

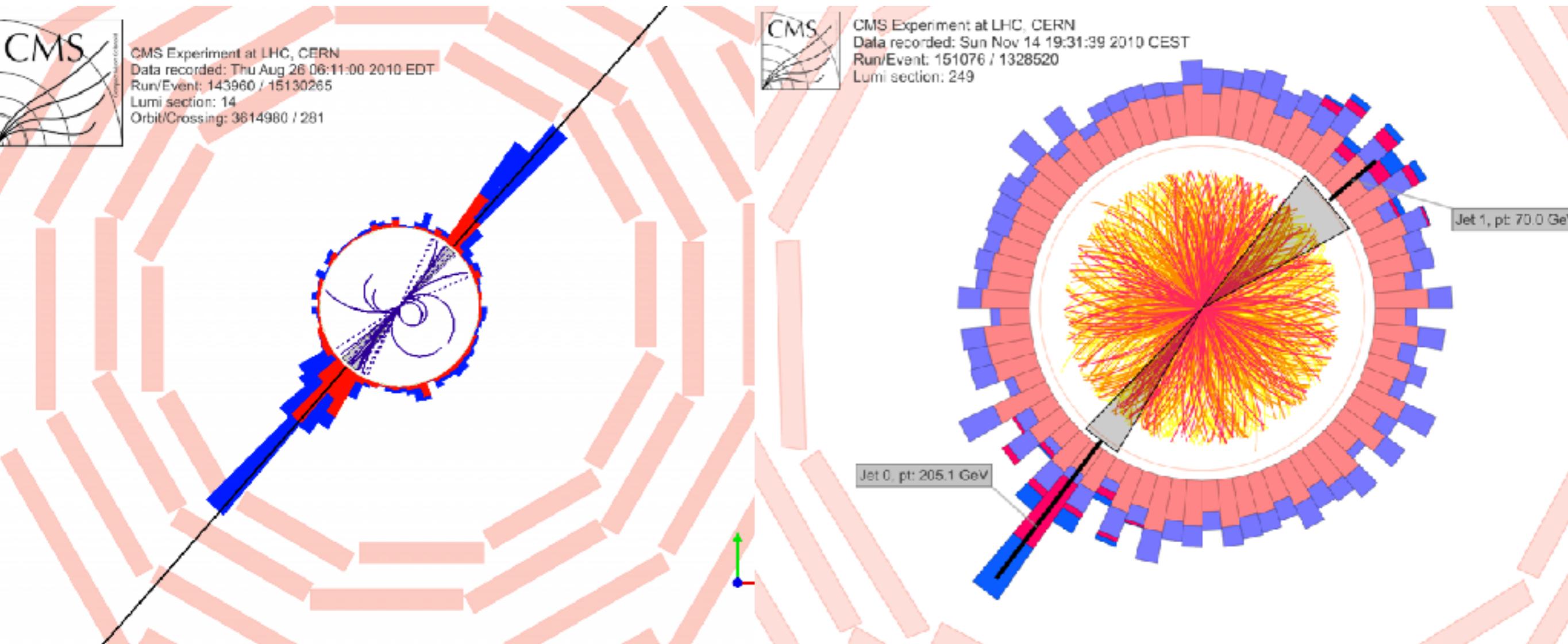


TOWARD A UNIFIED DESCRIPTION OF JET AND MEDIUM SCALES IN HEAVY-ION COLLISIONS

Konrad Tywoniuk

XIIIth Quark Confinement and the Hadron Spectrum, Maynooth, 31 Jul - 5 Aug 2018

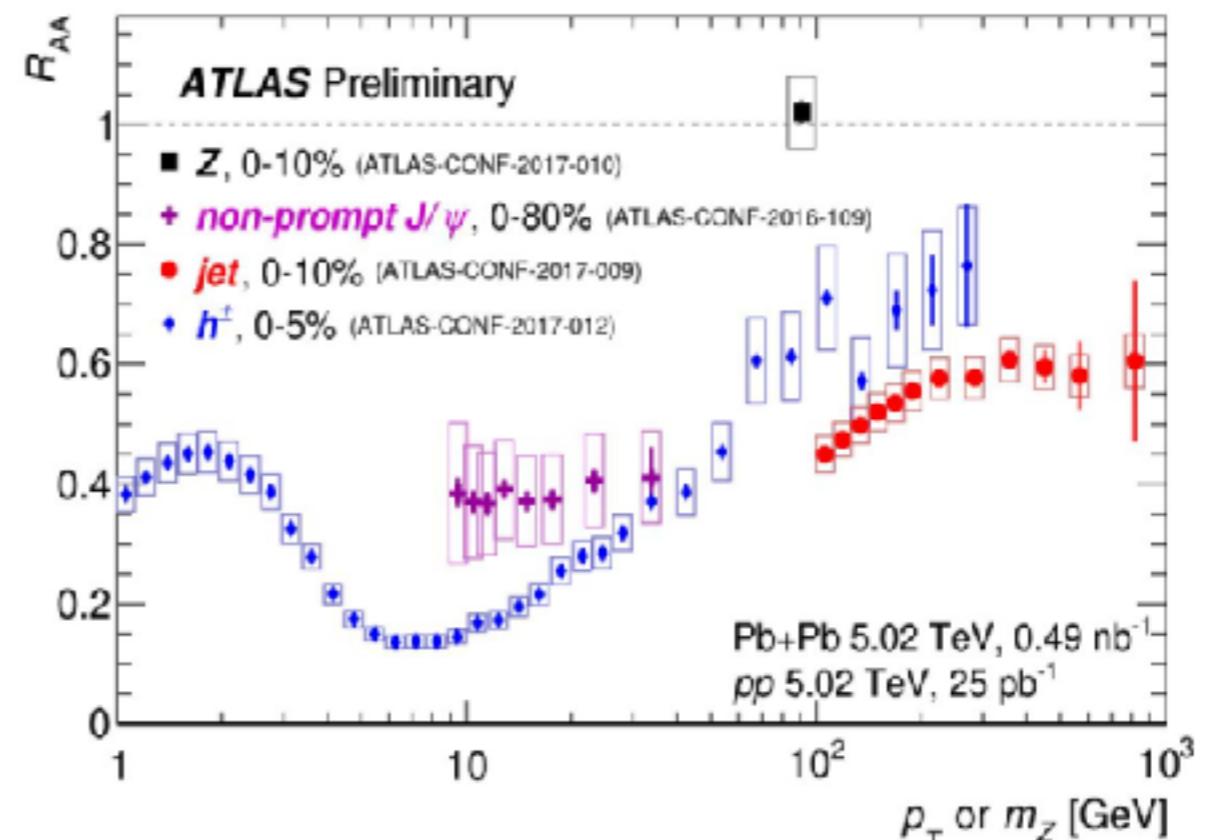
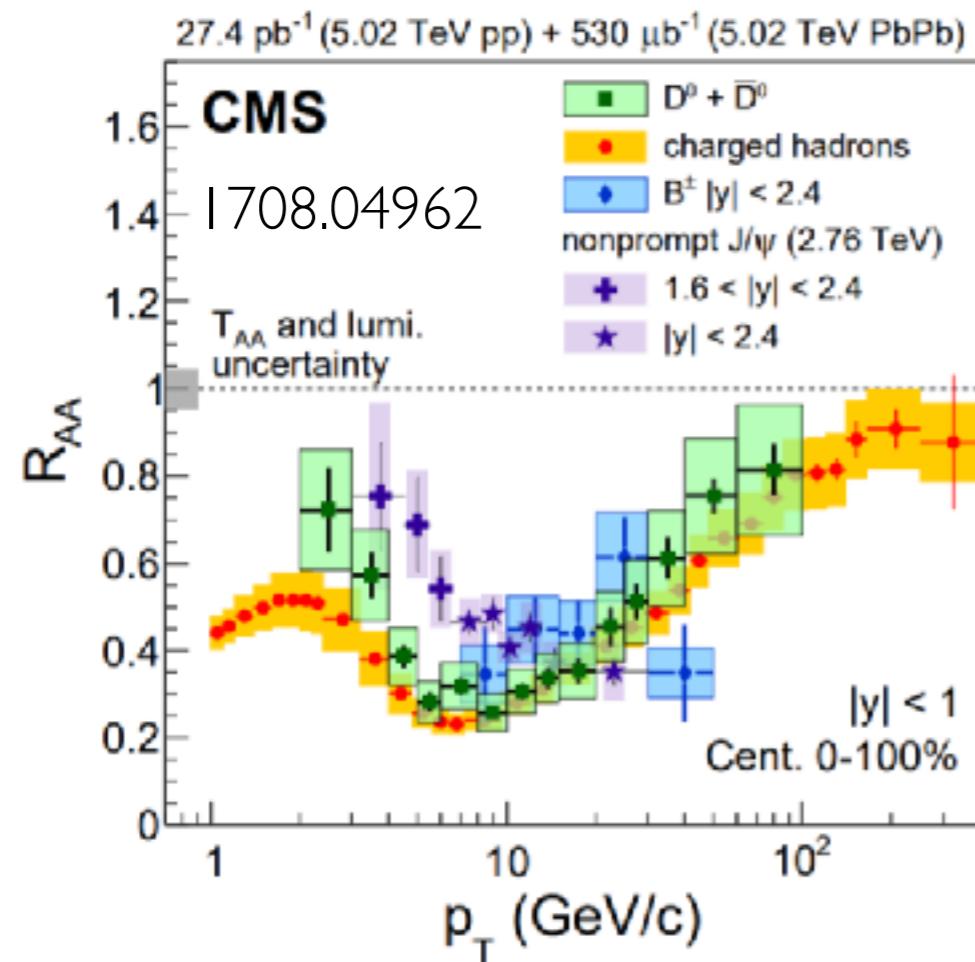
WHAT DO JETS LOOK LIKE?



proton-proton
two-jet event

heavy-ion
two-jet event

JET QUENCHING 101



- reduction of yields of hadrons & jets over a large range in p_T
- substructure modifications: broadening & softening
 - enhancement of soft & large-angle particles

MOTIVATION

- many experimental results & successful model implementations
- modeling jet quenching phenomena realistically involves “multi-stage” Monte Carlo approach
 - vacuum showering
 - medium modifications (interactions)
 - (modified) hadronization
- theoretical guidance at high- p_T ?
 - what's the role of modeling of medium vs phase space?

RADIATION IN THE MEDIUM

Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000); Zakharov (1996); Arnold, Moore, Yaffe (2002)

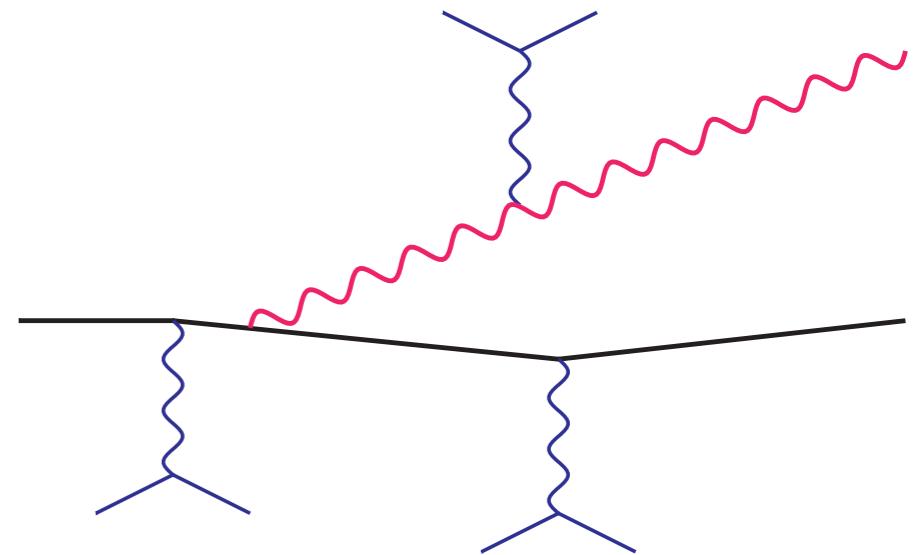
momentum broadening

$$\langle k_{\perp}^2 \rangle \sim \hat{q}t$$

modified splitting kinematics

lack of collinear singularity!

$$t_f = \frac{\omega}{k_{\perp}^2} \sim \sqrt{\frac{\omega}{\hat{q}}}$$



$$\omega \frac{dI}{d\omega} = \frac{\alpha_s C_R}{\pi} \frac{L}{t_f} = \frac{\alpha_s C_R}{\pi} \sqrt{\frac{\hat{q} L^2}{\omega}}$$

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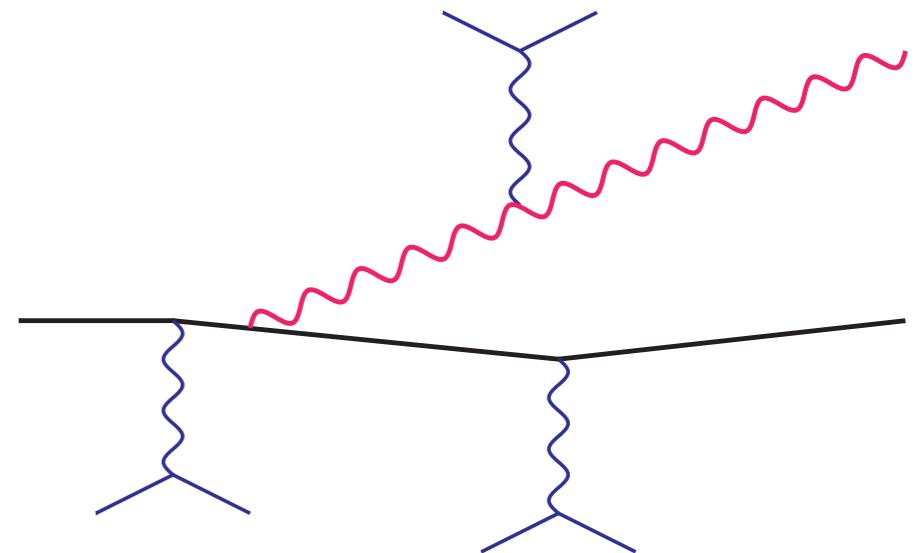
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rare, small-angle emission

$$\omega_c = \hat{q} L^2$$

$$\theta_{\text{br}}(\omega_c) \sim \sqrt{\frac{1}{\hat{q} L^3}} \equiv \theta_c$$

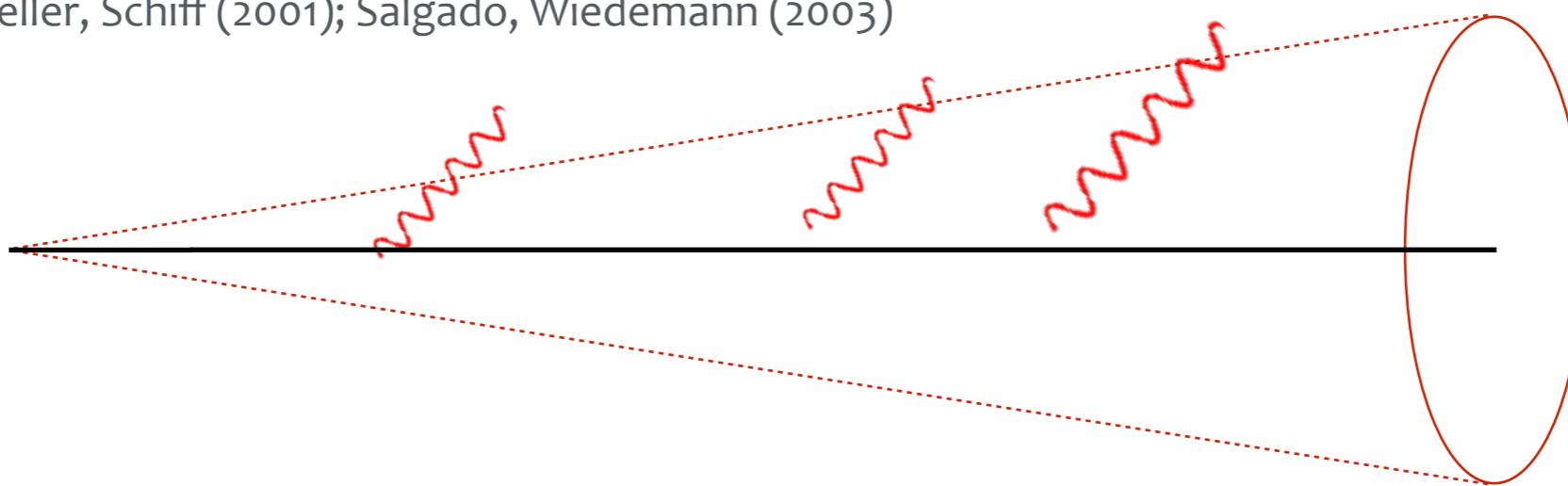
copious, large-angle emissions

$$\omega_s = \bar{\alpha}^2 \hat{q} L^2$$

$$\theta_{\text{br}}(\omega_s) \sim \frac{1}{\bar{\alpha}^{3/2}} \theta_c$$

QUENCHING WEIGHTS PARADIGM

Baier, Dokshitzer, Mueller, Schiff (2001); Salgado, Wiedemann (2003)



- number of radiated gluons become large: resummation
 - energy loss probability (quenching weight)
 - gluons carried to large angles & thermalized rapidly
- generically: QW for any energy loss
- no *a priori* dependence on jet scales

Strong quenching: energy loss dominated by *typical* emitted energy

$$\mathcal{P}(\epsilon) = \sqrt{\frac{\omega_s}{\epsilon^3}} e^{-\frac{\pi \omega_s}{\epsilon}} \quad \omega_s \sim \alpha_s^2 C_R^2 \hat{q} L^2$$

JET SPECTRUM IN HEAVY-ION COLLISIONS

quenching weight: probability distribution of losing energy

$$\frac{d\sigma_{\text{med}}}{dp_T^2 dy} = \int_0^\infty d\epsilon \mathcal{P}(\epsilon) \frac{d\sigma_{\text{vac}}(p_T + \epsilon)}{dp_T^2 dy}$$

quenching factor = nuclear modification factor

$$R_{\text{jet}} = \left(\frac{d\sigma_{\text{med}}}{dp_T^2 dy} \right) / \left(\frac{d\sigma_{\text{vac}}}{dp_T^2 dy} \right)$$

For $\epsilon/p_T \ll 1$ and large n : $\frac{1}{(p_T + \epsilon)^2} \approx \frac{1}{p_T^n} e^{-\epsilon n/p_T}$

$$R_{\text{jet}} \sim \tilde{\mathcal{P}}(n/p_T) \equiv \mathcal{Q}(p_T)$$

quenching factor is Laplace transform of energy loss probability

QUENCHING FACTOR FOR PARTON

$$\mathcal{Q}(p_T) = e^{-2\bar{\alpha}L\sqrt{n\pi\hat{q}/p_T}} \quad \bar{\alpha} = \frac{\alpha_s C_R}{\pi}$$

$$\mathcal{Q}_g(p_T) = (\mathcal{Q}_q(p_T))^{N_c/C_F}$$

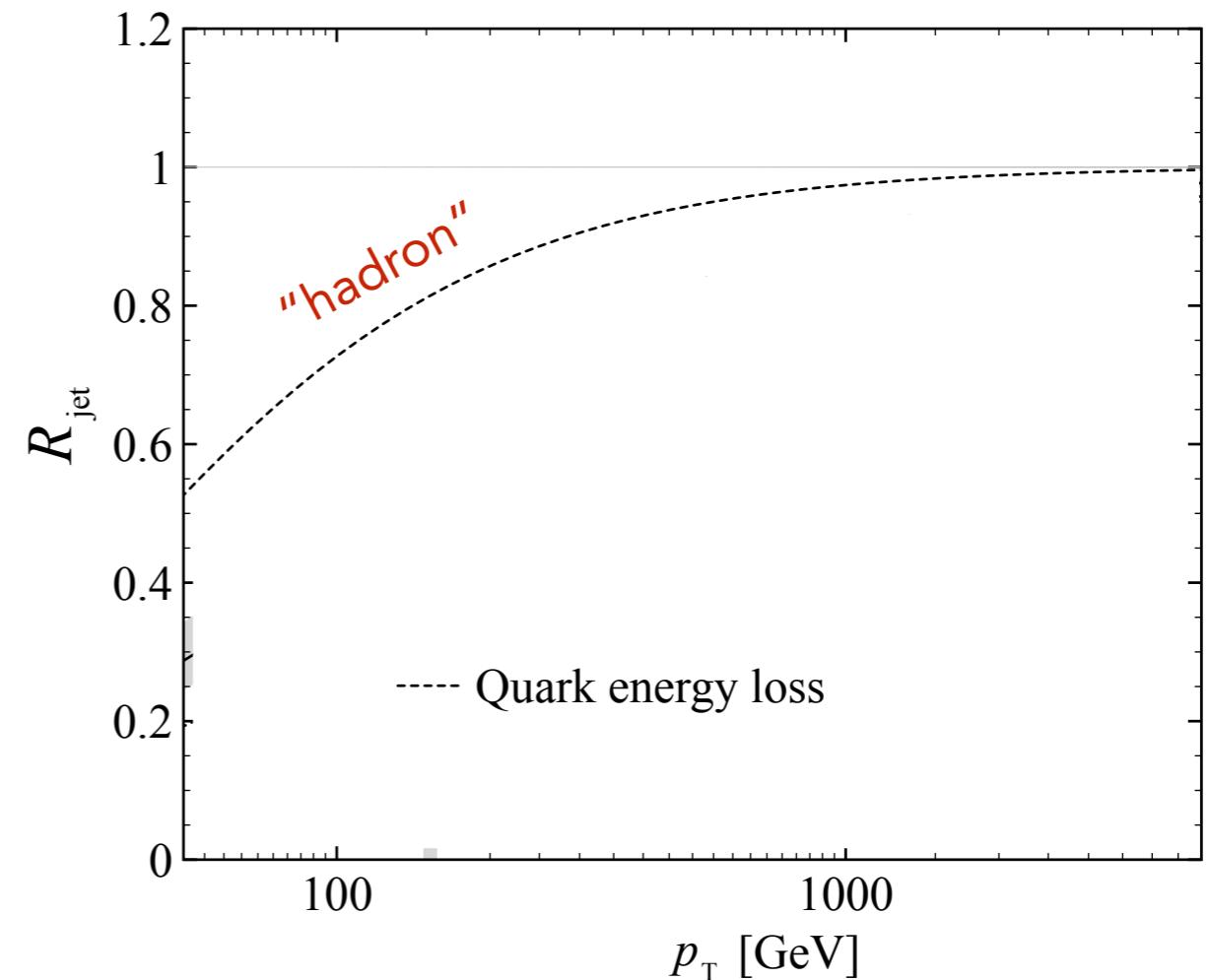
- form factor suppression related to multiplicity of virtual gluons

$$\mathcal{Q}(p_T) \sim e^{-N(\omega>p_T/n)}$$

- strong quenching for

$$p_T \ll n\bar{\alpha}^2\hat{q}L^2$$

- improvements: kinematics, spectra....



WHAT ARE THE HIGHER-ORDER CORRECTIONS TO THIS PICTURE?

When does the QW paradigm break down?

RADIATIVE CORRECTIONS

$$\frac{d\sigma}{dydp_T^2} = \frac{d\sigma_{\text{Born}}}{dydp_T^2} \left[1 + \alpha_s \left(\int d\Pi_{\text{real}} - \int d\Pi_{\text{virt}} \right) + \mathcal{O}(\alpha_s^2) \right]$$

- higher-order corrections not enhanced by phase space when balance between **real** & **virtual** emissions
 - for sufficiently inclusive observables
 - is this the case in the medium?

RADIATIVE CORRECTIONS

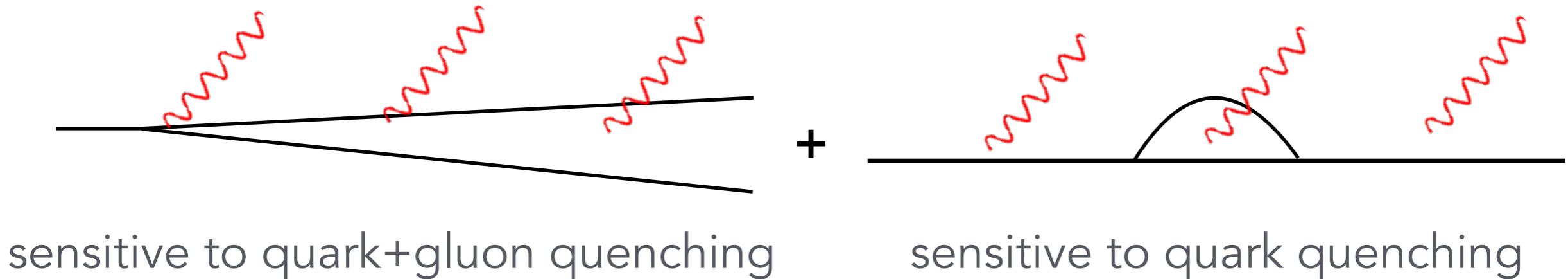
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- higher-order corrections not enhanced by phase space when balance between **real** & **virtual** emissions
 - for sufficiently inclusive observables
 - is this the case in the medium?

$$R_{\text{jet}} = Q^{(0)}(p_T) + Q^{(1)}(p_T) + \mathcal{O}(\alpha_s^2)$$

- expanding quenching factor corresponds to accounting for the quenching of higher-order emissions (substructure fluctuations)

FIRST CORRECTION TO QUENCHING



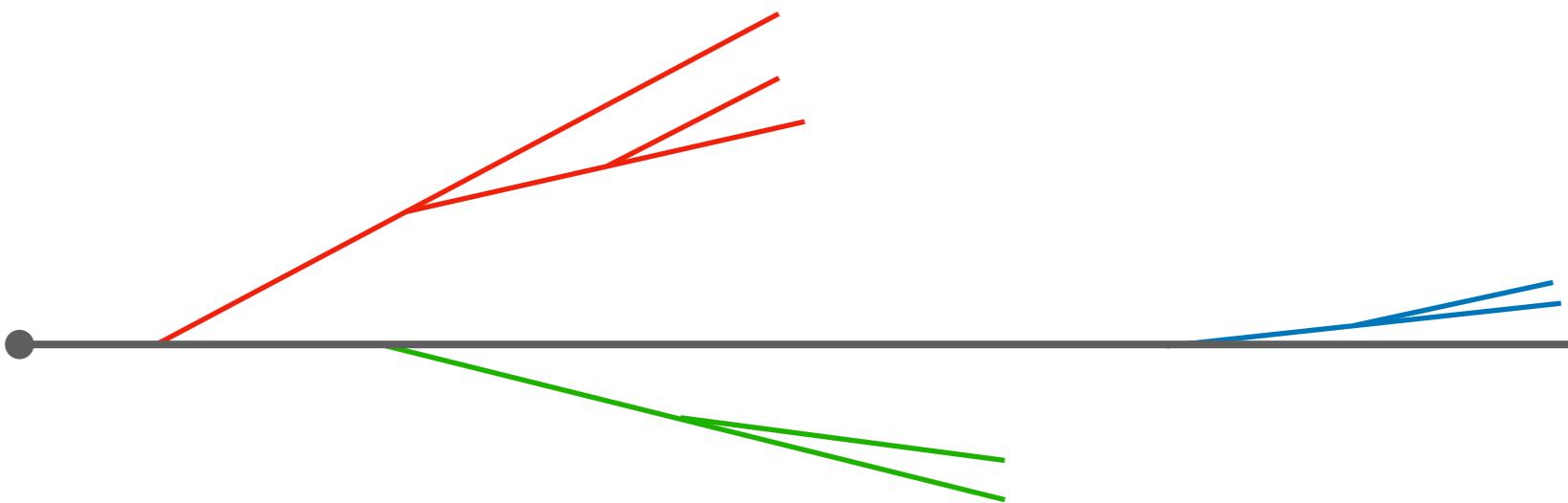
$$\mathcal{Q}^{(1)}(p_T) = \int_0^1 dz P_{gq}(z) \int_0^R \frac{d\theta}{\theta} \frac{\alpha_s(k_\perp)}{\pi} [\mathcal{Q}_{gq}(p_T) - \mathcal{Q}_q(p_T)]$$

$$\mathcal{Q}_{gq}(p_T) = \mathcal{Q}_q(p_T) \mathcal{Q}_{\text{sing}}(p_T)$$

- real & virtual are differently affected by energy loss effects!
- the mismatch is largest at short formation times
- *enhances a subset of higher-order corrections*

RECAP: JET EVOLUTION

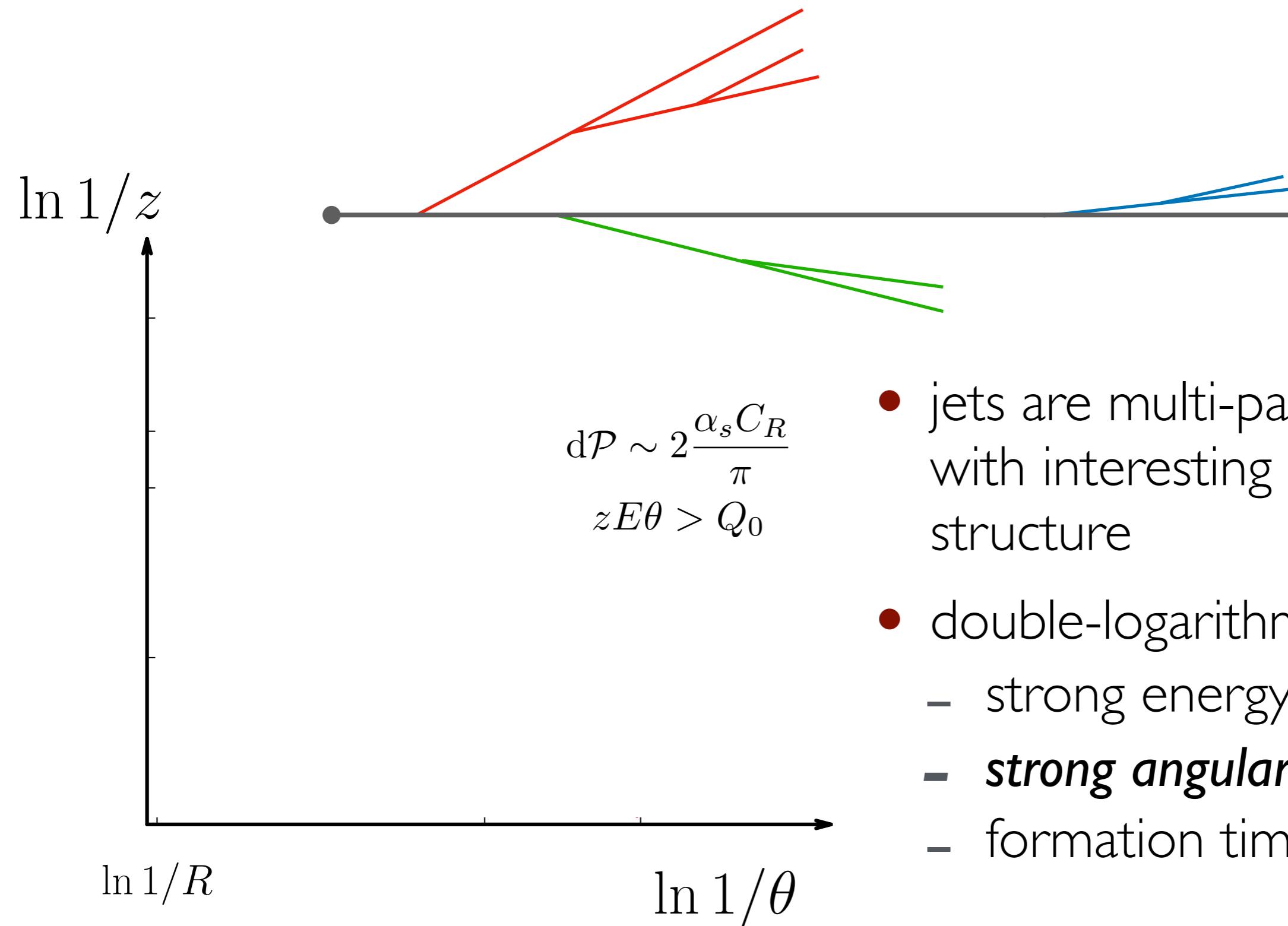
Bassetto, Ciafaloni, Marchesini (1983); Dokshitzer, Troyan, Khoze, Mueller (1991)



- jets are multi-particle objects with interesting space-time structure
- double-logarithmic regime
 - strong energy ordering
 - ***strong angular ordering***
 - formation time

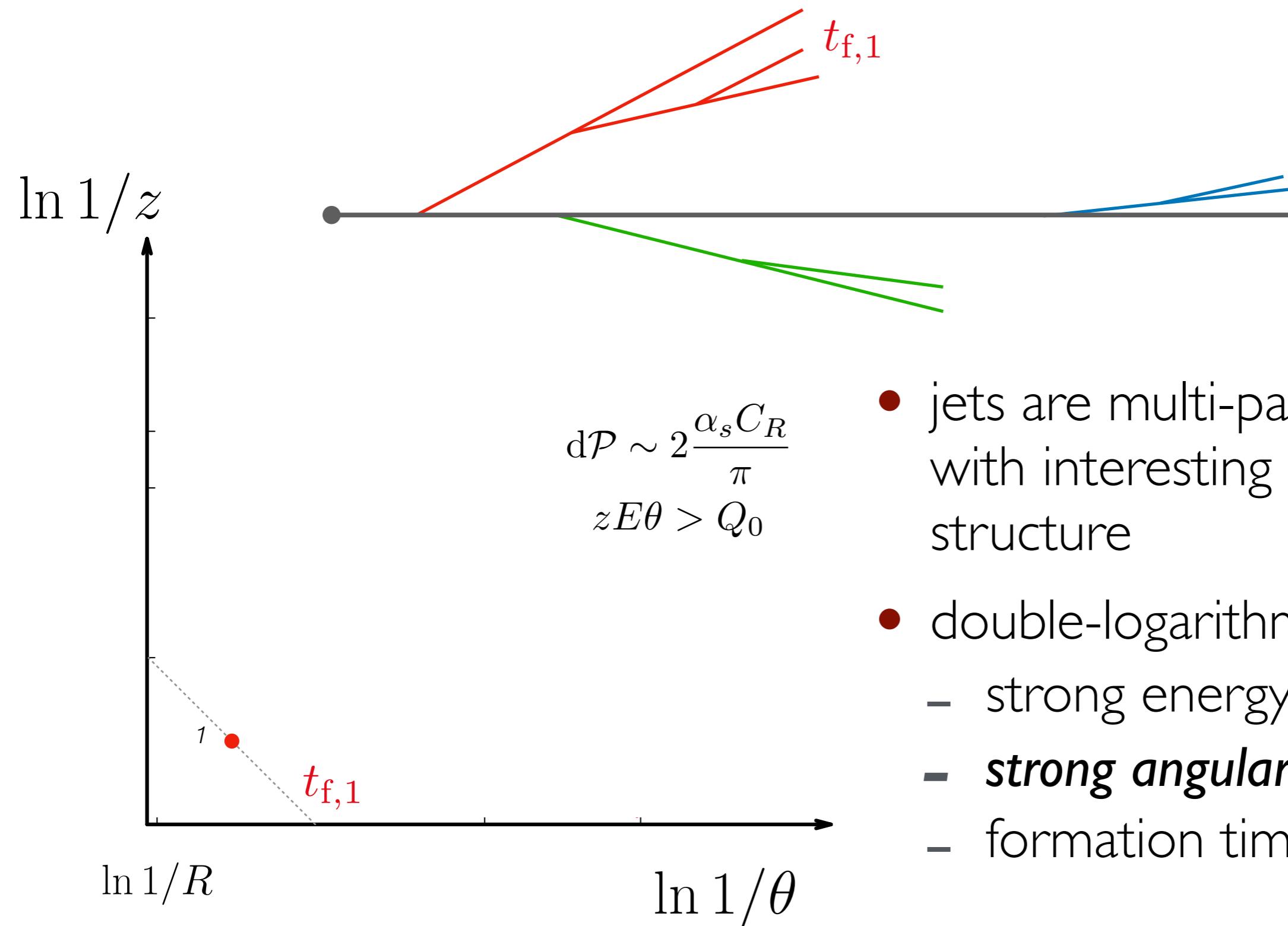
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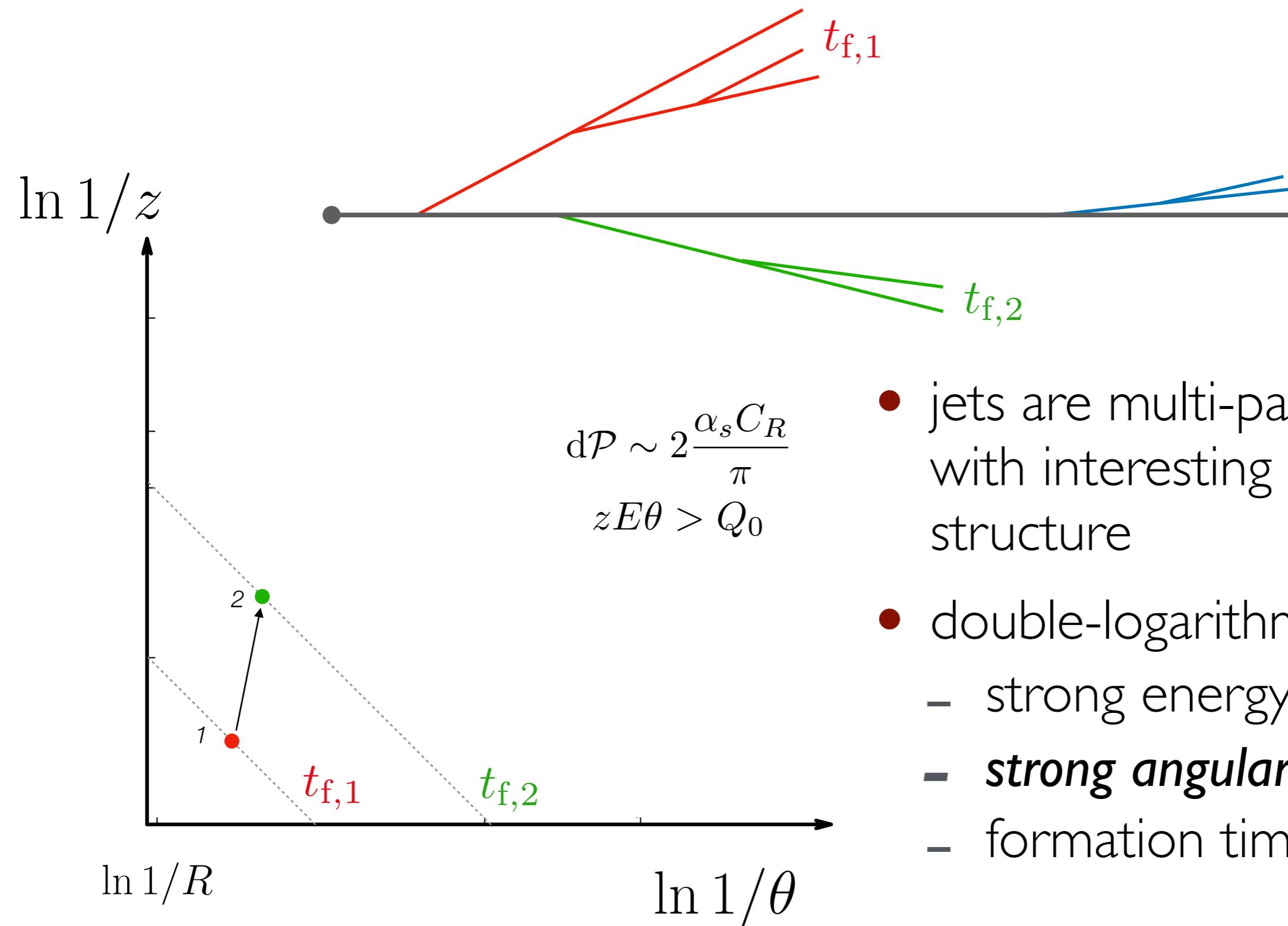
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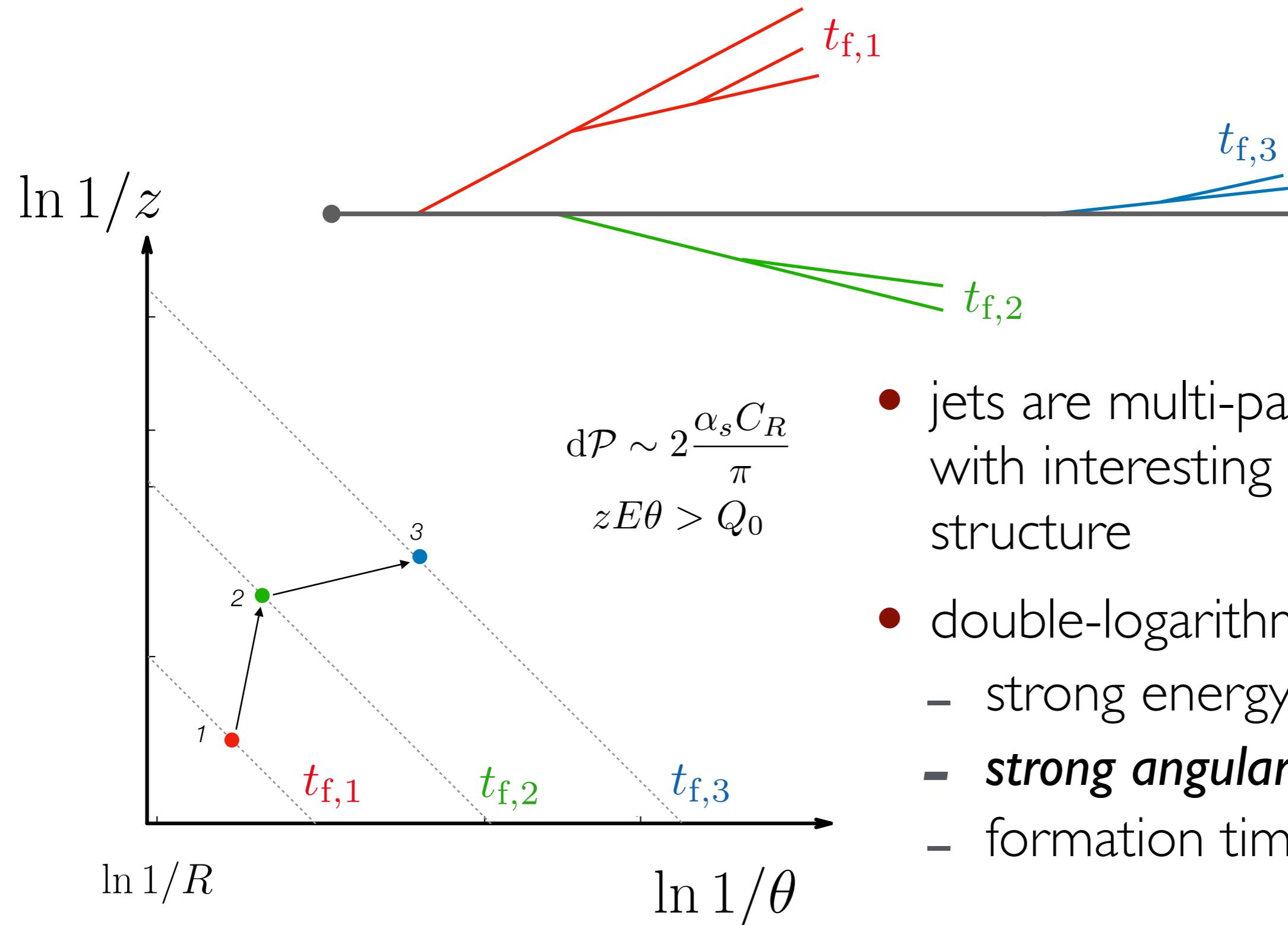
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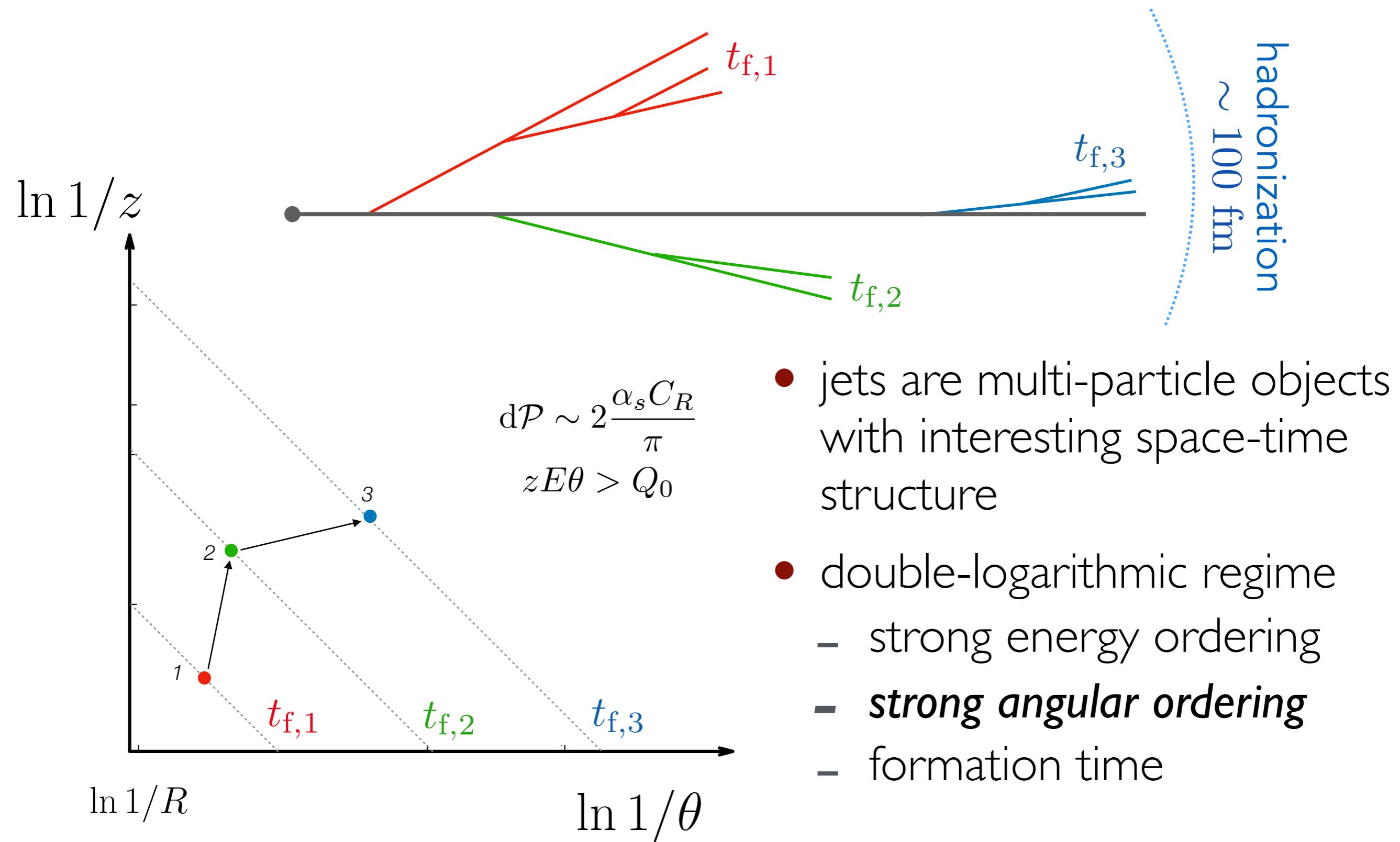
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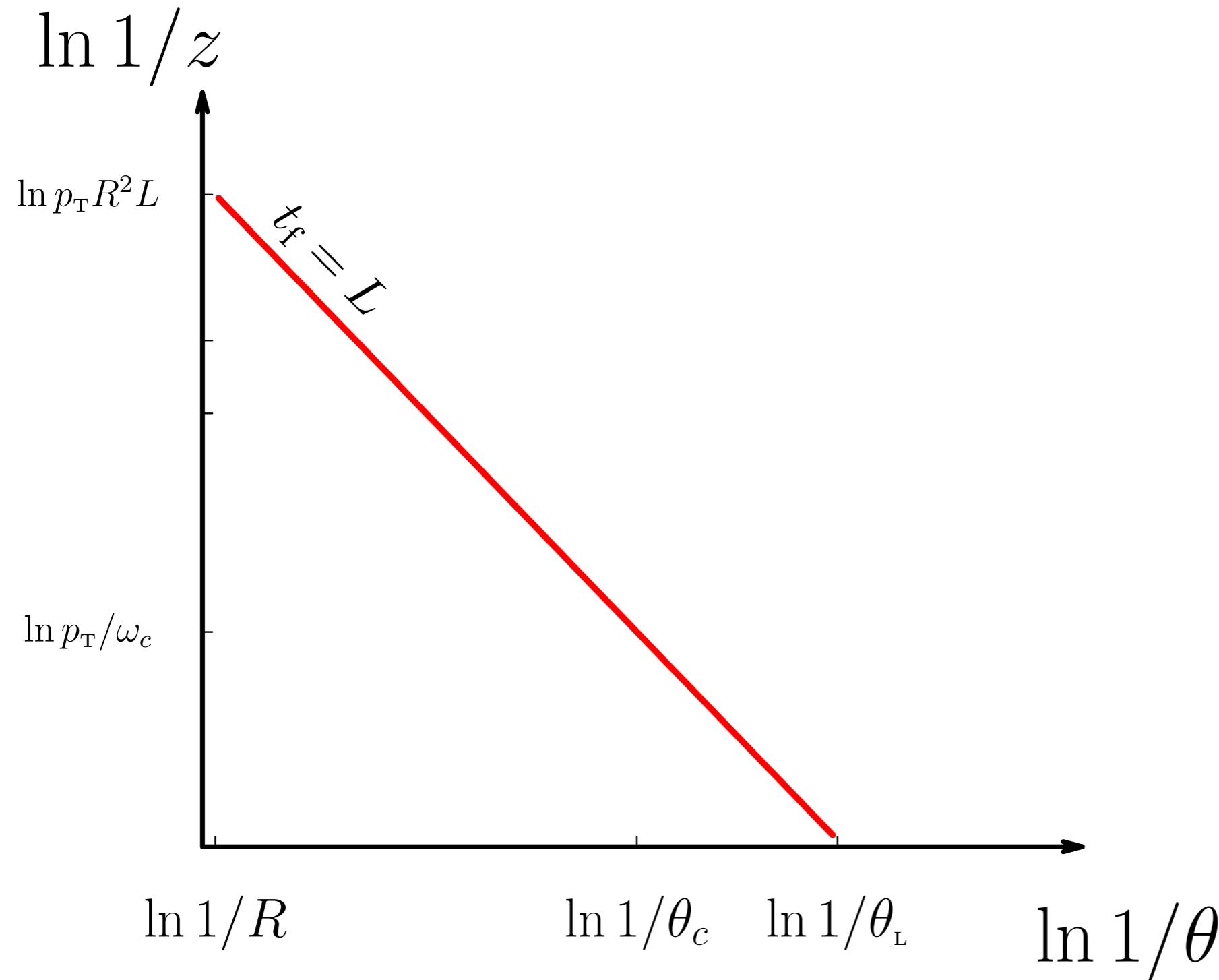
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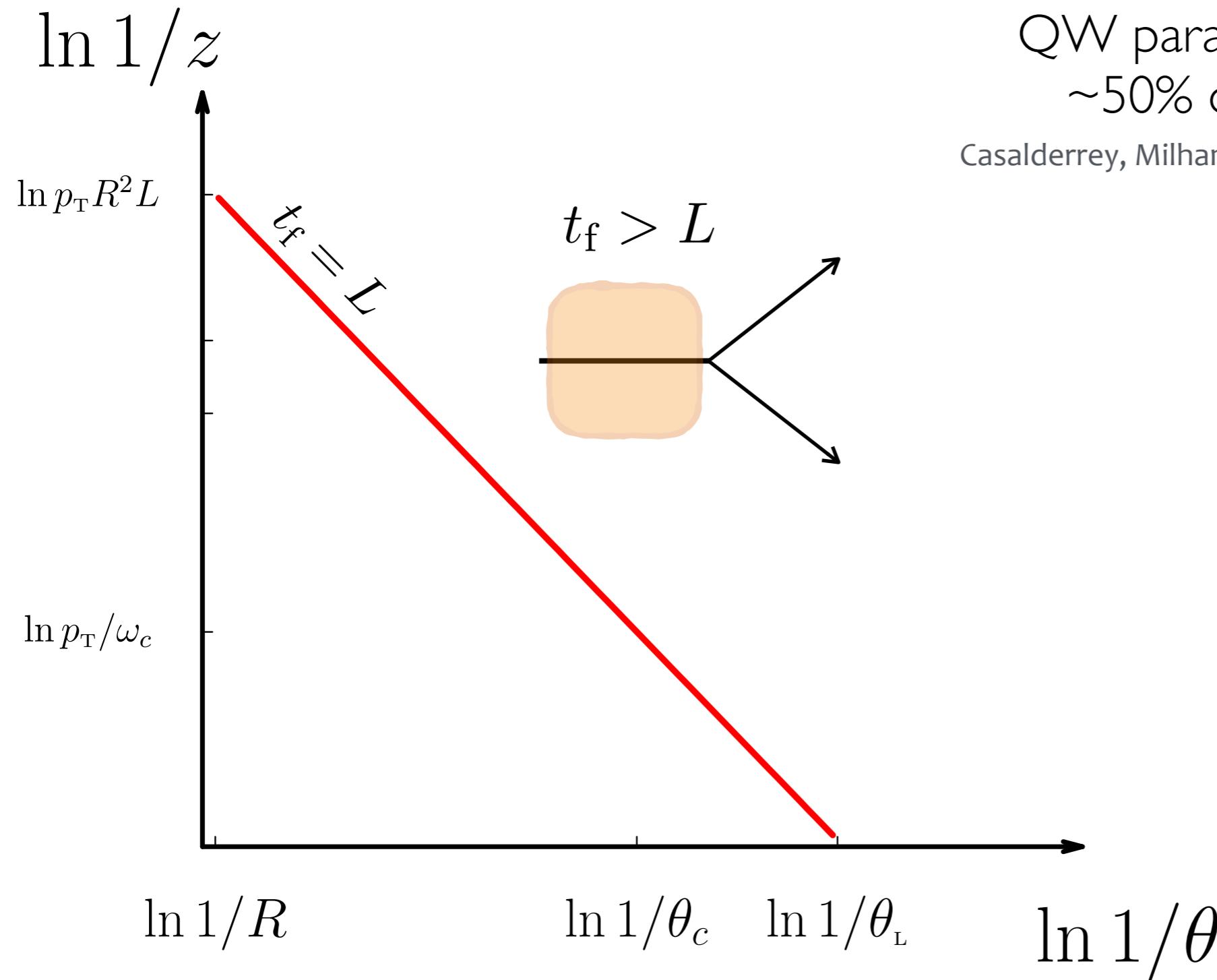
PHASE SPACE FOR MEDIUM EFFECTS

Essential length scale: size of the medium...



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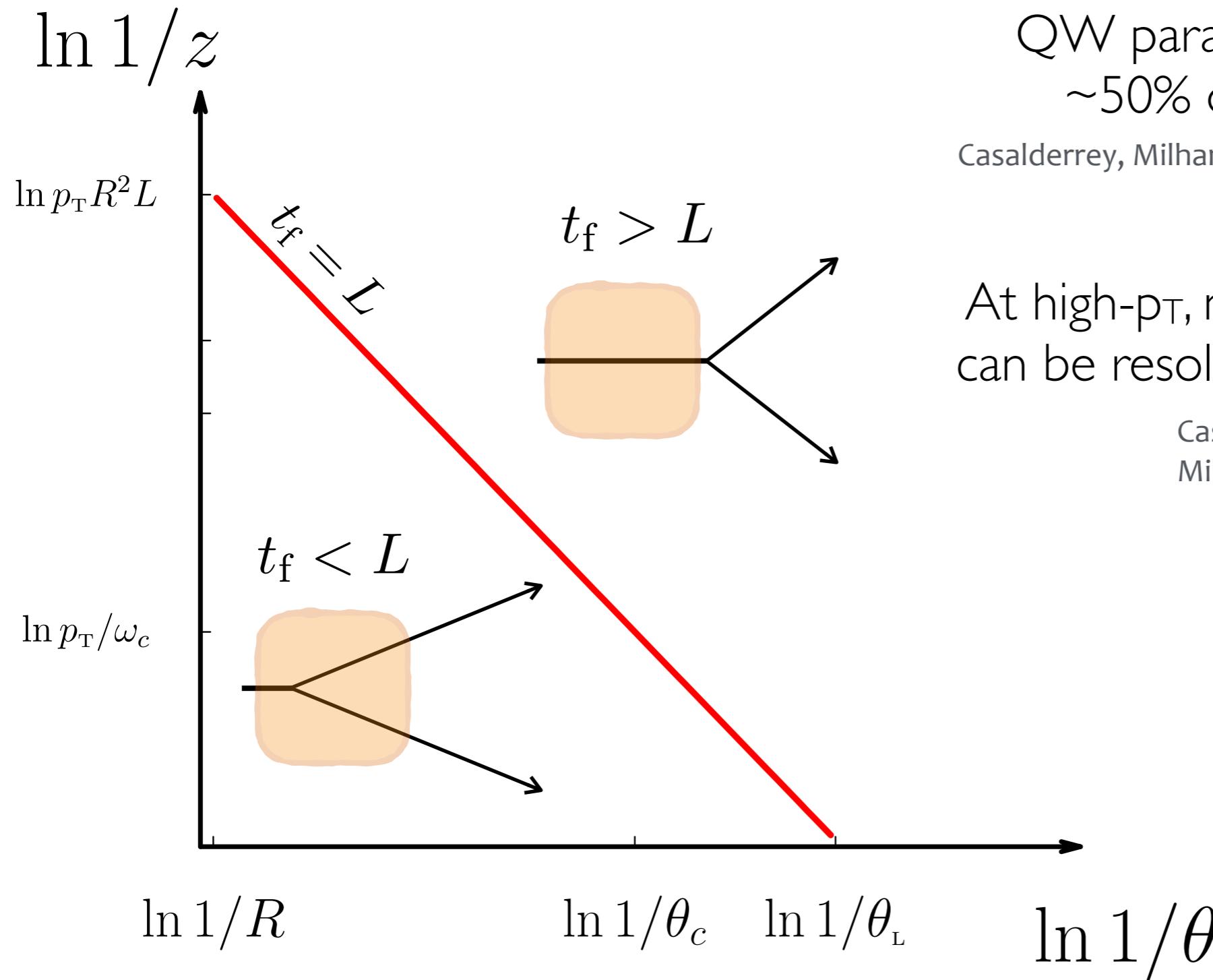


QW paradigm applies only to
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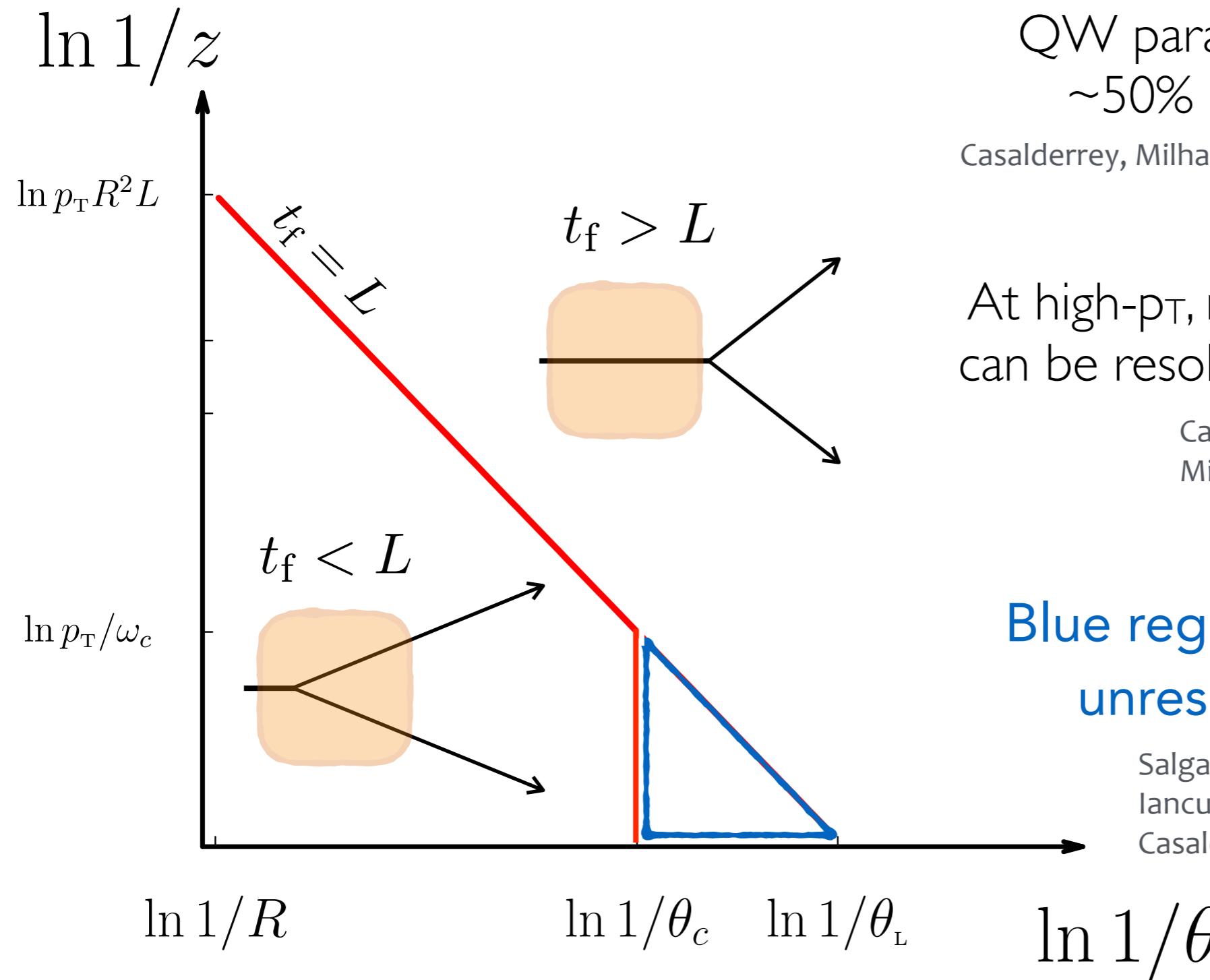
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Casalderrey et al. JHEP 1703 (2017) 135
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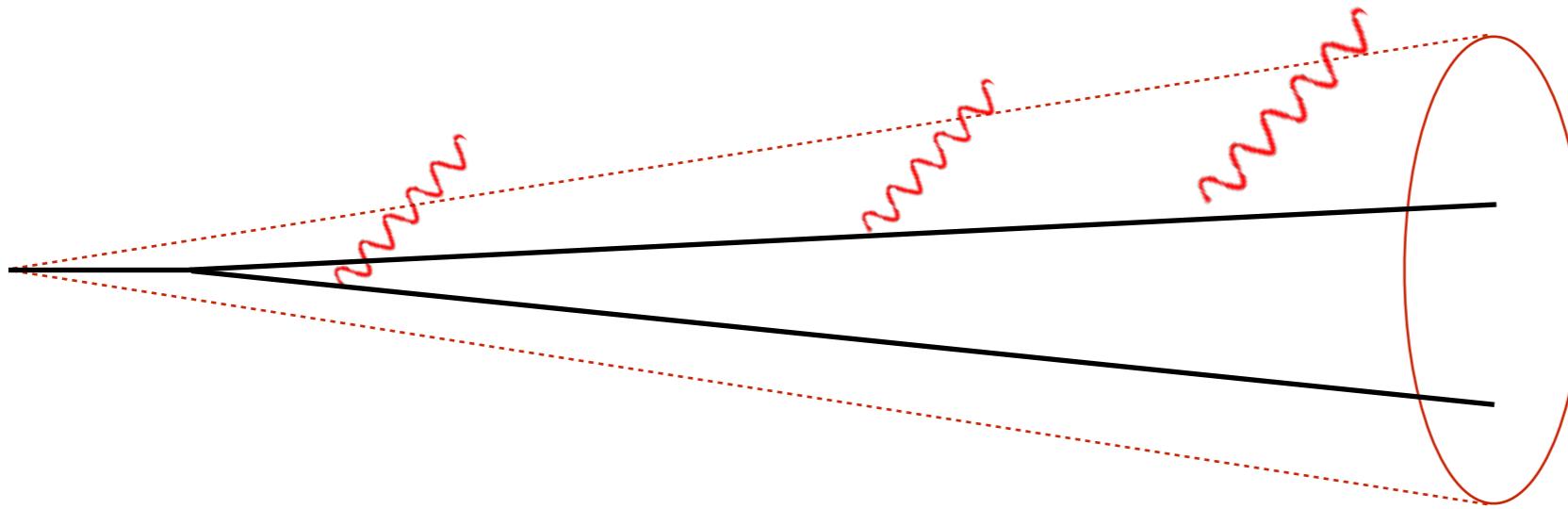
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**Blue region corresponds to
unresolved splittings.**

Salgado, Mehtar-Tani, KT (2010-2012)
Iancu, Casalderrey (2011)
Casalderrey, Salgado, Mehtar-Tani, KT (2013)

QUENCHING WEIGHTS 2.0

Y. Mehtar-Tani, KT arXiv:1706.06047 [hep-ph]

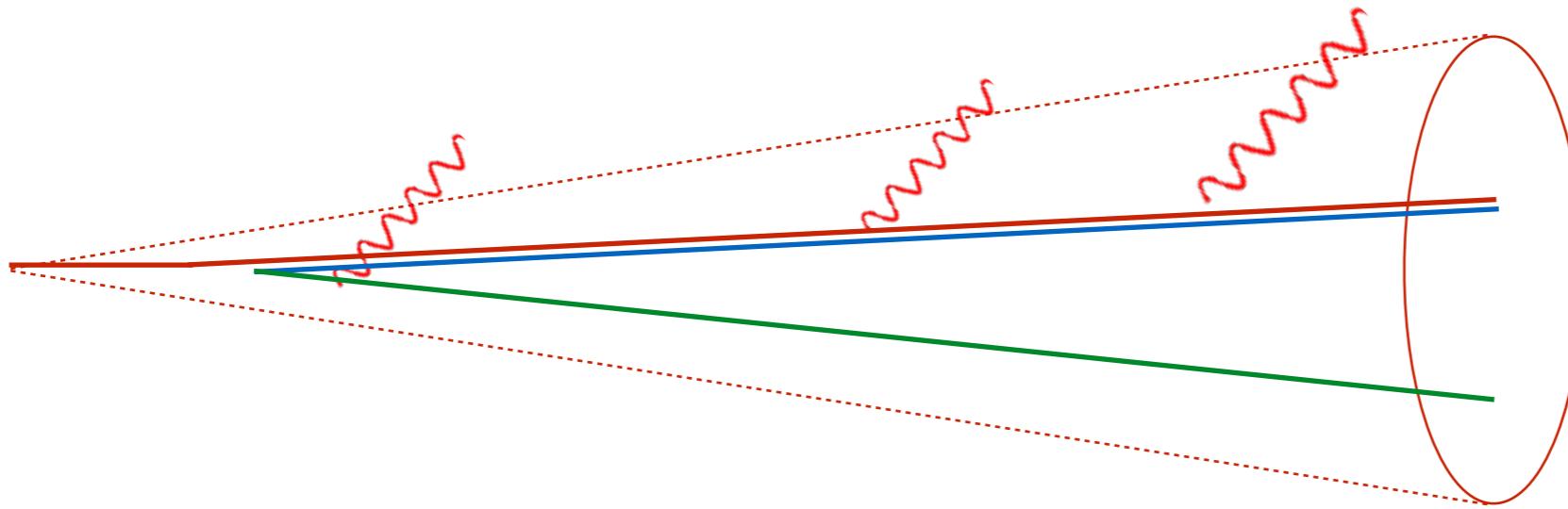


$$\mathcal{P}_{qg} = \mathcal{P}_q \otimes \mathcal{P}_{\text{sing}}$$

- two-prong QW: energy loss off total color charge + dipole created by collinear splitting
- highlights important role of interferences
 - before t_d : coherent energy loss (total charge)
 - after t_d : independent energy loss (resolved charge)

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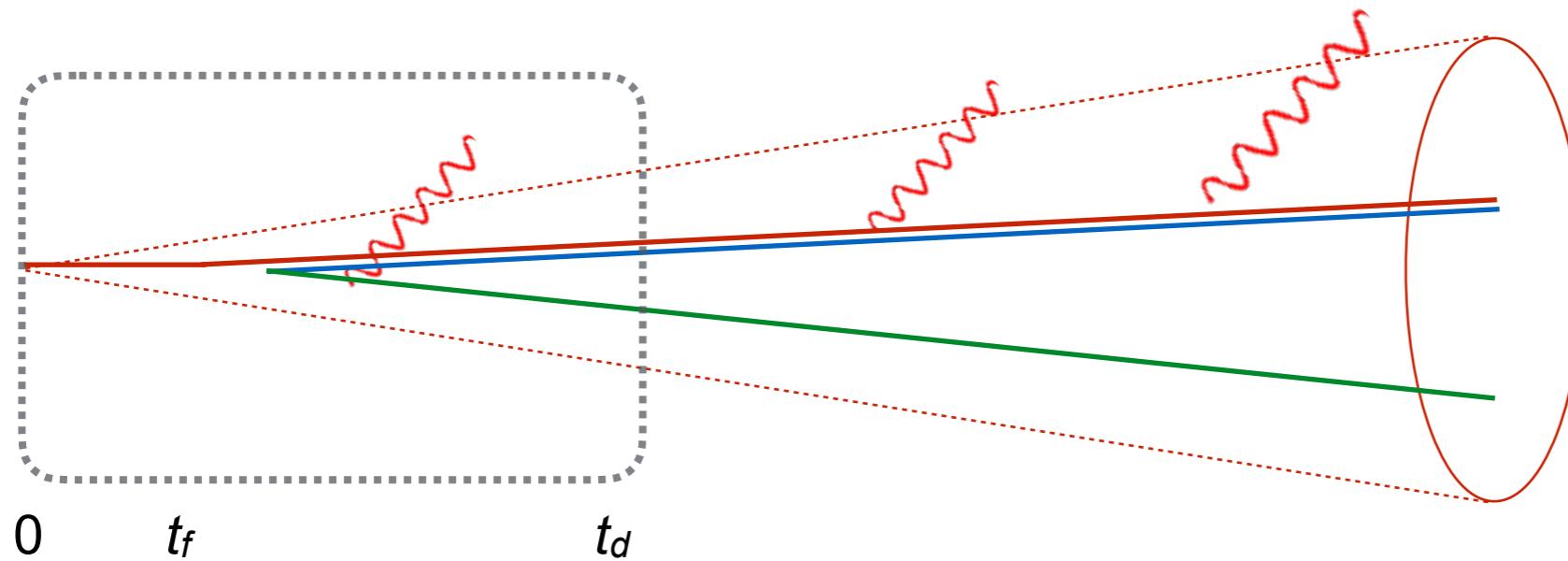


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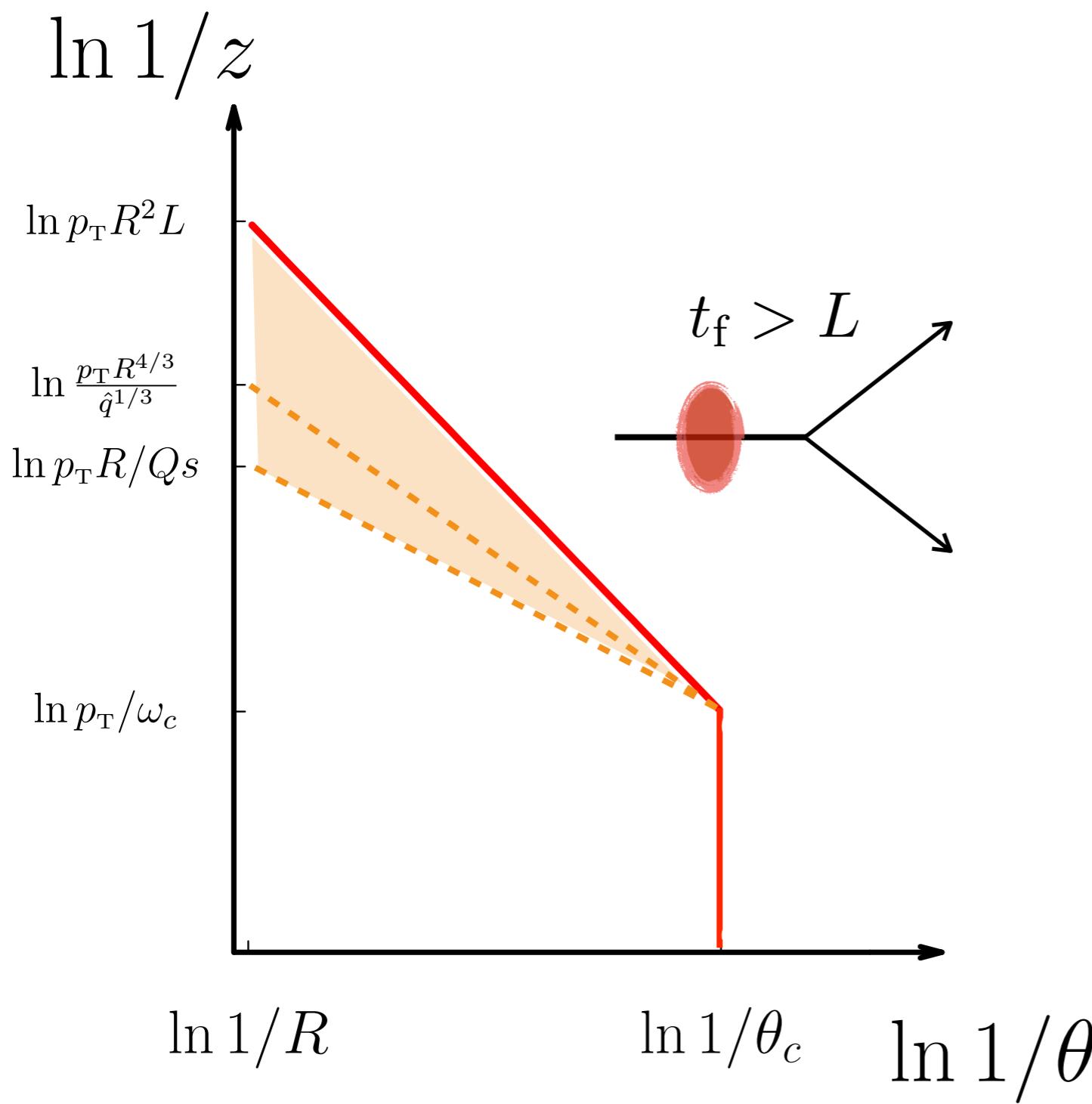
$$t_d \sim (\hat{q}\theta_{12}^2)^{-1/3}$$

$$t_d = L$$

$$\theta_c \sim (\hat{q}L^3)^{-1/2}$$

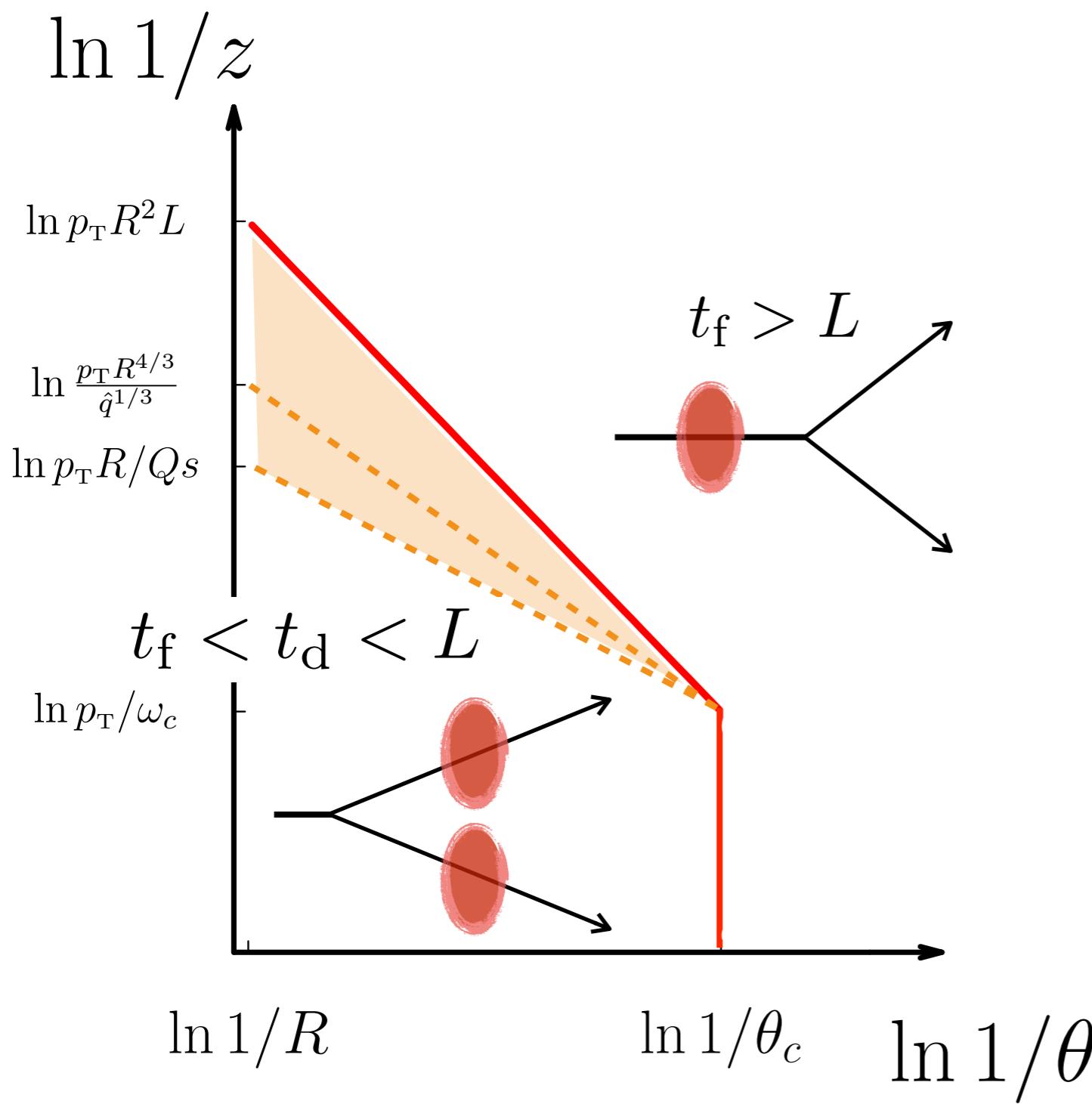
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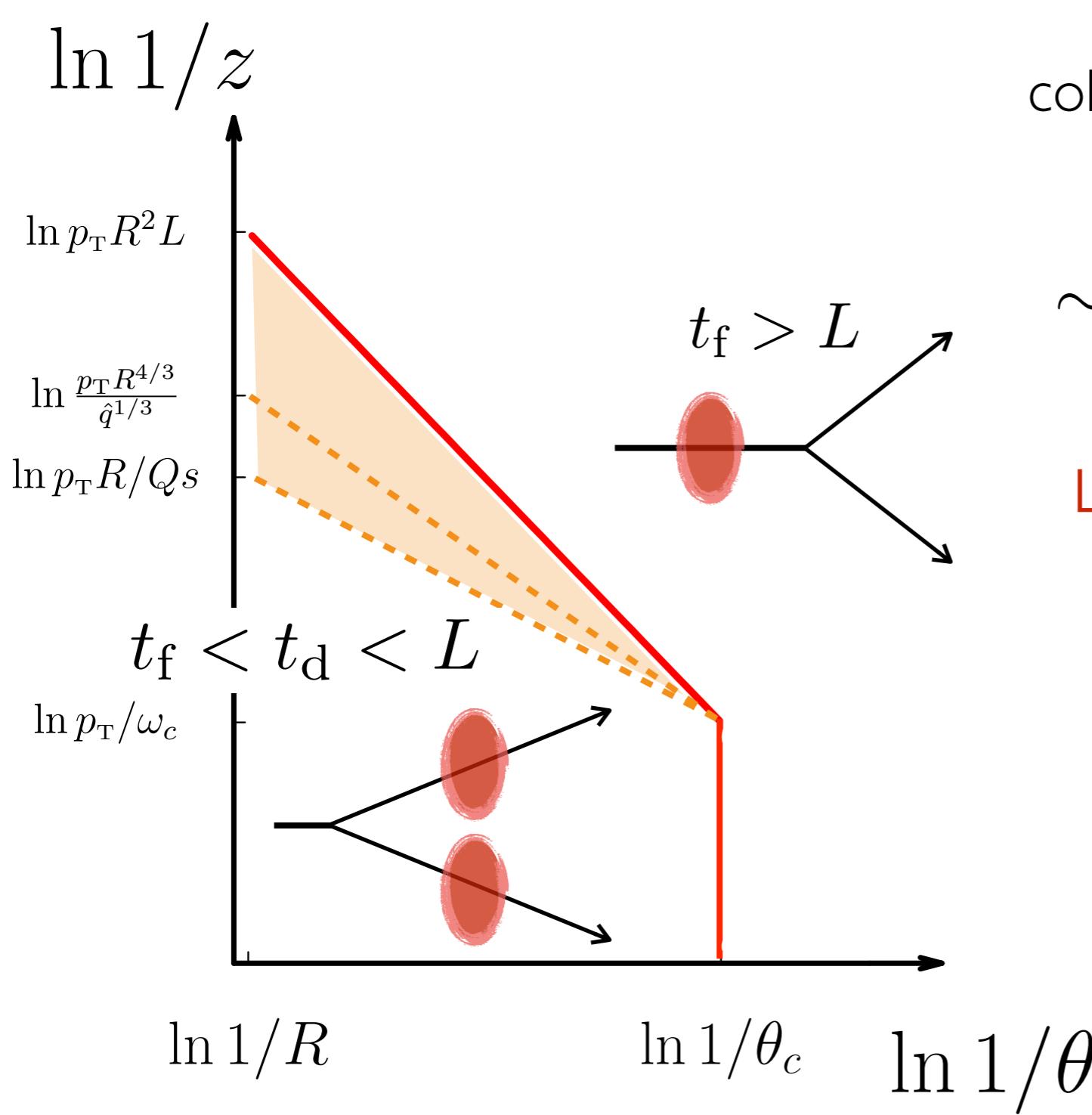
see also P. Caucal, Wed 17:20

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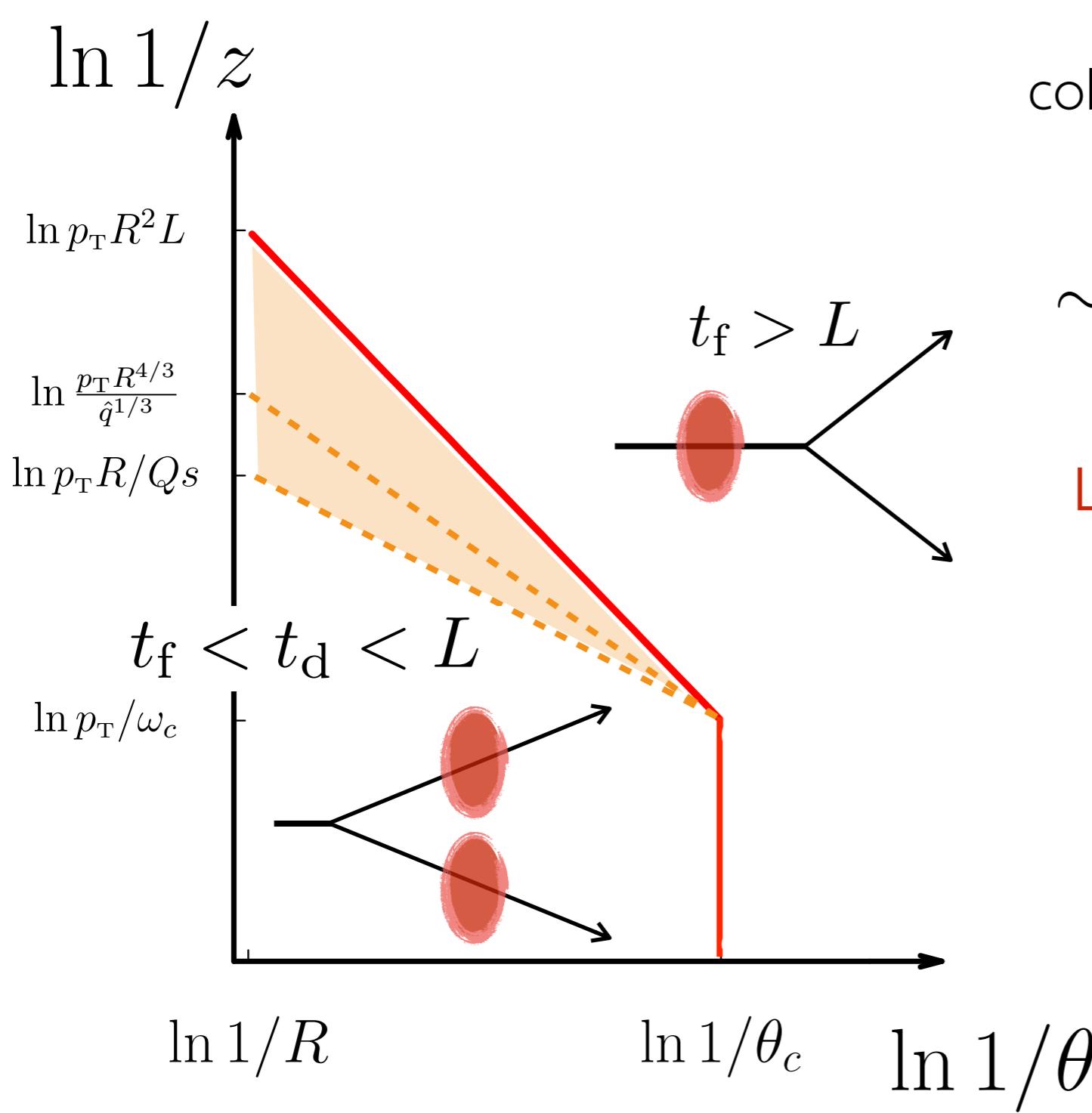
Leading-logs count the number of collinear modes resolved by the medium

$$\sim 2\bar{\alpha} \log \frac{R}{\theta_c} \log \frac{p_T}{\omega_c} [Q_q^2(p_T) - 1]$$

Log enhancement with jet scales
⇒ resummation

see also P. Caucal, Wed 17:20

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Dominance of virtual term
(strong quenching approximation $Q_q(p_T) \ll 1$)

see also P. Caucal, Wed 17:20

SUDAKOV JET SUPPRESSION

Y. Mehtar-Tani, KT arXiv:1707.07361 [hep-ph]

$$R_{\text{jet}} = \mathcal{Q}_q(p_{\text{T}}) \times \mathcal{C}(p_{\text{T}}, R)$$

jet loses energy via **total charge** & resolved substructure fluctuations

recall $\mathcal{Q}_q(p_{\text{T}}) = e^{-2\bar{\alpha}L\sqrt{n\hat{q}/(\pi p_{\text{T}})}}$

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Resummation of logs leads to exponentiation of NLO result

$$\mathcal{C}(p_{\text{T}}, R) \simeq \exp \left[-2\bar{\alpha} \ln \frac{R}{\theta_c} \left(\ln \frac{p_{\text{T}}}{\omega_c} + \frac{2}{3} \ln \frac{R}{\theta_c} \right) \right]$$

$$\mathcal{C}_g(p_{\text{T}}, R) = [\mathcal{C}_q(p_{\text{T}}, R)]^{N_c/C_F}$$

GOING BEYOND STRONG QUENCHING

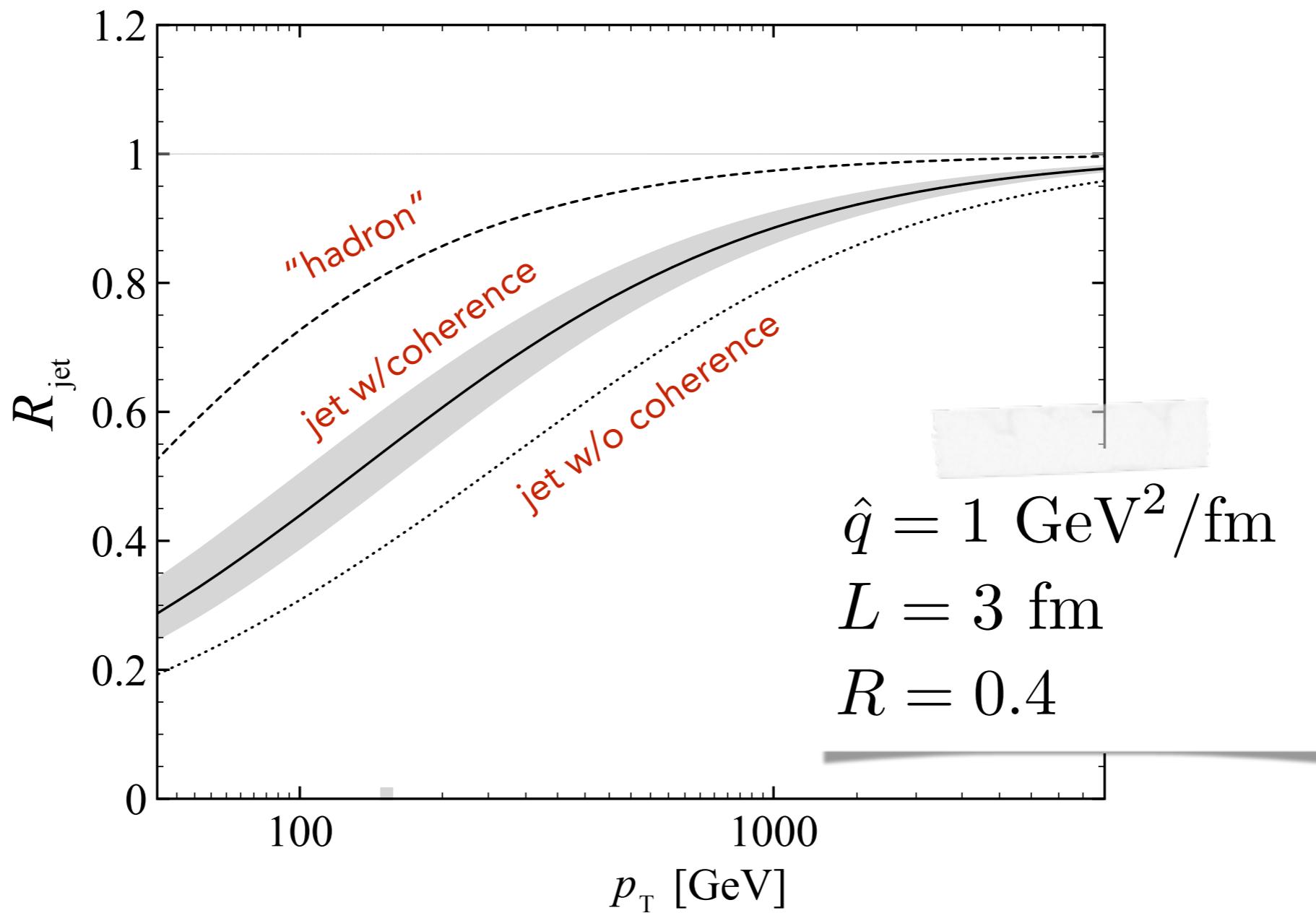
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- at finite quenching resummation of medium logs via set of **non-linear equations**
- running coupling

$$\begin{aligned} \mathcal{C}(1, p_{\text{T}}, R) = & 1 + \int_0^1 dz \int_{\theta_c}^R \frac{d\theta}{\theta} \frac{\alpha_s(k_{\perp})}{\pi} P_{gq}(z) \Theta(t_f < t_d) \\ & \times [\mathcal{C}(z, p_{\text{T}}, \theta) \mathcal{C}(1 - z, p_{\text{T}}, \theta) Q_q^2(p_{\text{T}}) - \mathcal{C}(1, p_{\text{T}}, \theta)] \end{aligned}$$

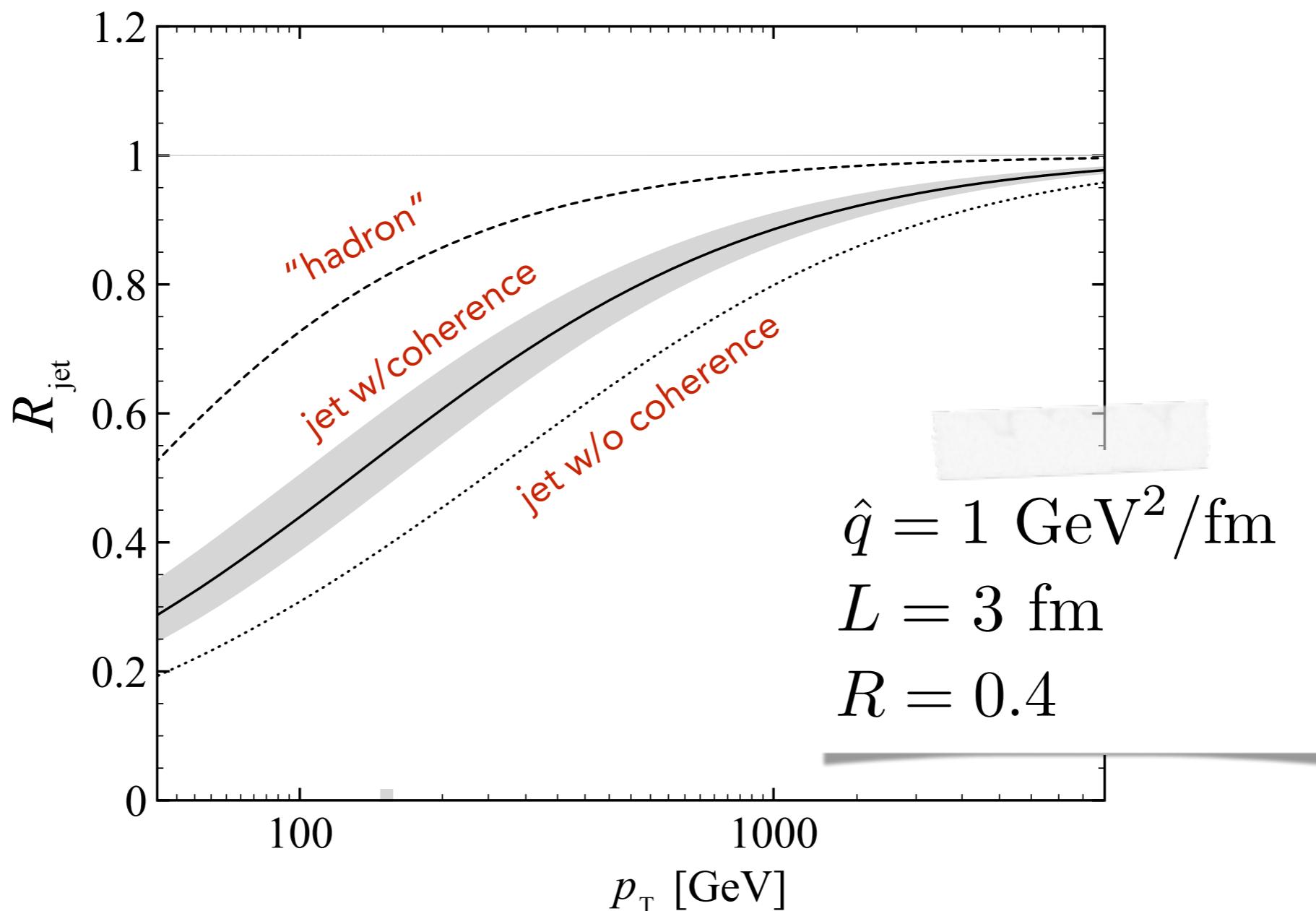
- can easily be generalized to **other models** of how jets are affected in medium
 - e.g. incoherent scenario = all jets inside the medium lose energy independently

JET SUPPRESSION: NUMERICS



Quantitative difference for incoherent scenario: $\log \mathcal{C}_{\text{incoh}} \sim \alpha_s \log^2 p_{\text{T}}$

JET SUPPRESSION: NUMERICS



Quantitative difference for incoherent scenario: $\log \mathcal{C}_{\text{incoh}} \sim \alpha_s \log^2 p_{\text{T}}$

Several improvements in the pipeline for phenomenological analysis!

CONCLUSIONS

- generalized energy loss probability
 - quenching of total charge (+mass effects)
 - novel Sudakov suppression factor (collimator)
- relating quenching to jet scales
 - analytic understanding
 - sensitivity to opening angle
- general features from hard scale analysis
 - assumptions about medium modifications leads to redrawing of phase space
 - guidance for (a large class of) MC modeling
 - importance of data scanning p_T & R

THANK YOU!