9th March 2022
Astronomy Colloquium at
上海交通大学

Relativistic signature of large-scale structure observations

~ Toward alternative test of gravity ~

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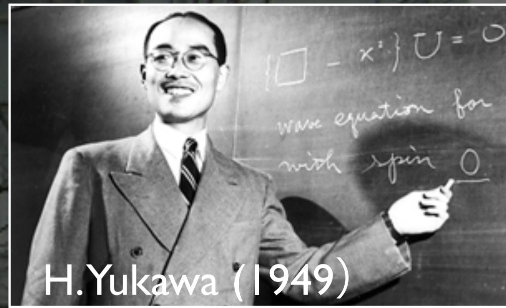
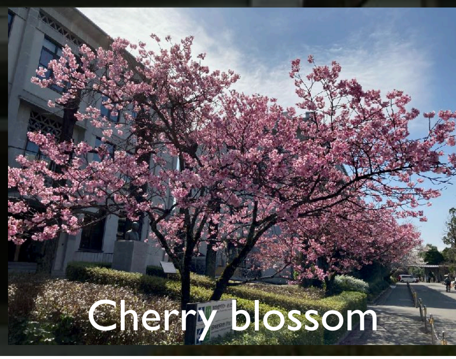
Yukawa Institute for Theoretical Physics



- Started in 1952 after Prof. H. Yukawa got Nobel physics prize
- Research institute at Kyoto University (~30 faculty members):

  High energy physics, Nuclear physics, Astrophyics & cosmology, Condensed matter physics, Quantum information physics

- Promoting workshops/conferences on various topics related to fundamental physics and hosting domestic & overseas researchers



Collaborators

Shohei Saga

(Institut d'Astrophysique de Paris)

Yann Rasera

(Observatoire de Paris)

Michel-Andrès Breton

(Institute of Space Sciences/Institut d'Estudis Espacials de Catalunya)

Outline

Relativistic distortions of observed large-scale structure as a novel cosmological signal, which will offer a new probe of gravity & cosmology

Introduction

Relativistic effects on large-scale galaxy distribution

Detectability of gravitational redshift effect and cosmological LPI test

Summary

Based on
Breton et al. arXiv:1803.04294
Saga et al. arXiv: 2004.03772, arXiv:2109.06012, arXiv:2112.07727

References

“Imprints of relativistic effects on the asymmetry of the halo cross-correlation function: from linear to non-linear scales”, M-A. Breton, Y. Rasera, AT, O. Lacombe & S. Saga, MNRAS 483, 2671 ('19), arXiv:1803.04294

“Wide-angle redshift-space distortions at quasi-linear scales: cross-correlation functions from Zel'dovich approximation”, AT, S. Saga, M-A. Breton, Y. Rasera & T. Fujita, MNRAS 491, 4162 ('20), arXiv:1908.03854

“Modelling the asymmetry of the halo cross-correlation function with relativistic effects at quasi-linear scales”, S. Saga, AT, M-A. Breton & Y. Rasera, MNRAS 498, 981 ('20), arXiv:2004.03772

“Detectability of the gravitational redshift effect from the asymmetric galaxy clustering”, S. Saga, AT & M-A. Breton, Y. Rasera, MNRAS 511, 2732 ('22), arXiv:2109.06012

“The RayGalGroupSims cosmological simulation suite for the study of relativistic effects: an application to lensing-matter clustering statistics”, M-A. Breton, Y. Rasera, P-S. Corasaniti, J. Allingham, F. Roy, V. Reverdy, T. Pellegrin, S. Saga, A. Taruya, S. Agarwal, S. Anselmi, A&A ('22, in press), arXiv:2111.08745

“Cosmological test of local position invariance from the asymmetric galaxy clustering”, S. Saga, AT & M-A. Breton, Y. Rasera, arXiv:2112.07727

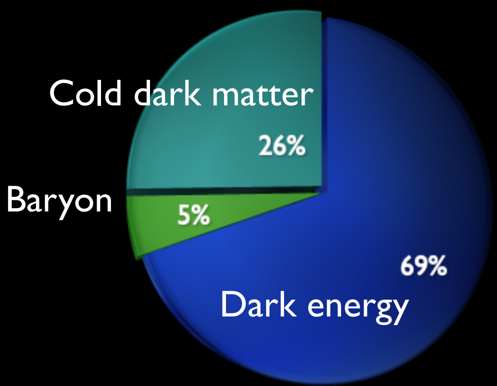
Dis/concordance cosmology

Lambda cold dark matter model

Characterized by 6 parameters

Minimal cosmological model that describes cosmic expansion and structure formation based on general relativity as underlying theory of gravity

Nevertheless, the model is not yet fully convincing:



- Mysterious components: Dark mater, Dark energy
- Untested hypothesis: General relativity, Gaussian initial condition, ...
- Tension: late-time vs early-time observations H_0, S_8, σ_8 (?)

Need further observational test !

Large-scale structure observations

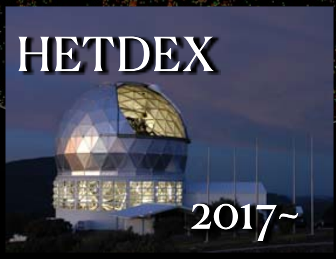
Matter inhomogeneities over ~Gpc carry carries ample cosmological information

In particular,

Angular position (***θ***) & redshift (*z*)

Mapping the 3D galaxy distribution with galaxy redshift surveys

is powerful to probe late-time universe out to z>1



Large-scale structure observations

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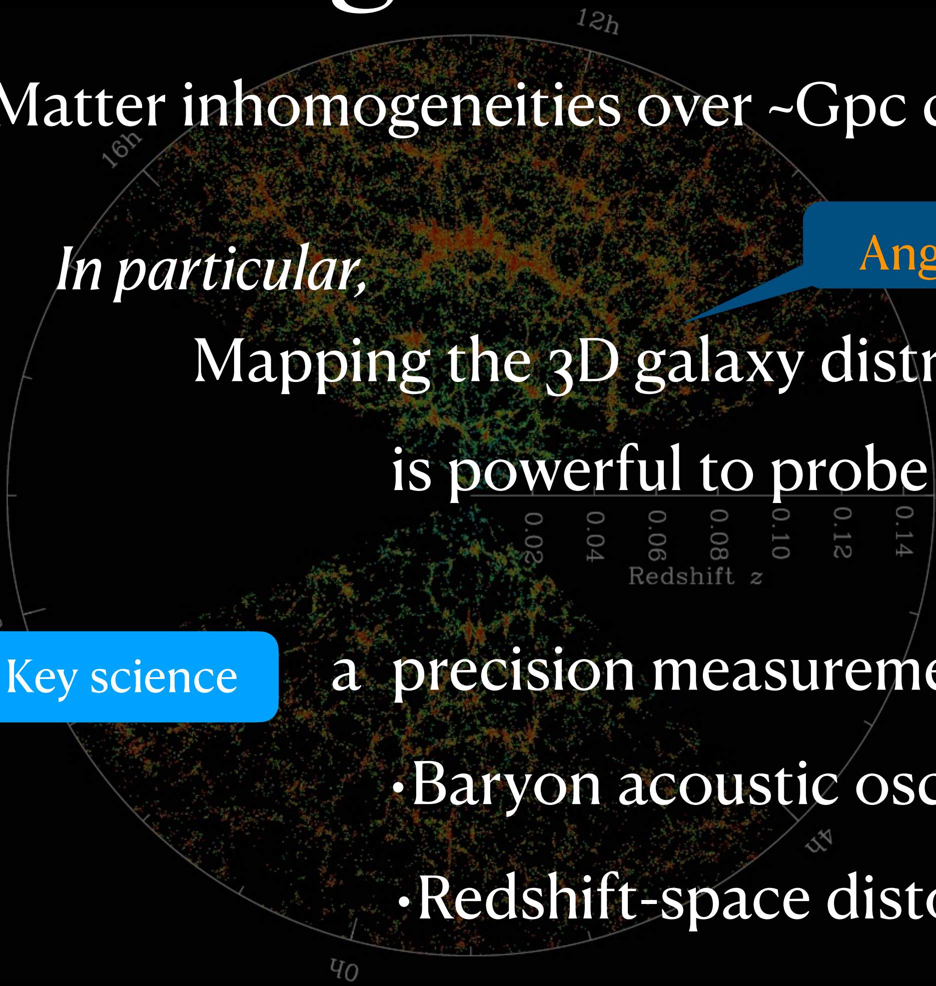


Angular position ($\boldsymbol{\theta}$) & redshift (z)

In particular,

Mapping the 3D galaxy distribution with galaxy redshift surveys

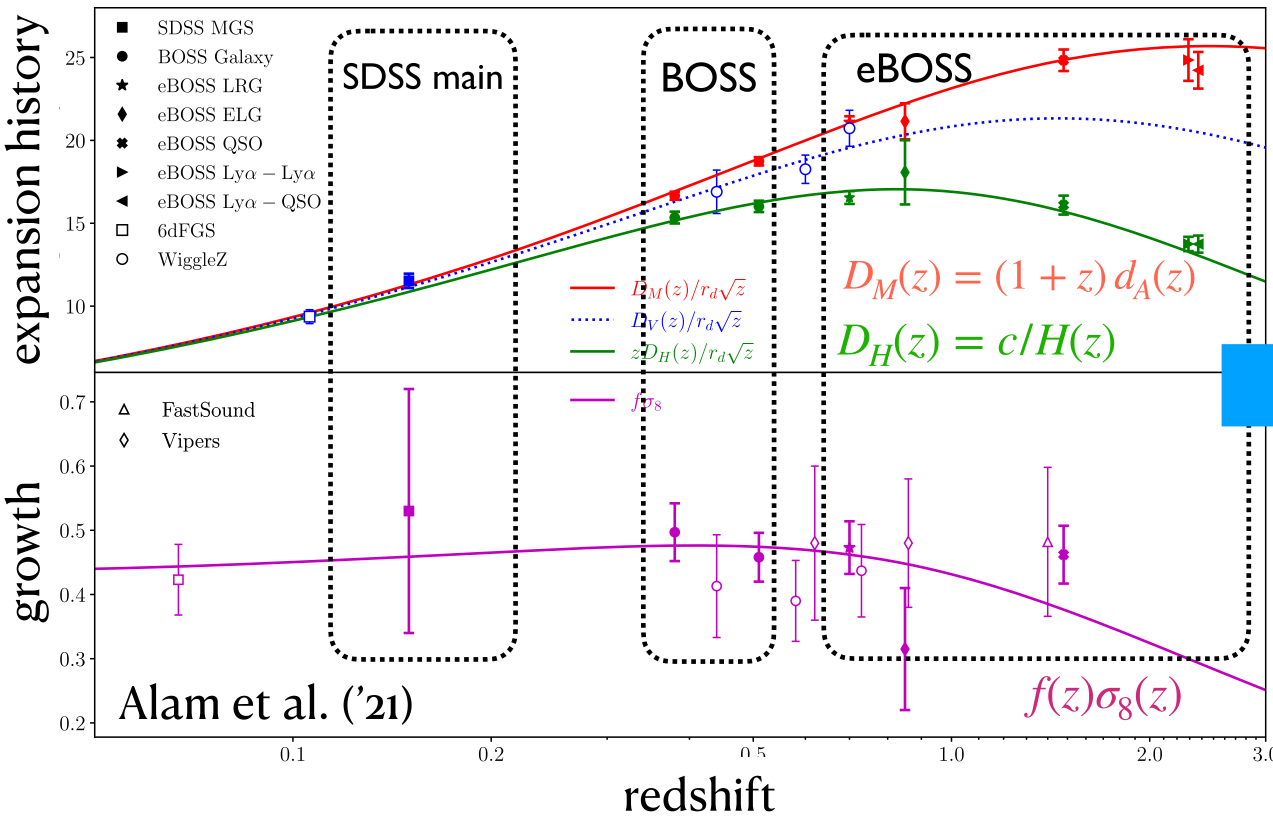
is powerful to probe late-time universe out to z>1

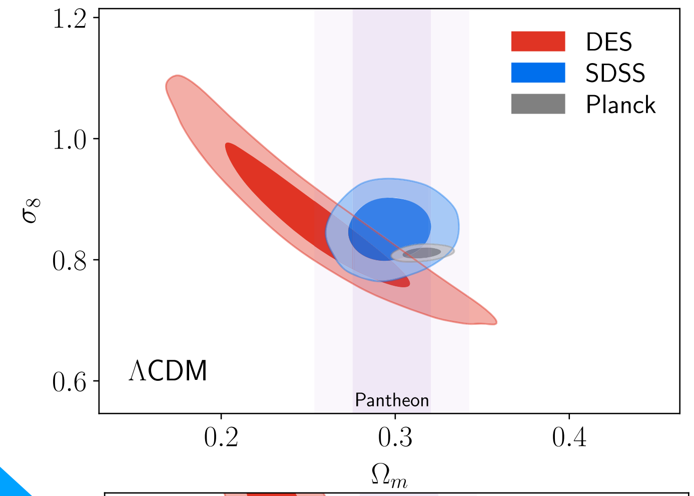
Key science

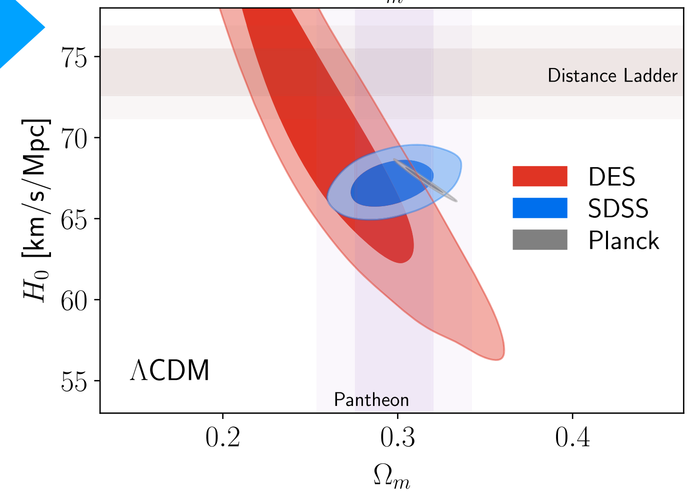
a precision measurement of

- Baryon acoustic oscillations $d_A(z)$ & $H(z)$ — Angular-diameter distance, Hubble parameter
- Redshift-space distortions $f(z)\,\sigma_8(z)$ — Growth of structure

Large-scale structure observations







Cosmology from anisotropic clustering

Both method uses *apparent* anisotropies of galaxy clustering

(Supposing that galaxy distribution is statistically homogeneous & isotropic)

These anisotropies comes not only from

Angular position & redshift — comoving position

Cosmology dependence of the conversion between $(\boldsymbol{\theta}, z) \longleftrightarrow (s_\perp, s_\parallel)$

Alcock & Paczynski ('79)

but also from the fact that

Measured redshift is not a cosmological redshift,

$\hat{x}$: line-of-sight direction

Doppler effect : $z \to z + (\mathbf{v}\cdot\hat{x})/c$

$\mathbf{v}$: Peculiar velocity of galaxy

Kaiser ('87)

Q Are there other missing effects detectable from future surveys ?
If yes, are they beneficial to constrain/test cosmology and/or gravity ?

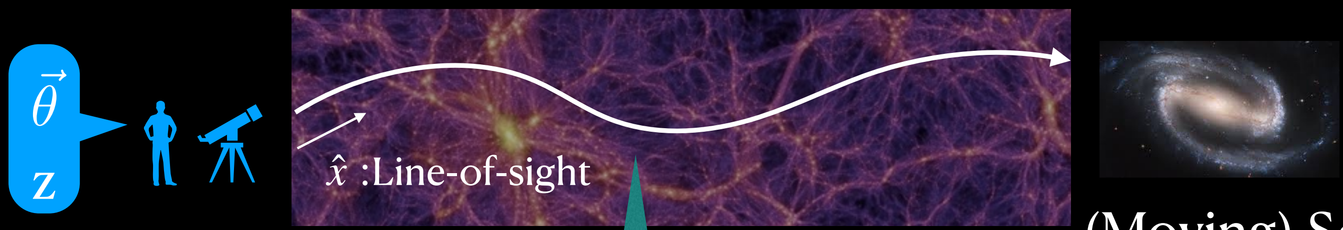
What galaxy surveys really measure ?

An improved statistical precision with gigantic galaxy survey
may open up a possibility to detect interesting signals

<u>Key point</u>

Our measurement comes from light, and the information transported by photons is altered during their path from the source to the observer

Angular position
redshift



Observer

(Moving) Source

Light path cannot be straight in the presence of matter distribution and receive relativistic corrections (e.g., *gravitational redshifts & lensing*)

Light propagation in an inhomogeneous universe

Formalism

Consider the photon path in the perturbed Friedmann universe:

Flat universe assumed

$$ds^2 = \left[-(1+2\Psi/c^2)(c\,dt)^2 + a^2(t)(1+2\Phi/c^2)\delta_{ij}dx^i dx^j\right]$$

Newton potential   Curvature potential

Solving photon's geodesic equation from source to observer

in the weak-field limit $(\Psi/c^2, \Phi/c^2 \ll 1)$

Null geodesic : $\frac{dk^a}{d\lambda} + \Gamma^a_{bc}k^b k^c = 0$ $k^a k_a = 0$ $k^a = \frac{dx^a}{d\lambda}$

Affine parameter

Redshift : $1 + z = \frac{(k_a u^a)_\mathrm{S}}{(k_a u^a)_\mathrm{O}}$ u^a Observer/source's 4-velocity

Generalized redshift space

Observed galaxy (comoving) position, $\vec{s}$:

e.g., Sasaki ('87), Pyne & Birkinshaw ('04), Yoo et al. ('09), Yoo ('10), Challinor & Lewis ('11), Bonvin & Durrer ('11), ...

$$\vec{s} = \vec{x} + \hat{x}\left\{\frac{c}{H}\,\delta z - \frac{1}{c^2}\int_0^{\chi(z_{\rm obs})} d\chi'(\psi-\phi)\right\} - \chi(z_{\rm obs})\,\vec{\alpha}$$

Shapiro time-delay

$\hat{x}$: line-of-sight direction

χ: comoving distance

Sky position

Distortion of photon path by gravitational lensing

deflection angle

$$\vec{\theta}_{\rm obs} = \vec{\theta}_{\rm source} - \vec{\alpha}\,; \qquad \vec{\alpha} = -\frac{1}{c^2}\int_0^{\chi(z_{\rm obs})} d\chi'\,\frac{\chi(z_{\rm obs})-\chi'}{\chi(z_{\rm obs})}\,\nabla_\perp(\Psi-\Phi)$$

Energy shift of photon by special & general relativistic effects

$$z = z_{\rm obs} - \delta z\,;$$

$$\delta z = (1+z_{\rm obs})\left\{\frac{\vec{\rm v}_{\rm s}\cdot\hat{x}}{c} - \frac{\psi_{\rm s}}{c^2} + \frac{1}{2}\frac{{\rm v}_{\rm s}^2}{c^2} - \frac{1}{c^2}\int_{t_{\rm s}}^{t_{\rm o}} dt'(\dot{\psi}-\dot{\phi})\right\}$$

Redshift

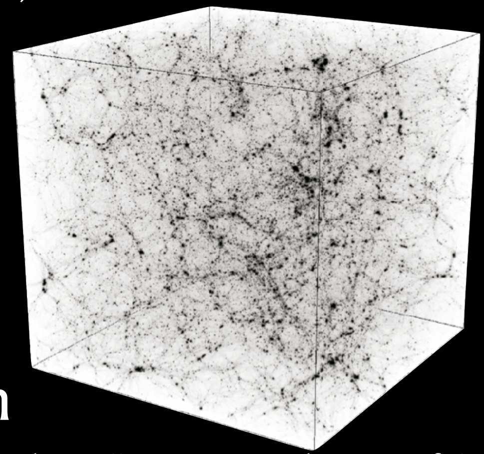
(For rest-frame observer)

Standard RSD (Doppler) | Gravitational redshift | Transverse Doppler | Integrated Sachs-Wolfe

Simulating relativistic RSD: *RayGalGroupSims*

M-A. Breton, Y. Rasera, AT, O. Lacombe & S. Saga ('19)
Y. Rasera, M-A. Breton, et al. ('21)

Using standard N-body code (RAMSES)



http://www.projet-horizon.fr/

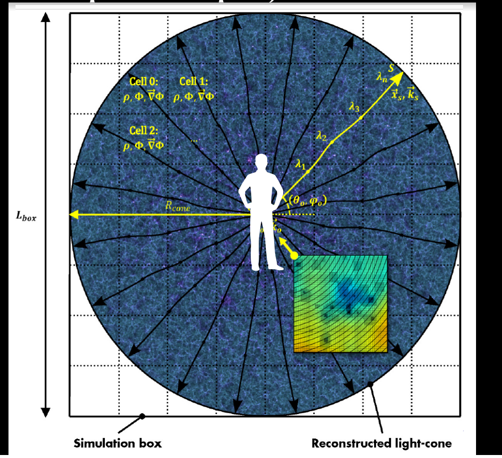
Dark matter/halo distributions at many redshifts

- Storing potential data on light cone
- Tracing back the light ray to the source by direct integration of geodesic equation (assuming $\Phi = -\Psi$)

→ distorted angular position & redshift: $$1+z = \frac{(g_{\mu\nu}k^\mu u^\nu)_\mathrm{s}}{(g_{\mu\nu}k^\mu u^\nu)_\mathrm{o}}$$

Weak lensing, RSD, ISW, transverse Doppler, gravitational redshift, Shapiro time-delay, ...

k^μ :null 4-vector u^μ :observer's or source's 4-vector



Simulating relativistic RSD: *RayGalGroupSims*

https://cosmo.obspm.fr/public-datasets/raygalgroupsims-relativistic-halo-catalogs/

RayGalGroupSims Relativistic Halo Catalogs and Light-Cone Data

The RayGalGroupSims suite consists of a set of N-body simulations of different cosmological models, which have been specifically designed to generate high resolution halo catalogs in redshift-space (light-cone) taking into account for all observable relativistic effects to first order in the weak field approximation.

To date we have realised two runs for LCDM and wCDM scenarios with parameters set to the WMAP-7 best-fit cosmological model (and within the Planck 2-sigma level contours). The simulations cover a $(2625\ \mathrm{Mpc/h})^3$ volume with $N_p=4096^3$ particles (the mass resolution is about $1.88 \cdot 10^{10}\ M_{sun}/h$ in LCDM and $2.01 \cdot 10^{10}$ in wCDM).

Full-sky light-cone data in the redshift range z ~ [0,0.5] are generated during the simulation run without the use of replica.

We also produce narrow light-cones: 1) an intermediate light-cone in the redshift range z ~ [0, 2] with a rotation of ϕ = 25 deg and θ = 25 deg, with a 50 x 50 deg² f.o.v; 2) a deep light-cone in the redshift range z ~ [0, 10] with a rotation of ϕ = 17 deg and θ = 25 deg, with a 20 x 20 deg² f.o.v

<u>RAMSES</u>   ΛCDM & wCDM (w=-1.2)

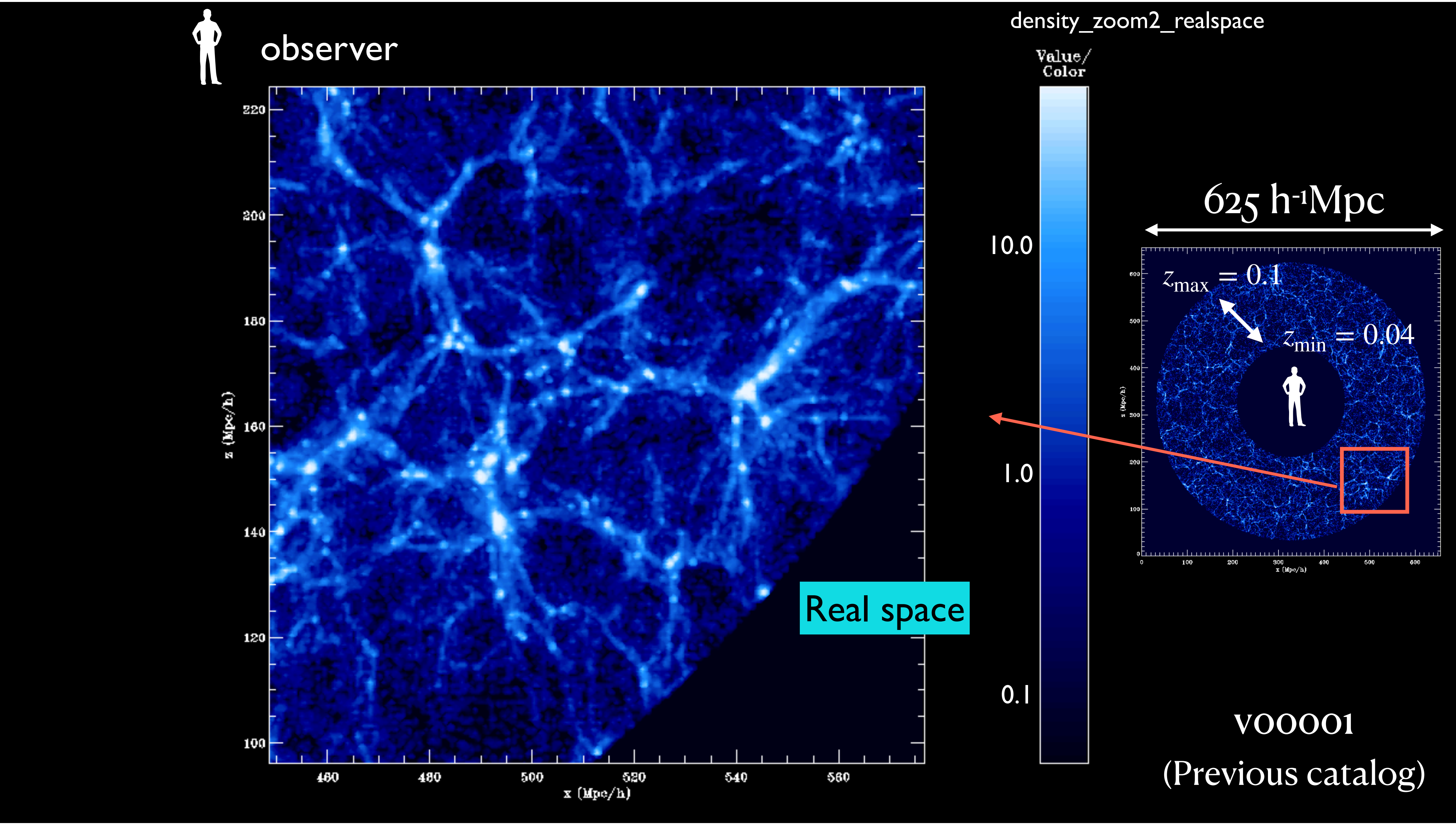
$$L_{\rm box} = 2{,}625\, h^{-1}\,\mathrm{Mpc}$$

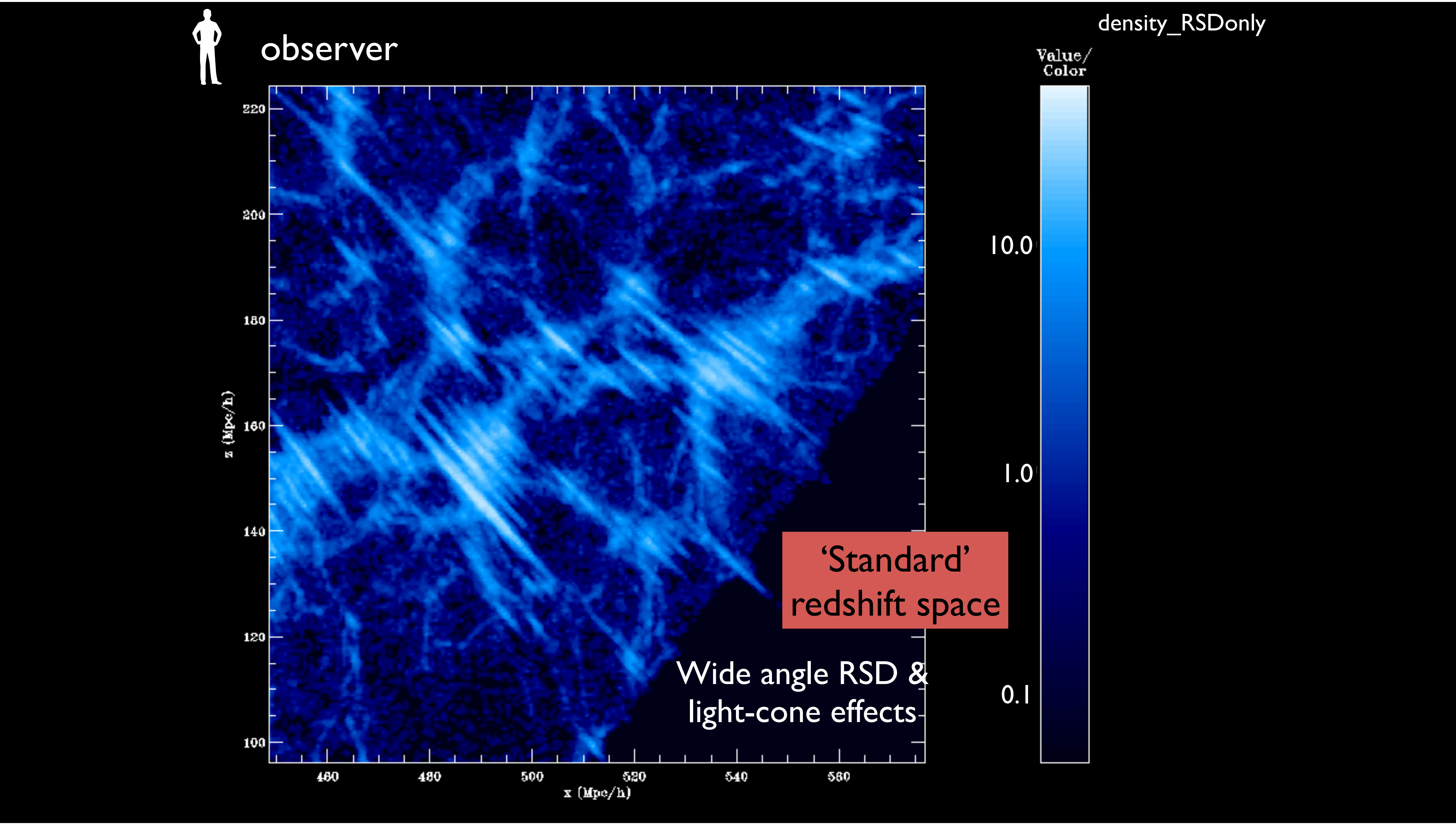
$$N_{\rm particle} = 4{,}096^3\ \ (m_{\rm DM} \simeq 2 \times 10^{10}\, h^{-1}\,\mathrm{M}_{\odot})$$

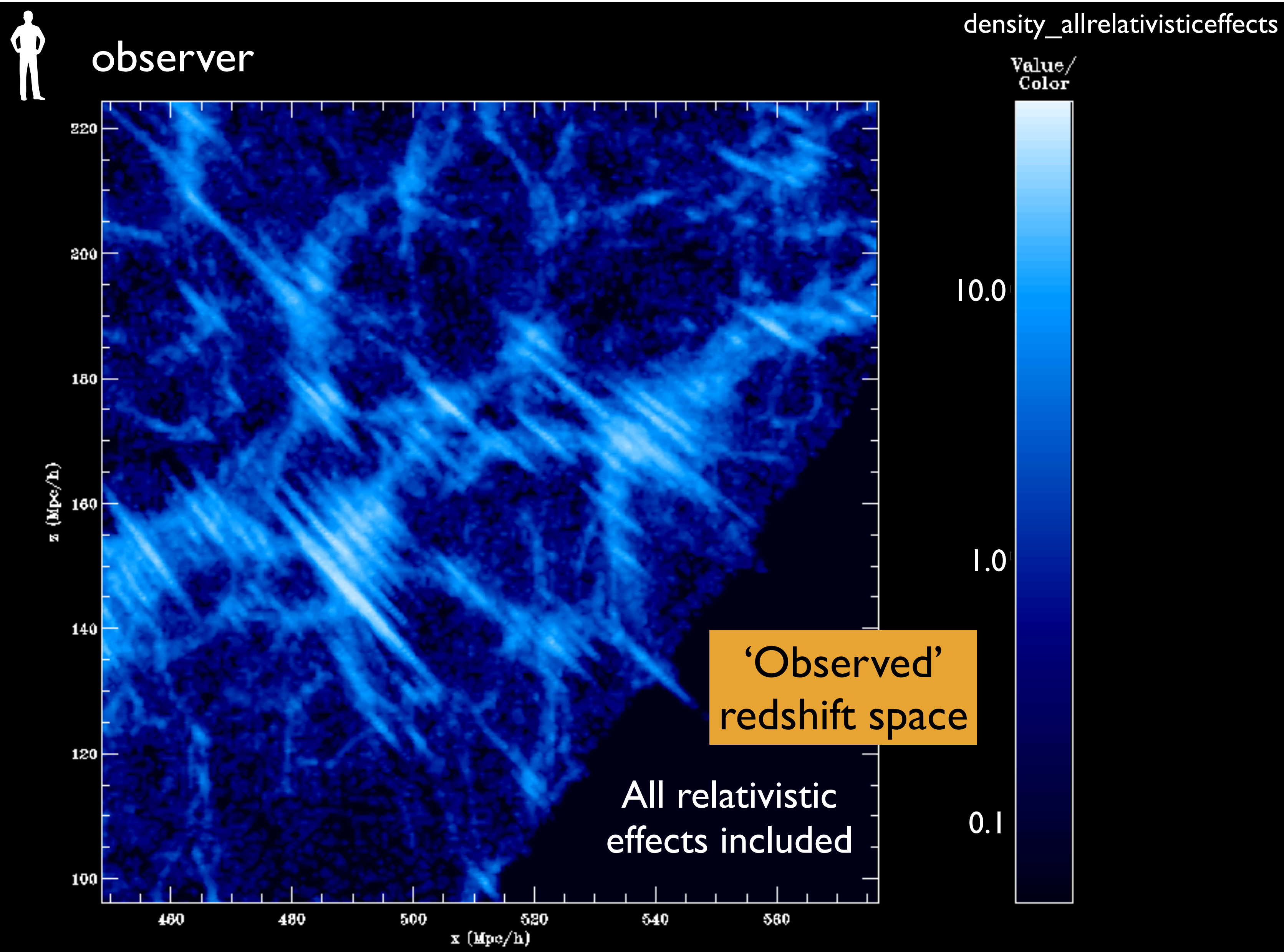
- Narrow light cone, 2500 deg^2 (z<2.0)
- Full-sky light cone, 41,253 deg^2 (z<0.5)

Each catalog contains

$\sim 1.3 \times 10^7$ halos, $\sim 2 \times 10^8$ DM particles (subsample)


observer
density_zoom2_realspace
Value/
Color
10.0
1.0
0.1
625 h-1Mpc
z_{max} = 0.1
z_{min} = 0.04
Real space
z (Mpc/h)
x (Mpc/h)
220
200
180
160
140
120
100
460
480
500
520
540
560
v00001
(Previous catalog)

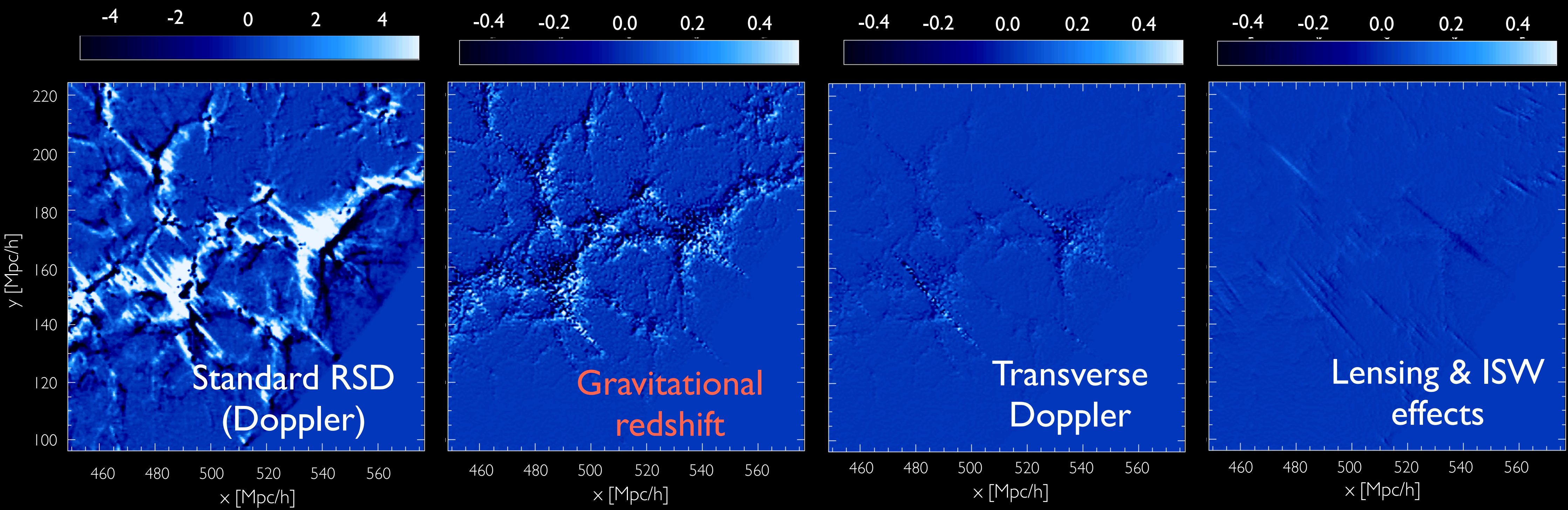

observer
density_RSDonly
Value/ Color
10.0
1.0
0.1
'Standard' redshift space
Wide angle RSD & light-cone effects
z (Mpc/h)
x (Mpc/h)
220
200
180
160
140
120
100
460
480
500
520
540
560



observer
density_allrelativisticeffects
Value/
Color
10.0
1.0
0.1
220
200
180
160
140
120
100
z (Mpc/h)
460
480
500
520
540
560
x (Mpc/h)
'Observed'
redshift space
All relativistic
effects included

Difference maps

Real-space density subtracted



While the Doppler effect gives the largest impact on observed density fields, we still see non-negligible contributions from *gravitational redshift (GRS) effect*

Q How can we detect it from galaxy surveys ?

Detecting gravitational redshift from galaxies

Consider static galaxies at cosmological distance

Observed redshift

$$z_{\rm obs} \equiv \frac{\Delta\lambda}{\lambda_0} \simeq z_{\rm true} - (1+z_{\rm true})\frac{\Phi_{\rm gal}}{c^2} > z_{\rm true}$$

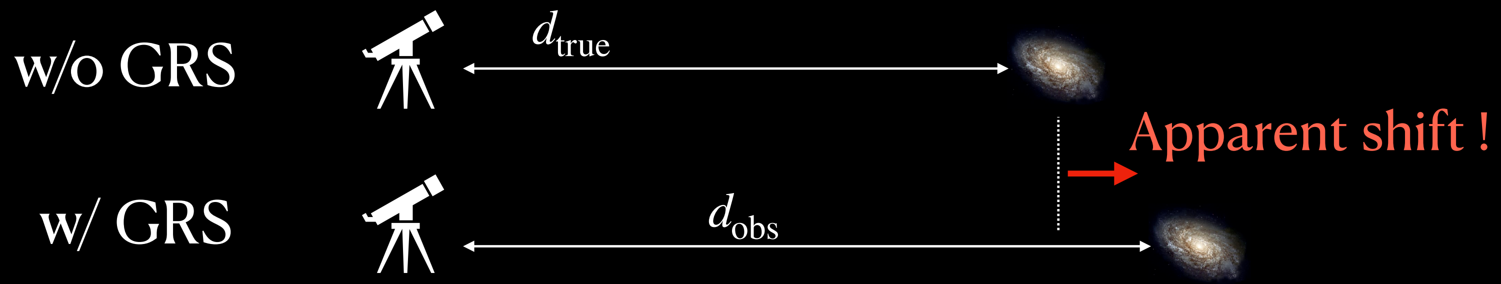
gravitational potential

$\frac{\Phi_{\rm gal}}{c^2} \approx -10^{-5}$

Cosmological redshift

Gravitational redshift (GRS)

Hubble-Lemaître law : $c\,z = H\,d$



However,

we cannot distinguish between cosmological & gravitational redshifts (GRS)

Detecting gravitational redshift from galaxies

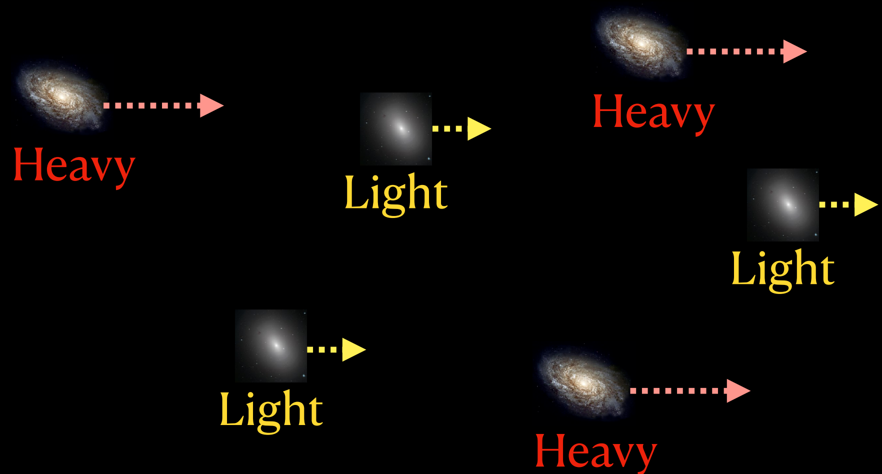
Consider static galaxies at cosmological distance

Suppose there are two galaxy populations

heavy (light) galaxies receive a larger (smaller) GRS correction

Using Hubble-Lemaître law

$$c\, z_{\rm obs} = H\, d_{\rm obs}$$



True galaxy position

Detecting gravitational redshift from galaxies

Consider static galaxies at cosmological distance

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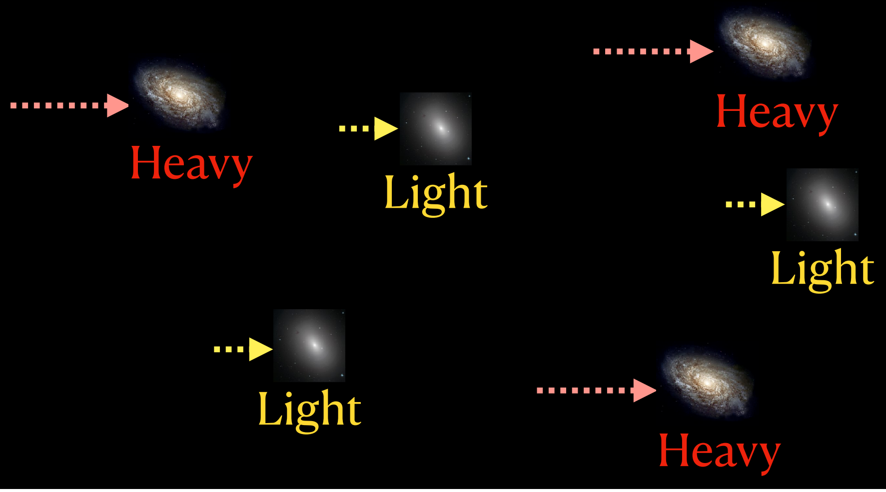
Observed galaxy position



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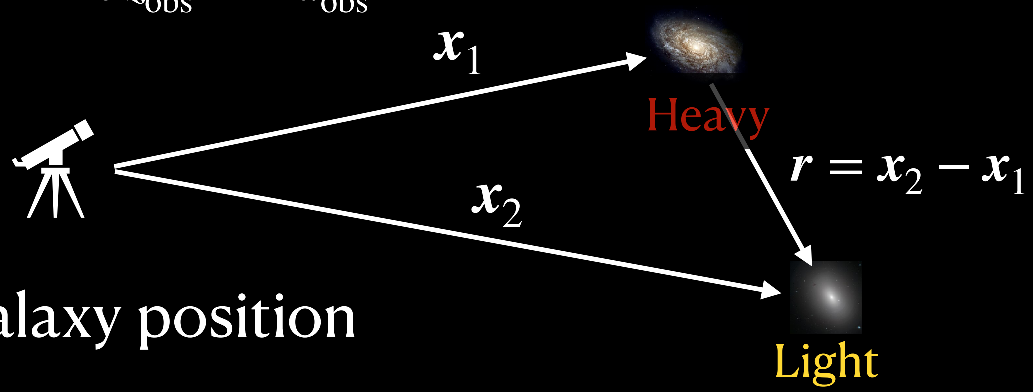


Observed galaxy position

Cross correlation between heavy & light galaxies

$$\xi(\boldsymbol{x}_1, \boldsymbol{x}_2) = \langle \delta_{\rm heavy}(\boldsymbol{x}_1)\delta_{\rm light}(\boldsymbol{x}_2)\rangle$$

Usually, this is a function of $|\boldsymbol{r}| = |\boldsymbol{x}_2 - \boldsymbol{x}_1|$

Detecting gravitational redshift from galaxies

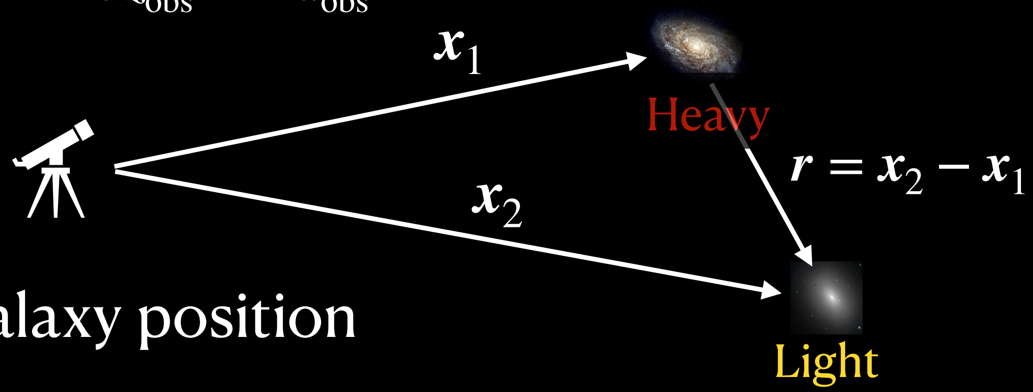
GRS effect can break *statistical homogeneity*:

$$\xi(r) \longrightarrow \left\{1 - \frac{1+z}{H}\frac{\Delta\Phi}{c^2}(\hat{d}\cdot\nabla_r)\right\}\xi(r)\,; \qquad \Delta\Phi = \Phi_{\rm heavy} - \Phi_{\rm light} < 0$$

directional dependence : $\boldsymbol{d} \equiv (\boldsymbol{x}_1 + \boldsymbol{x}_2)/2$

Using Hubble-Lemaître law

$$c\,z_{\rm obs} = H\,d_{\rm obs}$$



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directional dependence : $\boldsymbol{d} \equiv (\boldsymbol{x}_1 + \boldsymbol{x}_2)/2$

$\mu \equiv \hat{d}\cdot\hat{r}$

Dipole moment

$$\xi_{\rm dipole}(r) \equiv \frac{3}{2}\int_{-1}^{1} d\mu\,\mu\;\xi(\boldsymbol{x}_1,\boldsymbol{x}_2) \;\simeq\; \xi^{\rm sys}_{\rm dipole}(r) - \frac{1+z}{H(z)}\frac{\Delta\Phi}{c^2}\frac{\partial\xi(r)}{\partial r}$$

Negative (in our definition)

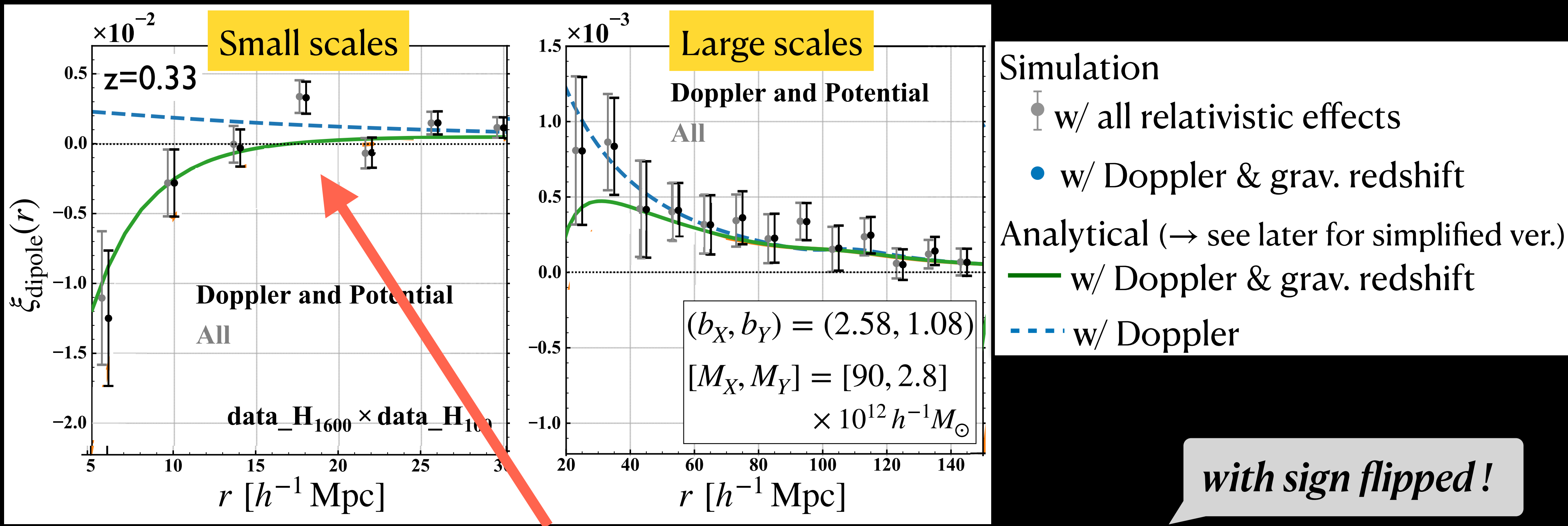
Q Can we measure the *relativistic* dipole ?

c.f. Bonvin et al. ('14)

Relativistic dipoles from simulated halos

S. Saga, AT, M-A. Breton & Y. Rasera, arXiv:2004.03772

Doppler & gravitational redshift effects are the most dominant relativistic effects



At small scales (<30 h^{-1}Mpc), gravitational redshift effect starts to be dominant

Analytic model predictions (linear theory + halo model) agree well with simulation

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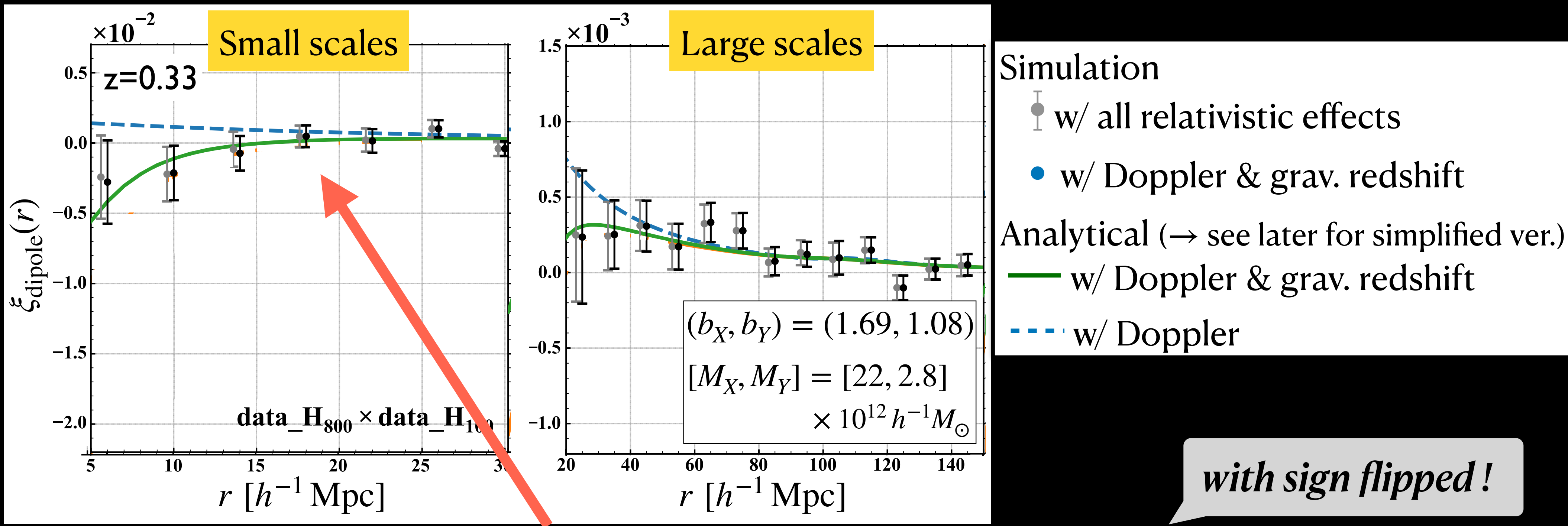


At small scales (<30 h^{-1}Mpc), gravitational redshift effect starts to be dominant

Analytic model predictions (linear theory + halo model) agree well with simulation

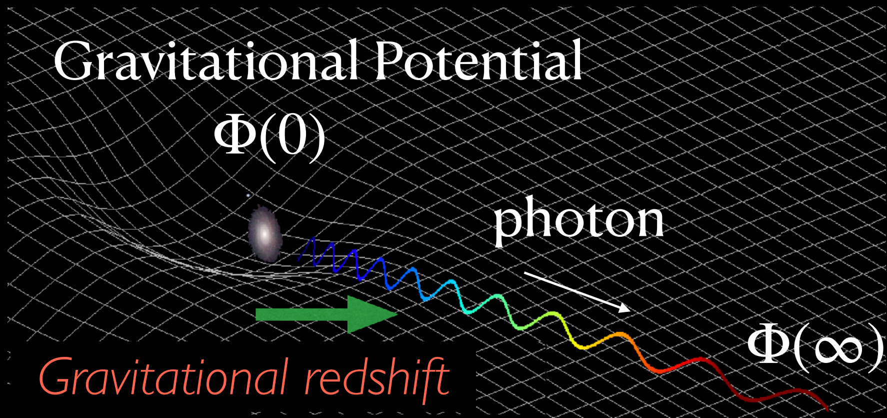
Detecting gravitational redshift effect

Detection & measurement of the gravitational redshift effect is very interesting and offers a unique test of gravity

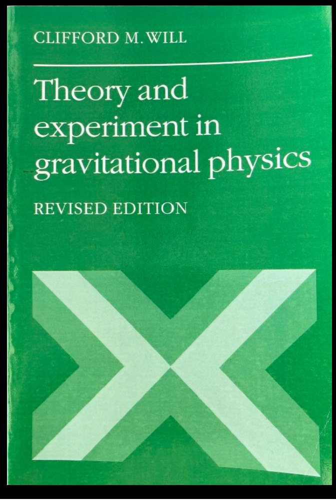
Frequency shift

$$\frac{\Delta\nu}{\nu_0} = \frac{\Delta\Phi}{c^2}$$

$$\Delta\Phi \equiv \Phi(0) - \Phi(\infty) < 0$$



C. Will ('81)



The effect has been predicted even before general relativity as a simple consequence of Einstein equivalence principle

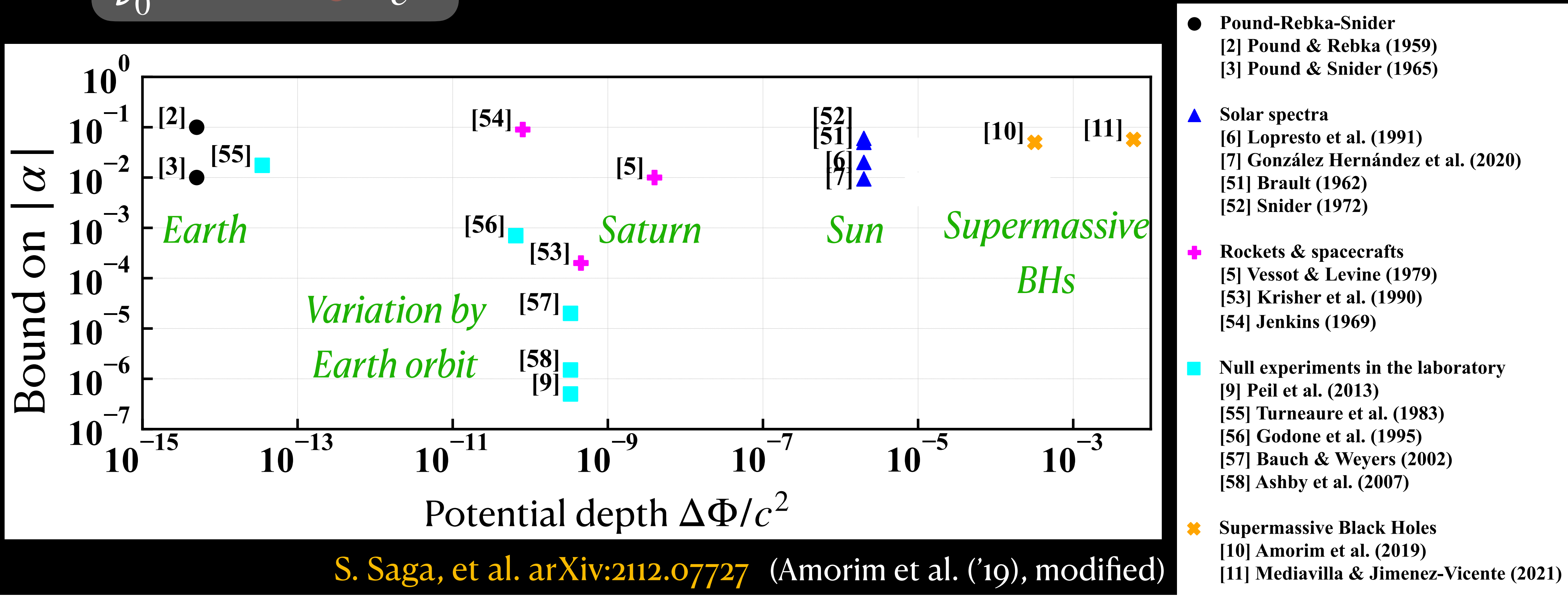
(=local position invariance)

Space-time independence on the outcomes of local experiments

Detecting gravitational redshift effect

$$\frac{\Delta\nu}{\nu_0} = (1 + \alpha)\frac{\Delta\Phi}{c^2}$$

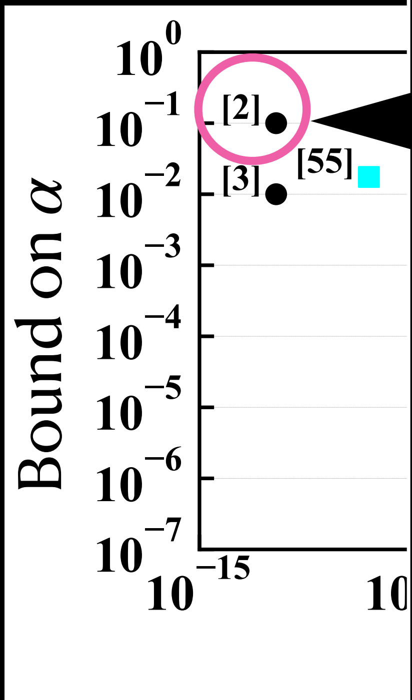
$\alpha \neq 0 \rightarrow$ violation of local position invariance (LPI)



S. Saga, et al. arXiv:2112.07727 (Amorim et al. ('19), modified)

Detecting gravitational redshift effect

$$\frac{\Delta\nu}{\nu_0} = (1 -$$



Pound-Rebka experiment

Pound & Rebka, PRL4, 337 ('60)

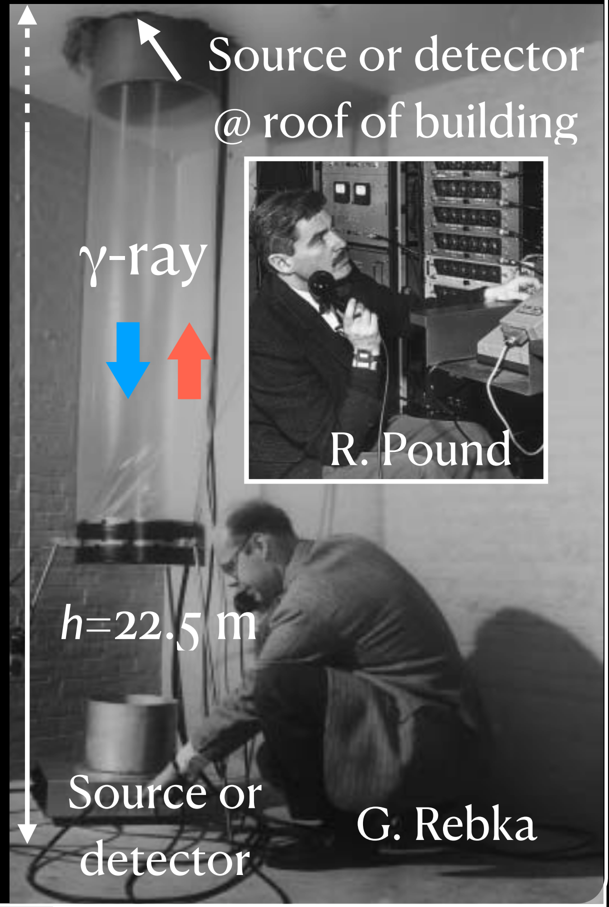
1st laboratory experiment of gravitational red-/*blue-shifts* caused by the Earth gravity

Making use of *Mössbauer* effect,

They measured frequency shift of ^{57}Fe γ-ray launching upward/downward:

$$\left.\frac{\Delta\nu}{\nu_0}\right|_{\rm red} - \left.\frac{\Delta\nu}{\nu_0}\right|_{\rm blue} = -2\frac{gh}{c^2} \simeq -4.92 \times 10^{-15}$$

Pound, Phys. Perspect. 2 ('00) 224 →



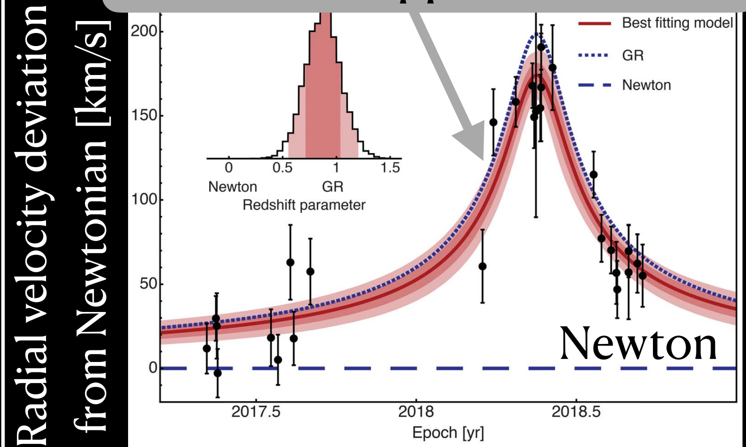
Detecting gravitational redshift effect

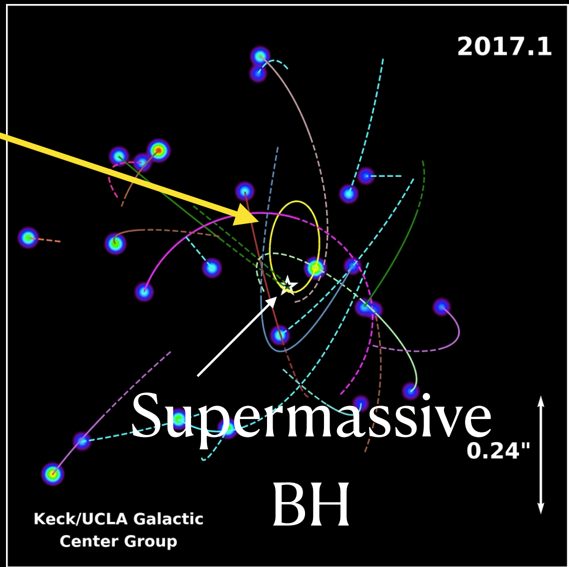
Galactic Center experiment

near the supermassive black hole

Do, Hees, Ghez et al. Science 365, 664 ('19)
Amorim, et al. Phys.Rev.Lett. 122, 101102 ('19)

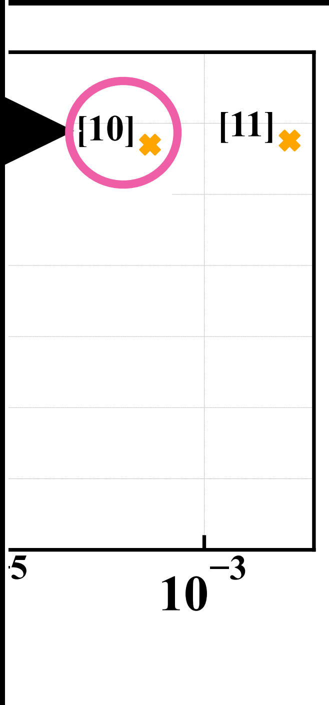
Gravitational redshift + transverse Doppler of So-2 star





http://www.astro.ucla.edu/~ghezgroup/gc/animations.html

local position invariance (LPI)



al. ('19), modified

- Pound-Rebka-Snider
  [2] Pound & Rebka (1959)
  [3] Pound & Snider (1965)
- Solar spectra
  [6] Lopresto et al. (1991)
  [7] González Hernández et al. (2020)
  [51] Brault (1962)
  [52] Snider (1972)
- Rockets & spacecrafts
  [5] Vessot & Levine (1979)
  [53] Krisher et al. (1990)
  [54] Jenkins (1969)
- Null experiments in the laboratory
  [9] Peil et al. (2013)
  [55] Turneaure et al. (1983)
  [56] Godone et al. (1995)
  [57] Bauch & Weyers (2002)
  [58] Ashby et al. (2007)
- Supermassive Black Holes
  [10] Amorim et al. (2019)
  [11] Mediavilla & Jimenez-Vicente (2021)

dshift effect

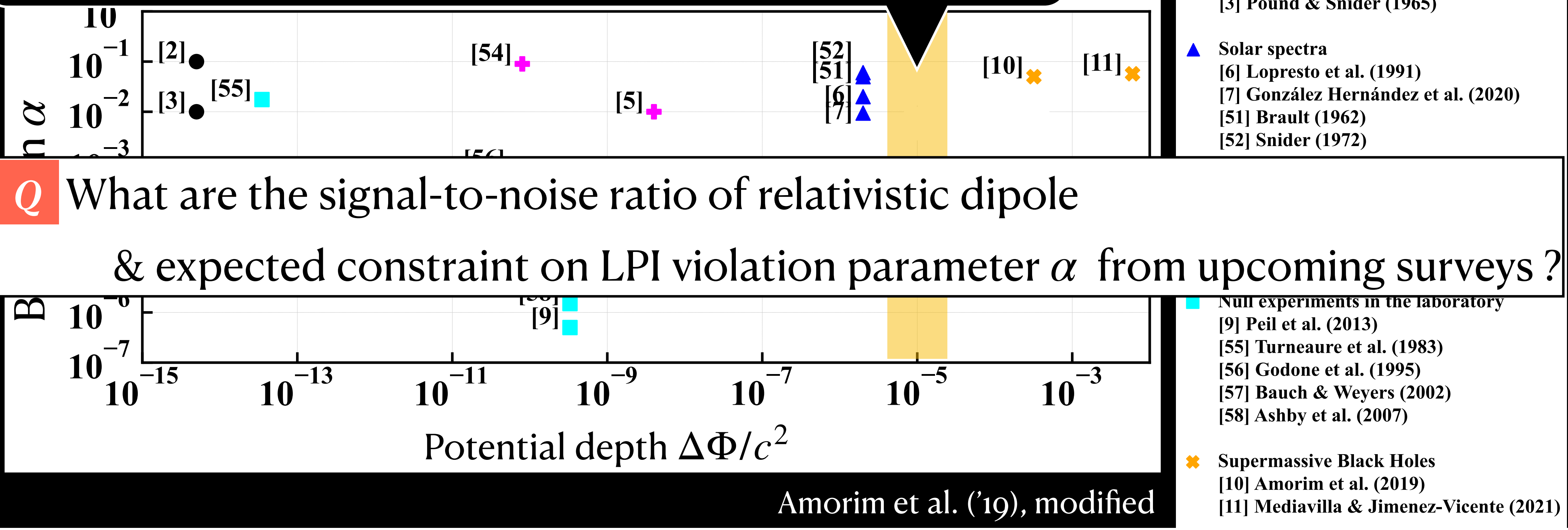
osition invariance (LPI)

New

Relativistic dipole experiment

from the *asymmetric* galaxy clustering can probe

- potential depth $\Delta\Phi \sim 10^{-5}$
- distant universe of $z \gtrsim 0.1$
- scales (separation) of $r \sim 5 - 10\,h^{-1}$ Mpc



Amorim et al. ('19), modified

Q What are the signal-to-noise ratio of relativistic dipole

& expected constraint on LPI violation parameter α from upcoming surveys ?

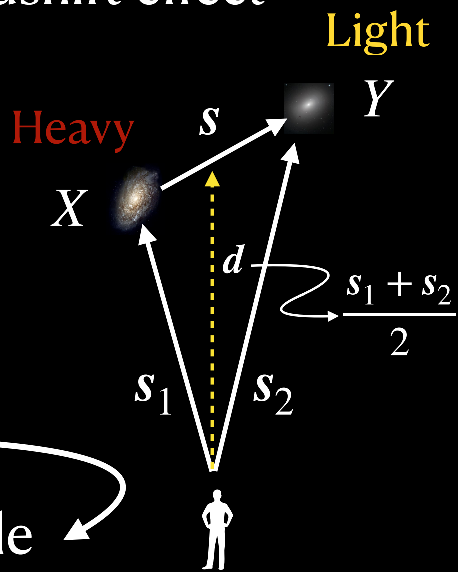
Modeling & forecasting relativistic dipole

S. Saga, AT & M-A. Breton, Y. Rasera, arXiv:2109.06012 & arXiv:2112.07727

Analytical model of *dipole* cross correlation with
- (wide-angle) Doppler effect
- gravitational redshift effect

$$\xi_{\mathrm{XY},1}(s,d) = 2f\,\Delta b\,\frac{s}{d}\left(\Xi_1^{(1)} - \frac{1}{5}\Xi_2^{(0)}\right) + \frac{1}{saH}\Delta\phi\left(b_{\mathrm{X}}b_{\mathrm{Y}} + \frac{3}{5}(b_{\mathrm{X}}+b_{\mathrm{Y}})f + \frac{3}{7}f^2\right)\Xi_1^{(-1)}$$

$$\Xi_\ell^{(n)}(s) \equiv \int \frac{k^2\,\mathrm{d}k}{2\pi^2}\frac{j_\ell(ks)}{(ks)^n}P_{\mathrm{L}}(k)$$



Assuming that observed galaxies reside at the center of halos,

- $b_{\mathrm{X}}, b_{\mathrm{Y}}, \&\ \Delta b \equiv b_{\mathrm{X}} - b_{\mathrm{Y}}$: Linear bias determined by halo mass
- $\Delta\phi \equiv \Phi_{\mathrm{X}} - \Phi_{\mathrm{Y}}$: potential at halo center described by NFW profile

Signal-to-noise ratio

$$\left(\frac{\mathrm{S}}{\mathrm{N}}\right)^2 \equiv \sum_{s,s'=s_{\min}}^{s_{\max}} \xi_{\mathrm{XY},1}(s)\,\mathrm{COV}^{-1}(s,s')\,\xi_{\mathrm{XY},1}(s')$$

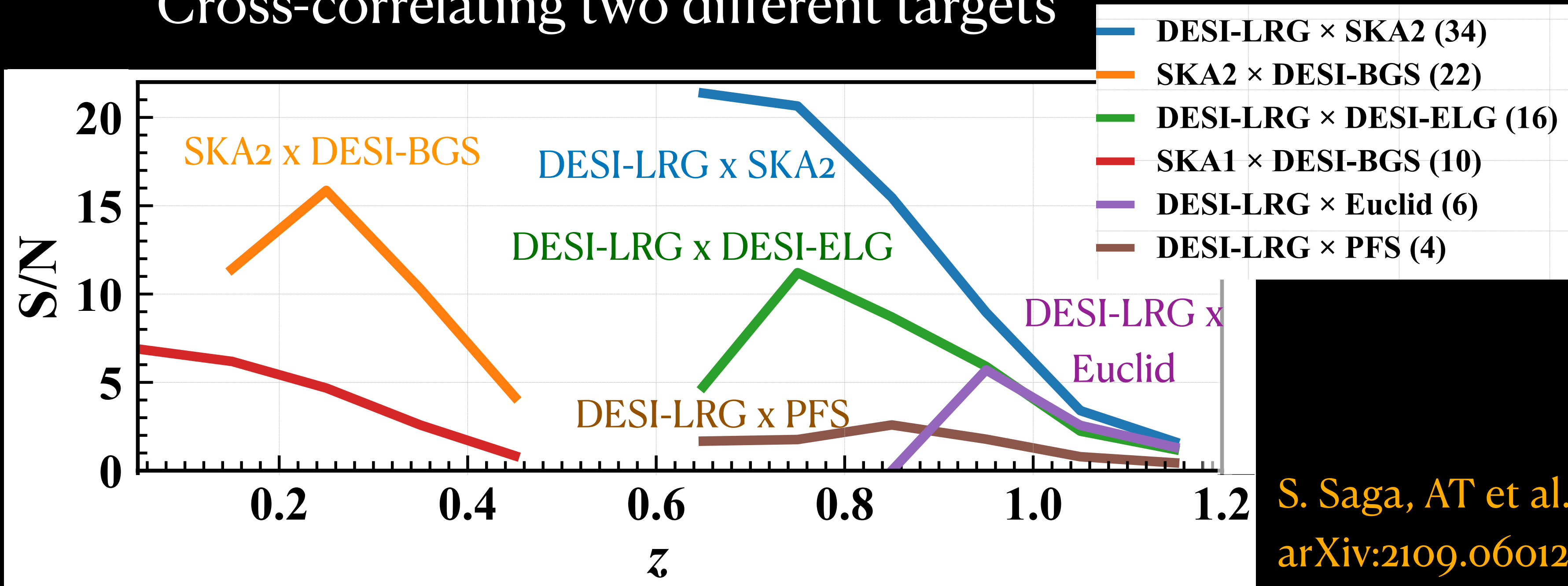
Fisher matrix

$\mathrm{COV}(s,s')$: Gaussian covariance

$$F_{n,ij} = \sum_{s_1,s_2=s_{\min}}^{s_{\max}} \frac{\partial\xi_{\mathrm{XY},1}(s_1,z_n)}{\partial\theta_i}\mathrm{COV}^{-1}(s_1,s_2,z_n)\frac{\partial\xi_{\mathrm{XY},1}(s_2,z_n)}{\partial\theta_j}$$

Signal-to-noise ratio from upcoming surveys

Cross-correlating two different targets



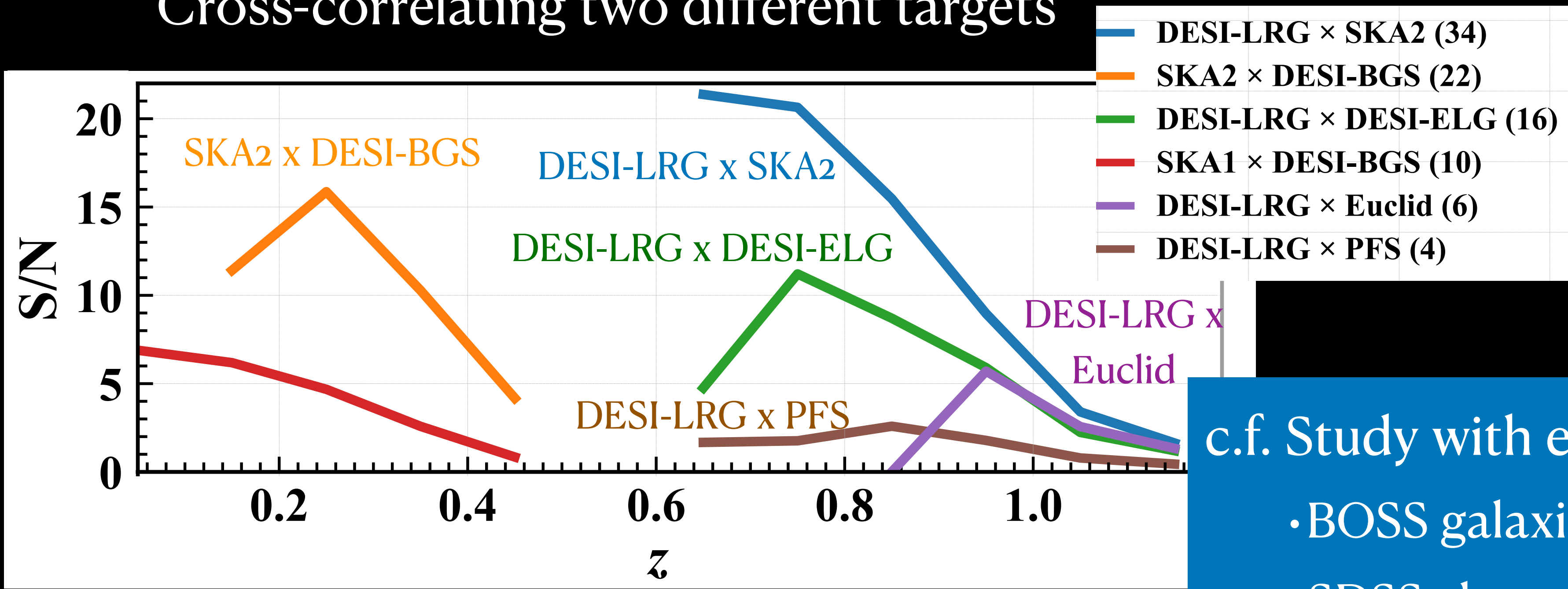
S. Saga, AT et al., arXiv:2109.06012

DESI x SKA2 is an idealistic setup, producing total S/N of ~34 (22) for LRG (BGS)

Combining DESI-LRG, Euclid & PFS will also achieve a solid detection of S/N~4–6

Signal-to-noise ratio from upcoming surveys

Cross-correlating two different targets



DESI x SKA2 is an idealistic setup, producing total

Combining DESI-LRG,

Euclid & PFS will also achieve a solid detection

c.f. Study with existing data

- BOSS galaxies: Alam et al. ('17)
- SDSS clusters:
  Wojtak et al. ('11); Sadeh et al. ('15); Jimeno et al. ('15)

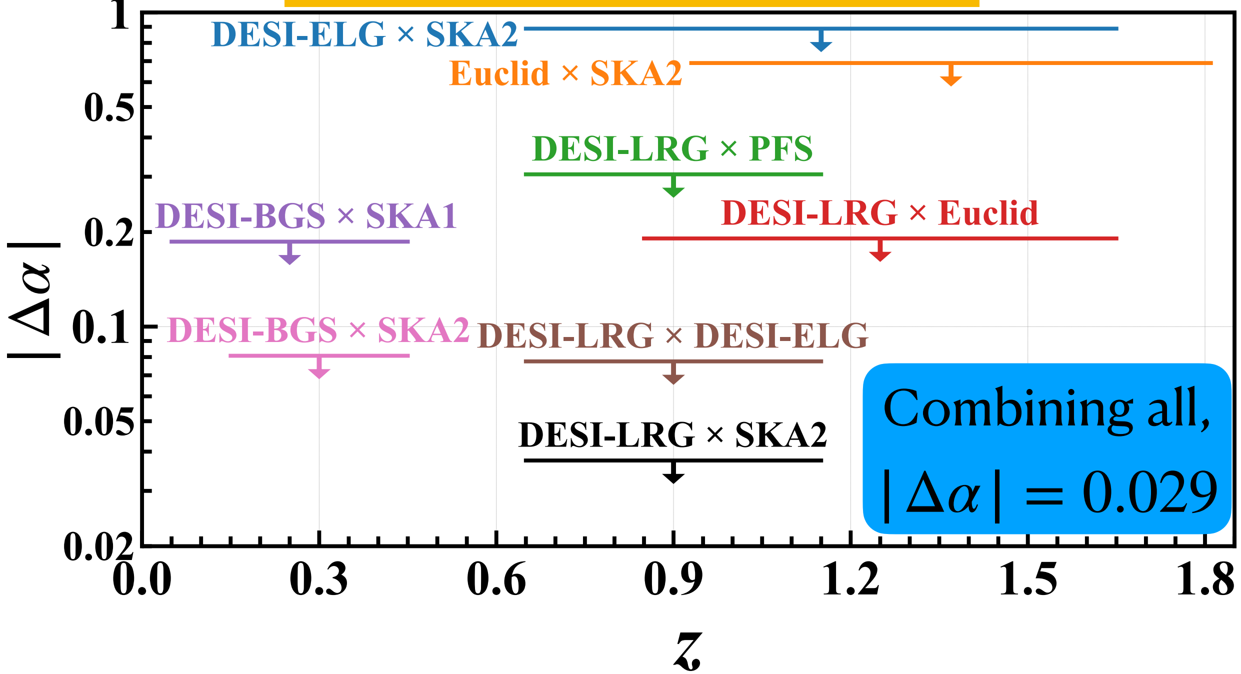
→ $< 3\sigma$ detection

Constraining LPI-violation parameter, α

S. Saga, AT et al., arXiv:2112.07727

$$z_{\rm grav} = (1 + \alpha)\frac{\Delta\Phi}{c^2}$$ ($\alpha = 0$ if LPI holds)

Results of Fisher forecast



1. Effect of off-centered galaxies:
   - Diminution of potential depth
   - Transverse Doppler effect

   →New parameters controlling this effect for each sample
2. Bias parameters, $b_{\rm X,Y}(M_{\rm X,Y})$: Prior from BAO/RSD observations

On top of the LPI-violation parameter, We have 4 parameters in each z-slice ($b_{\rm X/Y}$, $R_{\rm off,X/Y}$)

Summary

Relativistic effects on observed large-scale structure will be detected/measured and can be used for a fundamental test of gravity on cosmological scales

Simulating observed relativistic effects on large-scale structure, *RayGalGroupSims*

→Relativistic halo catalog arising from light propagation in an inhomogeneous universe

On top of the Doppler effect,

gravitational redshift is found to be the 2nd major relativistic effect on the observed galaxy distribution

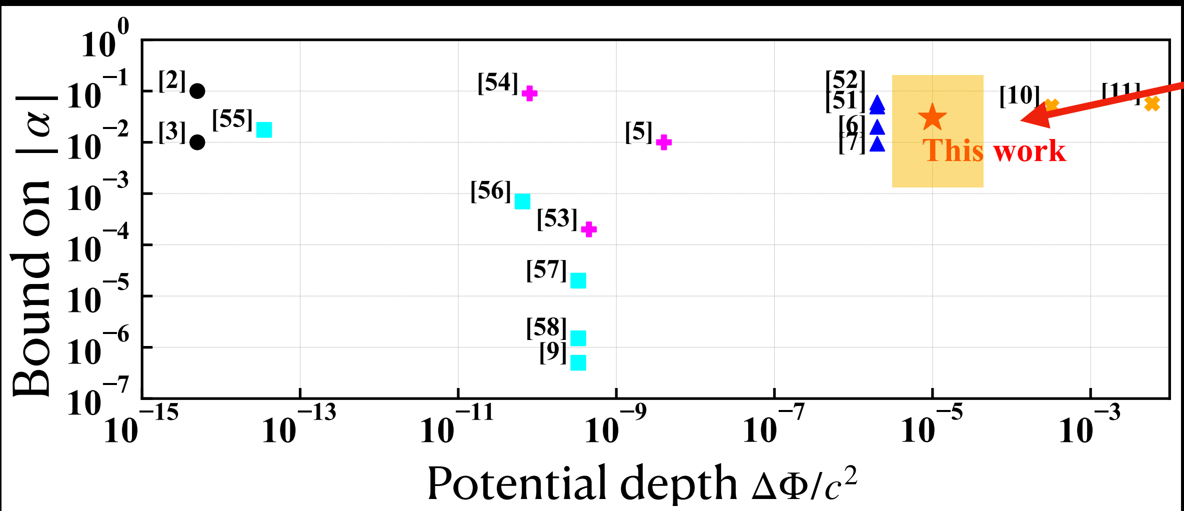
- Cross-correlating two different galaxy samples yields non-vanishing dipole (*relativistic dipole*)
- Upcoming surveys will detect such a dipole at high statistical significance (S/N>10) → test of local position invariance (LPI)

Summary

Relativistic effects on observed large-scale structure will be detected/measured and can be used for a fundamental test of gravity on cosmological scales

under the standard cosmological model

LPI-violation parameter, α, will be better constrained to $|\Delta\alpha| \lesssim \mathcal{O}(10^{-2})$



<u>To-do list</u>

- A more practical study with mock galaxy catalog
- An optimal way to measure dipole signals

Other fundamental tests of gravity is possible & deserve further investigation !!