Why 60 years birthday means new born in Chinese?

Chinese calendar

Initial Condition of N-body simulation in Modified Gravity from EFT point of view

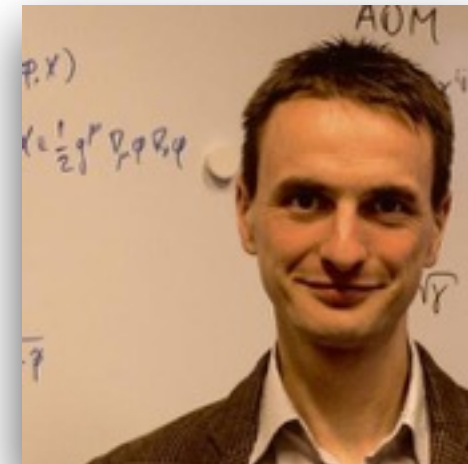
Bin HU

Lorentz Institute, Leiden University

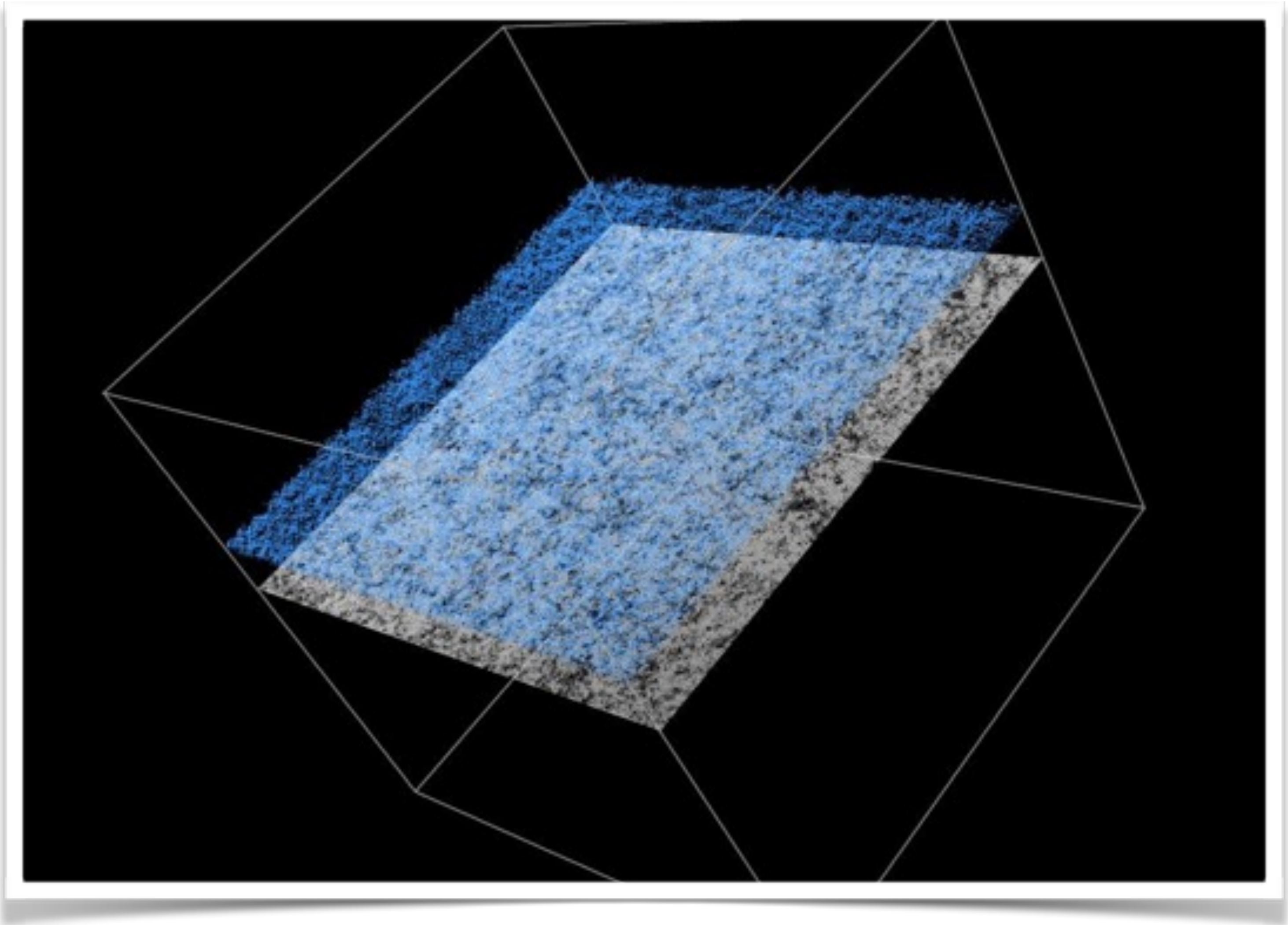
Instituut-Lorentz

From Inflation to Galaxies: a workshop in honor of Sabino Matarrese/Castiglioncello/Sep/2015

The interface between **EFTCAMB** with IC of N-body simulation of DE/MG— **FalconIC**



C++ code



[http://falconic.org]

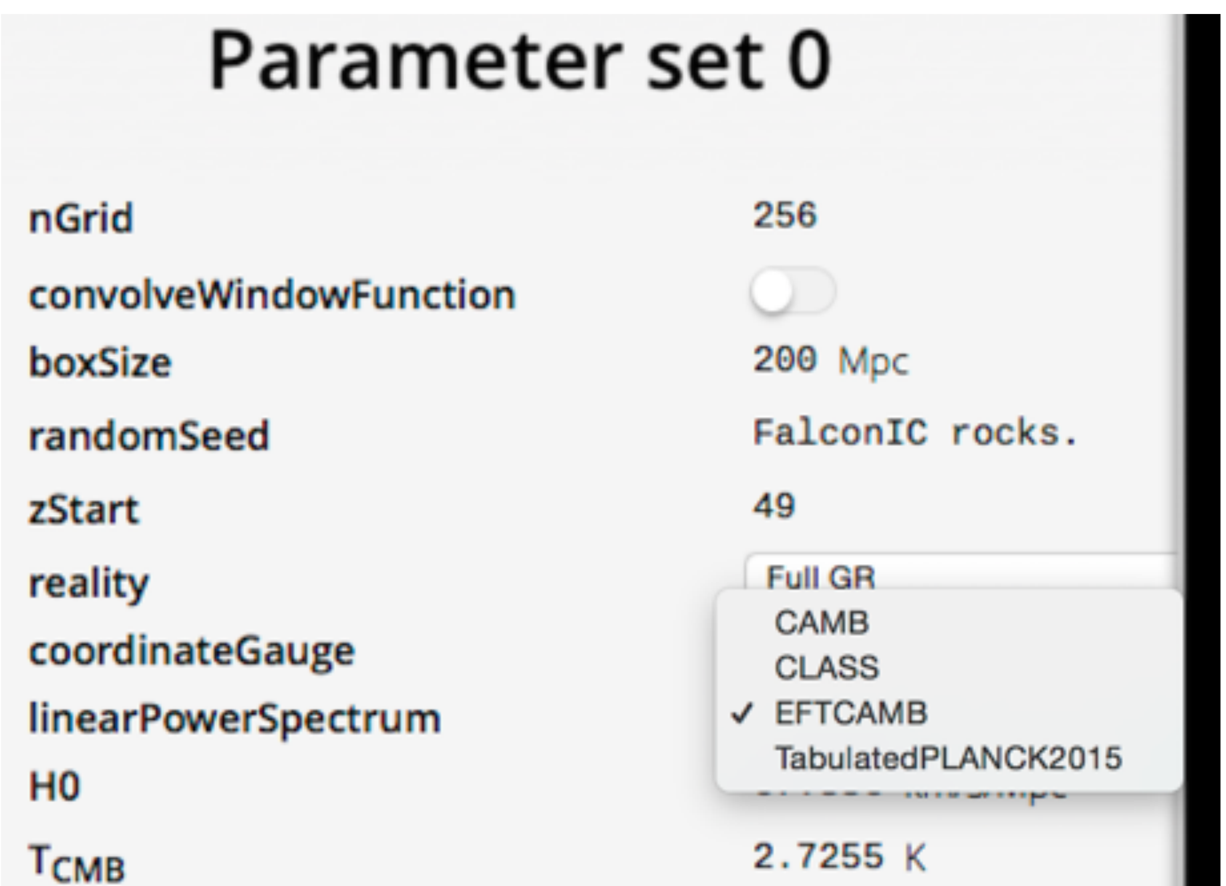
[Wessel Valkenburg, BH
arXiv:1505.05865, **to appear JCAP**]

FalconIC

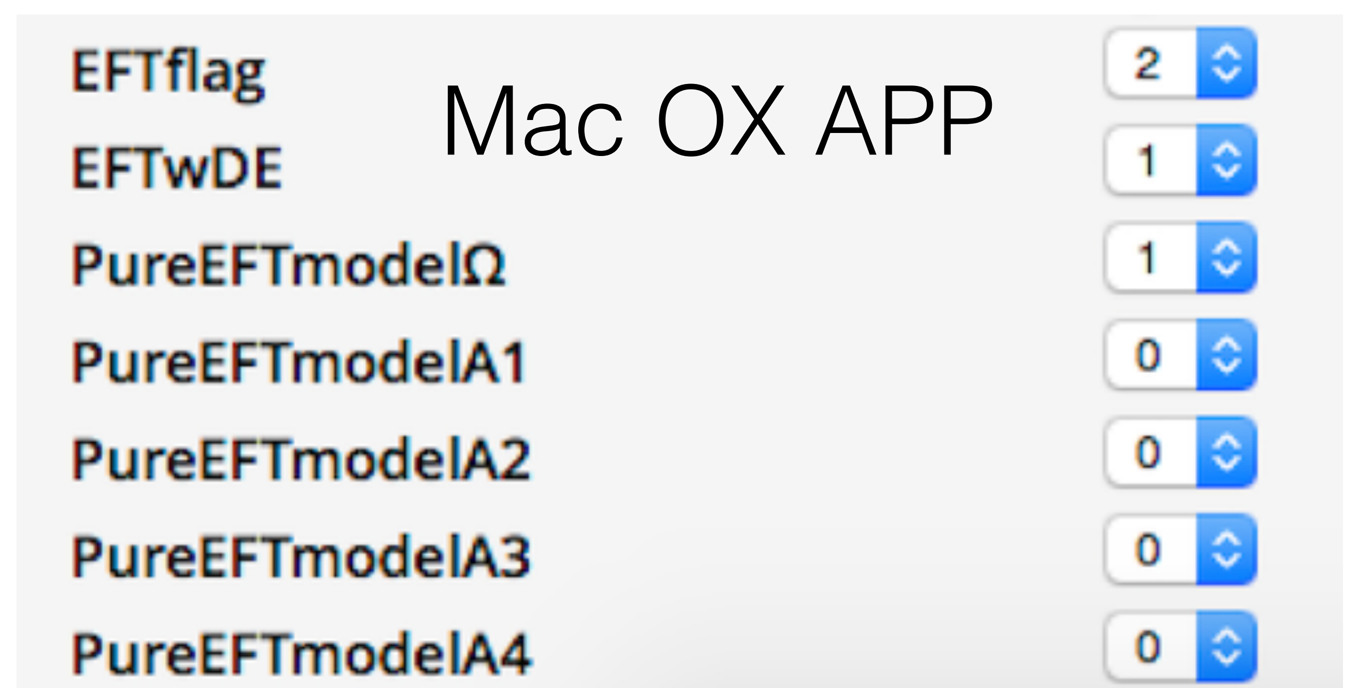
(developed by Wessel Valkenburg)

- Integrated with CAMB/CLASS/EFTCAMB
- Work for GR and DE/MG model
- Generates IC at arbitrary scales, of arbitrary size
- Compile with MPI and OpenMP

[http://falconic.org]



Mac OX APP



Zeldovich Approximation-I

Take the flat space-time, choose a coordinate frame $\{t, \vec{x}\}$

Define some conserved charge, e.g. mass

$$dM(\tau, \vec{x}) = \bar{\rho}(1 + D(\vec{x}))d^{N-1}x = \bar{\rho}d^{N-1}x',$$

Change to another frame {x\prime}, \rho is unperturbed

Euler frame

$$x^i = x^{i'} - \frac{\vec{\nabla}'}{\nabla'^2}D(\vec{x}')$$

Lagrangian frame

$$(1 + D(\vec{x})) = \left|\frac{\partial x^i}{\partial x^{j'}}\right|,$$

Jacobian

$$\boxed{\vec{v}^{(c)}(\tau, \vec{y}) = -\frac{\vec{\nabla}}{\nabla^2}\partial_t\rho(\tau, \vec{x}).}$$

ZA: Velocity is gradient of density

Zeldovich Approximation-II

In the linear sub-Horizon regime, GR gives

$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G\rho_m\delta_m = 0$$

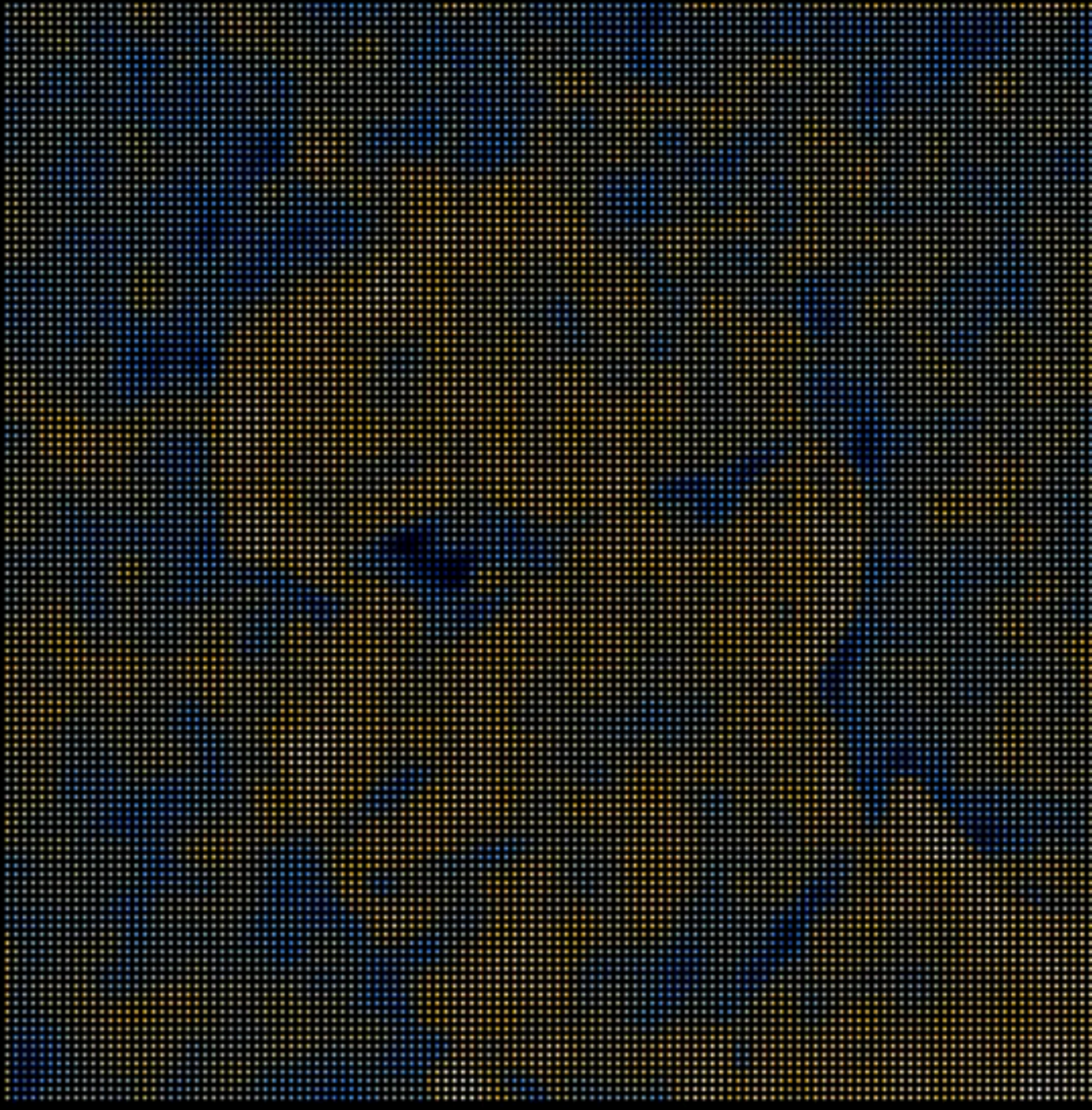
The growth rate of CDM only depends on time!

The displacement field $\vec{x} = \vec{y} - \mathcal{D}(\tau)\frac{1}{\nabla_y^2}\vec{\nabla}_y\Delta_c(\tau_i, \vec{y})$

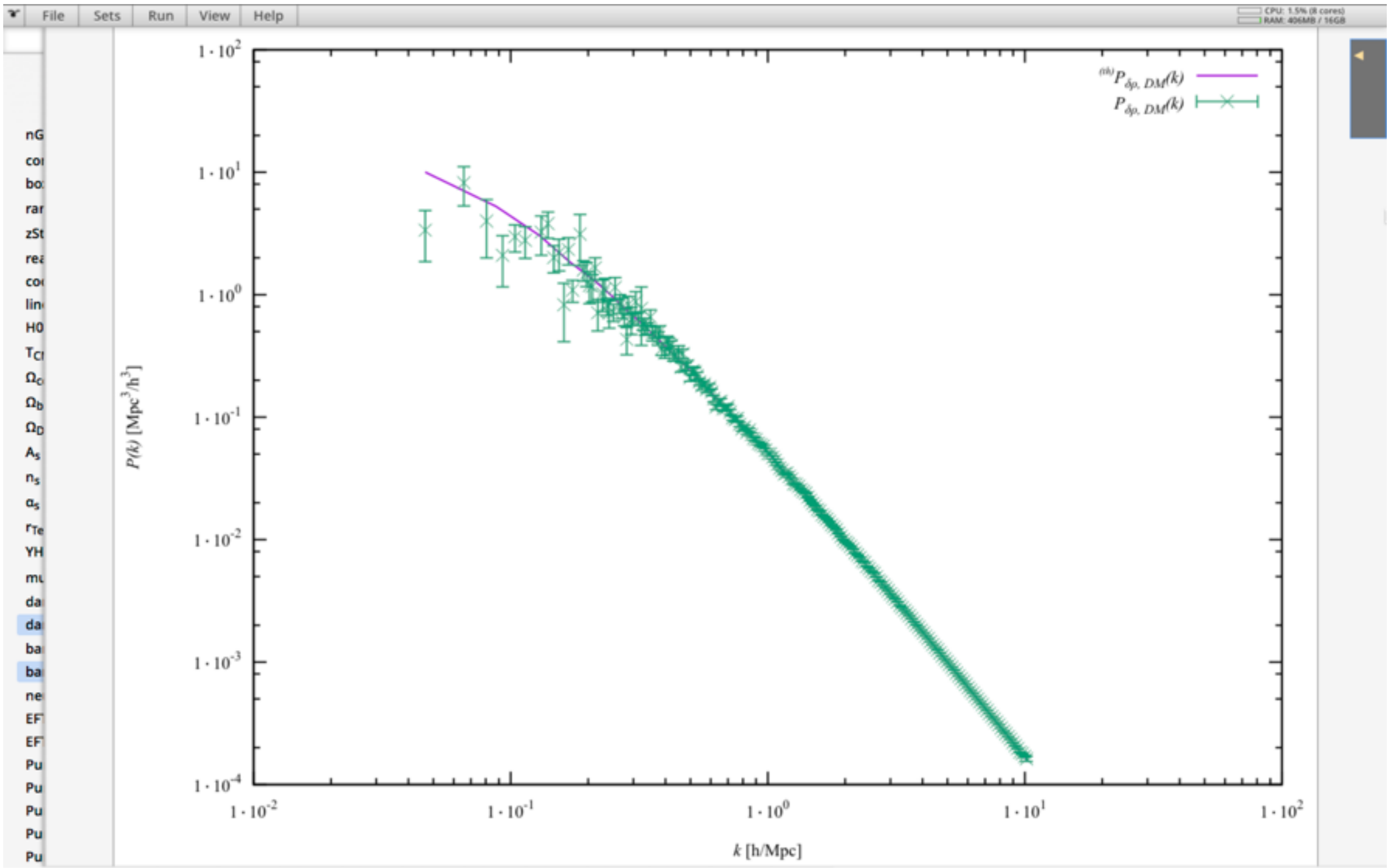
In GR: CDM particles trajectory is straight line!

Video of ZA

credit: Wessel Valkenburg



Matter Power Spectrum—Best-fit Planck15



Peter: The phase info was lost in p(k)

DE/MG:

Quasic-Static Approx:

$$\boxed{\begin{aligned} k^2\psi &= -4\pi G\,\mu(a,k)a^2\rho\Delta\ , \\ \frac{\phi}{\psi} &= \gamma(a,k)\ . \end{aligned}}$$

$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G_{\rm eff}(t,k)\rho_m\delta_m = 0$$

DE/MG: at linear regime
growth rate of CDM
depends on the scales!

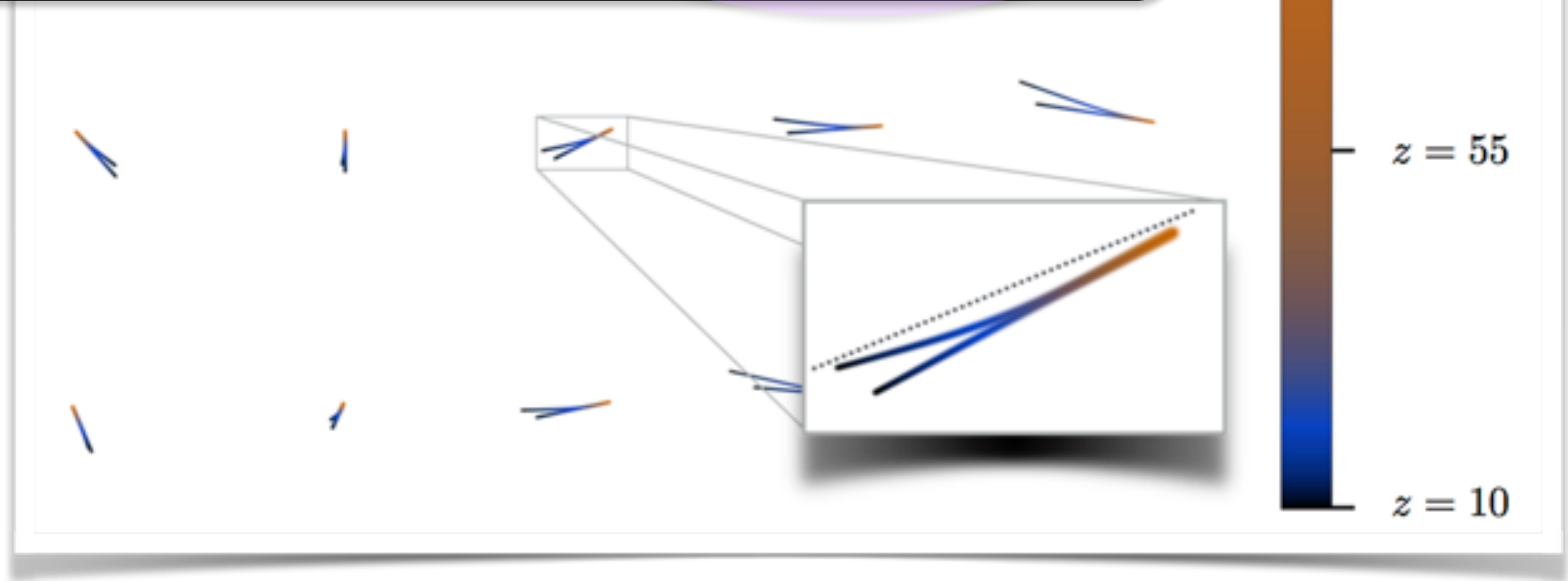
GR: The displacement field $\vec{x} = \vec{y} - \mathcal{D}(\tau)\frac{1}{\nabla_y^2}\vec{\nabla}_y\Delta_c(\tau_i,\vec{y})$

Beyond Zeldovich Approximation

DE/MG: at linear regime growth rate of CDM **depends** on the scales!

Deflection by the gravitational potential

$$\vec{x} = \vec{y} - \mathcal{D}(\tau,\vec{y})\frac{1}{\nabla_y^2}\vec{\nabla}_y\Delta_c(\tau_i,\vec{y}) - \Delta_c(\tau_i,\vec{y})\frac{1}{\nabla_y^2}\vec{\nabla}_y\mathcal{D}(\tau,\vec{y})\ .$$



Even at linear regime, trajectory of CDM particles are curved!

Modified Einstein Eq.

$$m_0^2(1+\Omega)G_{\mu\nu}[g_{\mu\nu}] = T^{(m)}_{\mu\nu}[\rho_m,\theta_m,\cdots] + T^{(\pi)}_{\mu\nu}[\pi,\dot{\pi},\cdots]\ ,$$

Define a conserved Fluid EMT ($\nabla^\nu T^{(Q)}_{\mu\nu} = 0$)

$$\boxed{\begin{aligned} m_0^2 G_{\mu\nu}[g_{\mu\nu}] &= T^{(m)}_{\mu\nu}[\rho_m,\theta_m,\cdots] + T^{(Q)}_{\mu\nu}[\rho_\pi,\theta_\pi,\rho_m,\cdots]\ , \\ T^{(Q)}_{\mu\nu}[\rho_\pi,\theta_\pi,\rho_m,\cdots] &\equiv \frac{1}{1+\Omega}\Big\{-\Omega T^{(m)}_{\mu\nu}[\rho_m,\theta_m,\cdots] + T^{(\pi)}_{\mu\nu}[\pi,\dot{\pi},\cdots]\Big\}\ . \end{aligned}}$$

- energy density $\rho = \bar{\rho} + \delta\rho = \bar{\rho}(1+\Delta_\rho) \equiv U^\mu U^\nu T_{\mu\nu}$,
- pressure $P = \bar{P} + \delta P = \bar{P}(1+\Delta_P) \equiv \frac{1}{3}\perp^{\mu\nu} T_{\mu\nu}$,
- energy flow (or heat transfer) $q^\mu \equiv \perp^{\mu\nu} U^\lambda T_{\nu\lambda}$,
- anisotropic shear perturbation $\Sigma^{\mu\nu}$,

At linear order the fluid variables via EFT pi field

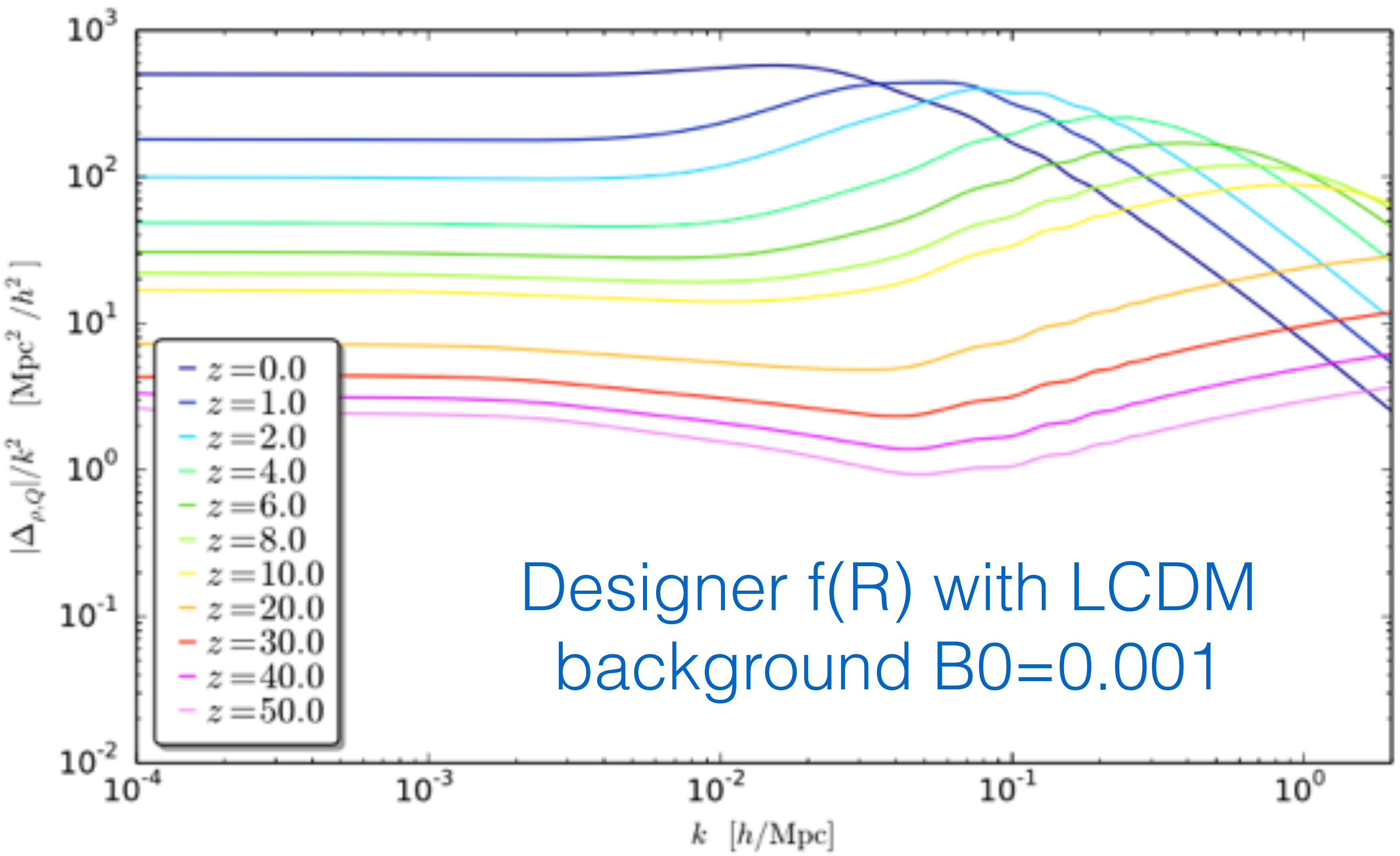
$$\delta\rho_Q^{(\mathrm{syn})} = \frac{1}{(1+\Omega)}\Big\{-\Omega\delta\rho_m^{(\mathrm{syn})} + \dot{\rho}_Q\pi + 2c(\dot{\pi}^{(\mathrm{syn})} + \mathcal{H}\pi^{(\mathrm{syn})}) - \frac{2m_0^2}{a^2}\left[\frac{\dot{\Omega}}{4}\dot{h} + \frac{\dot{\Omega}}{2}\Big(3(3\mathcal{H}^2 - \dot{\mathcal{H}})\pi^{(\mathrm{syn})} + 3\mathcal{H}\dot{\pi}^{(\mathrm{syn})} + k^2\pi^{(\mathrm{syn})}\Big)\right]\Big\}$$

$$(\rho_{\mathrm{DE}} + P_{\mathrm{DE}})\theta_Q^{(\mathrm{syn})} = \frac{1}{1+\Omega}\left[-\Omega(\rho_m + P_m)\theta_m^{(\mathrm{syn})} + (\rho_Q + P_Q)k^2\pi^{(\mathrm{syn})} + \frac{2m_0^2}{a^2}k^2\dot{\Omega}(\dot{\pi}^{(\mathrm{syn})} + \mathcal{H}\pi^{(\mathrm{syn})})\right],$$

$$\delta P_Q^{(\mathrm{syn})} = \frac{1}{1+\Omega}\Big\{-\Omega\delta P_m^{(\mathrm{syn})} + P_Q\dot{\pi}^{(\mathrm{syn})} + (\rho_Q + P_Q)(\dot{\pi}^{(\mathrm{syn})} + \mathcal{H}\pi^{(\mathrm{syn})}) + \frac{m_0^2}{a^2}\left[\frac{1}{3}\dot{\Omega}\dot{h} + \dot{\Omega}\ddot{\pi}^{(\mathrm{syn})} + (\ddot{\Omega} + 3\mathcal{H}\dot{\Omega})\dot{\pi}^{(\mathrm{syn})} + \left(\mathcal{H}\ddot{\Omega} + 5\mathcal{H}^2\dot{\Omega} + \dot{\mathcal{H}}\dot{\Omega} + \frac{2}{3}k^2\dot{\Omega}\right)\pi^{(\mathrm{syn})}\right]\Big\}$$

$$(\rho_{\mathrm{DE}} + P_{\mathrm{DE}})\sigma_Q^{(\mathrm{syn})} = \frac{1}{1+\Omega}\left[-\Omega(\rho_m + P_m)\sigma_m^{(\mathrm{syn})} + \frac{m_0^2}{3a^2}\dot{\Omega}\Big(\dot{h} + 6\dot{\eta} + 2k^2\pi^{(\mathrm{syn})}\Big)\right]$$

Transfer function of Q-fluid



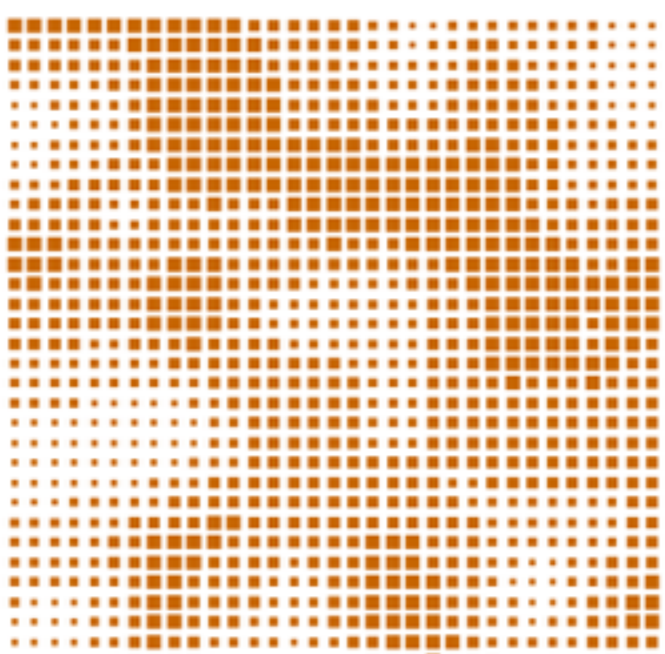
Take Newtonian limit

$$-k^2\psi = \frac{16\pi G}{3}\delta\rho_{\rm cdm} - \frac{\delta R}{6}\,.$$

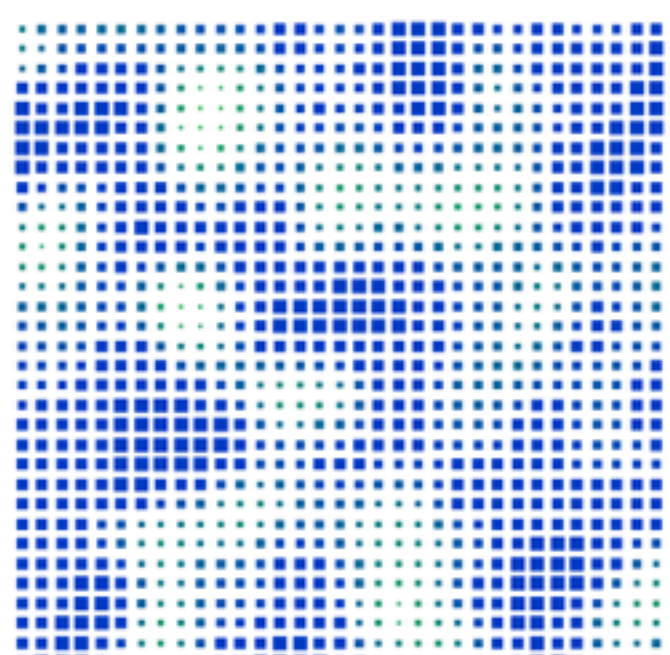
$$-k^2\psi = \frac{16\pi G}{3}(\delta\rho_{\rm cdm} + \delta\rho_Q)$$

$$\delta\rho_Q \propto -\delta R$$

In the CDM over dense regime, Q-fluid is under dense!

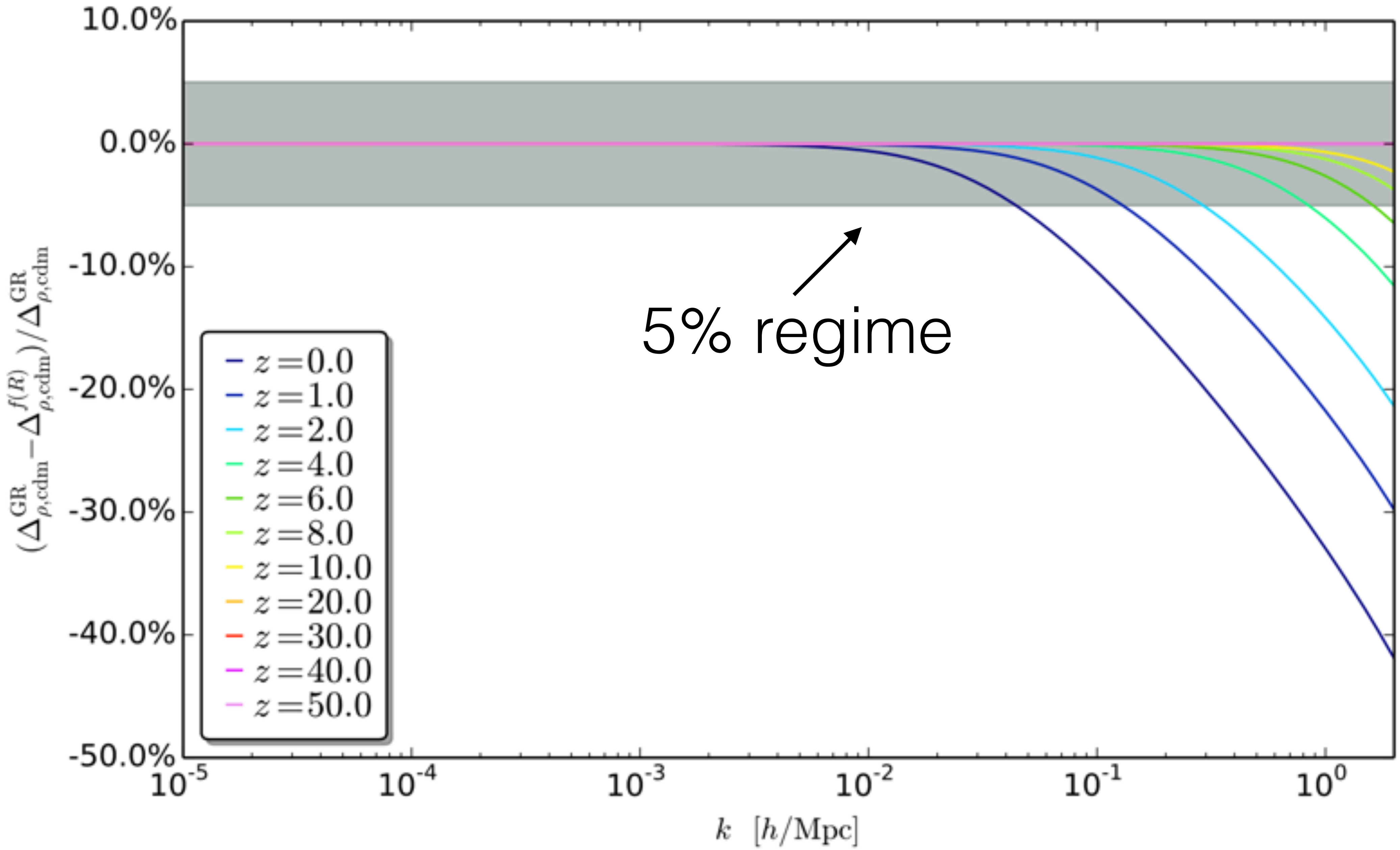


Dark Matter (Eulerian)

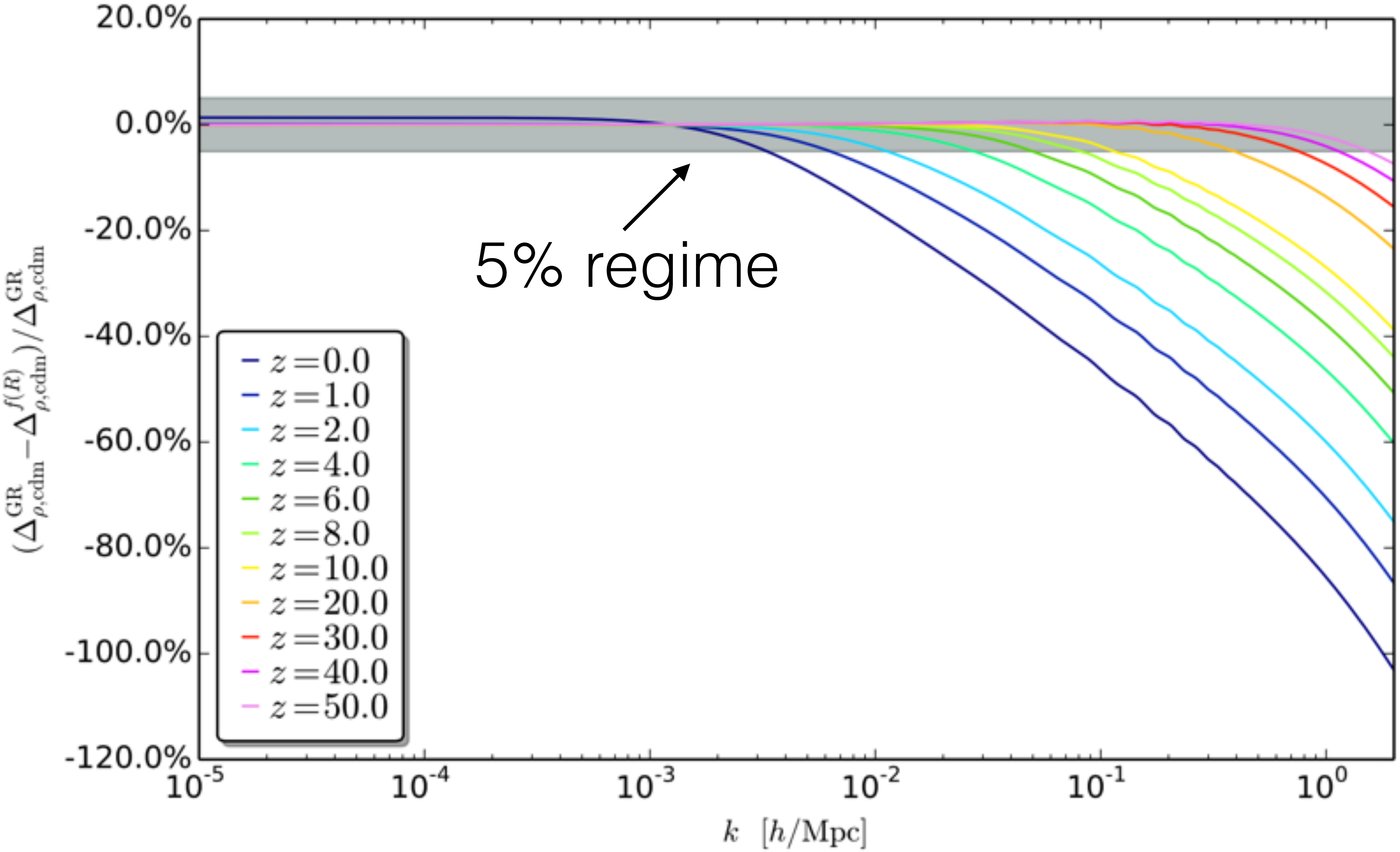


Q-fluid (Eulerian)

Transfer function of CDM

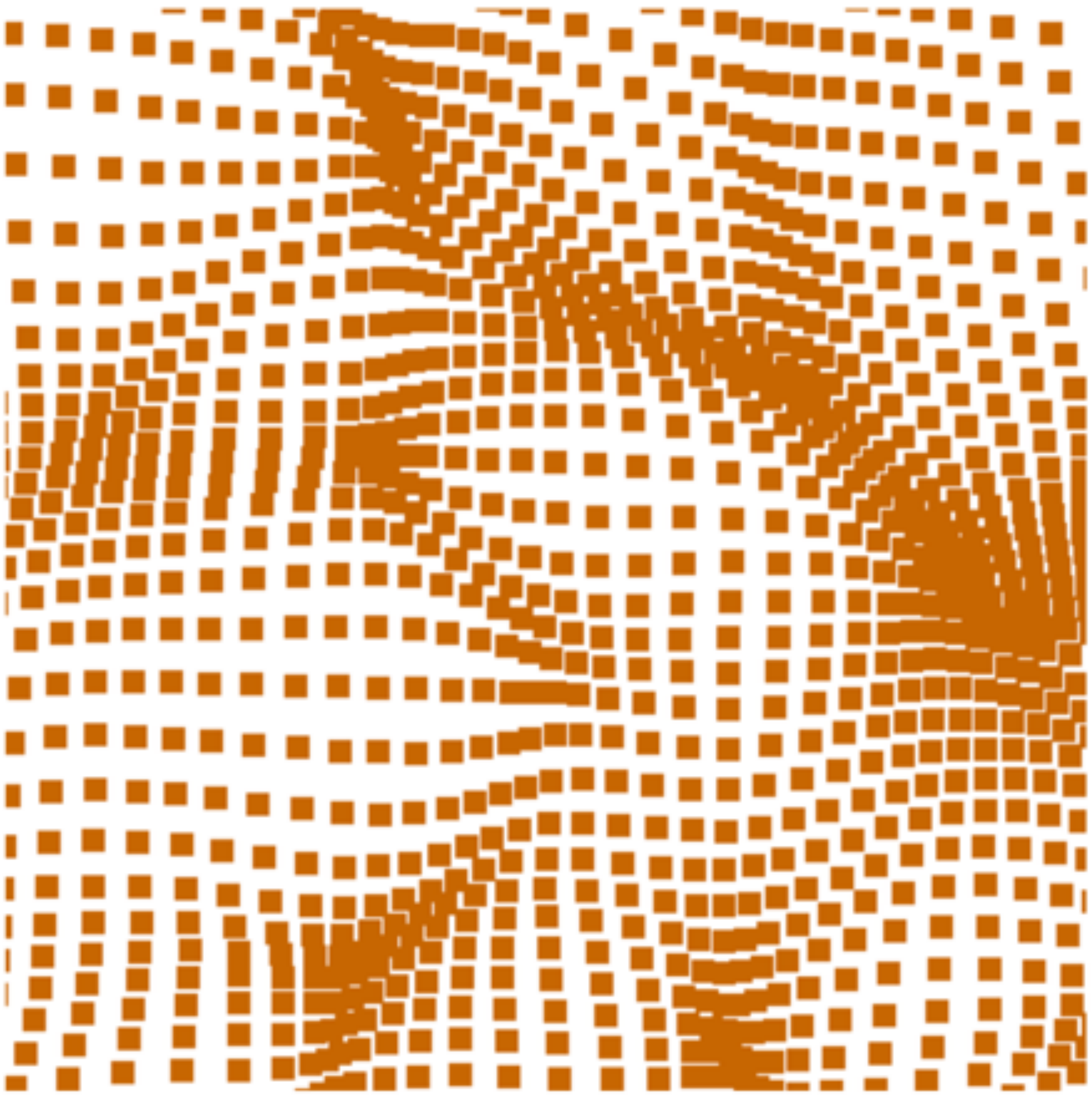


Designer f(R) with LCDM background
B0=0.001



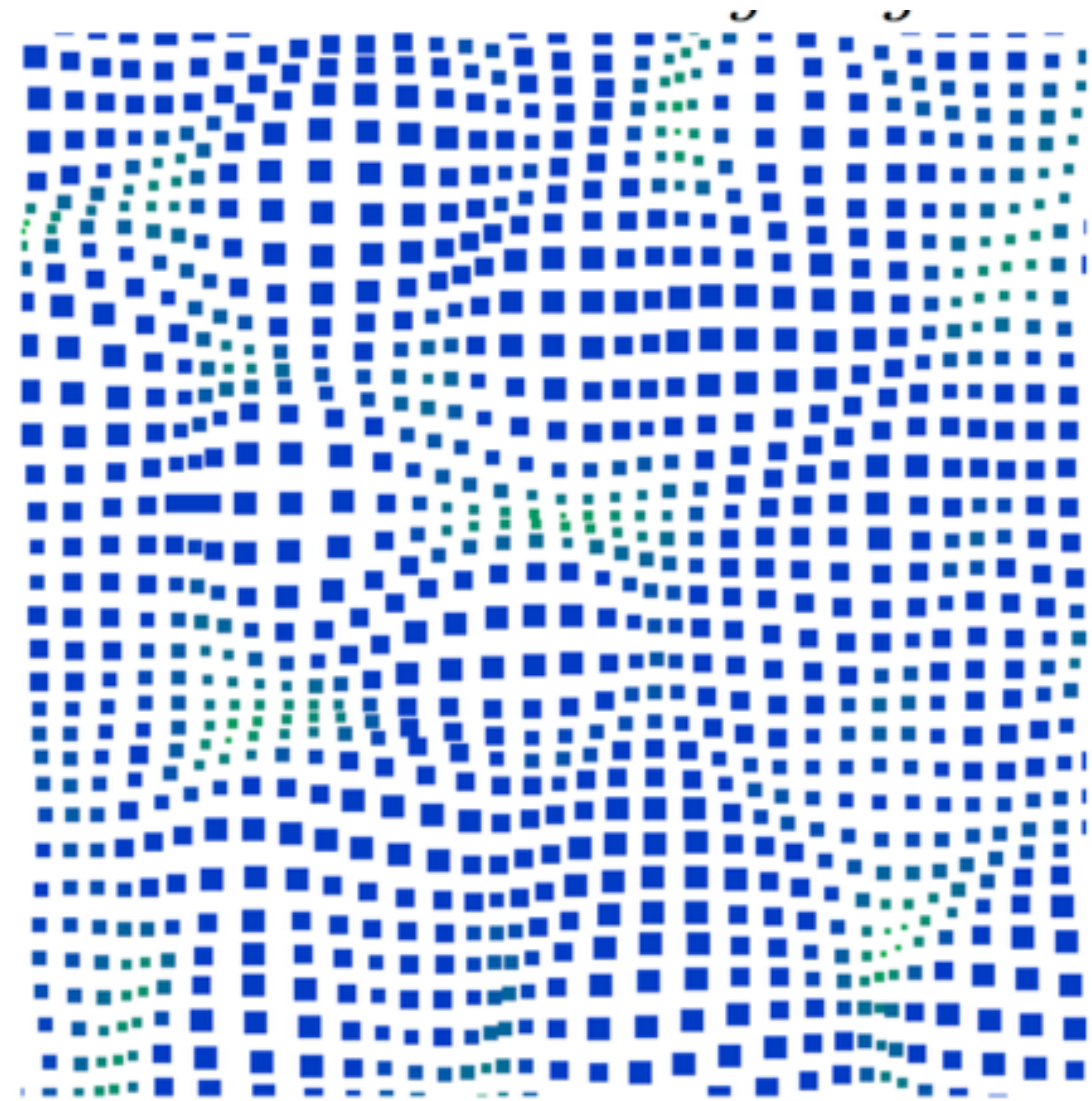
Designer f(R) with wCDM background
B0=0.01 and w=-0.95

(box size -> particle mass)



Dark Matter

(box color -> pressure)



Q-particles (Langrangian)

- CDM particle mass is conserved, Pressureless
- Q-paricle mass is non-conserved, Pressure

From IC to N-body (in progress)

On the linear regime:

1. Solve the linearised Klein-Golden eq.

$$A(\tau)\,\ddot{\pi} + B(\tau)\,\dot{\pi} + C(\tau)\,\pi + k^2\,D(\tau)\,\pi + E(\tau) = 0$$

e.g. 2. Solve the fluid (perfect/imperfect) conservation eq.

$$\nabla^\nu T^{(Q)}_{\mu\nu} = 0$$

On the non-linear regime:

1. Solve the NON-LINEAR Klein-Golden eq., like the potential

e.g. f(R) cs^2=1: $$\nabla^2 \delta f_R = \frac{1}{3c^2}[\delta R - 8\pi G \delta\rho]$$

See Marco Baldi talk for code comparison

2. Solve its world line eq., like CDM

e.g. collapsing DE, cs^2~0: $$\frac{\mathcal{D}^2 x^\mu}{\mathcal{D}t^2} = A^\nu$$

Conclusion

- The EFT of Cosmic Acceleration provides a generic and powerful framework to efficiently study DE/MG
- The EFT framework has been implemented in the Einstein/Boltzmann code CAMB, EFTCAMB (HiCLASS, E. Bellini et. al.)
- EFTCAMB is publicly available, does not rely on QSA,etc.
- IC for N-body can be important for some DE/MG
- The new release after Planck2015 come soon

EFTCAMB

萨宾诺，生日快乐！

Sabino, Happy Birthday!

Tanti auguri Sabino!