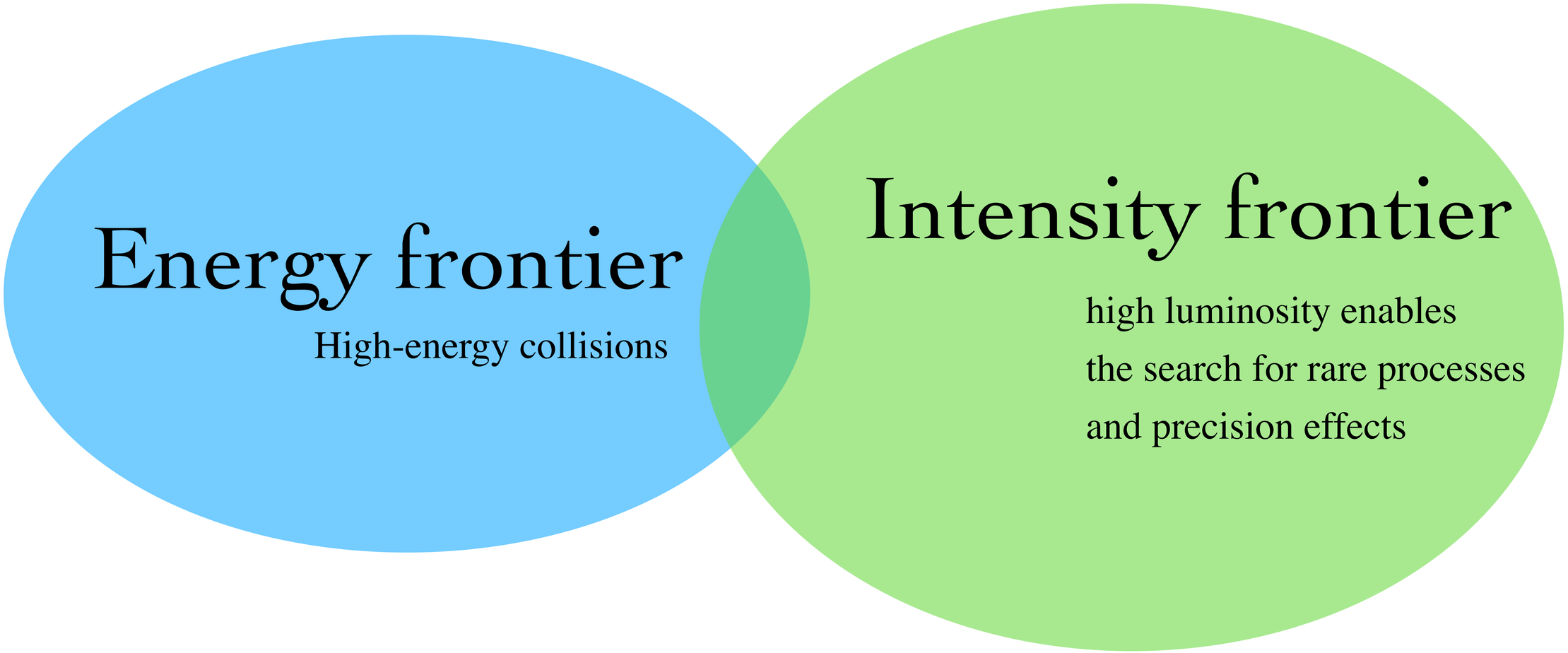
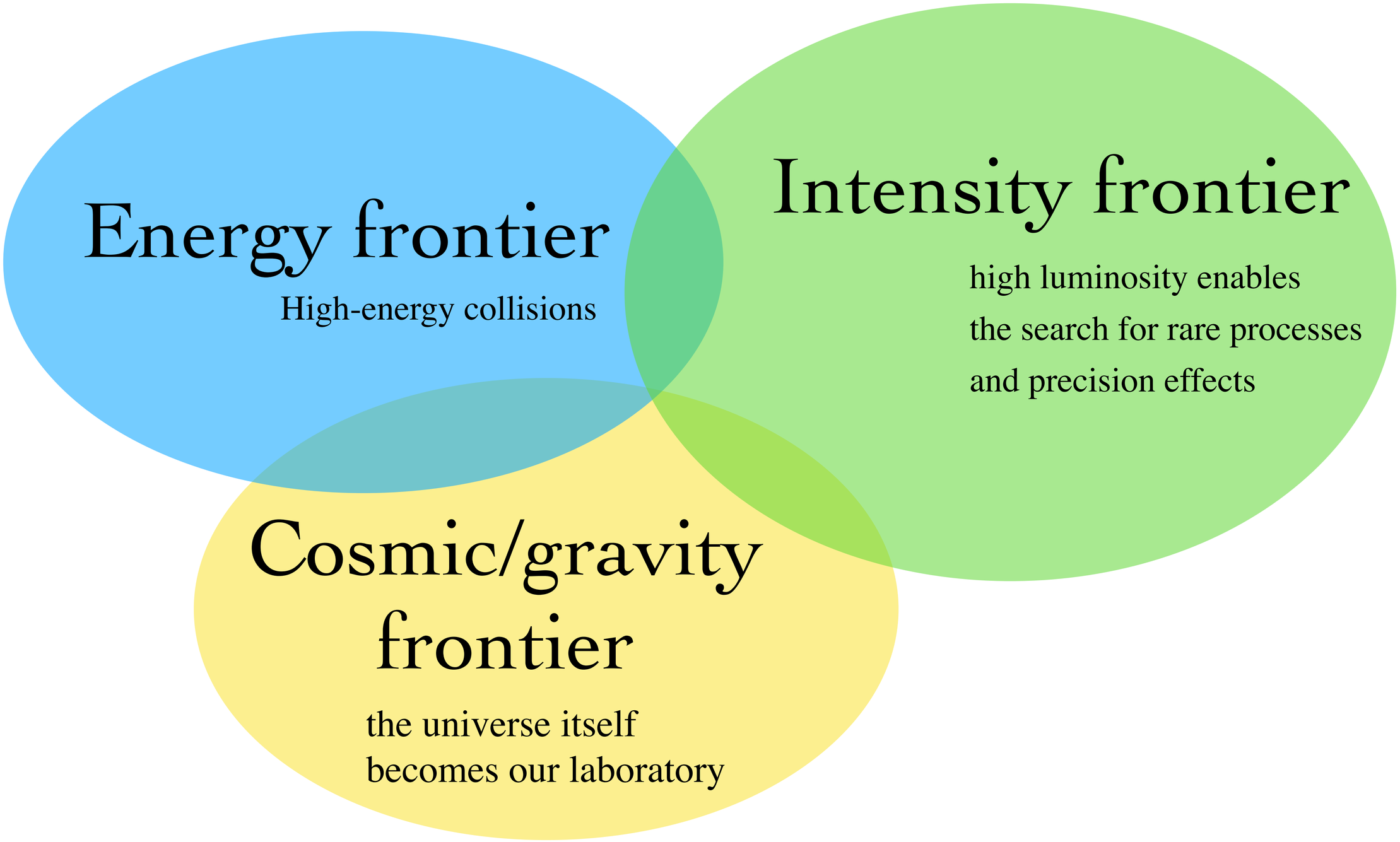
Higgs physics and Early Universe cosmology

Alfredo Urbano
Sapienza University of Rome & INFN, sez. ROMA 1

Higgs Hunting 2025
Paris, 15-17 July 2025

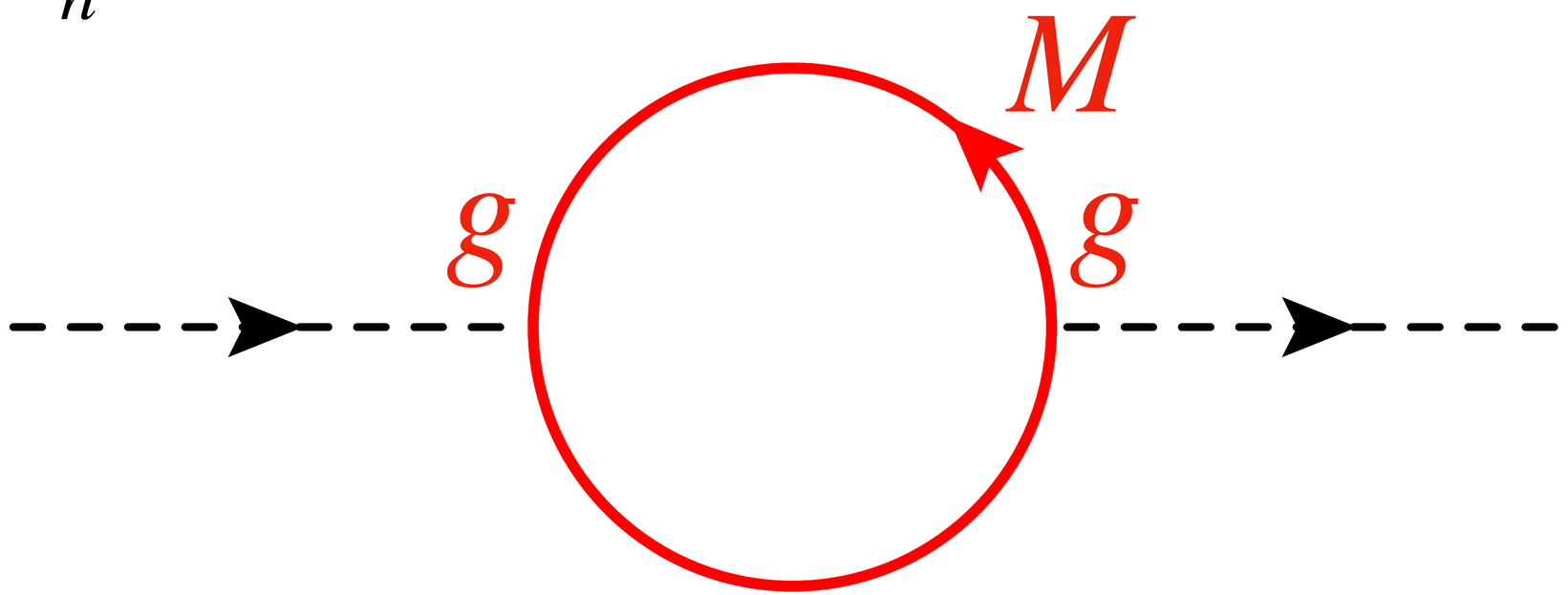

Energy frontier
High-energy collisions
Intensity frontier
high luminosity enables
the search for rare processes
and precision effects


Energy frontier
High-energy collisions
Intensity frontier
high luminosity enables
the search for rare processes
and precision effects
Cosmic/gravity
frontier
the universe itself
becomes our laboratory

Higgs and naturalness

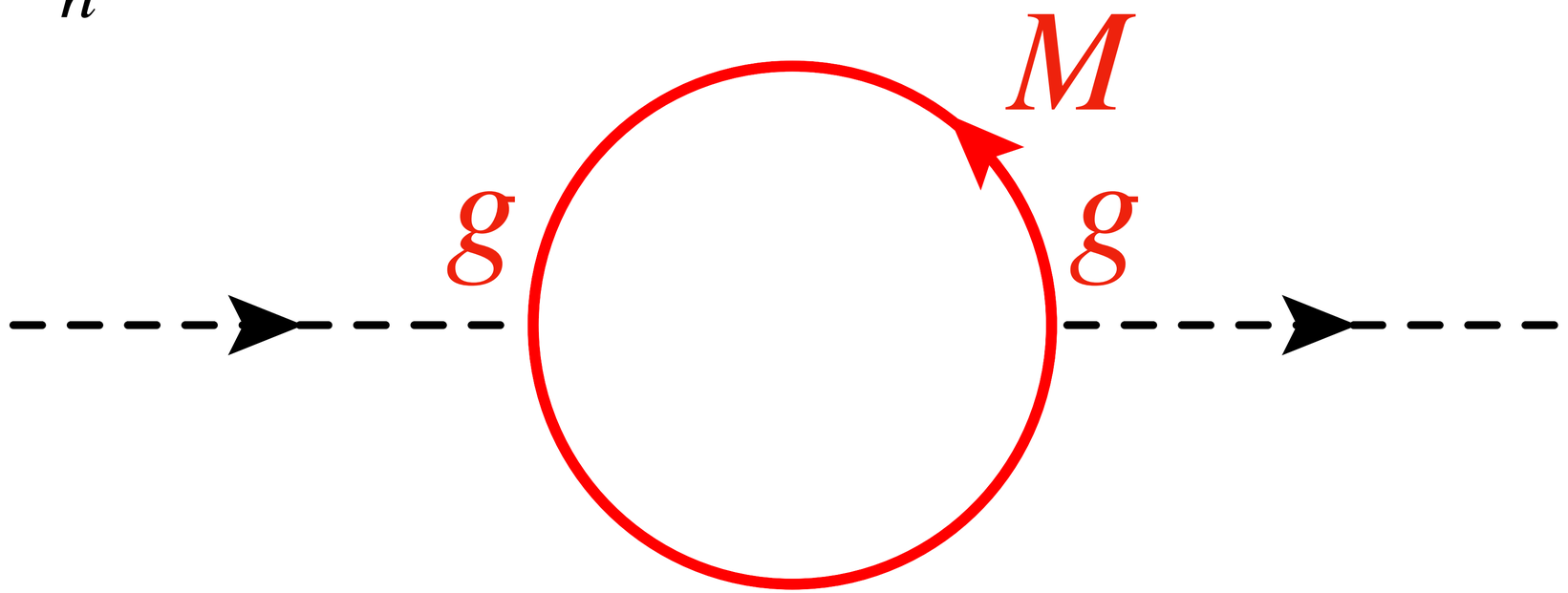
In a nutshell, a theory is natural if the contribution to the Higgs mass δM_h arising from quantum corrections is not larger than Higgs pole mass $M_h \approx 125$ GeV.

In a nutshell, a theory is natural if the contribution to the Higgs mass δM_h arising from quantum corrections is not larger than Higgs pole mass $M_h \approx 125$ GeV.



$$\delta M_h^2 \approx \frac{g^2 M^2}{(4\pi)^2}$$

In a nutshell, a theory is natural if the contribution to the Higgs mass δM_h arising from quantum corrections is not larger than Higgs pole mass $M_h \approx 125$ GeV.



$$M \lesssim \frac{4M_h\pi}{g}$$

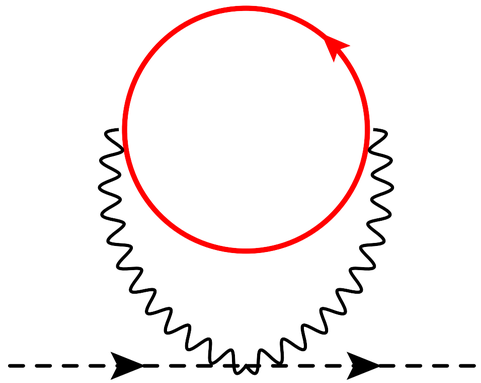
M [GeV]

10^7

10^5

10^4

10^3



Minimal Dark Matter

Cirelli, Fornengo, Strumia [arXiv:hep-ph/0512090]

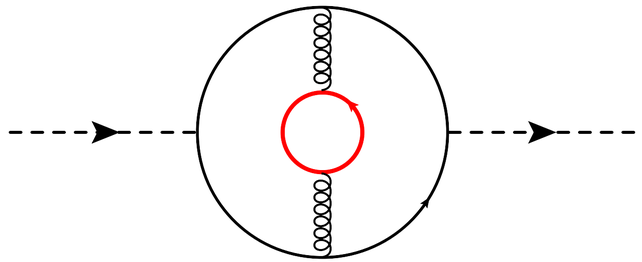
M [GeV]

10^7

10^5

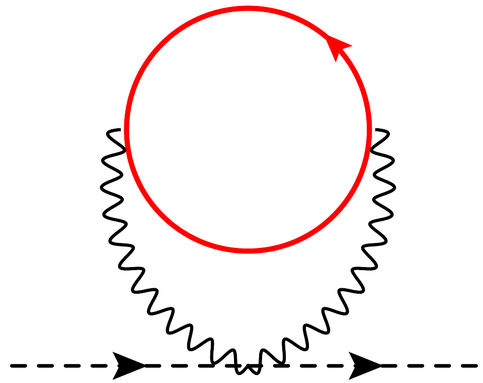
10^4

10^3



KSVZ fermions

Farina, Pappadopulo, Strumia [arXiv:1303.7244]



Minimal Dark Matter

Cirelli, Fornengo, Strumia [arXiv:hep-ph/0512090]

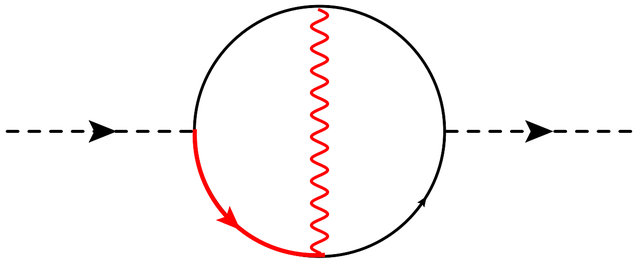
M [GeV]

10^7

10^5

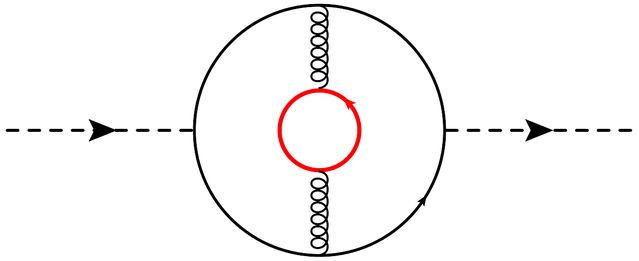
10^4

10^3



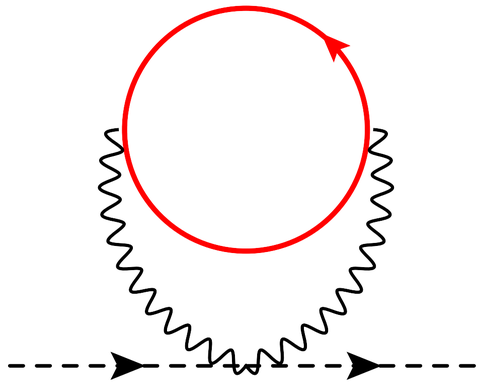
Vector Leptoquarks

Fileviez Pérez, Murgui, Patrone, Testa, Wise [arXiv:2308.07367]



KSVZ fermions

Farina, Pappadopulo, Strumia [arXiv:1303.7244]



Minimal Dark Matter

Cirelli, Fornengo, Strumia [arXiv:hep-ph/0512090]

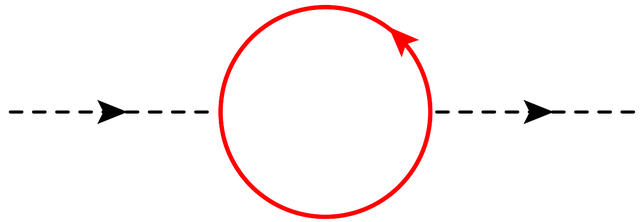
M [GeV]

10^7

10^5

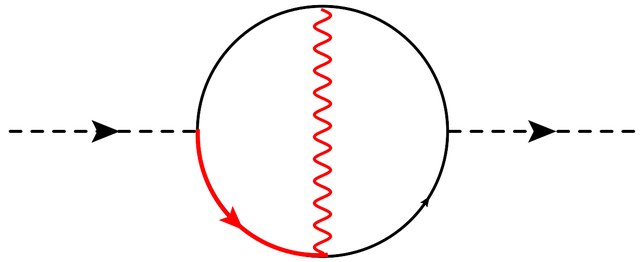
10^4

10^3



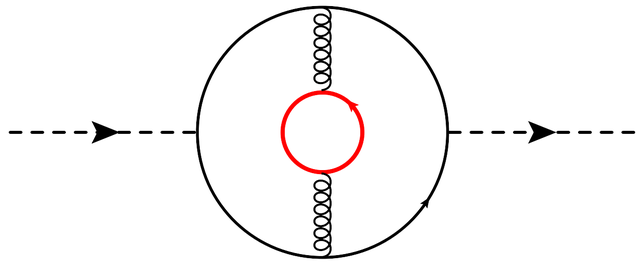
type-I Seesaw

Vissani [arXiv:hep-ph/9709409]



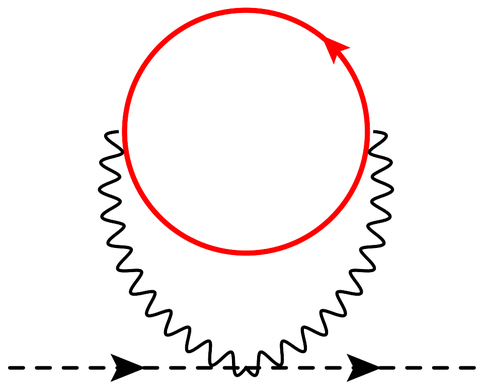
Vector Leptoquarks

Fileviez Pérez, Murgui, Patrone, Testa, Wise [arXiv:2308.07367]



KSVZ fermions

Farina, Pappadopulo, Strumia [arXiv:1303.7244]



Minimal Dark Matter

Cirelli, Fornengo, Strumia [arXiv:hep-ph/0512090]

What if we consider a mass scale completely decoupled from the SM?

In other words, what is the highest natural scale?

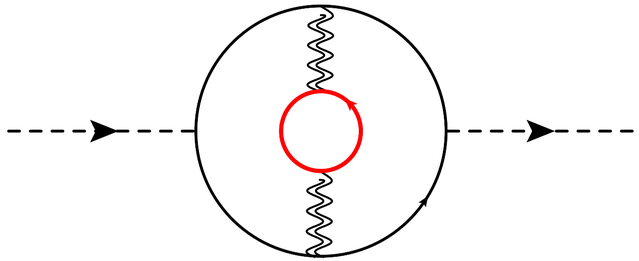
What if we consider a mass scale completely decoupled from the SM?

In other words, what is the highest natural scale?

The sole and unavoidable exception to this decoupling arises from gravitational interactions.

M [GeV]

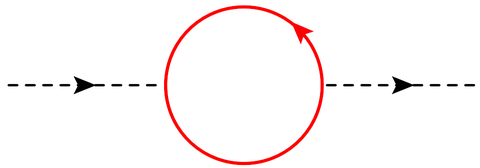
10^{14}



$$\delta M_h^2 \sim \frac{y_t^2 M^6}{M_{Pl}^4 (4\pi)^6}$$

de Gouvea, Hernandez, Tait [arXiv:1402.2658]

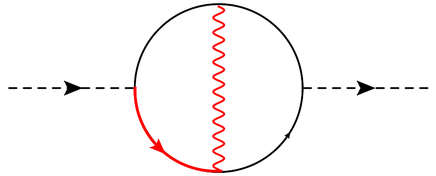
10^7



type-I Seesaw

Vissani [arXiv:hep-ph/9709409]

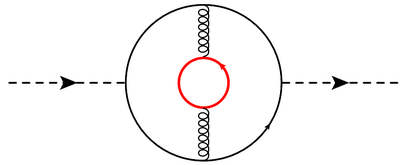
10^5



Vector Leptoquarks

Fileviez Pérez, Murgui, Patrone, Testa, Wise [arXiv:2308.07367]

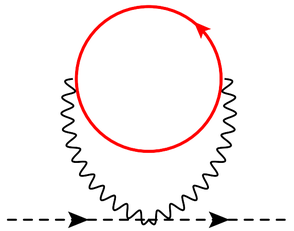
10^4



KSVZ fermions

Farina, Pappadopulo, Strumia [arXiv:1303.7244]

10^3

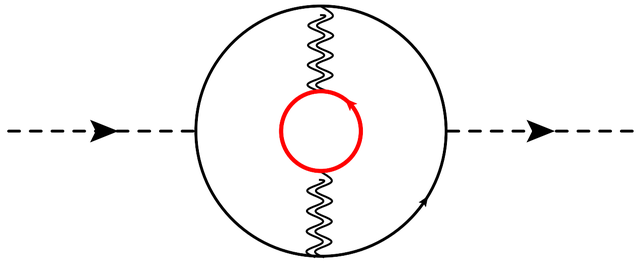


Minimal Dark Matter

Cirelli, Fornengo, Strumia [arXiv:hep-ph/0512090]

M [GeV]

10^{14}

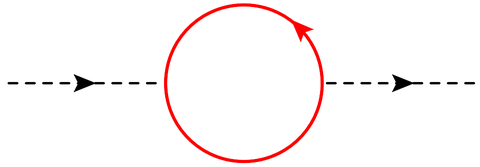


$$\delta M_h^2 \sim \frac{y_t^2 M^6}{M_{Pl}^4 (4\pi)^6}$$

de Gouvea, Hernandez, Tait [arXiv:1402.2658]

Inflation is a natural theory

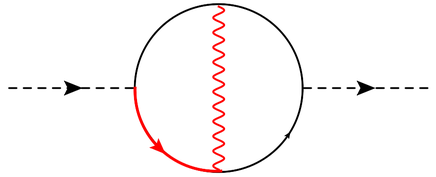
10^{7}



type-I Seesaw

Vissani [arXiv:hep-ph/9709409]

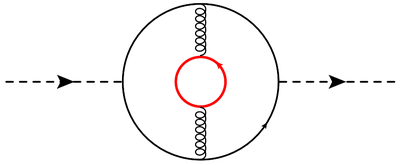
10^{5}



Vector Leptoquarks

Fileviez Pérez, Murgui, Patrone, Testa, Wise [arXiv:2308.07367]

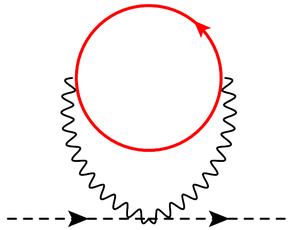
10^{4}



KSVZ fermions

Farina, Pappadopulo, Strumia [arXiv:1303.7244]

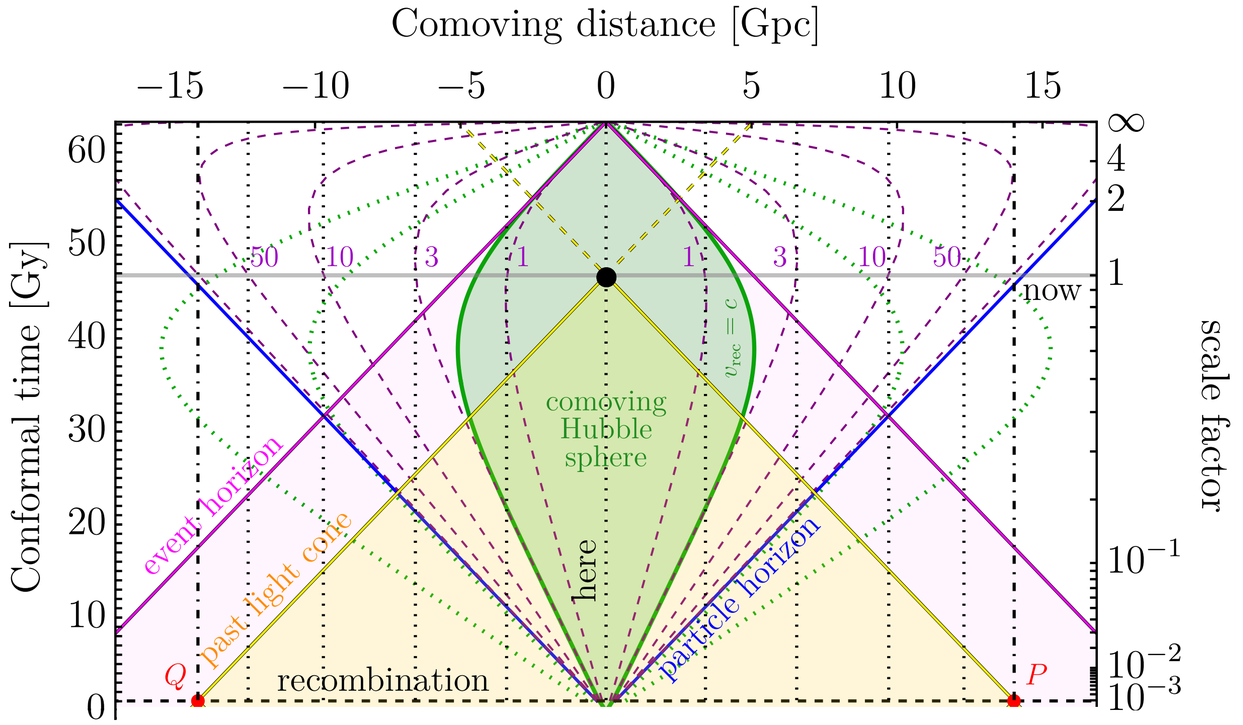
10^{3}



Minimal Dark Matter

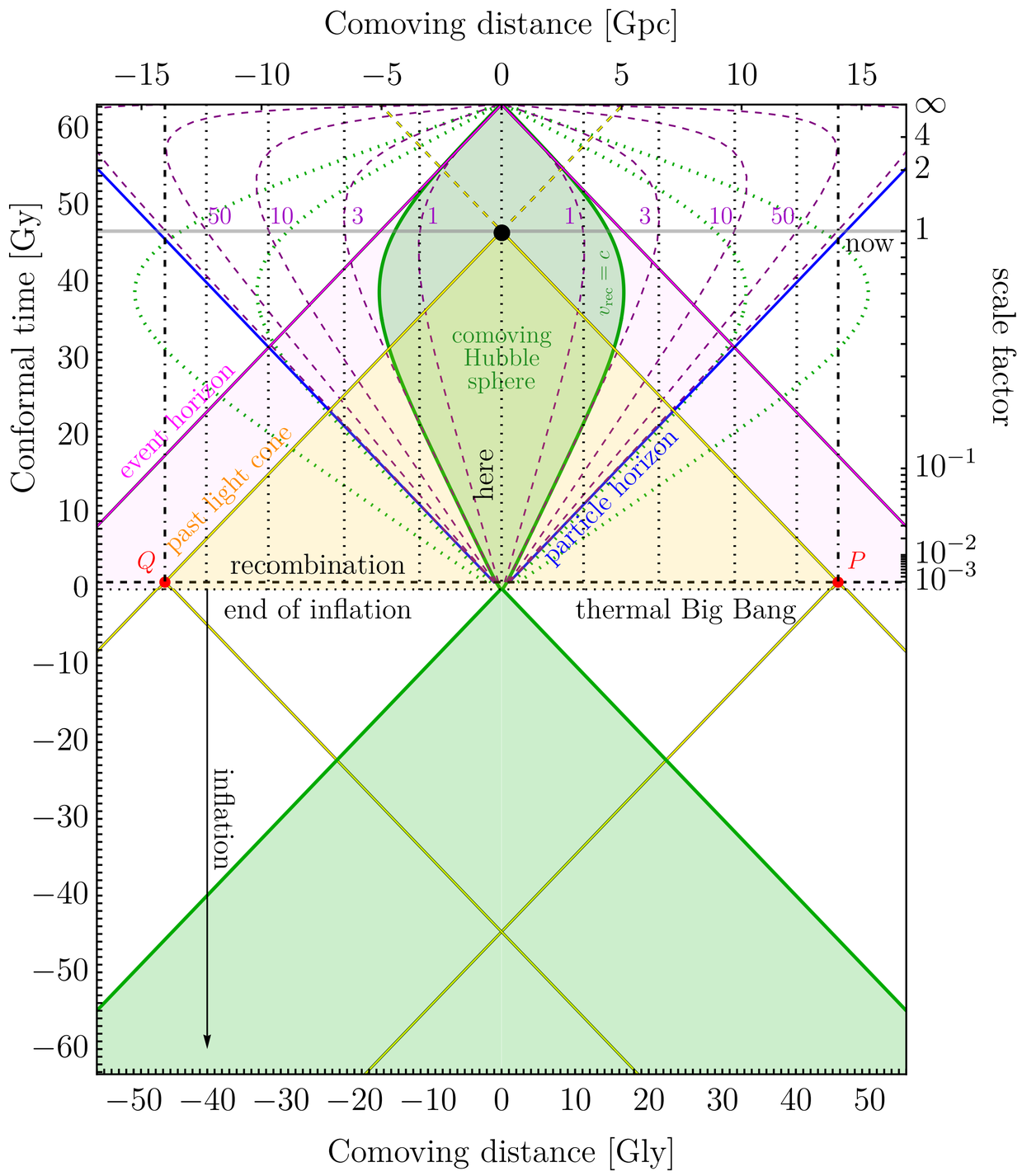
Cirelli, Fornengo, Strumia [arXiv:hep-ph/0512090]

Points like **Q** and **P** on opposite sides of the last scattering surface were never in causal contact before recombination — yet the CMB is remarkably uniform to one part in 10^5

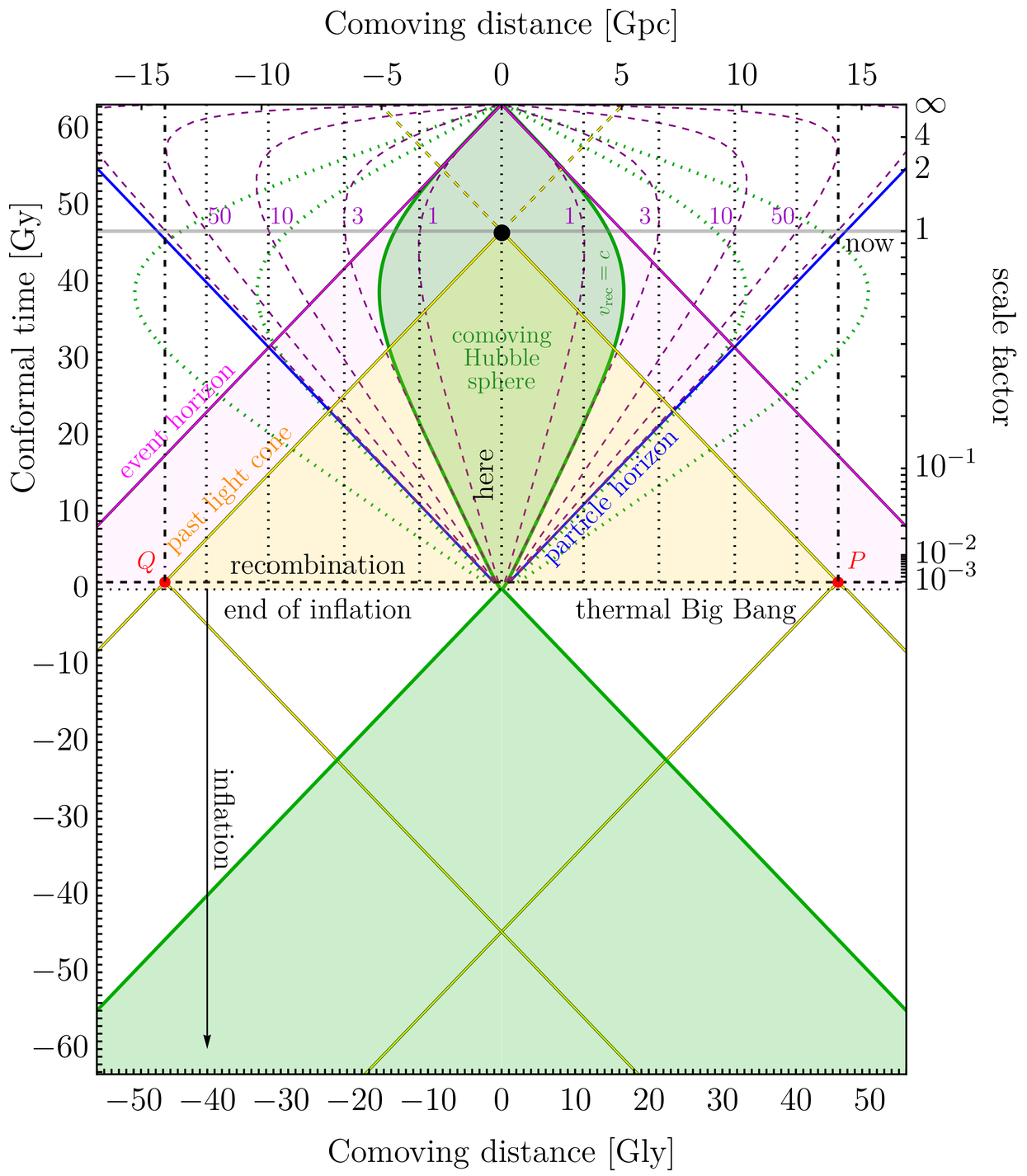


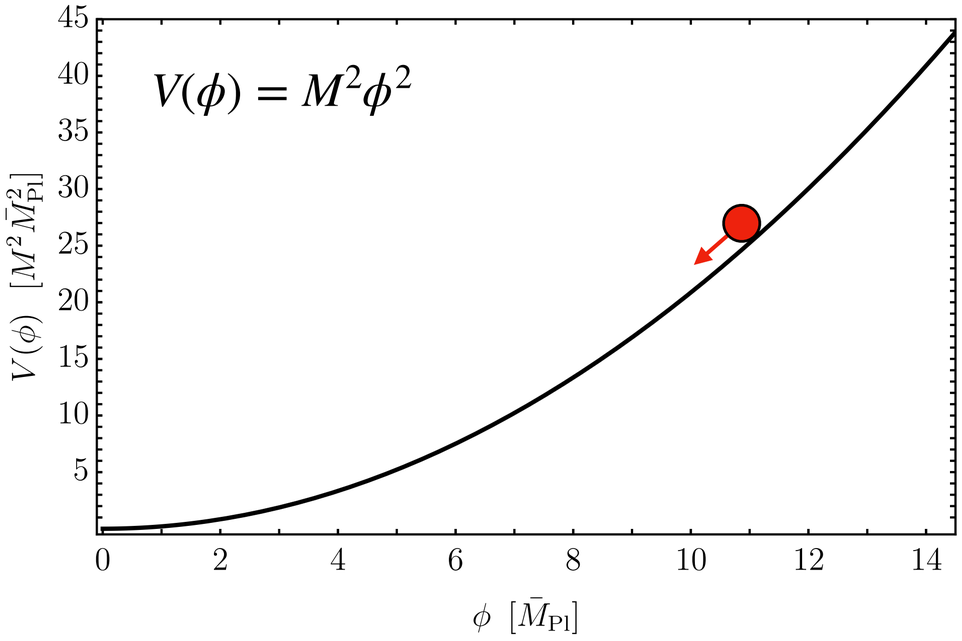
Points like **Q** and **P** on opposite sides of the last scattering surface were never in causal contact before recombination — yet the CMB is remarkably uniform to one part in 10^5

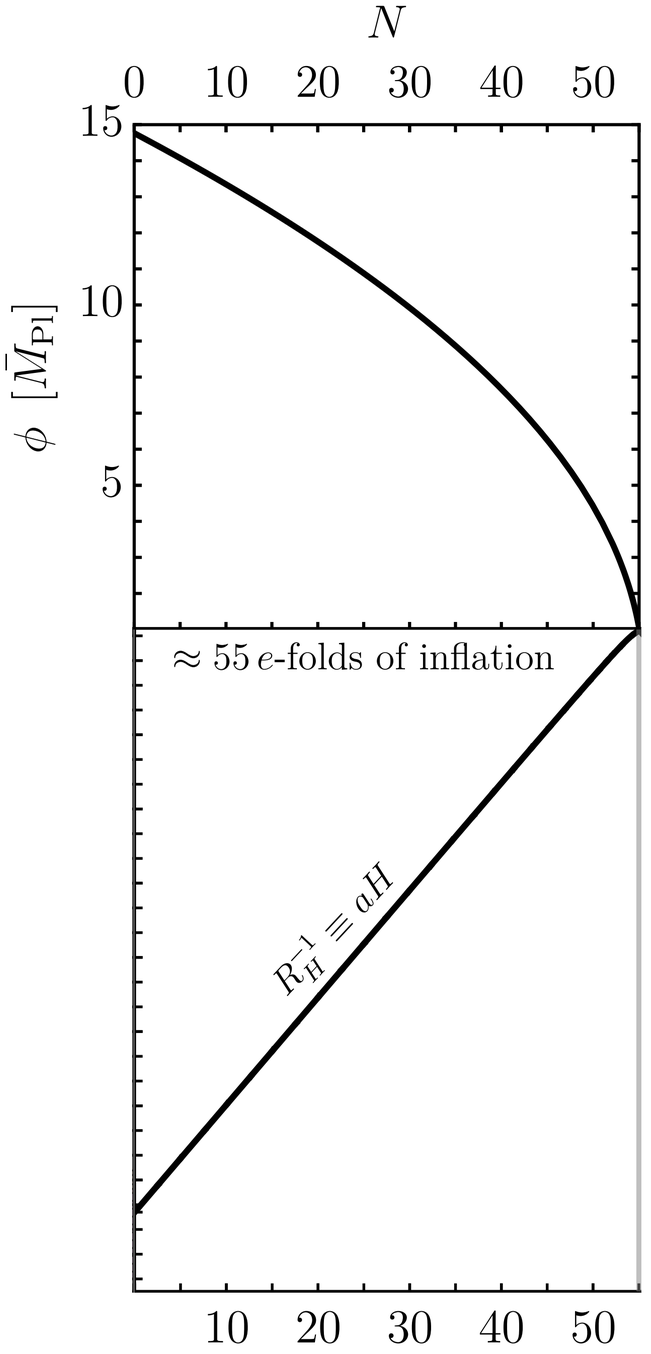
A phase of accelerated expansion $a(t) \sim e^{Ht}$ causes the comoving Hubble radius $R_H = 1/aH$ to shrink.
This allows distant regions today to have once been in causal contact



$$R = 12H^2 = 4\Lambda$$

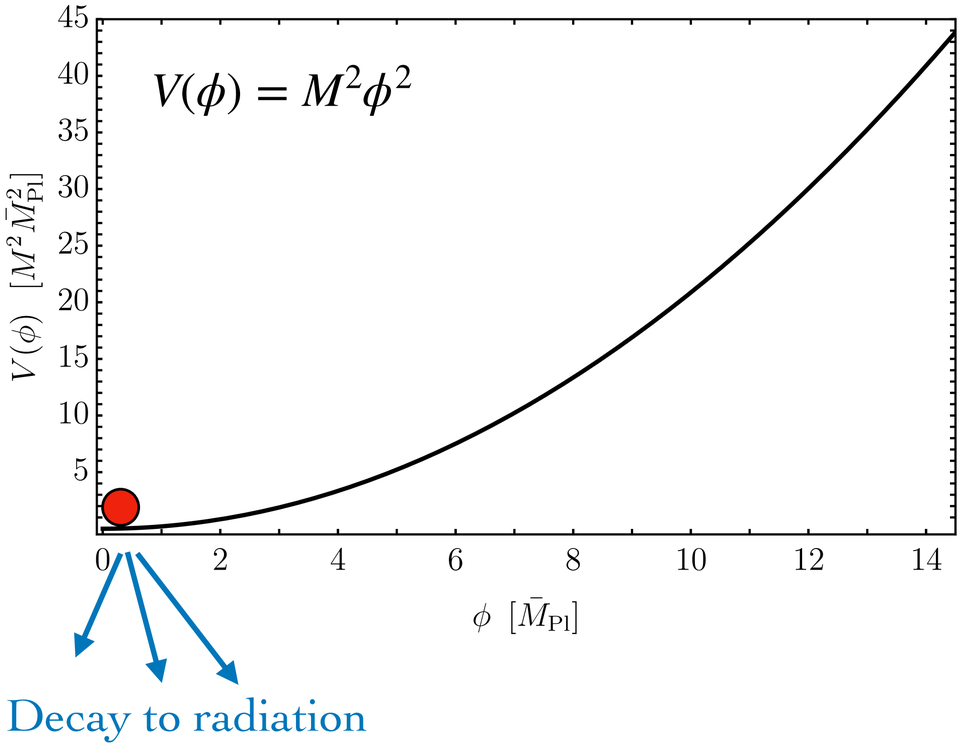


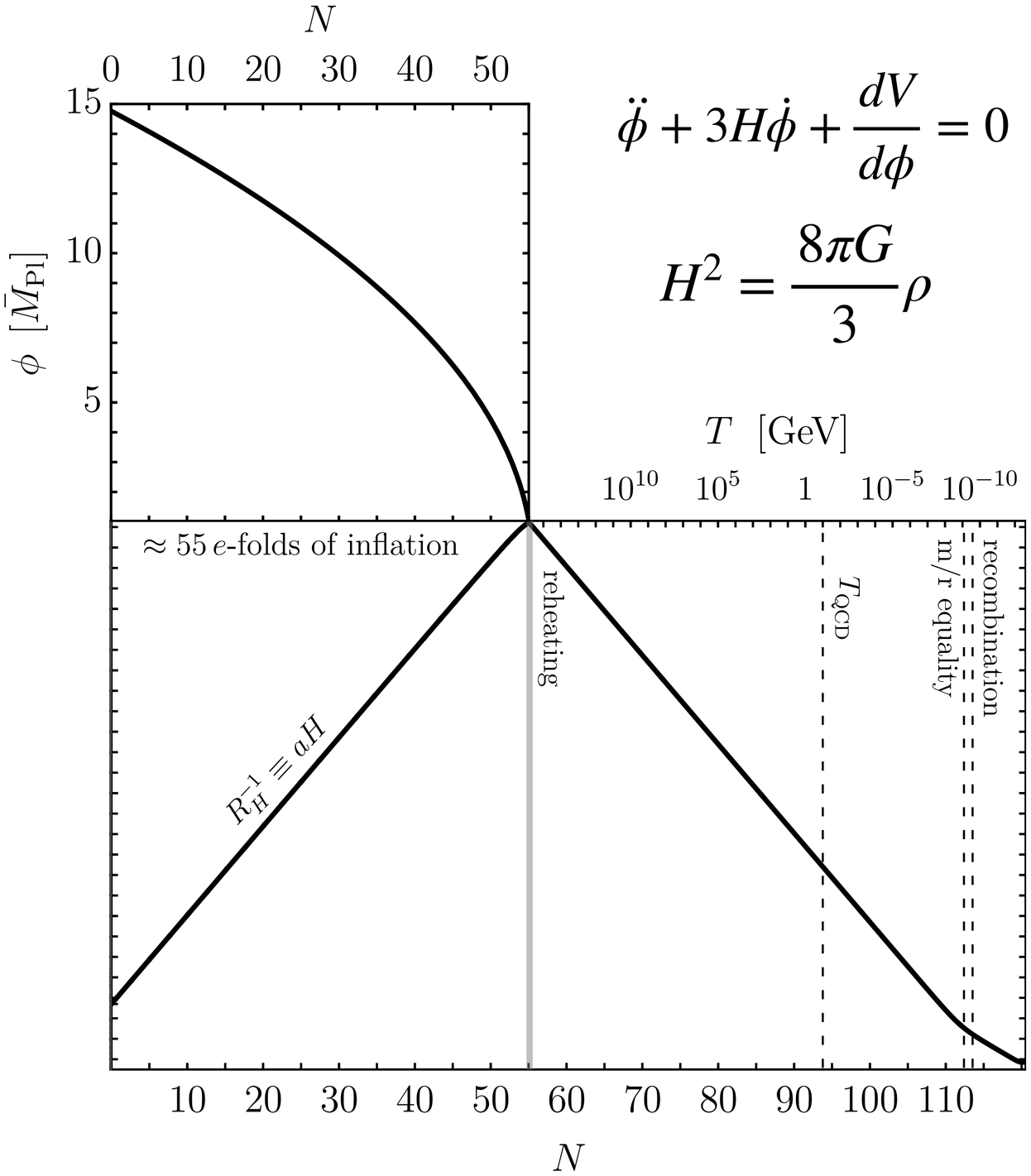


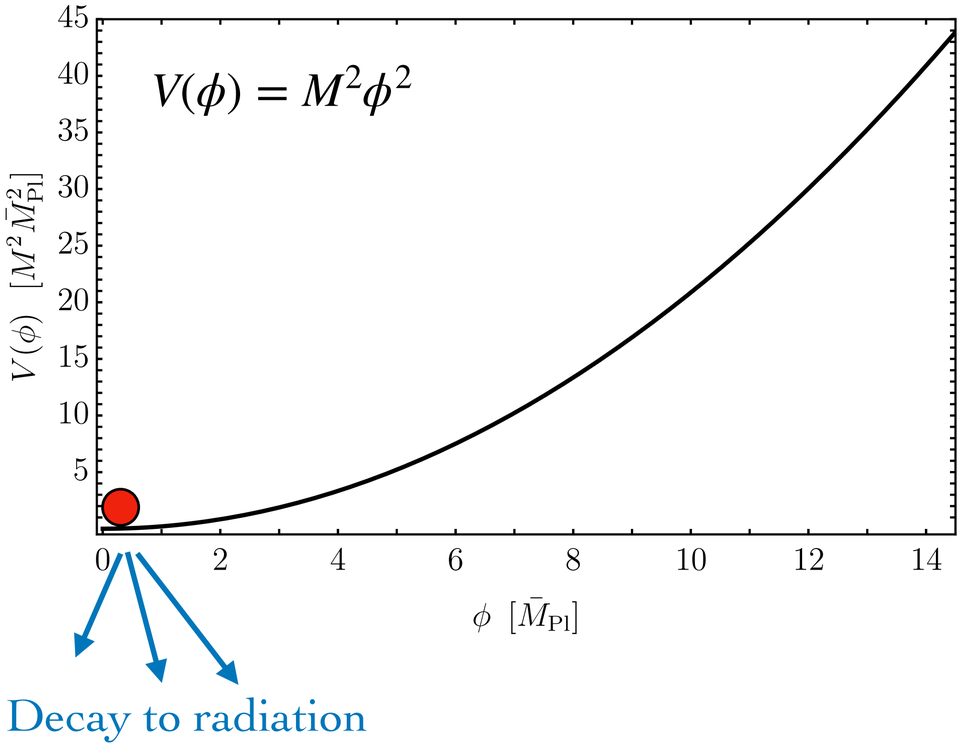


$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

$$H^2 = \frac{8\pi G}{3}\rho$$


$V(\phi) = M^2\phi^2$
$V(\phi)$ $[M^2\bar{M}_{\rm Pl}^2]$
ϕ $[\bar{M}_{\rm Pl}]$
Decay to radiation

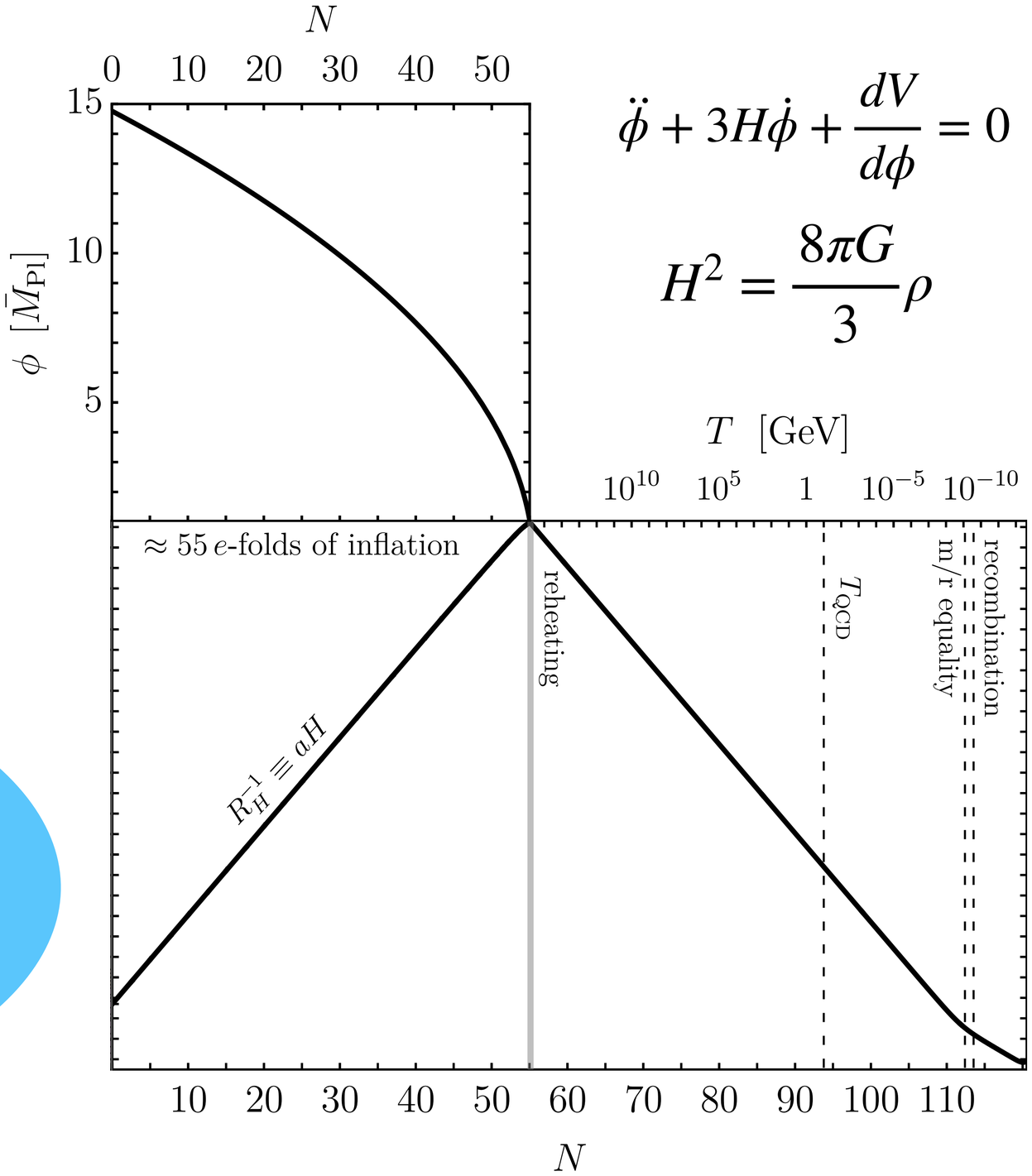

N
ϕ $[\bar{M}_{\rm Pl}]$
$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$
$H^2 = \frac{8\pi G}{3}\rho$
T [GeV]
10^{10} 10^{5} 1 10^{-5} 10^{-10}
$\approx 55\, e$-folds of inflation
$R_H^{-1} \equiv aH$
reheating
$T_{\rm QCD}$
m/r equality
recombination

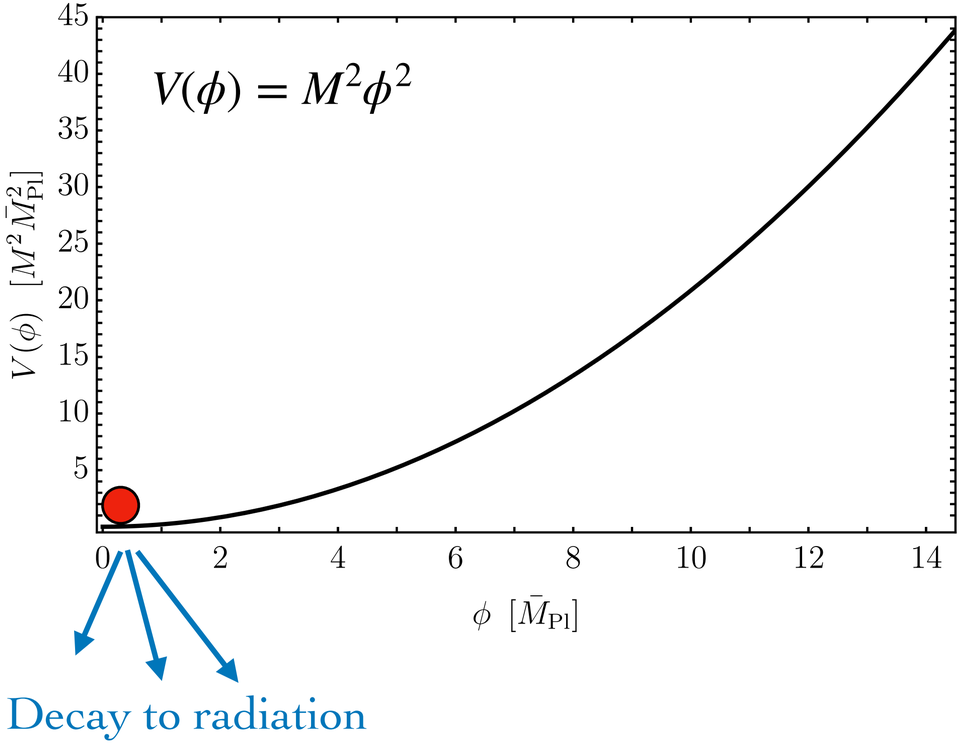


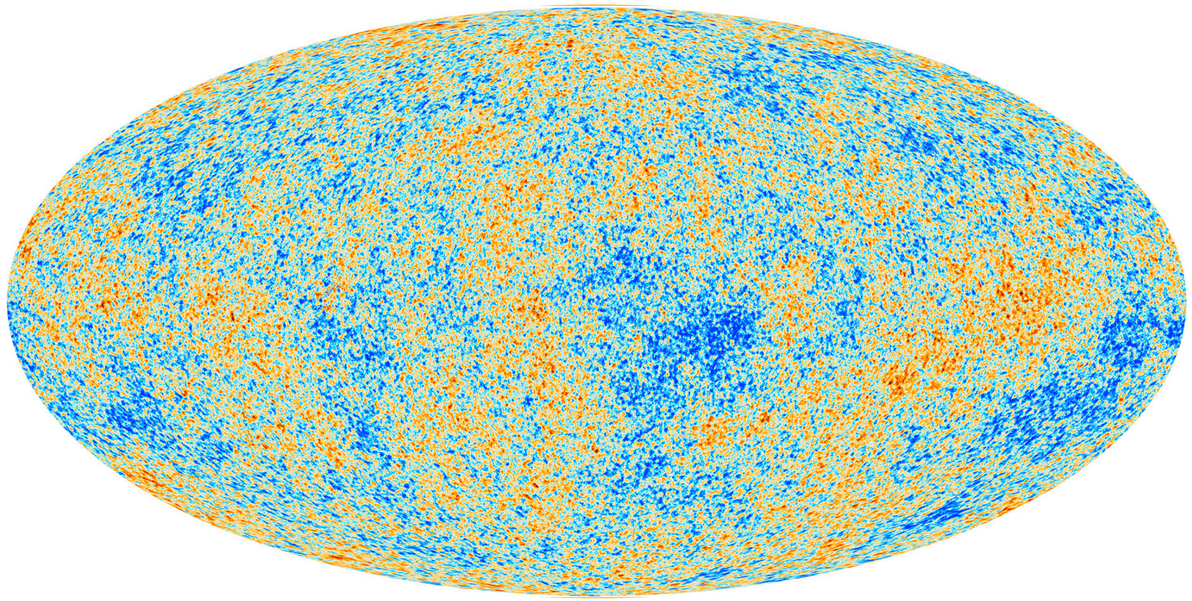
$$T_0 = 2.725\,K = 2.35 \times 10^{-13}\,\text{GeV}$$

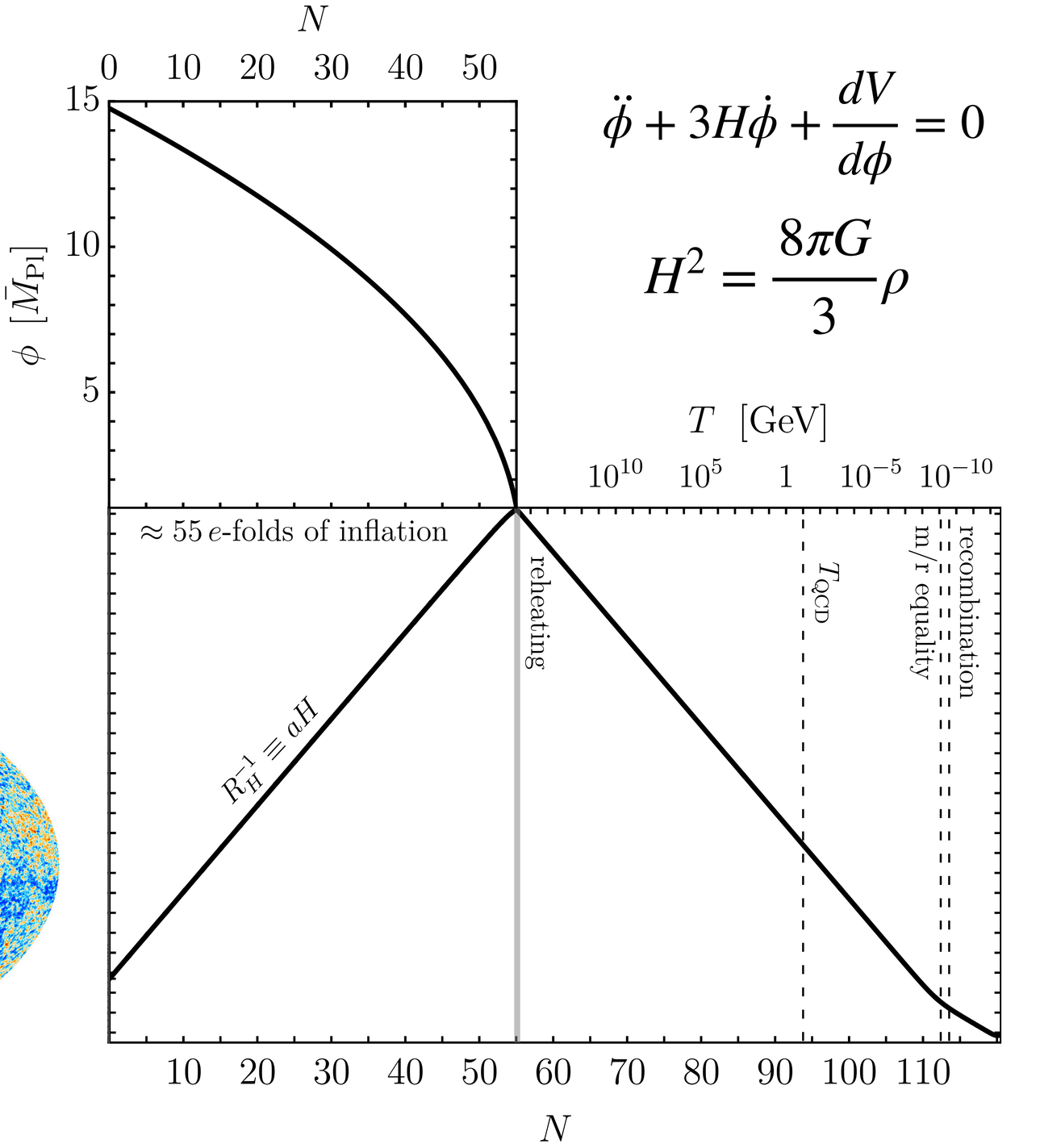
$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

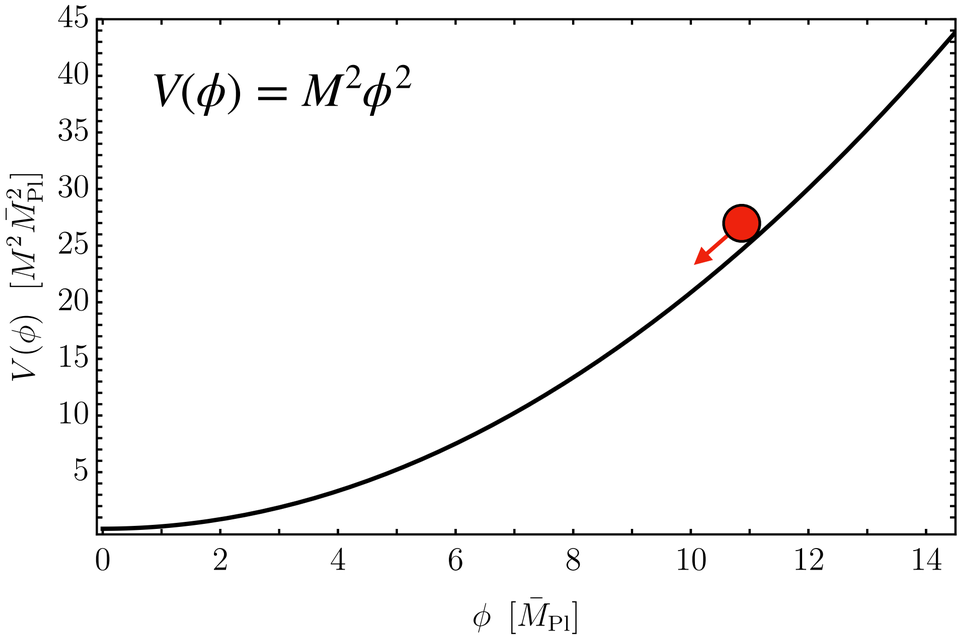
$$H^2 = \frac{8\pi G}{3}\rho$$



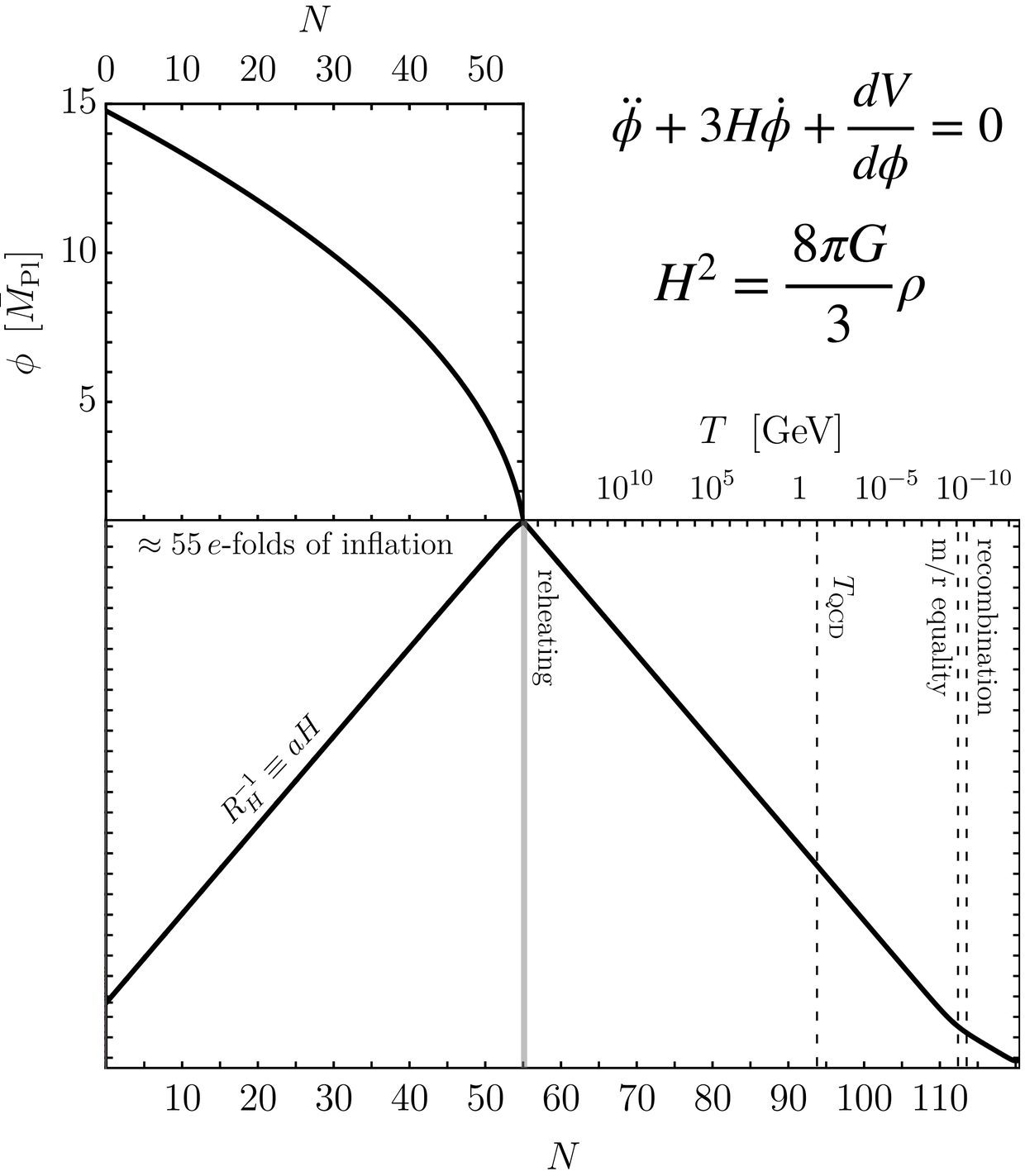

$V(\phi) = M^2\phi^2$
$V(\phi)$ $[M^2\bar{M}_{\rm Pl}^2]$
ϕ $[\bar{M}_{\rm Pl}]$
Decay to radiation

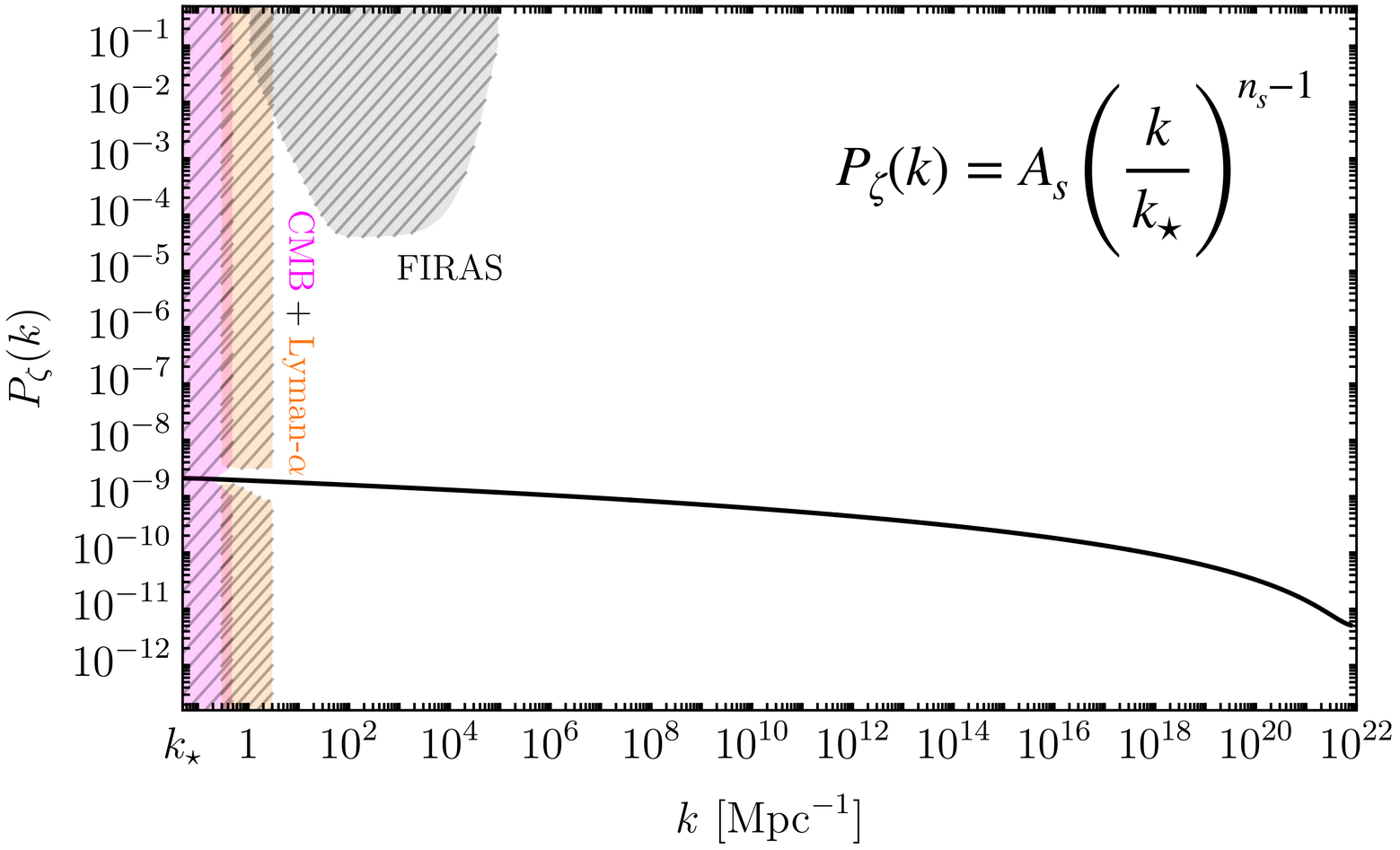



N
ϕ $[\bar{M}_{\rm Pl}]$
$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$
$H^2 = \frac{8\pi G}{3}\rho$
T [GeV]
$\approx 55\, e$-folds of inflation
$R_H^{-1} \equiv aH$
reheating
$T_{\rm QCD}$
m/r equality
recombination

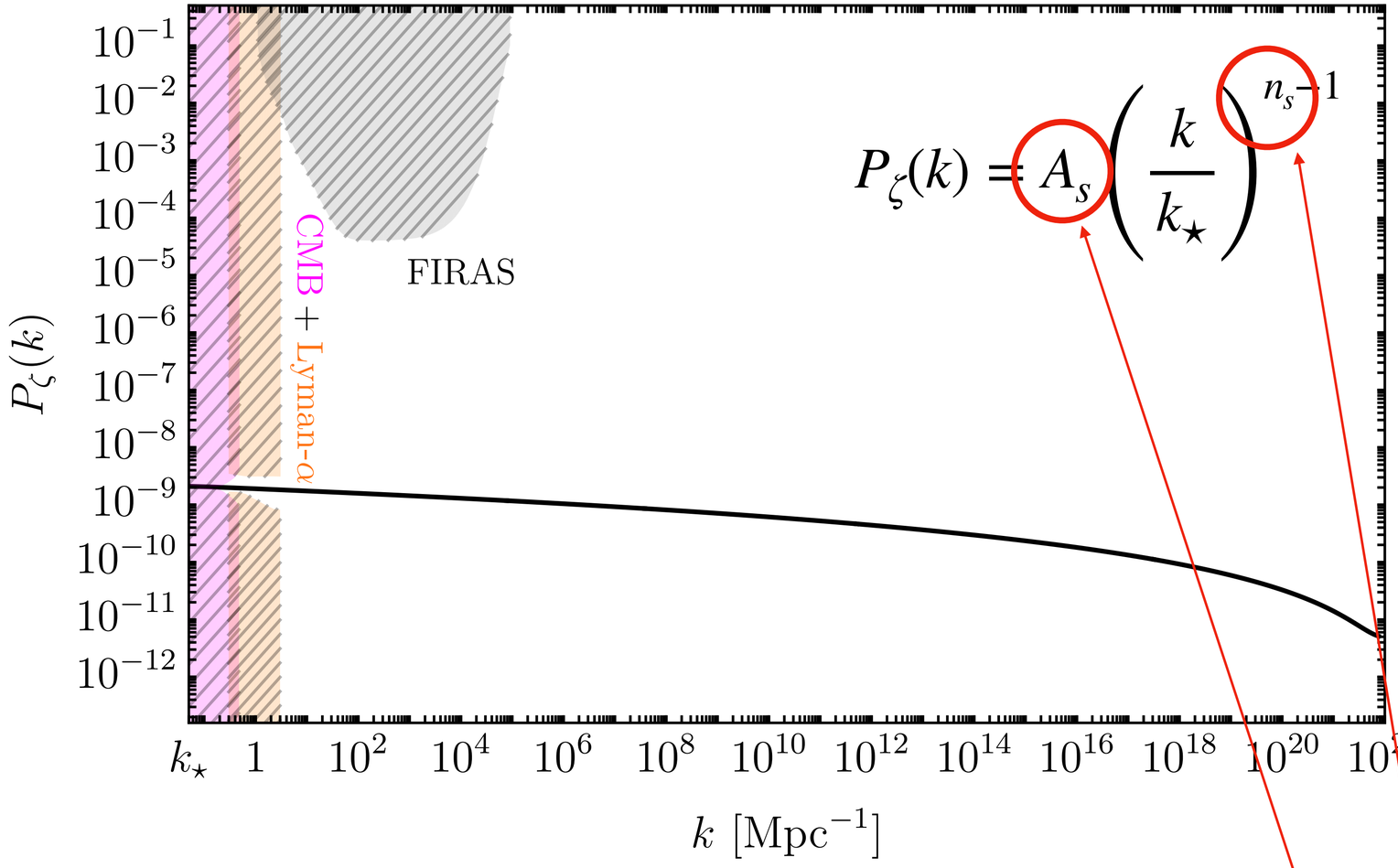


Inflation naturally produces tiny quantum fluctuations in the field and spacetime.
These primordial inhomogeneities seed the large-scale structures we observe today.





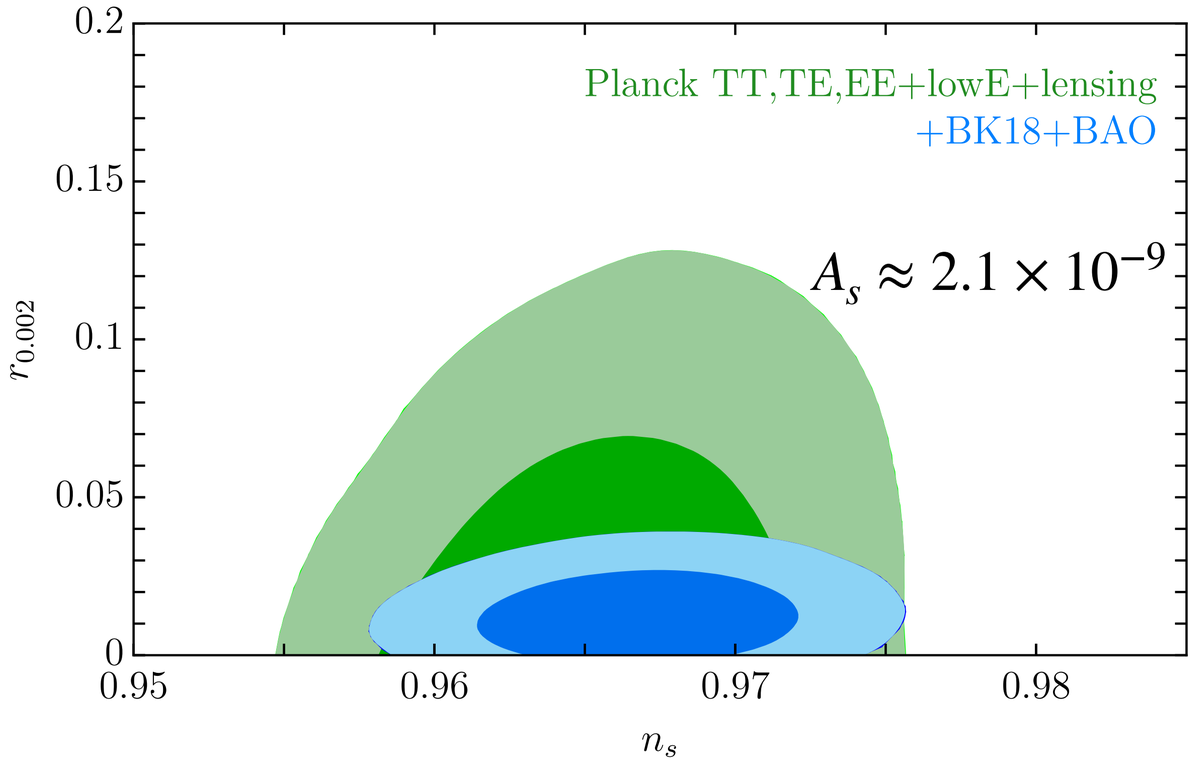
$$r \equiv \left. \frac{P_T(k)}{P_\zeta(k)} \right|_{k=0.002\ \mathrm{Mpc}^{-1}}$$

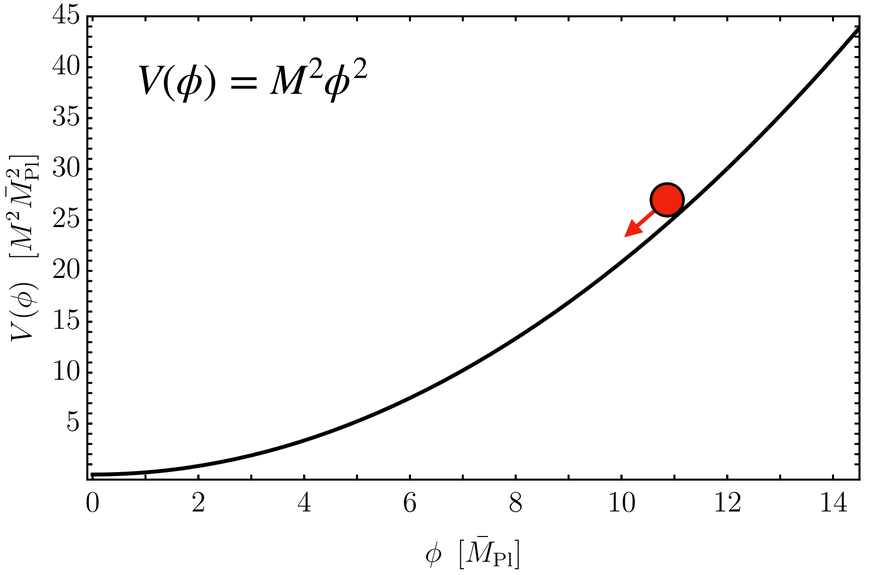


$$P_\zeta(k) \equiv A_s \left(\frac{k}{k_\star} \right)^{n_s - 1}$$

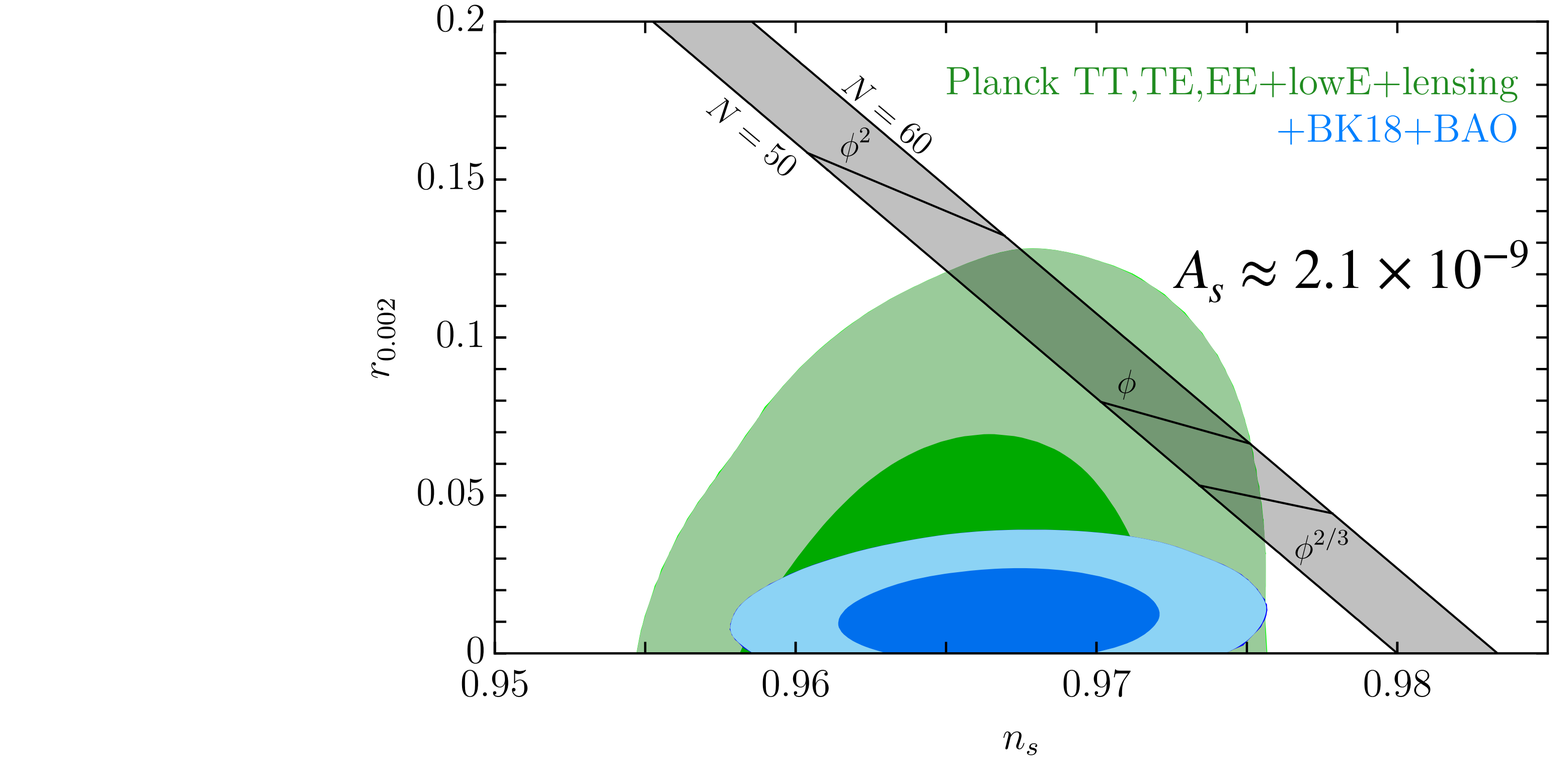
$$r \equiv \left. \frac{P_T(k)}{P_\zeta(k)} \right|_{k=0.002\ \mathrm{Mpc}^{-1}}$$

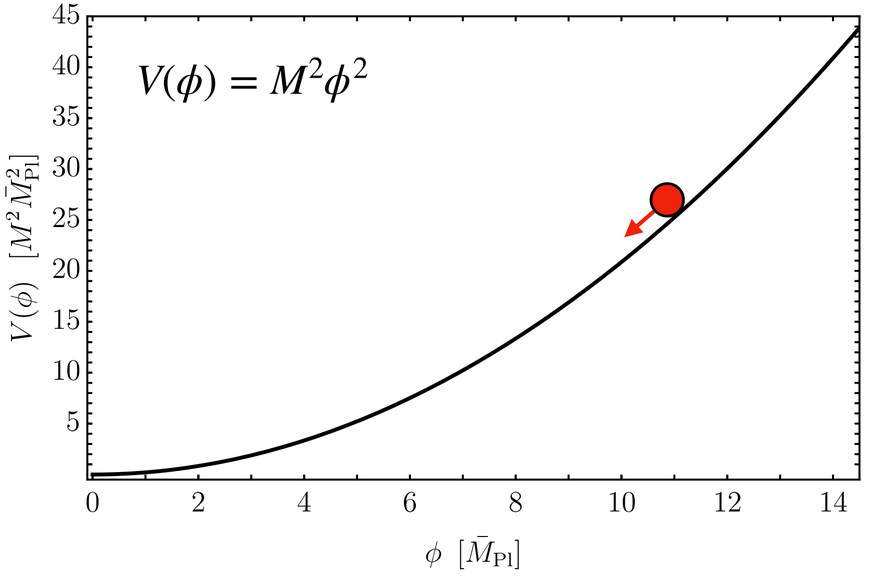
Key inflationary observables


Planck TT,TE,EE+lowE+lensing
+BK18+BAO
$A_s \approx 2.1 \times 10^{-9}$
$r_{0.002}$
n_s
0.2
0.15
0.1
0.05
0
0.95
0.96
0.97
0.98

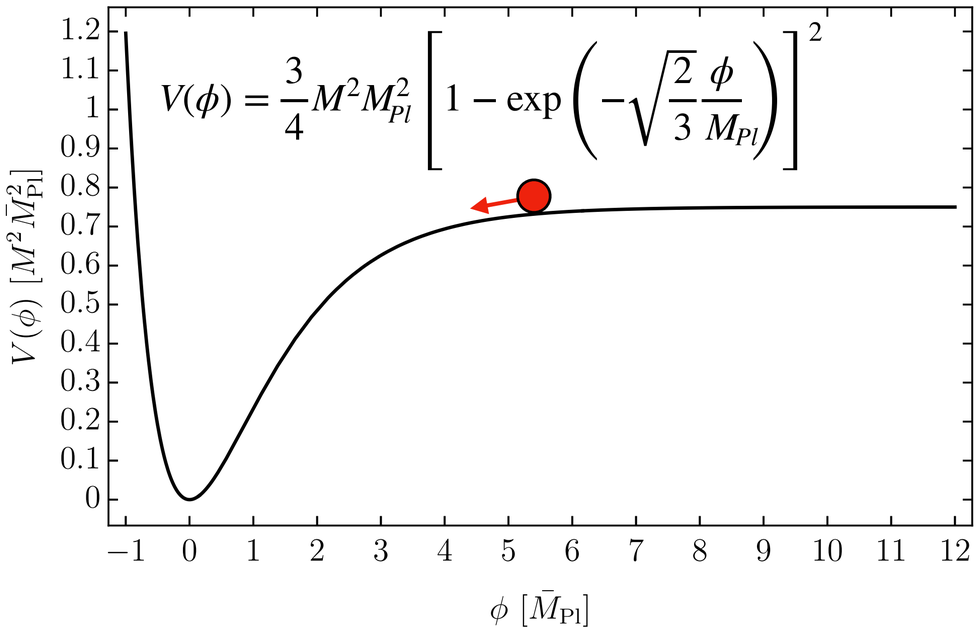


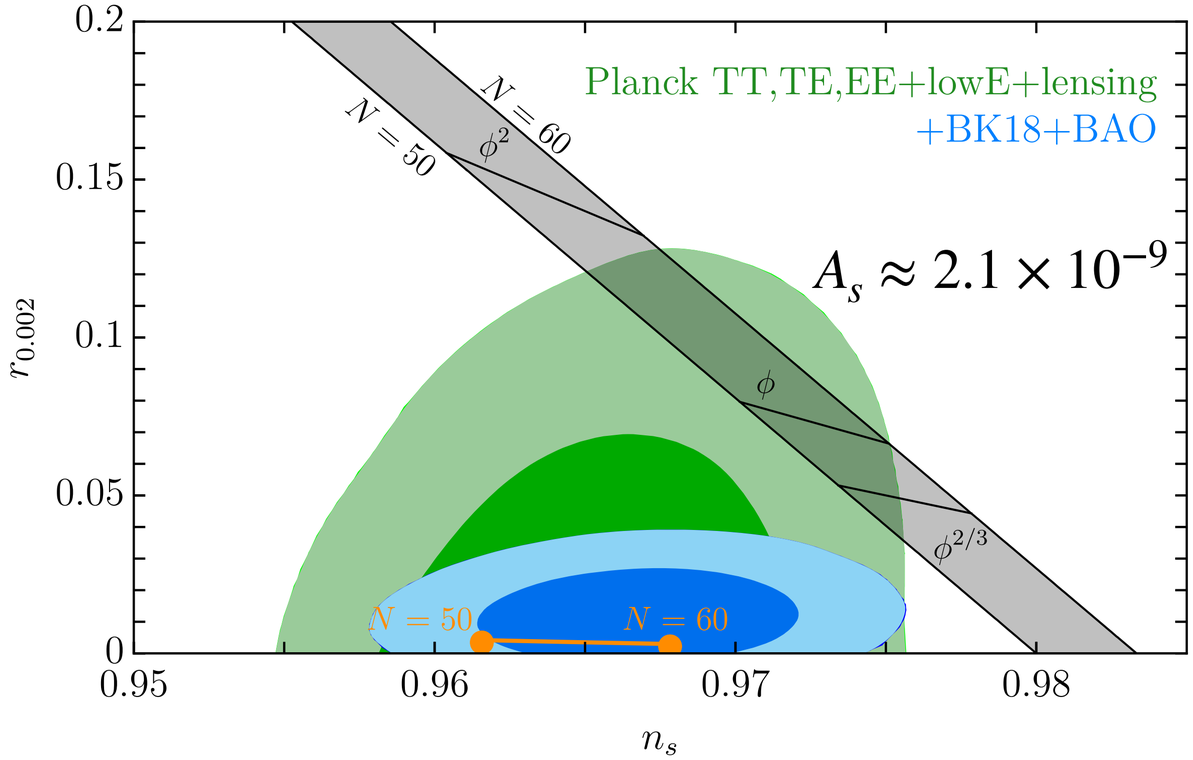
$$M \approx 10^{13}\,\mathrm{GeV}$$

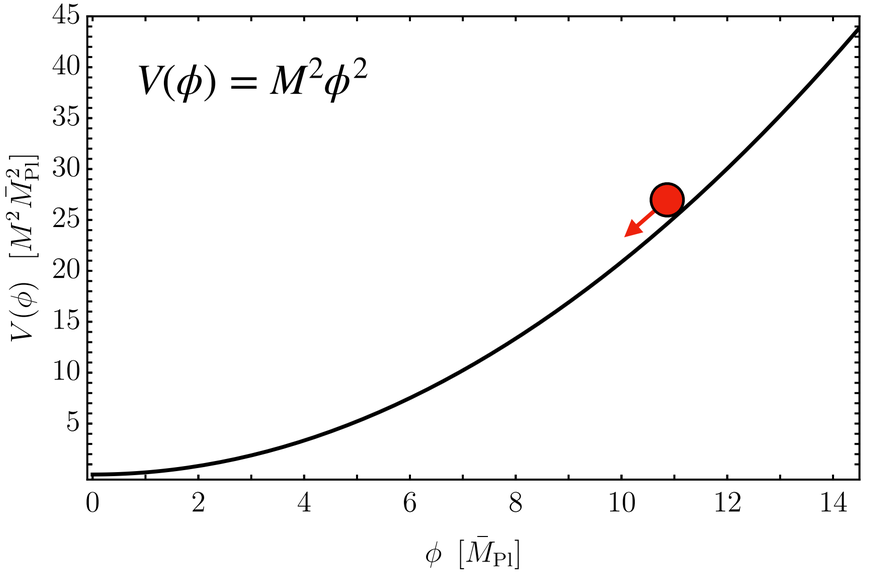




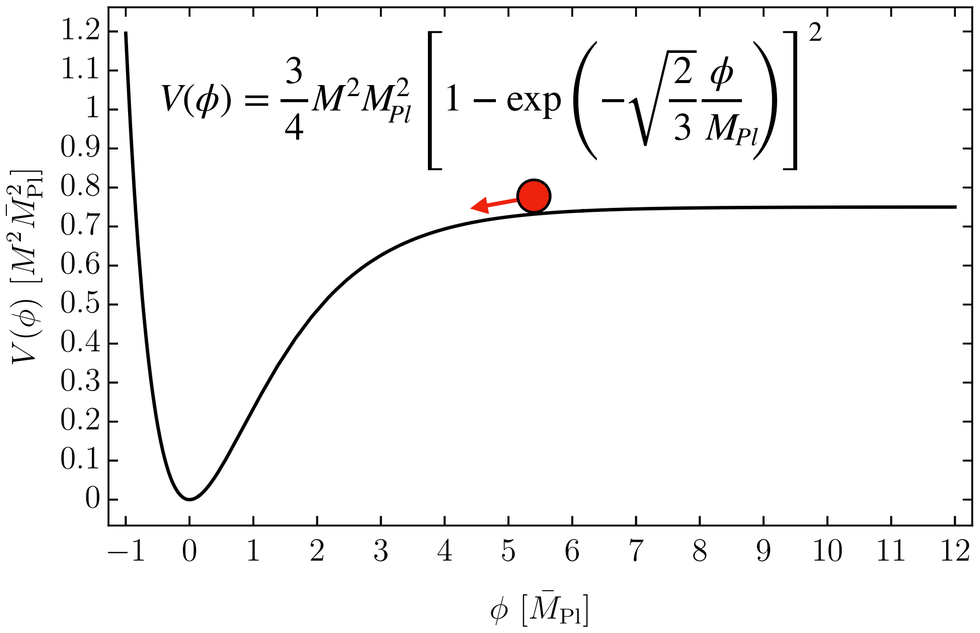
$$M \approx 10^{13}\,\mathrm{GeV}$$

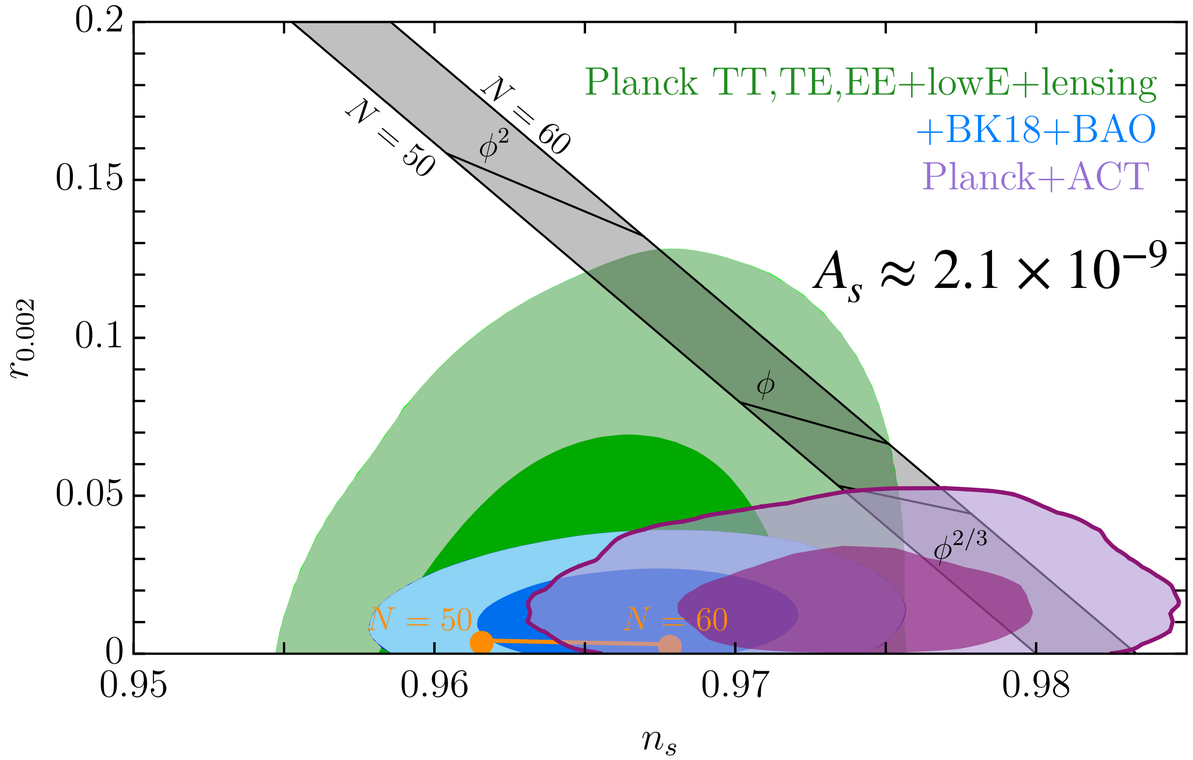






$$M \approx 10^{13}\,\mathrm{GeV}$$

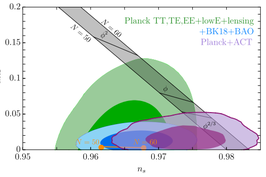


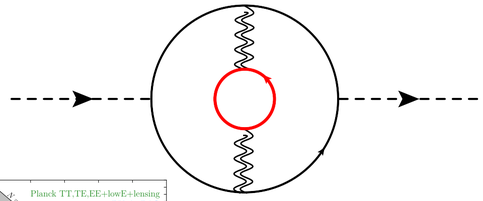


M [GeV]

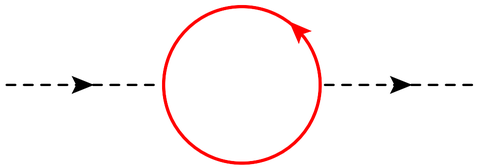
10^{14}

10^{13}

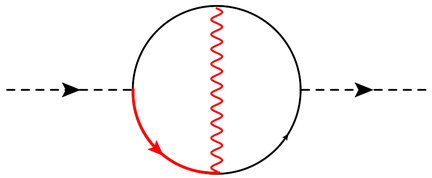




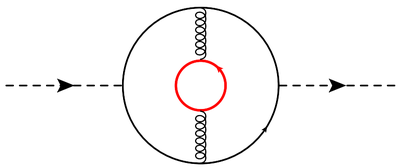
10^{7}



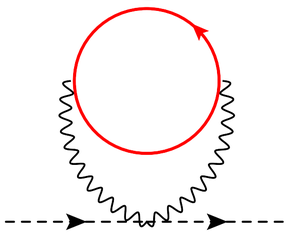
10^{5}



10^{4}



10^{3}

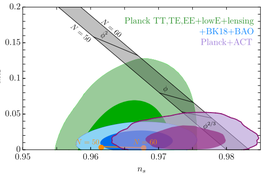


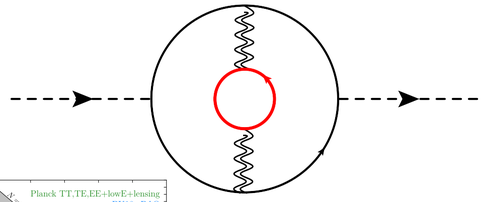
Is inflation a natural theory?

M [GeV]

10^{14}

10^{13}



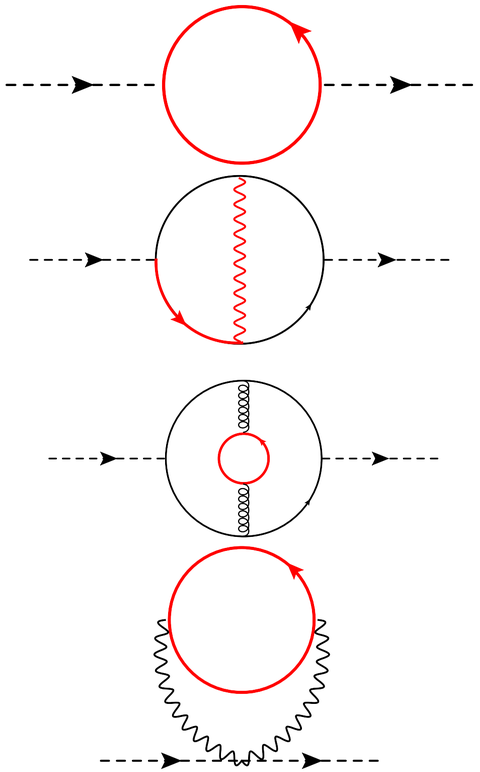


10^{7}

10^{5}

10^{4}

10^{3}



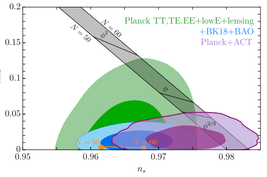
Is inflation a natural theory?

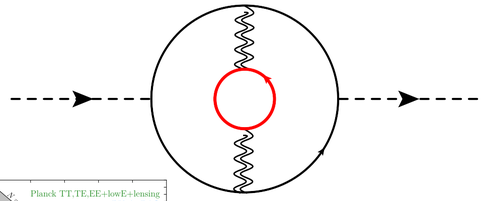
$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\left(\frac{1}{2}\bar{M}_{Pl}^2 \qquad\right)R + (D_\mu H)^\dagger (D^\mu H) - V(H^\dagger H)\right]$$

M [GeV]

10^{14}

10^{13}



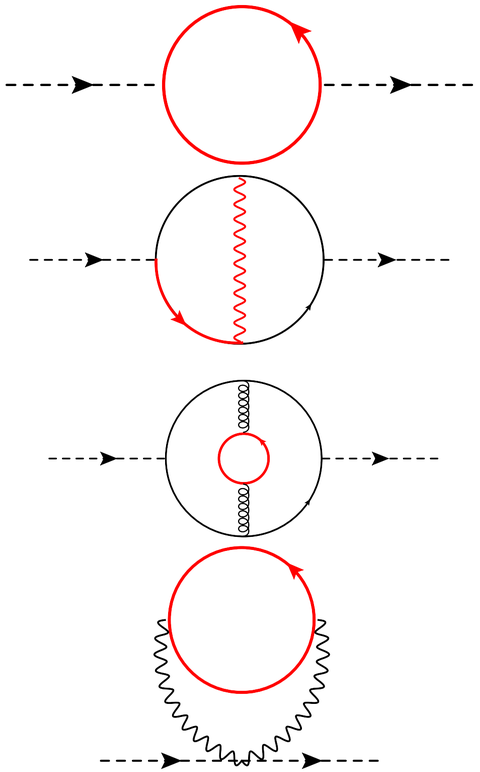


10^{7}

10^{5}

10^{4}

10^{3}



Is inflation a natural theory?

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\left(\frac{1}{2}\bar{M}_{Pl}^2 + \xi H^\dagger H\right)R + (D_\mu H)^\dagger (D^\mu H) - V(H^\dagger H)\right]$$

M [GeV]

10^{14}

10^{13}

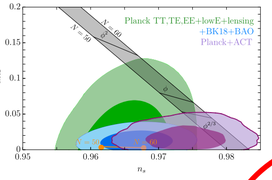
10^{11}

10^{7}

10^{5}

10^{4}

10^{3}



Is inflation a natural theory?

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\left(\frac{1}{2}\bar{M}_{Pl}^2 + \xi H^\dagger H\right)R + (D_\mu H)^\dagger (D^\mu H) - V(H^\dagger H)\right]$$

$$\delta M_h^2 = \xi \frac{4\,M^4}{(4\pi)^2 \bar{M}_{Pl}^2}$$

Catinari, Del Grosso, Di Giovanni, Urbano [arXiv:2504.17846]

M [GeV]

10^{14}

10^{13}

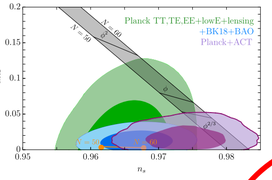
10^{11}

10^{7}

10^{5}

10^{4}

10^{3}

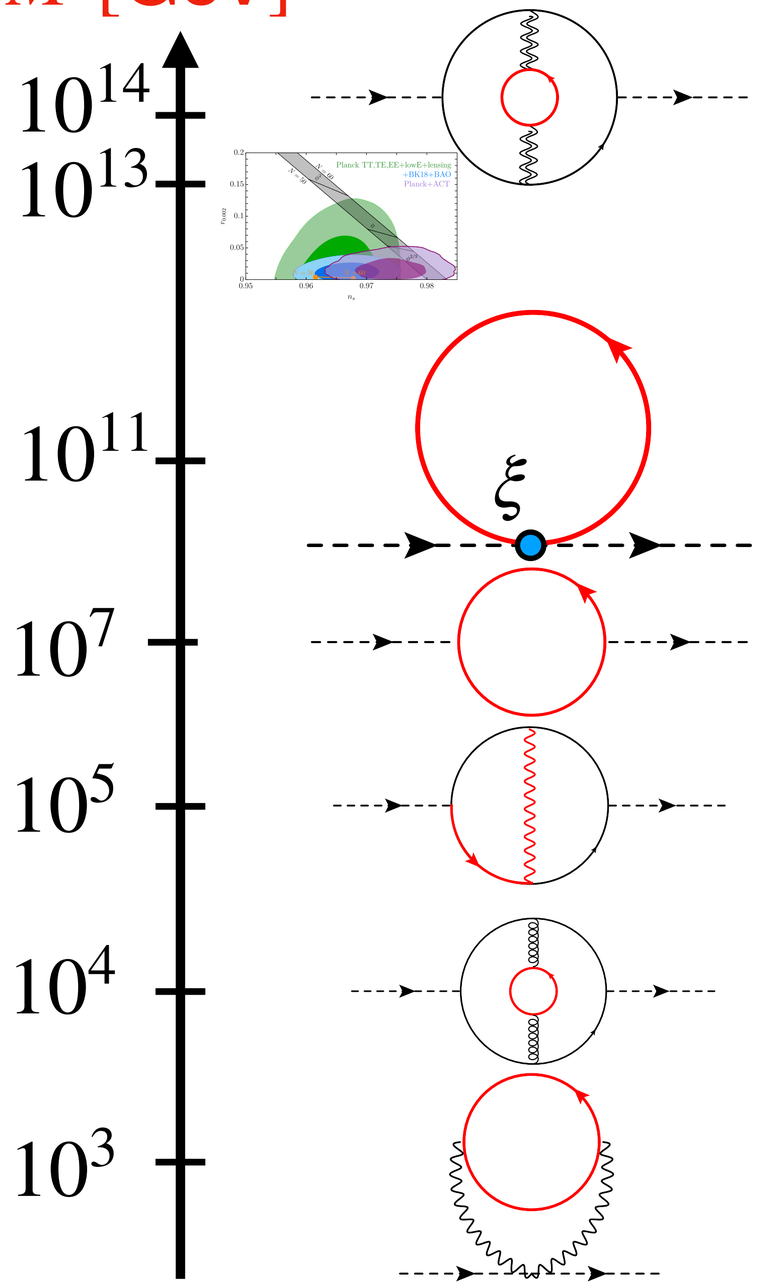


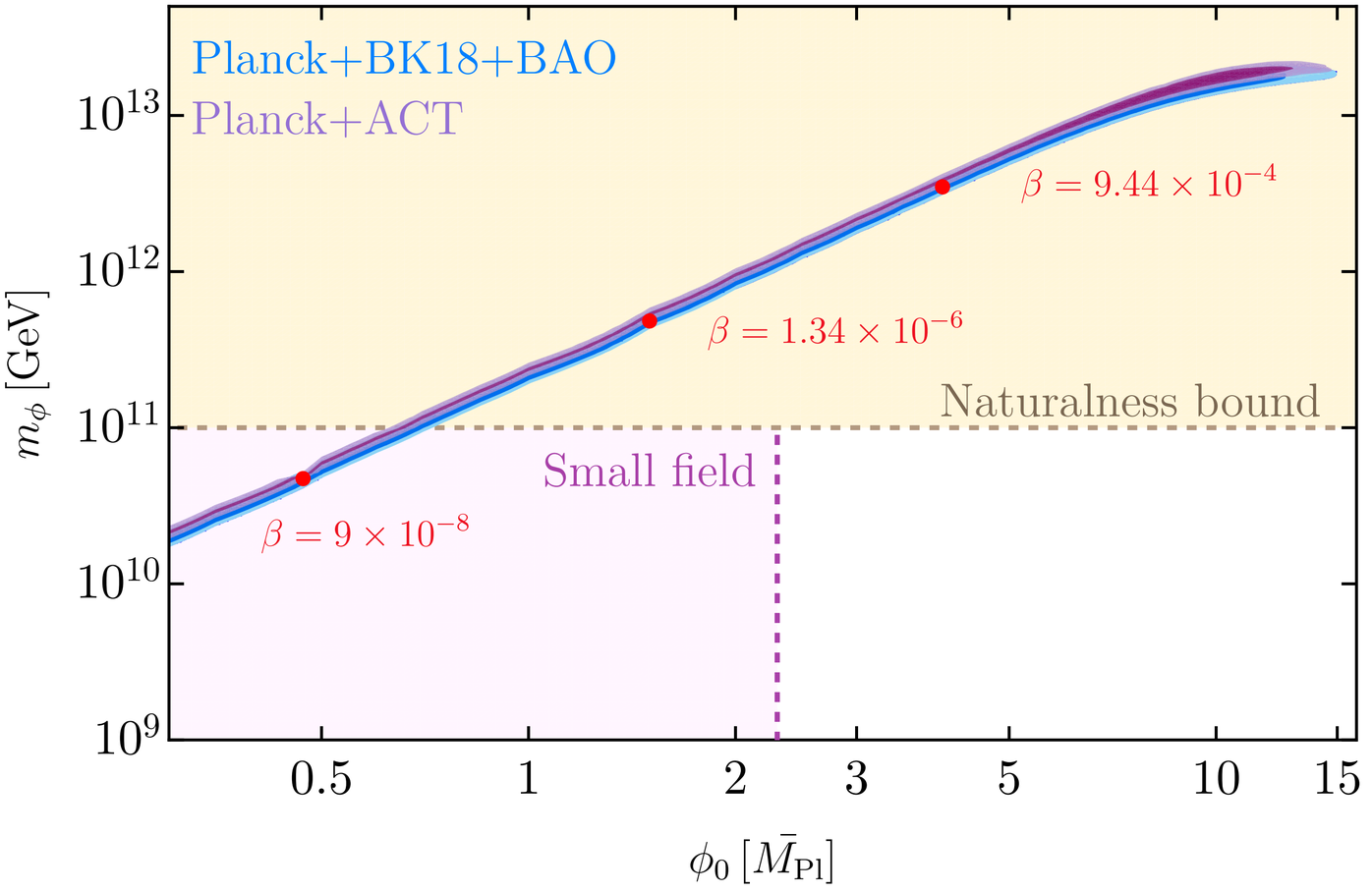
Is inflation a natural theory?

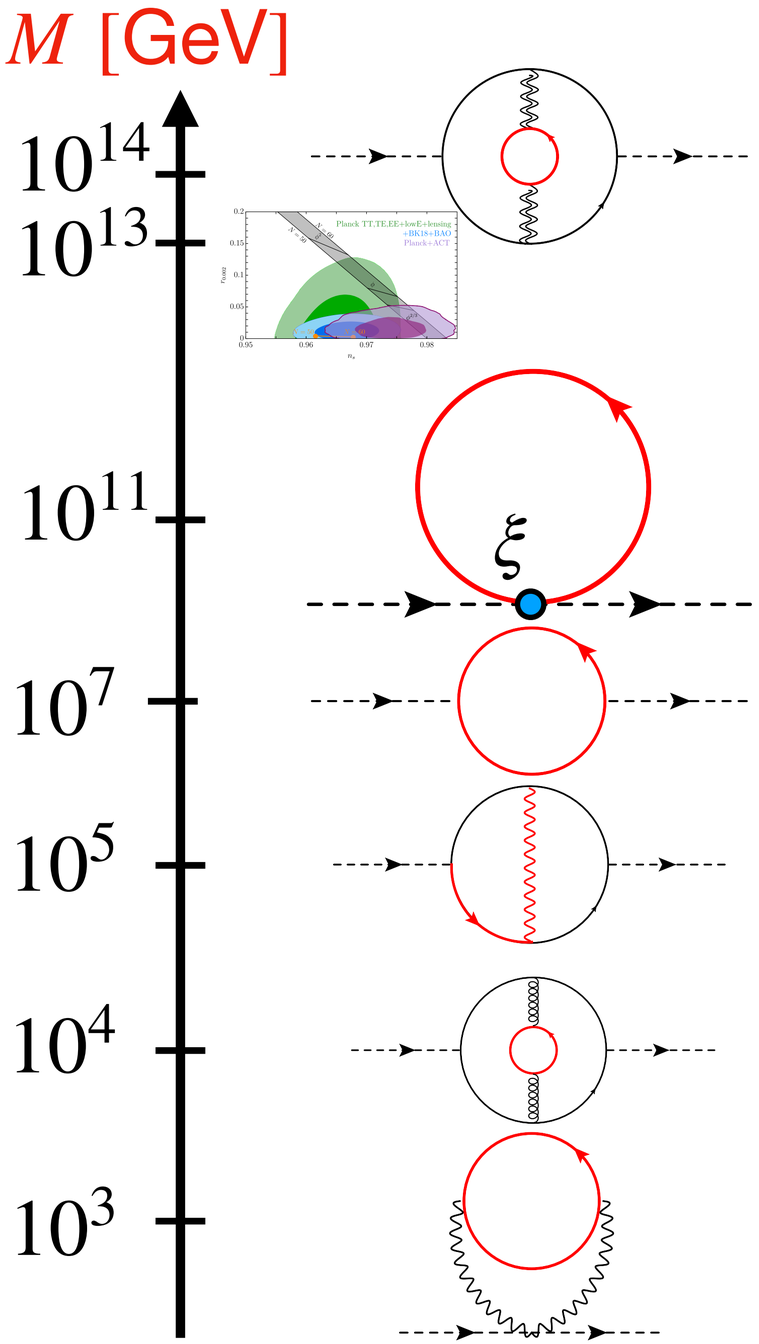
$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\left(\frac{1}{2}\bar{M}_{Pl}^2 + \xi H^\dagger H\right)R + (D_\mu H)^\dagger (D^\mu H) - V(H^\dagger H)\right]$$

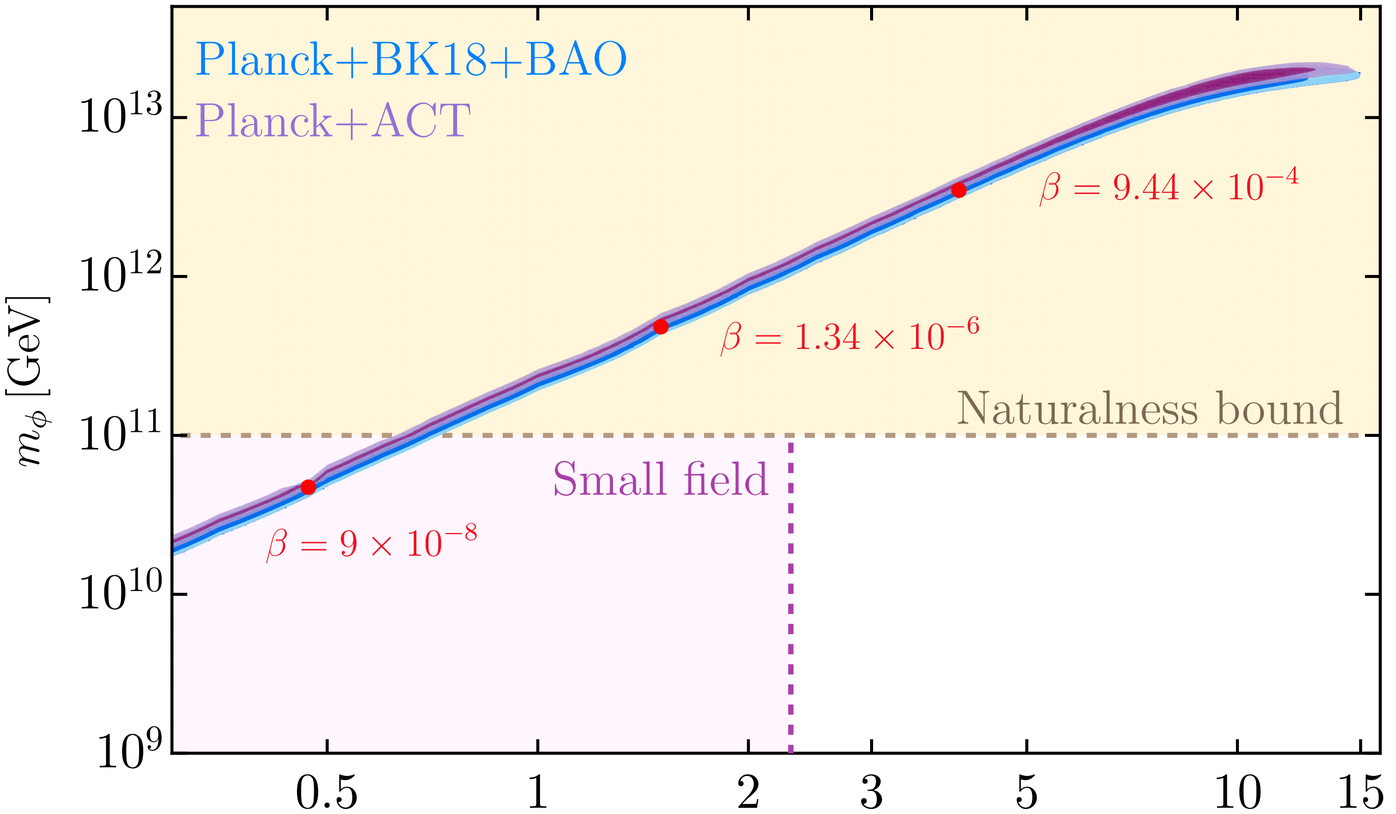
$$\delta M_h^2 = \xi \frac{4\,M^4}{(4\pi)^2 \bar{M}_{Pl}^2}$$

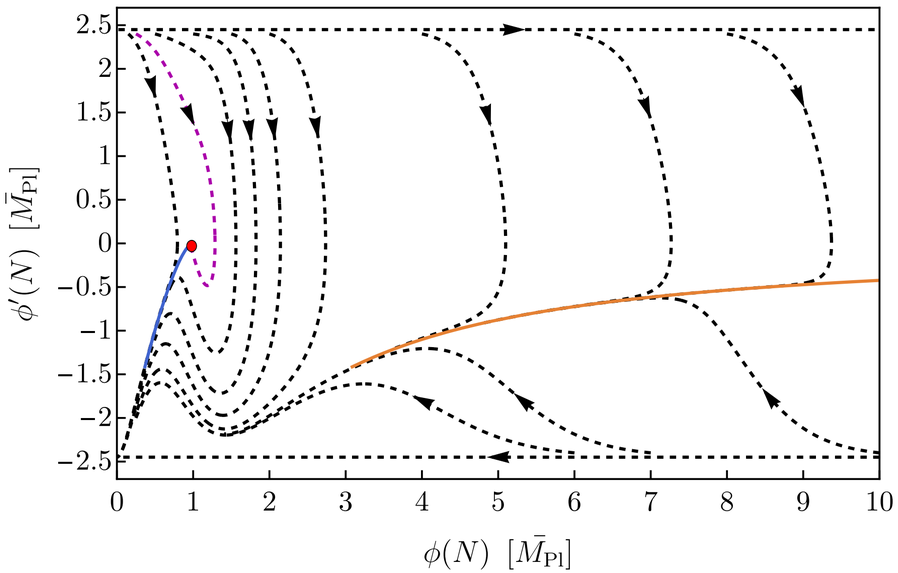
Catinari, Del Grosso, Di Giovanni, Urbano [arXiv:2504.17846]

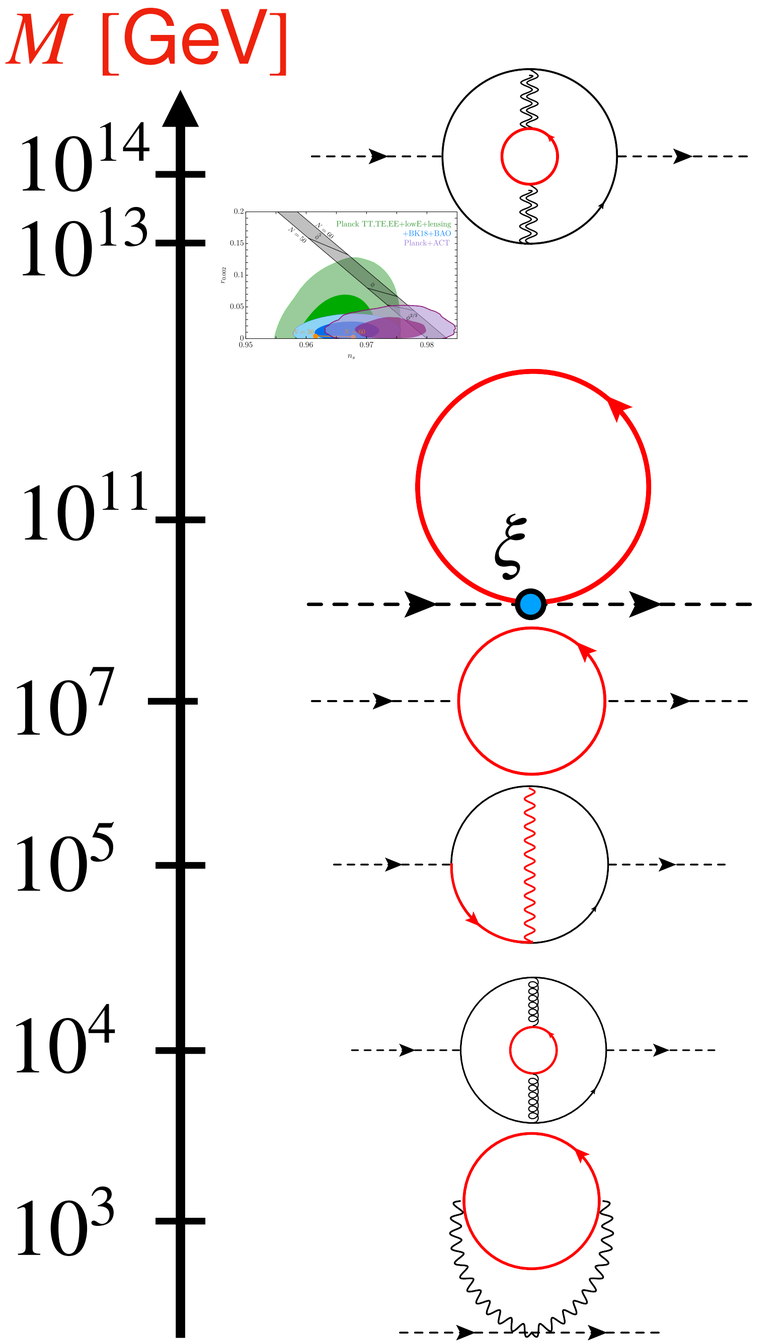

M [GeV]
10^14
10^13
10^11
10^7
10^5
10^4
10^3
ξ
Planck TT,TE,EE+lowE+lensing
+BK18+BAO
Planck+ACT

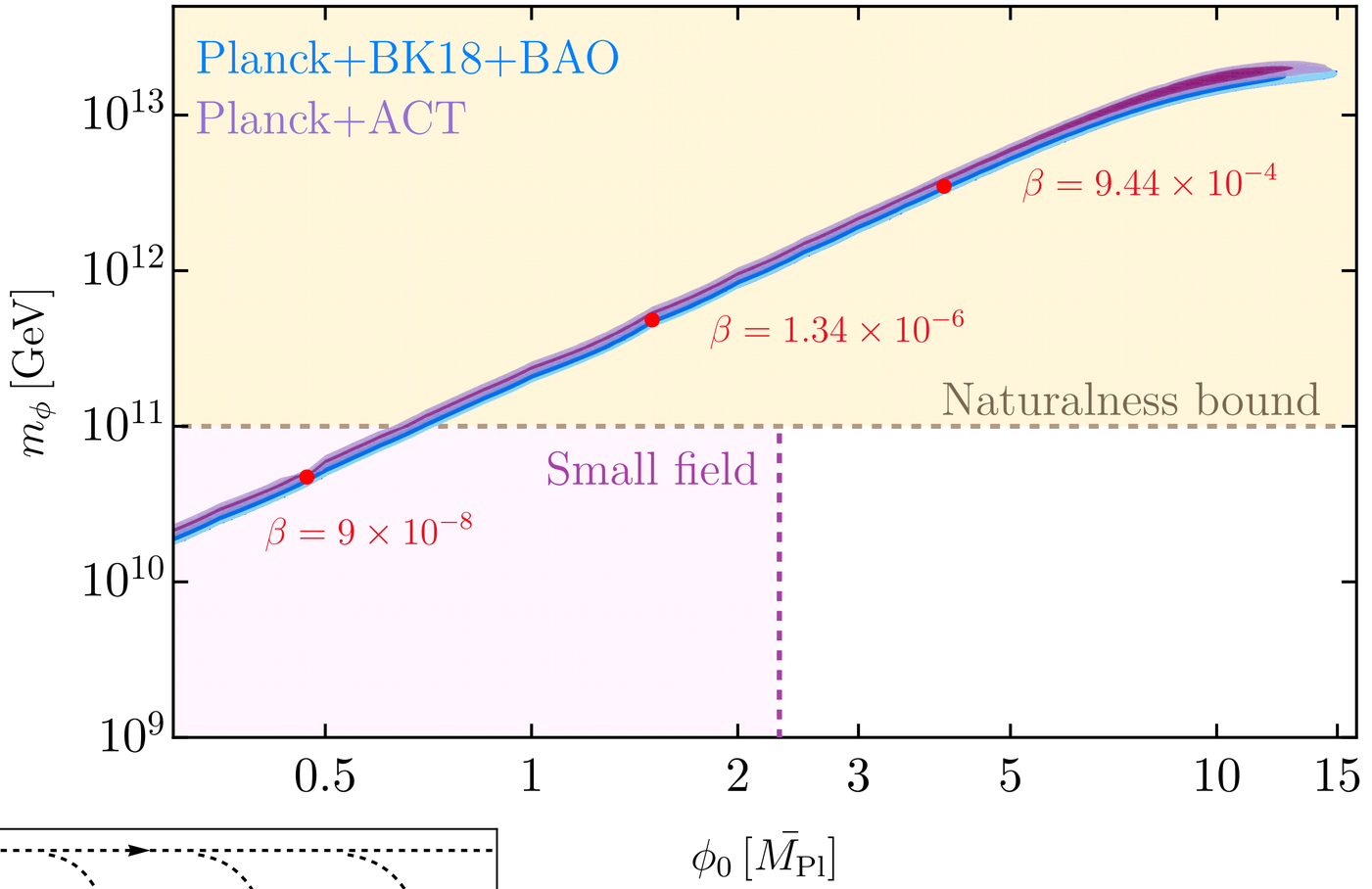

Planck+BK18+BAO
Planck+ACT
β = 9.44 × 10^−4
β = 1.34 × 10^−6
β = 9 × 10^−8
Naturalness bound
Small field
m_φ [GeV]
φ_0 [M̄_Pl]
10^13
10^12
10^11
10^10
10^9
0.5
1
2
3
5
10
15

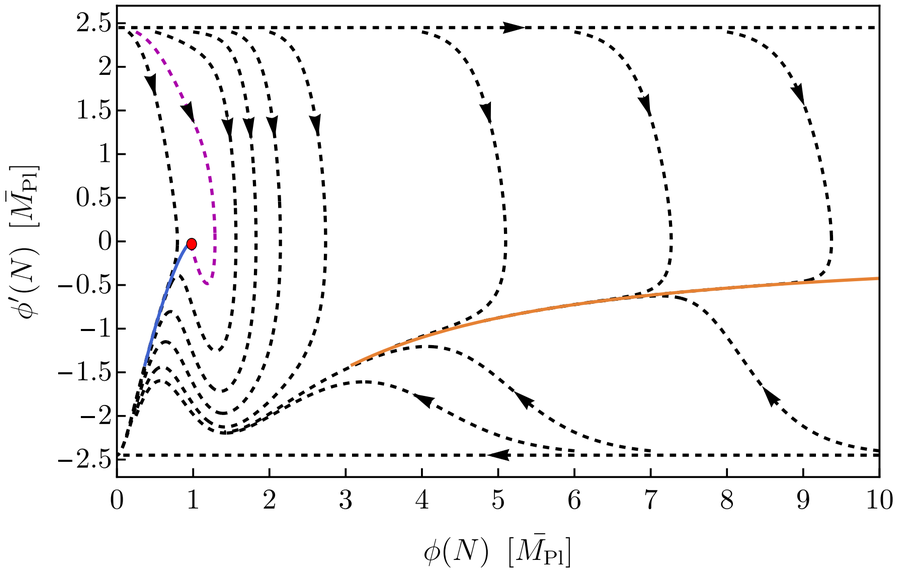

M [GeV]
10^14
10^13
10^11
10^7
10^5
10^4
10^3
ξ


Planck+BK18+BAO
Planck+ACT
β = 9.44 × 10^−4
β = 1.34 × 10^−6
β = 9 × 10^−8
Naturalness bound
Small field
m_φ [GeV]
φ_0 [M̄_Pl]


φ′(N) [M̄_Pl]
φ(N) [M̄_Pl]







Inflation is not natural

The Higgs as the inflaton (?)

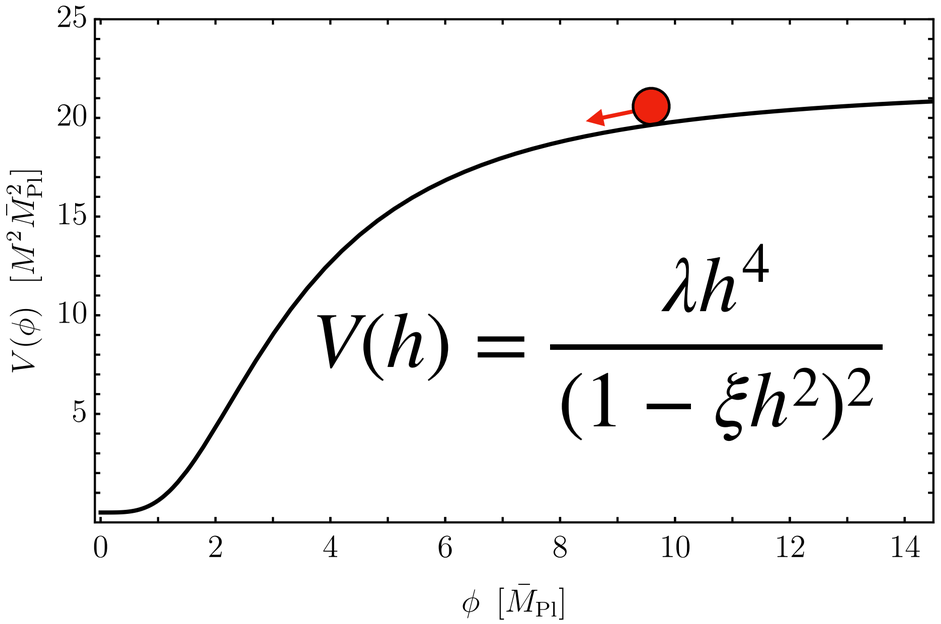
Bezrukov, Shaposhnikov [arXiv:0710.3755]

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\left(\frac{1}{2}\bar{M}_{Pl}^2 \qquad\qquad\right) R + (D_\mu H)^\dagger (D^\mu H) - V(H^\dagger H)\right]$$

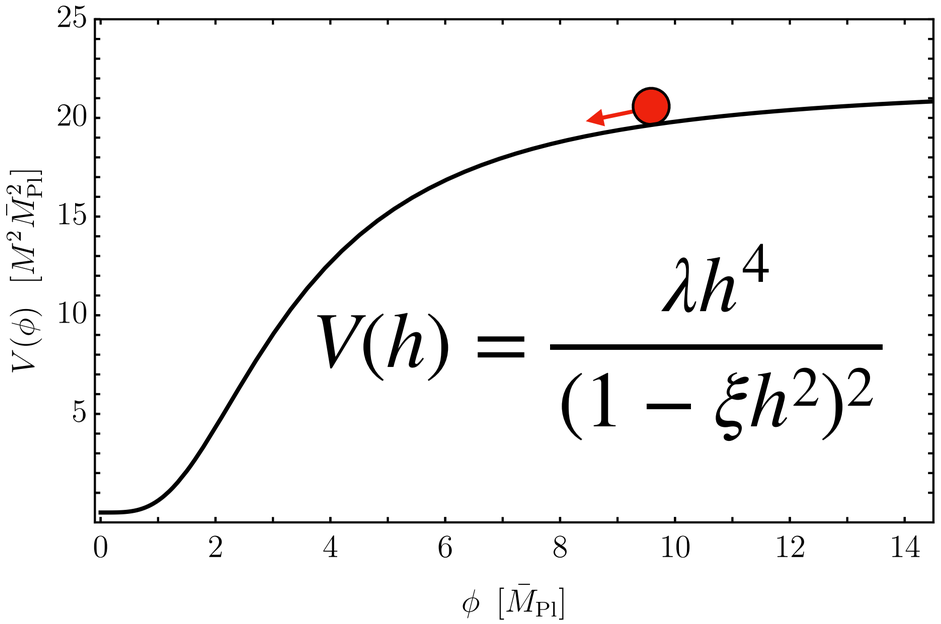
$$V(h) = \qquad \lambda h^4$$

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\left(\frac{1}{2}\bar{M}_{Pl}^2 + \xi H^\dagger H\right)R + (D_\mu H)^\dagger (D^\mu H) - V(H^\dagger H)\right]$$

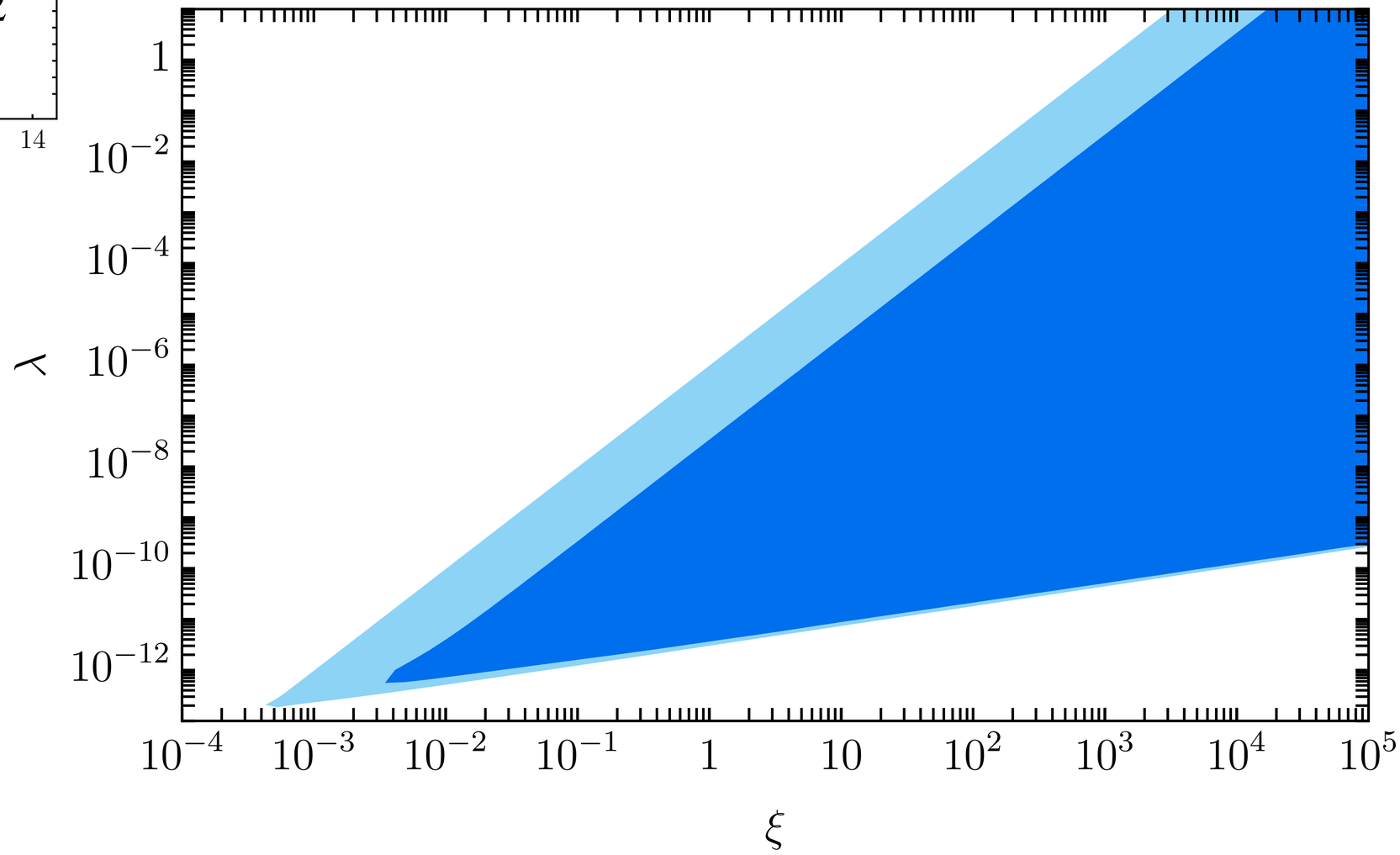
$$V(h) = \frac{\lambda h^4}{(1-\xi h^2)^2}$$

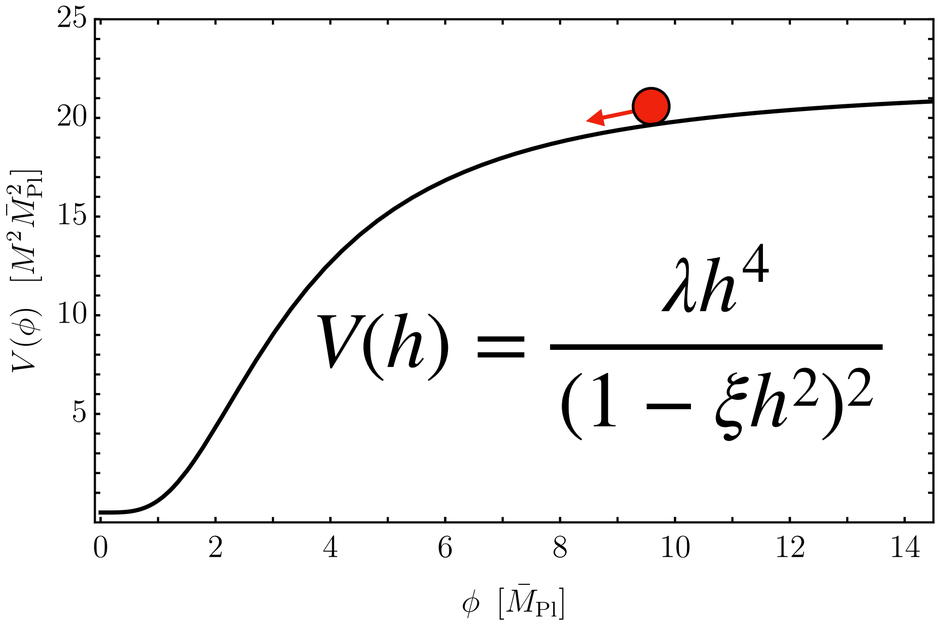


$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\left(\frac{1}{2}\bar{M}_{Pl}^2 + \xi H^\dagger H\right)R + (D_\mu H)^\dagger (D^\mu H) - V(H^\dagger H)\right]$$



$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\left(\frac{1}{2}\bar{M}_{Pl}^2 + \xi H^\dagger H\right)R + (D_\mu H)^\dagger (D^\mu H) - V(H^\dagger H)\right]$$

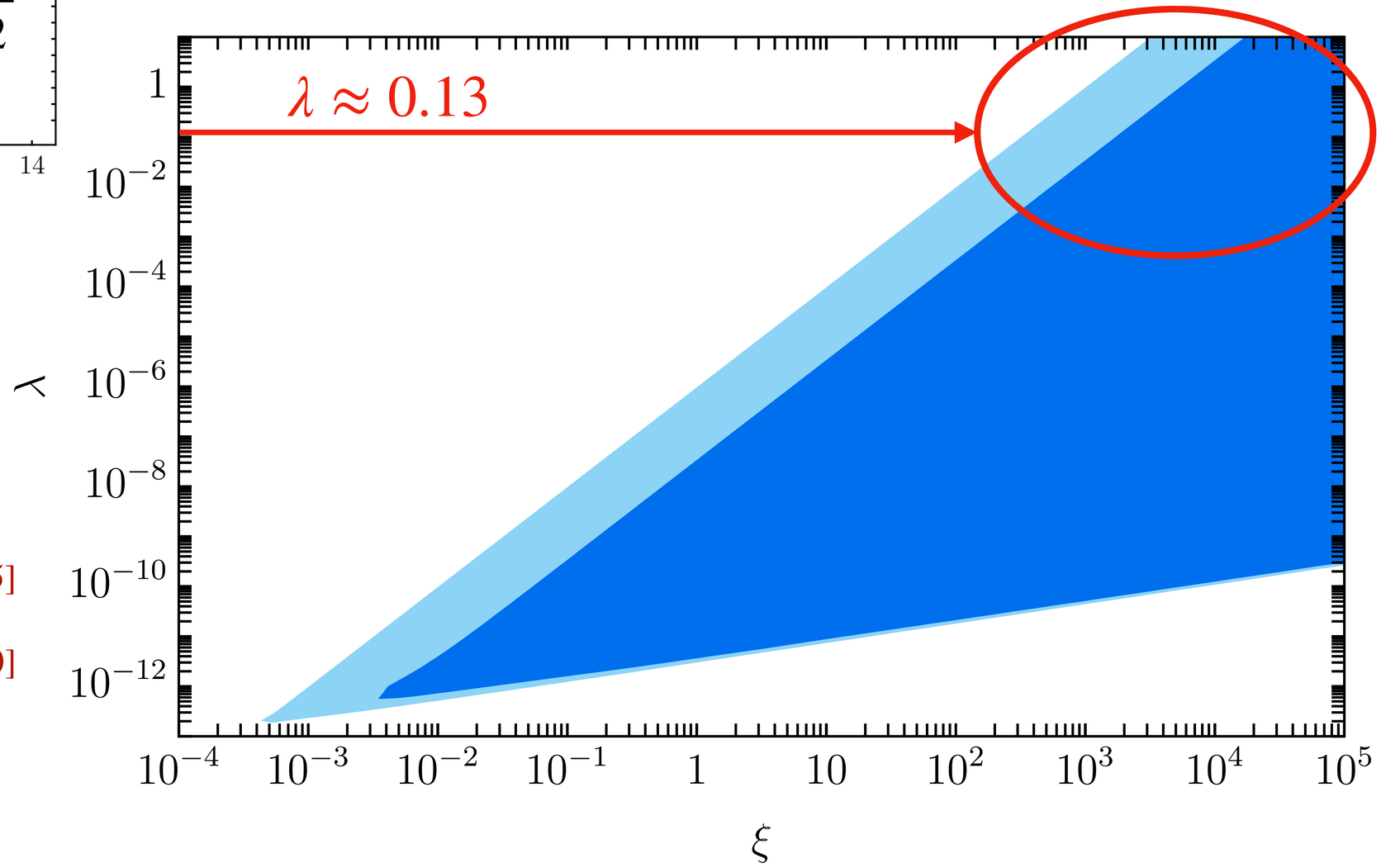


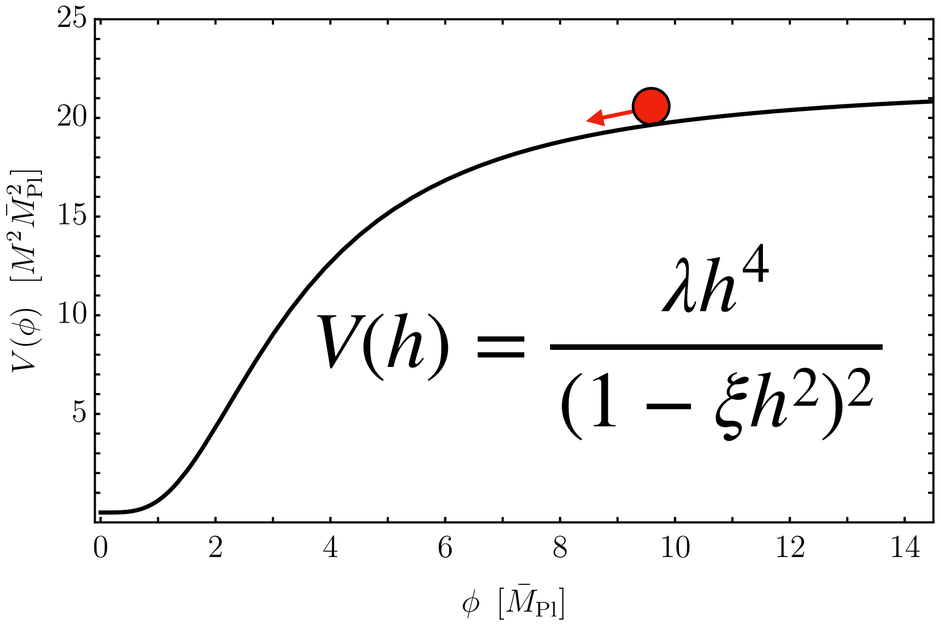


$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\left(\frac{1}{2}\bar{M}_{Pl}^2 + \xi H^\dagger H\right)R + (D_\mu H)^\dagger (D^\mu H) - V(H^\dagger H)\right]$$

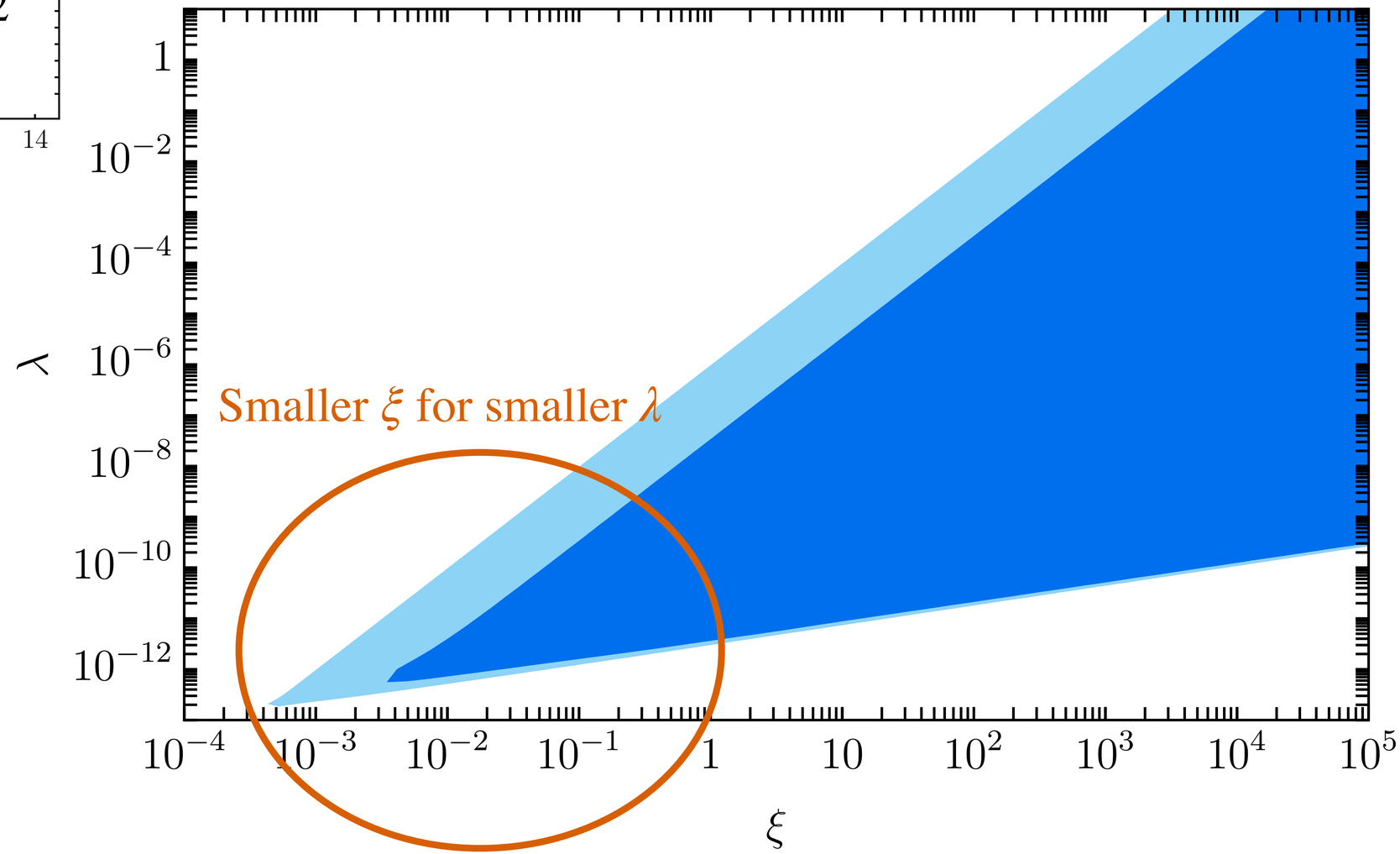
Breaking of perturbative unitarity well below the Planck scale when a perturbative expansion around the flat spacetime is performed

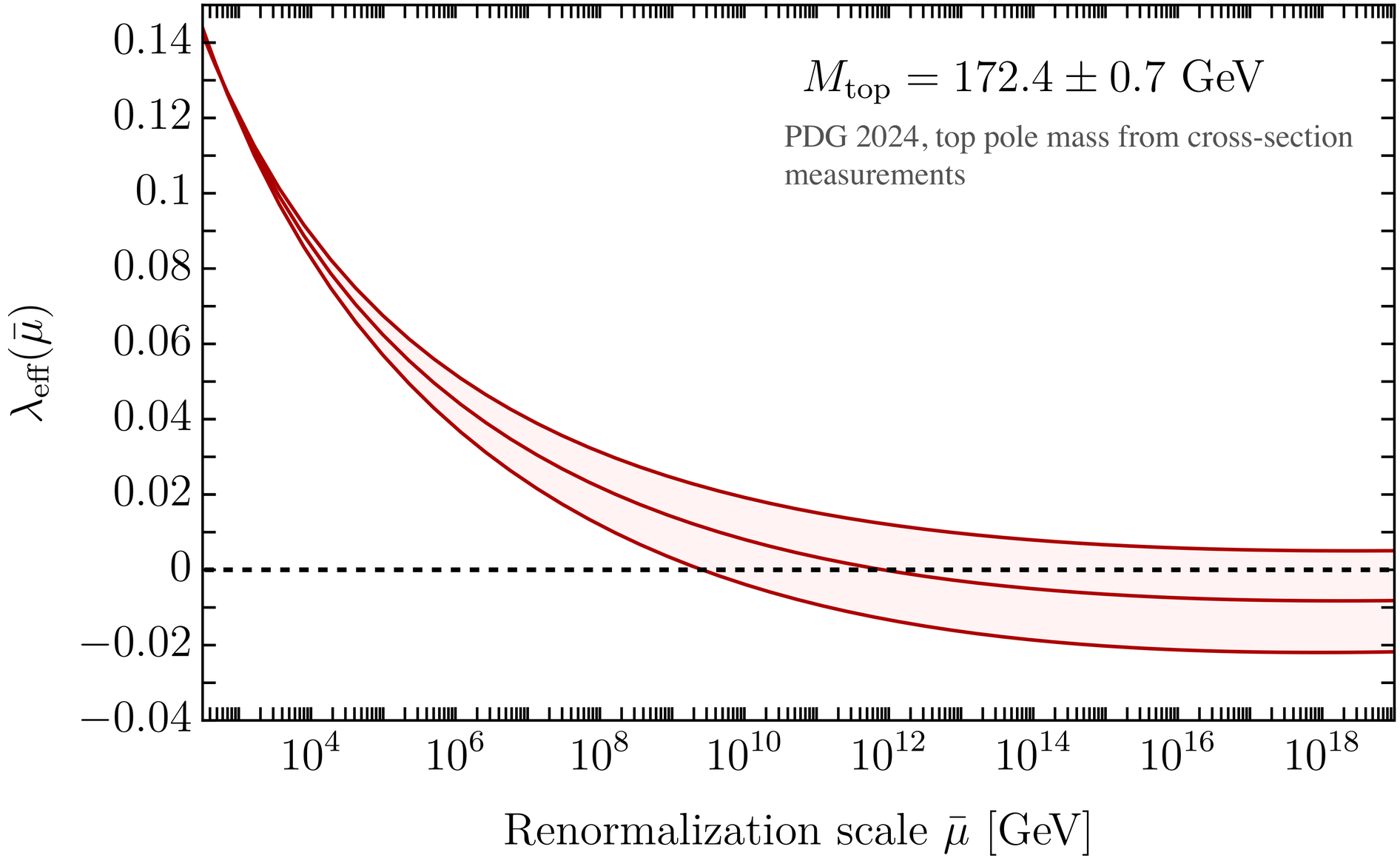
Burgess, Lee, Trott [arXiv:0902.4465]
Barbon, Espinosa [arXiv:0903.0355]
Burgess, Lee, Trott [arXiv:1002.2730]
Lerner McDonald [arXiv:0912.5463]





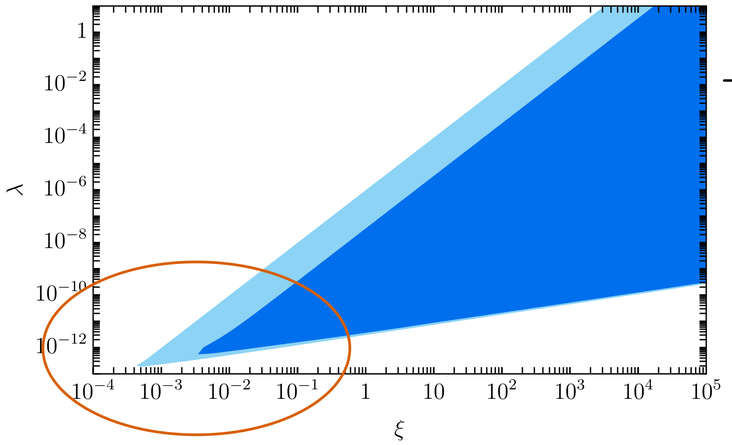
$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\left(\frac{1}{2}\bar{M}_{Pl}^2 + \xi H^\dagger H\right)R + (D_\mu H)^\dagger (D^\mu H) - V(H^\dagger H)\right]$$

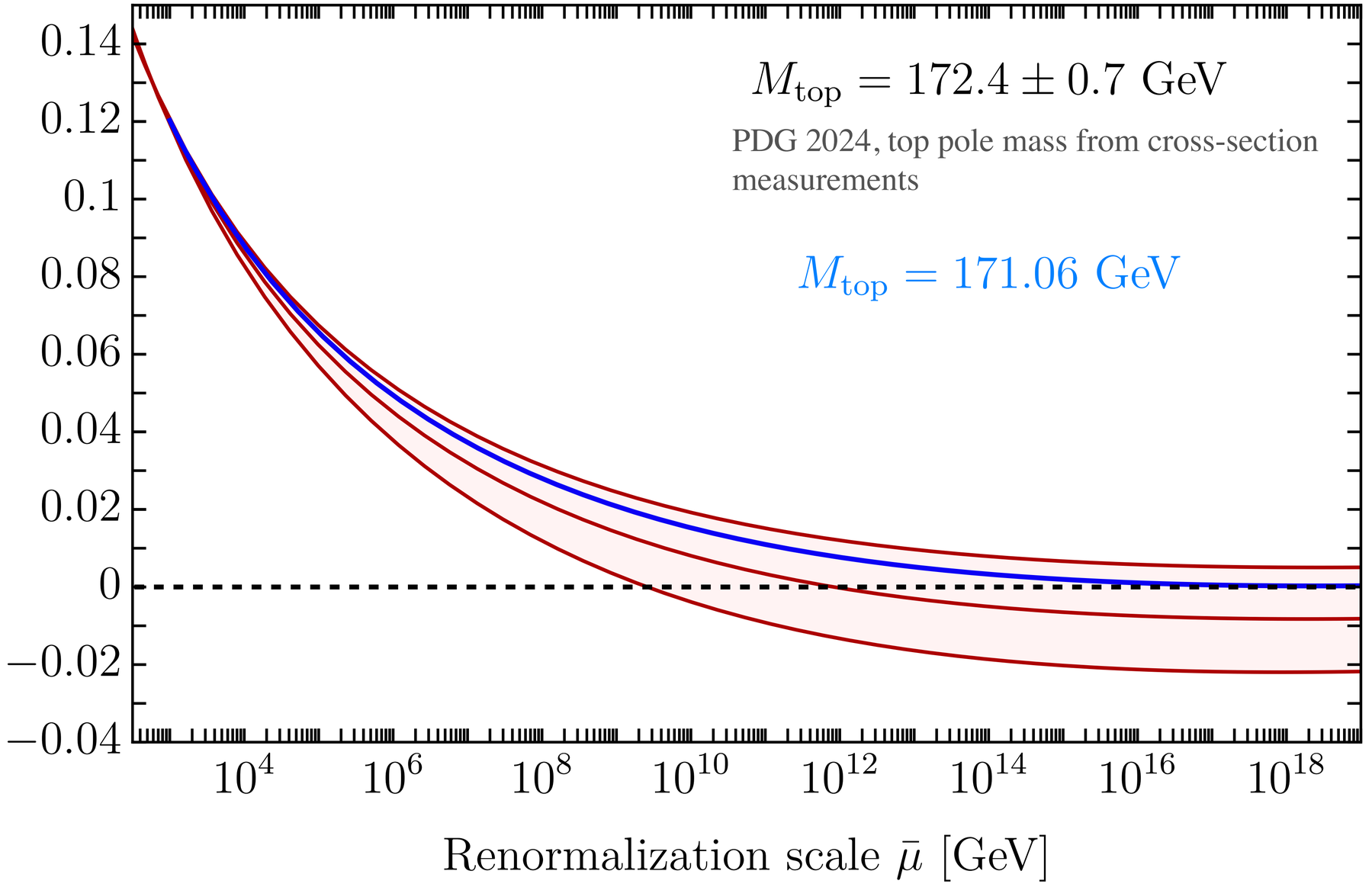


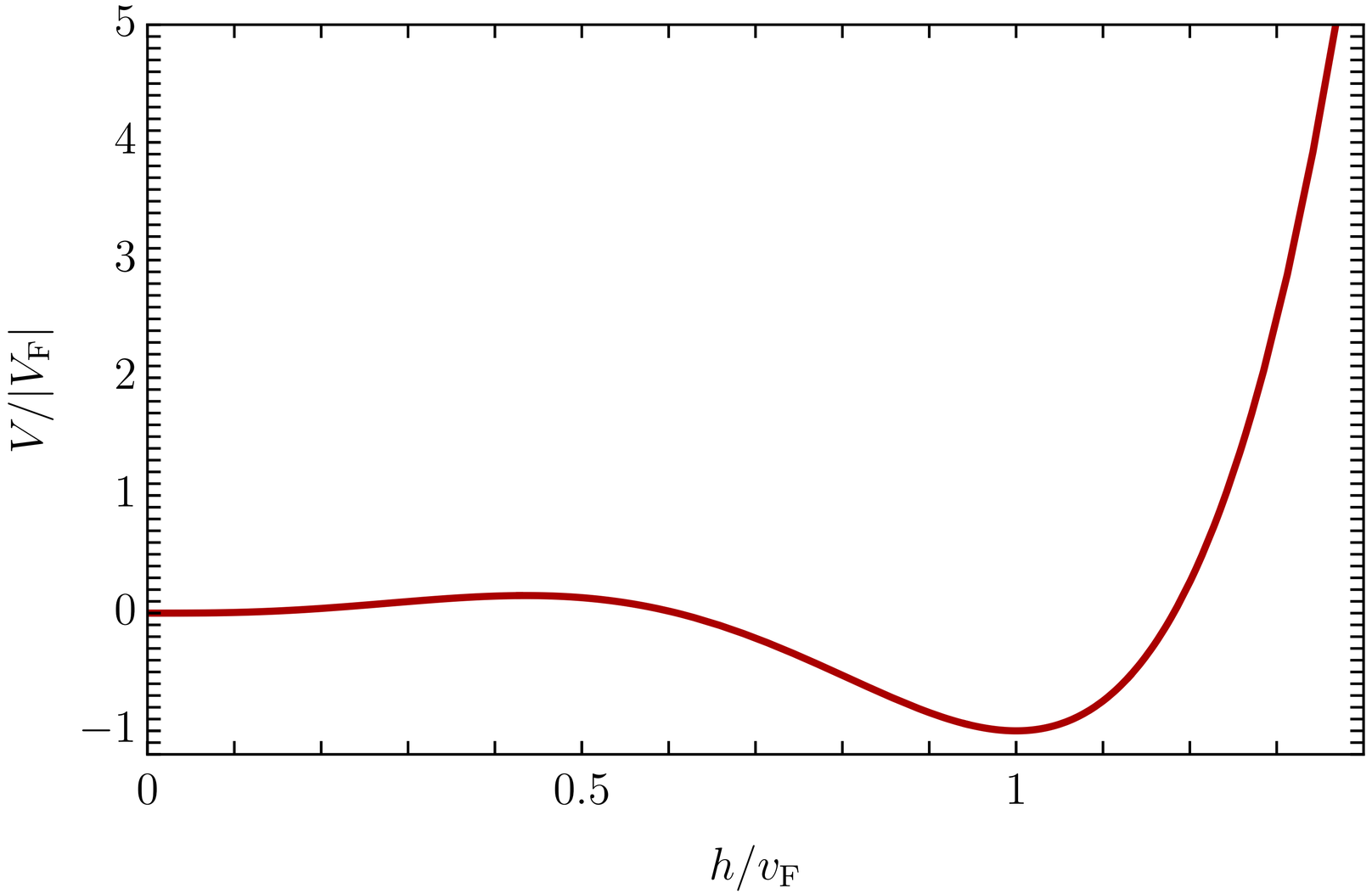

$M_{\text{top}} = 172.4 \pm 0.7$ GeV
PDG 2024, top pole mass from cross-section measurements
$\lambda_{\text{eff}}(\bar{\mu})$
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
Renormalization scale $\bar{\mu}$ [GeV]

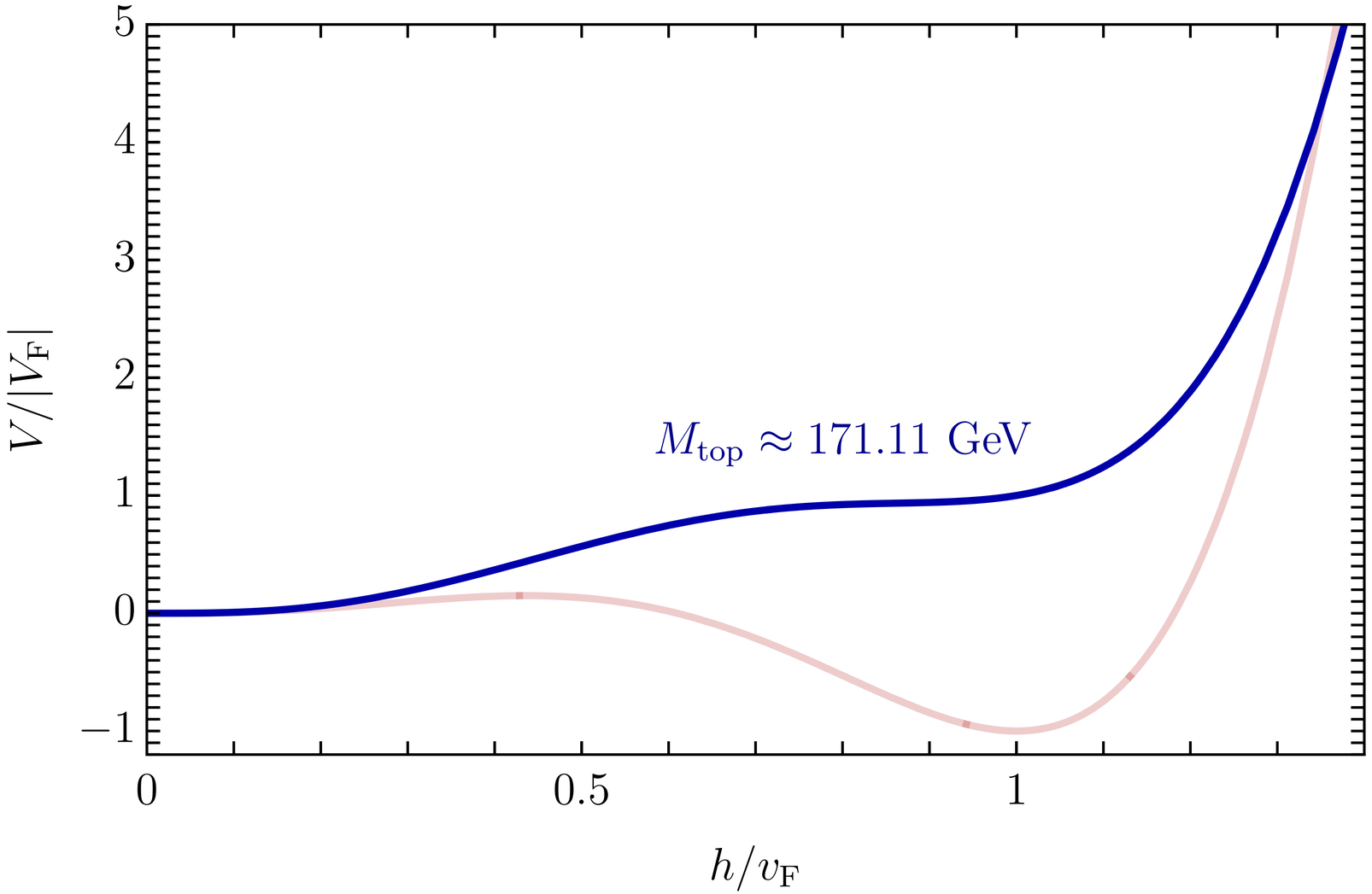
Critical Higgs Inflation

Bezrukov, Shaposhnikov [arXiv:1403.6078]
Hamada, Kawai, Oda, Park [arXiv:1408.4864]

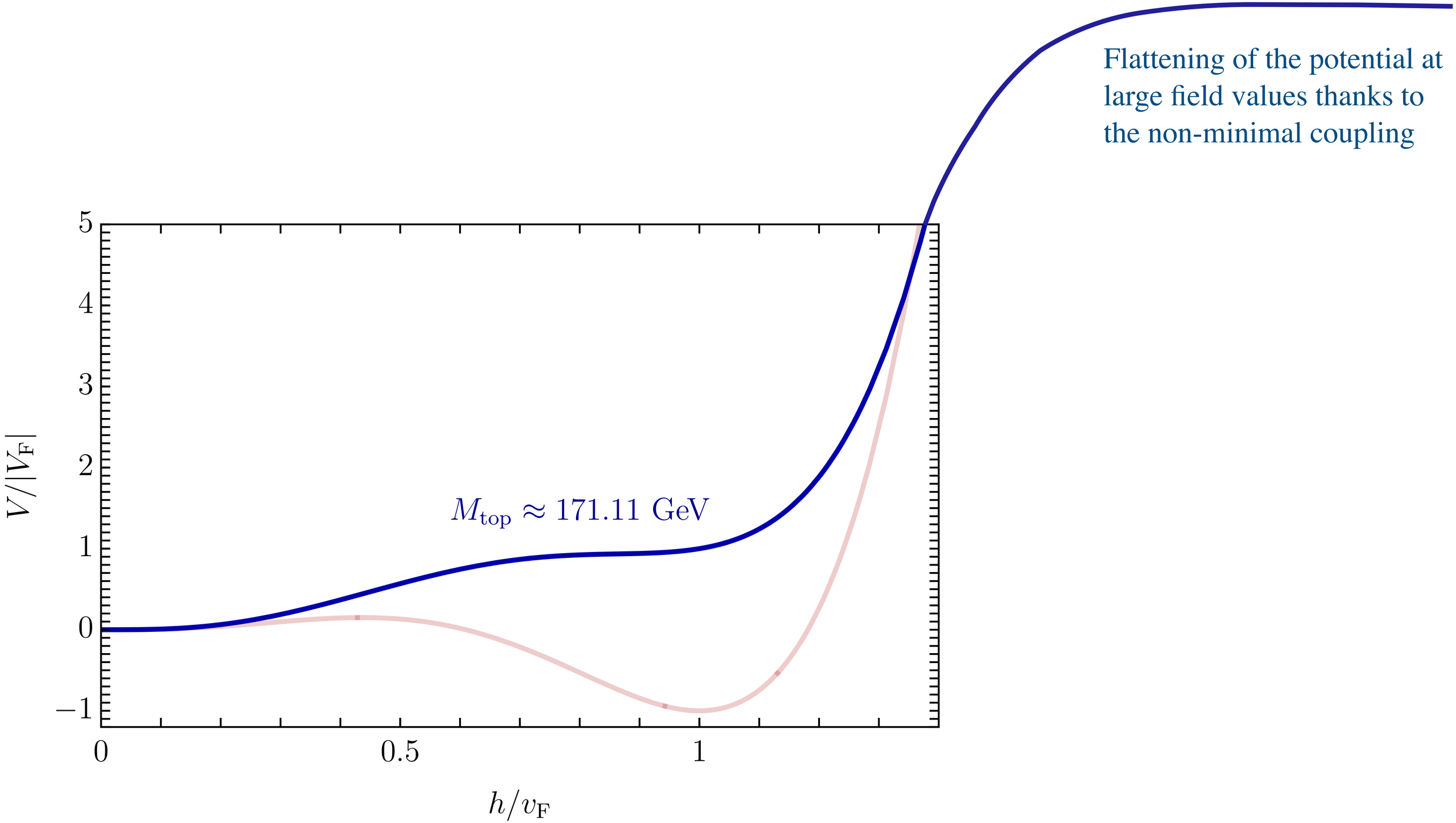


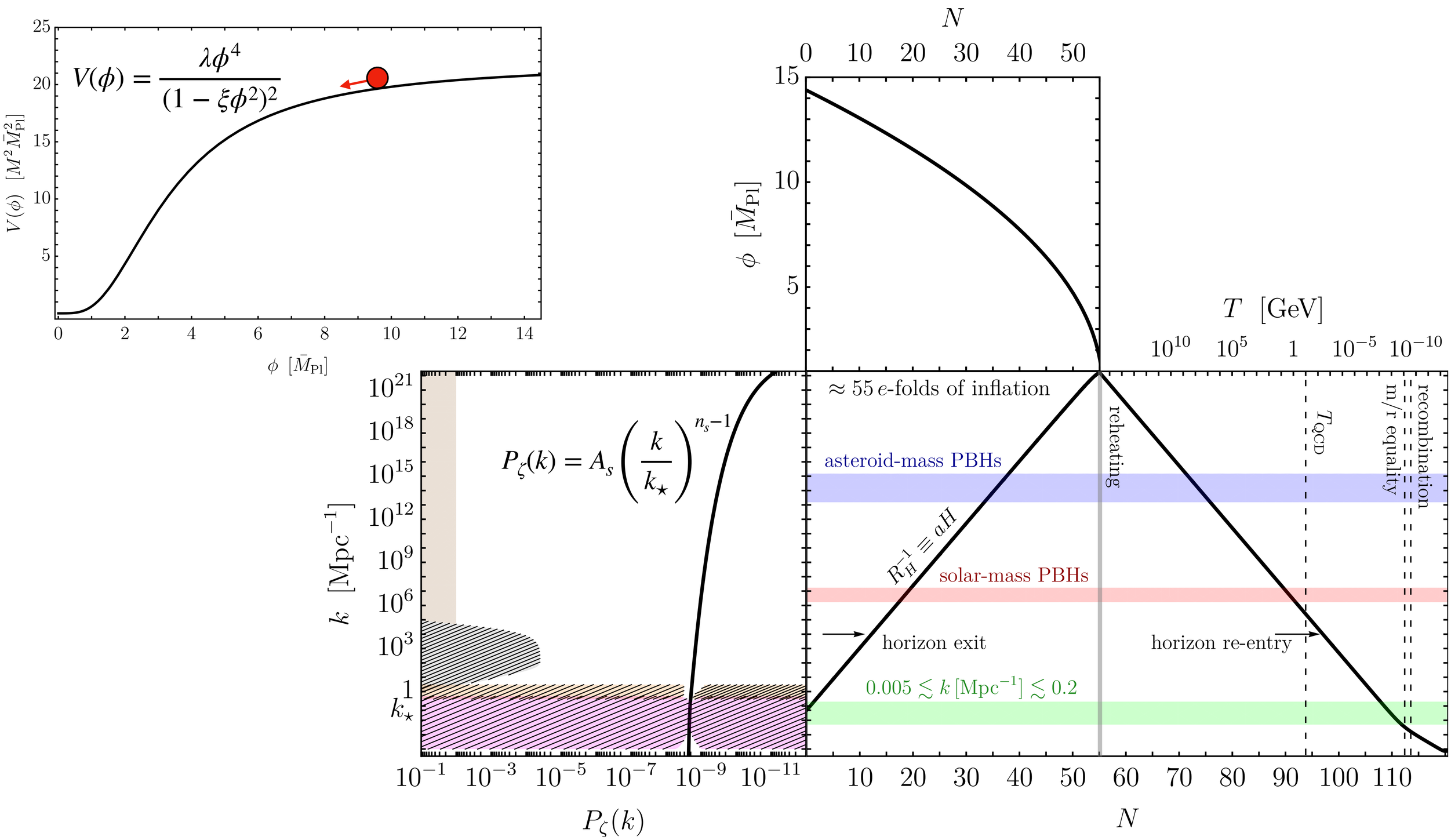


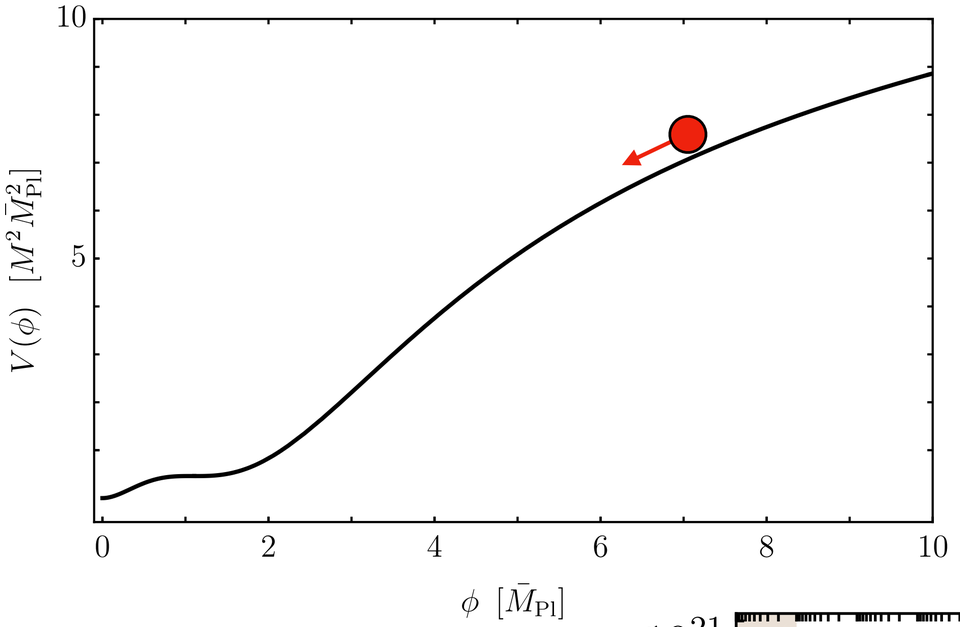

5
4
3
2
1
0
−1
0
0.5
1
$V/|V_{\mathrm{F}}|$
h/v_{F}

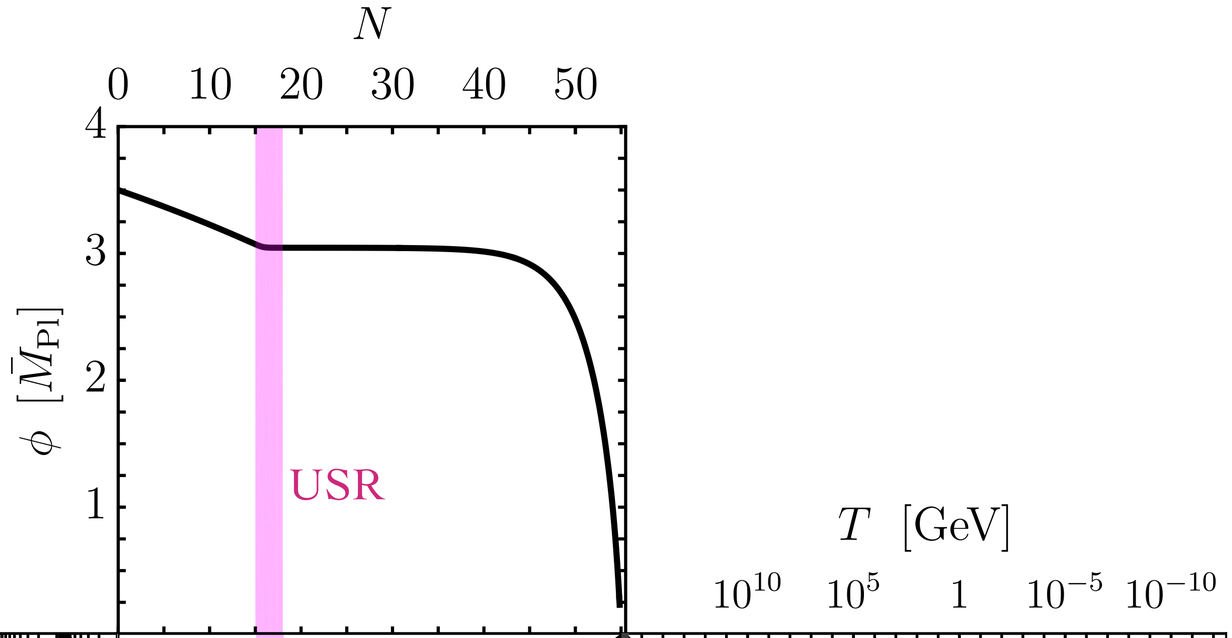

5
4
3
2
1
0
−1
0
0.5
1
$V/|V_{\rm F}|$
$h/v_{\rm F}$
$M_{\rm top} \approx 171.11$ GeV

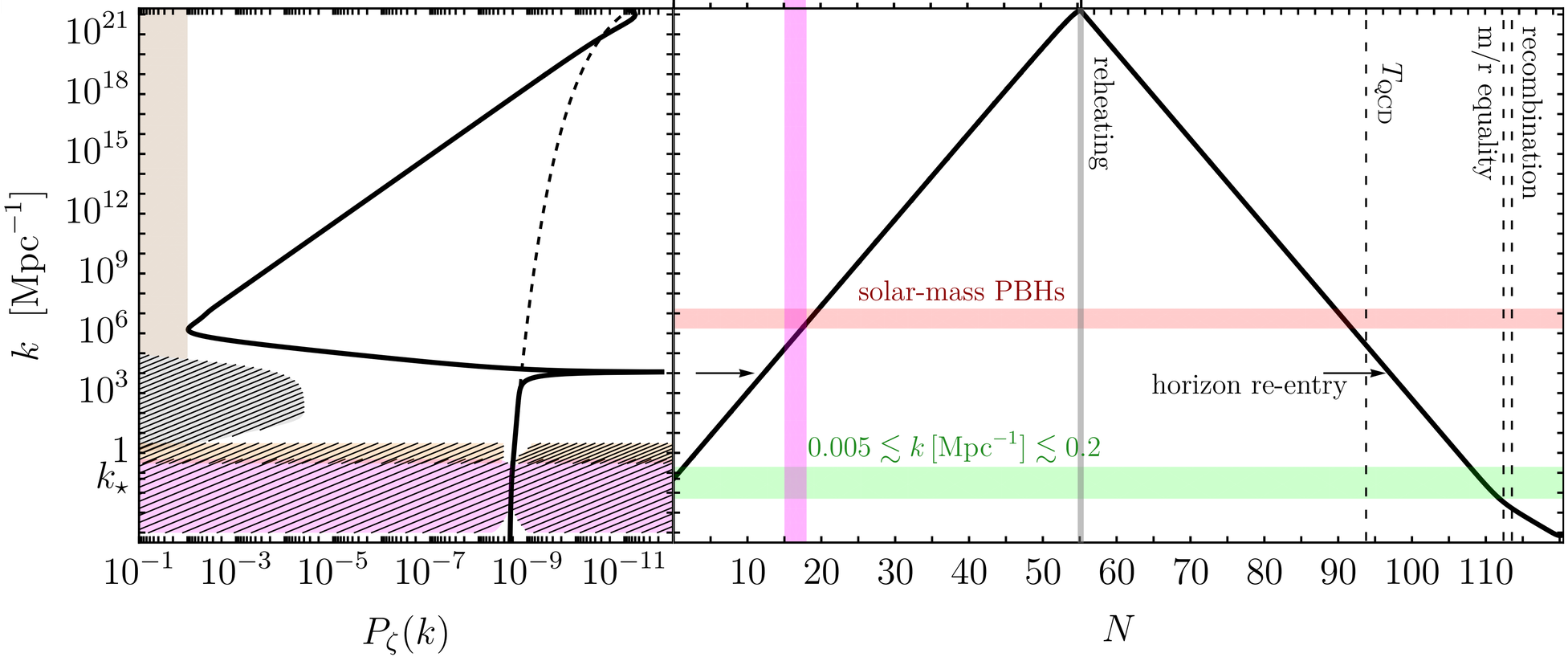
Flattening of the potential at large field values thanks to the non-minimal coupling




$V(\phi) = \dfrac{\lambda\phi^4}{(1-\xi\phi^2)^2}$
$V(\phi)\ \ [M^2\bar{M}_{\rm Pl}^2]$
$\phi\ \ [\bar{M}_{\rm Pl}]$
N
$\phi\ \ [\bar{M}_{\rm Pl}]$
$T\ \ [\mathrm{GeV}]$
$P_\zeta(k) = A_s\left(\dfrac{k}{k_\star}\right)^{n_s-1}$
$k\ \ [\mathrm{Mpc}^{-1}]$
$\approx 55\,e$-folds of inflation
asteroid-mass PBHs
solar-mass PBHs
$R_H^{-1} \equiv aH$
reheating
$T_{\rm QCD}$
m/r equality
recombination
horizon exit
horizon re-entry
$0.005 \lesssim k\,[\mathrm{Mpc}^{-1}] \lesssim 0.2$
$P_\zeta(k)$
N





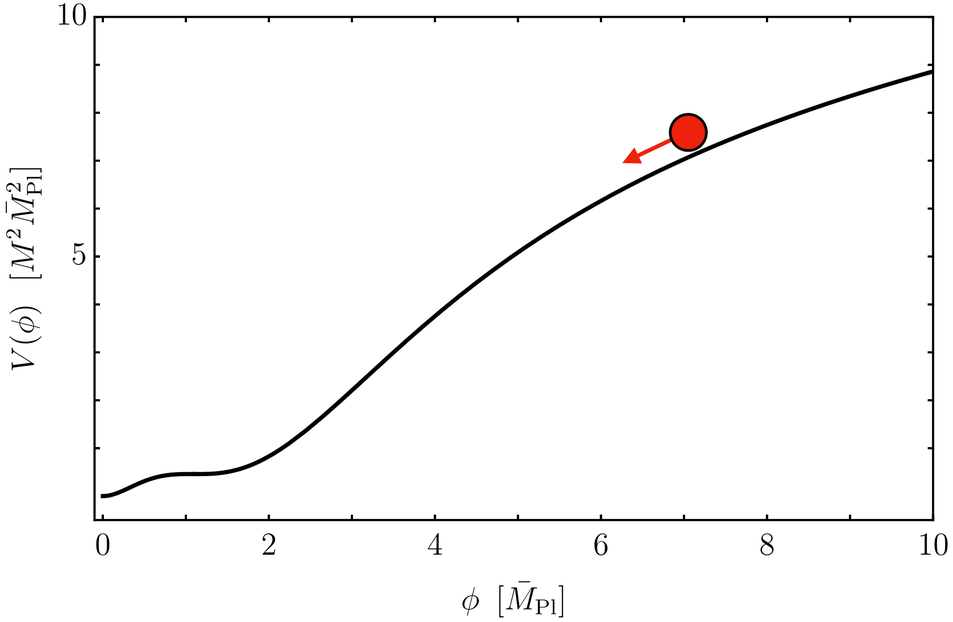


$$P_\zeta(k) = \frac{H^2}{8\pi^2 \bar{M}_{\rm Pl}^2 \epsilon}$$

PBH in Critical Higgs Inflation?

NO

Masina [arXiv:1805.02160]



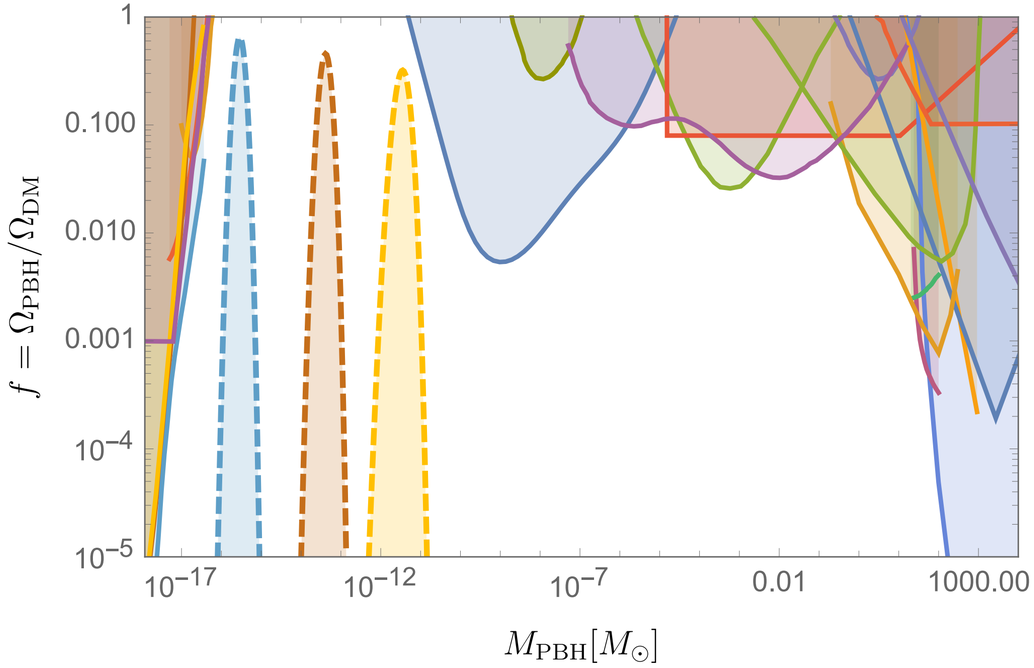
PBH in Critical Higgs Inflation?

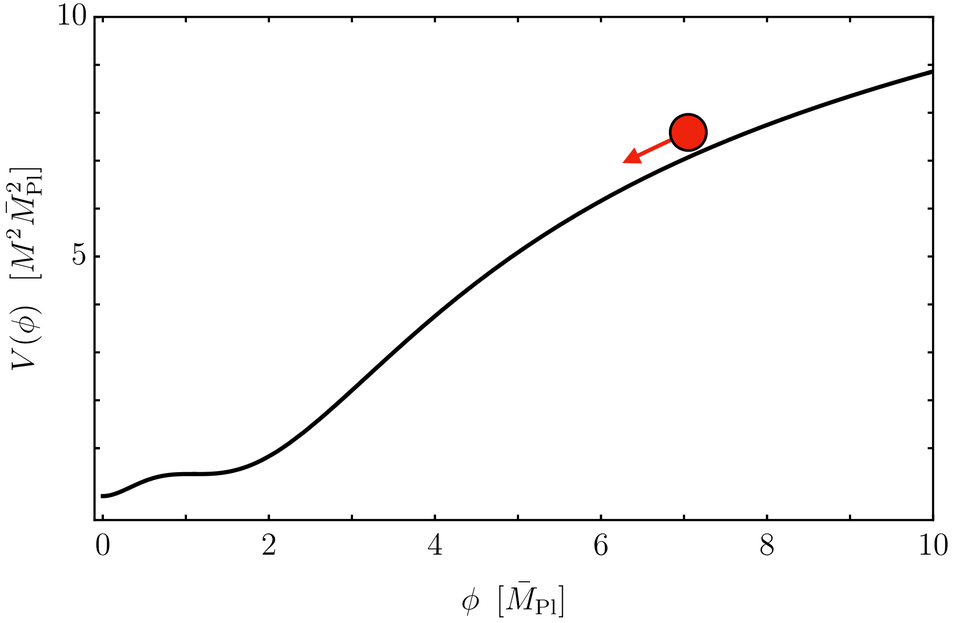
NO

Masina [arXiv:1805.02160]

However….

Cheong, Lee, Park [arXiv:1912.12032]

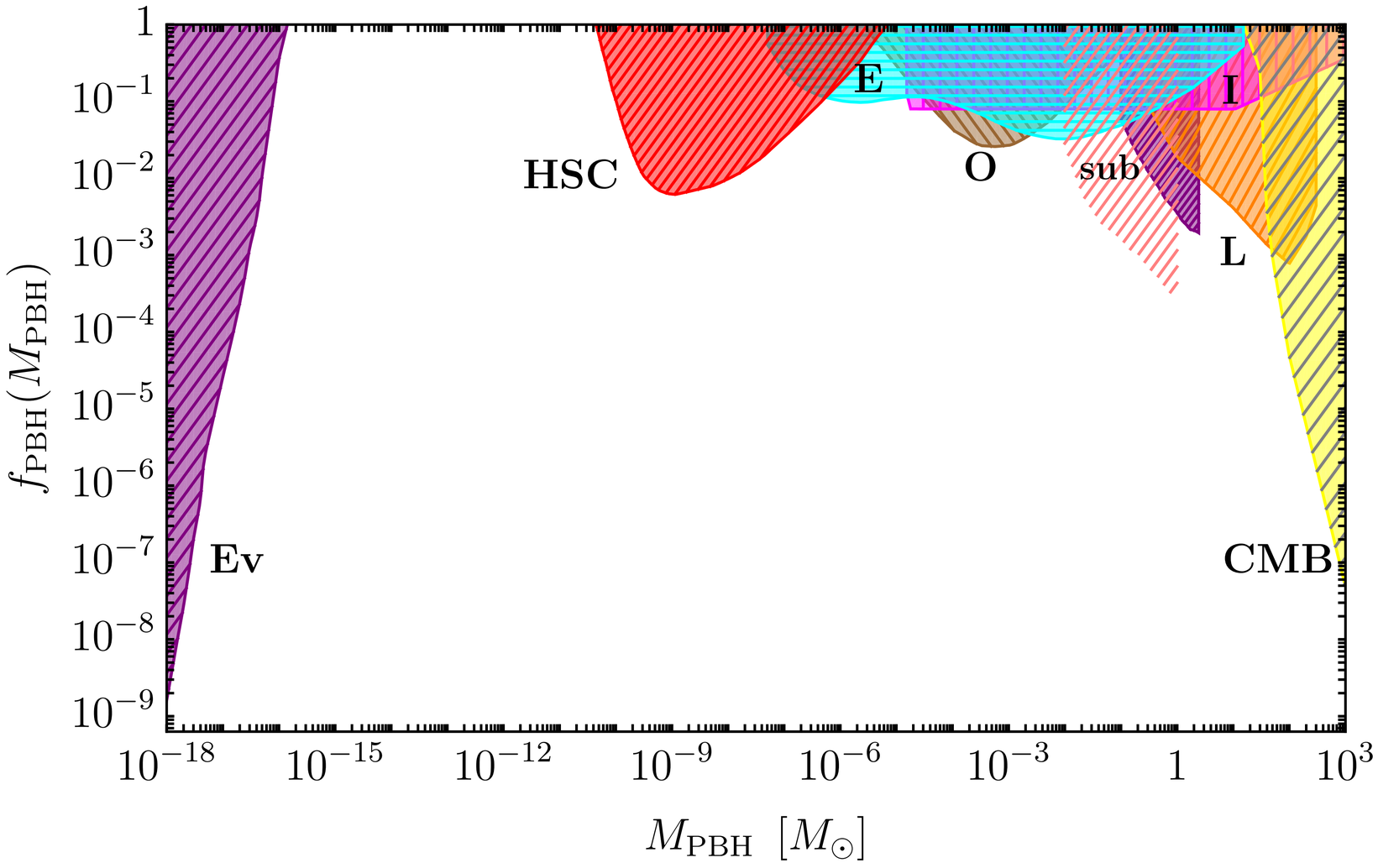


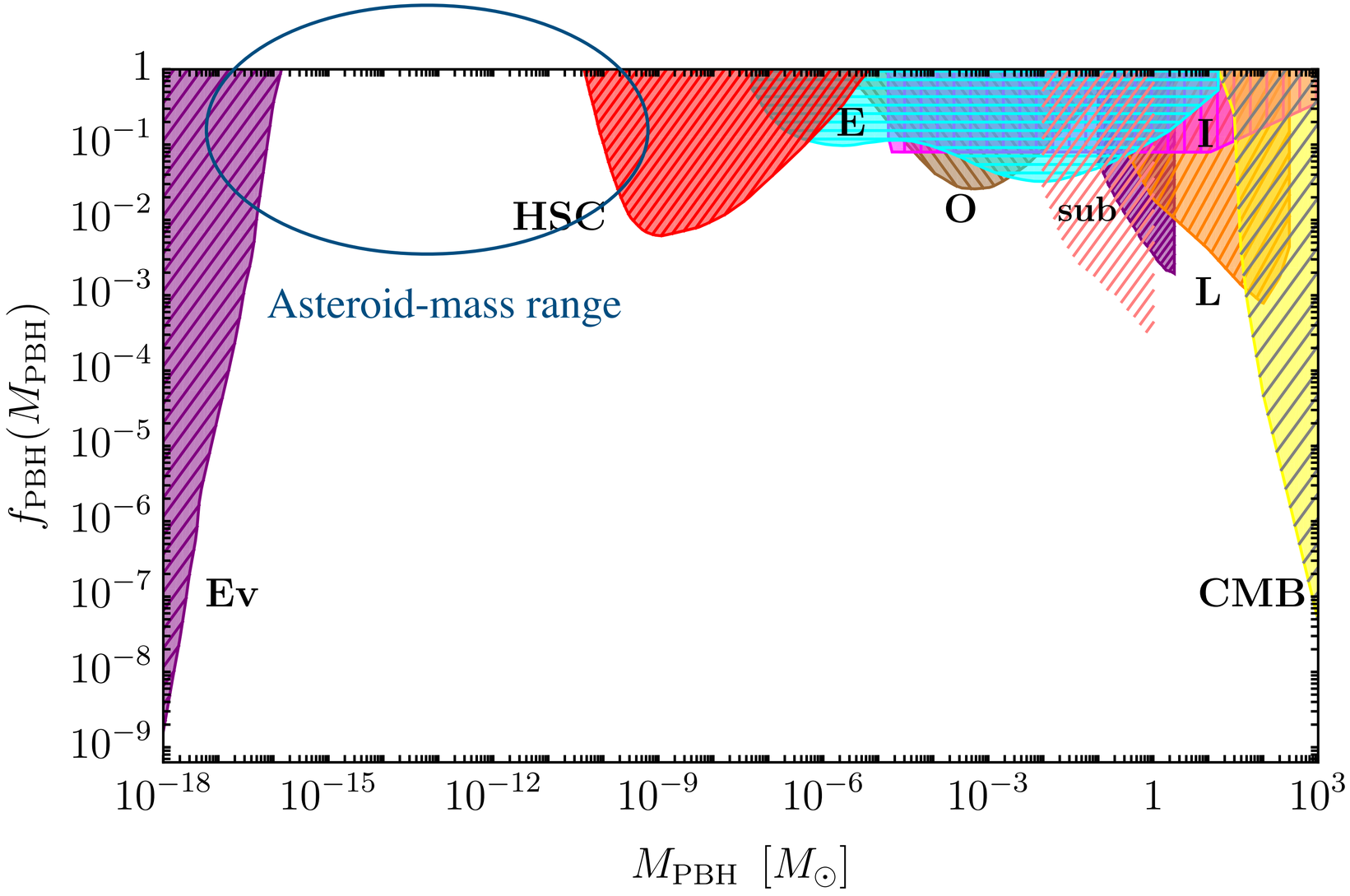


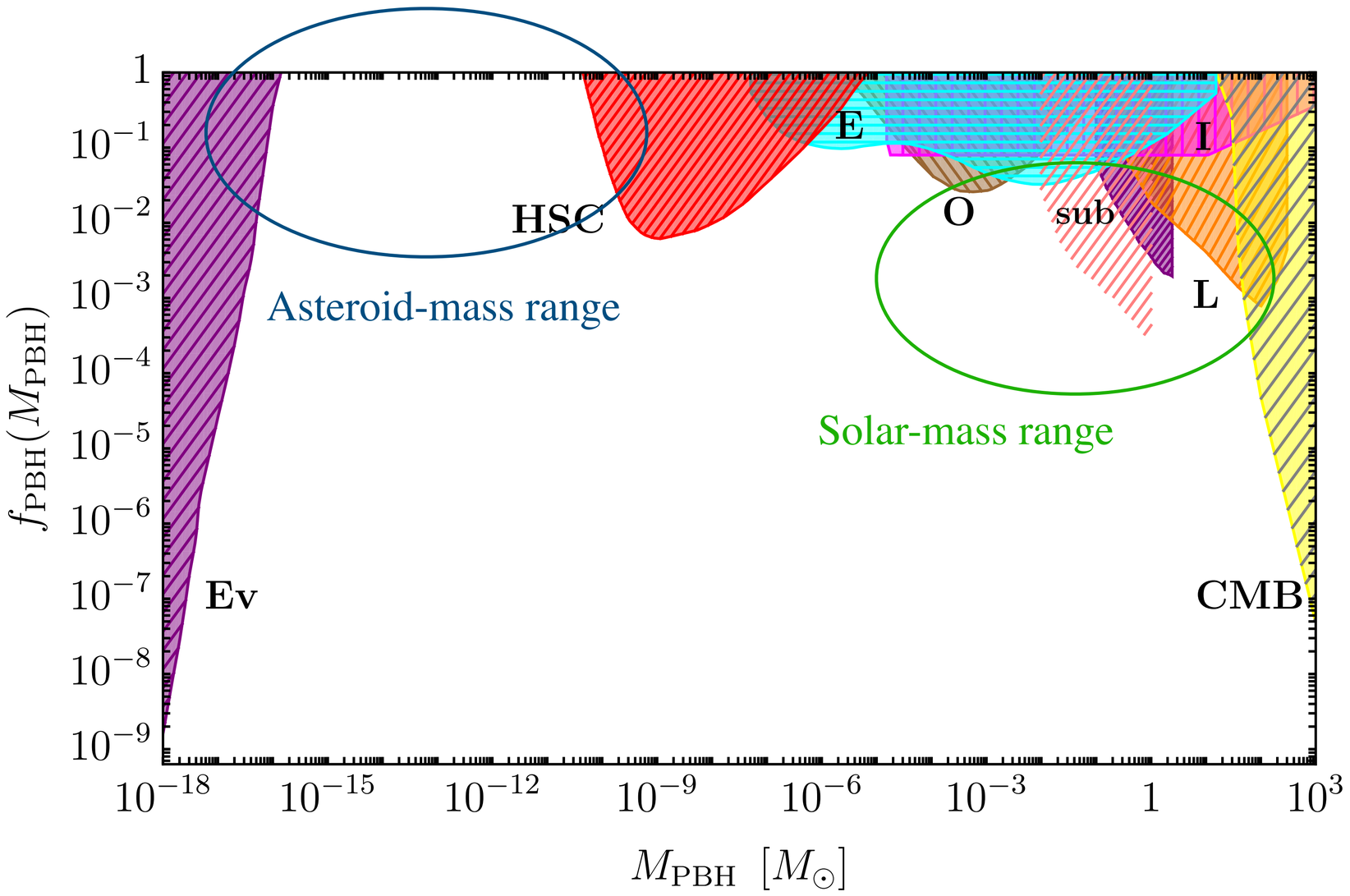
$$\mathcal{S} = \int d^4x\sqrt{-g}\left[F(h,R) + \frac{1}{2}\partial_\mu h\partial^\mu h - \frac{\lambda}{4}h^4\right]$$

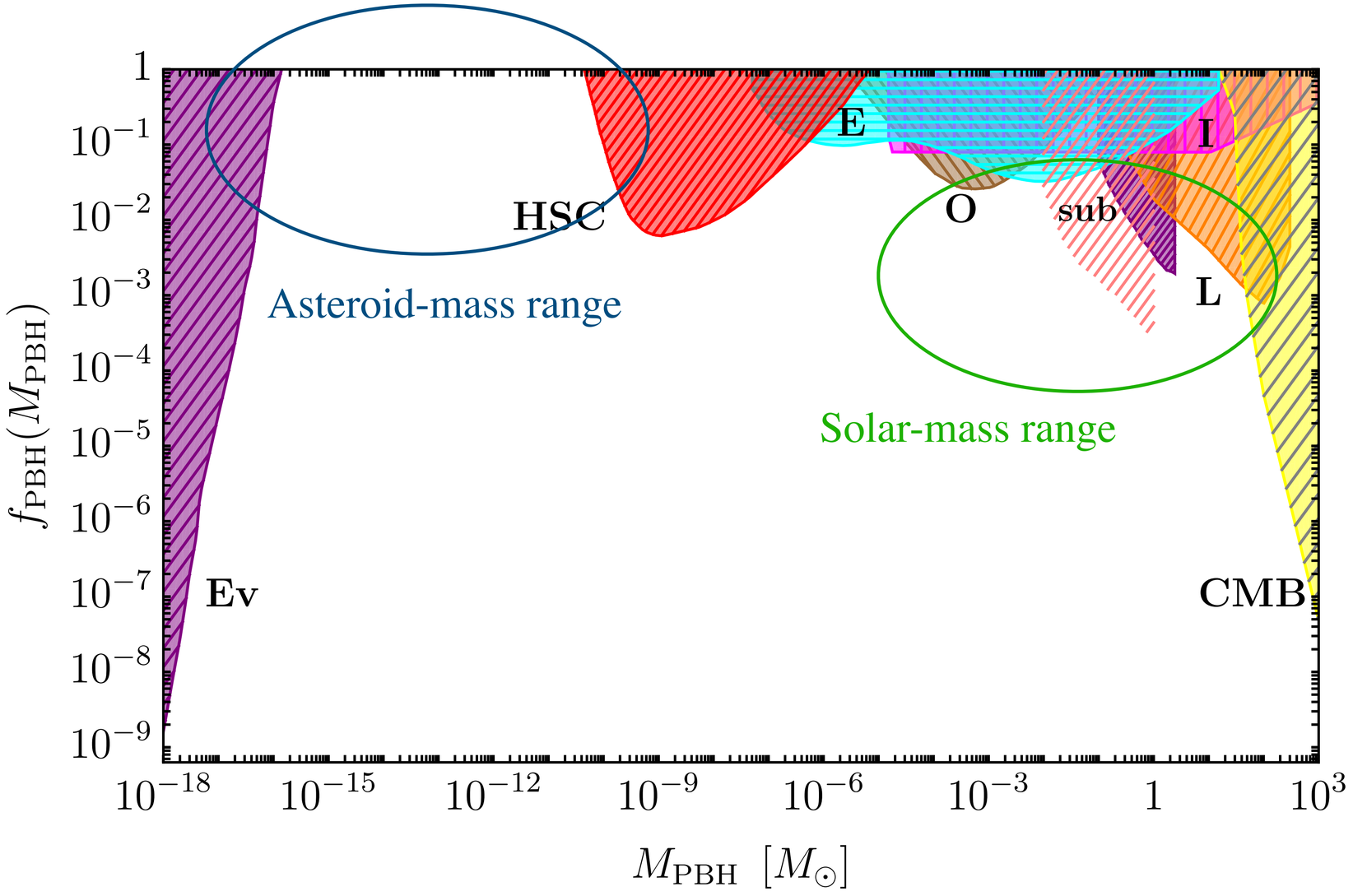
$$F(h,R) = \frac{M_{Pl}^2}{2}\left(R + \frac{\xi h^2}{M_{Pl}^2}R + \frac{R^2}{6M^2}\right)$$

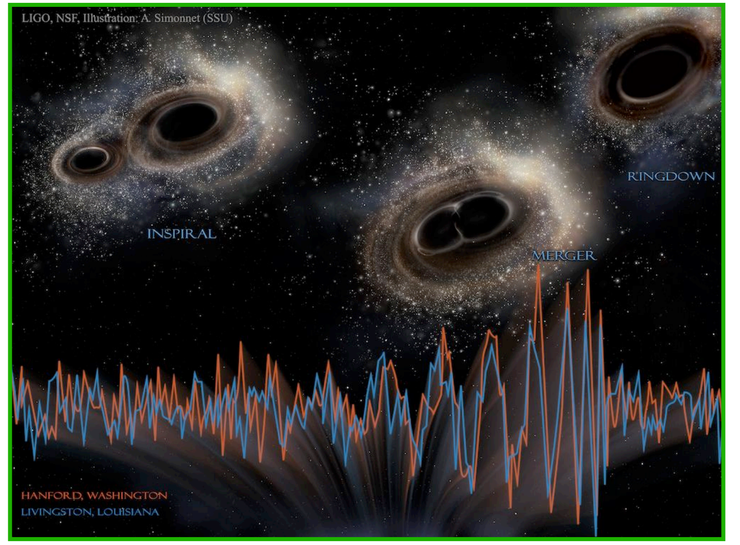
PBHs (and other Exotic Compact Objects)

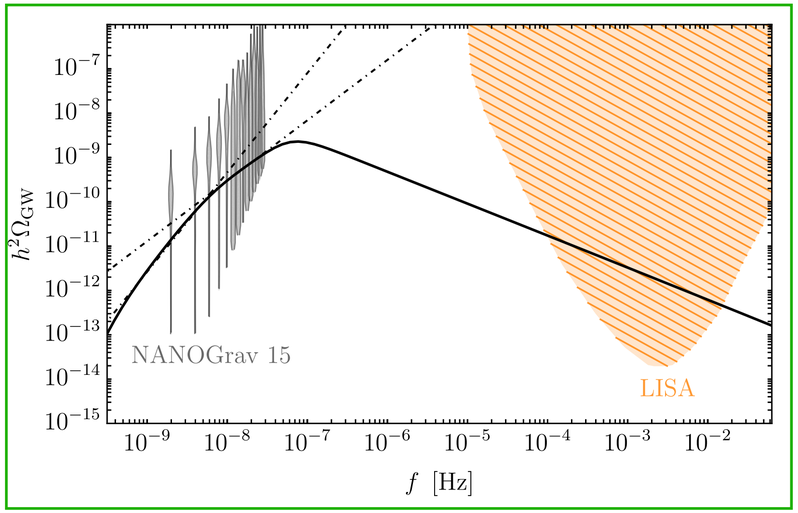

1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$f_{\rm PBH}(M_{\rm PBH})$
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
1
10^{3}
$M_{\rm PBH}\ [M_\odot]$
Ev
HSC
E
O
sub
I
L
CMB

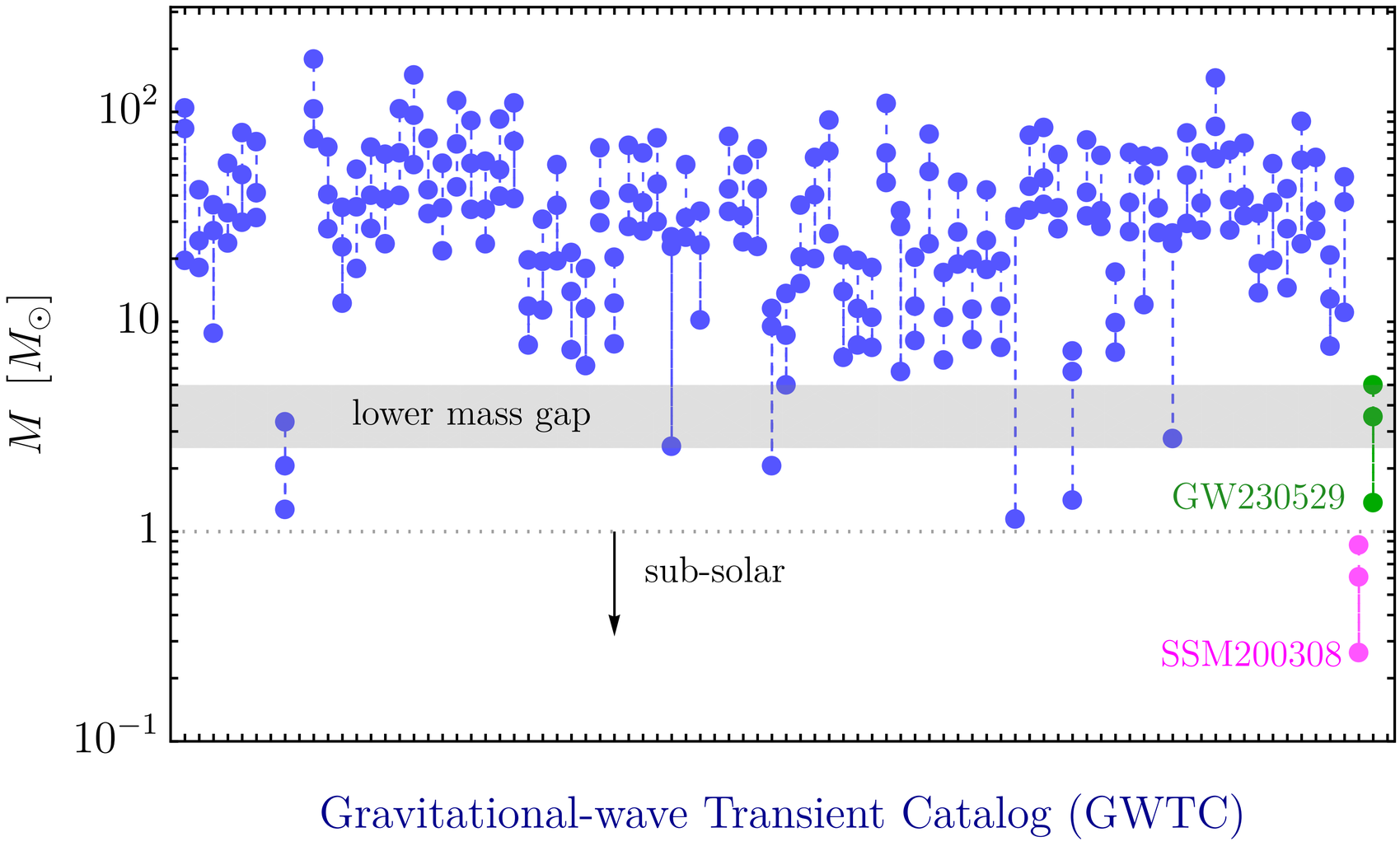

Asteroid-mass range
HSC
E
O
sub
I
L
Ev
CMB
$f_{\rm PBH}(M_{\rm PBH})$
$M_{\rm PBH}\ [M_\odot]$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
1
10^{3}


HSC
E
I
O
sub
L
Ev
CMB
Asteroid-mass range
Solar-mass range
$f_{\rm PBH}(M_{\rm PBH})$
$M_{\rm PBH}\ [M_\odot]$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
1
10^{3}


HSC
E
I
O
sub
L
Ev
CMB
Asteroid-mass range
Solar-mass range
$f_{\rm PBH}(M_{\rm PBH})$
$M_{\rm PBH}\ [M_\odot]$

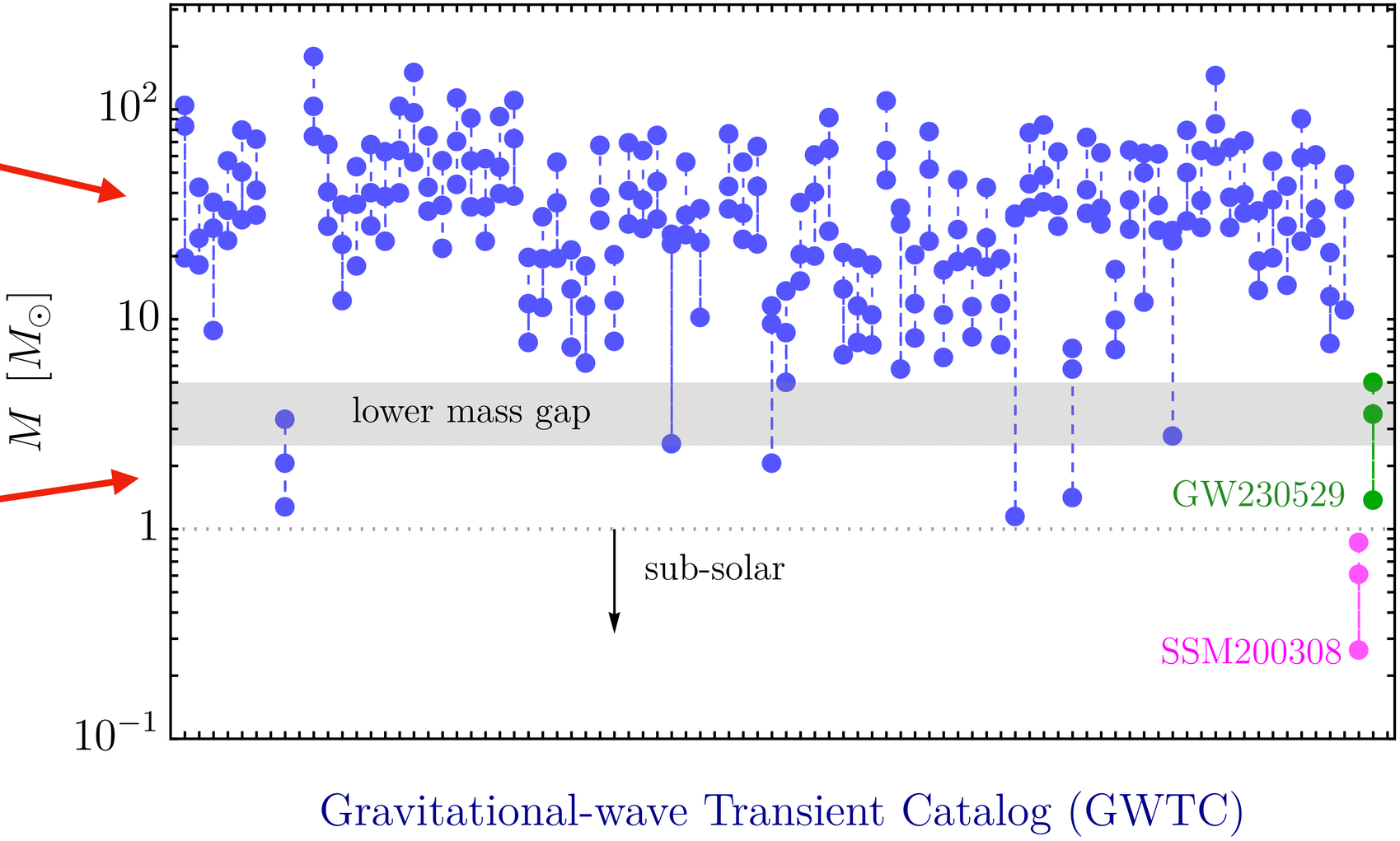

LIGO, NSF, Illustration: A. Simonnet (SSU)
INSPIRAL
MERGER
RINGDOWN
HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA


NANOGrav 15
LISA
$h^2\Omega_{\rm GW}$
f [Hz]


10^2
10
1
10^{-1}
$M\ [M_\odot]$
lower mass gap
sub-solar
GW230529
SSM200308
Gravitational-wave Transient Catalog (GWTC)

Astrophysical Black Holes

Neutron Stars

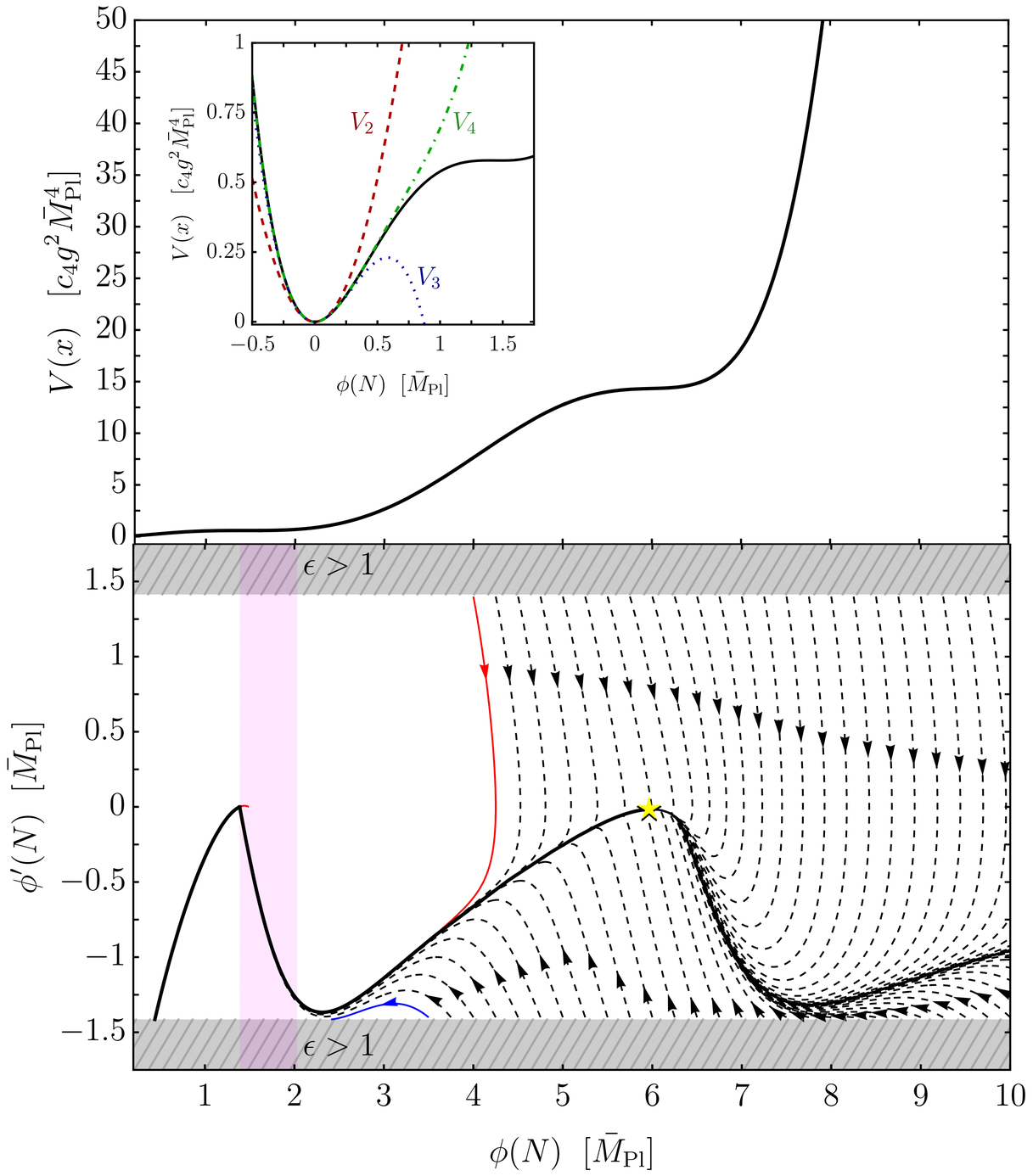


Gravitational-wave Transient Catalog (GWTC)

The **detection of gravitational waves (GWs)** from mergers in the **lower mass gap** or **subsolar mass region** would be an extraordinary and potentially revolutionary discovery in astrophysics and fundamental physics.

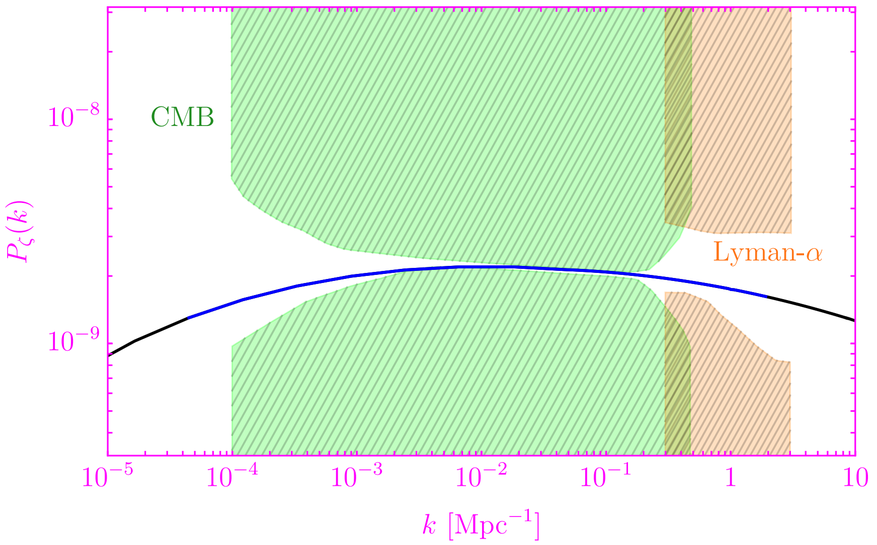
Allegrini, Del Grosso, Iovino, Urbano [arXiv:2412.14049]

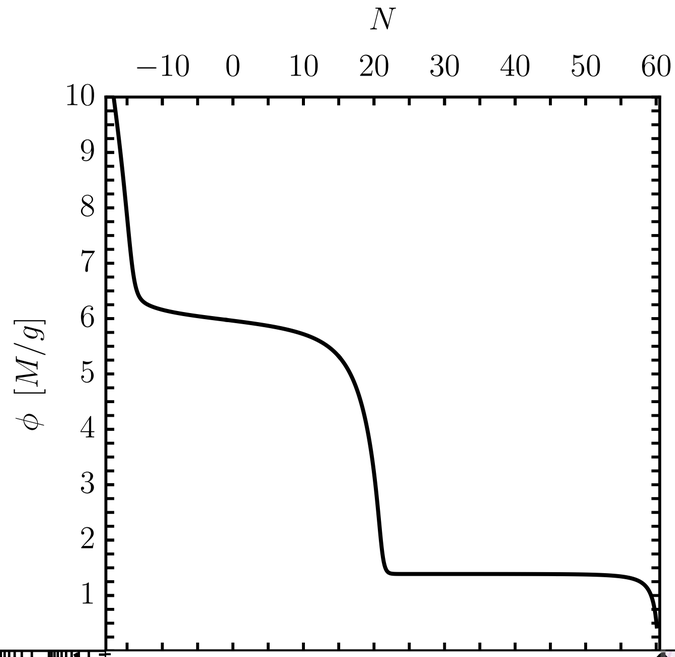
Sub-solar mass PBHs?

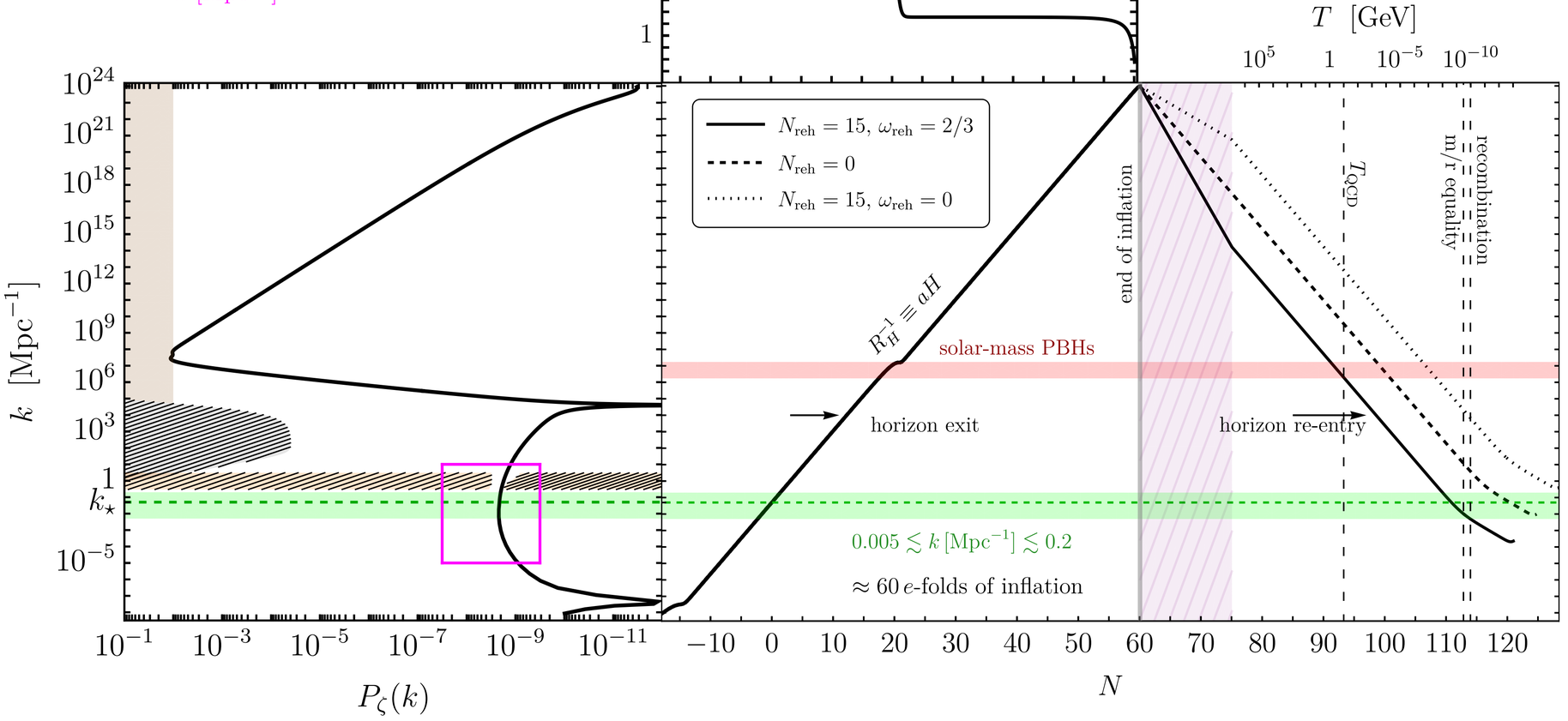


Allegrini, Del Grosso, Iovino, Urbano [arXiv:2412.14049]

Sub-solar mass PBHs?







Exotic Compact Objects (ECOs) are theoretical alternatives to astrophysical black holes. They mimic black holes externally but differ in internal structure.

Realistic ECOs are based on well-defined Lagrangian theories (e.g., boson stars) and arise in models of dark matter or beyond-Standard-Model physics.

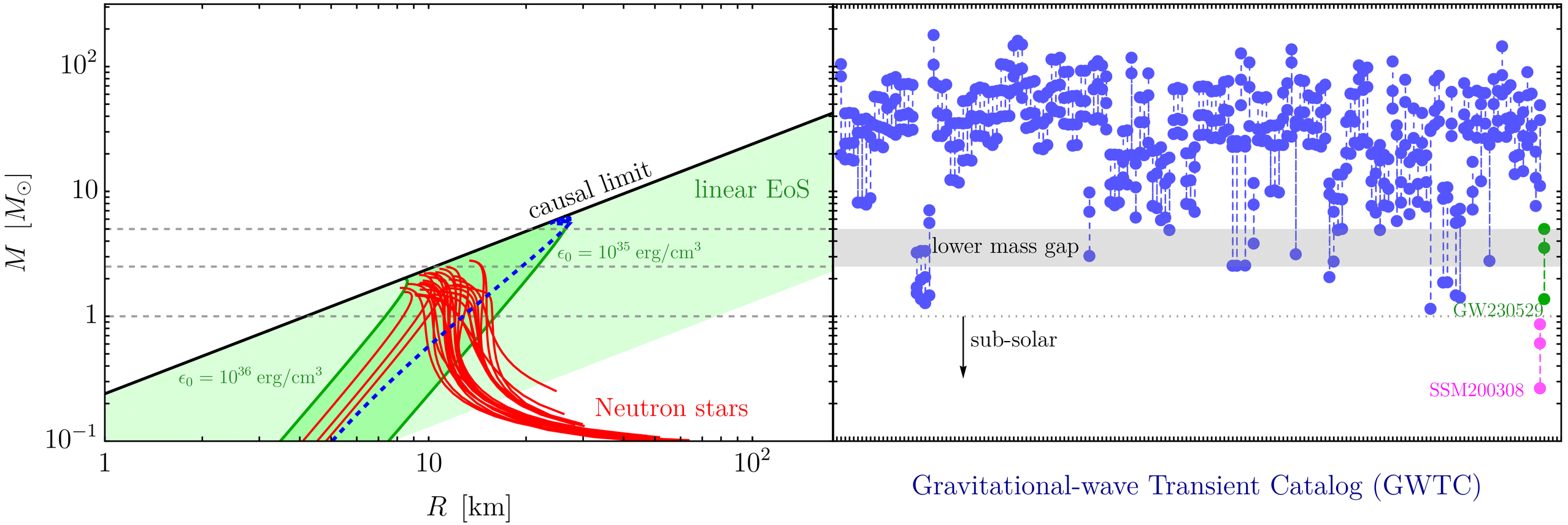
Speculative ECOs are constructed phenomenologically using exotic matter or modified spacetime geometries (e.g., gravastars, wormholes), often without a known underlying theory.

They may violate known energy conditions, causality, suffer from stability issues, or lack a well-defined formulation.

Russo, Urbano [to appear]

Sub-solar mass boson stars?

$$\mathscr{L}_\Phi = -g^{\mu\nu}(\partial_\mu \Phi^*)(\partial_\nu \Phi) - V(\Phi^*\Phi)$$

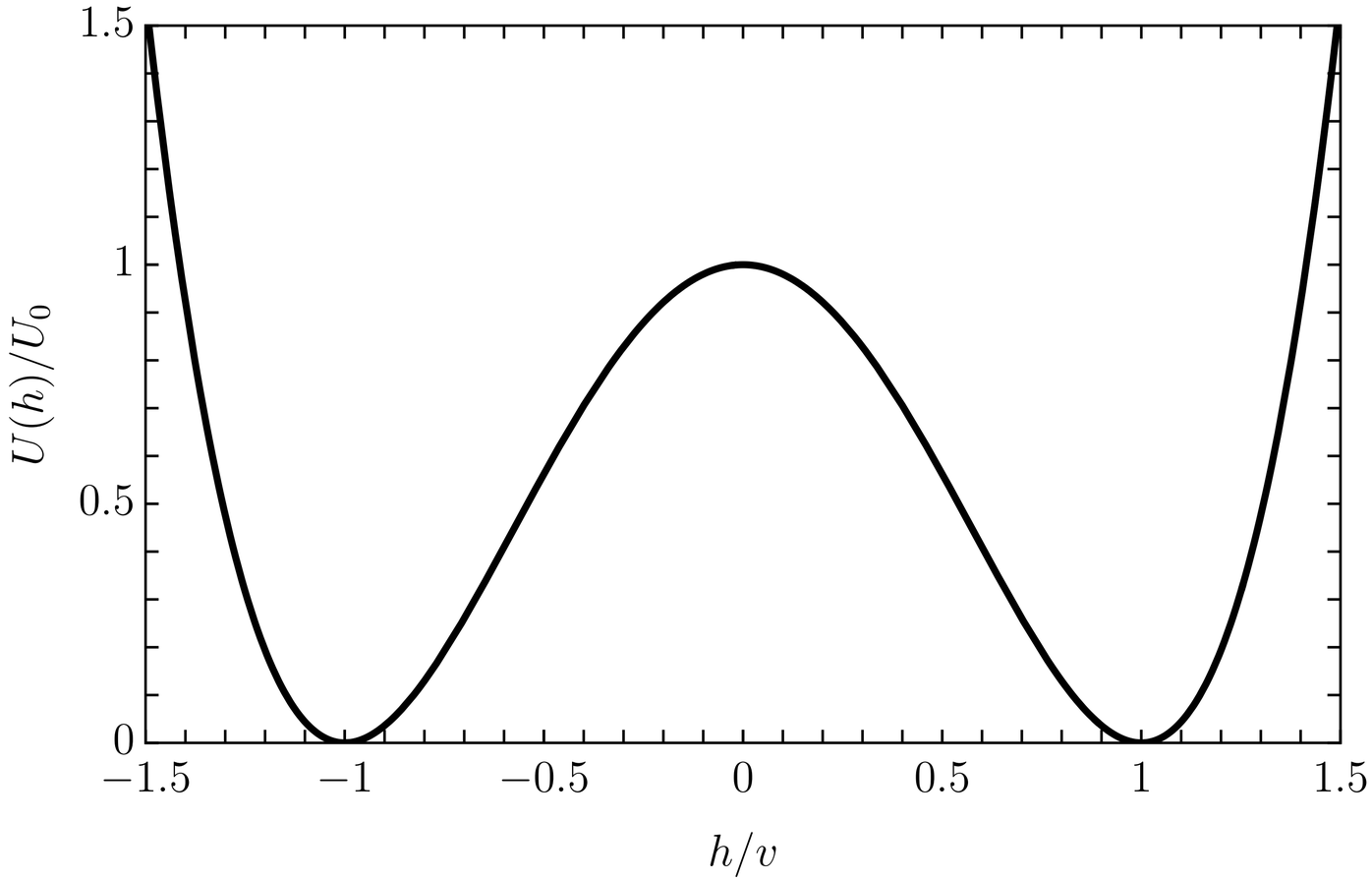


Del Grosso, Pani, Urbano [arXiv:2401.06716]

Sub-solar mass fermion-boson stars?

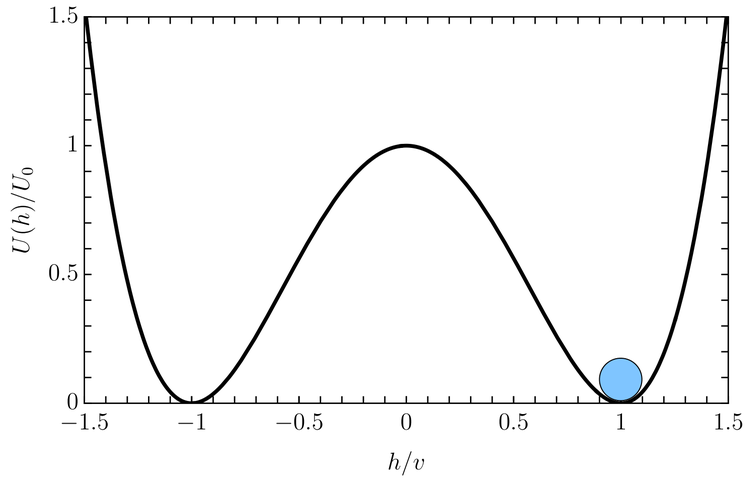
$$\mathcal{L} = \frac{R}{16\pi G} - \frac{1}{2}\partial_\mu h \partial^\mu h - \bar{\psi}\gamma^\mu D_\mu \psi - U(h) - \frac{f}{\sqrt{2}} h\, \bar{\psi}\psi$$

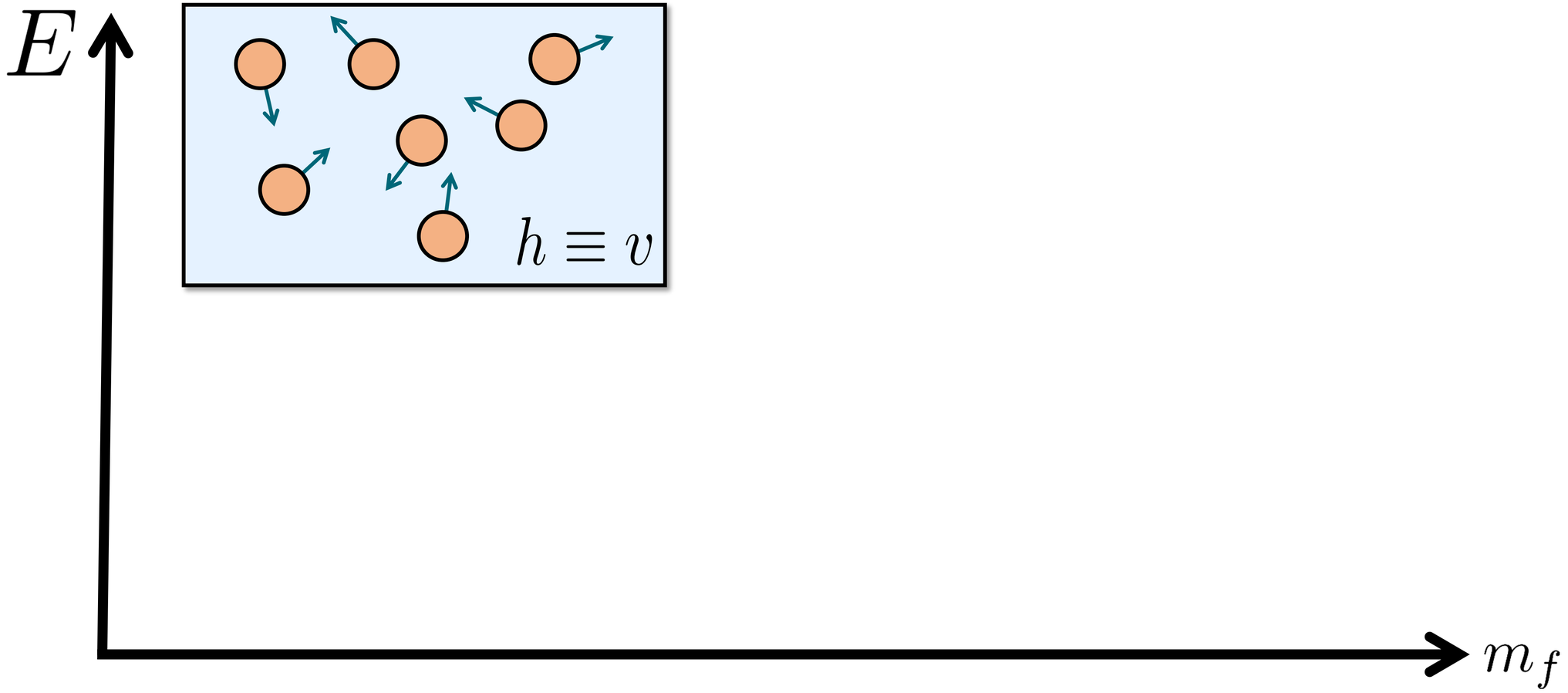
$$U(h) = \frac{\lambda}{16}\left(h^2 - v^2\right)^2$$



Del Grosso, Pani, Urbano [arXiv:2401.06716]

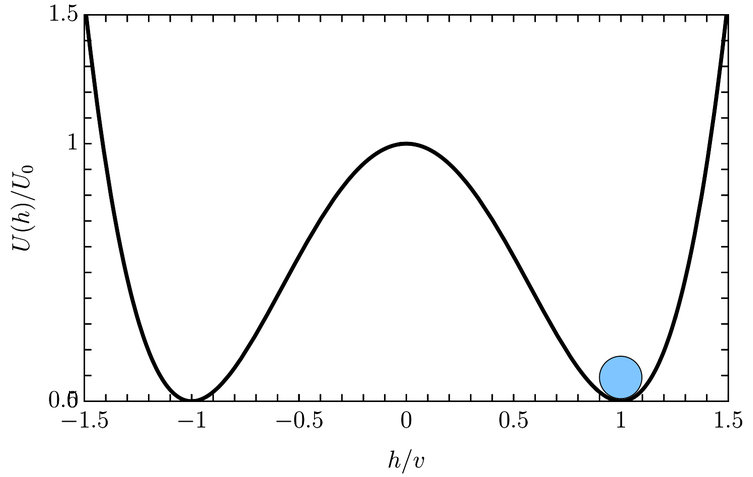
Sub-solar mass fermion-boson stars?



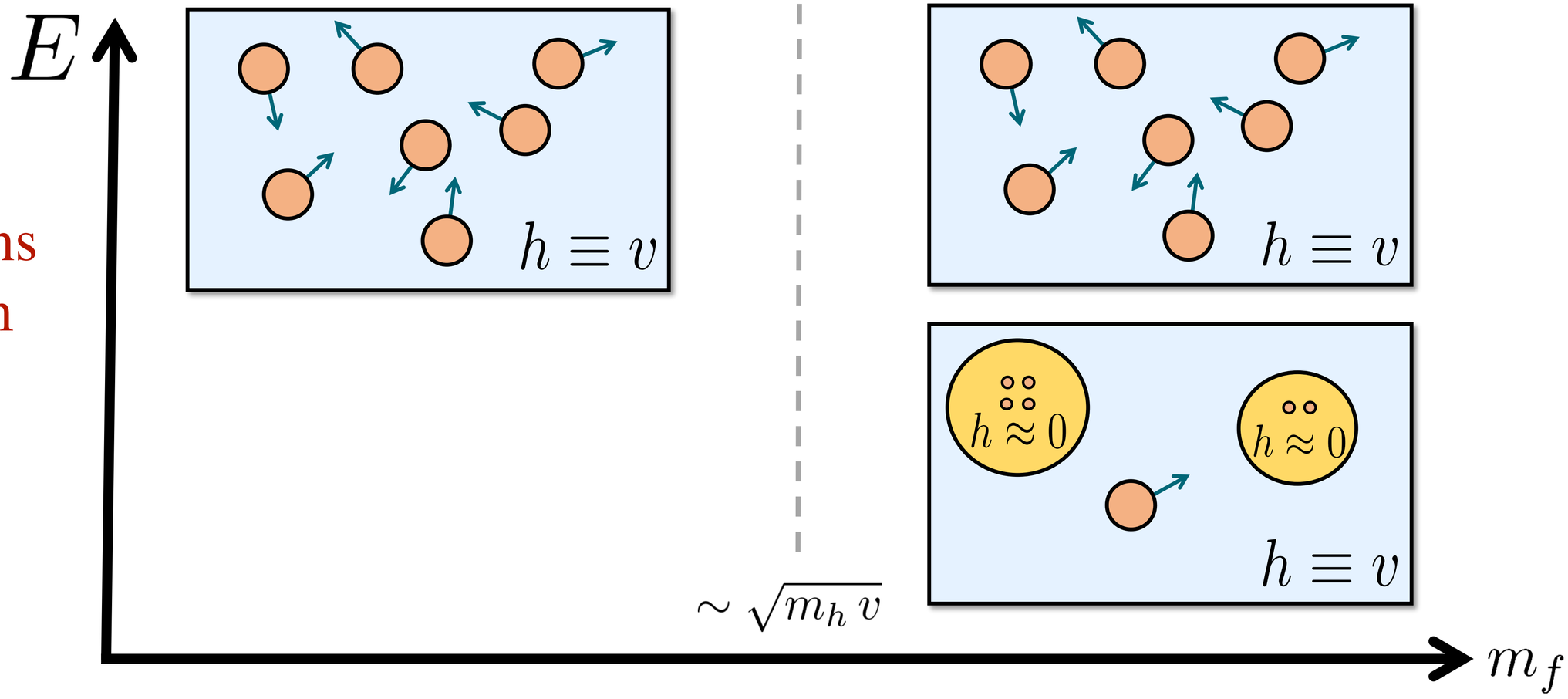


Del Grosso, Pani, Urbano [arXiv:2401.06716]

Sub-solar mass fermion-boson stars?



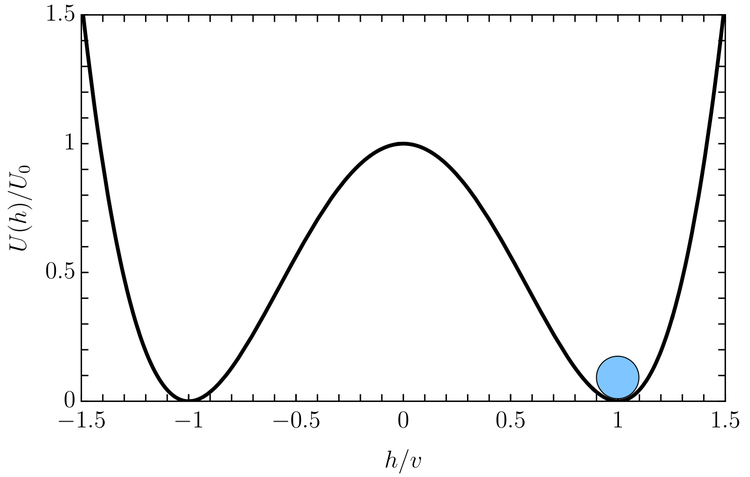
It becomes energetically convenient to confine fermions in false vacuum pockets



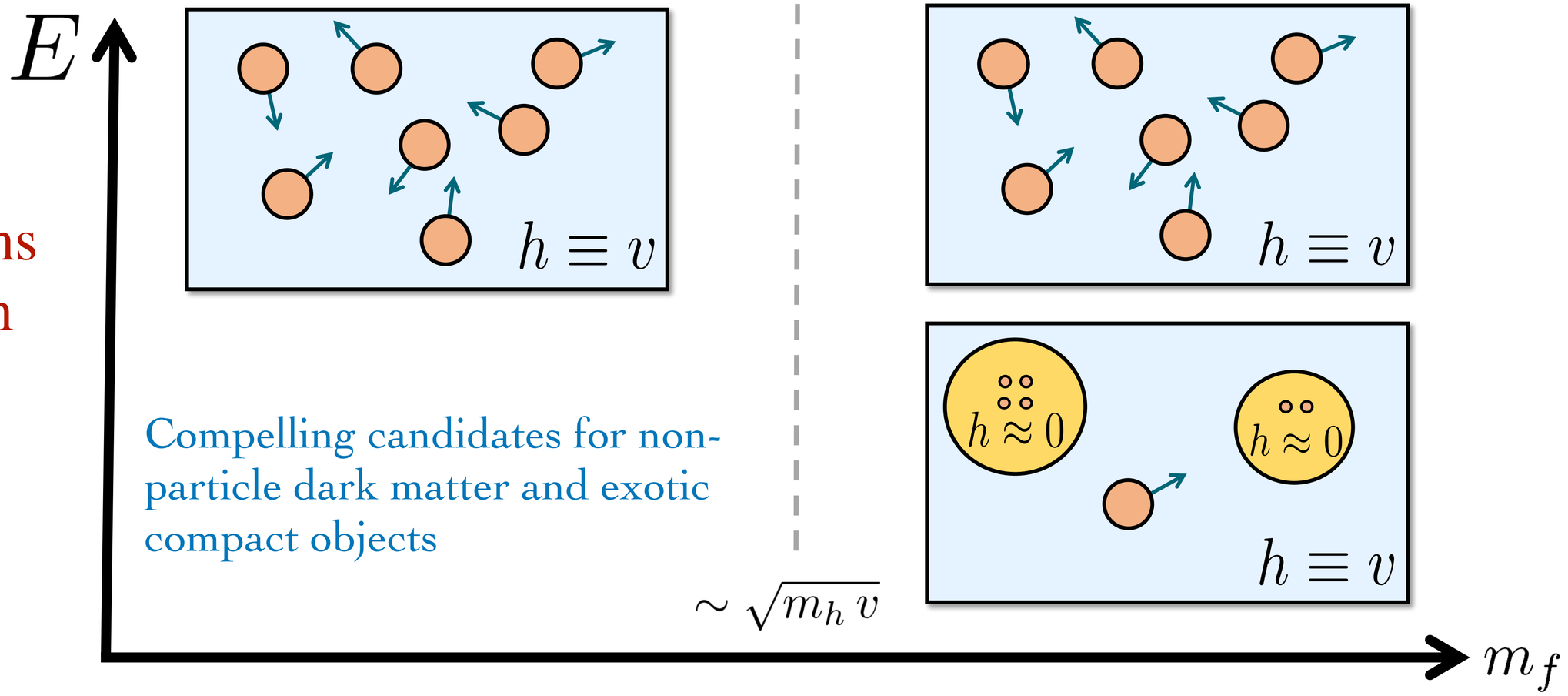
Del Grosso, Pani, Urbano [arXiv:2401.06716]

Sub-solar mass fermion-boson stars?

$$M_c \approx M_\odot \left(\frac{0.34\,\mathrm{GeV}}{q}\right)^2, \quad R_c \approx 5.5\,\mathrm{km}\left(\frac{0.34\,\mathrm{GeV}}{q}\right)^2$$



It becomes energetically convenient to confine fermions in false vacuum pockets

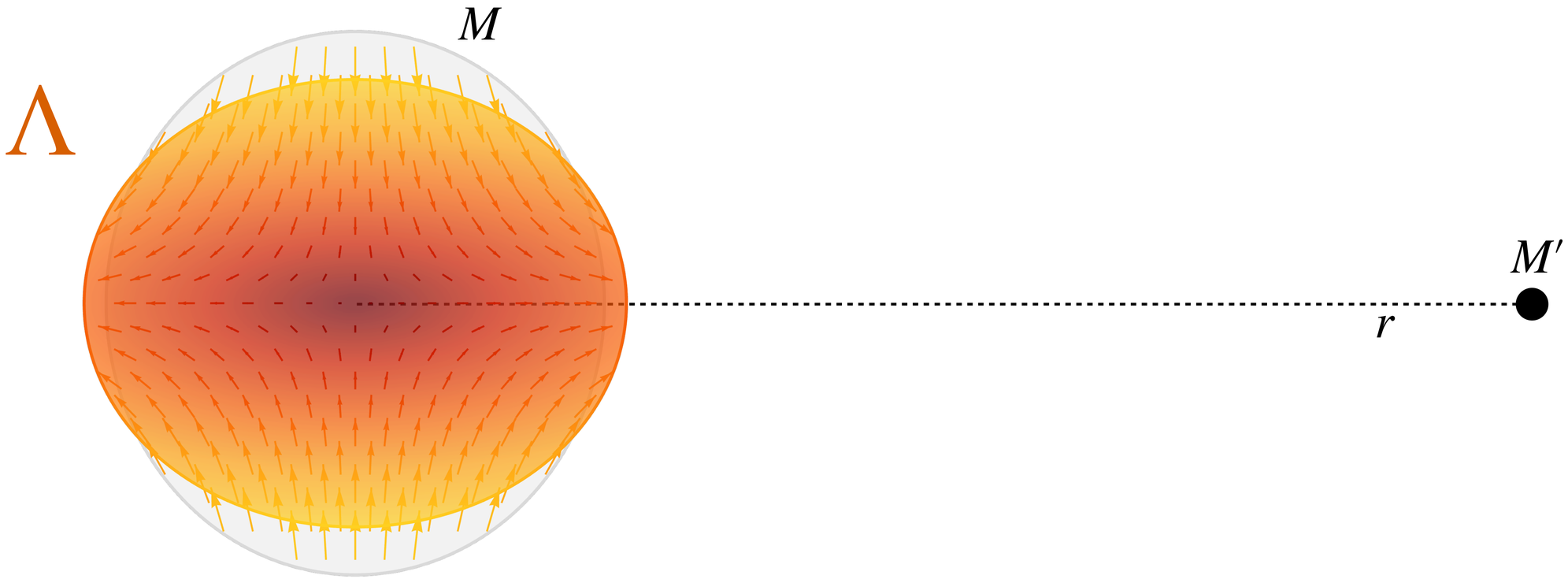


Compelling candidates for non-particle dark matter and exotic compact objects

How to discriminate among compact objects?

How to discriminate among compact objects?

How to discriminate among compact objects?

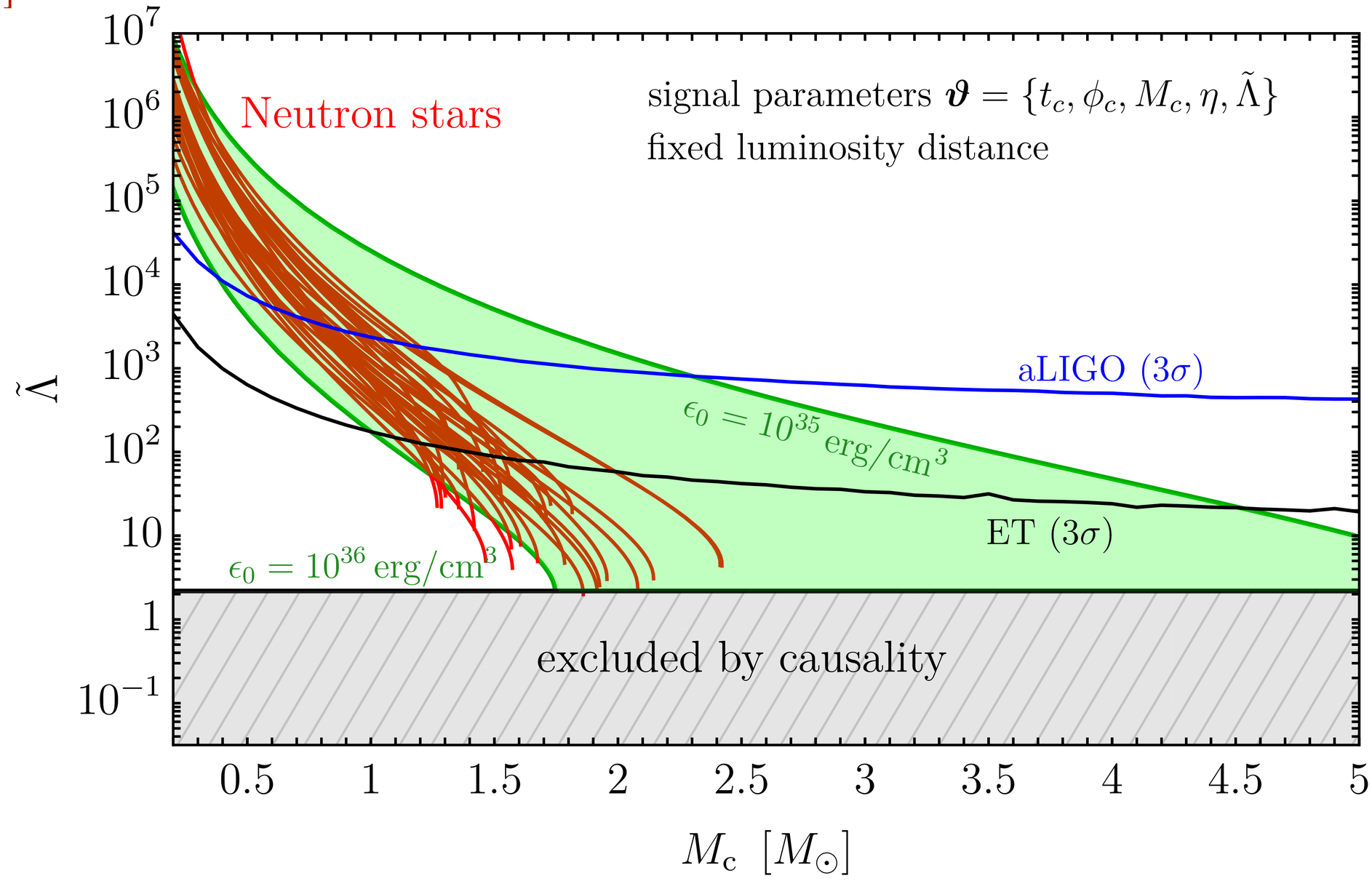


$\Lambda = 0$ in the case of Black Holes

$\Lambda \neq 0$ in the case of ECOs

How to discriminate among compact objects?

Russo, Urbano [to appear]



Conclusions

Conclusions

I only scratched the surface of a rich and extensive subject

The Higgs field can play a variety of roles in the early universe, and cosmological constraints and observables have the potential to teach us a great deal about its dynamics

Topics not covered

Electroweak phase transition

Oleksii's talk

Vacuum decay

Victor's talk