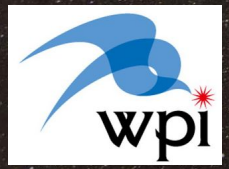
Primordial Black Holes from Scalar Fields

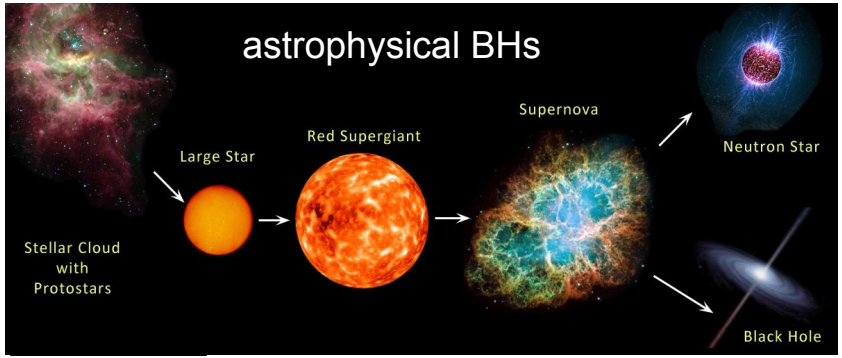
and Their Novel Manifestations

Volodymyr Takhistov

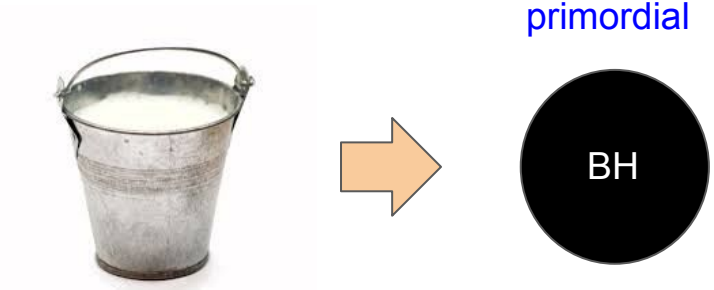
QUP & Theory Center, KEK & Kavli IPMU, U. Tokyo



Primordial Black Holes (PBHs)



In early Universe, just roughly take scoop of ~ 50% overdensity to make BH



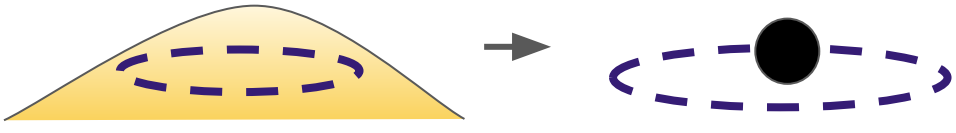
PBHs as dark matter

… a ***"Standard Model"*** candidate

→ *readily appear in theories of new physics*

“Standard” PBH Formation

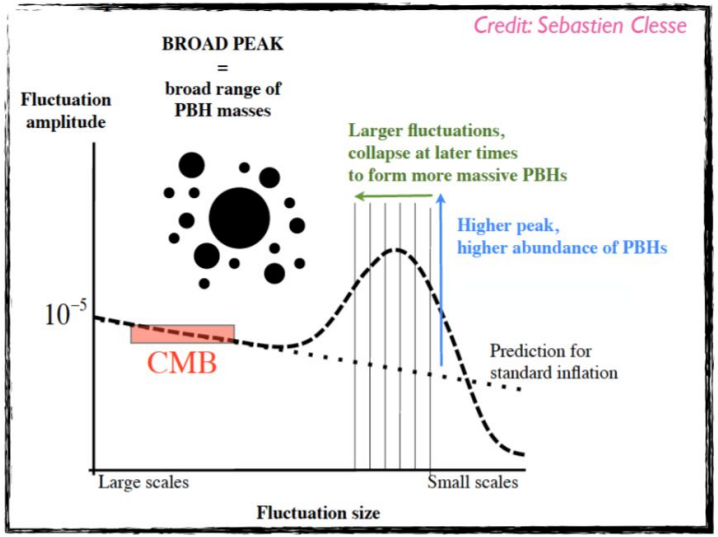
- Big perturbations ($\delta \sim 1$) enter horizon → collapse [Carr, Kawasaki, Sasaki, Riotto…many….]



$$M_H \approx \frac{c^3 t}{G} = 10^{15}\,\mathrm{g}\left(\frac{t}{10^{-23}\,\mathrm{s}}\right)$$

- Need to tune inflaton potential
  → sensitive to restrictions on scalar fields
  - Example: “string swampland conjectures”
    [Kawasaki, **VT,** *PRD*, (2018) 1810.02547]

…alternatives with interesting features?



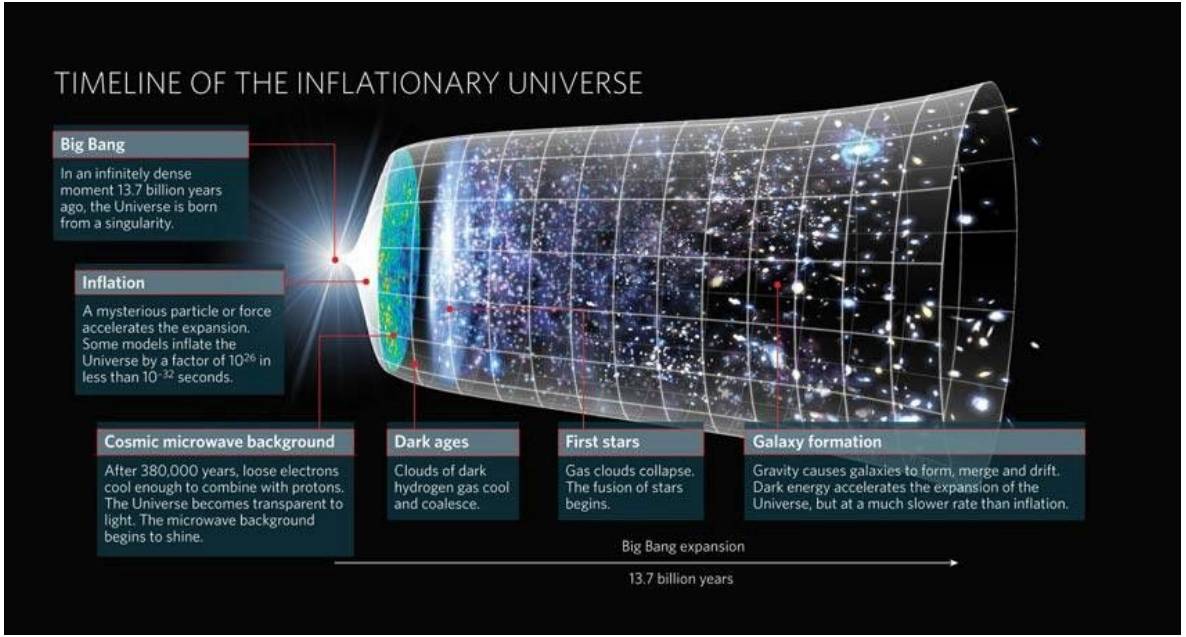
Scalar Fields Principal in Early Universe

- Scalars exist
  Soon celebrate 11th birthday of Higgs boson (July 2022)

- Inflaton drives rapid early expansion, resolving Big Bang problems

- Scalars expected ubiquitous from fundamental theory

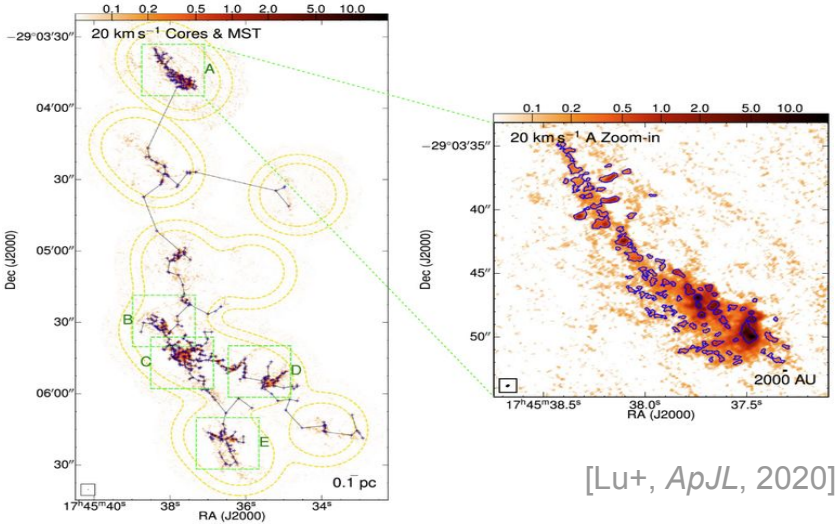
…what can they teach us about PBHs and vice versa?



Marvelous Manifestations of Scalar Fields

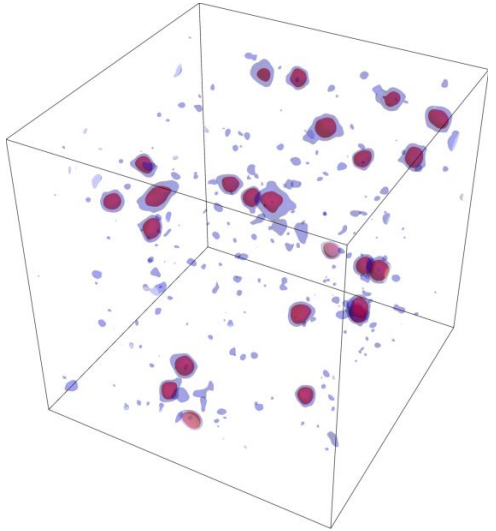
In early Universe, attractively self-interacting scalar fields can fragment into solitonic “lumps”

Jeans fragmentation analogy
(massive molecular Galactic Center clouds)



[Lu+, *ApJL*, 2020]

oscillon fragmentation
(string moduli fields)

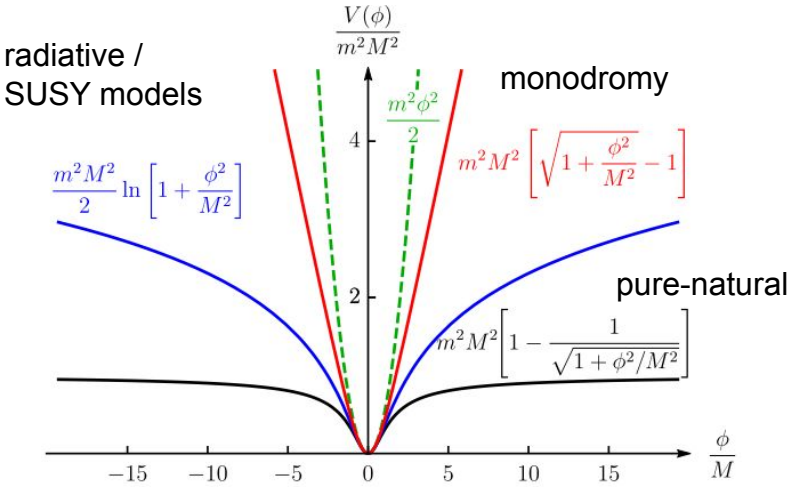


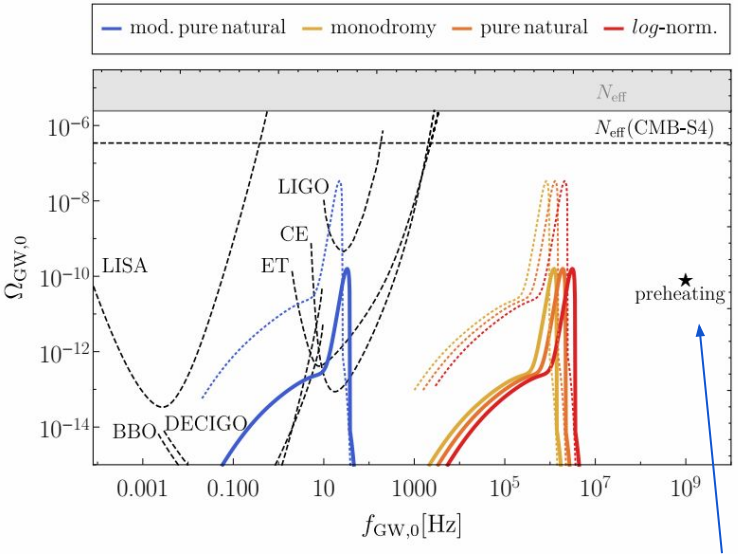
[Antusch+, 2017]

Marvelous Manifestations of Scalar Fields

In many theories inflaton can break to oscillons → decays result in dramatically enhanced GWs

→ **new route to probe inflationary physics independent of CMB !**



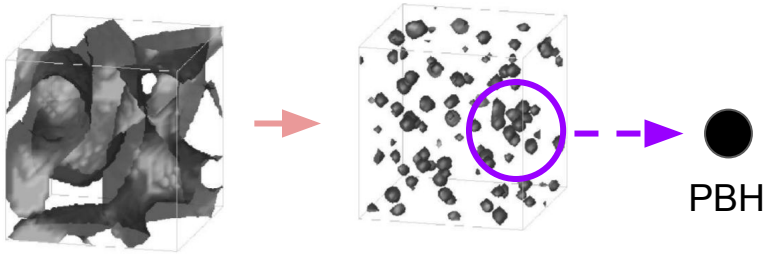


[Lozanov, **VT**, *Phys.Rev.Lett.*, (2023) 2204.07152]

~ Old GW results

Distinct PBH Features Possible

scalar fragmentation

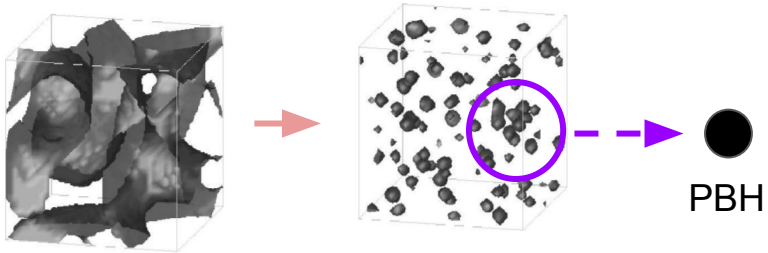


PBHs peaked in mass
+ big spin possible

inflaton oscillons
[Cotner, Kusenko, **VT**, *PRD*, (2018) 1801.03321;
Cotner, Kusenko, Sasaki, **VT**, *JCAP*, (2019) 1907.10613]

Distinct PBH Features Possible

scalar fragmentation

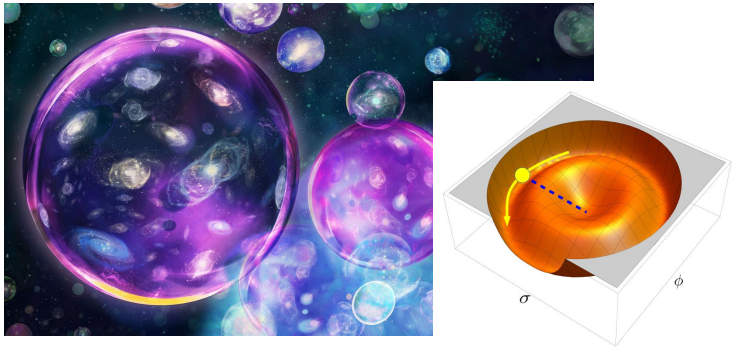


PBHs peaked in mass + big spin possible

inflaton oscillons

[Cotner, Kusenko, **VT**, *PRD*, (2018) 1801.03321;
Cotner, Kusenko, Sasaki, **VT,** *JCAP*, (2019) 1907.10613]

vacuum bubble "multiverse" in multi-field theories

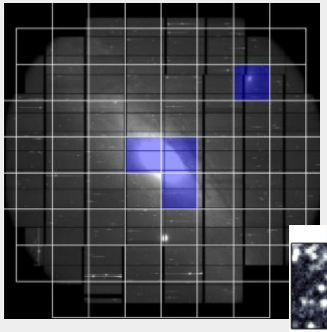


PBHs broadly distributed in mass

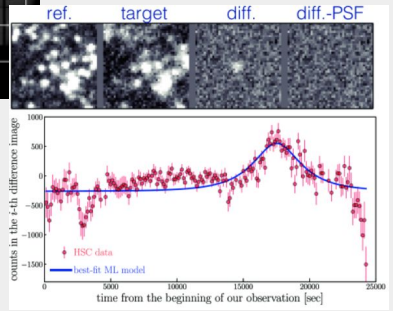
see also [Deng, Vilenkin, Sasaki…]

[Kusenko, Sasaki, Sugiyama, Takada, **VT,**
Vitagliano, *Phys.Rev.Lett.*, (2020) 2001.09160]

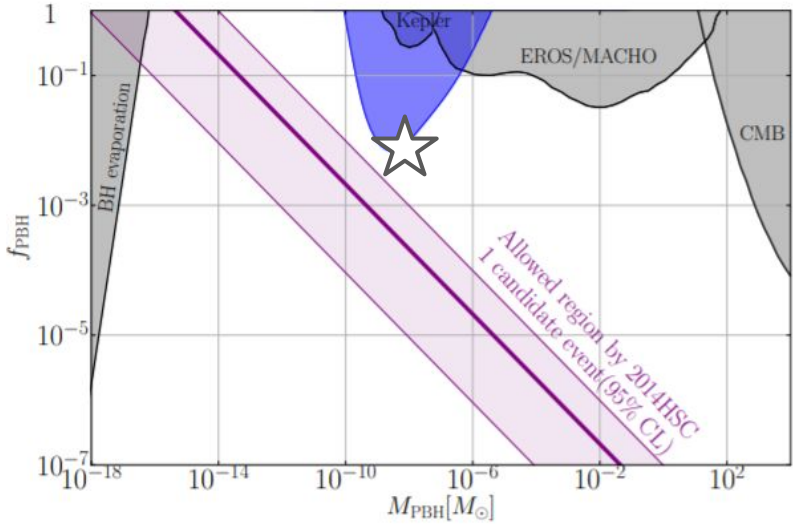
PBH DM from Bubble Multiverse: Detected by HSC ?!



Subaru (HSC)
Hyper-Suprime Cam
Andromeda
microlensing
event



[Niikura+, *Nature Astron.*, 2019]



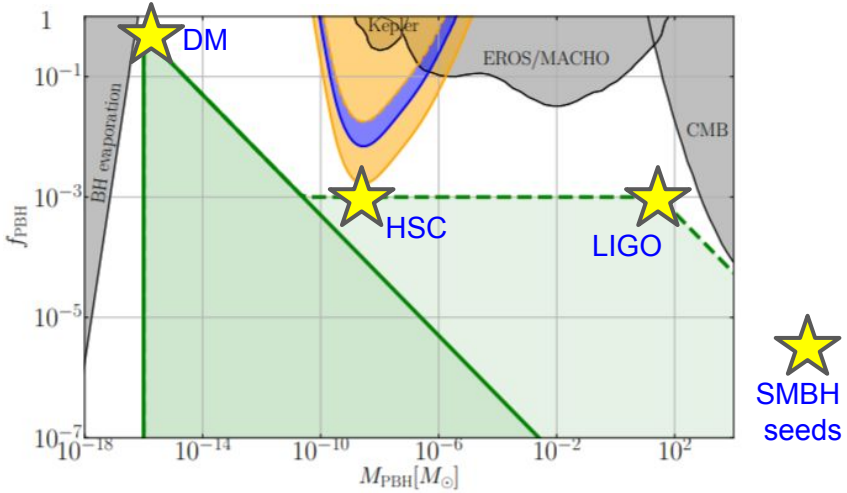
- **PBH DM from bubble multiverse consistent with detected HSC event !**

  → *tail of broad PBH distribution allows for indirect test of open DM window*

[Kusenko, Sasaki, Sugiyama, Takada, **VT,** Vitagliano, *Phys.Rev.Lett.*, (2020) 2001.09160]

PBH DM from Bubble Multiverse: Detected by HSC ?!

- Generalized model explains many observables simultaneously (DM, LIGO, SMBH seeds…)



- **Will be <u>definitively</u> tested with upcoming HSC data**

[Kusenko, Sasaki, Sugiyama, Takada, **VT,** Vitagliano, *Phys.Rev.Lett.*, (2020) 2001.09160]

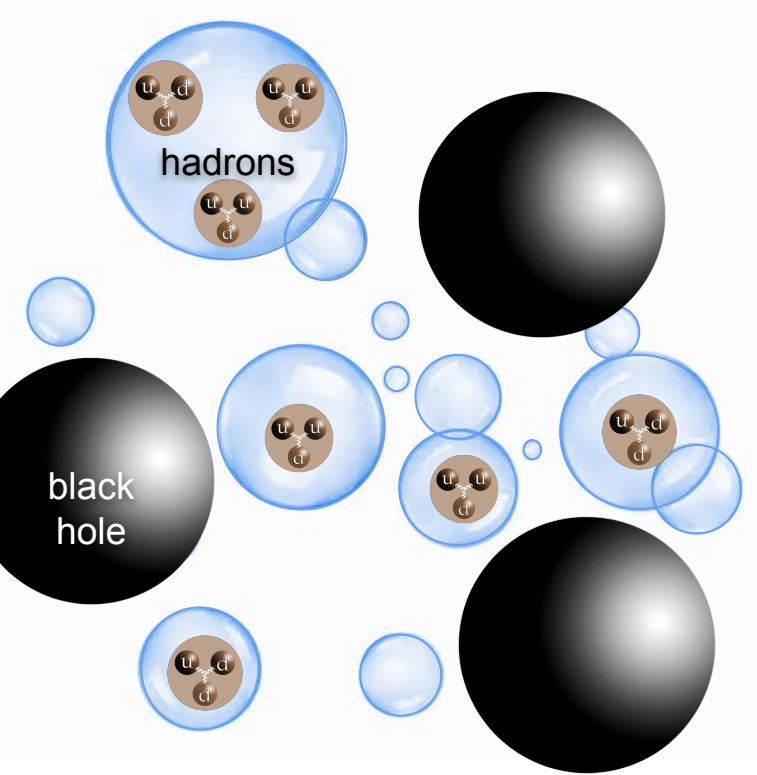
PBHs as Unique Probes of Fundamental Physics

- Scalars can also readily lead to new fundamental dynamics, such as high-T QCD phase transition
  [Ipek, Tait, PRL, 2018]

$$\mathcal{L} \supset -\frac{1}{4}\left(\frac{1}{g_{s0}^2}+\frac{S}{M}\right)G^a_{\mu\nu}G^{\mu\nu}_a+\dots$$

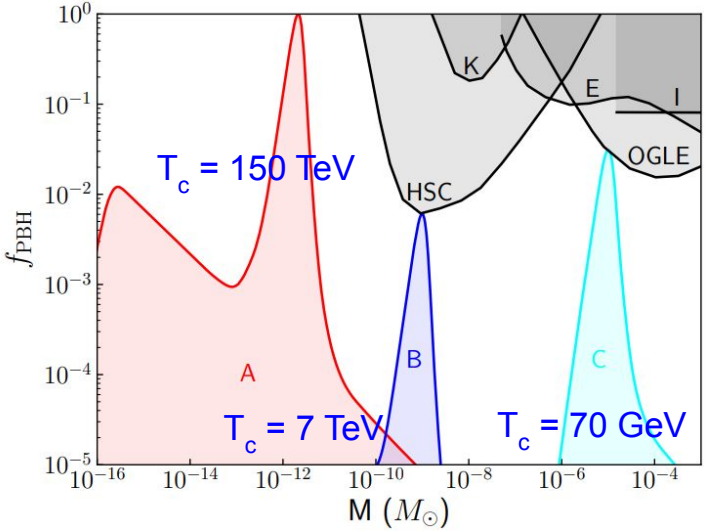
- Extreme early Universe conditions set unique laboratory to test unexplored QCD regimes

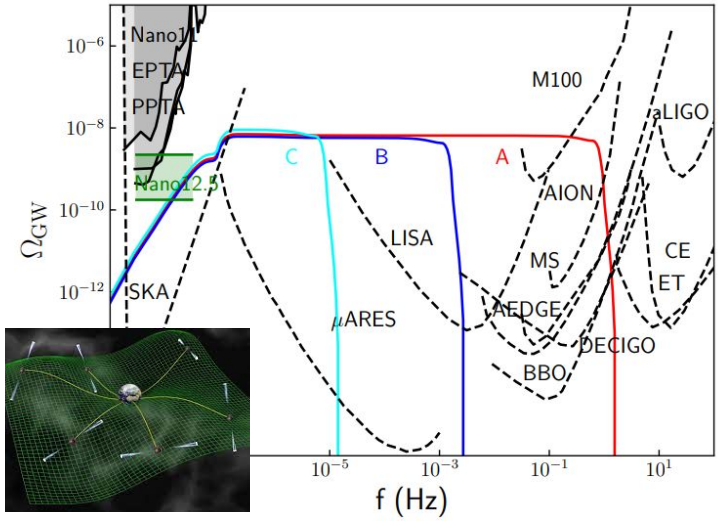
- High-T transition enhances collapse
  → **PBH formation**



[Lu, **VT**, Fuller, *Phys.Rev.Lett*, (2023) 2212.00156] *see talk by Philip Lu*

PBH Hints of Novel QCD Transition ?!





PBHs excellent proxies for exploring fundamental physics in unique ways

PBHs of High-T QCD transition CAN be ALL DM & GWs explain NANOGrav excess

→ distinct from SM QCD transition ~solar-mass PBHs, *cannot* be all DM

[Lu, **VT**, Fuller, *Phys.Rev.Lett*, (2023) 2212.00156] *see talk by Philip Lu*

Summary

- PBHs ~ “Standard Model” dark matter, very different from particle dark matter
- Generically appear in many theories, especially with scalars, with intriguing features
- **Manifestations could be already lurking in data and connect distinct areas of research!** ***…bubble multiverse? new QCD transition?***

→ essential to confront new observations !

(many other exciting observables not covered today: neutron star explosions, gas heating, Hawking evaporation…)

… Dark Matter ?