Large Scale Structure with interacting Vacuum: the non-linear regime in the post-Friedman approximation

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Credits

- Irene Milillo, Daniele Bertacca, MB and Andrea Maselli (2015), *The missing link: a nonlinear post-Friedmann framework for small and large scales* [arXiv: 1502.02985], Physical Review D, 92, 023519 (2015)
- MB, Dan B. Thomas and David Wands (2014), *Computing General Relativistic effects from Newtonian N-body simulations: Frame dragging in the post-Friedmann approach,* Physical Review D, **89**, 044010 [arXiv:1306.1562]
- Dan B. Thomas, MB, Kazuya Koyama, Baojiu Li and Gong-bo Zhao (2015) *f(R) gravity on non-linear scales: The post-Friedmann expansion and the vector potential* [arXiv:1503.07204], JCAP, *in press*
- Indications of a Late-Time Interaction in the Dark Sector, V. Salvatelli, N. Said, MB, A. Melchiorri & D. Wands, PRL 113, 181301 (2014). arXiv: 1406.7297
- A. Maselli, B. Bruni & D. Thomas, Interacting vacuum-energy in a Post-Friedmann expanding Universe (to be submitted)

interacting vacuum scenario

- back to basic: CDM and Vacuum only, interacting

(Wands, De-Santiago & Wang, arXiv:1203.6776;

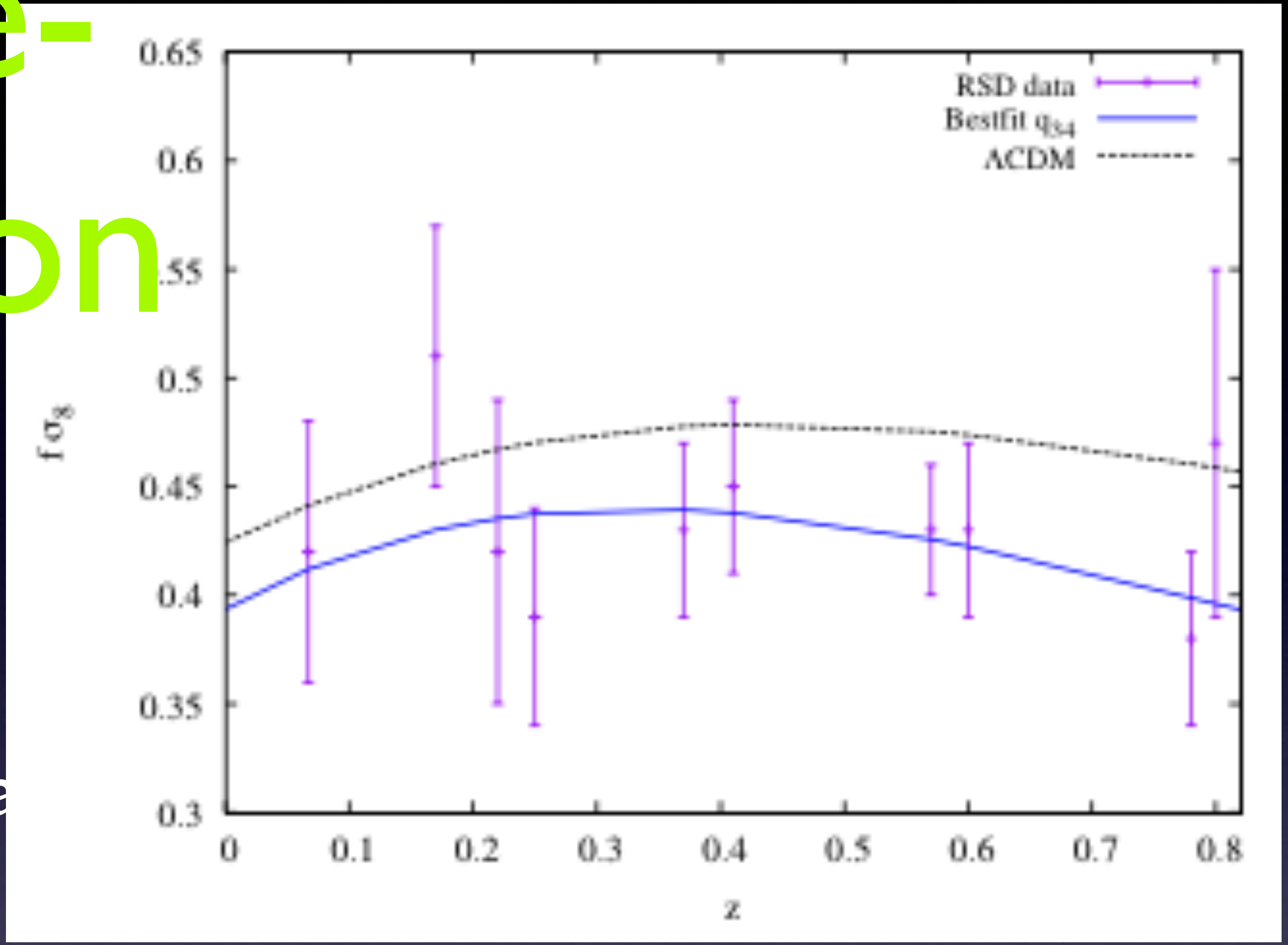
Wang, Wands, Zhao & Xu, arXiv:1404.5706)

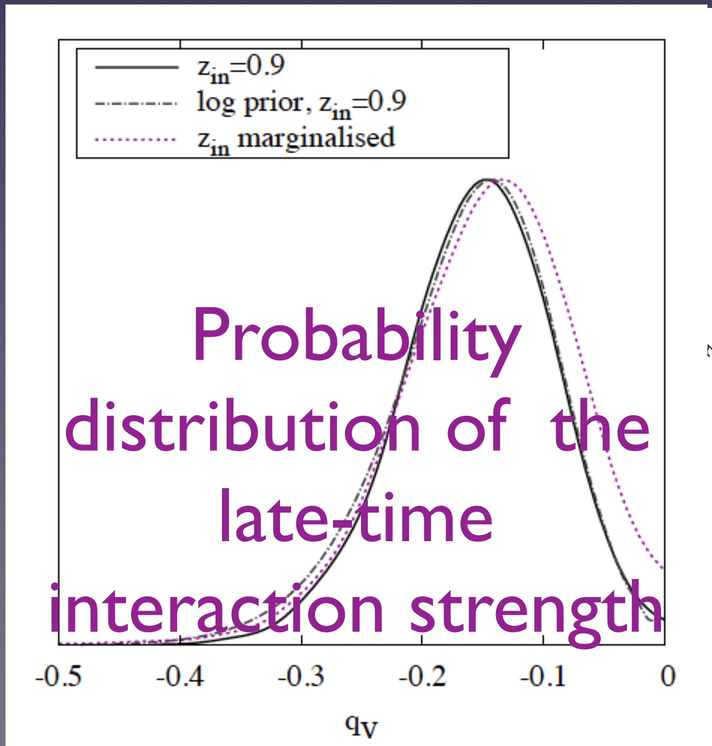
interacting vacuum scenario summary

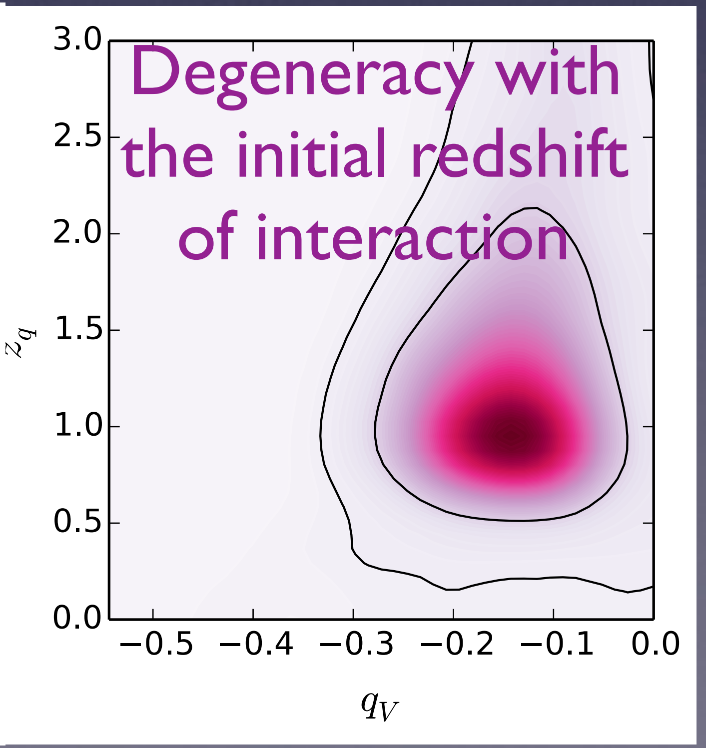
- V (vacuum) reduces to Λ for zero interaction
- we focus on subclass of models with $Q^\mu \propto u^\mu$, so that CDM follows geodesics, and gravitational clustering is like in ΛCDM
- for this case, sync-comoving gauge is special: Vacuum is homogeneous
- we first don't assume an interaction, rather ask the data (CMB +RSD) what it could be, bin by bin in z
- we then consider the simplest case of a single interaction bin at low z
- Indications of a Late-Time Interaction in the Dark Sector, V. Salvatelli, N. Said, MB, A. Melchiorri & D. Wands, PRL 113, 181301 (2014). arXiv:1406.7297

single bin late-time interaction

- z_{in} poorly constrained but degeneracy with q_V is weak
- changing flat prior [-10,0] to a log prior [-2,2] on q_V doesn't change the posterior much
- marginalising on $z_{in\ sl}$ slightly broaden the posterior
- model alleviate tensions: e.g. H_0 by Planck and HST



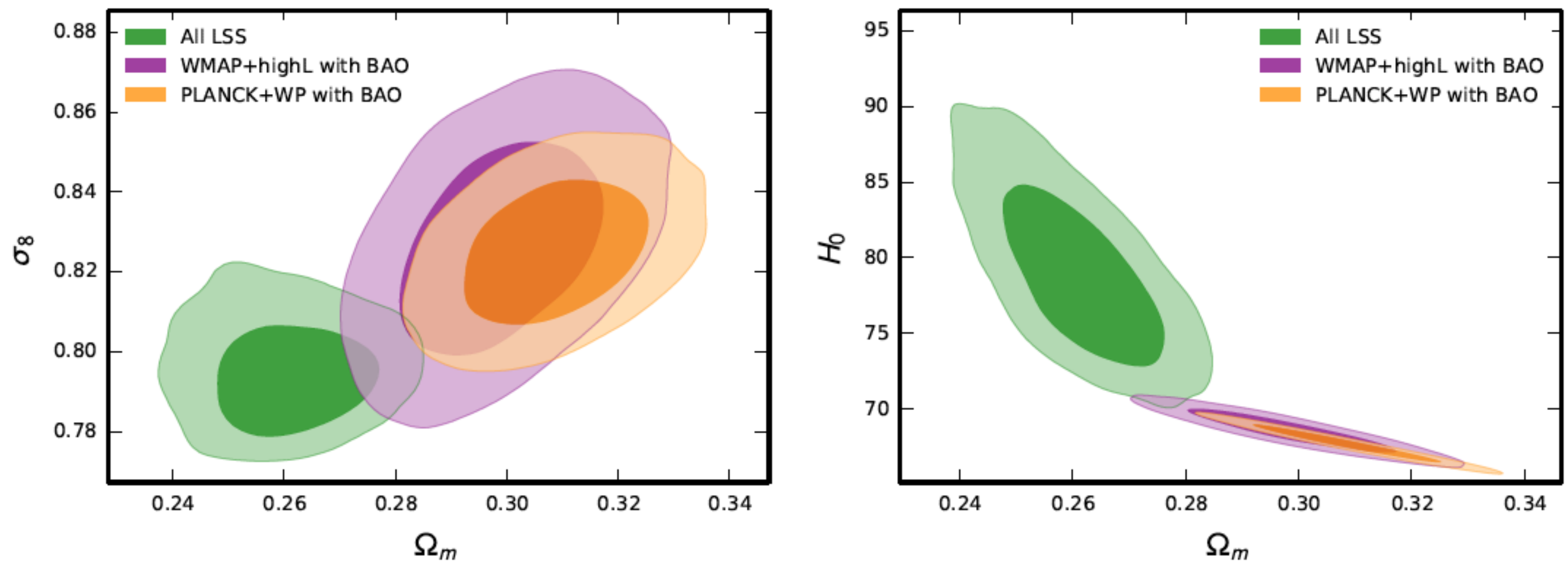




Tension between CMB+LSS

Battye, Charnock and Moss, arXiv:1409.2769

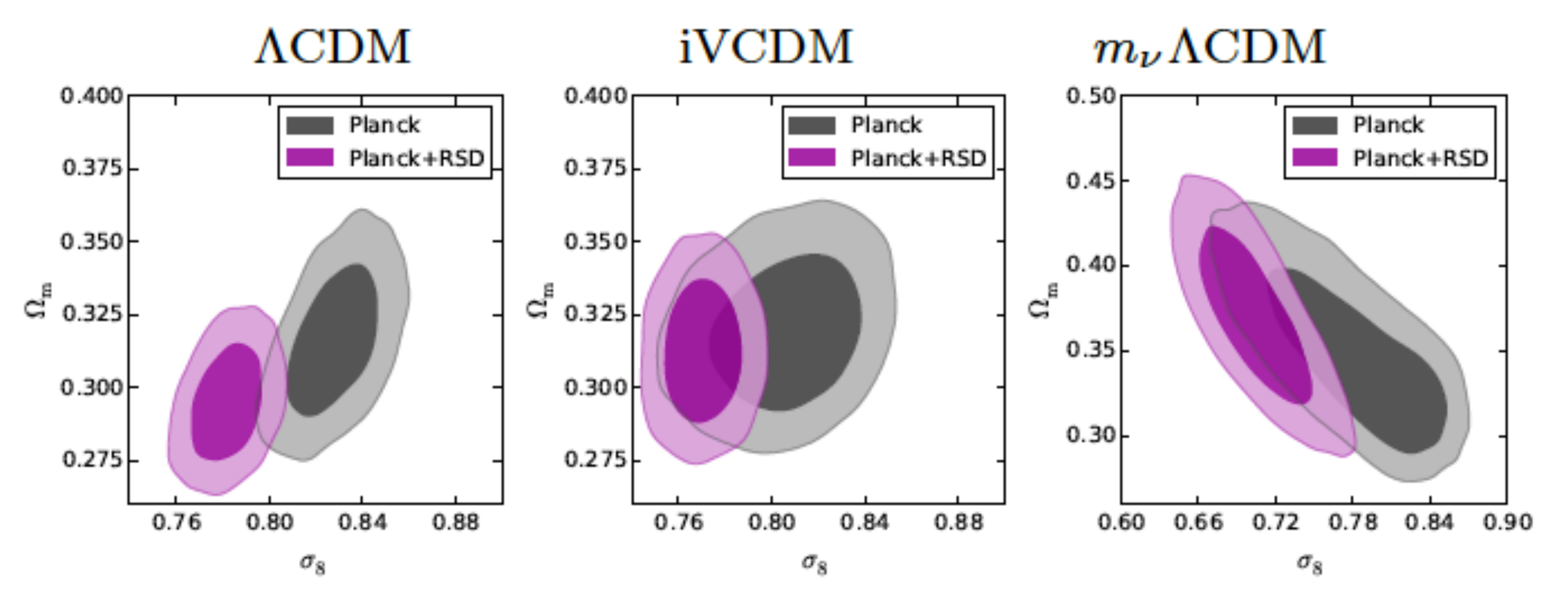
tension between WMAP/Planck vs LSS (RSD, SZ clusters and lensing)



see also Battye & Moss; Hamann & Hasenkamp; Wyman et al;
Leistedt, Peiris & Verde 2014

CMB-RSD tensions

- single-bin late-time interaction alleviates tension between Planck and RSD datasets
- does so better than massive neutrinos

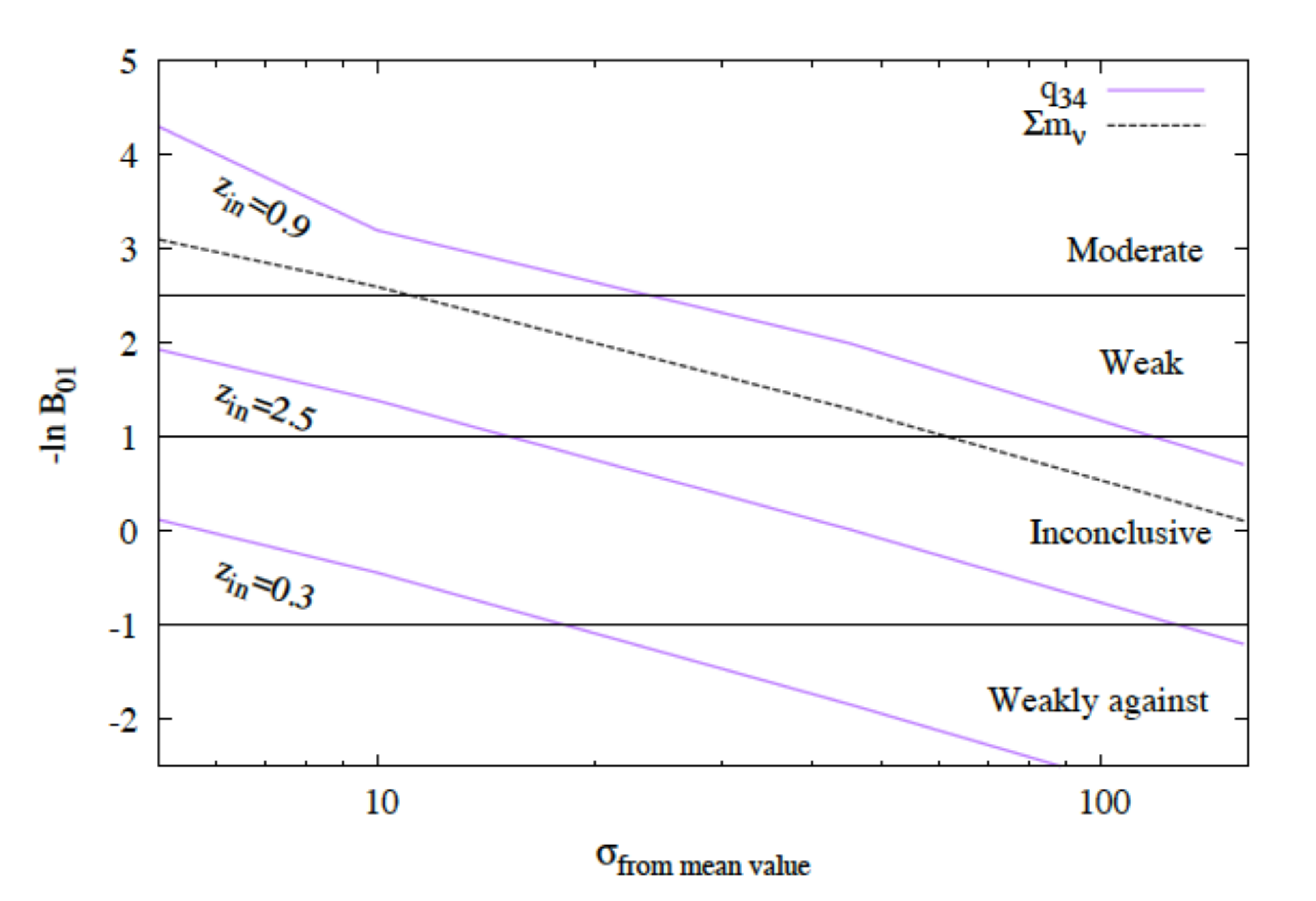


model comparison

- in our analysis we use the standard fixed value $\Sigma\, m_\nu$=0.06 eV
- we also looked at ΛCDM with varying $\Sigma\, m_\nu$, finding $\Sigma\, m_\nu$=0.06 eV
- both the single-bin late-time interaction model and the varying $\Sigma\, m_\nu$ model are 1-parameter nested extensions of ΛCDM
- this allows for a simple Bayesian comparison

Evidence for late-time interaction?

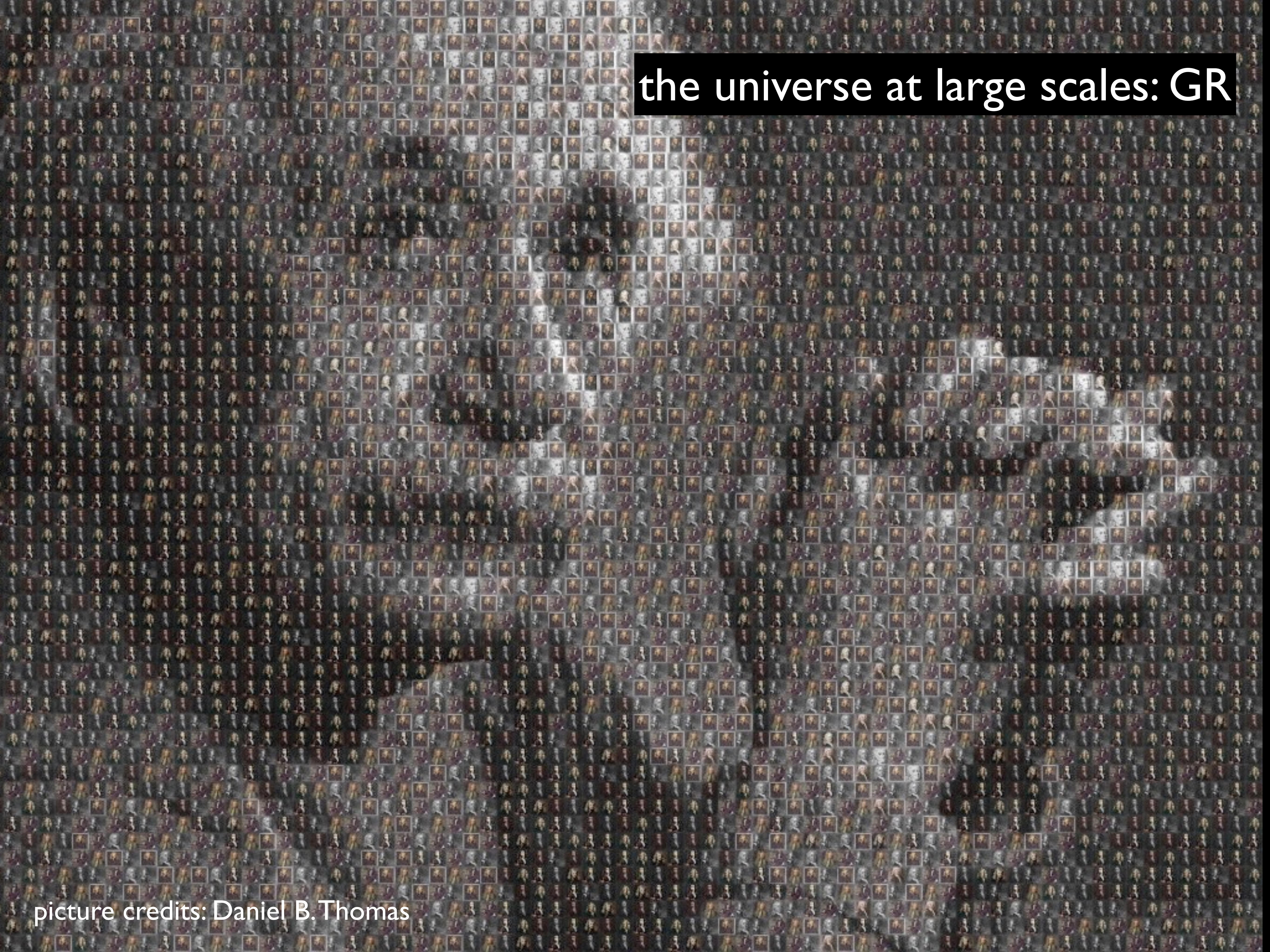
- Byesian evidence for nested models against ΛCDM, vs prior range allowed, shown here in terms of standard deviation from mean value, since q_{34} is a phenomenological parameter



linear vs nonlinear

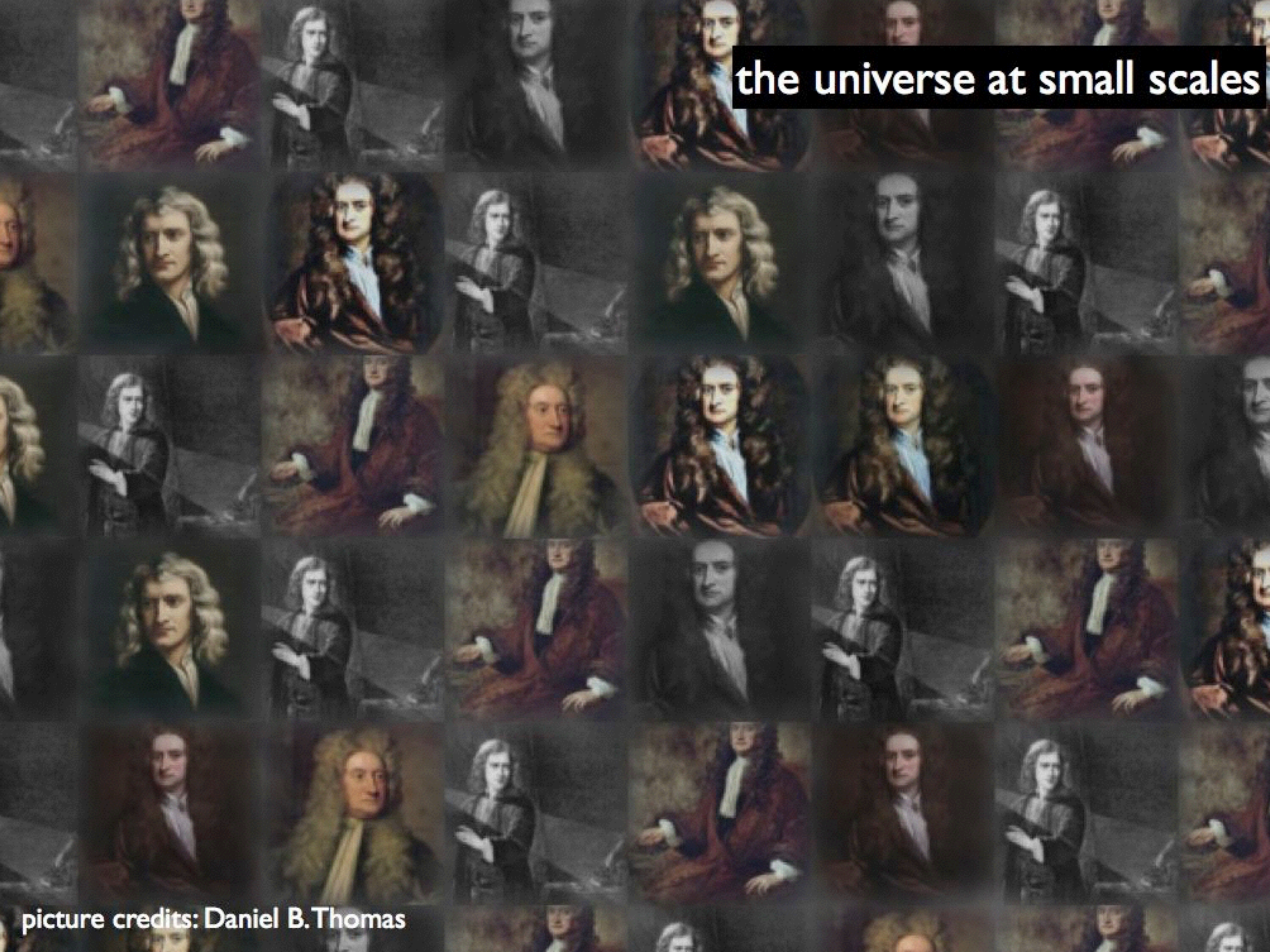
- this type of analysis is based on linear perturbation theory
- typically we model nonlinear structure formation with Newtonian N-body simulations...

the universe at large scales: GR



picture credits: Daniel B. Thomas

the universe at small scales



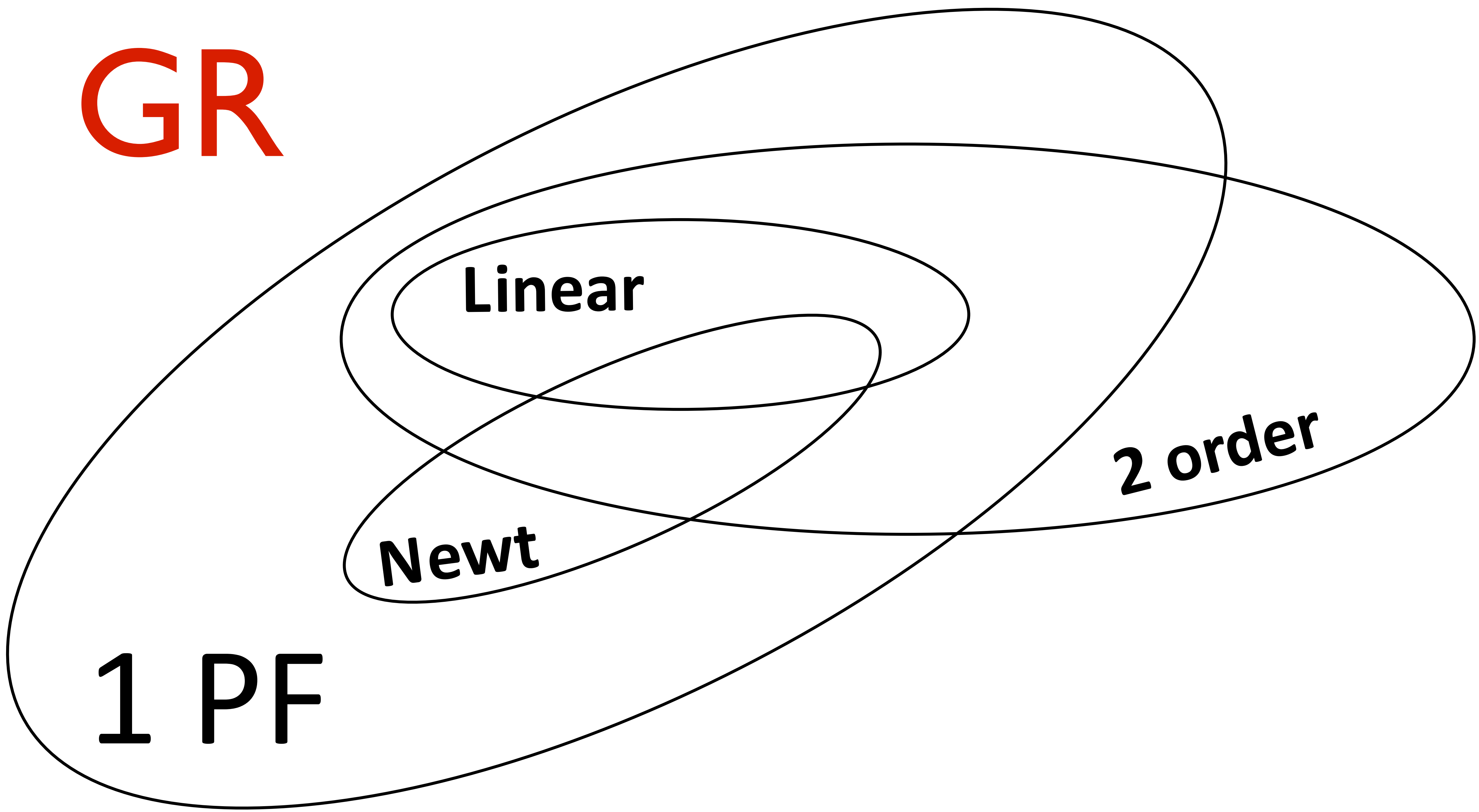
picture credits: Daniel B. Thomas

non-linear post-Friedmann framework in ΛCDM

- assume GR and a flat ΛCDM background
- perturbation theory is only valid for small δ, we want nonlinear δ
- current state:
  - non-linear relativistic approximate framework, incorporating fully non-linear Newtonian theory at small scales and standard relativistic perturbations at large scales ($\sim H^{-1}$ and beyond)
  - extract leading order relativistic corrections from standard Newtonian simulations, in a post-N fashion
- future goals:
  - incorporate GR corrections in simulations
  - ▸ more accurate ΛCDM cosmology

post-Friedmann framework

- spaces of equations (not solutions!)



Post-Newtonian cosmology

- post-Newtonian: expansion in 1/c powers (more later)
- various attempts and studies:
  - Tomita Prog. Theor. Phys. 79 (1988) and 85 (1991)
  - Matarrese & Terranova, MN 283 (1996)
  - Takada & Futamase, MN 306 (1999)
  - Carbone & Matarrese, PRD 71 (2005)
  - Hwang, Noh & Puetzfeld, JCAP 03 (2008)
- even in perturbation theory it is important to distinguish post-Newtonian effects, e.g. in non-Gaussianity and initial conditions. MB, J. C. Hidalgo, N. Meures, D. Wands, ApJ 785:2 (2014) [arXiv:1307:1478], cf. Bartolo et al. CQG 27 (2010) [arXiv:1002.3759]

post-N vs. post-F

- problems of standard post-Newtonian:
  - focus on equation of motion of matter, rather than on deriving a consistent approximate solution of field equations
  - derived metric OK for motion of matter, not for photons
- post-Friedmann: something in between: start with a post-M (weak field) approach on a FLRW background, Hubble flow is not slow but peculiar velocities are small $\dot{\vec{r}} = H\vec{r} + a\vec{v}$
- post-Friedmann: we don't necessarily follow an iterative approach; aim at resummed variables in order to match standard perturbation theory in some limit

metric and matter I

starting point: the 1-PN cosmological metric
(cf. Chandrasekhar 1965)

$$
\begin{aligned}
g_{00} &= -\left[1 - \frac{2U_N}{c^2} + \frac{1}{c^4}(2U_N^2 - 4U_P)\right] + O\left(\frac{1}{c^6}\right), \\
g_{0i} &= -\frac{a}{c^3}B_i^N - \frac{a}{c^5}B_i^P + O\left(\frac{1}{c^7}\right), \\
g_{ij} &= a^2\left[\left(1 + \frac{2V_N}{c^2} + \frac{1}{c^4}(2V_N^2 + 4V_P)\right)\delta_{ij} + \frac{1}{c^4}h_{ij}\right] + O\left(\frac{1}{c^6}\right),
\end{aligned}
$$

we assume a Newtonian-Poisson gauge: B_i is solenoidal and h_{ij} is TT, at each order 2 scalar DoF in g_{00} and g_{ij}, 2 vector DoF in frame dragging potential B_i and 2 TT DoF in h_{ij} (not GW!)

metric and matter II

having in mind Newtonian cosmology it is natural to define the peculiar velocity v^i such that

$$u^i = \frac{dx^i}{cd\tau} = \frac{dx^i}{cdt}\frac{dt}{d\tau} = \frac{v^i}{ca}u^0$$

$$u^0 = 1 + \frac{1}{c^2}\left(U_N + \frac{1}{2}v^2\right) + \frac{1}{c^4}\left[\frac{1}{2}U_N^2 + 2U_P + v^2 V_N + \frac{3}{2}v^2 U_N + \frac{3}{8}v^4 - B_i^N v^i\right]$$

$$u_i = \frac{a v_i}{c} + \frac{a}{c^3}\left[-B_i^N + v_i U_N + 2 v_i V_N + \frac{1}{2}v_i v^2\right],$$

$$u_0 = -1 + \frac{1}{c^2}\left(U_N - \frac{1}{2}v^2\right) + \frac{1}{c^4}\left[2U_P - \frac{1}{2}U_N^2 - \frac{1}{2}v^2 U_N - v^2 V_N - \frac{3}{8}v^4\right].$$

$$T^\mu{}_\nu = c^2 \rho u^\mu u_\nu,$$

$$\begin{aligned}
T^0{}_0 &= -c^2\rho - \rho v^2 - \frac{1}{c^2}\rho\left[2(U_N + V_N)v^2 - B_i^N v^i + v^4\right] \\
T^0{}_i &= c\rho a v_i + \frac{1}{c}\rho a\left\{v_i[v^2 + 2(U_N + V_N)] - B_i^N\right\}, \\
T^i{}_0 &= -c\frac{1}{a}\rho v^i - \frac{1}{c}\frac{1}{a}\rho v^2 v^i, \\
T^i{}_j &= \rho v^i v_j + \frac{1}{c^2}\rho\left\{v^i v_j[v^2 + 2(U_N + V_N)] - v^i B_j^N\right\}, \\
T^\mu{}_\mu &= T = -\rho c^2.
\end{aligned}$$

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$$u_i = \frac{av_i}{c} + \frac{a}{c^3}\left[-B_i^N + v_i U_N + 2v_i V_N + \frac{1}{2}v_i v^2\right],$$

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T^\mu{}_\mu &= T = -\rho c^2 .
\end{aligned}$$

note:

ρ is a non-perturbative quantity

Newtonian ΛCDM, with a bonus

- insert leading order terms in E.M. conservation and Einstein equations
- subtract the background, getting usual Friedmann equations
- introduce usual density contrast by $\rho=\rho_b(1+\delta)$

from E.M. conservation: Continuity & Euler equations

$$\dot{\delta} + \frac{v^i \delta_{,i}}{a} + \frac{v^i{}_{,i}}{a}(\delta + 1) = 0 \, ,$$

$$\dot{v}_i + \frac{v^j v_{i,j}}{a} + \frac{\dot{a}}{a} v_i = \frac{1}{a} U_{N,i} \, .$$

Poisson

$$G^0{}_0 + \Lambda = \frac{8\pi G}{c^4} T^0{}_0 \quad \rightarrow \quad \frac{1}{c^2}\frac{1}{a^2}\nabla^2 V_N = -\frac{4\pi G}{c^2}\bar{\rho}\delta$$

non-linear post-Friedmann framework in i-VCDM

- in synchronous comoving gauge with a geodesic interaction Vacuum is homogeneous, interactions only dynamical through the background
- how this translates in the Newtonian settings of N-body simulations?
- what is the leading order, in 1/c, of i-VCDM?

post-F vector potential in f(R)

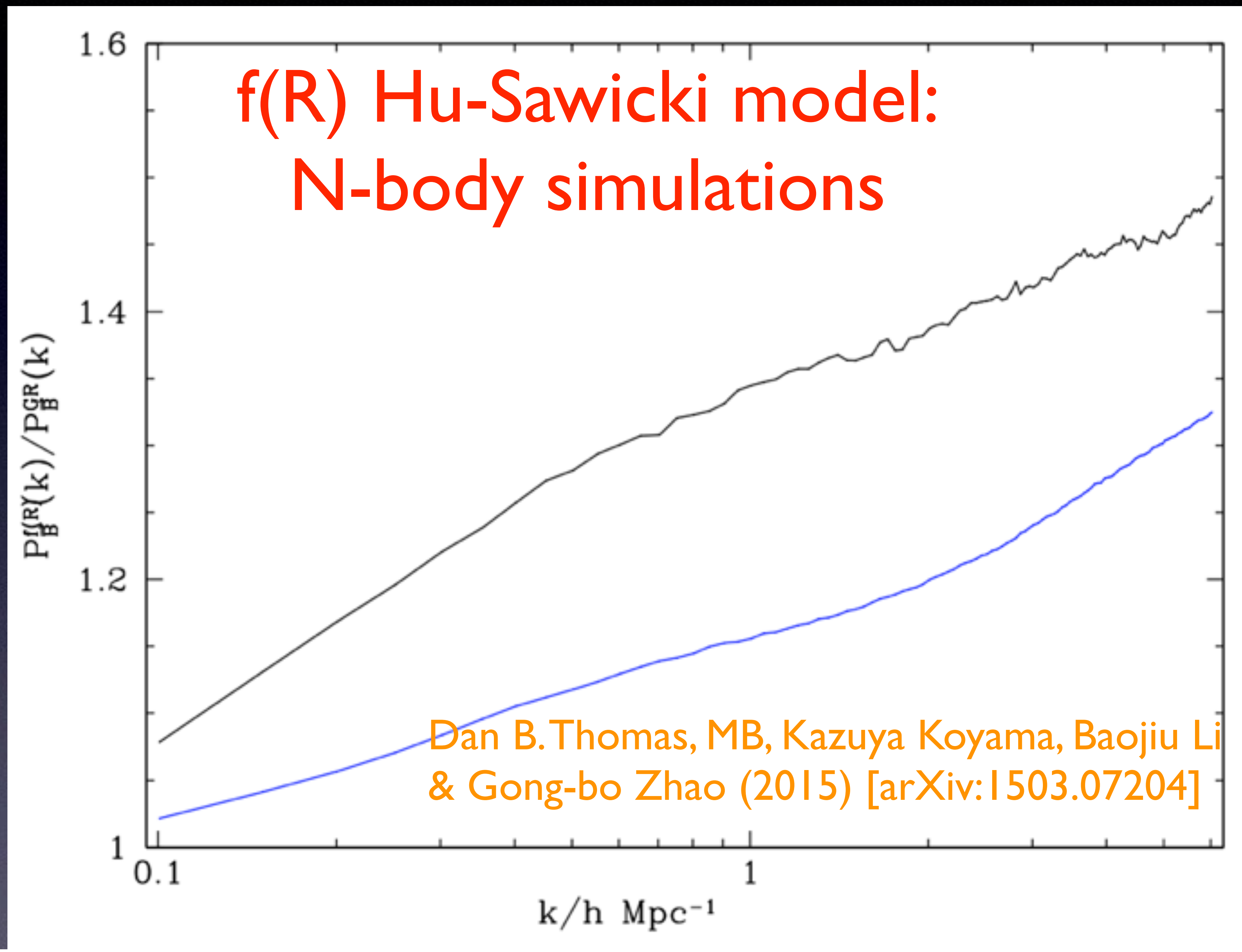

FIG. 3: The ratio of the vector potential power spectrum in $f(R)$ gravity to that in GR, for $|f_{R_0}| = 10^{-5}$. The blue curve shows the ratio at redshift one, and the black curve shows the ratio at redshift zero.

post-Friedmann framework in i-VCDM: results at leading order

- post-F in Poisson gauge, suitable to recover Newtonian-type Eulerian settings for N-body
- only the background is modified compared to the standard ΛCDM equations
- we can now safely proceed to produce N-body simulations for the i-VCDM scenario