Cosmic Calibration

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in collaboration with Derek Bingham, Salman Habib, David Higdon, Earl Lawrence, Juliana Kwan, Christian Wagner, Martin White

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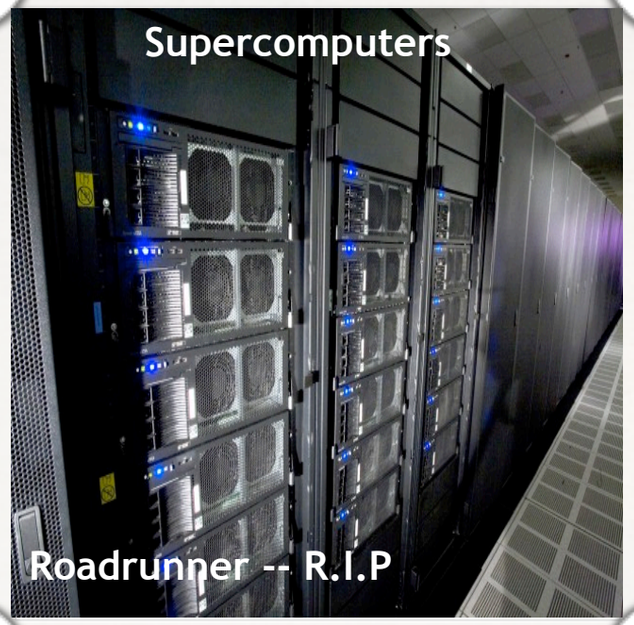
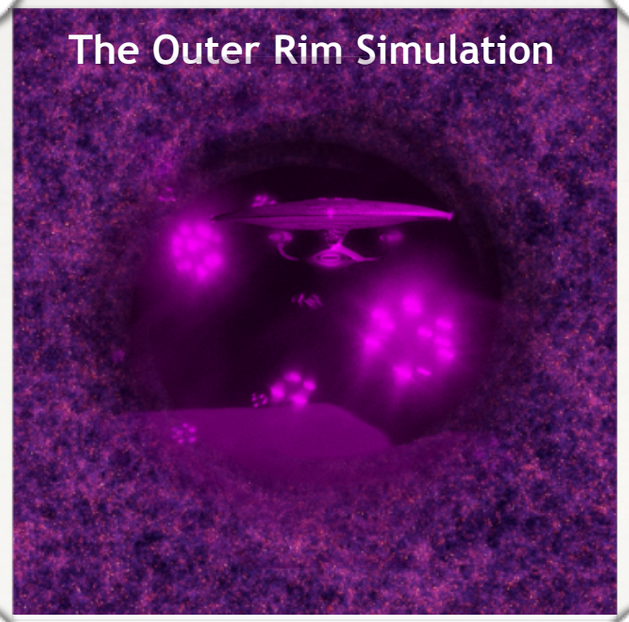
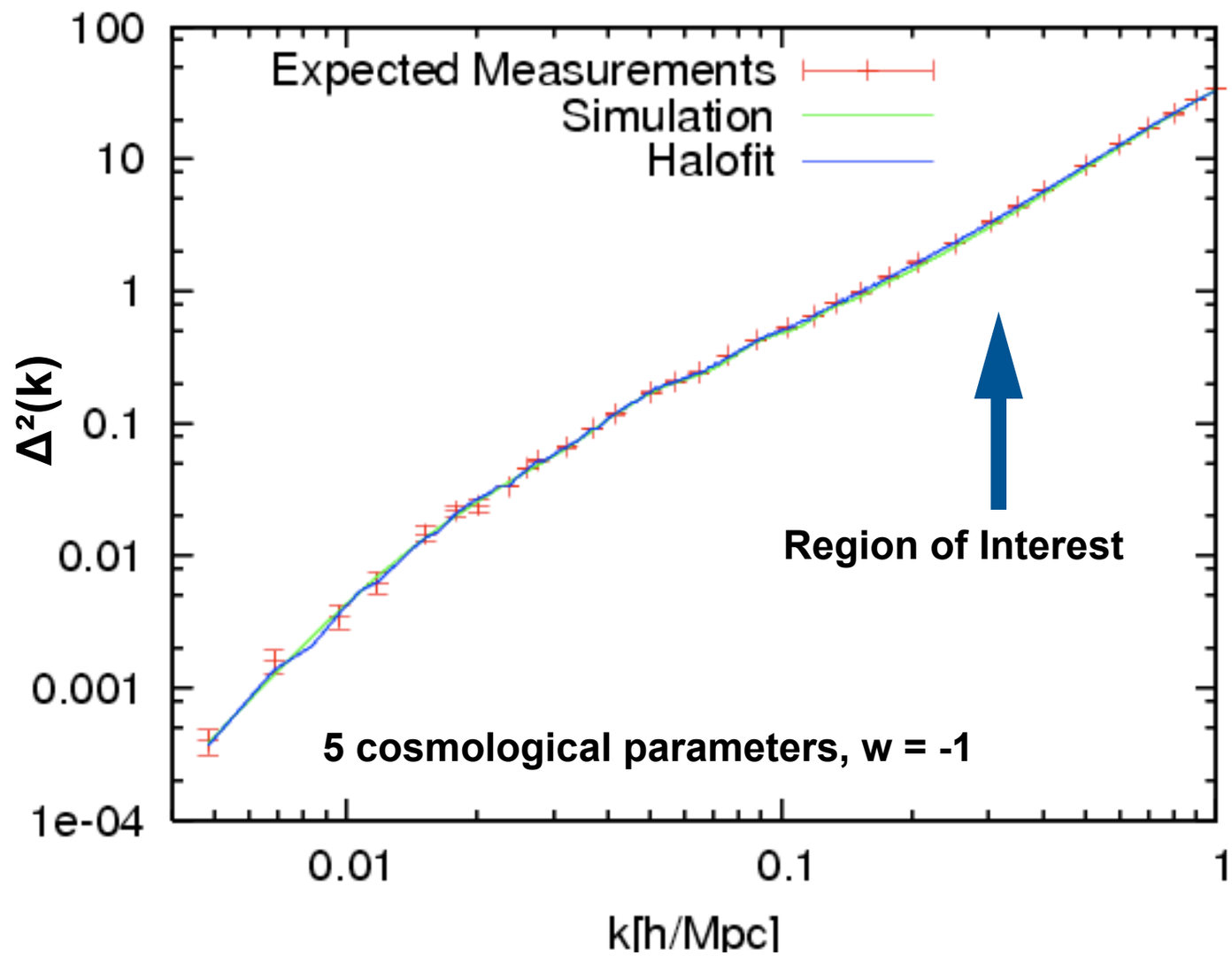




Why do we need higher accuracy in our predictions?

- Example in this talk: matter power spectrum
- Question: how badly will our constraints on dark energy be biased if we *do not* reach the same accuracy in our modeling as we might have in our data?
- Generate mock data set with the expected 1% error
- Analyze data with current method using HaloFit to model the matter power spectrum
  - HaloFit (Smith et al. 2003): semi-analytic fit for the power spectrum, based on modeling approach and tuned to simulations, accurate at the 5-10% level



$$\Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}; \; P(\vec{k}) = \langle \delta^2(\vec{k}) \rangle$$

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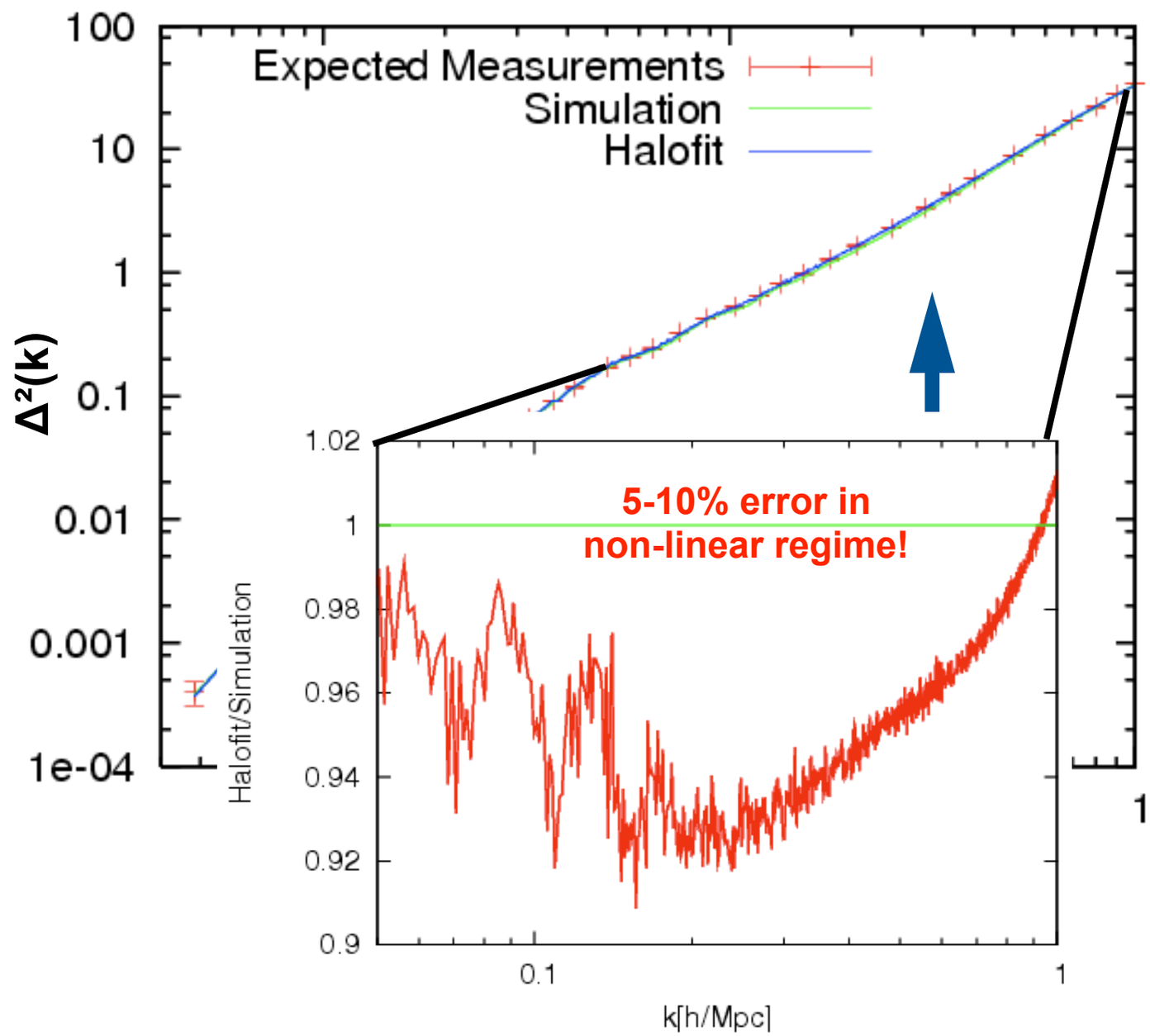
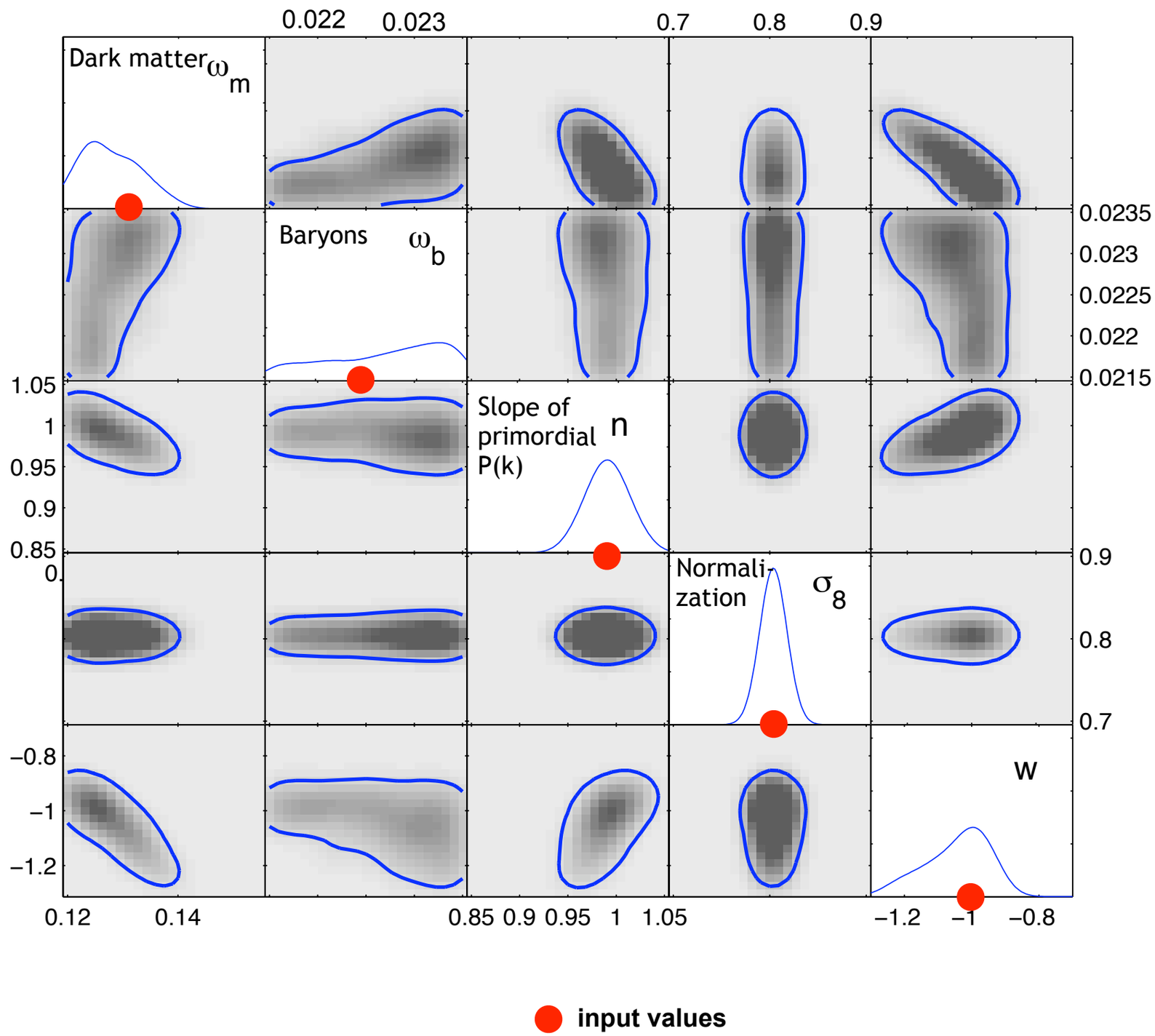


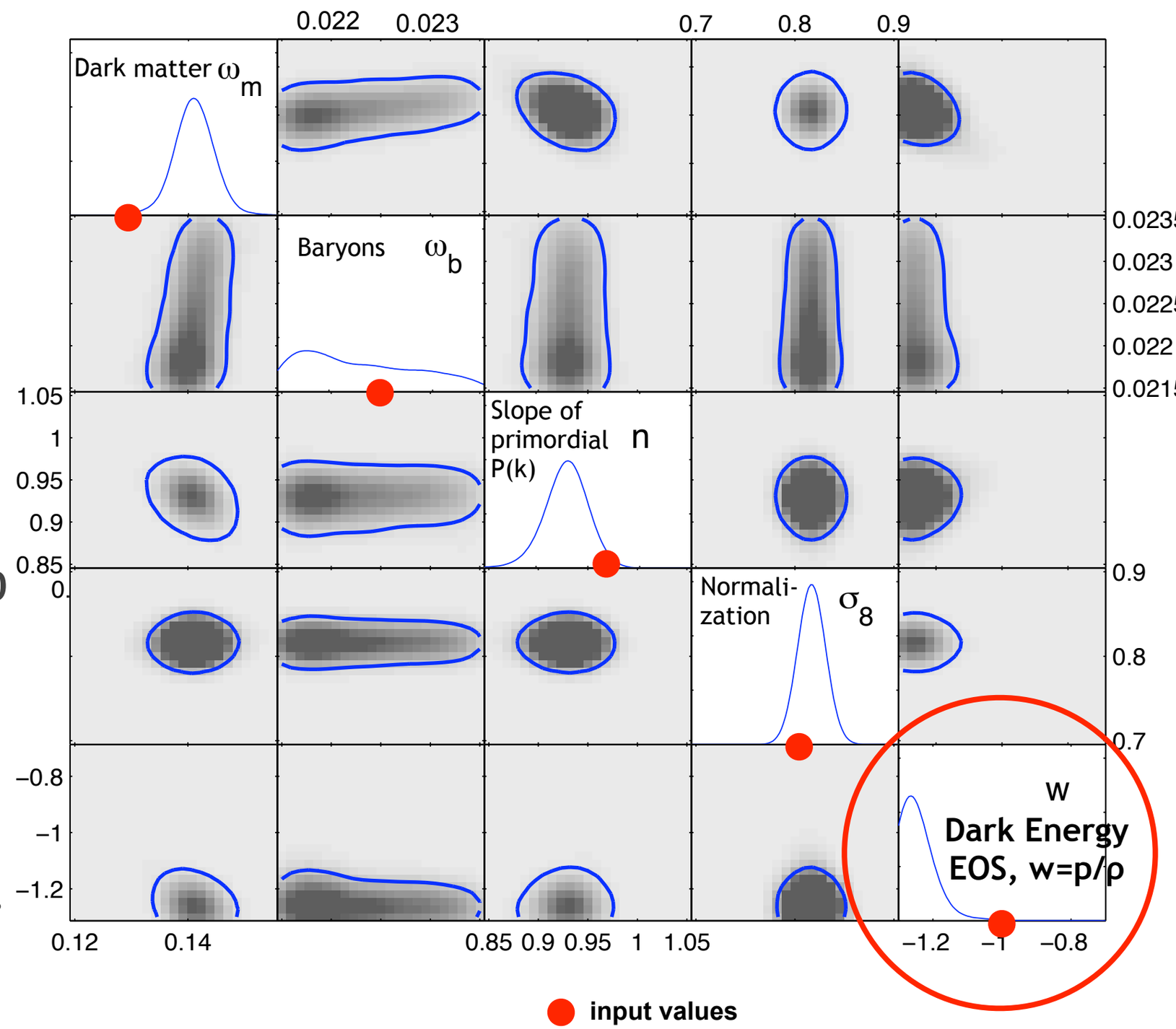
Warm up

- Generate mock data from Halofit
- Analyze data with Halofit
- Results look pretty good!



Analysis of the "True data"

- Generate mock data from high-resolution simulation
- Use Halofit for analysis; remember, halofit ~5-10% inaccurate on scales of interest
- Parameters are up to 20% wrong!
- Only solution: precision simulations
- Analysis takes at least 10,000 input power spectra for MCMC, each simulation takes ~20,000 CPU hours
- With a 2000 node cluster running 24/7, our analysis will take ~30 years, hmmm...

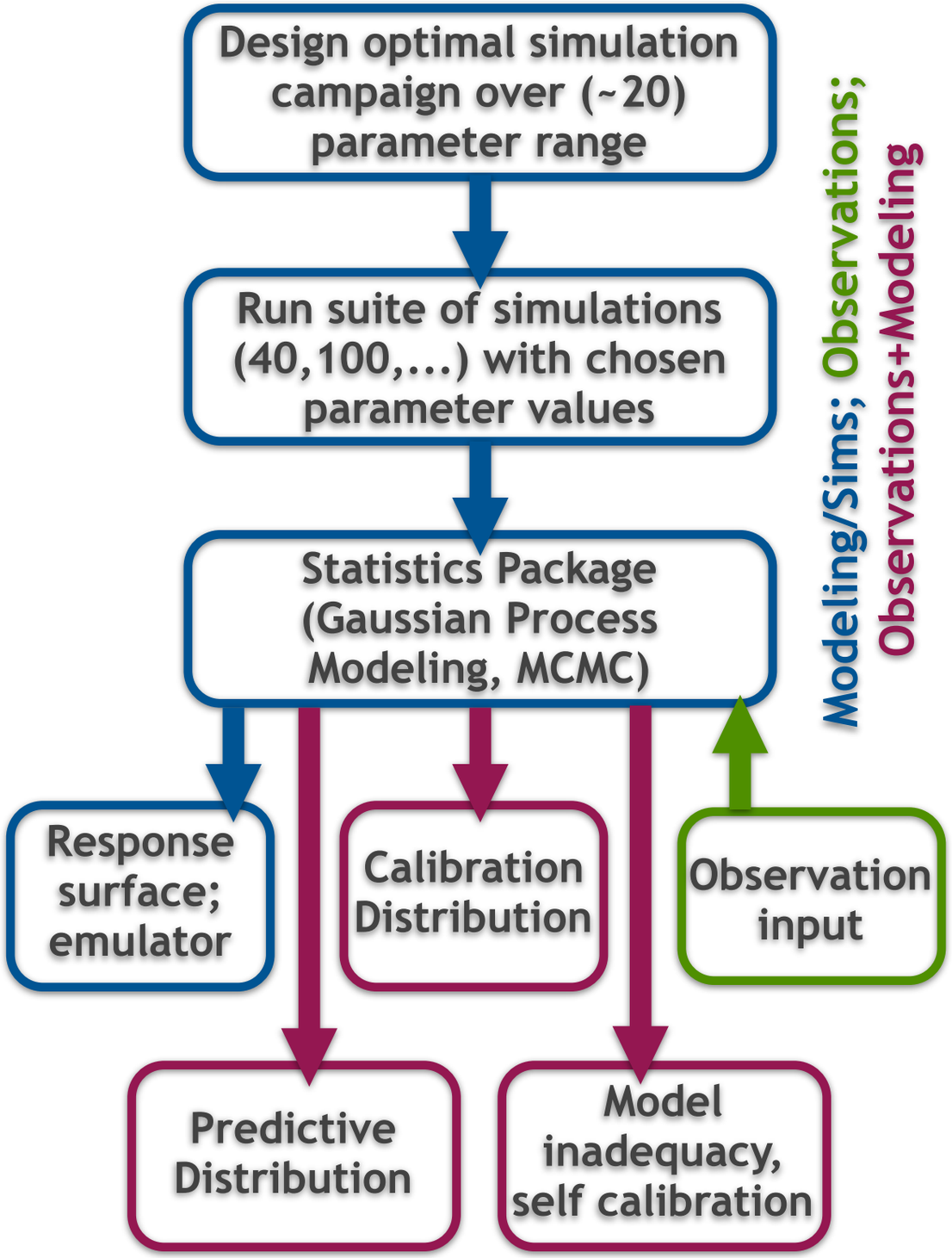


Cosmic Calibration: Solving the Inverse Problem

- **Challenge:** To extract cosmological constraints from observations in nonlinear regime, need to run Marko Chain Monte Carlo code; input: 10,000 - 100,000 different models
- **Current strategy:** Fitting functions for e.g. P(k), accurate at 10% level, as we saw this is not good enough!
- **Our alternative:** Emulators, fast prediction schemes built from a manageable set of simulations
- **Example here: Power spectrum emulator**
  - Step 1: Show simulations have required accuracy (Heitmann et al. 2005, 2008, 2010)
  - Step 2: Determine minimum number of simulations needed and develop sophisticated interpolation scheme that provides the power spectrum for any cosmology within a given parameter space prior (Heitmann et al. 2006, 2009; Habib et al. 2007)
  - Step 3: Carry out simulation and build final emulator (Lawrence et al. 2010, Heitmann et al. 2013)

Cosmic Calibration Framework

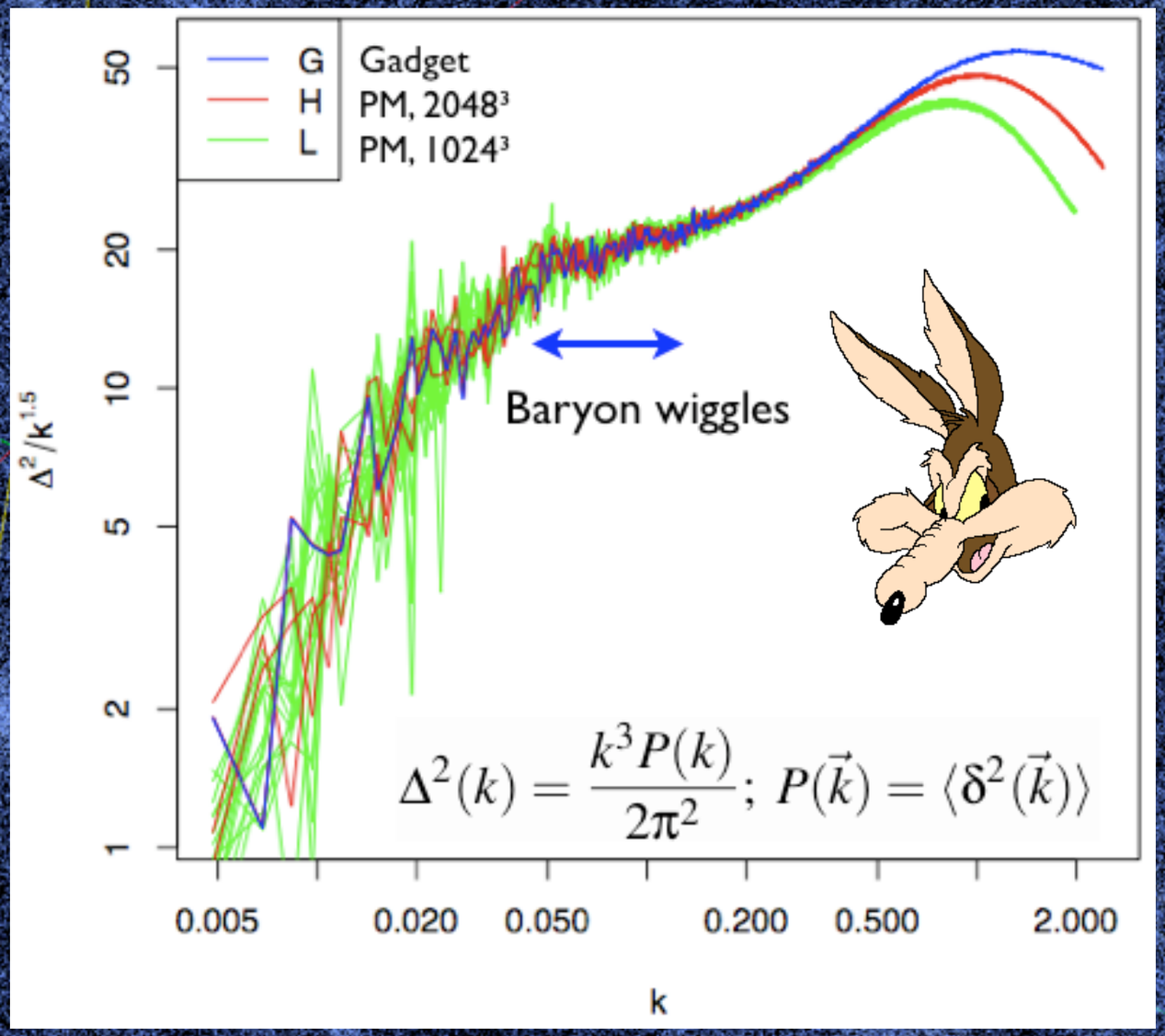
- Step 1: Design simulation campaign, rule of thumb: O(10) models for each parameter
- Step 2: Carry out simulation campaign and extract quantity of interest, in our case, power spectrum
- Step 3: Choose suitable interpolation scheme to interpolate between models, here Gaussian Processes
- Step 4: Build emulator
- Step 5: Use emulator to analyze data, determine model inadequacy, refine simulation and modeling strategy...



The Original Coyote Universe

Priors:

$0.020 \leq \omega_b \leq 0.025$
$0.11 \leq \omega_m \leq 0.15$
$0.85 \leq n_s \leq 1.05$
$-1.3 \leq w \leq -0.7$
$0.6 \leq \sigma_8 \leq 0.9$



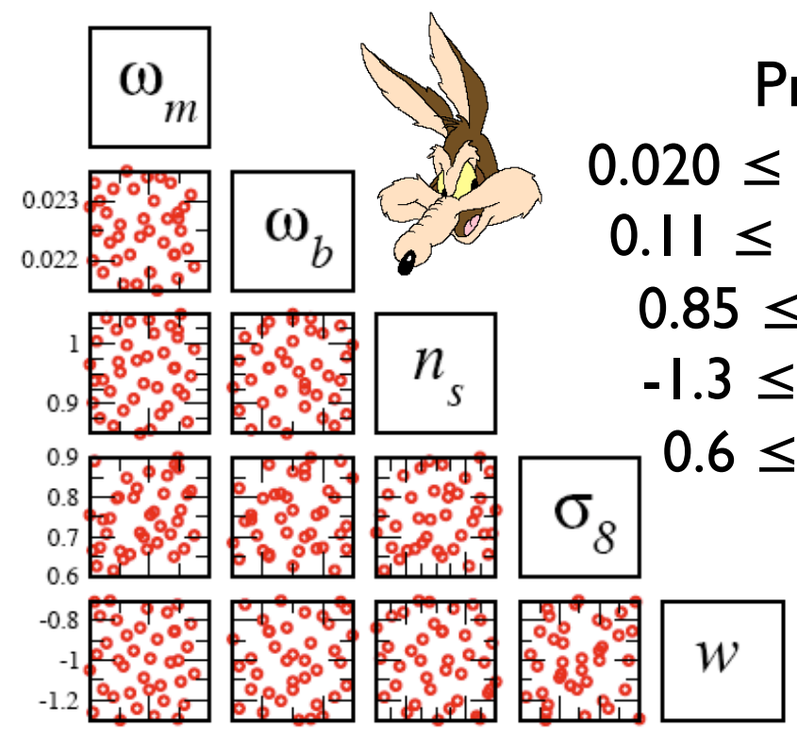
- 37 model runs + ΛCDM
  - 16 low resolution realizations (green)
  - 4 medium resolution realizations (red)
  - 1 high resolution realization (blue)
  - 11 outputs per run between z = 0 - 3
- Restricted priors to minimize necessary number of runs
- 1.3 Gpc boxes, $m_p \sim 10^{11} M_\odot$
- ~1000 simulations, 60TB

Background Visualization with ParaView by J. Woodring

The Simulation Design for wCDM Cosmologies

- "Simulation design": For a given set of parameters to be varied and a fixed number of runs, at what settings should the simulations be performed?
- Example: Five cosmological parameters, tens of high-resolution runs are affordable
- First idea: Grid
  - Space filling but poor projection properties
- Second idea: Random sampling
  - Good projection properties but poor space coverage
- Our approach: Orthogonal-array Latin hypercubes (OA-LH) design
  - Stratified random sampling approach
  - Good projection properties AND space filling

The Coyote Universe



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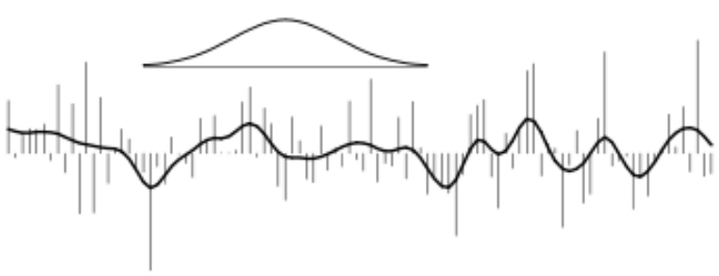
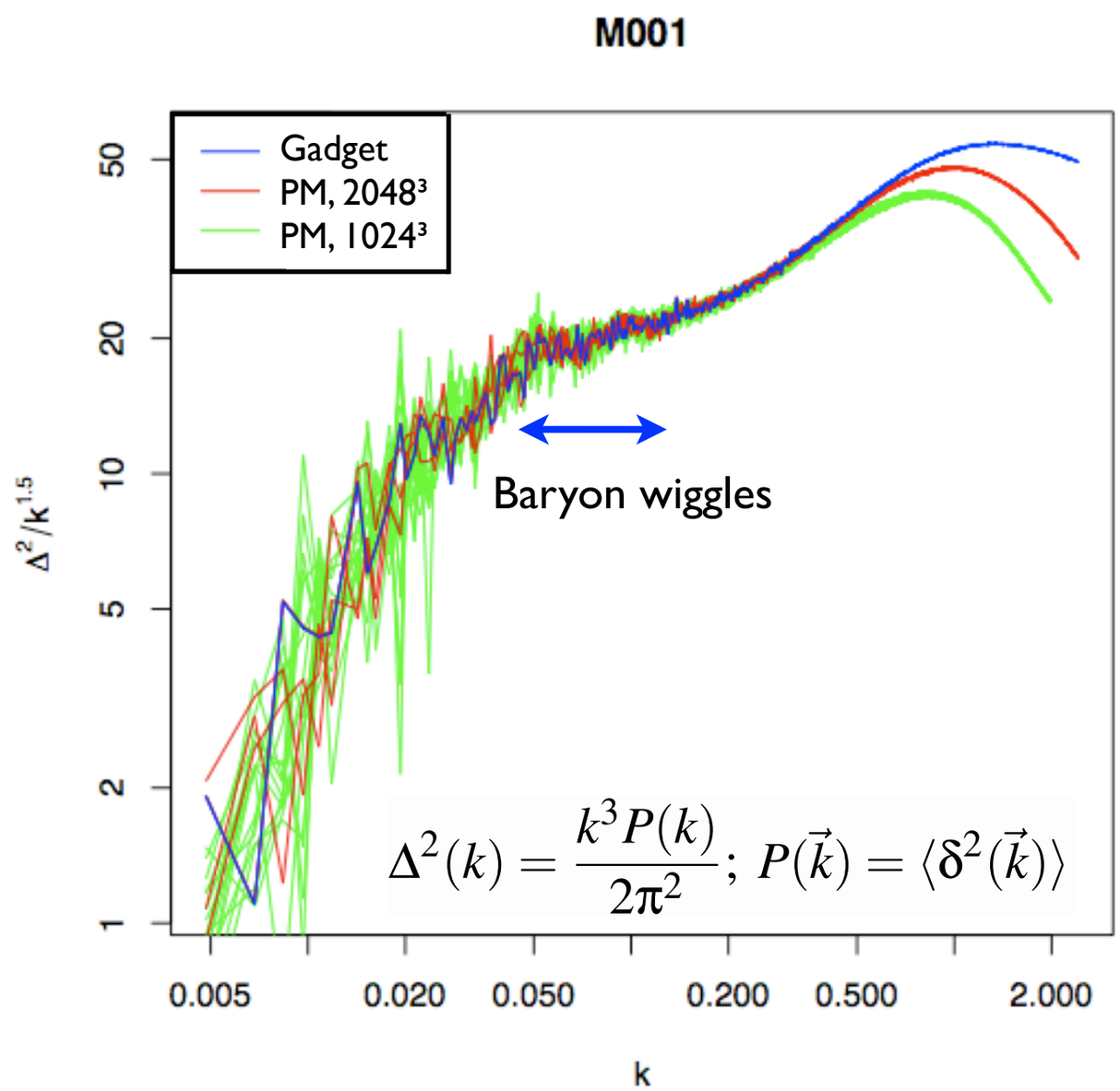
Priors are informed by current cosmological constraints, the tighter the priors, the easier to build a prediction tool. Restriction in number of parameters also helps!

Next step: Smooth Power Spectrum

- Each simulation represents one possible realization of the Universe in a finite volume
- Need smooth prediction for building the emulator for each model
- Major challenge: Make sure that baryon features are not washed out or enhanced due to realization scatter
- Construct smooth power spectra using a process convolution model (Higdon 2002)
- Basic idea: calculate moving average using a kernel whose width is allowed to change to account for nonstationarity





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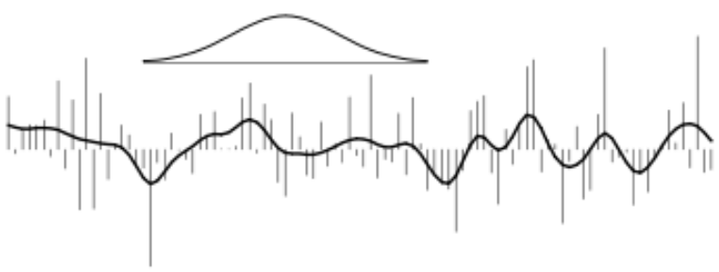
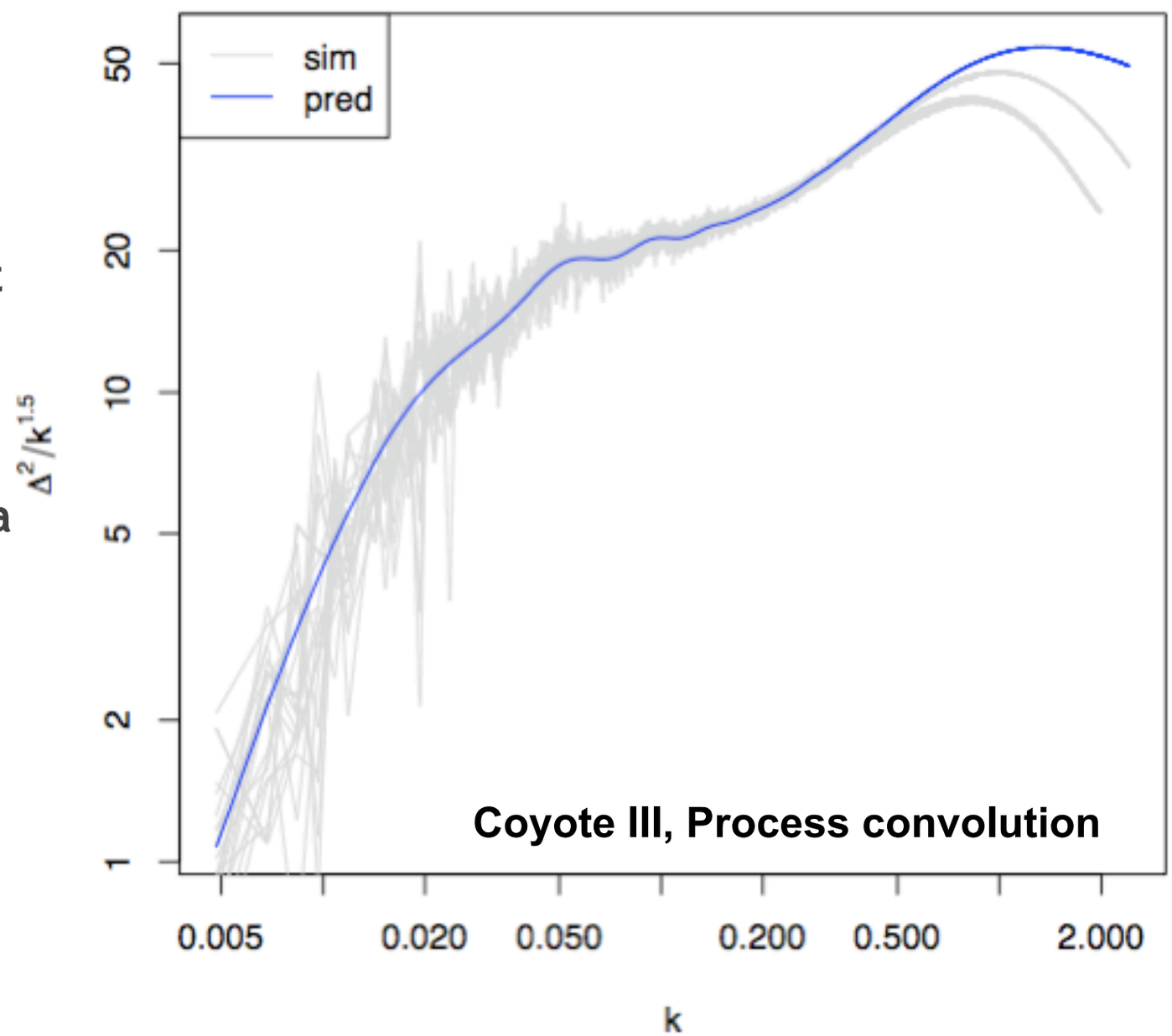
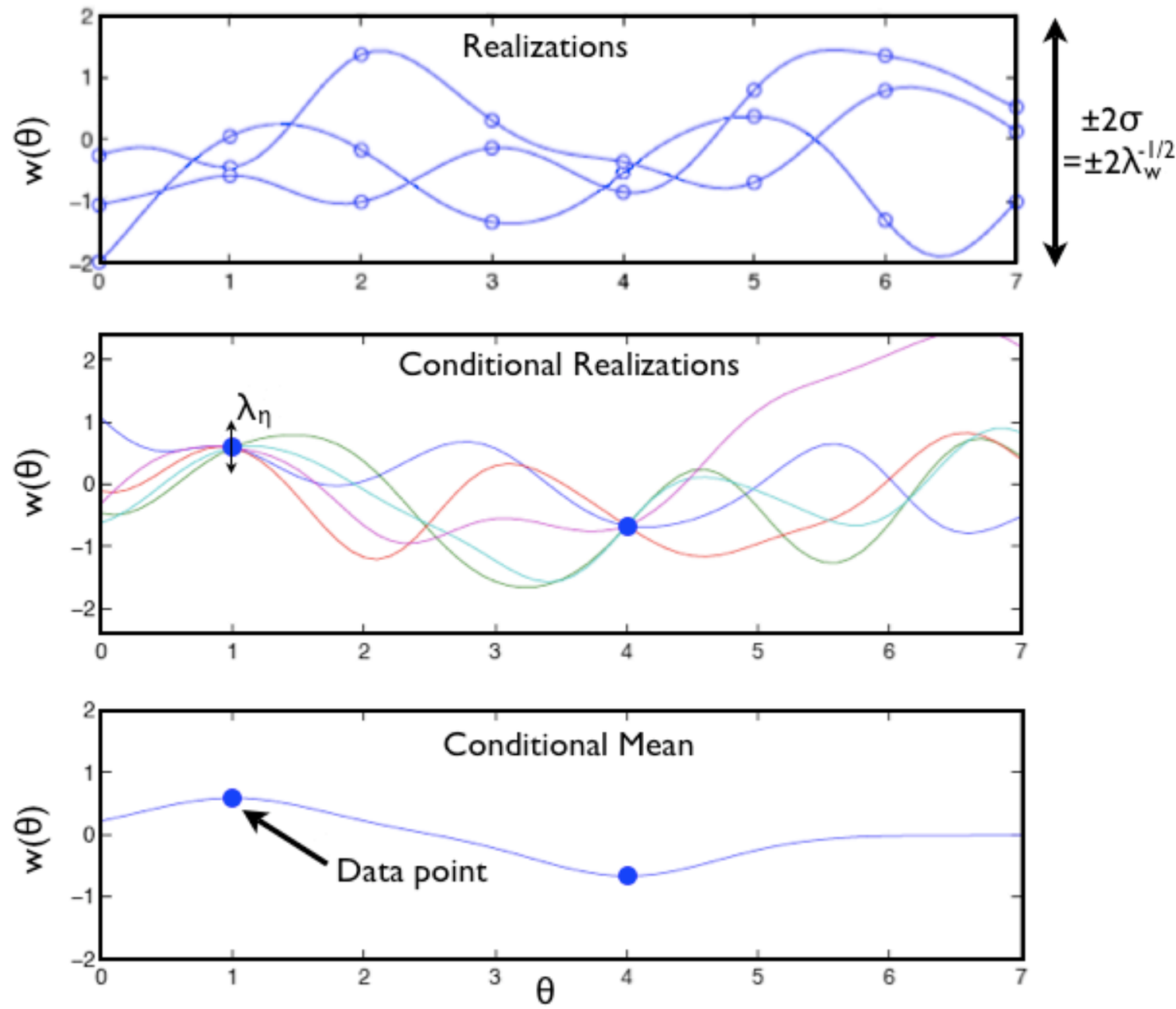




The Interpolation Scheme: Gaussian Processes + PCA

- After simulation design specification: Build non-parametric interpolation scheme
- Gaussian Process (GP): fits in function space
- GP involves matrix inversion in conditioning step ("curse of dimensionality")
- Data compression: Express power spectra in terms of principal component (PC) basis (can use other basis too)
- GP over over PC coefficients



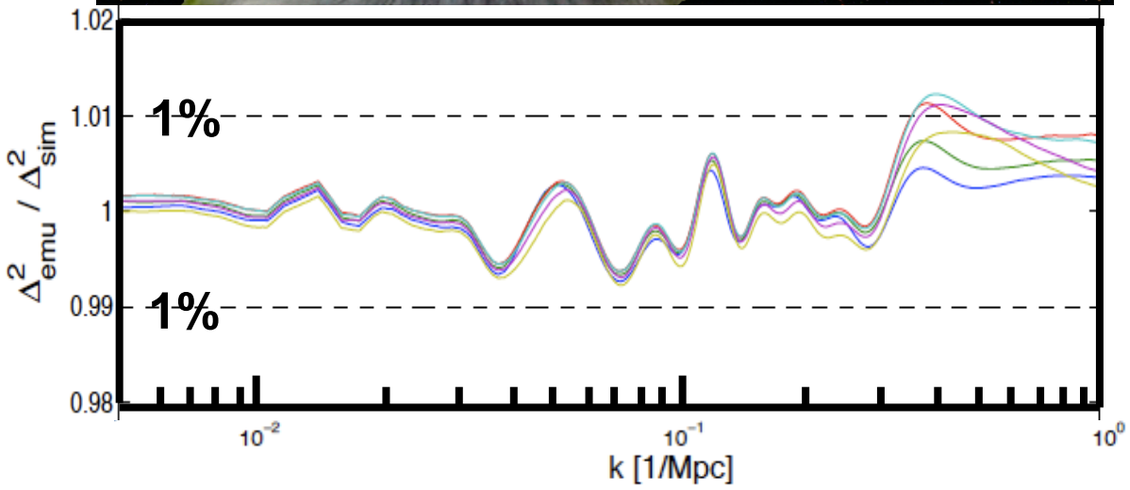
Cosmic Emulator in Action

- Instantaneous ‘oracle’ for nonlinear power spectrum, reduces compute time from weeks to negligible, accurate at 1% out to k~1/Mpc for wCDM cosmologies
- Enables direct MCMC with results from full simulations

The Cosmic Emu(lator)

- Prediction tool for matter power spectrum has been constructed
- Accuracy within specified priors between z=0 and z=1 out to k=1 *h*/Mpc at the 1% level achieved
- Emulator has been publicly released, C code
- Extension: Include *h* as sixth parameter, out to k=10 *h*/Mpc and z=4
  - Nested simulations to cover large k-range
  - Approach degrades accuracy to ~3%

Emulator performance: Comparison of prediction and simulation output for a model not used to build emulator at 6 redshifts.



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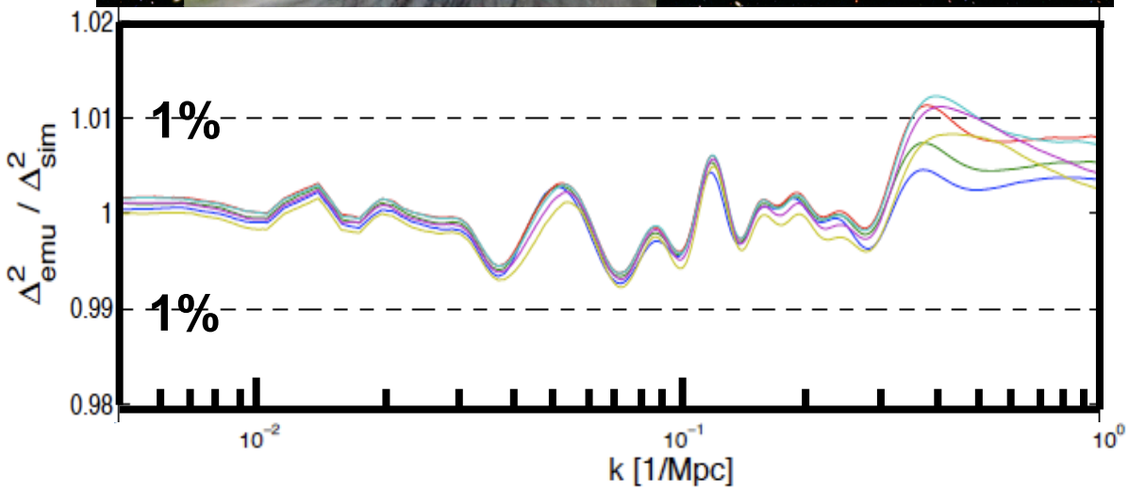

The Next Step: The Mira Universe

- 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 emulators for P(k), mass function, c-M relation, derived quantities...
- LCDM done, finalizing set-up based on this run

Parameters

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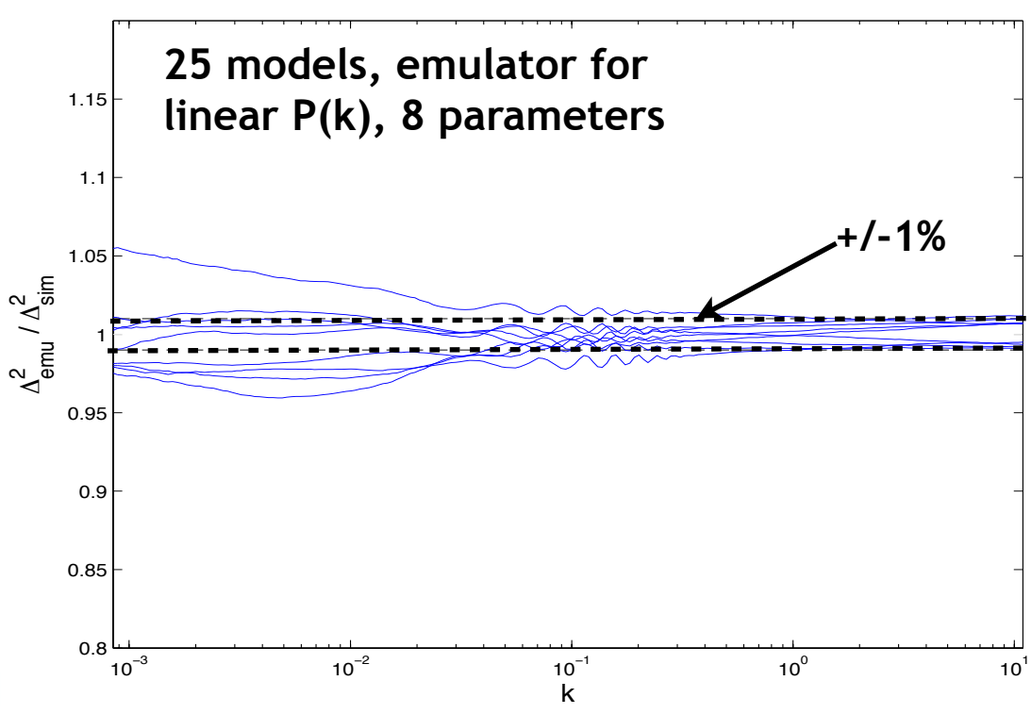
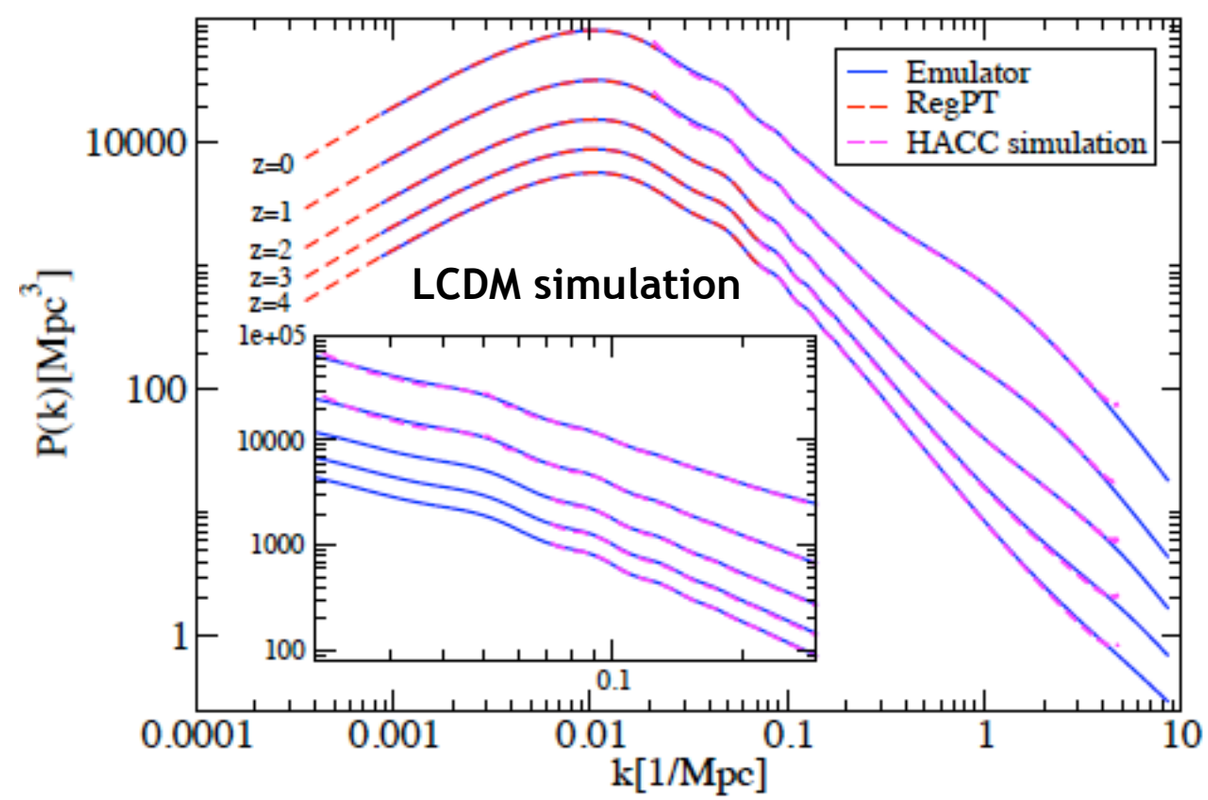
$$0.0 \leq \omega_\nu \leq 0.01.$$





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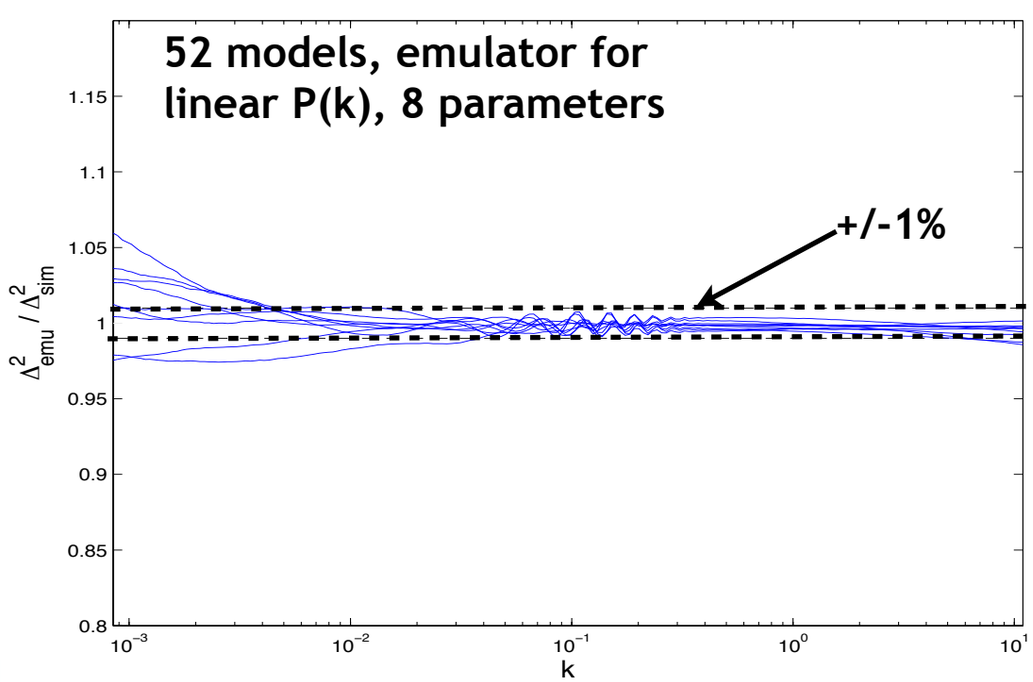

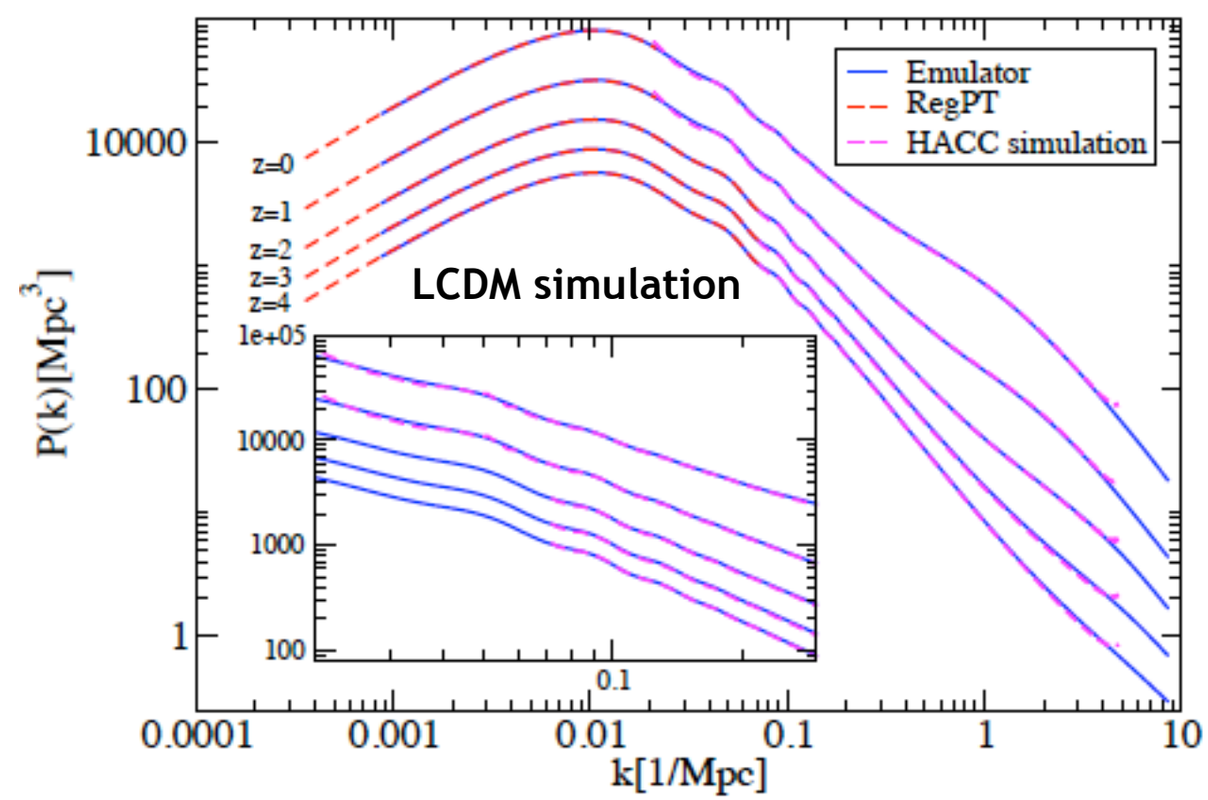

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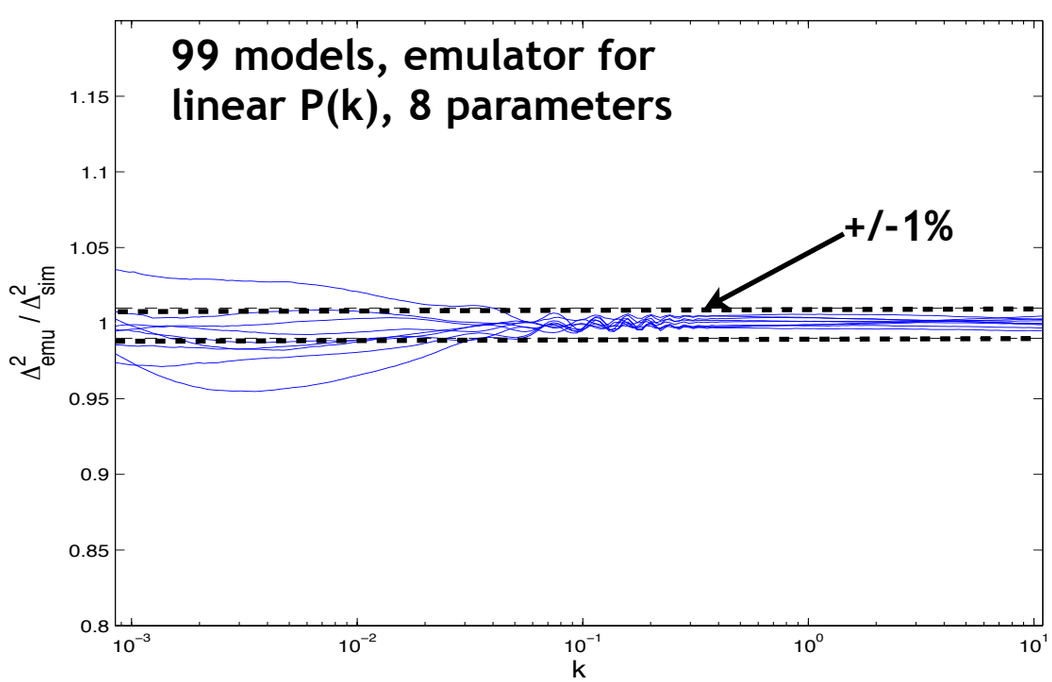

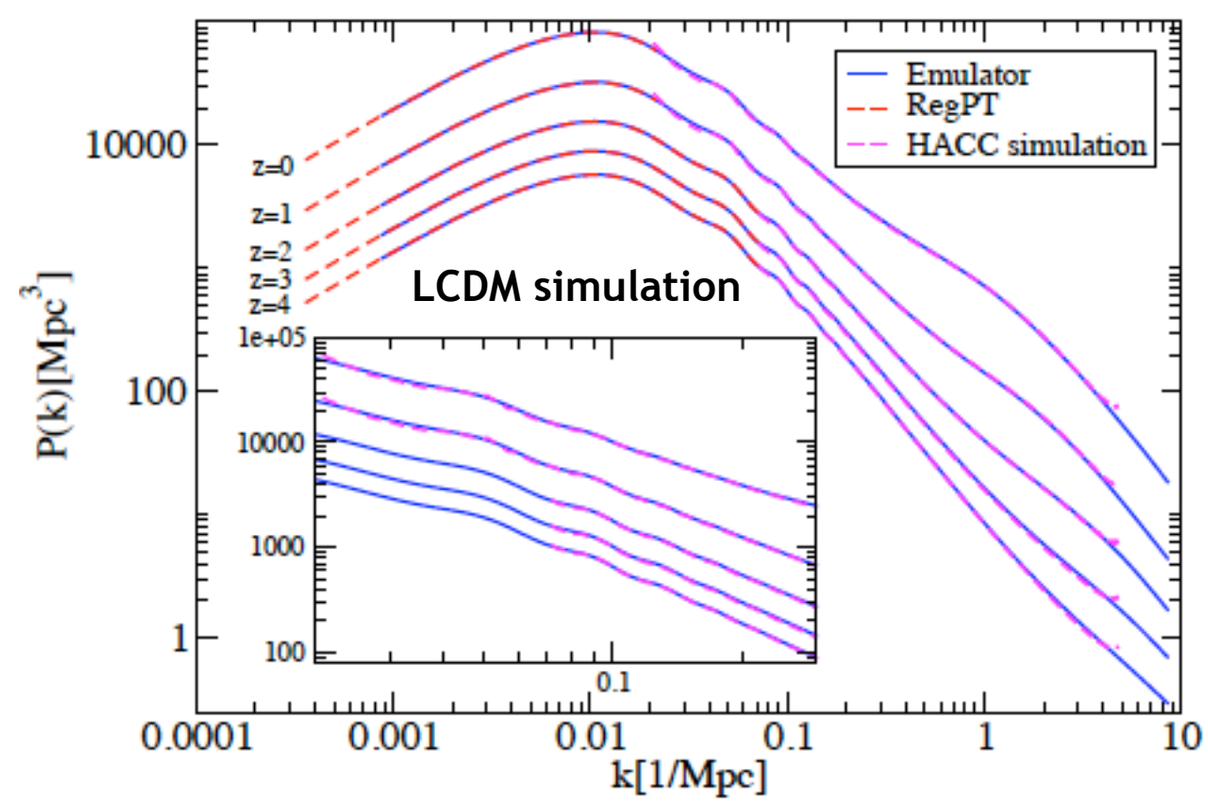

Summary and Outlook

- Precision cosmology needs high accuracy predictions! Can we avoid being theory limited?
- Cosmic Calibration Framework allows us to build fast prediction tools for ongoing and future surveys
- *The Mira Universe* will lead to an unprecedented set of simulations, spanning 8 cosmological parameters, including different dark energy models and neutrinos
- In this talk: Focus on power spectrum science but other emulators can be easily built, we have built in addition to matter power spectrum -- galaxy power spectrum, c-M relation (Kwan et al. 2012, Kwan et al. 2013)