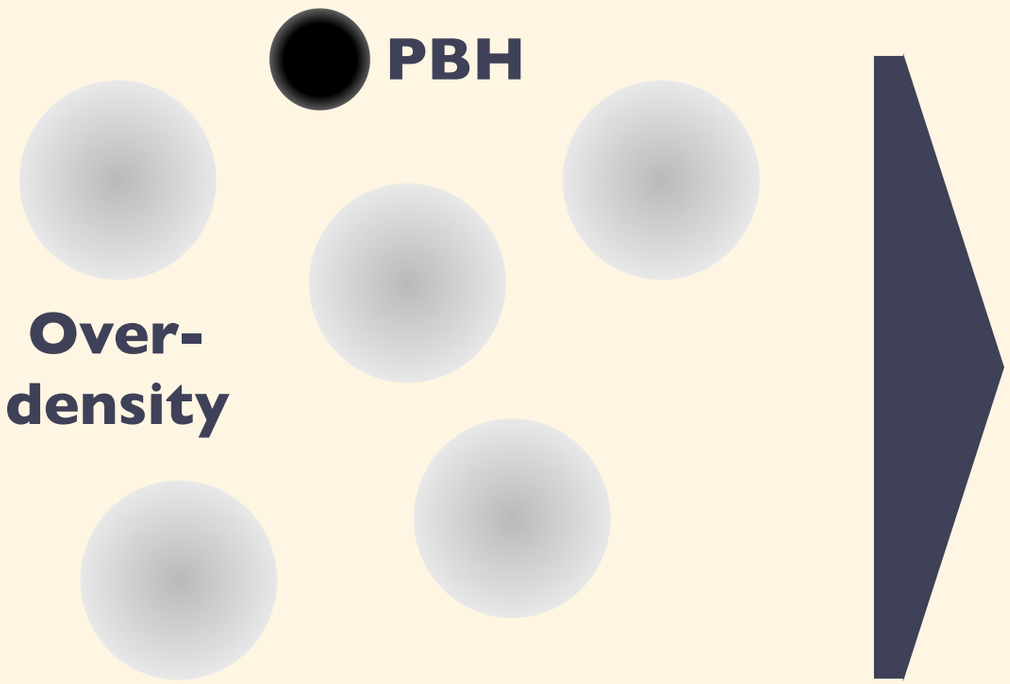

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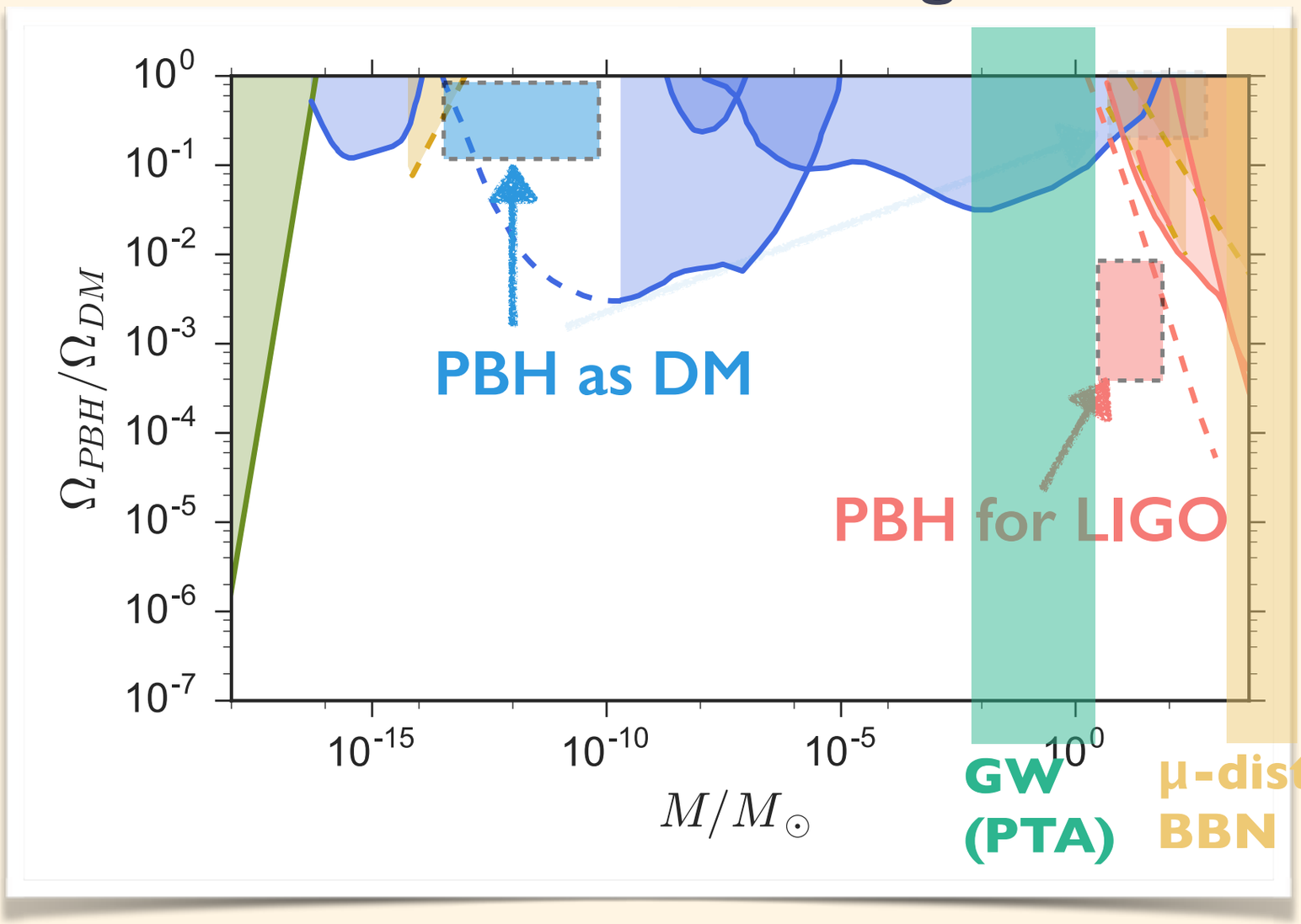
Current Constraints

Constraints on **PBHs from inflation** (*misleading)

- PBH as **all DM**: marginal, but still viable. Assume no enhanced **non-Gaussianity**.
  Nakama+1612.06264, 1710.06945
- PBH for **LIGO events**: **marginal**, but still **viable!**



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Summary & Questions

Inflation for PBHs needs **LARGE $P_\zeta(k) \sim 10^{-2}$**.

Footprints of **many** over-densities generated per one PBH:

- **CMB spectral distortion** @ 10^{4}–1 Mpc^{-1}; **BBN** @ 10^{5}-10^{4} Mpc^{-1}
- **Induced GWs**: PTA @ ~10^{6} Mpc^{-1}; eLISA @ 10^{11}-$10^{13}$$Mpc^{-1}$
- **UCMHs**…depends on DM models; but could be stringent.

PBHs for LIGO → need a sharp peak@ **$k \sim 10^{-2}$** Mpc^{-1}

Inomata, Kawasaki, **KM**, Tada, Yanagida; 1611.06130

PBHs for DM → could be broad. eLISA can probe them.

Inomata, Kawasaki, **KM**, Yanagida; 1711.06129

Concrete models for the large **non-Gaussianity**.

Models naturally predict the desired mass of PBHs.

Can we close the remaining window? (**10^{19} - 10^{23}g**)

Backup

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Metastability v.s. Inflation

Curvature coupling: $\xi R h^2$

Ema, **KM**, Nakayama; 1602.00483

- Perform classical lattice simulations to check our analytic estimation.

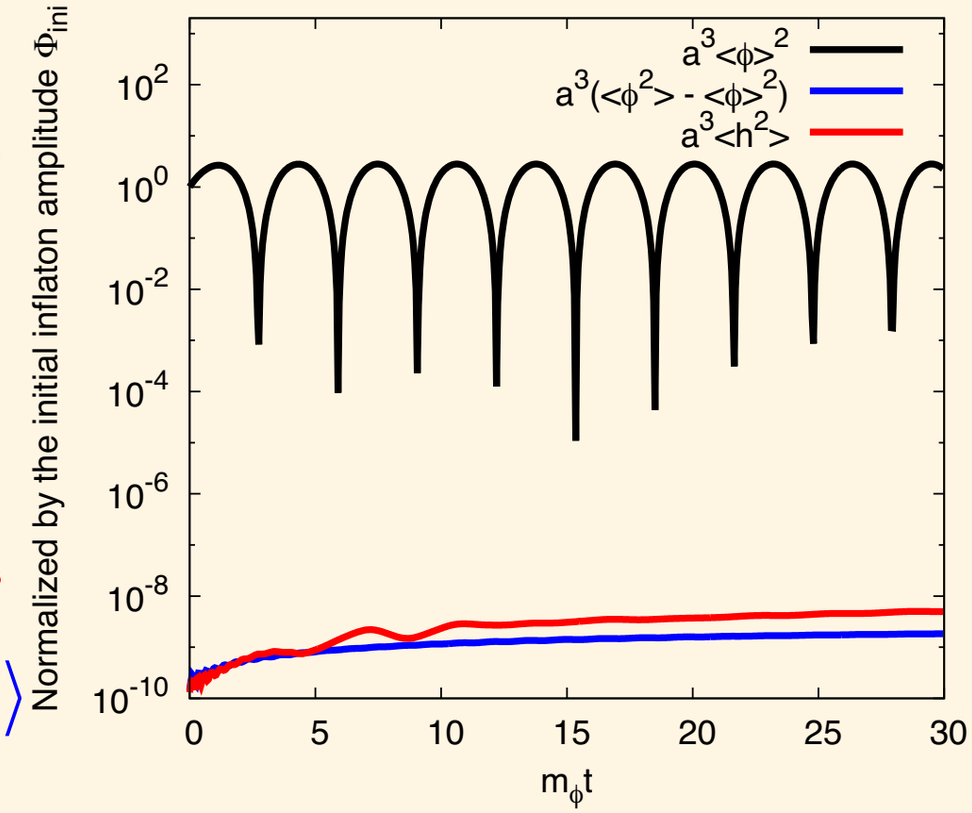
$\xi = 10$

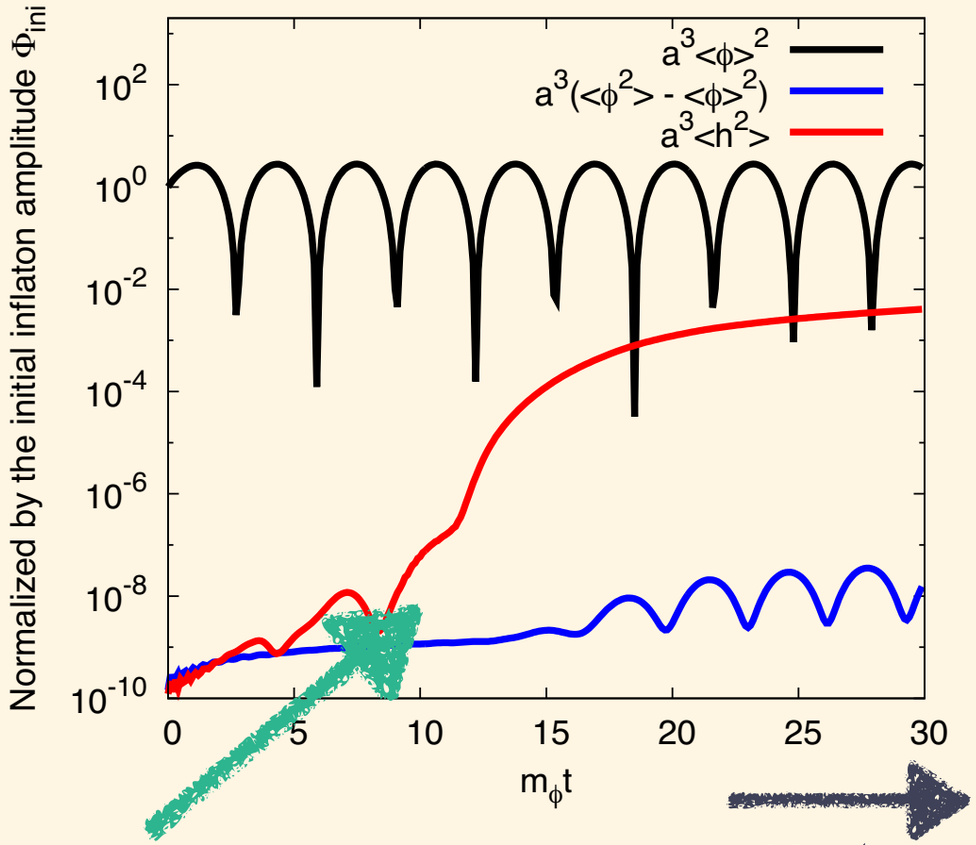
$\xi = 20$

$a^3\langle\phi\rangle^2$

$a^3\langle h^2\rangle$

$a^3\langle\delta\phi^2\rangle$





EW Vacuum Decay within few oscillations

Add a **h^6 term** for convergence of numerical computations.

Metastability v.s. Inflation

Ema, **KM**, Nakayama; 1602.00483

For the **quartic** coupling: $\mathbf{c^2\Phi^2h^2}$,…

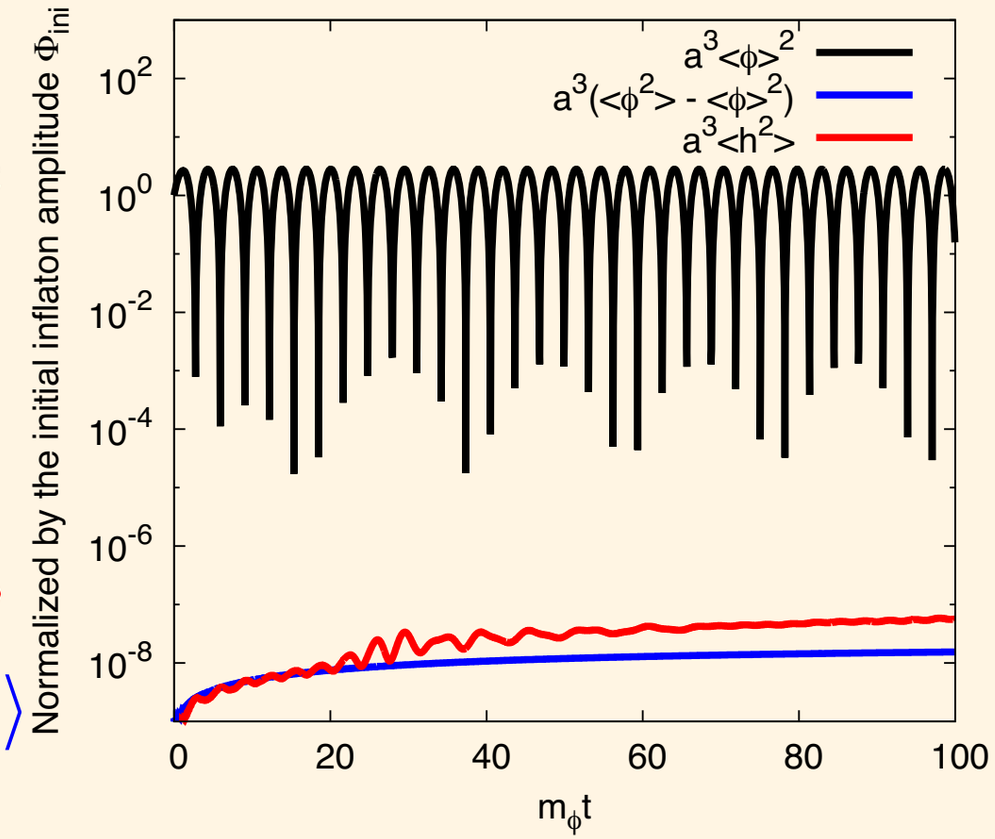
- Perform classical lattice simulations to check our analytic estimation.

$c = 1 \times 10^{-4}$

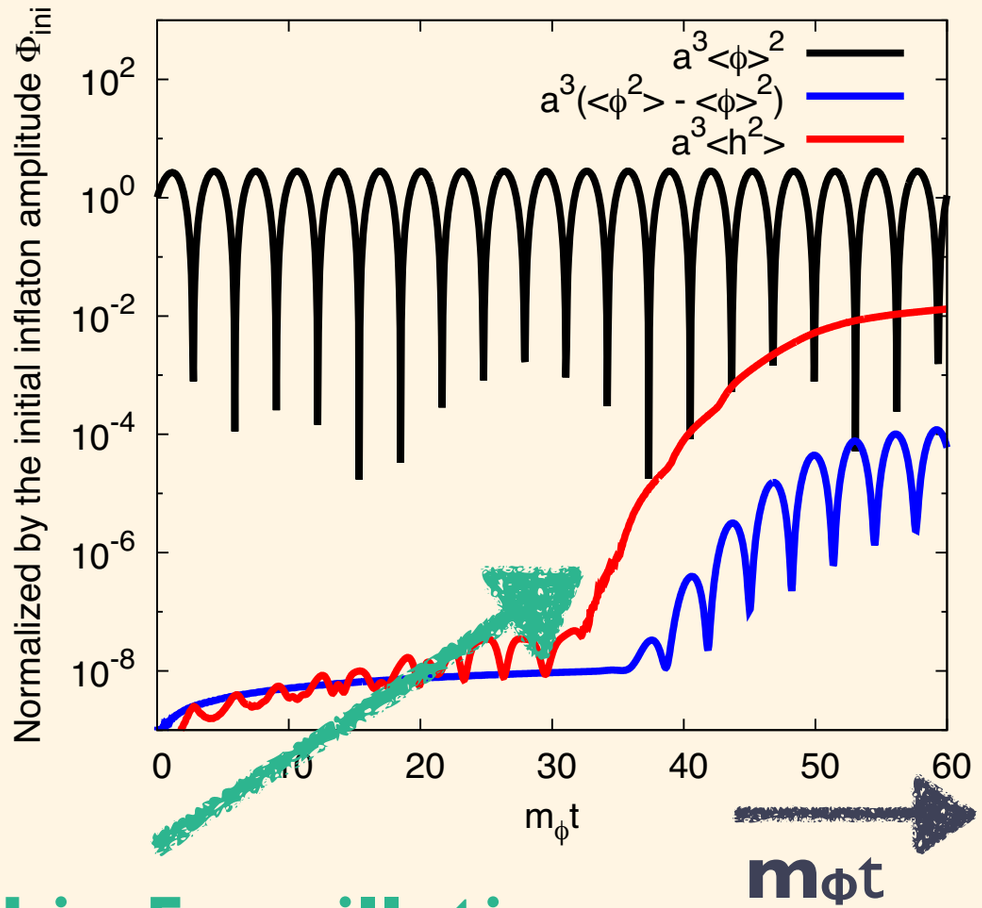
$a^3\langle\phi\rangle^2$

$a^3\langle h^2\rangle$

$a^3\langle\delta\phi^2\rangle$



$c = 2 \times 10^{-4}$



EW Vacuum Decay within 5 oscillations

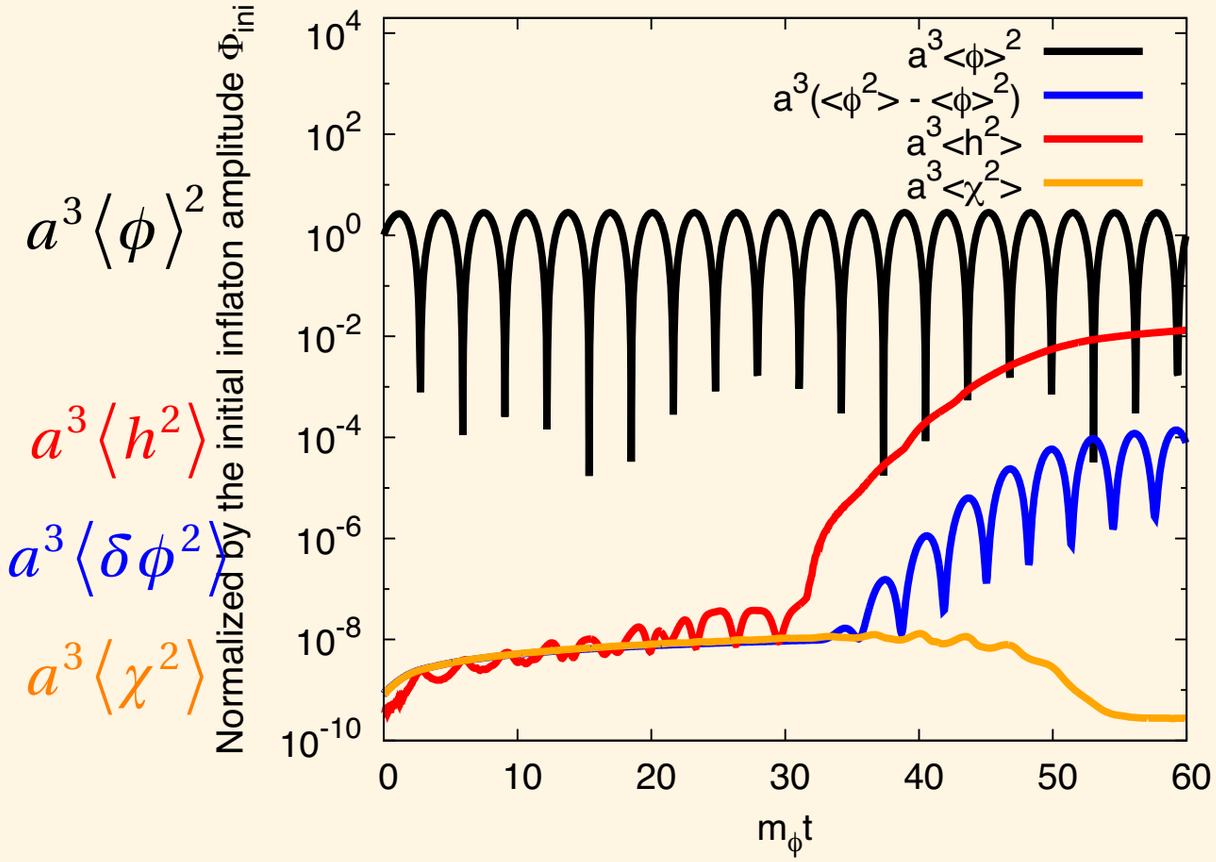
Add a **h^6 term** for convergence of numerical computations.

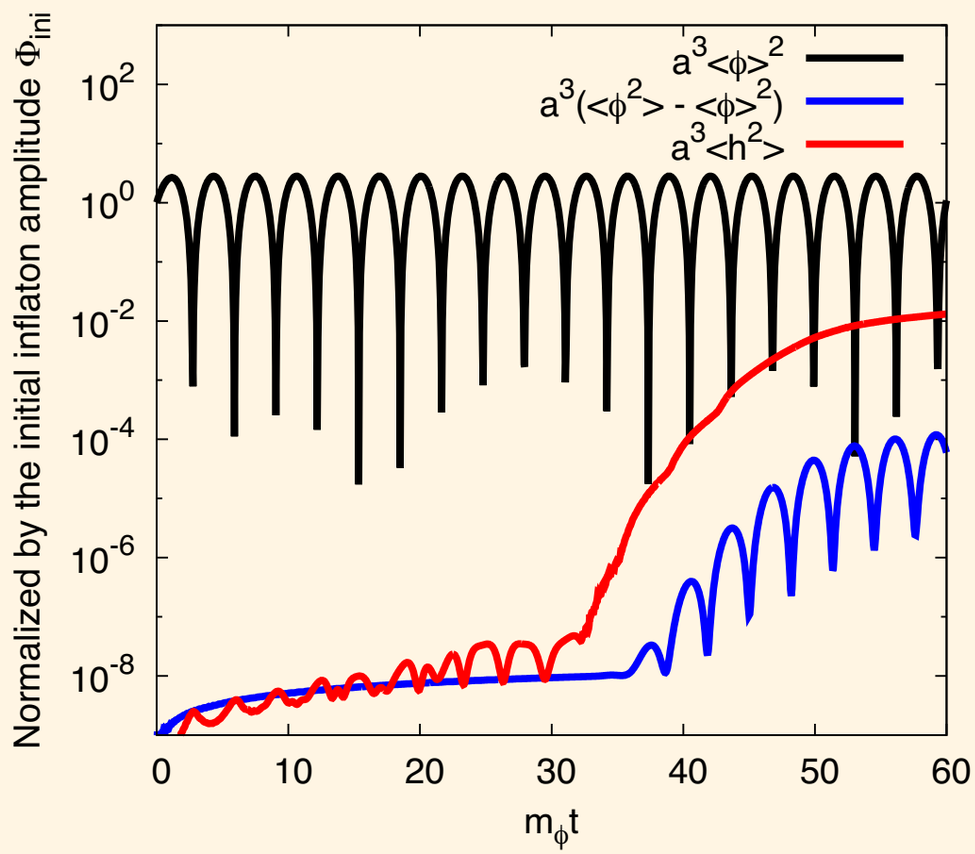
Production of EW gauges

To mimic **hh → ww, zz**, consider a toy model.

$$\mathscr{L}_{\rm int} = -\frac{1}{2} g_{h\chi}^2 h^2 \chi^2 - \frac{g_\chi^4}{4} \chi^4$$

Quartic $c = 2 \times 10^{-4}$





$$g_{h\chi} = g_\chi = 0.5$$

Ema, **KM**, Nakayama; 1602.00483
Figueroa+; 1709.00398

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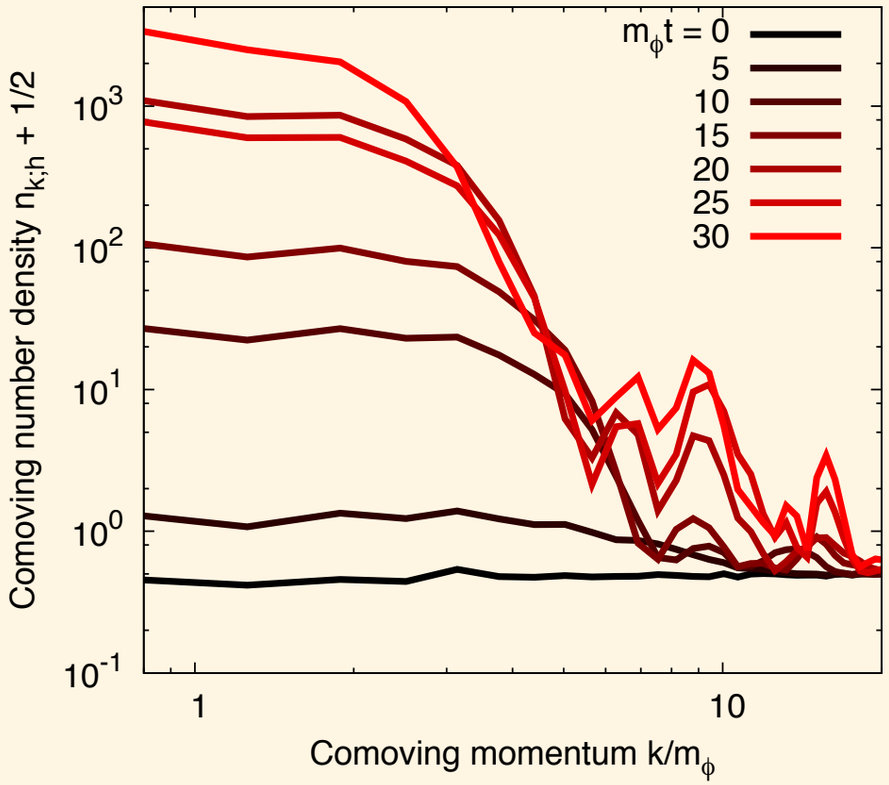
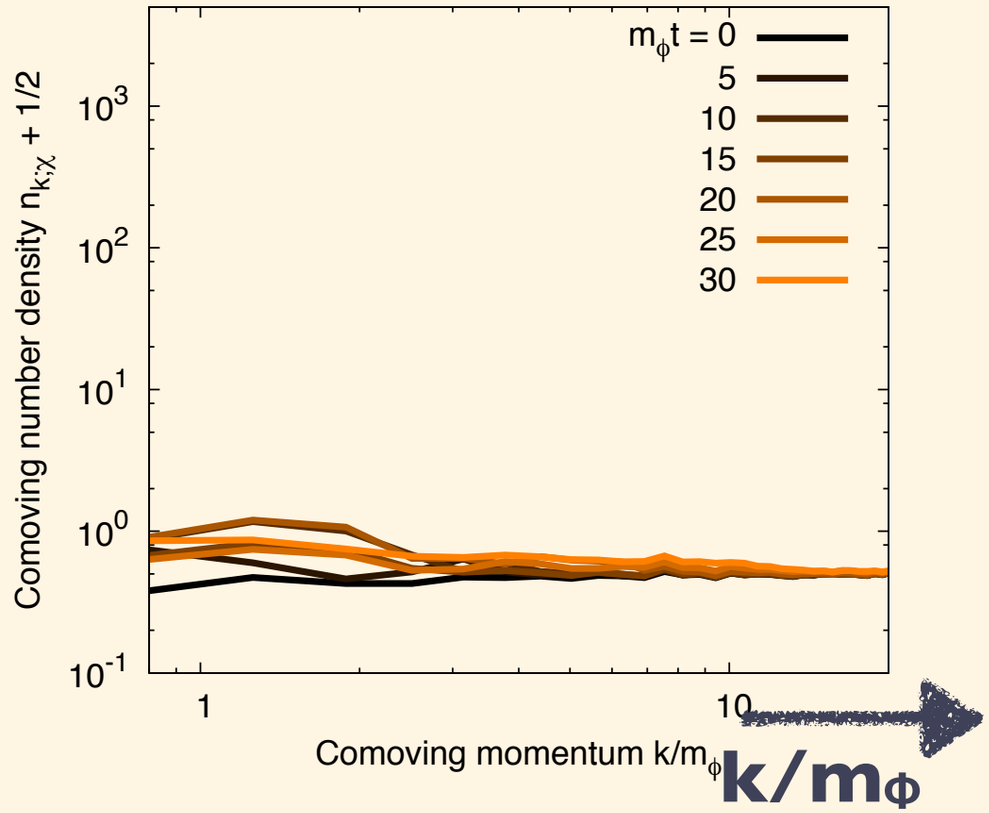
χ-production is not efficient!

Higgs #



χ #



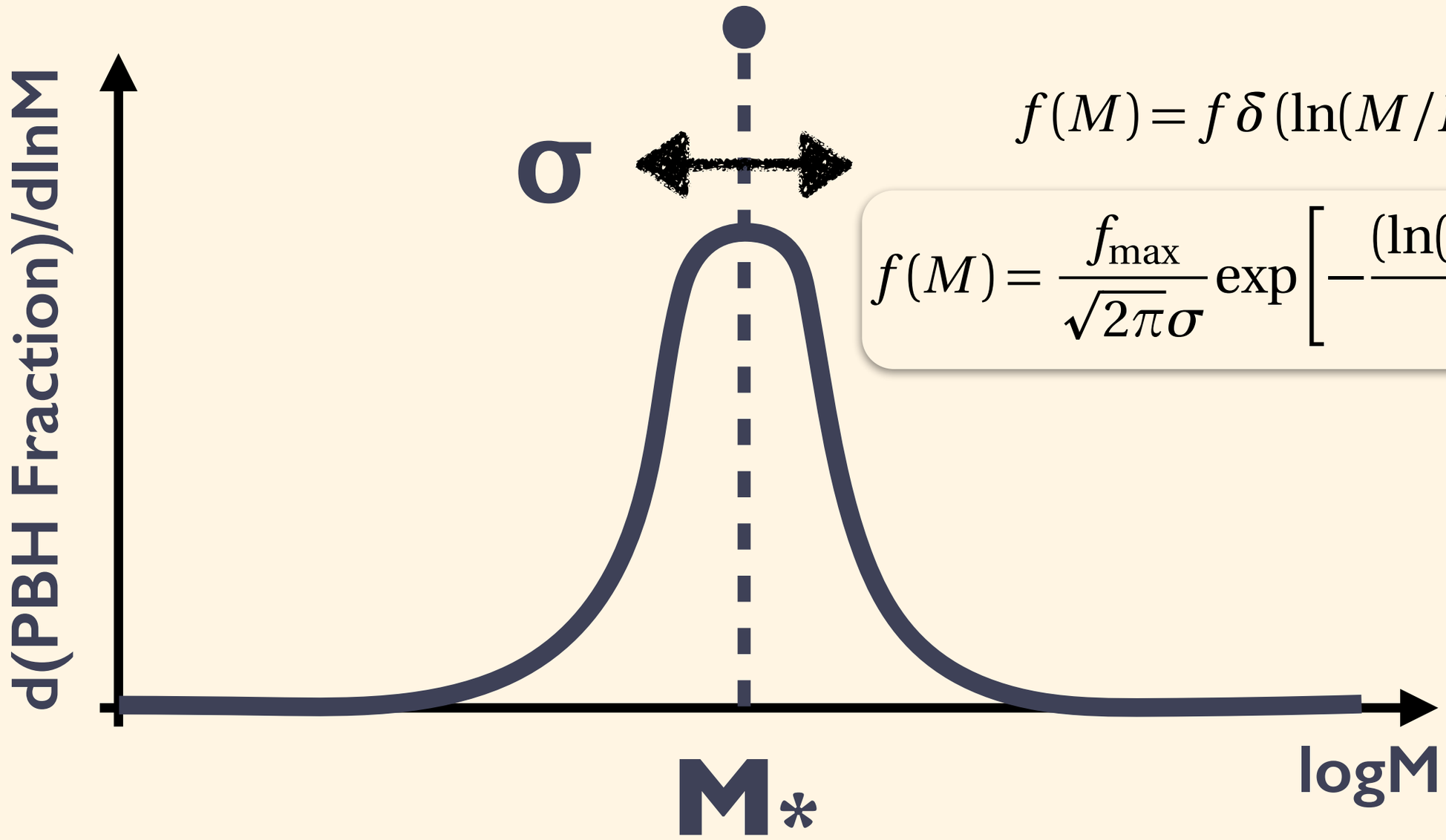
$$g_{h\chi} = g_\chi = 0.5$$

Ema, **KM**, Nakayama; 1602.00483
Figueroa+; 1709.00398

Current Constraints

Constraints **independent** of production mechanisms.

- Note: a **delta function** for PBH spectrum is assumed.



$$f(M) = f\,\delta(\ln(M/M_*))$$

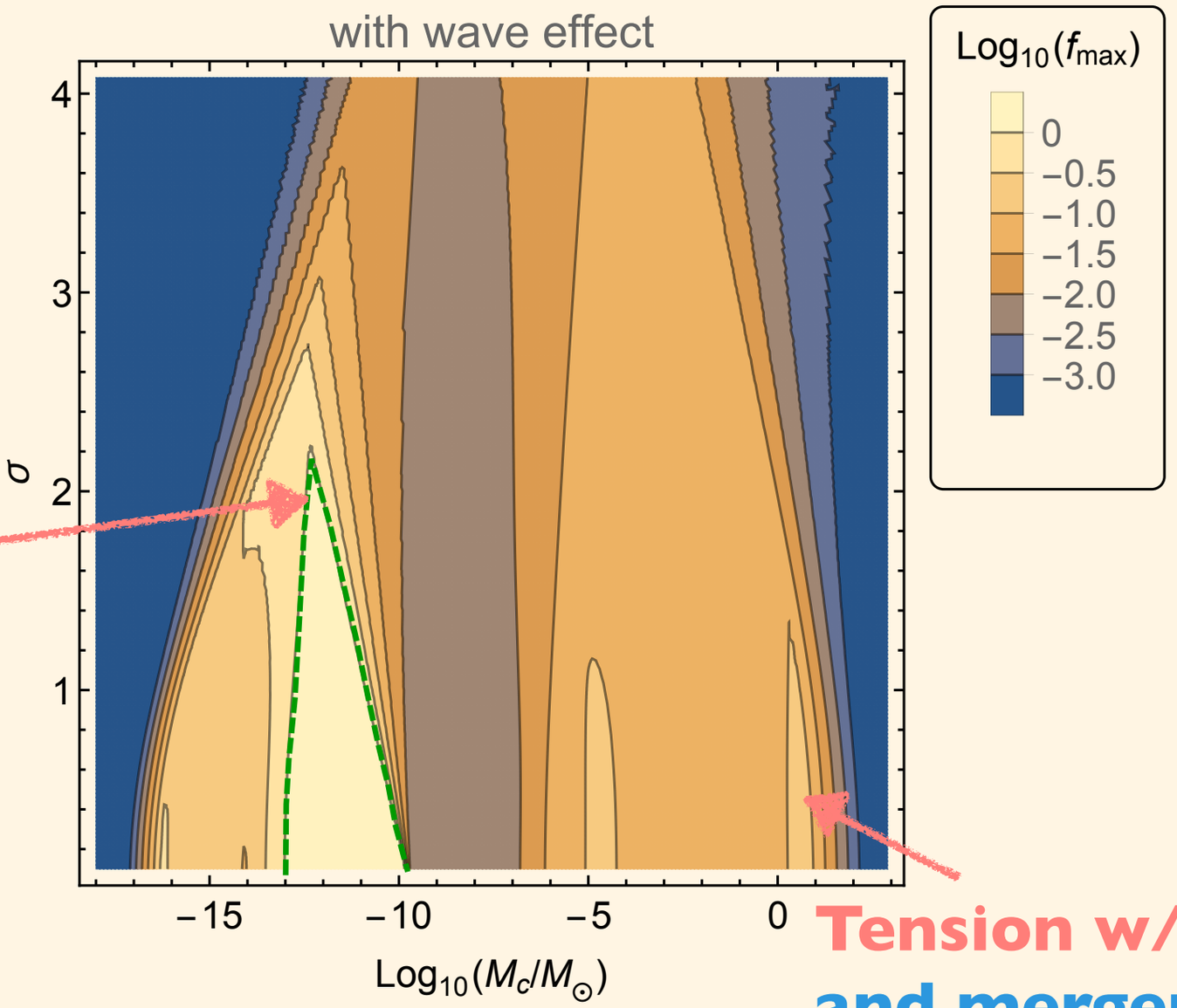
$$f(M) = \frac{f_{\max}}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(\ln(M/M_*))^2}{2\sigma^2}\right]$$

Current Constraints

Constraints **independent** of production mechanisms.

- Constraints on **extended** mass function.

[**KM+, 1701.02544**; Kuhnel+, 1701.07223; Carr+, 1705.05567;…]



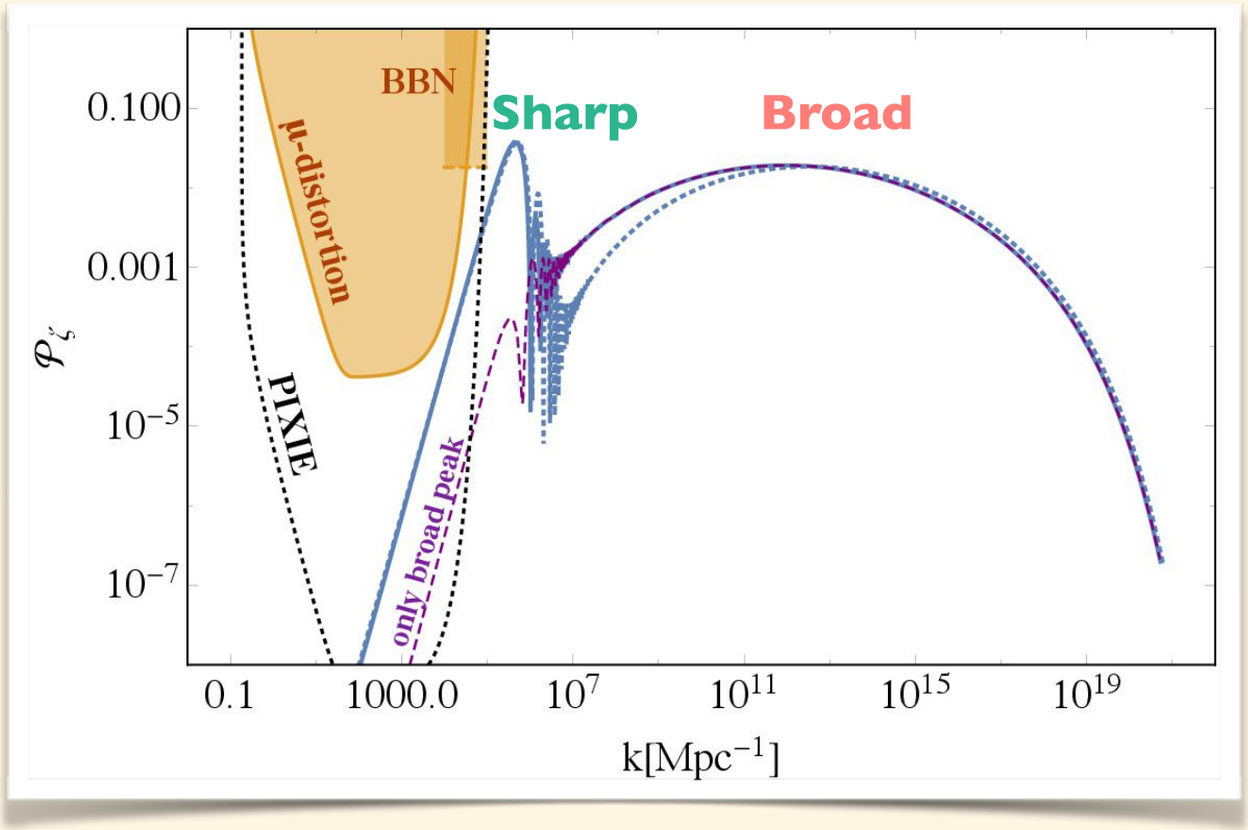
Large σ is allowed

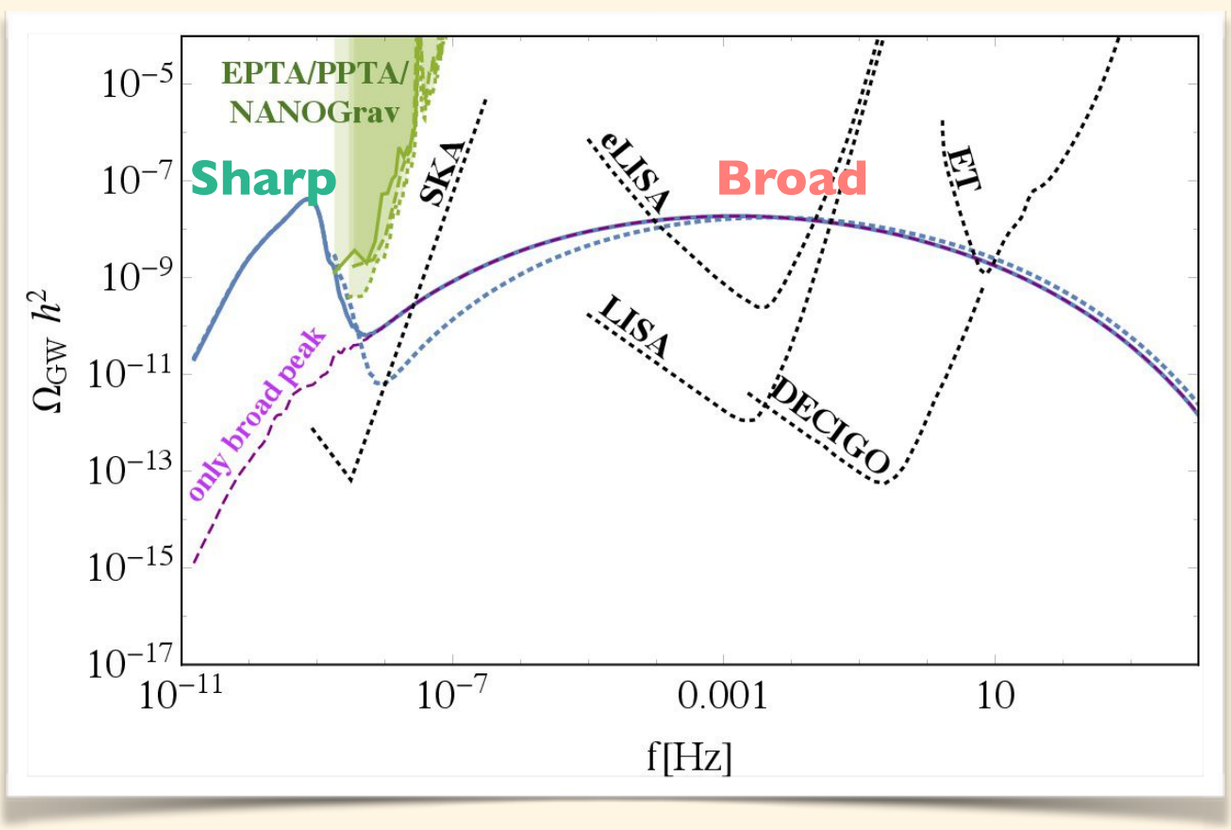
Tension w/ radio/X-ray and merger rate by LIGO

Double Inflation

PBHs for LIGO or DM from **Double Inflation**

- Total e-folds (N=50-60) = **1st-inflation** + **2nd inflation**





- PBHs for LIGO → **SKA** and future CMB observation.
- PBHs for DM → **eLISA** and LISA.

Double Inflation

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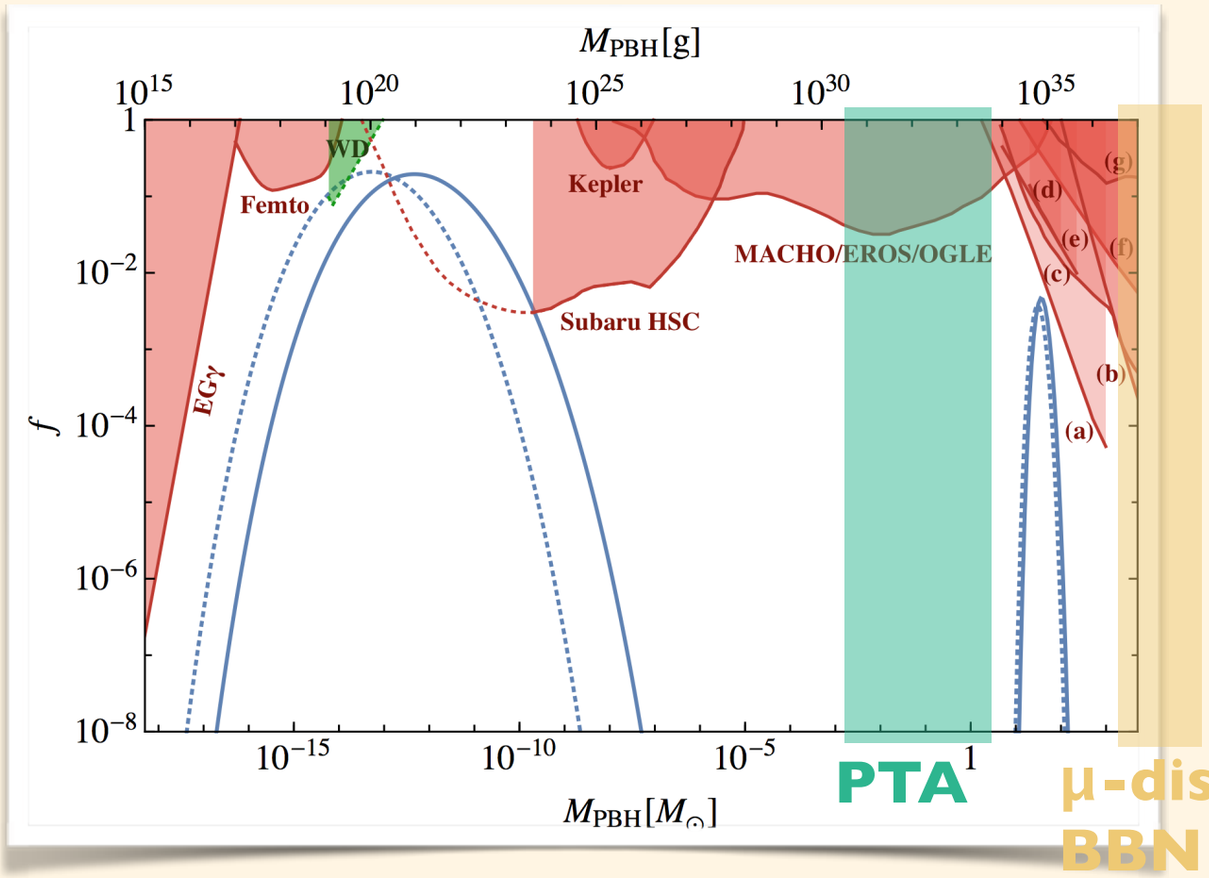

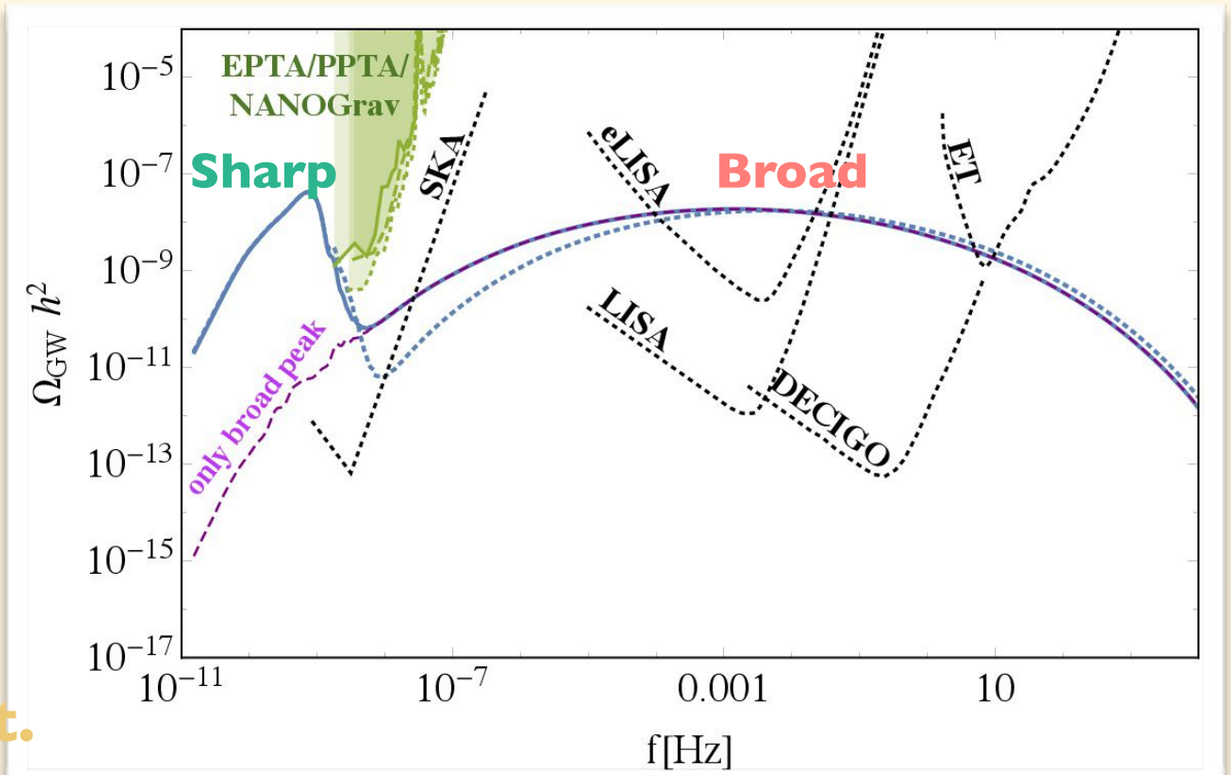

- PBHs for LIGO → **SKA** and future CMB observation.
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