Thermalization Process during Reheating

& Gravitational Waves

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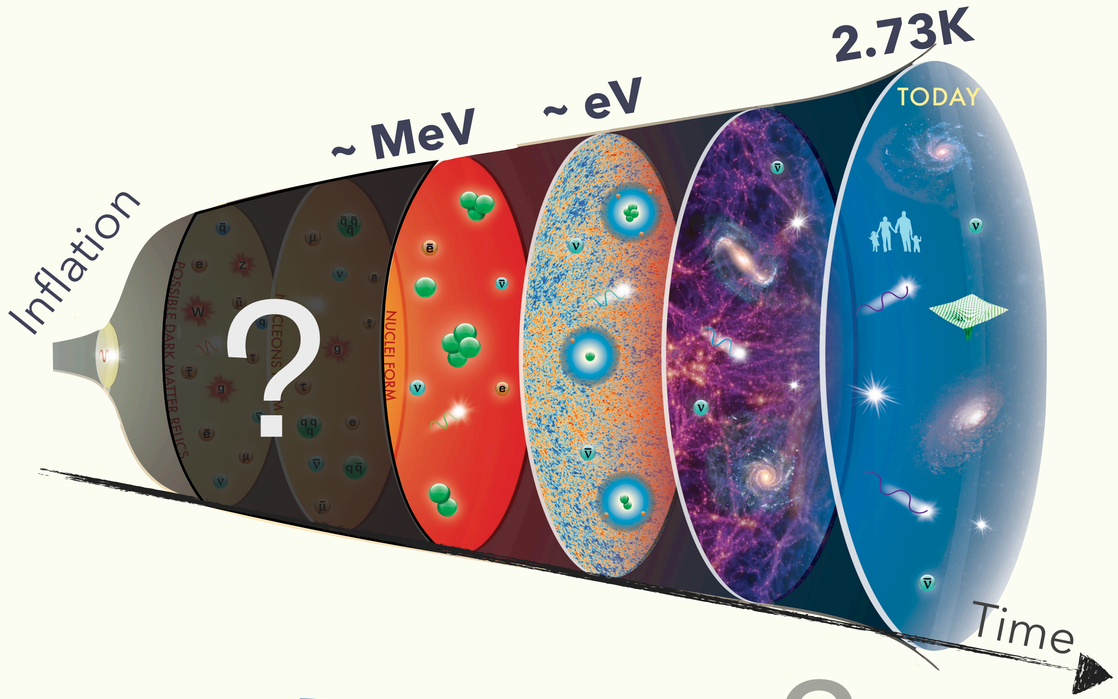
Based on work w/ K. Harigaya, T. Tsuji, M. Yamada

Beginning of the Hot Universe?

- Cosmic inflation (accelerated expansion)
  - Solves horizon/flatness problems
  - Provides the origin of density fluctuations
  - ◉ **Dilutes everything** including baryons, dark matter…



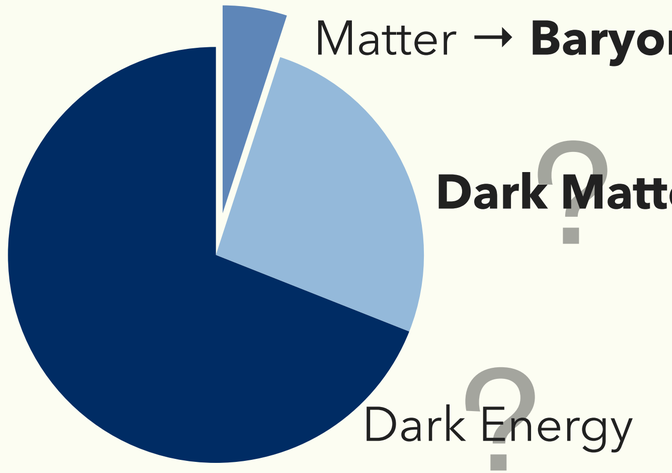
?

Reheating

?

Hot Universe

- Big Bang Nucleosynthesis
- Cosmic Microwave Background



Matter → **Baryon Asymmetry**

?

Dark Matter

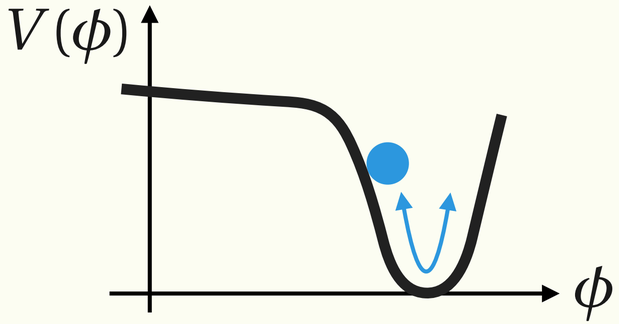
?

Dark Energy

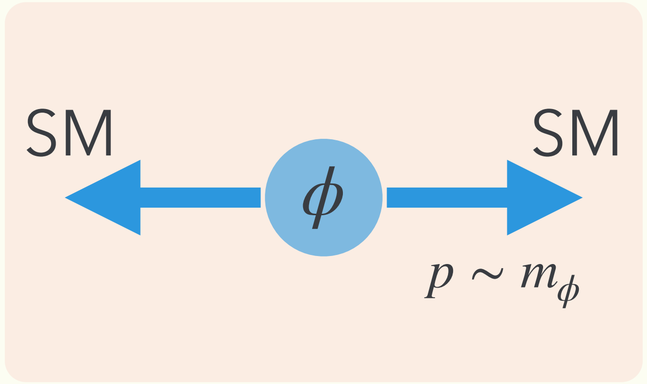
?

Reheating after Inflation

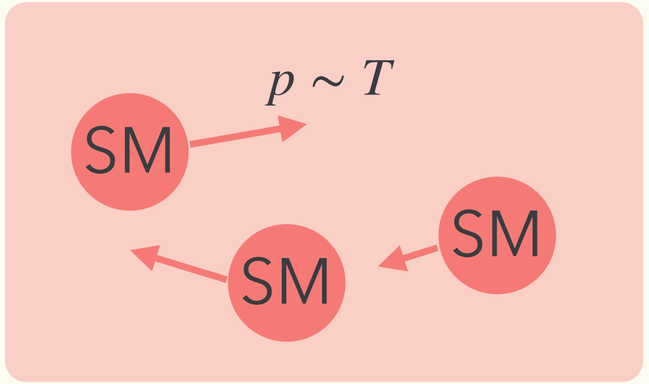
- Textbook picture of reheating after inflation



Inflaton oscillation



Inflaton decay



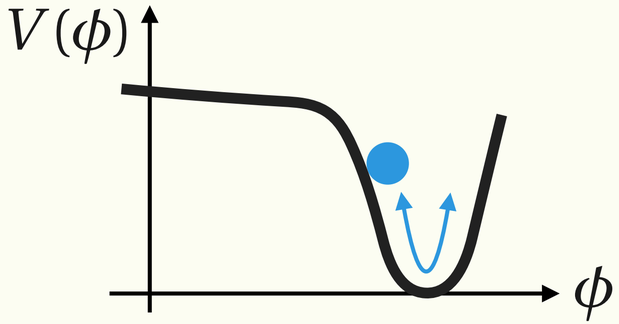
Thermal plasma

Time

$T_{\rm R} \sim \sqrt{M_{\rm Pl}\Gamma_\phi} \sim \sqrt{m_\phi/M_{\rm Pl}}\, m_\phi$ @ dim 5 Planck-suppressed decay

Reheating after Inflation

- Textbook picture of reheating after inflation



Inflaton oscillation

Inflaton decay

Thermal plasma

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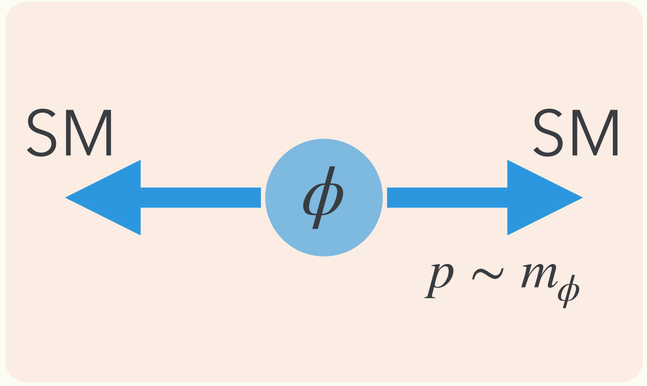
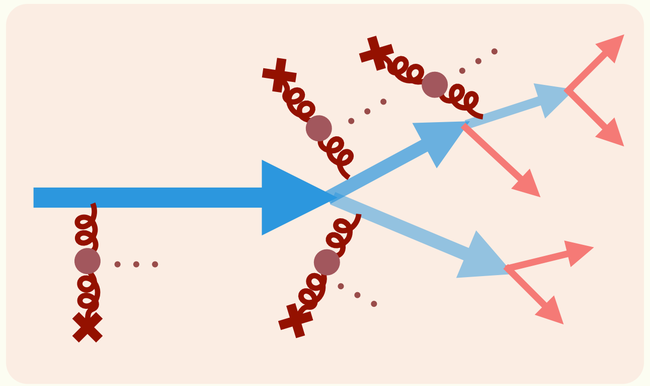
Beyond Instantaneous Thermalization

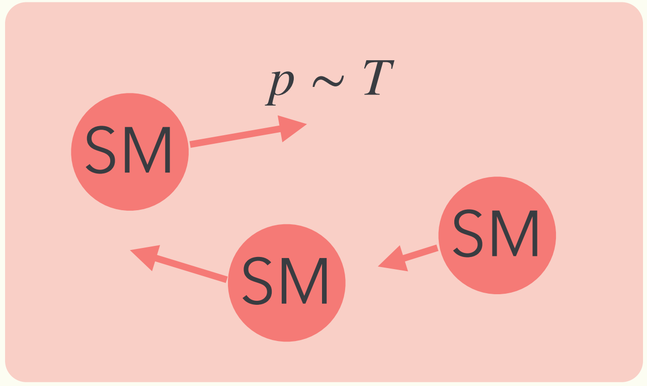
- In-medium cascades are the bottleneck



Inflaton decay



In-medium cascade



Thermal plasma

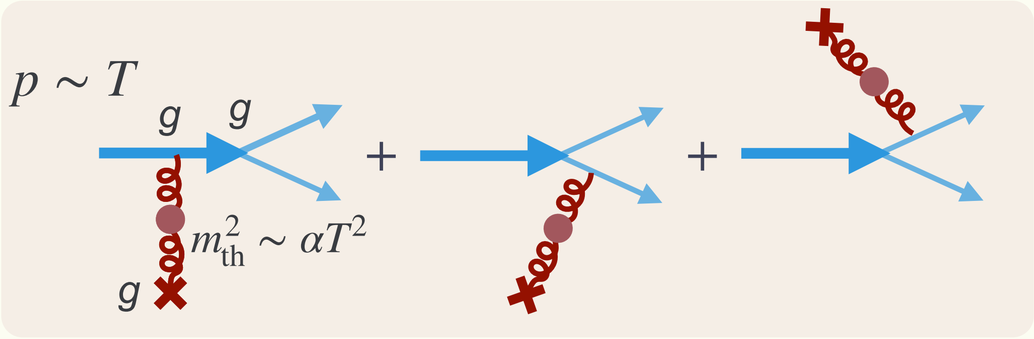
Thermalization during Reheating

via In-medium Cascades

In-medium Cascade of Energetic Particles

- Bethe–Heitler vs. Landau–Pomeranchuk–Migdal (LPM)

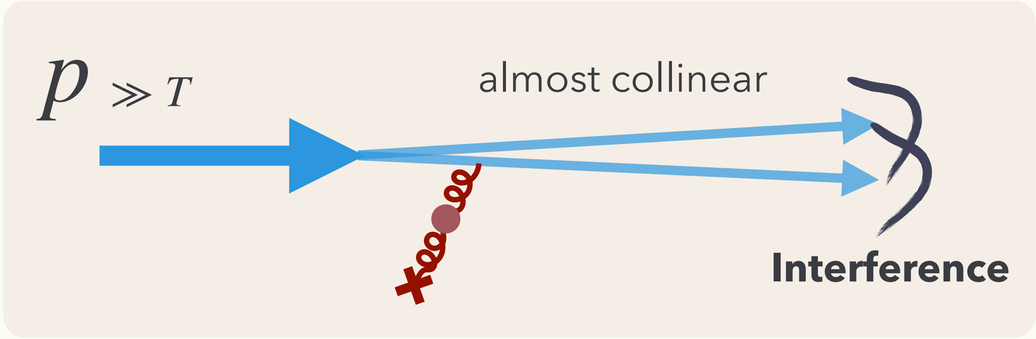
  - Bethe–Heitler formula



Scale-independent splitting

$$\Gamma_{\rm BH} \sim \alpha^3 \frac{T^3}{m_{\rm th}^2} \sim \alpha^2 T$$

  - **LPM** suppression [Landau, Pomeranchuk; Migdal]

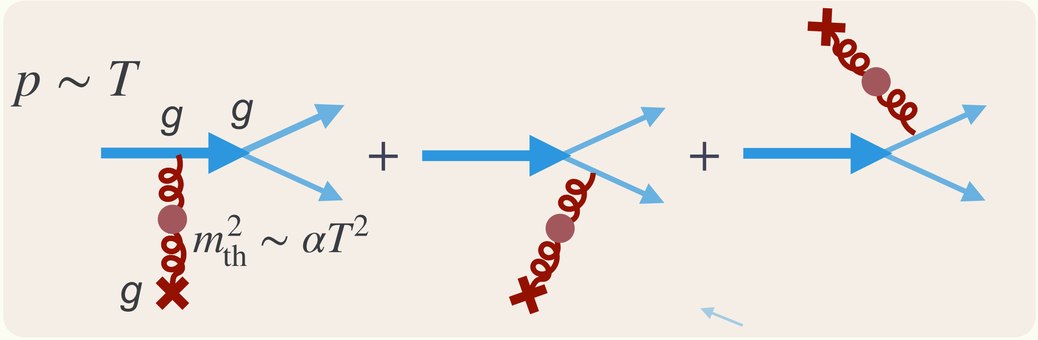


coherent multiple scatterings

In-medium Cascade of Energetic Particles

- Bethe–Heitler vs. Landau–Pomeranchuk–Migdal (LPM)

  - Bethe–Heitler formula



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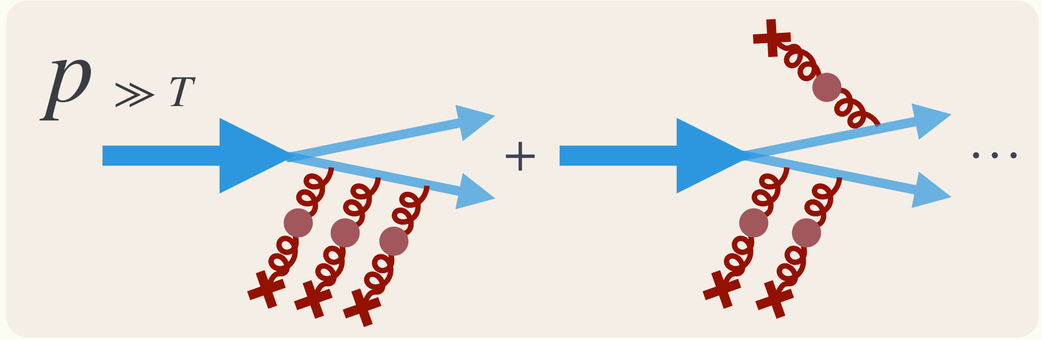


coherent multiple scatterings
p-dependent splitting: **LPM suppression**

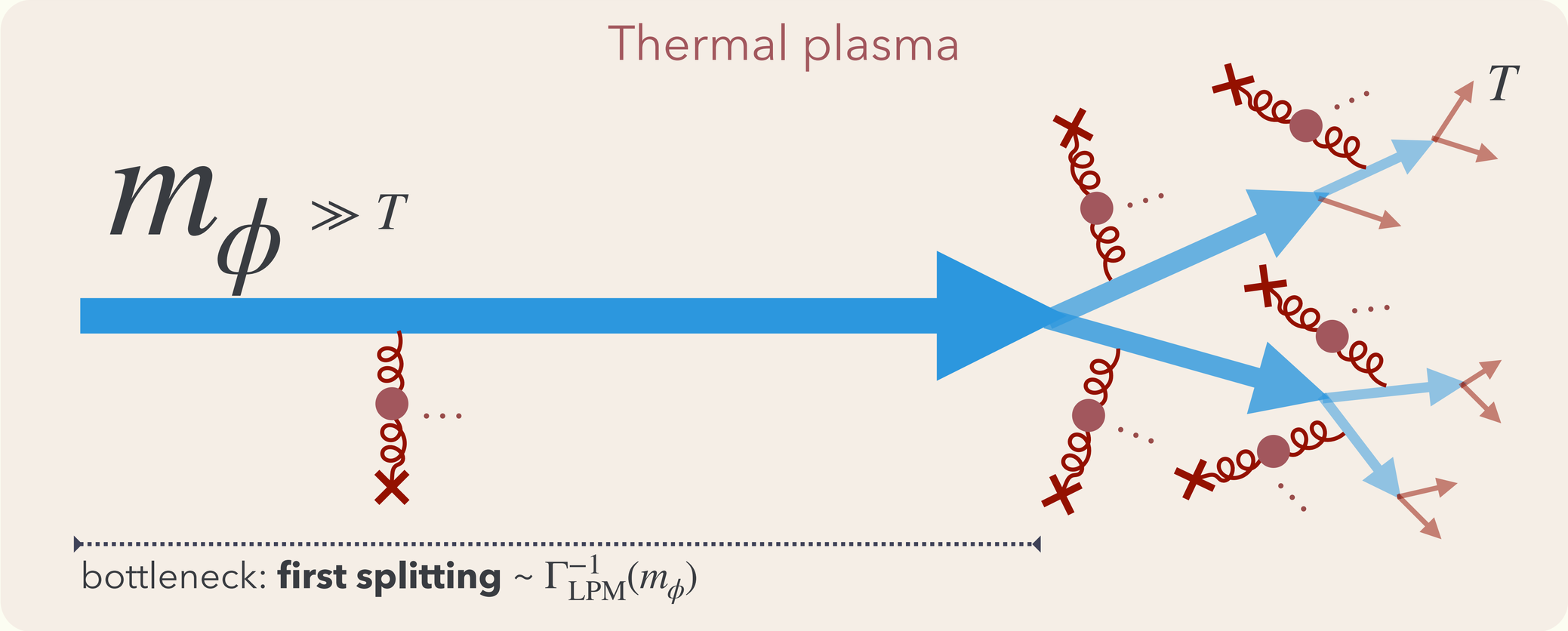
$$\Gamma_{\rm LPM} \sim \alpha t_{\rm form}^{-1}(p) \sim \alpha^2 T \times \sqrt{\frac{T}{p}}$$

[Arnold, Moore, Yaffe ’01,’02,’03; Arnold, Dogan ’08]

[**KM**+ 1312.3097, 1506.07661, 2402.14054]

In-medium Cascade of Energetic Particles

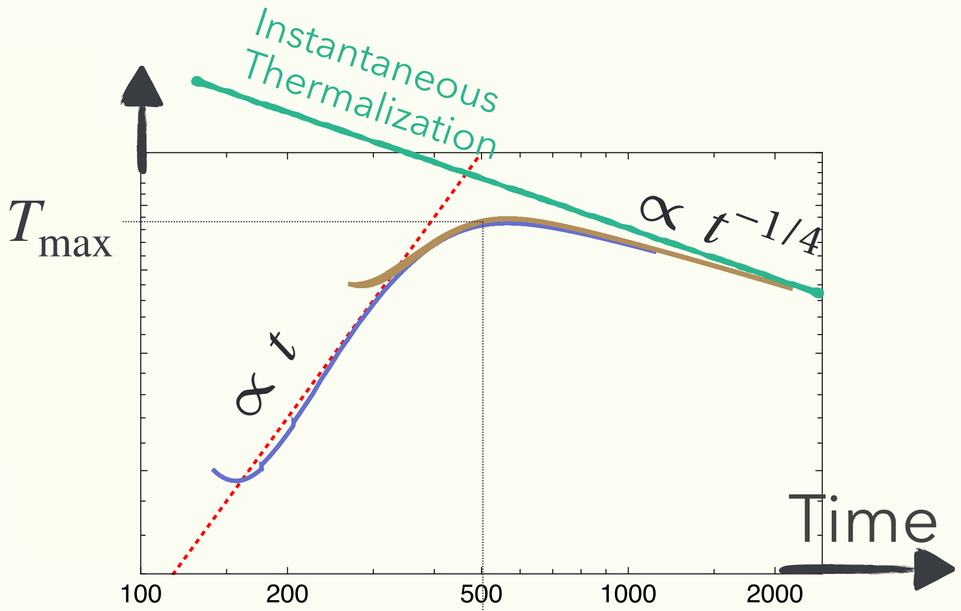
- Cascade via LPM-suppressed multiple splittings

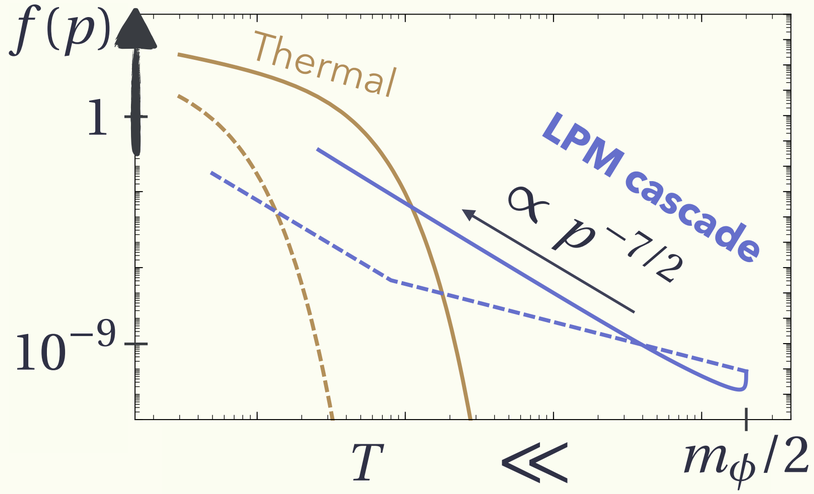


[**KM**+ 1312.3097, 1506.07661, 2402.14054]

Does This Change the Evolution of the Universe?

- Suppression of the Maximal Temperature





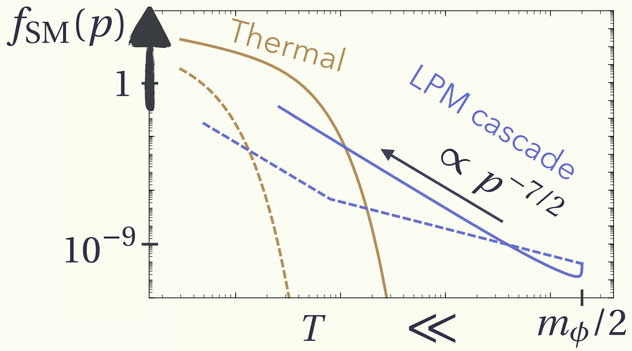
$$\Gamma_{\rm split}(m_\phi) \lesssim H \qquad \Gamma_{\rm split}(m_\phi) \gtrsim H$$

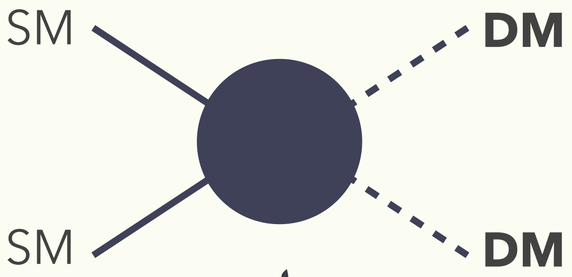
$$\frac{T_{\rm max}}{T_{\rm max}^{\rm (inst)}} \sim 10^{-3} \left(\frac{\alpha}{0.1}\right)^{\frac{4}{5}} \left(\frac{T_{\rm R}}{10^3\,{\rm GeV}}\right)^{\frac{3}{10}} \left(\frac{m_\phi}{10^{13}\,{\rm GeV}}\right)^{-\frac{9}{20}}$$

[**KM**+ 1402.2846, 1901.11027]

Does This Change the Evolution of the Universe?

- Non-thermal Heavy Dark Matter Production





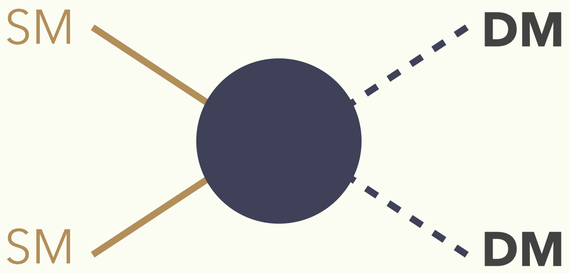
E.g. W W → DM DM

$$\langle \sigma v \rangle \simeq \frac{\alpha_{\rm DM}^2}{m_{\rm DM}^2} \quad \Rightarrow \quad \frac{\rho_{\rm DM}}{s} \simeq 0.11 \alpha_{\rm DM}^2 \frac{T_{\rm R}^3}{m_{\rm DM}^2}$$

"Universal" production

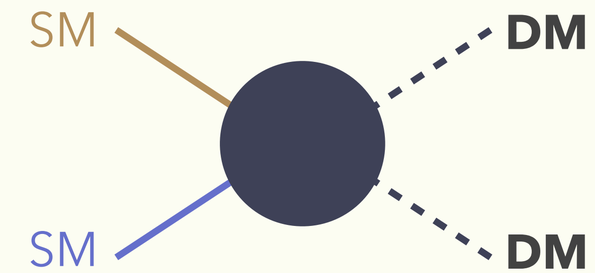
Thermal + Thermal

[Giudice, Kolb, Riotto '01]



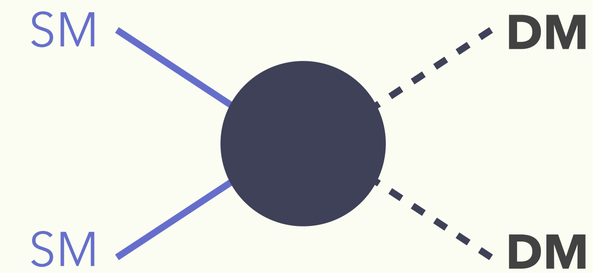
Thermal + **LPM**

[**KM**+ 1402.2846; Drees, Najjari '21]



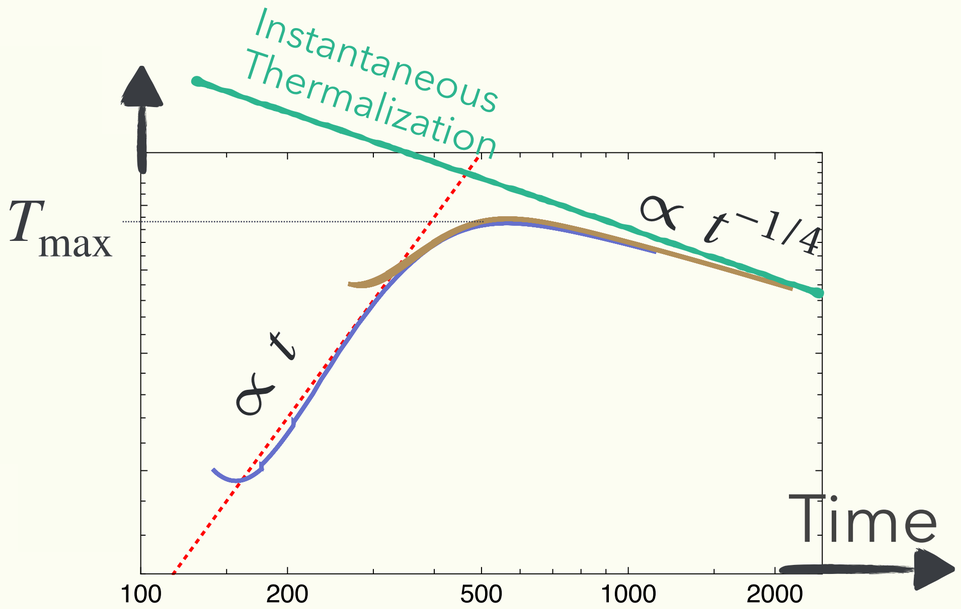
LPM + **LPM**

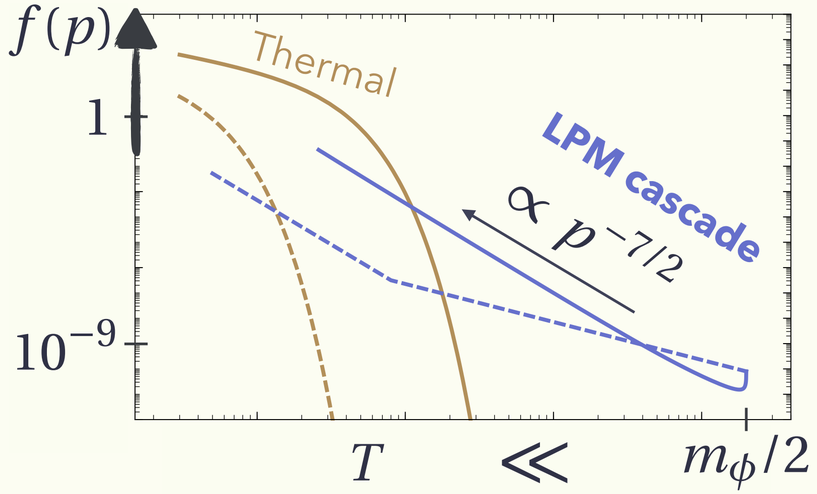
[**KM**+ 1901.11027; Garcia, Amin '18]



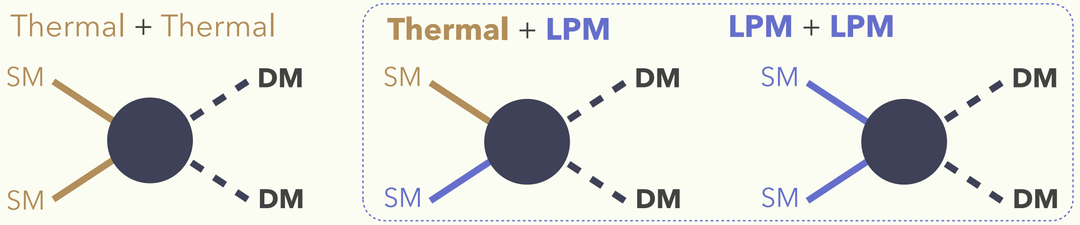
Thermalization & Reheating

- Implications: Suppression of the maximal T & DM production





$$\frac{T_{\rm max}}{T_{\rm max}^{\rm (inst)}} \sim 10^{-3} \left(\frac{\alpha}{0.1}\right)^{\frac{4}{5}} \left(\frac{T_{\rm R}}{10^3\,{\rm GeV}}\right)^{\frac{3}{10}} \left(\frac{m_\phi}{10^{13}\,{\rm GeV}}\right)^{-\frac{9}{20}}$$



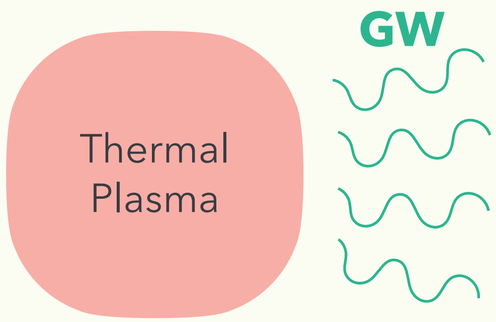
High-Frequency GWs

& In-medium Cascades

High-Frequency GWs as a Probe of Reheating

- Two generic, often dominant, contributions in the literature

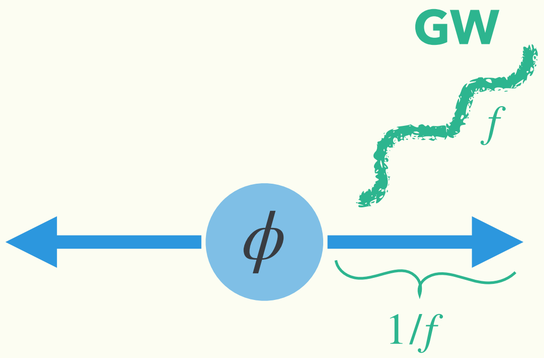
Inevitable Thermal GWs



Cosmic **Gravitational** Microwave Background

[Ghiglieri+ 1504.02569, 2004.11392;…; Bernal, Xu 2410.21385]

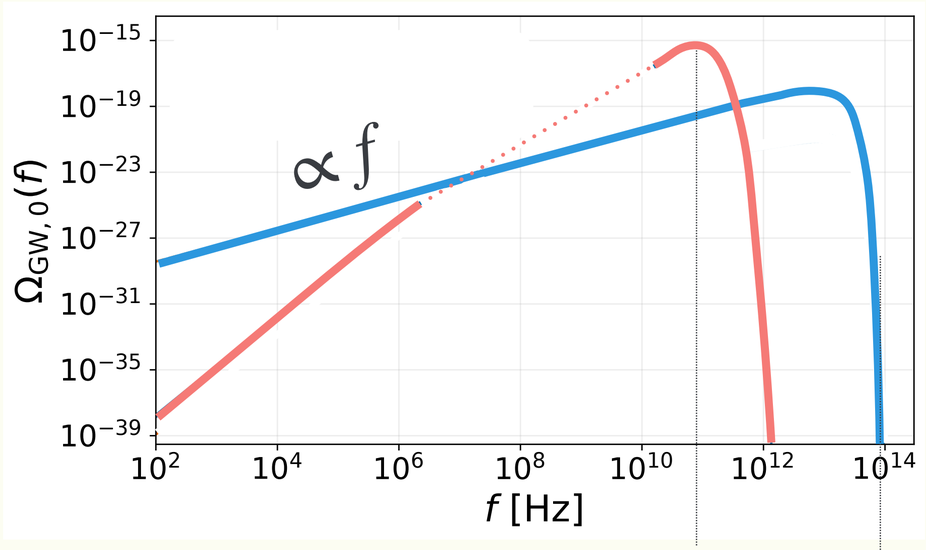
GW Emission @ Reheating



Graviton brems @ vacuum **persistent directional flow** $\propto f$

[Nakayama, Tang 1810.04975; …; Bernal+, 2311.12694; Cline, Xu 2605.16201]

[See e.g., Xu+ 2505.08868]



$80\,\mathrm{GHz}$

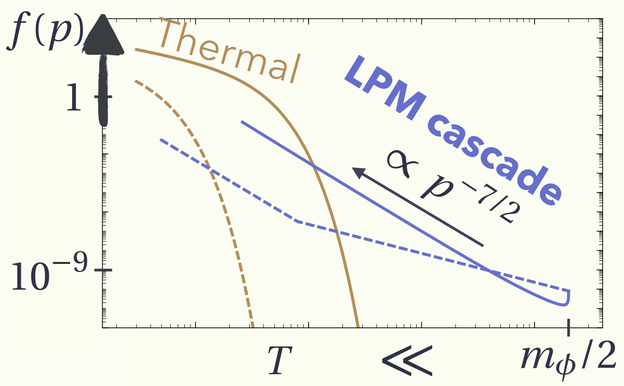
$$10^{5}\,\mathrm{GHz}\left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)^{-1}\left(\frac{m_\phi}{10^{13}\,\mathrm{GeV}}\right)$$

[**KM**, Tsuji 2609.01480]

High-Frequency GWs as a Probe of Reheating

- In-medium cascades change the spectrum qualitatively

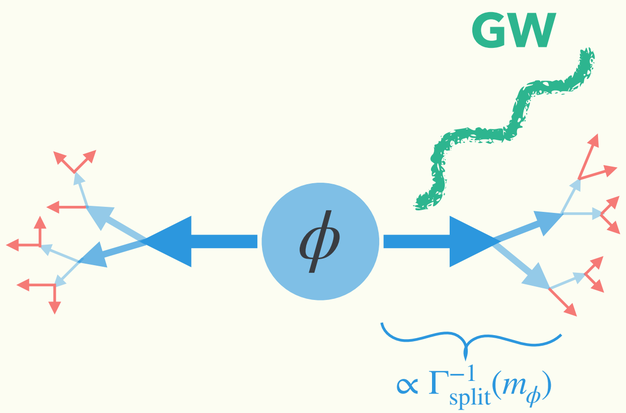
Inevitable Thermal GWs



Soft-Hard scattering

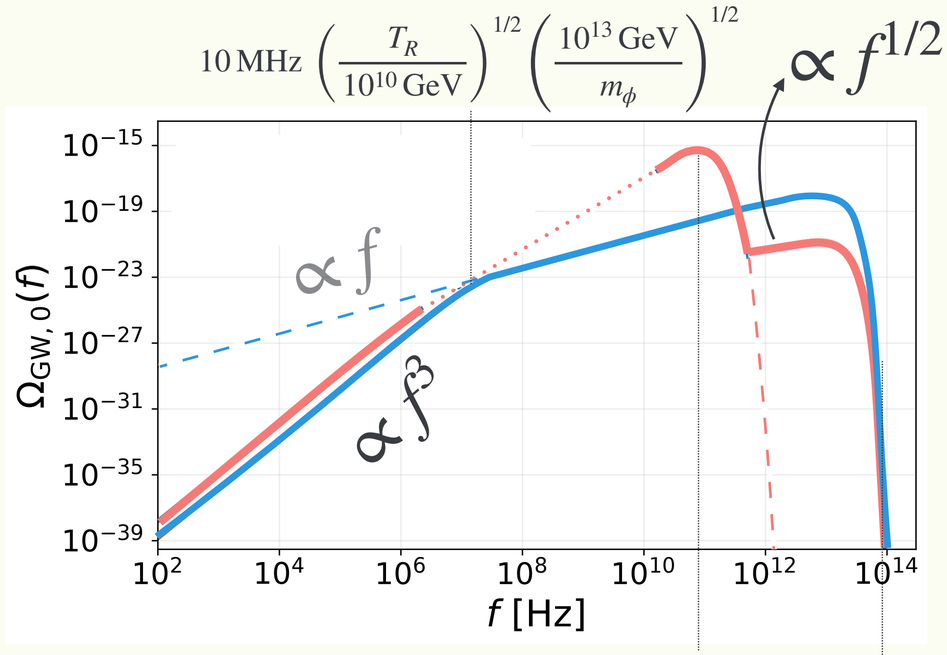
[**KM**, Tsuji 2609.01480]

GW Emission @ Reheating



Graviton brems @ finite T
Finite directional flow $\propto f^3$

[**KM**, Tsuji 2609.01480;
see also Murayama+ 2608.24994]

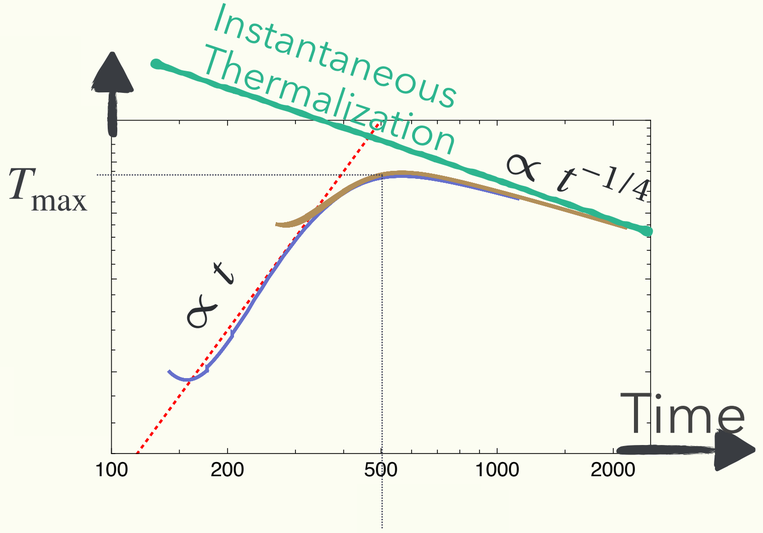


Summary

- Thermalization during Reheating & Its Implications

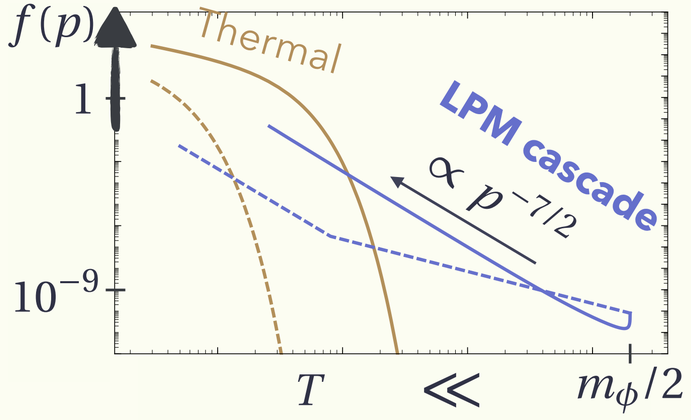
[**KM**, Tsuji 2609.01480]

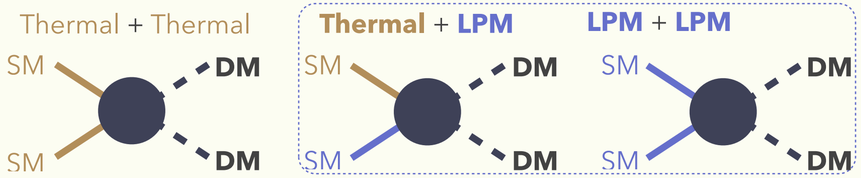
- **Suppression of $T_{\rm max}$**



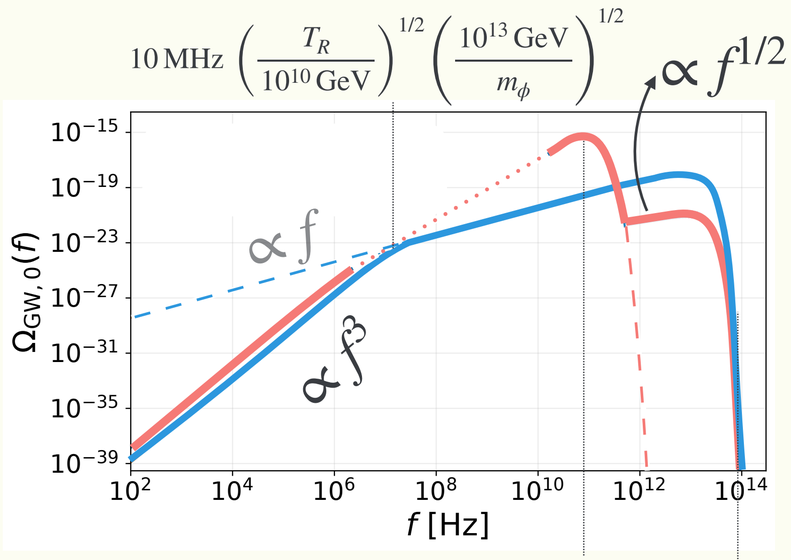
$$\frac{T_{\rm max}}{T_{\rm max}^{\rm (inst)}} \sim 10^{-3} \left(\frac{\alpha}{0.1}\right)^{\frac{4}{5}} \left(\frac{T_{\rm R}}{10^3\,{\rm GeV}}\right)^{\frac{3}{10}} \left(\frac{m_\phi}{10^{13}\,{\rm GeV}}\right)^{-\frac{9}{20}}$$

- **DM production during reheating**





- **Cascades leave imprints on HFGWs**



$80\,{\rm GHz}$

$$10^5\,{\rm GHz}\left(\frac{T_R}{10^{10}\,{\rm GeV}}\right)^{-1}\left(\frac{m_\phi}{10^{13}\,{\rm GeV}}\right)$$

Backup

Effective Kinetic Theory of SM

- LPM-suppressed splitting function for SM

[**KM**, Yamada 2208.11708;
Arnold, Morre, Yaffe '01,'02,'03; Arnold, Dogan '08]

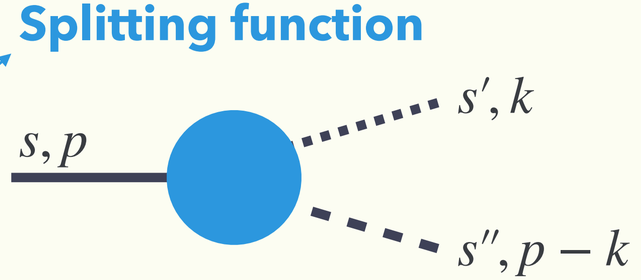
  - Kinetic equation

$$\mathscr{L} f_s(\boldsymbol{x},\boldsymbol{p},t) = \mathscr{S} + \mathscr{C}_{2\leftrightarrow 2}[f_s] + \mathscr{C}_{"1\leftrightarrow 2"}[f_s] \qquad \text{w/ } s = e_f, L_f, u_f, d_f, Q_f, \phi, B, W, g$$

Source (e.g., inflaton, PBHs, …) | Elastic scat. | **LPM-suppressed** splitting

  - **Splitting function** for effective "1 to 2" processes

$$\mathscr{C}_{"1\leftrightarrow 2"}[f_s] \supset -\frac{(2\pi)^3}{p^2 v_s}\sum_{s',s'}\int_0^p \mathrm{d}k\, \gamma_{s\leftrightarrow s's''}(p;k,p-k) f_s(p) + (\text{inverse})$$



Effective Kinetic Theory of SM (cont'd)

- LPM-suppressed splitting function for SM

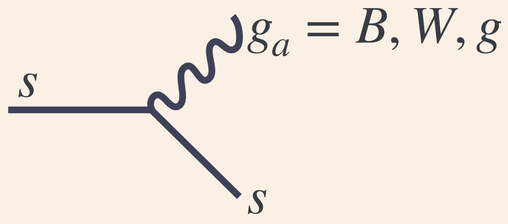
[**KM**, Yamada 2208.11708;
Arnold, Morre, Yaffe '01,'02,'03; Arnold, Dogan '08]

  - SM splitting function

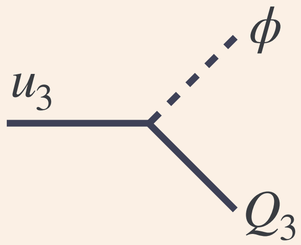
$$\gamma_{s\to s's''}(p;xp,(1-x)p)=\frac{1}{2}\frac{\alpha_{ss's''}}{(2\pi)^4\sqrt{2}}\times\frac{P^{(\mathrm{vac})}_{s\to s's''}(x)}{x(1-x)}\times\mu_\perp^2(1,x,1-x;s,s',s'')$$

vacuum DGLAP splitting function

SM gauge + top Yukawa

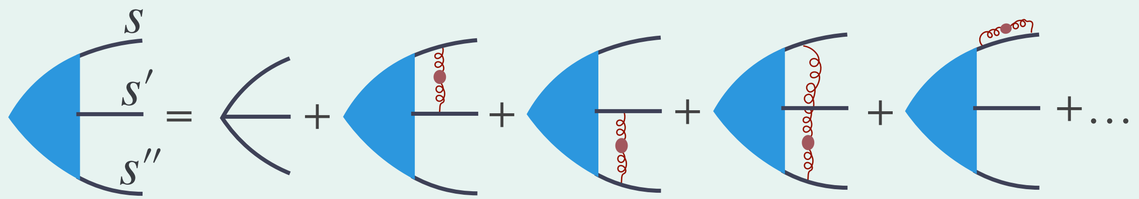


$$\alpha_{sg_as}=d^{(a)}_{\mathbf{R}_s}C^{(a)}_{\mathbf{R}_s}\alpha_a$$



$$\alpha_{u_3\phi Q_3}=y_t^2/(4\pi)$$

LPM suppression

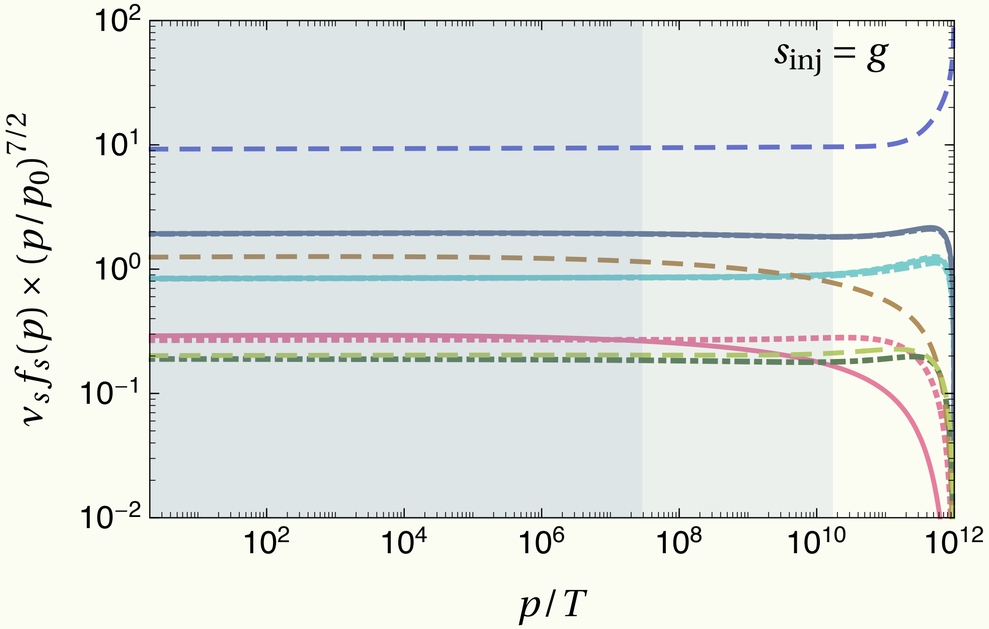


i.e., self-consistent equation for vertex func.

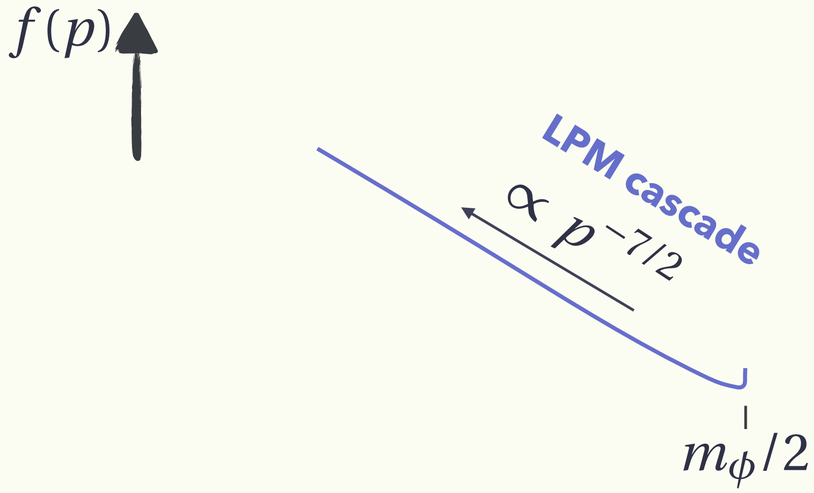
Does This Change the Evolution of the Universe?

- Universality in the Composition of LPM cascade

Inflaton → gluon + gluon



[**KM**, Yamada, 2208.11708]



Universality in the Spectrum

[**KM**, Yamada 2208.11708]