International Symposium on Cosmology and Particle Astrophysics
CosPA 2017 @ Kyoto
session K: GW 2
15:30 - 15:45, 14th. Dec, 2017

Monte Carlo approach for model classification in Horndeski theory

Shun Arai (Cosmology group in Nagoya University)

SA and Atsushi Nishizawa arXiv:1711.03776.
SA and Atsushi Nishizawa in progress.

Outline in this talk

- Observational confrontations to seek the true theory of gravity @ cosmological scale
- Numerical model classification and correlation between the EFT couplings
  e.g. Horndeski theory
- EFT of gravitation after GW170817: what GWs observations can do?
  SA and A.Nishizawa. in arXiv:1711.03776
- Summary

Quest for true theory of gravity

High energy (UV)

Fundamental
Quantum
Multi d.o.f
Particle physics
Singularities
⋮

Low energy (IR)

Effective
Classical
A few d.o.f
Astrophysics/Cosmology
95% dark components
⋮

Gravity Theories in "Gravity Zoo"

Horava-Lifshitz gravity
Loop quantum gravity
Supergravity
General Relativity
Einstein Aether theory
f(R) gravity
Galileon gravity
Massive gravity
Effective Field Theories

Observational confrontations to seek the true theory of gravity

the present universe

redshift z | cosmic expansion H

redshift z	
0.1	New! astrophysical GW
0.1~1	Type-Ia supernovae
~2	LSS
8~30	EoR + small scale issues
1100	CMB
	CνB
	primordial GW

The creation of the universe

the present universe

redshift z

cosmic expansion H

0.1

0.1~1

~2

8~30

1100

Observational controversies

- discrepancy of Hubble parameter
- tension of $\sigma_8 - \Omega_m$
- baryonic/non-liniear biases

⋮

- dependence of unknown priors
- intrinsic degeneracies in models

The creation of the universe

EFT - parameterization

T. Kobayashi, M. Yamaguchi, and J. Yokoyama 2011
E.Bellini & I.Sawicky JCAP 2014
D.Langlois et. al. 2017

In ADM formalism $\delta\phi(t) = 0$

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

R :3d Ricci scalar

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

α_K Kinetic term of scalar

α_B "Braiding" between kinetic term of scalar and tensor

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

e.g. Horndeski theory

G. Horndeski, 1974

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

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

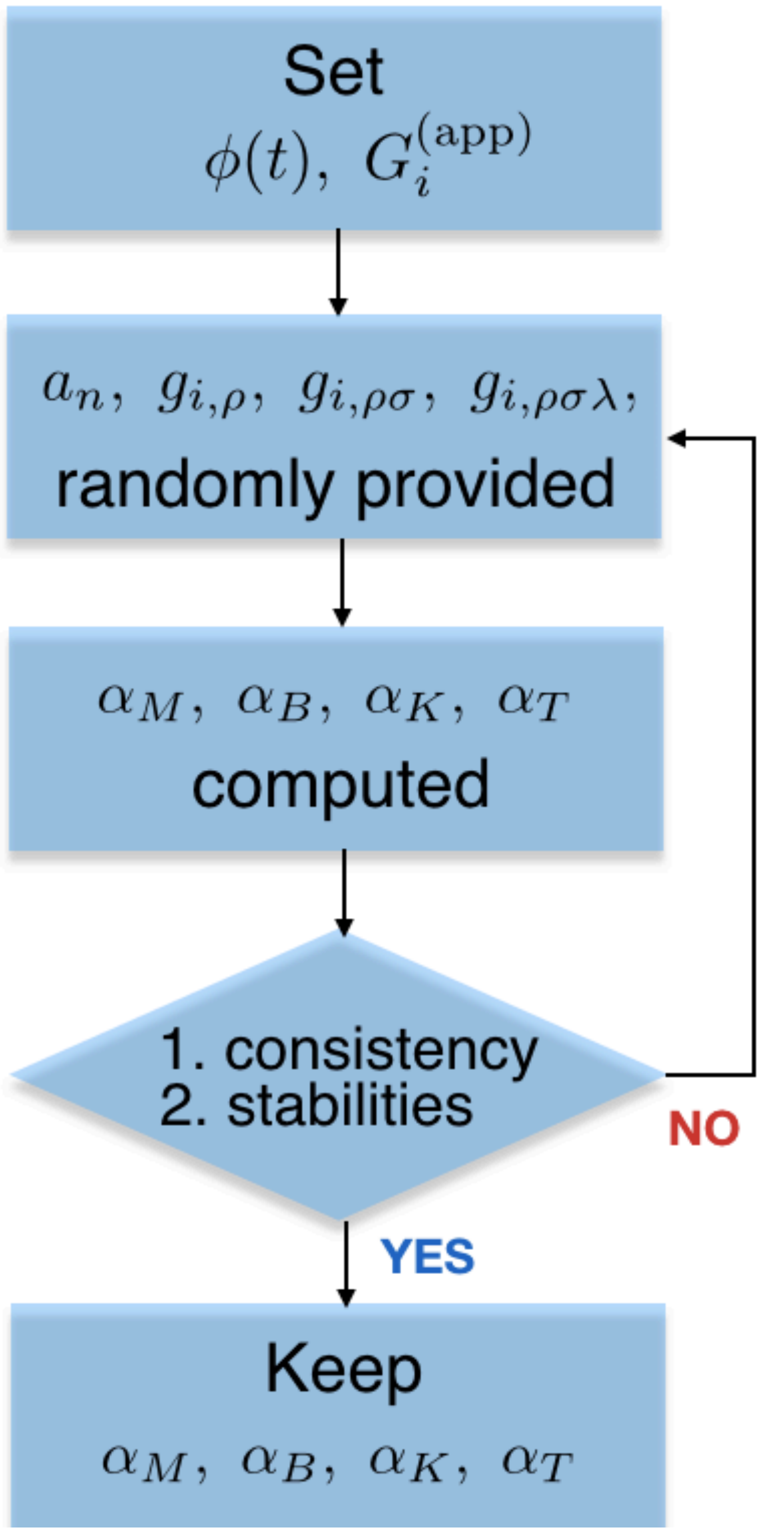
$$X \equiv -\phi^{;\mu}\phi_{;\mu}/2$$

$$\mathcal{L}_2 = G_2(\phi, X),$$
$$\mathcal{L}_3 = -G_3(\phi, X)\Box\phi,$$
$$\mathcal{L}_4 = G_4(\phi, X)R + G_{4X}(\phi, X)\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right],$$
$$\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5X}(\phi, X)\left[(\Box\phi)^3 + 2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\alpha}\phi_{;\alpha}{}^{\mu} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi\right]$$

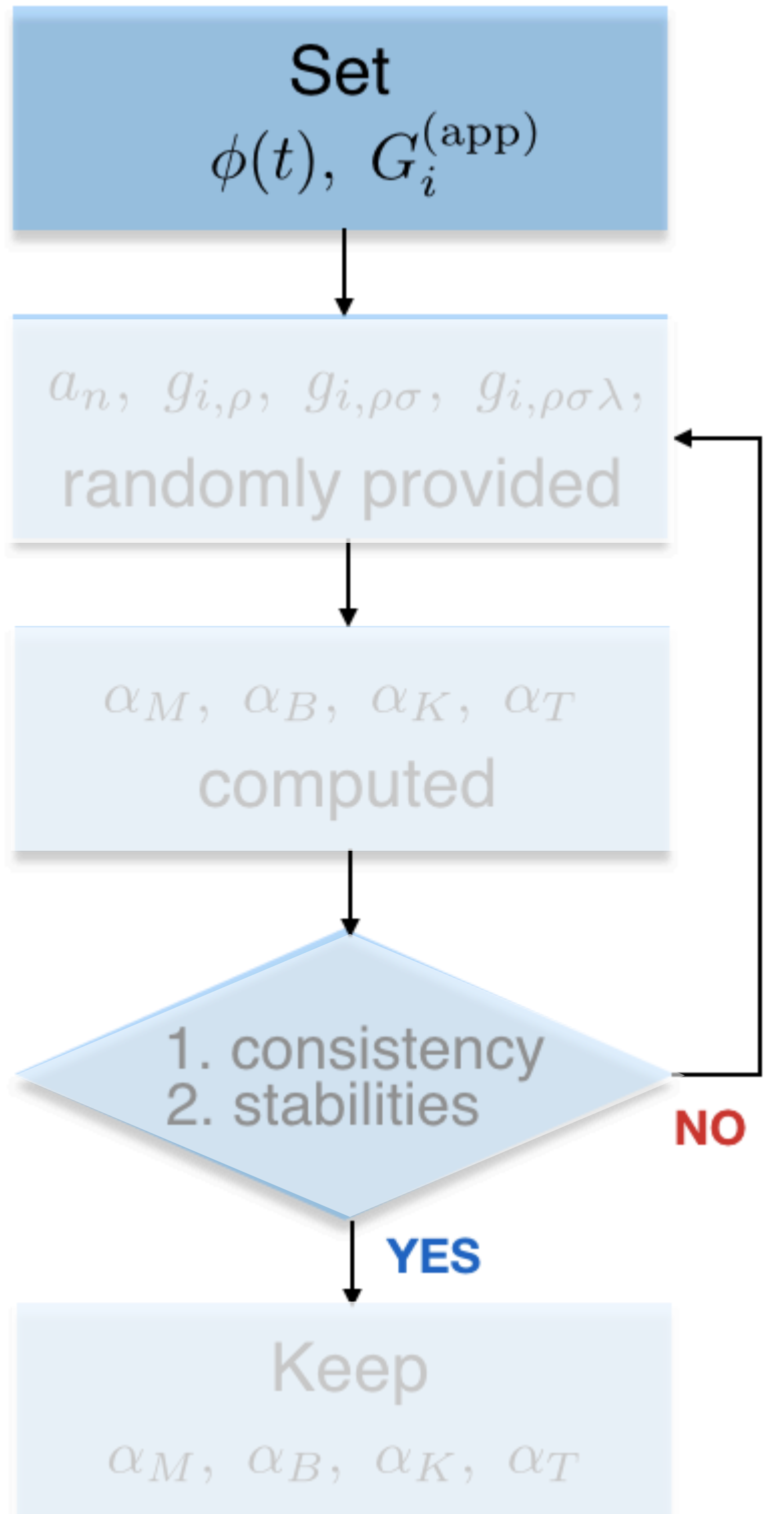
- General framework for1-scalar and 2-tensor d.o.f up to 2nd order space-time derivatives
- Phenomenologically it can explains cosmic acceleration
- Impossible to solve the cosmological evolution in model-independent way

Flow of the numerical model extraction

SA and A.Nishizawa. in arXiv:1711.03776



Numerical model classification and correlation between the EFT couplings



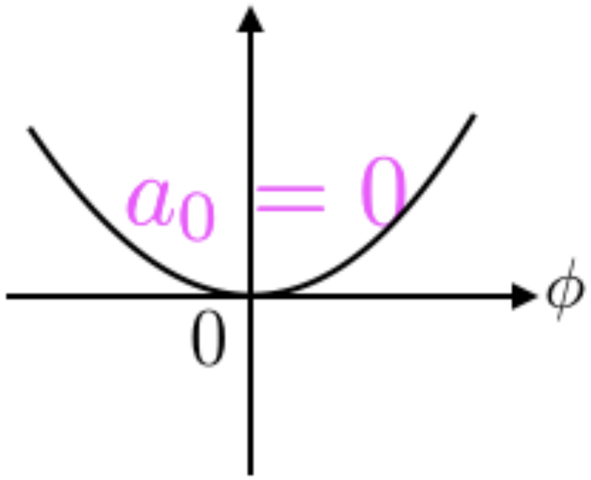
Numerical model classification and correlation between the EFT couplings

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

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

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

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



Planck 2015 best-fit : $H_0 = 67.8\ \mathrm{km \cdot s^{-1} Mpc^{-1}}$ $\Omega_{m0} = 0.3080$

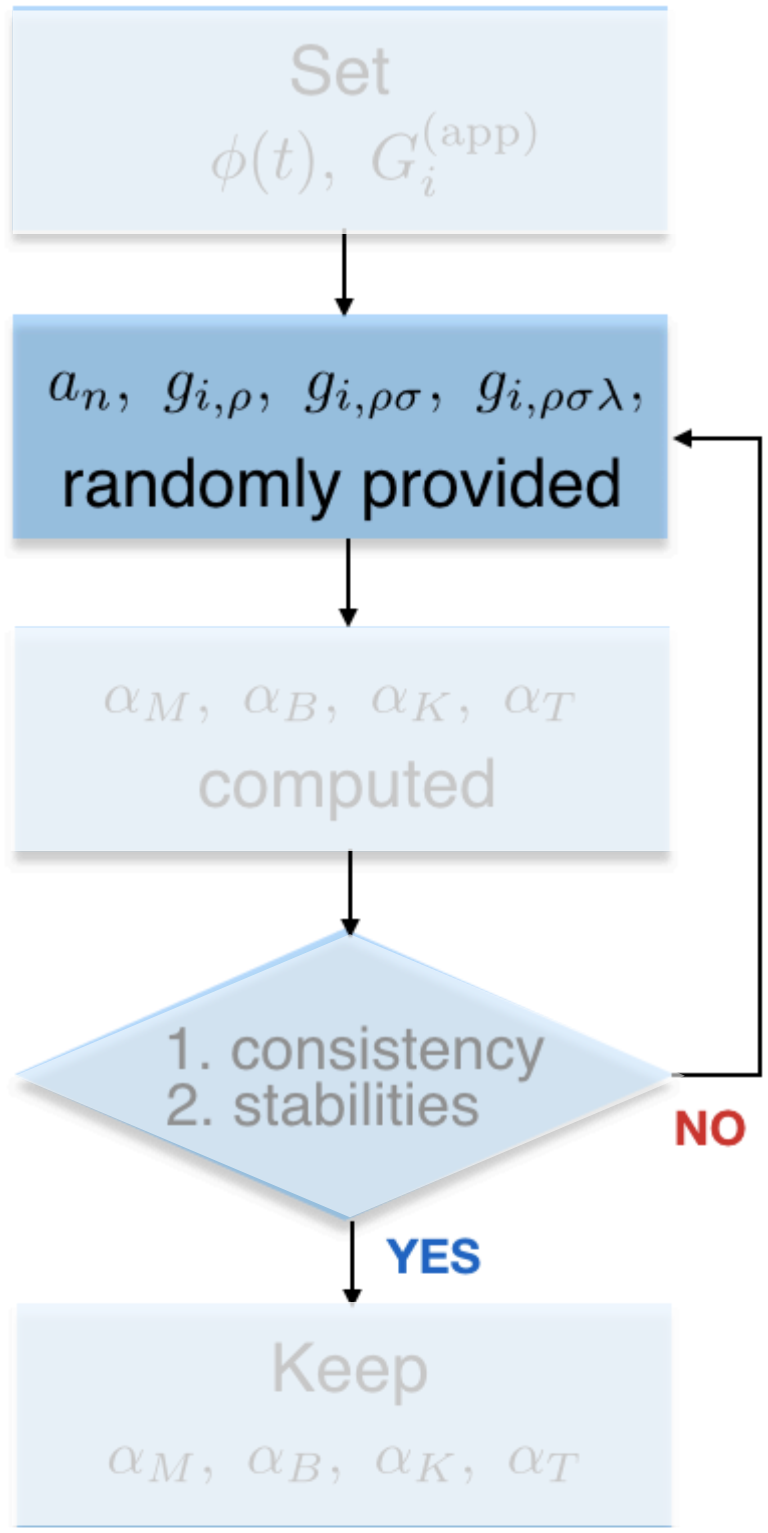
P.Ade. Planck2015

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

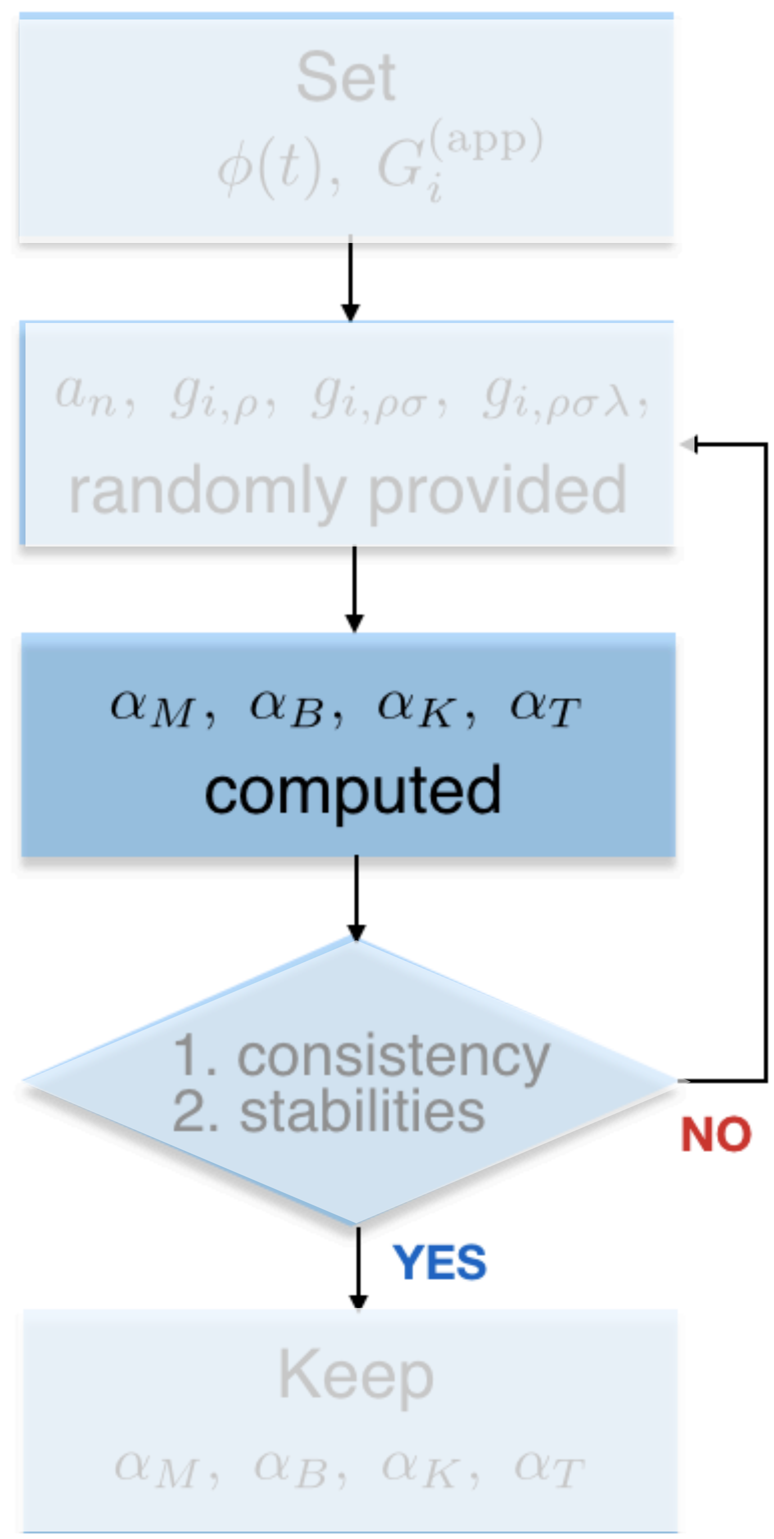
$$g_{i\rho}, g_{i\rho\sigma} (\rho, \sigma = \phi \text{ or } \mathrm{X})$$

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

Numerical model classification and correlation between the EFT couplings



Numerical model classification and correlation between the EFT couplings



Numerical model classification and correlation between the EFT couplings

Set

$$M_*^2 \equiv 2(G_4 - 2XG_{4X} + XG_{5\phi} - \dot{\phi}HXG_{5X})\,, \tag{A1}$$

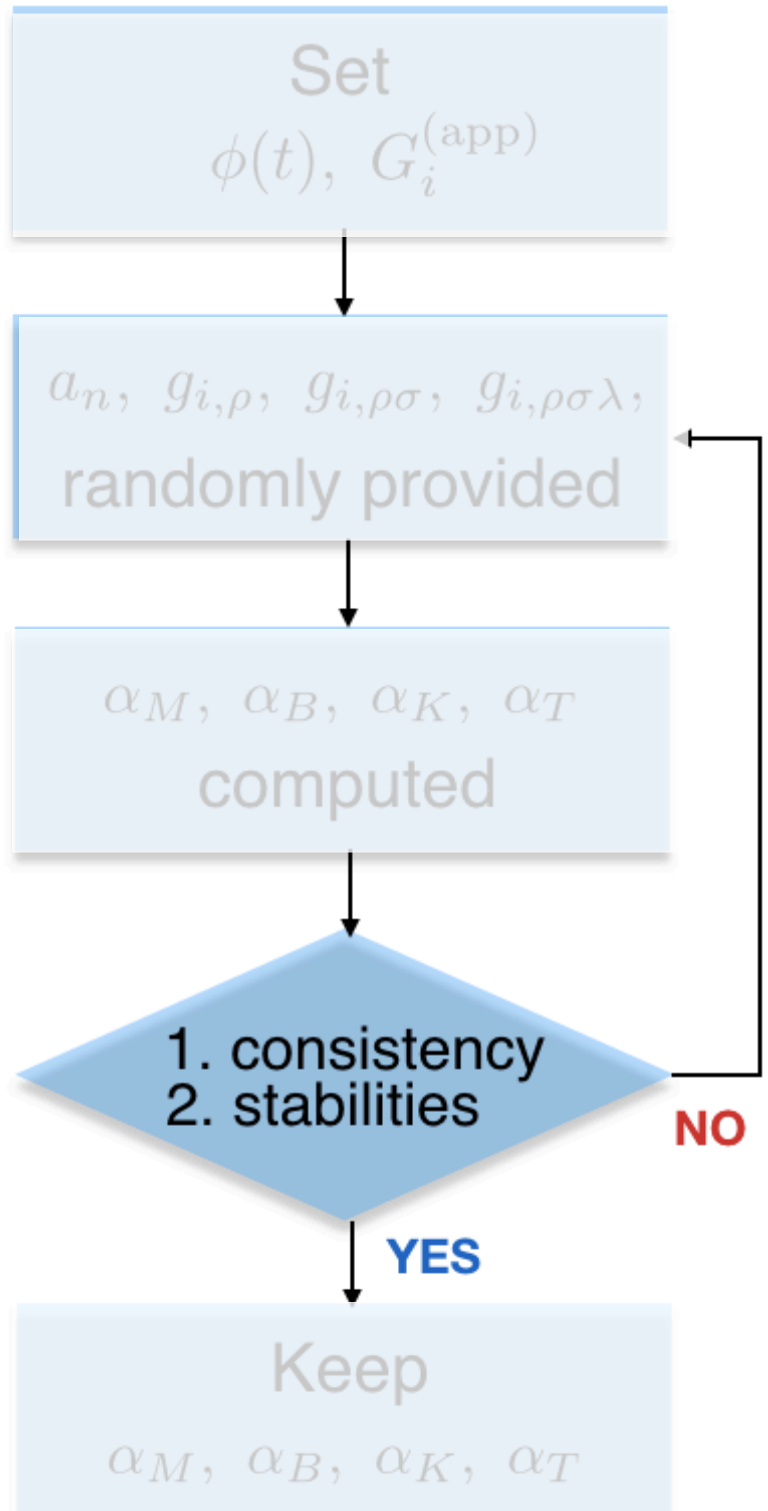
$$HM_*^2\alpha_M \equiv \frac{d}{dt}M_*^2\,, \tag{A2}$$

$$\begin{aligned} H^2M_*^2\alpha_K \equiv\ & 2X(G_{2X} + 2XG_{2XX} - 2G_{3\phi} - 2XG_{3\phi X}) \\ & + 12\dot{\phi}XH(G_{3X} + XG_{3XX} - 3G_{4\phi X} - 2XG_{4\phi XX}) \\ & + 12XH^2(G_{4X} + 8XG_{4XX} + 4X^2G_{4XXX}) \\ & - 12XH^2(G_{5\phi} + 5XG_{5\phi X} + 2X^2G_{5XXX}) \\ & + 4\dot{\phi}XH^3(3G_{5X} + 7XG_{5XX} + 2X^2G_{5XXX})\,, \end{aligned} \tag{A3}$$

$$\begin{aligned} HM_*^2\alpha_B \equiv\ & 2\dot{\phi}(XG_{3X} - G_{4\phi} - 2XG_{4\phi X}) \\ & + 8XH(G_{4X} + 2XG_{4XX} - G_{5\phi} - XG_{5\phi X}) \\ & + 2\dot{\phi}XH^2(3G_{5X} + 2XG_{5XX})\,, \end{aligned} \tag{A4}$$

$$M_*^2\alpha_T \equiv 2X(2G_{4X} - 2G_{5\phi} - (\ddot{\phi} - \dot{\phi}H)G_{5X})\,. \tag{A5}$$

Numerical model classification and correlation between the EFT couplings



Numerical model classification and correlation between the EFT couplings

Set

1. Consistency

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

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

N.B. Currently without any experimental prior (e.g. Planck 2015) but still reasonable

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

2. Stability

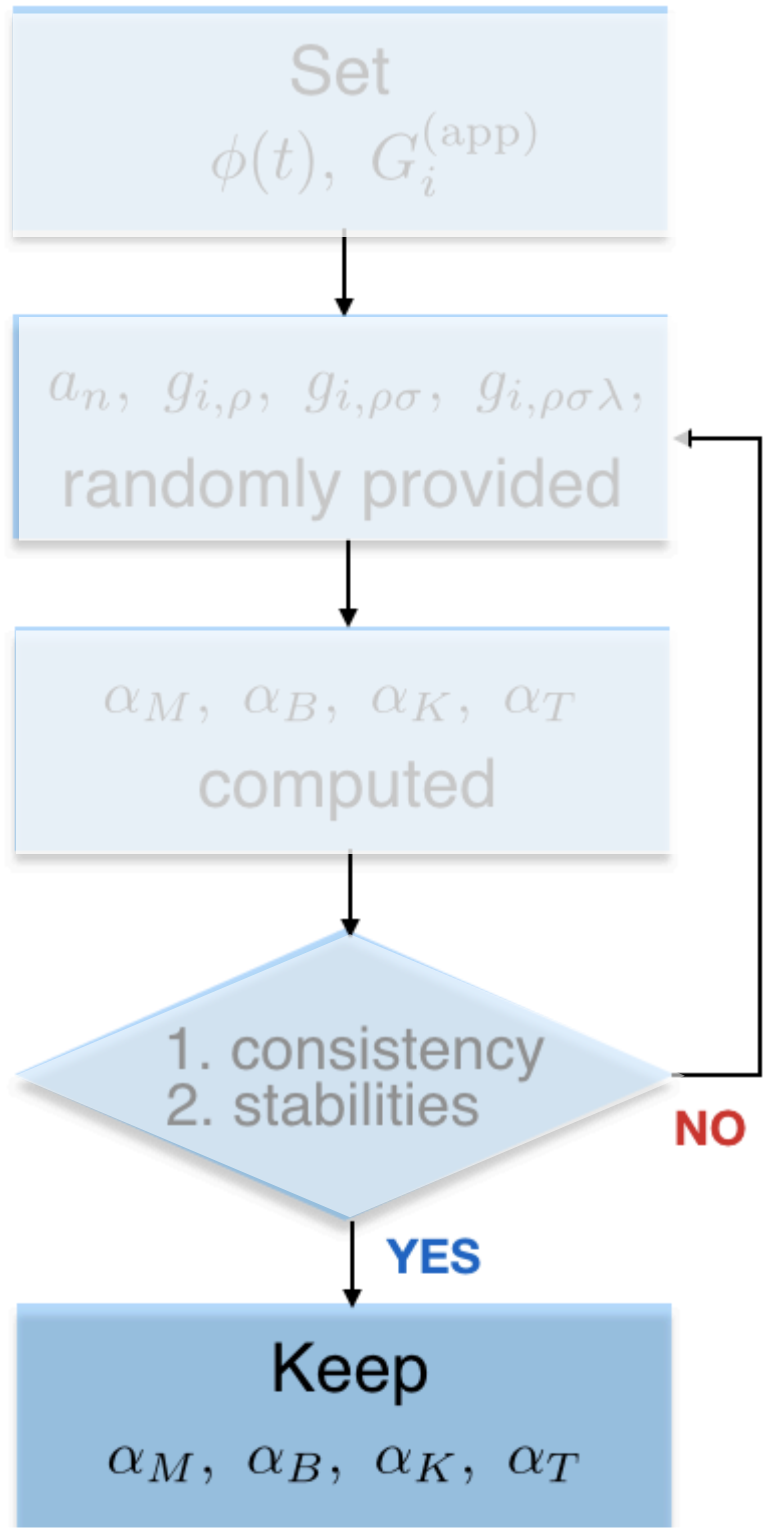
Avoiding ghost and gradient instabilities. i.e. $Q_\sigma > 0, c_\sigma^2 > 0$

for a quadratic action as

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

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

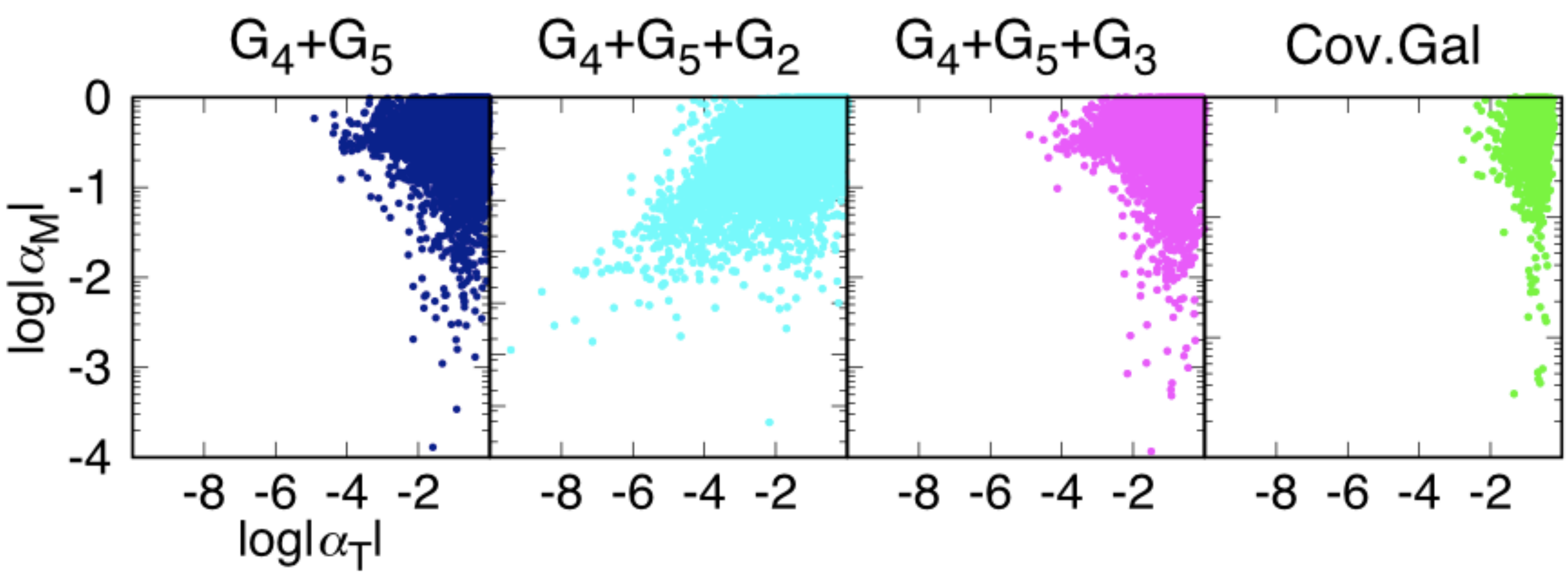
Numerical model classification and correlation between the EFT couplings



Model classification

SA and A.Nishizawa. in arXiv:1711.03776

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



GW observations can significantly distinguish the models

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.)

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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

Impact of GW170817 & GRB170817A

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

GW propagation in Horndeski theory

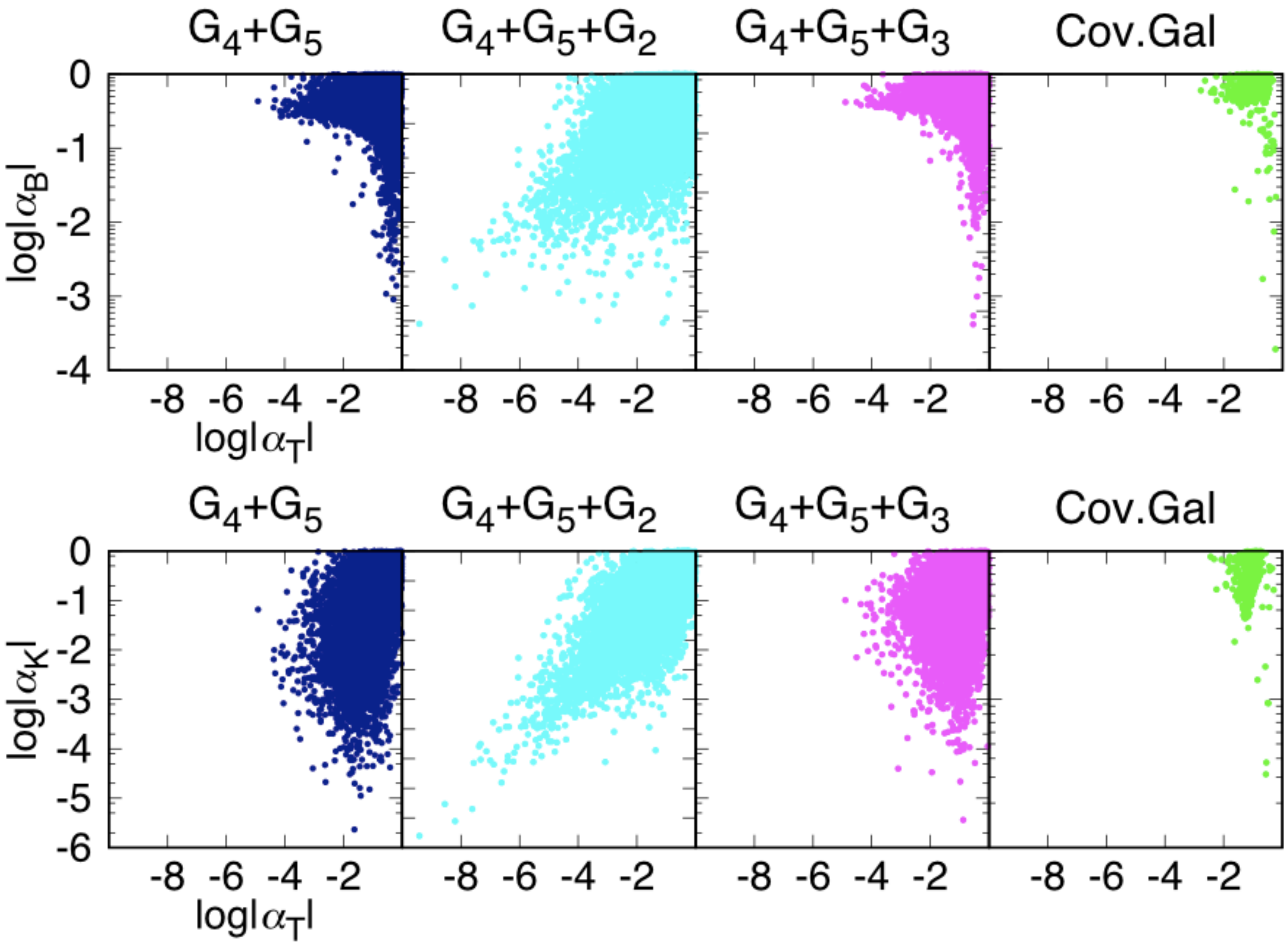
$$h''_{ij} + (2 + \alpha_M)\mathcal{H}h'_{ij} + ({\alpha_T}^2 - 1)k^2 = 0$$

luminosity distance

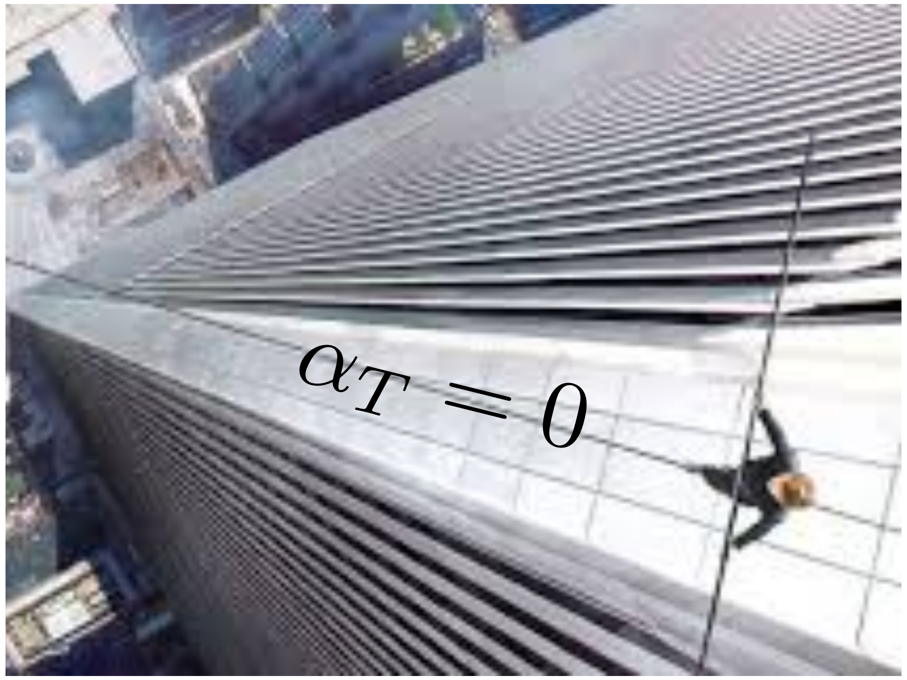
arrival time difference

$$|\alpha_{T,0}| < 10^{-15}$$

Breaking degeneracy between α parameters



Phenomenological implication for coupling hierarchy



unless we set $\alpha_T = 0$ or $|\dot{\phi}/H\phi| \ll 1$
other α parameters have to stay in

$$|\alpha_M| < \mathcal{O}(10^{-2})$$
$$|\alpha_K| < \mathcal{O}(10^{-5})$$
$$|\alpha_B| < \mathcal{O}(10^{-3})$$

ΛCDM model ?

Summary

We developed the numerical formulation to classify the models in the Horndeski theory based on α parameterization, reasonably including observational uncertainties.

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 models with G4 and G5 functions hardly account for cosmic accelerating universe and GW observation at the same time.

c.f. J.M.Ezquiaga and M.Zumalacarregui 2017

Unless $\alpha_T = 0$, it is inevitable to set all the αs to be smaller.

caveats

- $|\alpha_T| < 10^{-15}$ is confirmed only at one redshift
  → multiple GW detections are significant
  SA and A.Nishizawa. in arXiv:1711.03776
- Models with $\alpha_T = 0$ potentially predict large values for the αs
  → GW +Other cosmological observations are essential

Back Up

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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0.179	75	4
0.199	75	5
0.200	72.9	29.6
0.270	77	14

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

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

$$@ z \sim 0.1$$

Self Acceleration

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

$$\Omega(t) \qquad \nu \equiv \frac{1}{M_*^2 H}\frac{dM_*^2}{dt}$$

in the language of the EFT

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

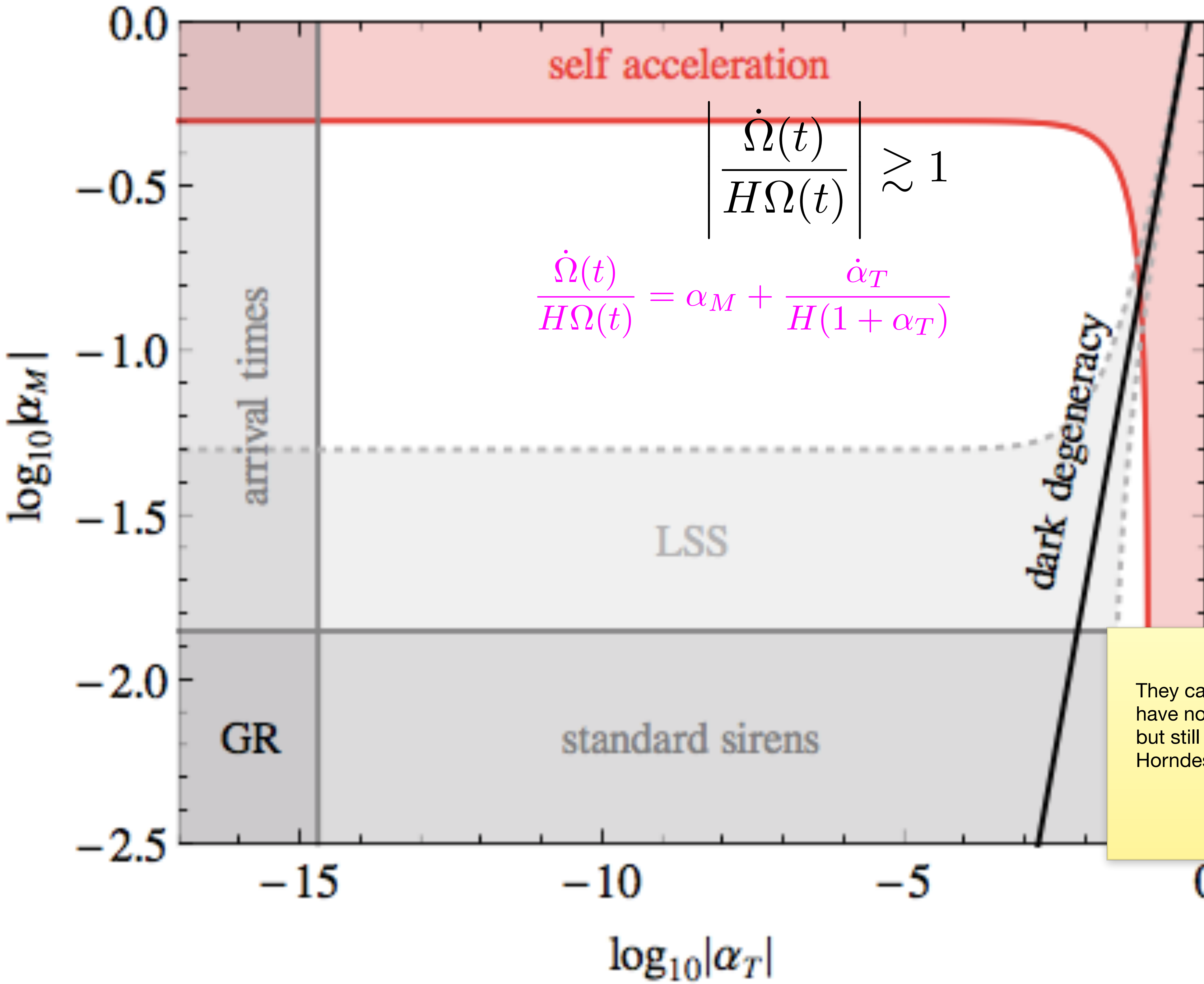
N.B 1. We here use the notation as same as EFT of DE.
N.B 2. This way of acceleration is ONLY seen in the Jordan frame.

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

L.Lombriser & A.Taylor JCAP 2016

Lombriser & Taylor 2016

L.Lombriser & A.Taylor JCAP 2016



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

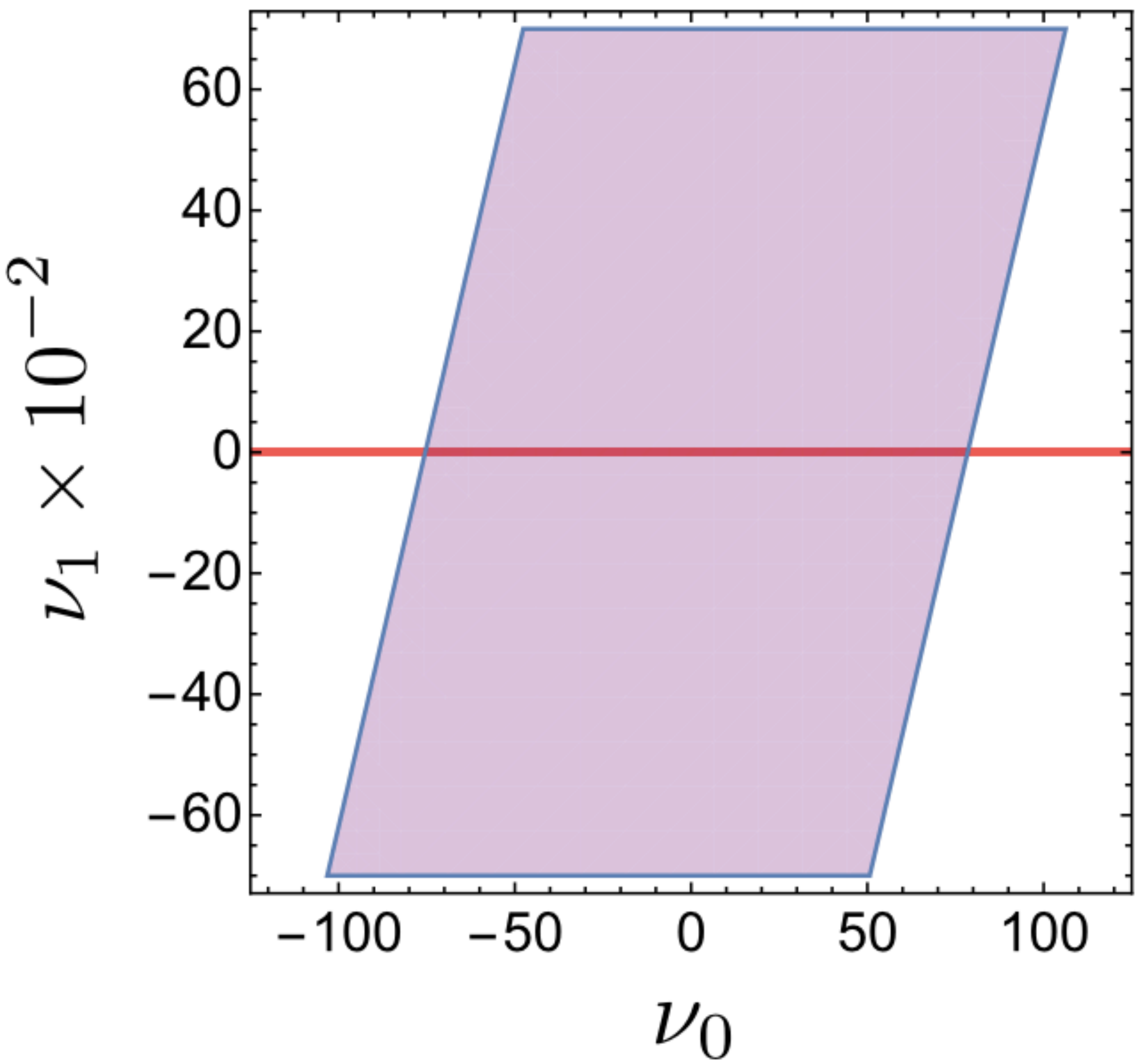
Models in the EFT-parameterization

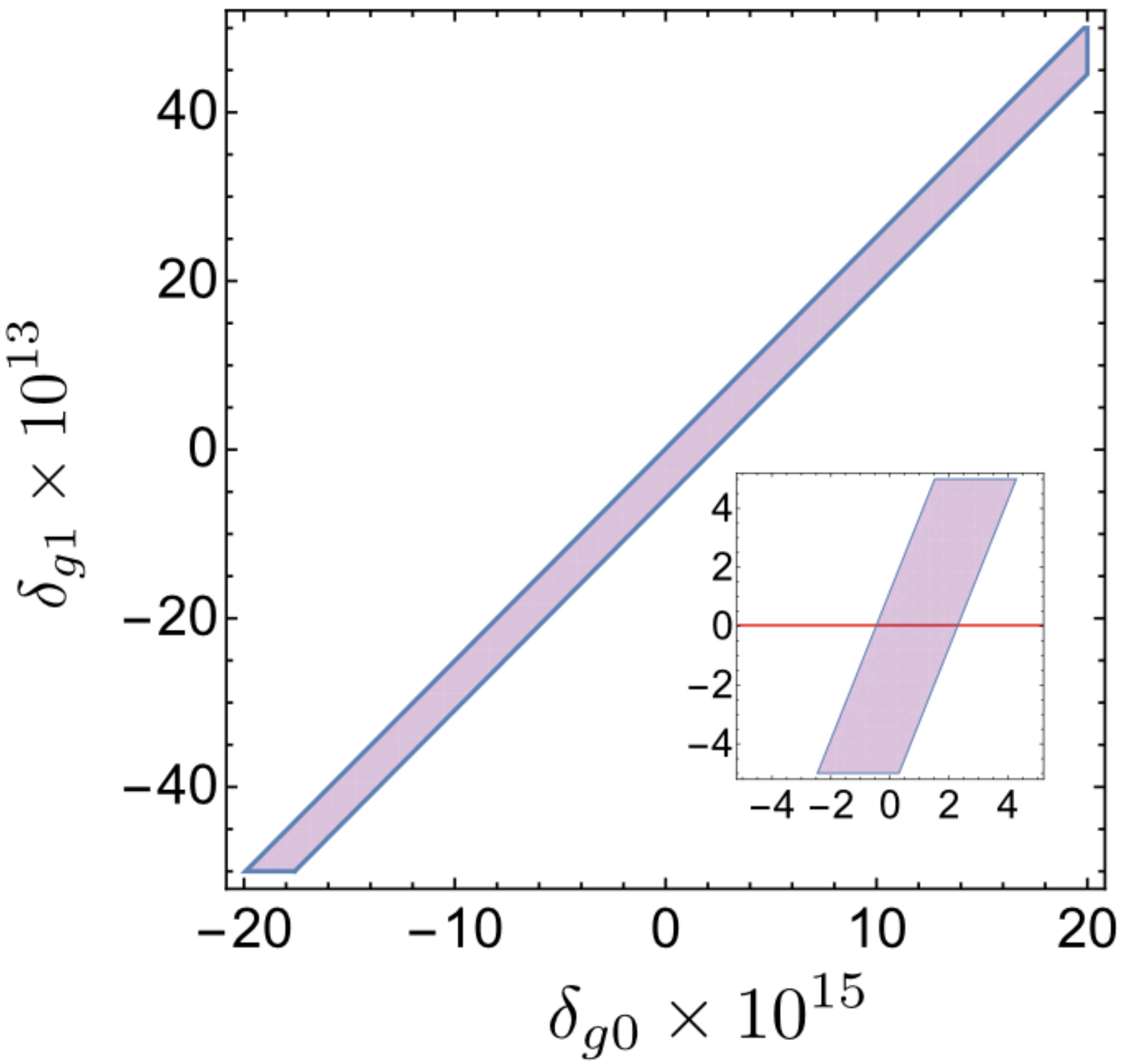
E.Bellini & I.Sawicky JCAP 2014

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]	$(1-\Omega_m)(1+w_X)$	0	0	0
k-*essence*/perfect fluid	[45, 46]	$\frac{(1-\Omega_m)(1+w_X)}{c_s^2}$	0	0	0
kinetic gravity braiding	[47–49]	$m^2(n_m+\kappa_\phi)/H^2 M_{Pl}^2$	$m\kappa/H M_{Pl}^2$	0	0
galileon cosmology	[57]	$-3/2\alpha_M^3 H^2 r_c^2 e^{2\phi/M}$	$\alpha_K/6 - \alpha_M$	$-2\dot{\phi}/HM$	0
BDK	[26]	$\dot{\phi}^2 K_{,\dot{\phi}\dot{\phi}} e^{-\kappa}/H^2 M^2$	$-\alpha_M$	$\dot{\kappa}/H$	0
metric $f(R)$	[3, 72]	0	$-\alpha_M$	$B\dot{H}/H^2$	0
MSG/Palatini $f(R)$	[73, 74]	$-3/2\alpha_M^2$	$-\alpha_M$	$2\dot{\phi}/H$	0
f(Gauss-Bonnet)	[52, 75, 76]	0	$\frac{-2H\dot{\xi}}{M^2+H\dot{\xi}}$	$\frac{\dot{H}\dot{\xi}+H\ddot{\xi}}{H(M^2+H\dot{\xi})}$	$\frac{\ddot{\xi}-H\dot{\xi}}{M^2+H\dot{\xi}}$

Observational bounds from GW170817

SA and A.Nishizawa. in arXiv:1711.03776





$$-75.3 \leq \nu_0 \leq 78.4$$

$$-4.7 \times 10^{-16} \leq \delta_{g0} \leq 2.2 \times 10^{-15}$$