Testing Gravity: Connecting **Th**eoretical developments to forthcoming **Obs**ervations

[Testing Gravity:Th×Obs]

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2023/11/20 MOGRA2023

Our review paper is now accessible!

PTEP

Prog. Theor. Exp. Phys. **2023** 072E01(105 pages)
DOI: 10.1093/ptep/ptad052

Cosmological gravity probes: Connecting recent theoretical developments to forthcoming observations

Shun Arai[1,⋆], Katsuki Aoki[2], Yuji Chinone[3,4], Rampei Kimura[5], Tsutomu Kobayashi[6], Hironao Miyatake[1,4,7], Daisuke Yamauchi[8], Shuichiro Yokoyama[1,4], Kazuyuki Akitsu[9], Takashi Hiramatsu[6], Shin'ichi Hirano[10], Ryotaro Kase[11], Taishi Katsuragawa[12], Yosuke Kobayashi[13], Toshiya Namikawa[4], Takahiro Nishimichi[2,4,14], Teppei Okumura[4], Maresuke Shiraishi[15], Masato Shirasaki[16,17], Tomomi Sunayama[13,18], Kazufumi Takahashi[2], Atsushi Taruya[2,4], and Junsei Tokuda[19,20]

- Prog. Theor. Exp. Phys. (2023)7, 072E01
- arXiv:2212.09094

A collective **dictionary** of gravity theory

How the effect of gravity are captured in **observations**

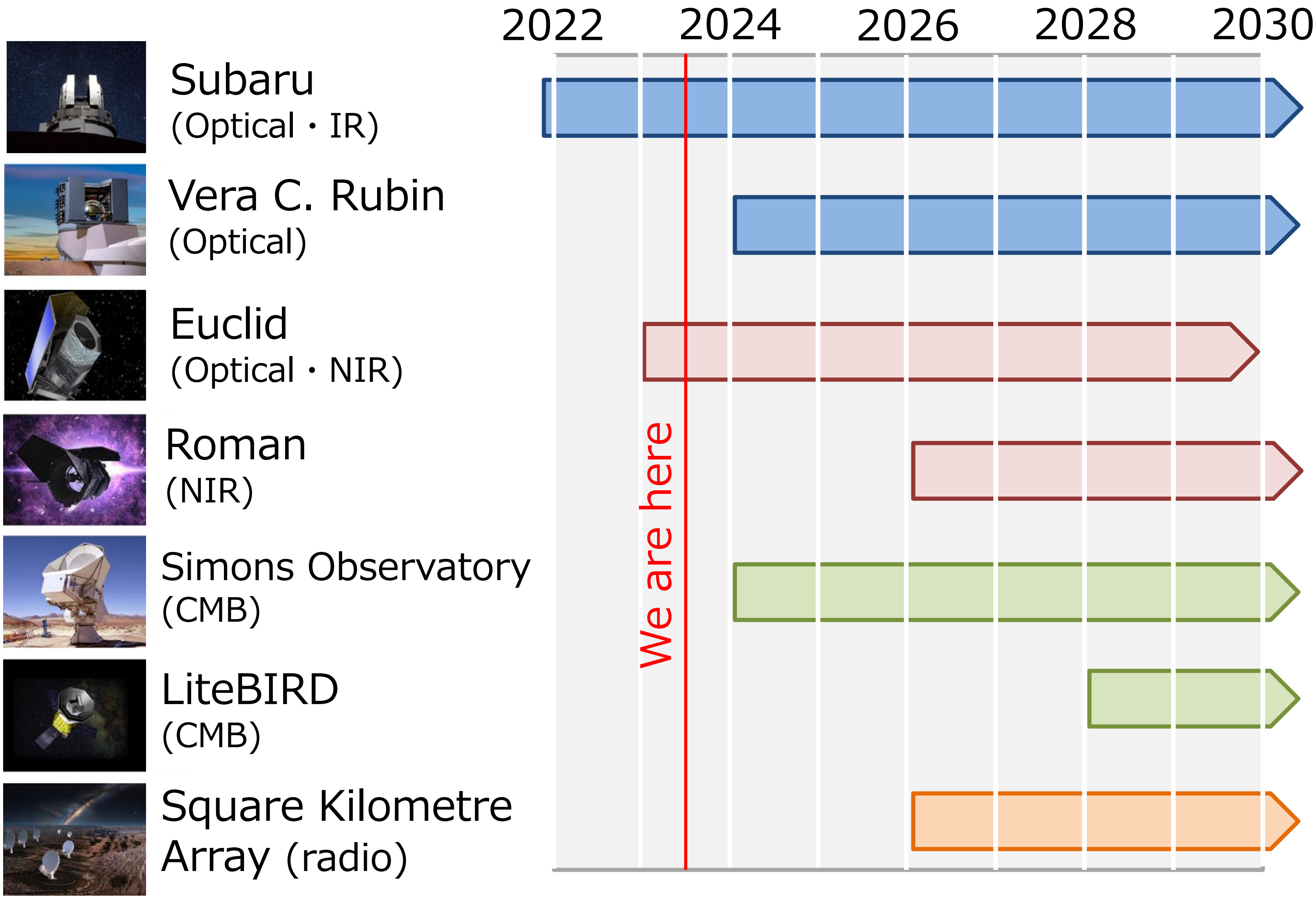
Concrete **predictions** from theories by analytic computations

Numerical tools

Our **high-priority** subjects

1. Current status

Golden Age of Observational Cosmology



Golden Age of Observational Cosmology

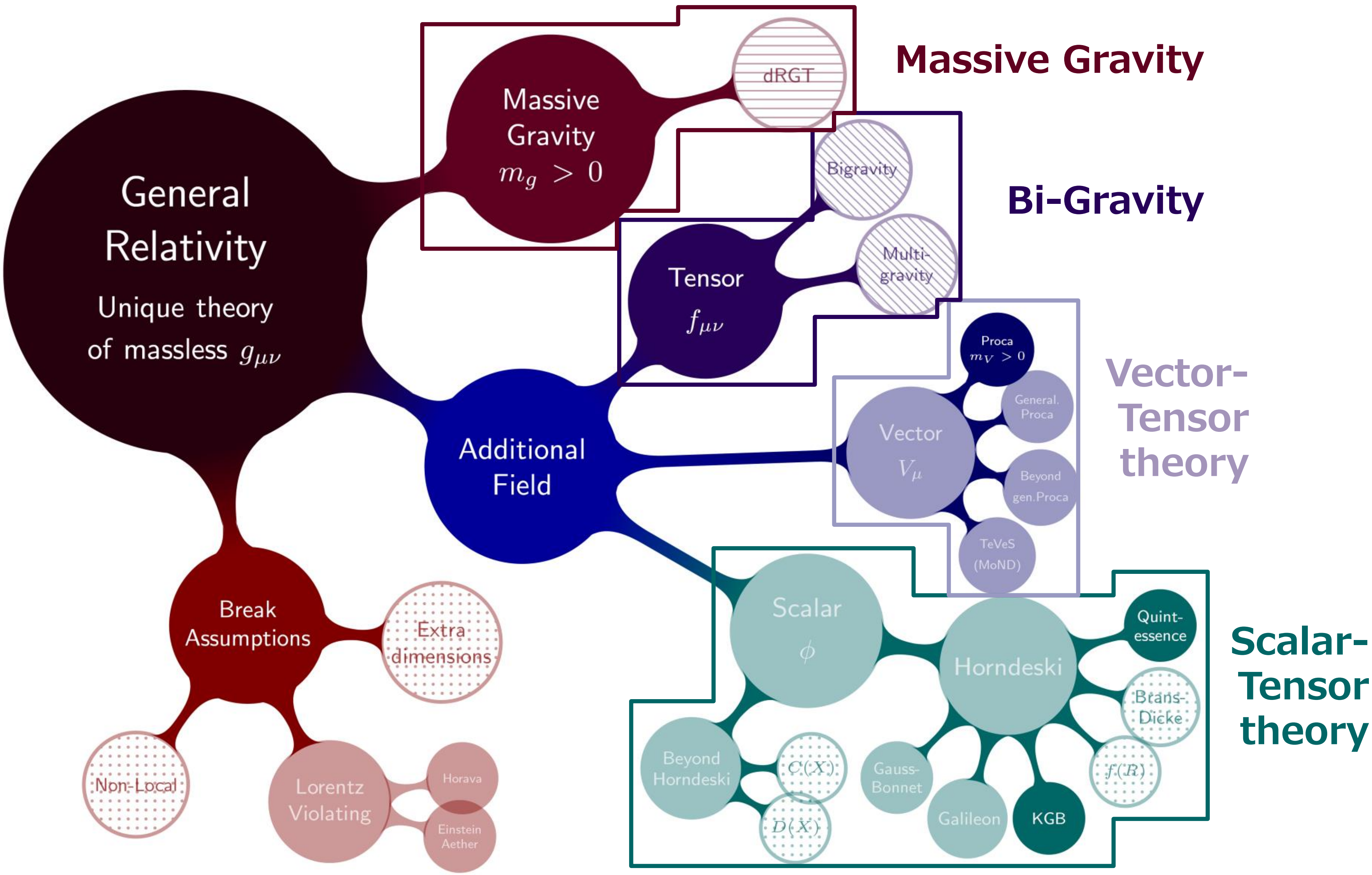
Near-future observations will provide **vast high-quality data** suitable for proving gravity theory on large scales.

↓

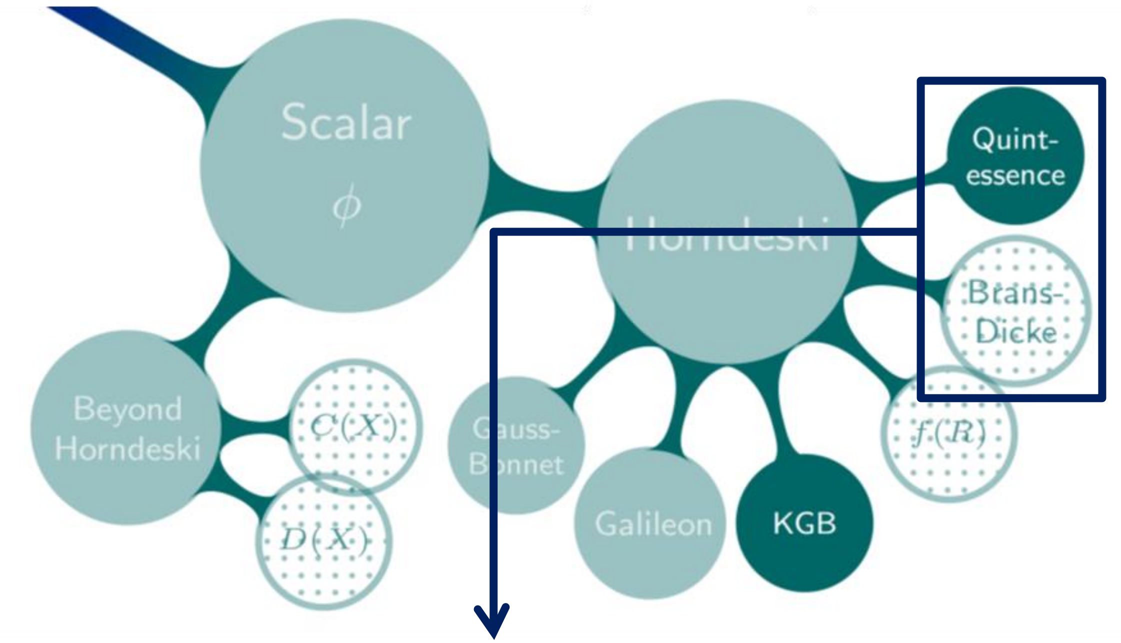
We now need to prepare **well-motivated theory** and **appropriate observables** that can indicate any signs beyond GR!

[Figure from Ezquiaga+Zumalacarregui, Front.Astro.Space.Sci 5(2018)44]

Landscape of Gravity Theory



Example: Scalar-Tensor Theories



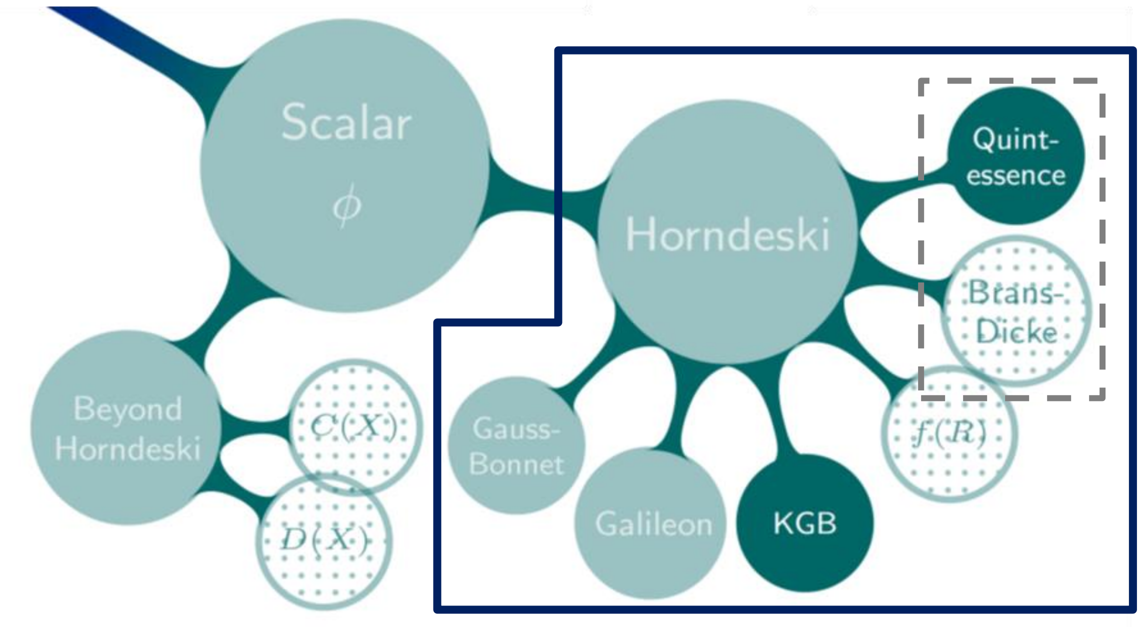
- (Old) well-known theories: Only <u>one</u> parameter

$$\mathcal{L} = \frac{1}{2}\left[\phi R - \frac{\omega}{\phi}(\partial\phi)^2\right]$$

[Brans+Dicke,Phys.Rev.124,925(1961),⋯]

The feasibility can be discussed on a **model-by-model** basis.

Example: Scalar-Tensor Theories



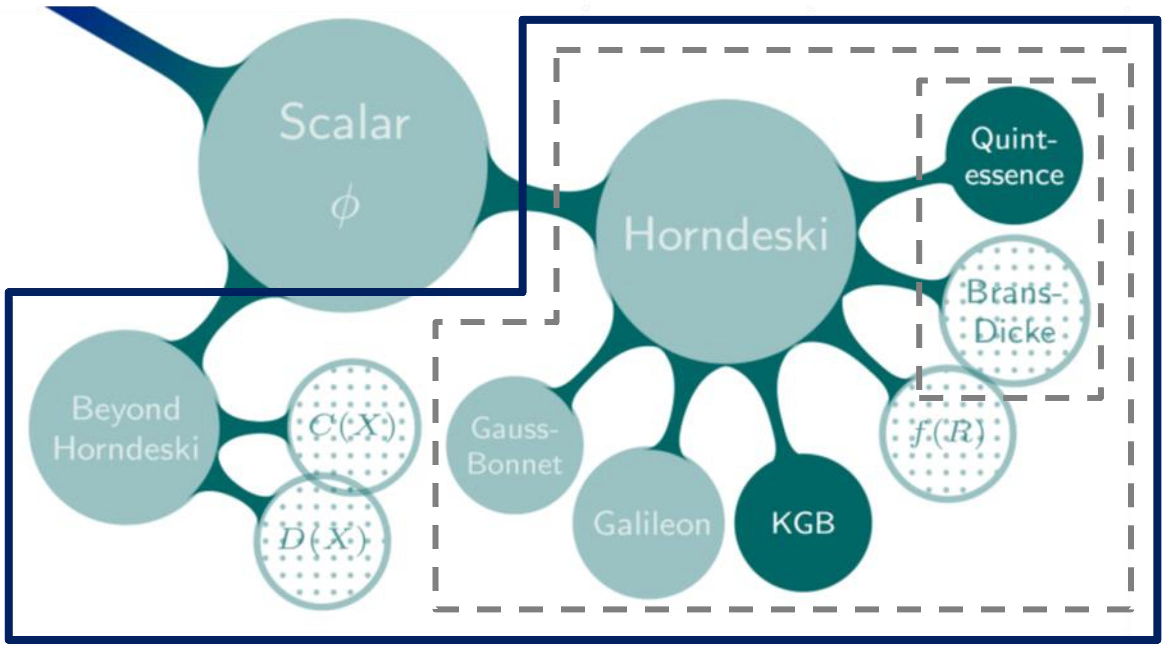
This provides
a bird's eye view
understanding.

◆ Horndeski theory: 4 arbitrary functional DoF

$$\mathcal{L} = P(\phi, X) - Q(\phi, X)\Box\phi + G_4(\phi, X)R - \frac{\partial G_4}{\partial X}\left(\nabla_\mu \nabla_\nu \phi\right)^2 + \cdots$$

[Horndeski,Int.J.Theor.Phys.10,363(1974),
Deffayet+,PRD84,063039(2011),
Kobayashi+Yamaguchi+Yokoyama,PTP126,511(2011)]

Example: Scalar-Tensor Theories



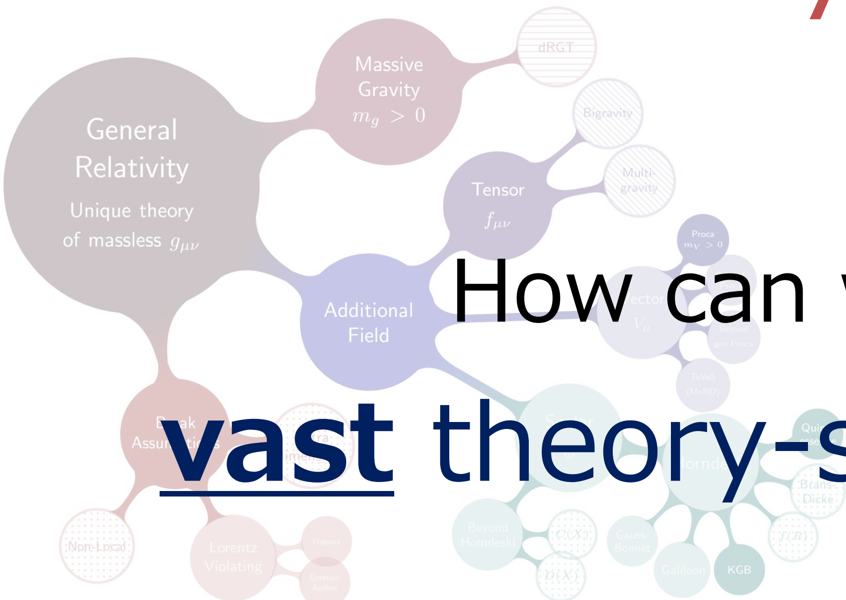
This gives a deeper understanding of its **stability**.

◆ DHOST (Degenerate Higher-Order Scalar-Tensor theory) : 15 DoF!

$$\mathcal{L} = \cdots + f(\phi, X)R + A_1(\phi, X)\left(\nabla_\mu \nabla_\nu \phi\right)^2 + \cdots$$

[Langlois+Noui,JCAP02,034(2015),
Crisostomi+,JCAP04,044(2016),
Ben Achour+,PRD93,124005(2016)]

Today's topic

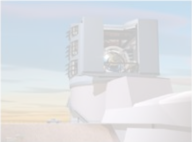


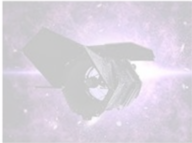
How can we compare

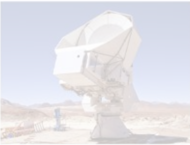
<u>vast</u> theory-space of gravity

to

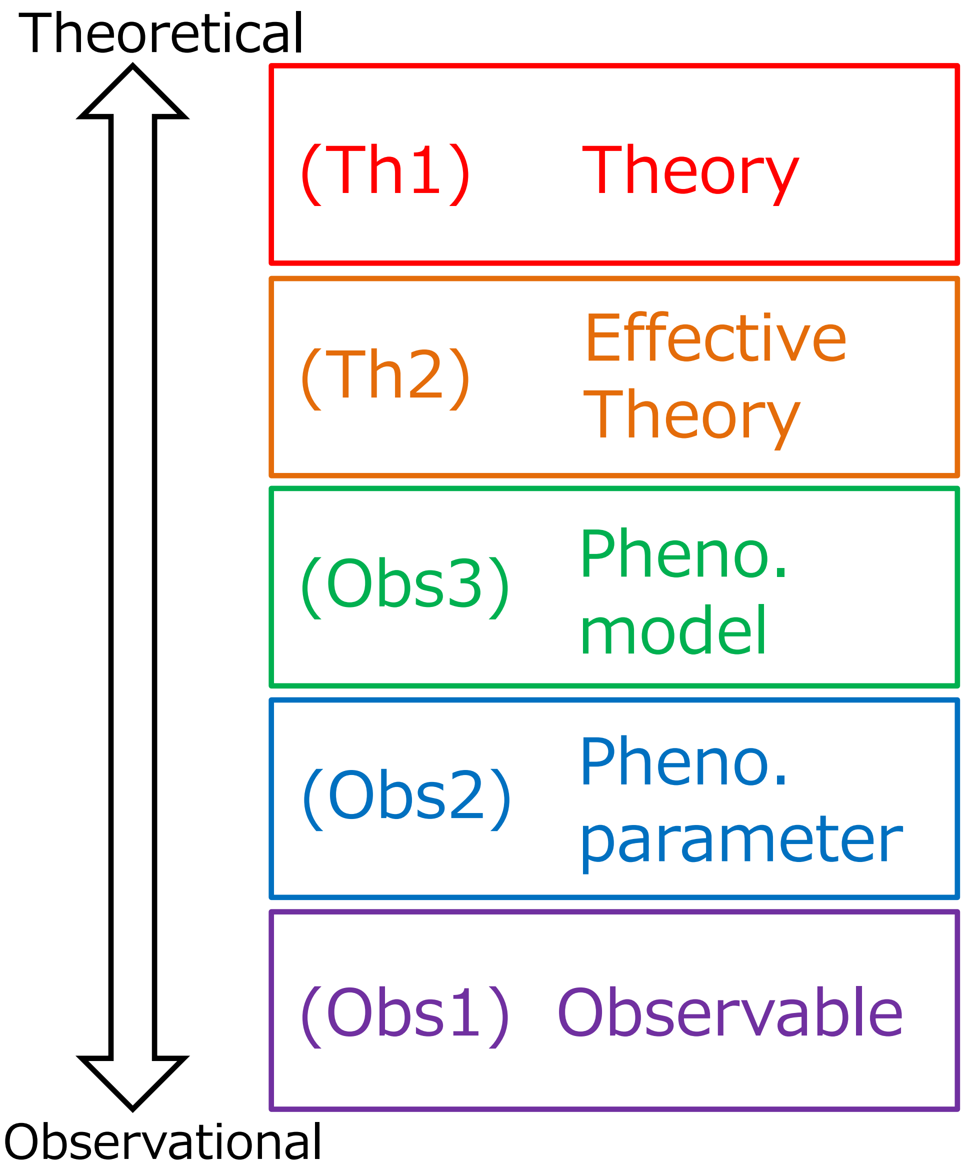
<u>forthcoming</u> cosmological observations ?







Take-Home Message



- Main message:
  A **hierarchical structure** exists in the cosmological test of gravity.

It is essential to link each hierarchy appropriately:

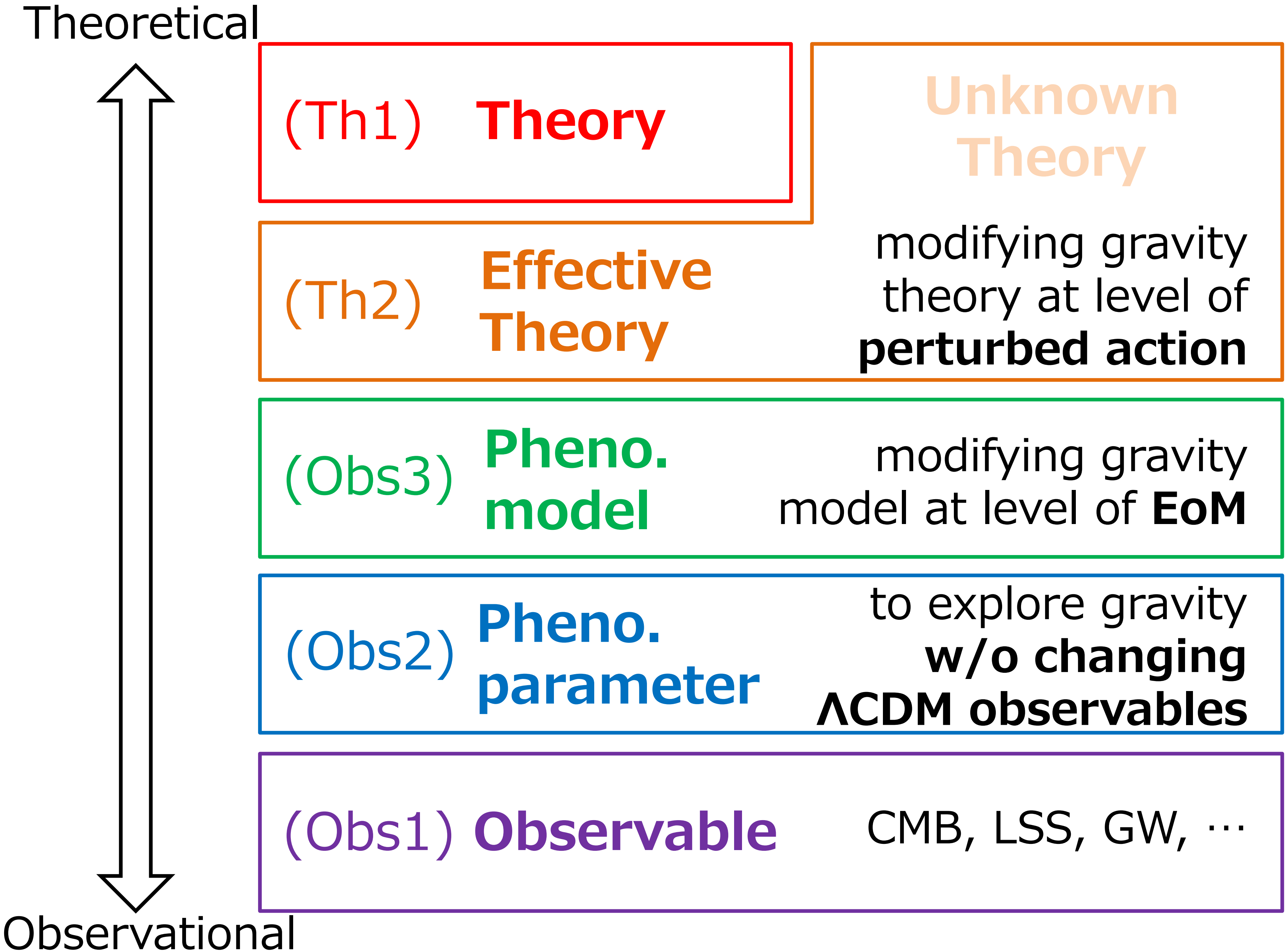
The key is to connect **Th**eoretical studies with **Obs**ervational ones!

2. Hierarchical structure from theory to observation (or vise versa)

(Th1) **Theory** F(R) , Horndeski, ···

Can we compare
(full-)theory of gravity
to
observational data
directly ?

(Obs1) **Observable** CMB, LSS, GW, ···



Theoretical
Observational
(Th1) Theory
Unknown Theory
(Th2) Effective Theory
modifying gravity theory at level of perturbed action
(Obs3) Pheno. model
modifying gravity model at level of EoM
(Obs2) Pheno. parameter
to explore gravity w/o changing ΛCDM observables
(Obs1) Observable
CMB, LSS, GW, ···

(Obs2) Pheno. parameter
: w/o changing ΛCDM observables

◆ Background level: Hubble expansion rate

$$H^2(a) = H_0^2 \left[\frac{\Omega_{\mathrm{m},0}}{a^3} + \Omega_{\mathrm{DE},0} \exp\left(-3 \int_1^a \left[1 + \boxed{w_{\mathrm{DE}}(a')} \right] \mathrm{d} \ln a' \right) \right]$$

Dark Energy Equation-of-State

◆ Perturbed level: Growth rate of density fluct.

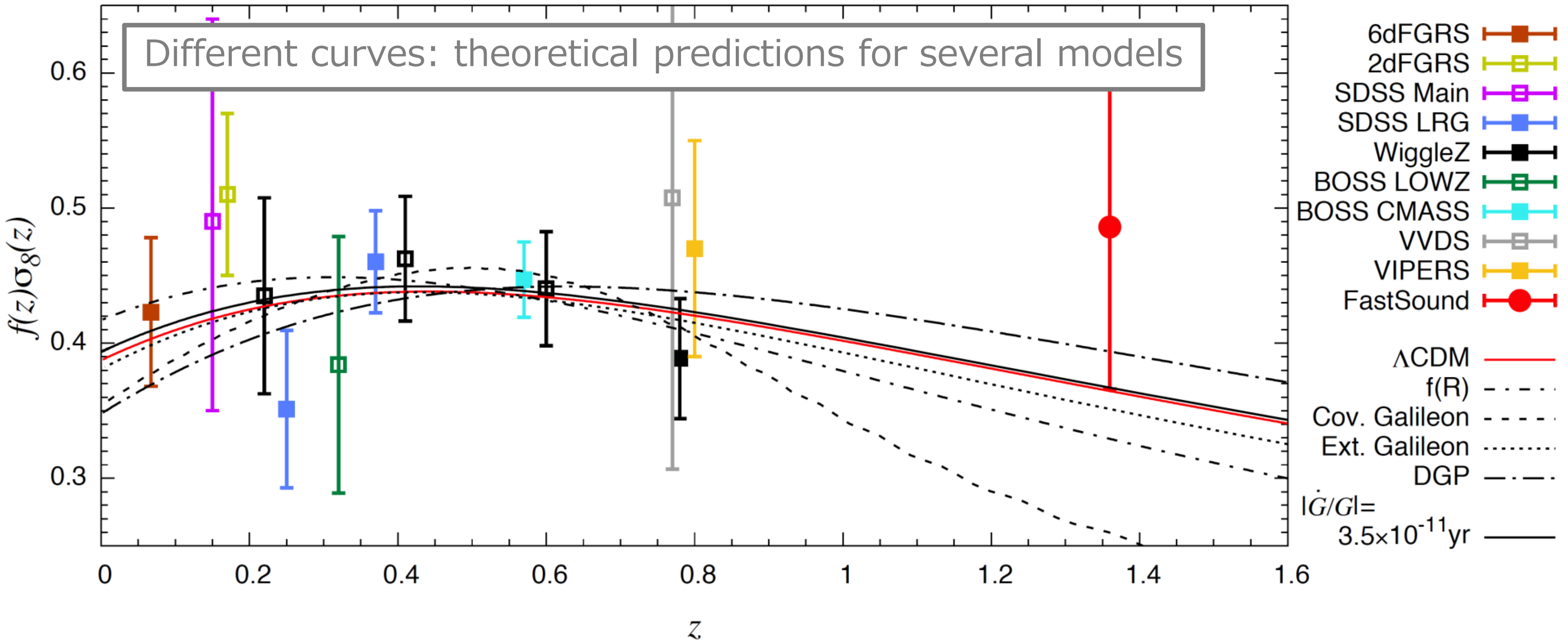
$$\delta(a, \boldsymbol{k}) = \exp\left(\int_0^a \boxed{f(a')} \, \mathrm{d} \ln a' \right) \delta_*(\boldsymbol{k})$$

Linear growth rate

(Obs2) Pheno. parameter
: w/o changing ΛCDM observables

◆ Measuring ***f*** from RSD is frequently used for test of gravity responsible for current acceleration.

FastSound [Okumura+] PASJ68,3,38(2016)



Q. Are $w_{\rm DE}$ & f enough to test gravity?

A. **NOT** enough. Even if $w_{\rm DE}$=-1, f=$f_{\rm GR}$, it is **NOT** necessary that our Universe is described by ΛCDM with GR.

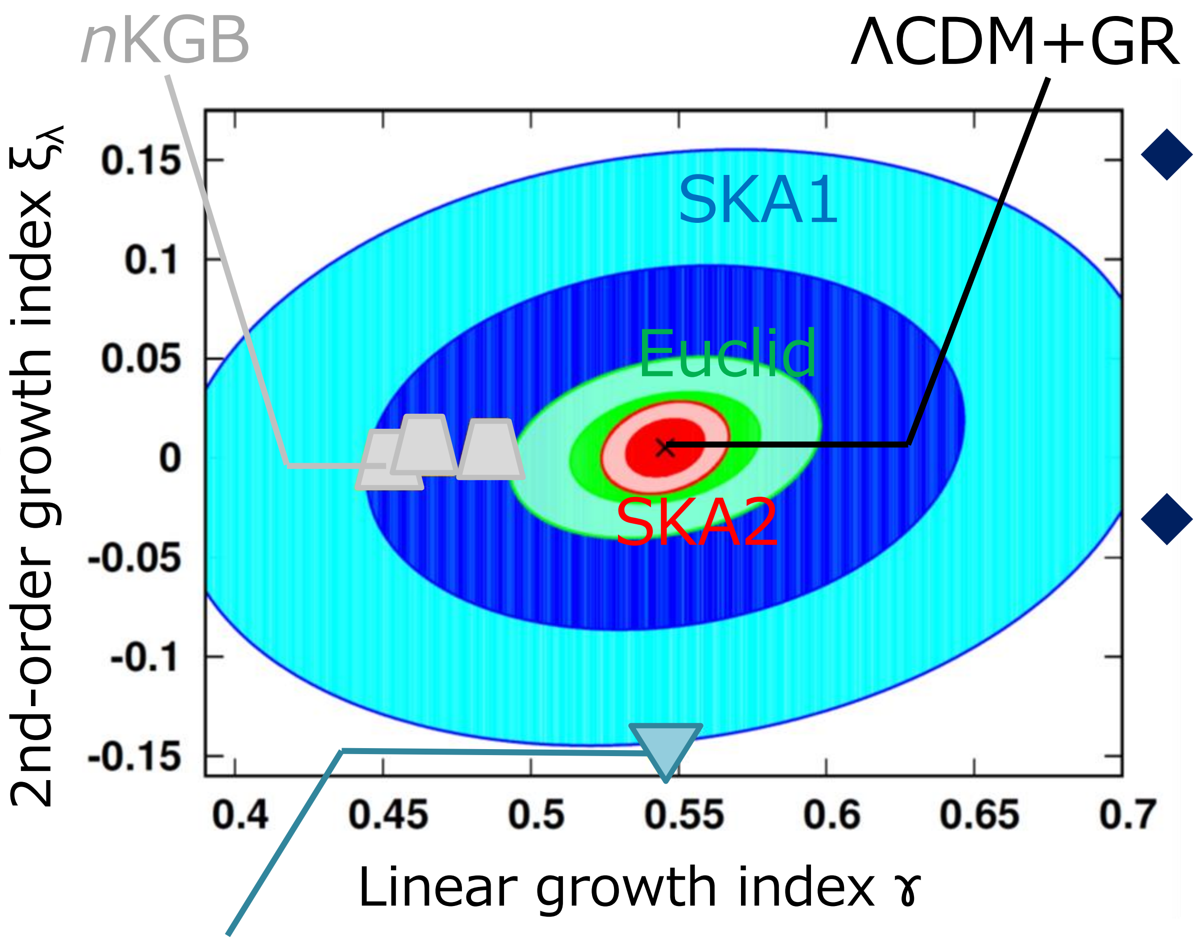
Nonlinear growth can carry new information that is not included in linear-order.

$$\delta(a,\boldsymbol{k}) = \delta_1(a,\boldsymbol{k}) + \int \frac{\mathrm{d}^3\boldsymbol{p}}{(2\pi)^3} \boxed{F_2(a,\boldsymbol{p},\boldsymbol{k}-\boldsymbol{p})}\, \delta_1(a,\boldsymbol{p})\delta_1(a,\boldsymbol{k}-\boldsymbol{p}) + \cdots$$

(quasi-)nonlinear growth

[Takushima+(2014,2015),**DY**+(2017),Namikawa+(2018), Hirano+(2018),Hirano+**DY**+(2020),**DY**+Sugiyama(2022), **DY**+(2023),Sugiyama+**DY**+(2023a,b),Yamashita+**DY**+(in prep.)]

(Obs2) Nonlinear growth
: to extract higher-order contributions



A model from Horndeski theory
(specific model with w_{DE}=-1, f=f_{GR})

- Nonlinear growth index (ξ_λ) can be used to distinguish various models!
- Note: Mapping of these parameters to specific theories is **not** fully understood.

DY+,PRD96,123516(2017)
Namikawa+,PRD98,043530(2018)

(Obs3) Pheno. model

: modifying gravity at level of EoM

◆ Non-relativistic matter feels

$$\ddot{\delta} + 2H\dot{\delta} + \frac{1}{a^2}\nabla^2\Phi = 0$$

Gravitational potential (δg_{00})

This term depends on gravity model via **Poisson equation**:

$$\nabla^2\Phi = 4\pi G a^2 \rho\delta$$

We add phenomenological functional DoF $\mu(a,k)$

(Obs3) Pheno. model

: modifying gravity at level of EoM

- Relativistic matter feels:

$$\nabla^2(\Phi + \Psi) = 8\pi G a^2 \rho \delta$$

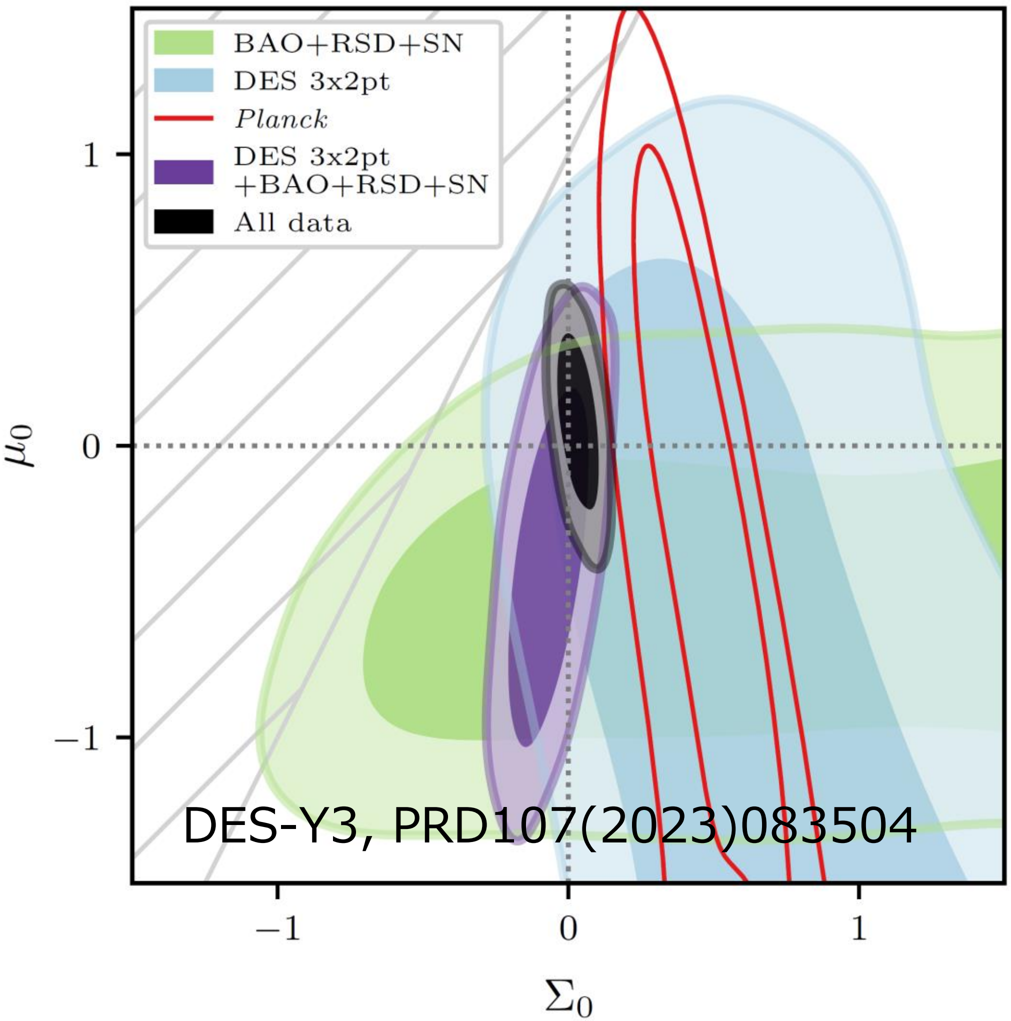
Gravitational potential (δg_{ij})

Phenomenological functional DoF $\Sigma(a, k)$

✓ Note: To practically obtain the constraints, a functional form of μ & Σ should be specified.

(Obs3) Pheno. model

: modifying gravity at level of EoM



- A specific choice of functional forms:

$$\mu(a) = 1 + \mu_0 \frac{\Omega_{\rm DE}(a)}{\Omega_{\rm DE,0}}$$

$$\Sigma(a) = 1 + \Sigma_0 \frac{\Omega_{\rm DE}(a)}{\Omega_{\rm DE,0}}$$

- Pheno. model is useful to investigate how signals deviate from standard ones, although the mapping is not fully understood.

(Th2) Effective Theory

: modifying at level of perturbed action

- We consider the perturbed action so that the physical meaning of pert. is obvious:

[Example] Effective 2nd-order Lagrangian

$$\mathcal{L} = \frac{1}{16\pi G}\left[(1+\alpha_{\mathrm{T}})\,{}^{(3)}R + \delta K^{i}{}_{j}\delta K^{j}{}_{i} - \delta K^{2} + \cdots\right]$$

→ Independently of the details of original theory,

this term always represents sound speed of GWs !

(Th2) Effective Theory
: modifying at level of perturbed action

- Even complex full theories can be described by linear theories with **a few** EFT parameters:

DHOST theory
Honrdeski theory
Brans-Dicke theory

$\alpha_K(t)$ Kineticity (kinetic term of additional field)
$\alpha_M(t)$ Planck-Mass run rate

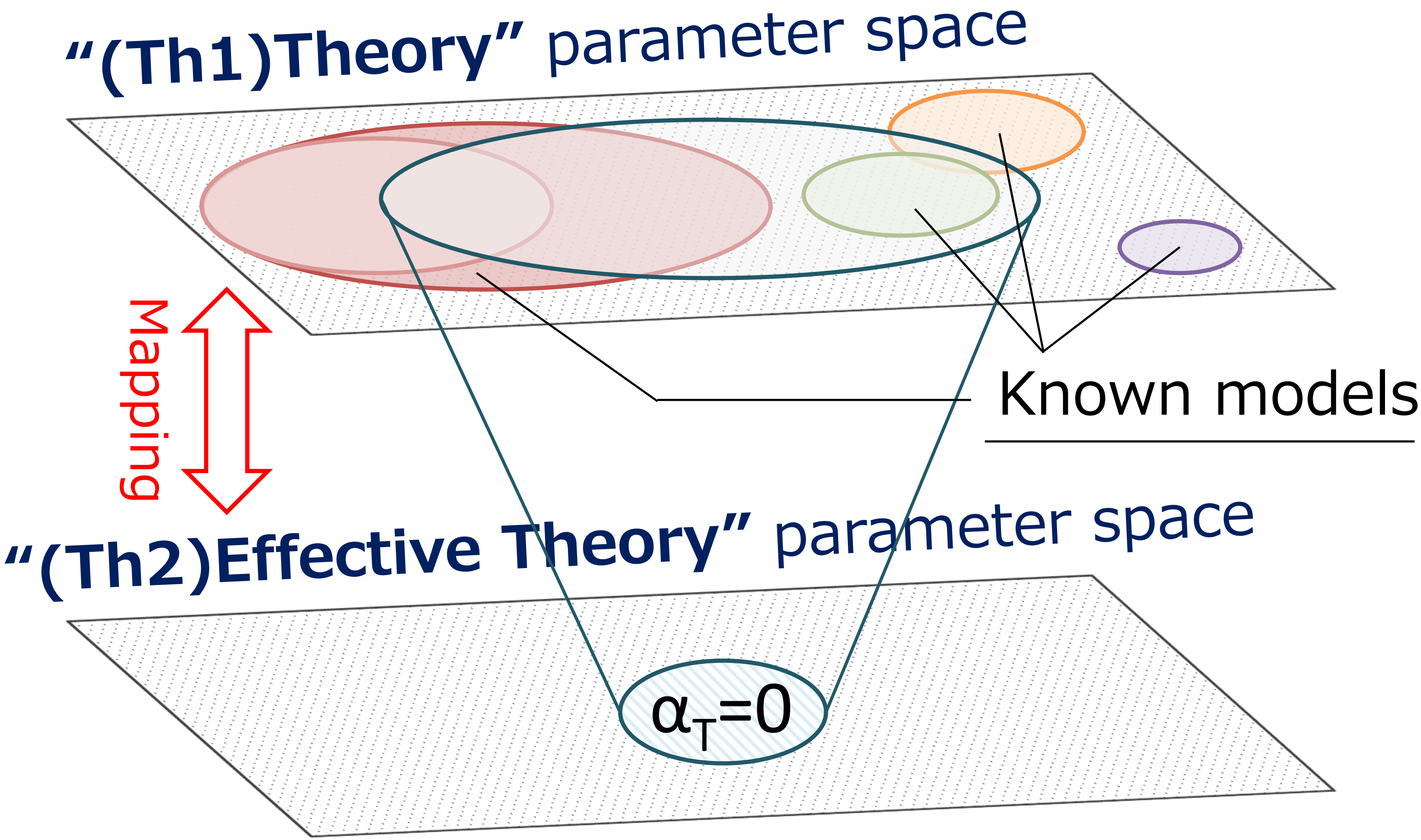
$\alpha_T(t)$ Tensor speed excess
$\alpha_B(t)$ Braiding (Mixing between field and metric pert.)

$\alpha_H(t)$ beyond-Horndeski
$\beta_1(t)$ beyond-GLPV (higher-order derivatives)

Scalar-Tensor Theories: Bellini+,JCAP07,050(2014), Langlois+,JCAP05,033(2017),⋯
Vector-Tensor Theories: Aoki+,JCAP01,056(2022), Fluid: Aoki+,JCAP08,072(2022)

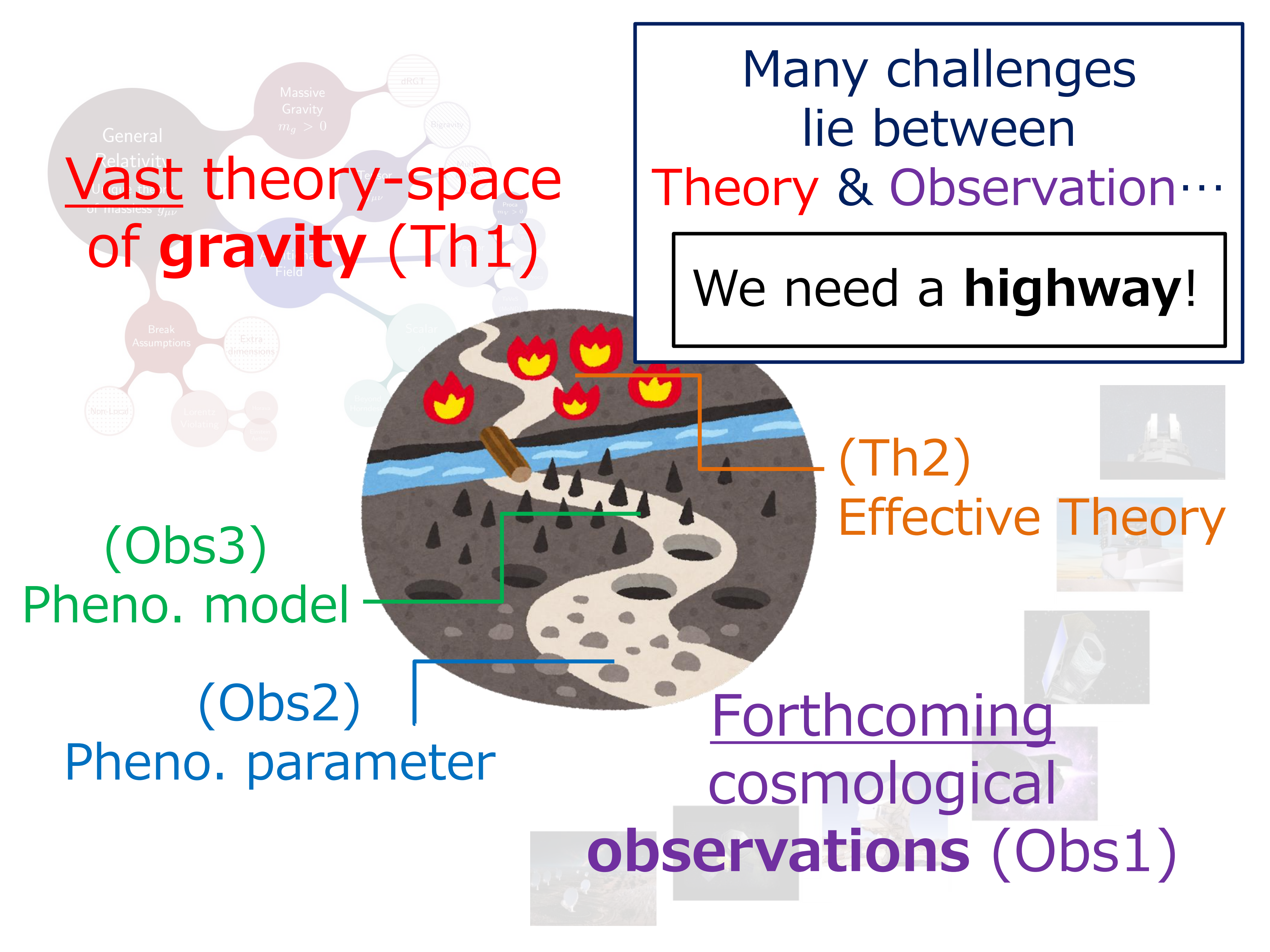
(Th2) Effective Theory

: modifying at level of perturbed action



3. Connecting Theoretical studies with Observations

(Th×Obs)



Vast theory-space of gravity (Th1)
Many challenges lie between Theory & Observation…
We need a highway!
(Th2) Effective Theory
(Obs3) Pheno. model
(Obs2) Pheno. parameter
Forthcoming cosmological observations (Obs1)

(Th2) Effective Theory → (Obs3) Pheno. model

We have already created a **dictionary** to connect (Th2) and (Obs3) in specific gravity theories.

□ Ex) Interaction between metric and scalar-field pert.

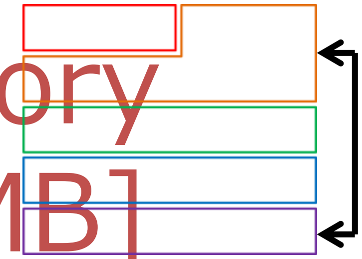
$$\mathcal{L}_{\mathrm{int}} = -2M_{\mathrm{Pl}}^2 a H \alpha_{\mathrm{B}} \Phi \nabla^2 \varphi$$

⇓

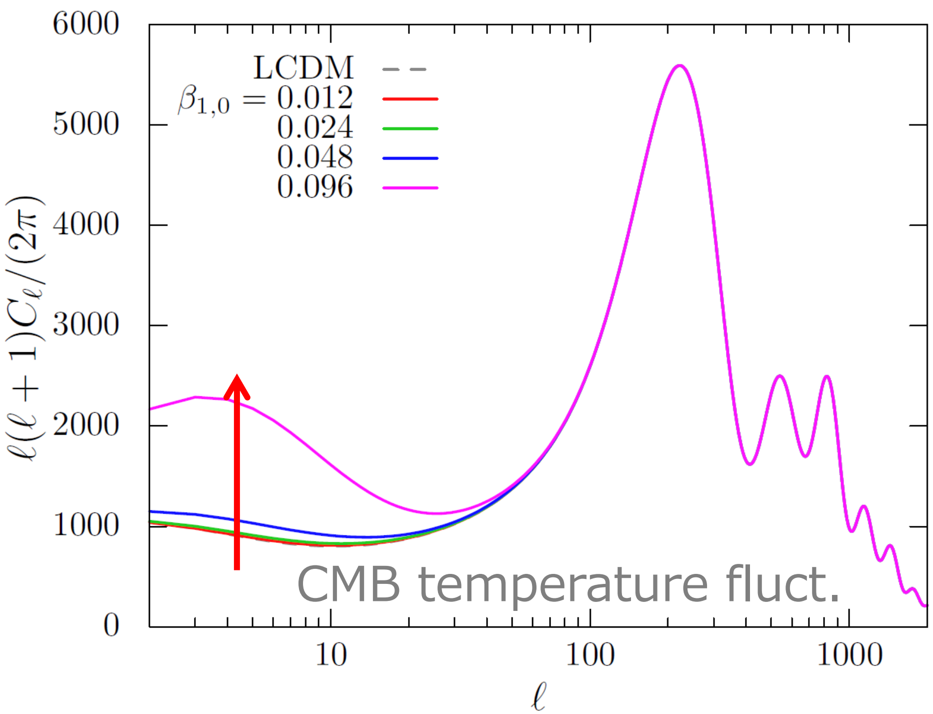
$$\mu = \Sigma = 1 - \frac{\alpha_{\mathrm{B}}^2}{\frac{\dot{H}}{H^2} + \frac{3}{2}\Omega_{\mathrm{m}} + \alpha_{\mathrm{B}}(1+\alpha_{\mathrm{B}}) + \frac{(H\alpha_{\mathrm{B}})^{\cdot}}{H^2}}$$

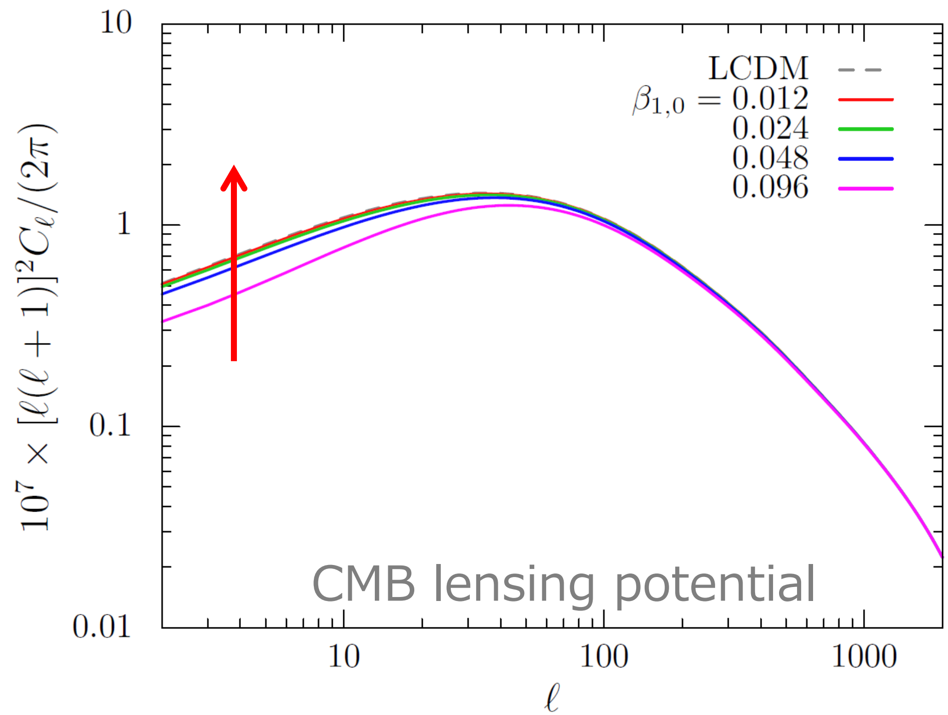
Horndeski theory : Pogosian+,PRD94,104014(2016),Gleyzes+,JCAP02,056(2016)
DHOST theory : Hirano+**DY**+,PRD99,104051(2019)/PRD102,103505(2020)
Vector-Tensor theory : Aoki+,JCAP01,056(2022),⋯

(Th2) Eff. Theo./(Th1) Theory → (Obs1) Observation[CMB]



- T. Hiramatsu (Rikyo U) developed the novel **Boltzmann code "CMB2nd"** that is utilized for computing CMB in the context of **DHOST**.





Hiramatsu+**DY**,PRD102,083525(2020), Hiramatsu, JCAP10(2022)035
Hiramatsu+Kobayashi, JCAP07, 040 (2022),···

We have started
new Japanese Working Group:

“Testing Gravity: Th×Obs”

- Start : Aug. 2020
- Aim : Several multi-wavelength wide-field cosmological surveys have been conducted and planned, hence immediate validation system of gravity model needs to be established. For this reason, the aim of this working group is **to strongly connect theoretical and observational studies in Japan**.
- Chairs : Miyatake, Yokoyama, Arai(Nagoya), **DY(OUS)**
- Members : >50

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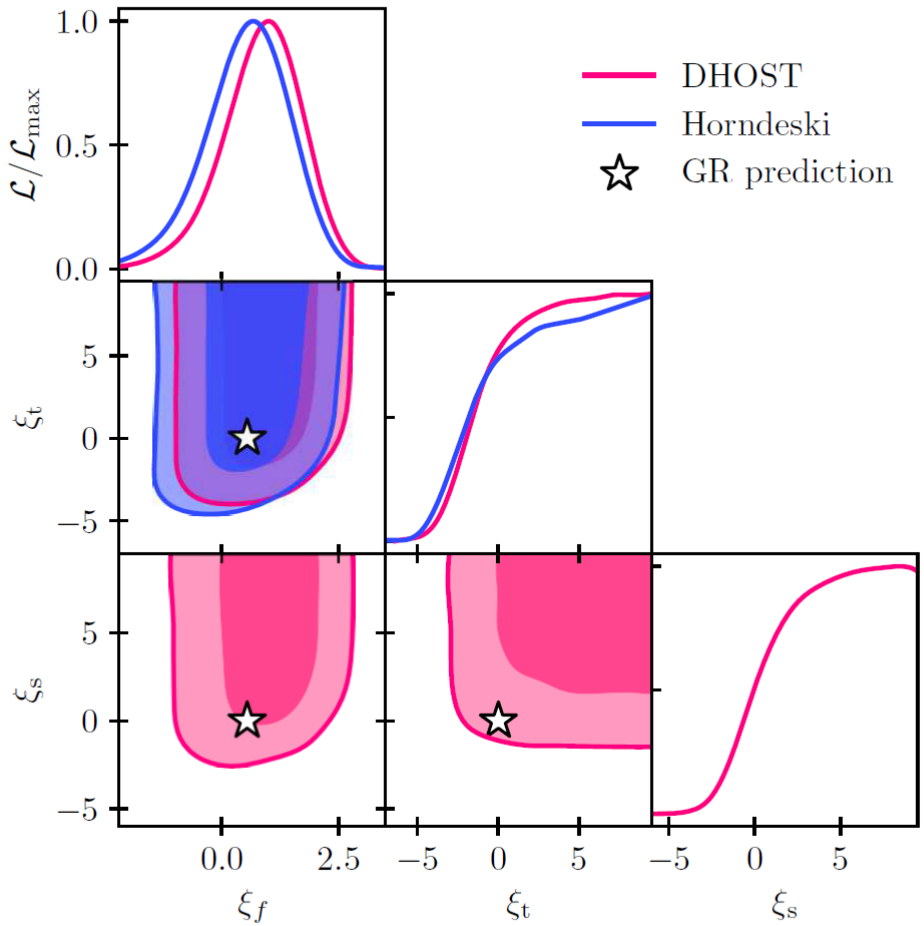
New Th×Obs project has started!



◆Requests from **Obs** side :
Novel technique
“anisotropic galaxy 3PCF“

+

◆Requests from **Theo** side :
Theoretical prediction of
nonlinear growth

New Th×Obs project
“Test of gravity from
anisotropic galaxy 3PCF”

Sugiyama+**DY**+, MNRAS523, 2, 3133
Sugiyama+**DY**+, MNRAS524, 2, 1651
[Analysis based on **DY**+Sugiyama,PRD105,063515(2022)]

What we have to do are…

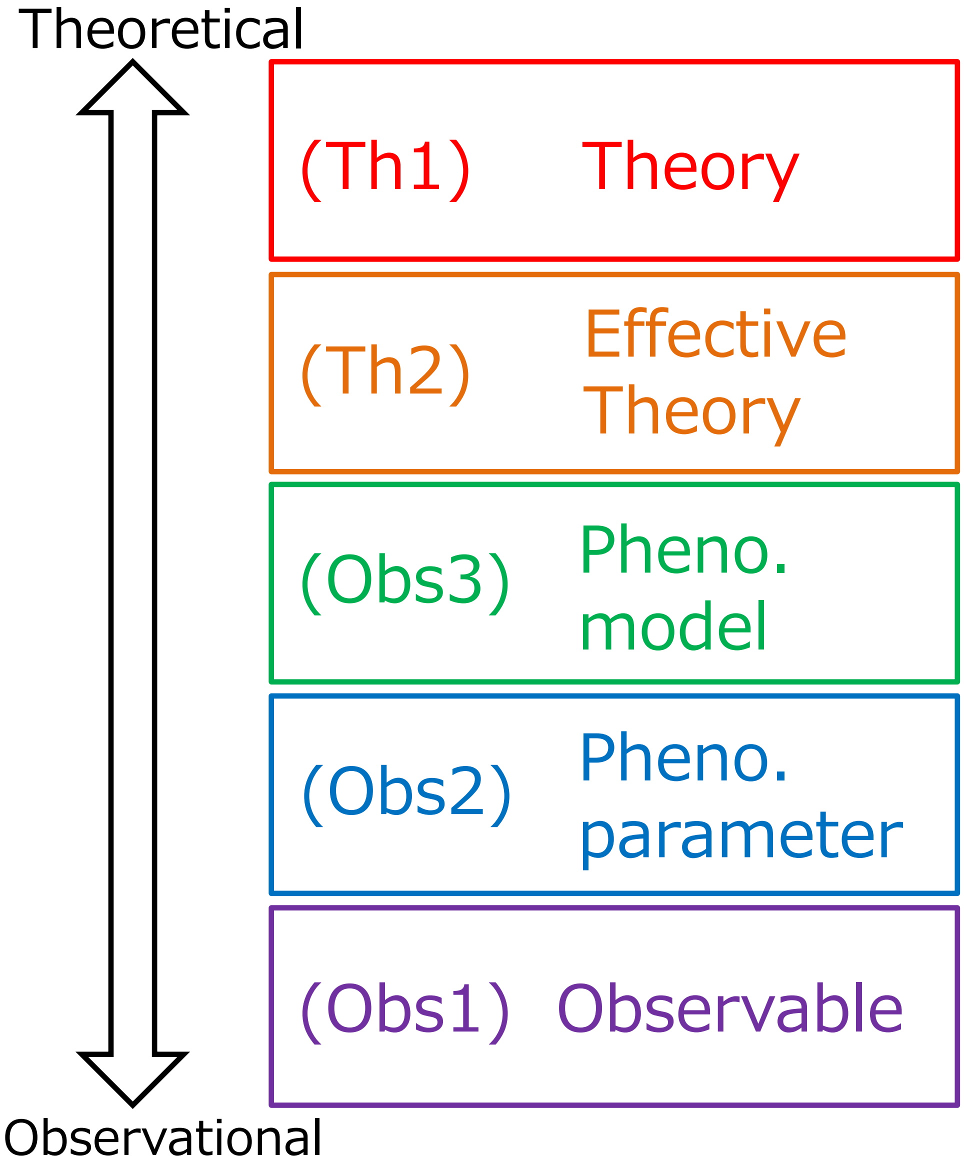
☐ Coupling between matter and gravity

- ✓ Most calculations are based on minimal coupling.
- ✓ **Nonminimal (e.g. disformal) coupling** may lead to strange phenomena in observables [Kimura+**DY**+Yamaguchi+(2018),Chibana+**DY**+Yamaguchi(2019)]

☐ Nonlinearity

- ✓ **Screening mechanism** should be considered. Beyond-Horndeski class such as DHOST leads to partial breaking of screening mechanism [Kobayashi+**DY**+(2015),Langlois+**DY**+(2018)]
- ✓ Deeper understanding of **nonlinear growth** of structure is also needed.

Summary



- Main message:
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The key is <u>to connect</u> <u>**Th**eoretical studies with</u> <u>**Obs**ervational ones</u>!

- Japanese working group "Testing Gravity: Th×Obs"
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