Primordial Black Holes (PBH) from bouncing cosmology

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About PBHs

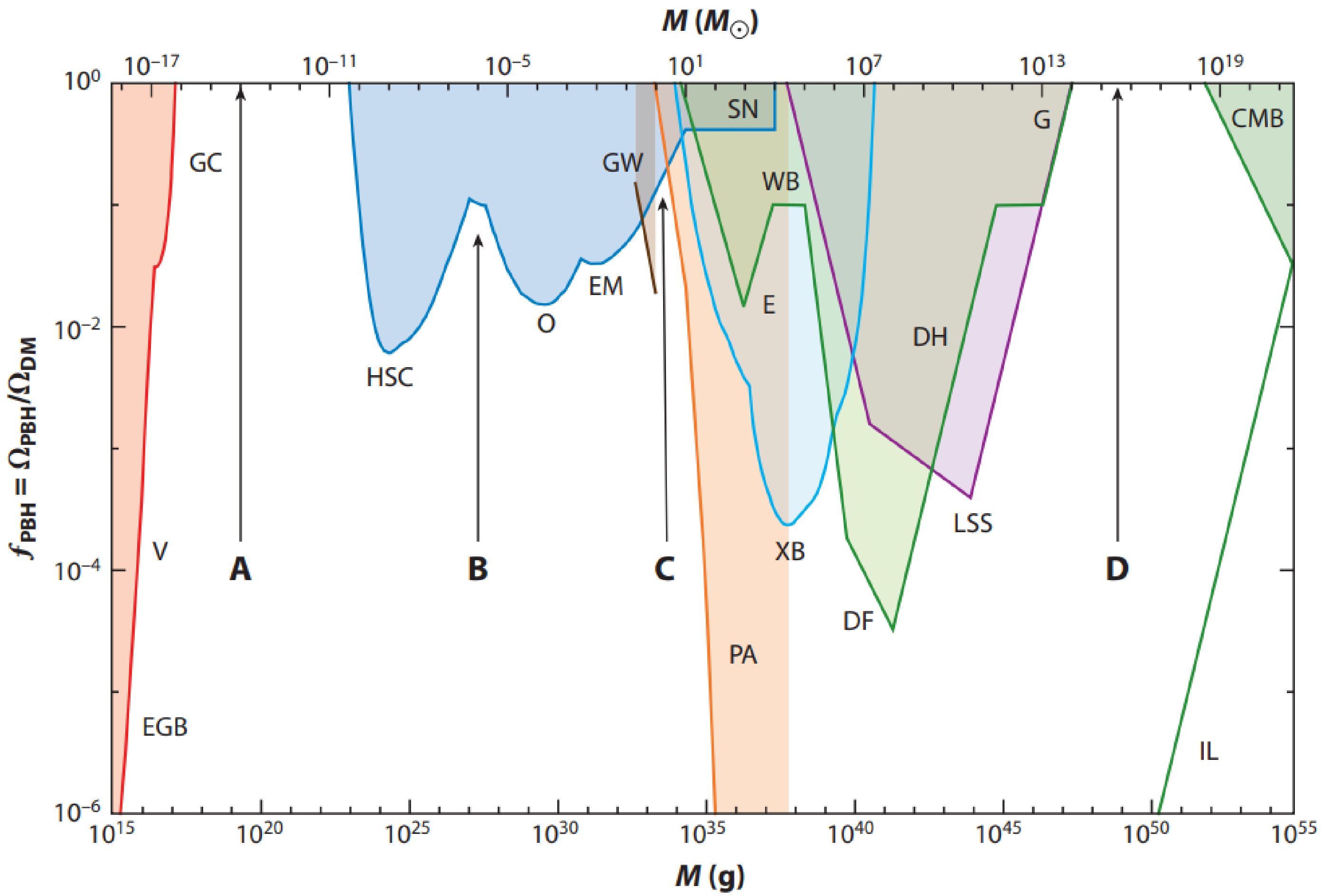
Exotic compact objects formed in early universe

Source: over-dense regions & new physics

Wild range of masses & spins

Candidates for cold dark matter (DM) & Supermassive Black holes

PBH as DM candidates



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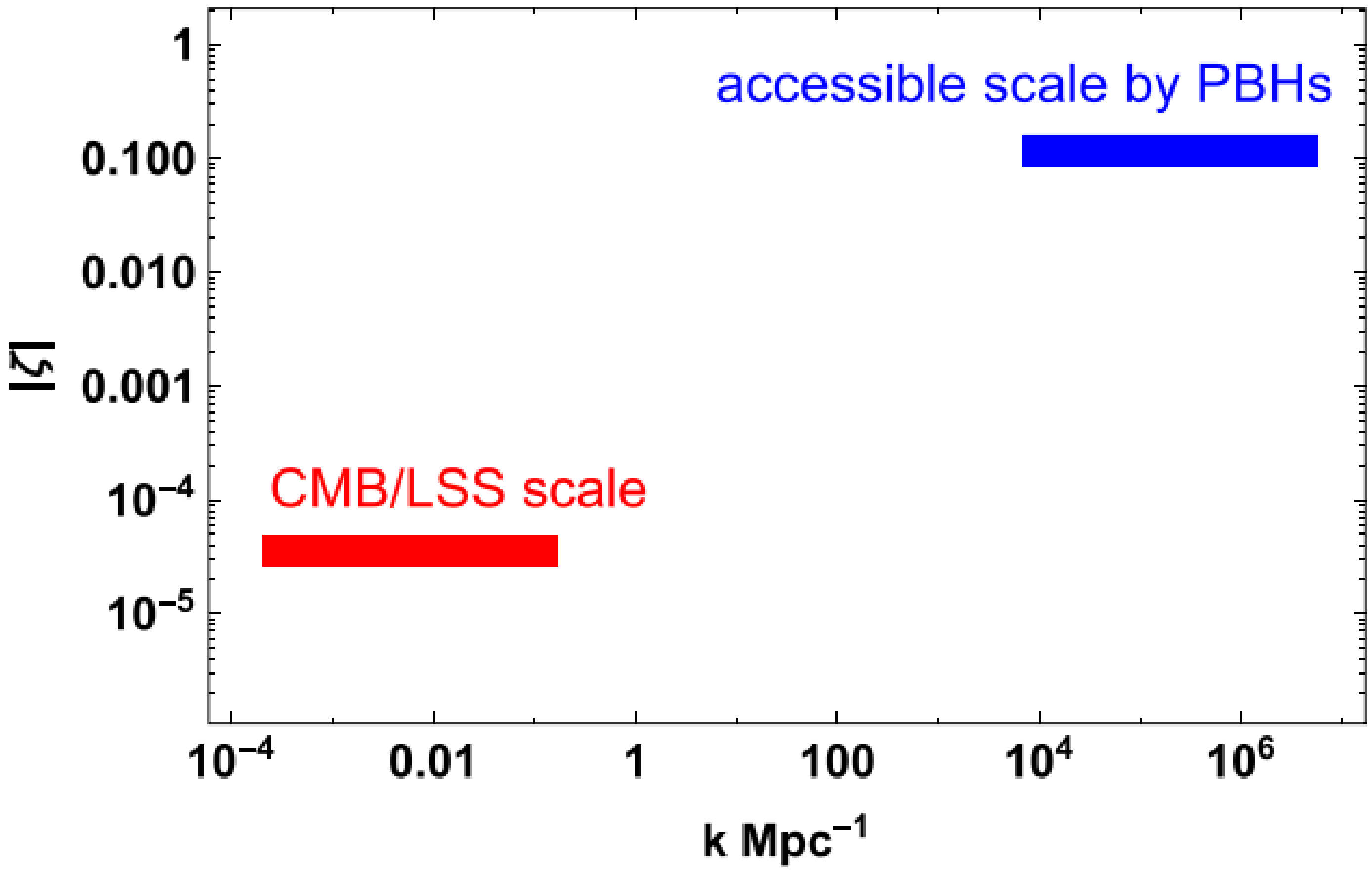
How to generate PBHs

- Over-dense regions ($\delta\rho/\rho$) from primordial density fluctuations
- Statistics: Power spectrum & probability distribution function (PDF)
- Enhancement of density fluctuations required



Class.Quant.Grav. 35 (2018) 6, 063001

PBH in bouncing comology

- Bouning cosmology: contraction, bounce and expansion
- Intuition: over-densed regions are more likely to form & merge in a contraction period than in an expansion period
- What really happens: PBHs are more UNLIKELY to form in bouncing cosmology than in inflationary cosmology (*JCAP* 11 (2016) 029, *Phys.Lett.B* 769 (2017) 561-568)

Problem: suppression from CMB & LSS

- Magnitude of density fluctuations are much smaller in a contraction period!
- Reason: in a contraction period the density fluctuations grows even in super-horizon scale
- To be compatible with CMB & LSS, the amplitude of density fluctuations must be small in the contraction period

PBH from bounce period

- Motivation: in bouncing period, Null Energy Condition is violated ($\rho+p<0$), new physics here! (2207.14532)
- Near the bounce point H=0, from Friedmann's equation $\rho = 3H^2$, we have $\rho=0$ and density contrast $\delta=\delta\rho/\rho$ diverges.
- Although the diverge is unphysical, we can infer
  - 1. PBH forms when δ~1->High possibility for PBH in bounce period
  - 2. Alternative description for PBH formation needed

Scalar perturbation

- Conventionally, we work with curvature perturbation ζ
- Dynamical eq: Mukhanov-Sasaki (MS) eq:

$$v_k'' + \left(c_s^2 k^2 - \frac{z_s''}{z_s} \right) v_k = 0$$

- Problem: ζ may be singular near bounce point (IGPG-07-7-1)
- Solution: do it locally
- Dynamical eq now: Raychaudhuri

$$\frac{dH}{dt_c} + H^2 = -\frac{1}{6}(\rho + 3P) - \frac{1}{3}\nabla \cdot \frac{\nabla P}{\rho + P}$$

Connection to background

- Now every variable becomes local, we need to relate them to the global ones

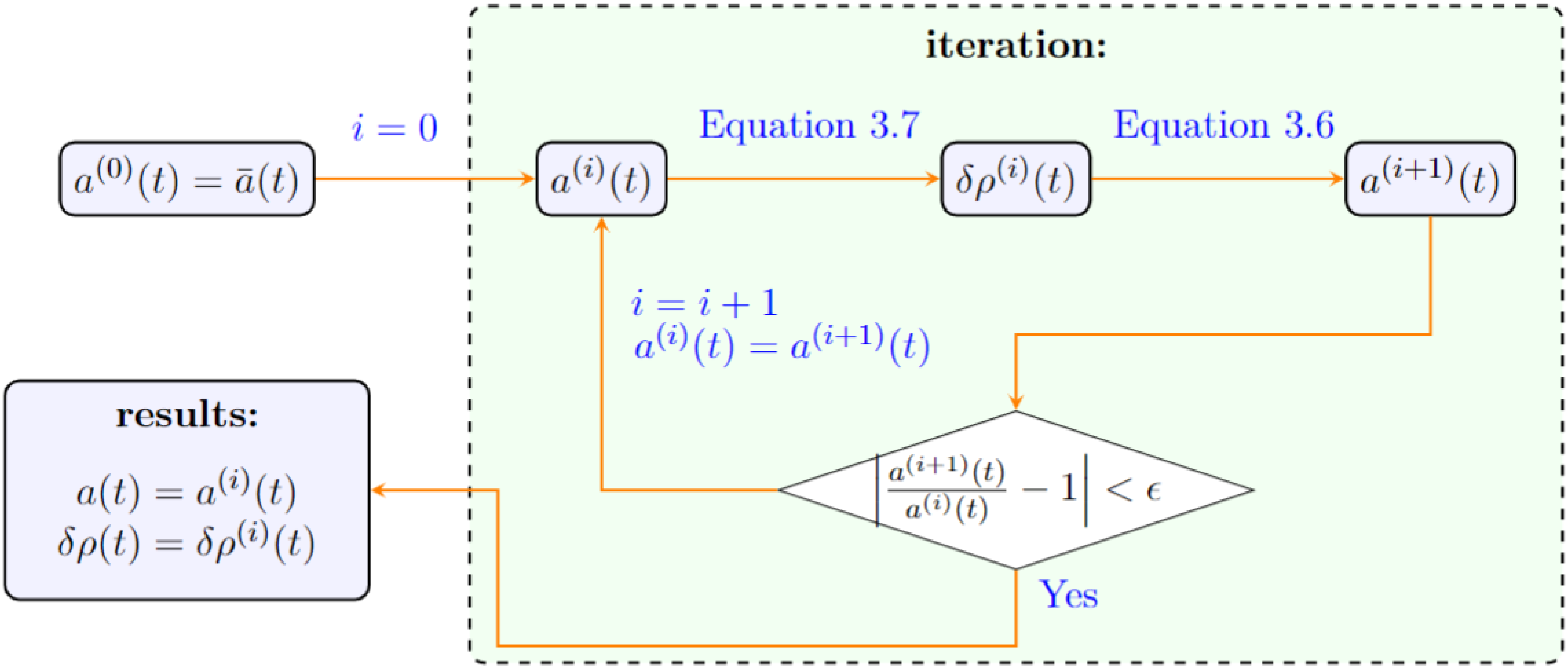
$$\nabla^2 \left(\frac{dt}{dt_c}\right) = \nabla^2 \left(\frac{\delta P}{\rho + P}\right) \qquad \frac{dt}{dt_c} \equiv \xi = 1 + \frac{\delta P}{\rho + P} = 1 + \frac{c_s^2 \delta\rho}{\rho + P}$$

- t: global cosmic time; t_c: local time for comoving observer
- Final equation:

$$-\frac{\xi\dot{\xi}\dot{\rho} + \xi^2\ddot{\rho}}{\rho + P} + \frac{4\xi^2\dot{\rho}^2 + 3\xi^2\dot{\rho}\dot{P}}{3(\rho + P)^2} = -\frac{1}{2}(\rho + 3P) + \frac{c_s^2 k^2}{a^2}\left[\frac{\delta\rho}{\rho + P} - \frac{(1 + c_s^2)\delta\rho^2}{(\rho + P)^2}\right]$$

Numerical estimation

- The dynamical equation is too complicated, and we evaluate it pure numerically in bouncing period
- The dynamics for scalar perturbation in contraction period is well-known, and can be applied directly
- We firstly evaluate $\delta\rho$ analytically in contraction period, and treat it as initial conditions for bouncing period. Then we evaluate it by iteration



$a^{(0)}(t) = \bar{a}(t)$
$i = 0$
iteration:
$a^{(i)}(t)$
Equation 3.7
$\delta\rho^{(i)}(t)$
Equation 3.6
$a^{(i+1)}(t)$
$i = i + 1$
$a^{(i)}(t) = a^{(i+1)}(t)$
$\left|\frac{a^{(i+1)}(t)}{a^{(i)}(t)} - 1\right| < \epsilon$
Yes
results:
$a(t) = a^{(i)}(t)$
$\delta\rho(t) = \delta\rho^{(i)}(t)$

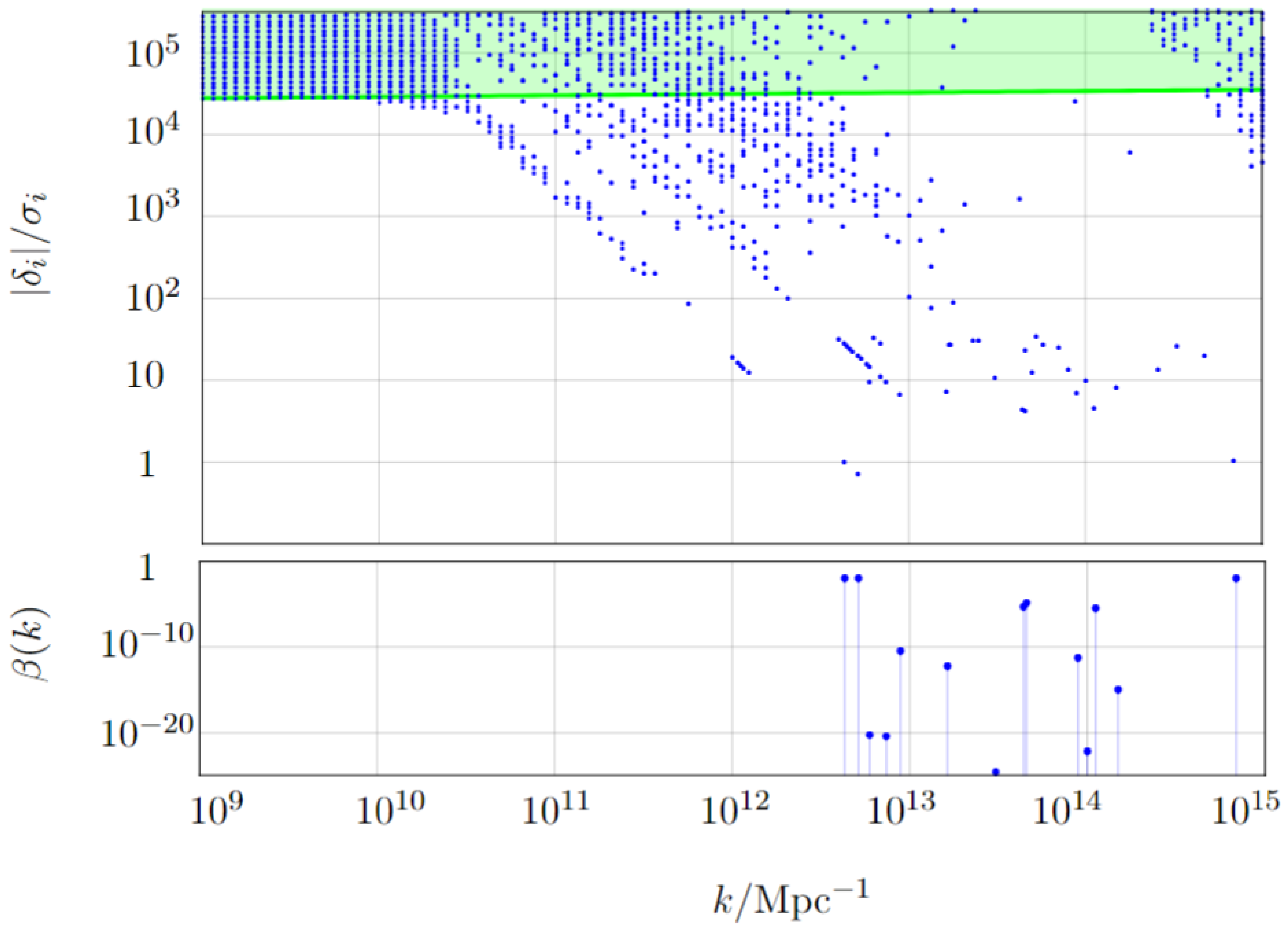
Result

Highly sensitive to parameters due to non-linearity

Pros: enhancement with certain parameters

Cons: hard to make robust predictions

One sample case of PBH enhancement



Conclusion & Outlook

- Physics in bouncing period can be a promising mechanism for PBH enhancement
- The current work faces two challenges:
  - Precision of Numerics
  - Highly non-linearity
- Future study:
  - subsequent evolutions like evaporation, acceration and merger
  - Improvement on numerics
  - More physics on bouncing period

Thank you!