第6回観測的宇宙論ワークショップ @弘前大学

10:05 - 10:35, 24th. Oct, 2017

モンテカルロ法による宇宙論的観測と整合的な修正重力理論の分類

+GW170817& GRB170817Aのインパクト

Shun Arai (Cosmology group in Nagoya University, D1)

Based on Shun Arai and Atsushi Nishizawa in progress.

Outline in this talk

- Introduction

- Model extraction based on consistency with current cosmic expansion e.g. Horndeski theory

- Gravitational Waves (GW) observations as a probe of Horndeski theory

  SA and A.Nishizawa. in preparation

  impact of GW170817 &GRB170817A

- Summary

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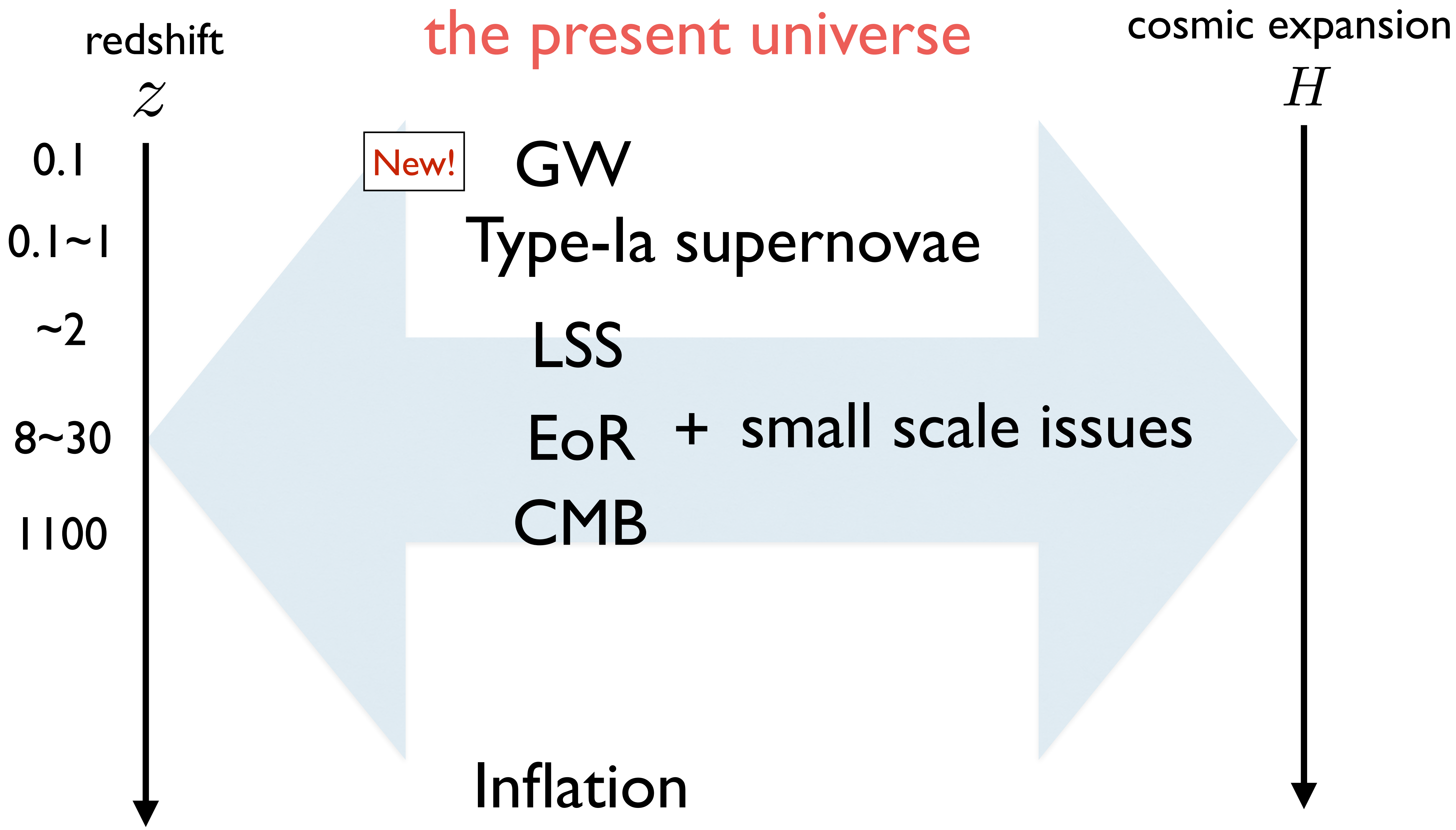
Model extraction consistent with current cosmic expansion

Observations of gravity cosmological scale



the present universe

redshift z

cosmic expansion H

0.1 New! GW

0.1~1 Type-Ia supernovae

~2 LSS

8~30 EoR + small scale issues

1100 CMB

Inflation

The creation of the universe

Model extraction consistent with current cosmic expansion

Observational constraints on cosmic expansion histories

O.Farooq et al. Astrophys. J. 835 (2017)

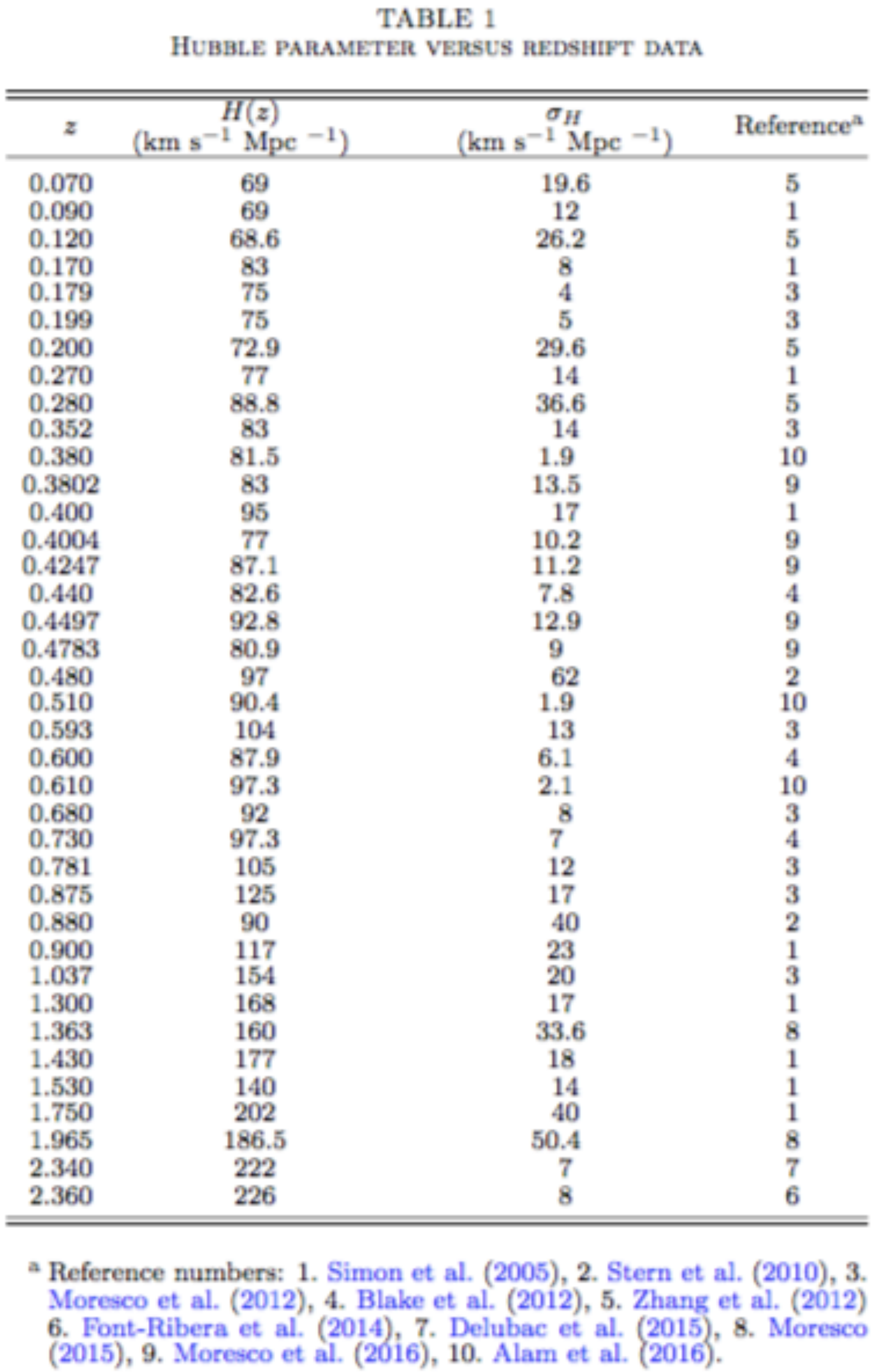
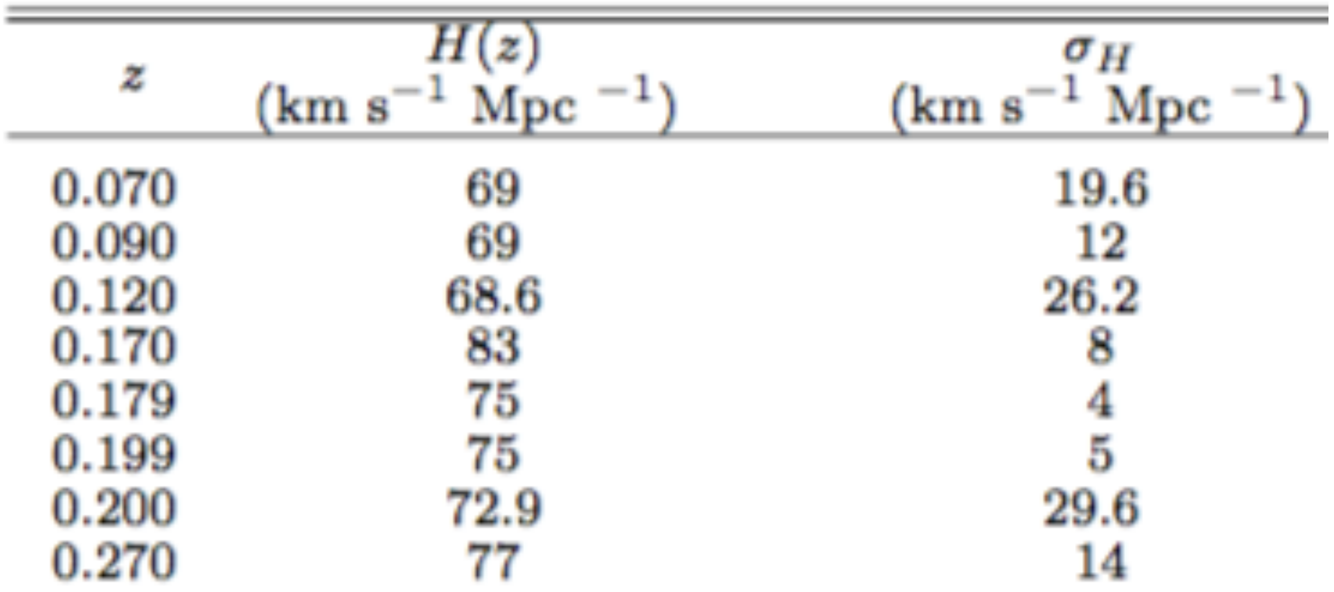


TABLE 1
HUBBLE PARAMETER VERSUS REDSHIFT DATA

z	$H(z)$ (km s^{-1} Mpc $^{-1}$)	σ_H (km s^{-1} Mpc $^{-1}$)	Reference[a]
0.070	69	19.6	5
0.090	69	12	1
0.120	68.6	26.2	5
0.170	83	8	1
0.179	75	4	3
0.199	75	5	3
0.200	72.9	29.6	5
0.270	77	14	1
0.280	88.8	36.6	5
0.352	83	14	3
0.380	81.5	1.9	10
0.3802	83	13.5	9
0.400	95	17	1
0.4004	77	10.2	9
0.4247	87.1	11.2	9
0.440	82.6	7.8	4
0.4497	92.8	12.9	9
0.4783	80.9	9	9
0.480	97	62	2
0.510	90.4	1.9	10
0.593	104	13	3
0.600	87.9	6.1	4
0.610	97.3	2.1	10
0.680	92	8	3
0.730	97.3	7	4
0.781	105	12	3
0.875	125	17	3
0.880	90	40	2
0.900	117	23	1
1.037	154	20	3
1.300	168	17	1
1.363	160	33.6	8
1.430	177	18	1
1.530	140	14	1
1.750	202	40	1
1.965	186.5	50.4	8
2.340	222	7	7
2.360	226	8	6

[a] Reference numbers: 1. Simon et al. (2005), 2. Stern et al. (2010), 3. Moresco et al. (2012), 4. Blake et al. (2012), 5. Zhang et al. (2012) 6. Font-Ribera et al. (2014), 7. Delubac et al. (2015), 8. Moresco (2015), 9. Moresco et al. (2016), 10. Alam et al. (2016).



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0.270	77	14

Simon et al. (2005)
Moresco et al. (2012)
Zhang et al. (2012)

$$\frac{\Delta H_{\mathrm{obs}}}{H_{\mathrm{obs}}} \simeq 17\%$$

$$@ z \sim 0.1$$

Model extraction consistent with current cosmic expansion

Horndeski theory

G. Horndeski, 1974

T. Kobayashi, M. Yamaguchi, and J. Yokoyama 2011

The most generic theory with a scalar whose EoM contains only up to 2nd order spacetime derivatives.

$$S_{\rm Horn} = \int d^4x\sqrt{-g}\sum_{i=2}^{5}\mathcal{L}_i$$

$$\mathcal{L}_2 = G_2(\phi, X),$$

$$\mathcal{L}_3 = -G_3(\phi, X)\Box\phi,$$

$$X \equiv -\phi^{;\mu}\phi_{;\mu}/2$$

$$\mathcal{L}_4 = G_4(\phi, X)R + G_{4X}(\phi, X)\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right],$$

$$\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5X}(\phi, X)\left[(\Box\phi)^3 + 2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\alpha}\phi_{;\alpha}{}^{\mu} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi\right]$$

Model extraction consistent with current cosmic expansion

α-parameterization

E.Bellini & I.Sawicky JCAP 2014

In ADM formalism

$$S^{(2)} = \int dt d^3x a^3 \frac{M^2}{2} \Big[\delta K_{ij} \delta K^{ij} - \delta K^2 + (1+\alpha_T)\left(R\frac{\delta\sqrt{h}}{a^3} + \delta_2 R \right) + \alpha_K H^2 \delta N^2 + 4\alpha_B H \delta K \delta N + (1+\alpha_{\cancel{H}}) R \delta N \Big] ,$$

R :3d Ricci scalar

α_M $\qquad \alpha_M \equiv \frac{1}{HM^2}\frac{dM^2}{dt}$

α_K Kineticity of scalar

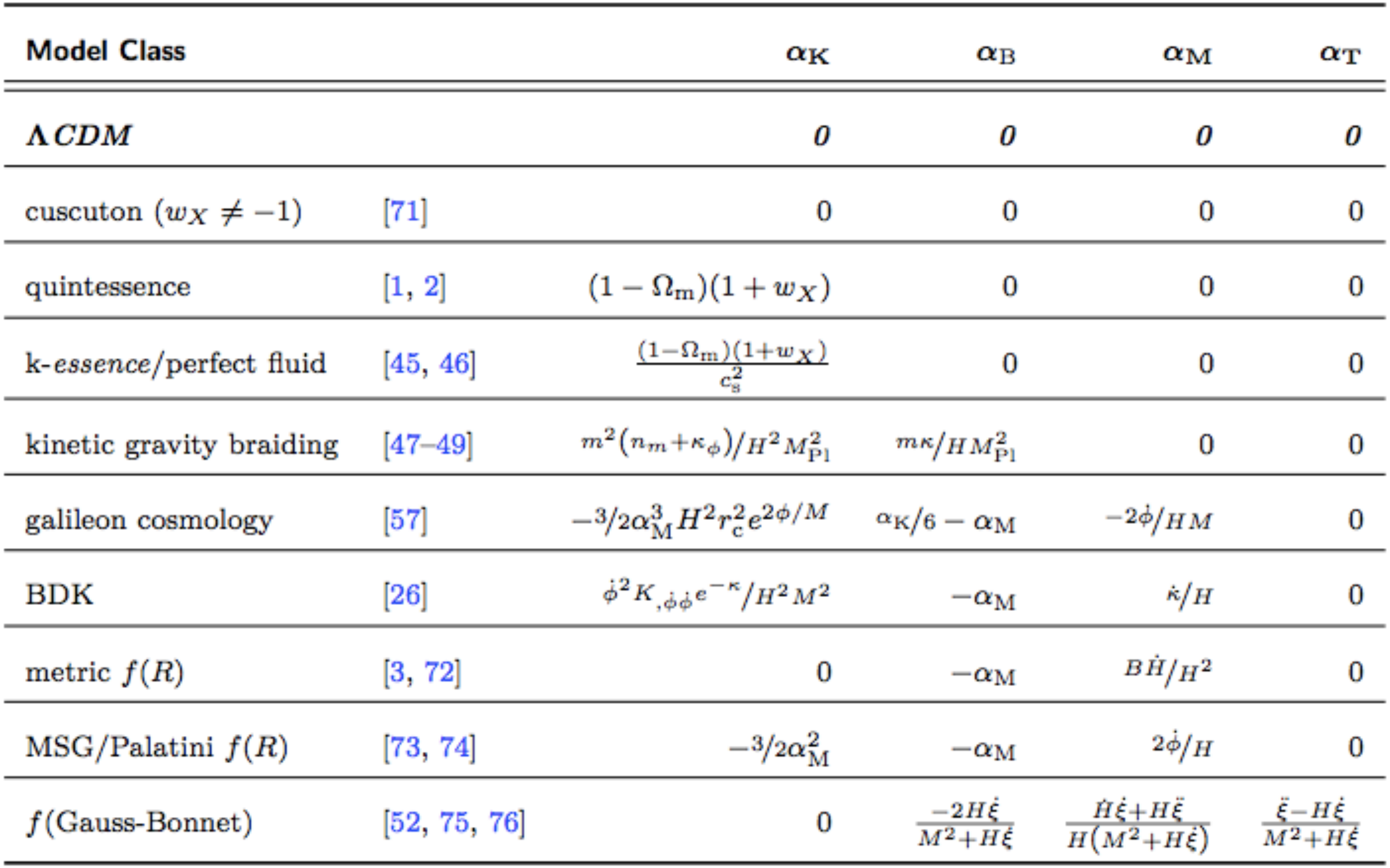
α_B “Braiding” between scalar and tensor

α_T phase velocity of tensor $\qquad \alpha_T \equiv c_T^2 - 1$

Model extraction consistent with current cosmic expansion

α-parameterization

E.Bellini & I.Sawicky JCAP 2014

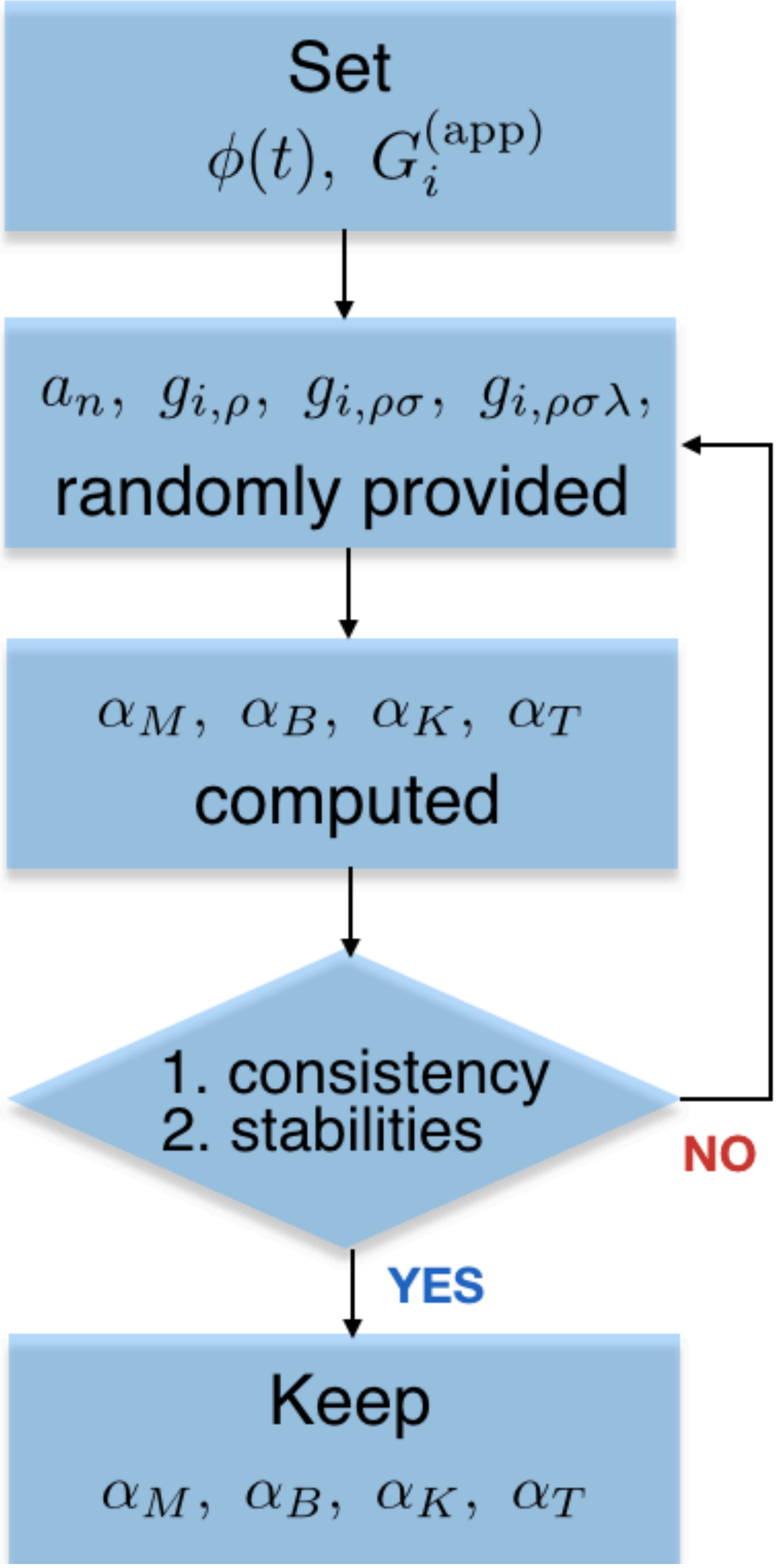


Model Class		α_K	α_B	α_M	α_T
ΛCDM		***0***	***0***	***0***	***0***
cuscuton ($w_X \neq -1$)	[71]	0	0	0	0
quintessence	[1, 2]	$(1-\Omega_{\mathrm{m}})(1+w_X)$	0	0	0
k-*essence*/perfect fluid	[45, 46]	$\frac{(1-\Omega_{\mathrm{m}})(1+w_X)}{c_{\mathrm{s}}^2}$	0	0	0
kinetic gravity braiding	[47–49]	$m^2(n_m+\kappa_\phi)/H^2M_{\mathrm{Pl}}^2$	$m\kappa/HM_{\mathrm{Pl}}^2$	0	0
galileon cosmology	[57]	$-3/2\alpha_{\mathrm{M}}^3 H^2 r_{\mathrm{c}}^2 e^{2\phi/M}$	$\alpha_{\mathrm{K}}/6 - \alpha_{\mathrm{M}}$	$-2\dot{\phi}/HM$	0
BDK	[26]	$\dot{\phi}^2 K_{,\dot{\phi}\dot{\phi}} e^{-\kappa}/H^2M^2$	$-\alpha_{\mathrm{M}}$	$\dot{\kappa}/H$	0
metric $f(R)$	[3, 72]	0	$-\alpha_{\mathrm{M}}$	$B\dot{H}/H^2$	0
MSG/Palatini $f(R)$	[73, 74]	$-3/2\alpha_{\mathrm{M}}^2$	$-\alpha_{\mathrm{M}}$	$2\dot{\phi}/H$	0
f(Gauss-Bonnet)	[52, 75, 76]	0	$\frac{-2H\dot{\xi}}{M^2+H\dot{\xi}}$	$\frac{\dot{H}\dot{\xi}+H\ddot{\xi}}{H(M^2+H\dot{\xi})}$	$\frac{\ddot{\xi}-H\dot{\xi}}{M^2+H\dot{\xi}}$

Model extraction consistent with current cosmic expansion

Flow of the model extraction

SA and A.Nishizawa. in preparation



Set

$\phi(t),\ G_i^{(\mathrm{app})}$

$a_n,\ g_{i,\rho},\ g_{i,\rho\sigma},\ g_{i,\rho\sigma\lambda};$

randomly provided

$\alpha_M,\ \alpha_B,\ \alpha_K,\ \alpha_T$

computed

1. consistency
2. stabilities

Keep

$\alpha_M,\ \alpha_B,\ \alpha_K,\ \alpha_T$

Model extraction consistent with current cosmic expansion

Set-up

SA and A.Nishizawa. in preparation

- time-dependence of $\phi(t)$

$$\phi(t) = \sqrt{M_{\rm pl}H_0}\left\{a_0 + a_1 H_0 t_{LB} + \frac{a_2}{2}(H_0 t_{LB})^2\right\}$$

$$a_0 \equiv 0$$

$$t_{LB} \equiv \int_0^z \frac{dz'}{H_{\Lambda\rm CDM}(z')\cdot(1+z')}$$

$$H_{\Lambda\rm CDM}(z) = H_0\left\{\Omega_{m0}(1+z)^3 + 1 - \Omega_{m0}\right\}^{1/2}$$

- approximation of the Horndeski functions

$$G_i^{(\rm app)} \supset \phi, X, \phi X, \phi^2, X^2 (i = 2, 3, 4, 5)$$

$$g_{i\rho}, g_{i\rho\sigma} (\rho, \sigma = \phi \text{ or X})$$

Model extraction consistent with current cosmic expansion

Criteria for model extraction

SA and A.Nishizawa. in preparation

1. Consistency

$$\left|1 - H/H_{\Lambda CDM}\right| < \Delta H_{\rm obs}/H_{\rm obs}$$

$$\frac{\Delta H_{\rm obs}}{H_{\rm obs}} \equiv 20\%$$

2. Stability

Avoiding ghost and gradient instabilities. i.e. $Q_\sigma > 0, c_\sigma^2 > 0$

for a quadratic action as

$$S^{(2)} = \int dt d^3x \sum_{\sigma=\mathrm{scalar,tensor}} \{Q_\sigma \dot{\sigma}^2 - c_\sigma^2 (\partial\sigma)^2\}$$

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  current cosmic expansion   e.g. Horndeski theory

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  as a probe of Horndeski theory
  impact of GW170817 &GRB170817A

- Summary

Modification of GW propagation

I. D. Saltas et. al PRL 2014
A.Nishizawa arXiv:1710.04825

$$h''_{ij} + (2+\nu)\mathcal{H}h'_{ij} + ({c_T}^2k^2 + a^2\mu^2)h_{ij} = a^2\Gamma\gamma_{ij}$$

ν	time variation of the effective Planck mass	time dependent gravitational coupling
c_T	propagation speed of GW	Lorentz symmetry/Equivalence principle
μ	graviton mass	massive gravity (Shinji-Mukohyama's talk)
Γ	additional sources of GW	Non-minimal coupling with other fields

Solution of modified GW propagation at cosmological scale

A.Nishizawa arXiv:1710.04825

Source-less system $\longrightarrow$ $\Gamma = 0$

solutions that alters in cosmological time scale:

$$h = \mathcal{C}_{\rm MG} h_{\rm GR} \quad \mathcal{C}_{\rm MG} \equiv e^{-\mathcal{D}} e^{-ik\Delta T}$$

amplitude

$$\mathcal{D} \equiv \frac{1}{2}\int^{\tau} d\tau' \nu \mathcal{H}$$

luminosity distance

phase

$$\Delta T \equiv \int^{\tau} d\tau' \left\{ (1 - c_T) - \cancel{\frac{a^2\mu^2}{2k^2}} \right\}$$

arrival time difference

e.g. GW and GRB

τ : conformal time

α & c_T in Horndeski theory

E.Bellini & I.Sawicky JCAP 2014

$$M_*^2(z) \equiv 2(G_4 - 2XG_{4X} + XG_{5\phi} - \dot{\phi}HXG_{5X})$$

$$\nu \equiv \frac{d\ln M_*^2}{d\ln a} = \alpha_M(z)$$

$$dt = a d\tau$$

$$\dot{A} \equiv \frac{dA}{dt}$$

$$H = \mathcal{H}/a$$

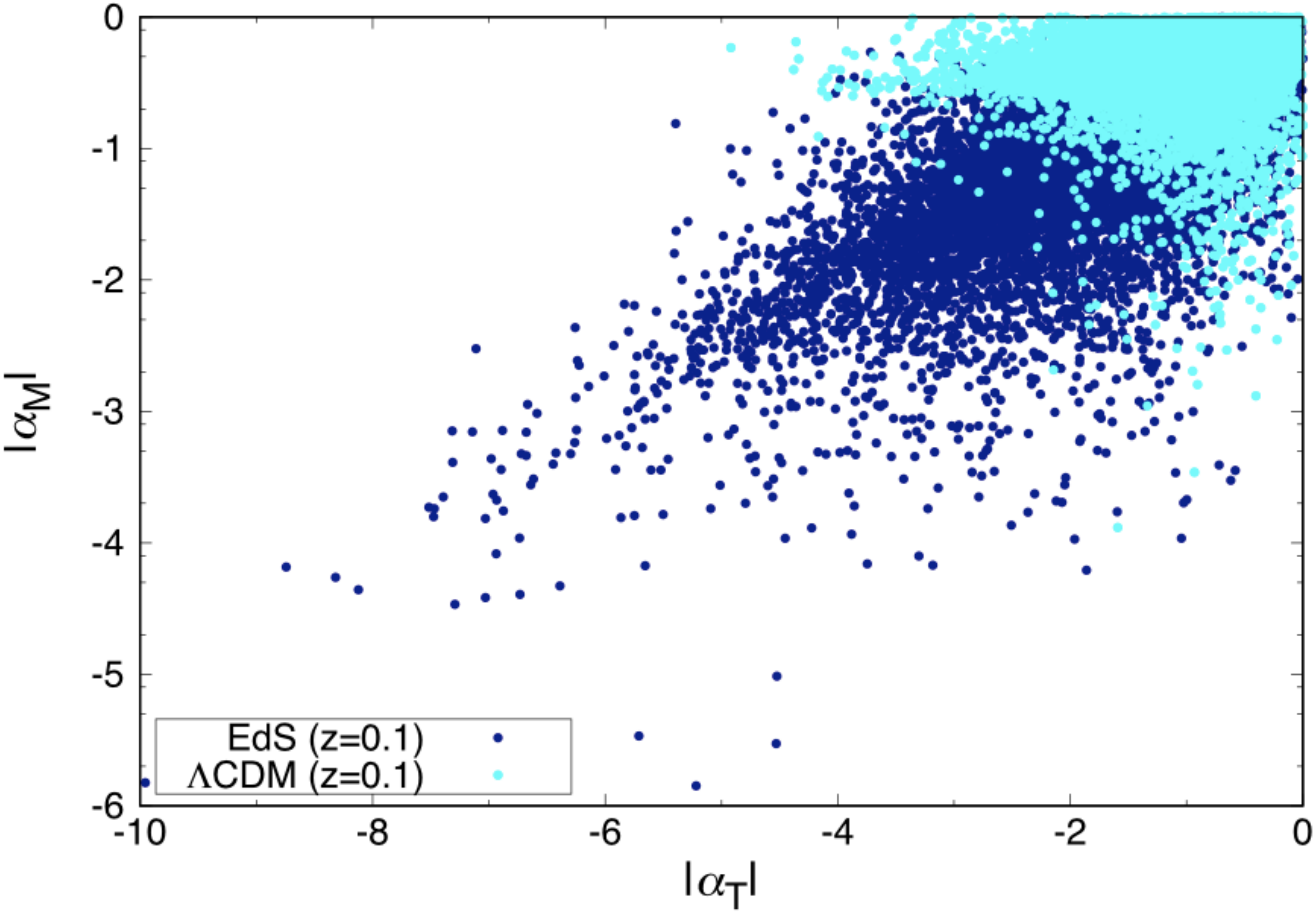
$${c_T}^2 - 1 \equiv \alpha_T = \frac{2X}{M_*^2}\left(2G_{4X} - 2G_{5\phi} - (\ddot{\phi} - \dot{\phi}H)G_{5X}\right)$$

- in GR, $\nu = 0$ $c_T = 1$
- G_4 or G_5 themselves can achieve accelerating universe

  "self acceleration" L.Lombriser & A.Taylor, JCAP 2016
- GW properties are only involved with G_4 and G_5

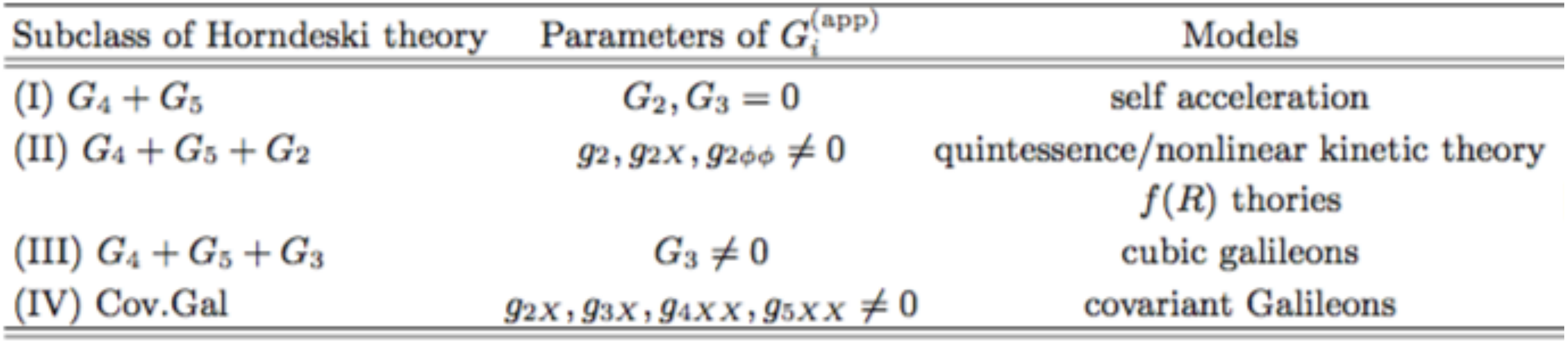
Different expansion histories

SA and A.Nishizawa. in preparation

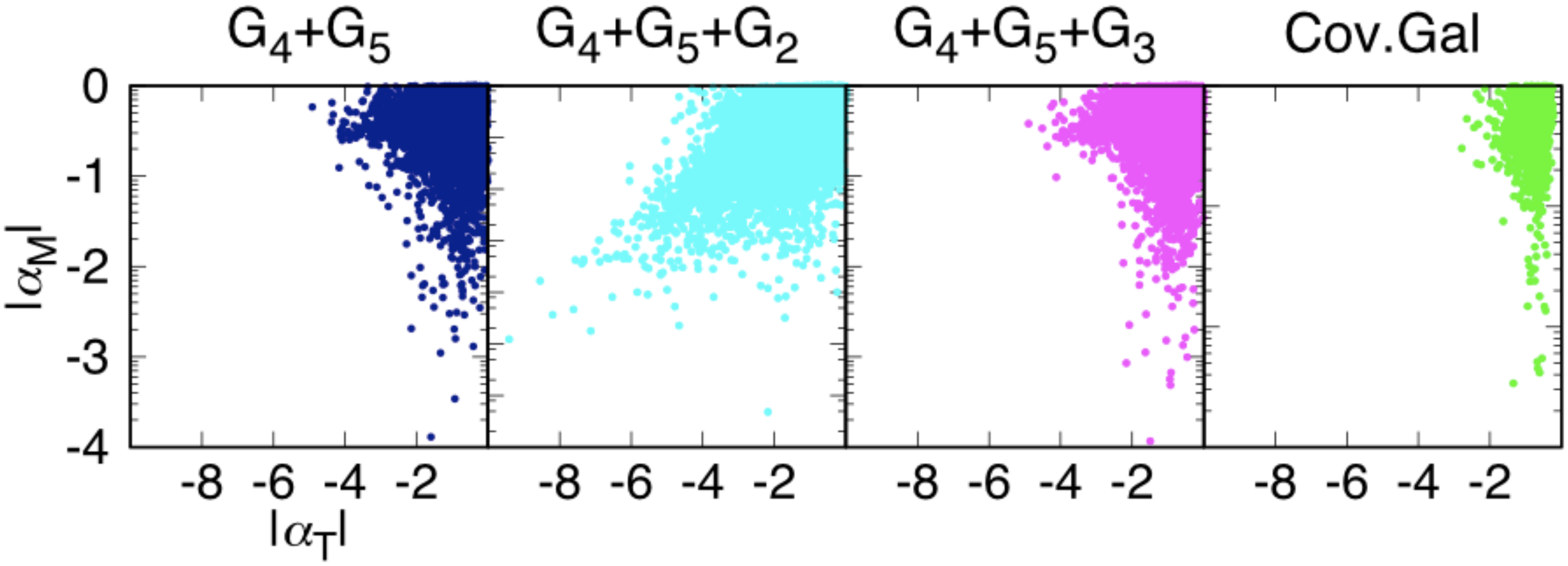


Model distribution

SA and A.Nishizawa. in preparation

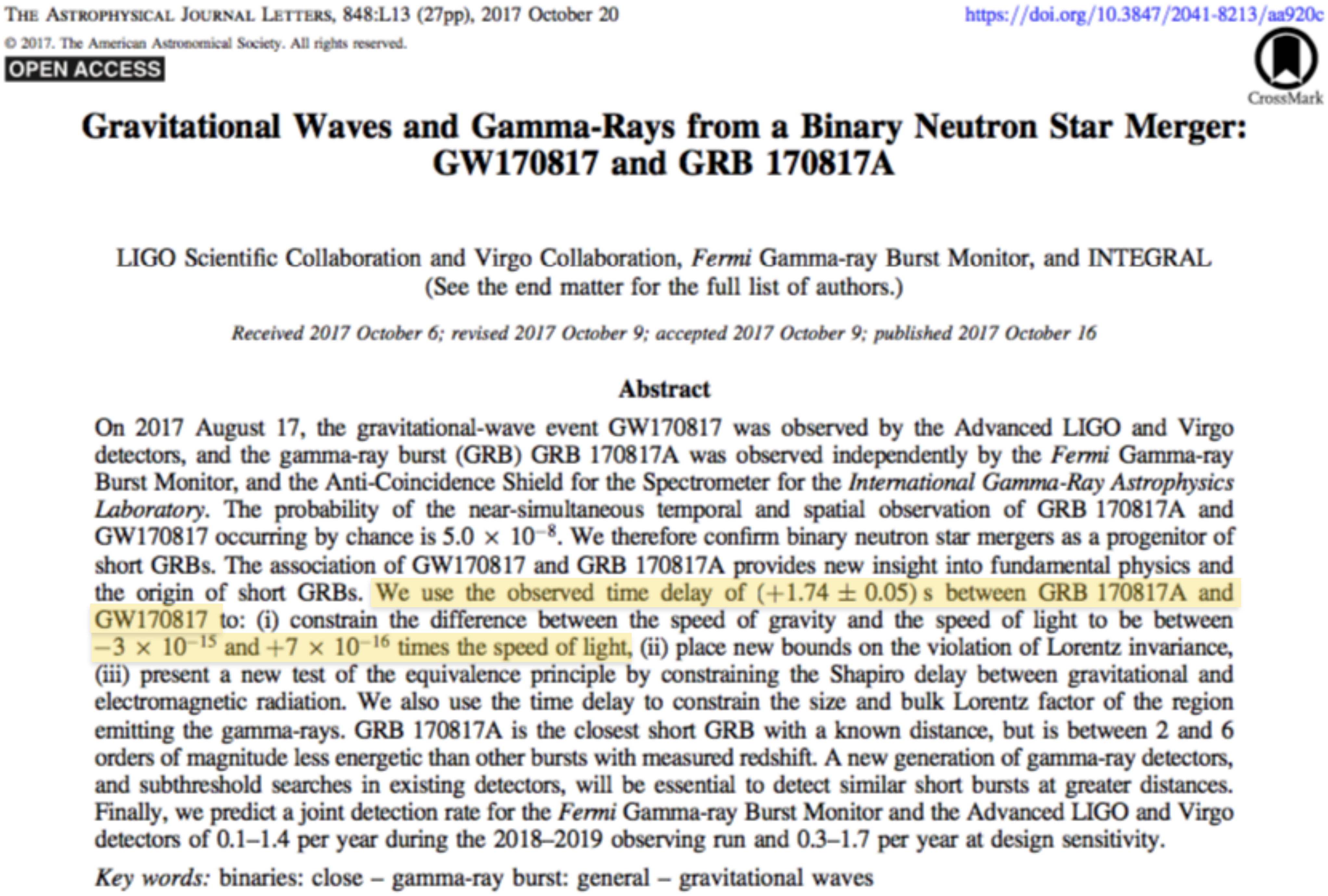


Subclass of Horndeski theory	Parameters of $G_i^{(\mathrm{app})}$	Models
(I) $G_4 + G_5$	$G_2, G_3 = 0$	self acceleration
(II) $G_4 + G_5 + G_2$	$g_2, g_{2X}, g_{2\phi\phi} \neq 0$	quintessence/nonlinear kinetic theory $f(R)$ thories
(III) $G_4 + G_5 + G_3$	$G_3 \neq 0$	cubic galileons
(IV) Cov.Gal	$g_{2X}, g_{3X}, g_{4XX}, g_{5XX} \neq 0$	covariant Galileons



Impact of GW170817 & GRB170817A

APJLett. 848:L13 2017



The Astrophysical Journal Letters, 848:L13 (27pp), 2017 October 20
https://doi.org/10.3847/2041-8213/aa920c

Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A

LIGO Scientific Collaboration and Virgo Collaboration, *Fermi* Gamma-ray Burst Monitor, and INTEGRAL
(See the end matter for the full list of authors.)

Received 2017 October 6; revised 2017 October 9; accepted 2017 October 9; published 2017 October 16

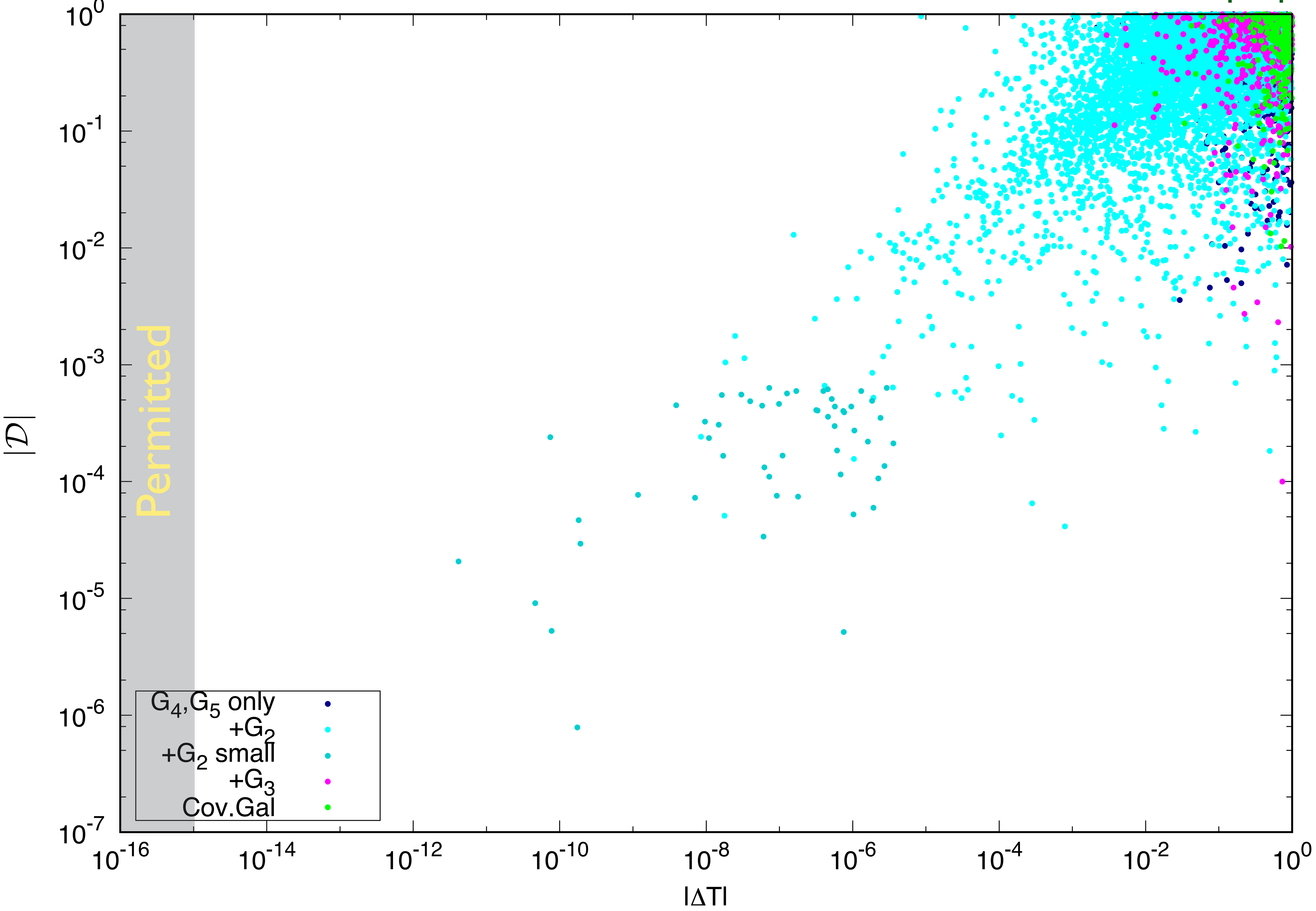
Abstract

On 2017 August 17, the gravitational-wave event GW170817 was observed by the Advanced LIGO and Virgo detectors, and the gamma-ray burst (GRB) GRB 170817A was observed independently by the *Fermi* Gamma-ray Burst Monitor, and the Anti-Coincidence Shield for the Spectrometer for the *International Gamma-Ray Astrophysics Laboratory*. The probability of the near-simultaneous temporal and spatial observation of GRB 170817A and GW170817 occurring by chance is 5.0×10^{-8}. We therefore confirm binary neutron star mergers as a progenitor of short GRBs. The association of GW170817 and GRB 170817A provides new insight into fundamental physics and the origin of short GRBs. We use the observed time delay of $(+1.74 \pm 0.05)$ s between GRB 170817A and GW170817 to: (i) constrain the difference between the speed of gravity and the speed of light to be between -3×10^{-15} and $+7 \times 10^{-16}$ times the speed of light, (ii) place new bounds on the violation of Lorentz invariance, (iii) present a new test of the equivalence principle by constraining the Shapiro delay between gravitational and electromagnetic radiation. We also use the time delay to constrain the size and bulk Lorentz factor of the region emitting the gamma-rays. GRB 170817A is the closest short GRB with a known distance, but is between 2 and 6 orders of magnitude less energetic than other bursts with measured redshift. A new generation of gamma-ray detectors, and subthreshold searches in existing detectors, will be essential to detect similar short bursts at greater distances. Finally, we predict a joint detection rate for the *Fermi* Gamma-ray Burst Monitor and the Advanced LIGO and Virgo detectors of 0.1–1.4 per year during the 2018–2019 observing run and 0.3–1.7 per year at design sensitivity.

Key words: binaries: close – gamma-ray burst: general – gravitational waves

Observational bounds from GW (preliminary)

SA and A.Nishizawa. in preparation



Summary of my talk

- We developed the numerical formulation to classify the models in the Horndeski theory based on α parameterization.

- Applying our method to GW observation, we obtain the distributions of the models in α_T-α_M plane.

- Considering the current observation of GW170817 and GRB170817A, the Horndeski theory hardly account for cosmic acceleration and GW propagation at the same time.

comments : quintessence or f(R) gravity survive so far!

Back Up

Self Acceleration

$$S_{\mathrm{Horn}} = \int d^4x\sqrt{-g}\underbrace{\frac{M_*^2(t)c_T^2(t)}{2}}_{\Omega(t)}R + \ldots$$

$$\nu \equiv \frac{1}{M_*^2 H}\frac{dM_*^2}{dt}$$

in the language of the EFT

G.Gubitosi et al. 2013 J.Gleyzes et al. 2013

N.B 1. We here use the notation as same as EFT of DE.

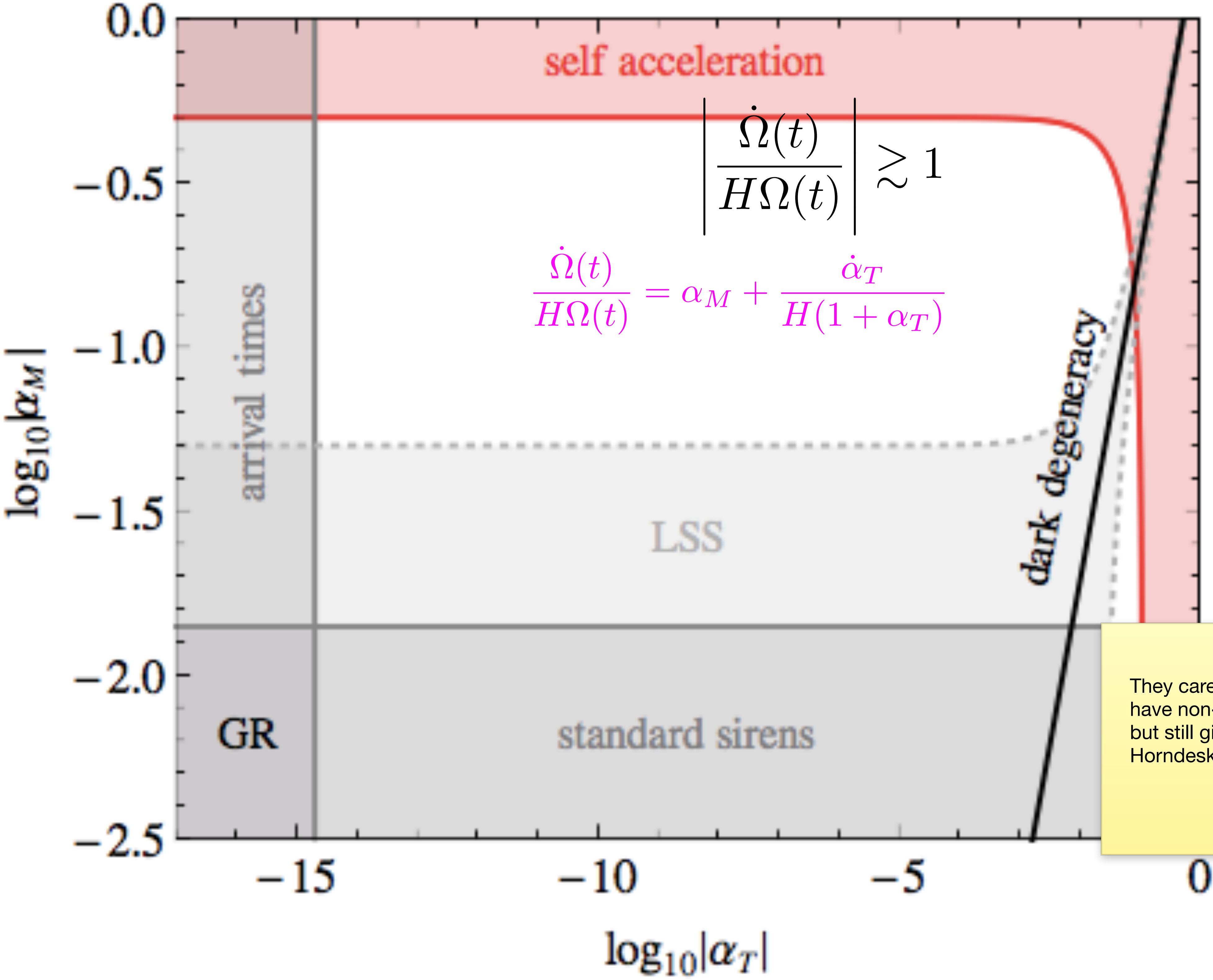
N.B 2. This way of acceleration is ONLY seen in the Jordan frame.

$$\left|\frac{\dot{\Omega}(t)}{H\Omega(t)}\right| \gtrsim 1$$

L.Lombriser & A.Taylor JCAP 2016

Lombriser & Taylor 2016

L.Lombriser & A.Taylor JCAP 2016



$$\left|\frac{\dot{\Omega}(t)}{H\Omega(t)}\right| \gtrsim 1$$

$$\frac{\dot{\Omega}(t)}{H\Omega(t)} = \alpha_M + \frac{\dot{\alpha}_T}{H(1+\alpha_T)}$$

They carefully consider models that have non-linear screening mechanism but still give general discussion of Horndeski theory