Black holes from a Higgs-like field in the radiation era

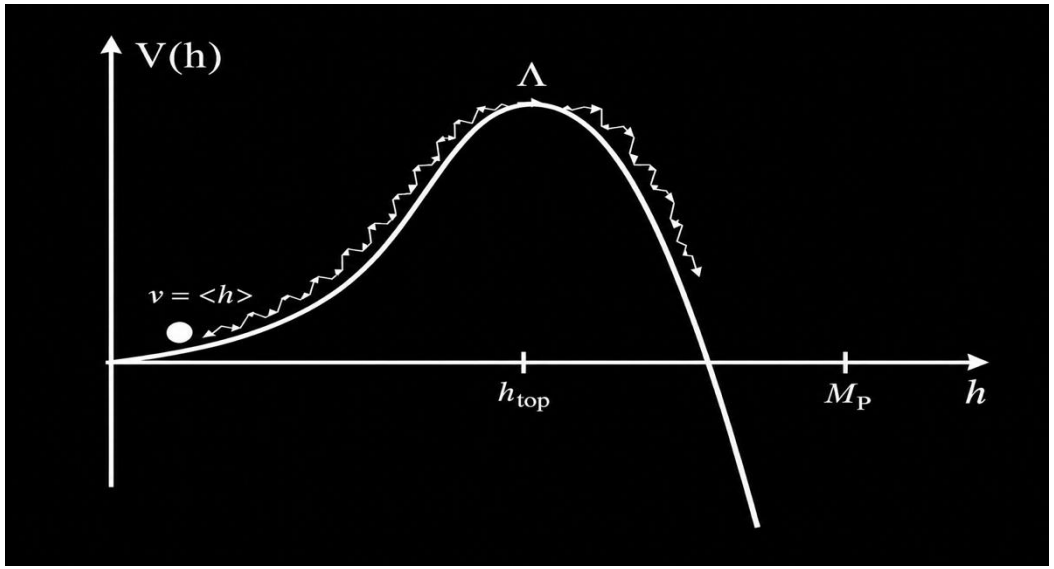
David J. Mulryne
VAST, Madrid, 2026

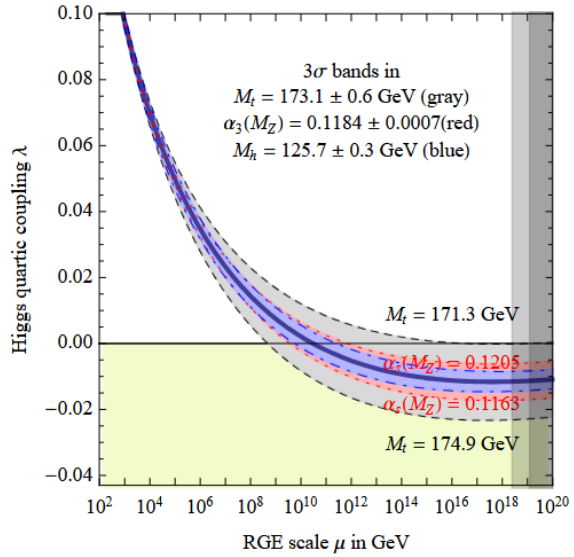
Work led by Ethan Milligan, with Luis Padilla and DJM, arXiv:2608.23367

Motivation

- Higgs metastability during inflation. Rare fluctuations may cross the barrier….

$$V_{\rm phys}(h_{\rm phys}) \simeq -b_{\rm phys} \ln\left(\frac{h_{\rm phys}^2}{h_{\rm max,phys}^2\sqrt{e}}\right)\frac{h_{\rm phys}^4}{4}$$





Degrassi, G. et al [arXiv:1205.6497]

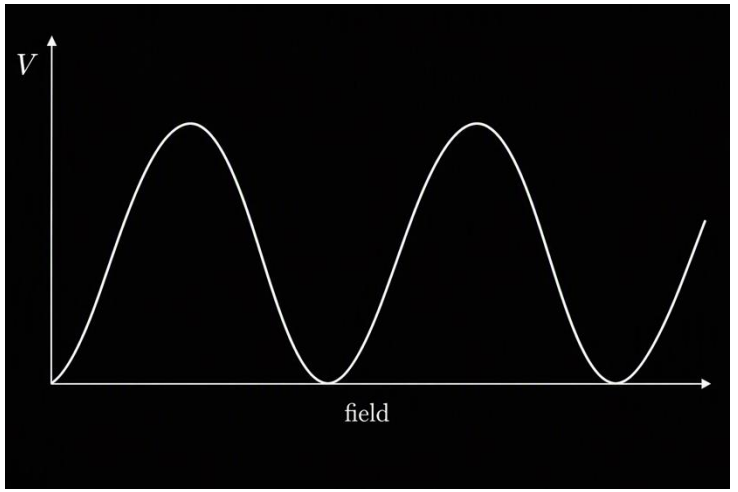
$$\delta h \sim \pm \frac{H}{2\pi} \gtrsim \Lambda$$

The story so far

- AdS-bubble catastrophe vs horizon formation. What is the true nonlinear fate? e.g.:
  - Espinosa, Giudice, and Riotto, “Cosmological implications of the higgs mass measurement”, ‘08
  - Espinosa *et al,* “The cosmological Higgstory of the vacuum instability”, ‘15
  - East *et al.,* “Spacetime Dynamics of a Higgs Vacuum Instability During Inflation”, ‘17
  - Luca, Kehagias, and Riotto, “On the cosmological stability of the higgs instability”, ‘22
  - Strumia and Tetradis, “Higgstory repeats itself”, ‘22

Meanwhile….

- Throat formation and primordial black holes in axion bubbles:



  - Garriga and Vilenkin, “Primordial black hole and wormhole formation by domain walls”, ‘16
  - Deng and Vilenkin, “Primordial black hole formation by vacuum bubbles”, ‘17
  - Ning *et al.*, “Numerical simulations of primordial black hole formation via delayed first-order phase transitions”, ‘26

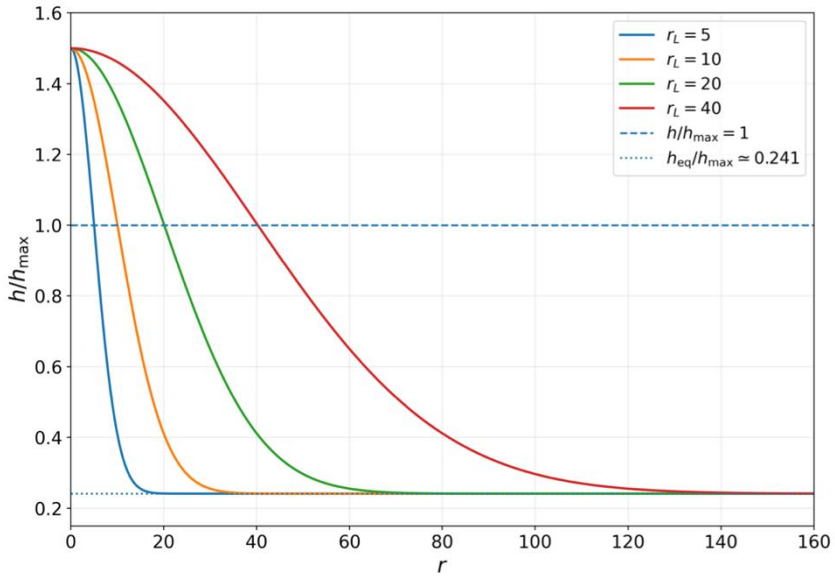
Our work

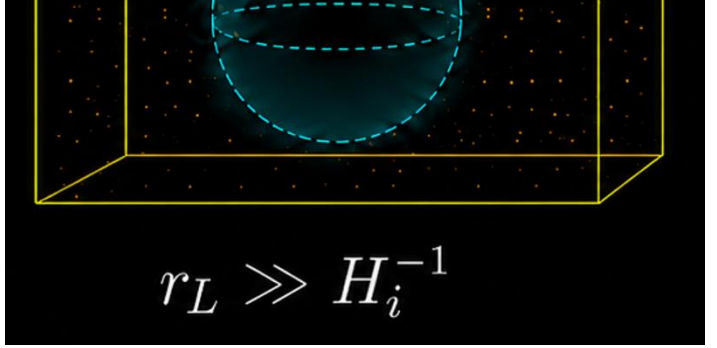
- What happens to over-the-barrier patches in the Higgs case during the radiation era?
- Scalar field with metastable *Higgs-like* potential + radiation fluid
- Numerical relativity: Spherically symmetric Einstein-Klein-Gordon evolution with radiation

$$S = \int d^4x\sqrt{-g}\left[\frac{{}^{(4)}R}{16\pi} - \frac{1}{2}g^{\mu\nu}\partial_\mu h\partial_\nu h - V(h) + \mathcal{L}_{\text{fluid}}\right]$$

$$ds^2 = -A(r,t)^2dt^2 + B(r,t)^2dr^2 + R(r,t)^2d\Omega^2 \qquad A(r,t) = 1$$

- Initially field must be light, and field density subdominant
- We choose an initial (Gaussian) field profile, with:





$$r \to \frac{r}{H_i}$$

$$\frac{h_{\rm max,phys}}{H_i} = 4, \qquad \frac{h_i}{h_{\rm max}} = 1.5, \qquad r_L = H_i r_{L,\rm phys} = 20$$

Sub vs supercritical

- As in axion work, we see two types of behaviour….
- Dependent on ratio of size of region over barrier

$$R_w = R(t_0, r_w)$$

to gravitational length

$$\ell_\sigma = \frac{1}{2\pi G\sigma}$$

- Where

$$\sigma_{\rm eff}(t_0) \equiv \int_{\mathcal{B}_w} d\ell\ \left[\rho_h(t_0,\ell) - \rho_{h,\rm bg}(t_0)\right], \qquad d\ell = B(t_0,r)dr$$

- Also related to

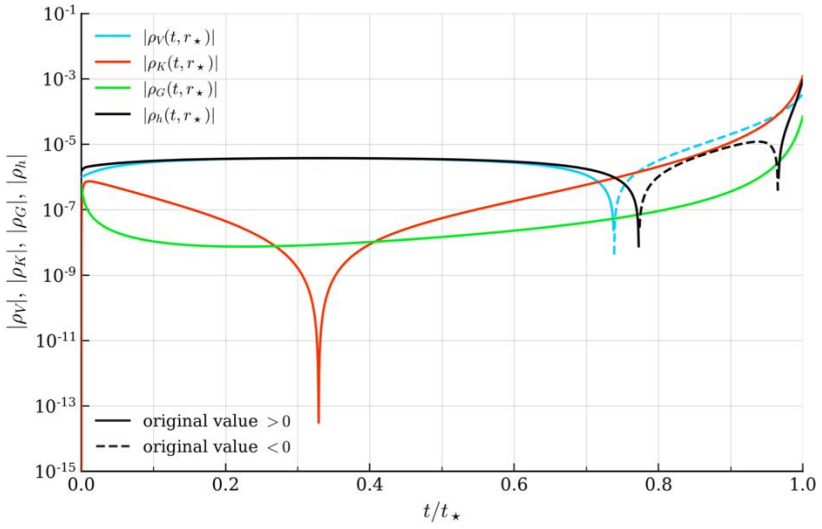
$$\frac{V[h(t,r)]}{\rho_{\rm fluid}(t,r)}$$

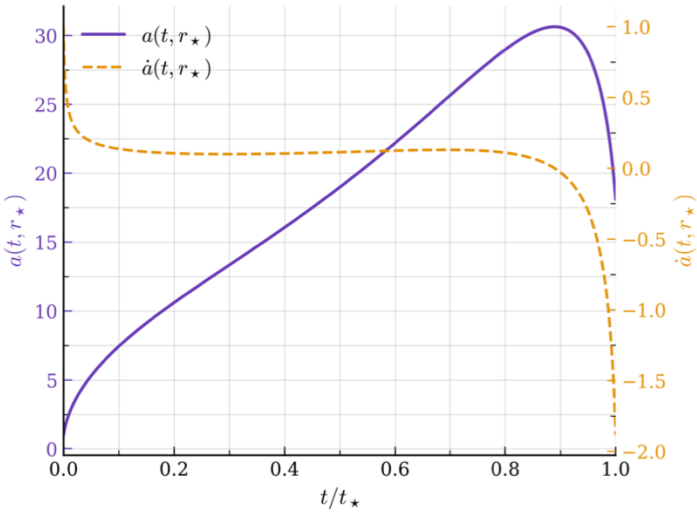
Regions and trapped surfaces

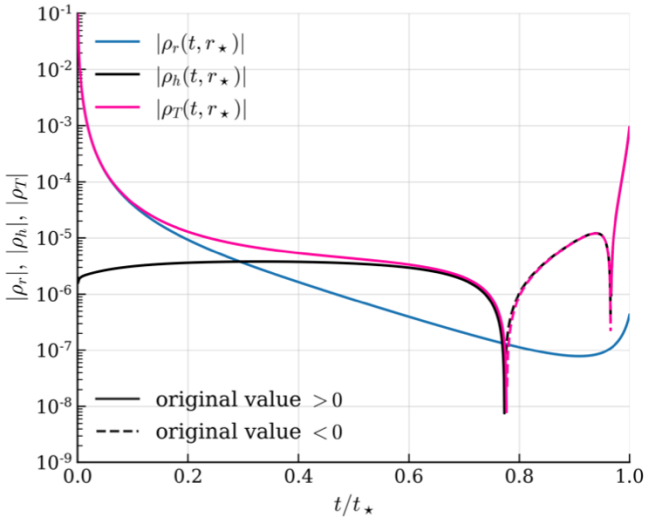
- Reminder! For a spatial 2-sphere, two future-directed null directions normal to S, outgoing (+) and ingoing (−) radial null congruences
- Associated expansion Θ
- Minkowski: $\Theta^- < 0 \text{ and } \Theta^+ > 0$
- Trapped: $\Theta^\pm < 0$
- Anti-trapped (Friedmann): $\Theta^\pm > 0$
- Marginally trapped surface: $\Theta^+ = 0 \text{ with } \Theta^- < 0$

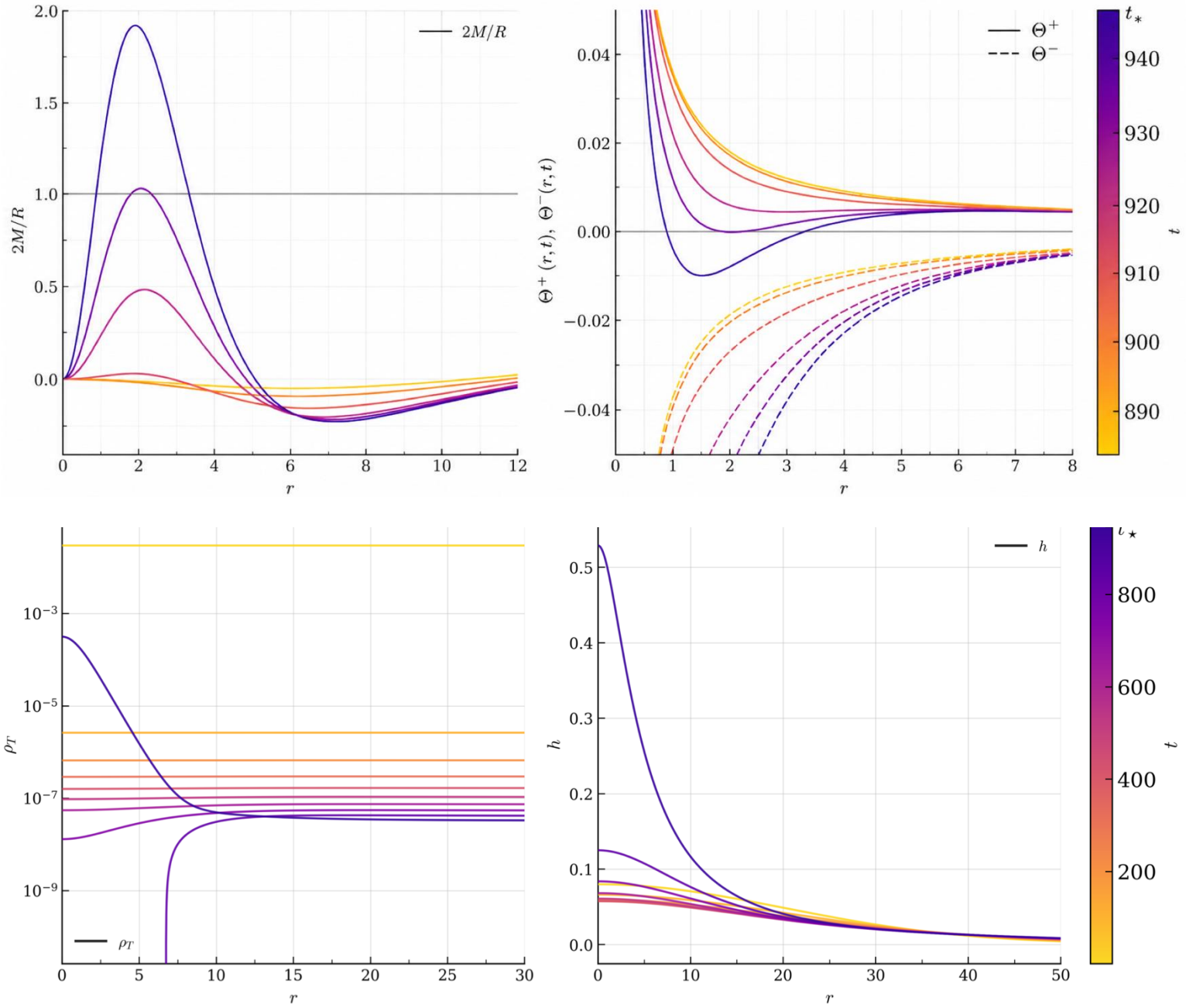
Sub and Supercritical

- Two phases, phase 1 shared between sub and supercritical cases:





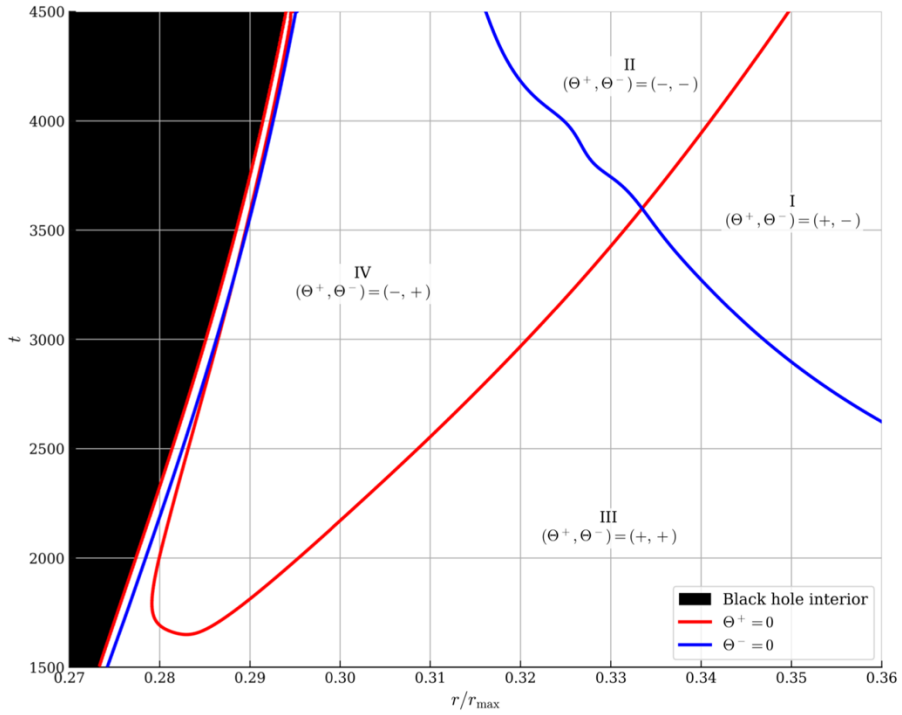


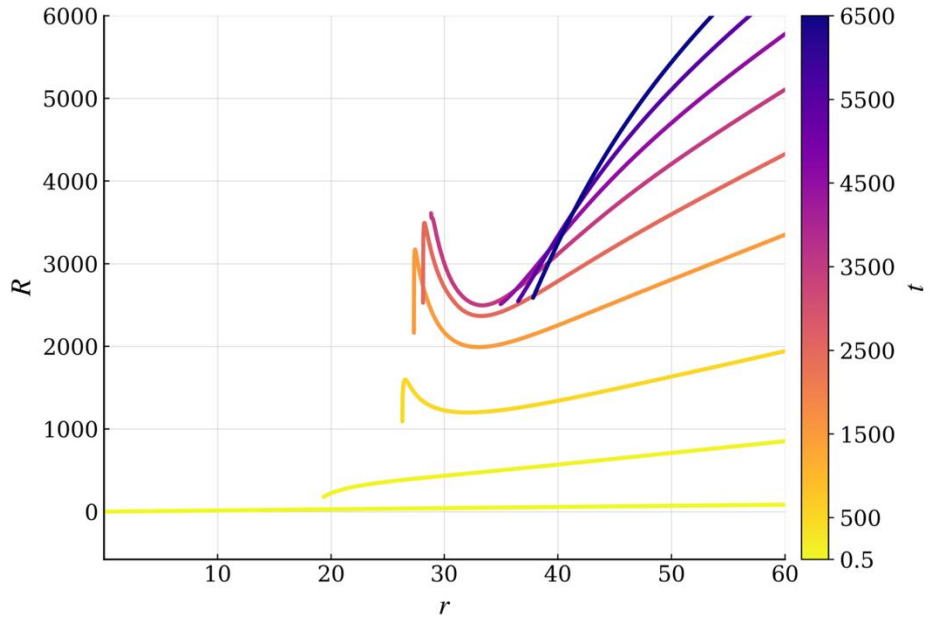

2M/R
r
Θ+
Θ−
Θ+ (r, t), Θ− (r, t)
t
ρT
h

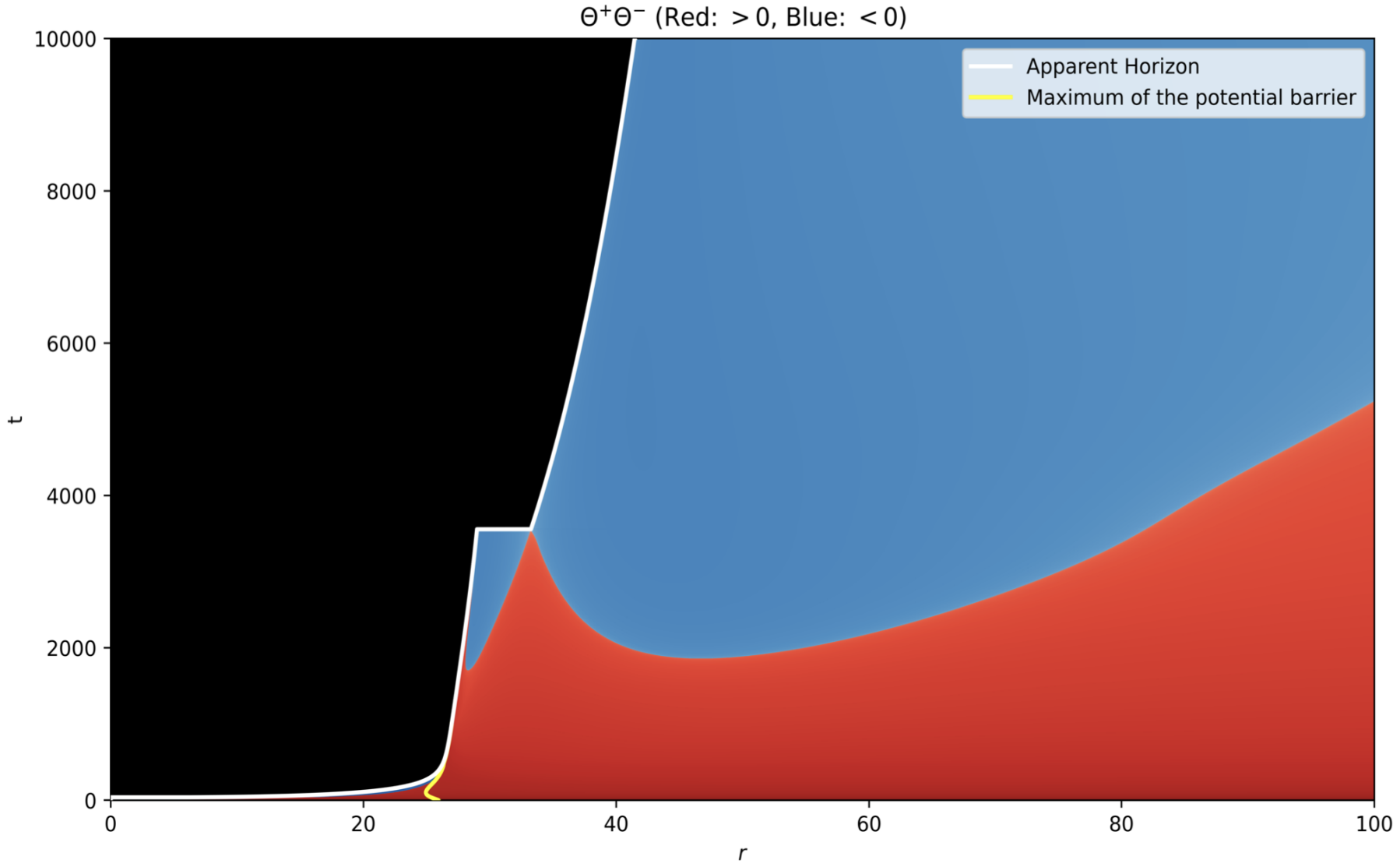
Supercritical

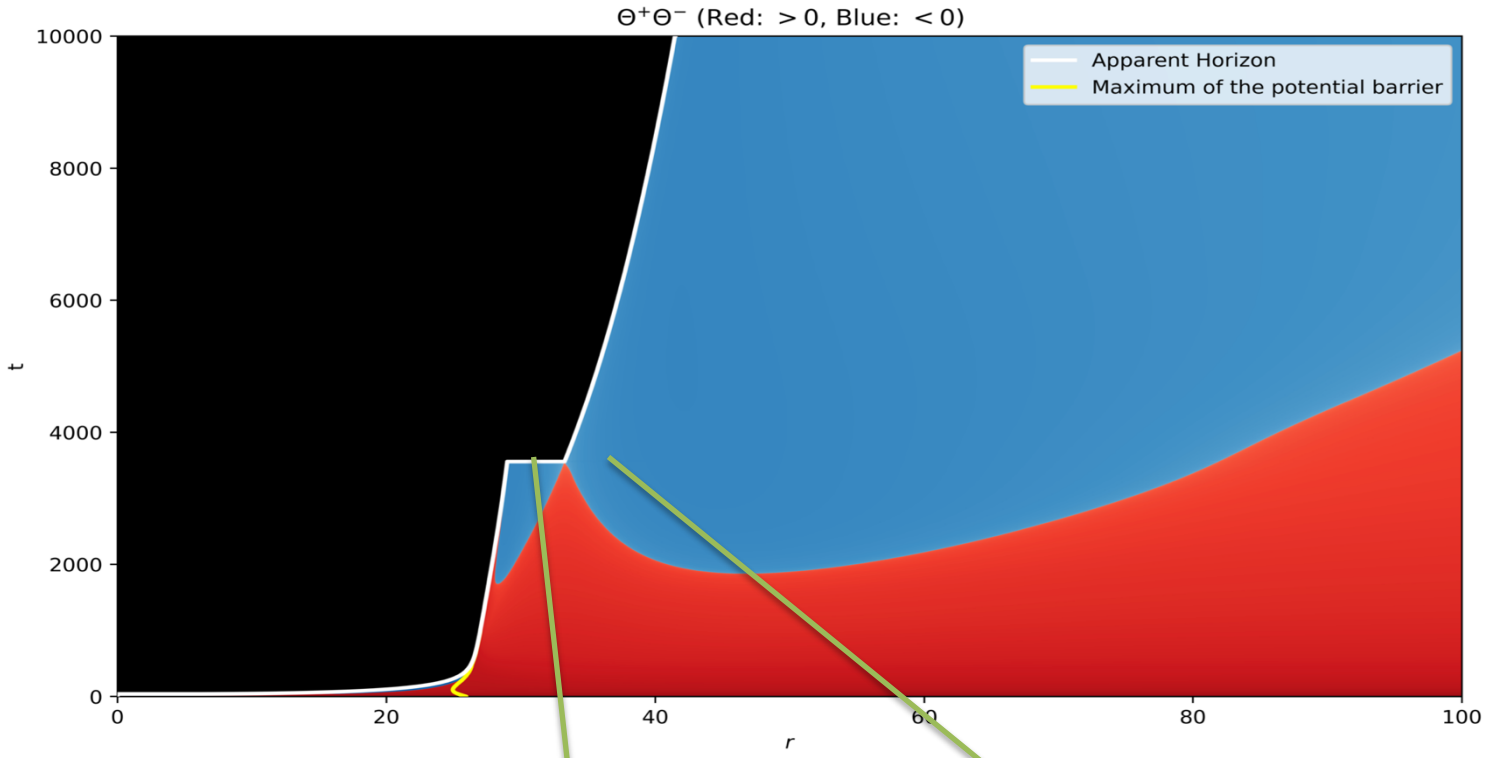
$$\left.\frac{R_w}{\ell_{\sigma,\mathrm{eff}}}\right|_{t_0} \gtrsim 1$$

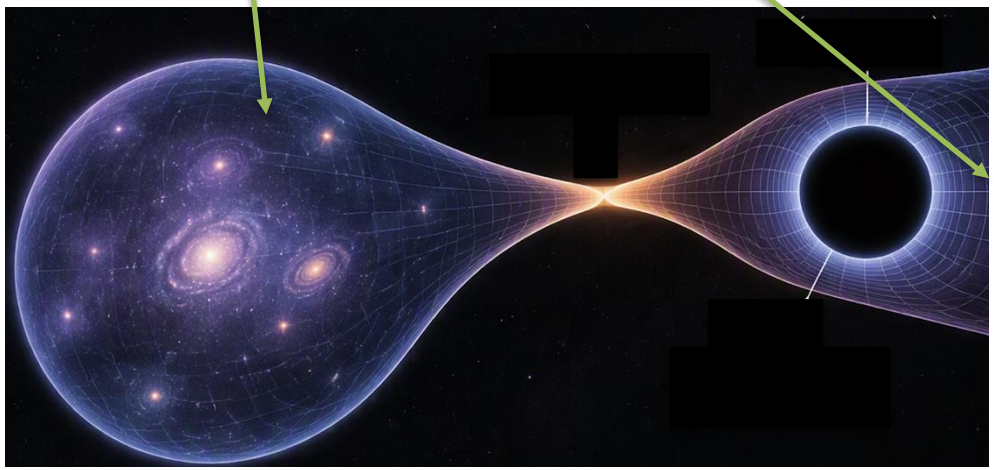
- After formation of first horizon, phase 2 starts:



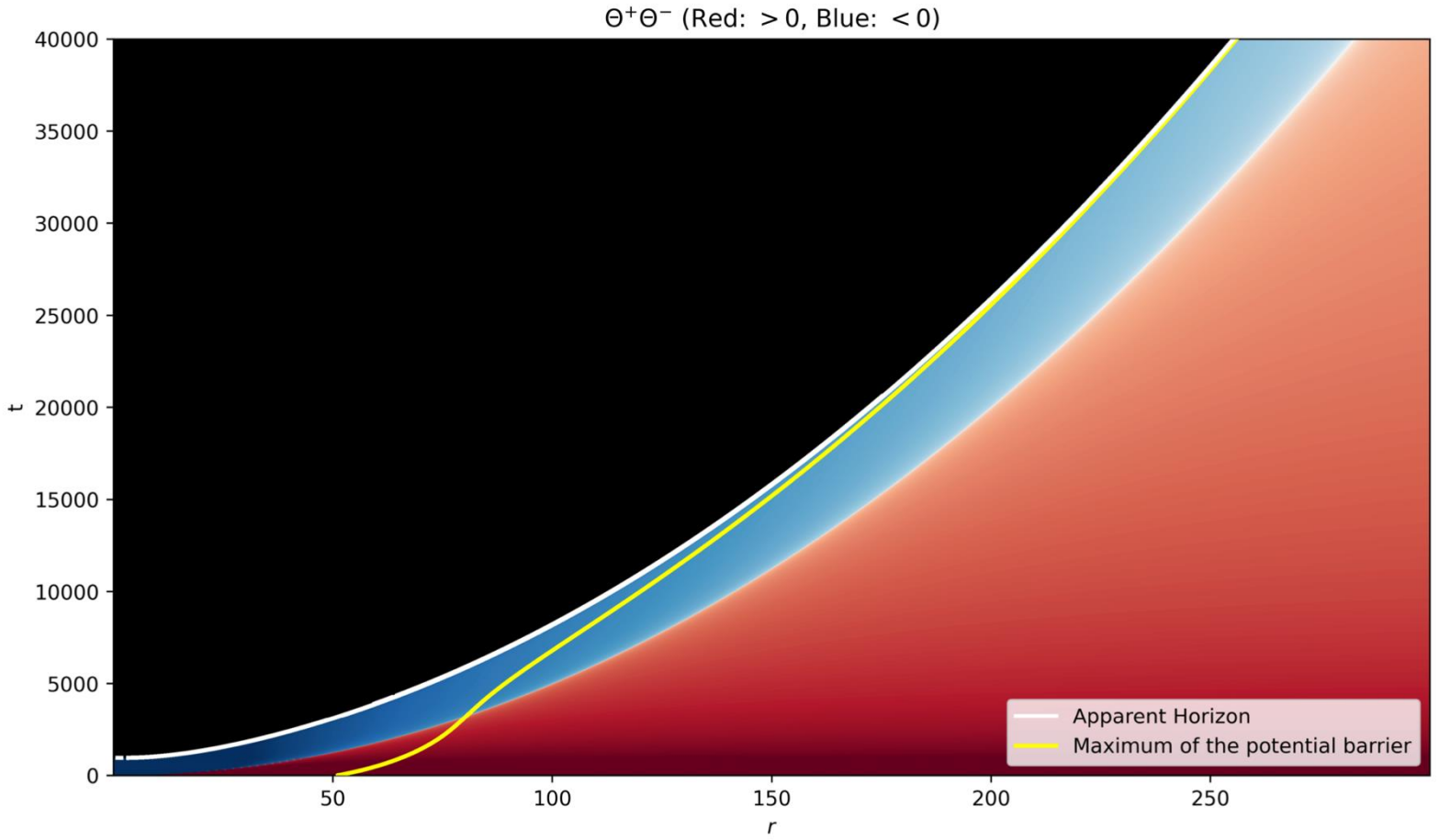



$\Theta^+\Theta^-$ (Red: >0, Blue: <0)
Apparent Horizon
Maximum of the potential barrier
10000
8000
6000
4000
2000
0
t
0
20
40
60
80
100
r


$\Theta^+\Theta^-$ (Red: >0, Blue: <0)
Apparent Horizon
Maximum of the potential barrier
10000
8000
6000
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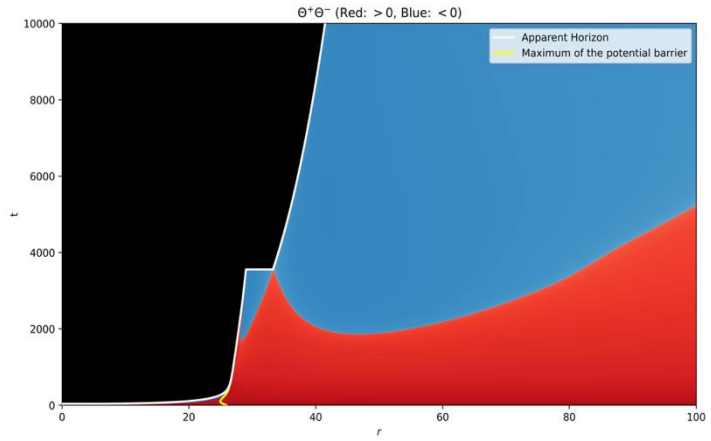


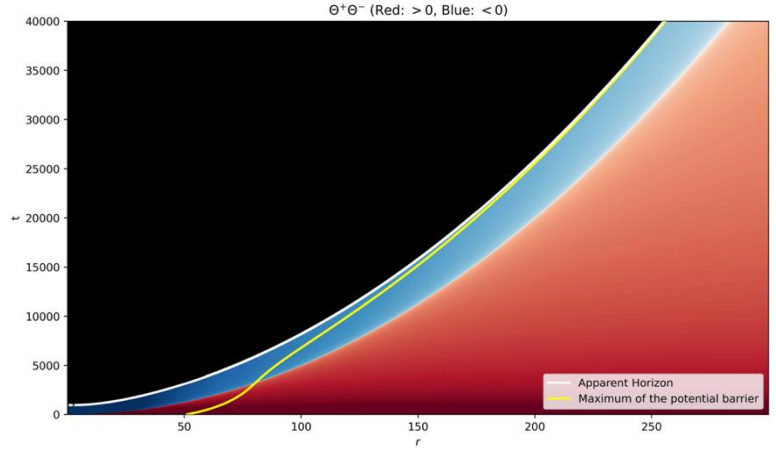
Subcritical

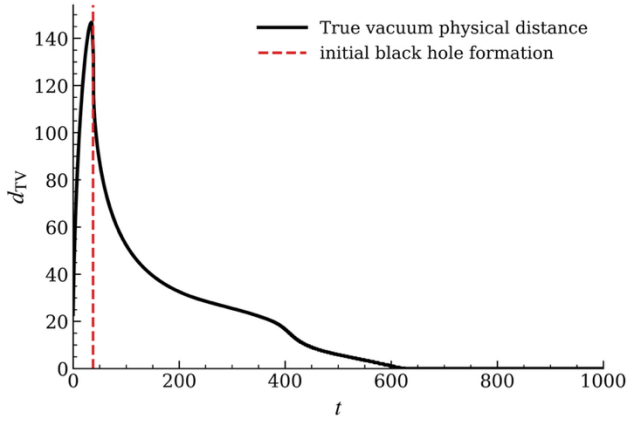


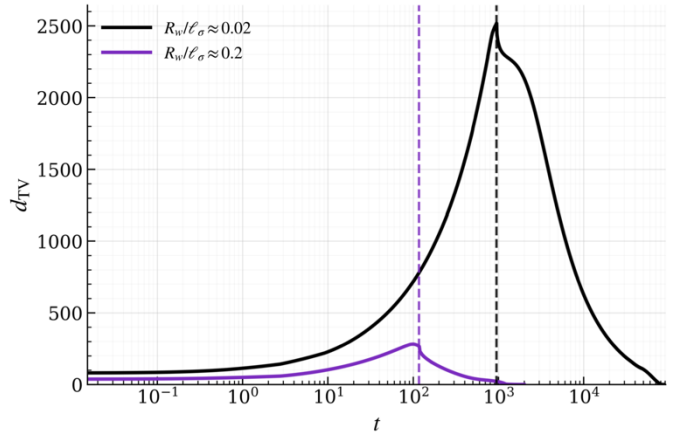
- c.f. type I vs type II perturbations

Main result



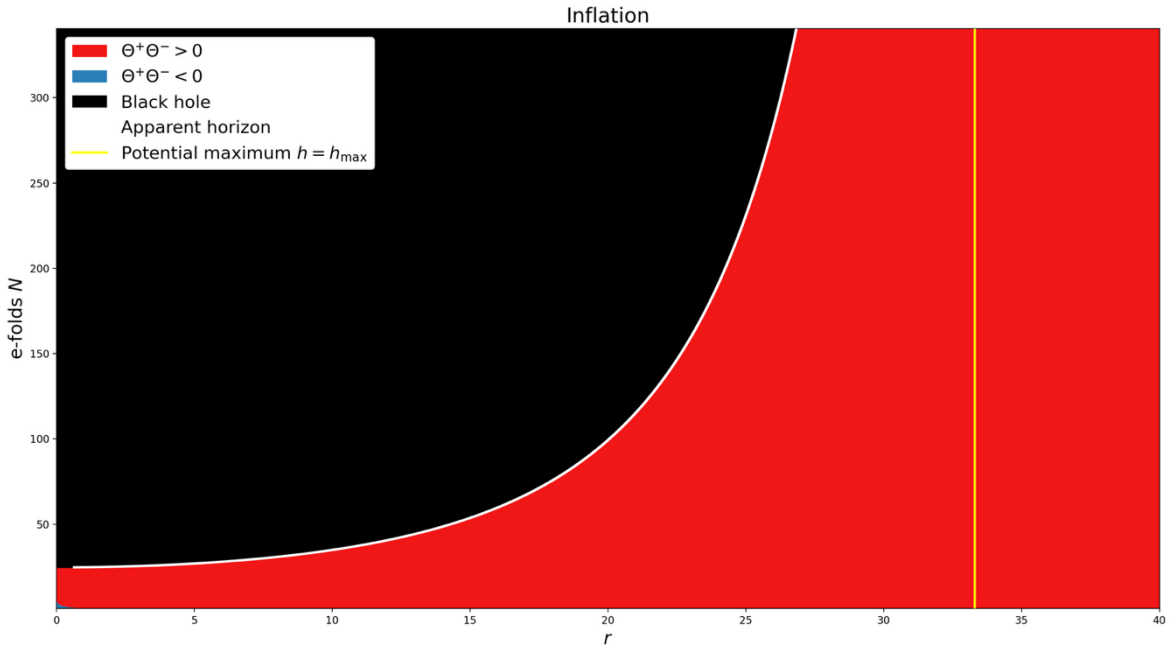


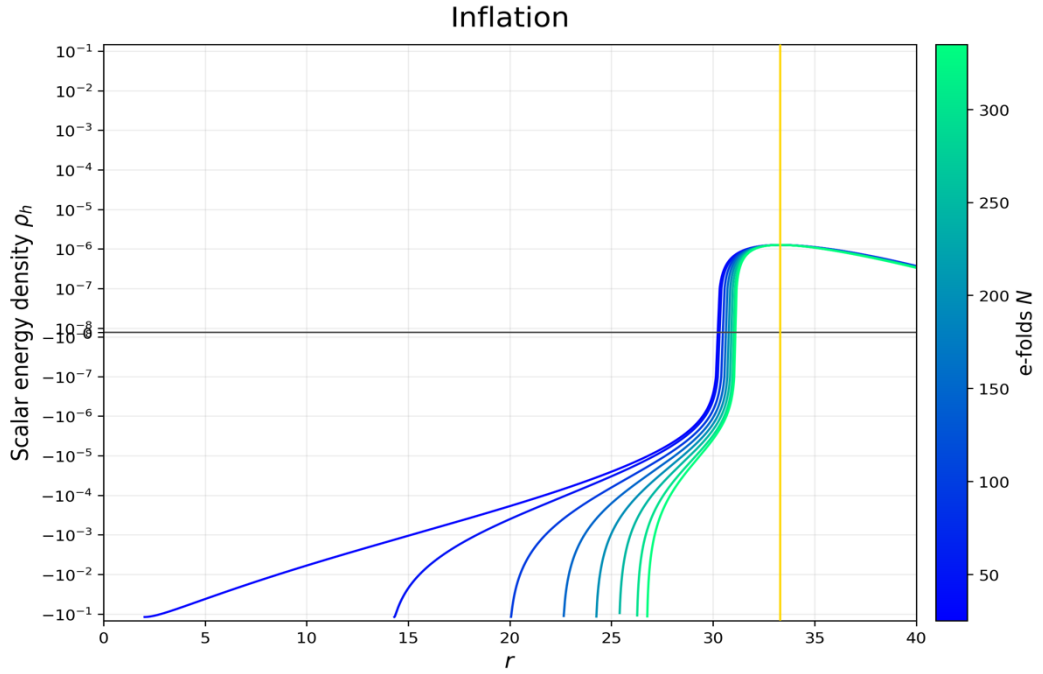




- In all cases the over the barrier region is engulfed. Moreover, we find the black holes then accret like those in radiation

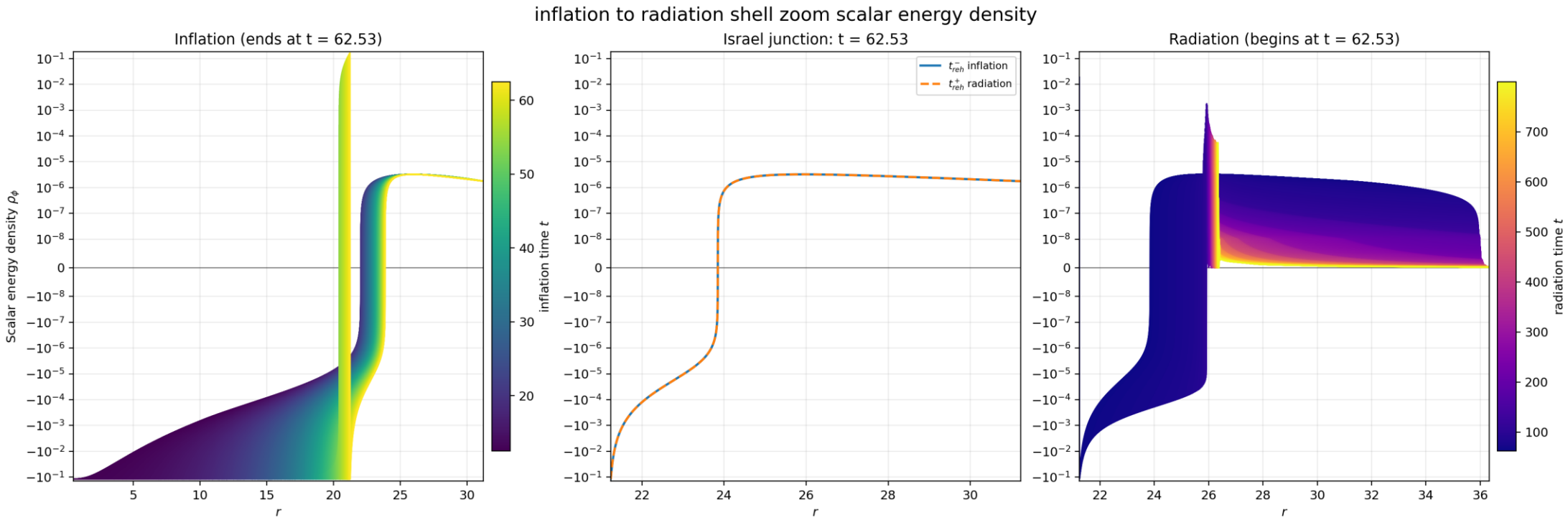
Reminder of the situation in de-Sitter (inflation)

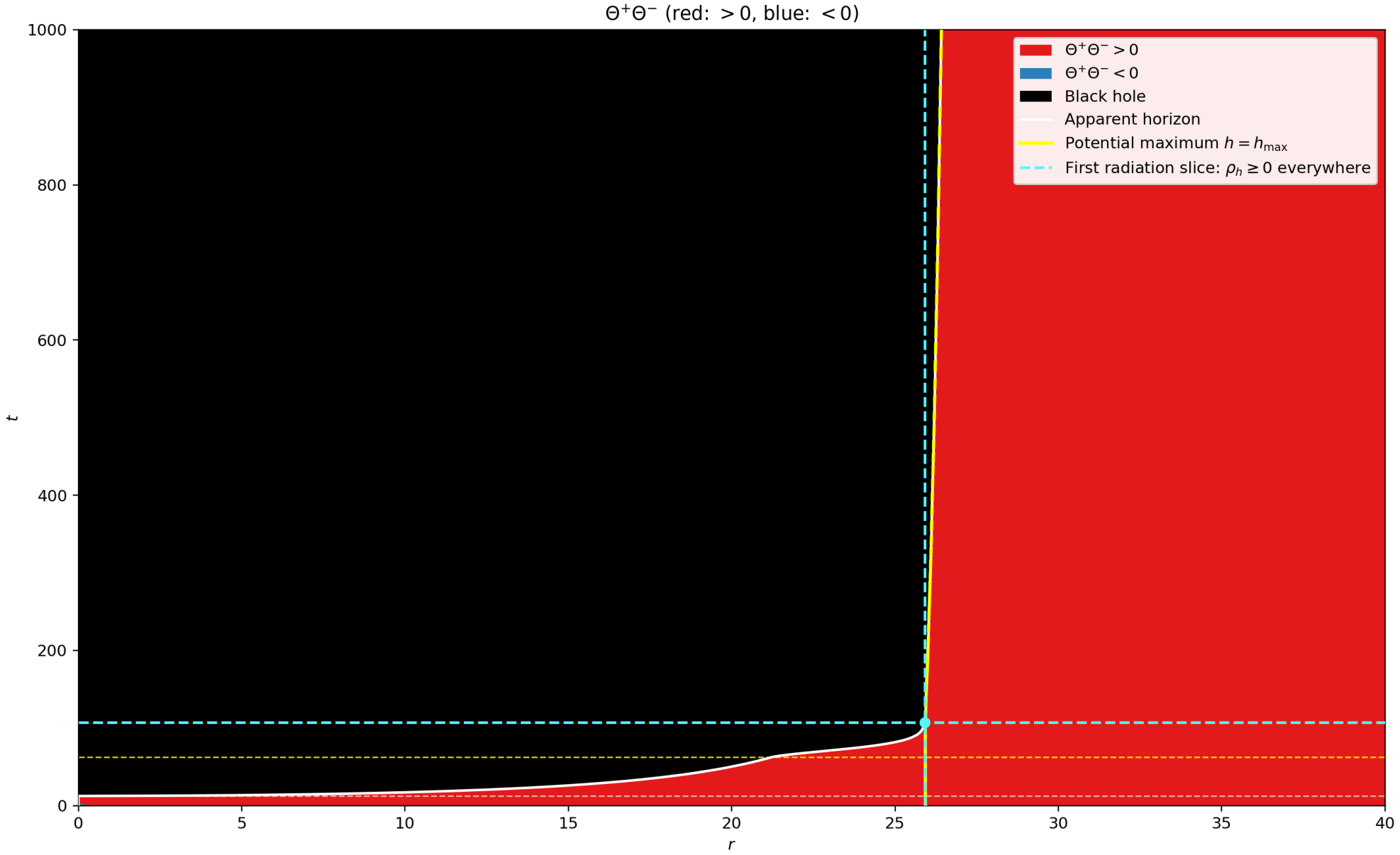




Inflation to radiation (preliminary)

- How to we reconcile with previous results? And does it matter if the black hole forms before reheating……




$\Theta^+\Theta^-$ (red: >0, blue: <0)
$\Theta^+\Theta^- > 0$
$\Theta^+\Theta^- < 0$
Black hole
Apparent horizon
Potential maximum $h = h_{\max}$
First radiation slice: $\rho_h \geq 0$ everywhere
t
r
0
200
400
600
800
1000
0
5
10
15
20
25
30
35
40

Conclusions and future directions

- Rich structure emerges when black holes form due to a Higgs potential, with positive maximum and negative true vacuum
- By the end, the unstable region is hidden behind horizons in both branches
- This is not true for the case where the black hole forms during inflation……
- ….but once radiation is entered, preliminary results show the negative energy region dissipates and the subsequent evolution is similar to the radiation only case
- What is the mass spectrum of the black holes? (ongoing)
- What happens in non-spherically symmetric cases? (ongoing)