13th January 2021
YITP lunch seminar

Gravitational redshift effect on large-scale structure

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Abstract

Gravitational redshift (GRS) is the phenomenon that a photon loses its energy when traveling up through a gravitational potential, hence causing the wavelength of the photon to increase (redder). GRS is a simple consequence of the equivalence principle, also predicted by general theory of gravity, and has been tested by both laboratory experiments and observations. In this talk, we consider the GRS effect on cosmological scales. Making use of the fact that the GRS effect can break statistical isotropy, we show that the GRS effect on large-scale galaxy distribution is detectable with high statistical significance via upcoming galaxy surveys, thus serving as a fundamental test of gravity in cosmology.

Plan of talk

Gravitational redshift effects on the observed large-scale structure via upcoming galaxy surveys

Gravitational Red-Shift (GRS) effect

GRS effect on large-scale galaxy distribution

Summary

Refs. Breton, Rasera, AT, Lacombe & Saga, MNRAS 483, 2671 ('19)
AT, Saga, Breton, Rasera & Fujita, MNRAS 491, 4162 ('20)
Saga, AT, Breton & Rasera, MNRAS 498, 981 ('20)
Saga, AT & Rasera (in prep.)

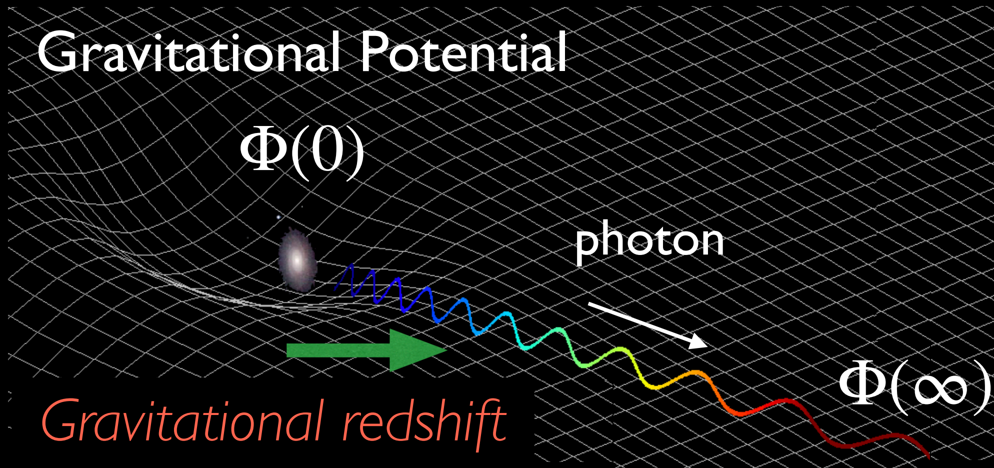
Gravitational redshift (GRS) effect

Energy loss of photon when it travels up through gravitational potential well ⟶ shift of frequency to *decrease*

(c.f. Doppler shift)

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

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



GRS has been predicted even before general relativity as a simple consequence of equivalence principle

Observing GRS is an important classical test of general relativity

Pound-Rebka experiment

Pound & Rebka, PRL4, 337 ('60)

1st Laboratory experiment in 1959

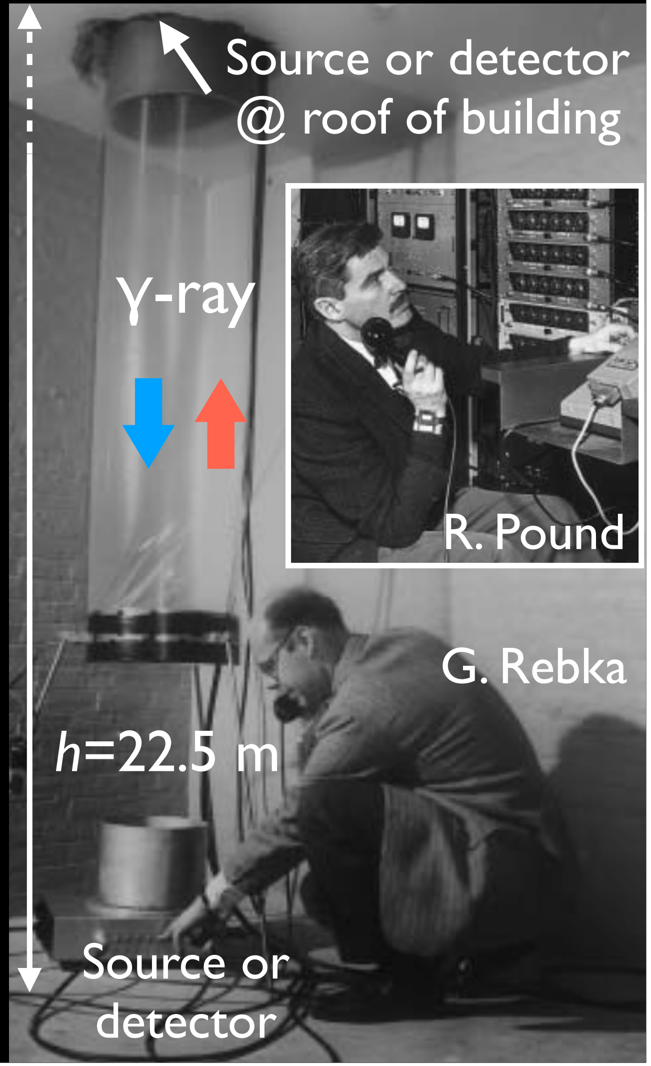
Measurement of gravitational red-/*blue-shifts* caused by the Earth gravitational field

Making use of *Mössbauer* effect,

Pound & Rebka 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 →



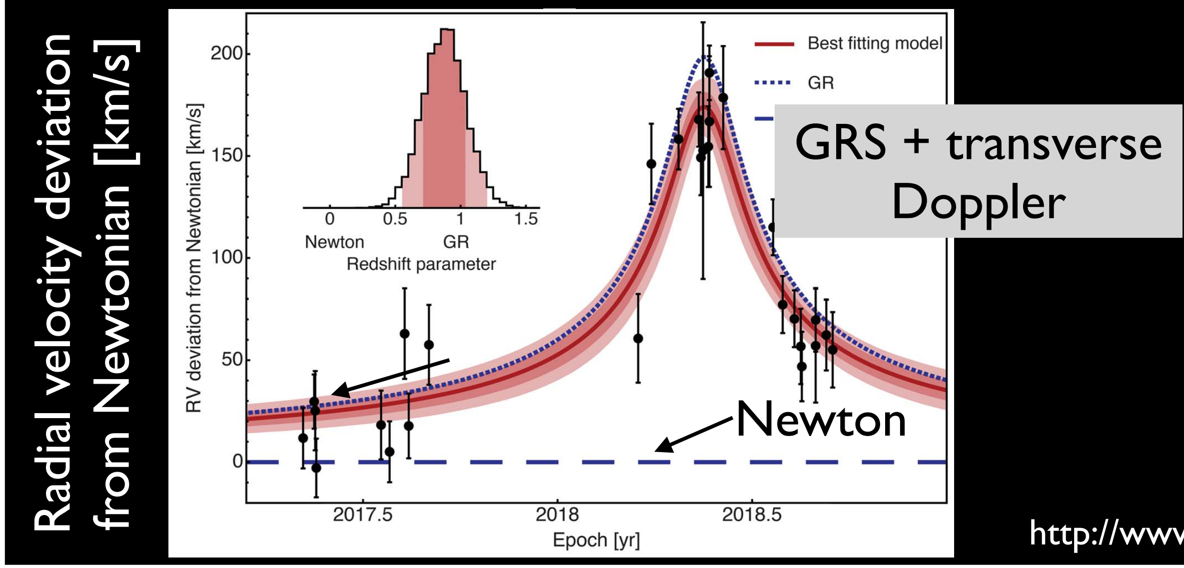
GRS at Galactic center

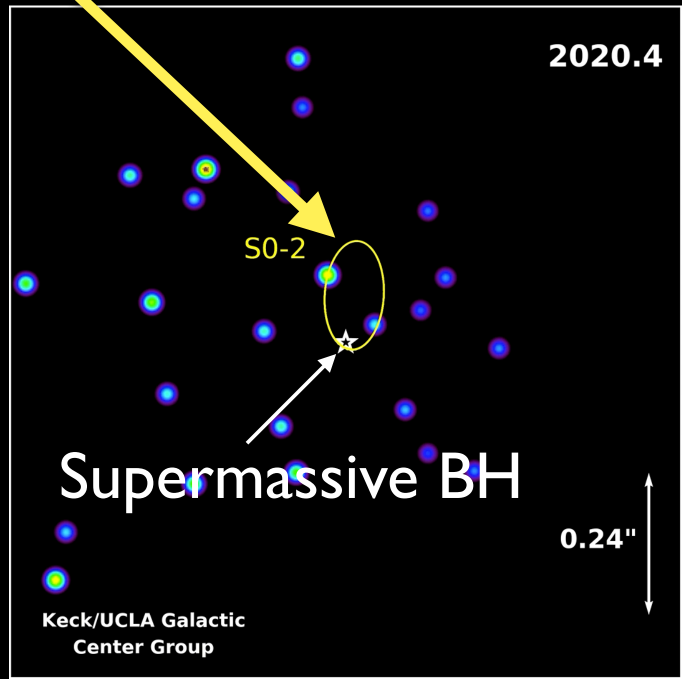
(Gravitational Red-Shift)

Do, Hees, Ghez et al. Science 365, 664 ('19)

Relativistic redshift of the star S0-2 orbiting the Galactic Center supermassive black hole

Tuan Do[1*], Aurelien Hees[2,1], Andrea Ghez[1], Gregory D. Martinez[1], Devin S. Chu[1], Siyao Jia[3], Shoko Sakai[1], Jessica R. Lu[3], Abhimat K. Gautam[1], Kelly Kosmo O'Neil[1], Eric E. Becklin[1,4], Mark R. Morris[1], Keith Matthews[5], Shogo Nishiyama[6], Randy Campbell[7], Samantha Chappell[1], Zhuo Chen[1], Anna Ciurlo[1], Arezu Dehghanfar[1,8], Eulalia Gallego-Cano[9], Wolfgang E. Kerzendorf[10,11,12,13], James E. Lyke[7], Smadar Naoz[1,14], Hiromi Saida[15], Rainer Schödel[9], Masaaki Takahashi[16], Yohsuke Takamori[17], Gunther Witzel[1,18], Peter Wizinowich[7]





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

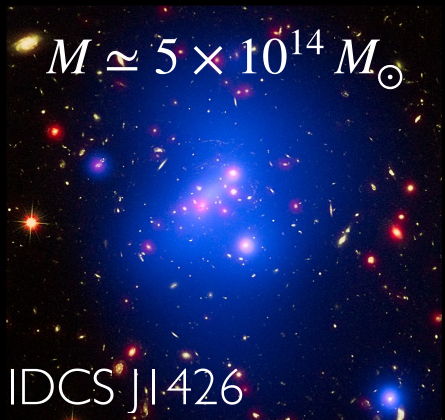
GRS on cosmological scales

(Gravitational Red-Shift)

- Fundamental test of gravity   (c.f. redshift-space distortions)
- Hint on the nature of dark energy /cosmic acceleration

Previous works

Galaxy clusters   (size ~ 1 Mpc) 3×10^6 light years



Wojtak, Hansen & Hjorth ('11)
Sadeh, Feng & Lahav ('15)

Marginal detection due to several systematics

Q Can we detect GRS of the large-scale galaxy distribution ?
(scale ~ 10 Mpc)

GRS of galaxy distribution

Consider static galaxies at cosmological distance

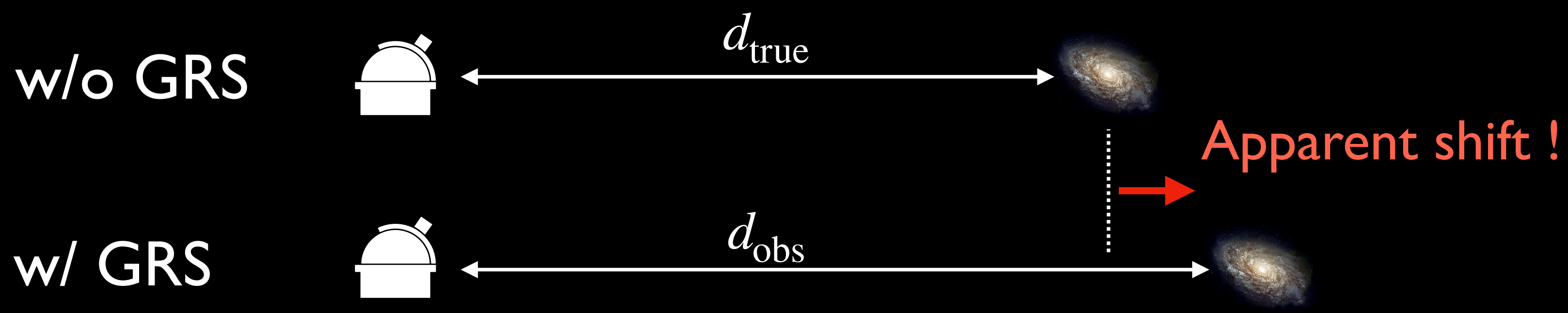
Observed redshift

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

cosmological — GRS

gravitational potential: $\dfrac{\Phi_{\rm gal}}{c^2} \simeq -10^{-5}$

Hubble-Lemaître law : $c\,z = H\,d$



However,
we cannot distinguish between cosmological & gravitational redshifts

Detecting GRS of galaxy distribution

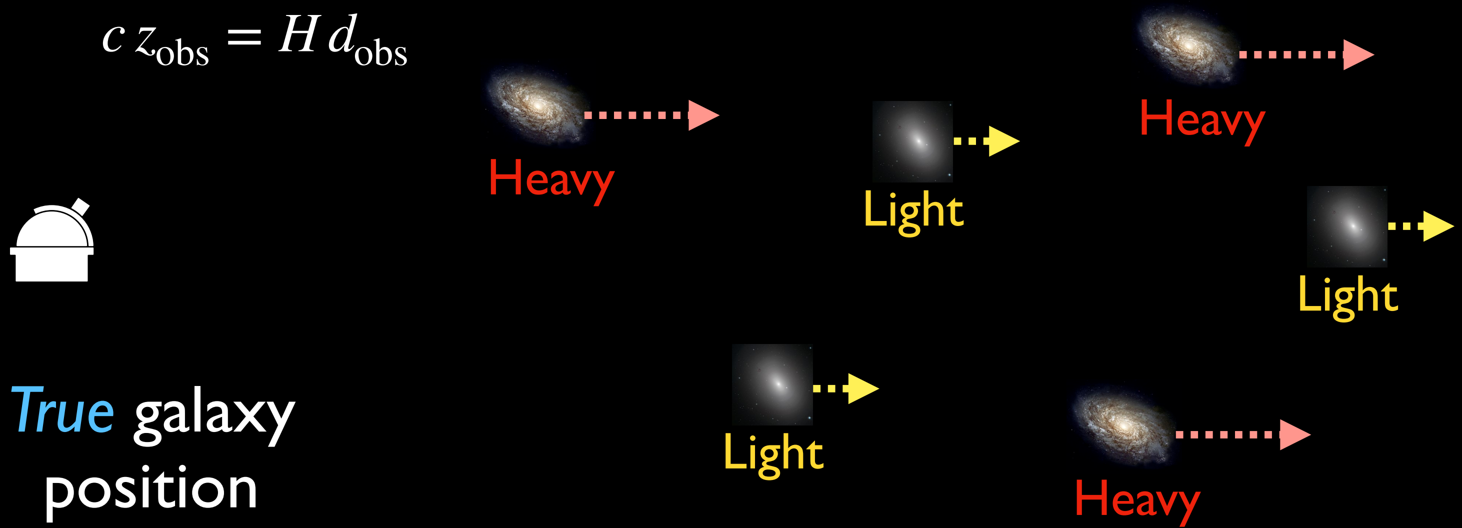
Consider static galaxies at cosmological distance

Suppose there are two galaxy populations

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

Using Hubble-Lemaître law

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



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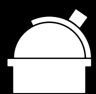

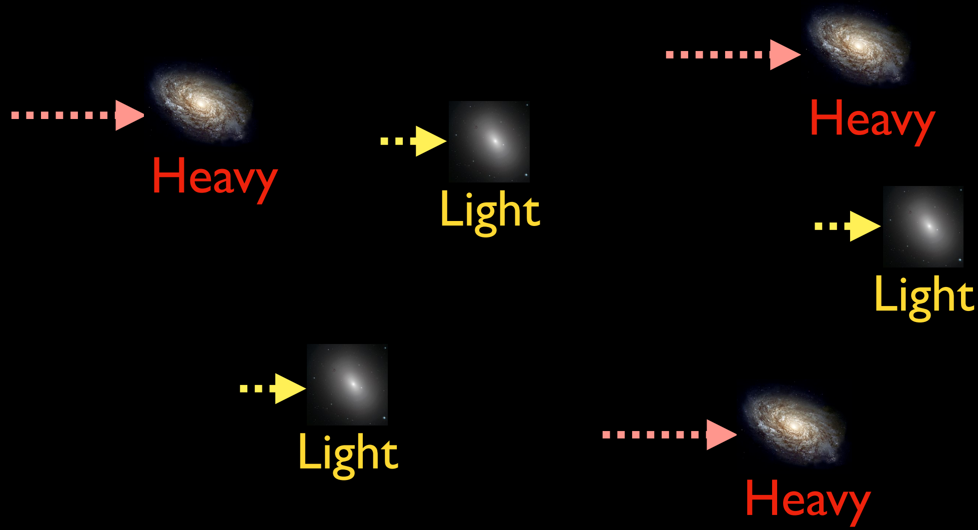

Observed galaxy position

GRS of galaxy distribution

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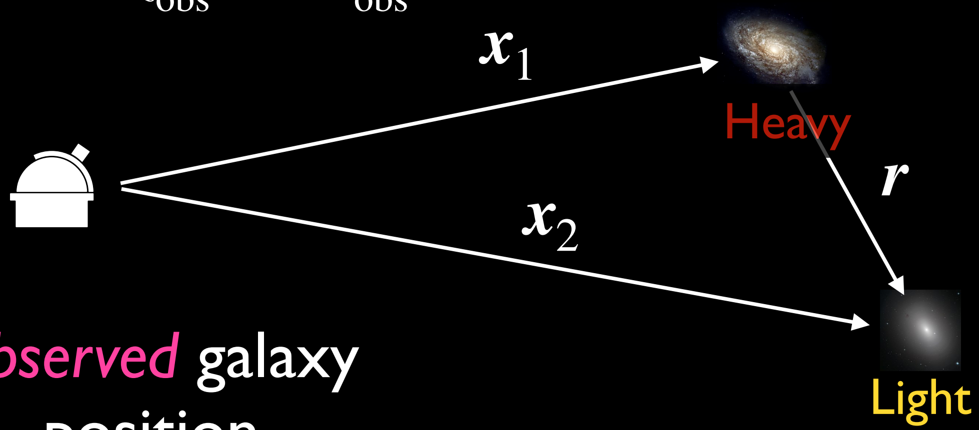


Observed galaxy position

Cross correlation between heavy & light galaxies

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

Usually, this is a function of

$$|\boldsymbol{r}| = |\boldsymbol{x}_2 - \boldsymbol{x}_1|$$

GRS of galaxy distribution

GRS effect can break *statistical isotropy*:

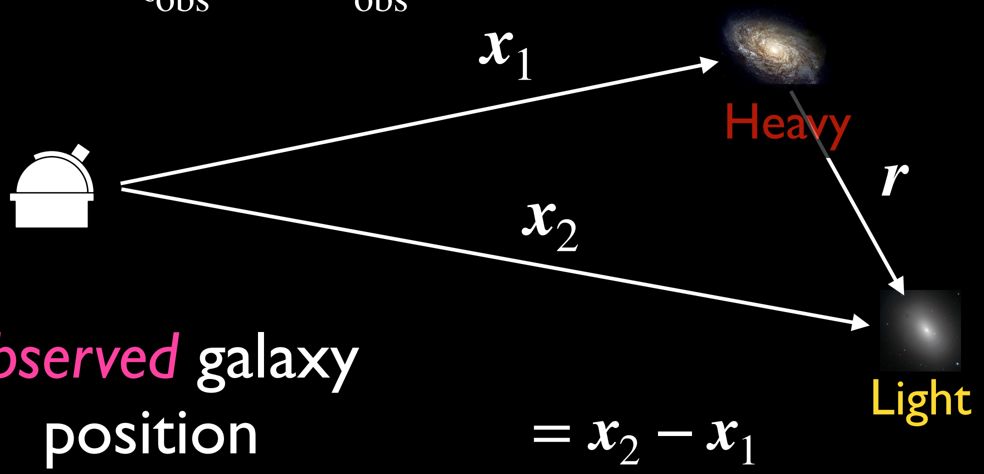
$$\xi(r) \longrightarrow \left\{ 1 - \frac{1+z}{H} \frac{\Delta\Phi}{c^2} (\hat{d} \cdot \nabla_r) \right\} \xi(r) \, ; \quad \Delta\Phi = \Phi_{\rm heavy} - \Phi_{\rm light} < 0$$

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

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

Dipole moment:

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

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

Negative

(in our definition)

Q Can we detect it ?

Numerical & analytical modeling

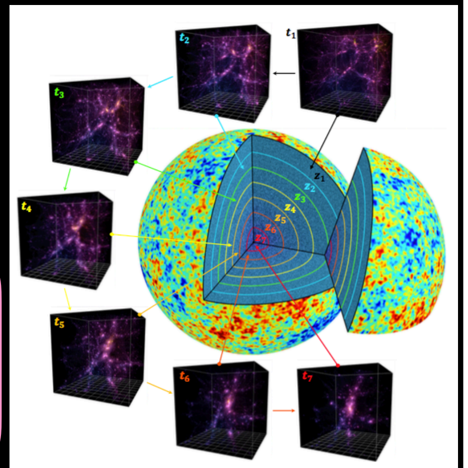
- Based on 'standard' N-body simulation,

  we created a relativistic galaxy (halo) catalog

Breton et al. MNRAS 483, 2671 ('19)

Solving photon geodesic eq. in an inhomogeneous universe,

observational effects arising from special/general relativity are all included in the catalog :



- Classical Doppler
- Transverse Doppler
- GRS
- Gravitational lensing
- Integrated Sachs-Wolfe
- Shapiro time-delay, …

- Based on perturbation theory of large-scale structure,

  we developed an *analytic model* of dipole correlation function taking the major relativistic effects into account

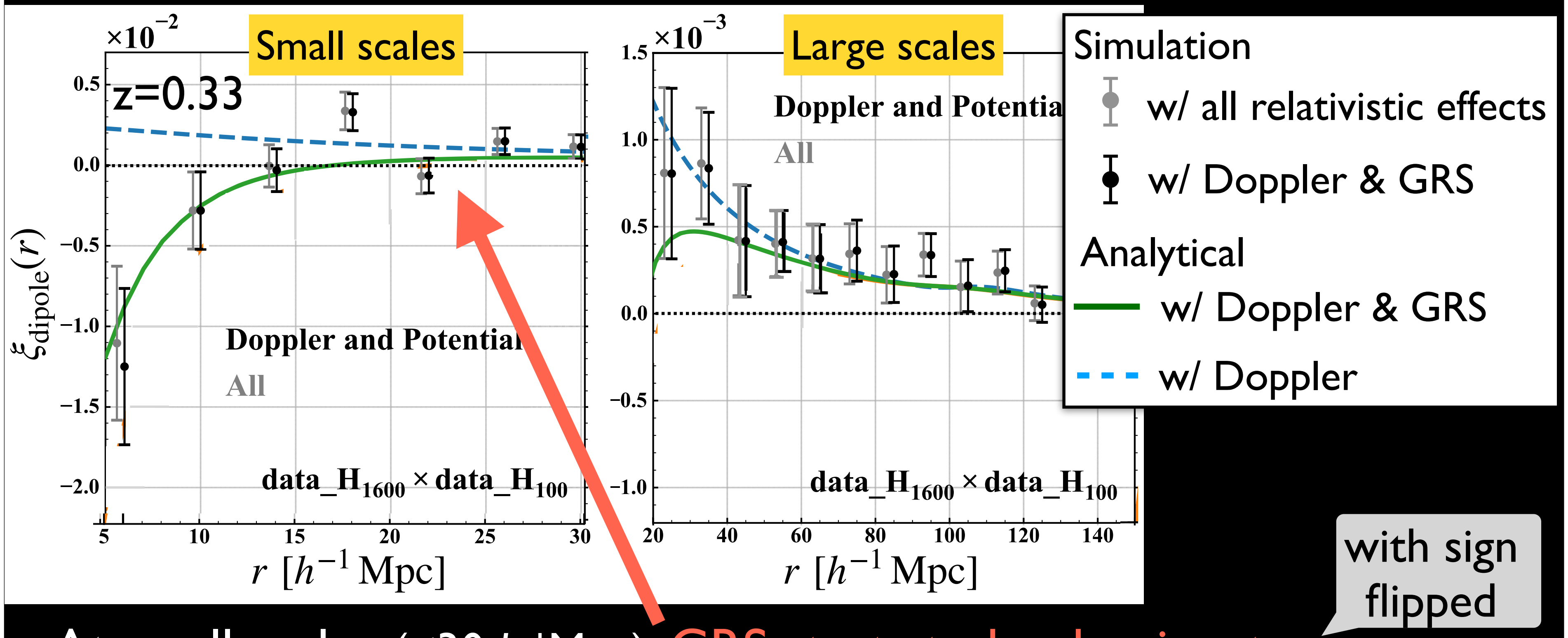
  Doppler & *GRS*

Saga et al. MNRAS 498, 981 ('20)

Results: dipole cross correlation

Saga, AT et al. MNRAS 498, 981 ('20)

Doppler and GRS effects are found to be the most dominant relativistic effects



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

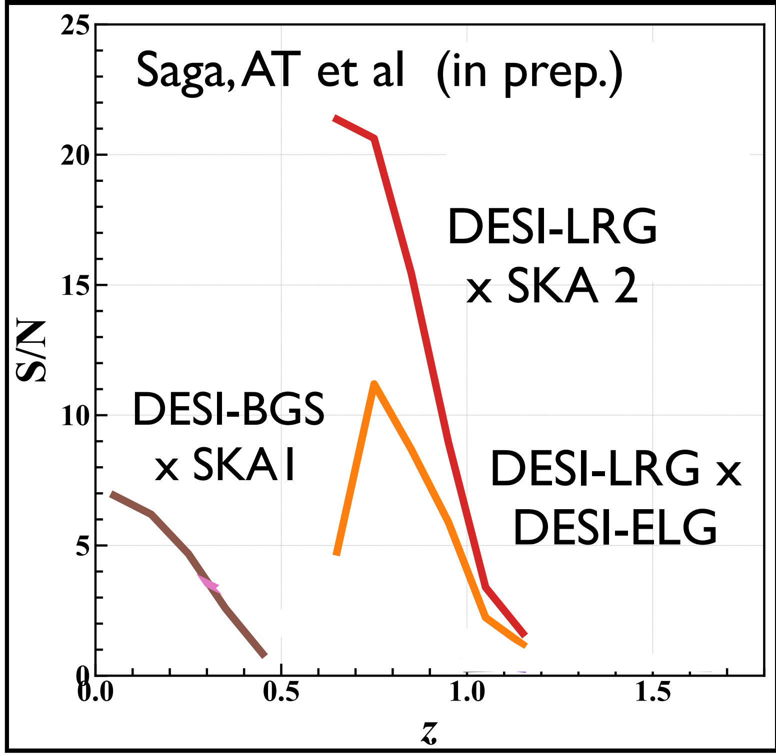
Analytic model predictions agree well with simulation

Detectability of relativistic dipole

To detect GRS from the dipole cross correlation,

- Surveys observing multiple galaxy populations
- Synergy between surveys

are important



Forecast study with analytical model suggests

High-S/N ratio (S/N>10)

is expected from upcoming surveys

competitor of Subaru-PFS

Summary

Gravitational redshift (GRS) effect of large-scale galaxy distribution as a fundamental test of gravity on cosmological scales

- GRS effect can break statistical isotropy:

  Cross correlation between heavy and light galaxies gives rise to non-zero *dipole* moment

- Numerical simulation suggests GRS effect dominates the dipole at small scales, in good agreement with analytical model

- GRS effect is detectable with high S/N ratio (>10) from upcoming surveys (DESI, SKA)

  c.f. 2.7σ detection from BOSS (Alam et al. '18)

GRS effects on large-scale structure provides a more stringent test of gravity, giving some hints on dark energy/cosmic acceleration