Complementary Probes of weakly coupled BSM: *Gravitational Waves versus Laboratory*

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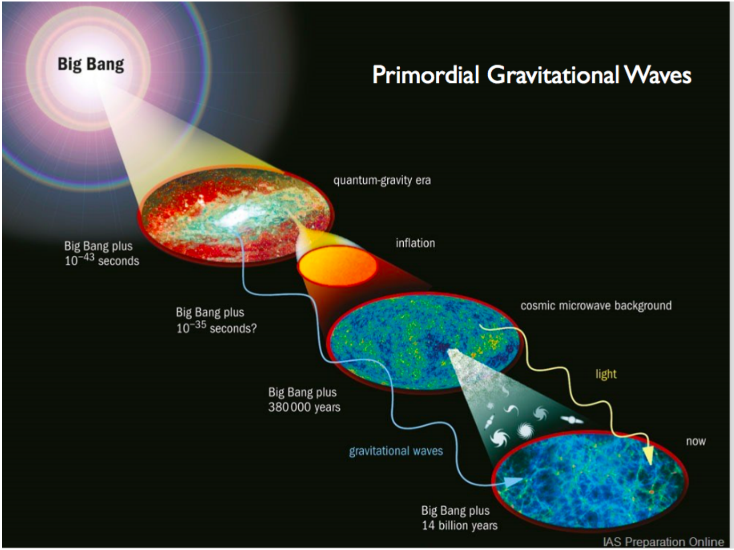
2301.05672

Outline of talk:

- Existing complementary probes: GW versus Lab from strong firt-order phase transition (very briefly)
- Non-thermal Dark Matter Production from Heavy Scalar Decay.
- Non-standard cosmological era.
- Inflationary Scenarios
- Laboratory versus GW probes
    - Intensity and Lifetime Frontier Experiments
    - Inflationary Tensor Perturbations
    - Complementarity of GW with Lab
- Conclusion

History of the Universe

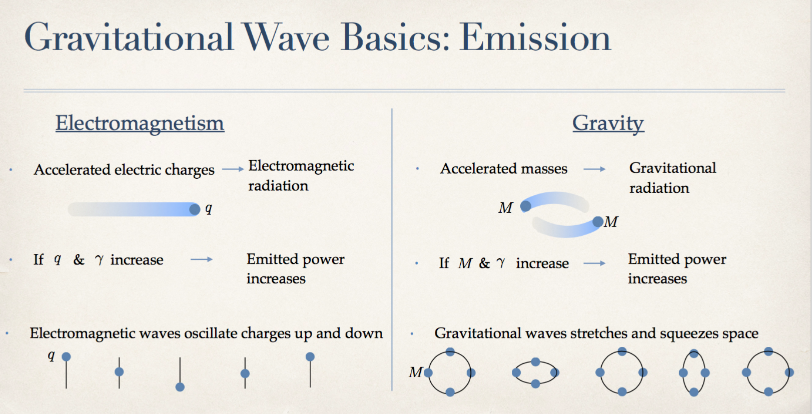


IAS Preparation Online

Gravitational Waves

- Gravitational Waves (GW) first detected in 2016.
- New Window into the Early Universe.
- New Probes of Particle Phenomenology beyond TeV (LHC scale). Also beyond weak-scale couplings.
- Existing Complementarity: GW versus lab.

GW - - A Primer



Gravitational Wave Basics: Emission

Electromagnetism

- Accelerated electric charges → Electromagnetic radiation
- If q & γ increase → Emitted power increases
- Electromagnetic waves oscillate charges up and down

Gravity

- Accelerated masses → Gravitational radiation
- If M & γ increase → Emitted power increases
- Gravitational waves stretches and squeezes space

GW - - A Primer

perturbations of the background metric: $ds^2 = a^2(\tau)(\eta_{\mu\nu} + h_{\mu\nu}(\mathbf{x},\tau))dx^\mu dx^\nu$

scale factor: cosmological expansion background metric GW

governed by linearized Einstein equation $(\tilde{h}_{ij} = a h_{ij},\ \mathrm{TT\ \text{-}\ gauge})$

$$\tilde{h}''_{ij}(\boldsymbol{k},\tau) + \left(k^2 - \underbrace{\frac{a''}{a}}_{\sim a^2H^2}\right)\tilde{h}_{ij}(\boldsymbol{k},\tau) = \underbrace{16\pi G\, a\, \Pi_{ij}(\boldsymbol{k},\tau)}_{\text{source term from } \delta T_{\mu\nu}}$$

source: anisotropic stress-energy tensor

$k \gg aH:\ h_{ij} \sim \cos(\omega\tau)/a\,, \quad k \ll aH:\ h_{ij} \sim \mathrm{const.}$

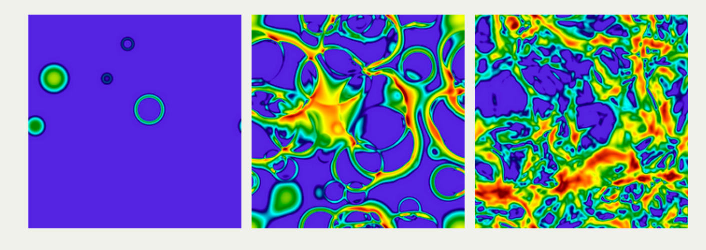
a useful plane wave expansion: $h_{ij}(\boldsymbol{x},\tau) = \sum_{P=+,\times}\int_{-\infty}^{+\infty}\frac{dk}{2\pi}\int d^2\hat{\boldsymbol{k}}\; h_P(\boldsymbol{k})\;\underbrace{T_k(\tau)}_{\sim a(\tau_i)/a(\tau)}\;e^{P}_{ij}(\hat{k})\,e^{-ik(\tau-\hat{\boldsymbol{k}}\boldsymbol{x})}$

transfer function , expansion coefficients , polarization tensor $P = +, \times$

Phase Transition

Phase Transitions:

- Bubbles nucleate and grow.
- Expand in plasma.
- Bubbles and fronts collide - - violent process.
- Sound Waves left behind in thermal plasma.
- Turbulence, damping.



Phase Transition GW - Parameter Dependence

- Total GW energy budget from 3 sources

$$h^2\Omega_{\mathrm{GW}} = h^2\Omega_\phi + h^2\Omega_{\mathrm{SW}} + h^2\Omega_{\mathrm{MHD}}$$

Depends on two important parameters:

- Vacuum energy density: $\alpha = \frac{\rho_{\mathrm{vac}}}{\rho^*_{\mathrm{rad}}}$ with $\rho^*_{\mathrm{rad}} = g_* \pi^2 \frac{T_*^4}{30}$
- (Inverse) Bubble nucleation rate: $\beta / H_* = T \sqrt{\frac{d^2 S_E(T)}{dT^2}} \Big|_{T=T_*}$

-

$$h^2\Omega_\phi \propto \left(\frac{\beta}{H_*}\right)^{-2}, \quad h^2\Omega_{\mathrm{SW}} \propto \left(\frac{\beta}{H_*}\right)^{-1}, \quad h^2\Omega_{\mathrm{MHD}} \propto \left(\frac{\beta}{H_*}\right)^{-1}$$

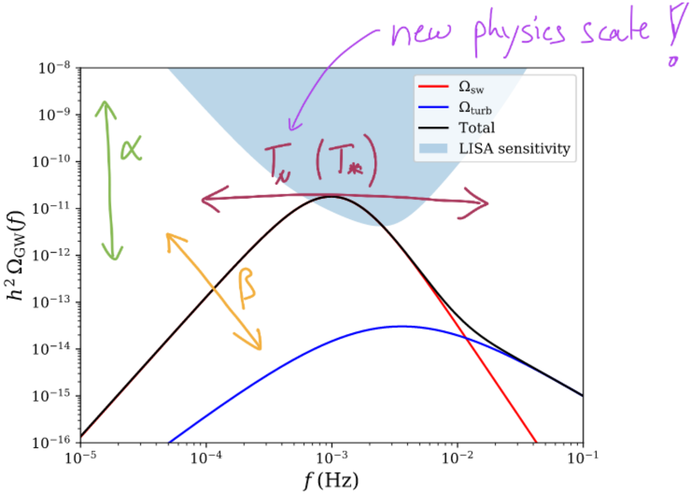
- The bubble nucleation rate per unit volume at a finite temperature is given by

$$\Gamma(T) = \Gamma_0 e^{-S(T)} \simeq \Gamma_0 e^{-S_E^3(T)/T},$$

-

Other important parameter: bubble wall speed v_w, efficiency factors.

Phase Transition GW - Parameter Dependence



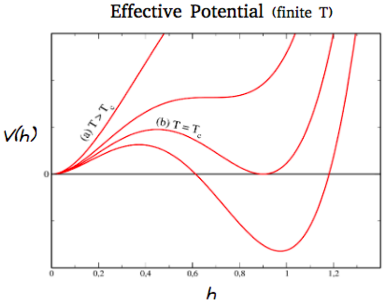
new physics scale !

T_n (T_*)

α

β

Phase Transitions



Effective Potential (finite T)

- **Decay rate** $\Gamma(T) \approx T^4 \exp\left(-\frac{S_3(T)}{T}\right)$
- **O(3) symmetric action**

$$S_3(T) = 4\pi \int dr r^2 \left[\frac{1}{2}\left(\frac{d\phi}{dr}\right)^2 + V(\phi, T)\right]$$

- **Bubble profile (bounce)**

$$\frac{d^2\phi}{dr^2} + \frac{2}{r}\frac{d\phi}{dr} - \frac{\partial V(\phi,T)}{\partial \phi} = 0$$

$$\phi(r \to \infty) = 0 \quad \text{and} \quad \dot{\phi}(r = 0) = 0$$

Nucleation temperature:

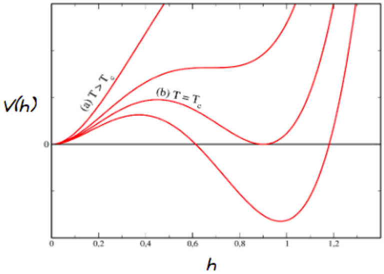
One Higgs bubble per Horizon volume (on average)

$$N(T_n) = \int_{t_c}^{t_n} dt \frac{\Gamma(t)}{H(t)^3} = \int_{T_n}^{T_c} \frac{dT}{T}\frac{\Gamma(T)}{H(T)^4} = 1$$

*Linde, Phys. Lett. **B100** (1981) 37; Nucl. Phys. **B216** (1983) 421*

Phase Transitions

Effective Potential (finite T)



- ▶ GW frequency ~ size of bubbles @ collision
- ▶ For $T_* \sim 100$ GeV and $\dfrac{\beta}{H_*} \sim 100$, GW frequency (redshifted to today!) ~ **mHz**

Two KEY Phase Transition Quantities:

❍ (Available) Transition Energy (normalized)

$$\alpha_e \equiv \frac{4}{3}\frac{\Delta e(T_{\rm n})}{w_+(T_{\rm n})}$$

❍ Duration of the Transition (-1)

$$\frac{\beta}{H} \equiv -\frac{dS_3}{dt}\bigg|_{t=t_n} \approx T\frac{d(S_3/T)}{dT}\bigg|_{T=T_n}$$

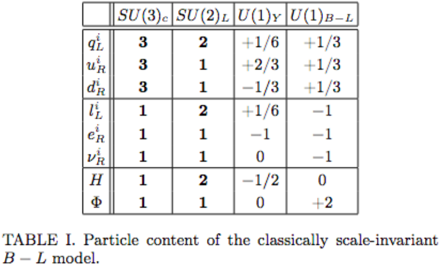
(Related to the change of the Decay Rate)

Average number of bubbles per horizon at the time of bubble coalescence/percolation

(Transition Completes, T_*)

H_*

Scale-Invariant B-L extended SM



	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
q_L^i	$\mathbf{3}$	$\mathbf{2}$	$+1/6$	$+1/3$
u_R^i	$\mathbf{3}$	$\mathbf{1}$	$+2/3$	$+1/3$
d_R^i	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$+1/3$
l_L^i	$\mathbf{1}$	$\mathbf{2}$	$+1/6$	-1
e_R^i	$\mathbf{1}$	$\mathbf{1}$	-1	-1
ν_R^i	$\mathbf{1}$	$\mathbf{1}$	0	-1
H	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0
Φ	$\mathbf{1}$	$\mathbf{1}$	0	$+2$

TABLE I. Particle content of the classically scale-invariant $B-L$ model.

Phase Transition GW - Finite Temperature

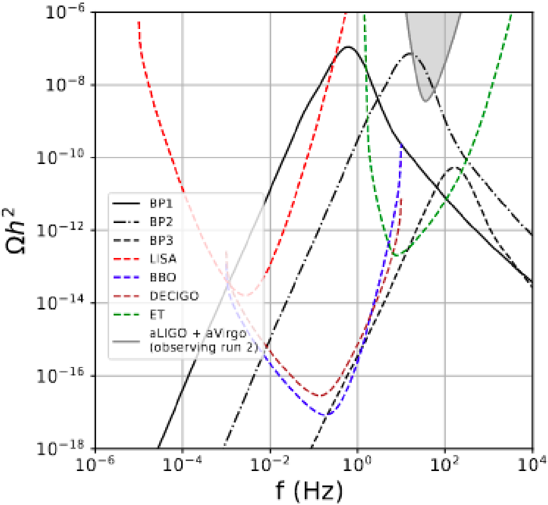
$$\mathcal{V}(\phi,T) = \mathcal{V}_0(\phi) + \mathcal{V}_{\rm CW}(\phi) + \mathcal{V}_T(\phi,T)\,,$$

- Tree-level: $$\begin{aligned}\mathcal{V}_0 &= -\mu^2|H|^2 + \lambda|H|^4 + \kappa|\Phi|^2|H|^2 + \lambda_a\left(|\Phi|^2 - \frac{1}{2}f_a^2\right)^2 . \\ &= \frac{\lambda_a}{4}\left(\phi^2 - f_a^2\right)^2 + \left[\frac{\kappa}{2}\phi^2 - \mu^2\right]\left(\frac{1}{2}h^2 + \frac{1}{2}G_0^2 + G_+G_-\right) \\ &\quad + \lambda\left[\frac{1}{2}h^2 + \frac{1}{2}G_0^2 + G_+G_-\right]^2 .\end{aligned}$$
- One-loop: $$\mathcal{V}_{\rm CW}(\phi) = \sum_i (-1)^F n_i \frac{m_i^4(\phi)}{64\pi^2}\left[\log\frac{m_i^2(\phi)}{\Lambda^2} - C_i\right] .$$
- Finite-temperature: $$\mathcal{V}_T(\phi,T) = \sum_i (-1)^F n_i \frac{T^4}{2\pi^2} J_{B/F}\left(\frac{m_i^2(\phi)}{T^2}\right) ,$$
- Temperature-dependent mass terms:

$$\begin{aligned}\Pi_h(T) = \Pi_{G_{0,\pm}}(T) &= \frac{1}{48}\left(9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda + 4\kappa\right)T^2 , \\ \Pi_\phi(T) &= \frac{1}{3}\left(\kappa + 2\lambda_a\right)T^2 .\end{aligned}$$

[Dolan, Jackiw (PRD '74); Arnold, Espinosa (PRD '93); Curtin, Meade, Ramani (EPJC '18)]

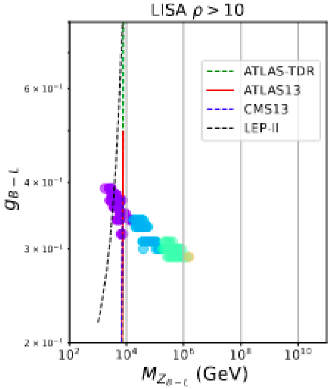
GW spectrum from Phase Transition



GW versus Lab complementarity: colliders

Signal-to-noise ratio (ρ)

$$\rho = \sqrt{t_{\rm obs} \int_{f_{\rm min}}^{f_{\rm max}} df \left[\frac{\Omega_{\rm GW}(f)\, h^2}{\Omega_{\rm expt}(f)\, h^2}\right]^2}, \tag{1}$$

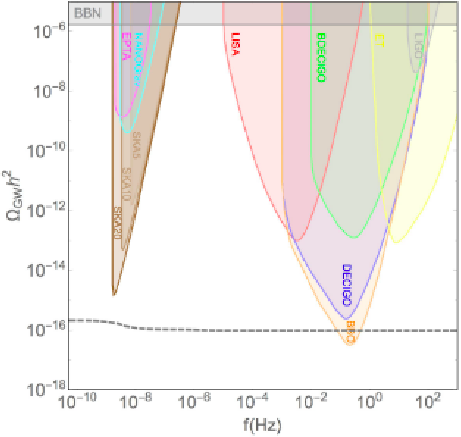


Dasgupta (2022) Complementarity probes of BSM: Lab versus GW from SFOPT.

Inflationary Tensor Perturbations

Can we do such complementary with other Primordial GW sources ?

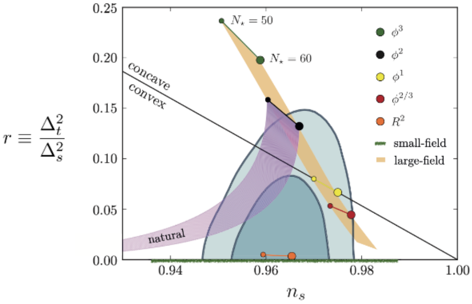
Inflationary Tensor Perturbations

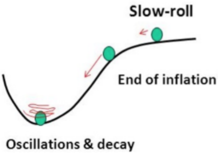


Bernal (2020)

Inflation - - UV completion

Well known story about the inflation scalar field inflaton rolling down a potential with little or no interactions:

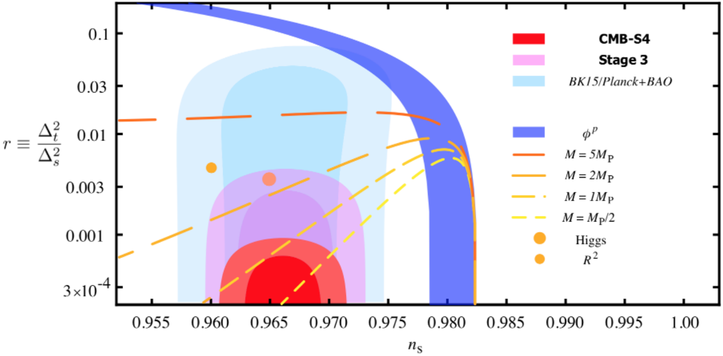




Little or no interactions

Inflation - - UV completion

Going to be more well-known in very near future:



Non-Gaussianity parameters:
$f_{NL}^{\text{local}} = -0.9 \pm 5.1$, $f_{NL}^{\text{equilibrium}} = -26 \pm 47$, $f_{NL}^{\text{orthogonal}} = -38 \pm 24$.
Detection of CMB BB-modes will tell us the scale of inflation.

Inflation - - UV completion

However huge gap in our knowledge in between the inflation ending & the beginning of radiation-domination era:

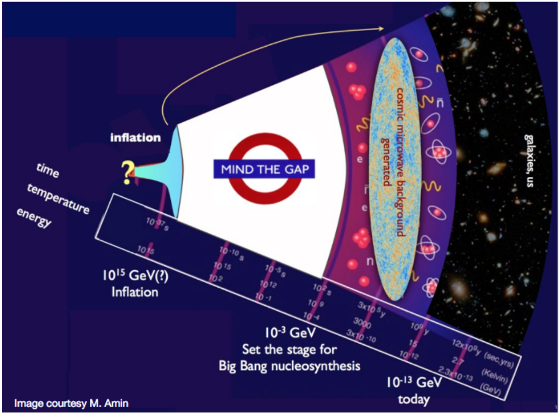
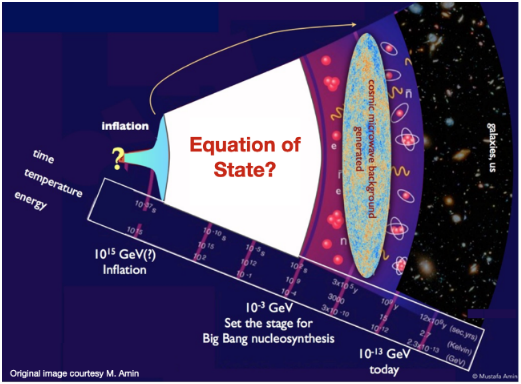


Image courtesy M. Amin

Inflation - - UV completion

What dominated this era ? New gravity ? New Matter ? Predictions from UV-completions.



Original image courtesy M. Amin

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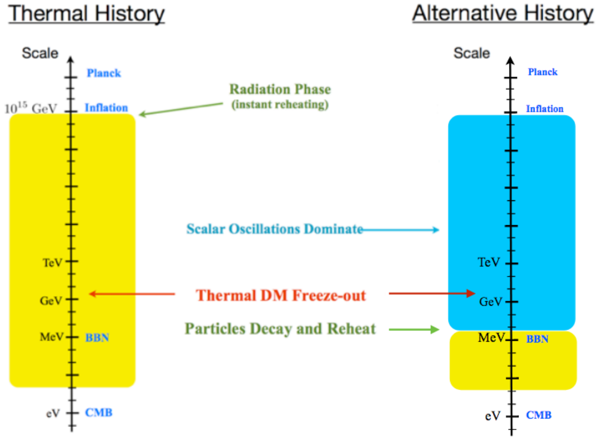
Inflation - - UV completion

Non-thermal History of the Universe during this era, motivated from string theory, UV-completion of gravity (See for instance Sinha (2015)):



Probe of this era via PGW.
Watson slides PHENO (2020)

The idea: Naively

Propagation of Primordial GW generated during Inflation:

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + \frac{k^2}{a^2}h_{ij} = 16\pi\,G\,\Pi^{TT}_{ij}\,, \tag{2}$$

Solution:

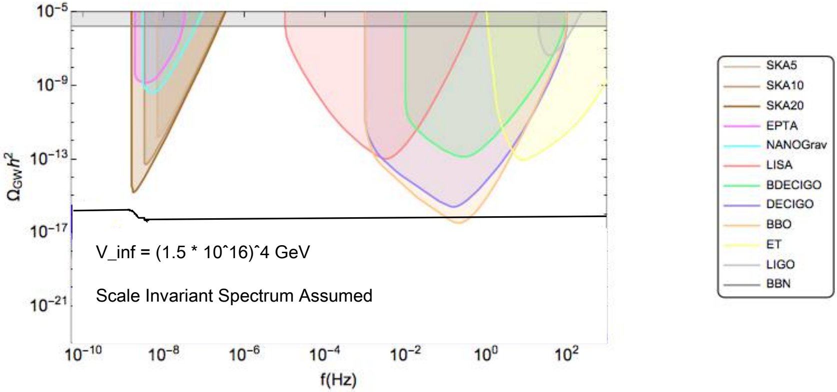
$$h_{ij}(t,\vec{x}) = \sum_P \int \frac{d^3k}{(2\pi)^3}\,h^P(t,\vec{k})\,\epsilon^P_{ij}(\vec{k})\,e^{i\,\vec{k}\cdot\vec{x}}, \tag{3}$$

$$h^P_{\vec{k}} = h^P_{\vec{k},\,0}\,U(t,k)\,, \tag{4}$$

$$\Pi_{ij} = \frac{T_{ij} - p\,g_{ij}}{a^2} \tag{5}$$

$$\Omega_{GW}(\eta,k) = \frac{1}{12\,a^2(\eta)\,H^2(\eta)}\mathcal{P}_T(k)\,\left[U'(\eta,\,k)\right]^2 \tag{6}$$

On the GW sensitivity Map

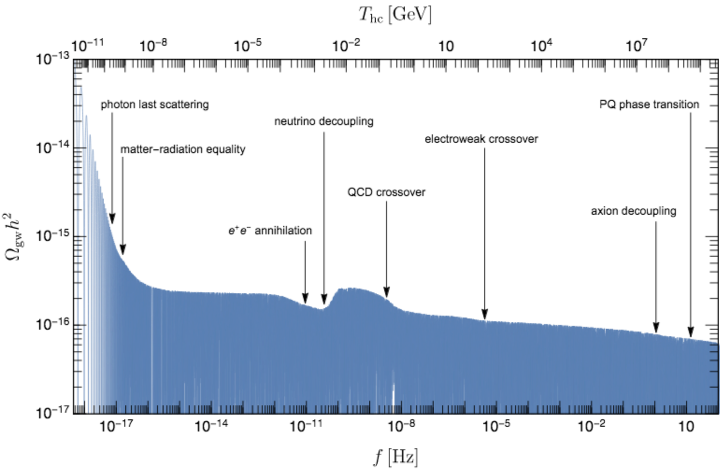


V_inf = (1.5 * 10ˆ16)ˆ4 GeV

Scale Invariant Spectrum Assumed

$P_T = \frac{2}{3\pi^2}\frac{V_{inf}}{M_{pl}^4}$. UV-completion: Trans-Planckian Censorship may constrain V$_{inf}$.
Signal-building: What non-standard cosmology enhances the signal to be detected ?

On the GW sensitivity Map



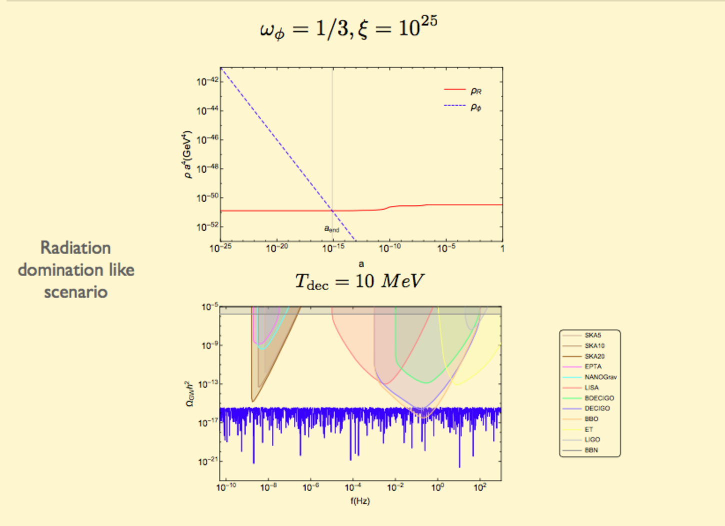
Impact on PGW spectrum from thermal history of the Universe.

Ringwald (2020)

Non-standard Cosmology

- History of the Universe before BBN is unknown.
- Non-standard cosmology predicts scalar field ϕ and its energy density dominates in the Early Universe.
- Its Equation-of-state ω_ϕ.
- Modifies the Hubble expansion: $H^2 \propto \rho_\phi \propto a^{-\frac{3}{2}(1+\omega_\phi)}$.
- PGW relic for modes coming into the horizon for modes coming inside the horizon during the ϕ-dominated era $\Omega_{GW} \propto k^{-2\frac{1+3\omega}{1-3\omega}}$.
- Independent parameter $\xi = \frac{\rho_\phi}{\rho_R}$.

On the GW sensitivity Map

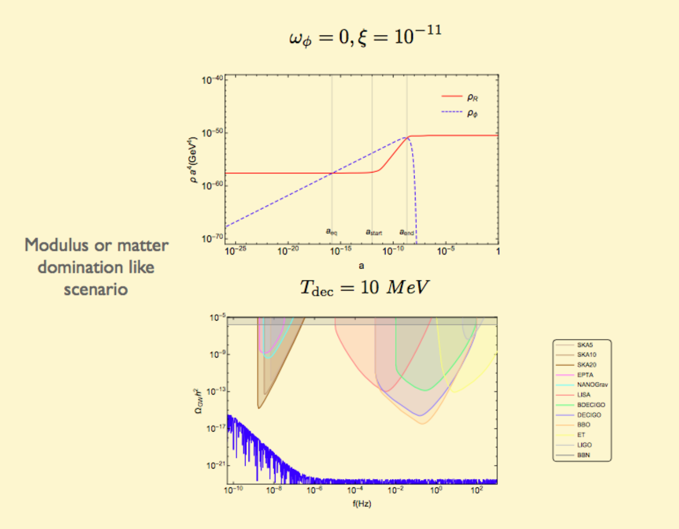


$$\omega_\phi = 1/3, \xi = 10^{25}$$

Radiation domination like scenario

$$T_{\rm dec} = 10\ MeV$$

On the GW sensitivity Map

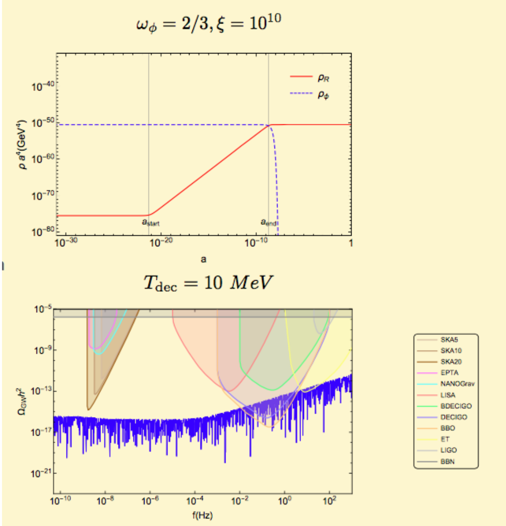


$\omega_\phi = 0, \xi = 10^{-11}$

Modulus or matter domination like scenario

$T_{\rm dec} = 10\ MeV$

On the GW sensitivity Map

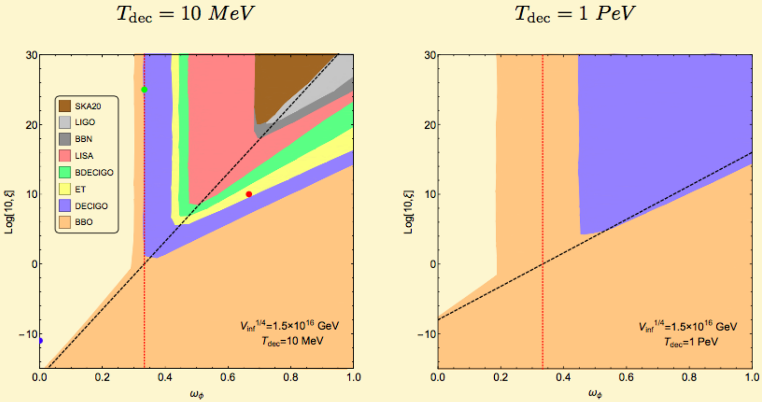


$\omega_\phi = 2/3, \xi = 10^{10}$

$T_{\rm dec} = 10\ MeV$

On the GW sensitivity Map

Scanning over the parameter space of $[\omega_\phi, \xi]$:



Inflationary Tensor Perturbation

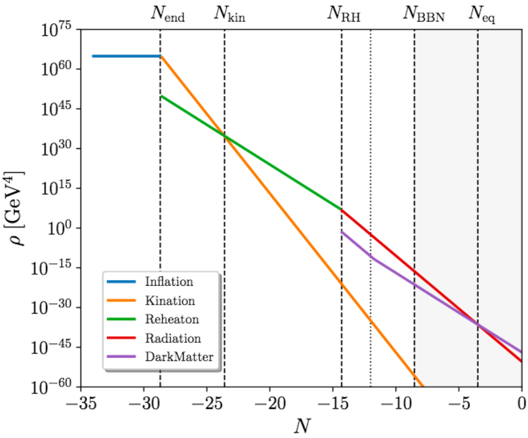


FIG. 1. *Evolution of the different components present in the Universe along the cosmological history. The vertical dotted line stands for the time where DM becomes non-relativistic.The parameters used in the figure are* $\eta = 10^{-15}$, $m_S = 1\,\mathrm{GeV}$, $m_{\rm DM} = 1\,\mathrm{MeV}$, $\Gamma_S = 10^{-15}\,\mathrm{GeV}$, *and* $w_{\rm kin} = 1$. *In the x-axis,* $N = \ln(a)$ *stands for the number of e-folds before present time.*

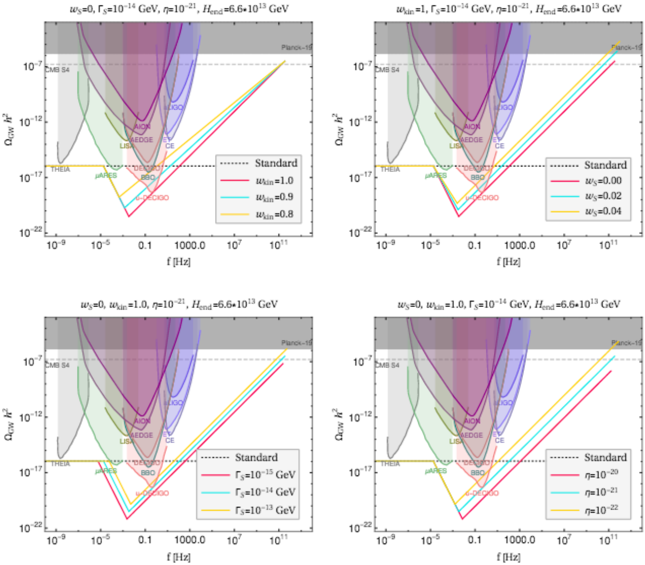
Independent parameters

DM is produced via freeze-in from heavy scalar S (we call it reheaton) decay:

$$\{\rho_{\rm inf}\,,\ w_{\rm kin}\,,\ w_{\rm S}\,,\ \eta\,,\ \Gamma_S\,,\ m_S\,,\ m_{\rm DM}\}$$

$\eta = \frac{\rho_{\rm S}}{\rho_{\rm inf}}$

Inflationary Tensor Perturbation



Signal to Noise Ratio (SNR > 10)

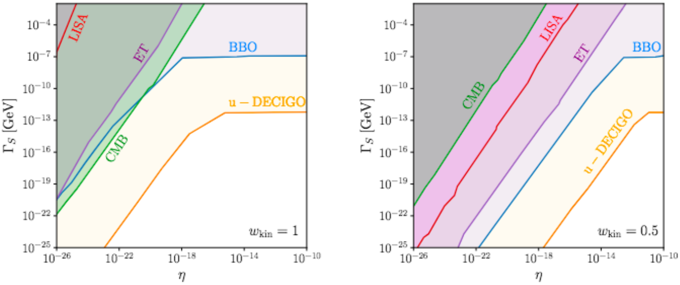


FIG. 3. *The allowed region of $\Gamma_S - \eta$ parameter space from $N_{\rm eff}$ bounds and future reaches in GW detectors (LISA, ET, BBO, u-DECIGO) after 4 years of exposure. The green shaded region above the green line (denoted by CMB) is disallowed by the $N_{\rm eff} < 0.3$ constraint. The other colored lines correspond to SNR$=1$ for different GW detectors, the region above then denoting SNR>1. The left and right panel correspond to $w_{\rm kin} = 1$ and 0.5 with the other parameters fixed at* $\{w_S,\ H_{\rm end},\ m_{\rm DM},\ m_S\} = \{0,\ 6.6\times 10^{13}{\rm GeV},\ 10^{8}{\rm GeV},\ 10^{12}{\rm GeV}\}$.

Inflationary Tensor Perturbation

Microscopic Higgs-portal simple model:

$$\mathcal{L} \supset -g_\chi S\bar{\chi}\chi - V_{\rm SM}(H) - V_{\rm reh}(S) - \lambda_{HS}|H|^2|S|^2 + H.c.. \qquad (7)$$

Mass eigenstates:

$$\begin{aligned} \tilde{H} &\approx H - S\sin\theta\,, \\ \tilde{S} &\approx S + H\sin\theta\,. \end{aligned} \qquad (8)$$

where $\tan 2\theta = \frac{2v_S v_h \lambda_{HS}}{(m_H^2 - m_S^2)}\mathrm{v}_S$ being the vev of the S field and v_S is the EW vev.

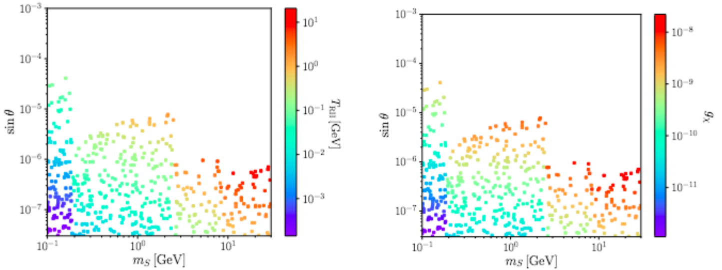


FIG. 4. *Scan over the energy fraction η, the reheaton decay width Γ_S and the dark-matter mass $m_{\rm DM}$. We assumed $w_{\rm kin} = 1$ and excluded points for which the Freeze-In production of DM exceeds 1% of the total relic density.*

Final Complementarity: Lab versus GW

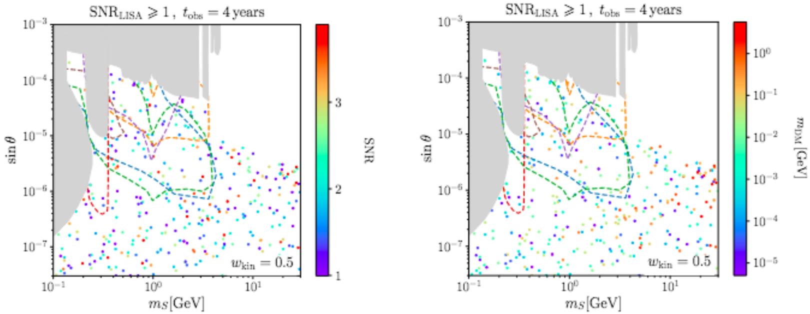


Figure: Comparison between the points in parameter space which will detected by LISA after 4 years of exposure (with SNR 1) and the sensitivity limits which will be probed in future long-lived particle searches. The dashed contours depict such regions for FASER II (orange), DUNE (red), DarkQuest-Phase 2 (purple), MATHSULA (green), PS191 (brown), and SHIP (blue).

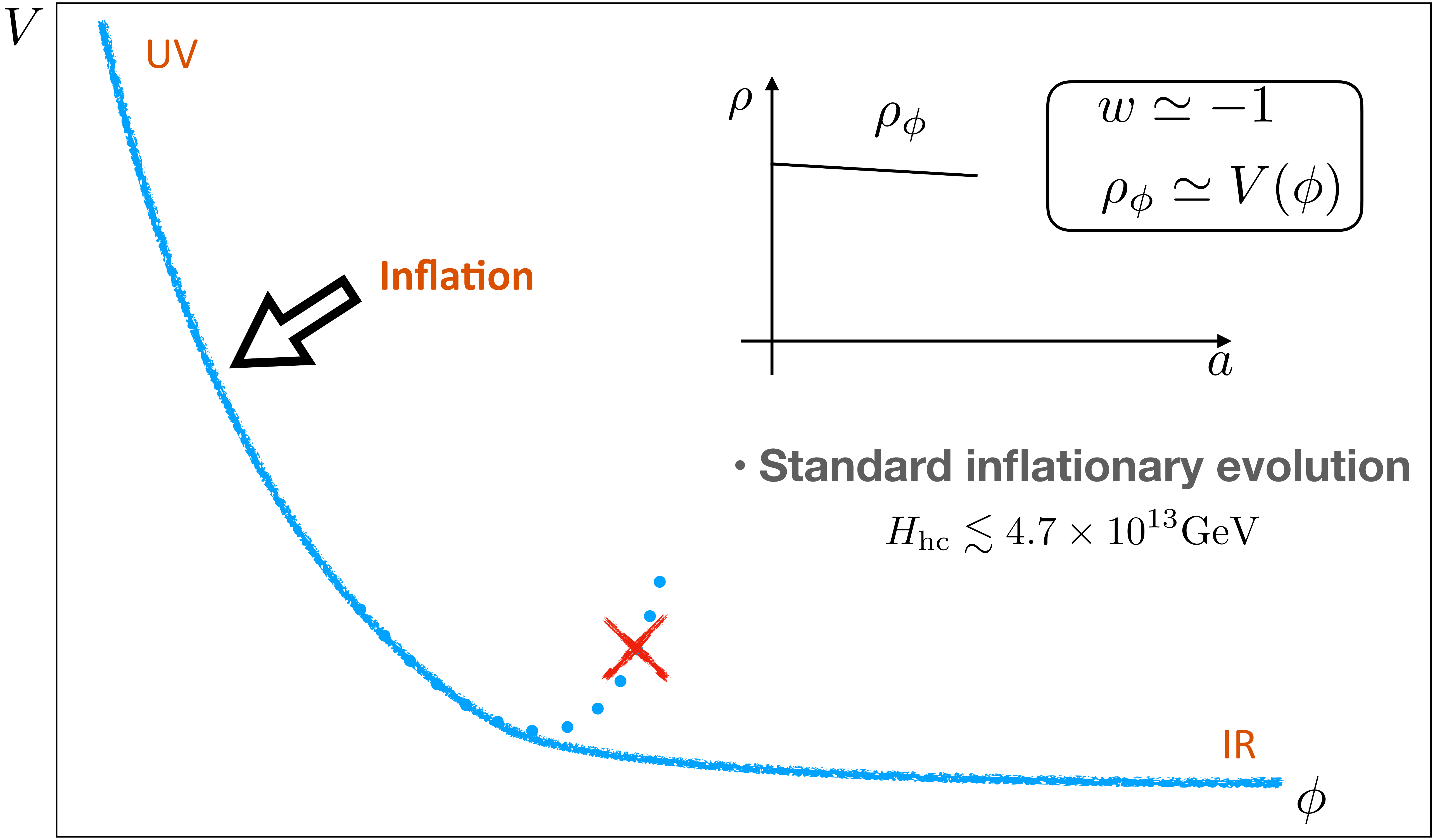
Conclusions

- Huge degenracy in cosmological signals. Need for complementarity, or else observing a GW signal may have several BSM implications.
- Complementarity between the Sky and the Lab observables via RGE and temperature corrections: GW from PT.
- GW detectors will be probing the pre-BBN era.
- New complementarity between inflationary tensor perturbations and long lived particle searches proposed for the first time.
- The same decay with of heavy scalar which controls the non-standard cosmological era also responsible for BSM searches as they can be produced and made decay via mixing with the Higgs.
- Gravitational Wave tests intermediate and high scale non-thermal freeze-in DM physics with complementary laboratory signatures.

Thank You

QUINTESSENTIAL INFLATION

Runaway potential:



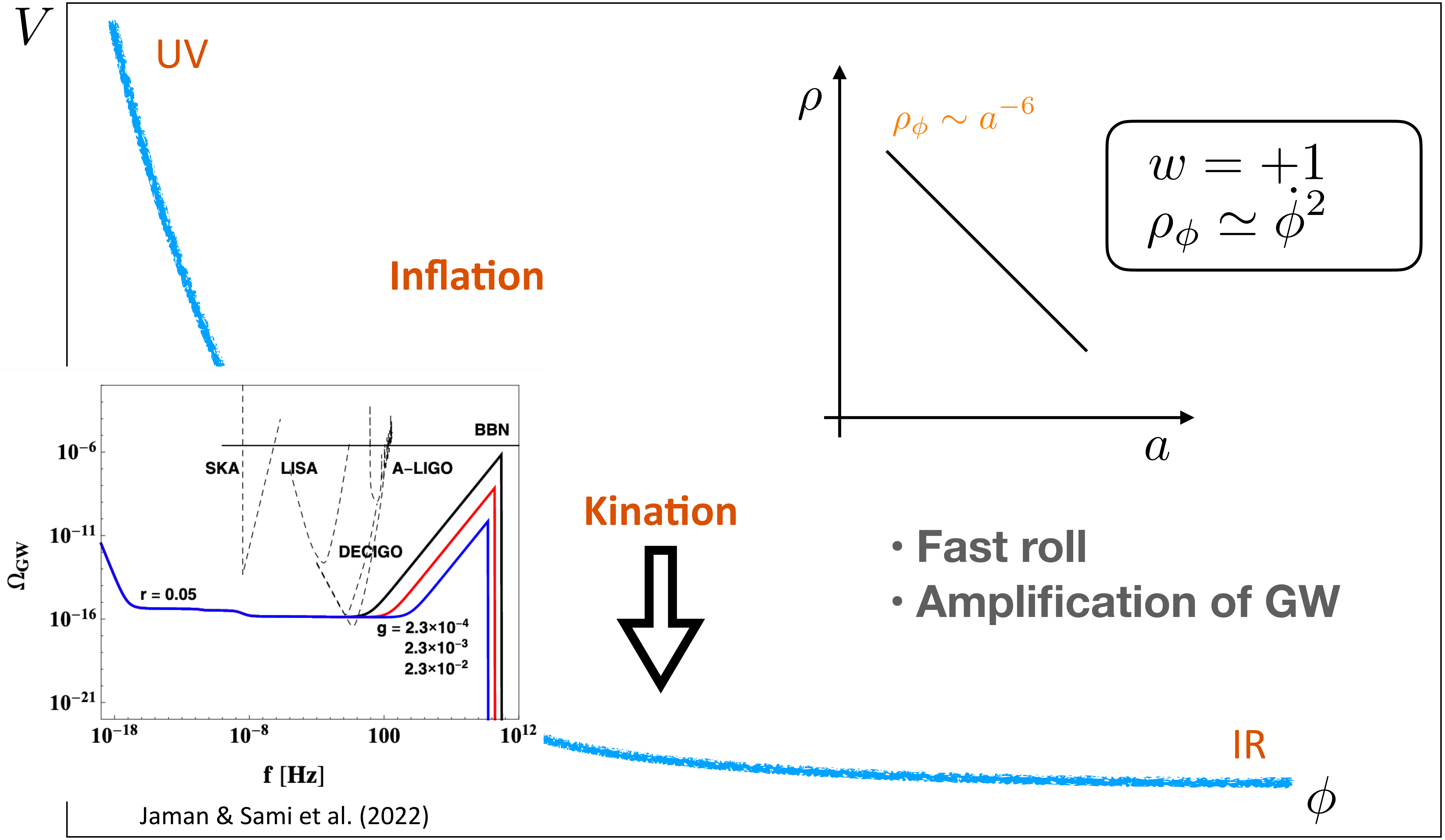
$$\boxed{\begin{array}{l} w \simeq -1 \\ \rho_\phi \simeq V(\phi) \end{array}}$$

- **Standard inflationary evolution**

$$H_{\rm hc} \lesssim 4.7 \times 10^{13} {\rm GeV}$$

QUINTESSENTIAL INFLATION

Runaway potential:



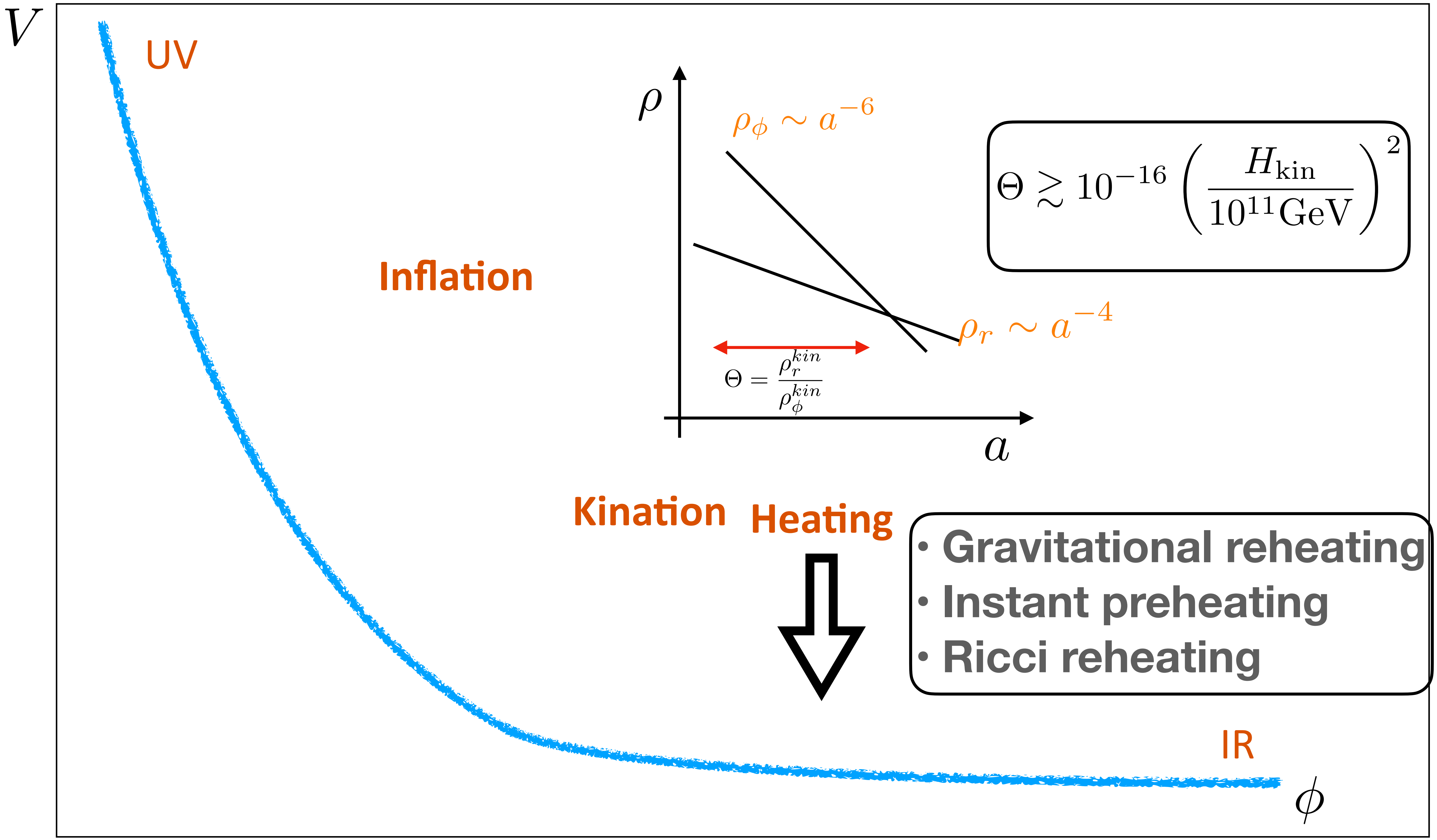
$$w = +1$$
$$\rho_\phi \simeq \dot{\phi}^2$$

- **Fast roll**
- **Amplification of GW**

Jaman & Sami et al. (2022)

QUINTESSENTIAL INFLATION

Runaway potential:

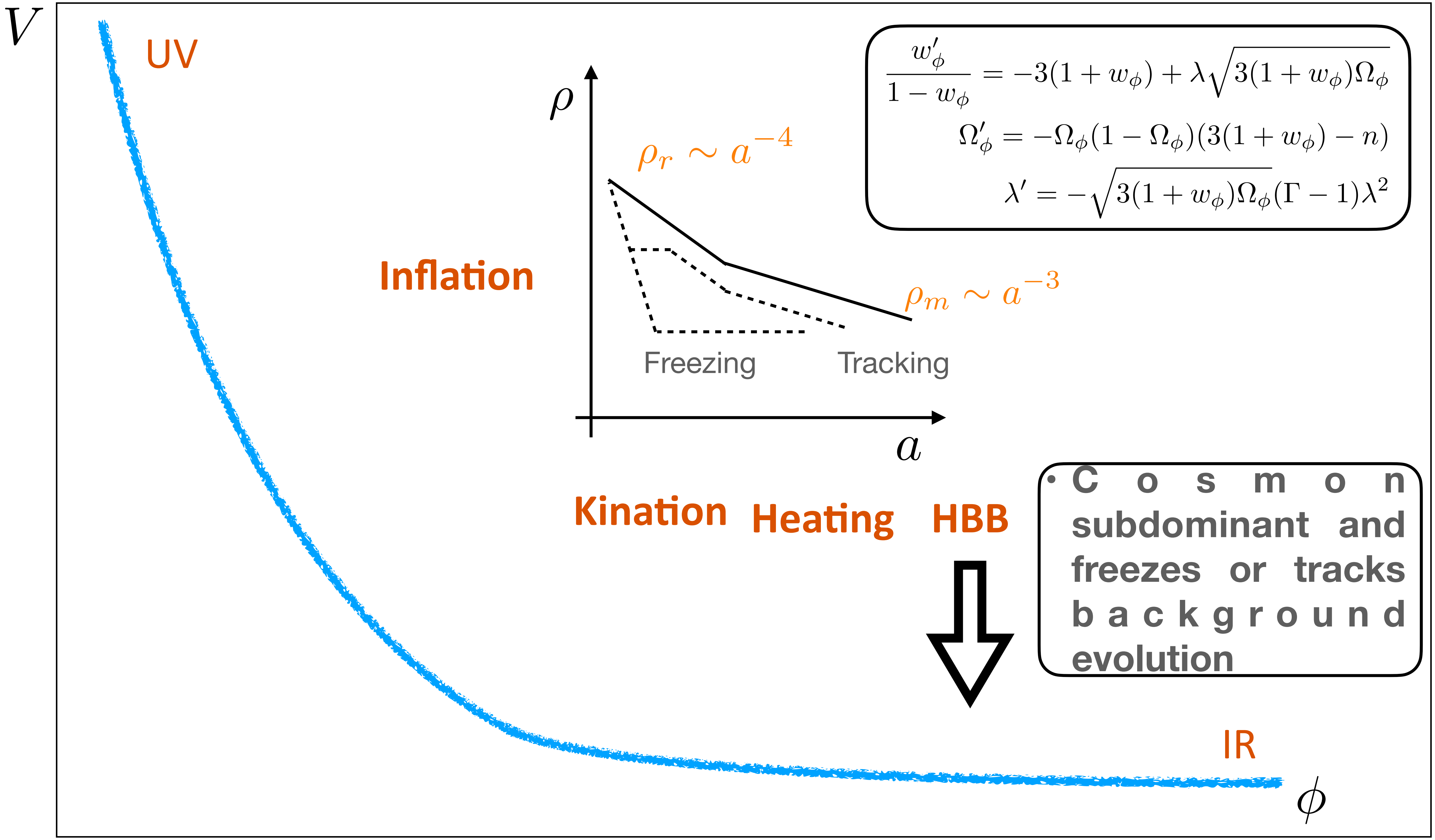


$$\Theta \gtrsim 10^{-16} \left(\frac{H_{\rm kin}}{10^{11} {\rm GeV}} \right)^2$$

- Gravitational reheating
- Instant preheating
- Ricci reheating

QUINTESSENTIAL INFLATION

Runaway potential:



$$\frac{w'_\phi}{1-w_\phi} = -3(1+w_\phi)+\lambda\sqrt{3(1+w_\phi)\Omega_\phi}$$

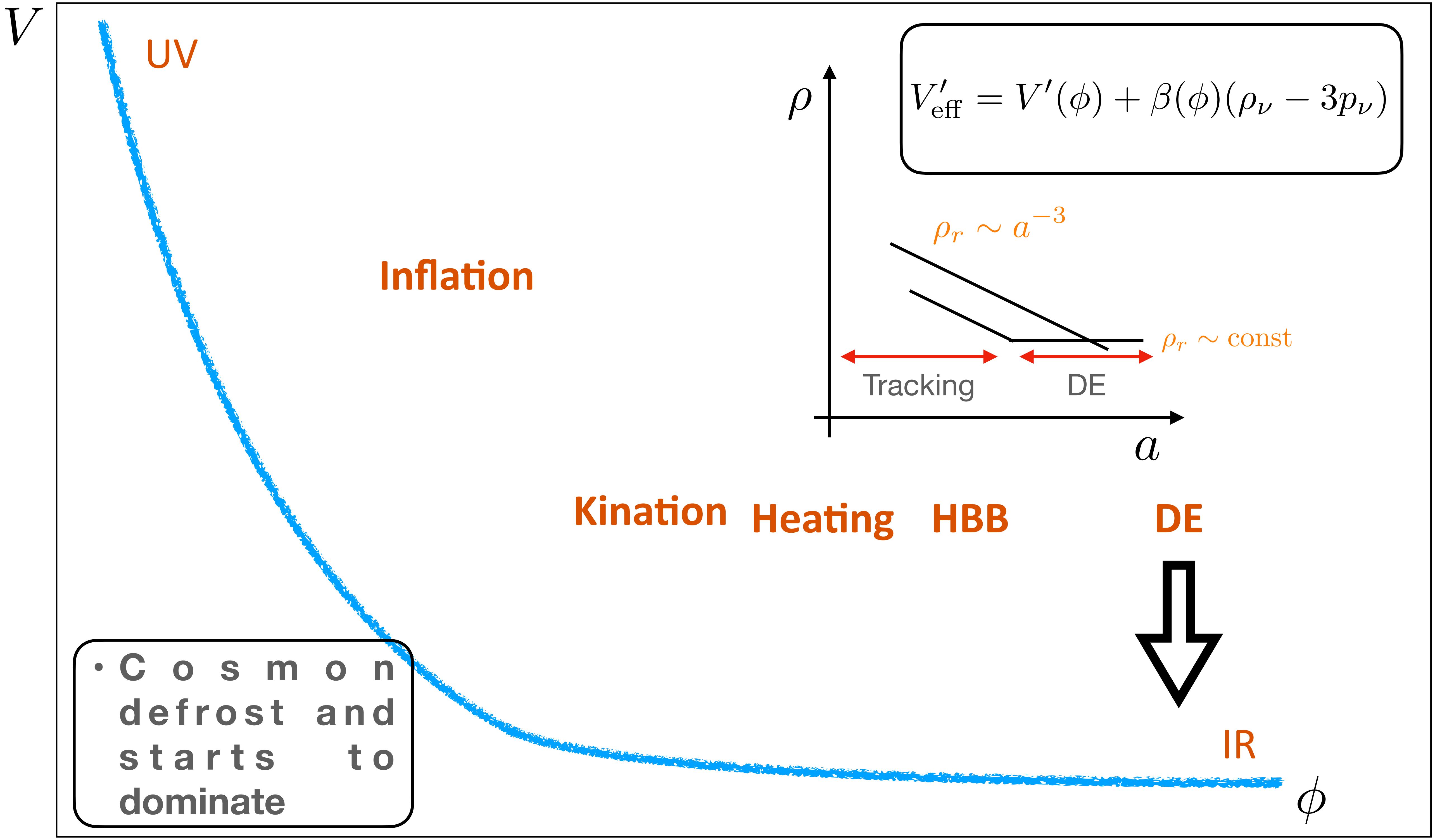
$$\Omega'_\phi = -\Omega_\phi(1-\Omega_\phi)(3(1+w_\phi)-n)$$

$$\lambda' = -\sqrt{3(1+w_\phi)\Omega_\phi}(\Gamma-1)\lambda^2$$

- Cosmon subdominant and freezes or tracks background evolution

QUINTESSENTIAL INFLATION

Runaway potential:



$$V'_{\text{eff}} = V'(\phi) + \beta(\phi)(\rho_\nu - 3p_\nu)$$

- Cosmon defrost and starts to dominate