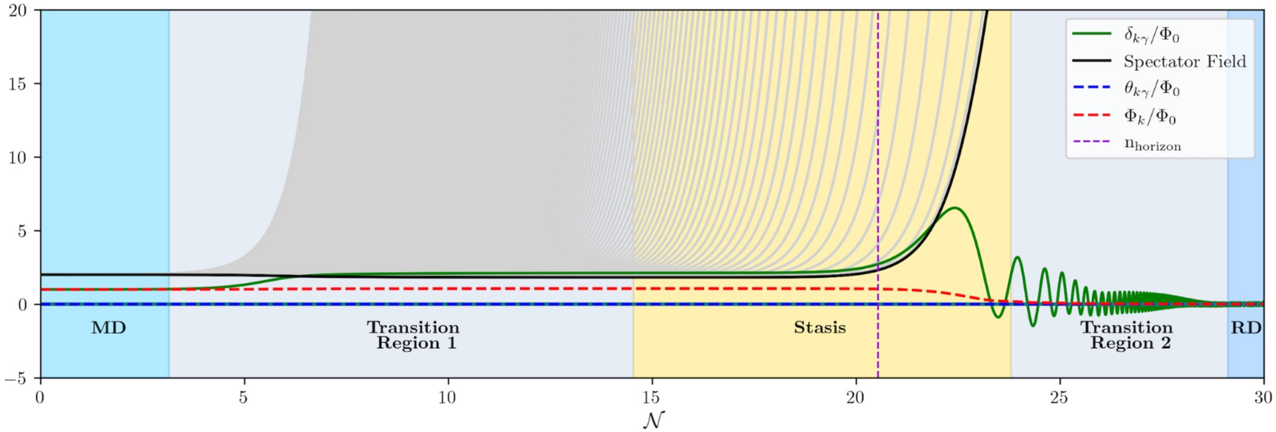
Cosmic Stasis and the Growth of Density Perturbations



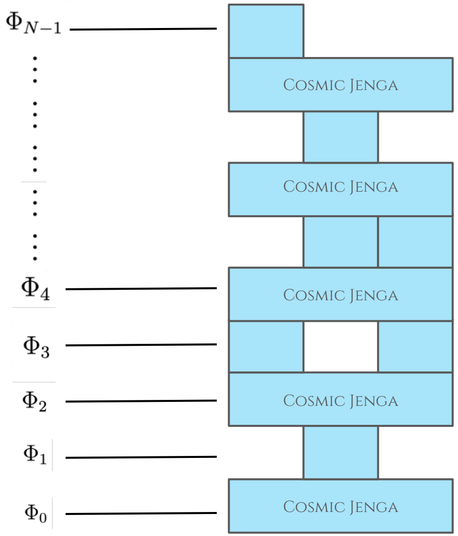
Anna Paulsen

Undergraduate Student at Lafayette College → Brown

Based on work done in collaboration with: Keith R. Dienes, Lucien Heutier, Dan Hoover, Fei Huang, Timothy M.P. Tait, and Brooks Thomas
[arXiv:2405.xxxxx]

A System of Towers of Unstable States

- Many theories beyond the Standard Model predict towers of massive, unstable states that have varying masses, cosmological abundances, and lifetimes



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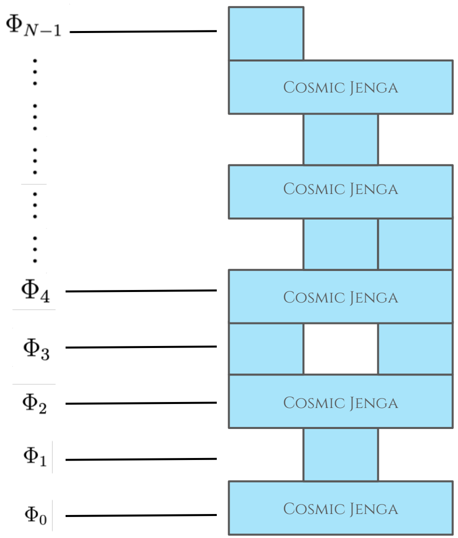
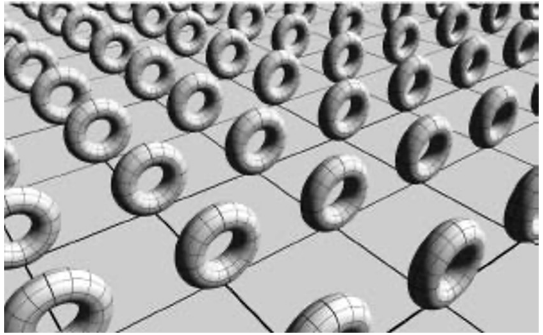


- These towers are generally a feature of theories with extra spacetime dimensions.



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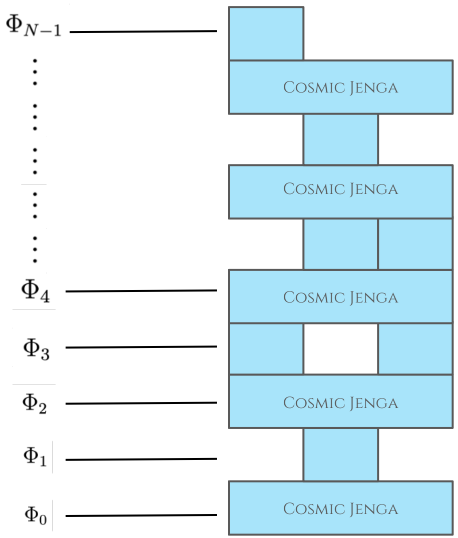

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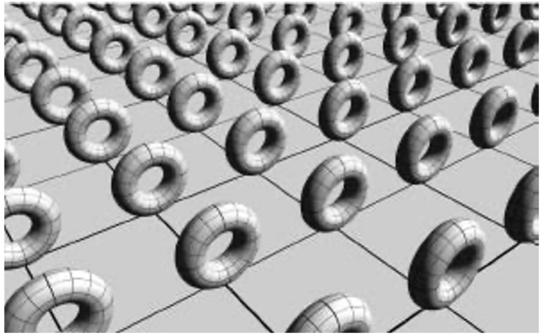

- In some instances, such states can give rise to astrophysical signals that can be observed; in others, they are too heavy/short lived.

Theory Underpinning Stasis

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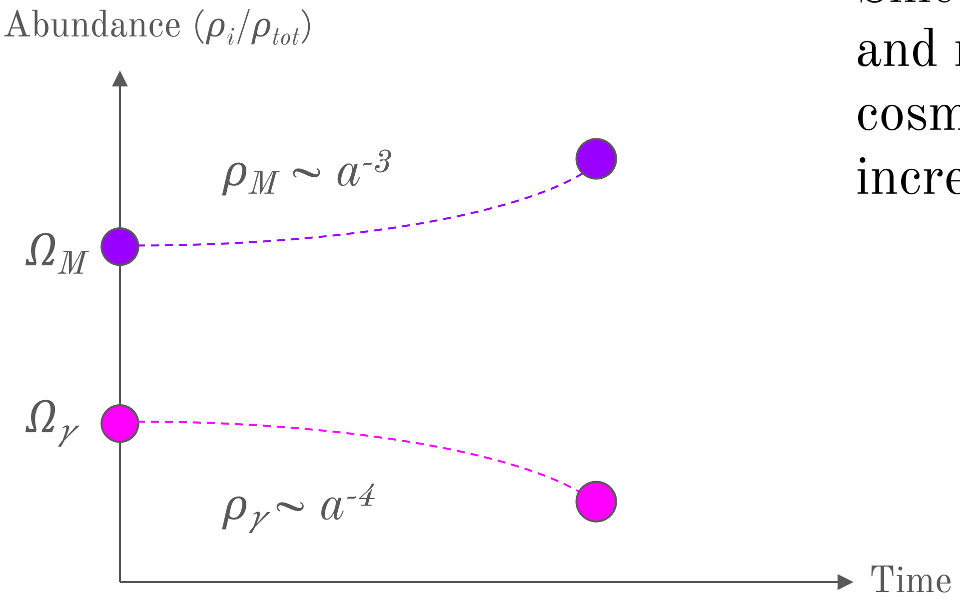

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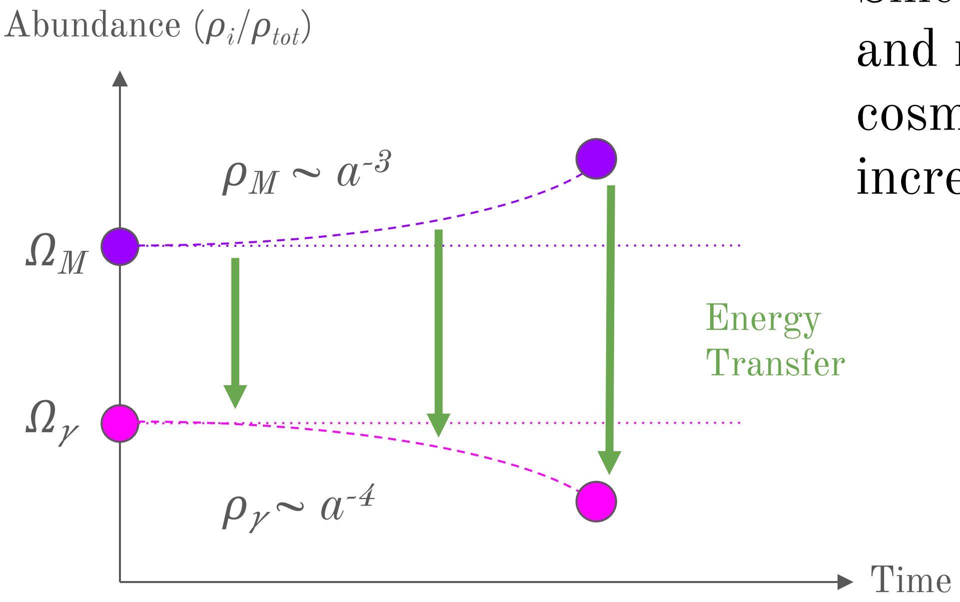

- Since the energy densities of matter and radiation scale differently under cosmic expansion, we find Ω_M to increase and Ω_γ to decrease typically.

- In order to compensate for this effect, we need a <u>continuous transfer of energy density</u> from matter to radiation

Theory Underpinning Stasis

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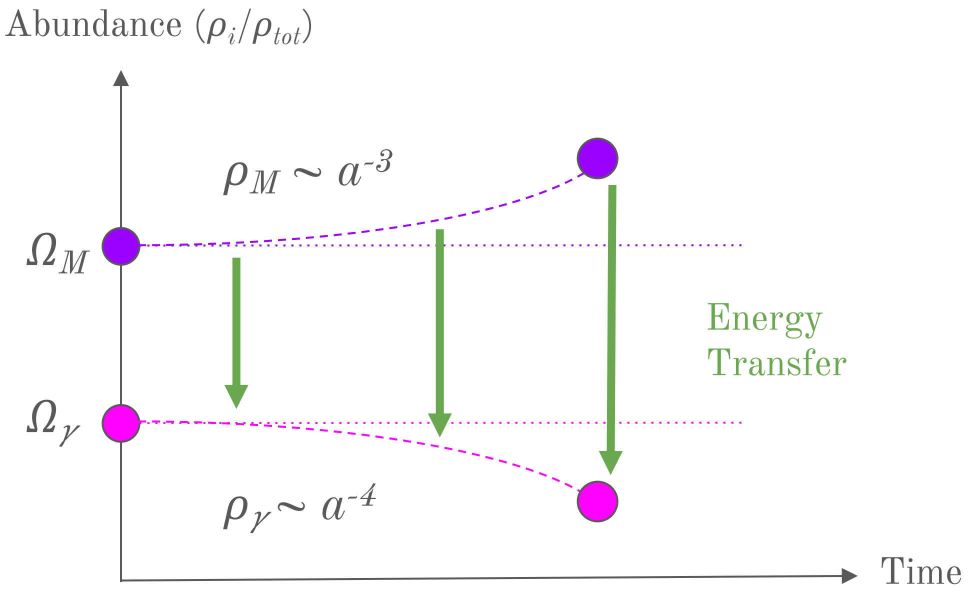

Boltzmann Equations

$$\frac{d\rho_M}{dt} = -3H\rho_M - P^{(\rho)}_{M\gamma}(t)$$

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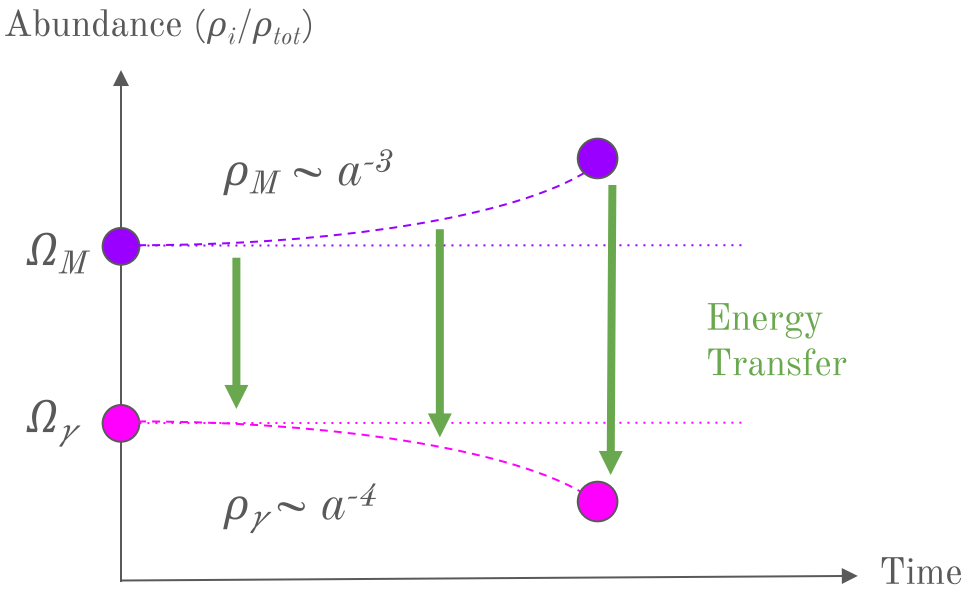

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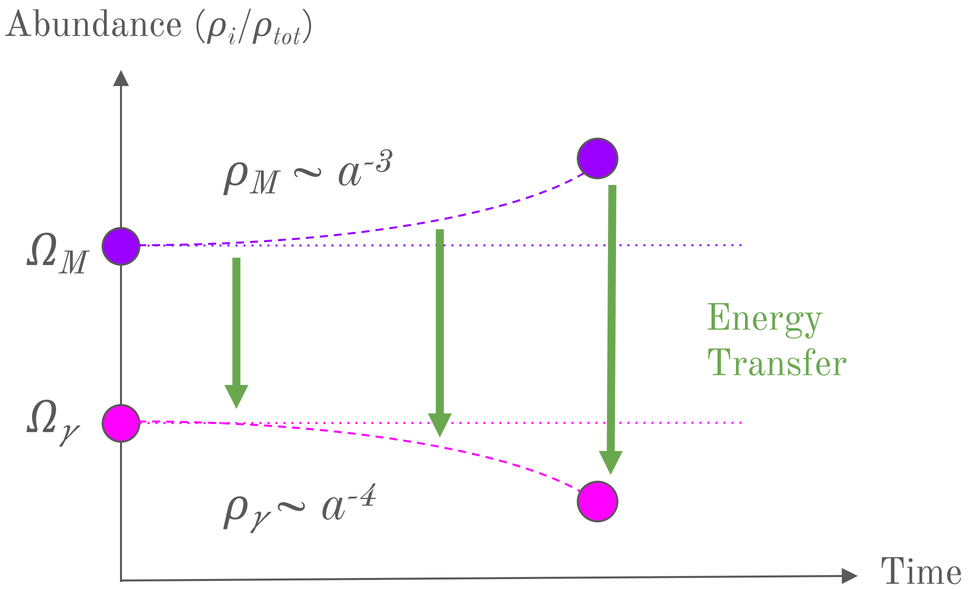

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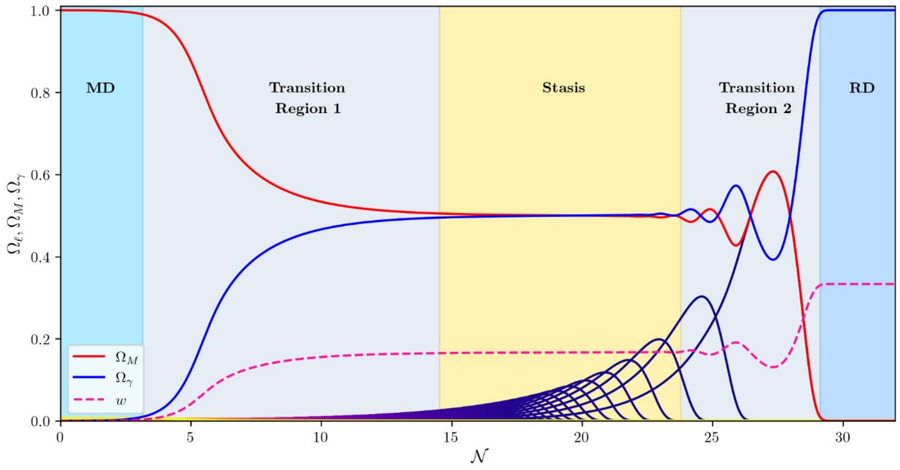

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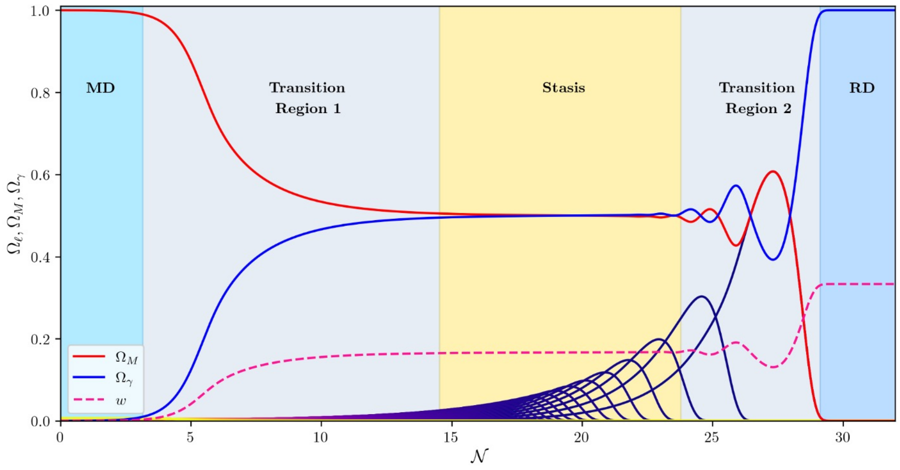

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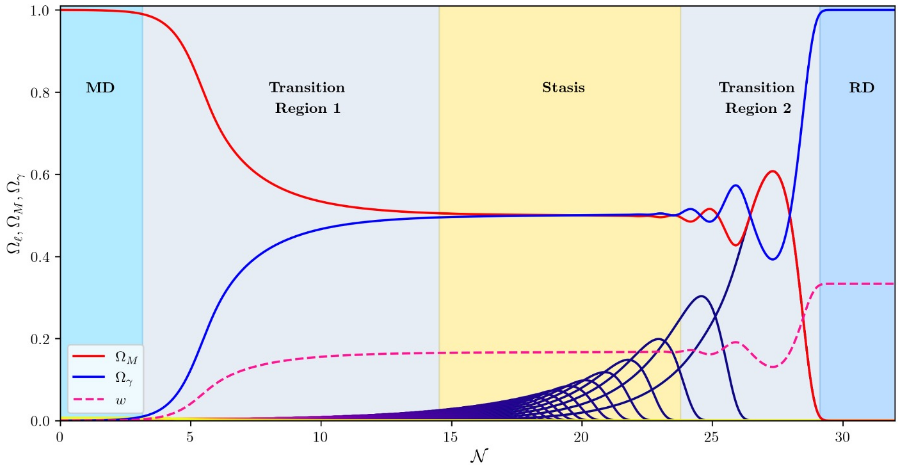

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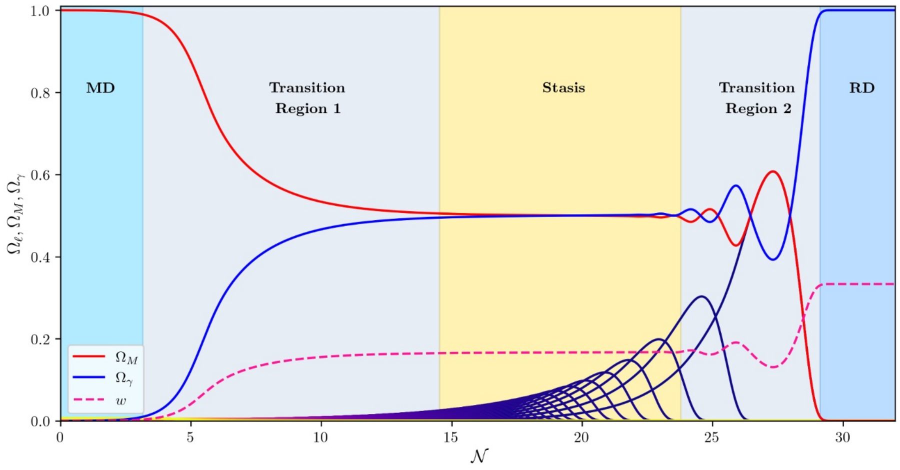
Let’s see how!



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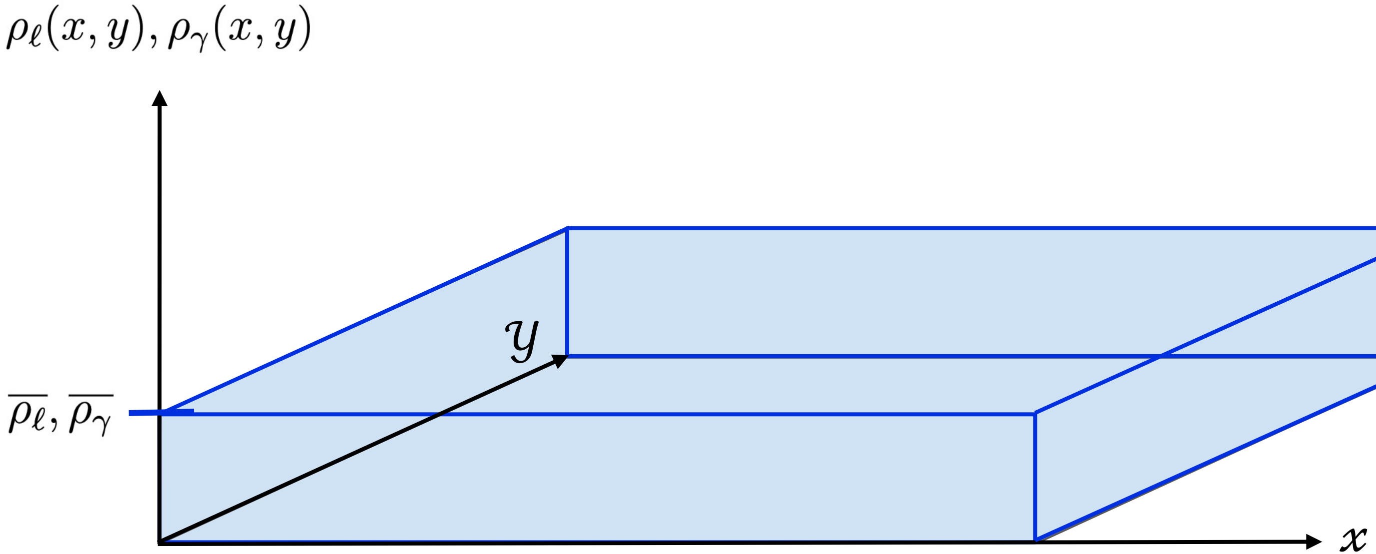

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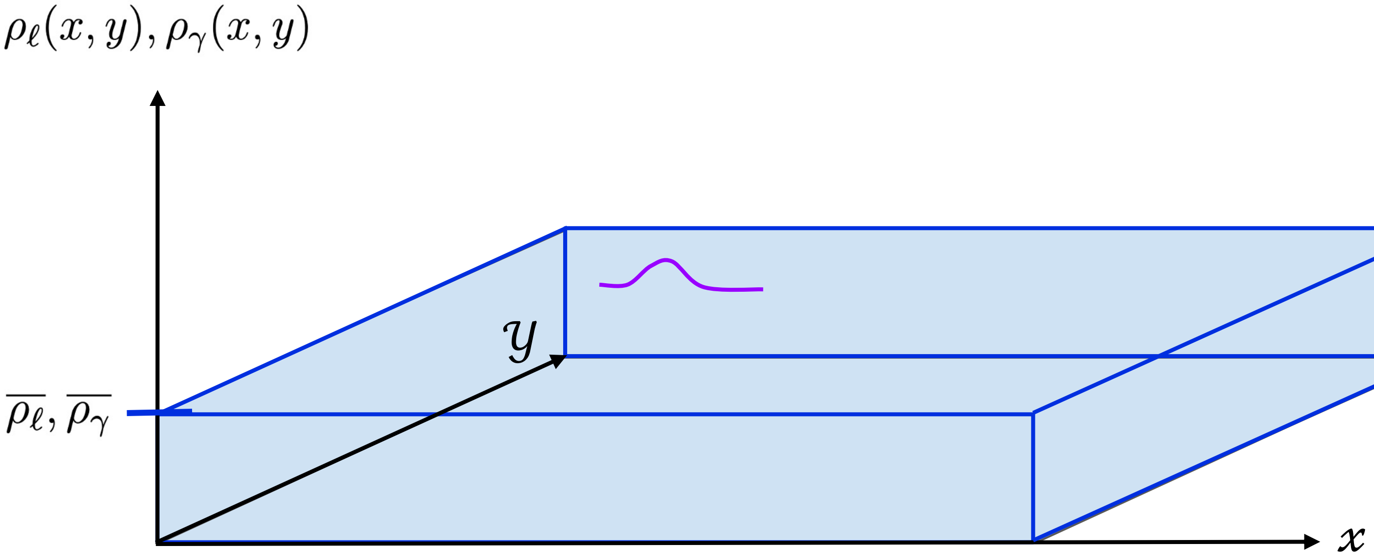

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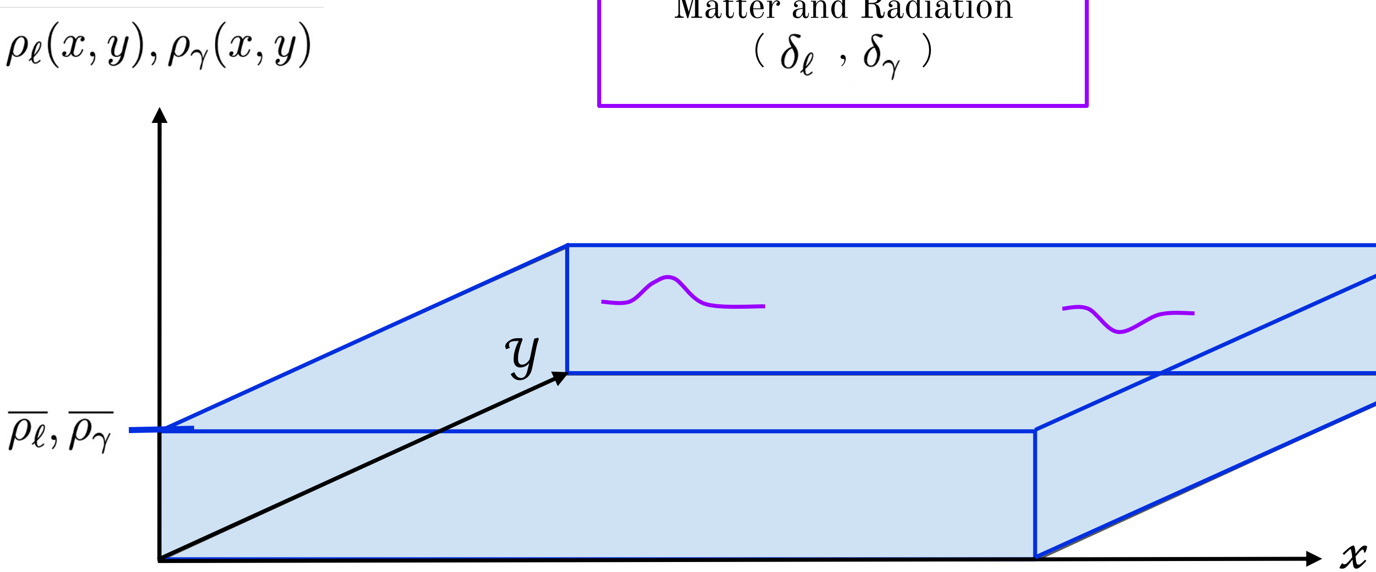

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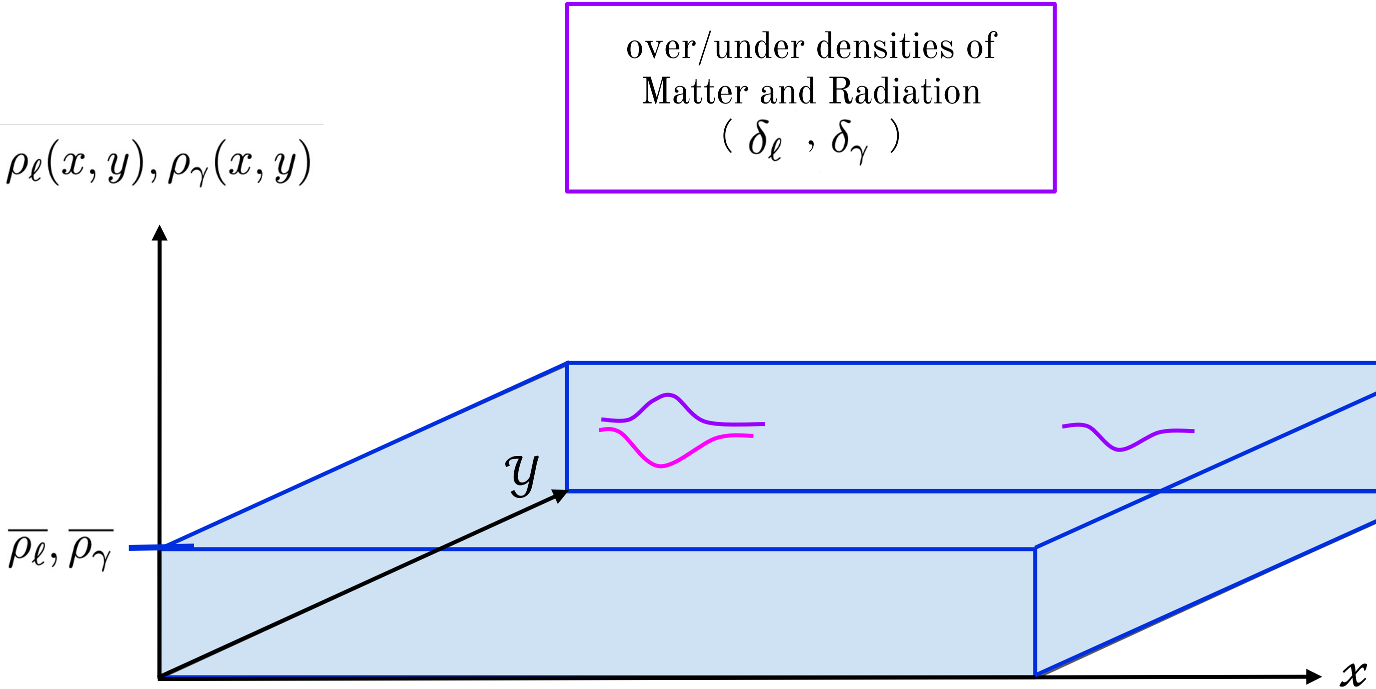

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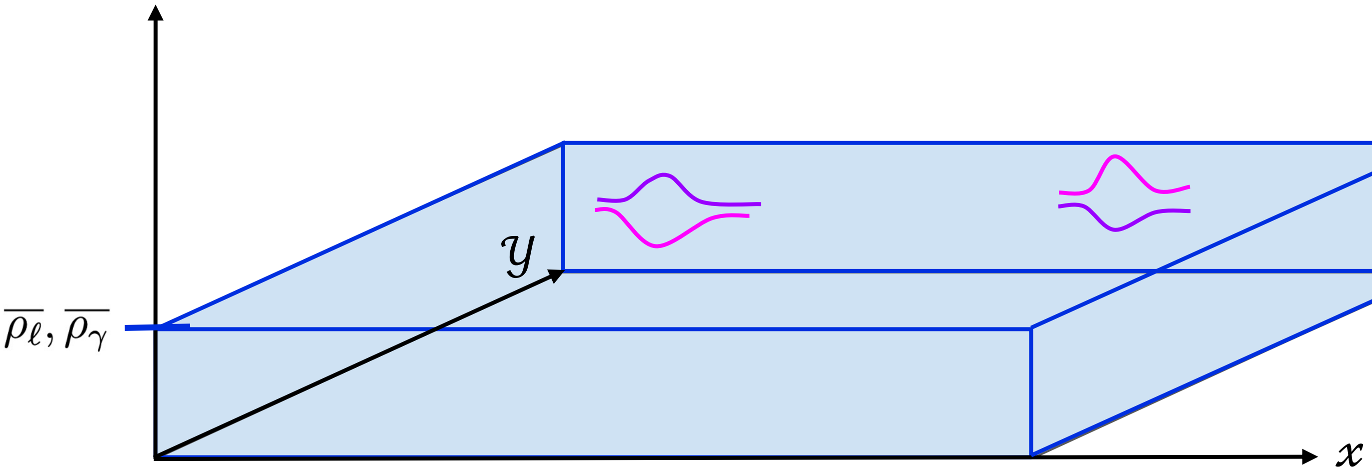
$\rho_\ell(x, y), \rho_\gamma(x, y)$



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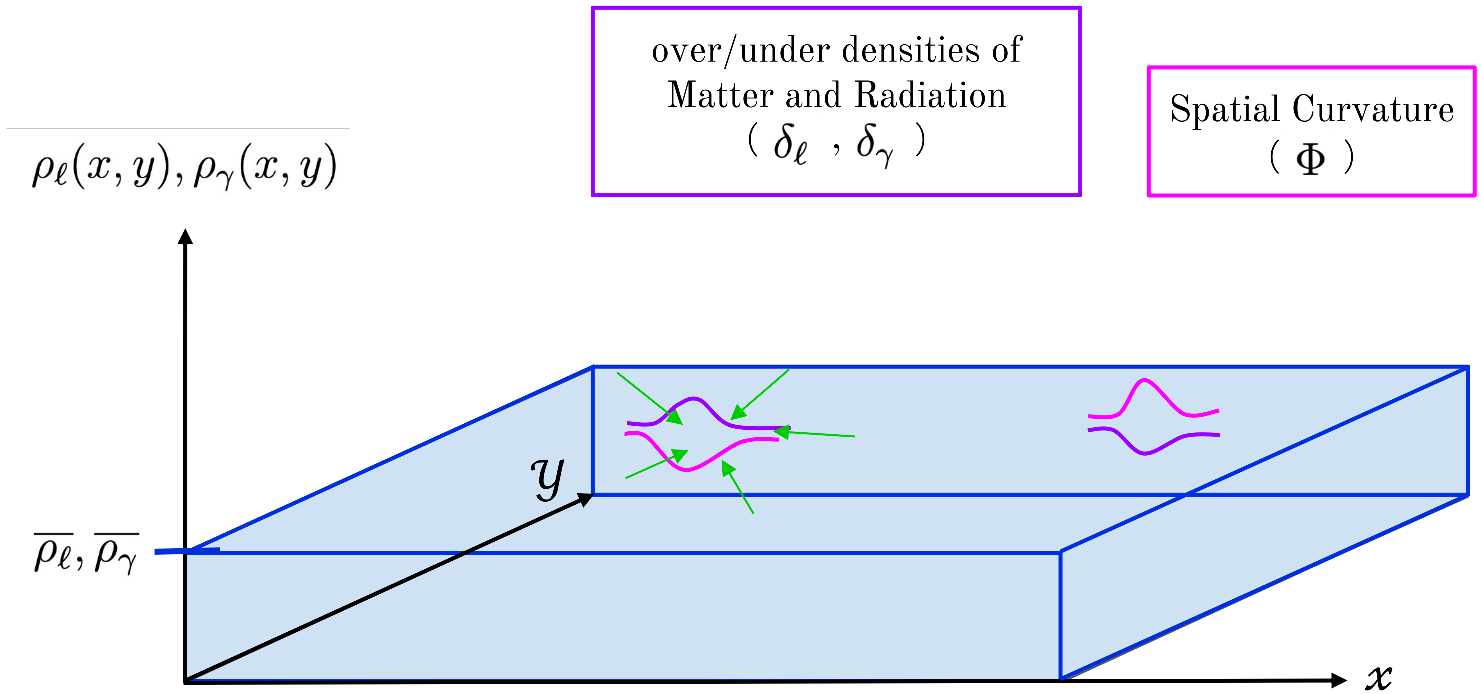

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$(\delta_\ell \, , \delta_\gamma)$

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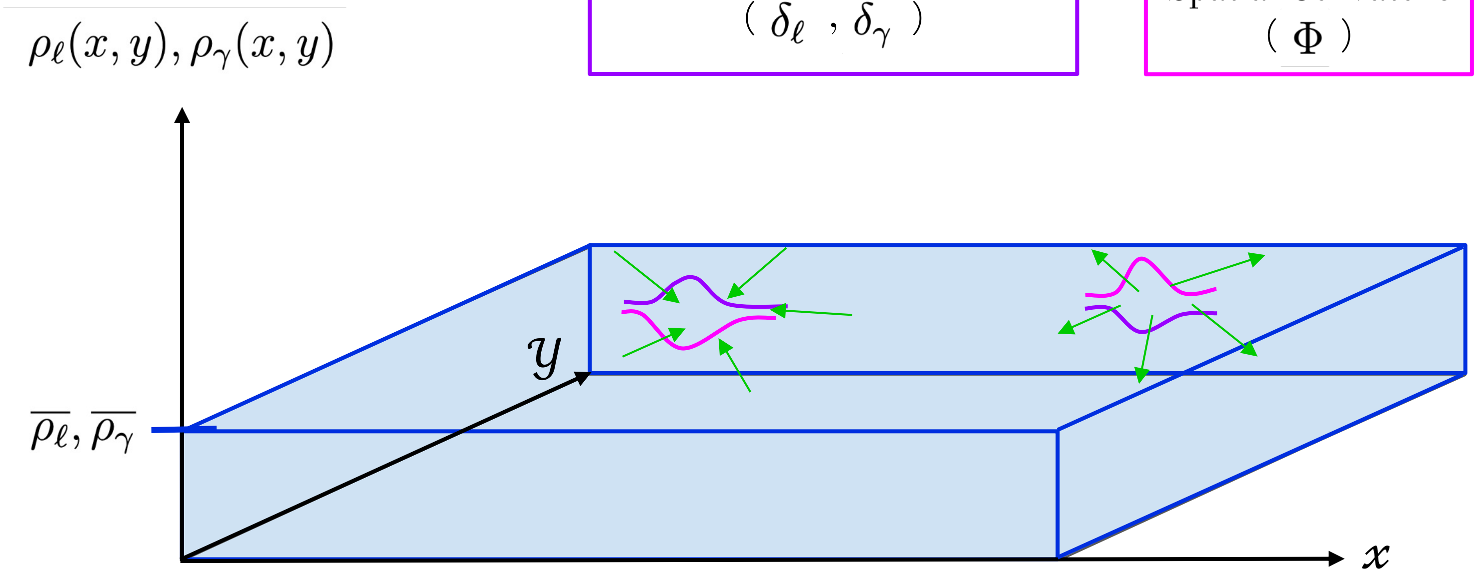
Divergence
velocity
$(\tilde{\theta}_\ell \, , \tilde{\theta}_\gamma)$

$$\tilde{\theta} = \frac{1}{H^{(0)}} \vec{\nabla} \cdot \vec{V}$$



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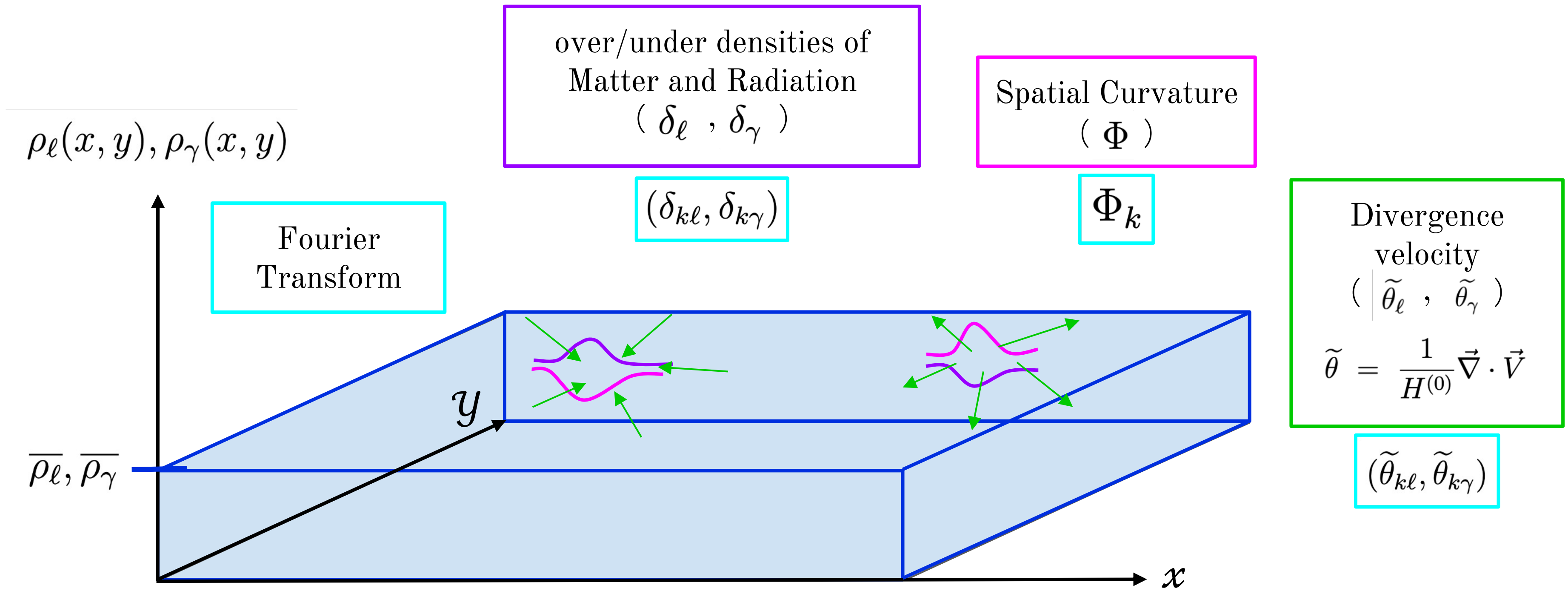


Perturbing the System

Einstein Field Equation

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G T_{\mu\nu}$$

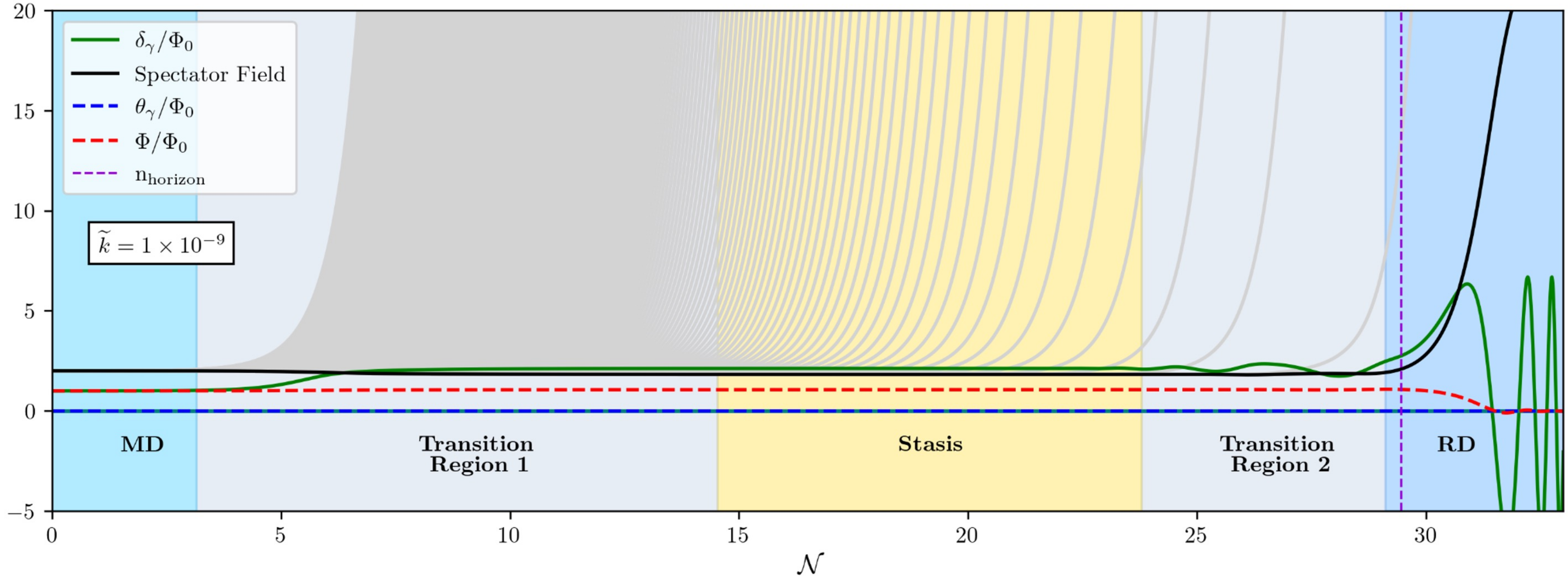
Scalar Perturbations to 1st Order

$$\begin{aligned}
\delta'_{k\ell} &= \left(\frac{\widetilde{k}^2}{a^3E^2} + \frac{3}{a} + \frac{\widetilde{\Gamma}_\ell}{aE}\right)\Phi_k - \frac{1}{a^2E}\widetilde{\theta}_{k\ell} - \frac{3}{2aE^2}\left(\widetilde{\overline{\rho}}_\gamma \delta_{k\gamma} + \sum_{m=0}^{N-1}\widetilde{\overline{\rho}}_m \delta_{km}\right)\\
\widetilde{\theta}'_{k\ell} &= -\frac{1}{a}\widetilde{\theta}_{k\ell} - \frac{\widetilde{k}^2}{a^2E}\Phi_k\\
\delta'_{k\gamma} &= \left(\frac{4\widetilde{k}^2}{3a^3E^2} + \frac{4}{a}\right)\Phi_k - \frac{4}{3a^2E}\widetilde{\theta}_{k\gamma} - \frac{2}{aE^2}\left(\widetilde{\overline{\rho}}_\gamma \delta_{k\gamma} + \sum_{\ell=0}^{N-1}\widetilde{\overline{\rho}}_\ell \delta_{k\ell}\right) + \frac{1}{aE}\sum_{\ell=0}^{N-1}\widetilde{\Gamma}_\ell \frac{\widetilde{\overline{\rho}}_\ell}{\widetilde{\overline{\rho}}_\gamma}\left(\delta_{k\ell} - \delta_{k\gamma} - \Phi_k\right)\\
\widetilde{\theta}'_{k\gamma} &= \frac{\widetilde{k}^2}{4a^2E}\delta_{k\gamma} - \frac{\widetilde{k}^2}{a^2E}\Phi_k + \frac{1}{aE}\sum_{\ell=0}^{N-1}\widetilde{\Gamma}_\ell \frac{\widetilde{\overline{\rho}}_\ell}{\widetilde{\overline{\rho}}_\gamma}\left(\frac{3}{4}\widetilde{\theta}_{k\ell} - \widetilde{\theta}_{k\gamma}\right)\\
\Phi'_k &= -\left(\frac{\widetilde{k}^2}{3a^3E^2} + \frac{1}{a}\right)\Phi_k + \frac{1}{2aE^2}\left(\widetilde{\overline{\rho}}_\gamma \delta_{k\gamma} + \sum_{\ell=0}^{N-1}\widetilde{\overline{\rho}}_\ell \delta_{k\ell}\right).
\end{aligned}$$

Dienes, Heutier, Hoover, Huang, AP, Tait, Thomas [arXiv:2405.xxxxx]

Numerical 1st Order Results (Linear y-axis)

Entering Horizon in Radiation Dominated Region



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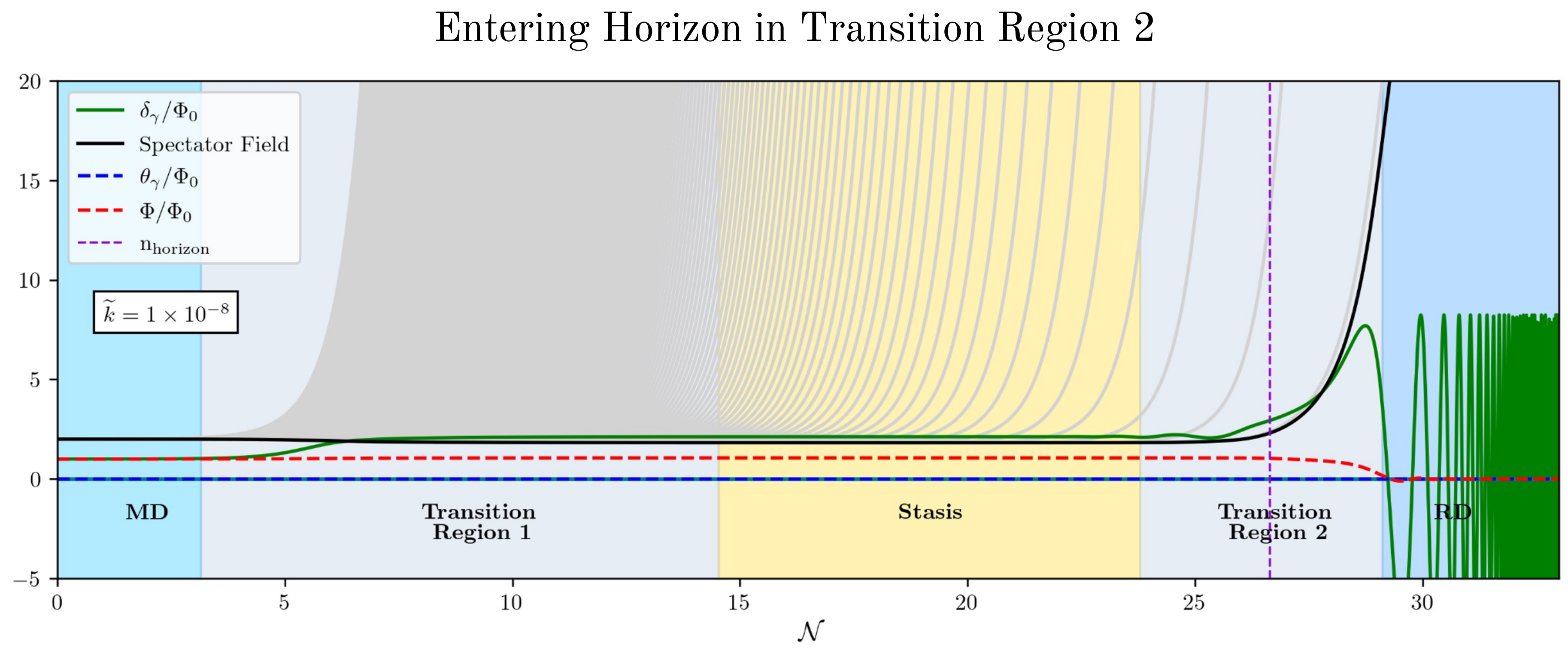

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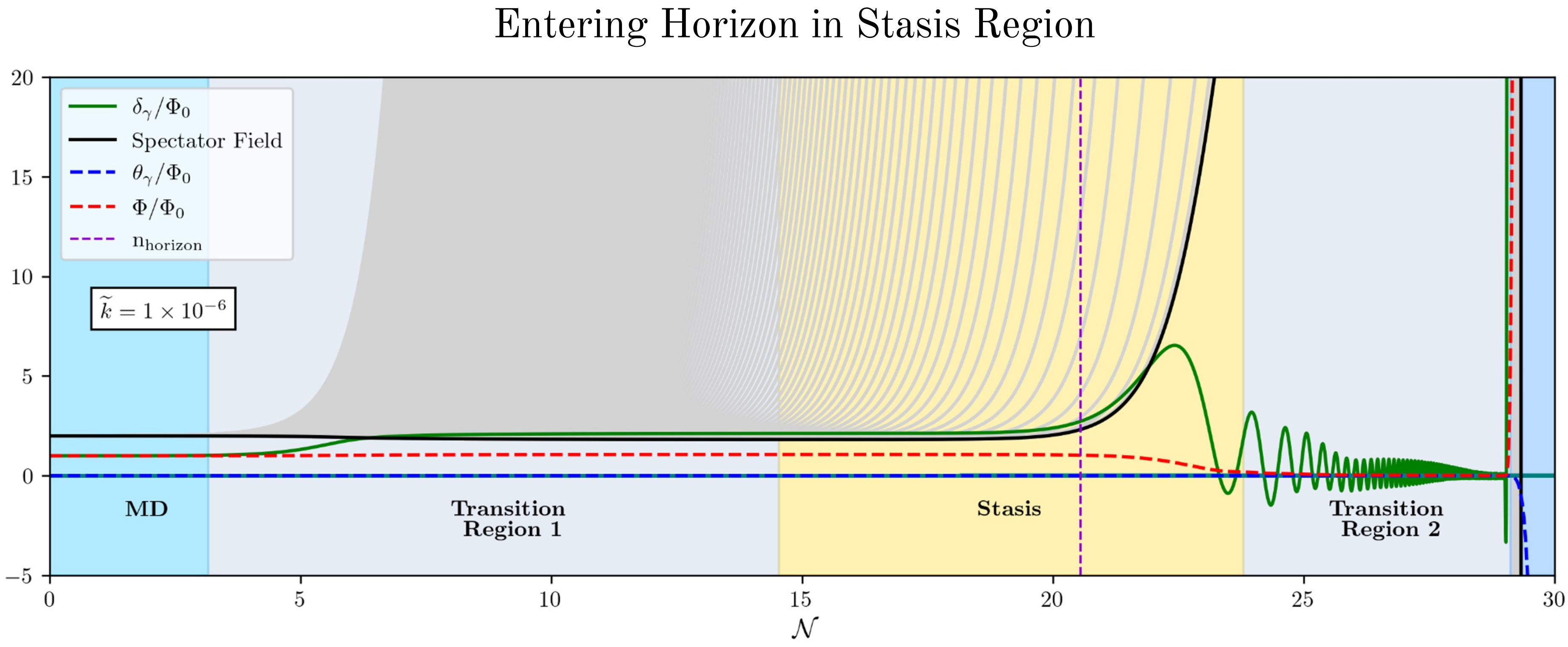

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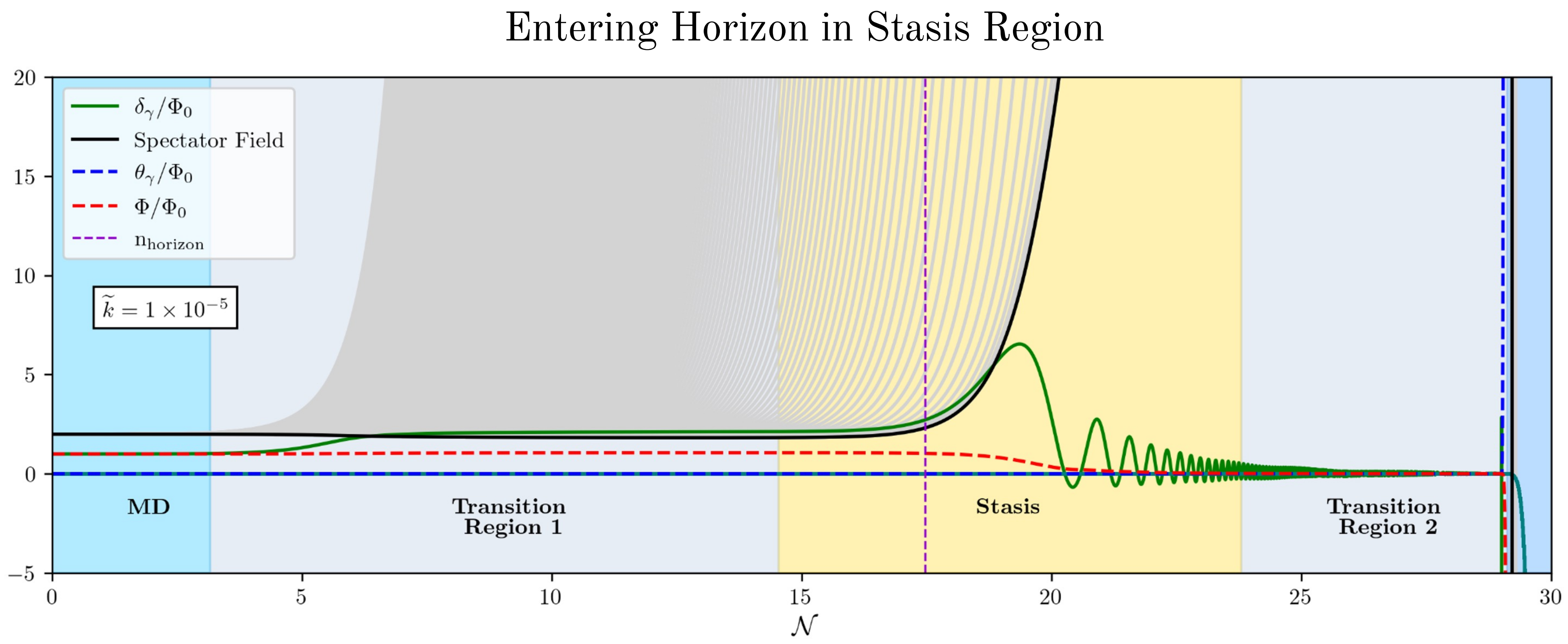

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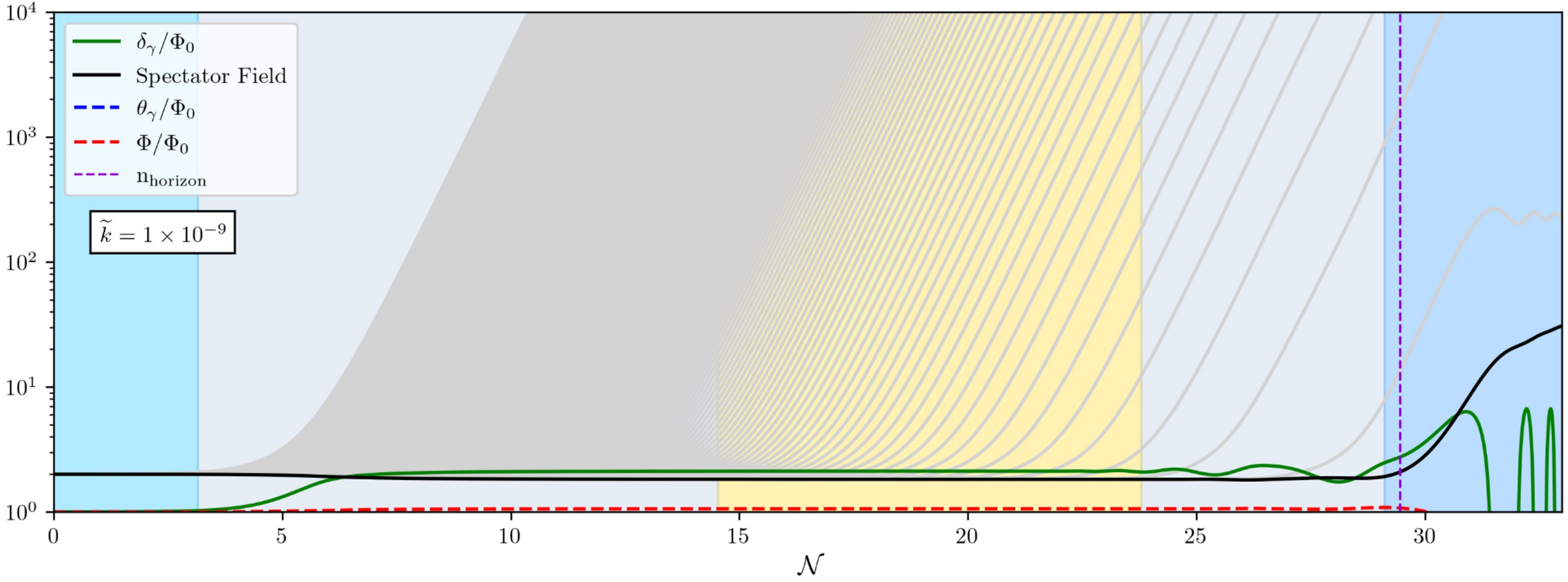

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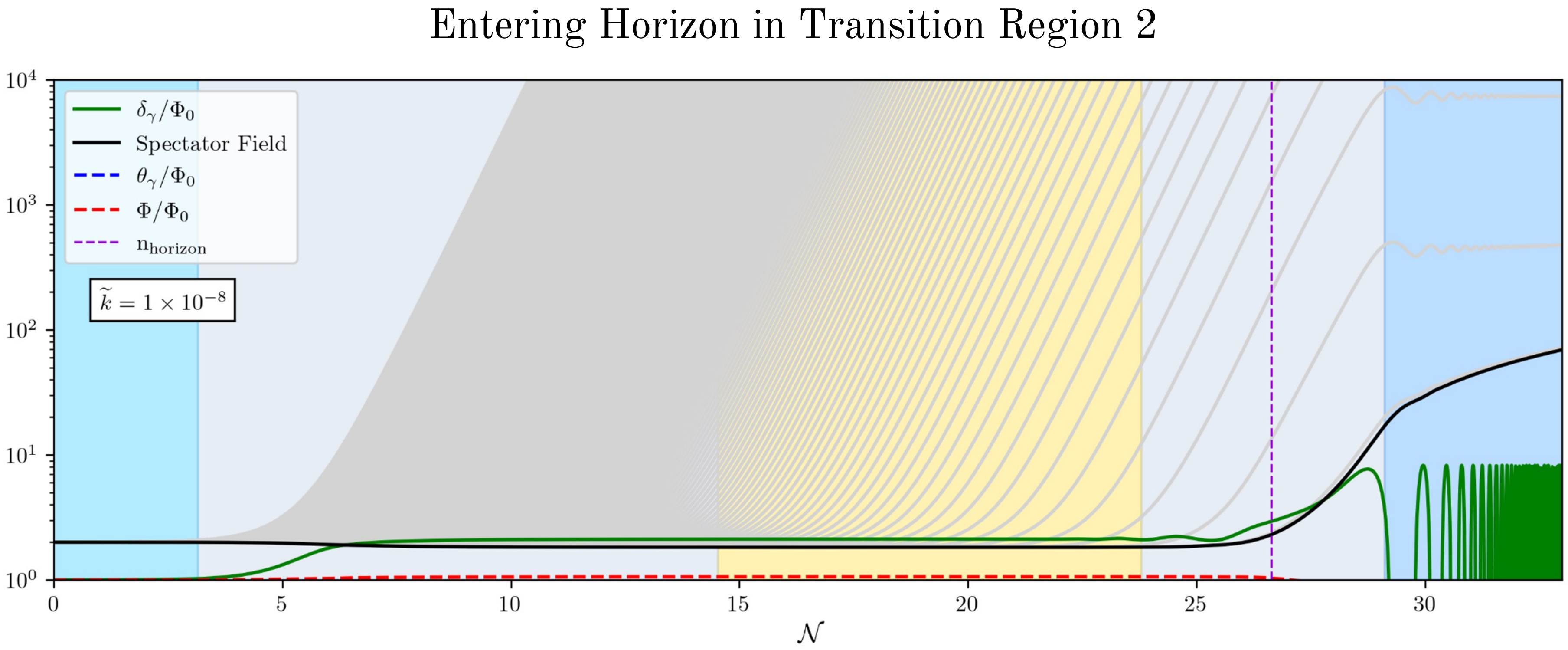

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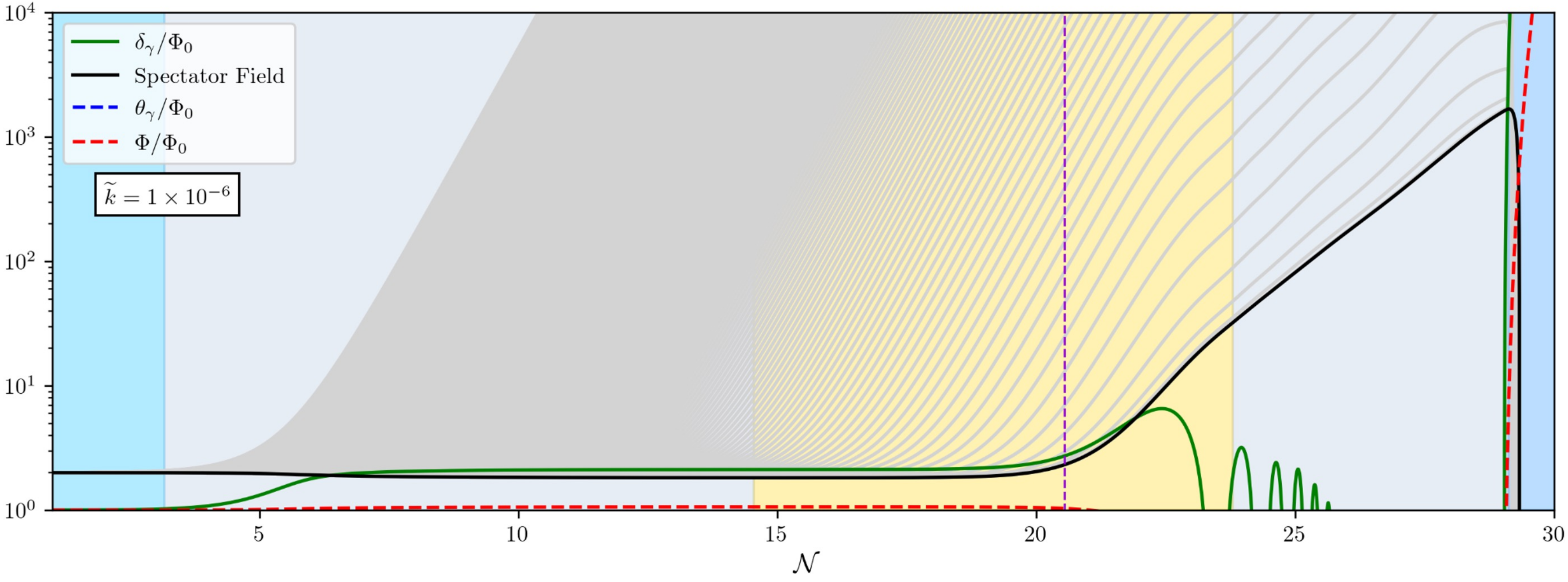
Entering Horizon in Stasis Region



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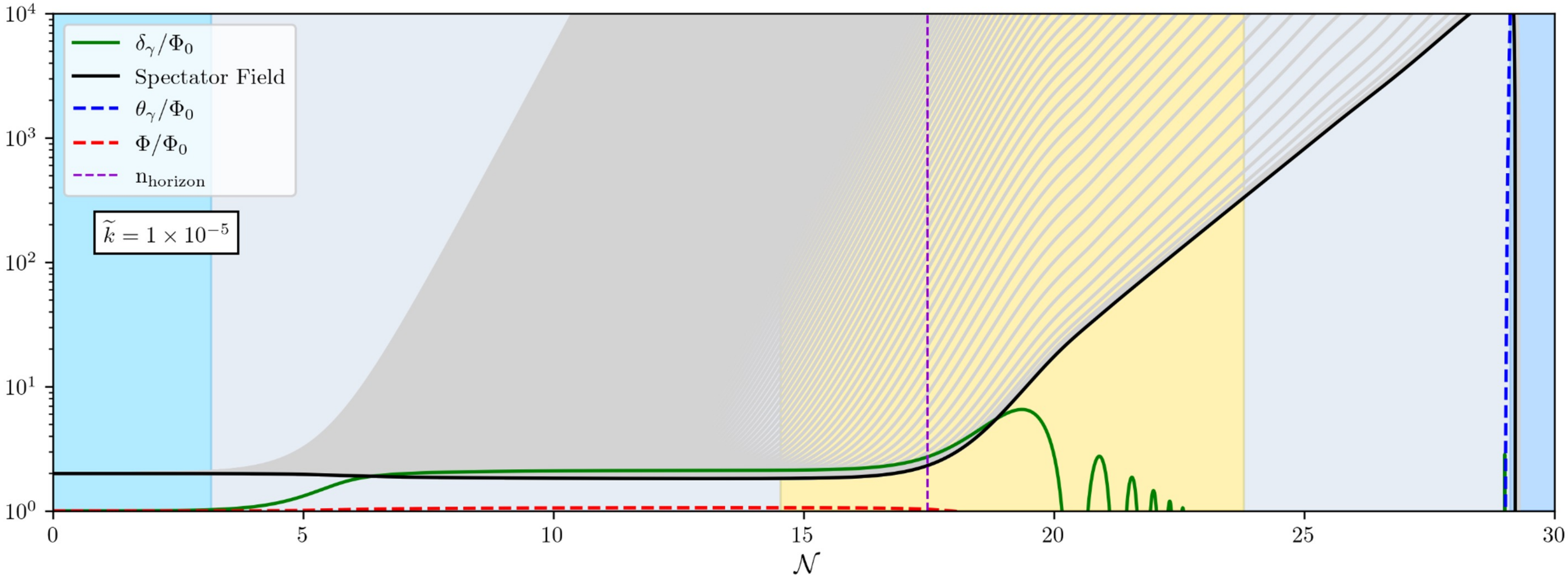
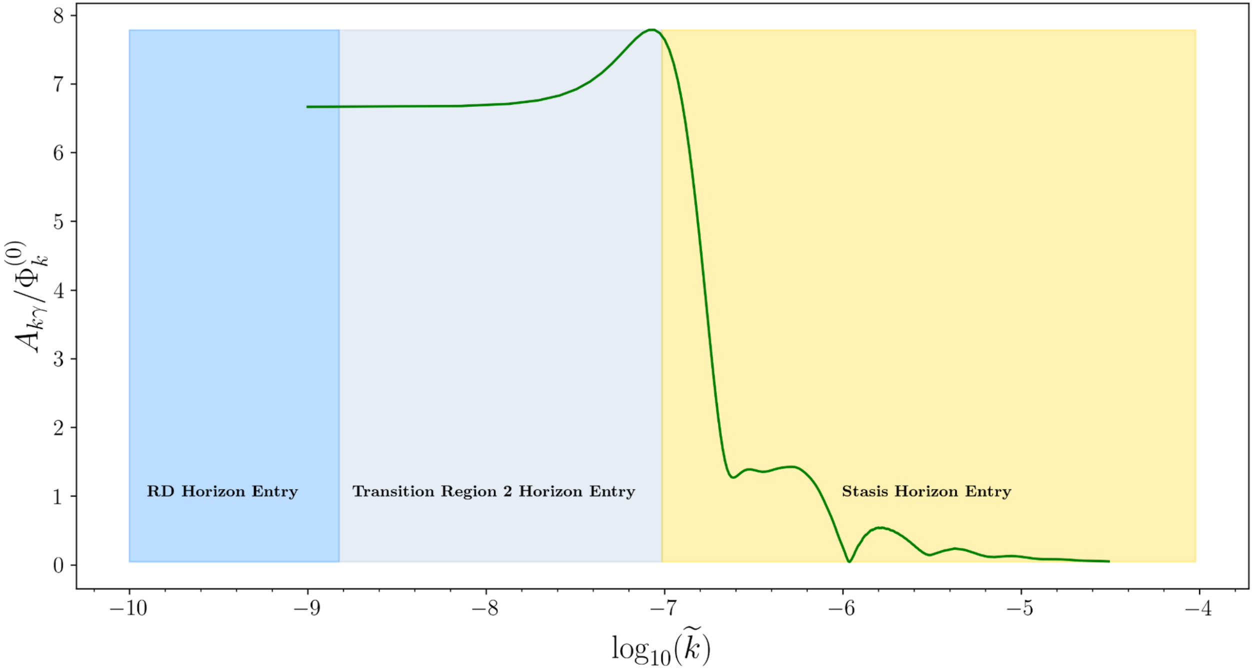


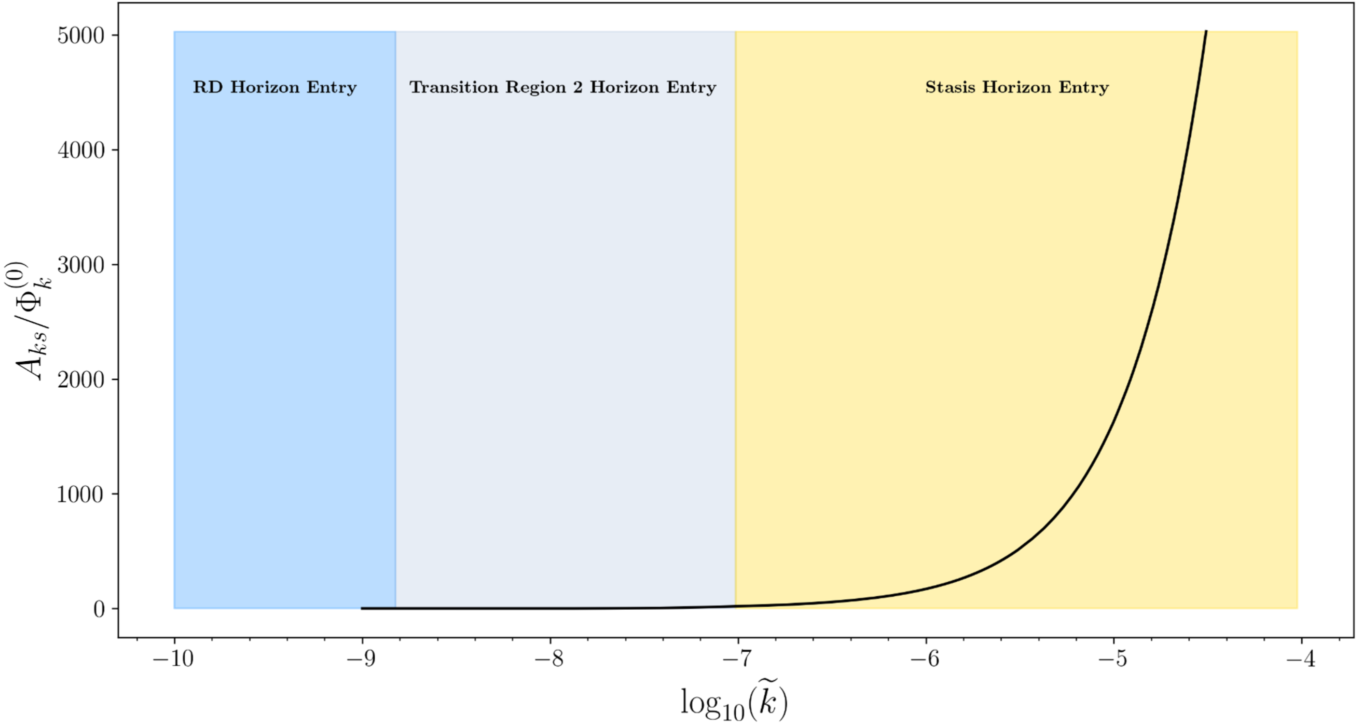
Simulation Results

Takeaway: As the wavenumber increases, we enter the horizon earlier, and we see the amplitude of the radiation perturbation become increasingly suppressed.



Simulation Results

Takeaway: The enhancement scales as a power law of a during stasis and transition region 2.



Summary

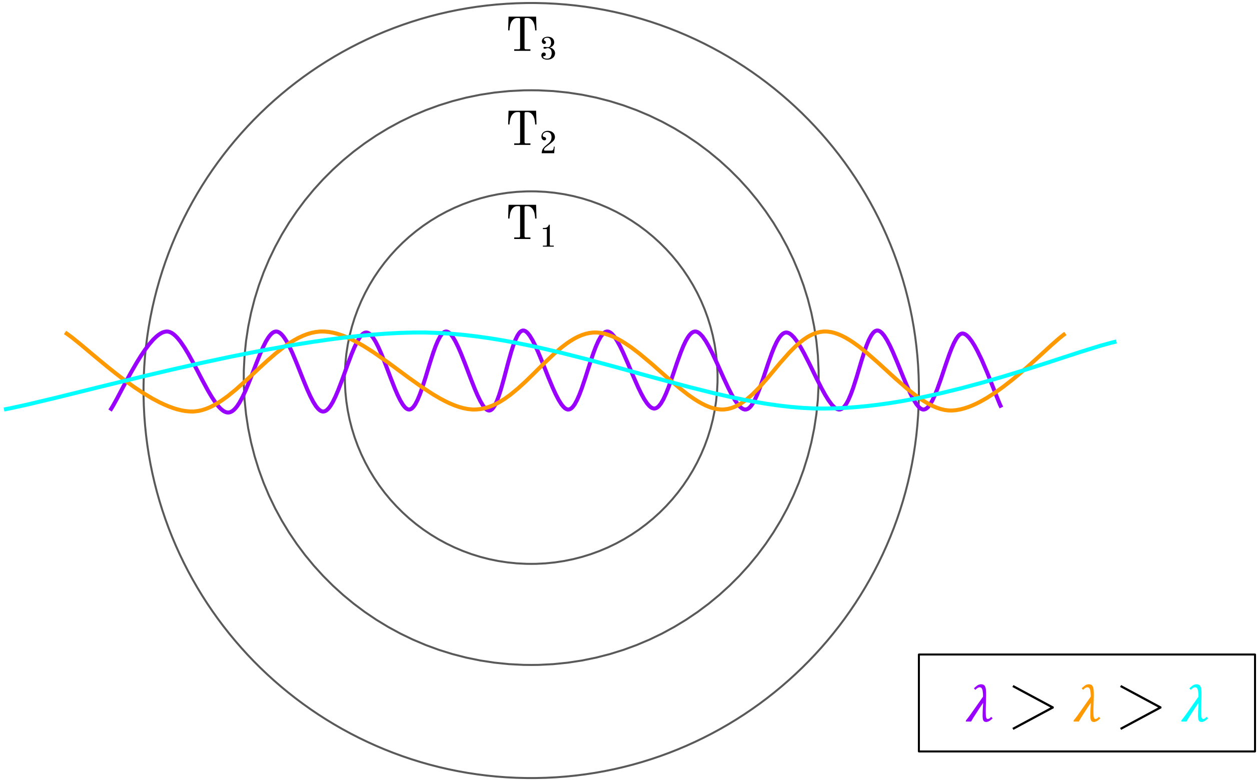
- Stable-mixed component cosmological eras – stasis eras – can arise naturally in many extensions of the Standard Model.
- Sequential particle decay enables the compensatory effect that underpins stasis.
- We care about perturbations during these periods because of their implications on the early formation of structures in our universe.

Cite: https://science.nasa.gov/mission/webb/early-universe/

Bonus Slides

What do you mean by “entering the horizon”?

We can think of the horizon as a kind of “switch” that turns on some terms in the differential equations



More on the "Coupling of Dark Matter and Radiation"[4]

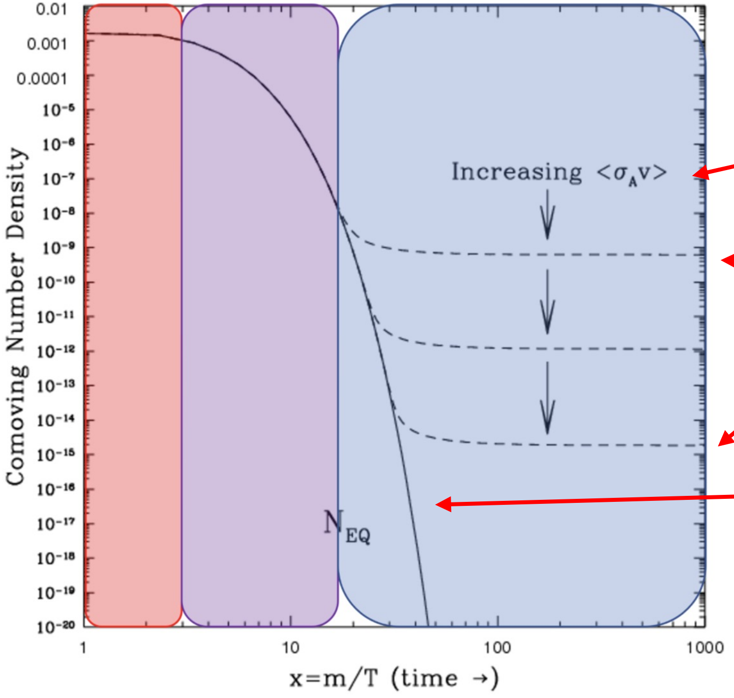
Initially, DM particles (χ) were in thermal equilibrium with the 'thermal bath' (f) of the hot, dense early universe, engaging in frequent interactions with other particles and radiation.

We can represent this as the following: $ff \Leftrightarrow \chi\chi$ "Initial condition"

For simplicity, let's denote the 'production' of DM as $ff \rightarrow \chi\chi$ and the 'annihilati $\chi\chi \rightarrow ff$ s .

As the universe expanded and cooled, the energy in the thermal bath decreased, leading to a reduction in interactions between dark matter and other particles.

Eventually, the decreased energy and expanding space caused dark matter to 'decouple' from the thermal bath, significantly reducing its interactions to negligible levels



https://www.particlebites.com/?p=7004

Rate at which DM annihilates

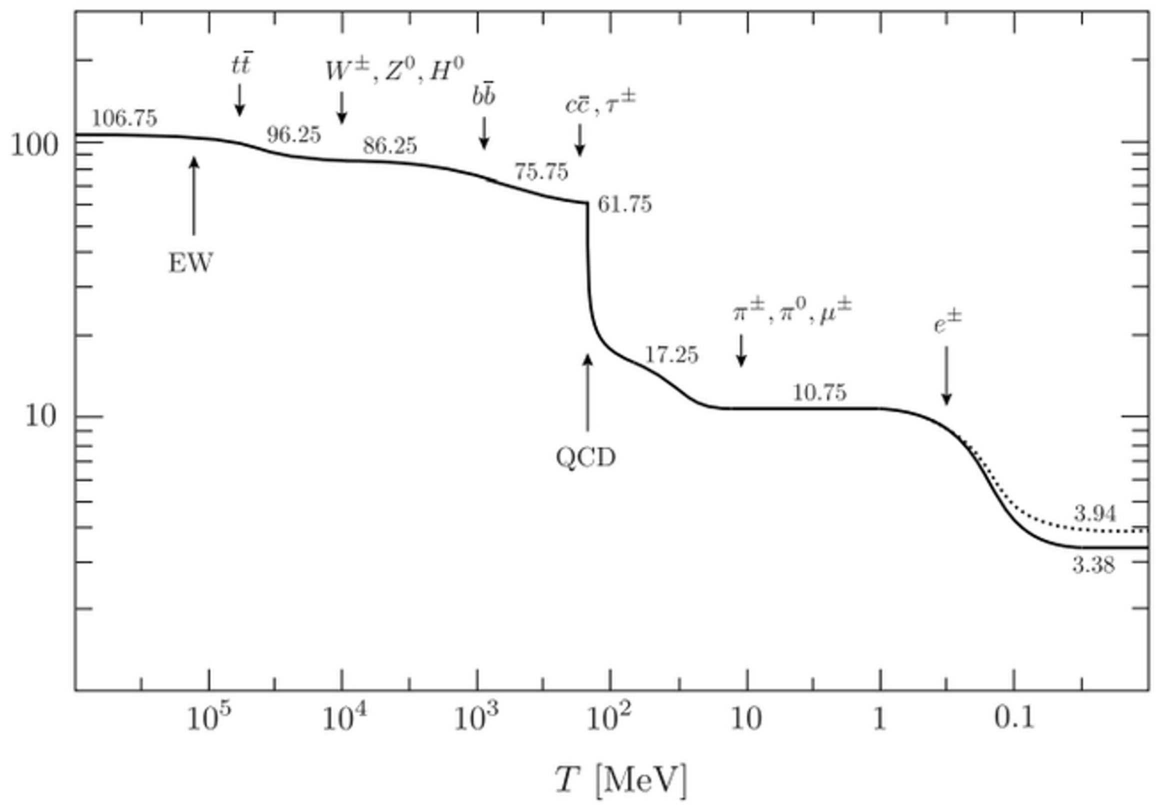
"Frozen out" DM densities

Comoving DM density that remains in thermal equilibrium

For even more info: Consider BTOH or this link “headcount” of all the types of particles and their possible states that contribute to the energy density of the universe

relativistic degrees of freedom

$g_\star(T)$



Temperature

https://www.researchgate.net/figure/Evolution-of-the-effective-number-of-relativistic-degrees-of-freedom-g-solid-line-and_fig2_335910362