FROM

LARGE COLD SIMULATIONS

TO

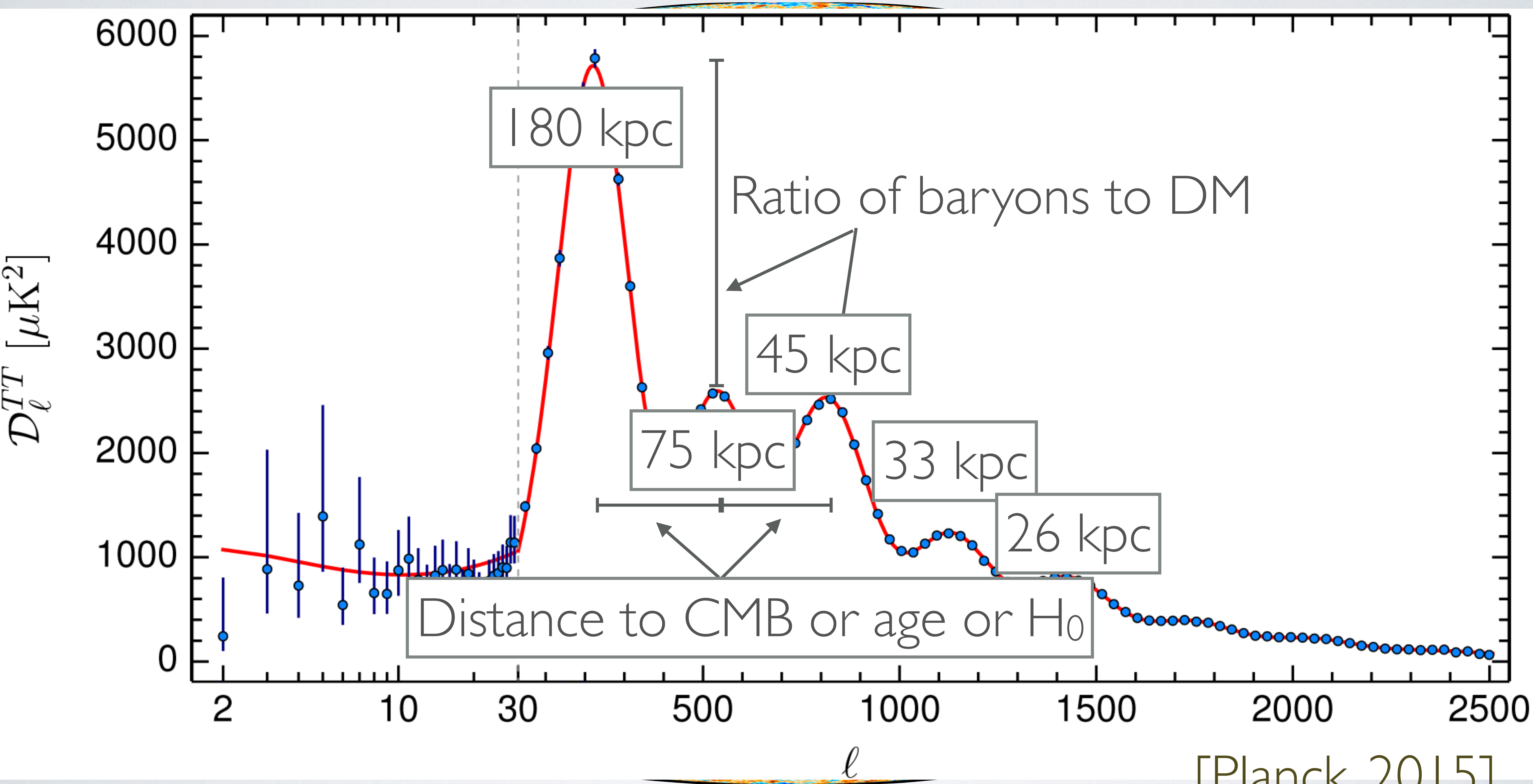
FUNDAMENTAL PARTICLE PROPERTIES

Wessel Valkenburg

OUTLINE

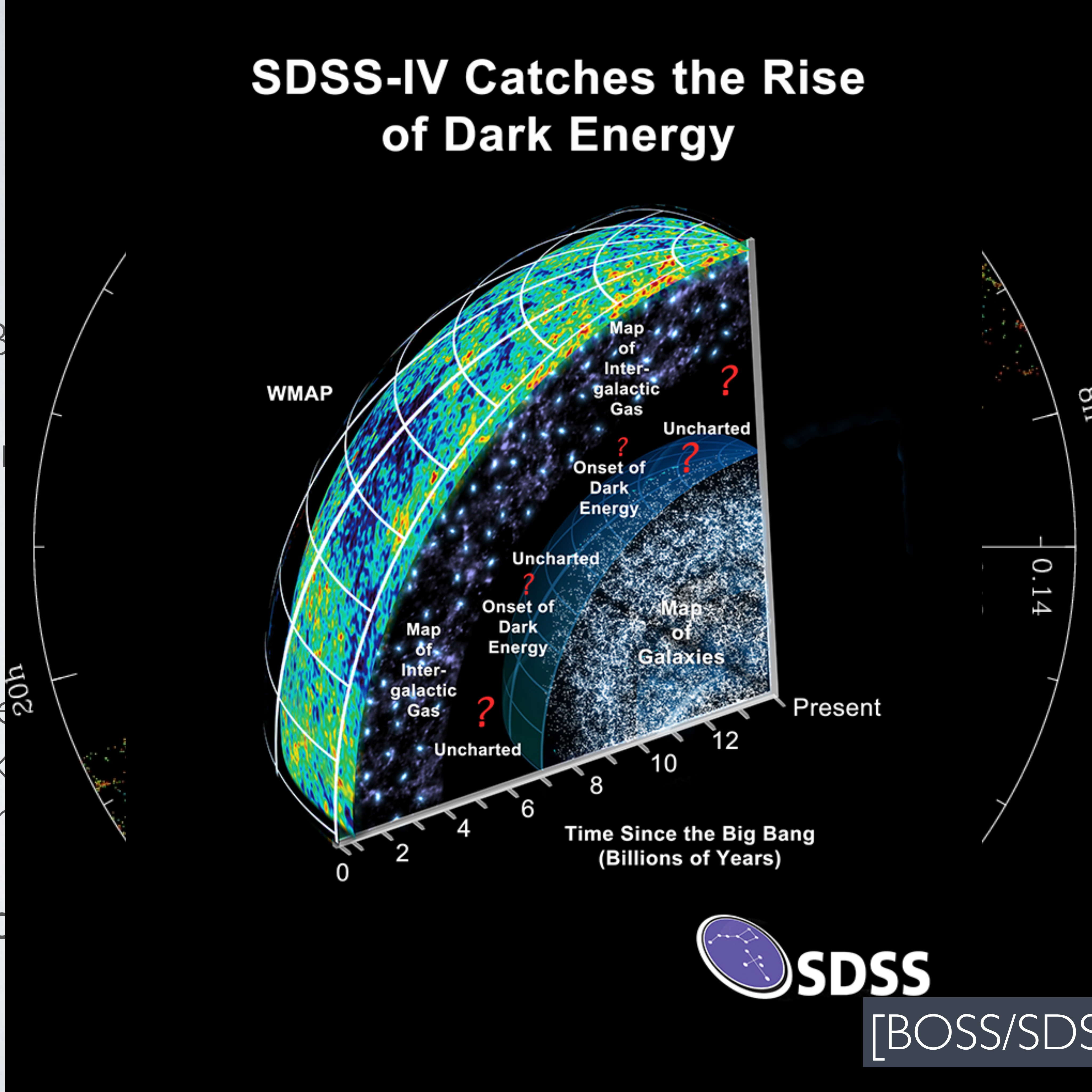
- What we know about Dark Matter (lower bounds)
- Gravitational evolution of structure in Universe
- General relativity and Newtonian gravity
- Dark Matter mass from simulations?
- Setup with multiple matter types: source of inaccuracy

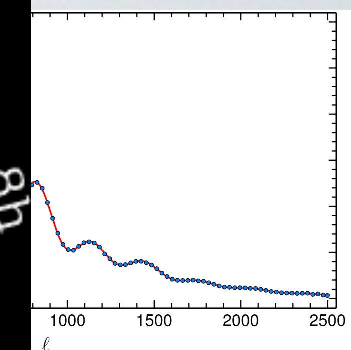
DARK MATTERS?



[Planck, 2015]

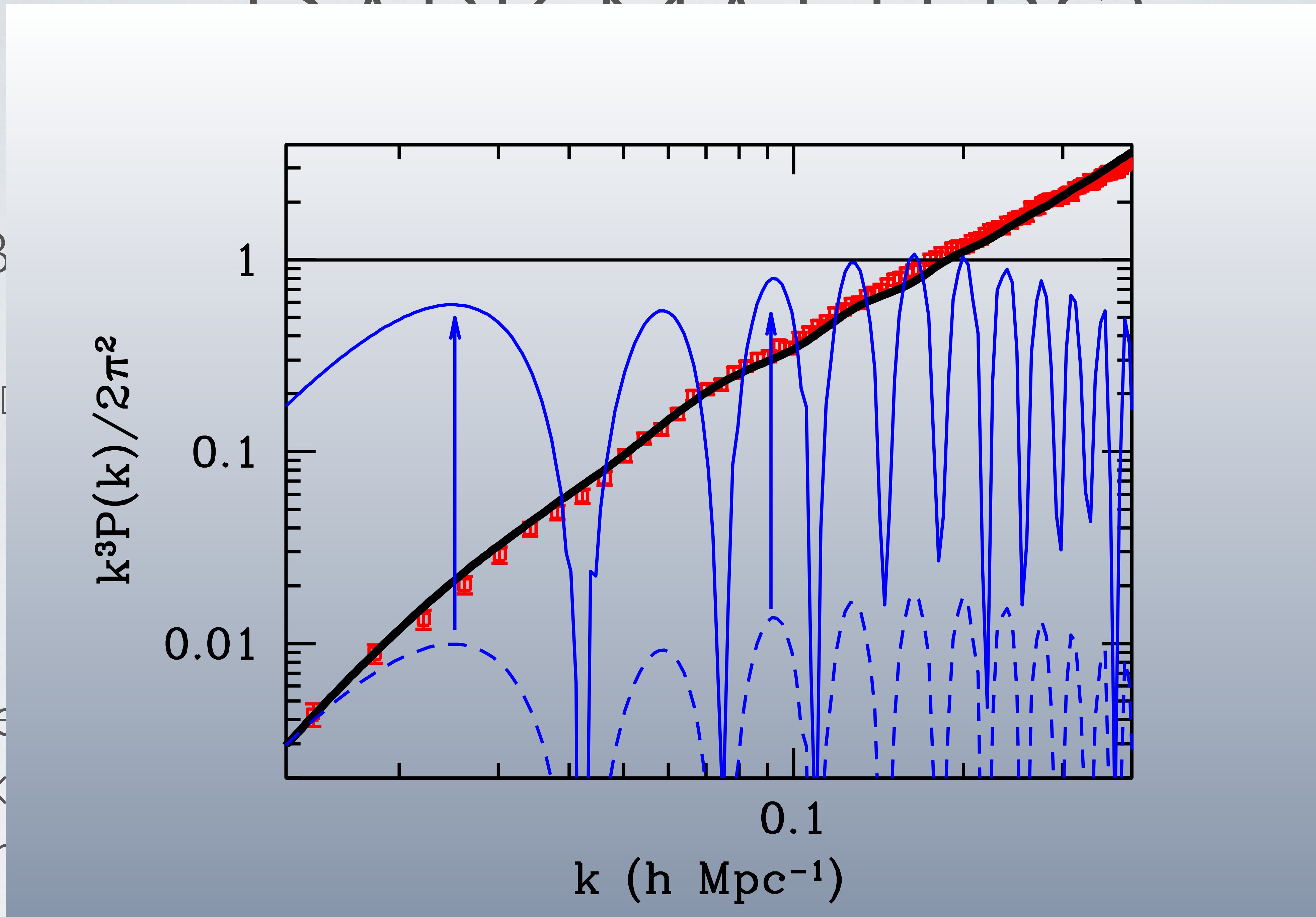
- CMB
  - Ω
    at
  - Σ
- Large
  galax
  redsh
  - f



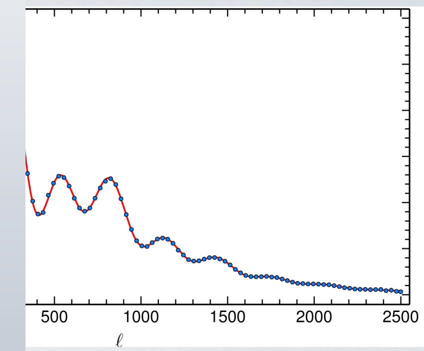


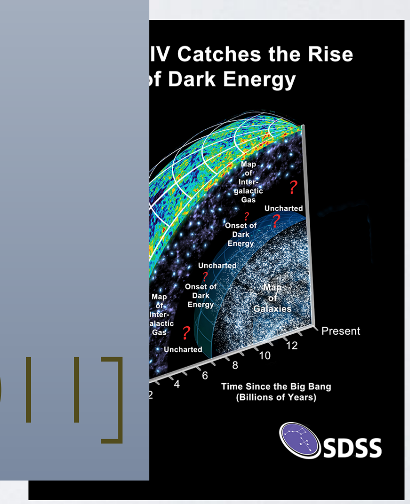
[BOSS/SDSS, 2014]

- CMB
  - Ω
    at
  - Σ
- Large
  galax
  redsh
  - f c



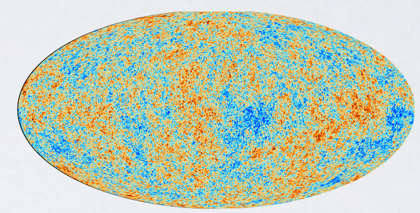
[Dodelson, 2011]

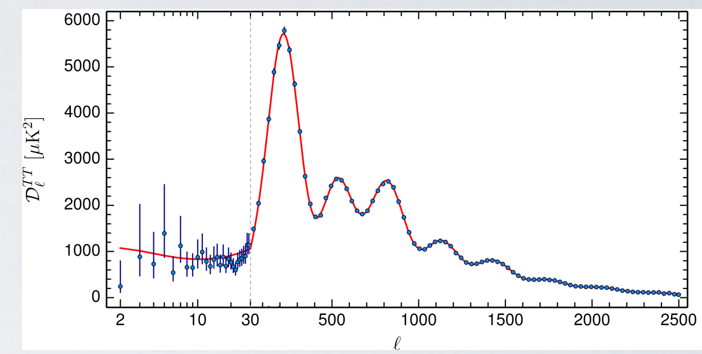


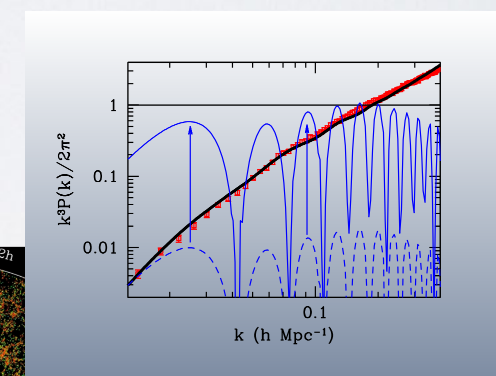


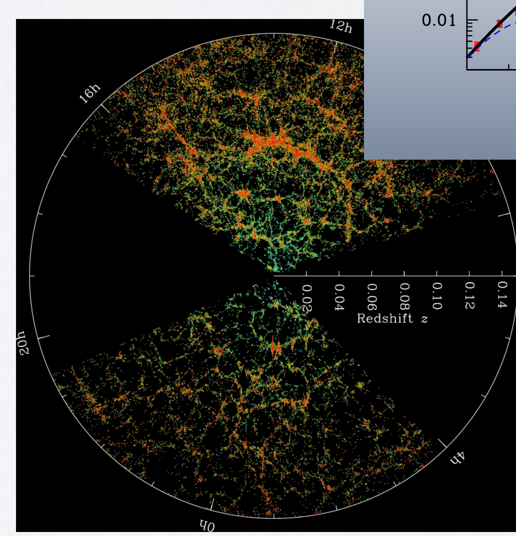
DARK MATTERS?

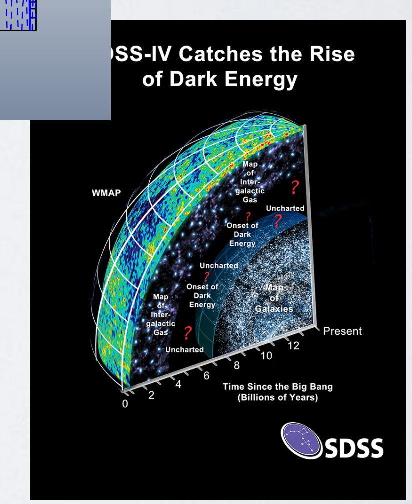
- CMB:
  - Ω_{DM} = 0.308±0.012 at O(20 kpc)
  - $\Sigma\, m_\nu < 0.72$ eV (eISW)
- Large scale structure from galaxy surveys, weak lensing, redshift space distortions, … :
  - f σ_8, Ω_M (not DM!)









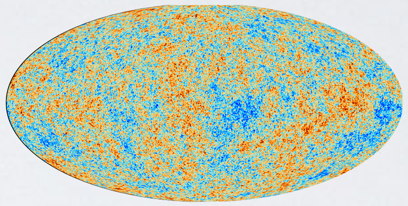


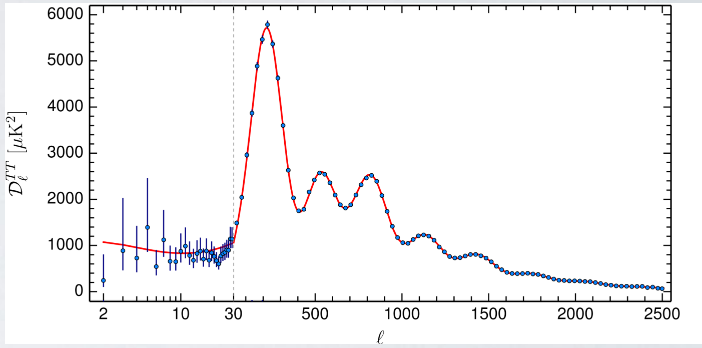
MOND

MOdified Newtonian Dynamics

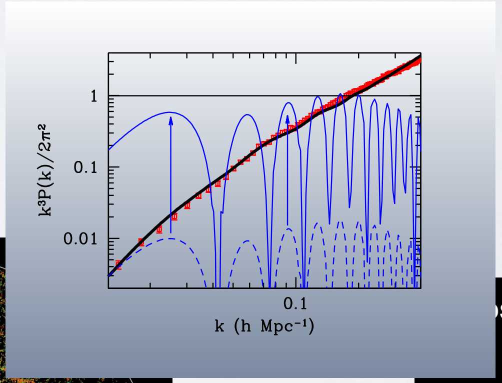
- Just kidding.
- But compute! Don't discard on religious grounds.
- Bullet cluster, and this is true, the best experts say it, falsifies ΛCDM at 5σ.

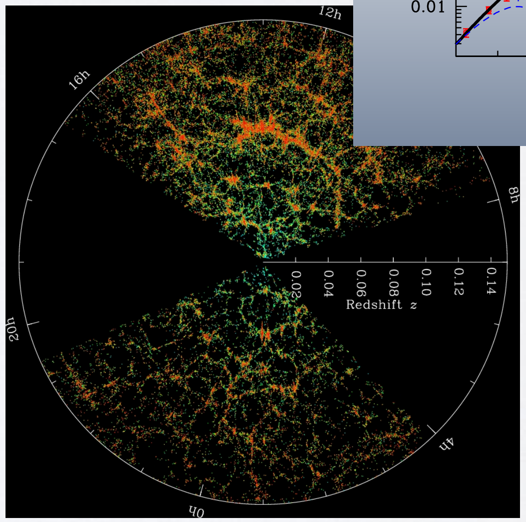
PERTURBATION THEORY

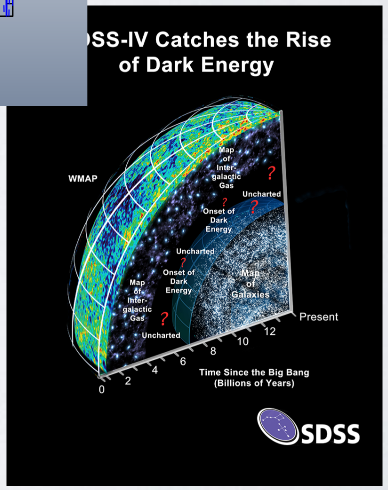




- Both CMB & LSS sensitive to *linear* density fluctuations.
- CMB is insensitive to CDM properties
  - (other than coupling to baryons/photons)

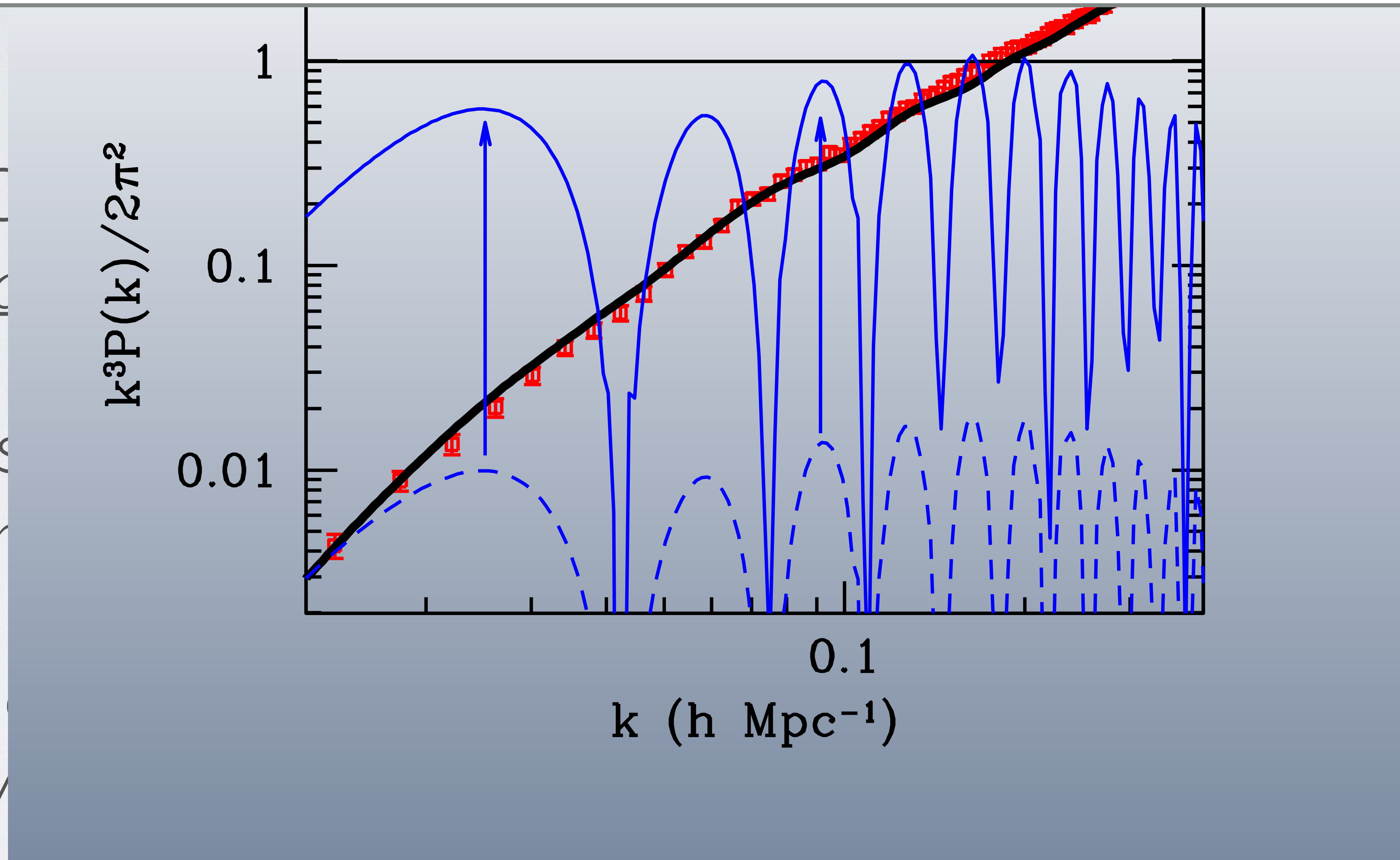


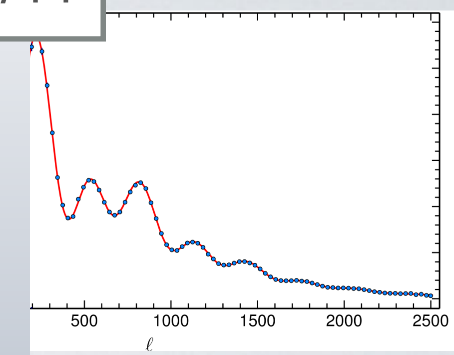




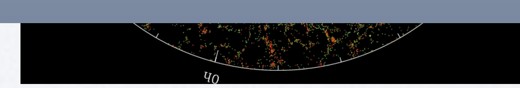
PERTURBATION THEORY

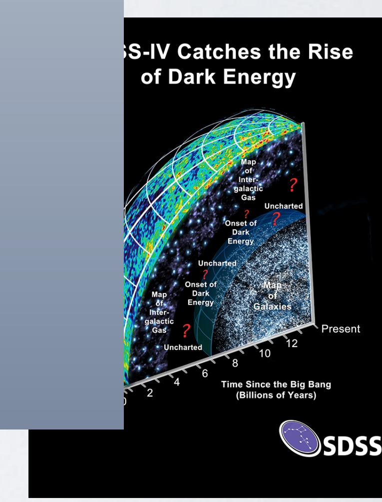
crosses 1 at k ~ 0.2 h/Mpc or roughly 30 Mpc/h



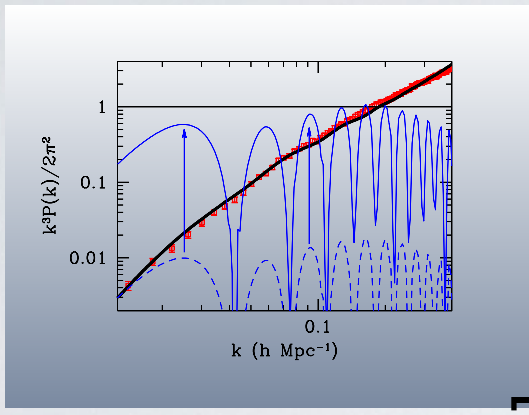


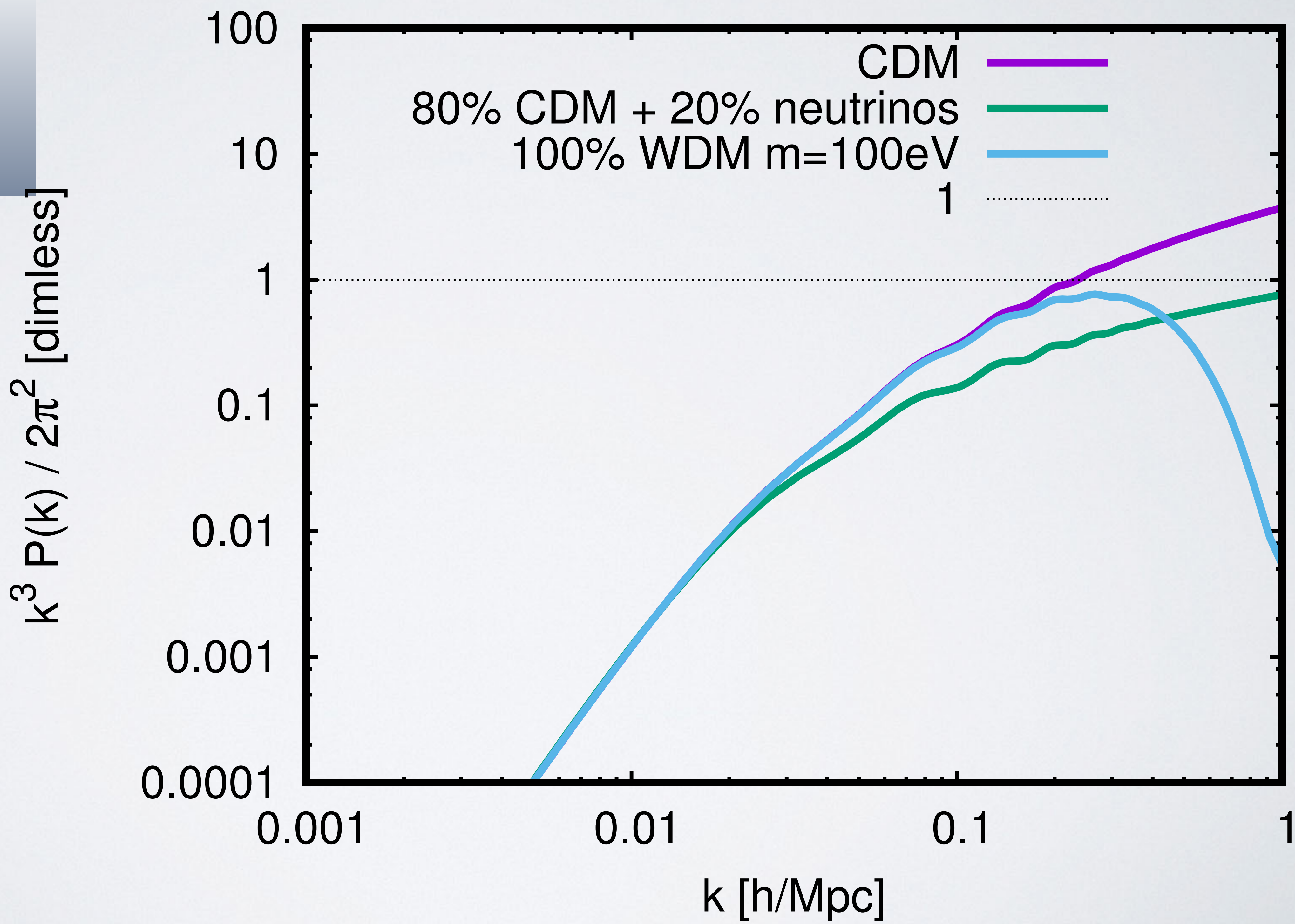
- Both C
  to *linea*
- CMB is
  proper
  - (oth
    bary

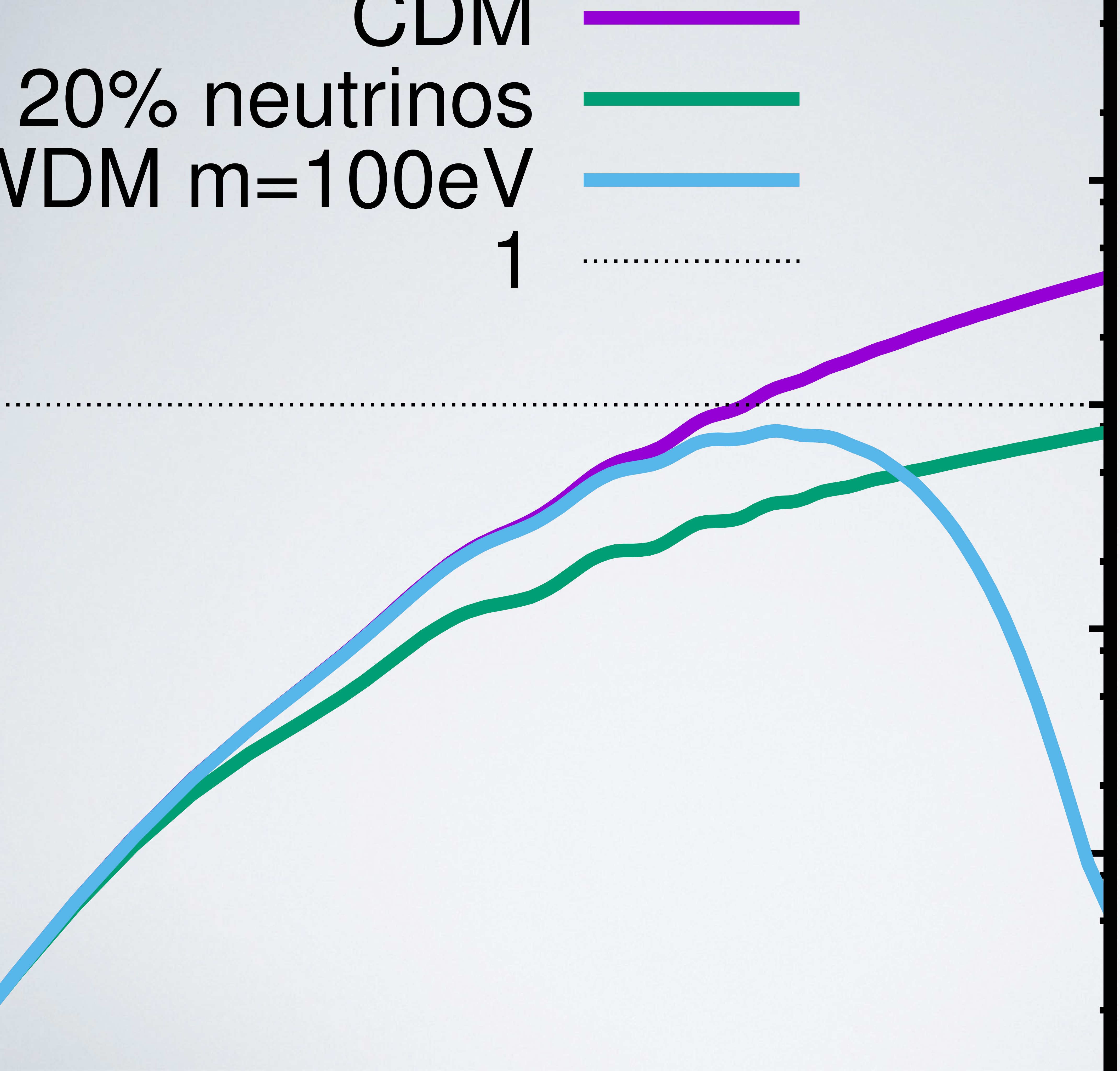




PERTURBATION THEORY

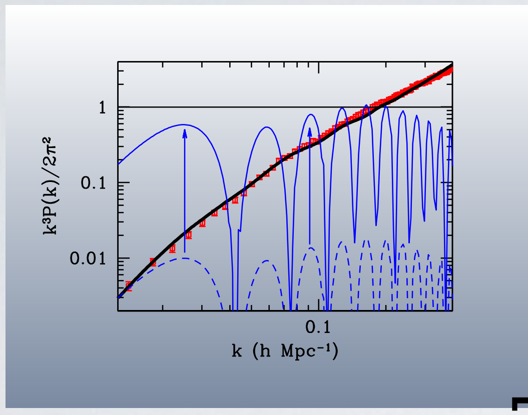


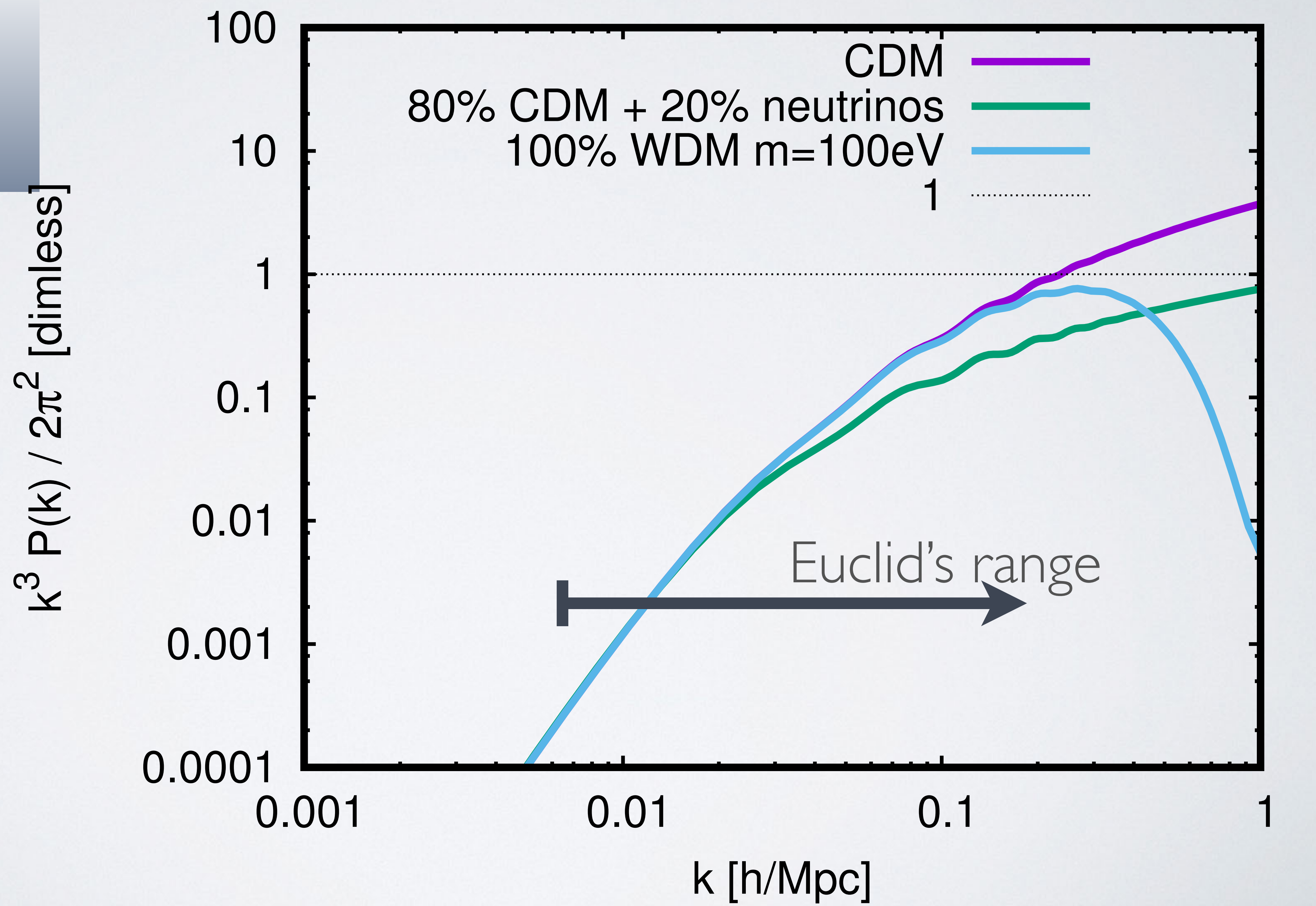




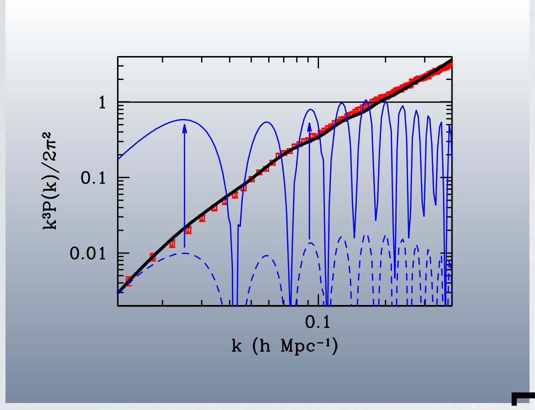
CDM
20% neutrinos
WDM m=100eV
1

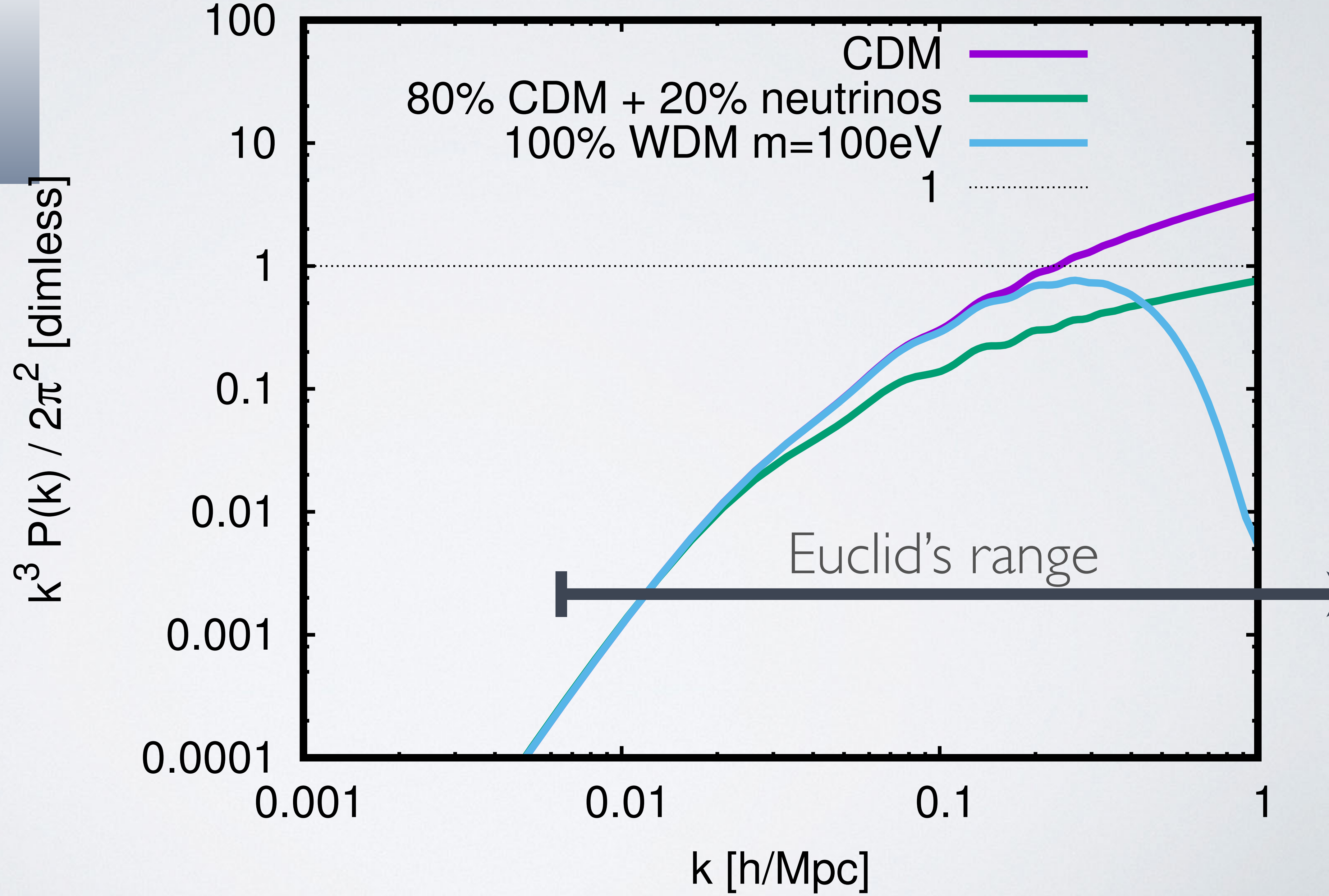
PERTURBATION THEORY



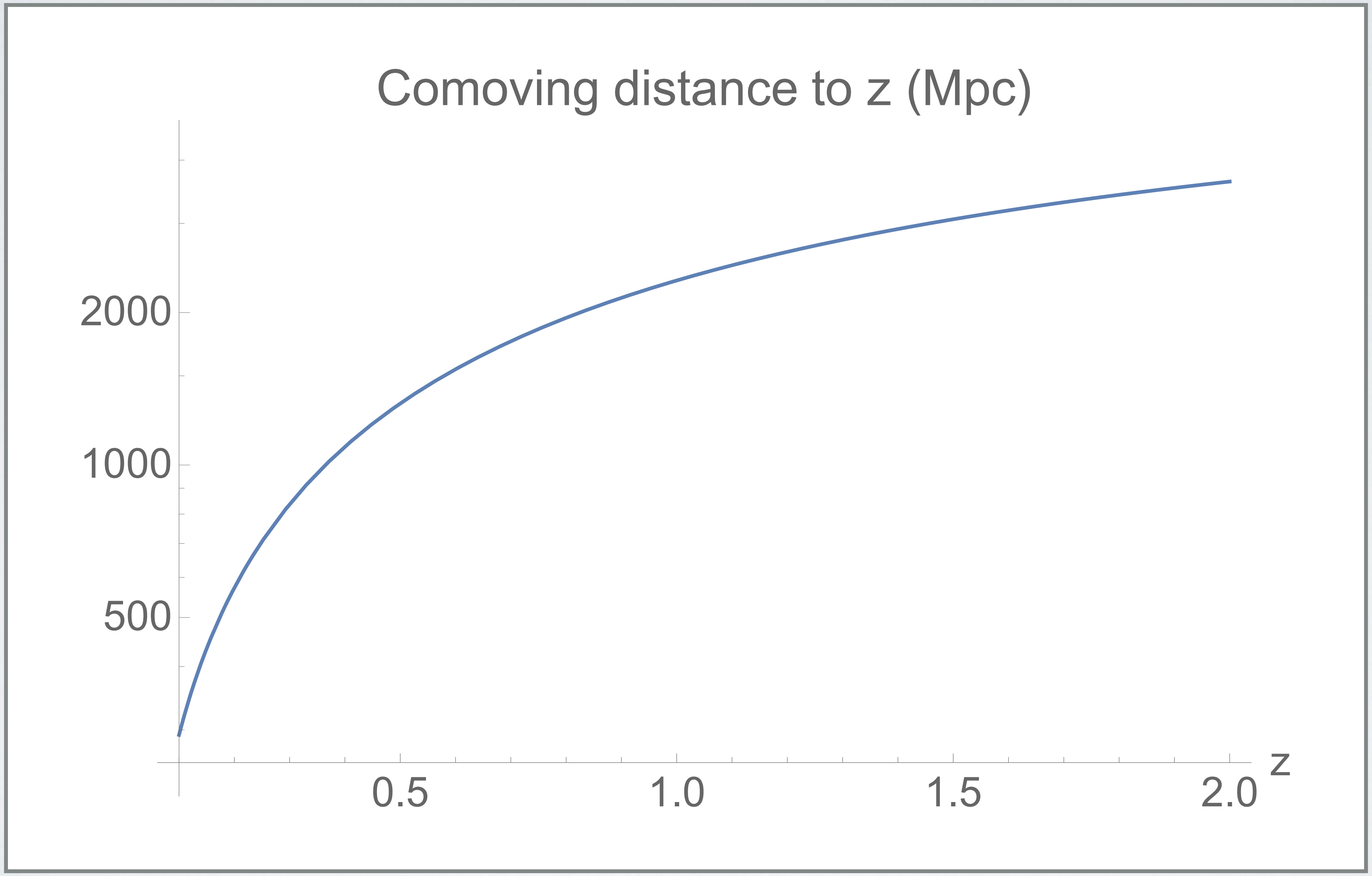


PERTURBATION THEORY

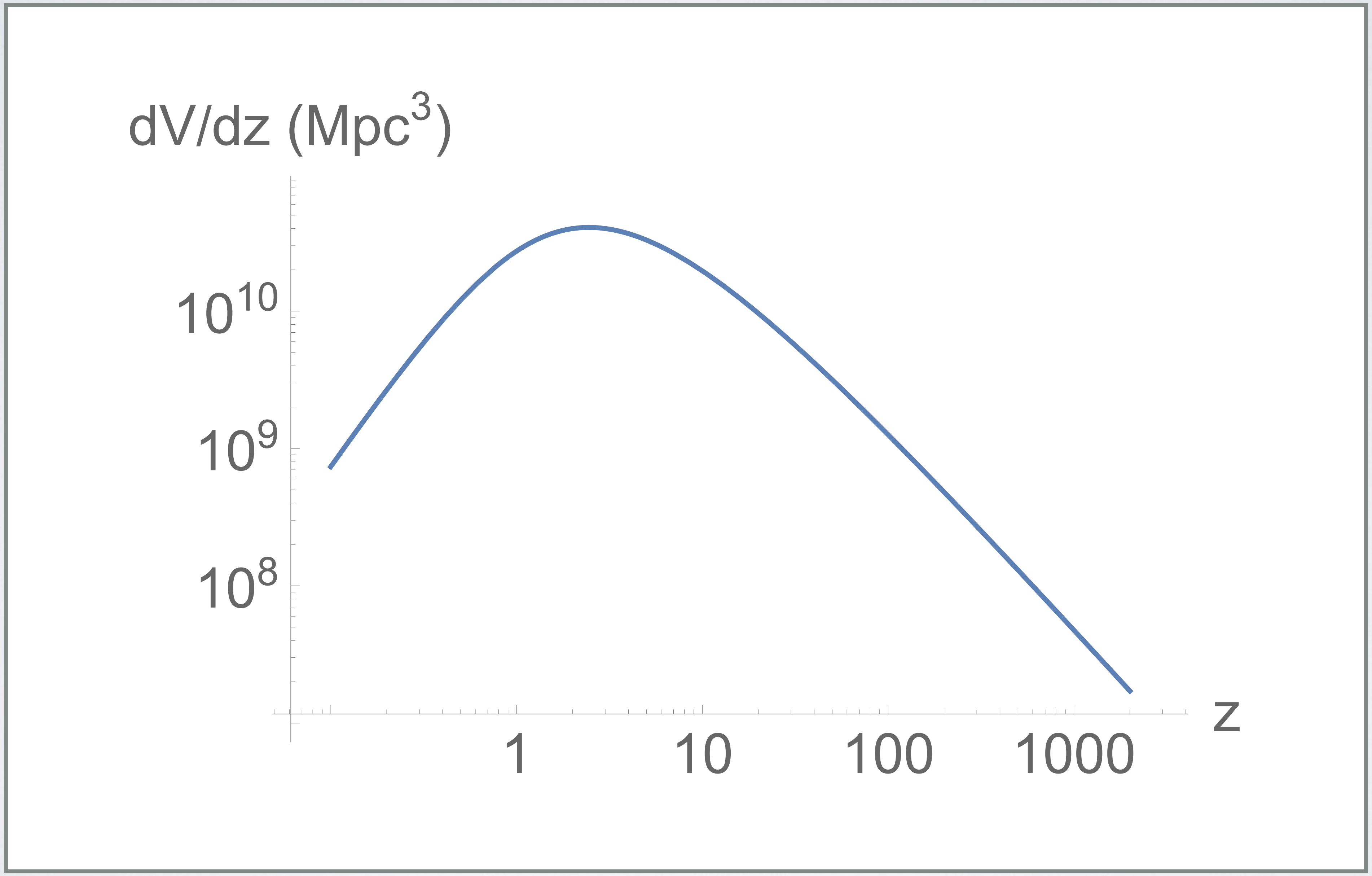




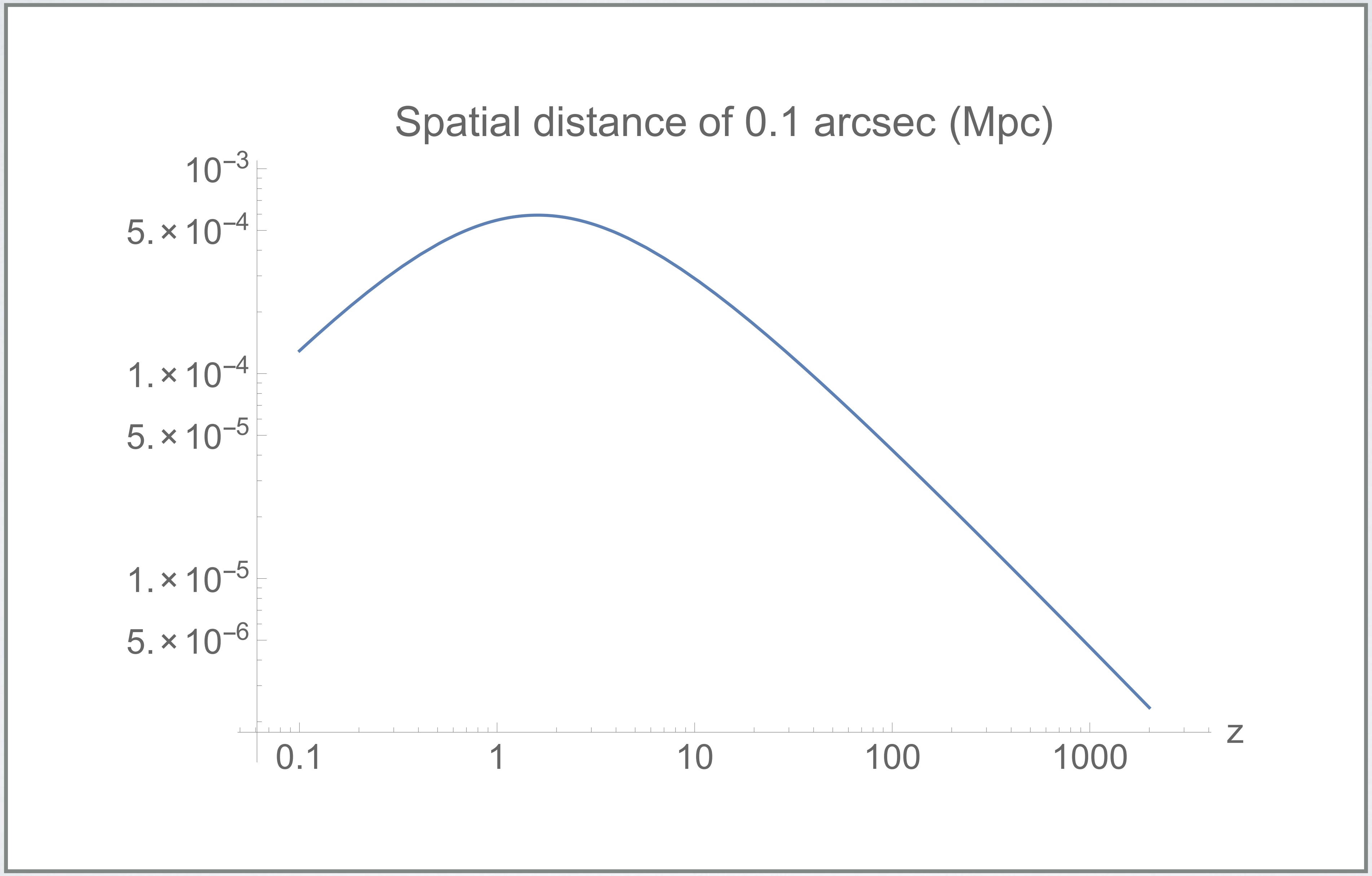
OBSERVING PERTURBATIONS



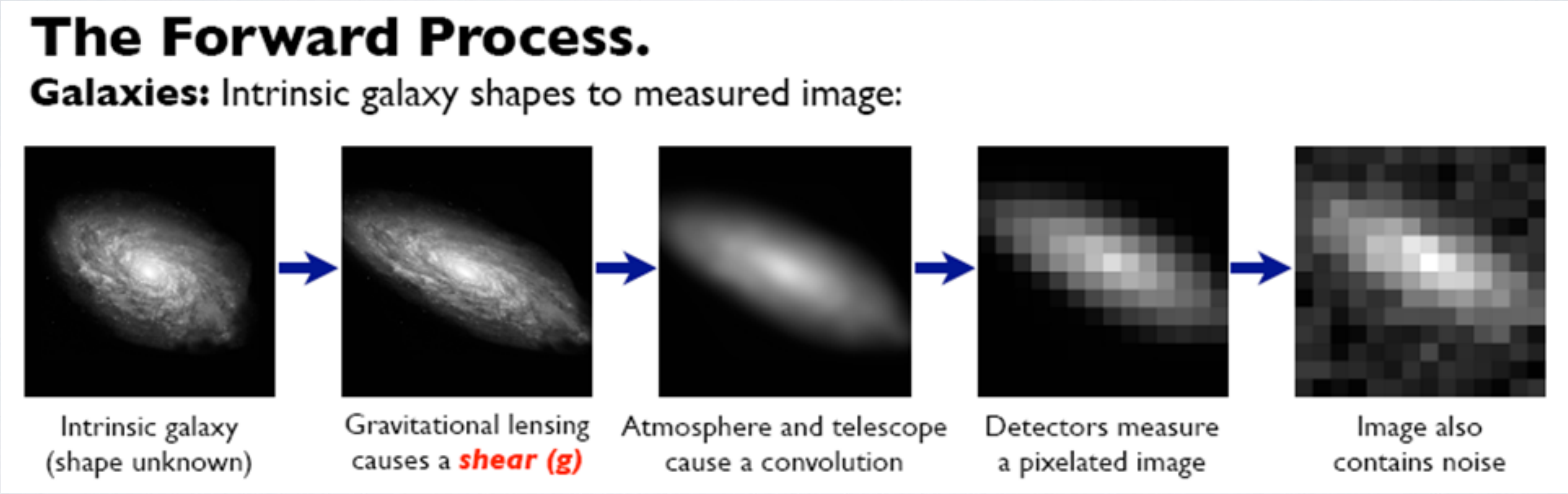
OBSERVING PERTURBATIONS



OBSERVING PERTURBATIONS



OBSERVING PERTURBATIONS



[Bridle et al., 2008]

[Ma & Bertschinger, 1995]

RELATIVISTIC PERTURBATIONS

$$ds^2 = a^2(\tau)[-d\tau^2 + (\delta_{ij} + h_{ij})dx^i\, dx^j]$$

$$h_{ij}(\boldsymbol{x}, \tau) = \int d^3k e^{i\boldsymbol{k}\cdot\boldsymbol{x}}[\hat{\boldsymbol{k}}_i \hat{\boldsymbol{k}}_j h(\boldsymbol{k}, \tau) + (\hat{\boldsymbol{k}}_i \hat{\boldsymbol{k}}_j - \tfrac{1}{3}\delta_{ij})6\eta(\boldsymbol{k}, \tau)]$$

$$k^2\eta - \frac{1}{2}\frac{\dot{a}}{a}\dot{h} = 4\pi G a^2\, \delta T^0{}_0(\mathrm{Syn}) ,$$

density perturbation

$$k^2\dot{\eta} = 4\pi G a^2(\bar{\rho} + \bar{P})\theta(\mathrm{Syn}) ,$$

(scalar) velocity perturbation

$$\ddot{h} + 2\frac{\dot{a}}{a}\dot{h} - 2k^2\eta = -8\pi G a^2\, \delta T^i{}_i(\mathrm{Syn}) ,$$

pressure perturbation

$$\ddot{h} + 6\ddot{\eta} + 2\frac{\dot{a}}{a}(\dot{h} + 6\dot{\eta}) - 2k^2\eta = -24\pi G a^2(\bar{\rho} + \bar{P})\sigma(\mathrm{Syn})$$

shear perturbation

[Ma & Bertschinger, 1995]

RELATIVISTIC PERTURBATIONS

$$ds^2 = a^2(\tau)[-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j]$$

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu - \frac{2}{3}\dot{h} ,$$

Example: massless neutrinos

$$\dot{\theta}_\nu = k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) ,$$

$$\dot{F}_{\nu 2} = 2\dot{\sigma}_\nu = \frac{8}{15}\theta_\nu - \frac{3}{5}kF_{\nu 3} + \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\eta} ,$$

$$\dot{F}_{\nu l} = \frac{k}{2l+1}[lF_{\nu(l-1)} - (l+1)F_{\nu(l+1)}] , \quad l \geq 3 .$$

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu - \frac{2}{3}\dot{h}\,,$$

$$\dot{\theta}_\nu = k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right),$$

$$\dot{F}_{\nu 2} = 2\dot{\sigma}_\nu = \frac{8}{15}\theta_\nu - \frac{3}{5}kF_{\nu 3} + \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\eta}\,,$$

RELATIVISTIC SIMULATIONS

$$\dot{F}_{\nu l} = \frac{k}{2l+1}\left[lF_{\nu(l-1)} - (l+1)F_{\nu(l+1)}\right], \quad l \geq 3\,.$$

$$ds^2 = a^2(\tau)[-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j]$$

- Very nice.
- So now, let's just do that at the full nonlinear glory:
  go to lagrangian description and simulate particles.
- Eulerian: describe quantities at fixed coordinates
- Lagrangian: moving labels, EOM for labels.
  - If invertible map between labels and spacetime: LPT
  - Otherwise: infer eulerian quantities by measuring / counting.
- The two can mix: in Lagrangian picture, flows can exist between in other quantities. Choose your frame wisely.

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu - \frac{2}{3}\dot{h}\,,$$

$$\dot{\theta}_\nu = k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right),$$

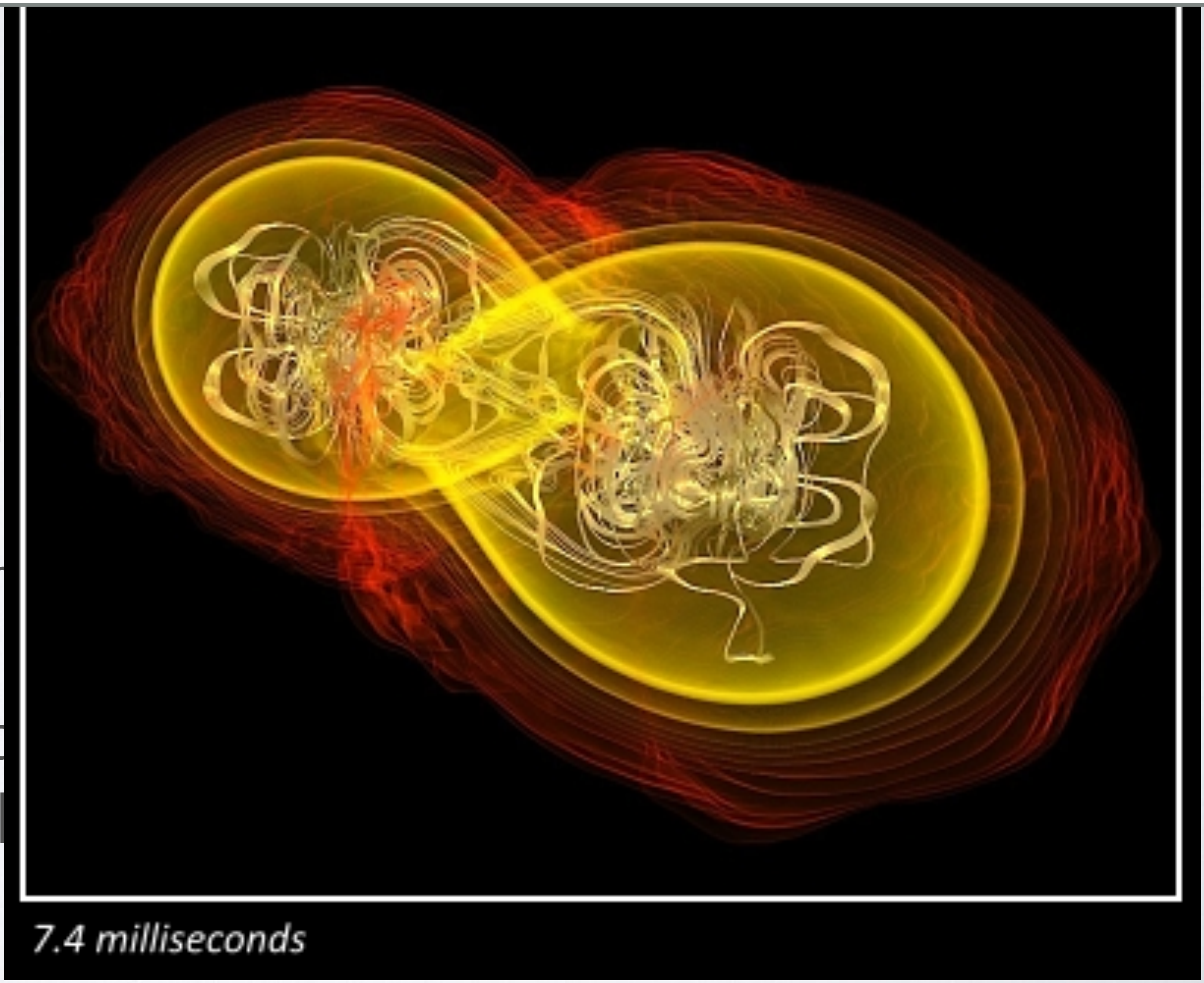
$$\dot{F}_{\nu 2} = 2\dot{\sigma}_\nu = \frac{8}{15}\theta_\nu - \frac{3}{5}kF_{\nu 3} + \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\eta}\,,$$

RELATIVISTIC SIMULATIONS

$$\dot{F}_{\nu l} = \frac{k}{2l+1}\left[lF_{\nu(l-1)} - (l+1)F_{\nu(l+1)}\right], \quad l \geq 3\,.$$

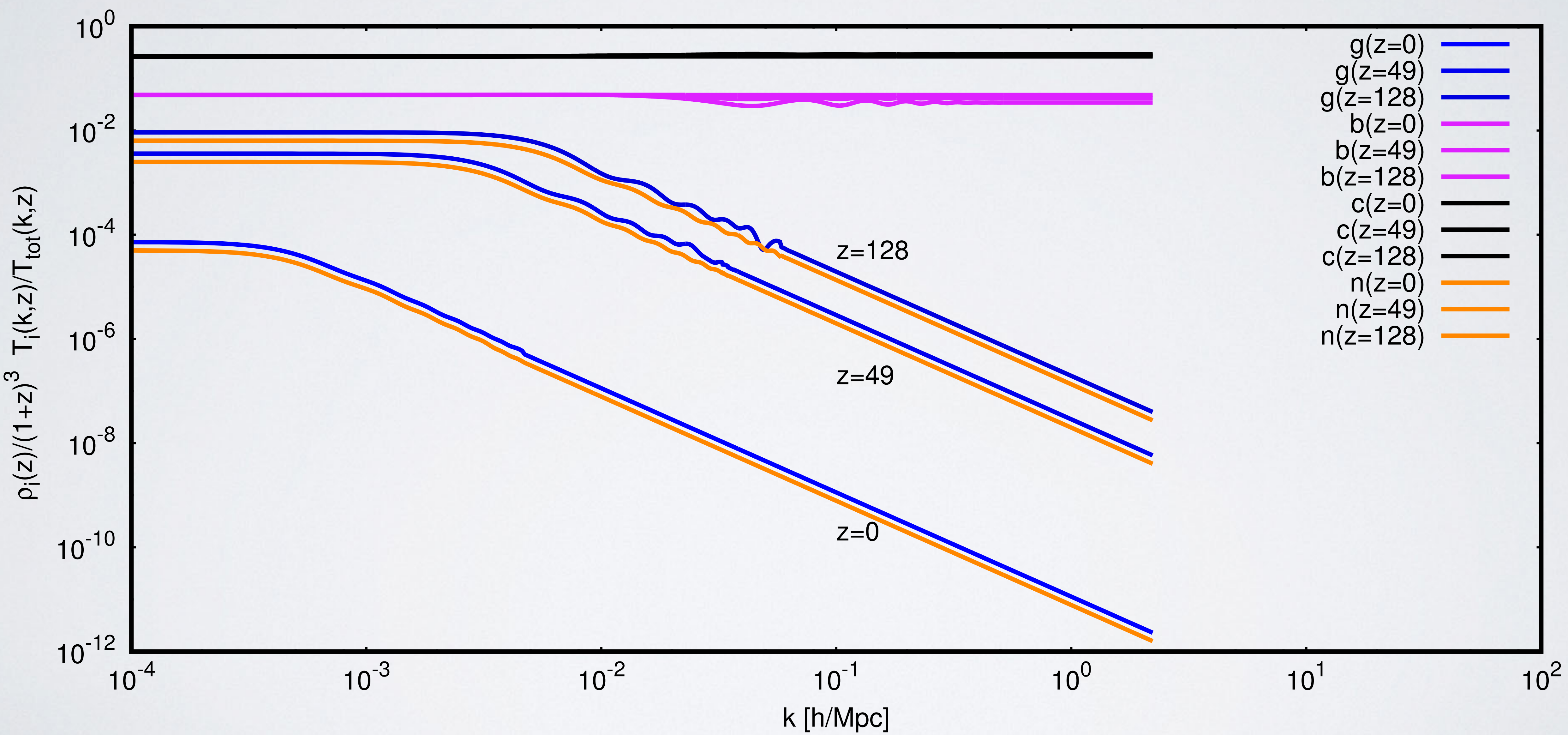
$$ds^2 = a^2(\tau)[-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j]$$

Colliding neutron stars [Koppitz, Rezzolla, 2011]



- Wave hands:
  - GR Simulations are
  - Solve full 10 Einstei
  - State-of-the-art sim
    - Coordinate freed
      very close thoug

DO YOU NEED RELATIVISTIC SIMULATIONS?



[Fidler et al., 2015]

DO YOU NEED RELATIVISTIC SIMULATIONS?

$$\mathrm{d}s^2 = a^2\Big(-(1+2\tilde{A})\mathrm{d}\tilde{\eta}^2 - 2\partial_i\tilde{B}\,\mathrm{d}\tilde{x}^i\mathrm{d}\tilde{\eta}$$

$$+\Big[\delta_{ij}(1+2\tilde{H}_\mathrm{L}) - 2D_{ij}\tilde{H}_\mathrm{T}\Big]\mathrm{d}\tilde{x}^i\mathrm{d}\tilde{x}^j\Big)$$

In comoving gauges

$$\Phi = H_\mathrm{L} + \frac{\boldsymbol{\nabla}^2}{3}H_\mathrm{T} - \frac{\dot{a}}{a}\left(v - \dot{H}_\mathrm{T}\right) \qquad \boldsymbol{\nabla}^2\Phi = -4\pi G\bar{\rho}a^2\delta\,.$$

$$\boldsymbol{\nabla}^2\left[H_\mathrm{L} + \frac{\boldsymbol{\nabla}^2}{3}H_\mathrm{T} - \frac{\dot{a}}{a}(v - \dot{H}_\mathrm{T})\right] = -4\pi G\bar{\rho}a^2\delta,$$

$$\frac{\dot{a}}{a}\xi - \dot{H}_\mathrm{L} - \frac{\boldsymbol{\nabla}^2}{3}\dot{H}_\mathrm{T} = 0\,,$$

$$\xi + H_\mathrm{L} + \frac{\boldsymbol{\nabla}^2}{3}H_\mathrm{T} - \left[\frac{\partial}{\partial\eta} + 2\frac{\dot{a}}{a}\right](v - \dot{H}_\mathrm{T}) = 8\pi G a^2 p\Pi\,.$$

$$\dot{\delta}_\alpha + \boldsymbol{\nabla}\cdot\boldsymbol{v}_\alpha = -3\dot{H}_\mathrm{L}\,,$$

$$\left(\frac{\partial}{\partial\eta} + \frac{\dot{a}}{a}\right)\boldsymbol{v}_\alpha = \boldsymbol{\nabla}\Phi + \boldsymbol{\nabla}\gamma$$

[Fidler et al., 2015]

DO YOU NEED RELATIVISTIC SIMULATIONS?

In comoving gauges

$$\Phi = H_{\mathrm{L}} + \frac{\boldsymbol{\nabla}^2}{3} H_{\mathrm{T}} - \frac{\dot{a}}{a}\left(v - \dot{H}_{\mathrm{T}}\right) \qquad \boldsymbol{\nabla}^2 \Phi = -4\pi G \bar{\rho} a^2 \delta \,.$$

$$\dot{\delta}_\alpha + \boldsymbol{\nabla} \cdot \boldsymbol{v}_\alpha = \cancel{-3\dot{H}_{\mathrm{L}}}$$

$$\left(\frac{\partial}{\partial \eta} + \frac{\dot{a}}{a}\right) \boldsymbol{v}_\alpha = \boldsymbol{\nabla}\Phi \cancel{- \boldsymbol{\nabla}\gamma}$$

Possible when pressure and shear vanish.

DO YOU NEED RELATIVISTIC SIMULATIONS?

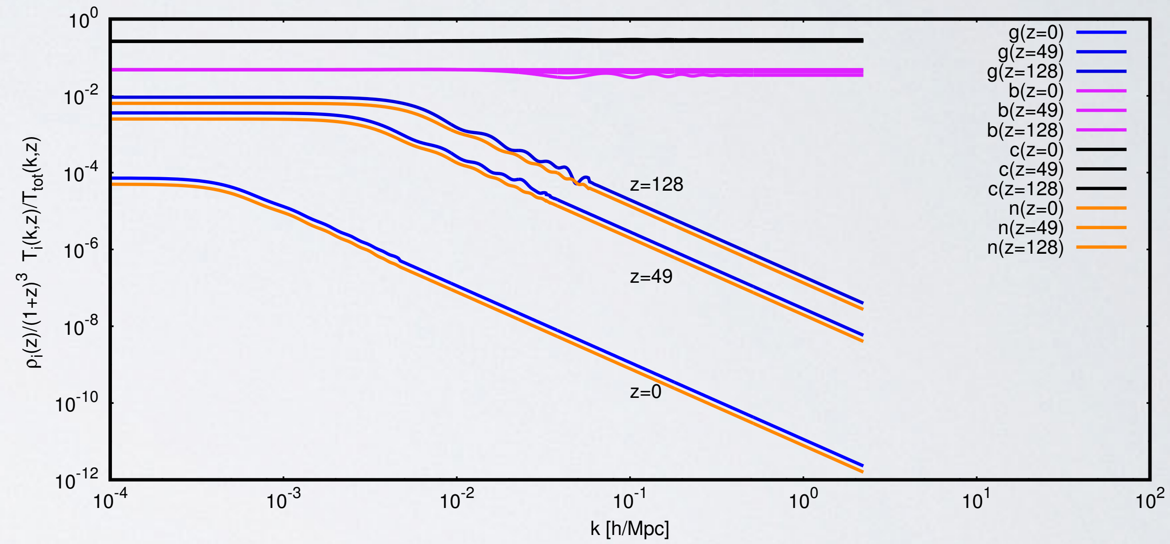
- With solely shear- and pressureless matter: not at linear level.
- Hubble radius: no thing.
- Sound horizon: a thing.
- No pressure - no sound horizon.
- Nonlinear scales: newtonian equations describe planetary motion "well enough"
  - Don’t tell Mercury
- Dynamic range of computer does not go from galaxy clustering down to black holes.

DO YOU NEED RELATIVISTIC SIMULATIONS?

- But if you care about 1% effect, you do.

- 2nd-order PT GR simulations at UniGe: CDM and neutrinos. [Durrer, Kunz, Adamek, Daverio].

- Newtonian CDM + linear radiation perturbations [Brandbyge et al.].



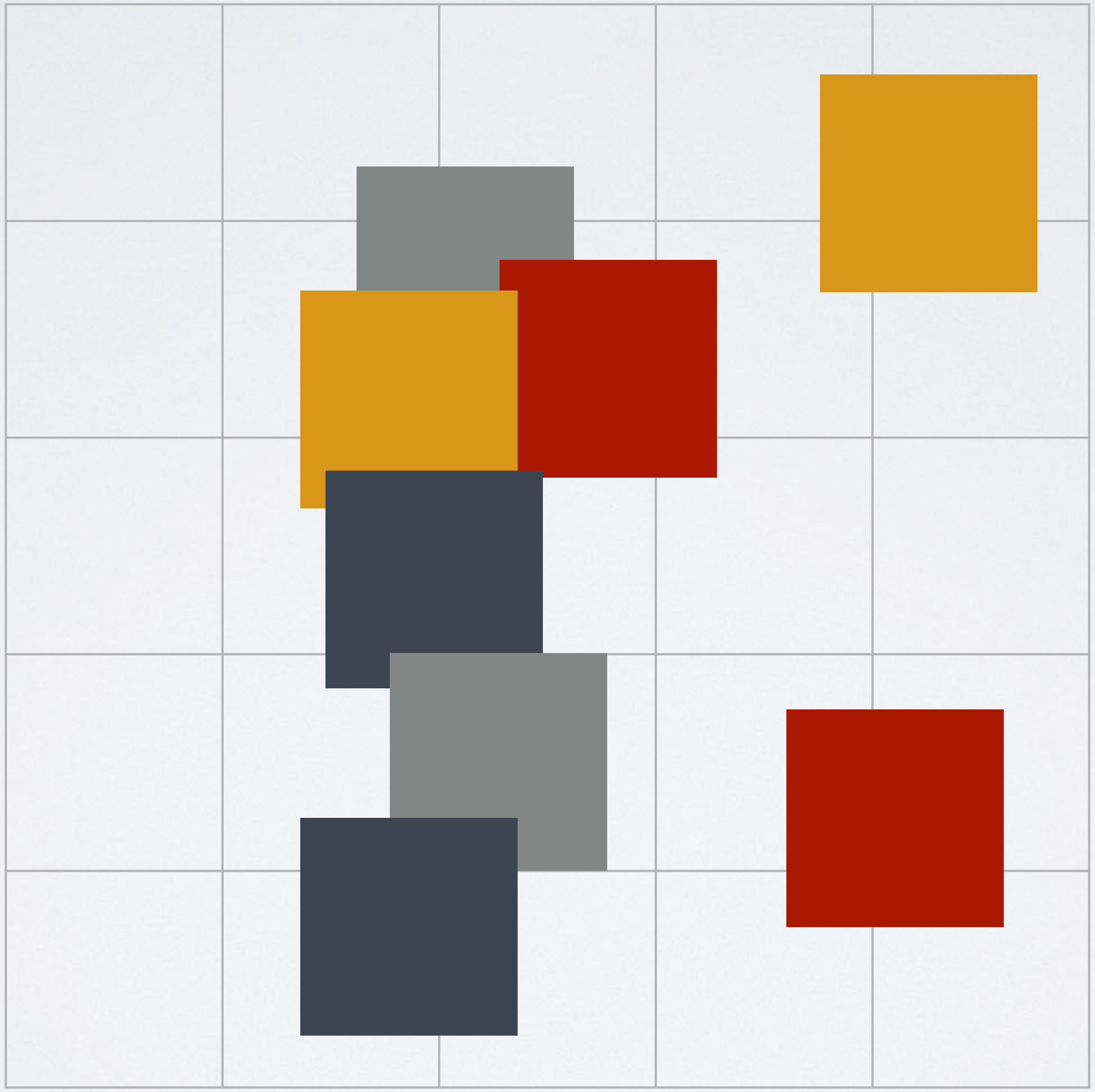
STATE OF NEWTONIAN SIMULATIONS

- I promised to talk about fundamental properties of DM…
- Linear cosmology sensitive to mass or thermal velocity at best.

STATE OF NEWTONIAN SIMULATIONS

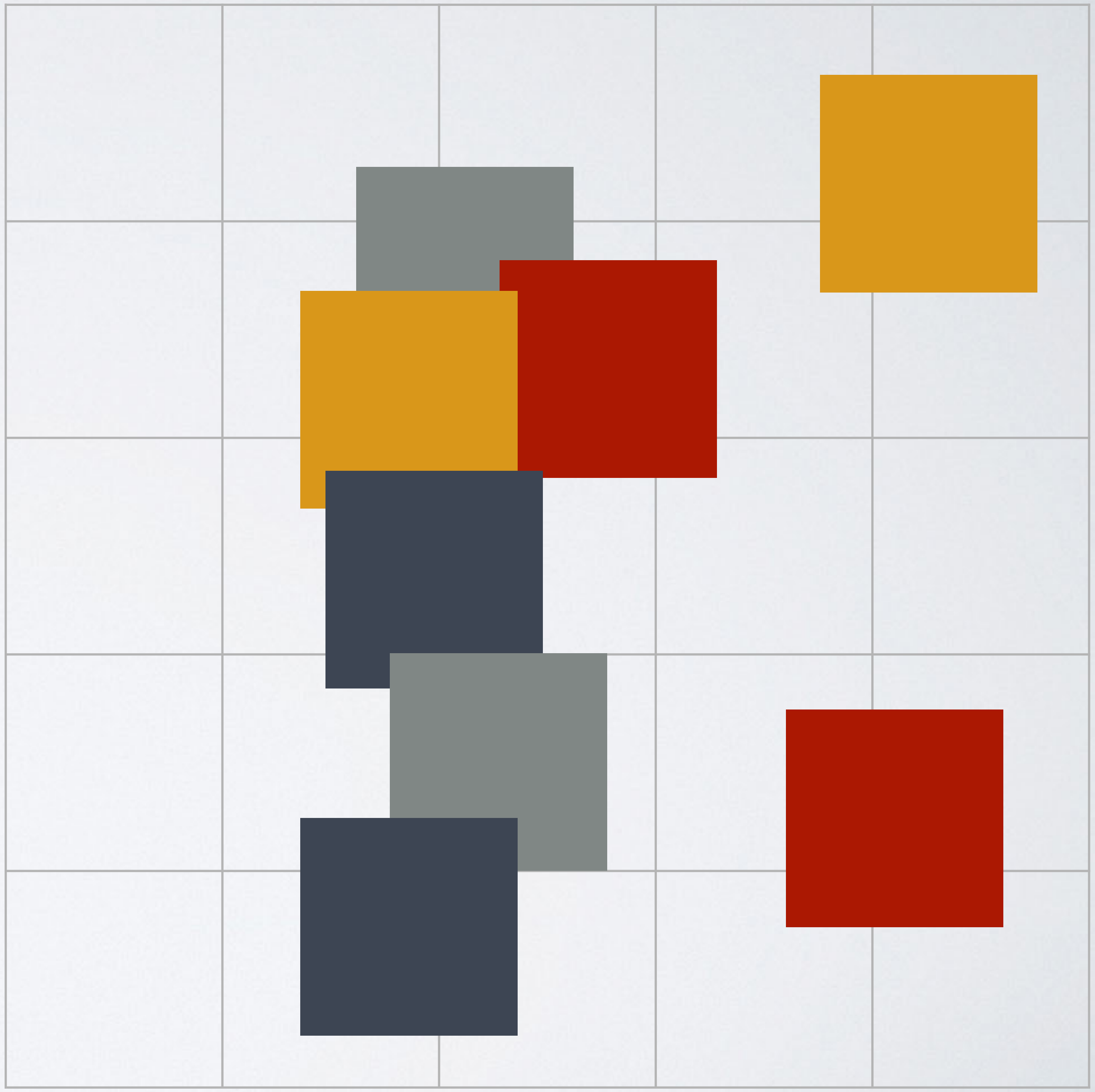
- Next up: a quick introduction to simulations

STATE OF NEWTONIAN SIMULATIONS



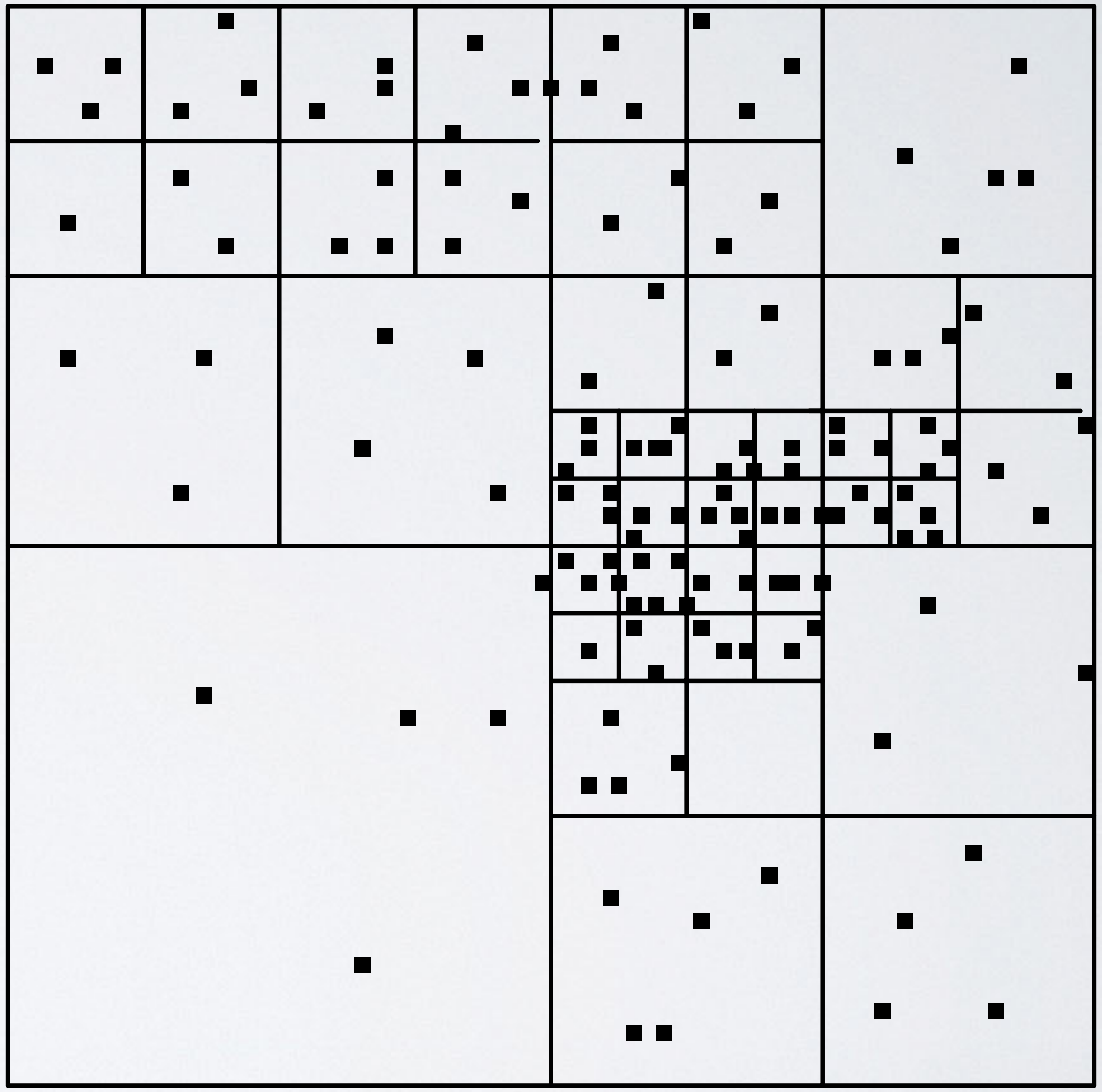
STATE OF NEWTONIAN SIMULATIONS

- Particle - Particle:
  - N^2 operations
  - Slow but exact
- Particle - Mesh:
  - Use FFT for poisson-solver
  - N log N operations.
  - Fast but low resolution



STATE OF NEWTONIAN SIMULATIONS

- Particle - Particle:
  - N^2 operations
  - Slow but exact
- Particle - Mesh:
  - Use FFT for poisson-solver
  - N log N operations.
  - Fast but low resolution
- Particle - Tree:
  - Tunable resolution
  - Fast multipole method: N operations (linear!)



[e.g. Beatson, Greengard, 1997]

NONLINEAR STRUCTURE

- 2pt correlations no longer carry much information
- What are the parameters that describe output and discriminate models?
- It's a mess…

Halo masses

Halo shapes

Filament distribution

Halo substructure

Void abundance

Delaunay-tesselation field estimator

Halo velocities

Origami

many more…

NONLINEAR STRUCTURE

- My favourite measure:

Abundance of high-velocity cluster collisions

Bullet Cluster: A Challenge to ΛCDM Cosmology

Jounghun Lee

Department of Physics and Astronomy, FPRD, Seoul National University, Seoul 151-747, Korea: jounghun@astro.snu.ac.kr

Eiichiro Komatsu

Texas Cosmology Center and Department of Astronomy, The University of Texas at Austin, 1 University Station, C1400 Austin, TX 78712, USA

BARYON PHYSICS

- I will not go into detail.
- Lagrangian: Smoothed Particle Hydrodynamics (SPH)
- Eulerian: Adaptive Mesh Refinement
- Mix: moving meshes.

WHAT'S IN IT FOR YOU?

- Crucial to get handle on accuracy.
  - Various test cases agreed on in community
  - Physics is too complex to model from first principles
  - Quite ad hoc.
- One big drawback:
  - IR-end know analytically, UV end NOT
  - As opposed to e.g. black-hole mergers.

shock treatment

removal of spurious structure

AGN feedback: huge effect

WHAT'S IN IT FOR YOU?

The galaxy population in cold and warm dark matter cosmologies

Lan Wang[1⋆], Violeta Gonzalez-Perez[2,3], Lizhi Xie[4], Andrew P. Cooper[2], Carlos S. Frenk[2], Liang Gao[1], Wojciech A. Hellwing[3,5], John Helly[2], Mark R. Lovell[6,7], and Lilian Jiang[2]

regions within them that are as empty as the observed Local Void. Thus, a highly complete census of the Local Volume and future surveys of void regions could provide constraints on the nature of dark matter.

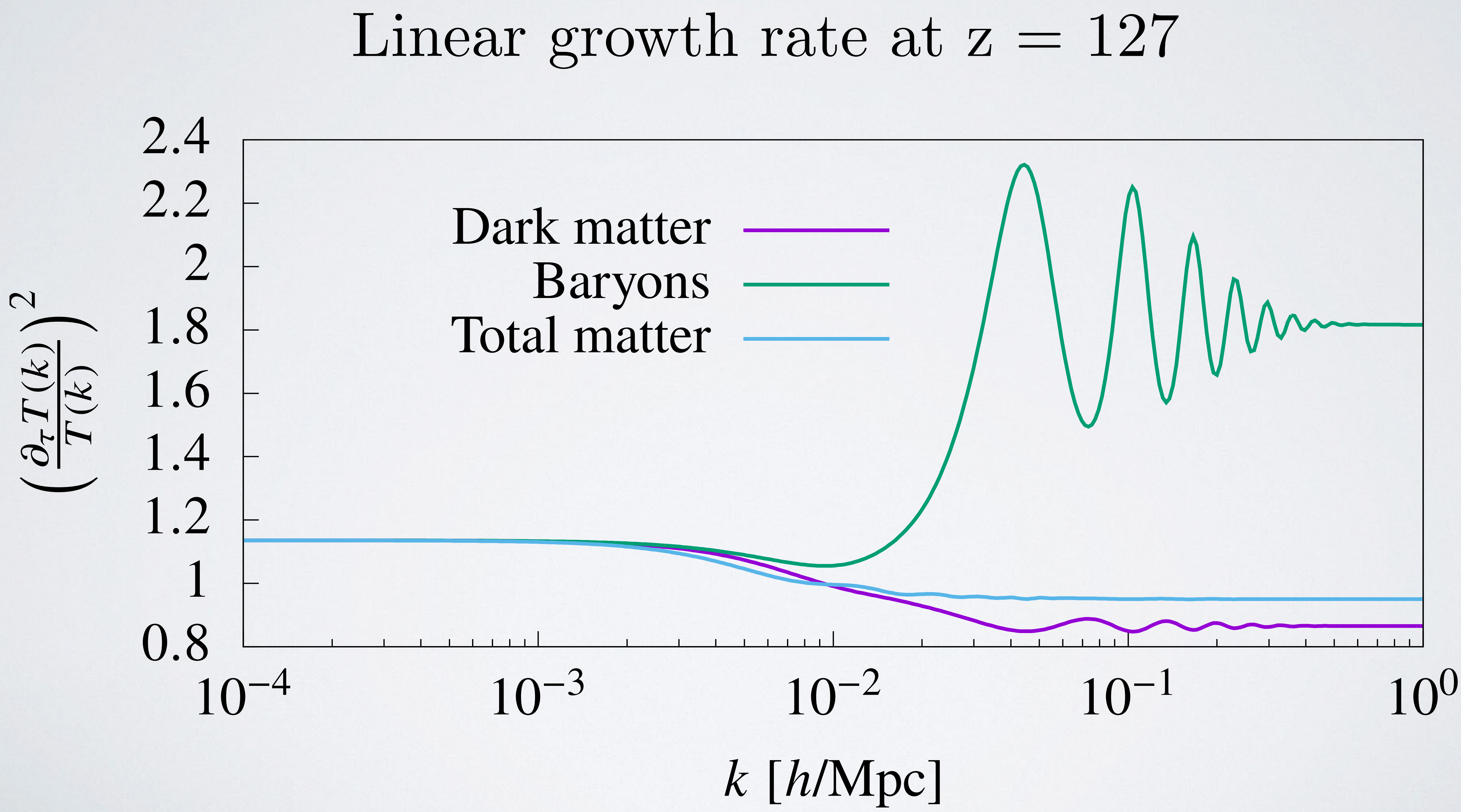
WHAT'S IN IT FOR YOU?

- It is as accurate as the last error you found.
  - That propagates into all conclusions you draw.
- I found one!

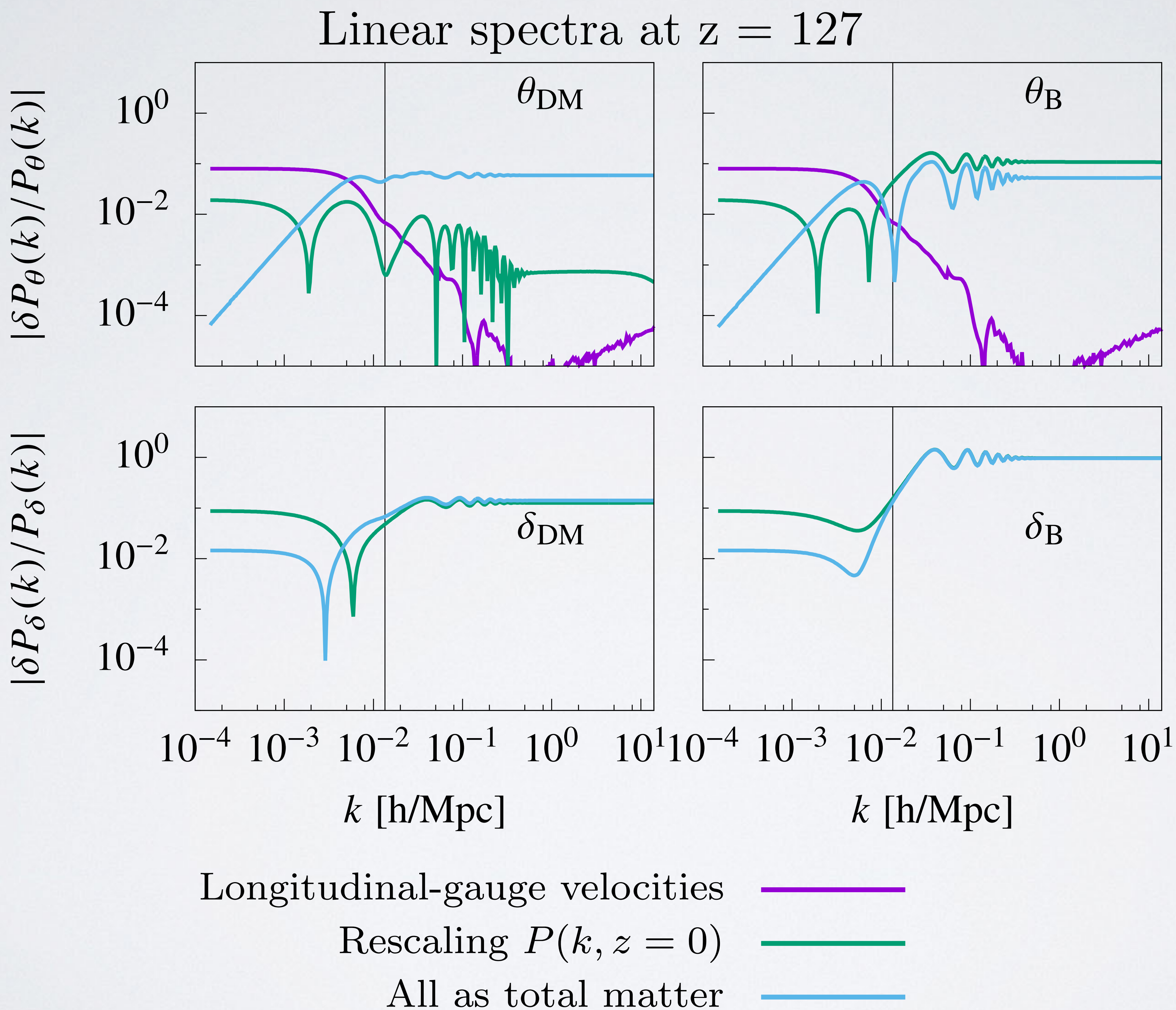
PT: GR
SIMULATION: NEWTONIAN

- Interface from GR to start of simulation has long been hand-waved.
- N-body gauge gives clarity

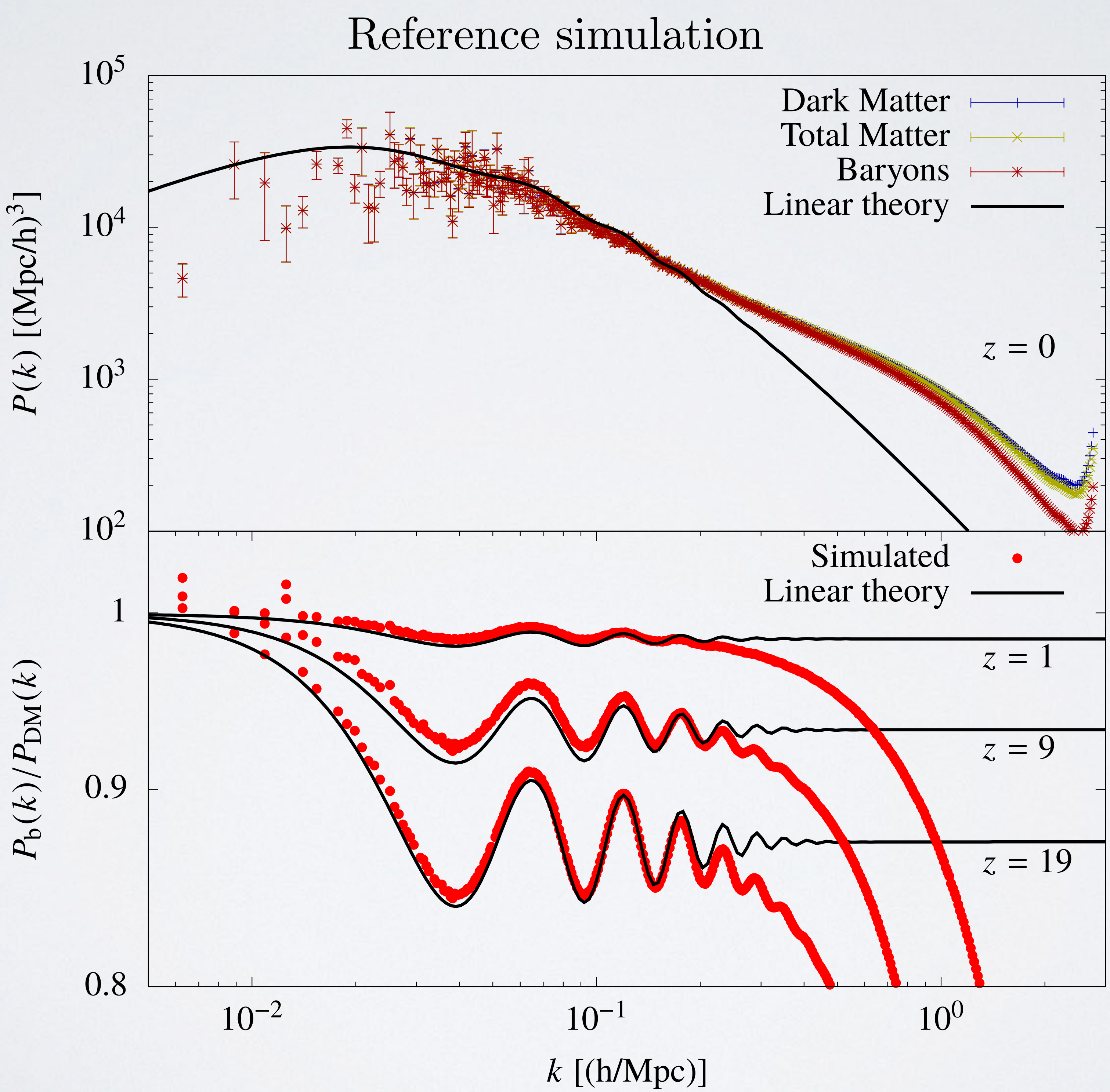
PT: GR
SIMULATION: NEWTONIAN



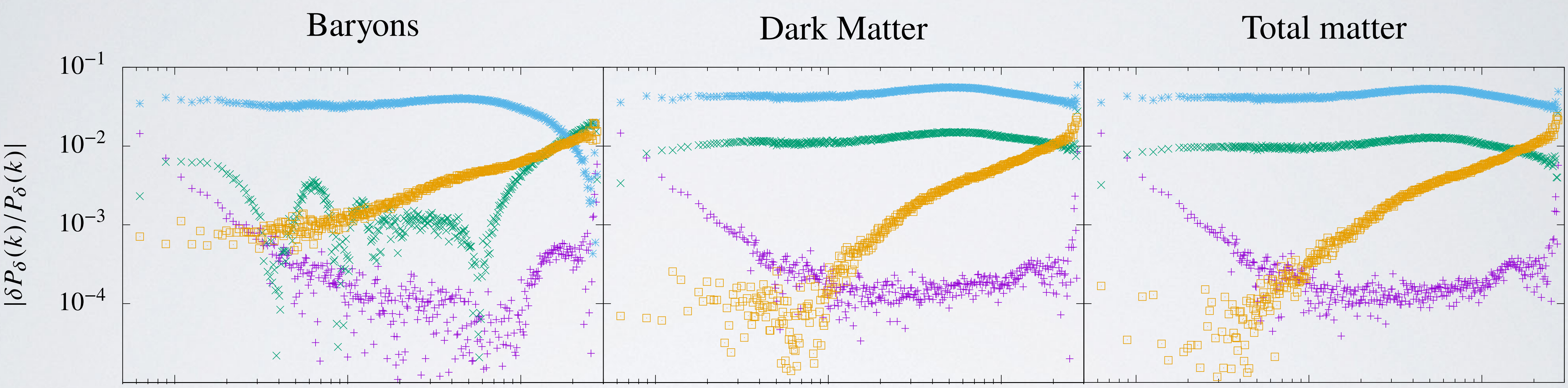
OLD APPROXIMATIONS



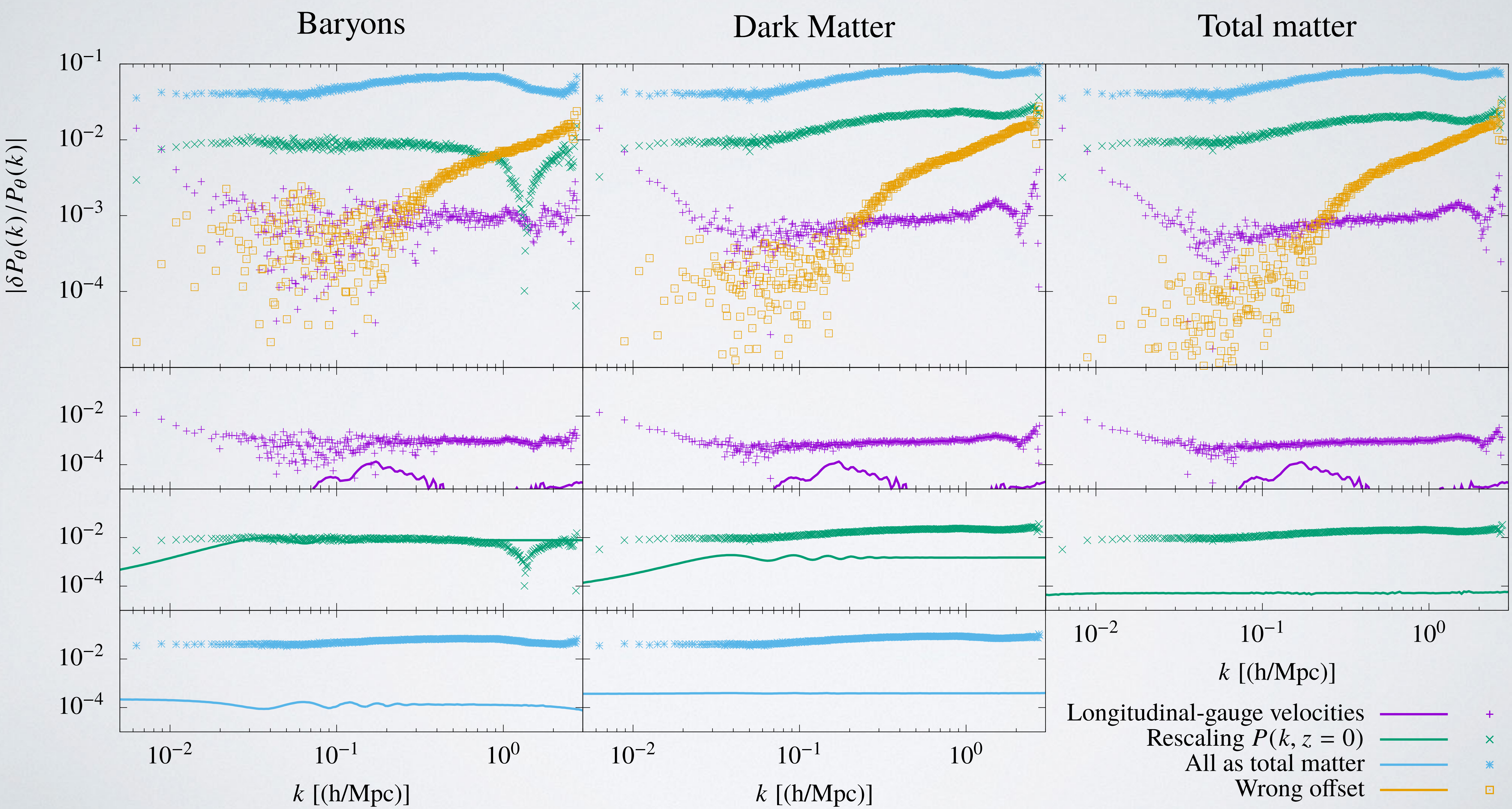
LONG LIVE THE HPC-QCD GRID AT CERN



ERRORS IN CONTEMPORARY SIMULATIONS



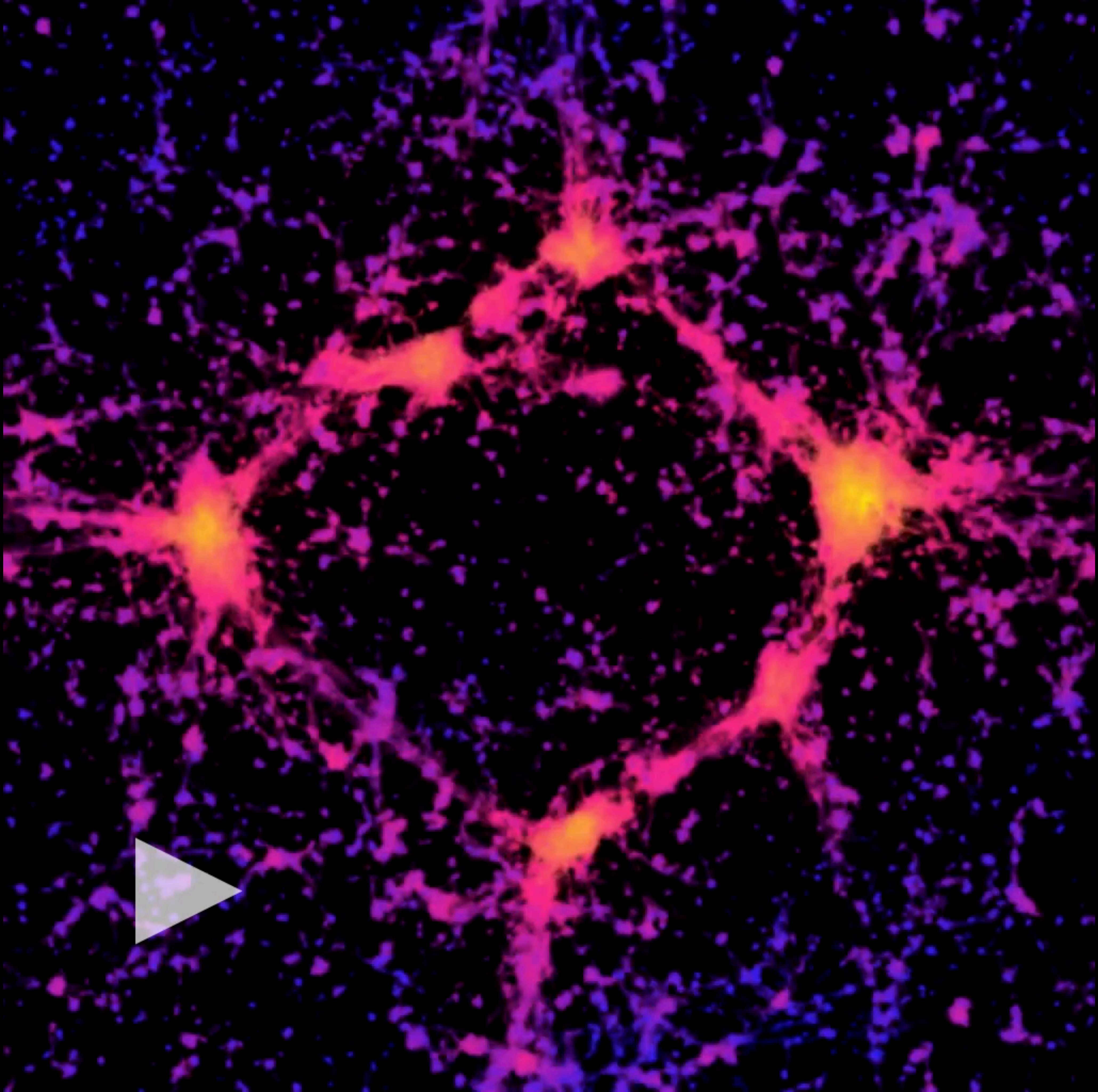
ERRORS IN CONTEMPORARY SIMULATIONS



ERRORS IN CONTEMPORARY SIMULATIONS

- up to 10% is however still smaller than the ad-hoc modelled effect of AGN’s, starting at 10%.

THE PROMISED PRETTY PICTURE



CONCLUSIONS

- I do not want you to think that simulations are dirty
- but to respectfully think that there is some cleaning left to be done
- DM only simulations differ from reality by up to 10%
- Baryon-DM simulations idem
- Newtonian simulations miss 1% radiation