MG Millennium simulations:
a new precision era in modified gravity research

Presented by

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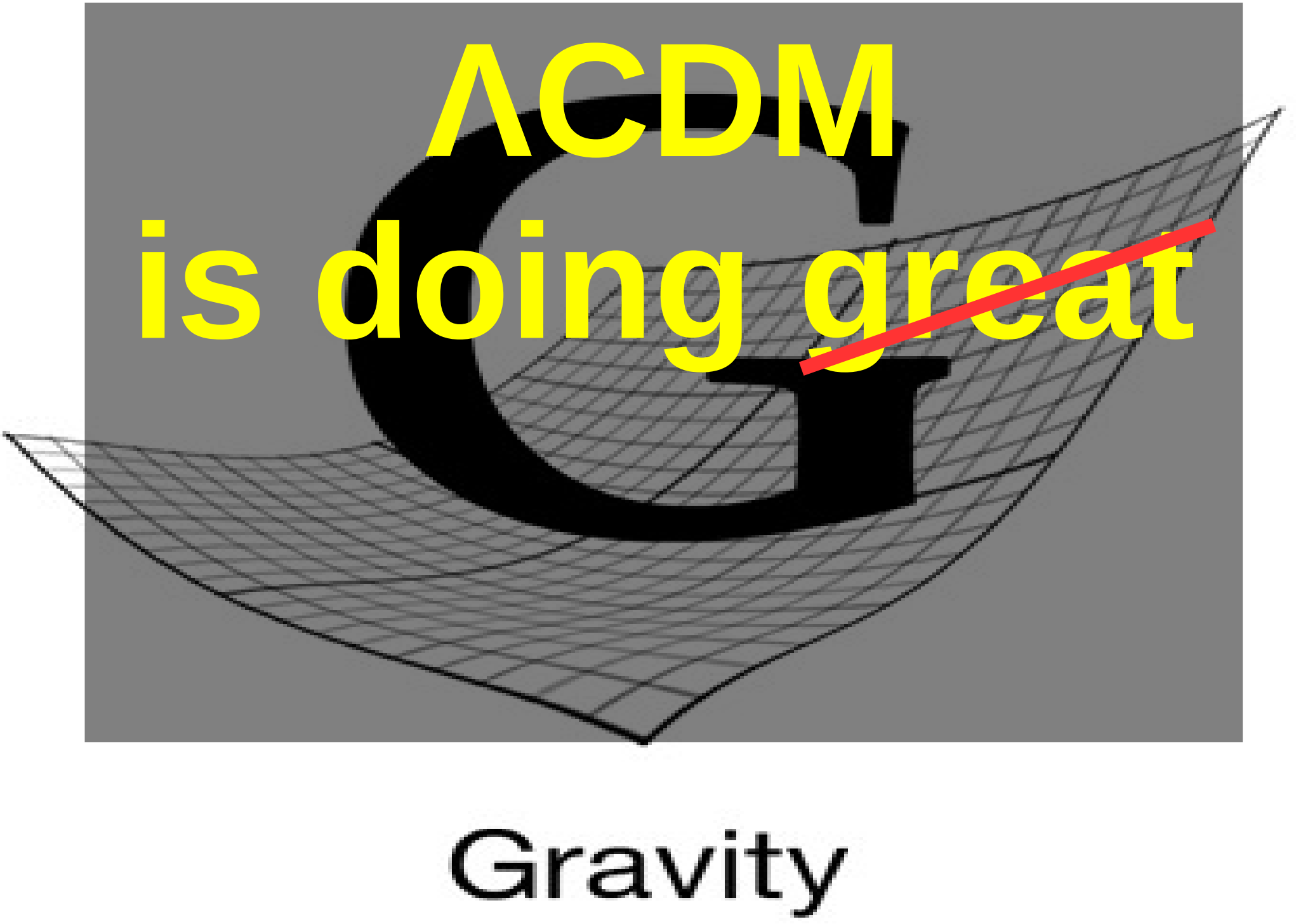
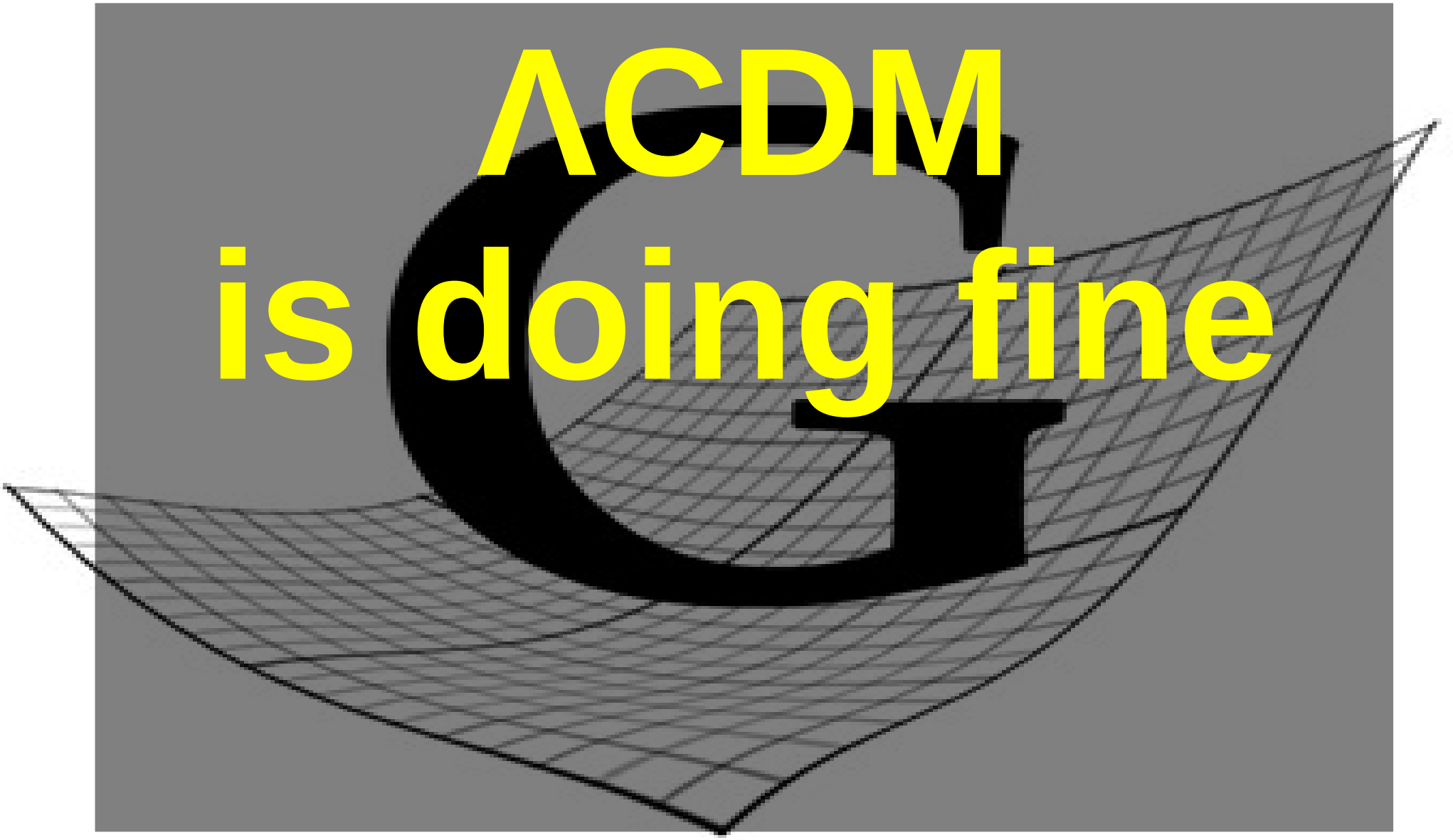
DEX XIII, Edinbra, January orbit #2017

VIRGO/DESI ModGrav team:

Baojiu Li, Alex Barreira, Sownak Bose, Claudio Llinares, Kazuya Koyama, Gong-Bo Zhao, Jianhua He,...


ΛCDM
is doing great
Gravity


ΛCDM
is doing fine
Gravity

cold dark matter

ΛCDM: the standard model of cosmology

cosmological constant

Why is this the standard model?

New tests and possible problems

Gravity

BECAUSE WE DON'T HAVE ANYTHING BETTER!

Global acceleration – possible scenarios

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m\right]$$ → No acceleration

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + \frac{\Lambda}{8\pi G}\right]$$ → Standard LCDM model

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + \frac{\nabla_\mu\varphi\nabla^\mu\varphi}{2} + V(\varphi)\right]$$

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + f\left(\nabla_\mu\varphi\nabla^\mu\varphi\right)\right]$$

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + f(R)\right]$$

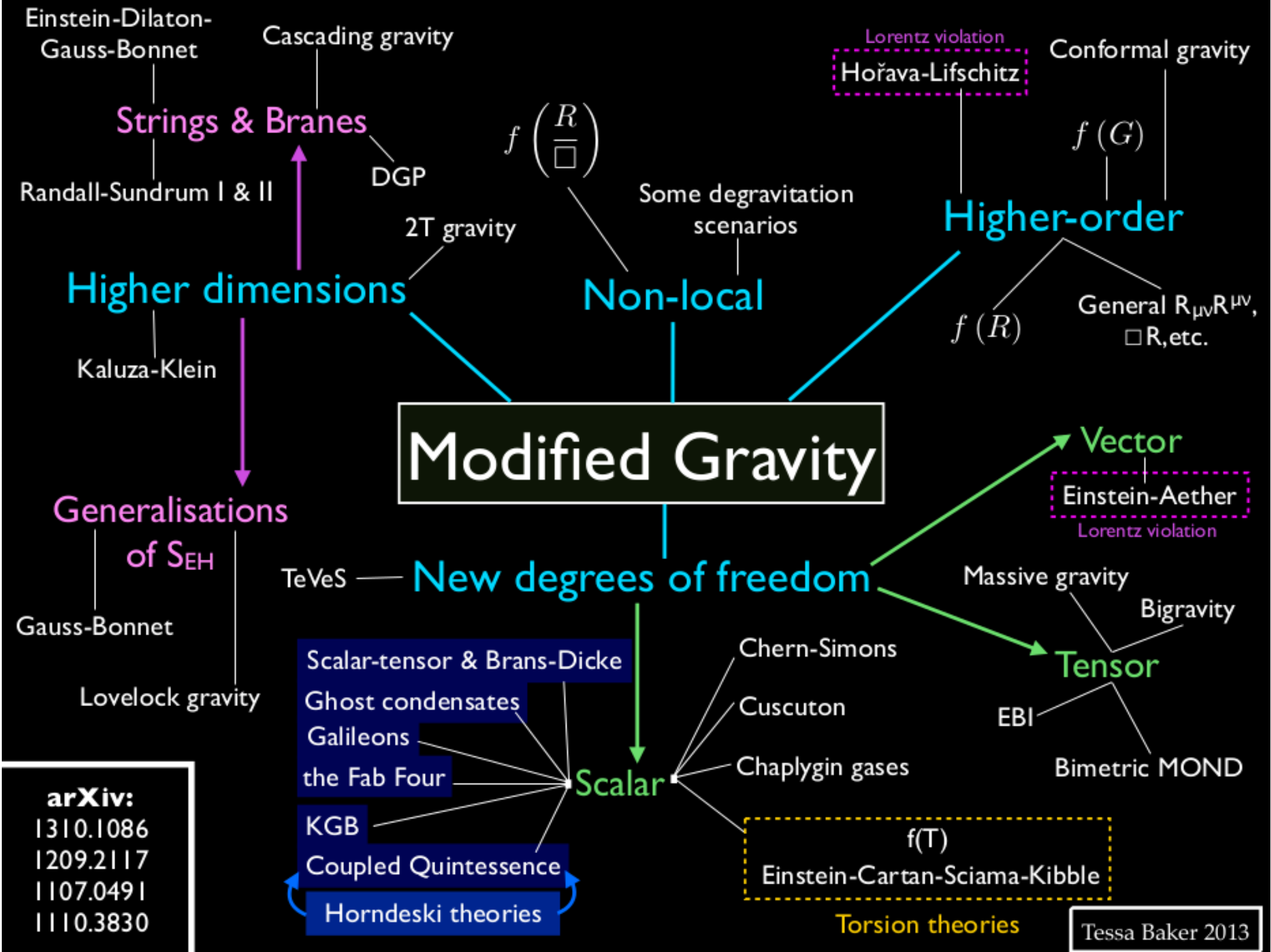
$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + f(\varphi)R + \frac{w(\varphi)\nabla_\mu\varphi\nabla^\mu\varphi}{2} + V(\varphi)\right]$$

GR curvature term

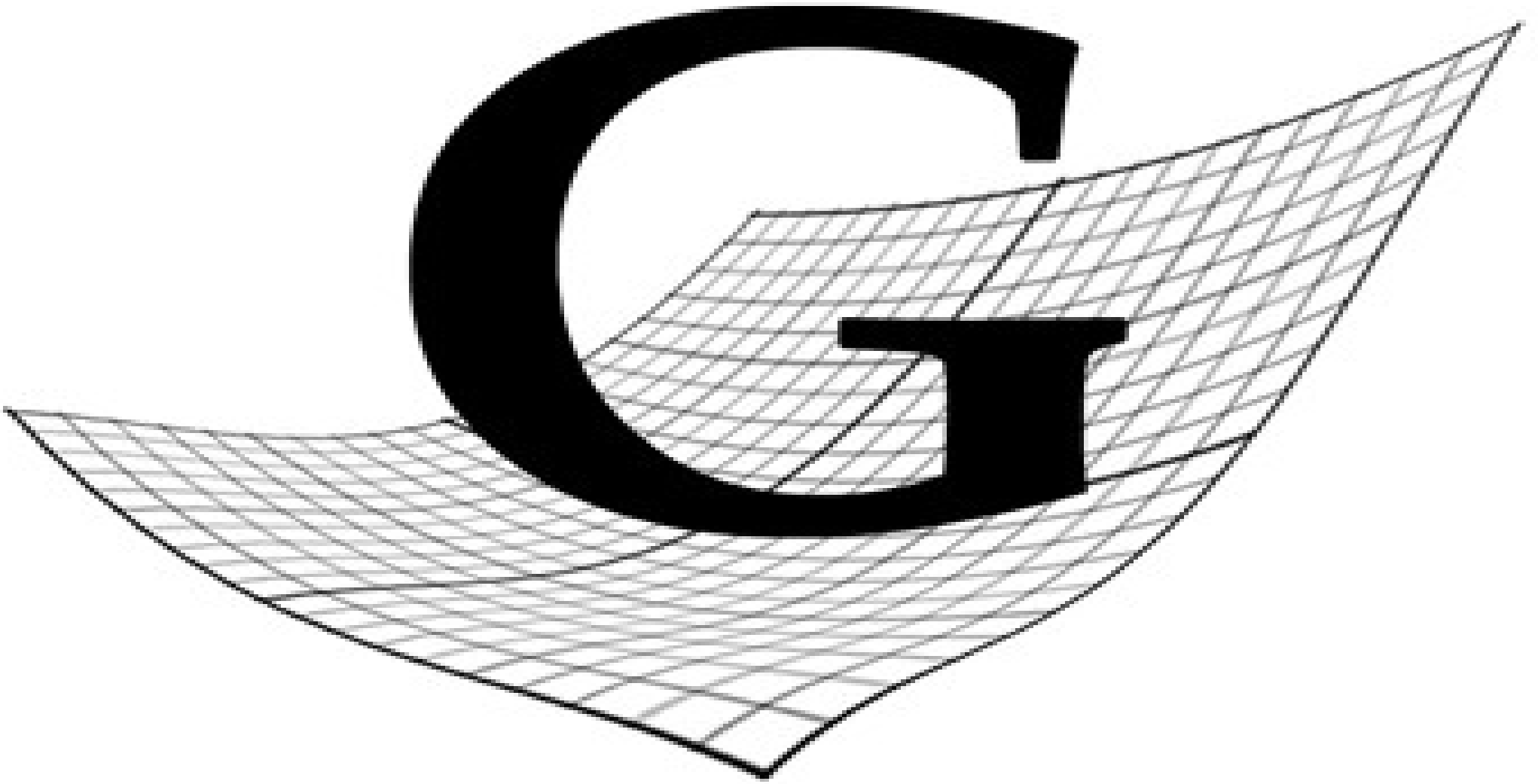
Particle physics and DM

Stuff that accelerates

Slide credit: Dottore Alexandre Barreira


Einstein-Dilaton-Gauss-Bonnet
Cascading gravity
Strings & Branes
Randall-Sundrum I & II
DGP
Lorentz violation
Hořava-Lifschitz
Conformal gravity
$f\left(\frac{R}{\Box}\right)$
$f(G)$
2T gravity
Some degravitation scenarios
Higher-order
Higher dimensions
Non-local
$f(R)$
General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$, etc.
Kaluza-Klein
Modified Gravity
Vector
Einstein-Aether
Lorentz violation
Generalisations of S_{EH}
TeVeS
New degrees of freedom
Massive gravity
Bigravity
Gauss-Bonnet
Scalar-tensor & Brans-Dicke
Chern-Simons
Tensor
Ghost condensates
Cuscuton
EBI
Galileons
the Fab Four
Chaplygin gases
Bimetric MOND
Scalar
KGB
Coupled Quintessence
Horndeski theories
f(T)
Einstein-Cartan-Sciama-Kibble
Torsion theories
Lovelock gravity
arXiv:
1310.1086
1209.2117
1107.0491
1110.3830
Tessa Baker 2013

Now, is it worth a major campaign?



Gravity

XXI century precison cosmology:

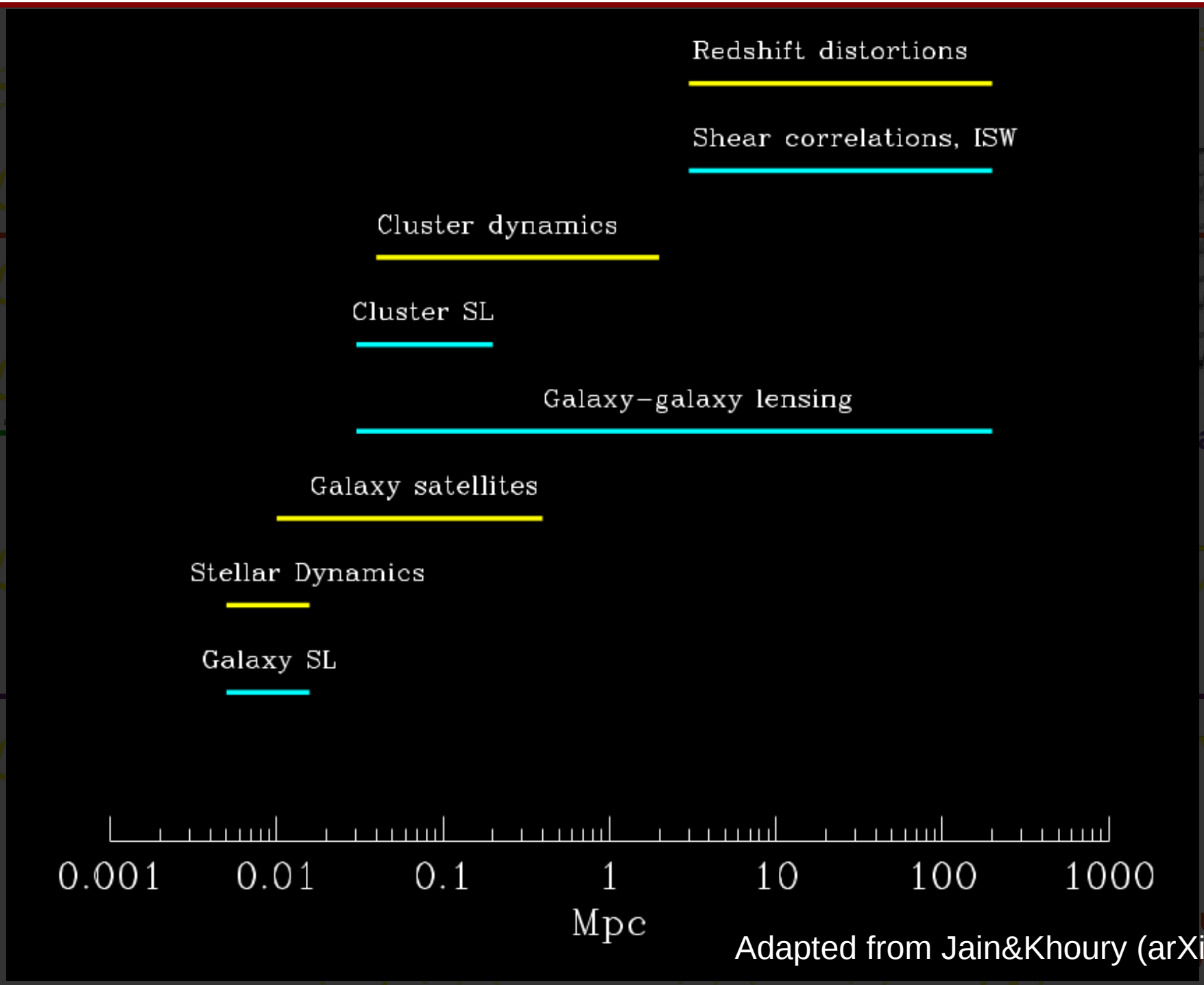
one of the goals is test GR on (intermediate) cosmological scales

SDSS

DARK ENERGY SURVEY

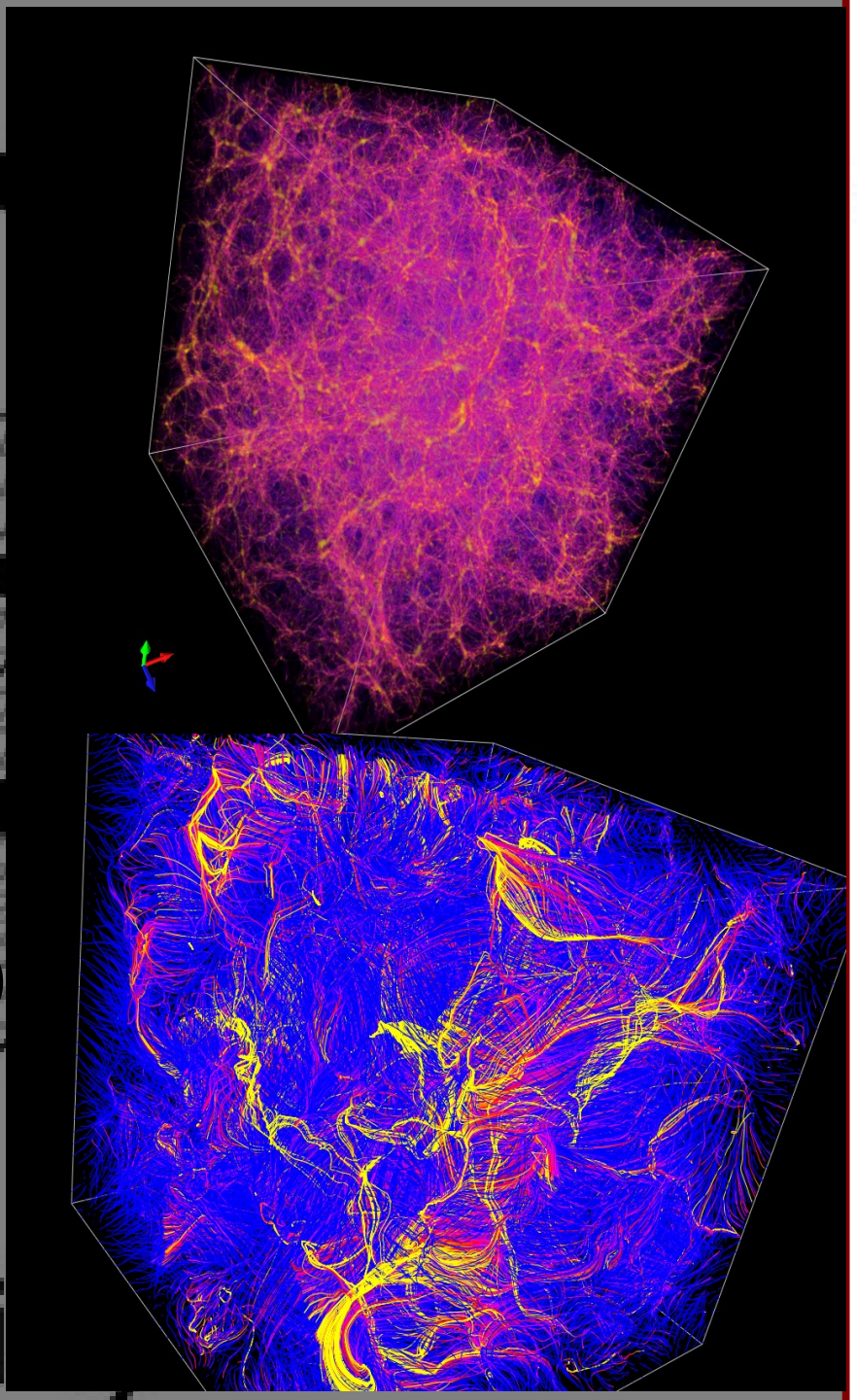
euclid

How to test different scenarios?

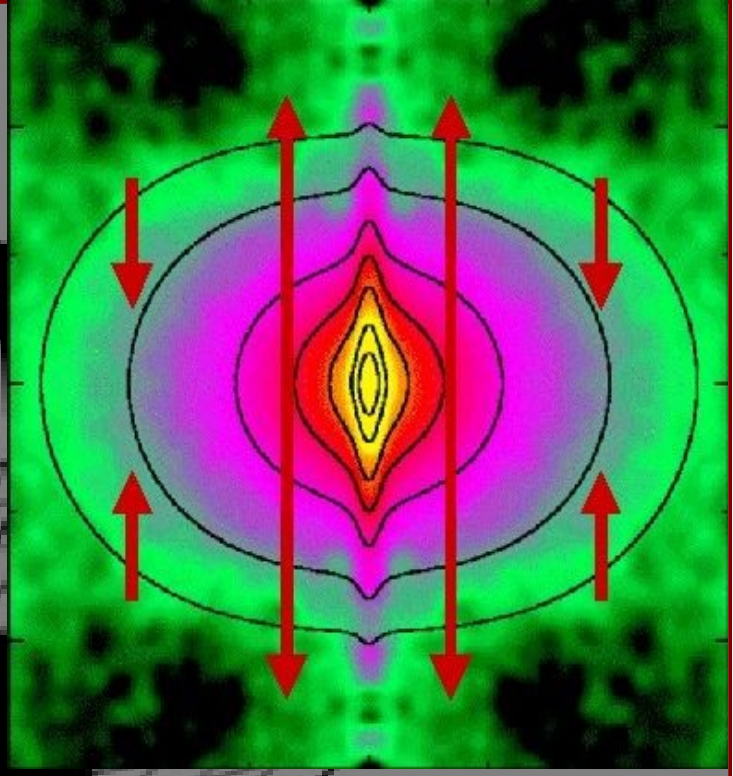


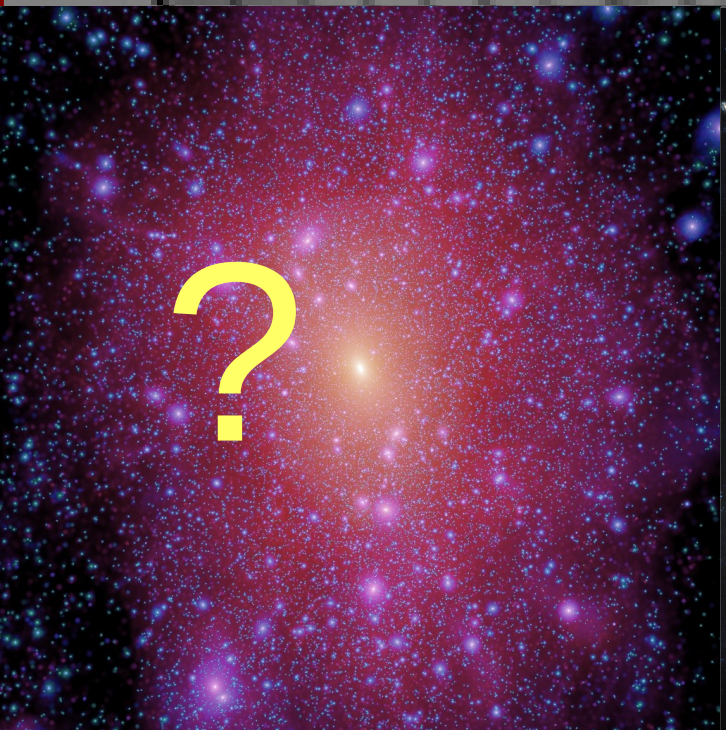
Adapted from Jain&Khoury (arXiv:1004.3294)

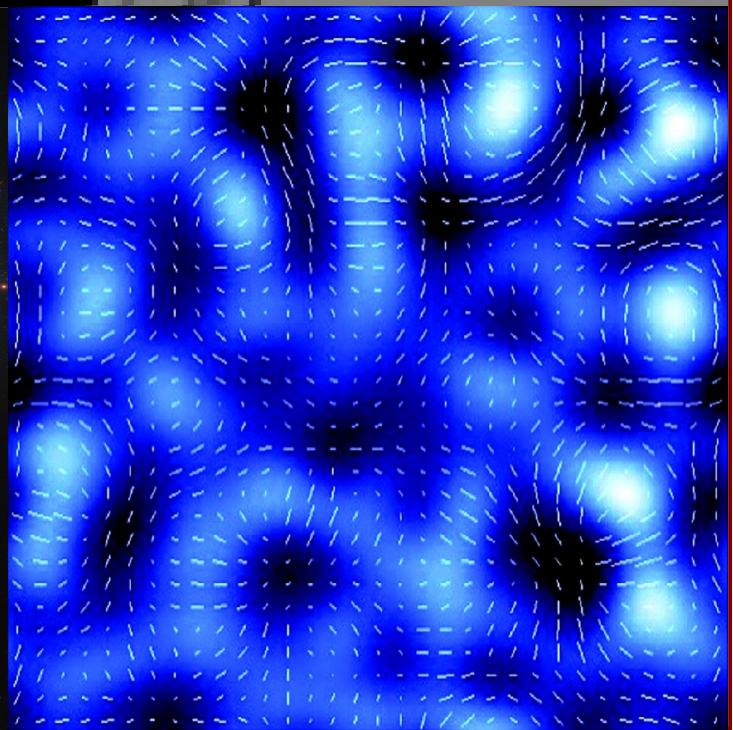
- Modified Gravity (MG) simulations are much more expensive than vanila GR
- Hence, most of the currently avaiable MG simulations have relatively low-resolution
- Usually low-resolution some big boxes are avaiable (i.e. 1024^3 with L~1Gpc/h)
- Or medium resolution small boxes (512^3 with L~250Mpc/h)



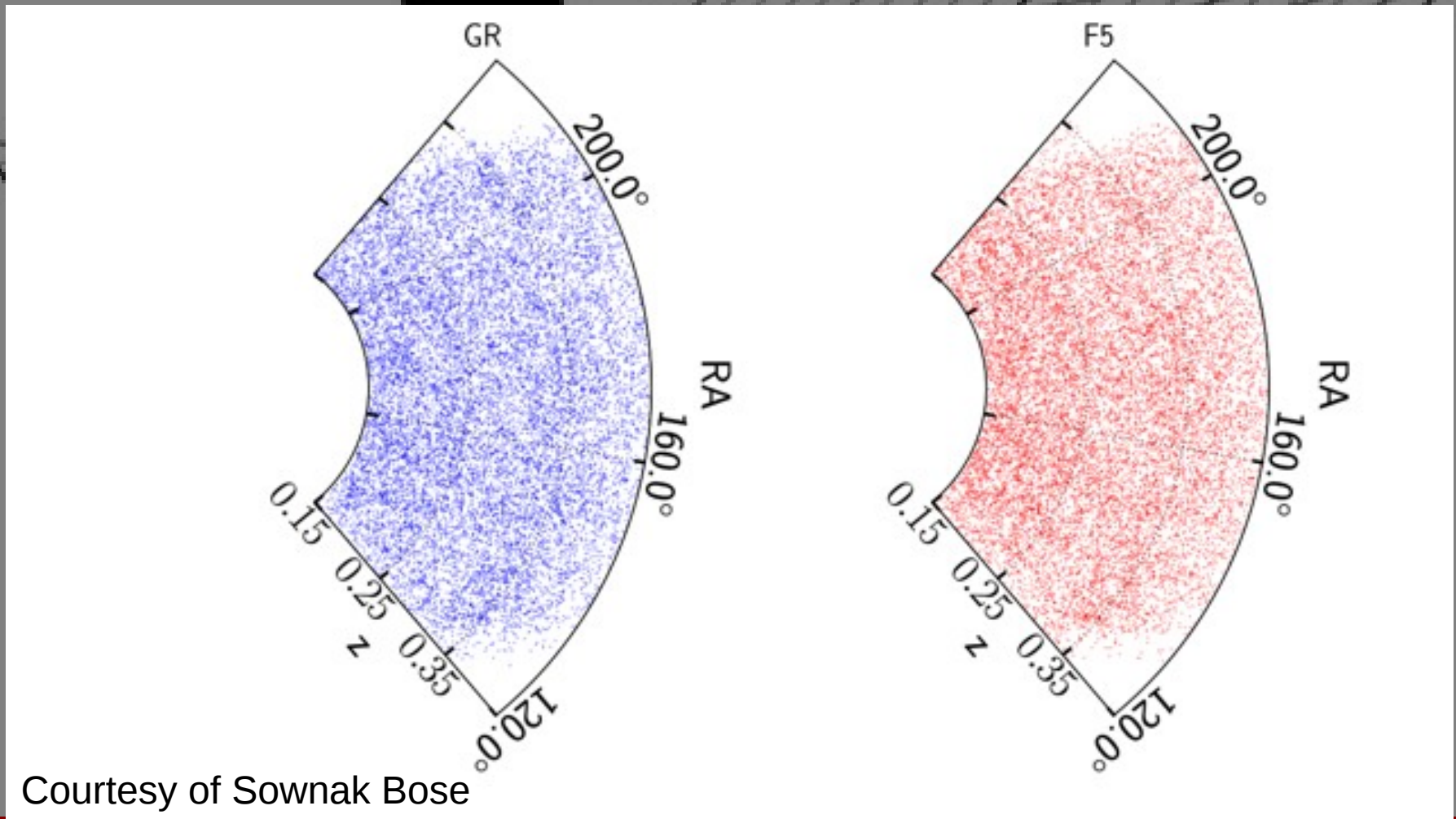
- Effects on the properties of large-scale structures are fairly reckognized and assessed (lensing, RSD, clustering, etc.)
- Effects on halo and galaxy formations much less studied and determined





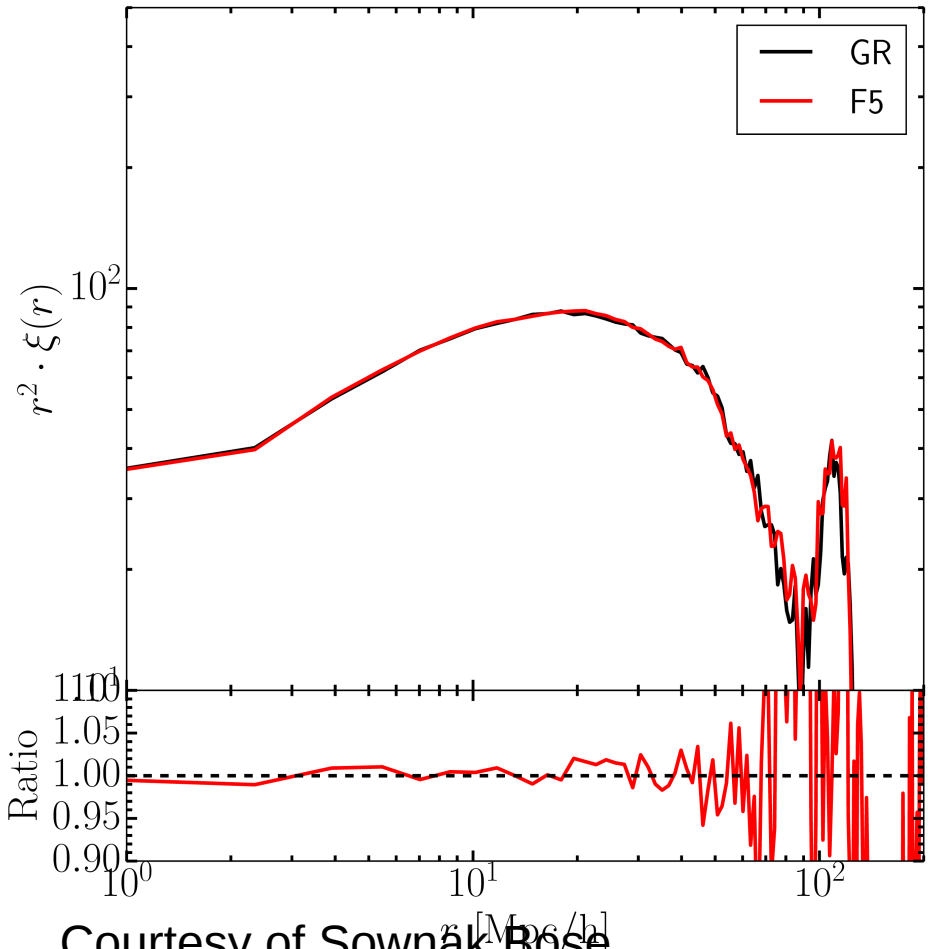


- With low resolution only simpler galaxy modelling methods are avaiable:
- Abundance matching, HOD, etc.
- These are rather agnostic about the fine details of galaxy formation baryonic physics



Courtesy of Sownak Bose

- LOWZ DR10
- HOD parameters choosen to achieve target number density of the galaxy sample n=4e-4 gals/Mpc^3



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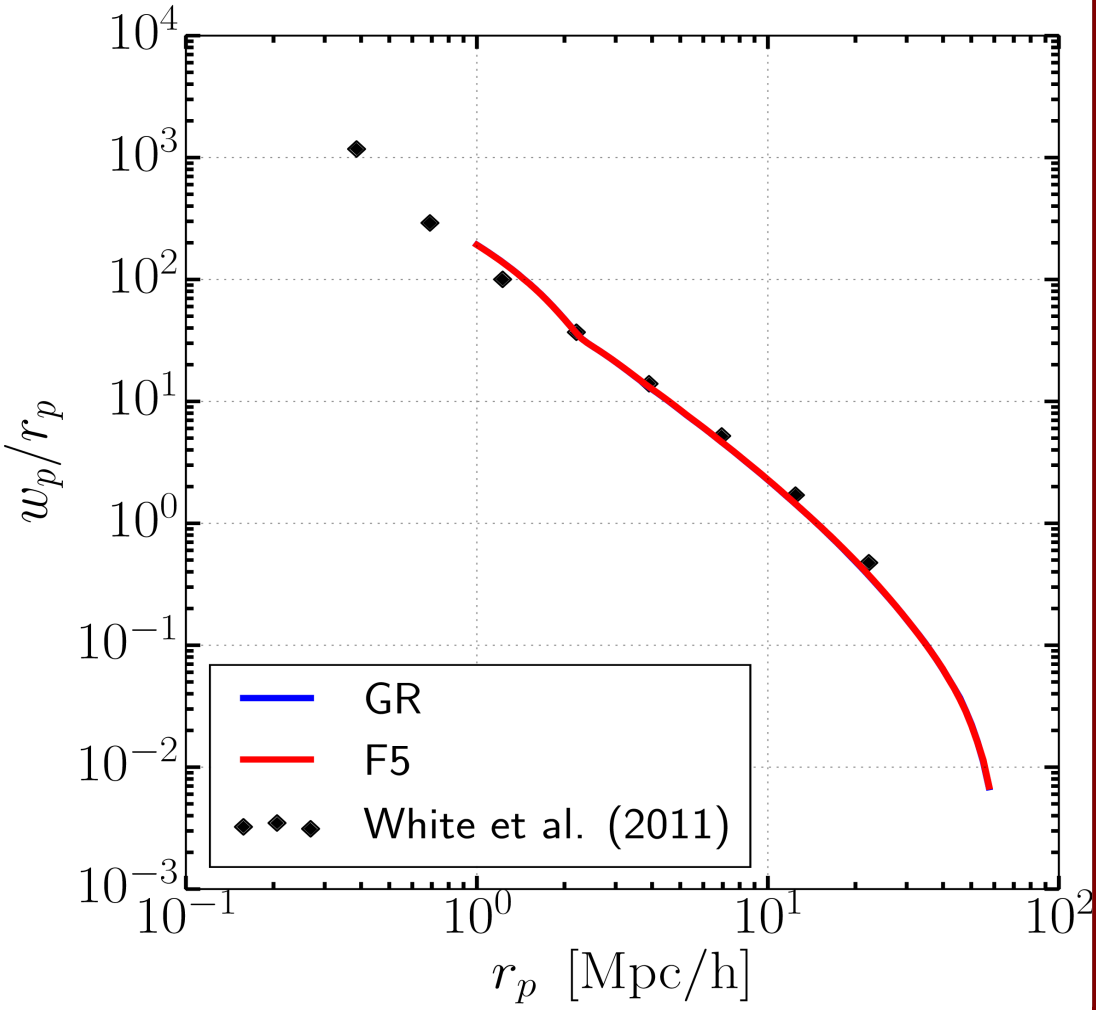
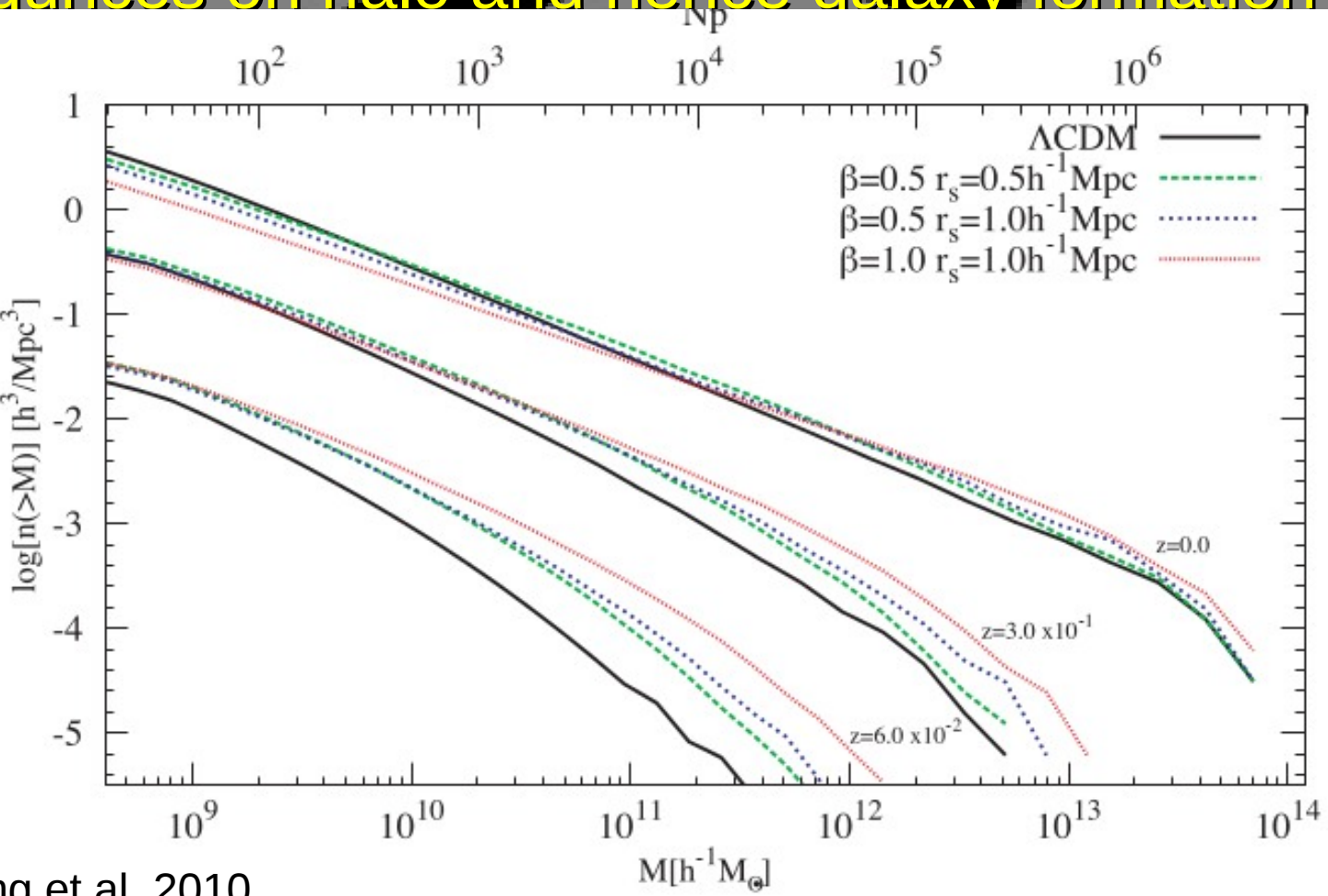


- But... modifed growth history and the non-negligible 5th force on the intergalatic scales may have profound consequnces on halo and hence galaxy formation



Hellwing et al. 2010

Figure 3. The CMFs for all haloes containing 20 and more particles calculated at redshifts $z = 6$, 3 and 0. Mass functions for redshifts $z = 6$ ($z = 3$) were scaled down by 10^{-2} (10^{-1}) for clarity.

Courtesy of Sownak Bose

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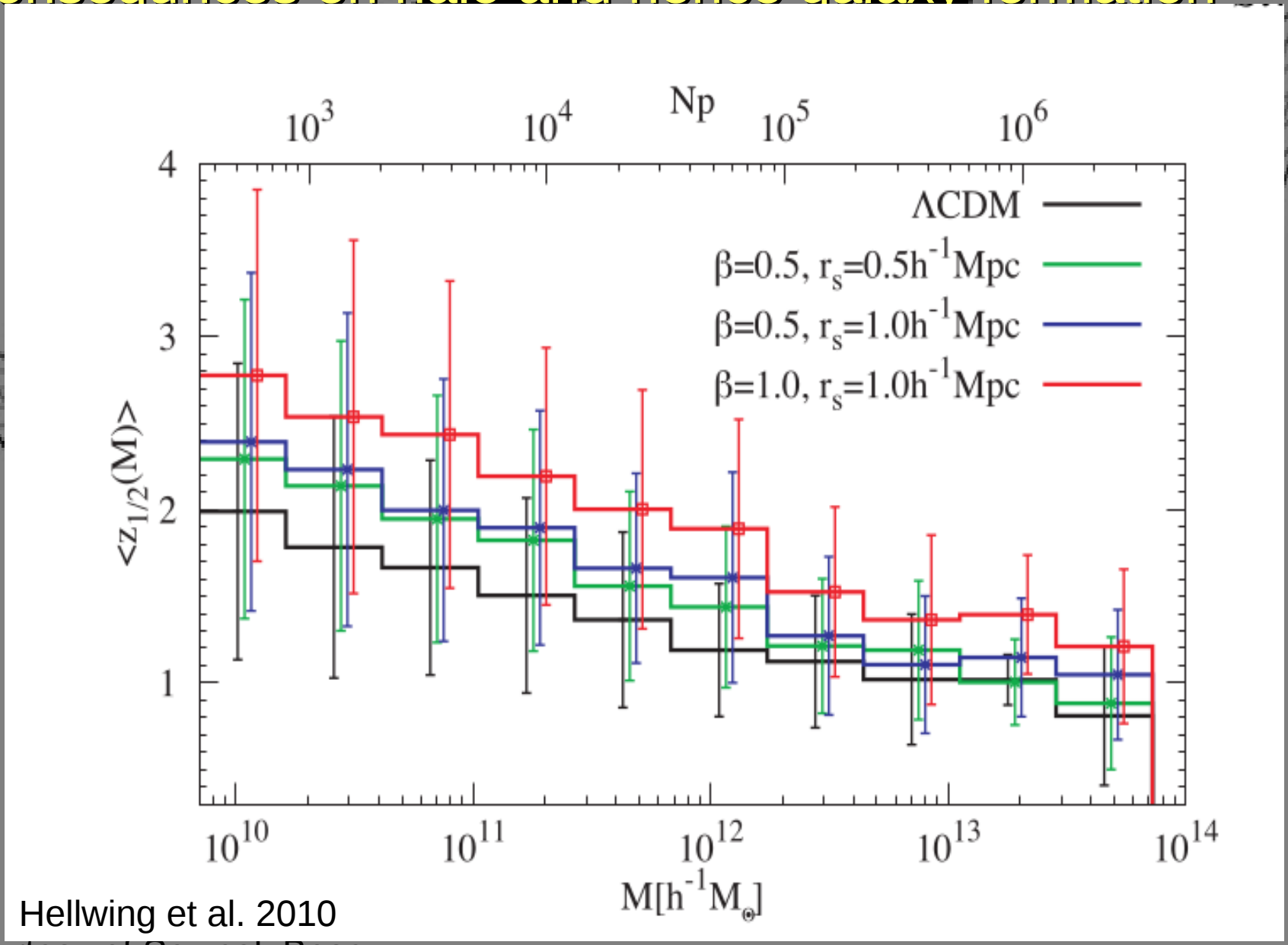

Hellwing et al. 2010

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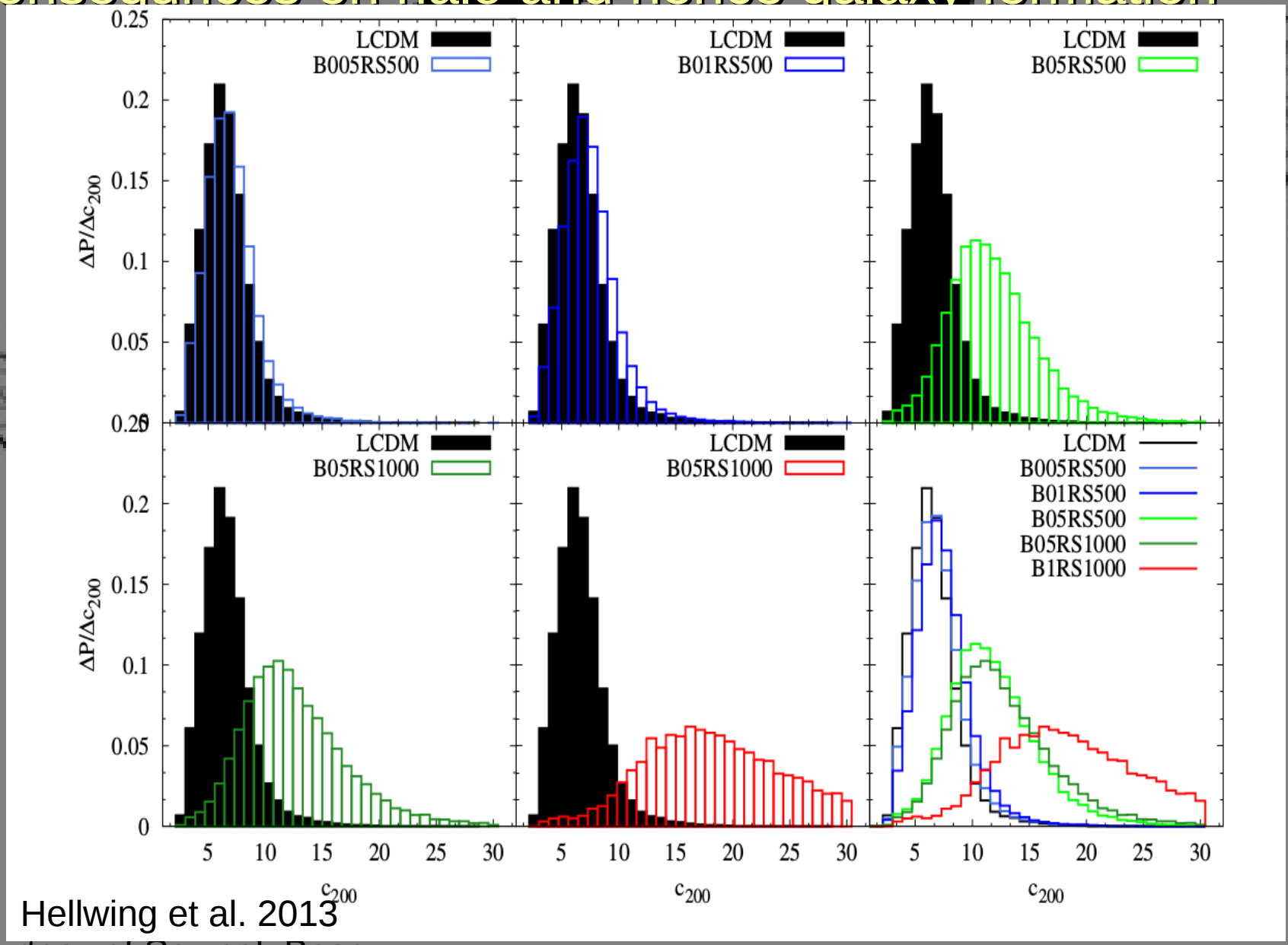


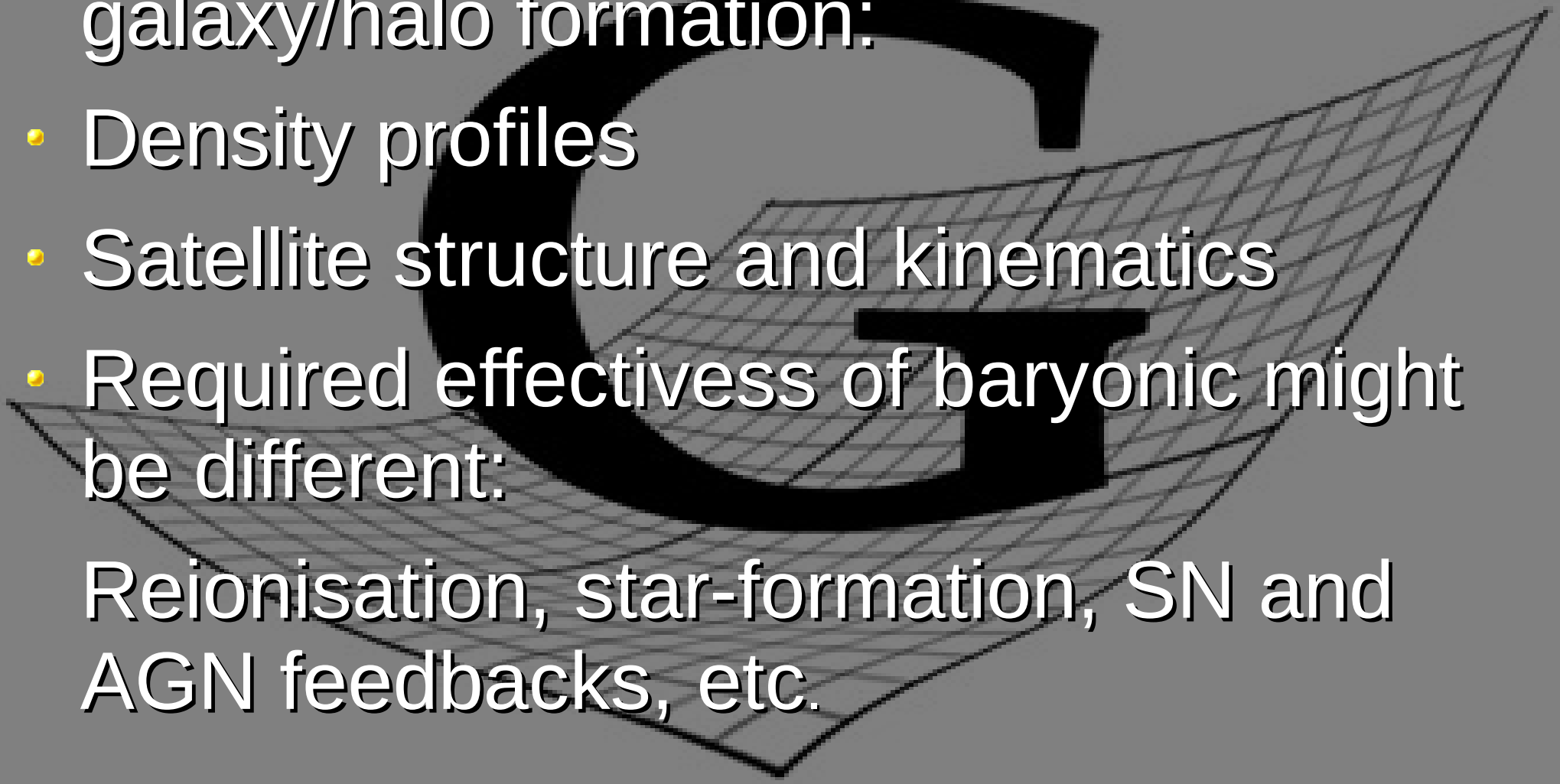
Hellwing et al. 2013

Courtesy of Sownak Bose

MG will affect many aspects of galaxy/halo formation:

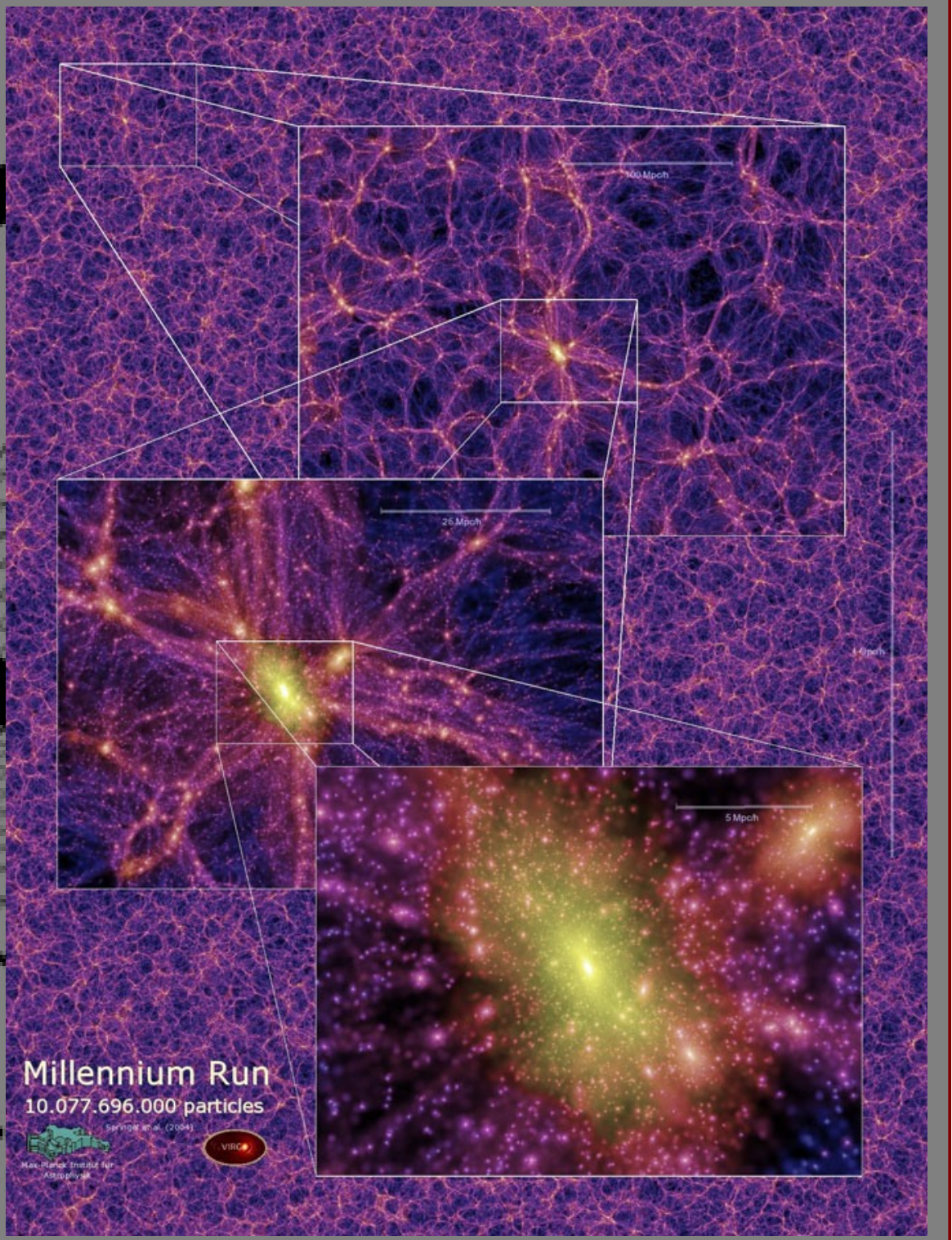
- Density profiles
- Satellite structure and kinematics
- Required effectivess of baryonic might be different:

Reionisation, star-formation, SN and AGN feedbacks, etc.



Hellwing et al. 2013
Courtesy of Sownak Bose

- A need for a new high-resolution run with at least Millennium simulation resolution
- Now it is possible thanks to Alex, Baojiu and Sownak addition to ECOSMOG/ AMR-MG algorithm that speeds-up the calculations for the nDGP model by one order of magnitude
- MG-Millennium run is now feasible!



MG-Millennium in a nut-shell:
Model: nDGP with r_cH~1 (effective linear growth rate ehanced by ~10%), Vainshtein screening (no env dep.)
Cosmology: PLANCK2015

Resolution: BOX 676.7Mpc/h N_p=2400^3, m_p~1.8x10^9Ms/h

Snapshots: ~160, 2 runs: LCDM and MG

We got 6+(2 each year) mln of CPU hours allocated on the „Ωκεανός” (supercomputer at ICM@Warsaw)

OKEANOS in the details:
26016 cores
5.333 Gb of RAM per core

YOU can use the computer as well:
hellwing@port.ac.uk