# Testing gravity with cosmology

**Emilio Bellini**

08th October 2024

$1^{st}$ *Smashing Workshop*

## The standard cosmological model ($\Lambda$CDM)

$$\boxed{\underbrace{\mathrm{GR}}_{\text{Gravity}} + \underbrace{\Lambda + \mathrm{CDM} + \mathrm{SM}}_{\text{Ingredients}}}$$

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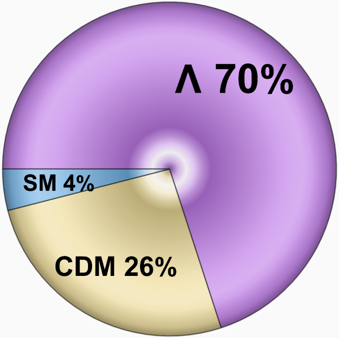


- 96% unknown!
- **Λ**: accelerating universe
- **CDM**: more matter than observed
- **SM**: standard model particles

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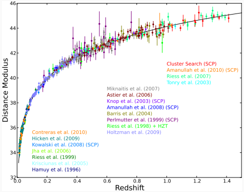


Expansion history

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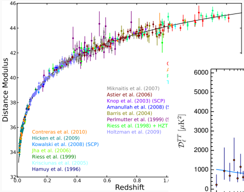


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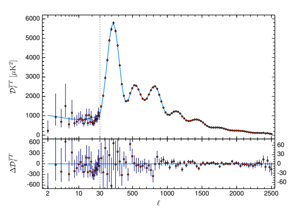


Cosmic Microwave Background

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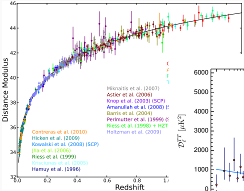


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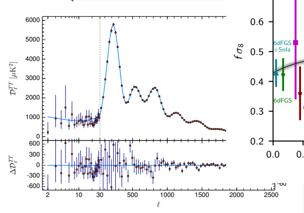


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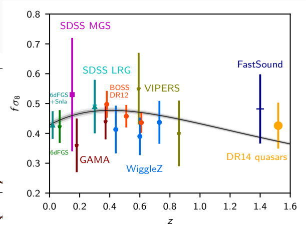


Large Scale Structure

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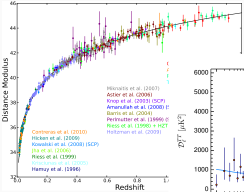


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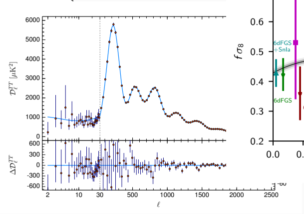


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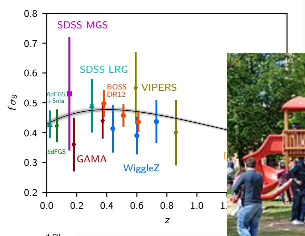


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Earth Experiments

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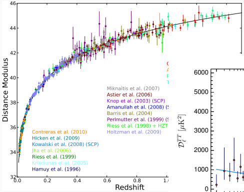


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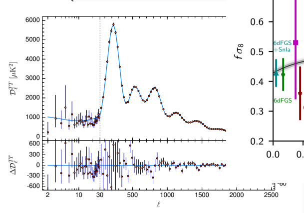


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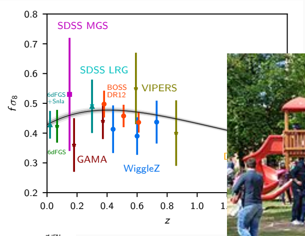


Large Scale Structure

Earth Experiments

- $\Lambda$ explains accelerated expansion but too small ($\rho_\Lambda/\rho_v \sim 10^{-120}$)
- $\Lambda$CDM fits well each dataset, but tensions when combining them
- Tests of GR on local scales, but cosmology is $10^{15}$ larger

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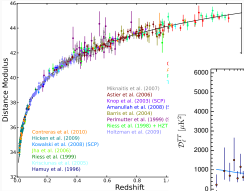


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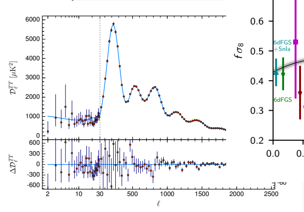


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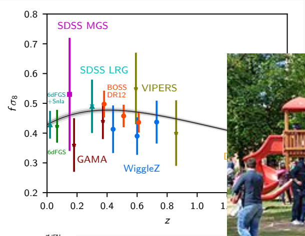


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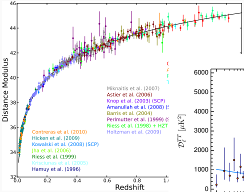
*In Physics we have Heroes, not Prophets* - S. Weinberg

# A full pipeline

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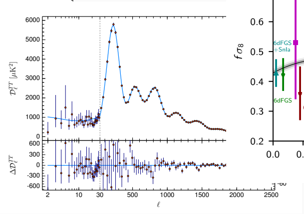


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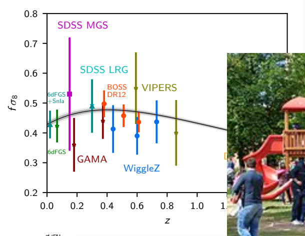


Large Scale

Earth Experiments

Scales in cosmology::
- largest observable scales: homogeneous and isotropic universe
- large scales: small perturbations around it (easy)
- small scales: large perturbations (difficult)

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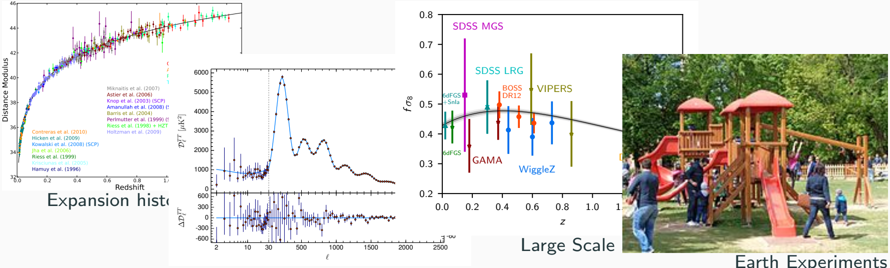


Expansion histo[ry]

Cosmic Microwave Background

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**Data** → ← **Theory**

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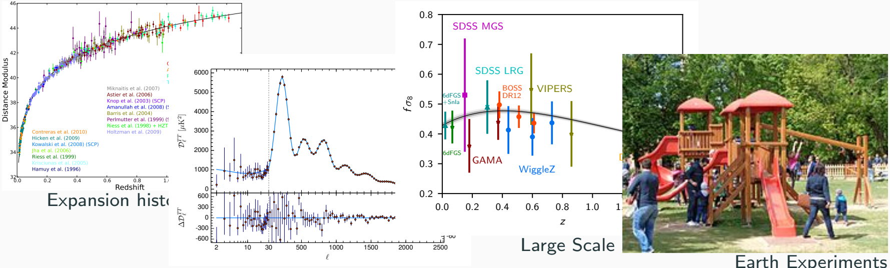


Expansion hist

Cosmic Microwave Background

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**Data** **Comparison** **Theory**

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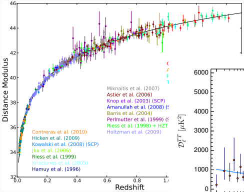

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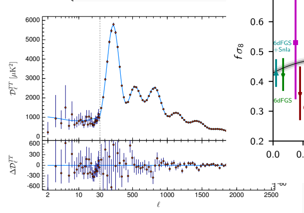
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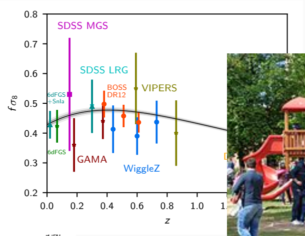

Large Scale


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**Data** ⇨ **Comparison** ⇦ **Theory**

- increased accuracy of data → better theory modeling
- different gravity → different modeling

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# The linear universe

[Zumalacàrregui, EB, *et al.* (2017)]
[EB, Sawicki,Zumalacàrregui (2020)]

www.hiclass-code.net

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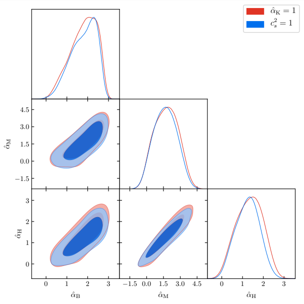
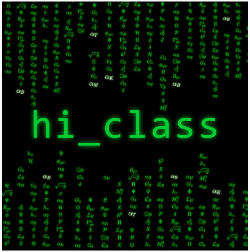
## Results

- No significant evidence of MG ($2\sigma$, mostly low-l in the CMB)
- *kineticity* ($\alpha_\mathrm{K}$) unconstrained
- Current data: $\mathcal{O}(1)$ constraints
- Next generation: $\mathcal{O}(0.1)$ constraints

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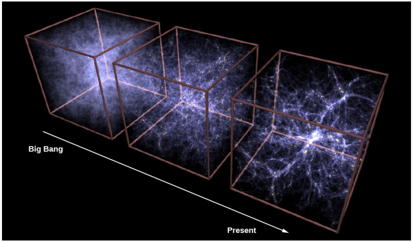
# The Large-Scale Structure pressing challenges



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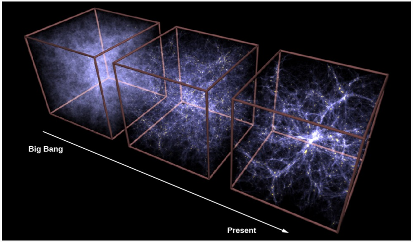


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- not interested in full distribution, but on statistical properties
- data from highly non-linear scales (very small scales)

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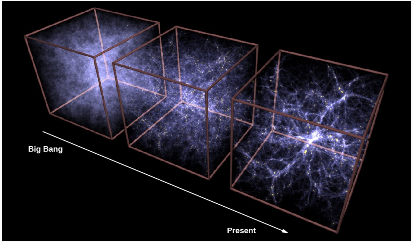


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**Tools:**

- Einstein-Boltzmann solvers, e.g. `hi_class`. Large scales, few seconds
- N-body simulations. Very accurate on small scales. Hours, days
- Fitting formulas from N-body simulations. Model dependent

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Testing gravity can be slow!

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↓

**Emulating the Large-Scale Structure**

- with Machine Learning easily speed up by a factor $\sim 10^2$ w.r.t. standard pipelines
- start with Feed Forward Neural Networks, and improve if needed
- start with toy model to better control the pipeline, and add more models later
- use `hi_class` and N-body simulations to train the emulator

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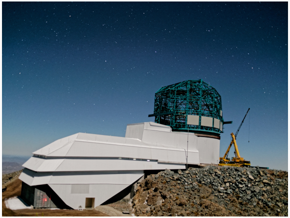

Vera Rubin Observatory (SMASH research line)

- Most of the effort for ΛCDM!
- Work within "Beyond wCDM" topical team
- Integrate my emulator in their pipeline

# The plan

Build the emulator

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- start with simple models and add more models later for risk mitigation
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# Thank you!