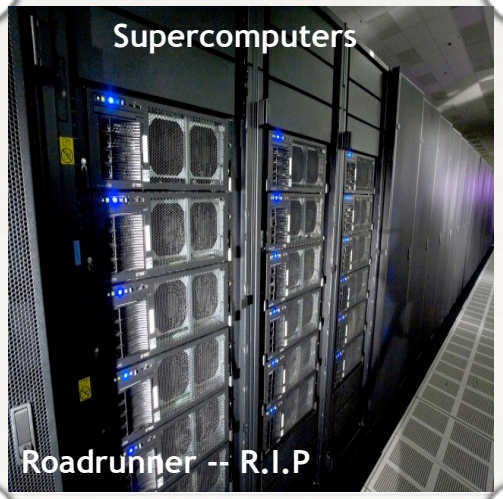
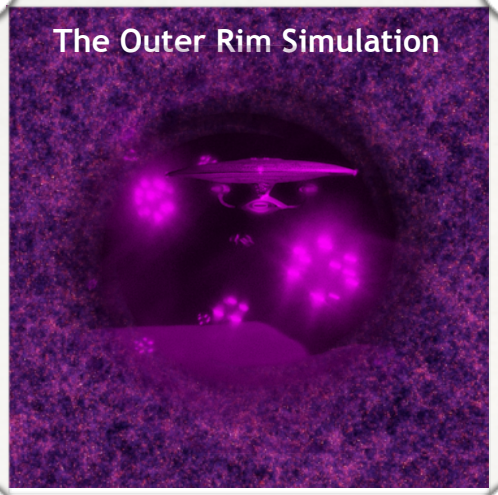
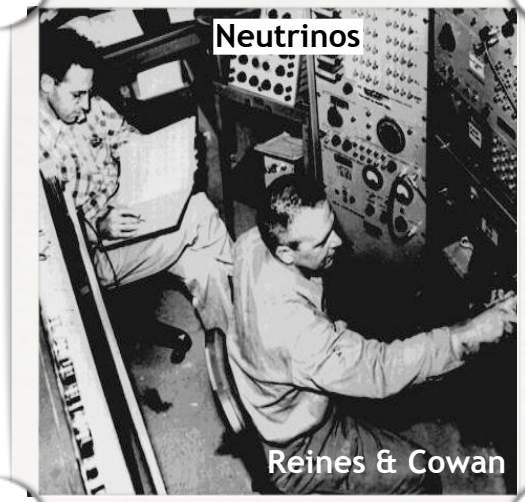
Large-Scale Structure Formation with Massive Neutrinos

Katrin Heitmann

Fermilab Particle Astrophysics Seminar, February 24, 2014







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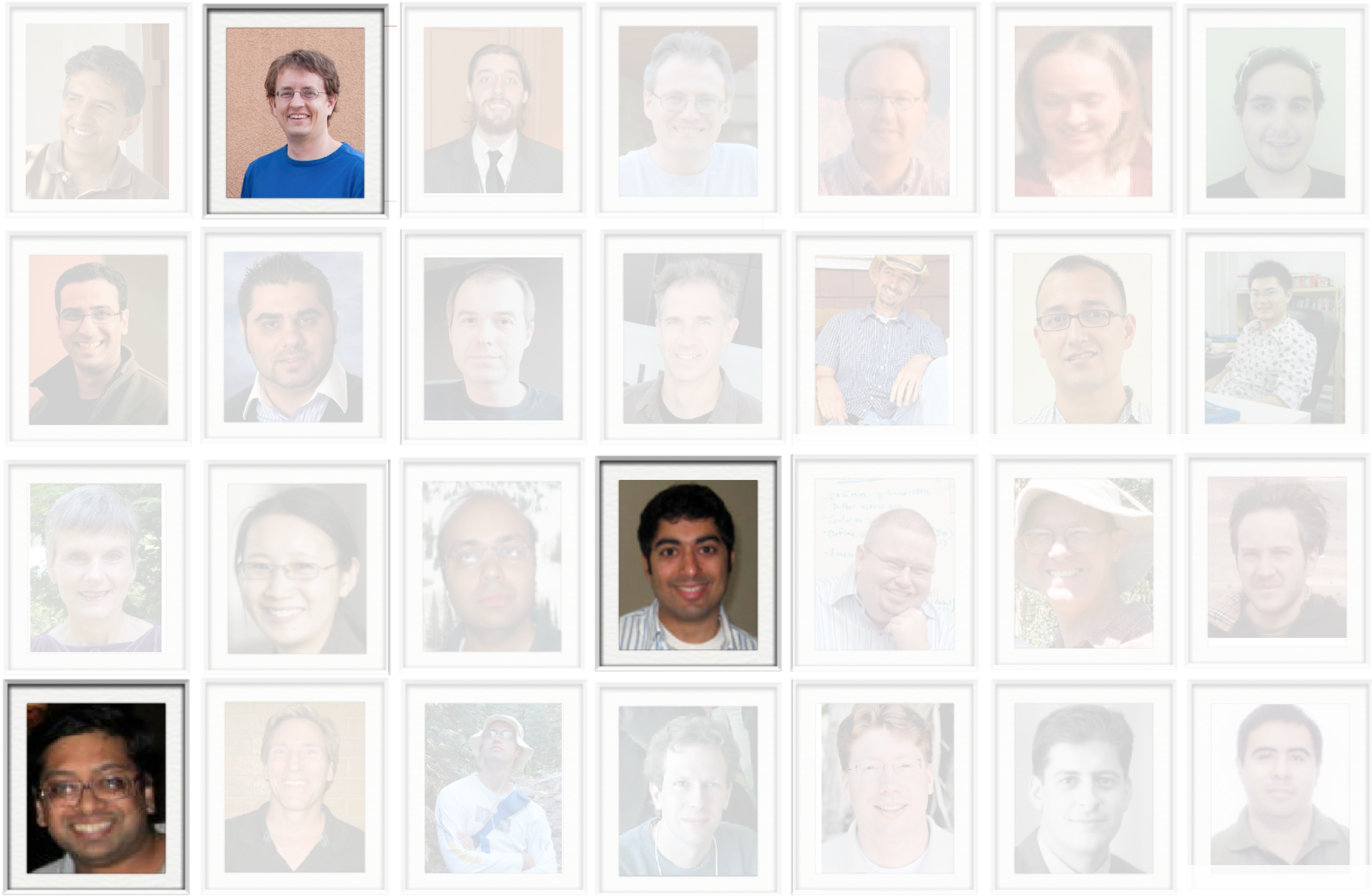
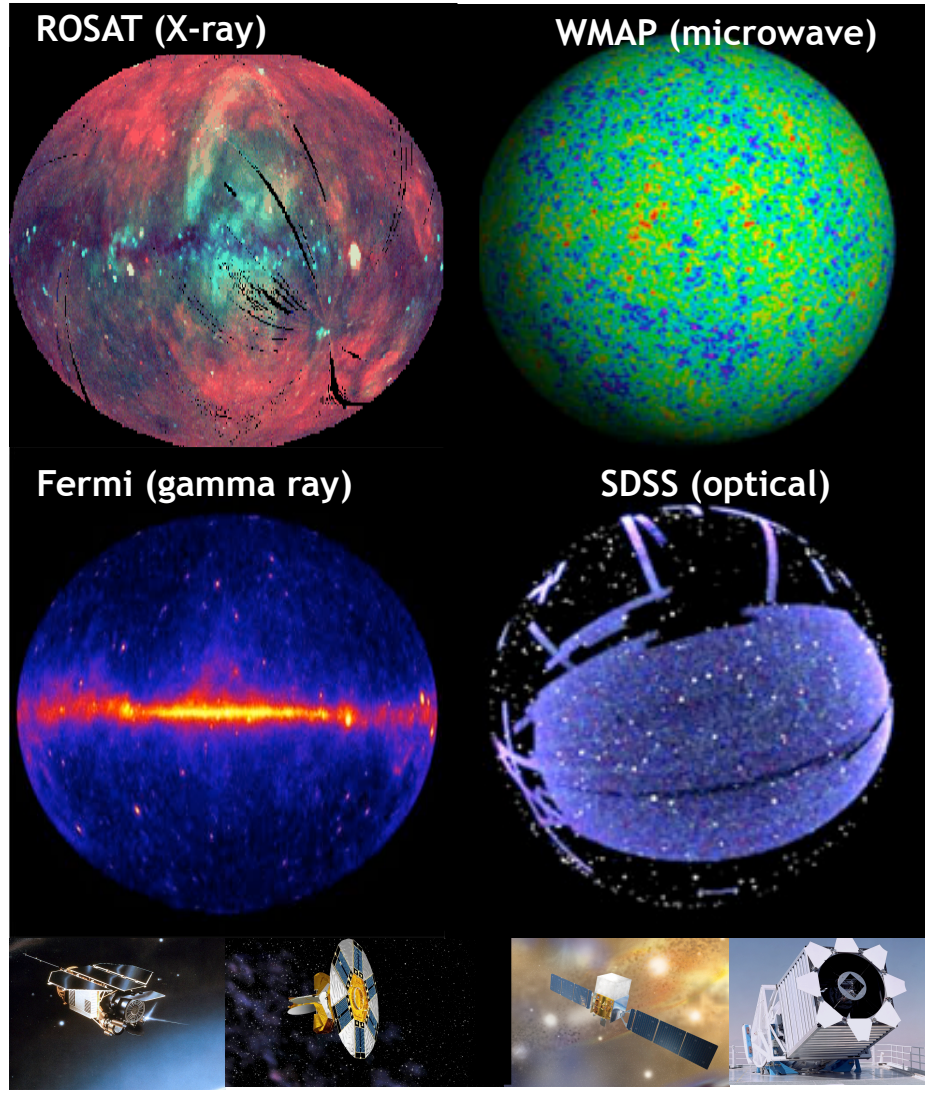


The Story

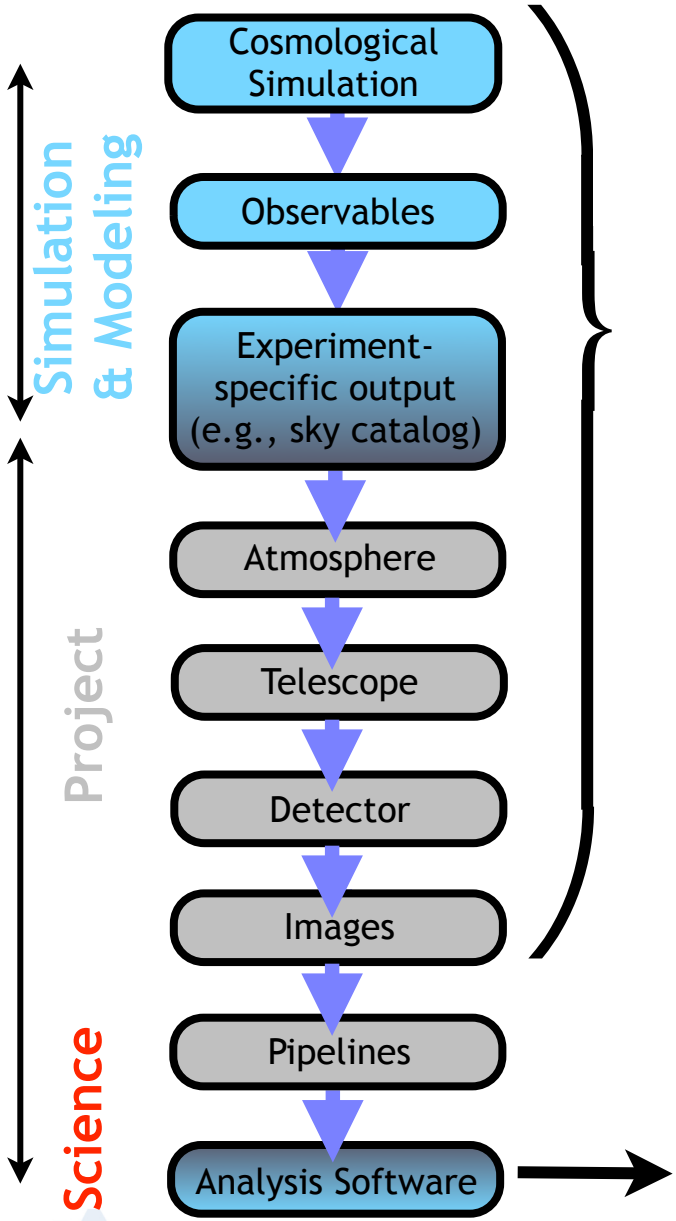
- **Surveys and Simulations**
  - The role of large simulations in contemporary cosmology
  - Computing the Universe: Connecting theory, simulations, and observations
  - HACC (Hardware/Hybrid Accelerated Cosmology Code): An N-body code designed for extreme scaling
- **Neutrinos and Cosmology**
  - What can we learn about the lightest massive particles in the Universe from cosmological observations of large scale structure?
  - Simulating neutrinos
  - Results from our effort
- **What's next --**

Modern Cosmology and Sky Maps

- Modern cosmology is the story of mapping the sky in multiple wavebands
- Maps cover measurements of objects (stars, galaxies) and fields (temperature)
- Maps can be large (Sloan Digital Sky Survey has~200 million galaxies, many billions for planned surveys)
- Statistical analysis of sky maps
- All precision cosmological analyses constitute a statistical inverse problem: from sky maps to scientific inference
- Therefore: *No* cosmology without (large-scale) computing

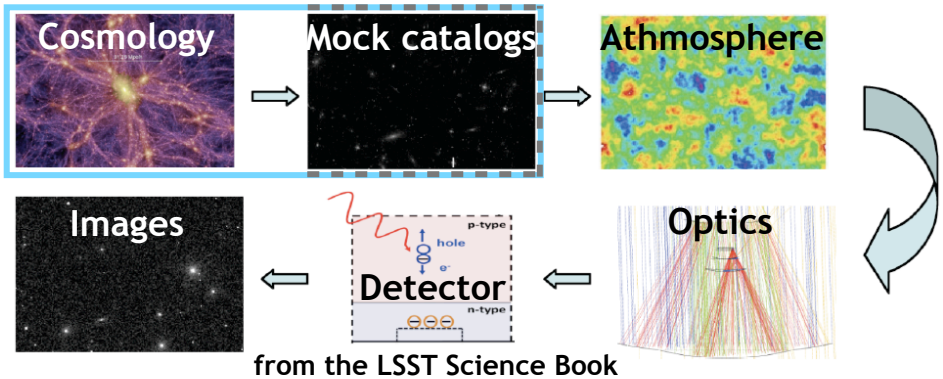


Roles of Cosmological Simulations in DE Survey Science



(1) Cosmology simulations and the survey

- First part of end-to-end simulation
- Control of systematics

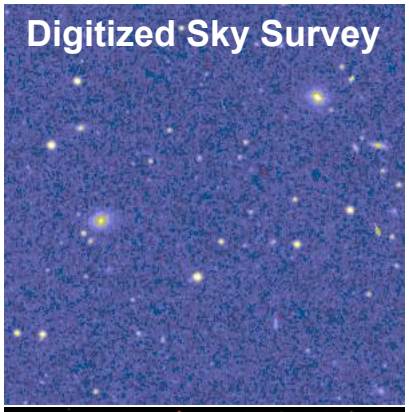


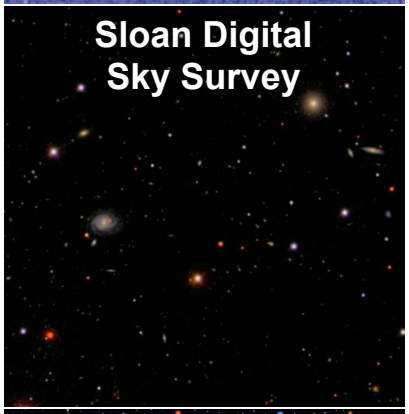
from the LSST Science Book

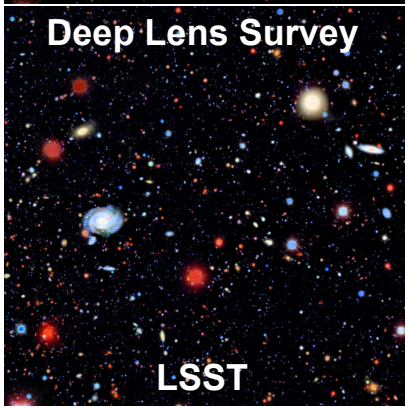
(2) Solving the Inverse Problem, Extracting Dark Energy Science

- Fast, very accurate predictions tools (emulators) for physics and observables of interest
- Astrophysical systematics, e.g. baryonic effects
- Predictions for covariances

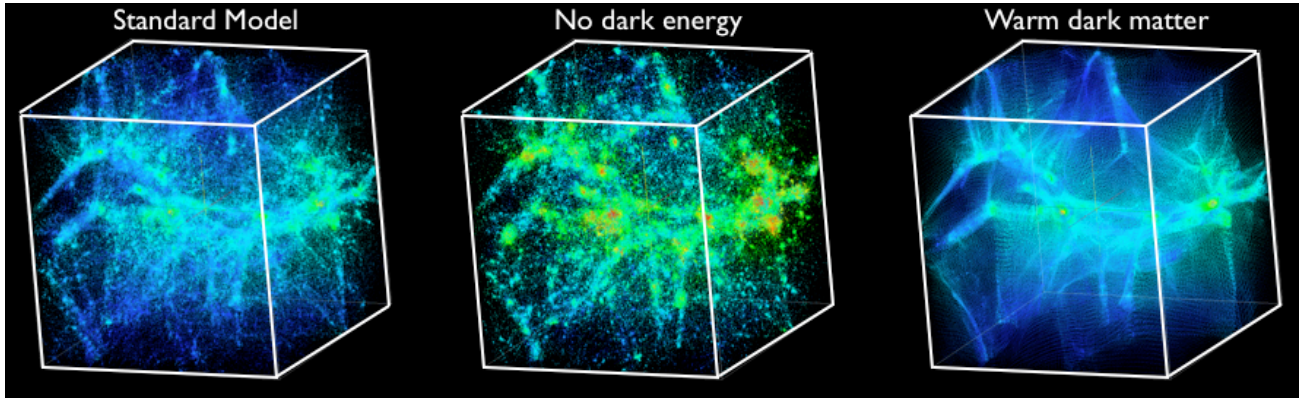
Precision Cosmology: “Inverting” the 3-D Sky



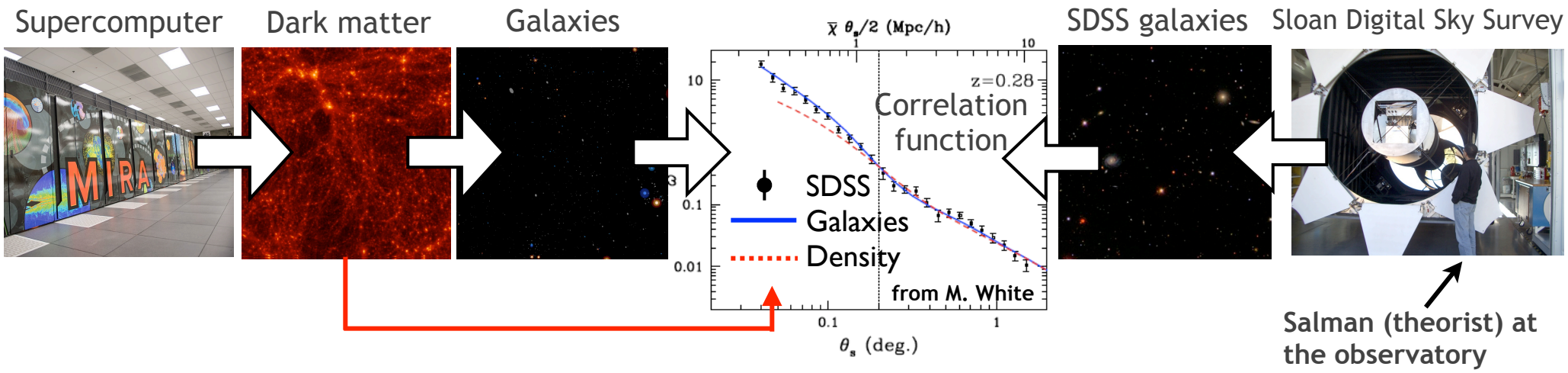




- **Standard Model of Cosmology:** Verified at the 5-10% level across multiple observations, describes make-up and evolution of the Universe
- **Next generation observatories:** aim to push the current boundaries by orders of magnitude
- Scales that are resolved by future surveys become smaller and smaller, demanding (i) ever larger simulations with increased mass and force resolution; (ii) more detailed physics
- **Next frontier:** Nonlinear regime of structure formation
- **Future Targets:** Aim to control survey measurements to the ~1% level, **can theory and simulation keep up?**



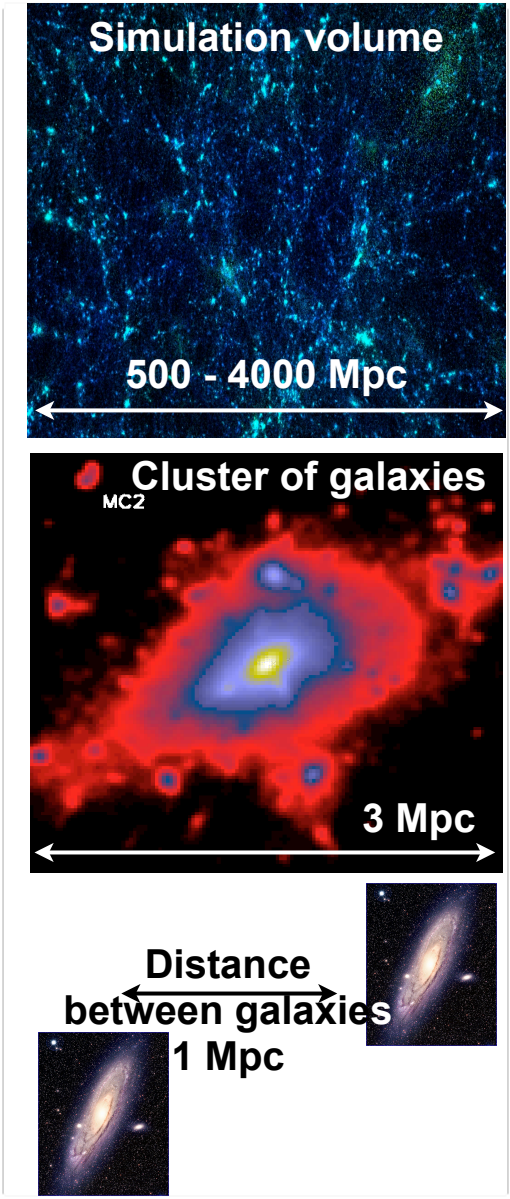
Connecting Theory and Observations



- Simulate the formation of the large scale structure of the Universe via dark matter tracer particles
- Take dark energy into account in the expansion history
- Measure the high-density peaks (dark matter halos) in the mass distribution
- “Light traces mass” to first approximation, therefore populate the halos with galaxies, number of galaxies depends on mass of halo (constraints from observations), more on this later!
- Galaxy population prescription (hopefully) independent of cosmological model

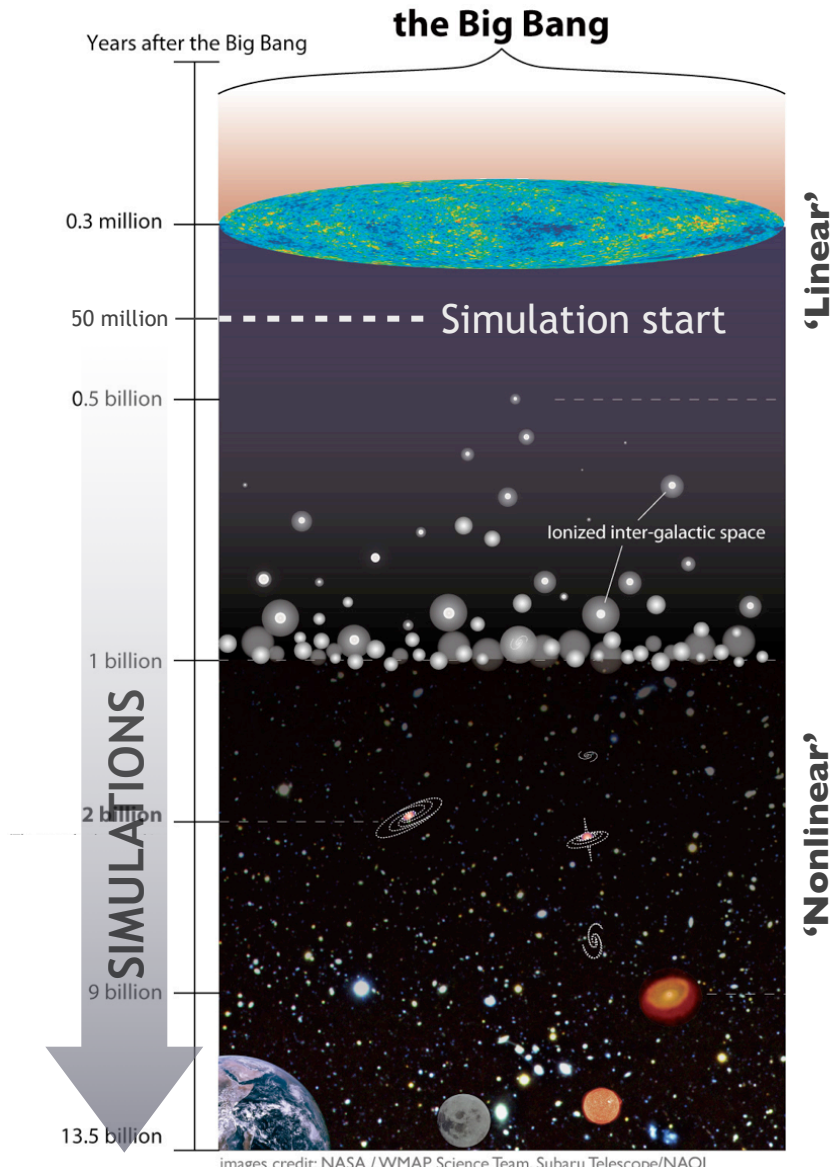
Computing the Universe: Simulating Surveys

- **Simulation Volume:** Large survey sizes impose simulation volumes ~(4 Gpc)^3, memory required ~100TB - 1PB
- **Number of Particles:** Mass resolution depends on ultimate object to be resolved, ~$10^8 M_\odot - 10^{10} M_\odot$, N~ $10^{11} - 10^{12}$
- **Force Resolution:** ~kpc, yields a (global) spatial dynamic range of 10^6
- **Throughput:** Large numbers of simulations required (100's --1000's), development of analysis suites, and emulators; peta-exascale computing exploits
- **Computationally very challenging! HACC is aimed to meet these requirements**



Structure Formation: The Basic Paradigm

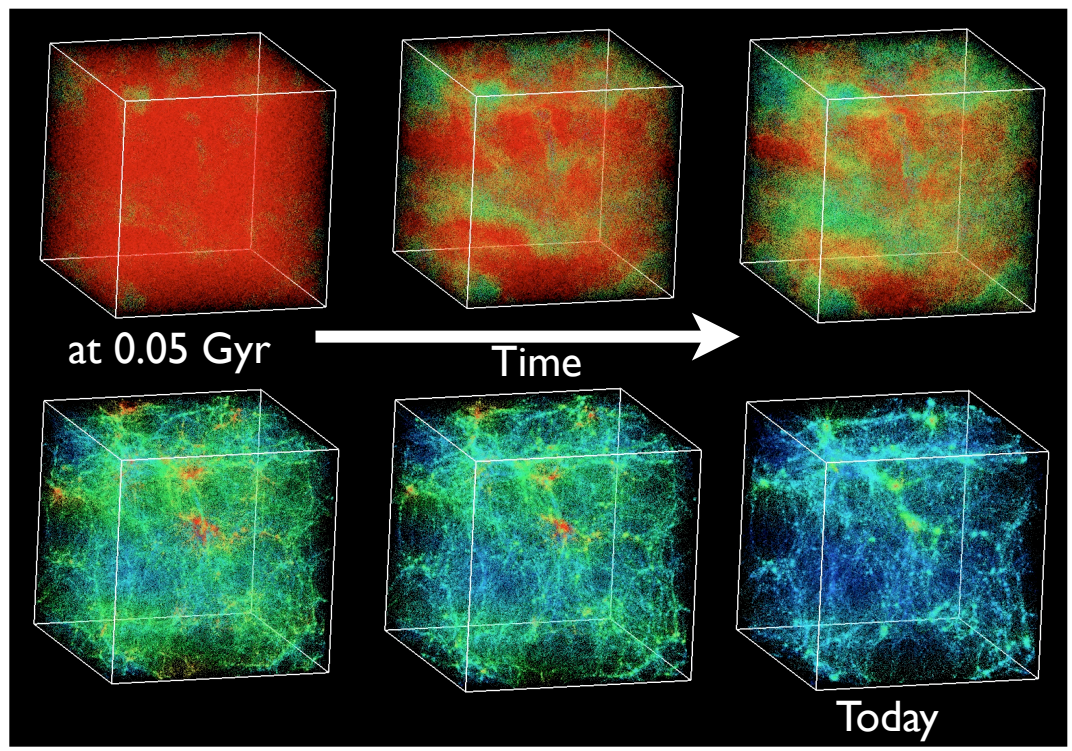
- **Solid understanding of structure formation; success underpins most cosmic discovery**
  - Initial conditions determined by primordial fluctuations
  - Initial perturbations amplified by gravitational instability in a dark matter-dominated Universe
  - Relevant theory is gravity, field theory, and atomic physics ('first principles')
- **Early Universe:** Linear perturbation theory very successful (CMB)
- **Latter half of the history of the Universe:** Nonlinear domain of structure formation, impossible to treat without large-scale computing



Computing the Universe: Basics

- Gravity dominates at large scales, key task: solve the Vlasov-Poison equation (VPE)
- VPE is 6-D and cannot be solved as PDE, therefore N-body methods
- Particles are tracers of the dark matter in the Universe, mass typically at least ~10^9 $M_\odot$
- At smaller scales, add gas physics, feedback etc., sub-grid modeling inevitable

$$
\begin{aligned}
\frac{\partial f_i}{\partial t} + \dot{\mathbf{x}}\frac{\partial f_i}{\partial \mathbf{x}} - \nabla\phi\frac{\partial f_i}{\partial \mathbf{p}} &= 0, \qquad \mathbf{p} = a^2\dot{\mathbf{x}}, \\
\nabla^2\phi &= 4\pi G a^2(\rho(\mathbf{x},t) - \langle\rho_{\rm dm}(t)\rangle) = 4\pi G a^2 \Omega_{\rm dm}\delta_{\rm dm}\rho_{\rm cr}, \\
\delta_{\rm dm}(\mathbf{x},t) &= (\rho_{\rm dm} - \langle\rho_{\rm dm}\rangle)/\langle\rho_{\rm dm}\rangle), \\
\rho_{\rm dm}(\mathbf{x},t) &= a^{-3}\sum_i m_i \int d^3\mathbf{p} f_i(\mathbf{x},\dot{\mathbf{x}},t).
\end{aligned}
$$



> "The Universe is far too complicated a structure to be studied deductively, starting from initial conditions and solving the equations of motion."
>
> *Robert Dicke (Jayne Lectures, 1969)*

Computing the Universe: HACC

Habib et al. J. Phys. Conf. Ser. 2009; Pope et al. Comp. Sci. Eng. 2010; Habib et al. SC12, arXiv:1211.4864, Habib et al. SC13

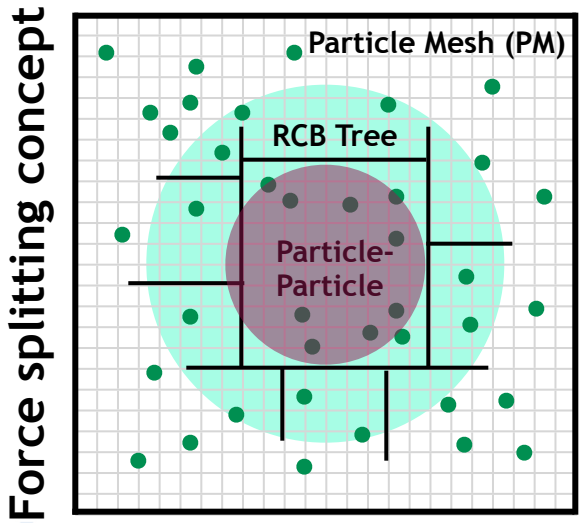
- **HACC: Hardware/Hybrid Accelerated Cosmology Code for N-body simulations at extreme scales**
- **Why did we write a new N-body code?**
  - **Portability:** Ever changing landscape of supercomputers poses huge challenge
  - **Scalability:** How to use more than 1 Million cores efficiently?
  - **Flexibility:** It's always easier to modify our own code!
- **HACC has run on all available architectures successfully at scale!**

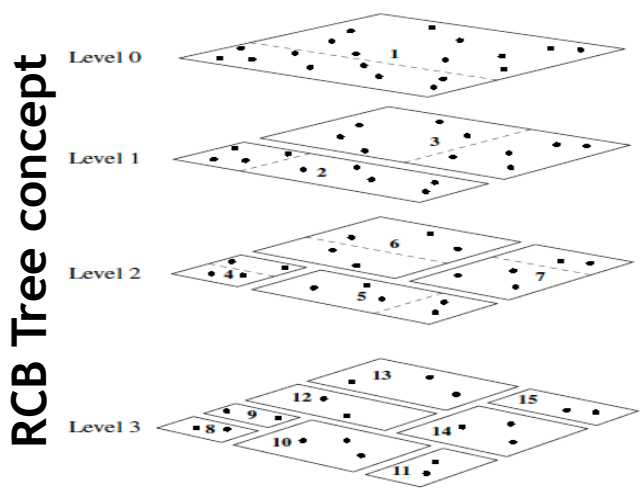
- **Edison@Berkeley Nat. Lab.**
- **"Standard cluster"**
- **124,608 cores**
- **2.39 PFlop/s**

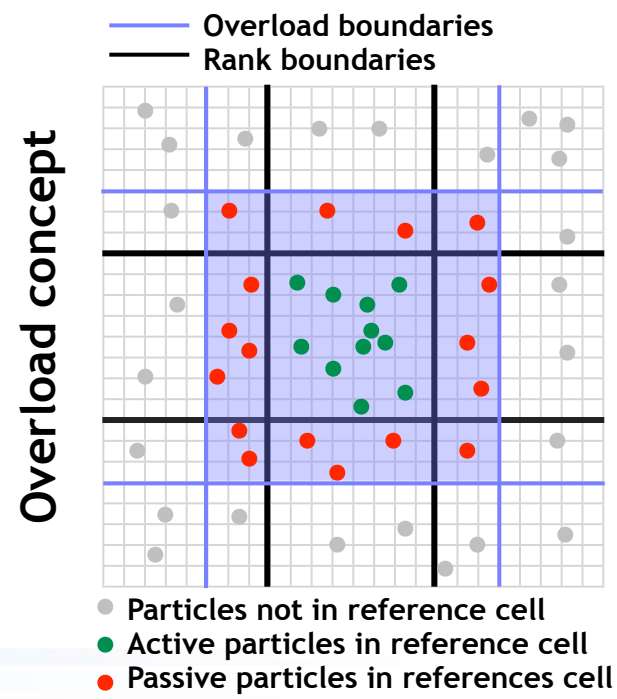
*** NVIDIA math: 20,000 laptops = 1 PFlop/s**

HACC in a Nutshell

- **Long-range/short range force splitting:**
  - **Long-range:** Particle-Mesh solver, C/C++/MPI, unchanged for different architectures, FFT performance dictates scaling (custom pencil decomposed FFT)
  - **Short-range:** Depending on node architecture switch between tree and particle-particle algorithm; tree needs "thinking" (building, walking) but computationally less demanding (BG/Q, X86), PP easier but computationally more expensive (GPU)
- **Overload concept to allow for easy swap of short-range solver and minimization of communication (reasignment of passive/active in regular intervals)**
- **Adaptive time stepping, analysis on the fly (e.g. halo finding, power spectra ...), I/O**







Computing the Universe: The Baryons

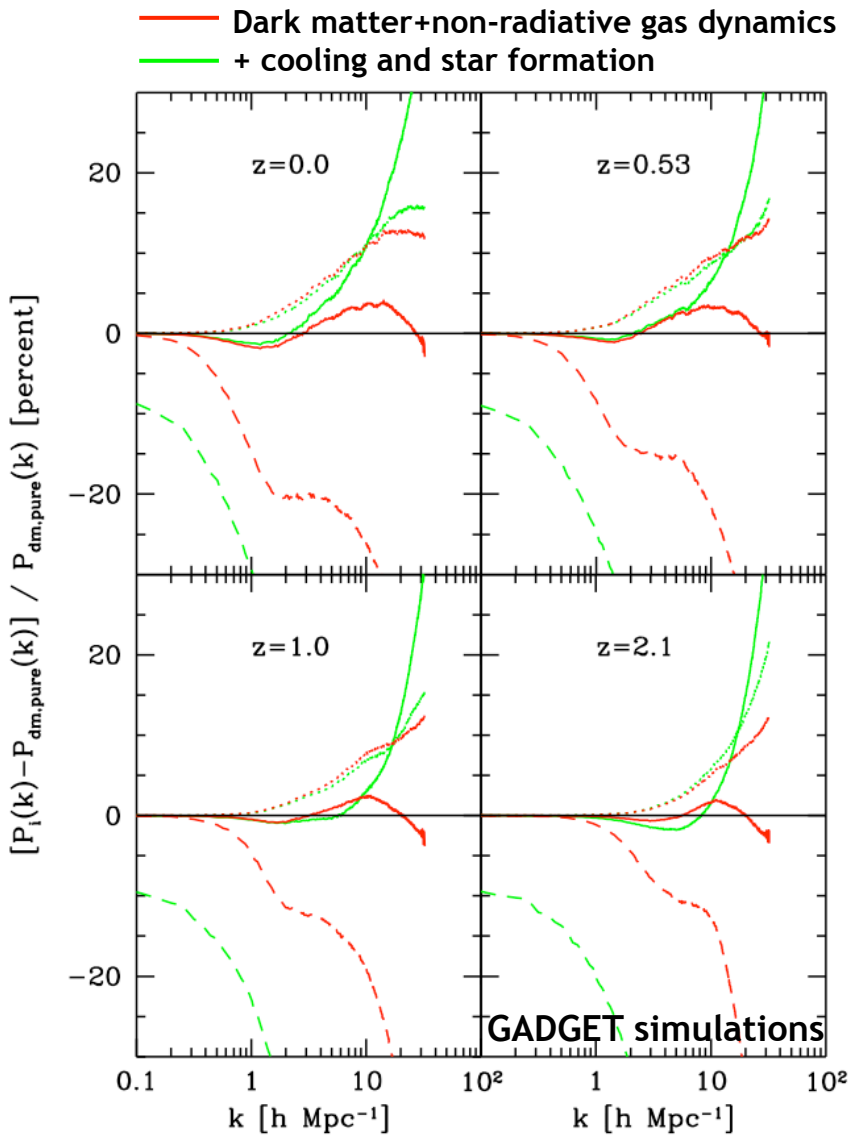
Computing the Universe: The Baryons

- **For astrophysicists:**
  - **Exciting Science:** Galaxy formation, reionization, ...
- **For cosmologists:**
  - How to put galaxies in halos? Intractable from first principles for sky catalogs .. therefore we need modeling approach (will come back to this)
  - Baryons physics is an “annoying” systematic that can alter the mass distribution and needs to be modeled out or predicted
  - **Major problem:** Modeling is difficult, we do not understand the physics in detail and simulations are very expensive compared to gravity-only
  - The smaller the scales, the more we have to worry!
  - **For dark energy:** Find probes that do not depend on small scale structures, e.g. baryon acoustic oscillations, but some of the best probes (weak lensing?) force us to think about the baryons
- **Here: Two brief examples**
  - Simulating the power spectrum including baryons
  - Comparing observations and simulations for clusters

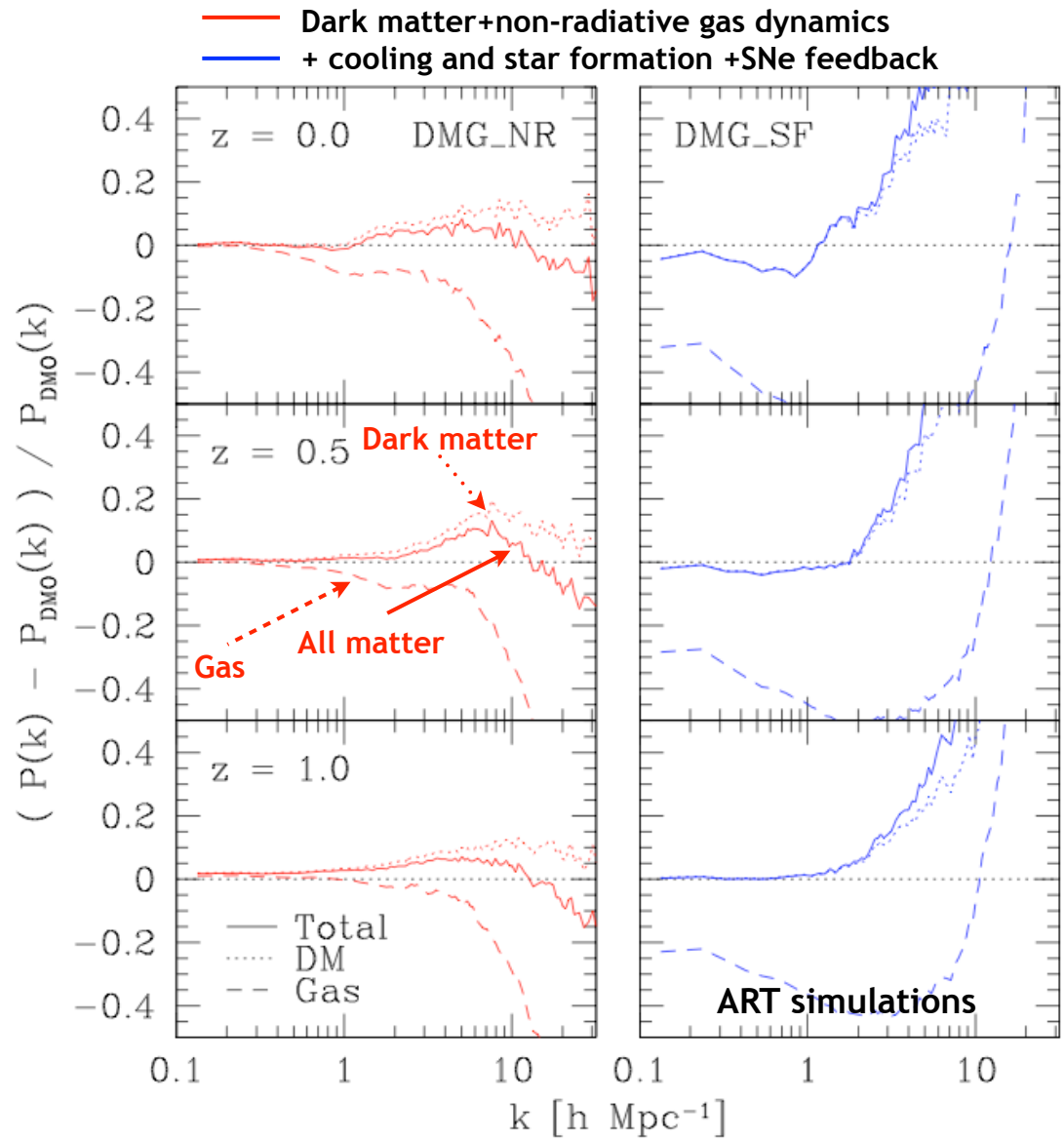
The Baryons and the Power Spectrum

- **The Question:** How much do the baryons alter the matter power spectrum as measured by, e.g., weak lensing at what scales?
- **Important also for the neutrino simulations:** Baryons will completely dominate the uncertainty on small scales, difficult to disentangle from neutrino effects
- **Two early papers based on halo model approach:**
  - White 2004: *Baryonic cooling leads to an increase of the mass power spectrum at k~10 h/Mpc of a few percent*
  - Zhan & Knox 2004: *Effect of intracluster medium (hot baryons) suppress the power spectrum at a similar level*
- **Next: Simulations will answer the question!** ....since simulations are always right! ;-)
  - Compare power spectrum from gravity-only simulation to hydro-simulations

The Baryons and the Power Spectrum, Simulations

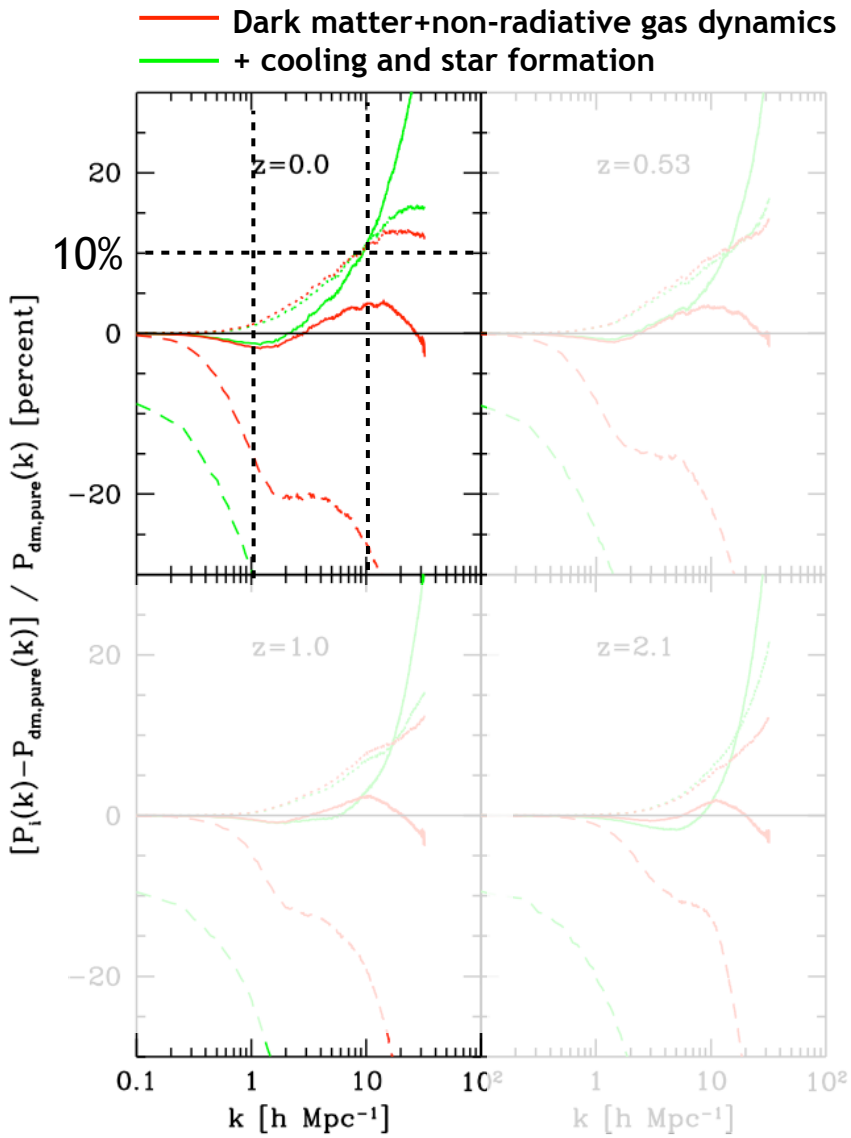


Jing et al. ApJ, 640, L119, 2006



Rudd et al. ApJ, 672, 19, 2008

The Baryons and the Power Spectrum, Simulations



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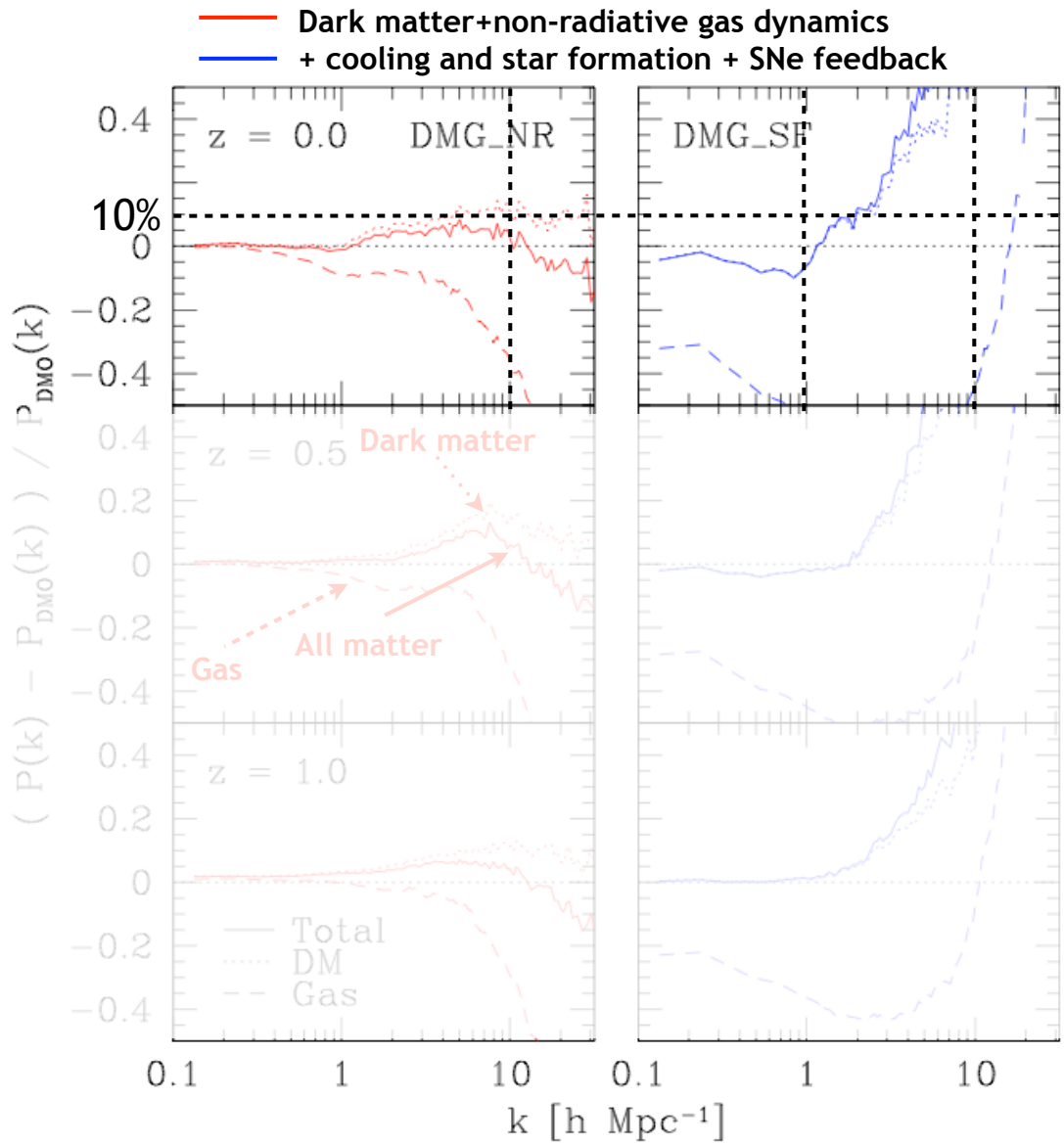
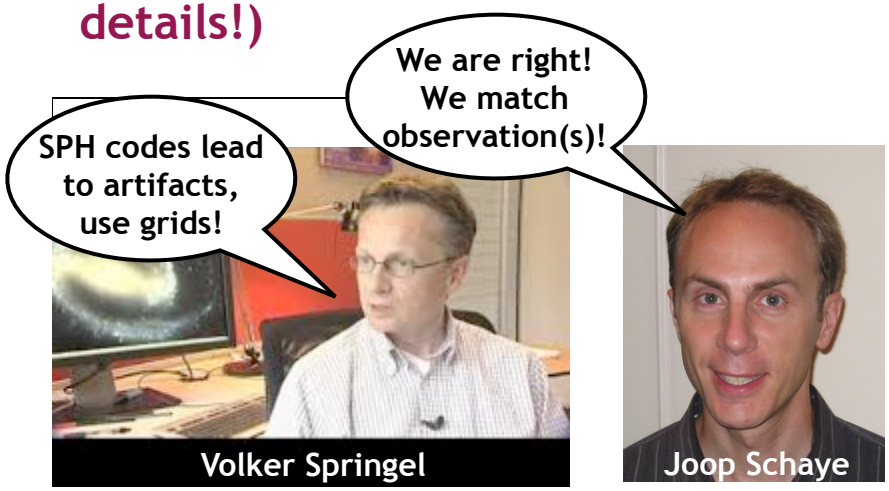
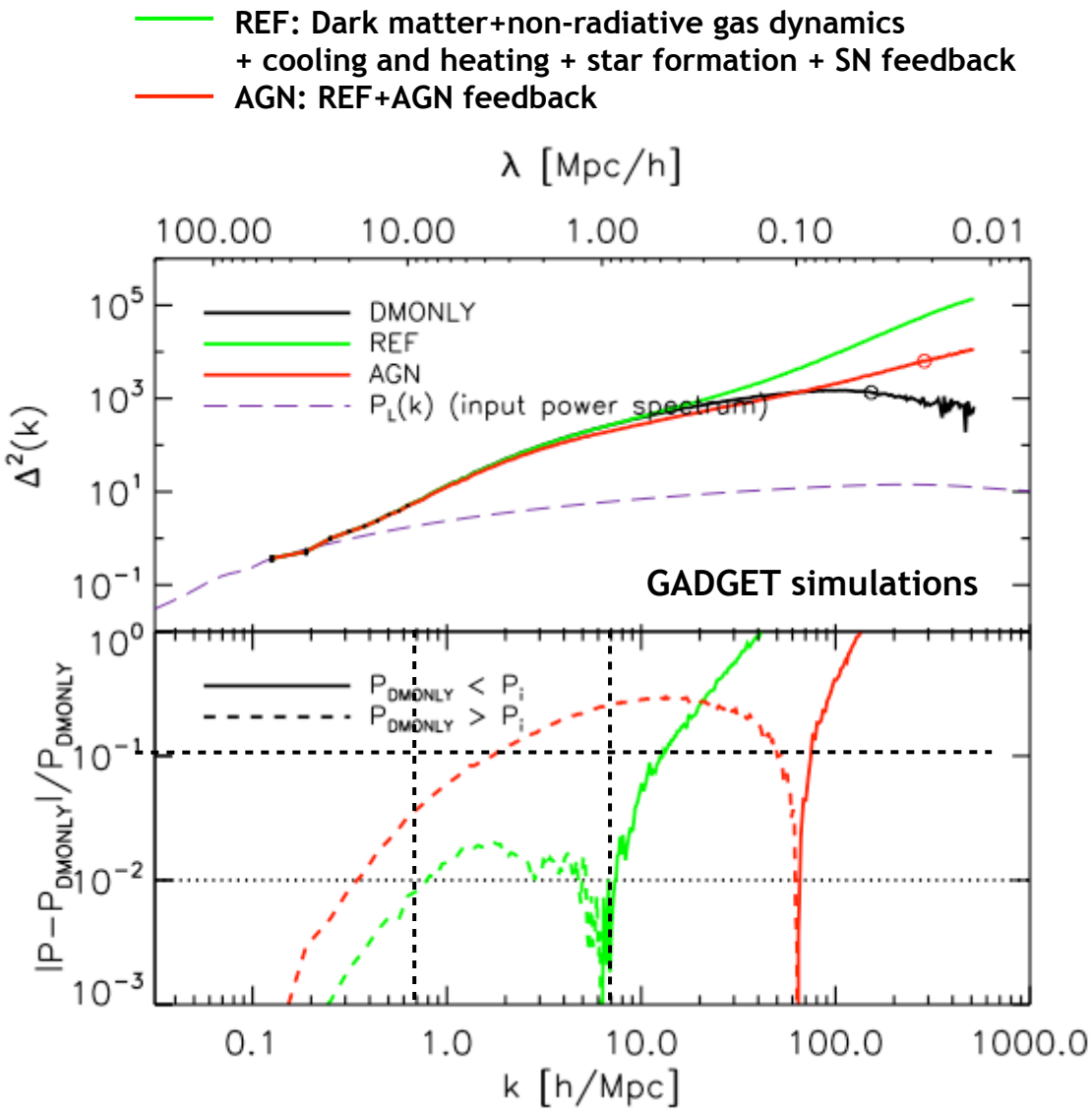


Rudd et al. ApJ, 672, 19, 2008

The Baryons and the Power Spectrum, Simulations

- Different groups find different effects of different magnitude
- Questions about physics included, implementation (AMR/SPH), implementation of the additional physics ... long list of uncertainties
- Hope: Bracket the physics that is included at the extremes, model it out (Talk to Nick, Andrew H., Scott, Andrew Z., Tim... about more details!)

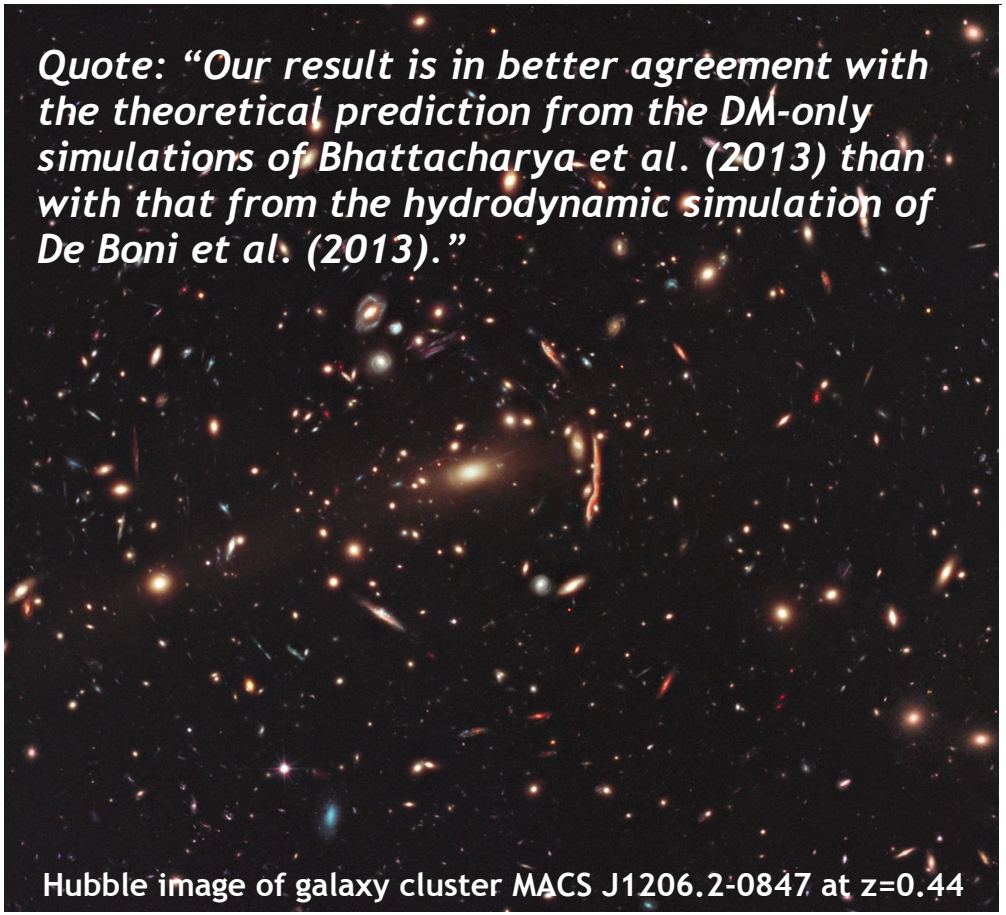


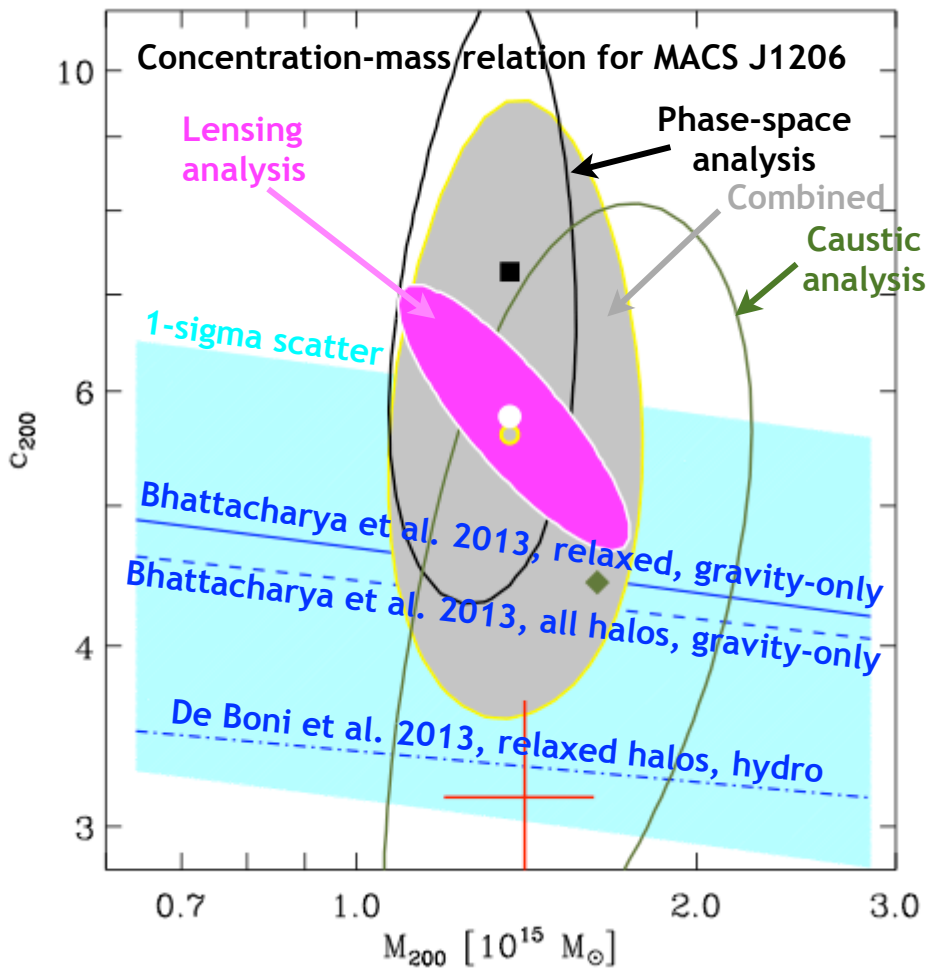


Van Daalen et al. MNRAS, 415, 4, 2011

Observations Meeting Simulations: Cluster Profiles

- Example 1: One cluster from the CLASH (Cluster Lensing And Supernova survey with Hubble) sample, observation of 25 galaxy clusters with HST, strong and weak lensing maps

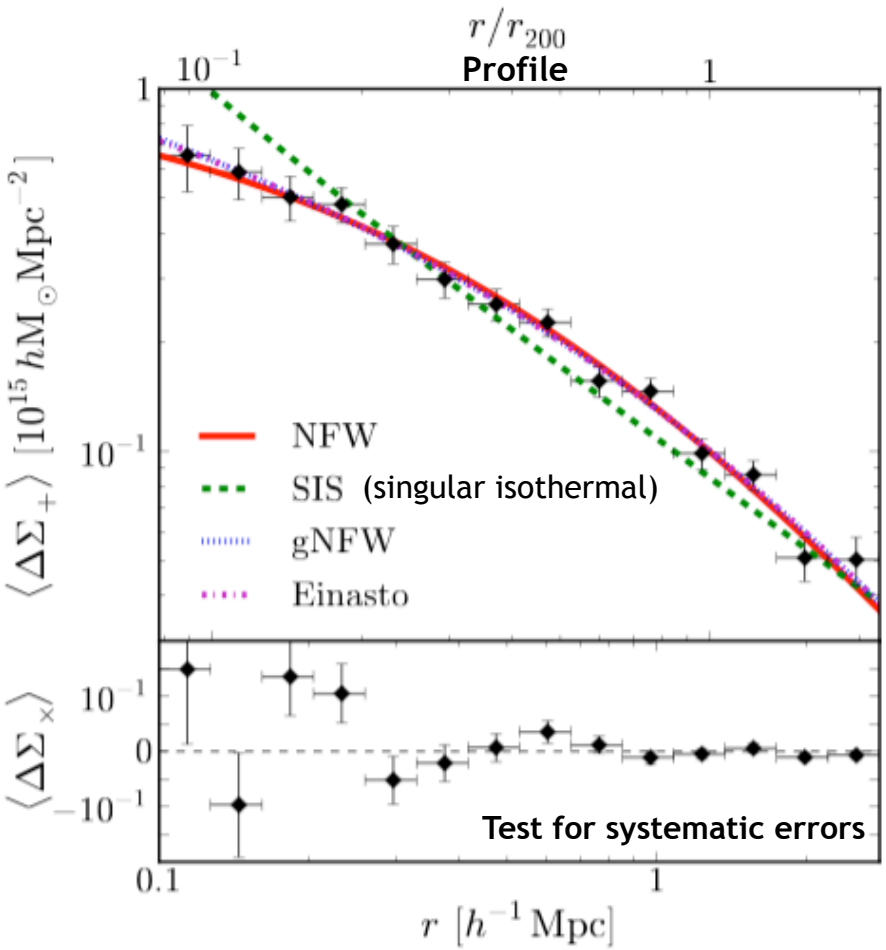


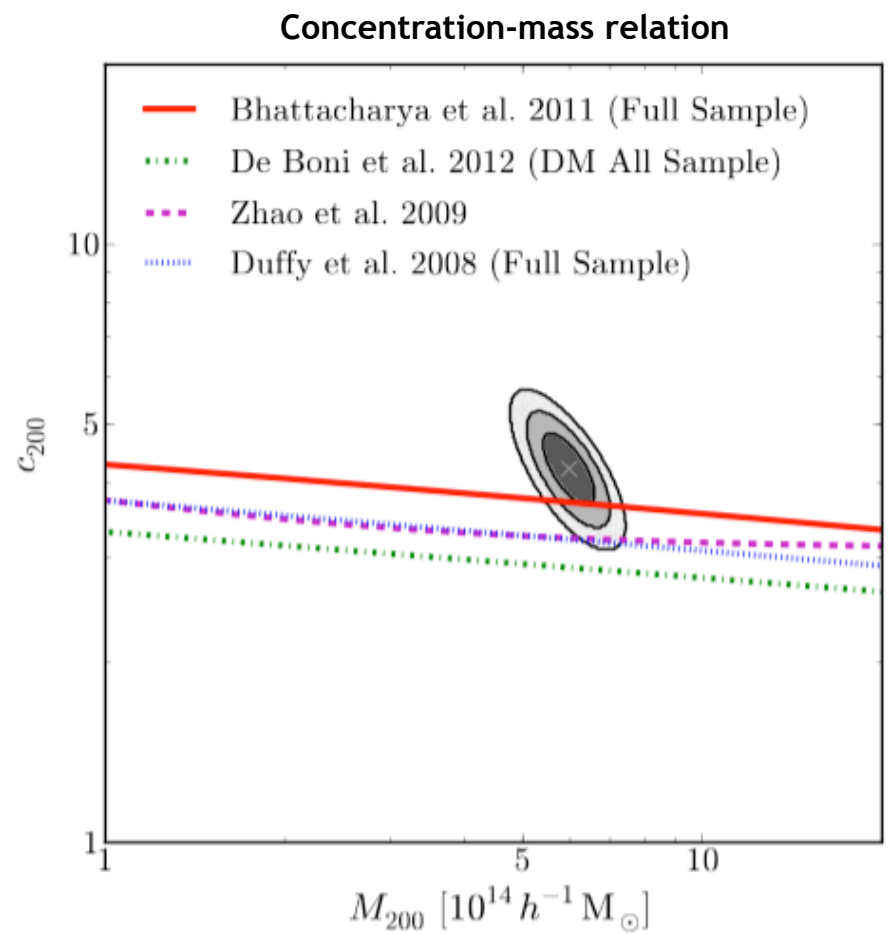


A. Biviano et al. A&A, 558, A1 (2013)

Observations and Simulations of Clusters

- Example 2: Weak-lensing analysis of 50 stacked clusters at 0.15 < z < 0.3, observed with Suprime-CAM on the Subaru Telescope (LoCuSS)
- Stacked tangential shear profile in units of projected mass density





Oguri et al. ApJ, 769, L35 (2013)

Computing the Universe: SHAM, HAM, CAM, SAM ...

- **So for now:** Let's return to the problem of modeling the galaxies on top of high-quality gravity-only simulations
- **Advantage of Post-processing:** Flexibility in how we model the galaxies, can be tailored to galaxies of interest and the resolution of the simulations
- **Halo Occupation Distribution (HOD):** Very popular for building mocks for LRGs (SDSS, BOSS); populate halos with central and satellite galaxies depending on their mass (for SDSS LRG HOD see, e.g. Zheng et al. 2009), moderate mass resolution required, parameters set by matching to observations
- **Sub-Halo Abundance Matching (SHAM):** Takes into account information about subhalo population as well as formation history of halos (see e.g. Conroy et al. 2006), requires rather high mass resolution
- **Conditional Abundance Matching (CAM):** Include merger tree information, Andrew H. local expert! "*The Dark Side of Galaxy Color*"
- **Semi-Analytic Modeling (SAM):** Extract merger trees (including subhalos) from high-resolution simulations and model star formation, feedback, gas cooling on top of those, zoo of parameters (~250), but: diverse set of galaxy properties will be predicted, in principle, will give answers at unobserved redshifts

Computing the Universe: The Argonne Effort

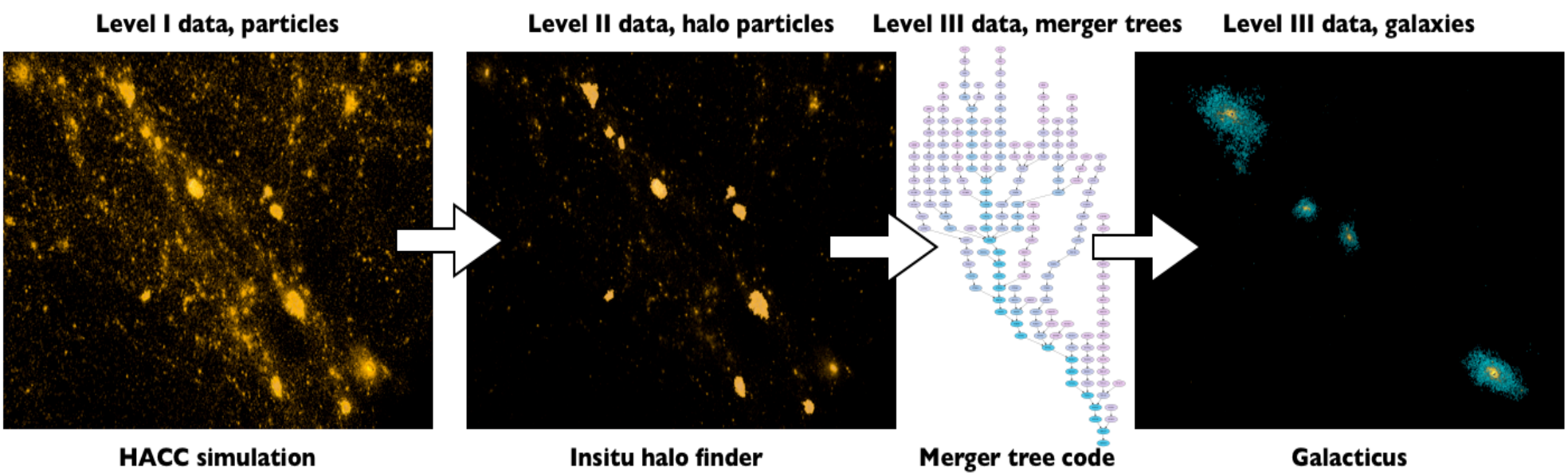
- Gravity only simulations of varying sizes and cosmologies
  - **Outer Rim Simulation:** 4.225 Gpc, 1.1 trillion particles, ~$10^9 M_\odot$, WMAP-7
  - **QContinuum Simulation:** 1.3 Gpc, 0.5 trillion particles, ~$10^8 M_\odot$, WMAP-7

  } **SAMs**

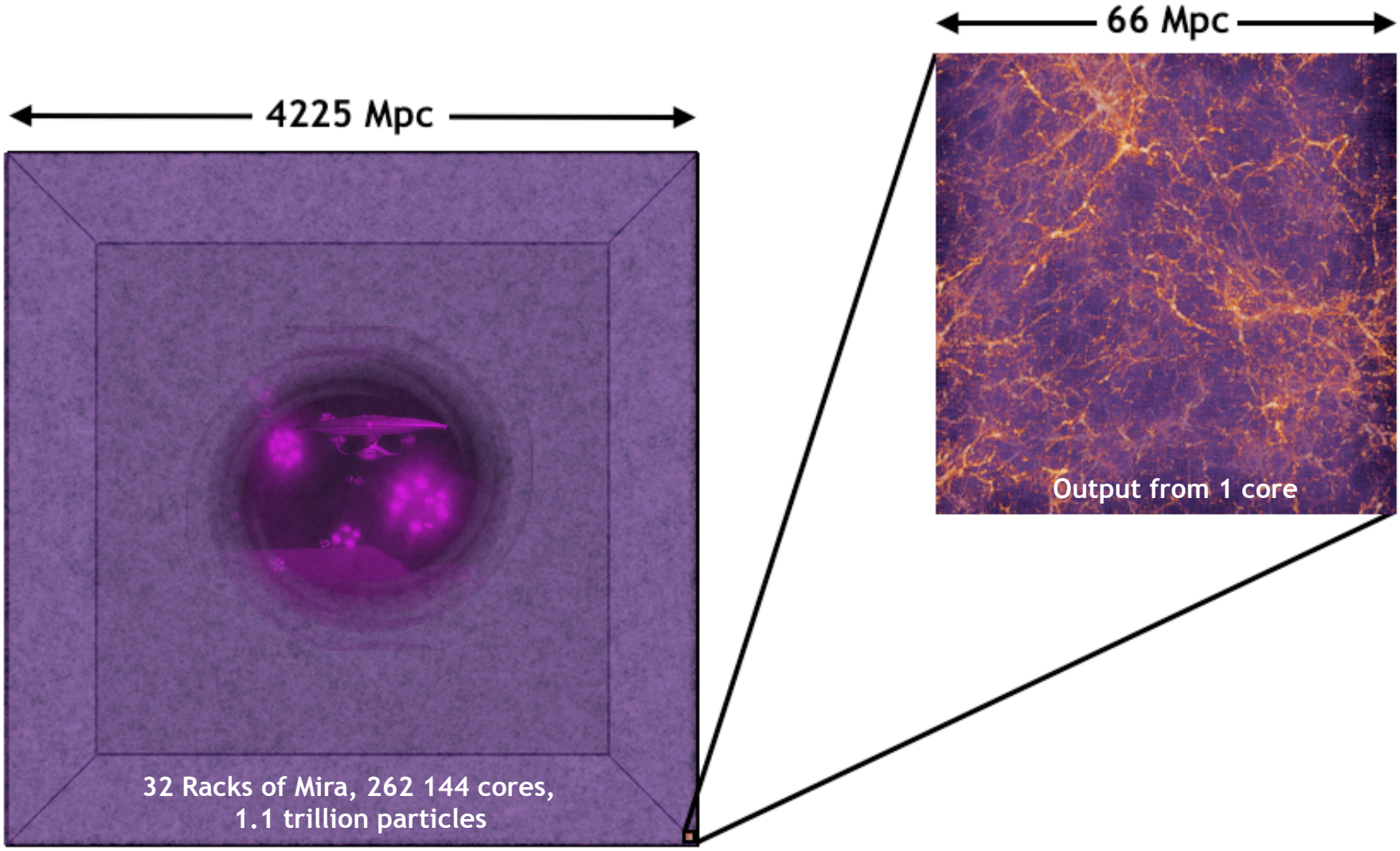
  - **Mira Universe:** Set of simulations including neutrinos, dynamical dark energy, 2.1 Gpc, 30 billion particles, ~$10^{10} M_\odot$
  - **MockBOSS Simulations:** 5.5 Gpc, 69 billion particles, WMAP-7 and Planck with range of σ_8 (in coll. with Padmanabhan, Sunayama, Eisenstein, White), ~$10^{11} M_\odot$

  } **HODs**

- Build mock catalogs with SAMs (Galacticus by A. Benson) and HODs (see e.g. J. Kwan et al. arXiv:1311.6444 for HOD based galaxy power spectrum emulator)



The Outer Rim Simulation



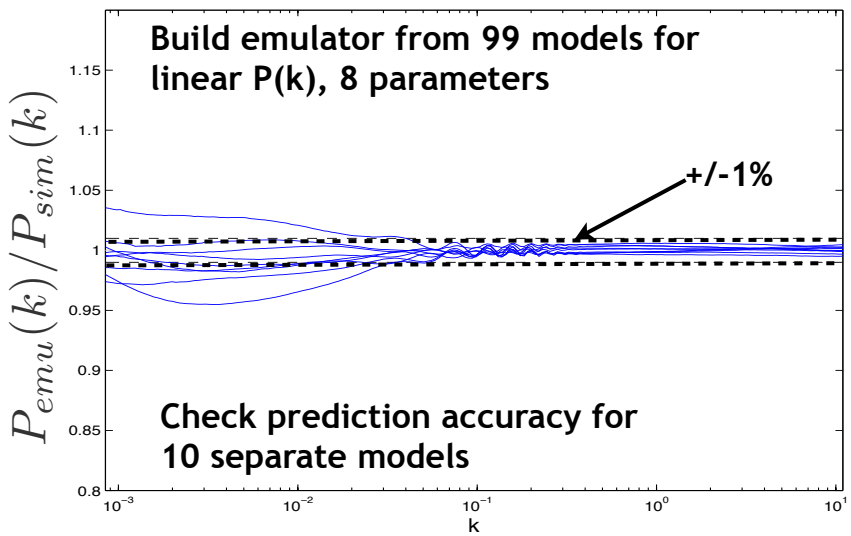
The Mira Universe

- Extend parameter space to include varying *w(z)* and massive neutrinos
- Build "nested designs": enable to build emulator from first set of 25 models, improve with additional 27 models, final precision with 99 models overall
- Various predictions for P(k), mass function, c-M relation, derived quantities...
- LCDM done, 6 *w(z)* simulations done, investigation on massive neutrino implementation done

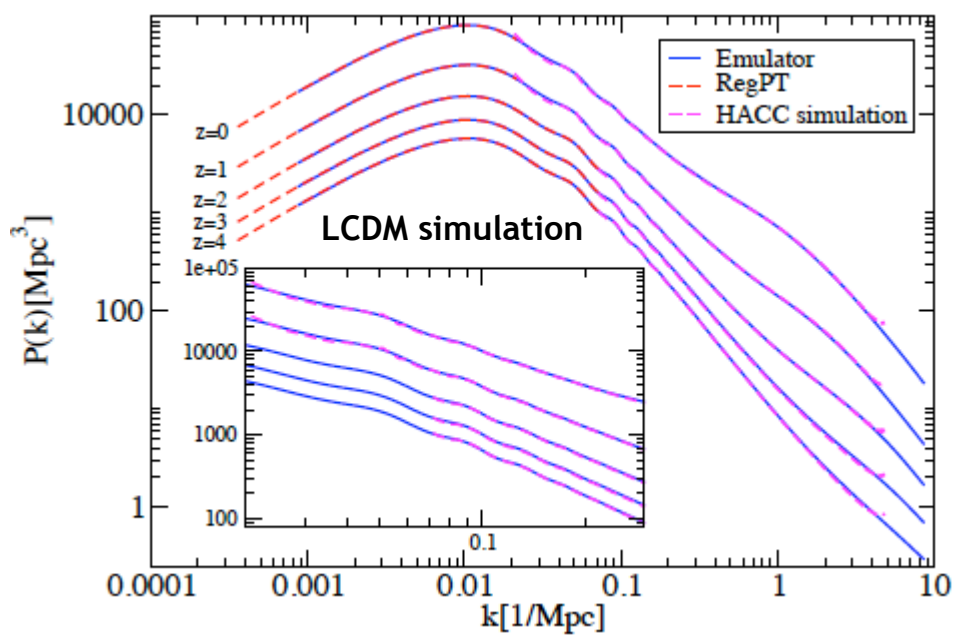
Parameters

$$0.12 \leq \omega_m \leq 0.155$$
$$0.0215 \leq \omega_b \leq 0.0235$$
$$0.7 \leq \sigma_8 \leq 0.9$$
$$0.55 \leq h \leq 0.85$$
$$0.85 \leq n_s \leq 1.05$$
$$-1.3 \leq w_0 \leq -0.7$$
$$-1.5 \leq w_a \leq 1.15$$
$$0.0 \leq \omega_\nu \leq 0.01.$$

New!

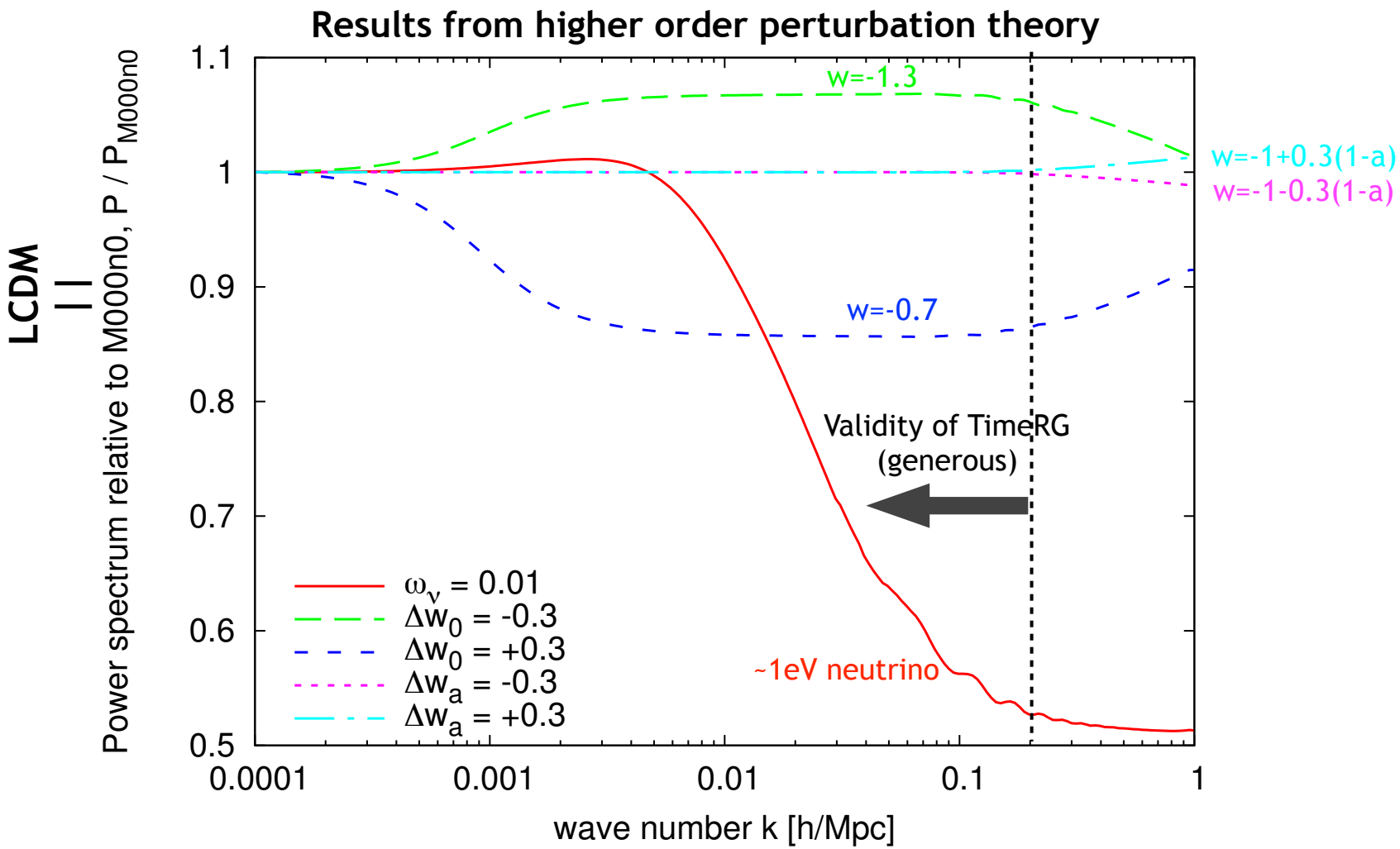


Heitmann et al., in prep.



Neutrinos and Dark Energy: Effects on Matter Power Spectrum

- Need to study neutrinos and dynamical dark energy simultaneously due to degenerate effects on e.g. the power spectrum (see, e.g., Santos et al. 2013 for Euclid forecasts)

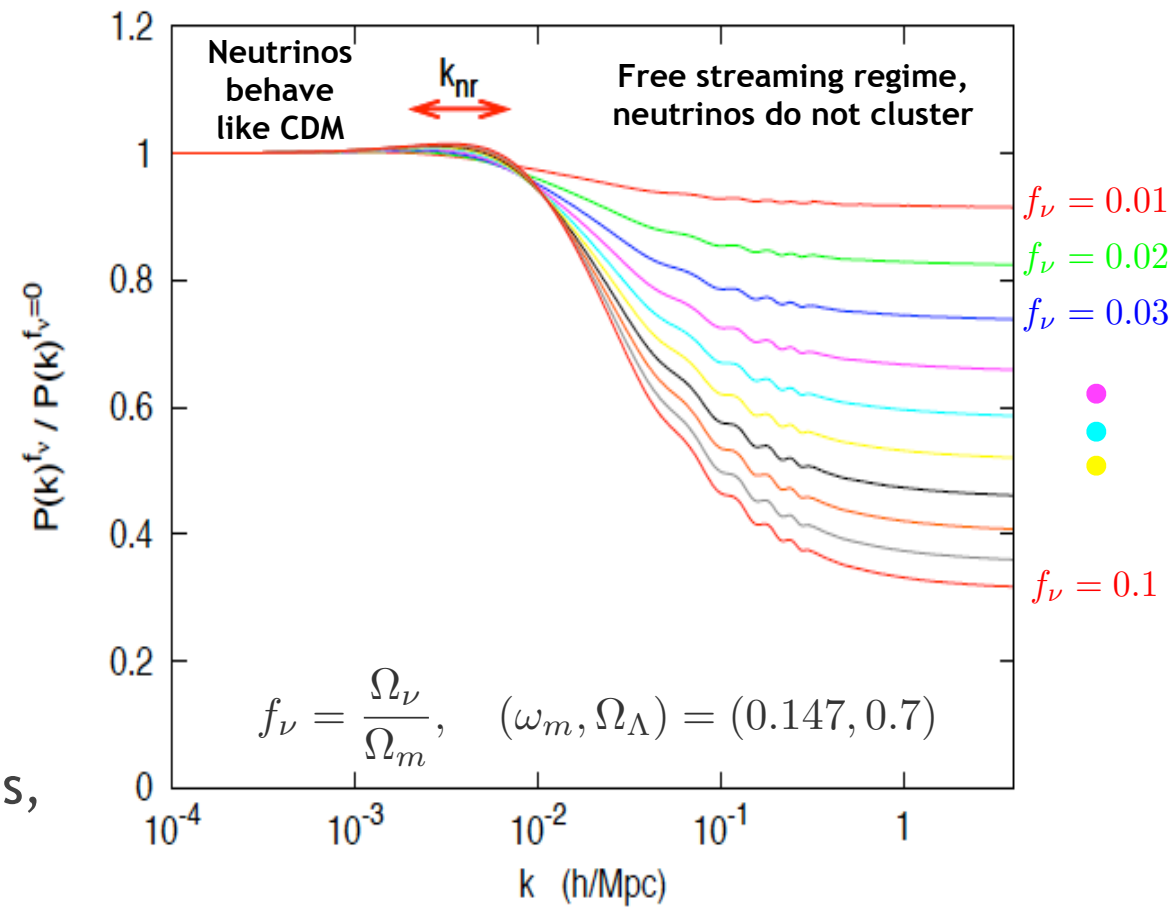


Upadhye et al., arXiv:1309.5872, to appear in Phys. Rev. D

Neutrinos and Large Scale Structure

- Cosmology (CMB and large scale structure) provides constraints on the mass sum of neutrinos and the number of relativistic species
- Massive neutrinos have **scale dependent** effect on power spectrum
  - **On large scales:** Neutrino fluctuations grow like dark matter fluctuations
  - **On small scales:** Free-streaming suppresses the growth of neutrino fluctuations, $k_{nr} = 0.018\Omega_m^{1/2} h^{-1}\mathrm{Mpc}$

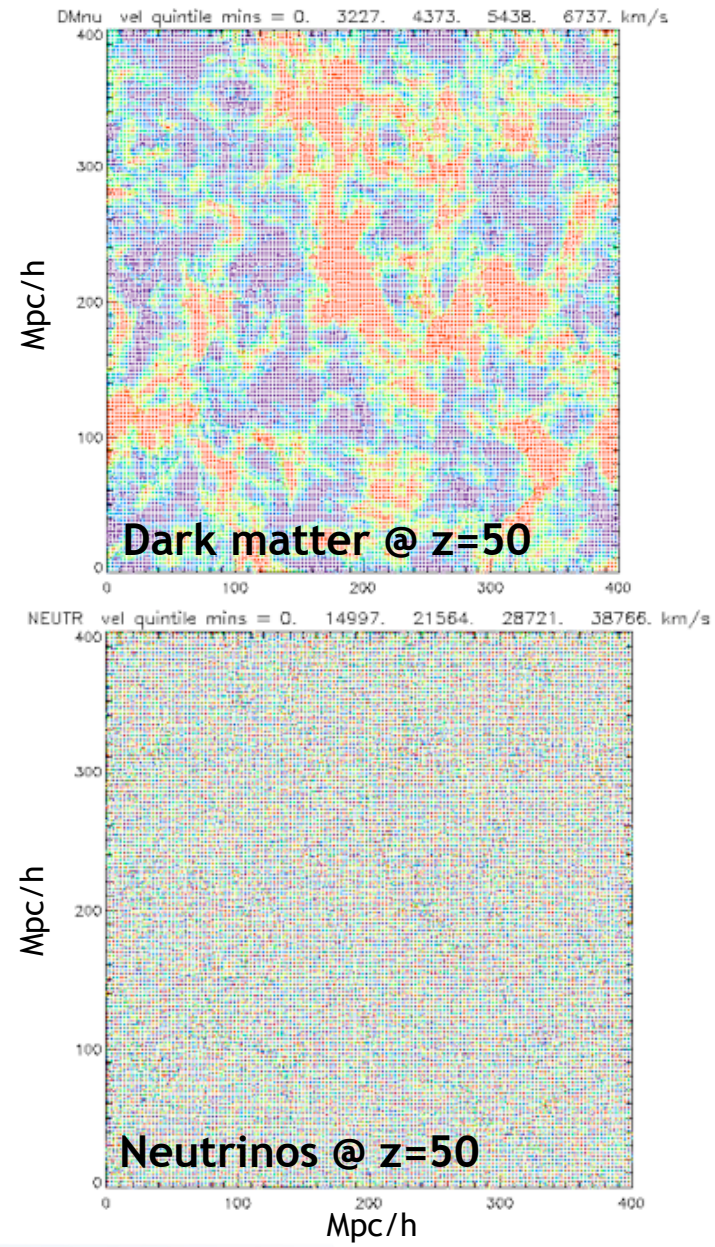
Influence of three massive neutrinos on the linear matter power spectrum



Lesgourgues & Pastor, Phys. Rept. 429, 307, 2006

Simulating Neutrinos

- Two species approach
- Initialize both species via the Zel'dovich approximation (or 2LPT) taking into account the correct transfer function and growth function
- **For neutrinos:** Growth function is scale dependent, also add thermal velocity component, drawn from a Fermi-Dirac distribution
- Use multiple neutrino tracer particles (treated in pairs) to prevent anisotropy noise
- Evolve both species forward in time as usual
- **Two problems:**
  - Large neutrino velocities
  - Large difference in particle masses



Neutrino Simulation Approaches

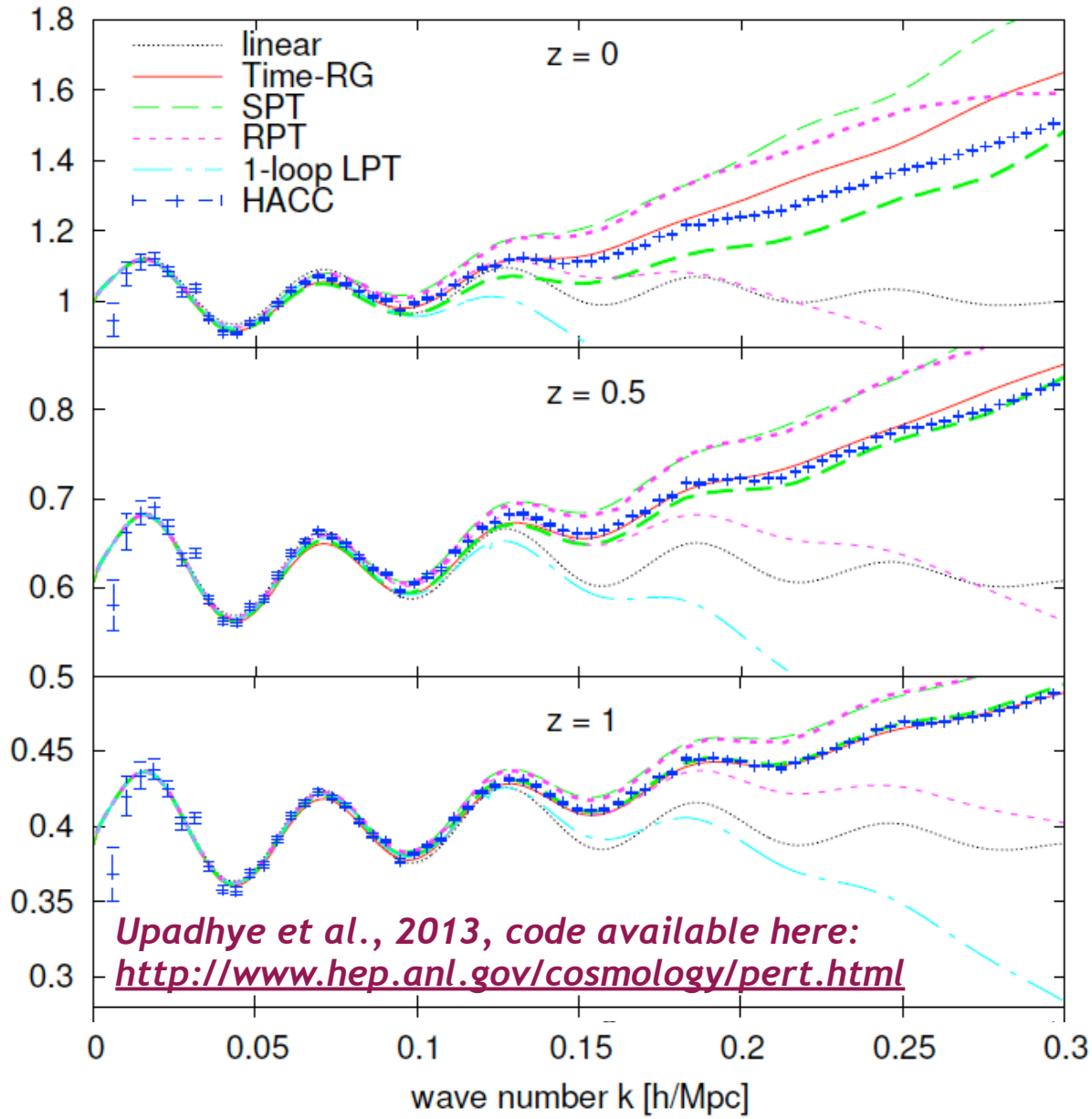
- **Different approaches to deal with these challenges, some examples:**
- **Klypin et al. 1993:** PM simulations with separate species, high mass neutrinos $(\Omega_c = 0.6, \Omega_\nu = 0.3, \Omega_b = 0.1)$
- **Gardini et al. 1999:** P3M simulations starting at *z=10*, acknowledge problems, **switch on gravity for neutrinos very late**
- **Brandbyge et al. 2008:** 2-species, **starting simulations at z=4**
- **Brandbyge et al. 2009:** 1 species (CDM/B), starting simulations at *z=49*, include **linear theory neutrino perturbation** (via CAMB) in calculation of gravitational potential, computational less expensive, small scales?
- **Brandbyge et al. 2010:** 2-species, **combine grid+particle methods,** start neutrinos on coarse grid, late in evolution use particle methods to get higher resolution
- **Viel et al. 2010, Bird et al. 2011:** Solve neutrinos on **PM grid** and increase number of neutrino particles (Ly-alpha and power spectrum studies)
- **Agarwal & Feldman 2011: Neglect nonlinear evolution of neutrinos ******

Our Approach

- **We do not model the nonlinear evolution of the neutrinos in the N-body code, instead evolve the *cb (cold dark matter-baryon)* component only including the neutrinos in the background evolution**
- **Total matter power spectrum:** $P(k,a) = \left[f_{cb}\sqrt{P_{cb}^{nl}(k,a)} + f_{\nu}\sqrt{P_{\nu}^{lin}(k,a)} \right]^2$
- **Simplified neutrino treatment, assumptions:** Neutrinos are massive enough to behave matter-like at z=0, but light enough to not cluster strongly on small scales
  - **Initial conditions:** (i) Include neutrino contribution in the transfer function and generate a linear power spectrum at z=0 normalized to a given σ_8 (ii) Move P_{cb} back to initial redshift with scale-independent growth function, growth function contains all species in the homogenous background, a scale-dependent growth function would be incorrect, since the evolution to *z=0* is carried out with scale-independent growth function **Note:** Initializing the simulation with the CAMB power spectrum at the initial redshift would have led to inconsistent results at *z=0* (the largest scales in the simulation would have not matched linear theory
  - **Evolution:** Include massive neutrinos in the background evolution equation via *H(z)*, but do not source the neutrino growth in the Poisson equation

The TimeRG Approach

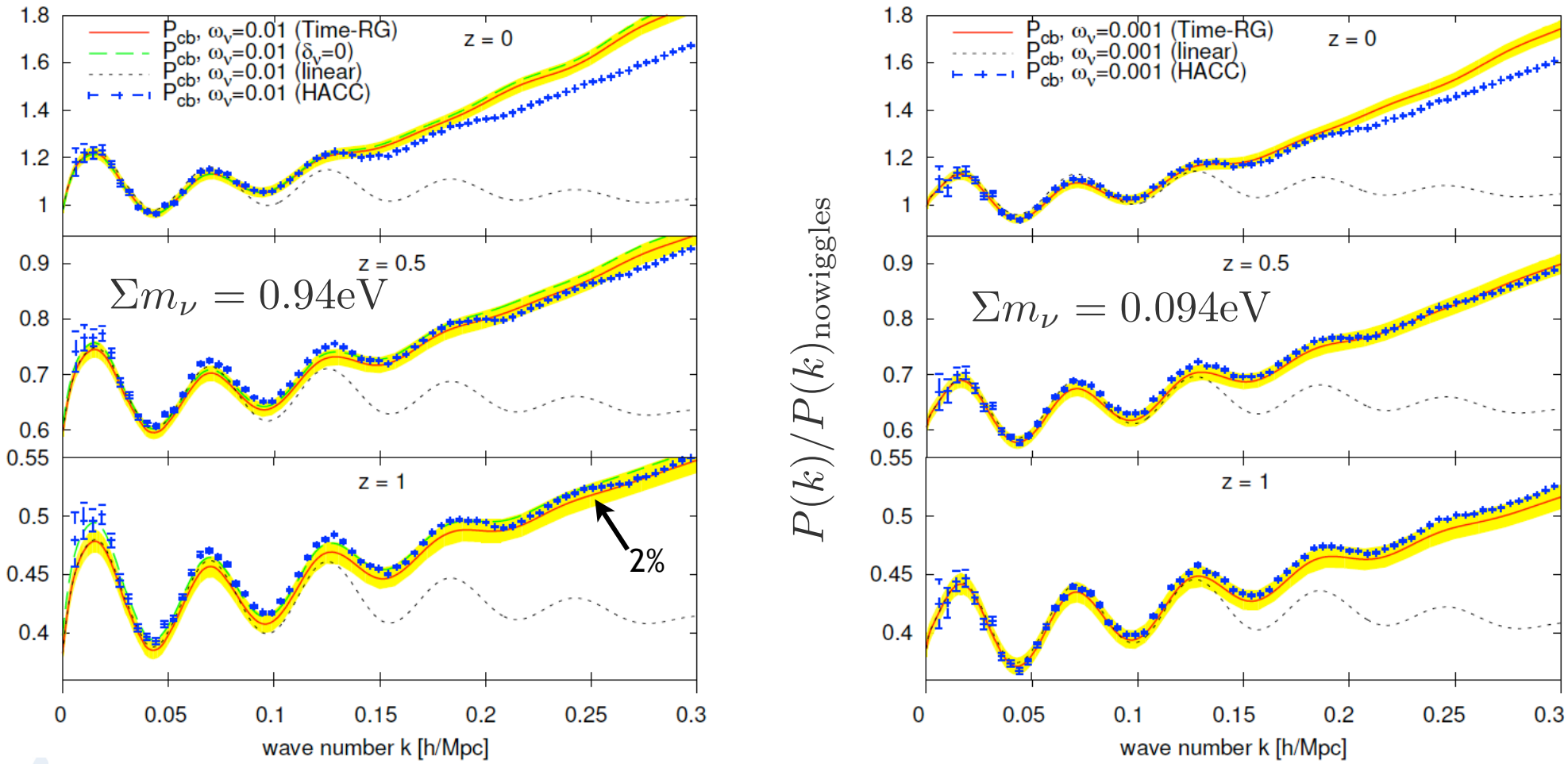
- **Standard Perturbation Theory:** Solve nonlinear perturbation equations by means of series expansion in linear perturbation in EdS, keep 1-loop corrections (see e.g. Makino et al. 1992)
- **Beyond EdS:** Replace expansion factor *a* by growth function *D(a)*
- **SPT can be extended to next order:** Include 2-loop terms (see e.g. Carlson et al. 2009, Copter code)
- **Extension to neutrinos:** Scale-dependent growth function
- Rather than treating *D* as a time variable, integrate evolution equation for power spectrum directly, "TimeRG" approach, includes all 1-loop and some 2-loop terms (Pietroni 2008)
- **Here:** Build upon Copter Code and include massive neutrinos and *w(z)*



Upadhye et al., 2013, code available here:
http://www.hep.anl.gov/cosmology/pert.html

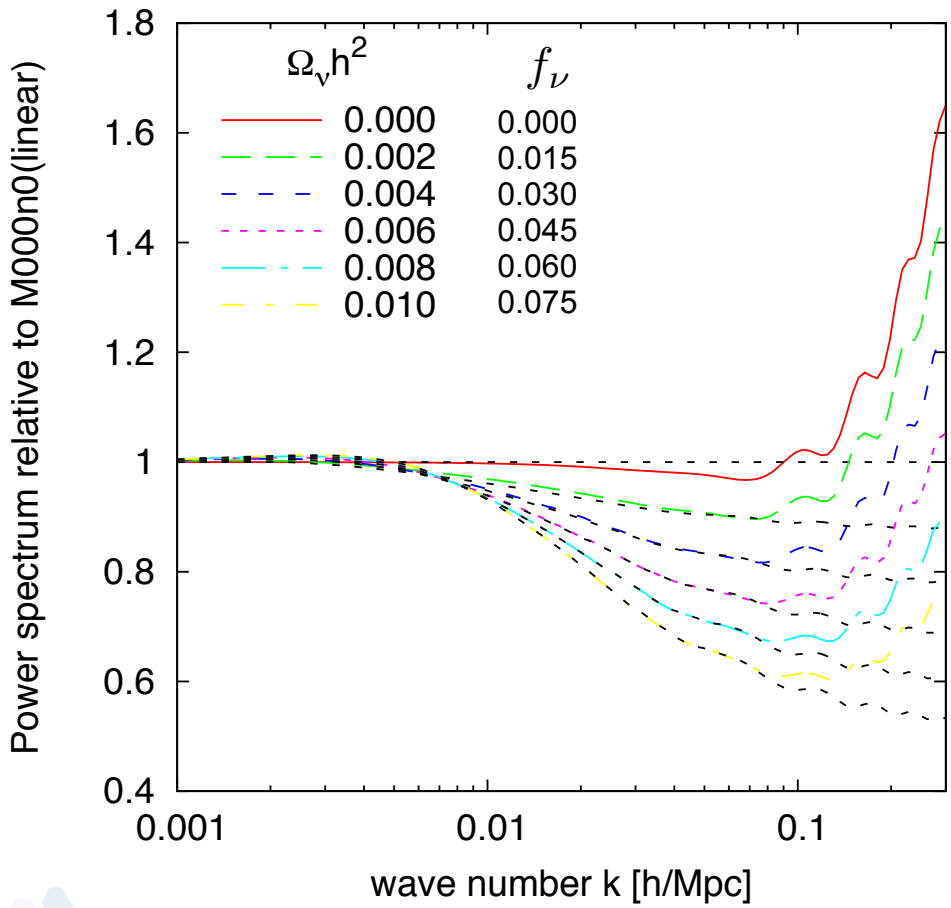
Results for the Power Spectrum

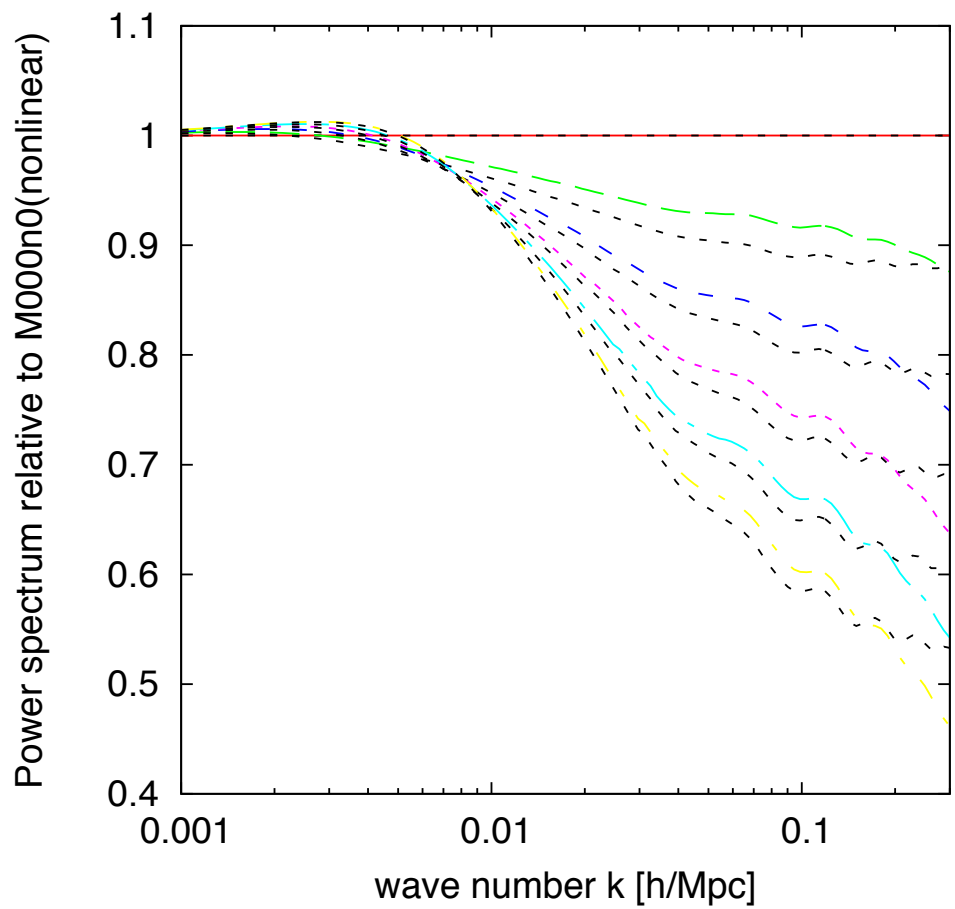
- **Simulations:** 2.1 Gpc box, PM runs (sufficient at large scales), *cb* component only
- **Green:** Drop back-action of neutrino density perturbation on dark matter to mimic simulation approach -- works well for small neutrino masses (right panels) and at redshift of relevance for observations



Results for the Power Spectrum

- **Black:** (Linear + neutrinos)/Linear LCDM as on Lesgourgues & Pastor plot
- **Color left panel:** (Nonlinear + neutrinos)/Linear LCDM, showing enhancement due to nonlinear growth
- **Color right panel:** (Nonlinear + neutrinos)/Nonlinear LCDM, showing net effect of nonlinear growth





Neutrinos and the Mass Function

- **Simulations:** 2.1 Gpc box, 33 billion particles, shown is the *cb* mass component
- **Halo finder:** Friends-of-friends, linking-length of b=0.2

□ **LCDM, WMAP-7**

○ **LCDM + 0.94 eV neutrinos**

z=0

z=1

z=2

Biswas et al., in prep.

Neutrinos and the Mass Function

- Ratio with respect to mass function fit by Bhattacharya et al. 2011

See also Ichiki & Takada 2012 and LoVerde & Zakdarriaga 2013

Summary and Outlook

- Precision cosmology needs high accuracy predictions! Can we avoid being theory limited?
- HACC is a large scale computational tool to address this challenge
- *The Mira Universe* will lead to a large set of simulations, spanning 8 cosmological parameters, including different dark energy models and neutrinos
  - **Next step for the available LCDM/neutrino simulations:** Build "DES-like" light-cone mock catalog based on HOD approach, study different cosmological probes and cross-correlations
  - **Finalize mass function results for LCDM/neutrino/*w(z)* results**
  - **Continue simulation campaign**
- *The Outer Rim Simulation* and *the QContinuum Simulation* provide high mass resolution results covering large volumes, SAMs will be used to provide galaxy catalogs for LSST-DESC (in collaboration with UWashington)
- **N-body simulations will be still very important for survey science and precision cosmology in the coming years --**