Bardia Najjari and Manuel Drees

PASCOS22 — Max Planck Institute for Nuclear Physics — Jul. 26

Multi-Species Thermalization Cascade of Energetic Particles in the Early Universe

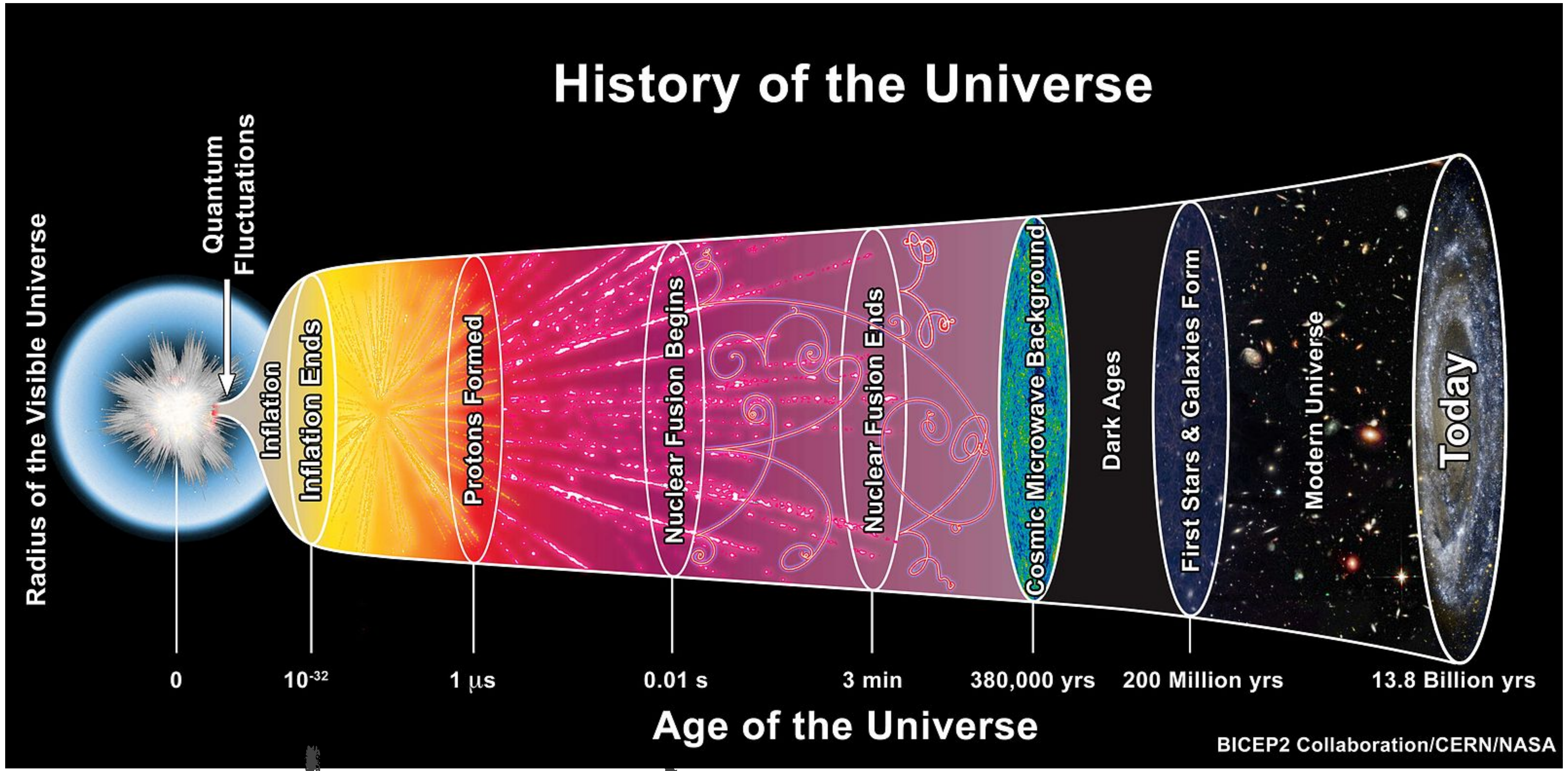
Based on **arXiv:2205.07741**

UNIVERSITÄT BONN

bctp Bethe Center for Theoretical Physic

Matter: sources of energetic particles

- room for modification of thermal history prior to BBN



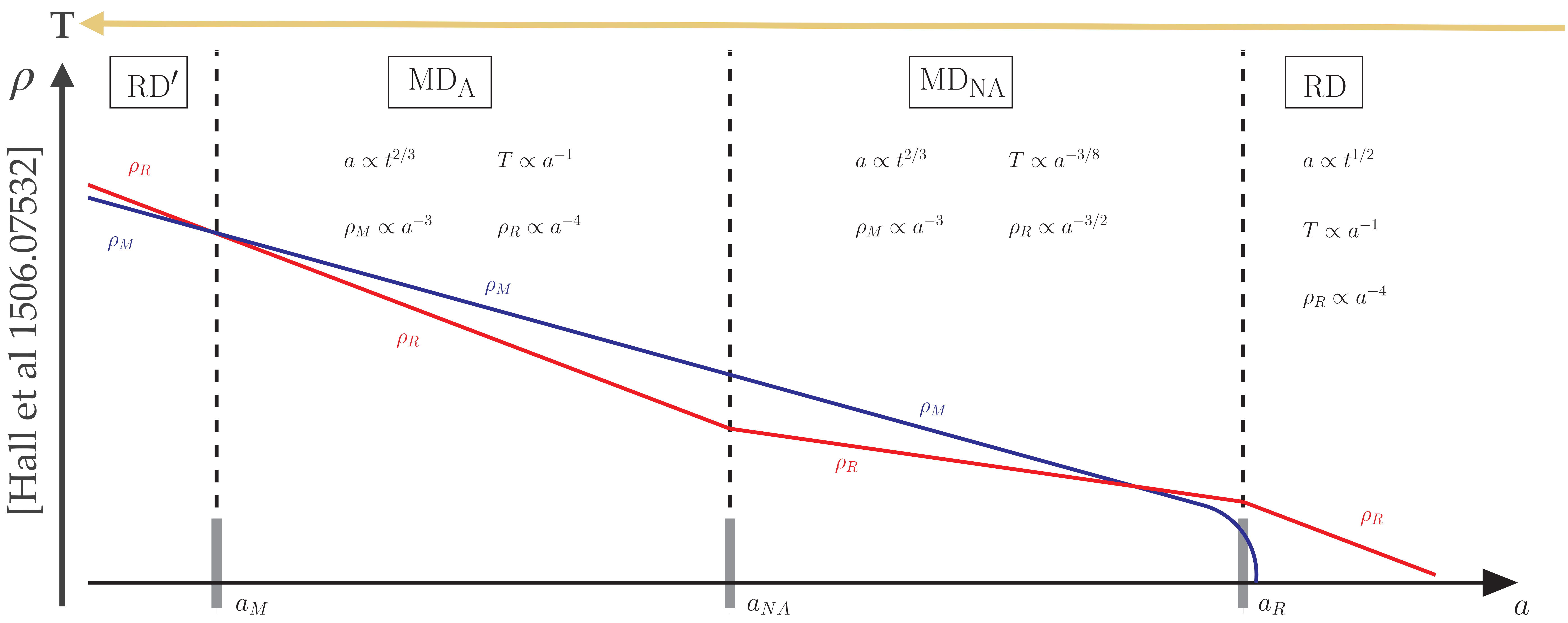
- massive inflaton
- moduli fields
- (non)-thermal relics

room for modifications

e.g. Matter

Evolution of a universe with matter

- matter $\omega = 0 \rightarrow$ universe moves toward MD era



Boltzmann equation:

$$\frac{d\rho_M}{dt} + 3H\rho_M = -\Gamma_M \rho_M$$

$$\frac{d\rho_R}{dt} + 4H\rho_R = +\Gamma_M \rho_M$$

Instantaneous Thermalization

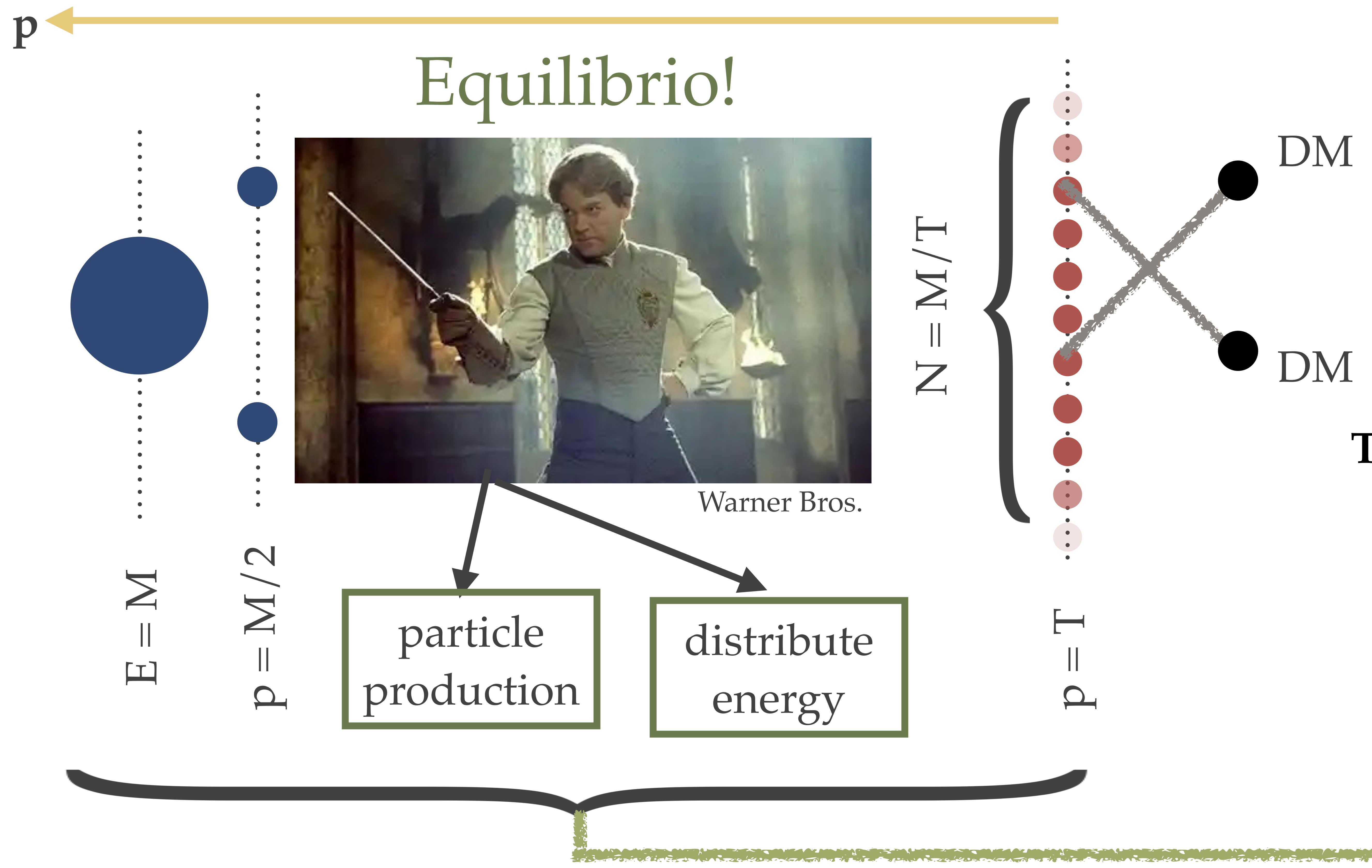
- captures: modified Hubble rate - entropy production $\longrightarrow$ FO - FI - ….

[Maldonado & Unwin 1902.10746]
[Beranal et al 1906.04183]

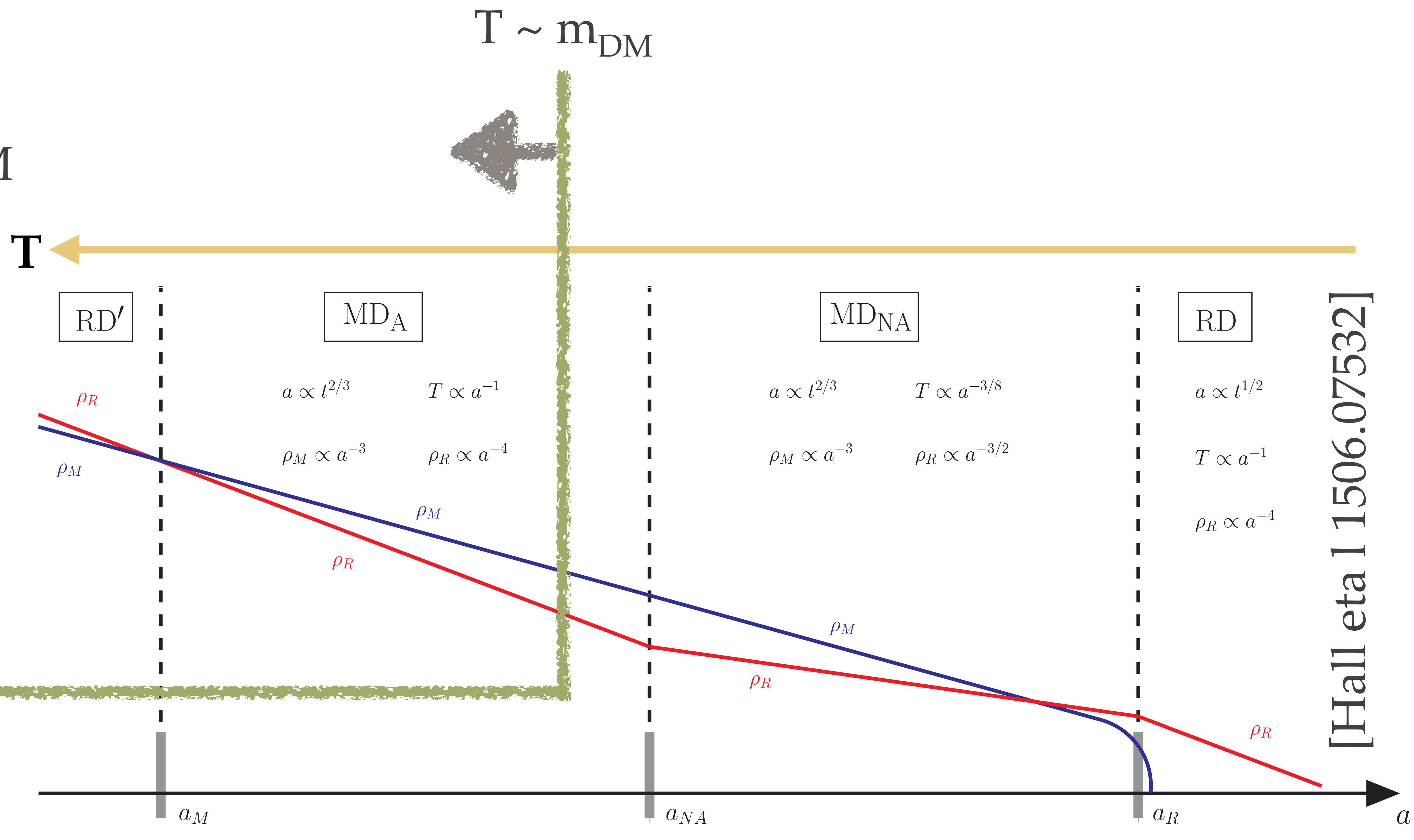
- misses: physics of particles with p > T

Instantaneous thermalization

- look at an instant
- consider a single decaying matter particle

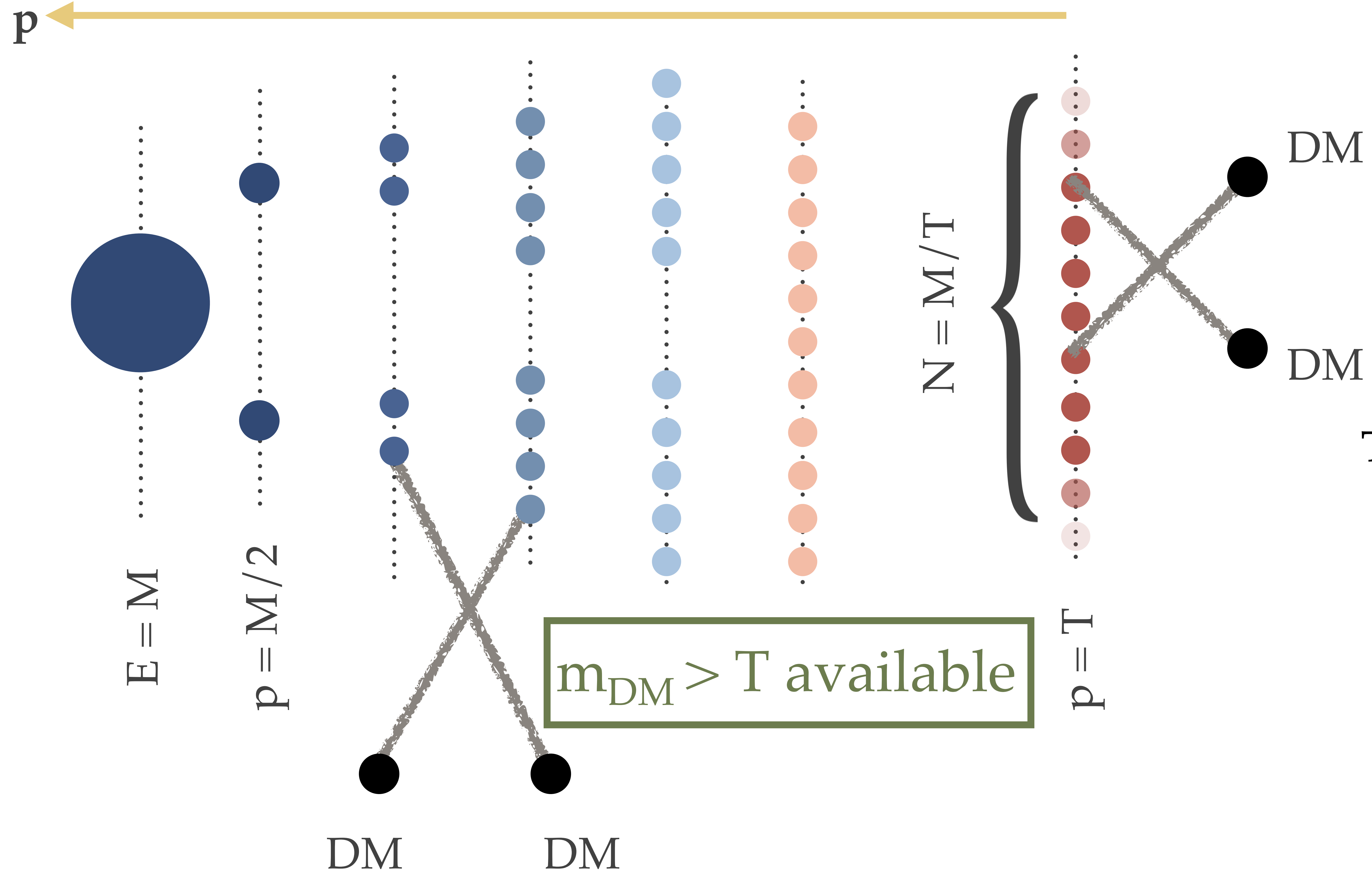


- look at e.g. DM freeze-in

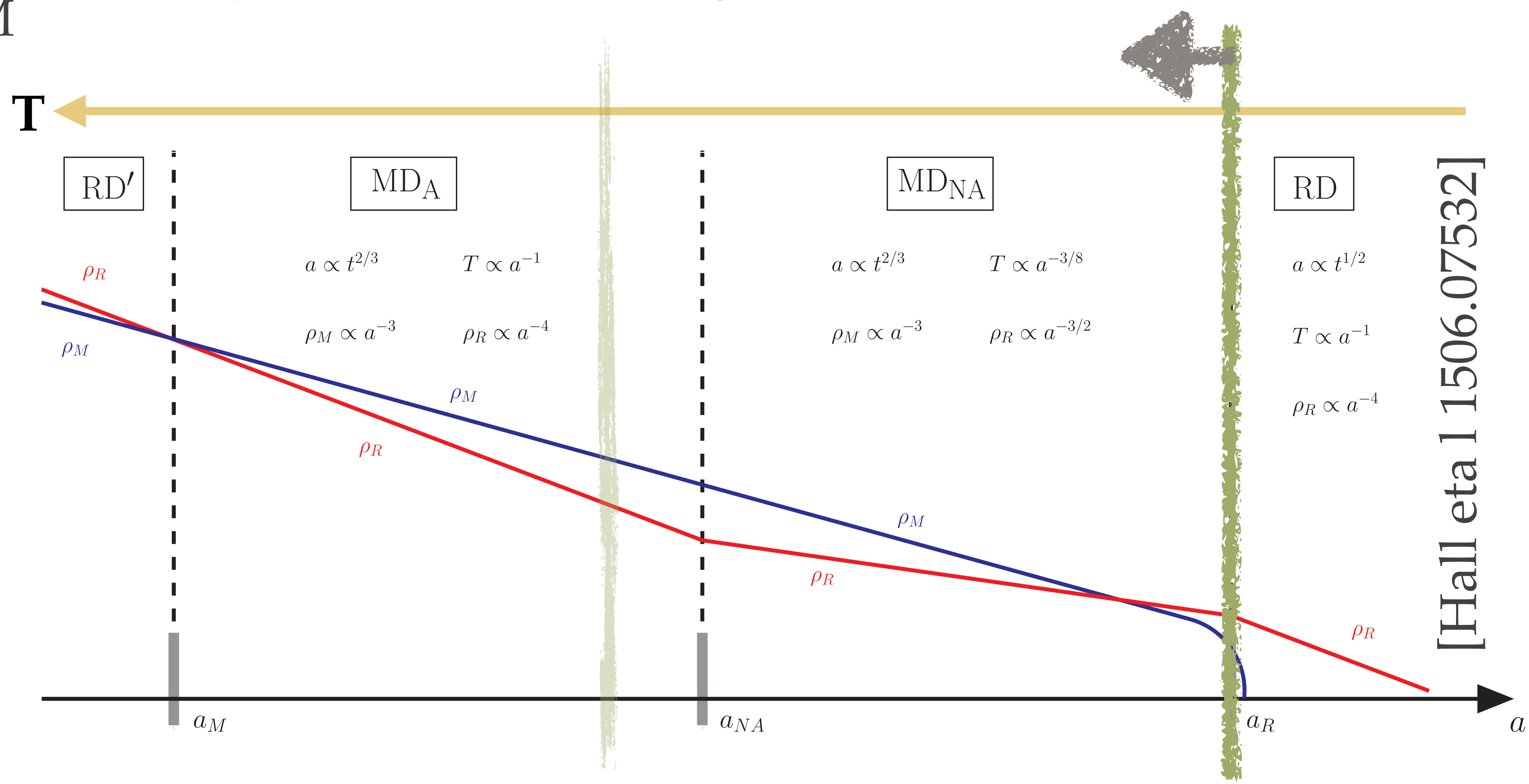


Instantaneous thermalization: what we miss

- look at a Hubble era → constant T
- consider a single decaying matter particle



- particles as heavy as M/2 produced
- production continues up to RH
- smaller dilution

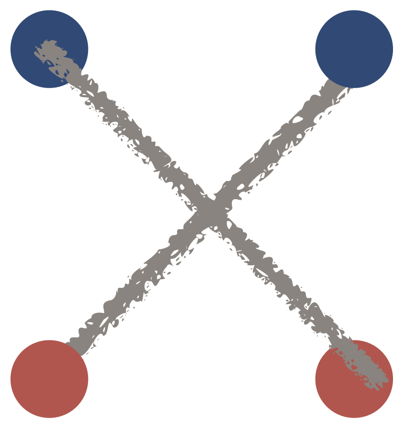
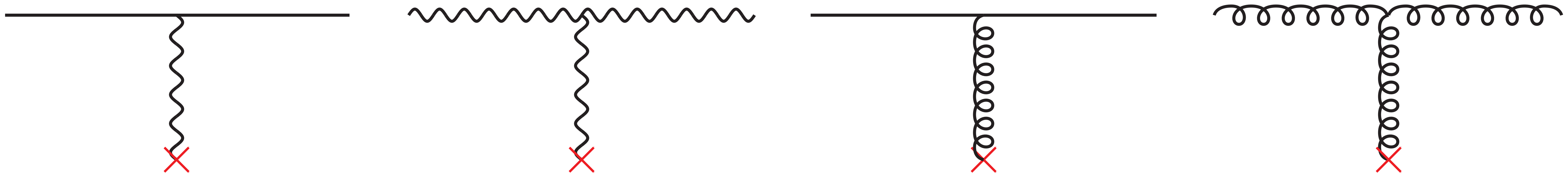


- need particle interactions

Thermalization in gauge theory

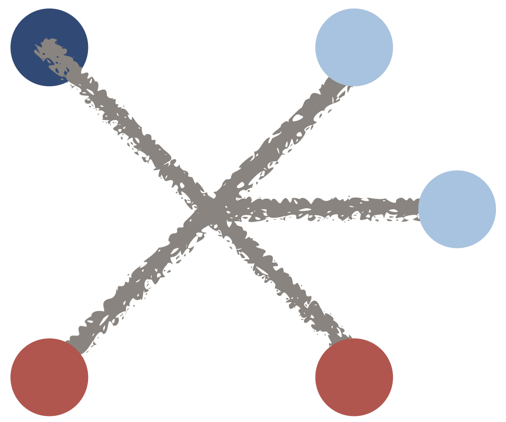
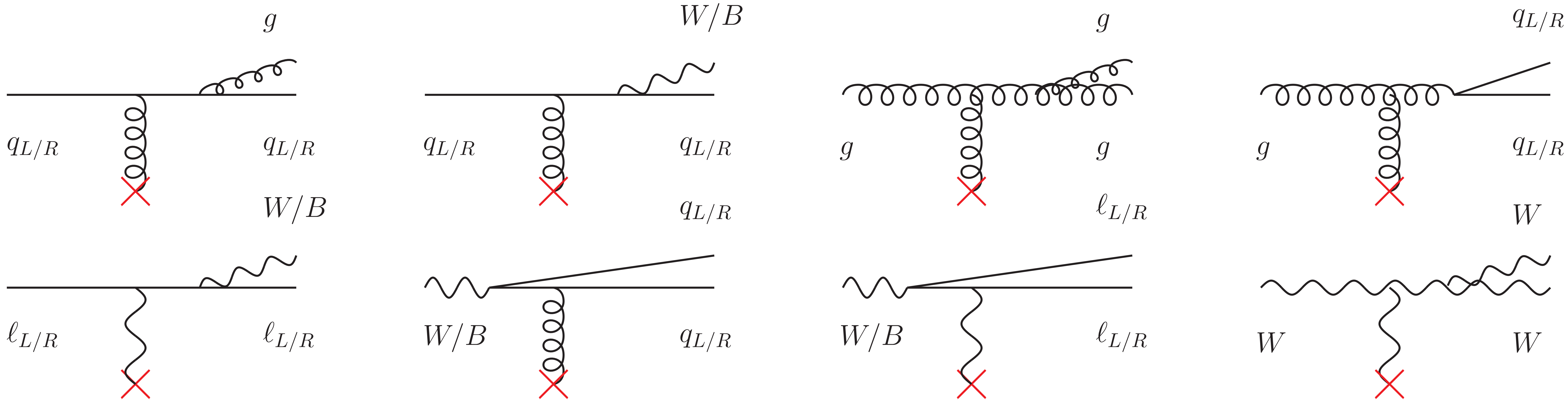
[Davidson & Sarkar 0009078 - Drees & Allahverdi 0205246]
[Kurkela & Moore 1107.5050 - Kurkela & Lu 1405.6318]

- TB particles provide large scattering target density

(1)  $\equiv$ 

- suppressed except forward t/u-channel gauge mediated process

$\sigma \sim \alpha^2/m_{\text{th}}^2 = \alpha/T^2$ $\quad \Delta p \sim \sqrt{\alpha}T \sim m_{\text{th}}$ $\quad dp/dt \sim \alpha^{3/2}T^2$

(2)  $\equiv$ 

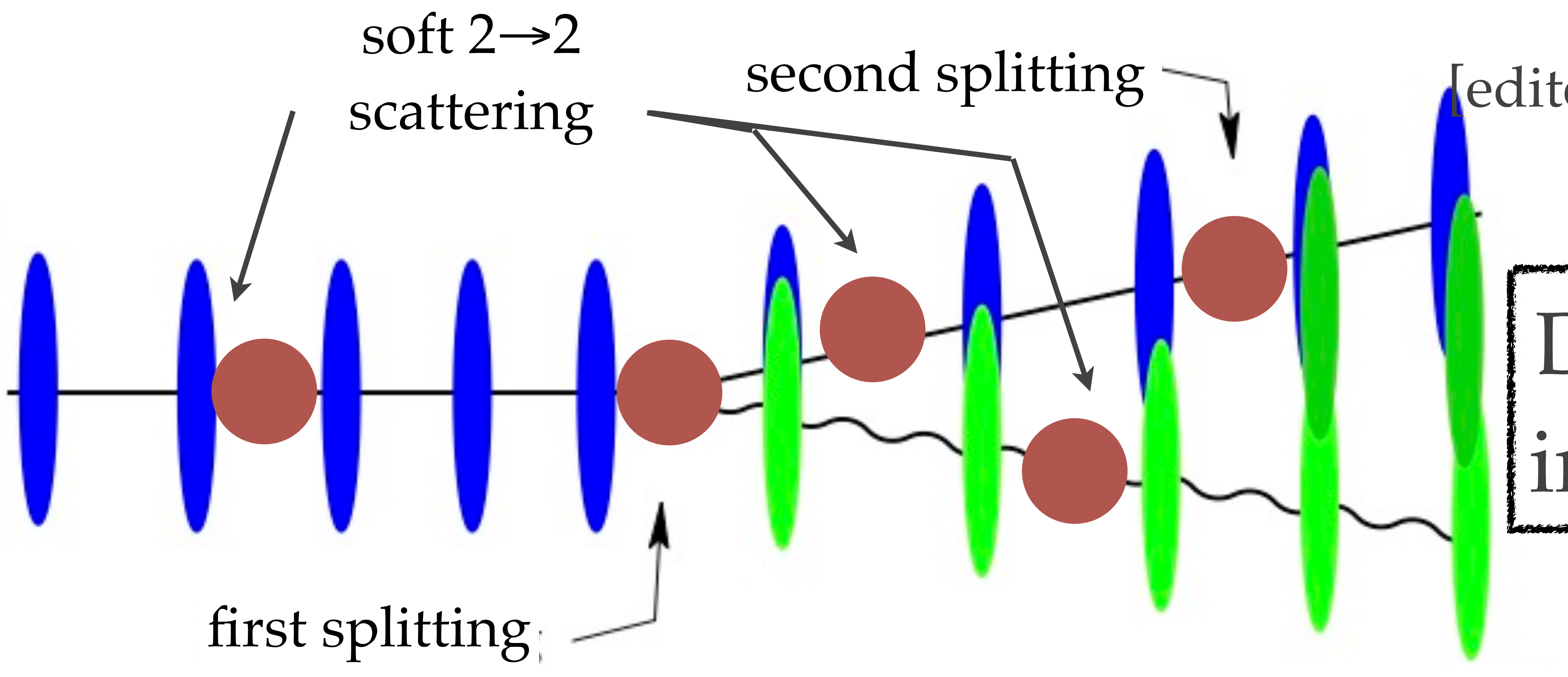
$\sigma \sim \alpha^3/m_{\text{th}}^2 = \alpha^2/T^2$ $\quad \Delta p \sim p/2$ $\quad dp/dt \sim \alpha^2 pT$

✓ +particle production

Thermalization & the LPM effect

[AMY hep-ph/0209353 - Arnold et al 0804.3359/ JHEP06(2002)030 / JHEP11(2001)057]

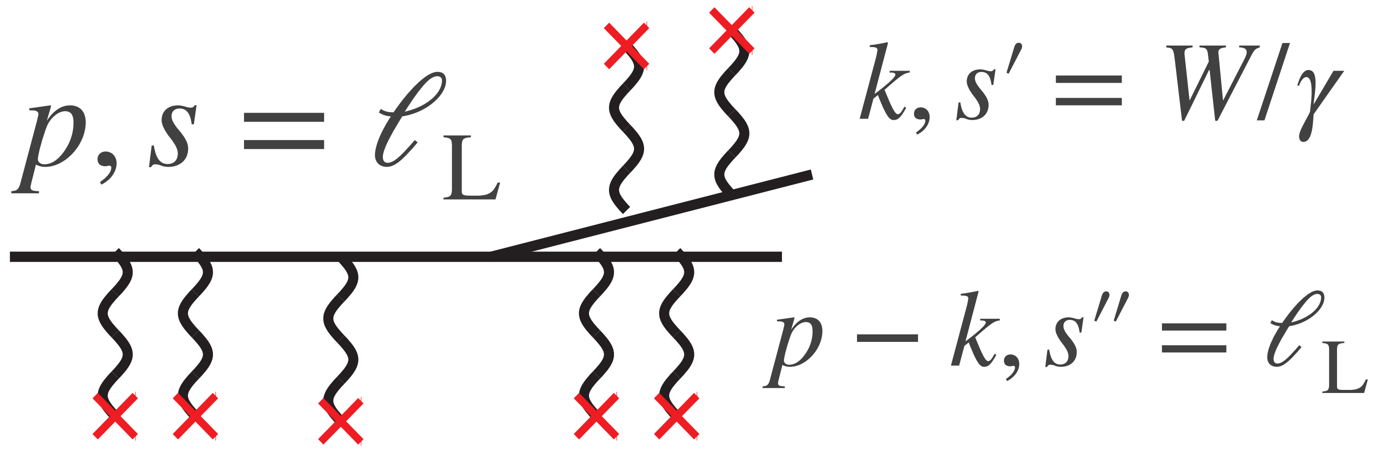
- collinearity of the 2→3 processes is boon & bane



[edited-hep-ph/0408347]

Destructive interference

$$R_{\rm LPM}(k) \propto \begin{cases} \sqrt{\dfrac{kT}{p^2}} & s' = \texttt{Abelian GB} \\ \sqrt{\dfrac{T}{\min(k, p-k)}} & \texttt{others} \end{cases}$$



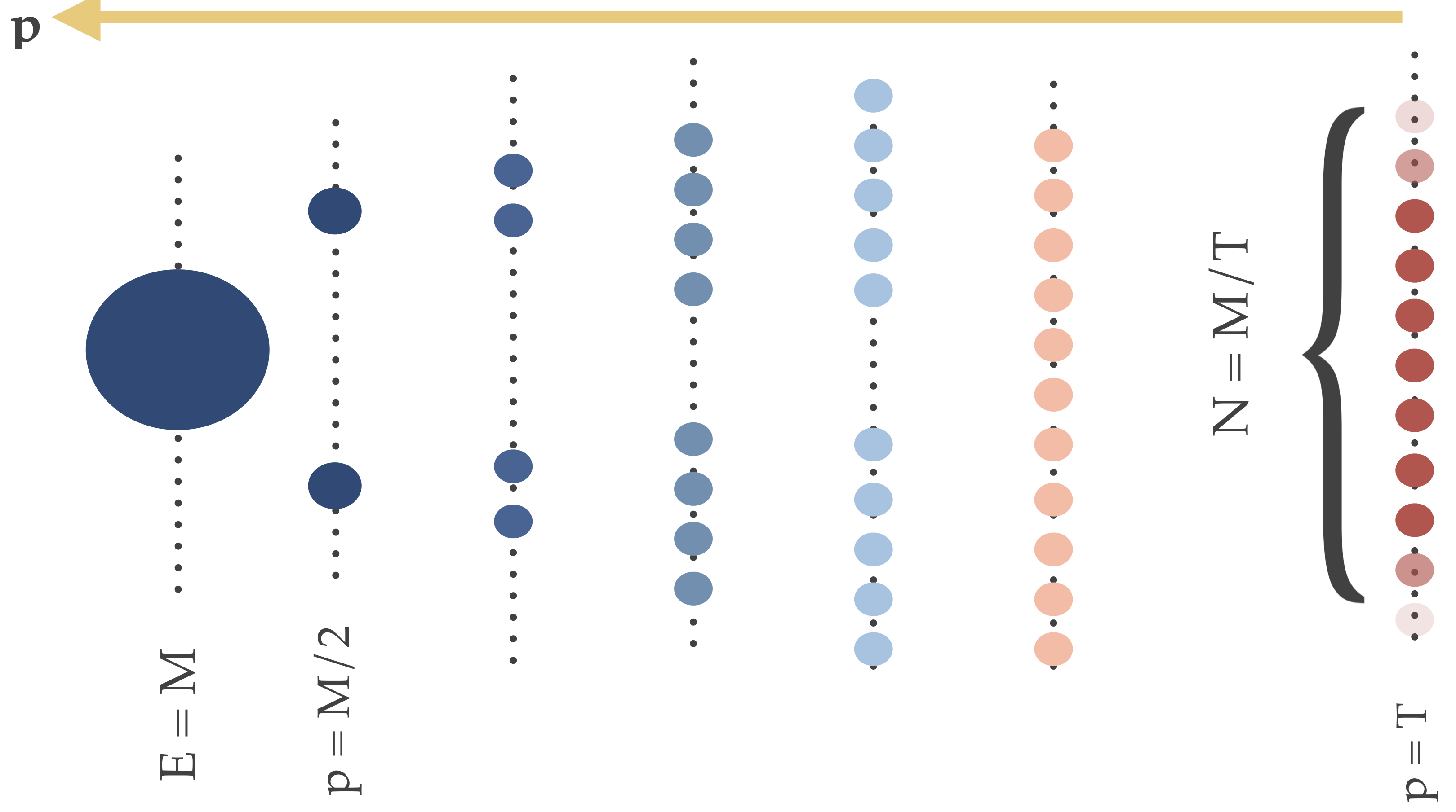
- the vacuum rate is dressed by a suppression factor

$$\frac{d\Gamma^{\rm split}_{\rm LPM}(s(p)\to s'(k)+s''(p-k))}{dk} = \underbrace{\frac{d\Gamma^{\rm split}_{\rm vac}(s(p)\to s'(k)+s''(p-k))}{dk}}_{\supset\ \textbf{DGLAP splitting functions}} \times R_{\rm LPM}$$

- extensively studied for QCD→ extend to include the chiral SM particles ✓

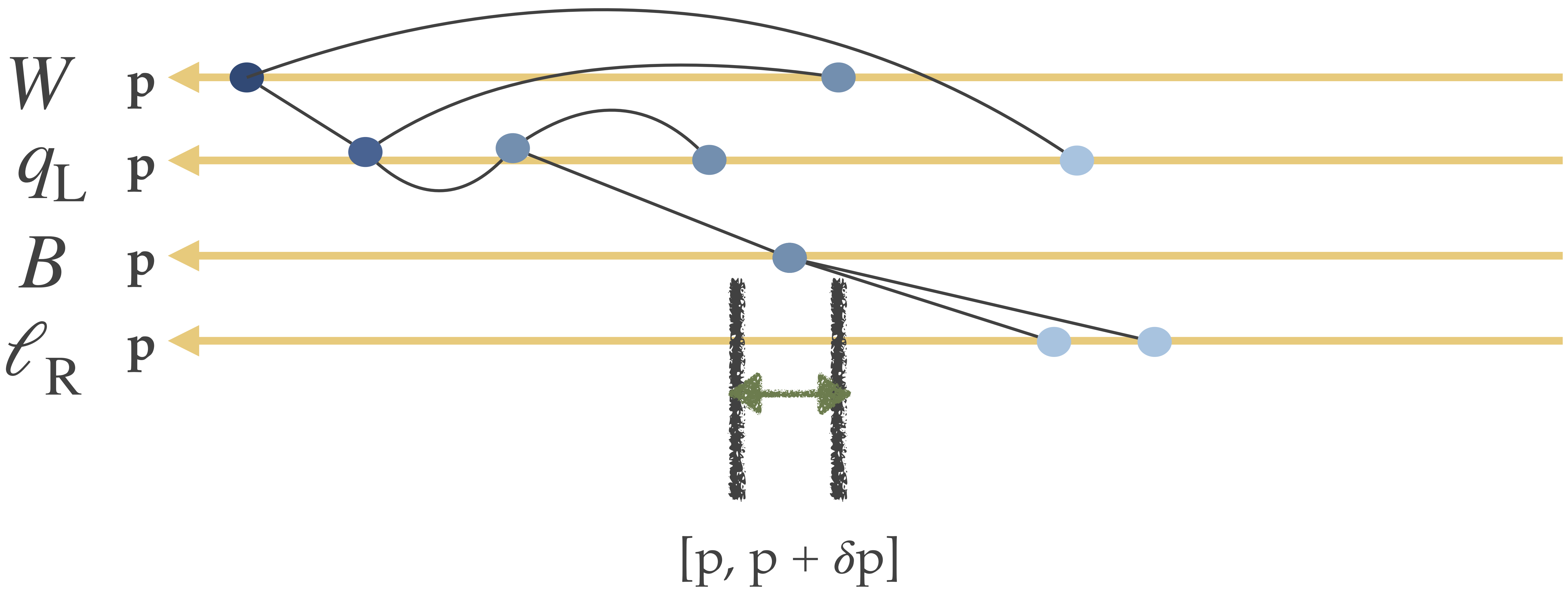
Boltzmann equation

- $\tilde{n}(p) \equiv dn(p)/dp$ given by detailed balance of species s of energy p



$$2n_{\rm M}\Gamma_{\rm M}Br_s \cdot \delta(p - M/2) + \sum_{s',s''}\int_{p+\kappa T}^{M/2} \tilde{n}_{s'}(k)\frac{d\Gamma^{\rm split}_{\rm LPM}(s'(k) \to s(p)s''(k-p))}{dp}dk$$

$$= \sum_{s',s''}\int_{\kappa T}^{p-\kappa T} \tilde{n}_s(p)\frac{d\Gamma^{\rm split}_{\rm LPM}(s(p) \to s'(k)s''(p-k))}{dk}dk$$

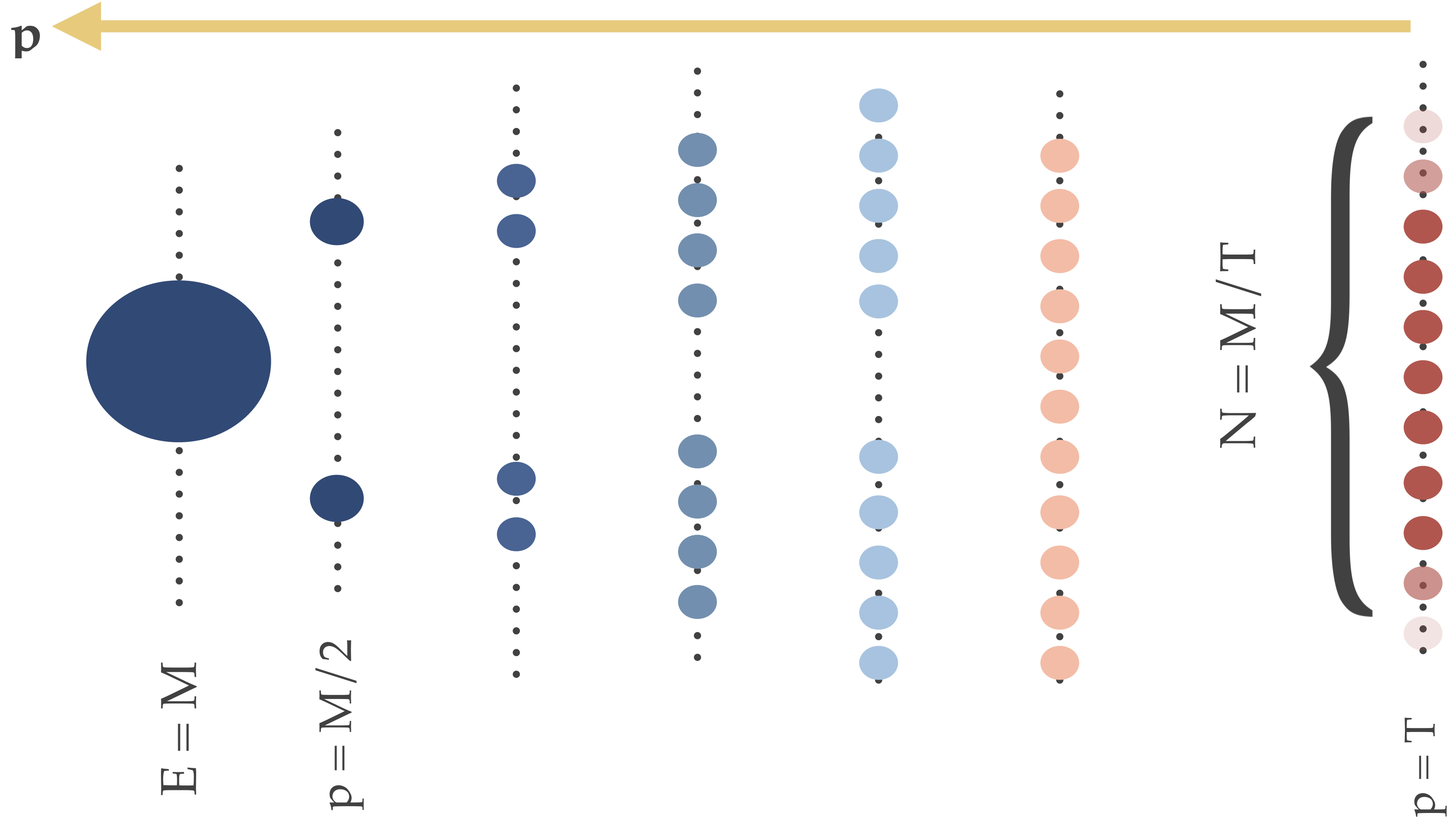


Balance:

- how often a species is produced

Boltzmann equation

- $\tilde{n}(p) \equiv dn(p)/dp$ given by detailed balance of species s of energy p



$$2 n_{\mathrm{M}} \Gamma_{\mathrm{M}} Br_s \cdot \delta(p - M/2) + \sum_{s',s''} \int_{p+\kappa T}^{M/2} \tilde{n}_{s'}(k) \frac{d\Gamma^{\mathrm{split}}_{\mathrm{LPM}}(s'(k) \to s(p) s''(k-p))}{dp} dk$$

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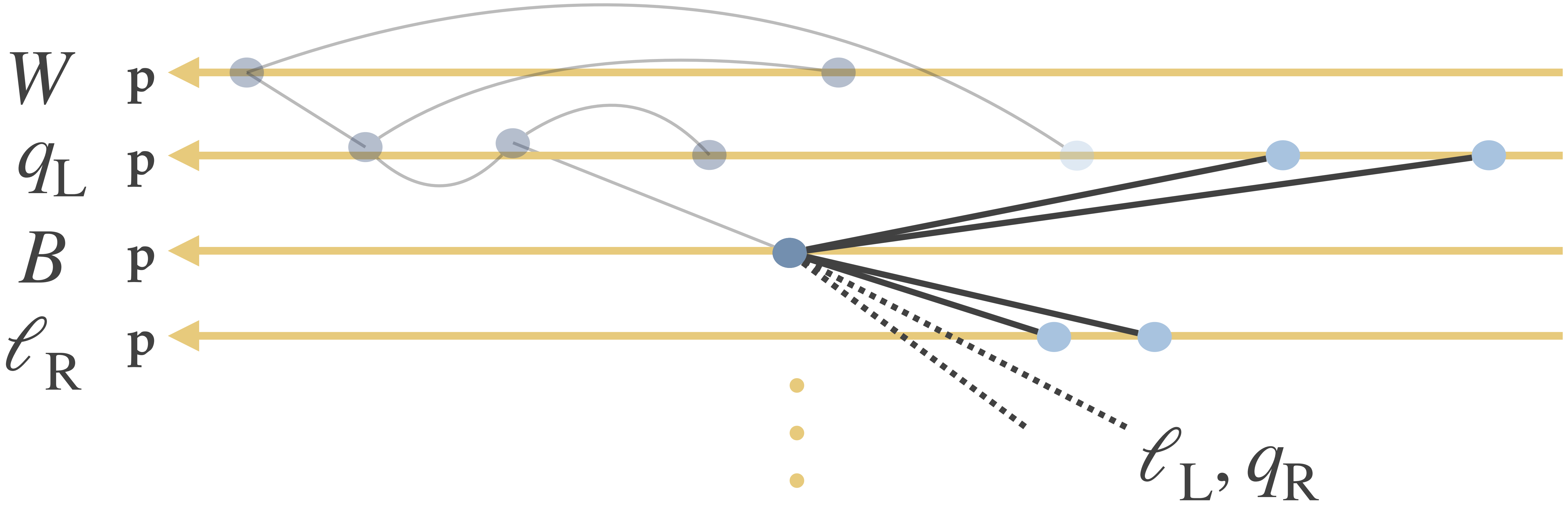


Balance:

- how often a species is produced
- how often it “splits away”

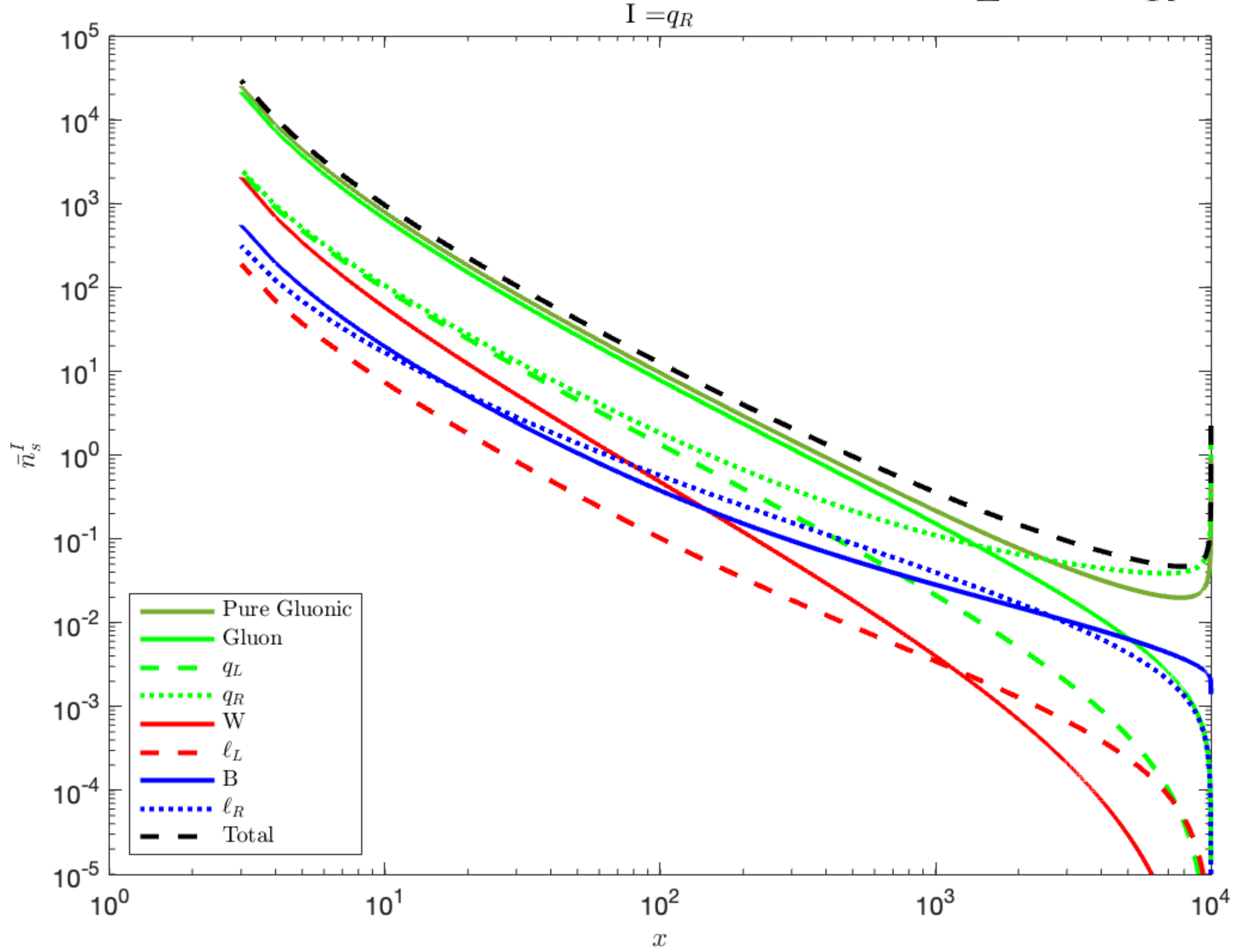
- thermal. for a single species e.g. gluons → previously in

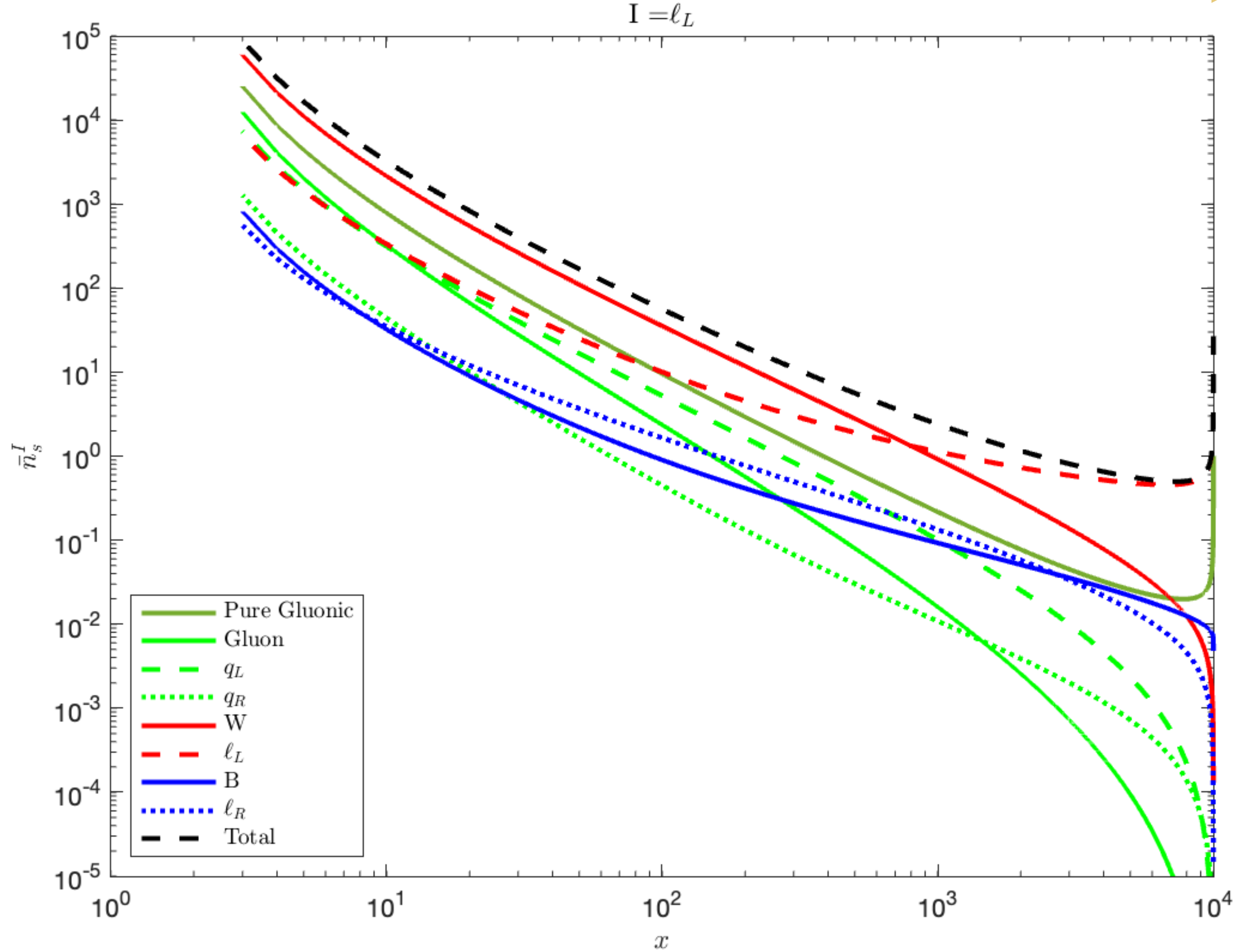
[Harigaya et al *JHEP* 05 (2014) 006 - *Phys.Rev.D* 89 (2014) 8 - Drees & BN JCAP 10 (2021) 009]

Spectra of SM particles

- disregard Higgs → $s \in \{q_L, q_R, \ell_L, \ell_R, g, W, B\}$
- go dimensionless: $x = p/T$ and $\tilde{N}^*_{\rm M} = \frac{2n_{\rm M}\Gamma_{\rm M}}{\Gamma^{\rm split}_{\rm LPM}(s^*, M/2)}$, $\bar{n}_s(x) = T\bar{n}_s(p) = T\frac{\tilde{n}_s(p)}{\tilde{N}^*_{\rm M}}$
- SU(3) - SU(2) - U(1) A (solid) F$_L$ (dashed) F$_R$ (dotted)

p →





Spectra of SM particles

- disregard Higgs → $s \in \{q_L,\, q_R,\, \ell_L,\, \ell_R,\, g,\, W,\, B\}$
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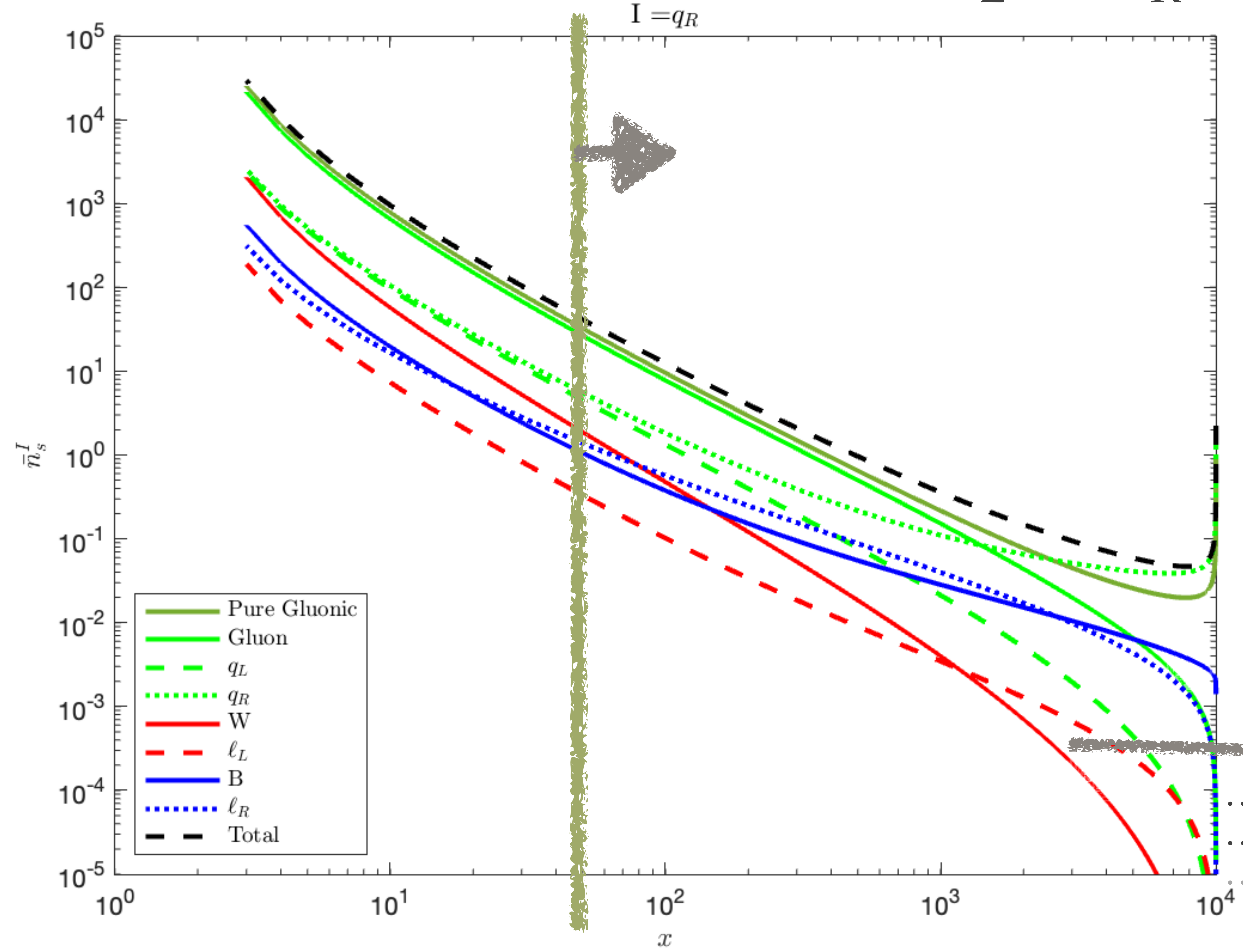
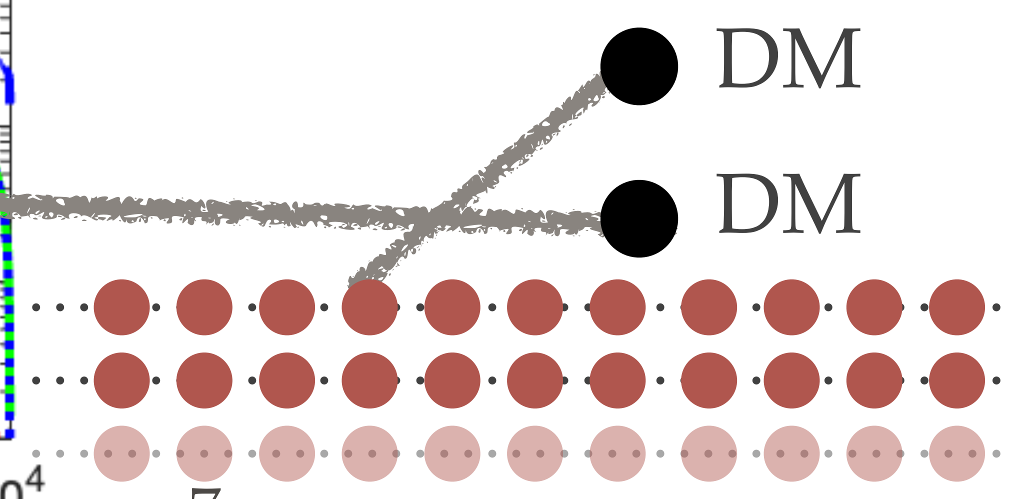
- SU(3) - SU(2) - U(1) A F$_{\mathrm{L}}$ F$_{\mathrm{R}}$



- semi-thermal and non-thermal production
- example: heavy leptophilic DM
- m_{DM} → energy threshold p_{Thr} → x_{Thr}

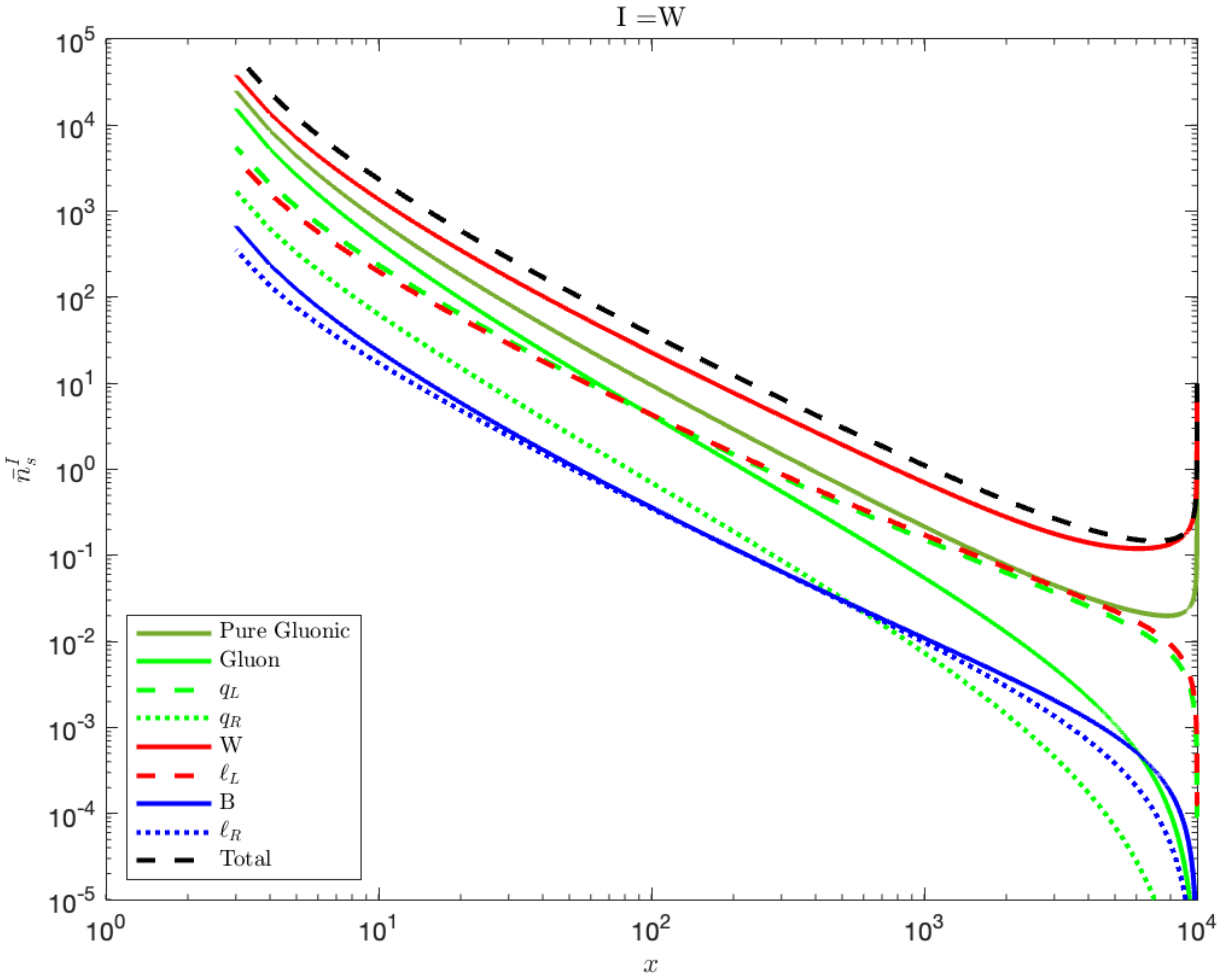
$$\frac{dn^{\mathrm{ST}}_\chi(T)}{dt} + 3Hn^{\mathrm{ST}}_\chi = \sum_{s,\, s'} \int n_{s'}(T)\,\langle\sigma^{\mathrm{ST}}_\chi v\rangle(p,T)\,\tilde{n}_s(p,T)\,dp$$

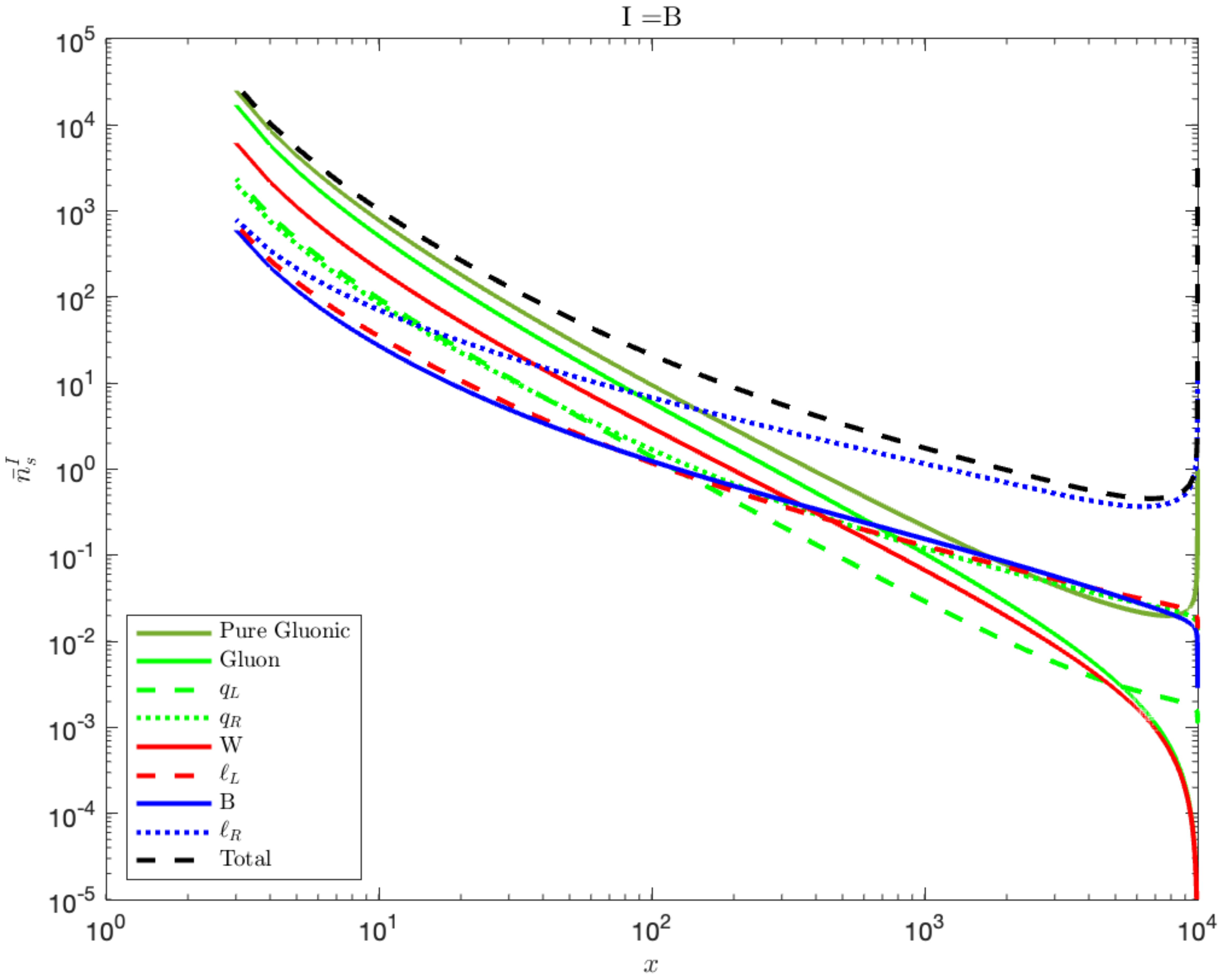


Summary and outlook

- non-equilibrium matter components abundant in cosmology
- matter particles decay to radiation with $p >> T \rightarrow$ thermalization
- thermalization proceeds via LPM suppressed splittings $2 \rightarrow 3$
- coupled set of integral equations needs to be solved numerically
- plasma flows towards a QGP BUT spectra show Large deviations
- **spectra can be used for various calculations: DM + RH neutrinos +…**
- looking ahead: showering matter decays - include Higgs & SUSY particles in thermalization cascade

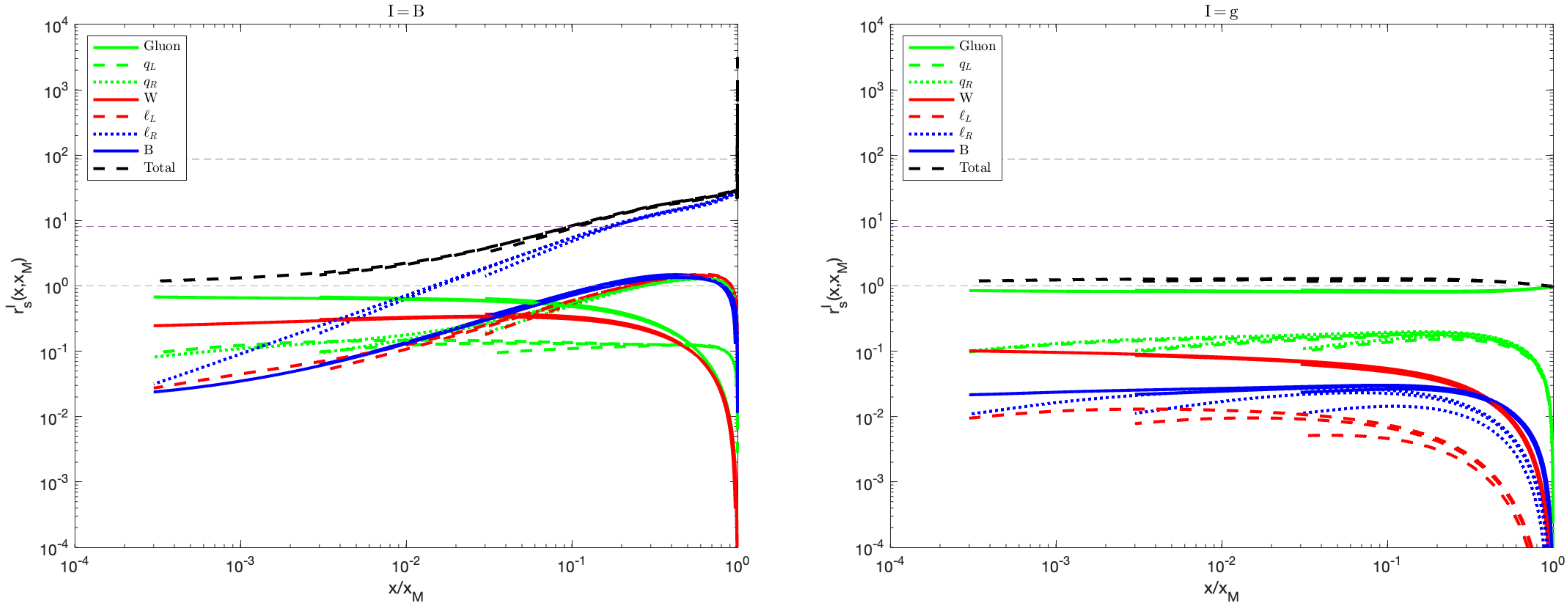
Gauge boson injection





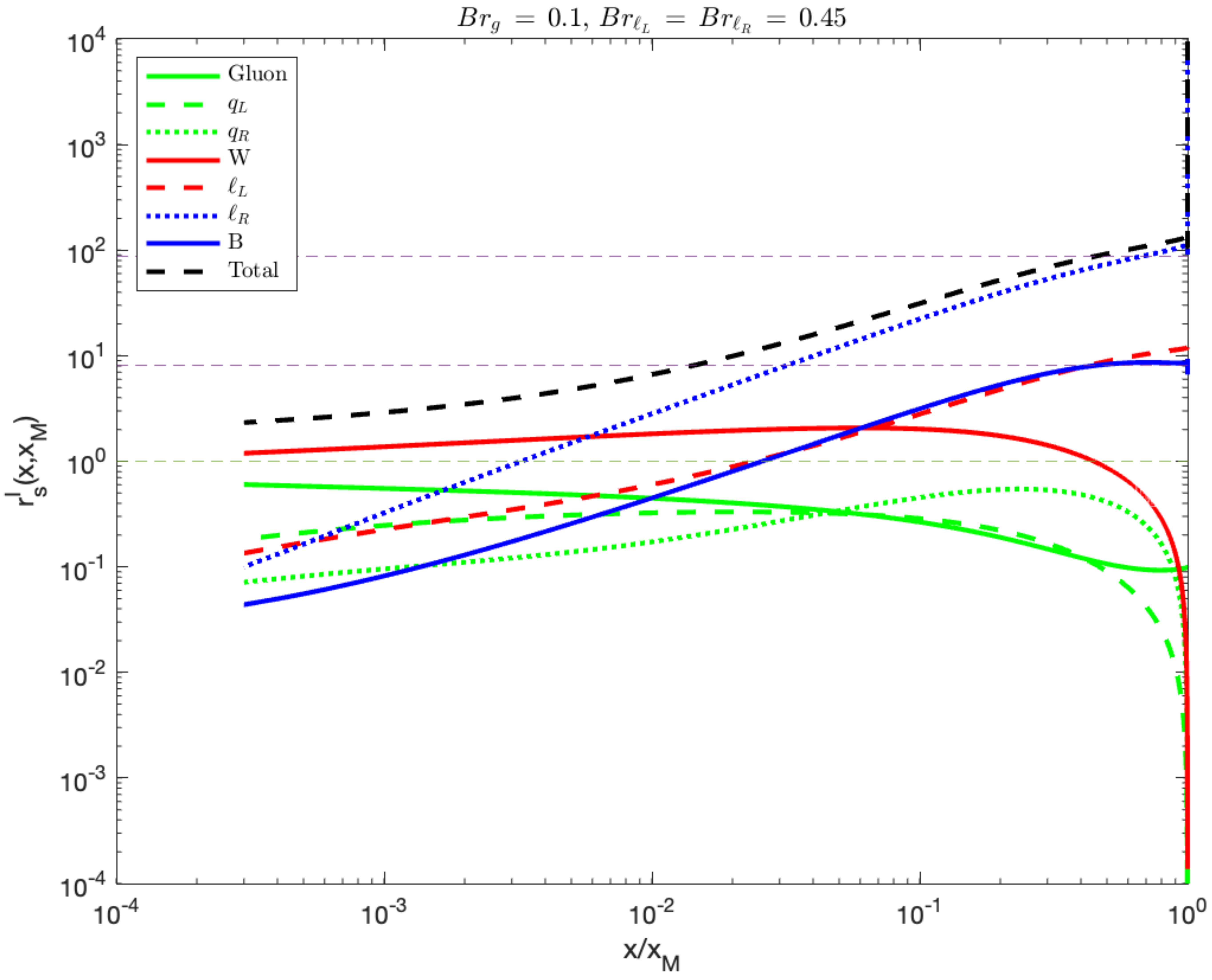
M/T and Scaling behavior

$$r^{\mathrm{I}}_s(x, x_{\mathrm{M}}) = \frac{\bar{n}^I_s(x, x_{\mathrm{M}})}{\bar{n}^g_{gg}(x, x_{\mathrm{M}})}$$



Generic branching – linearity of Boltzmann system

$$\bar{n}_s(x, x_{\mathrm{M}}) = \sum_{I \in \mathbb{S}} Br_{\mathrm{I}} \bar{n}_s^{\mathrm{I}}(x, x_{\mathrm{M}})$$

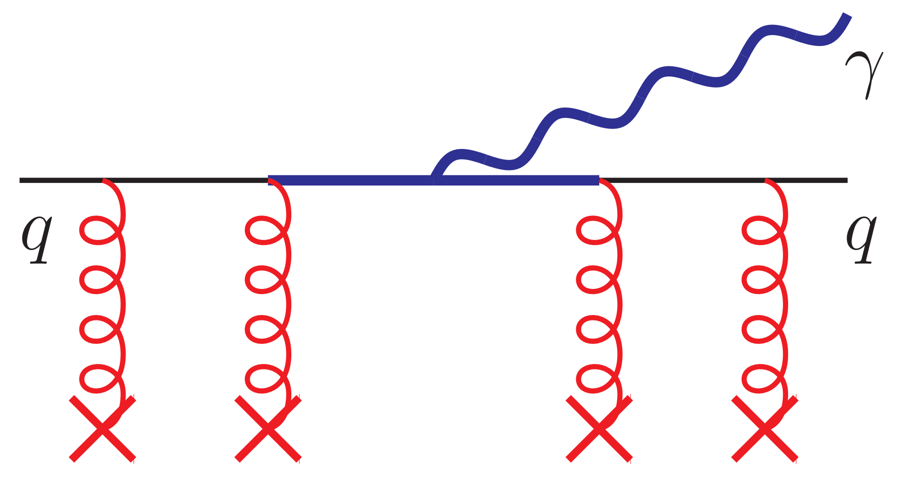


LPM suppressed rates

$$\frac{d\Gamma^{\rm split}_{\rm LPM}\left(s(p)\to s'(k)+s''(p-k)\right)}{dy}=\frac{(2\pi)^3}{p\nu_s^G}\gamma_{s\to s's''}\left(p,yp,(1-y)p\right)\qquad m^2_{G,{\rm th}}=\frac{1}{3}g_G^2T^2\left(C_A^G+\sum_f\frac{d_f}{d_A}N_fC_F^G\right)$$

$$\gamma_{A\to AA}(p;yp,(1-y)p)=\frac{d_A^{G'}C_A^{G'}\alpha_{G'}}{(2\pi)^4\sqrt{2}}\frac{1+y^4+(1-y)^4}{y^2(1-y)^2}\cdot\left[m^2_{\rm th}\,\hat\mu^2_\perp(1,y,1{-}y;A,A,A)\right]_G\,;$$

$$\gamma_{F\to AF}(p;yp,(1-y)p)=\frac{d_F^{G'}C_F^{G'}\alpha_{G'}}{(2\pi)^4\sqrt{2}}\frac{1+(1-y)^2}{y^2(1-y)}\cdot\left[m^2_{\rm th}\,\hat\mu^2_\perp(1,y,1{-}y;F,A,F)\right]_G\,;$$



$$\gamma_{A\to FF}(p;yp,(1-y)p)=\frac{d_F^{G'}C_F^{G'}\alpha_{G'}}{(2\pi)^4\sqrt{2}}\frac{y^2+(1-y)^2}{y(1-y)}\times N_{fl}\cdot\left[m^2_{\rm th}\,\hat\mu^2_\perp(1,y,1{-}y;A,F,F)\right]_G\,.$$

$$\hat\mu^2_\perp\left(y_1,y_2,y_3;s_1,s_2,s_3\right)\simeq\frac{g_GT}{m_{G,{\rm th}}}\left[\frac{2}{\pi}y_1y_2y_3\frac{p}{T}\right]^{1/2}\left\{\left[\frac{1}{2}\left(C_{s_2}+C_{s_3}-C_{s_1}\right)y_1^2+\frac{1}{2}\left(C_{s_3}+C_{s_1}-C_{s_2}\right)y_2^2+\frac{1}{2}\left(C_{s_1}+C_{s_2}-C_{s_3}\right)y_3^2\right]\ln(\sqrt{p/T})\right\}^{1/2}$$

LPM suppressed rates

for SU(N) $C_F = \left(N^2 - 1\right)/2N, \quad C_A = N, \quad d_F = N, \quad d_A = N^2 - 1$

while for U(1) $C_F^s = Y_s^2, \quad C_A = 0, \quad d_F = 1, \quad d_A = 1$

$$\gamma_{A\to AA}(p;yp,(1-y)p) = \frac{d_A^{G'} C_A^{G'} \alpha_{G'}}{(2\pi)^4\sqrt{2}} \frac{1+y^4+(1-y)^4}{y^2(1-y)^2} \cdot \left[m_{\rm th}^2\, \hat{\mu}_\perp^2(1,y,1{-}y;A,A,A)\right]_G ;$$

$$\gamma_{F\to AF}(p;yp,(1-y)p) = \frac{d_F^{G'} C_F^{G'} \alpha_{G'}}{(2\pi)^4\sqrt{2}} \frac{1+(1-y)^2}{y^2(1-y)} \cdot \left[m_{\rm th}^2\, \hat{\mu}_\perp^2(1,y,1{-}y;F,A,F)\right]_G ;$$

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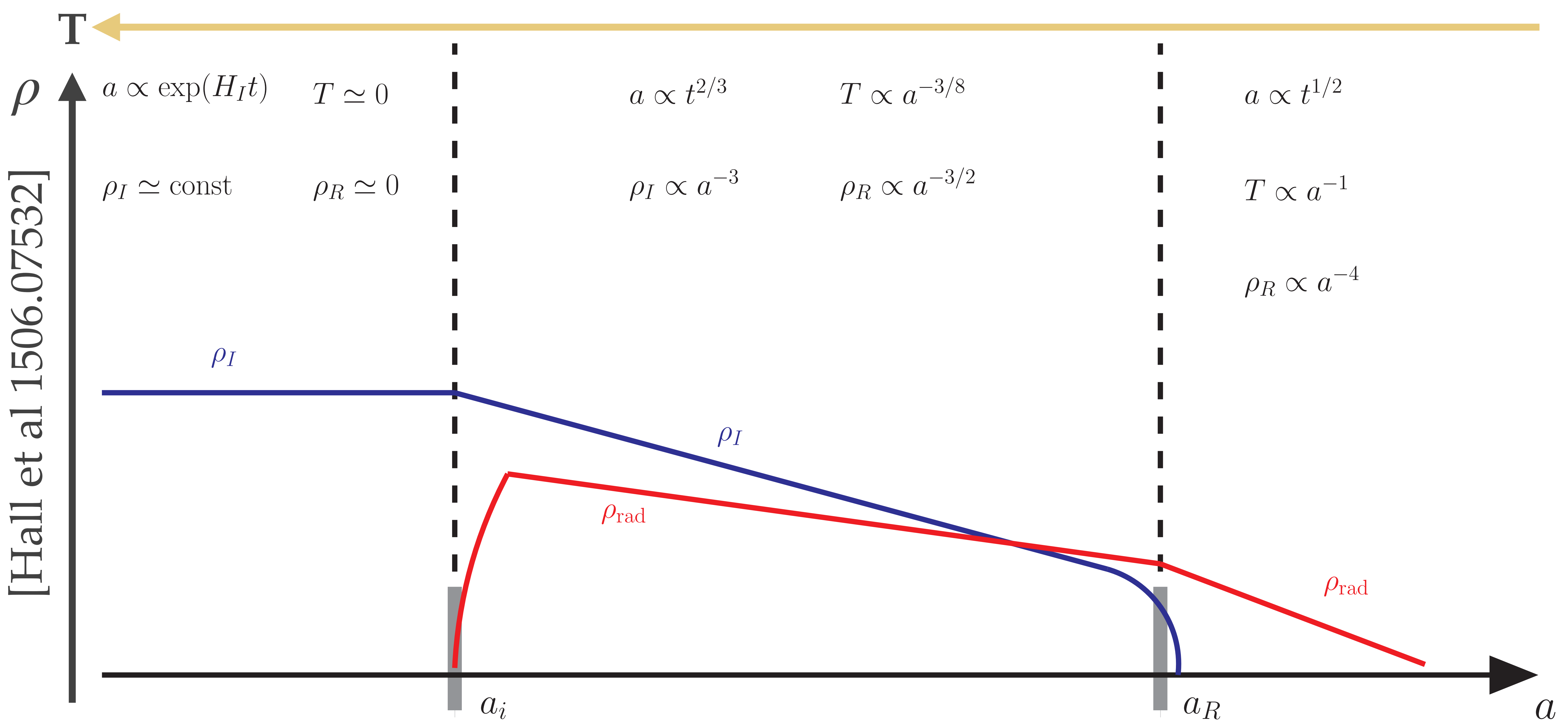
$$\hat{\mu}_\perp^2\left(y_1,y_2,y_3;s_1,s_2,s_3\right) \simeq \frac{g_G T}{m_{G,\rm th}}\left[\frac{2}{\pi}y_1y_2y_3\frac{p}{T}\right]^{1/2}\left\{\left[\frac{1}{2}\left(C_{s_2}+C_{s_3}-C_{s_1}\right)y_1^2+\frac{1}{2}\left(C_{s_3}+C_{s_1}-C_{s_2}\right)y_2^2+\frac{1}{2}\left(C_{s_1}+C_{s_2}-C_{s_3}\right)y_3^2\right]\ln(\sqrt{p/T})\right\}^{1/2}$$

Evolution after infation

- inflationary MD era reheats to an RD universe



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