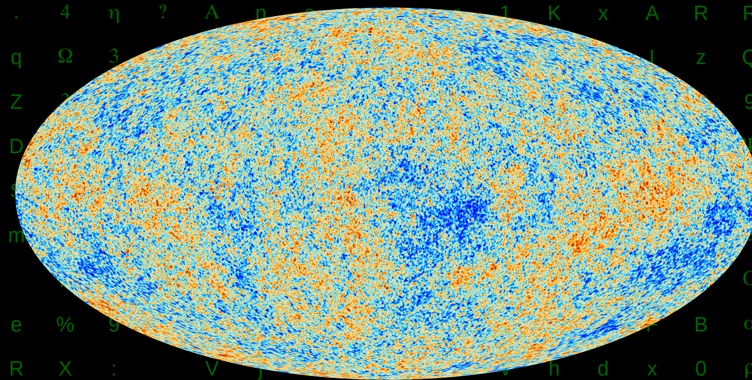
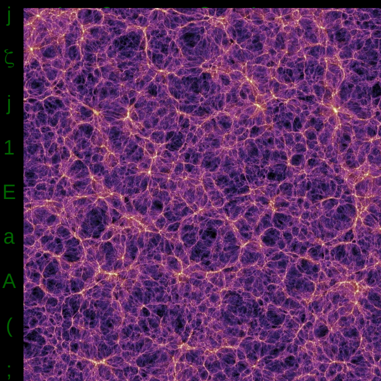
Cosmo Tools 2018





23rd-27th April, Aachen

School designed to help young researchers understand the black box of cosmology codes.

Lecturers:

- Thejs Brinckmann
- Jens Chluba
- Christian Fidler
- Will Handley
- Felix Kahlhoefer
- Julien Lesgourgues
- Matteo Martinelli
- Ruediger Pakmor
- Janina Renk
- Jesus Torrado
- Thomas Tram
- Wessel Valkenburg
- Joe Zuntz

Local Organisers:

- Thejs Brinckmann
- Christian Fidler
- Deanna C Hooper
- Julien Lesgourgues

International Advisory Committee:

- Jens Chluba
- Antony Lewis
- Savvas Nesseris
- Volker Springel
- Thomas Tram

Registration Deadline:
15th March 2018

Website:
indico.cern.ch/e/CosmoTools2018

Institute for Theoretical Particle Physics and Cosmology

RWTH AACHEN UNIVERSITY

CosmoTools18, TTK, RWTH Aachen University, 23-27.04.2018

CMB Physics and Introduction to Boltzmann Codes

- Linear perturbation theory and CMB physics
- History of Boltzmann codes
- Main tasks, bottlenecks

J. Lesgourgues
Institut für Theoretische Teilchenphysik und Kosmologie (TTK), RWTH Aachen University

Reduction of cosmological perturbations

- Bardeen scalars, vectors and tensors
  - S: density, pressure, forces: generalisation of newtonian gravity
  - V: vorticity, gravity-magnetism: usually irrelevant in cosmology (excepted phase transitions, defects…)
  - T: gravitational waves

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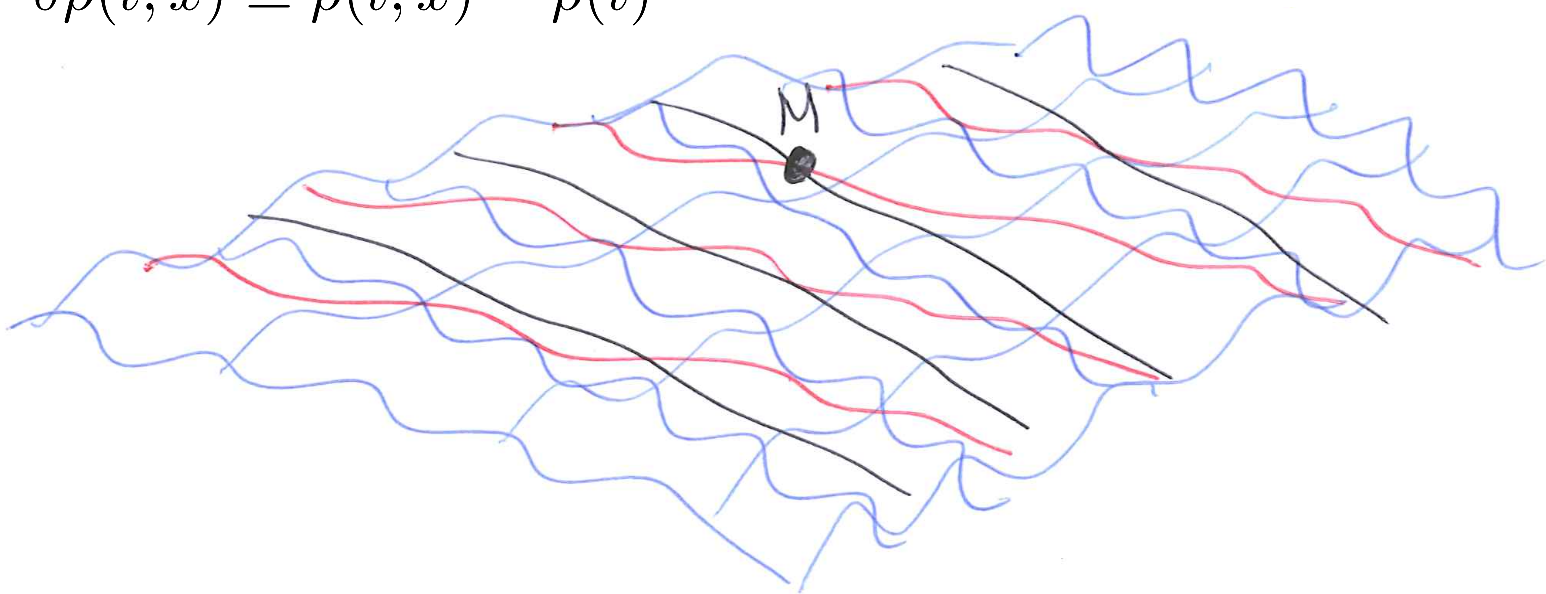
- Gauge freedom: $\delta\rho(t,\vec{x}) \equiv \rho(t,\vec{x}) - \bar{\rho}(t)$



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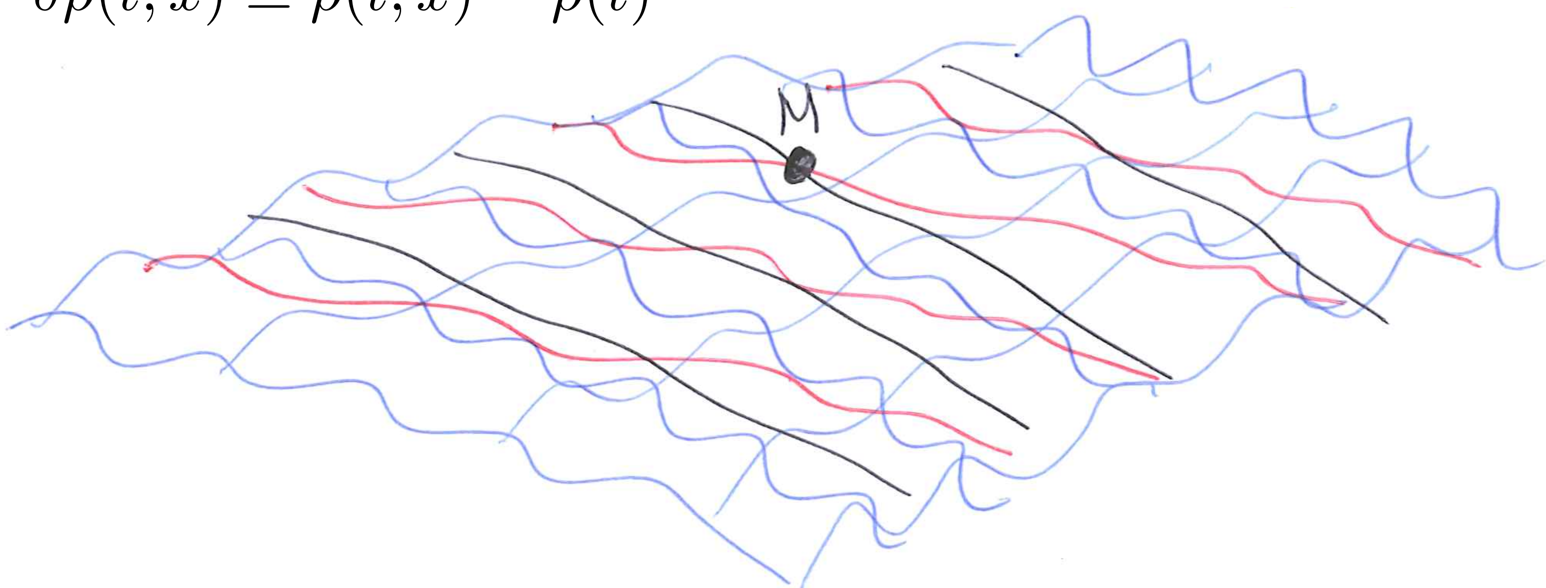

- Reduction to
    - 2 Scalars metric perturbations (newtonian, synchronous, N-body gauges…)
    - 2 Tensors metric perturbations (effectively one)

Principles of linear cosmological perturbation theory

- Linear perturbations theory: independent Fourier modes with system of linear differential equation
- Isotropy: system depends on k, not $\vec{k}$
- Full solution reads

$$
\begin{aligned}
f_1(t,\vec{k}) &= \sum_i T_1^{(i)}(t,k)\ A^{(i)}(\vec{k}) \\
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- Can match the first one with the unique solution found when there is initially only one perturbed d.o.f (inflaton, temperature of thermal bath) which plays the role of a time clock: adiabatic mode. Then

$$f_j(t,\vec{x}) = \bar{f}_j(t+\delta t(t,\vec{x})) = \bar{f}_j(t) + \dot{\bar{f}}_j(t)\;\delta t(t,\vec{x})$$

and $A^{(1)}(\vec{k})$ can be matched to initial curvature perturbation $\mathcal{R}(\vec{k})$. Then $f_j(t,\vec{k}) = T_j(t,k)\;\mathcal{R}(\vec{k})$

- Other isocurvature/entropy modes disfavoured by observations, but Boltzmann codes allowing for arbitrary mixture keep the complexity of the full expansion (loops over ICs)

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- Other isocurvature/entropy modes disfavoured by observations, but Boltzmann codes allowing for arbitrary mixture keep the complexity of the full expansion (loops over ICs)
- Solve for (deterministic) transfer functions rather than (stochastic) perturbations
- Observables = correlators of $f_j(t,\vec{k})$ = (transfer functions)*power* x (correlators of $\mathcal{R}(\vec{k})$)

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Evolution equations for each Fourier mode

- In general: one Boltzmann equation for species (more for photons, to follow polarisation)

$$\frac{D}{d\tau}\left(\bar{f}(\tau,p)\left[1+\Psi(\tau,\vec{k},p,\hat{n})\right]\right) = \text{scattering term}$$

- Dependence on momentum modulus trivial for photons (blackbody)
- Dependence on direction w.r.t. k captured by Legendre expansion, everything encoded in the transfer functions

$$\Delta_\ell(\tau,k) \equiv F_\ell(\tau,k) \equiv 4\Theta_\ell(\tau,k)$$

- Temperature C_ℓ 's are simply $\left(\Theta_\ell(\tau_0,k)\right)^2$ convolved with primordial spectrum
- Inconvenient: follow thousands of $\Theta_\ell(\tau,k)$'s accurately until today

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- Perfect fluid or pressure-less component: 2 equations (conservation+Euler)

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- Components of Einstein equation often kept as evolution equation to close the system (gauge-dependent; 0 or 1 for scalars, 1 or 2 for vectors/tensors)

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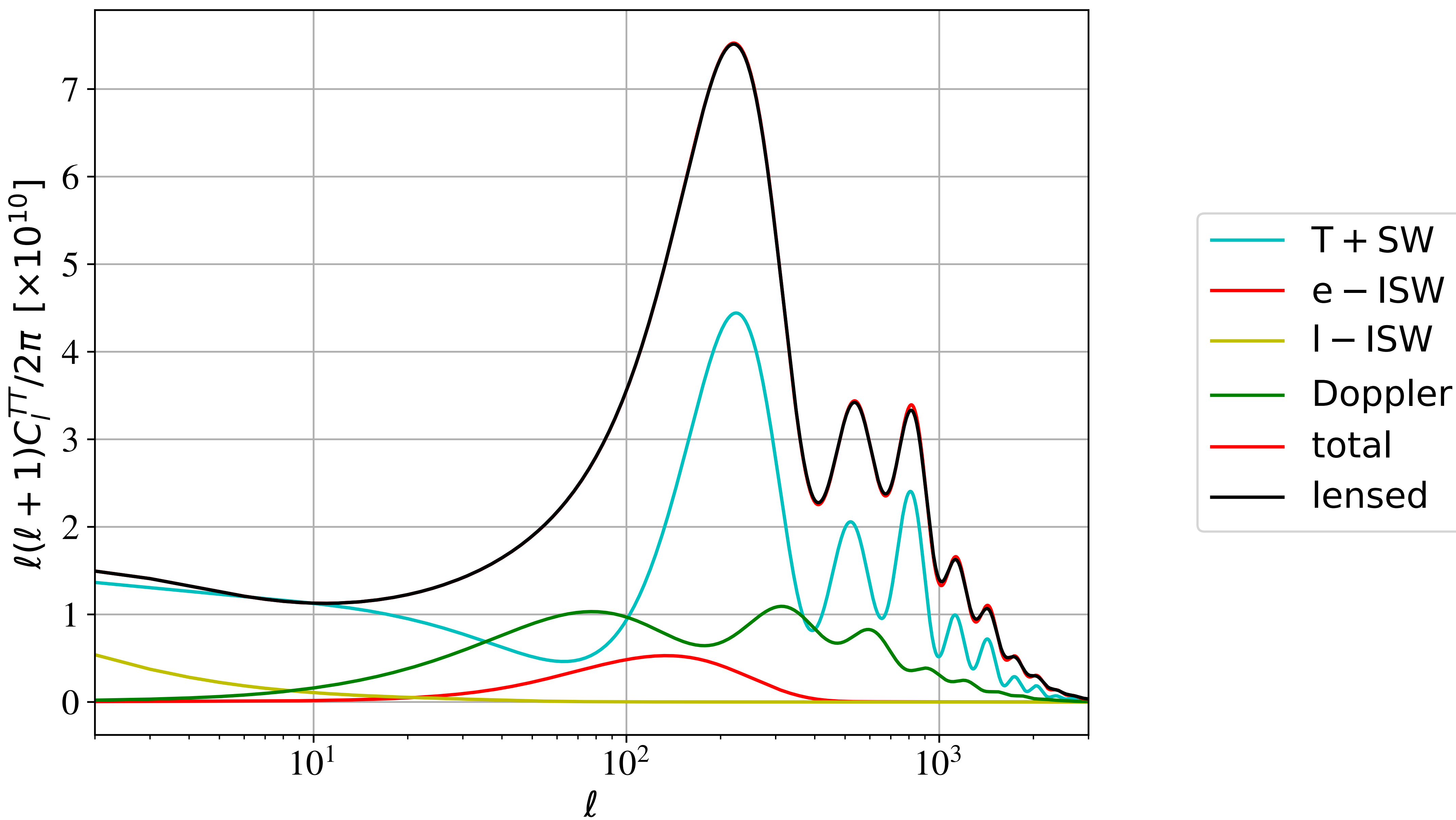
Line-of-sight integral

- "True" line-of-sight integral of the Boltzmann equation (in real space in one direction):

$$(\Theta + \psi)|_{\rm obs} = \int_{\eta_{\rm ini}}^{\eta_0} d\eta \left[g \left(\Theta_0 + \psi + \hat{n} \cdot \vec{v}_{\rm b} \right) + e^{-\tau} (\phi' + \psi') \right]$$

(Polarisation corrections neglected)

- Leads to different effects in the CMB:



Line-of-sight integral

- Fourier transform of line-of-sight integral (Seljak & Zaldarriaga 96):

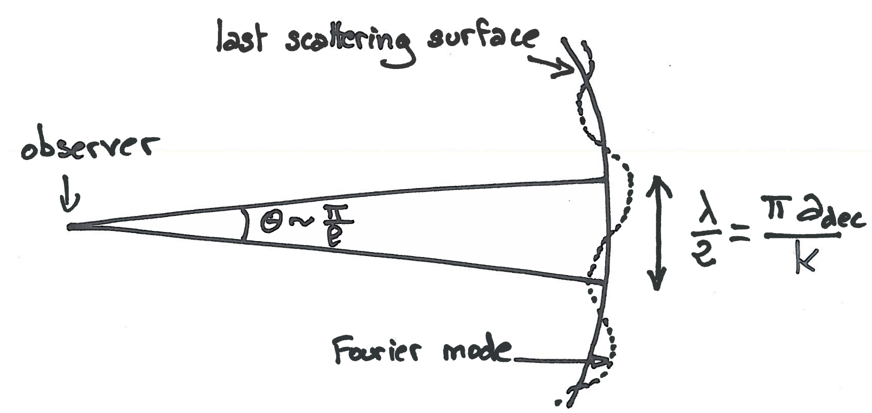
$$\Theta_l(\tau_0, k) = \int_{\tau_{\rm ini}}^{\tau_0} d\tau \; \{\underbrace{g\,(\Theta_0 + \psi)}_{\rm TSW} + \underbrace{\left(g\,k^{-2}\theta_{\rm b}\right)'}_{\rm Doppler} + \underbrace{e^{-\kappa}(\phi' + \psi')}_{\rm ISW}\} \; j_l(k(\tau_0 - \tau))$$

(Polarisation corrections neglected)

- Only first photon multipoles close to recombination time are important!
- Separation of “physical complexity” and “geometrical complexity”
- Spherical Bessel function: projection from Fourier to multipole space

  - For mode orthogonal to l-o-s:

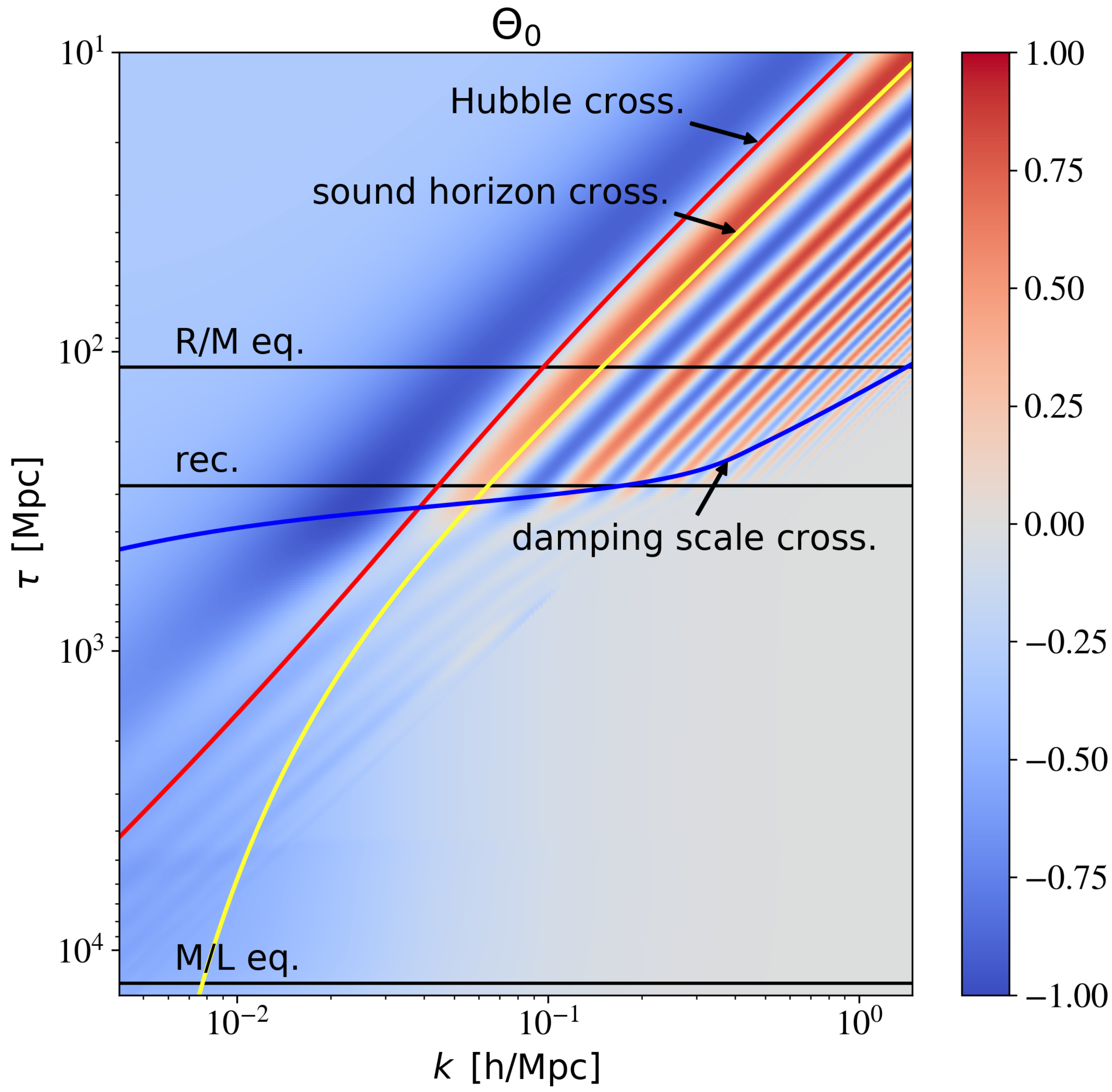
    main peak in Bessel at $l \simeq k(\tau_0 - \tau)$ ensures correct projection $\frac{\lambda}{2} = \theta\, d_a(z_{\rm dec})$ with $\theta = \frac{\pi}{\ell}$



  - For other modes: other peaks of Bessel function

- But Bessel functions oscillatory, slow convergence of the integral…

Evolution of Transfer Functions: metric



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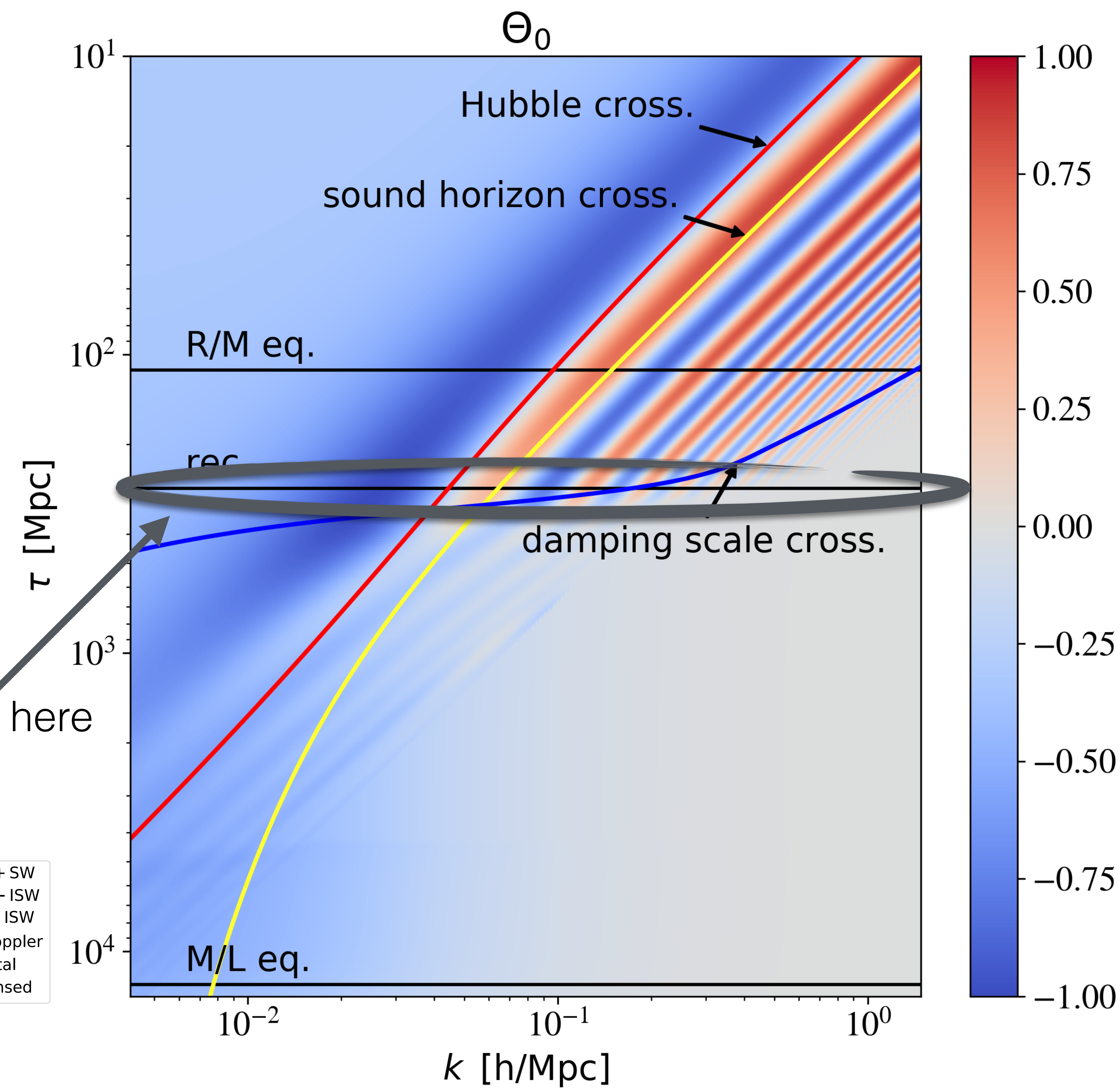
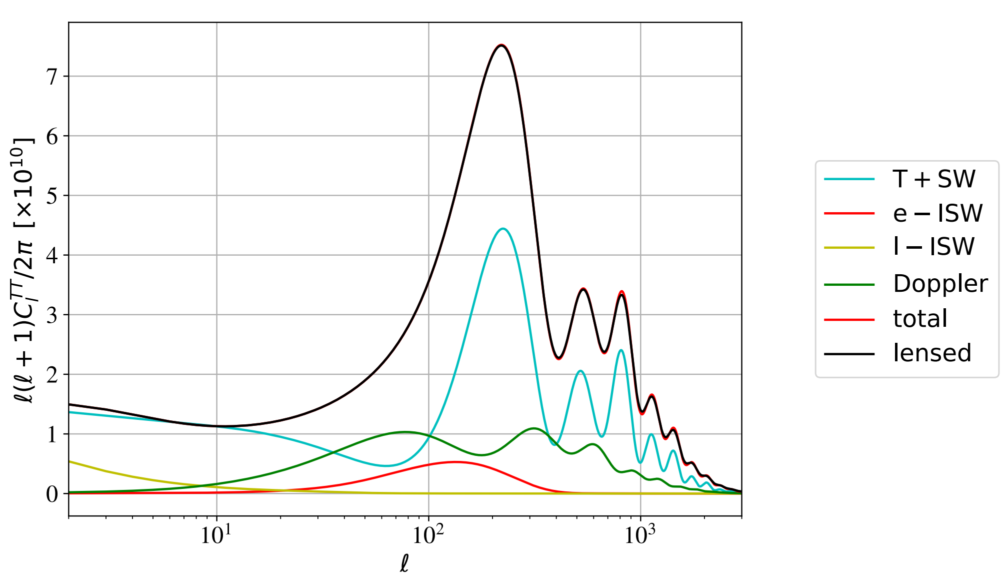


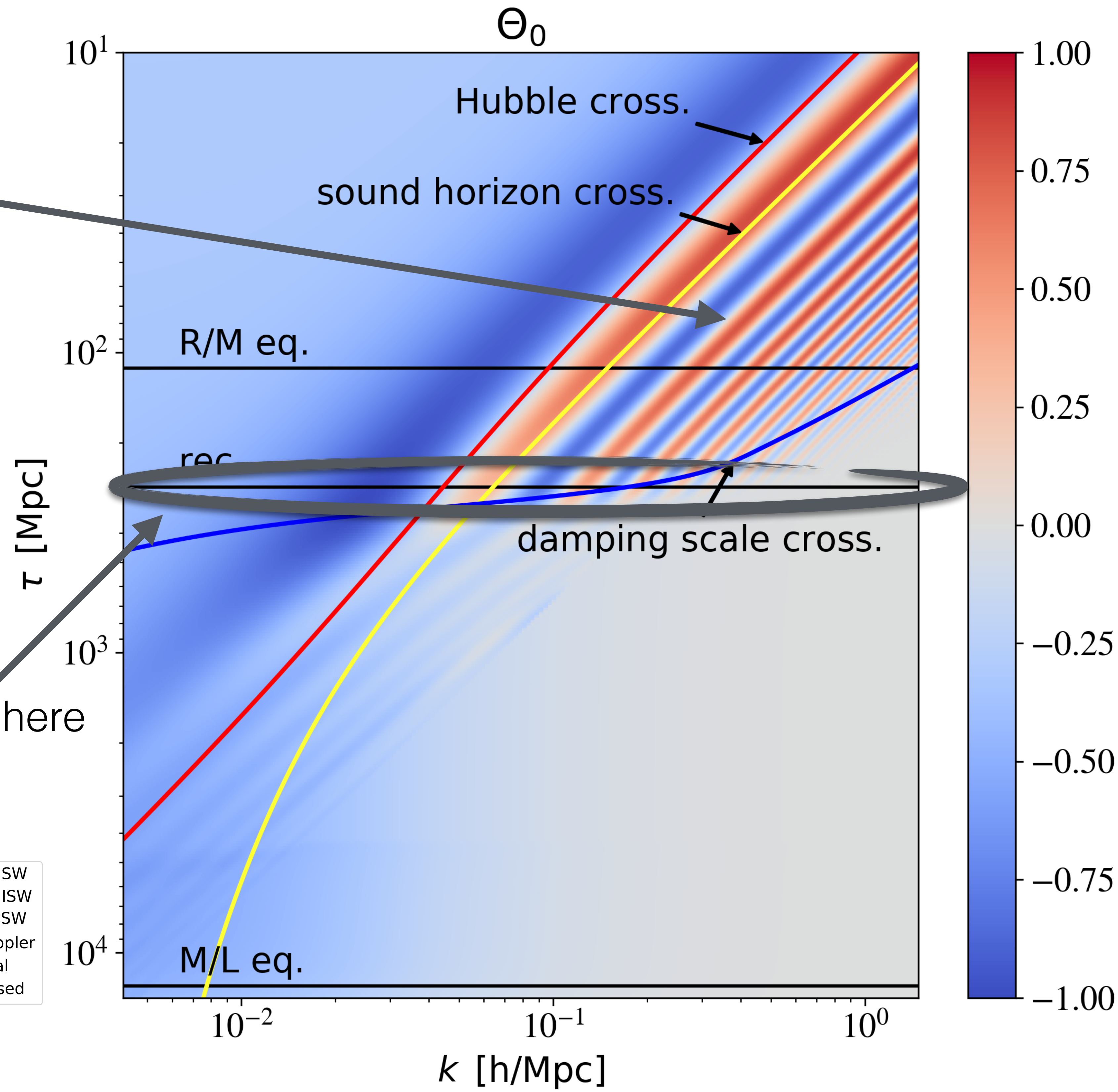
CMB patterns mainly come from here



Evolution of Transfer Functions: metric

45° symmetry comes from

$$\cos(kc_s\tau)$$



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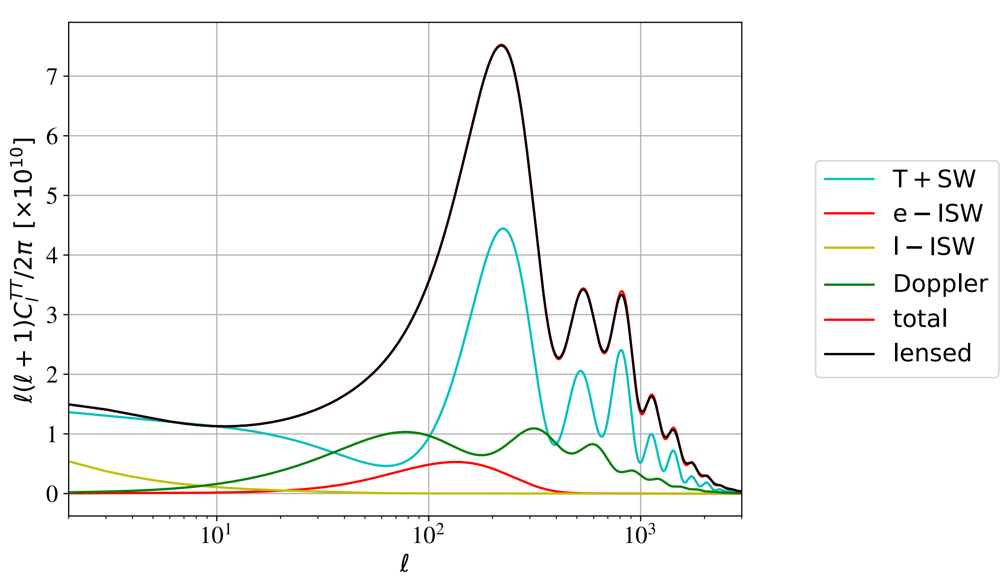
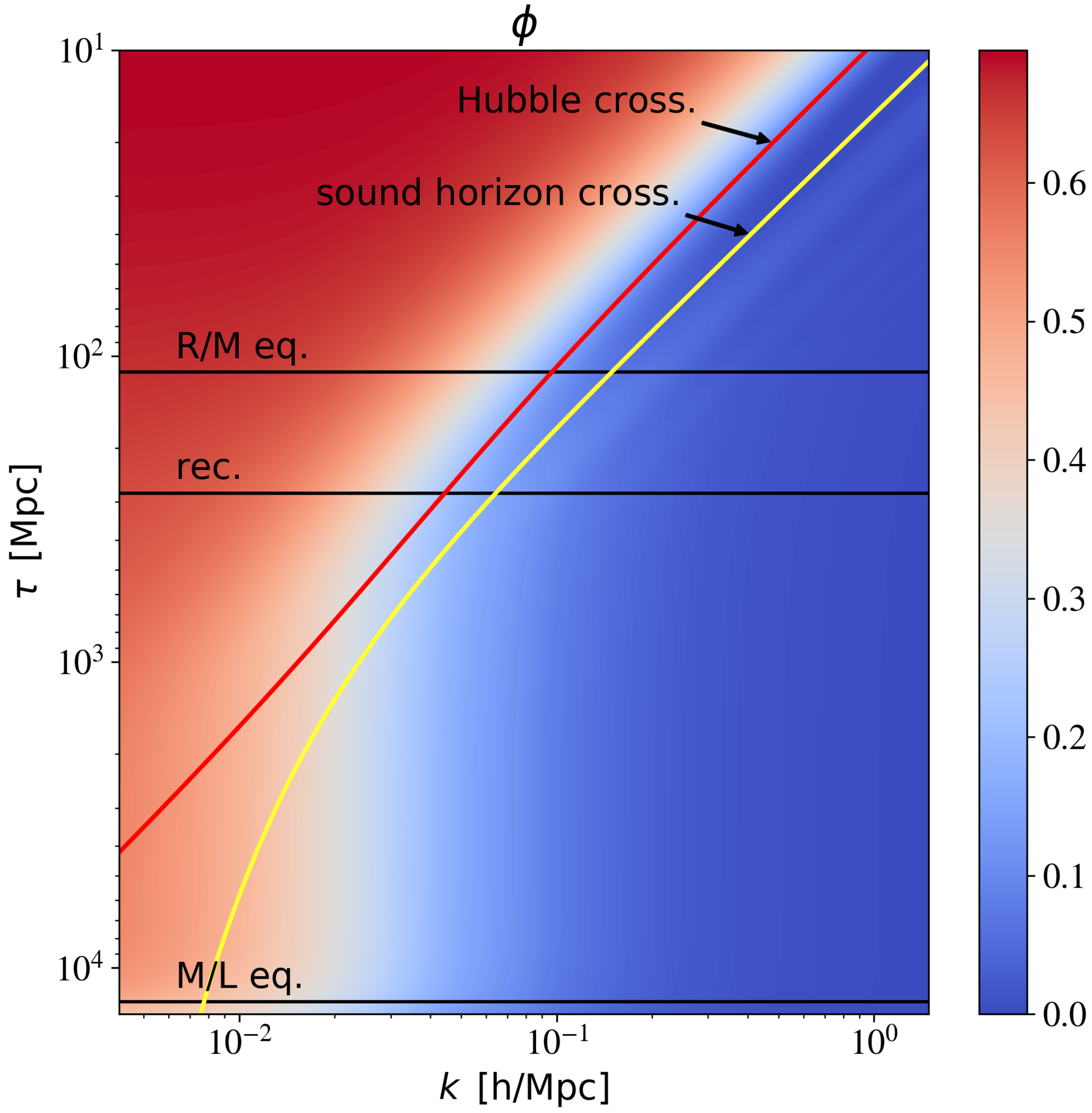


Evolution of Transfer Functions: metric

Metric $\phi(\tau, k)$:



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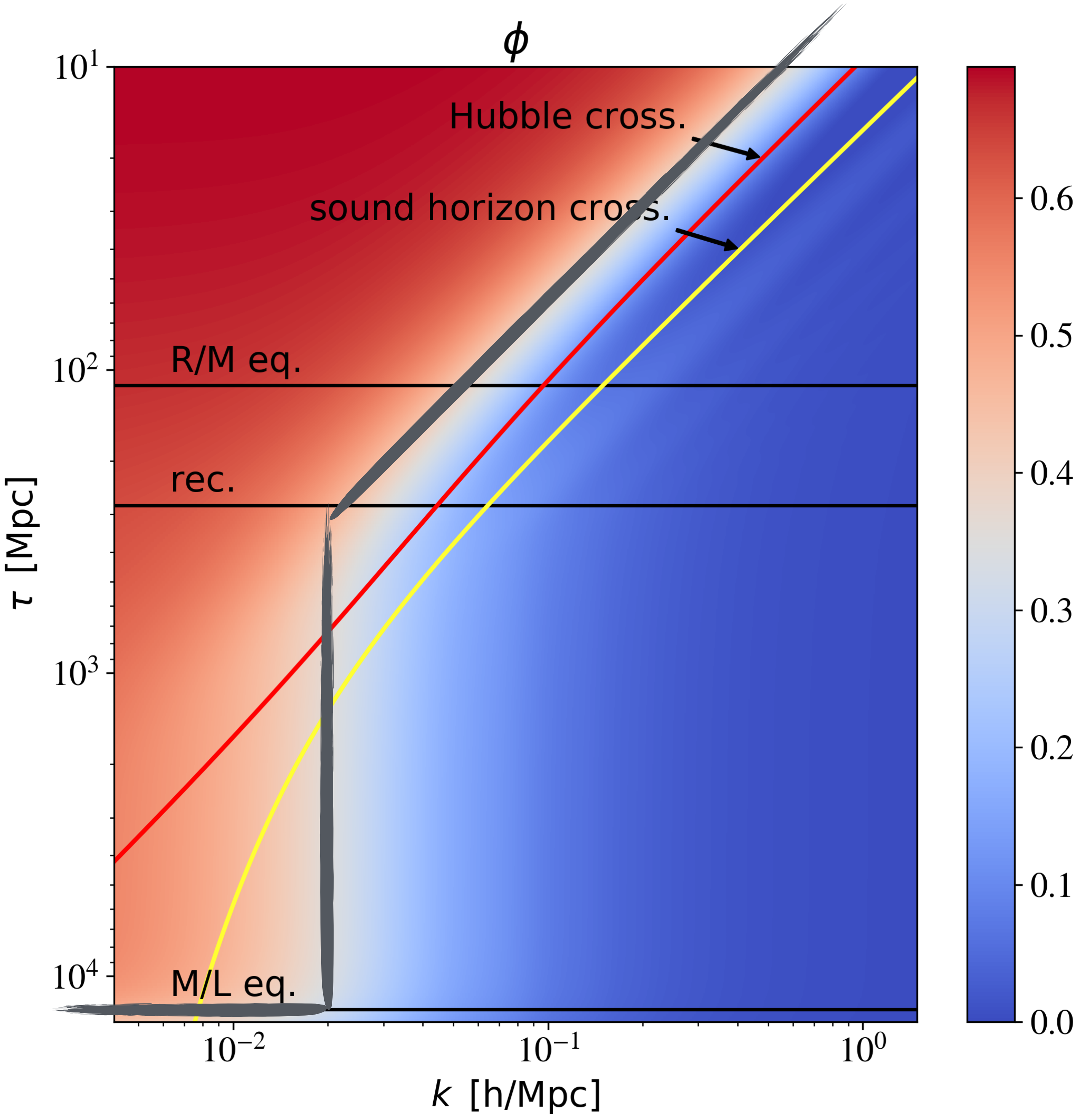
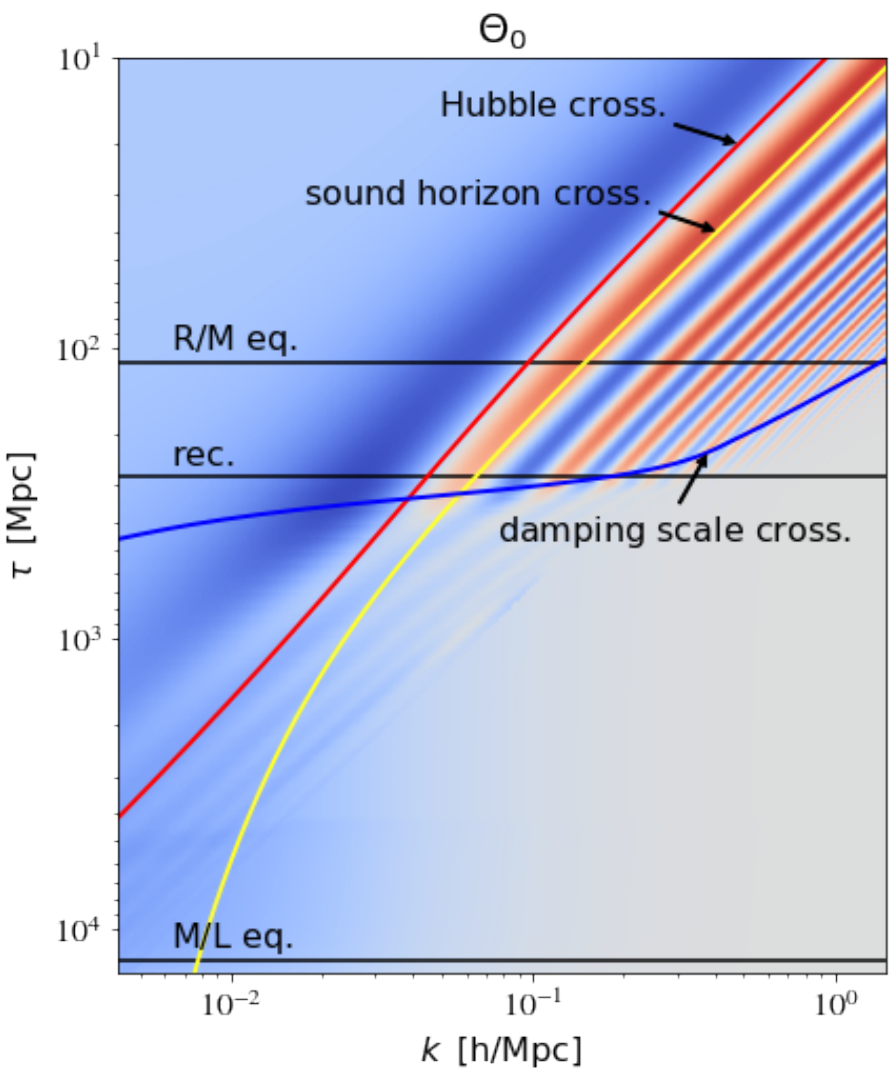
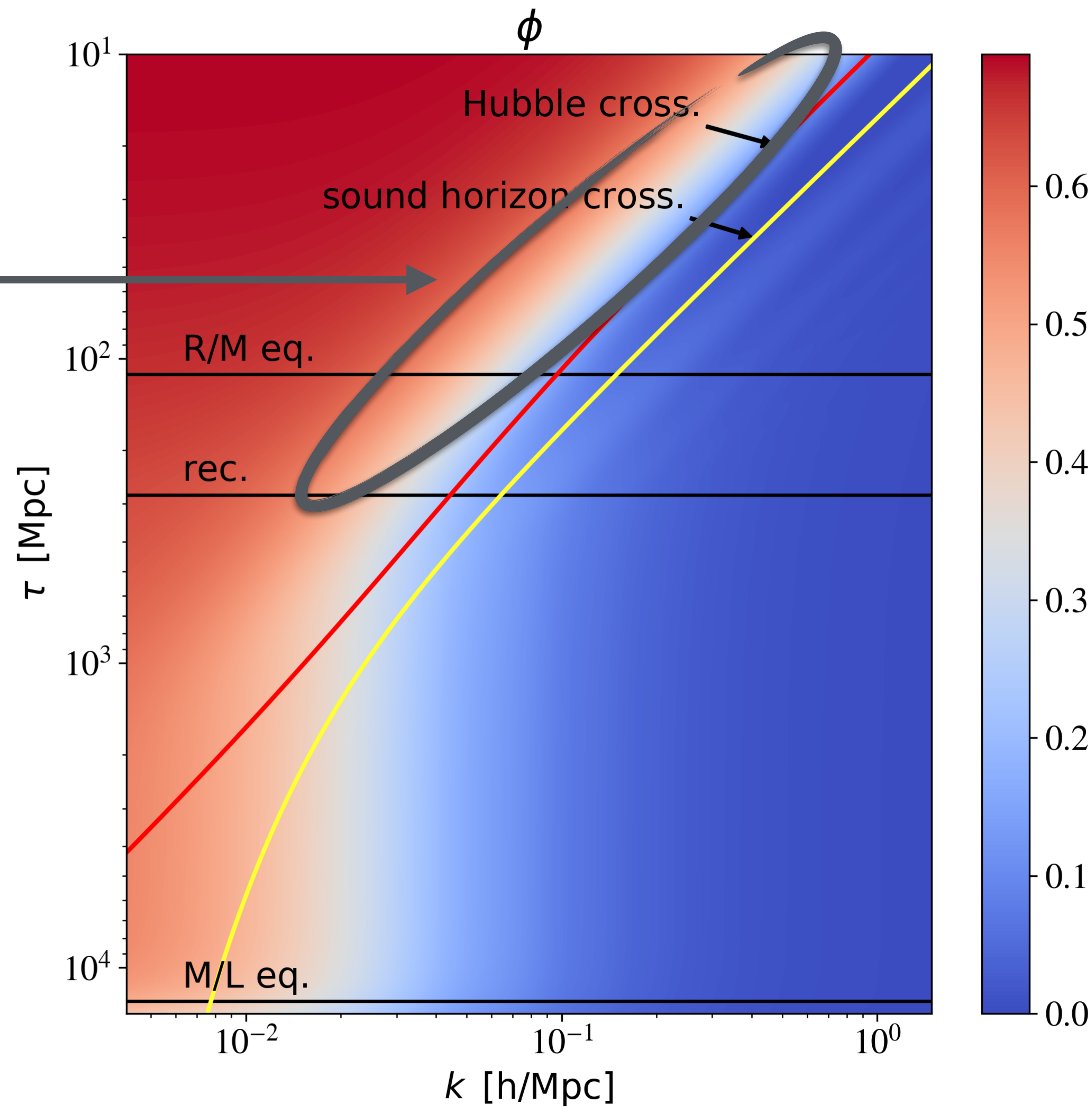


Evolution of Transfer Functions: metric

$$\frac{R'}{1+R}\phi' + \phi''$$ gravity boost





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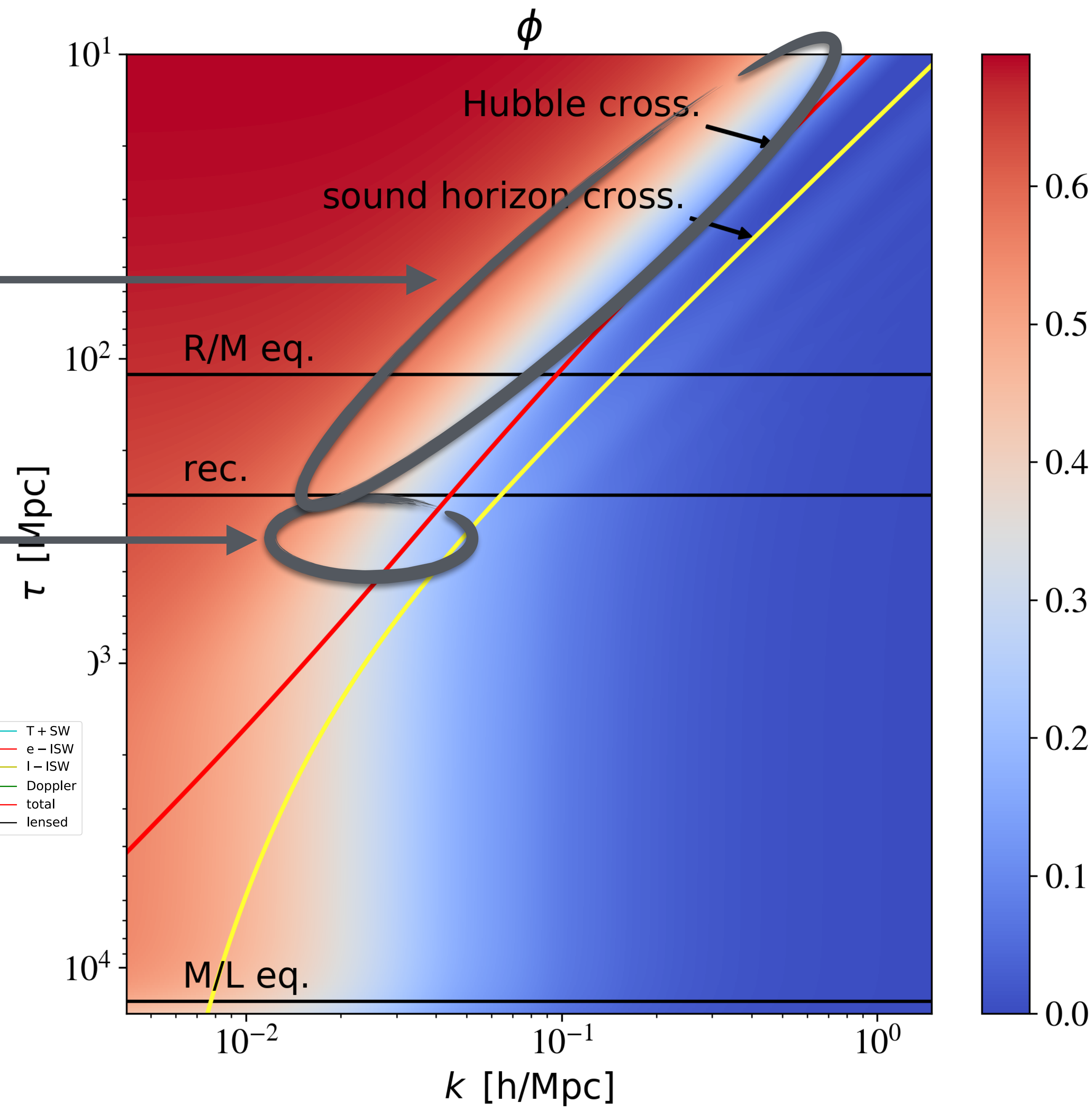

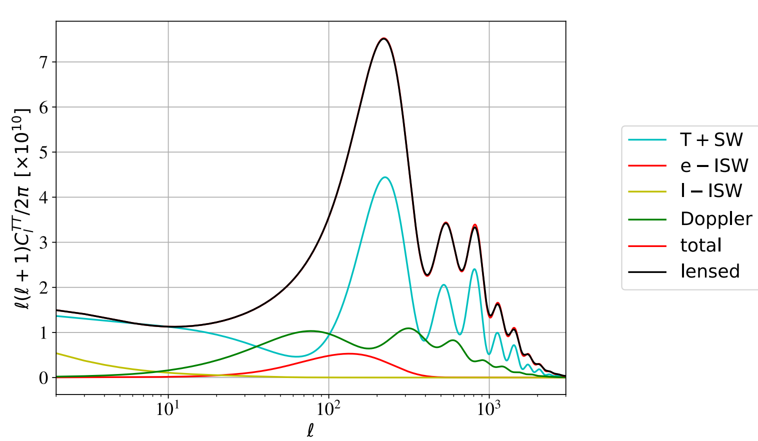

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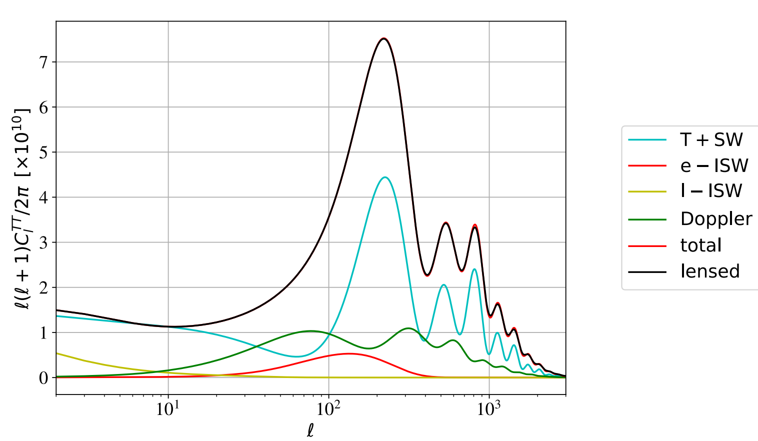
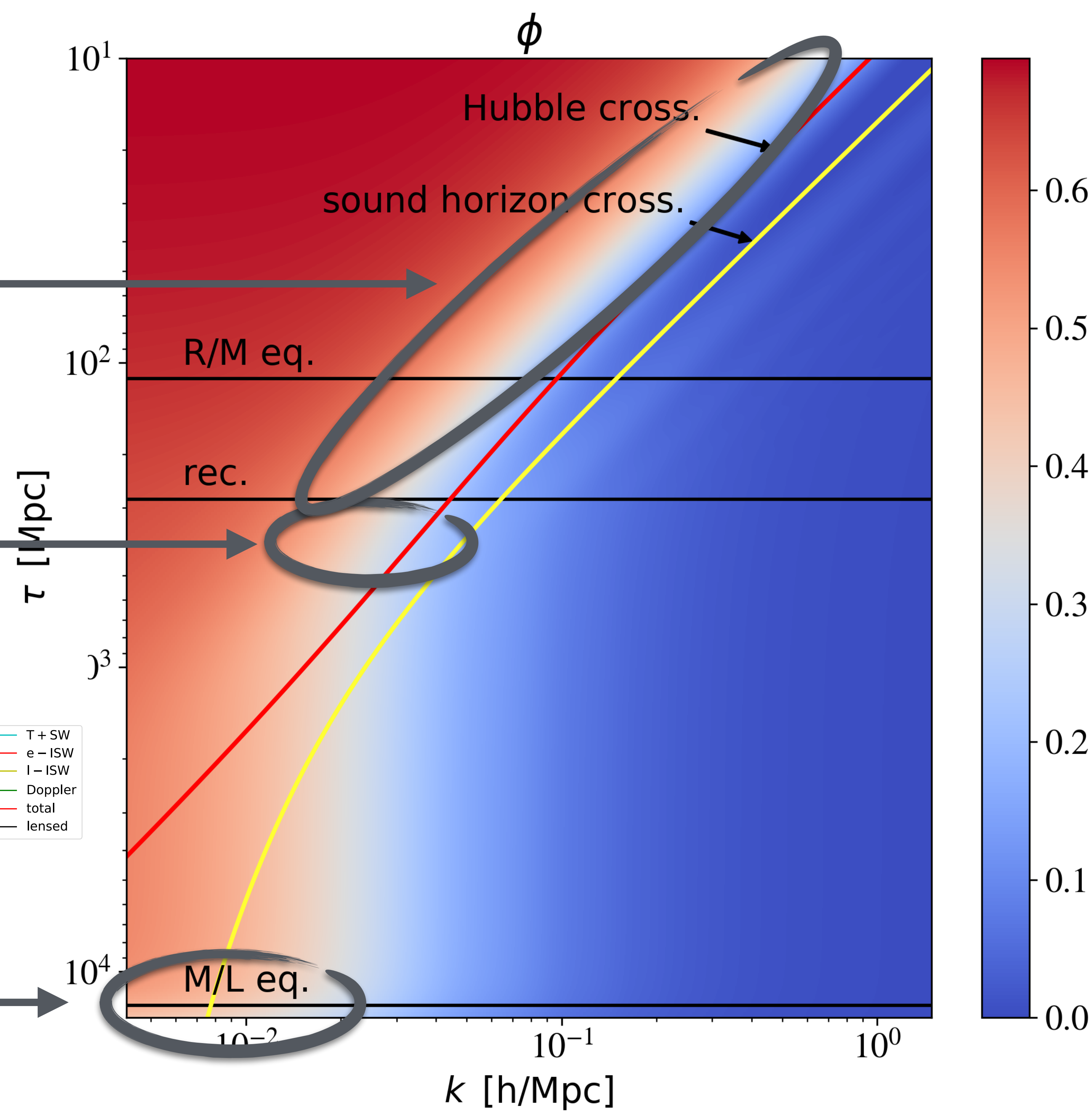


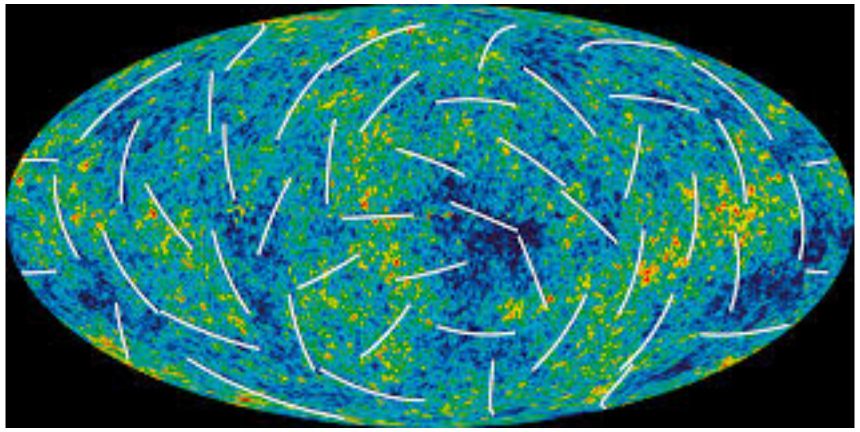
$$\underbrace{e^{-\kappa}(\phi' + \psi')\}}_{\text{ISW}}$$ late ISW



Polarisation

- Possible confusion:

  - Observed polarisation map = map of spin-2 quantity, can be decomposed in two scalar maps (E and B modes)



  - In isotropic and homogeneous universe, the polarisation of propagating photons can be described with one single function of direction for each wavenumber: only two Boltzmann hierarchies, one for T and one for P (F_l and G_l in Ma & Bertschinger 95)

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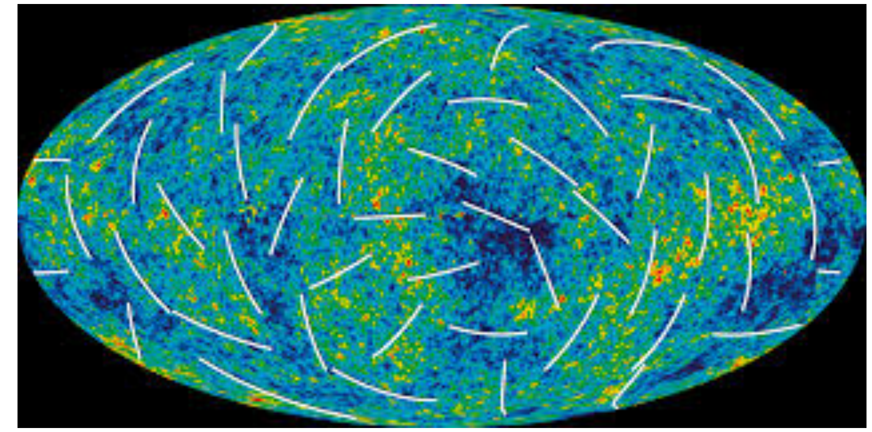

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- When generalising equations to vector/tensors and non-flat spherical/hyperbolic universes, authors of the 90's (Seljak & Zaldarriaga, Hu & White, …) introduced 3 coupled hierarchies for T, E, B, used in CAMB
- Tram & JL 1305.3261 rederived all cases in terms of two hierarchies (T and P); E and B modes recovered from different line-of-sight expressions

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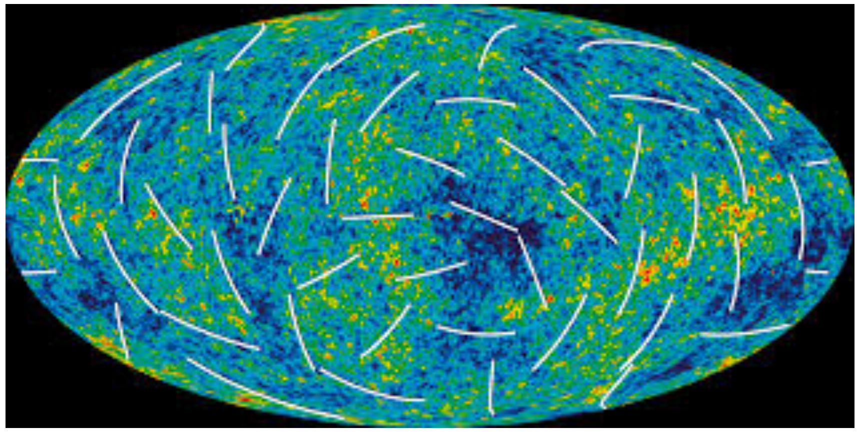

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- Polarisation makes line-of-sight integral more complicated: need for derivation by part of source terms (CMBFAST/CAMB) or extra convolutions with $j_l'(x)$, $j_l''(x)$ (CLASS)

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Spatial curvature

- Expansion not in Fourier modes but in eigenfunctions of Laplacian operator in spherically/hyperbolically curved space (Seljak, Zaldarriaga, Bertschinger 97; Hu & White 97):
  - Extra corrections in equations of motion
  - Hyperspherical Bessel functions with two real arguments instead of one

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- (Hyper)spherical Bessel functions always computed on the fly by modern Boltzmann code, using more or less fast/approximate methods (forward/backward recurrences, WKB, …), see Tram 1311.0839

- This algorithm + interpolation scheme for Bessel functions crucial for code performances, see JL & Tram 1312.2697

History of Boltzmann codes

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- 2017: Zurich group releases PyCosmo in python, currently computing only transfer functions and P(k) for restricted flat cosmologies (thus no Cl's)

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- Transfer functions in harmonic space: $\Delta_l(k)$ (CMB, cosmic shear, number counts)

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- Background quantities: scale factor, densities, pressures, horizons, distances…
- Thermodynamical quantities: scattering rate, optical depth, visibility…
- "Perturbations": transfer functions $T_j(t,k)$
- Initial conditions: analytic adiabatic/isocurvature or inflation simulator
- Linear spectra in Fourier space: $P_L(z,k)$
- Non-linear spectra in Fourier space: corrections from Halofit, HMcode, …
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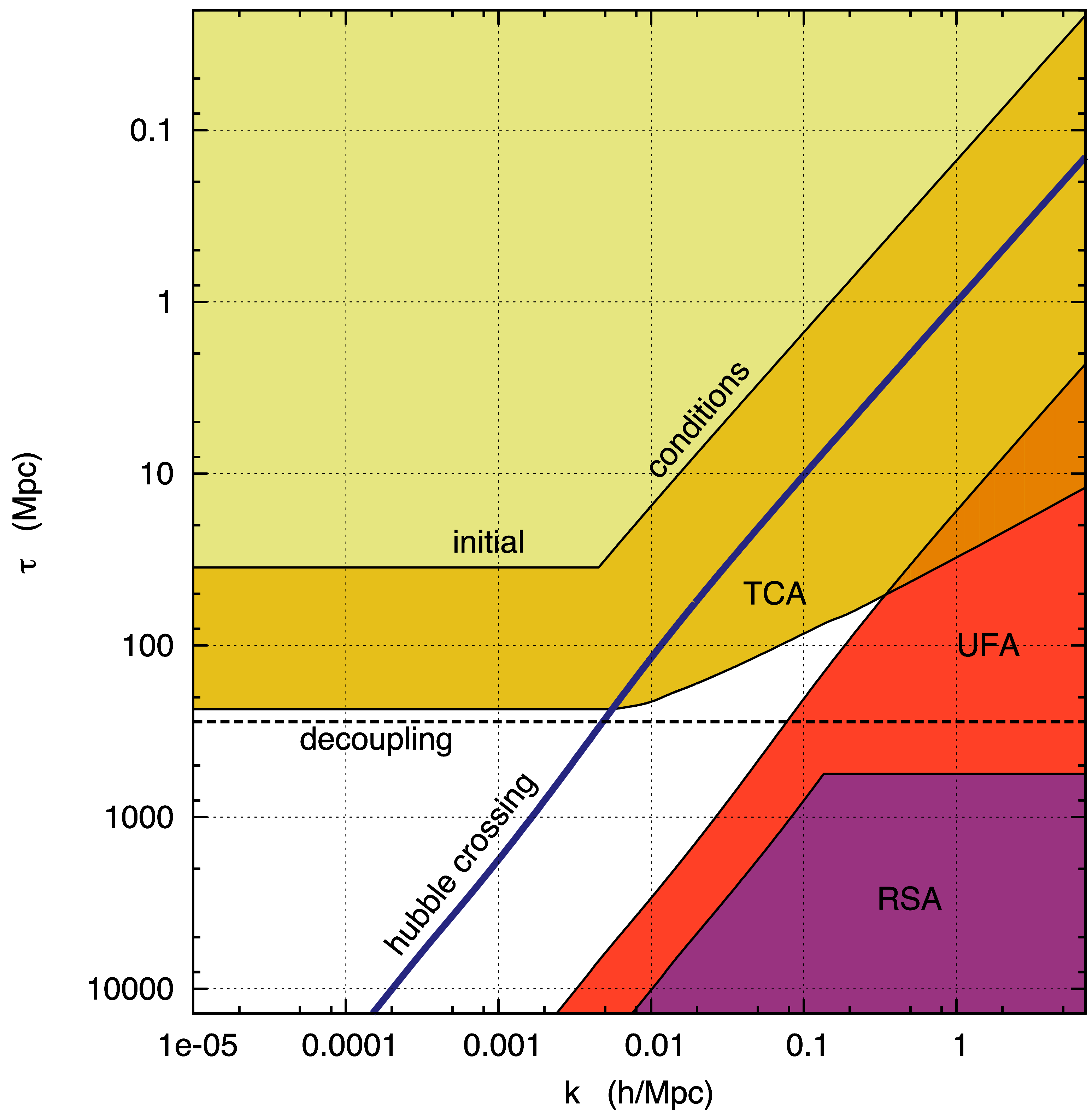
> - Fully parallelisable
> - depends on discretisation, interpolation, integration schemes
> - Significant speed up requires mathematical

Evolution of Transfer Functions: metric



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Evolution of Transfer Functions: metric

Analytical solutions up to ICs
(super-Hubble,
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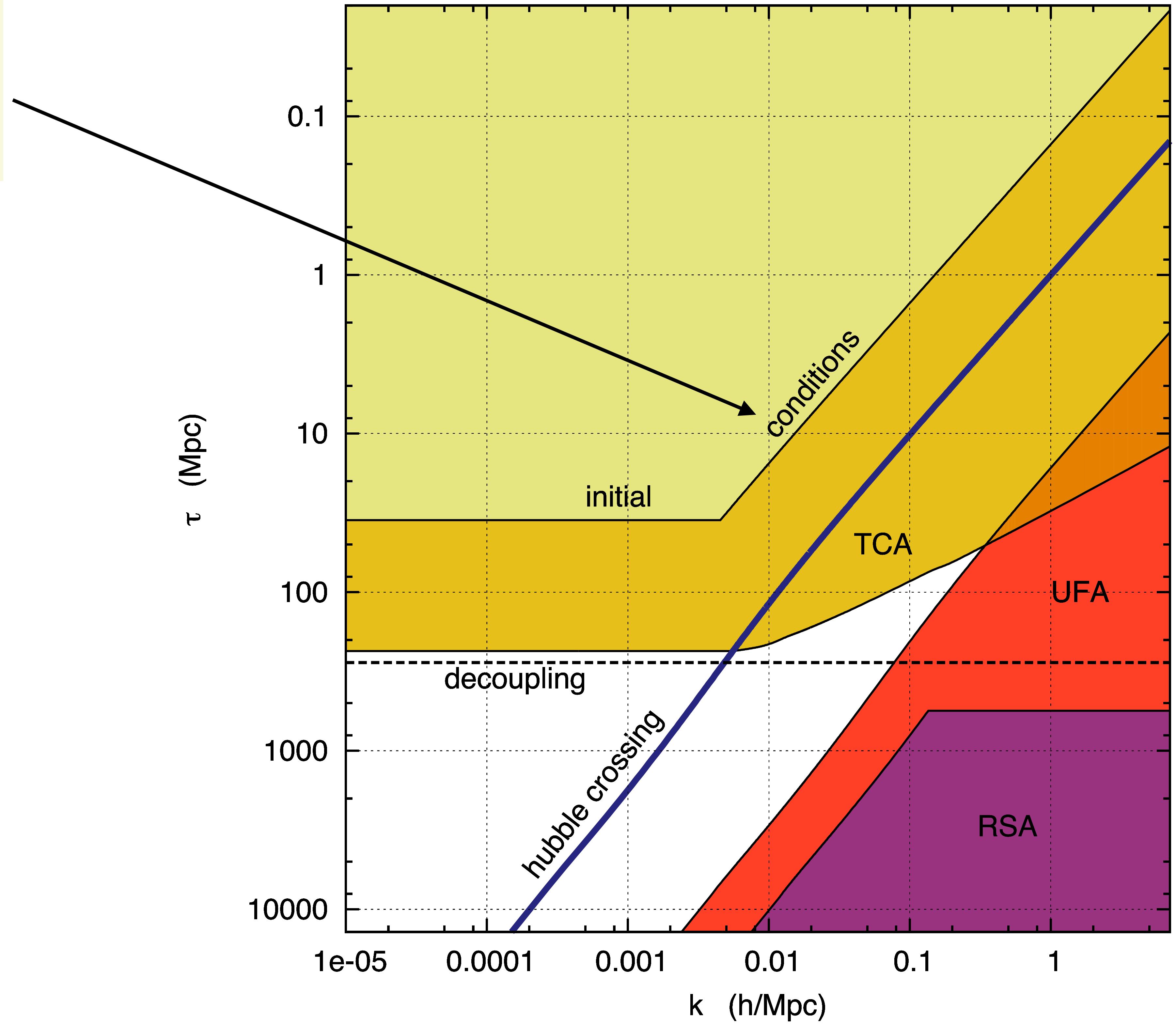

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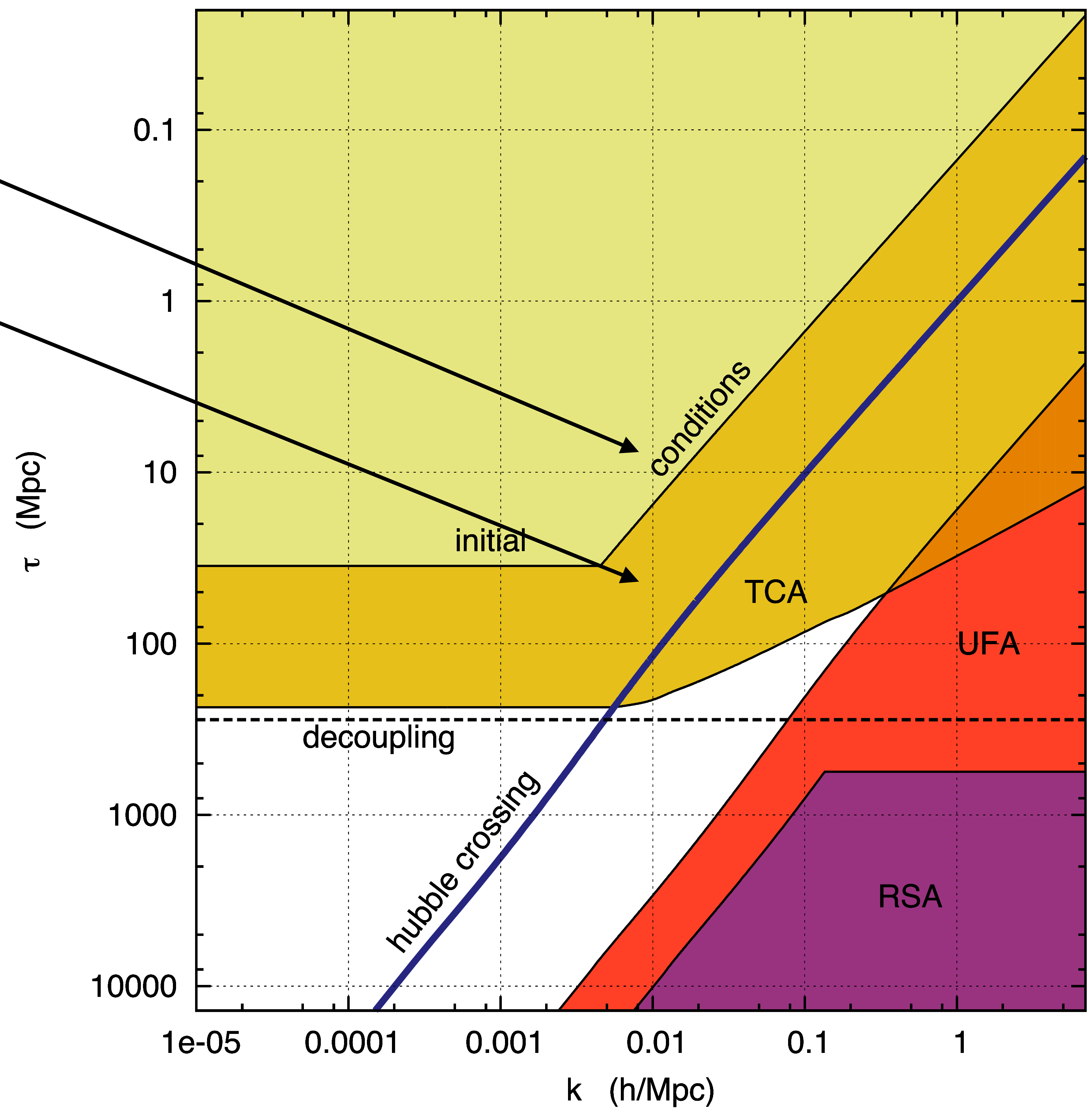

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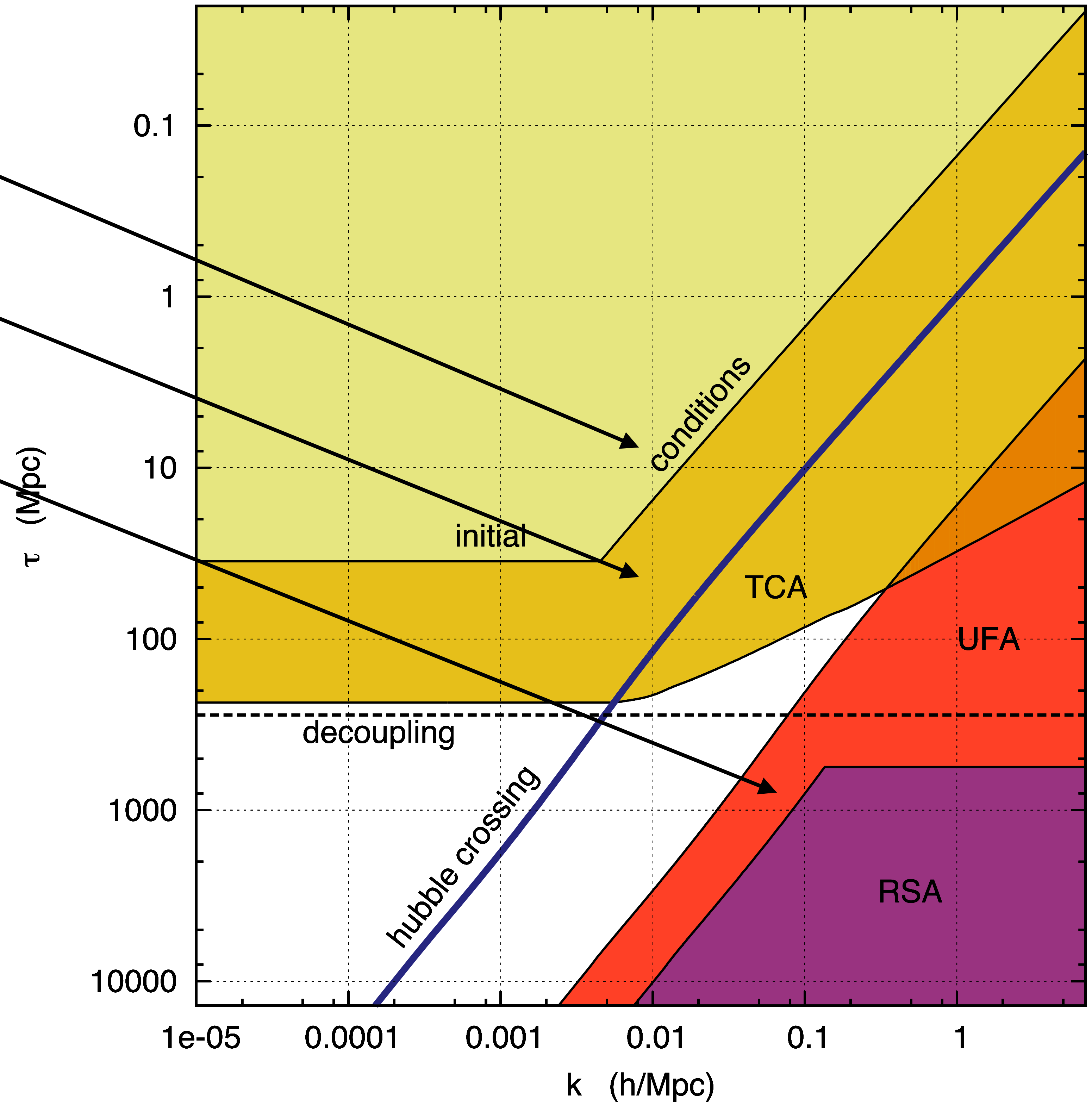

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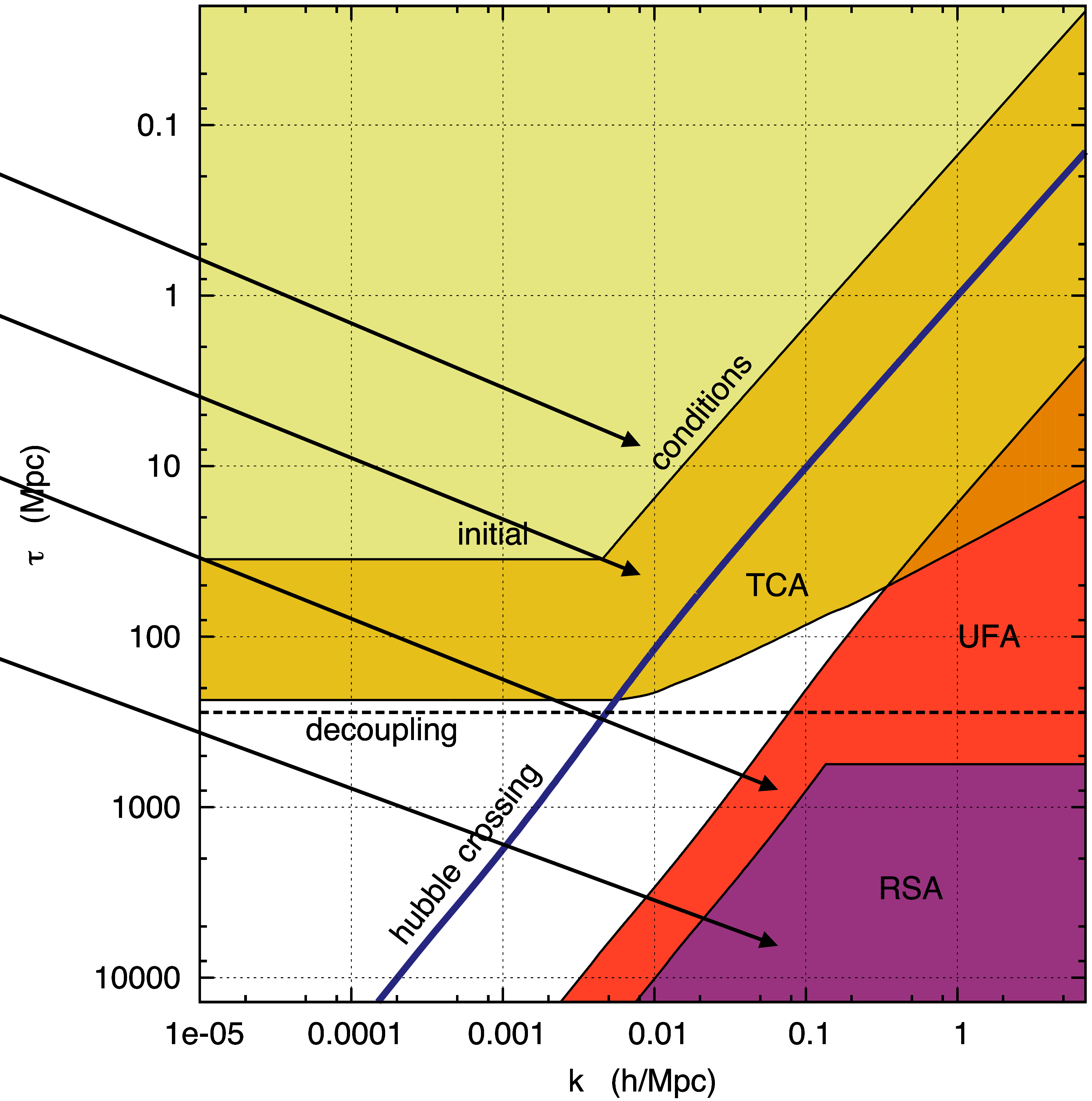

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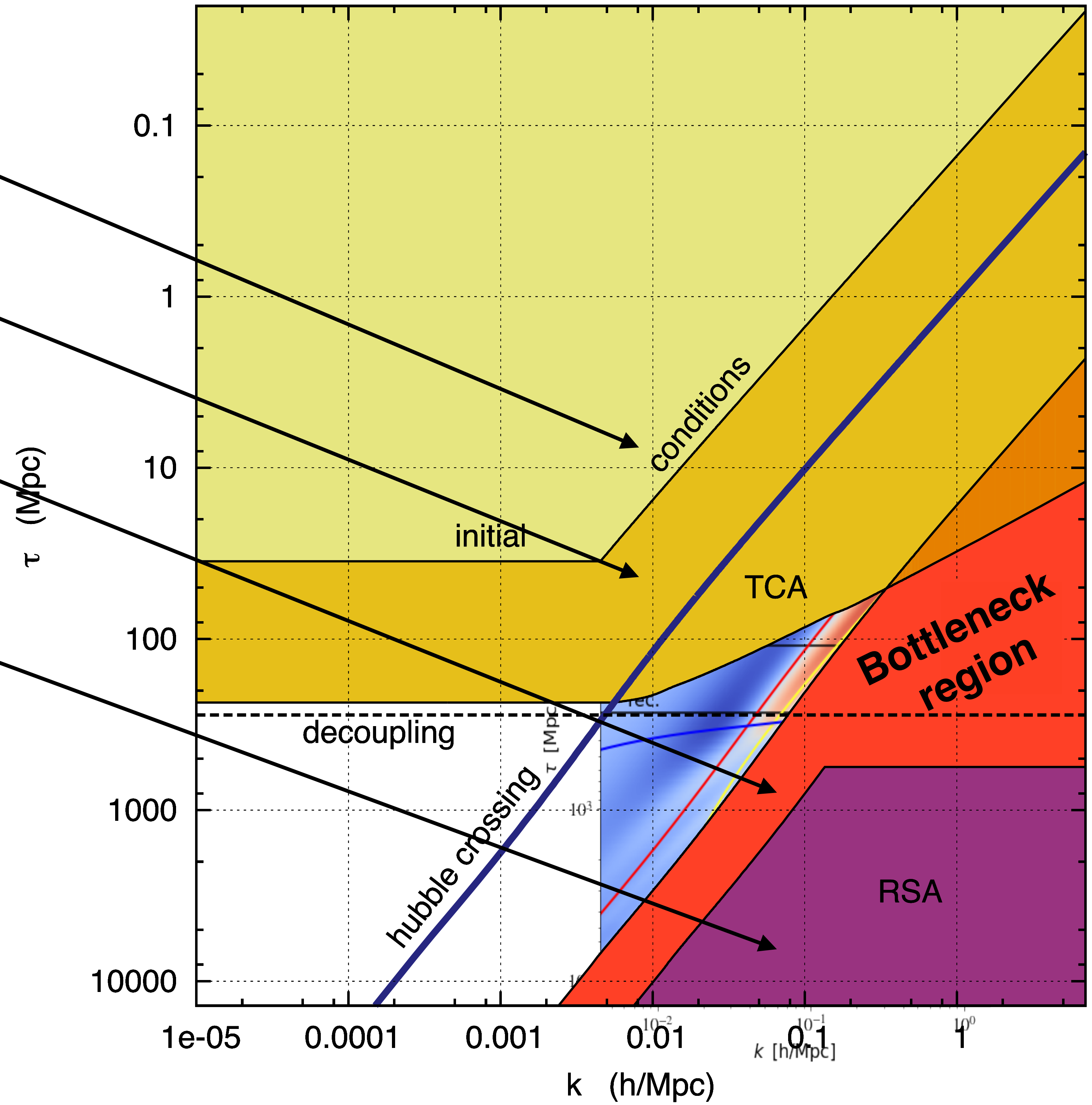

Thank you