Primordial Neutron Stars

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Relics in Standard Cosmology

Primordial Black Holes: well understood, widely studied relics of the early universe

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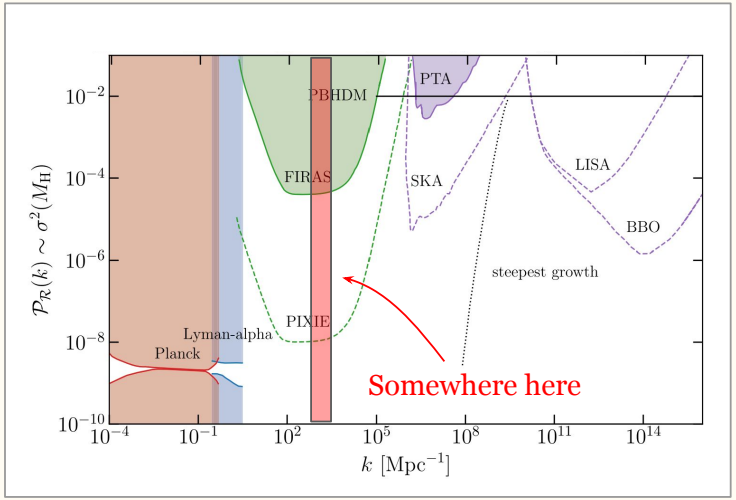
2007.10722

<u>1:</u> Requires fluctuations on huge scales!

Baryons in Horizon: $n_B R_H^3 \sim M_\odot/m_B$

$$k = 10^3\,\mathrm{Mpc}^{-1} \times \left(\frac{Y}{10^{-10}}\right)^{\frac{1}{3}} \left(\frac{M_\odot}{M_{H,B}}\right)^{\frac{1}{3}}$$



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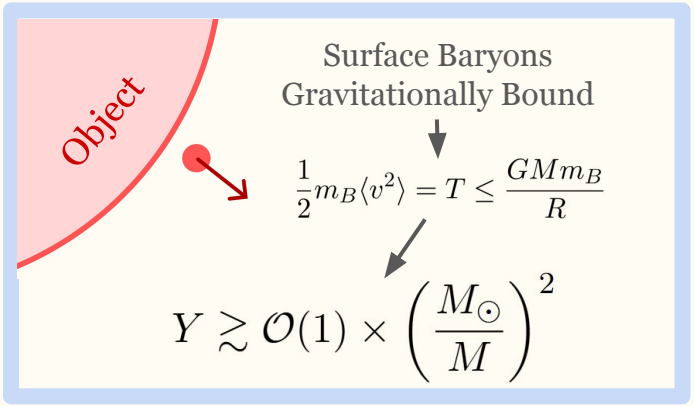

What's Needed to Form Baryonic Relics?

Clearly we need to modify Standard Cosmology: **we need way more baryons**!!

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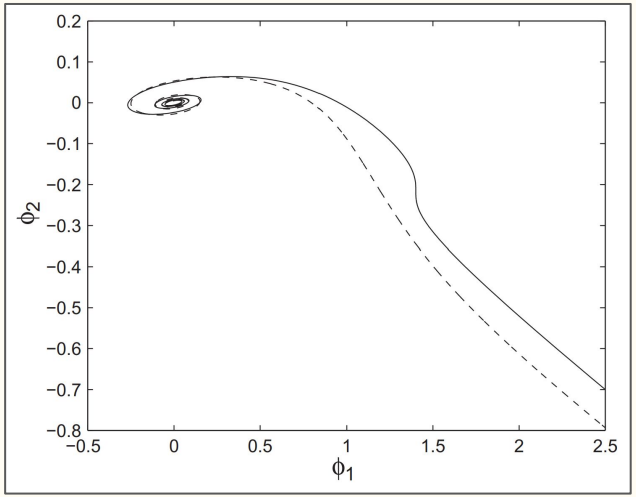
Complex scalar field with baryon number (in its phase), broken by potential:

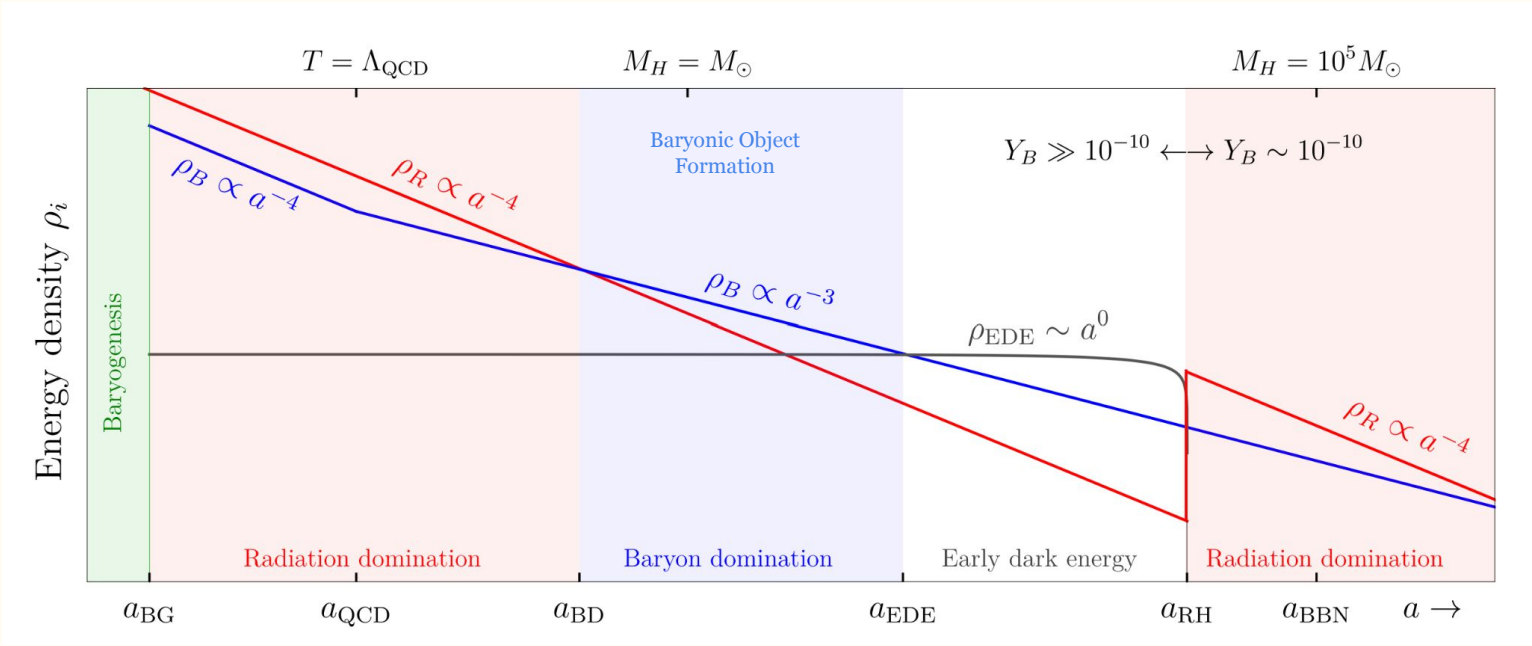
$$V(\phi) = m_\phi^2|\phi|^2 + \frac{\lambda}{2}|\phi|^2 + \frac{\lambda'}{2}[\phi^4 + \phi^{*4}]$$

As it condenses and decays, it can generate a baryon asymmetry

(Allahverdi 2012)

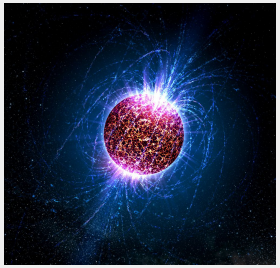


Cosmological Timeline



Recovering BBN

To recover BBN, we require a reheat temperature of T > few MeV

Our Sun (ideal gas)	White Dwarf (electron degeneracy)	Neutron Star (neutron degeneracy)
		
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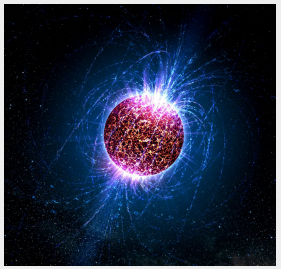

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Recovering BBN

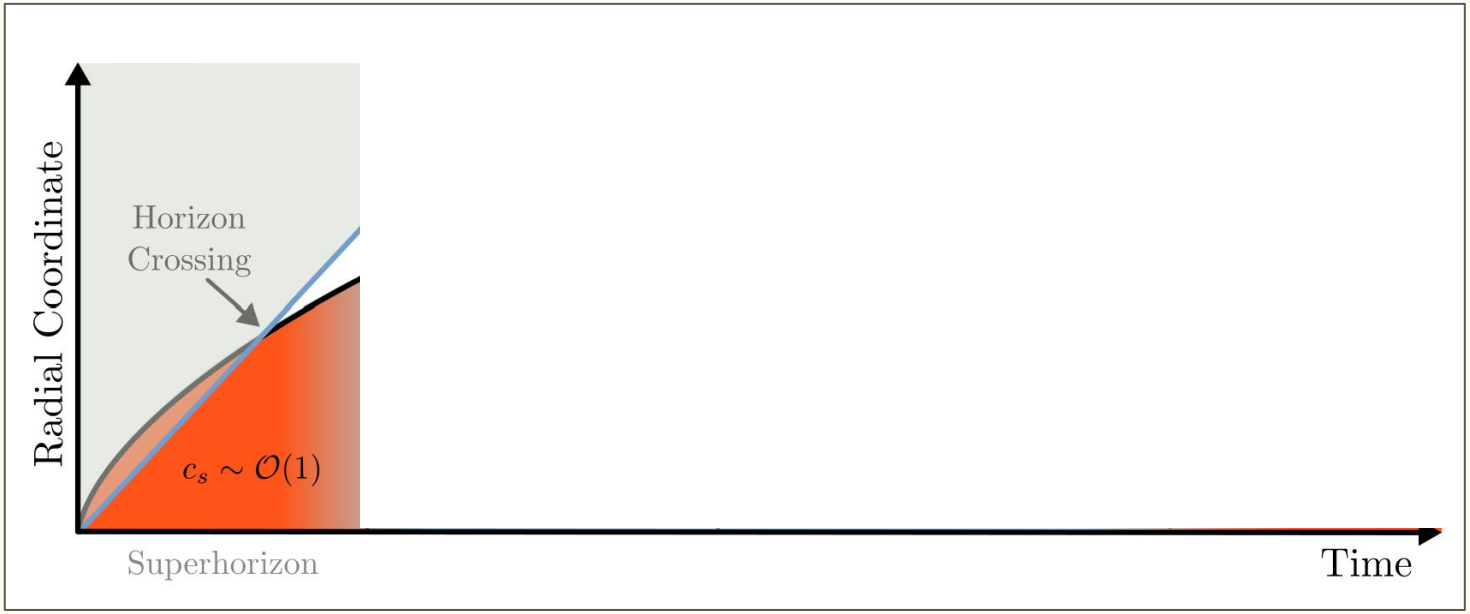
Q1: In what cosmologies can we form primordial baryonic objects?

A: In cosmologies with **O(1) baryon to photon ratio** and **early baryon domination**!

Q2: What baryonic objects can survive BBN temperatures?

A: **Only neutron stars**! (or PBH)

Primordial Neutron Star Timeline



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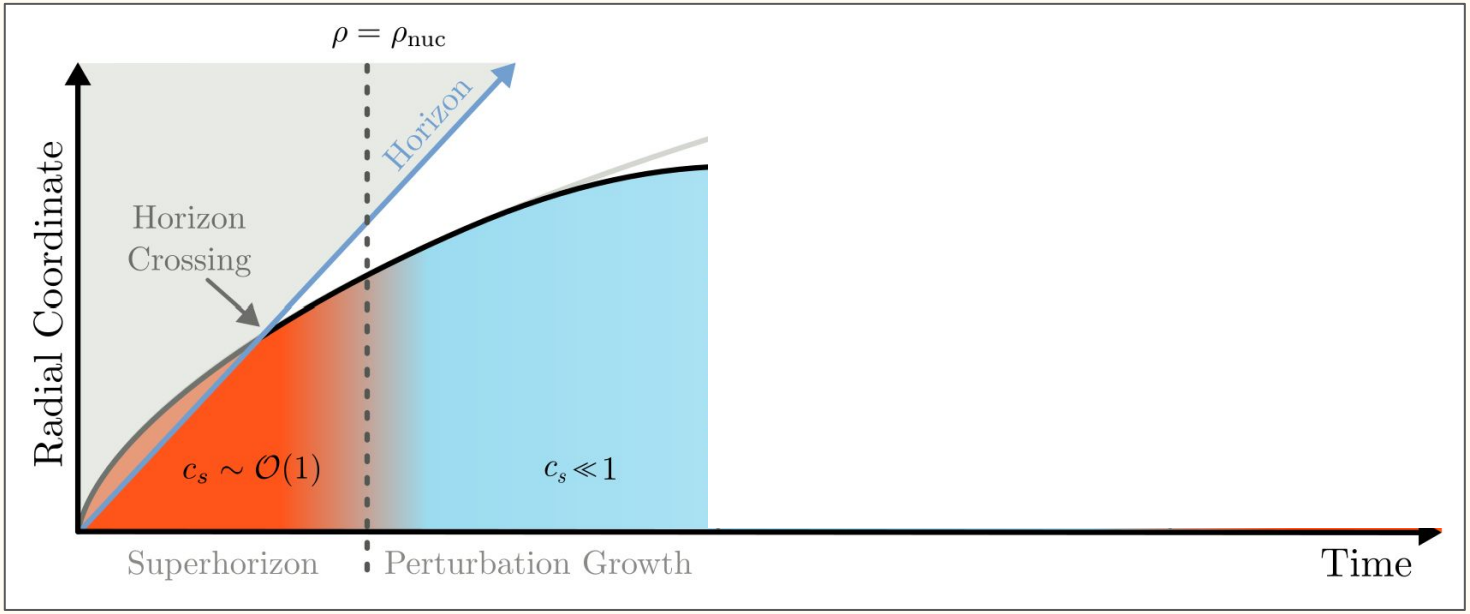

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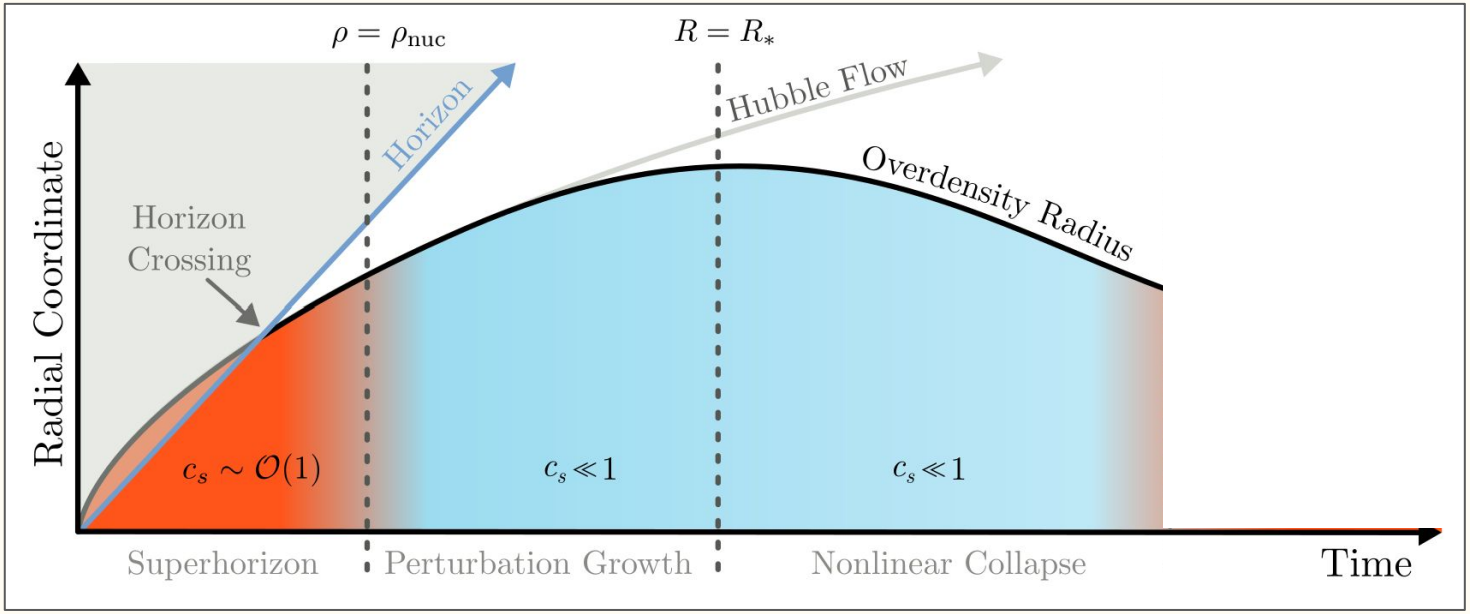

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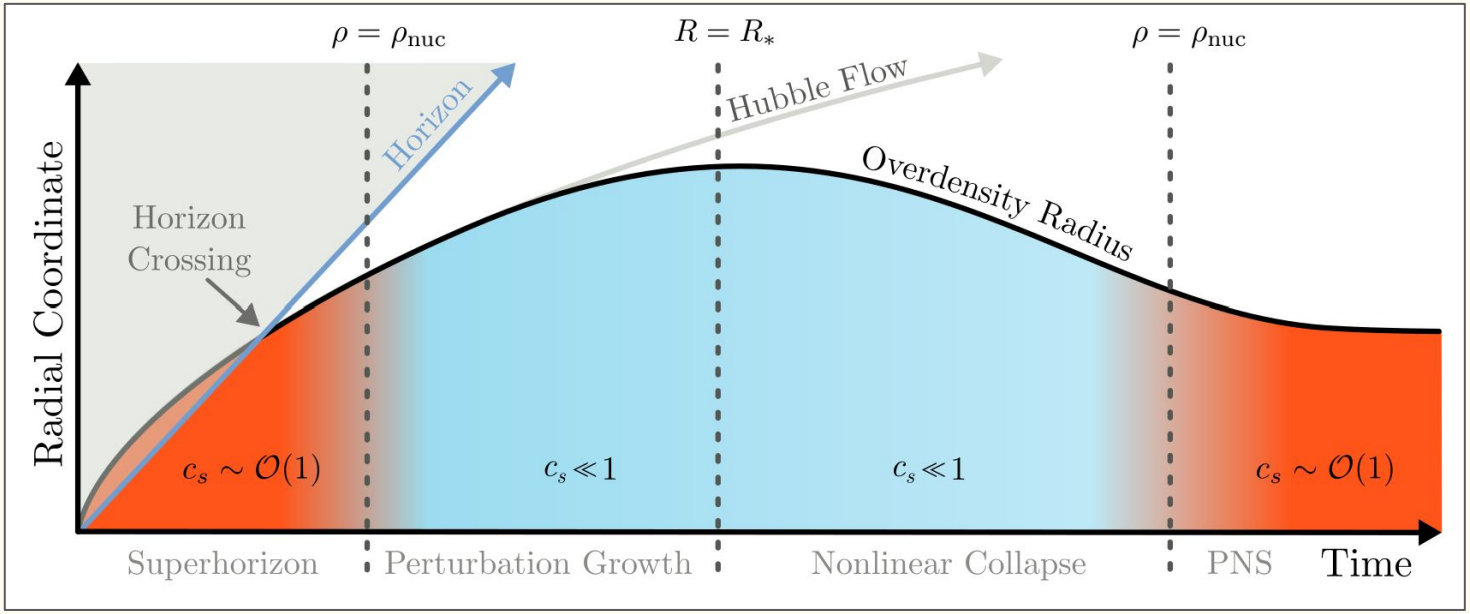


Why Care? Phenomenological Implications

Could be a subcomponent of Dark Matter

Subject to lensing constraints that prevent it from being all of DM

Offer the first mechanism for <1 solar mass neutron stars

NS in this range cannot be formed through astrophysical means

Potential connection to the galactic center excess

Origin of a diffuse cloud of unresolved millisecond pulsars?

Thank you!

Questions Yet to be Resolved

CCSN provides an important motivating analogy, but there are three main differences:

- Initial fluid is composed of **light elements**, not iron
- **Variable initial radius**, could be 20km or could be 1000km
- Initial conditions are **nonspherical** - this changes collapse dynamics considerably

Main Open Problem: the collapse of overdensities to NS is currently understood through analogy/heavy approximations

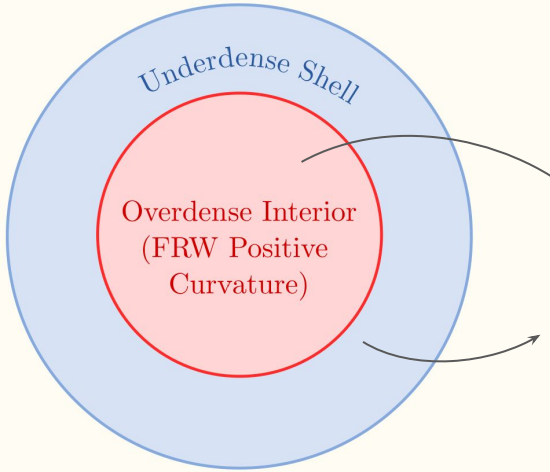
- Dynamics requires numerical fluid simulation with particle transport, vorticity, etc.
- With cleaner understanding of NS feasibility range, one can compute the neutron star relic density (which otherwise is impossible to compute)

Other questions:

- What is the stellar capture rate? Can any fraction of PNS be pulsars?
- Can PNS mergers be observed with gravitational wave observatories?

Carr's Analysis for PBH

Simplified scenario, but exact in GR:



Background: Regular Flat FRW

$$ds^2 = dt^2 - a(t)^2(dr^2 + r^2 d\Omega^2)$$

Interior Closed (Positive Curvature) FRW Metric

$$ds^2 = dt^2 - \lambda^2 a(t)^2(d\chi^2 + \sin^2(\chi) d\Omega^2)$$

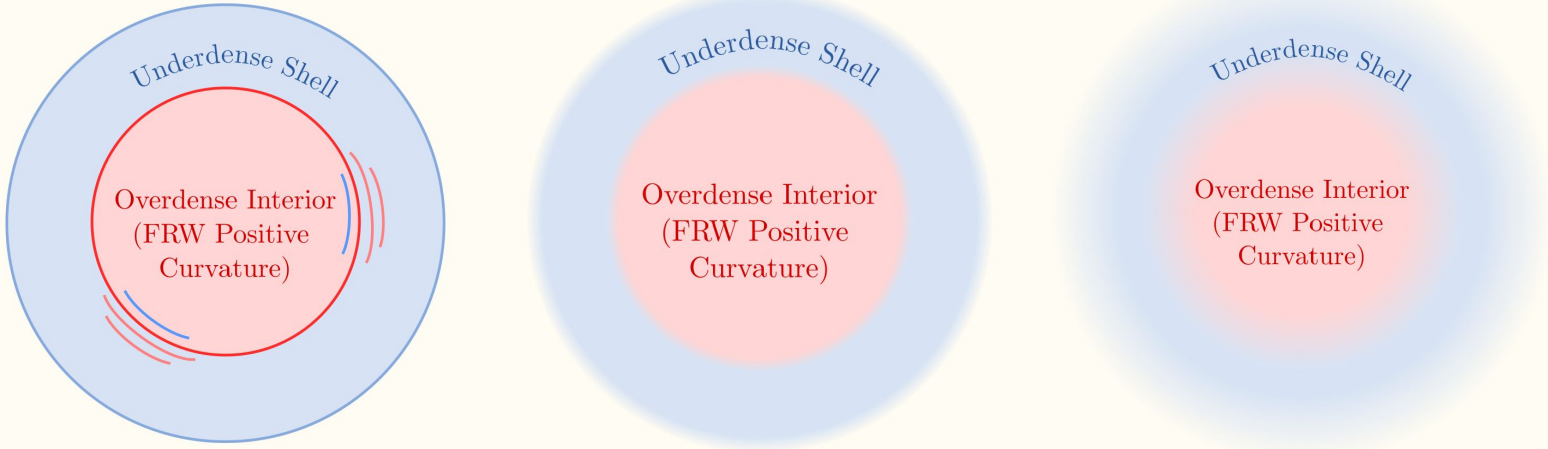
Shell: whatever is necessary for smoothness

This model is accurate if pressure is negligible

Carr criterion for PBH formation: At maximum radius (assuming negligible pressure), does the overdensity exceed the Jeans length?

Carr's Analysis

Including Pressure

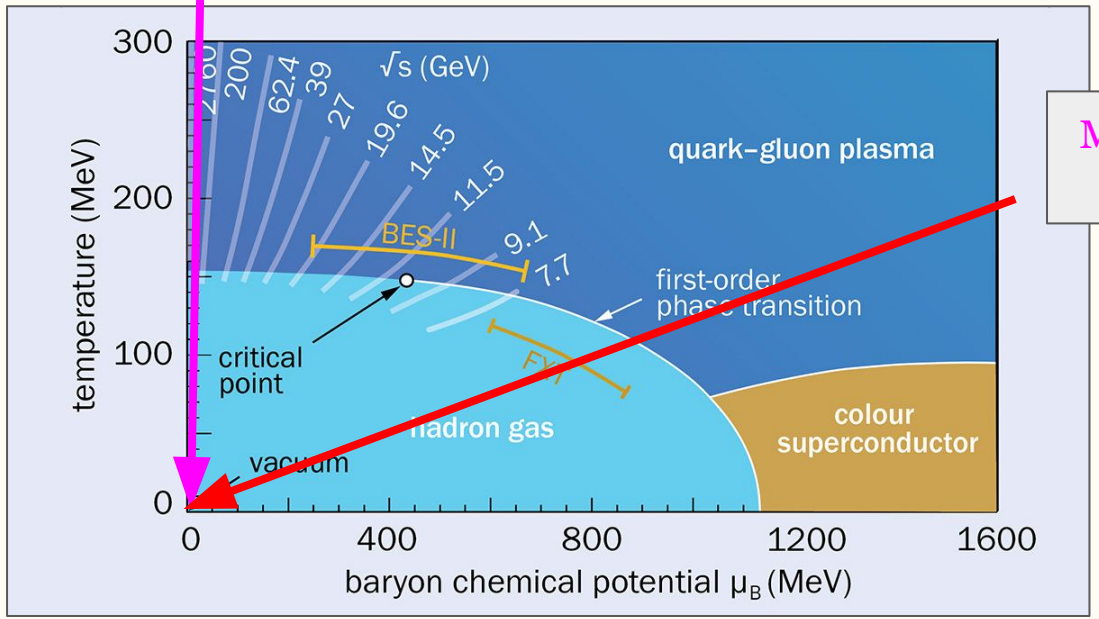


Question: can this pressure gradient be sufficient to prevent complete collapse?

Questions Yet to be Resolved

Standard Cosmology - First Order

$$\mu_B \propto T \propto a^{-1}$$



Modified Cosmology - Second Order?