Dark Energy

Filippo Vernizzi - IPhT, CEA Saclay

COSMO 2017, Paris - August 28, 2017

Dark Energy and Modified Gravity

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Effective Theory of Dark Energy and Modified Gravity

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Acceleration

In 1998, the Universe started accelerating… Confirmed by many independent datasets

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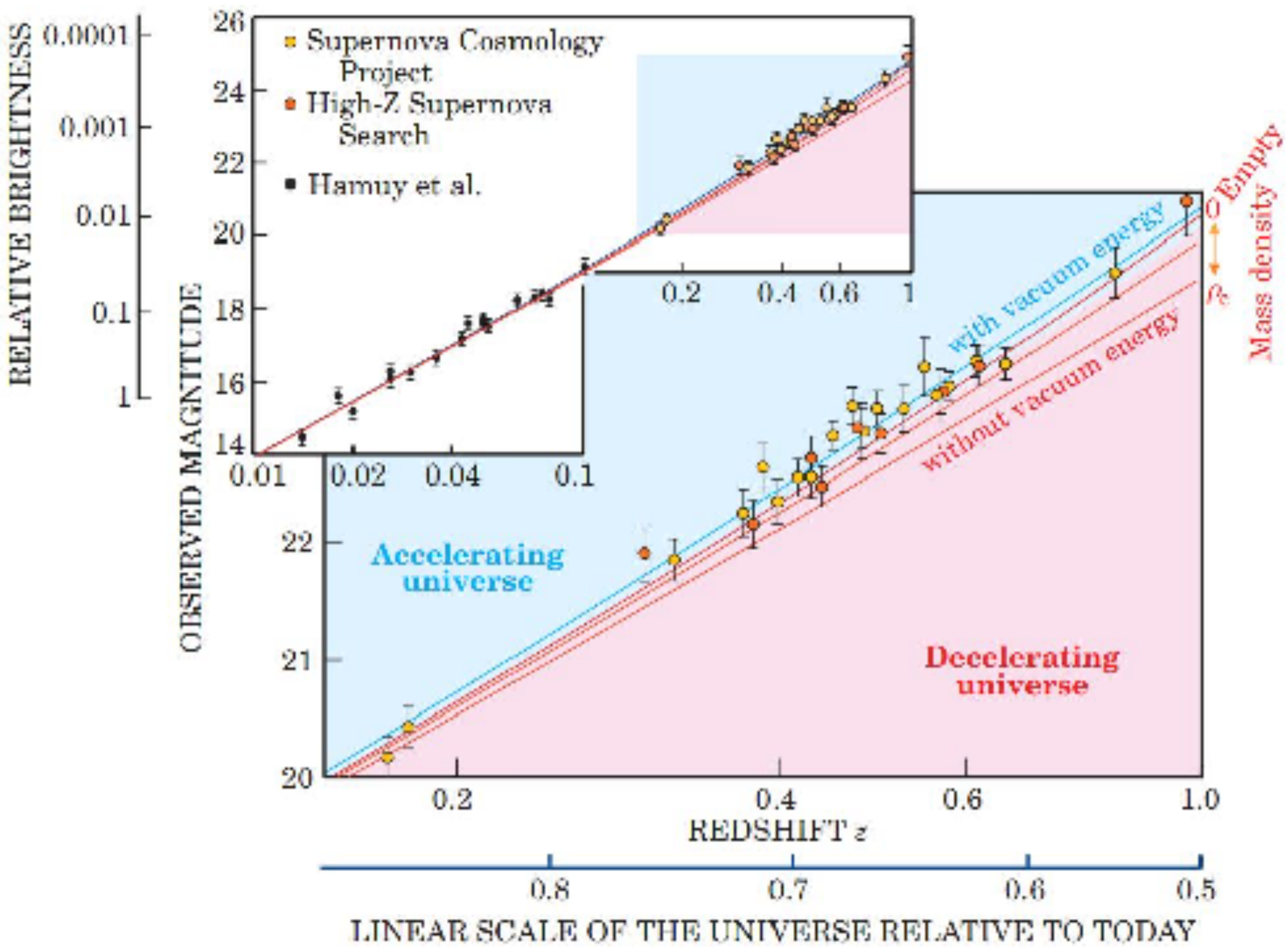
- Luminosity distance/redshift relation SNIa:



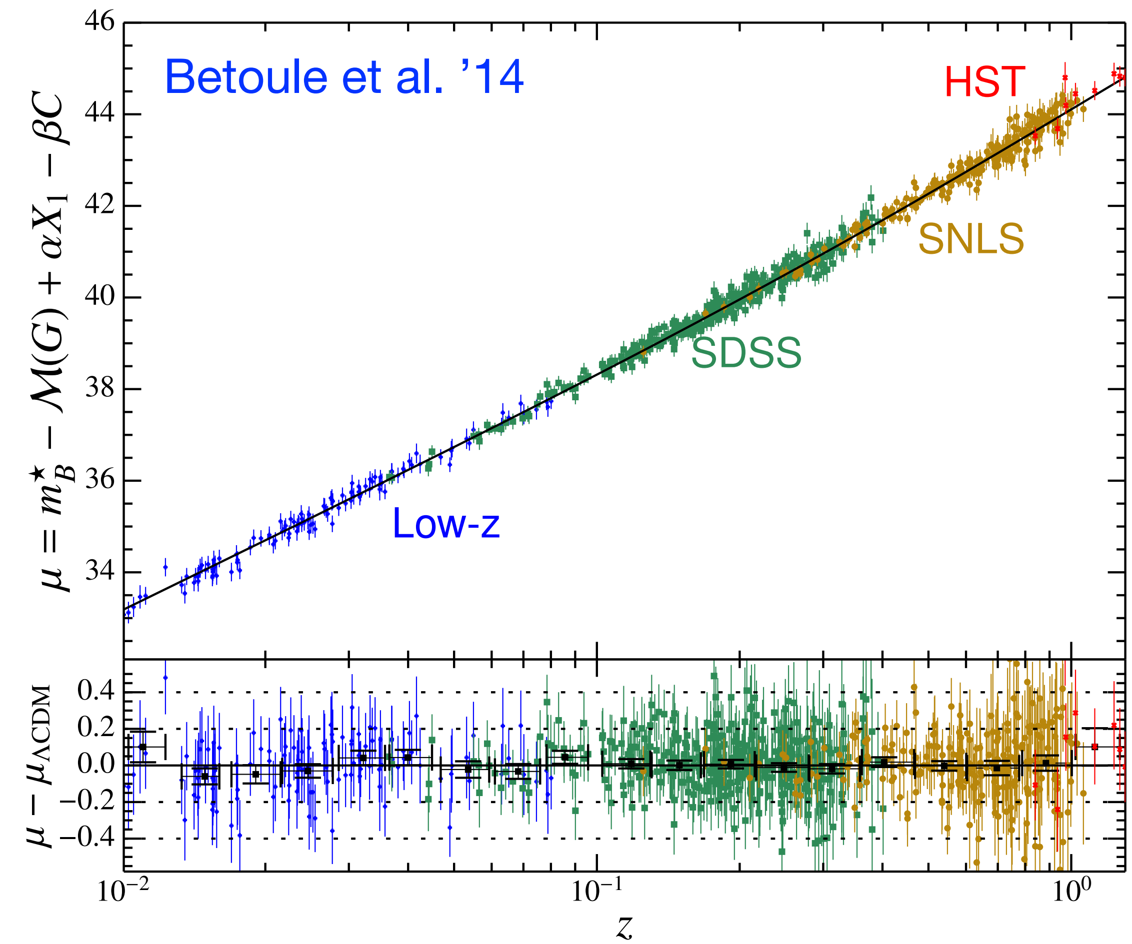


Fig. 8. *Top:* Hubble diagram of the combined sample. The distance modulus redshift relation of the best-fit ΛCDM cosmology for a fixed $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ is shown as the black line. *Bottom:* Residuals from the best-fit ΛCDM cosmology as a function of redshift. The weighted average of the residuals in logarithmic redshift bins of width $\Delta z/z \sim 0.24$ are shown as black dots.

Acceleration

In 1998, the Universe started accelerating… Confirmed by many independent datasets

Standard cosmology governed by General Relativity $G_{\mu\nu}(g) = 8\pi G T_{\mu\nu}$

Acceleration implies some form of unknown matter with negative pressure: **dark energy**

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) > 0$$

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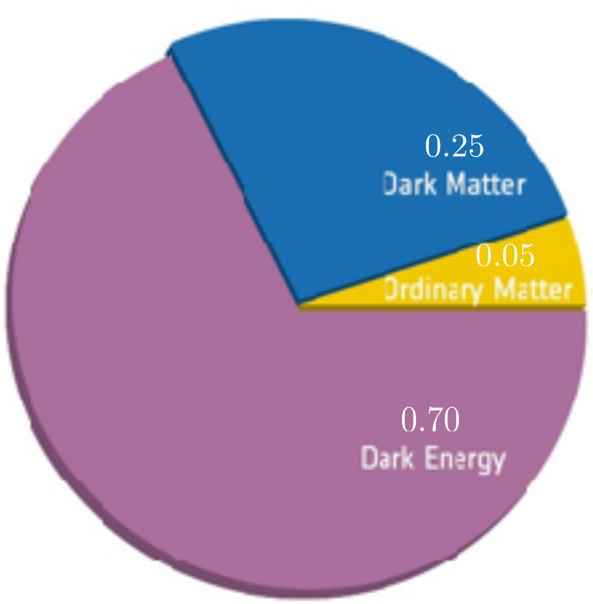
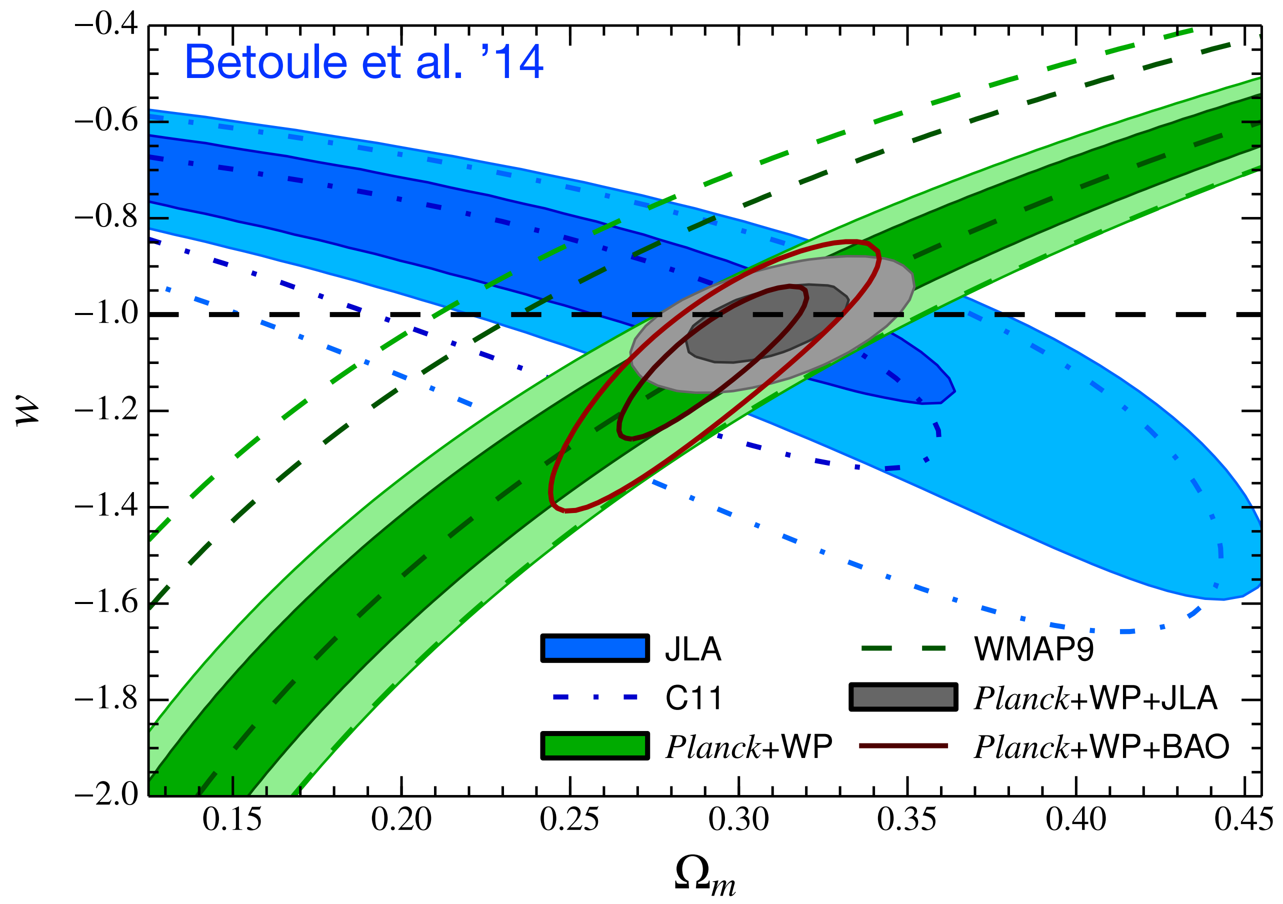
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) > 0$$

$$w = \frac{p_{\rm de}}{\rho_{\rm de}} \approx -1 \qquad \Omega_{\rm de} \approx 0.7$$





Cosmological Constant

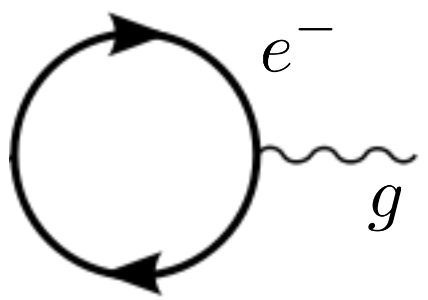
$T_{\mu\nu}^{(\mathrm{de})} = -\Lambda g_{\mu\nu}$: CC, **simplest** explanation, **consistent** with all data

But $\Lambda = \rho_{\mathrm{de}} \simeq (10^{-3}\mathrm{eV})^4$ unnaturally small

Extremely **sensitive** to **UV physics.** Cancelation with vacuum energy of each particle at any loop-order in perturbation theory

e.g. Burgess 13; Padilla 15

$$\Lambda_{\mathrm{obs}} = \Lambda_{\mathrm{bare}} + \sum_i c_i m_i^4$$



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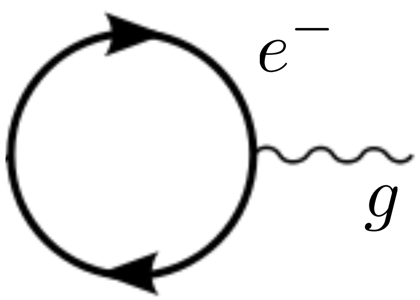
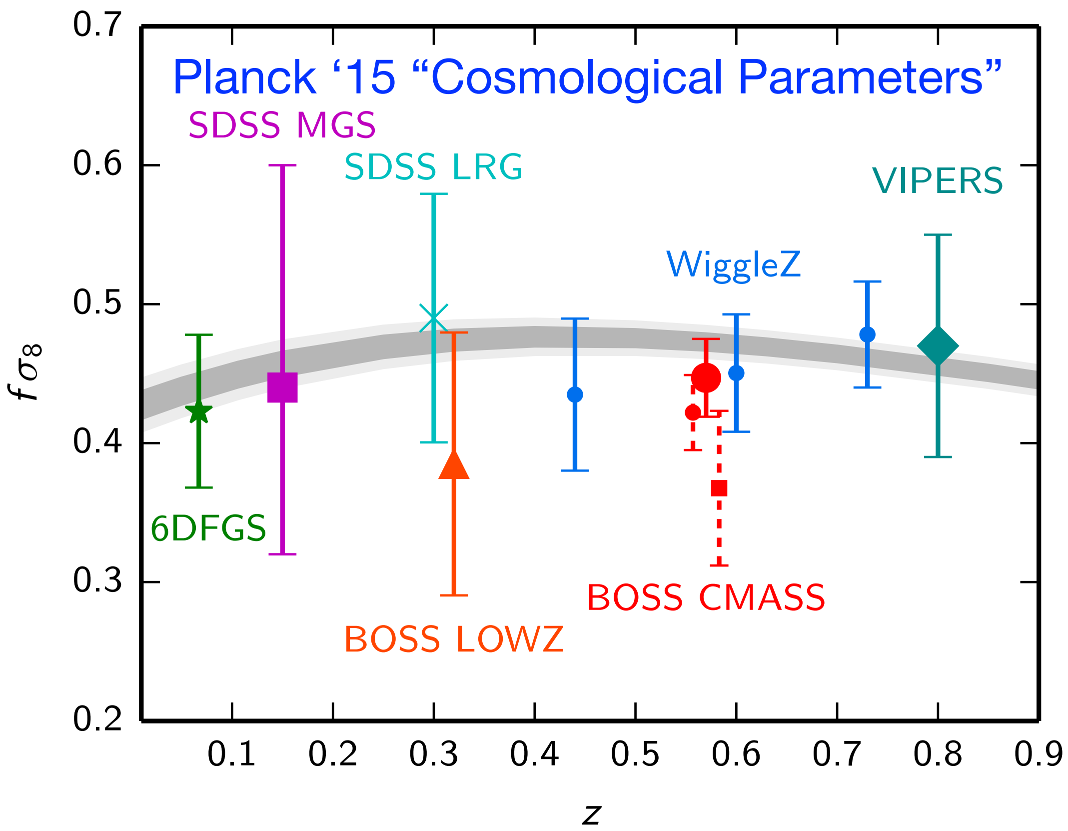


e.g. Burgess 13; Padilla 15

Several attempts to explain smallness. E.g., **Anthropic** (Weinberg 89), **Relaxation** (Abbott 85; Alberte et al 16), **Sequestering** (Kaloper & Padilla 13), **Nonlocal** (Carroll and Remmen 17), etc

Not a CC

Explanation may be associated to some **dynamical mechanism**: new field or modification of gravity on large scales.



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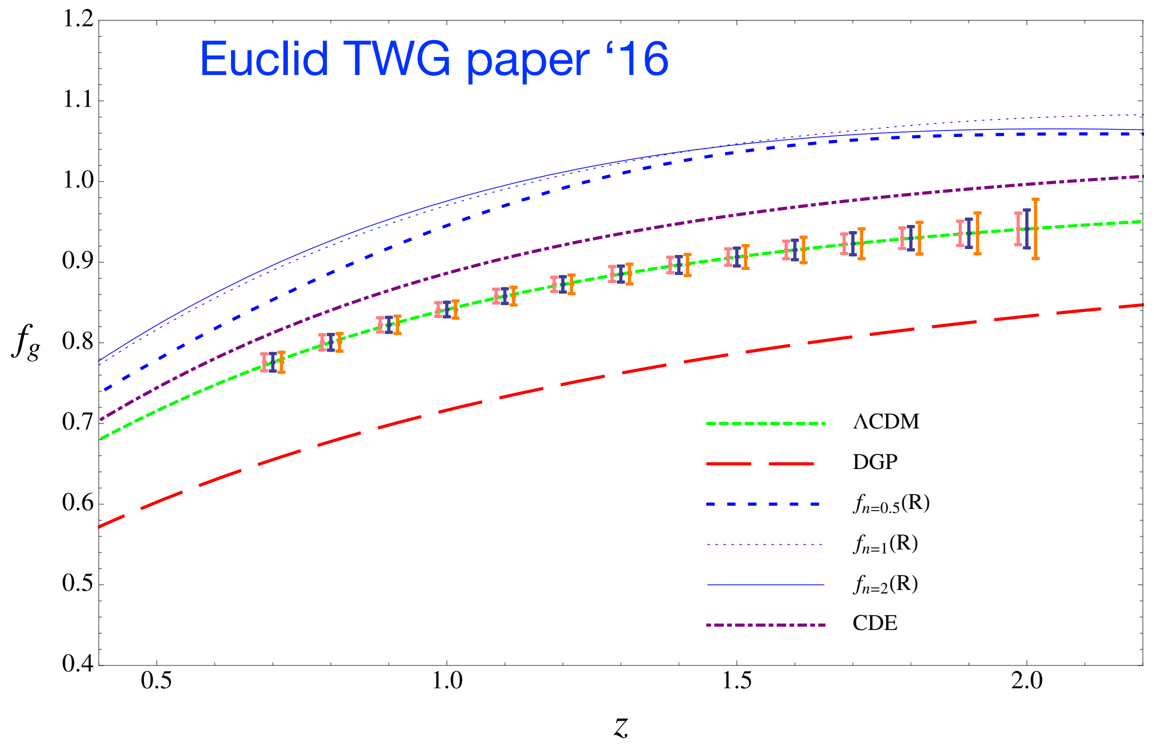

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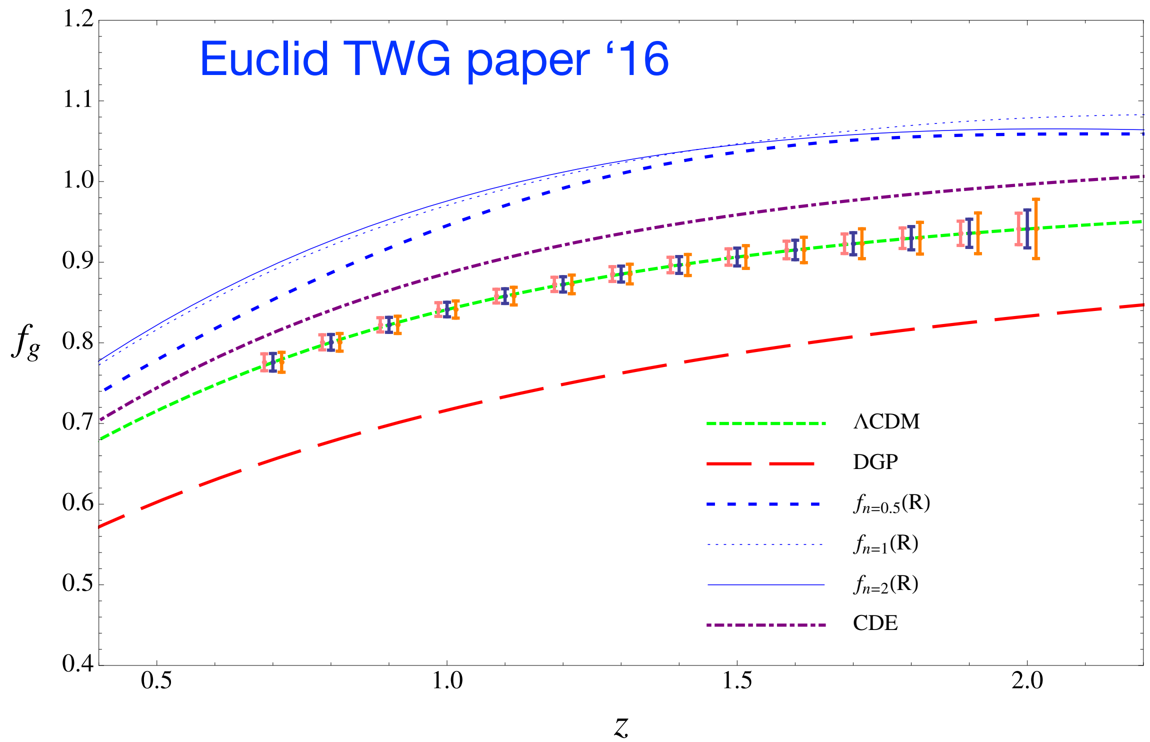
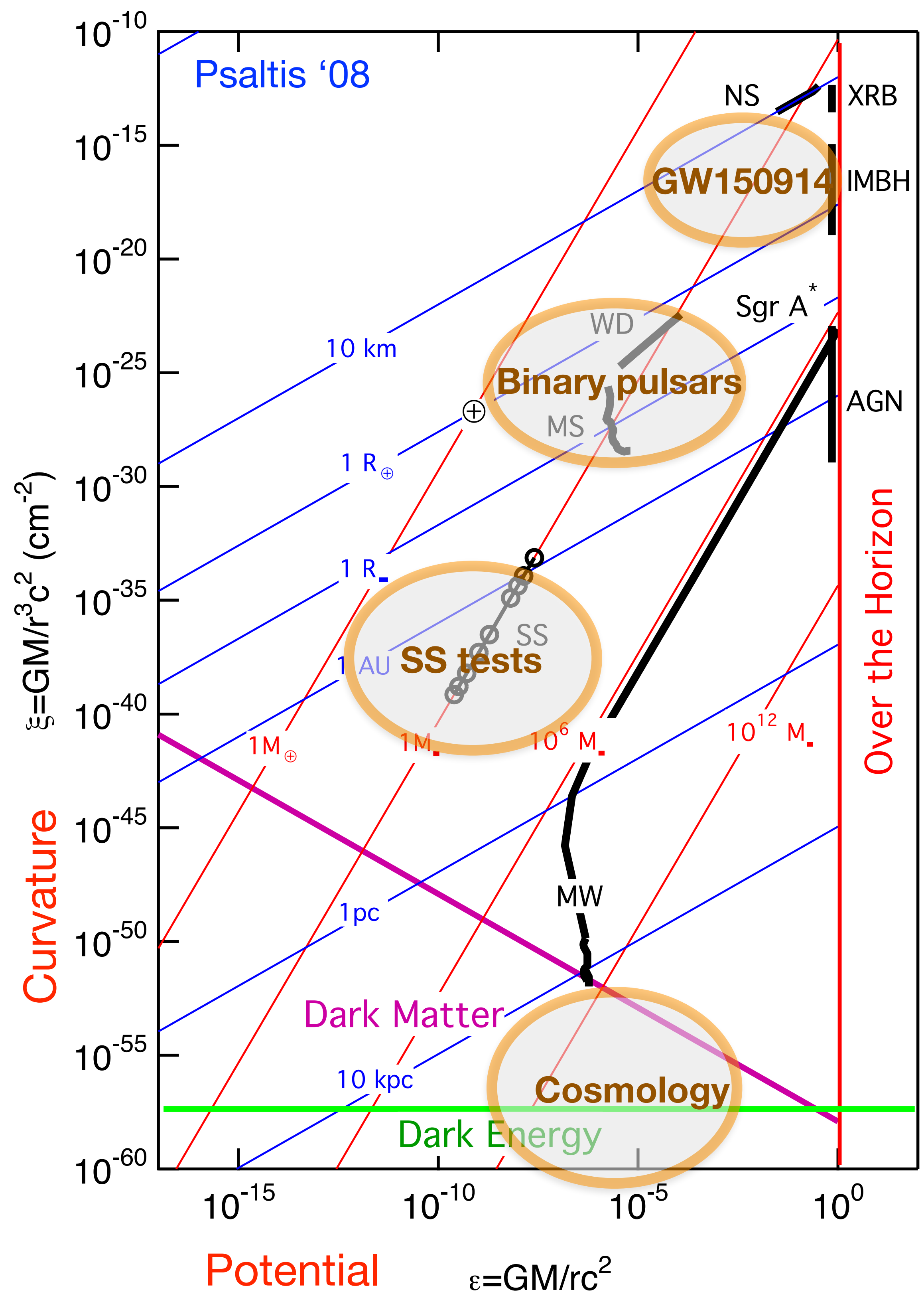
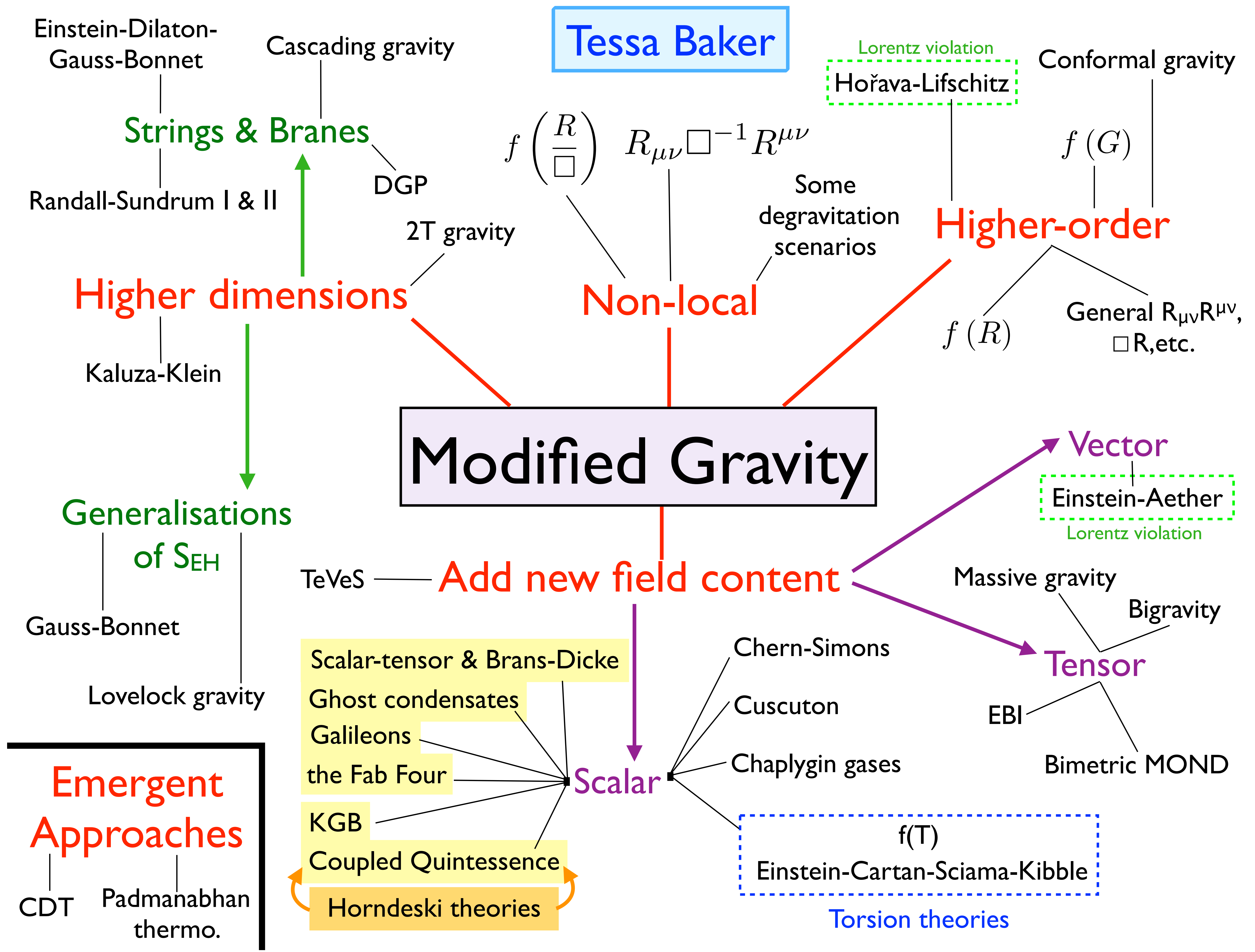
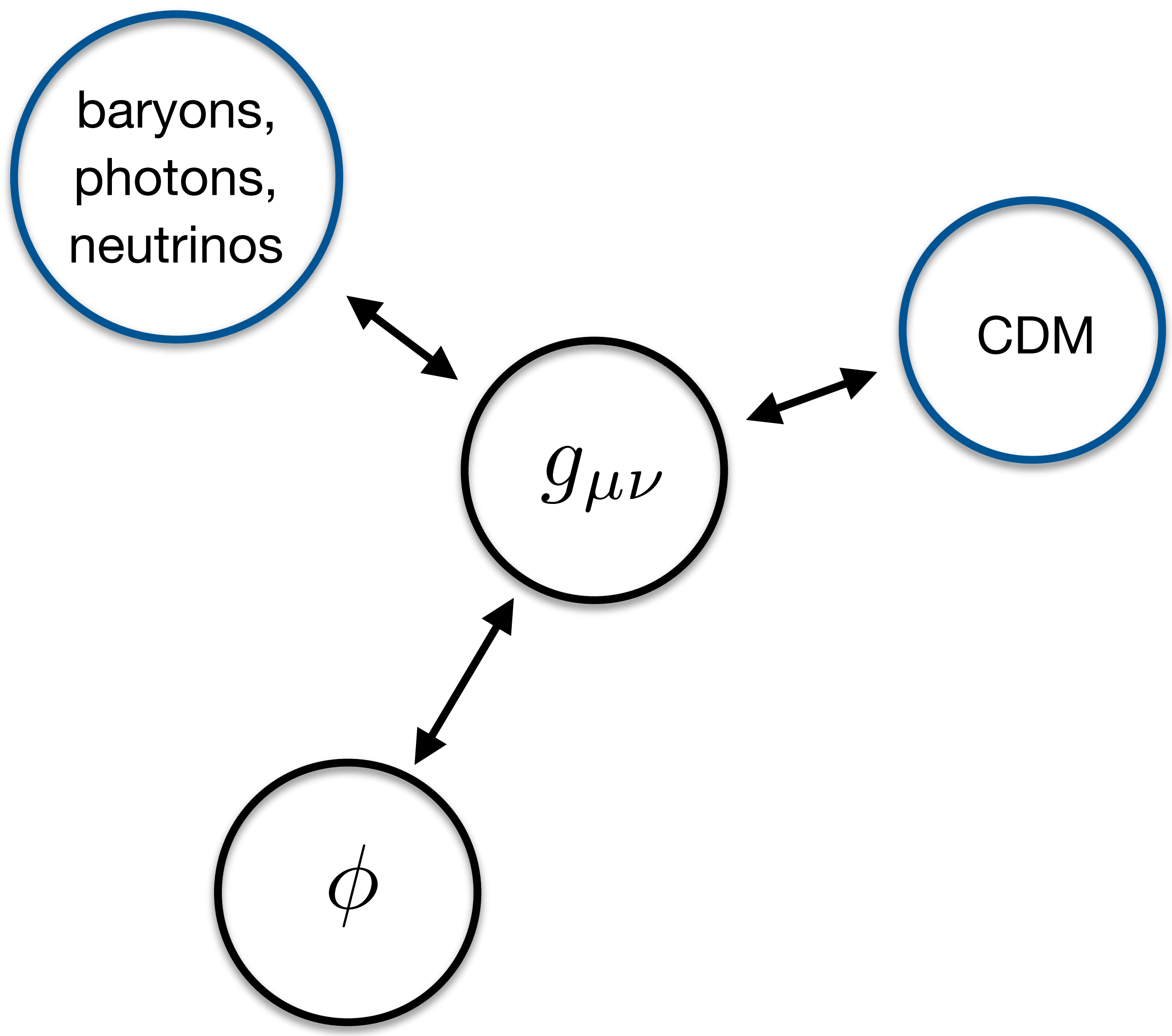




Gravity **tested** over specials ranges of scales and masses. Cosmology is a **window** for testing it on very large distances


Tessa Baker
Modified Gravity
Higher dimensions
Strings & Branes
Einstein-Dilaton-Gauss-Bonnet
Cascading gravity
DGP
Randall-Sundrum I & II
2T gravity
Kaluza-Klein
Generalisations of S_{EH}
Gauss-Bonnet
Lovelock gravity
Non-local
$f\left(\frac{R}{\Box}\right)$
$R_{\mu\nu}\Box^{-1}R^{\mu\nu}$
Some degravitation scenarios
Higher-order
Lorentz violation
Hořava-Lifschitz
Conformal gravity
$f(G)$
$f(R)$
General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$,etc.
Add new field content
TeVeS
Vector
Einstein-Aether
Lorentz violation
Tensor
Massive gravity
Bigravity
EBI
Bimetric MOND
Scalar
Scalar-tensor & Brans-Dicke
Ghost condensates
Galileons
the Fab Four
KGB
Coupled Quintessence
Horndeski theories
Chern-Simons
Cuscuton
Chaplygin gases
f(T)
Einstein-Cartan-Sciama-Kibble
Torsion theories
Emergent Approaches
CDT
Padmanabhan thermo.

Focus on **single scalar** DOF: scalar-tensor theories. (see Naruko's talk for vector-tensor)



Theoretical requirements

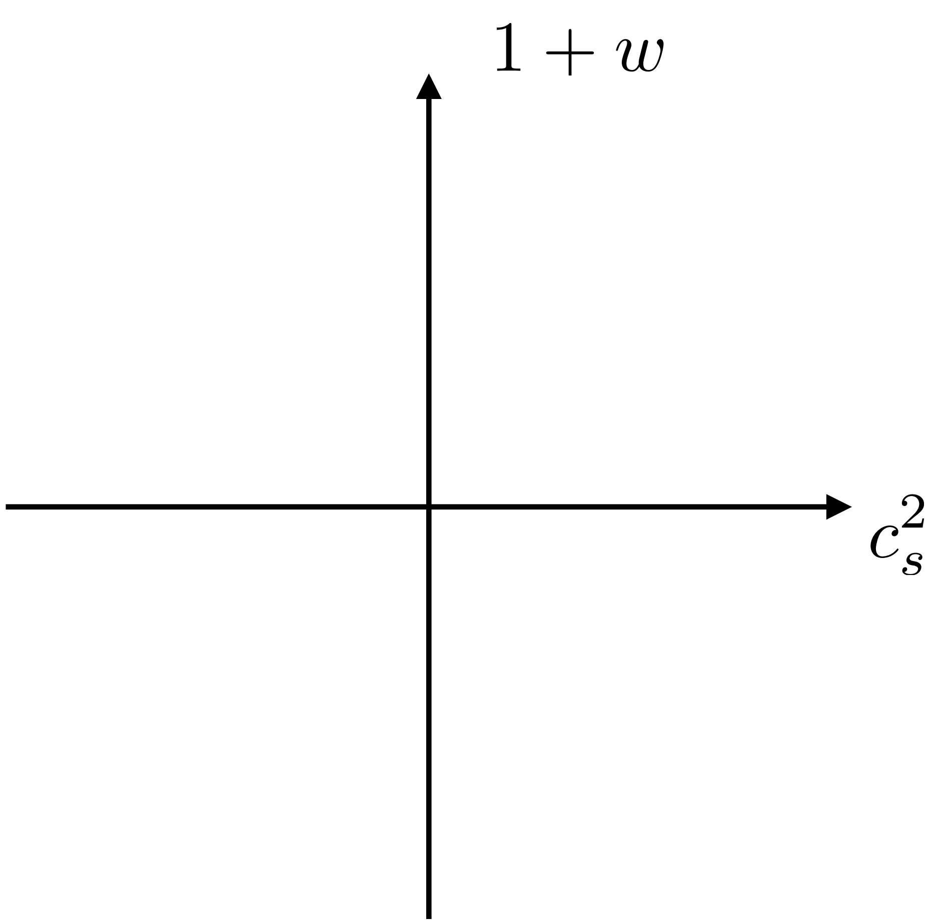
$$\mathcal{L} = -\frac{1}{2} Z^{\mu\nu}(\phi, X)\partial_\mu\phi\partial_\nu\phi - V(\phi) \qquad X = g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$

Kinetic term Potential

Expand kinetic term around an FRW background: $\phi = \bar{\phi}(t) + \varphi(t, \vec{x})$

$$\mathcal{L} = \frac{1}{2} Z(\bar{\phi}) \left[\dot{\varphi}^2 - c_s^2(\bar{\phi})(\nabla\varphi)^2\right] \qquad c_s^2 = \frac{\rho_{\rm de} + p_{\rm de}}{Z}$$

Time-dependent kinetic energy and sound speed



Creminelli, D'Amico, Noreña, FV 08

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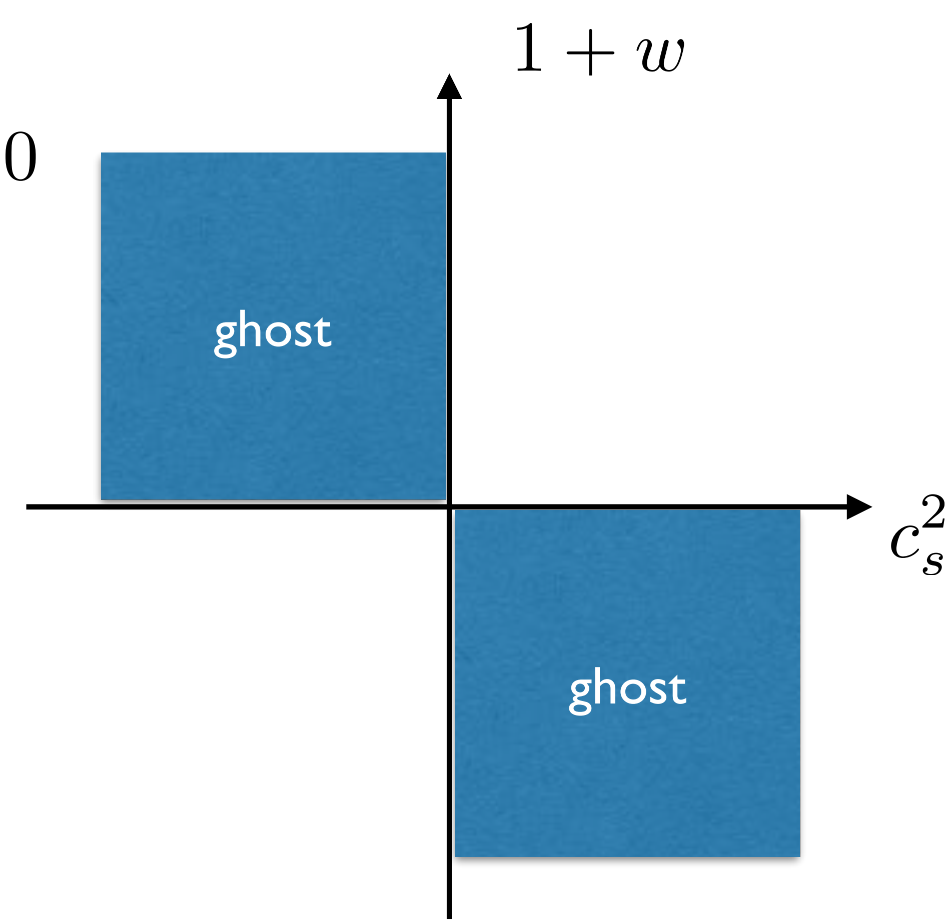

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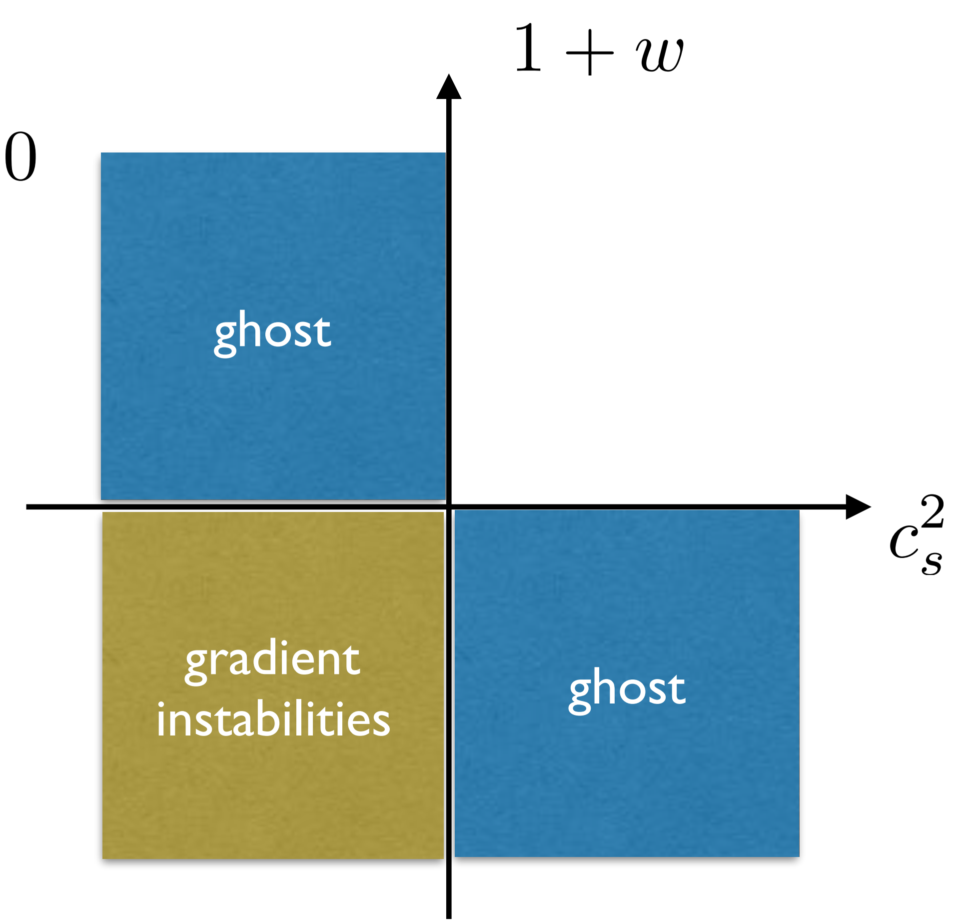

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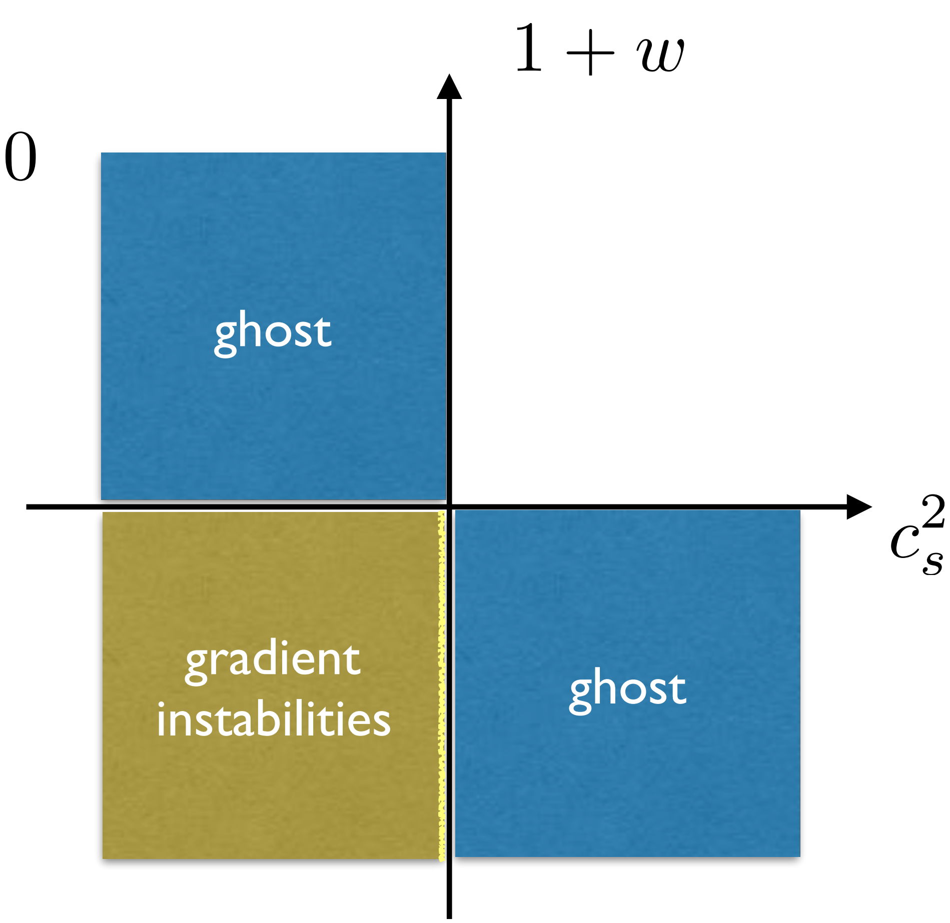


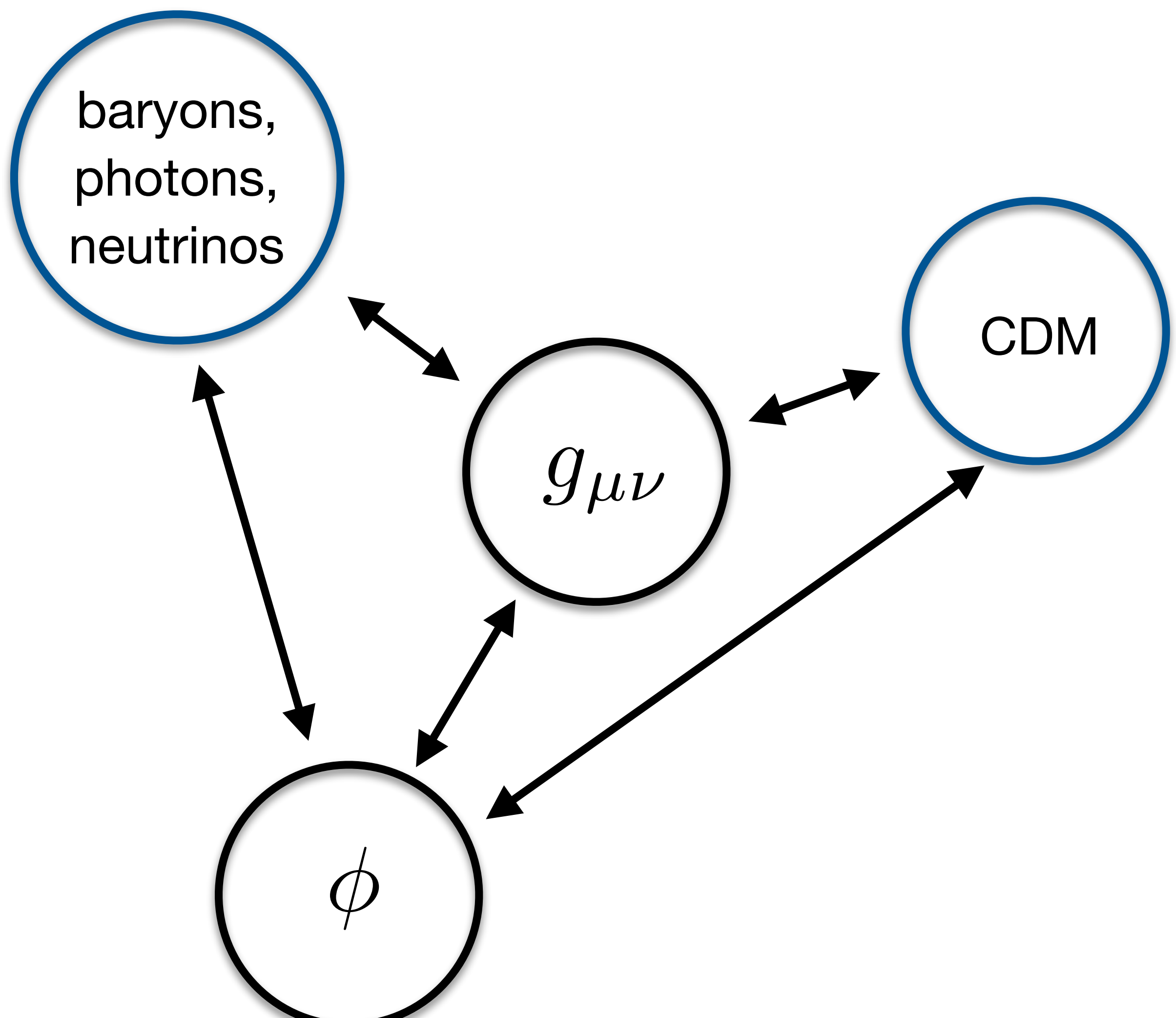
Creminelli, D'Amico, Noreña, FV 08

Gradient instabilities can be cured by higher-order operators for $c_s^2 \approx 0$

Arkani-Hamed et al. 03; Creminelli et al 06

(see also Melville's talk)

$$\mathcal{L} = -\frac{1}{2} Z^{\mu\nu}(\phi, X)\partial_\mu\phi\partial_\nu\phi - V(\phi) + \beta(\phi) T^\mu_\mu$$ Coupling to matter



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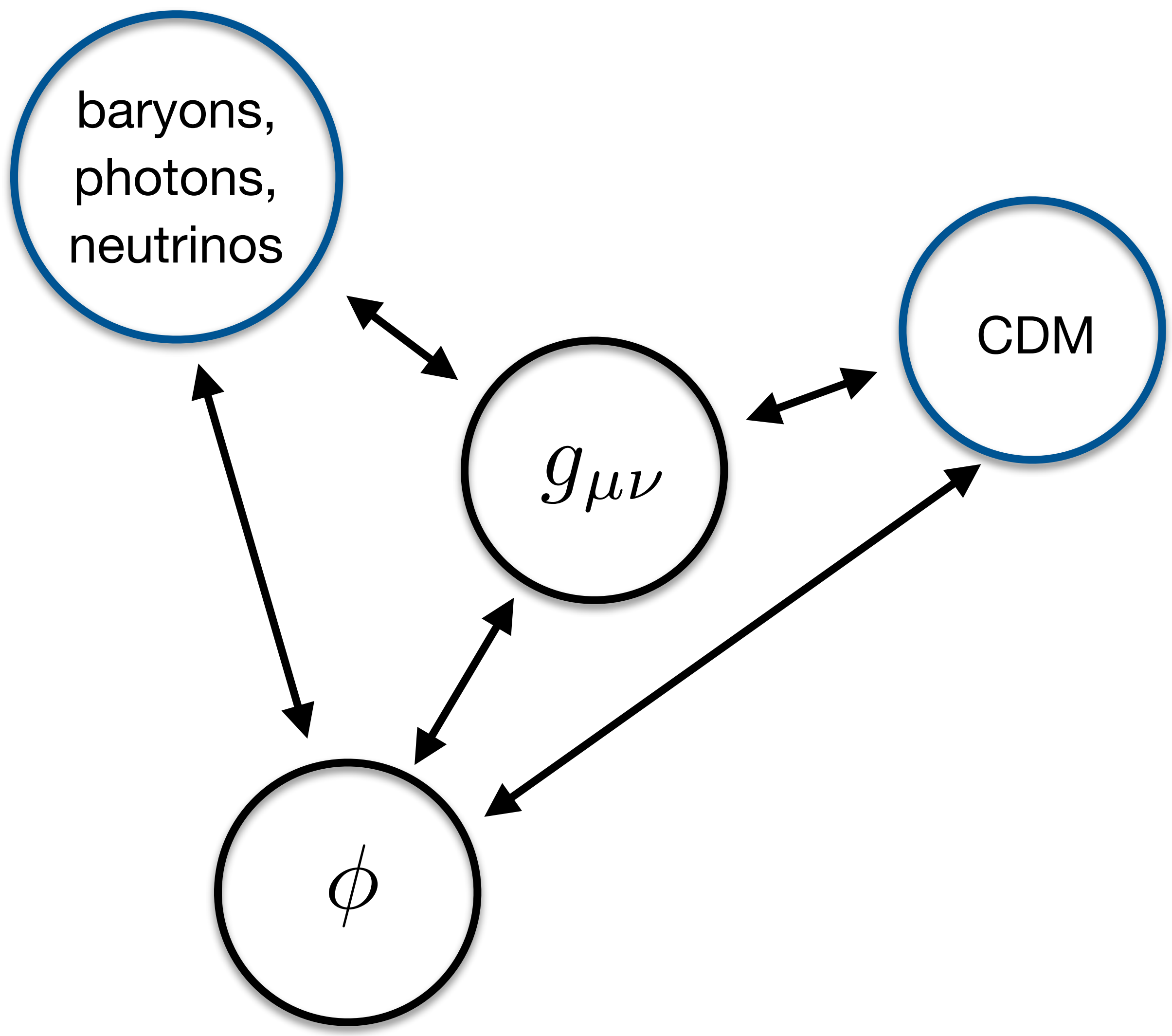
Acceleration can be explained by non-minimal coupling: **self-acceleration**



Fifth force

$$\mathcal{L} = -\frac{1}{2} Z^{\mu\nu}(\phi, X)\partial_\mu\phi\partial_\nu\phi - V(\phi) + \beta(\phi)T^\mu_\mu$$

Expand solution and specialise to point source and quasi-static approximation

$$Z(\bar{\phi})\left(\ddot{\varphi} - c_s^2(\bar{\phi})\nabla^2\varphi\right) + m^2(\bar{\phi})\varphi = \beta'(\bar{\phi})M\delta^{(3)}(\vec{x})$$

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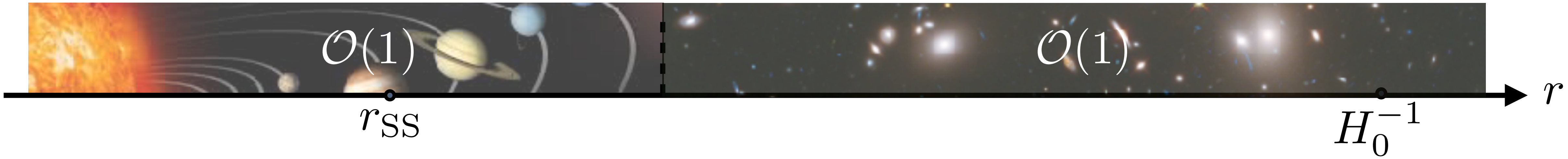

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Chameleon: scalar acquires a large mass in high density region, due to coupling to matter

Khoury and Weltman 03

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Symmetron: coupling vanishes in high-density region, where symmetry is restored

Hinterbichler and Khoury 10

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Symmetron: coupling vanishes in high-density region, where symmetry is restored

Vainshtein: higher-derivative self-interactions suppress the scalar at short scales

Vainshtein 72

Vainshtein screening

Review by Babichev and Deffayet 13

- Originally introduced in Massive Gravity, rediscovered in DGP

Ex:
$$\mathcal{L} = -(\partial\phi)^2 + \frac{(\partial\phi)^2\Box\phi}{\Lambda^3} + \beta(\phi)T^\mu_\mu$$

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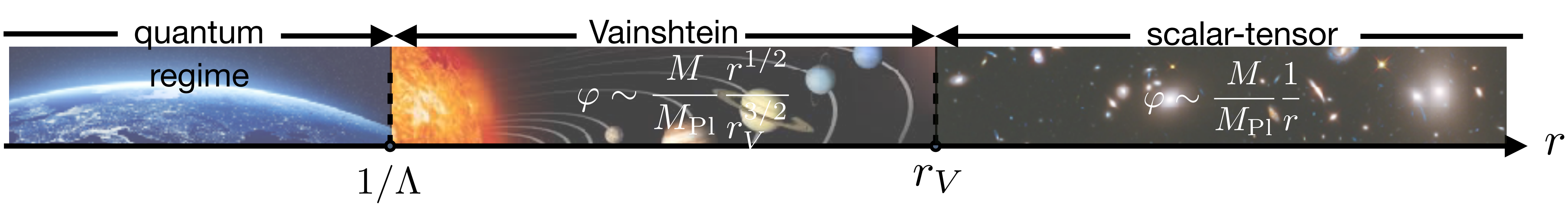
Classical nonlinearities $$\frac{\Box\phi}{\Lambda^3} \sim 1 \quad \Rightarrow \quad r_V \sim \left(\frac{M}{M_{\rm Pl}\Lambda^3}\right)^{\frac{1}{3}} \qquad \varphi \sim \frac{M}{M_{\rm Pl}}\frac{1}{r}$$

Quantum corrections $$\frac{\partial}{\Lambda} \sim 1 \quad \Rightarrow \quad \frac{1}{r\Lambda} \sim 1 \qquad \Lambda \sim (M_{\rm Pl}H_0^2)^{\frac{1}{3}} \sim \frac{1}{10^7\,{\rm cm}}$$



Horndeski theories

Most general Lorentz-invariant scalar-tensor theories with 2nd-order EOM. **No extra modes**: 1 scalar + 2 tensor polarisations

Horndeski 73, Deffayet et al. 11
(see Nishi and Ramirez's talk)

$$\mathcal{L}_{\rm H}^{(2)} = G_2(\phi, X) \qquad\qquad X = \nabla_\mu\phi\nabla^\mu\phi$$

$$\mathcal{L}_{\rm H}^{(3)} = G_3(\phi, X)\Box\phi$$

$$\mathcal{L}_{\rm H}^{(4)} = G_4(\phi, X)R - 2G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right]$$

$$\mathcal{L}_{\rm H}^{(5)} = G_5(\phi, X)G^{\mu\nu}\nabla_\mu\nabla_\nu\phi + \frac{1}{3}G_{5,X}(\phi, X)\left[(\Box\phi)^3 - 3\Box\phi(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3\right]$$

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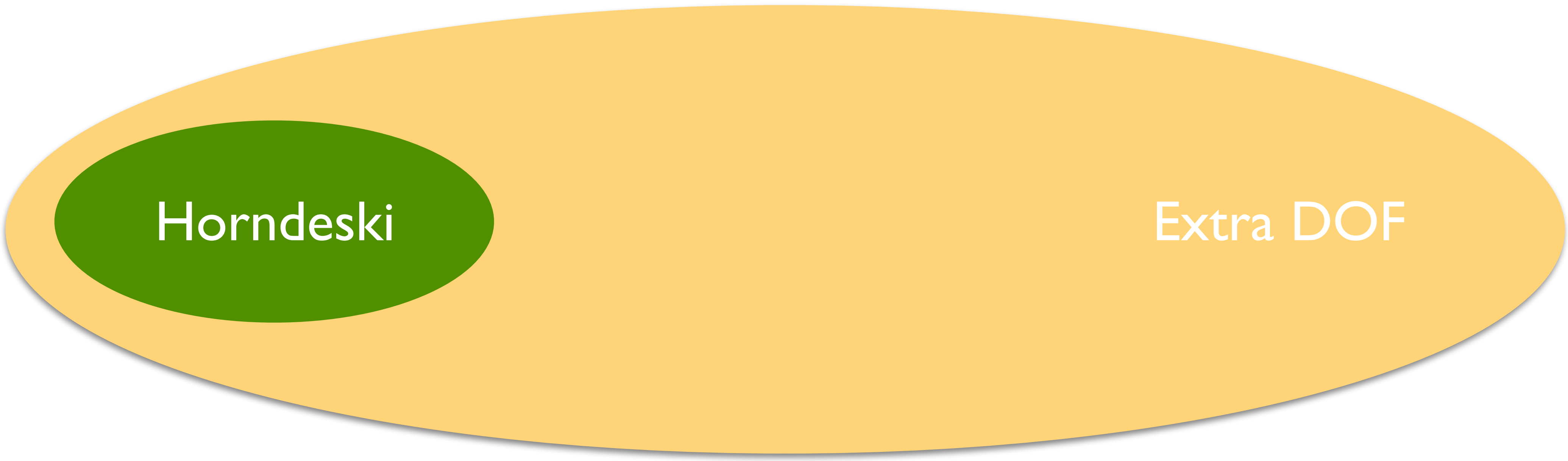


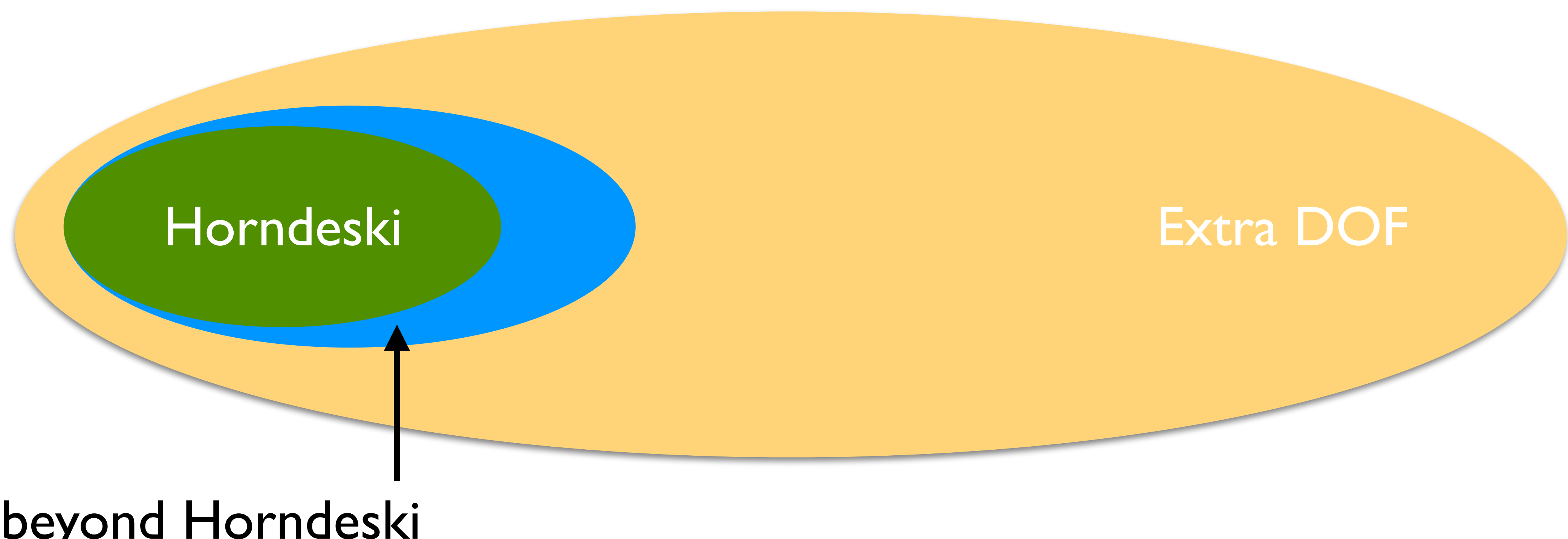
second-order
equations of motion

Beyond Horndeski

Add a new combination $\mathcal{L}_{\rm BH} = \sum_i \mathcal{L}_{\rm H}^{(i)}(\phi, X) + \mathcal{L}_{\rm GLPV}(\phi, X)$

$$\mathcal{L}_{\rm GLPV} = F_4(\phi, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\nabla_\mu\phi\nabla_{\mu'}\phi(\nabla_\nu\nabla_{\nu'}\phi)(\nabla_\rho\nabla_{\rho'}\phi)$$
$$+ F_5(\phi, X)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\mu'\nu'\rho'\sigma'}\nabla_\mu\phi\nabla_{\mu'}\phi(\nabla_\nu\nabla_{\nu'}\phi)(\nabla_\rho\nabla_{\rho'}\phi)(\nabla_\sigma\nabla_{\sigma'}\phi)$$

with $XG_{5,X}F_4 = 3F_5\left(G_4 - 2XG_{4,X}\right)$



Zumalacarregui, Garcia-Bellido 13
Gleyzes, Langlois, Piazza, FV 14;

Degeneracy

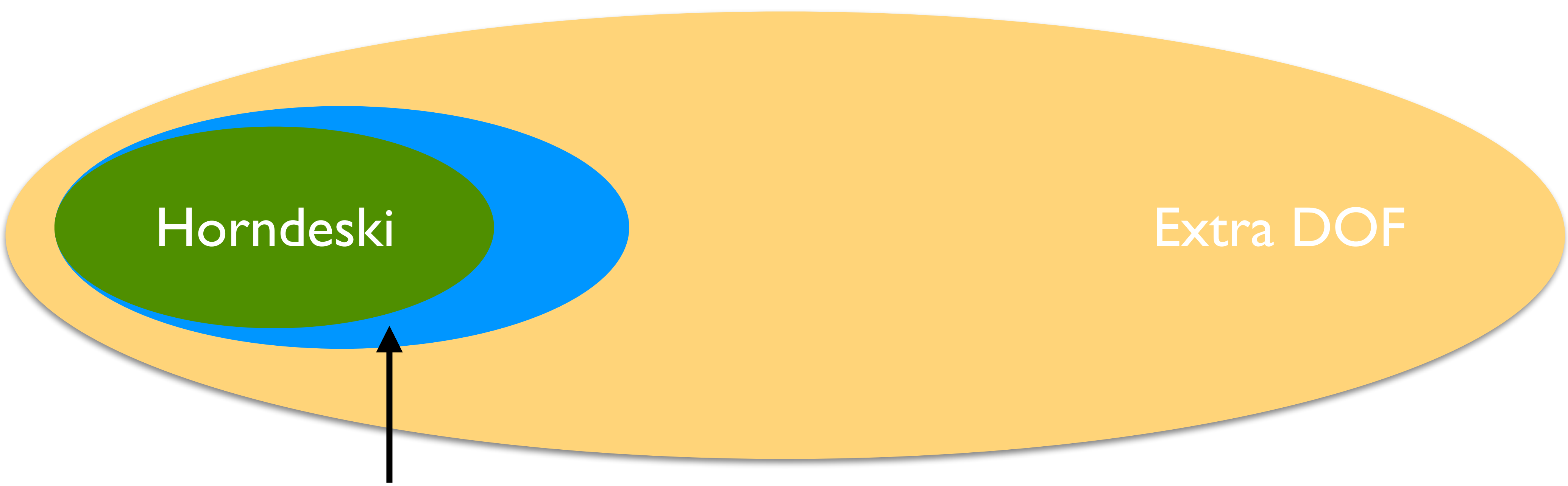
Higher derivatives $\Rightarrow$ extra ghost DOF, only for **non degenerate** theories

Ex 1: **1 variable** mechanical system

$$\mathcal{L} = \frac{1}{2}\ddot{\phi}^2 + \frac{m}{2}\dot{\phi}^2 \qquad \Rightarrow \qquad \begin{aligned} \ddot{Q} &= mQ + \lambda \\ \dot{\lambda} &= 0 \\ \dot{\phi} &= Q \end{aligned}$$

$$Q = \dot{\phi}$$

2 DOF!



beyond Horndeski

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Ex 2: **2 variables** mechanical system

$$\mathcal{L} = \frac{1}{2}\ddot{\phi}^2 + \frac{m}{2}\dot{\phi}^2 + \frac{k}{2}\dot{\chi}^2 + b\ddot{\phi}\dot{\chi}$$

$$Q = \dot{\phi}$$

$$\Rightarrow \begin{pmatrix} \ddot{Q} \\ \ddot{\chi} \end{pmatrix} \begin{pmatrix} 1 & b \\ b & k \end{pmatrix} = \begin{pmatrix} mQ + \lambda \\ 0 \end{pmatrix}$$

$$\dot{\lambda} = 0$$

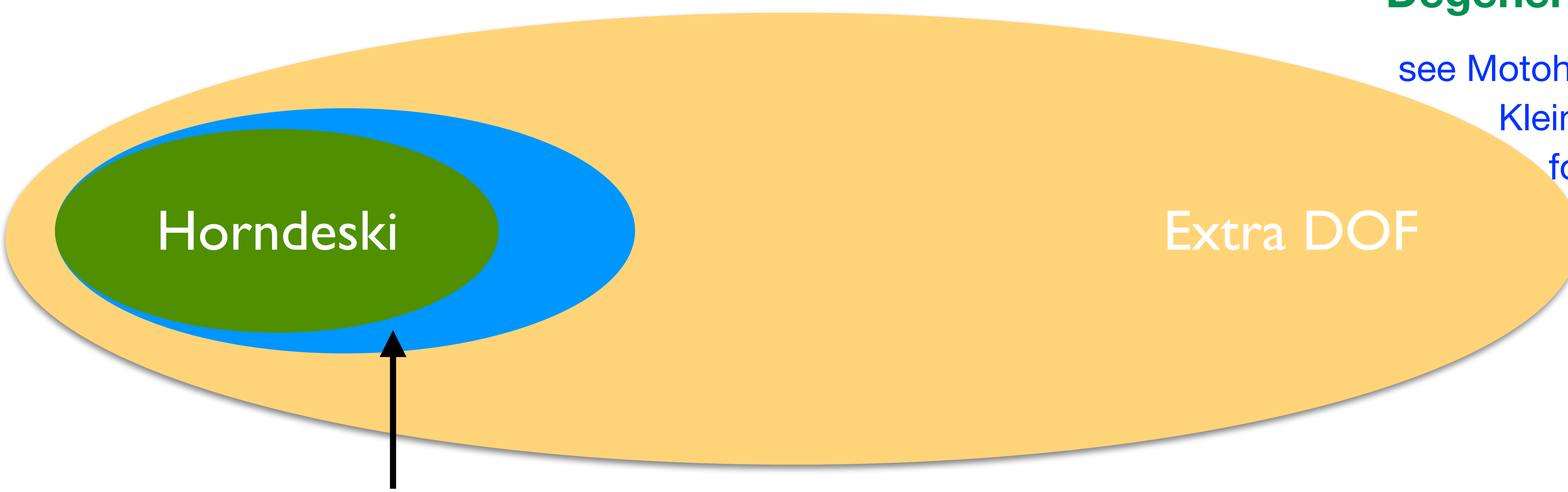
$$\dot{\phi} = Q$$

$k \neq b^2$ 3 DOF

$k = b^2$ 2 DOF!

Degenerate!

see Motohashi et al 16
Klein & Roest 16
for multifields



beyond Horndeski

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$$\phi(t) \leftrightarrow \phi(x^\rho)$$

$$\chi(t) \leftrightarrow g_{\mu\nu}(x^\rho)$$

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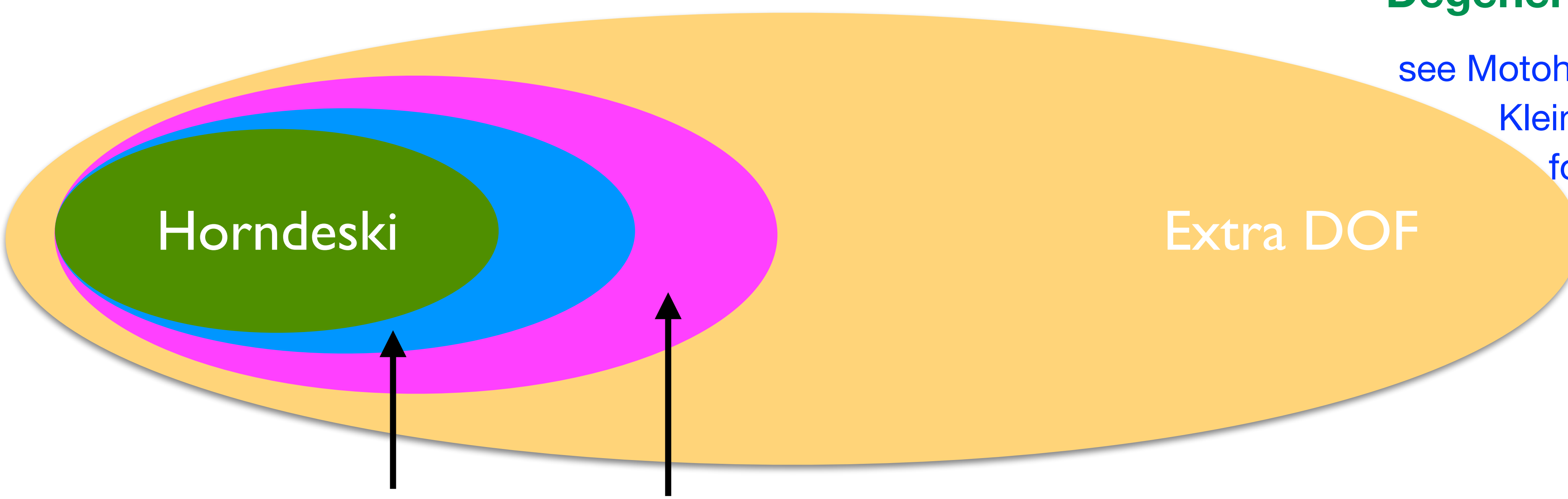

beyond Horndeski
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More degenerate theories:
DHOST/EST
Langlois, Noui 15, 16;
Crisostomi, Koyama, Tasinato 16;

DHOST/EST theories

Degenerate **H**igher-**O**rder **S**calar-**T**ensor theories or **E**xtended **S**calar **T**ensor theories

$$\mathcal{L}^{(2)}_{\mathrm{DHOST}} = f_2(\phi, X) R + \sum_i^5 C_i^{(2)\,\mu\nu\rho\sigma}(\phi, X) \nabla_\mu \nabla_\nu \phi \, \nabla_\rho \nabla_\sigma \phi$$

Langlois, Noui 15;
Crisostomi at al. 16;
de Rham, Matas 16

(see Crisostomi's talk; see also Saito's talk)

DHOST/EST theories

Degenerate **H**igher-**O**rder **S**calar-**T**ensor theories or **E**xtended **S**calar **T**ensor theories

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Langlois, Noui 15;
Crisostomi at al. 16;
de Rham, Matas 16

(see Crisostomi's talk; see also Saito's talk)

- In general, **3 degeneracy** conditions **(7 classes)** associated to second-class constraints

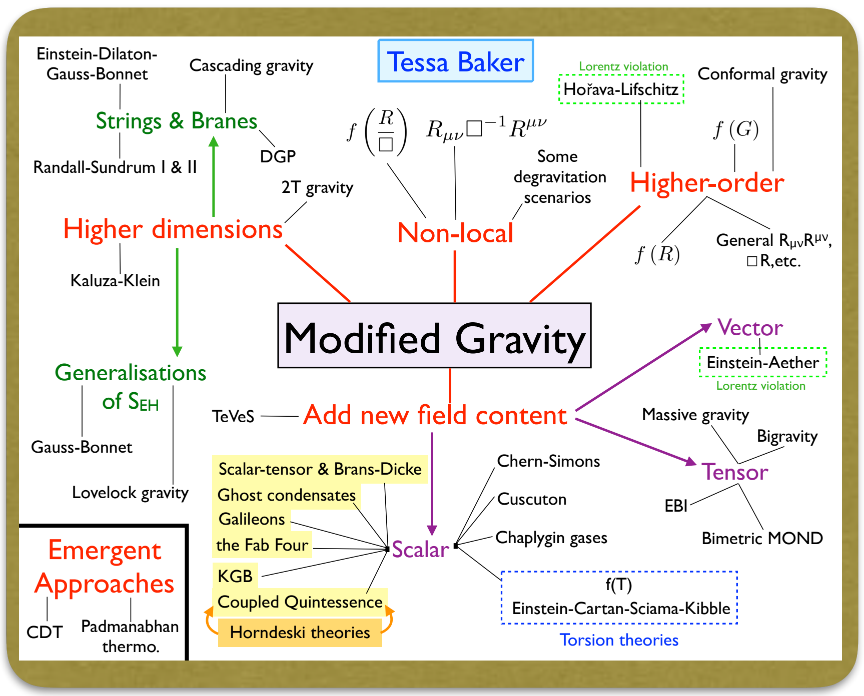
- Structure preserved by general **disformal** transformations of the metric:

$$g_{\mu\nu} \to C(\phi, X)g_{\mu\nu} + D(\phi, X)\partial_\mu\phi\partial_\nu\phi$$

(see also Takahashi's talk)

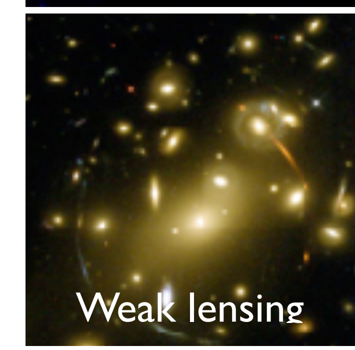
- **Quadratic** + **cubic** theories: **9 subclasses**, **25 combinations** of quadratic and cubic theories

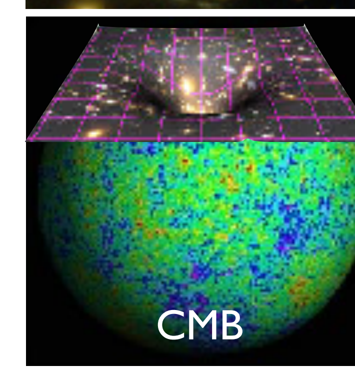
Models

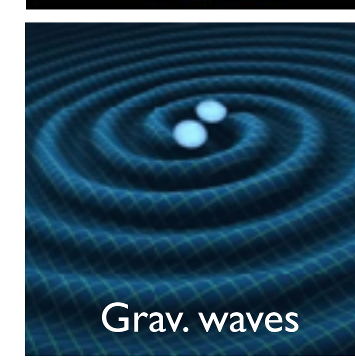


Many models of modified gravity, each with its own theoretical motivation and phenomenology

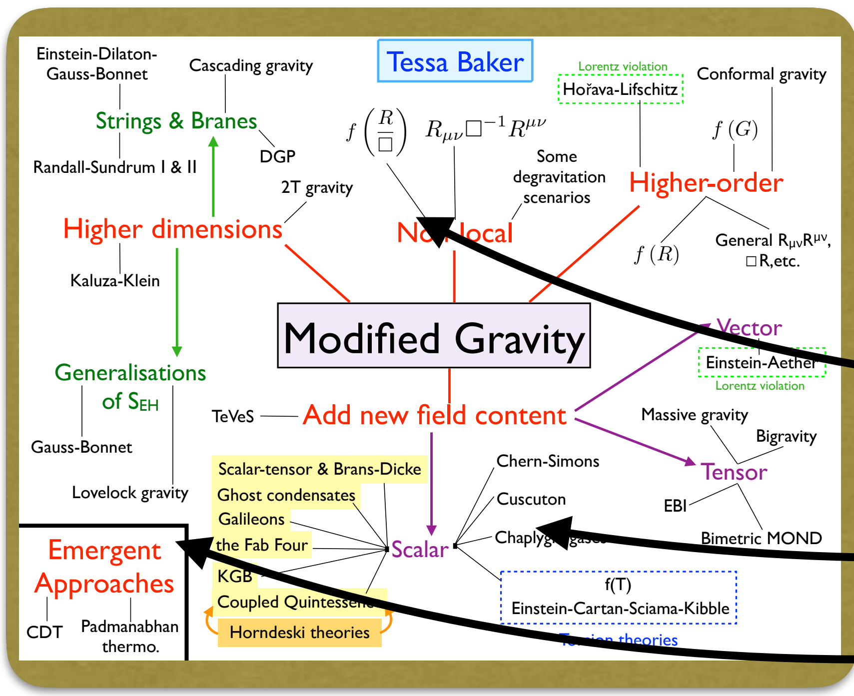
Observations



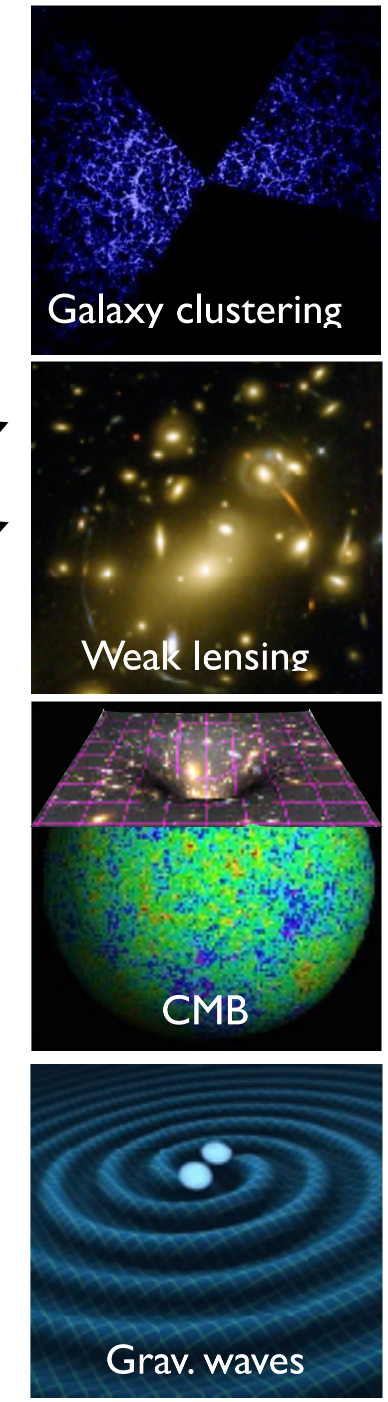




Models



Observations



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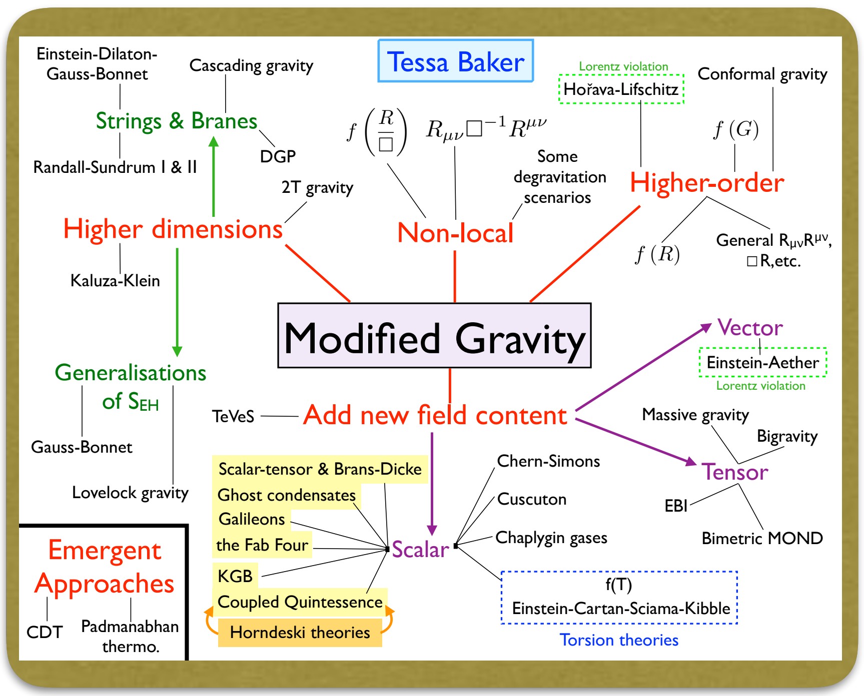
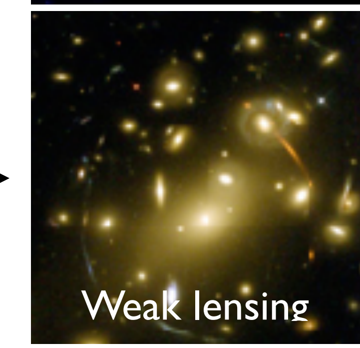


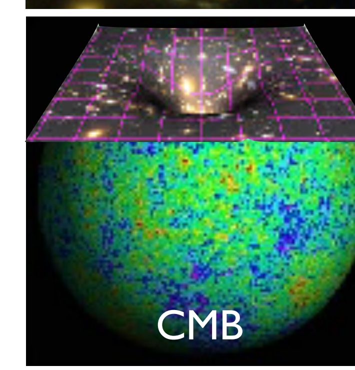
ETofDE

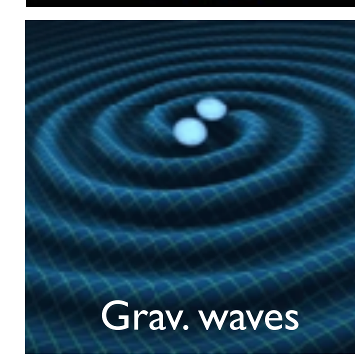
$$\alpha_K(t),\ \alpha_B(t),\ \alpha_M(t),$$
$$\alpha_T(t),\ \alpha_T(t),\ \ldots$$

Bridge models and observations in a minimal and systematic way

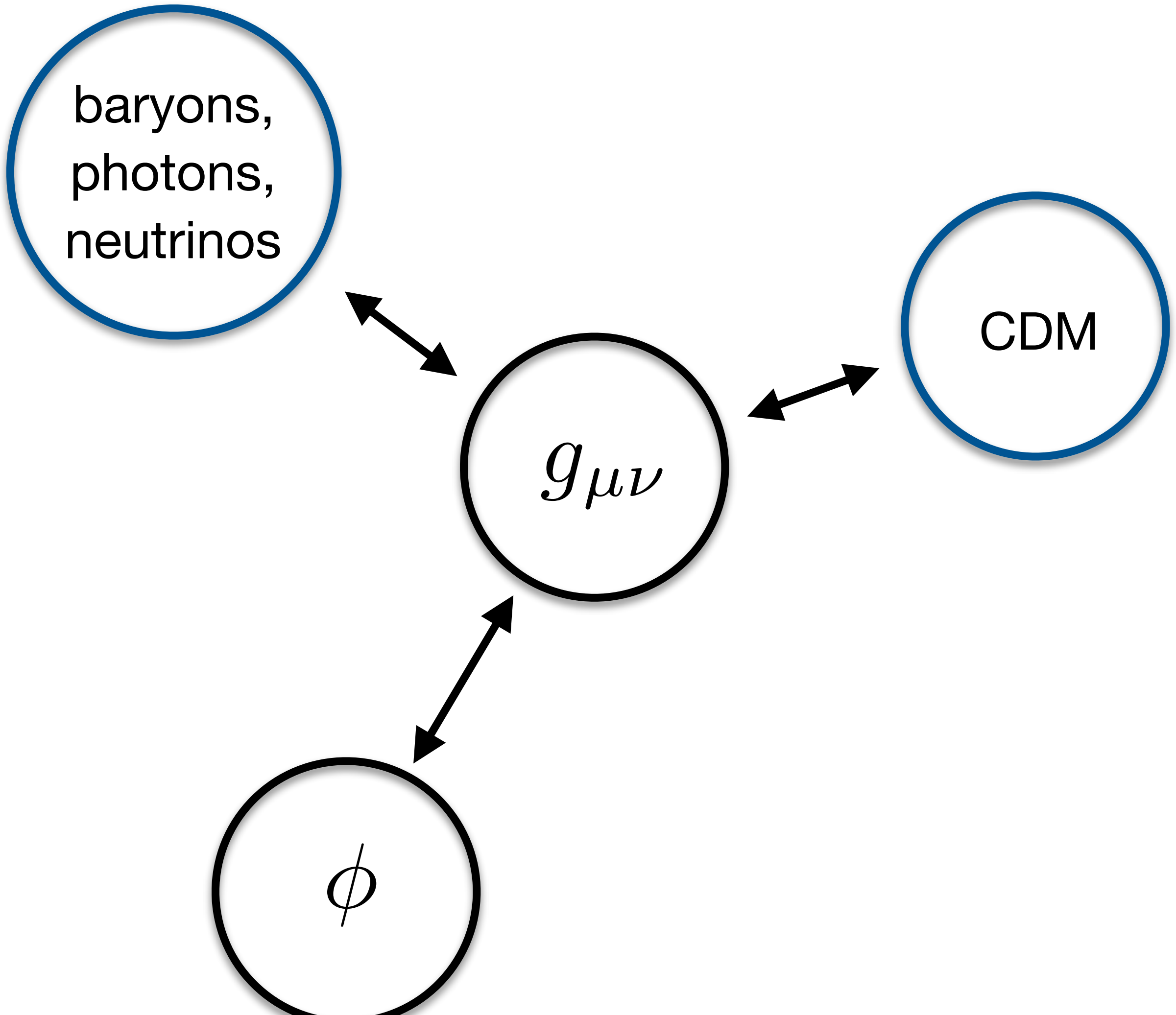
Observations



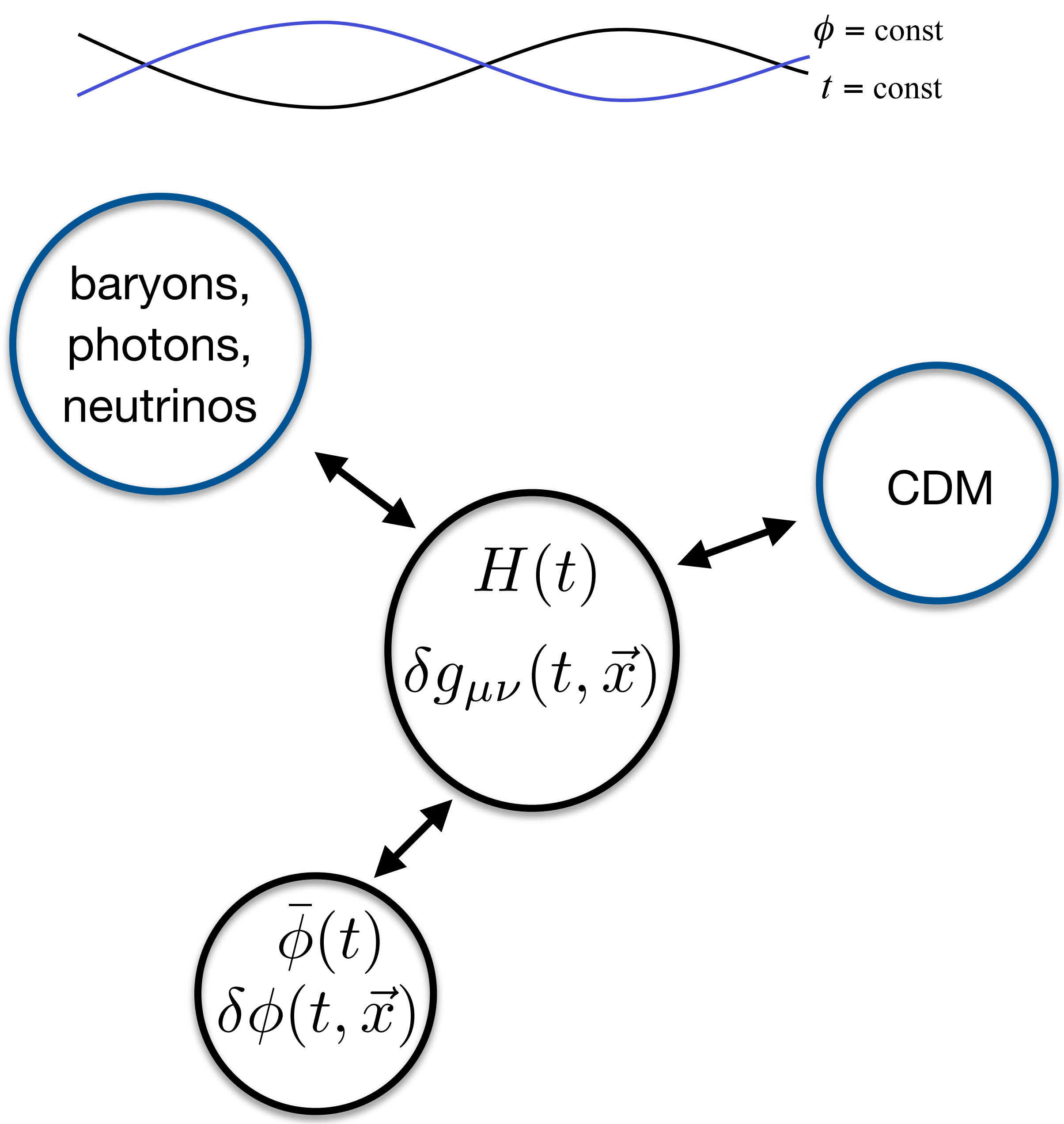




Jordan frame

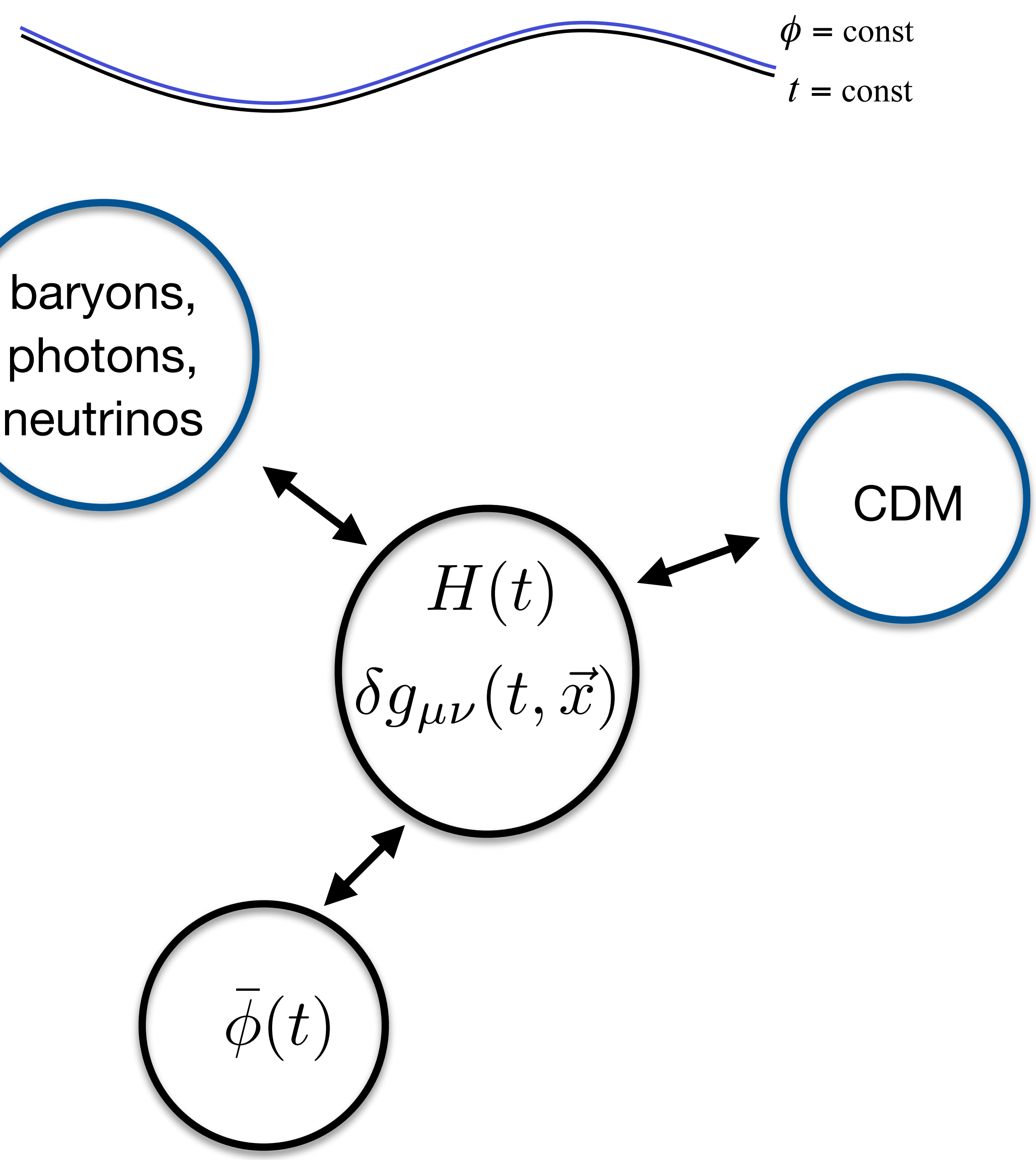


FLRW background



Time reparametrisation invariance broken, $\dot{\phi}(t) \neq 0$

Uniform field slicing $\delta\phi(t,\vec{x}) = 0$



Spatial reparametrisation invariance preserved on these hypersurfaces

Action: most general function of the metric perts, **preserving spatial-diff** invariance

Cheung et al. `07

EFT Lagrangian

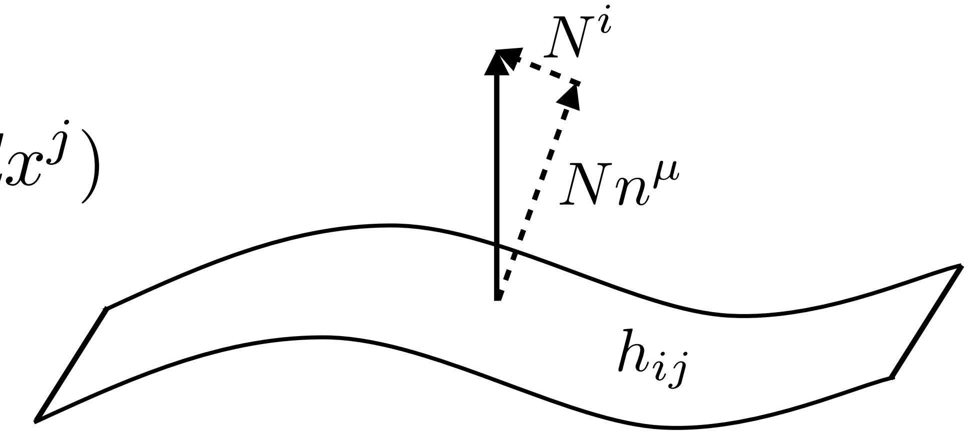
Gubitosi, Piazza, FV 12
Gleyzes, Langlois, Piazza, FV 13
Bloomfield et al. 12, 13

$$S^{(2)} = \int d^4x \sqrt{h} \frac{M^2}{2} \left[\delta K_i^j \delta K_j^i - \delta K^2 + {}^{(3)}R + \delta N {}^{(3)}R + \sum_i \alpha_i(t) \mathcal{O}_i^{(2)}(\delta N, \delta K, \ldots) \right]$$

ADM decomposition

$$ds^2 = -N^2 dt^2 + h_{ij}(N^i dt + dx^i)(N^j dt + dx^j)$$

$$N \sim \dot{\phi} \, , \; K_{ij} \sim \dot{h}_{ij} \; , \; {}^{(3)}R \sim \partial^2 h$$



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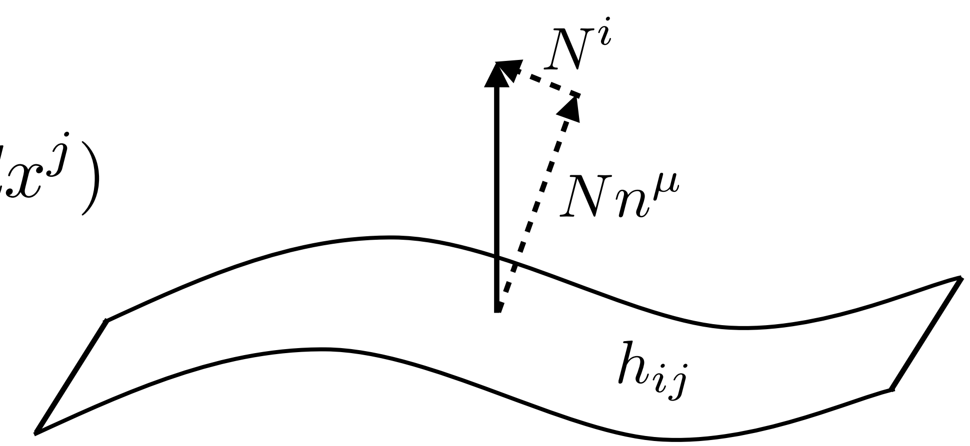

- New operators describe **deviations from GR** (ΛCDM). Ordered in **number of perturbations** and **derivatives**
- **Time-dependent couplings** (functions $\alpha_i(t)$), due to expansion around FLRW background
- Functions $\alpha_i(t)$ **independent** of background evolution $H(t) = \dot{a}/a$

We fit to data $H(t)$ and $\alpha_i(t)$ (agnostic of their time dependence and parametrization)

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Gubitosi, Piazza, FV 12
Gleyzes, Langlois, Piazza, FV 13
Bloomfield et al. 12, 13

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Notation of Bellini, Sawicki '14 for the alphas

α_i	α_K	α_B	α_M	α_T	α_H
$\mathcal{O}_i^{(2)}$	δN^2	$\delta N \delta K$	$\frac{dM^2}{d\ln a}$	${}^{(3)}R$	$\delta N {}^{(3)}R$
quintessence, k-essence	✓				
Cubic Galileon	✓	✓			
Brans-Dicke, f(R)	✓	✓	✓		
Horndeski	✓	✓	✓	✓	
Beyond Horndeski	✓	✓	✓	✓	✓

5 functions of time instead of 5 functions of $\phi, (\partial\phi)^2$; minimal number of parameters

$$N \sim \dot\phi\ , \ \ K_{ij} \sim \dot h_{ij}\ ,\ \ {}^{(3)}R \sim \partial^2 h$$

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Beyond Horndeski	✓	✓	✓	✓	✓

5 functions of time instead of 5 functions of $\phi, (\partial\phi)^2$; minimal number of parameters

Stability conditions easy to implement

	Scalar	Tensor
No ghosts	$\alpha_K + 6\alpha_B^2 > 0$	$M^2 > 0$
No gradient inst.	$c_s^2(\alpha_i) \geq 0$	$\alpha_T \geq -1$

EFT Lagrangian

Gubitosi, Piazza, FV 12
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Bloomfield et al. 12, 13

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H					
H					✓

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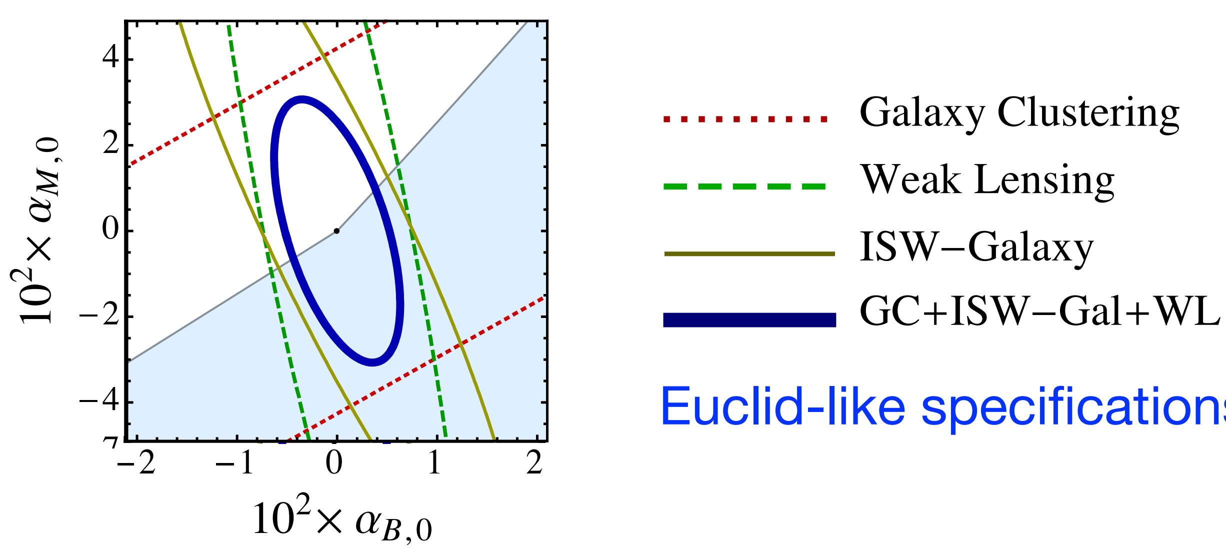
Gleyzes, Langlois, Mancarella FV '15



Euclid-like specifications

EFT Lagrangian

Gubitosi, Piazza, FV 12
Gleyzes, Langlois, Piazza, FV 13
Bloomfield et al. 12, 13

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Brans-Dicke, f(R)	✓	✓	✓		
Horndeski	✓	✓	✓	✓	
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Stability conditions easy to implement

	Scalar	**Tensor**
No ghosts	$\alpha_K + 6\alpha_B^2 > 0$	$M^2 > 0$
No gradient inst.	$c_s^2(\alpha_i) \geq 0$	$\alpha_T \geq -1$

Can be applied to **non-singular cosmologies**
(see Akama and Kobayashi's talk)

Higher-Order theories

$$S^{(2)} = \int d^4x \sqrt{h} \frac{M^2}{2} \left[\delta K_i^j \delta K_j^i - \delta K^2 + {}^{(3)}R + \delta N {}^{(3)}R + \sum_i \alpha_i(t) \mathcal{O}_i^{(2)}(\delta N, \delta K, \ldots) \right]$$

All quadratic operators **up to two** derivatives

Langlois, Mancarella, Noui, FV 17

α_i	α_K	α_B	α_M	α_T	α_H	α_L	β_1	β_2	β_3
$\mathcal{O}_i^{(2)}$	δN^2	$\delta N \delta K$	$\frac{dM^2}{d\ln a}$	${}^{(3)}R$	$\delta N {}^{(3)}R$	δK^2	$\delta \dot{N}^2$	$\delta \dot{N} \delta K$	$(\partial_i \delta N)^2$
quintessence, k-essence	✓								
Cubic Galileon	✓	✓							
Brans-Dicke, f(R)	✓	✓	✓						
Horndeski	✓	✓	✓	✓					
Beyond Horndeski	✓	✓	✓	✓	✓				
DHOST/EST theries	✓	✓	✓	✓	✓	✓	✓	✓	✓

Higher-Order theories

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α_i	α_K	α_B	α_M	α_T	α_H	α_L	β_1	β_2	β_3
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- Generic scalar dispersion relation: $\mathcal{E}_1 \omega^4 + \mathcal{E}_2 \omega^2 k^2 + \mathcal{E}_3 \omega^2 + \mathcal{E}_4 k^4 + \mathcal{E}_5 k^2 = 0$
- **Two types** of degeneracy conditions lead to $\omega^2 - c_s^2 k^2 = 0$

$$\mathcal{C}_{\rm I}: \quad \alpha_L = 0 \,, \qquad \beta_2 = f_2(\beta_1) \,, \qquad \beta_3 = f_3(\beta_1)$$

$$\mathcal{C}_{\rm II}: \quad \beta_1 = f_1(\alpha_T, \alpha_H, \alpha_L) \,, \quad \beta_2 = f_2(\alpha_T, \alpha_H, \alpha_L) \,, \quad \beta_3 = f_3(\alpha_T, \alpha_H, \alpha_L)$$

$c_s^2 \propto -c_T^2$ **ruled out!**

Higher-Order theories

$$S^{(2)} = \int d^4x \sqrt{h} \frac{M^2}{2} \left[\delta K_i^j \delta K_j^i - \delta K^2 + {}^{(3)}R + \delta N {}^{(3)}R + \sum_i \alpha_i(t) \mathcal{O}_i^{(2)}(\delta N, \delta K, \ldots) \right]$$

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Langlois, Mancarella, Noui, FV 17

α_i	α_K	α_B	α_M	α_T	α_H	α_L	β_1	β_2	β_3
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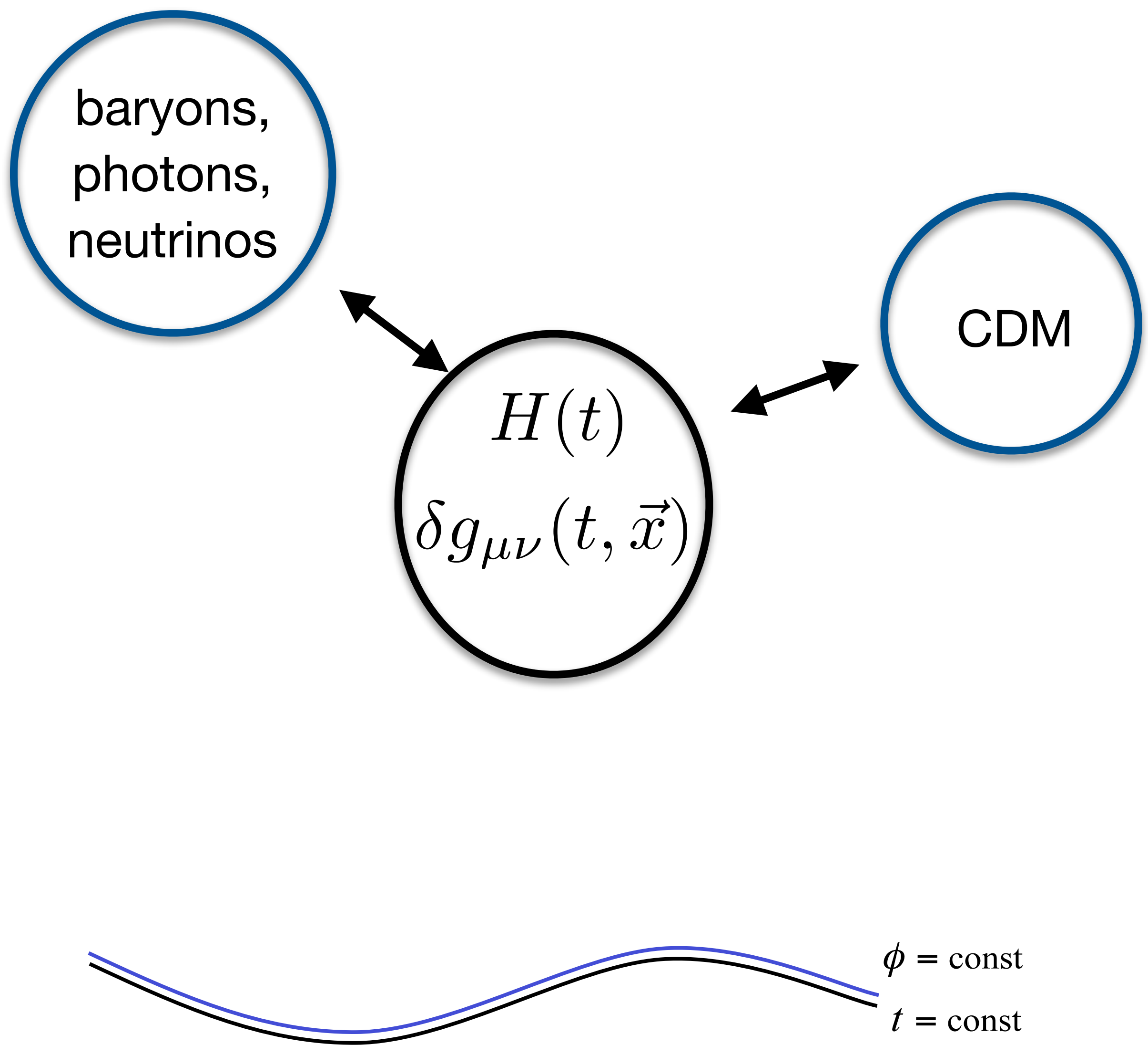
$$\mathcal{C}_{\rm I}: \quad \alpha_L = 0\,, \qquad \beta_2 = f_2(\beta_1)\,, \qquad \beta_3 = f_3(\beta_1)$$

- Class $\mathcal{C}_{\rm I}$ can be brought to **Horndeski frame**: $\alpha_H = 0,\ \beta_J = 0$

DHOST I $\xrightarrow{C(X)}$ Beyond Horndeski $\xrightarrow{D(X)}$ Horndeski

- Changing frame changes matter couplings (Horndeski vs Jordan): **Matter matters**!

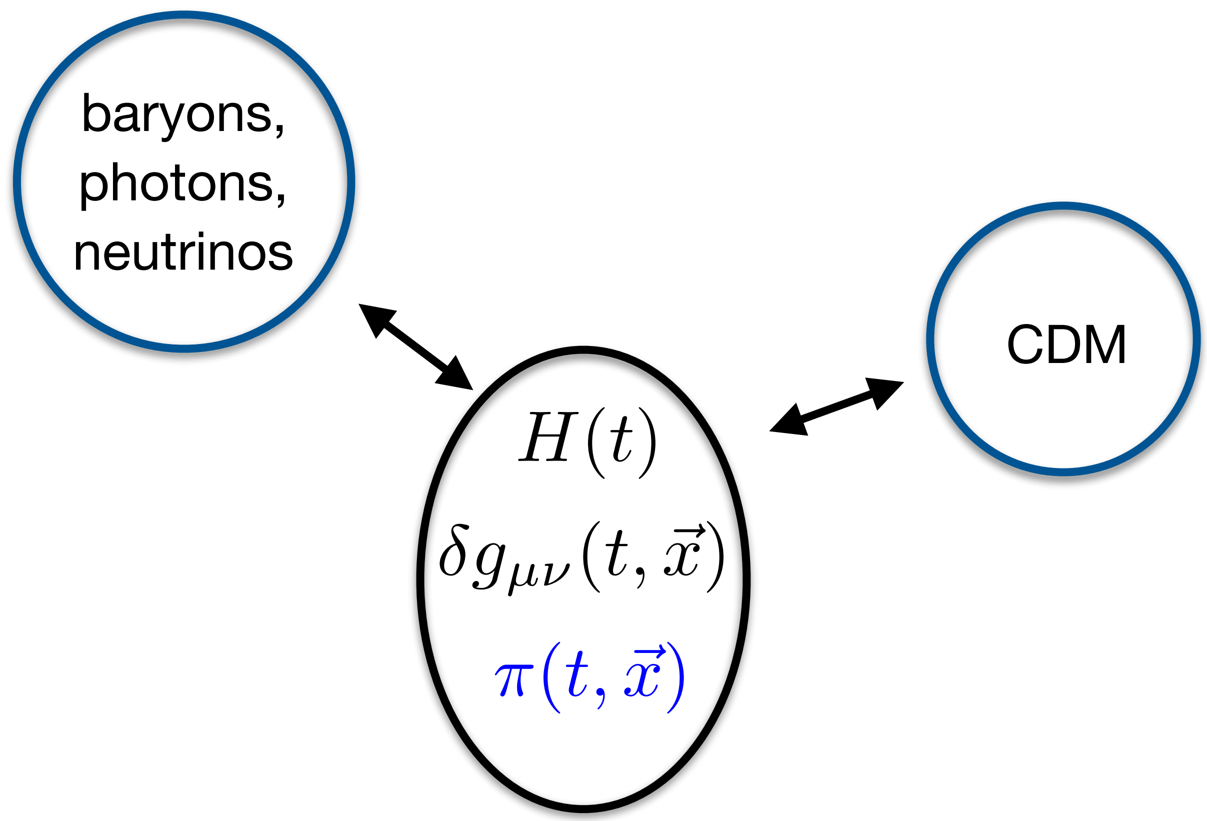
Uniform field slicing $\delta\phi(t,\vec{x})=0$

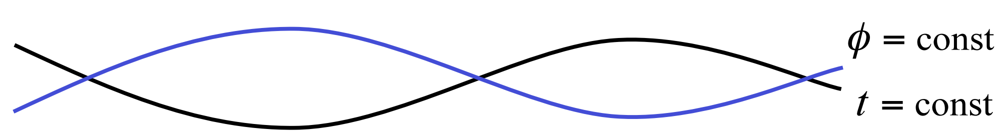


Uniform field slicing $\delta\phi(t, \vec{x}) = 0$

Newtonian gauge $ds^2 = -(1 + 2\Phi)dt^2 + a^2(t)(1 - 2\Psi)d\vec{x}^2$

$$t \to t + \pi(t, \vec{x})$$

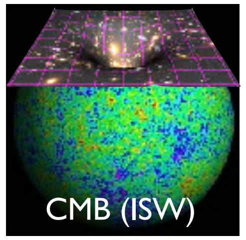




Phenomenology

$$dt^2 = -(1+2\Phi)dt^2 + a^2(t)(1-2\Psi)d\vec{x}^2$$

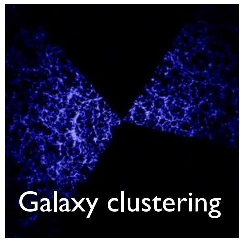
Quasi-static approximations

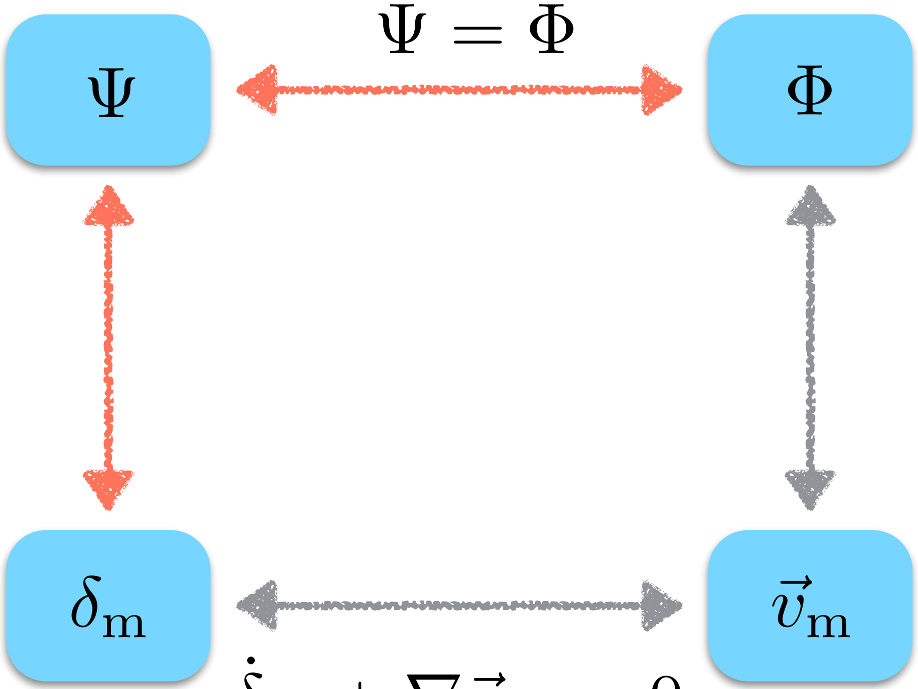


$$\nabla^2(\Psi + \Phi) = 8\pi G a^2 \rho_m \delta_m$$

$$\Psi = \Phi$$

$$\nabla^2 \Psi = 4\pi G a^2 \rho_m \delta_m$$





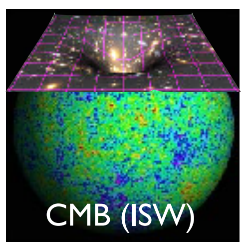
$$\dot{\vec{v}}_m + H\vec{v}_m = -\nabla\Phi$$

$$\dot{\delta}_m + \nabla\vec{v}_m = 0$$

Phenomenology

$$dt^2 = -(1+2\Phi)dt^2 + a^2(t)(1-2\Psi)d\vec{x}^2$$

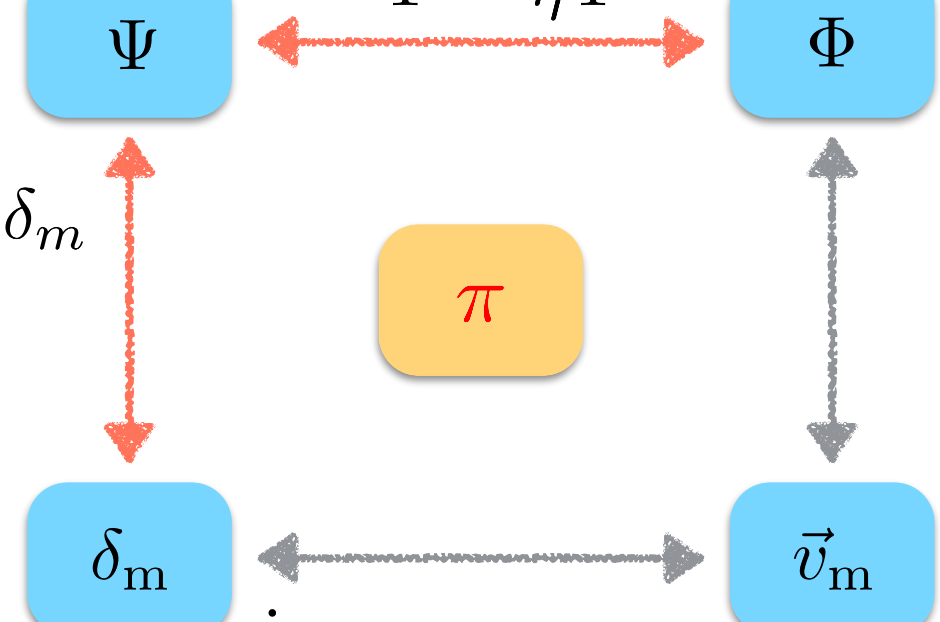
Quasi-static approximations



$$\nabla^2(\Psi+\Phi) = 8\pi G(1+\Upsilon_{\rm lens})a^2\rho_m\delta_m$$

$$\Upsilon_{\rm lens} = \Upsilon_{\rm lens}(\alpha_i)$$

$$\Psi = \eta\Phi$$



$$\nabla^2\Psi = 4\pi G(1+\Upsilon_\Psi)a^2\rho_m\delta_m$$

$$\Upsilon_\Psi = \Upsilon_\Psi(\alpha_i)$$

$$\dot{\vec{v}}_m + H\vec{v}_m = -\nabla\Phi$$

$$\dot{\delta}_m + \nabla\vec{v}_m = 0$$

Einstein-Boltzmann solvers

- Full Einstein-Boltzmann solver: $$\frac{df_I}{d\eta} = C_I[f_I] \; , \qquad I = \gamma, \nu, b, \mathrm{CDM}$$

$$\frac{\delta S^{(2)}}{\delta \pi} = 0 \qquad \& \qquad G_{ij}^{\mathrm{modified}} = 8\pi G \sum_I T_{ij}^{(I)}$$

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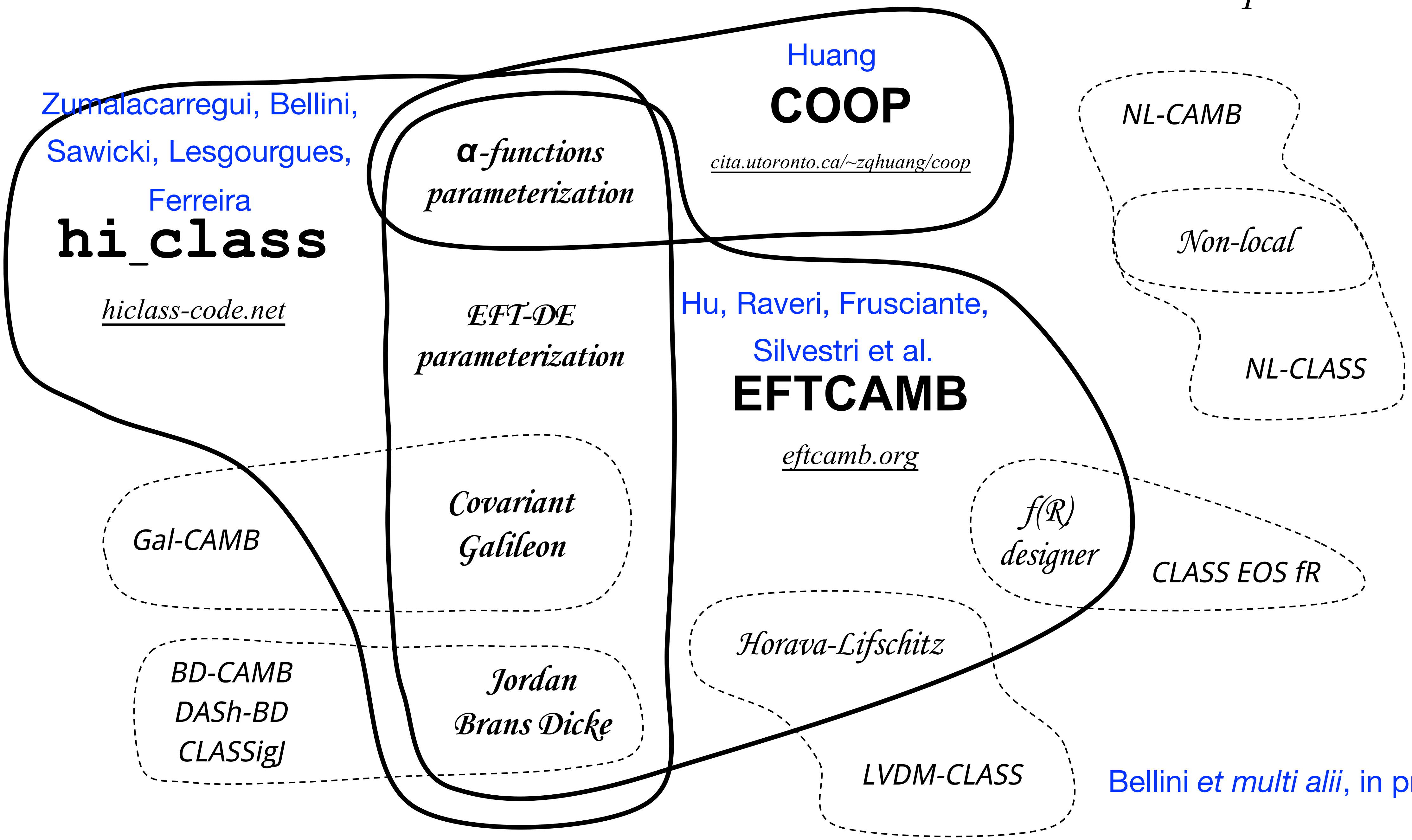

Bellini *et multi alii*, in prep.

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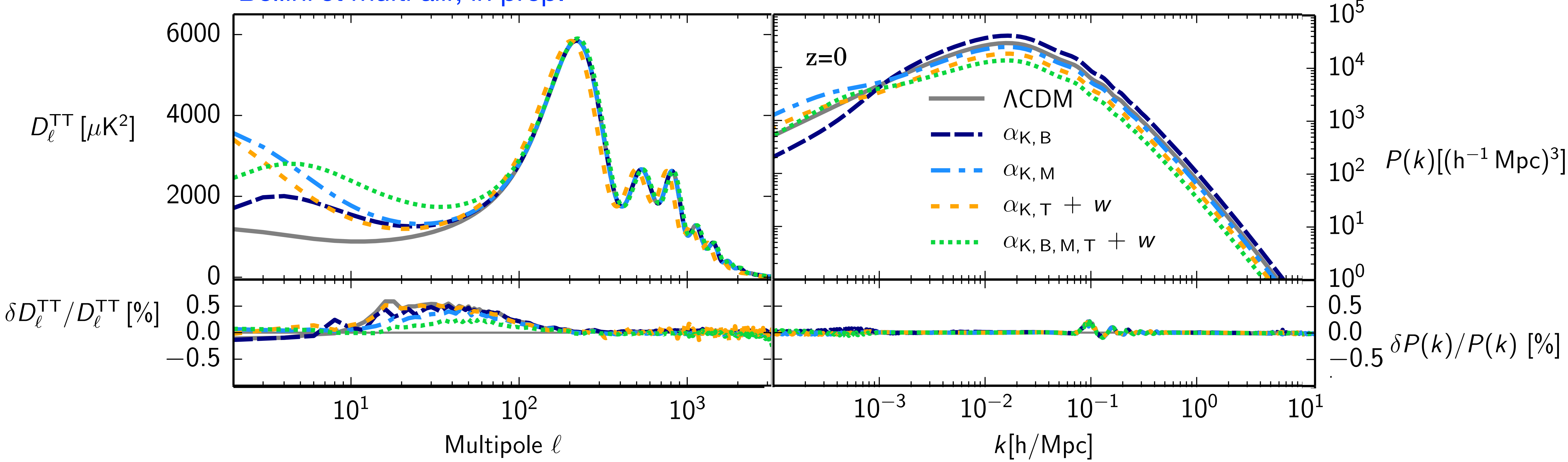
Codes **agree** at **sub-percent** level, in most cases

- EFTCAMB (from CMBFAST) (Hu, Raveri, Frusciante, Silvestri et al.)
- hi_class (from CLASS) (Zumalacarregui, Bellini, Sawicki, Lesgourgues, Ferreira et al.)

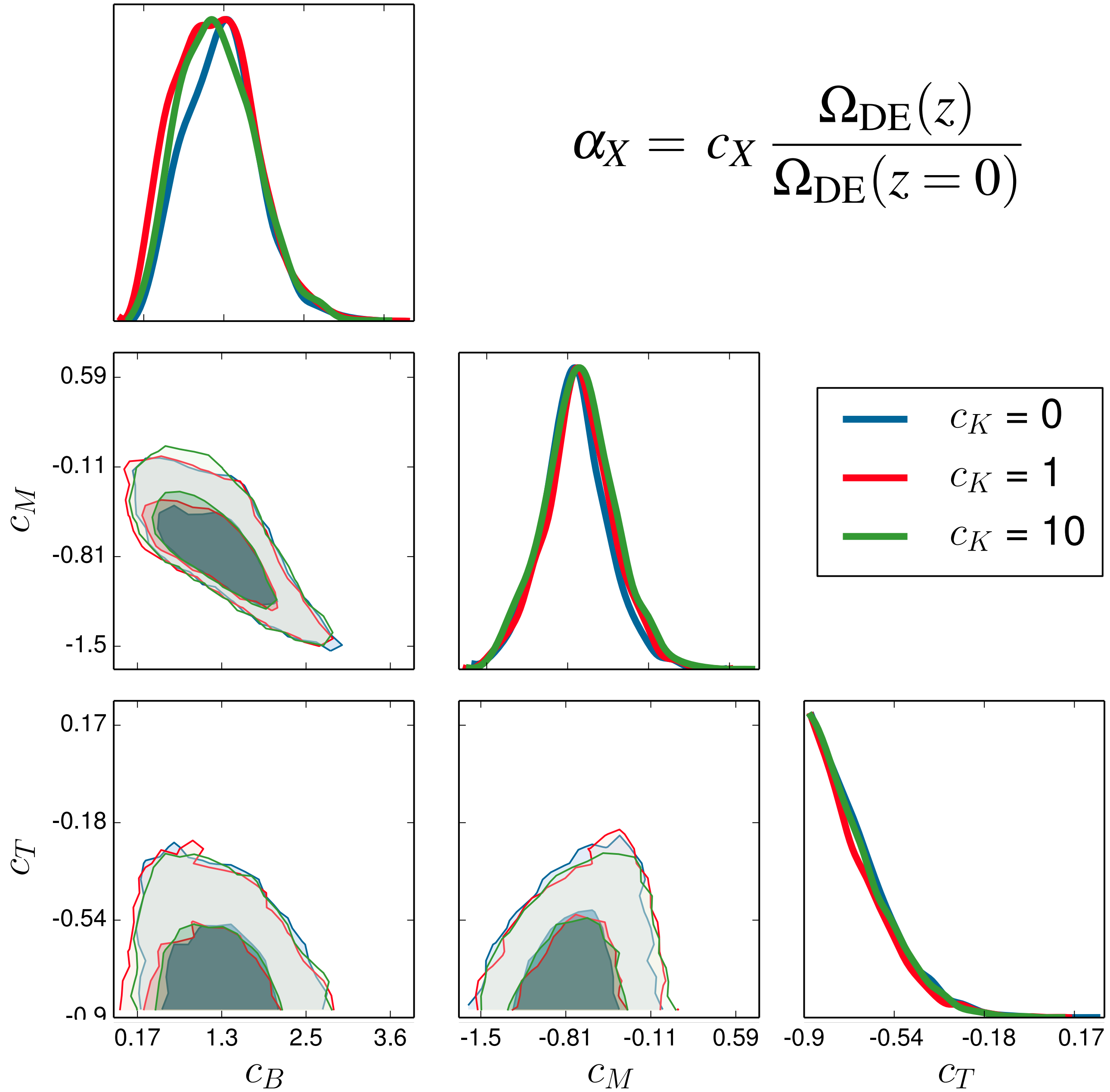
Bellini *et multi alii*, in prep.



Current Constraints

MCMC analysis using hi_class, from a combination of **CMB** (Planck2015WP), **P(k)** (WiggleZ), **BAO** (6dFGS, SDSS-MGS, BOSS) and **RSD** (6dFGS, MGS, LRG, Vipers, BOSS, WiggleZ)

Bellini, Cuesta, Jimenez, Verde 15



$$\alpha_X = c_X \frac{\Omega_{\rm DE}(z)}{\Omega_{\rm DE}(z=0)}$$

"The improvement in the fit at the expense of adding extra parameters, quantified in terms of difference of log likelihood is not significant"

Log ($E_{Hordenski}/E_{\Lambda CDM}$) = 0.09

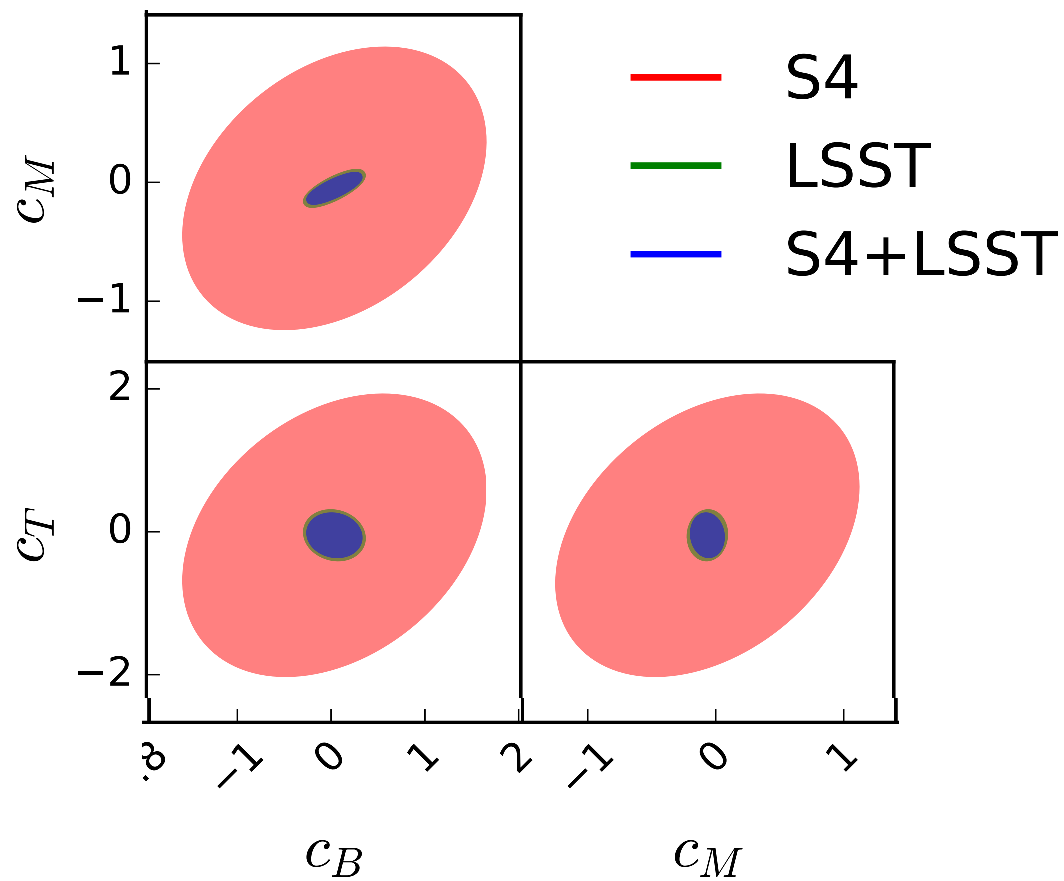
No evidence against ΛCDM

Future constraints

Fisher matrix analysis using hi_class, from a combination of **stage 4 CMB** experiment and **LSST** telescope

Alonso et al. 16

Case	$> \omega_{\rm BD}$, 95% C.L.	$\sigma(c_B)$	$\sigma(c_M)$	$\sigma(c_T)$	$\sigma(c_K)$	$\sigma(w)$	$\sigma(\sum m_\nu)$ [meV]
S4	2.9×10^3	0.796	0.746	1.26	4.9	0.112	71
LSST	1.2×10^4	0.193	0.089	0.205	8.8	0.016	45
S4+LSST	1.3×10^4	0.169	0.072	0.179	3.5	0.011	22



$$\alpha_X = c_X \frac{\Omega_{\rm DE}(z)}{\Omega_{\rm DE}(z=0)}$$

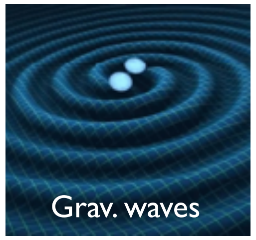
$$\sigma(\alpha_X) \sim \mathcal{O}(0.1)$$

Cassini (Bertotti et al. 03): $\omega_{\rm BD} > 40\,000$

This work: $\omega_{\rm BD} > 20\,000$

GW complementarity

Friction term and **speed** of gravitational waves is affected



$$\ddot{\gamma}_{ij} + H(3+\alpha_M)\dot{\gamma}_{ij} - (1+\alpha_T)\frac{\nabla^2}{a^2}\gamma_{ij} = 0 \qquad c_T^2 = 1 + \alpha_T$$

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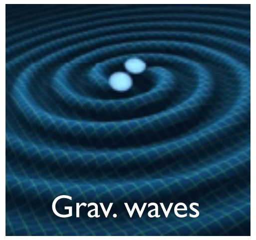


Effect simultaneously in **slip** parameter   Saltas et al. 14, 16

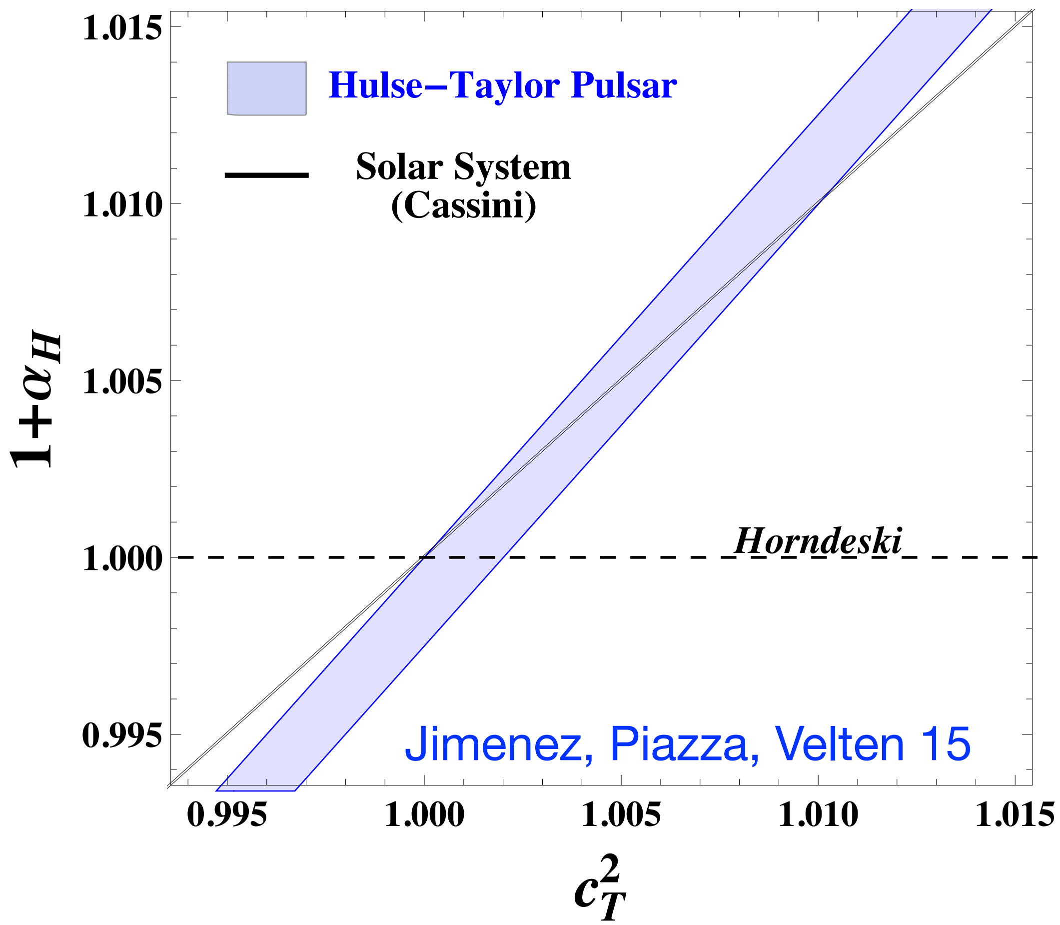
$$\Psi = \eta(\alpha_T, \alpha_M, \alpha_H)\Phi$$

Vainshtein screening ineffective for time-dependent cosmological VEV   Babichev, Deffayet, Esposito-Farese 11

Jimenez, Piazza, Velten 15

$$\dot{P}_{\rm MG} = \frac{G_{\rm gw}}{G_N}\frac{c}{c_T}\dot{P}_{\rm standard} = \frac{(1+\alpha_H)^2}{c_T^3}\dot{P}_{\rm standard}$$

$$\eta = \frac{1+\alpha_H}{c_T^2}$$



GW complementarity

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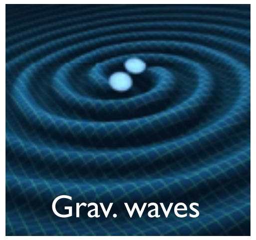

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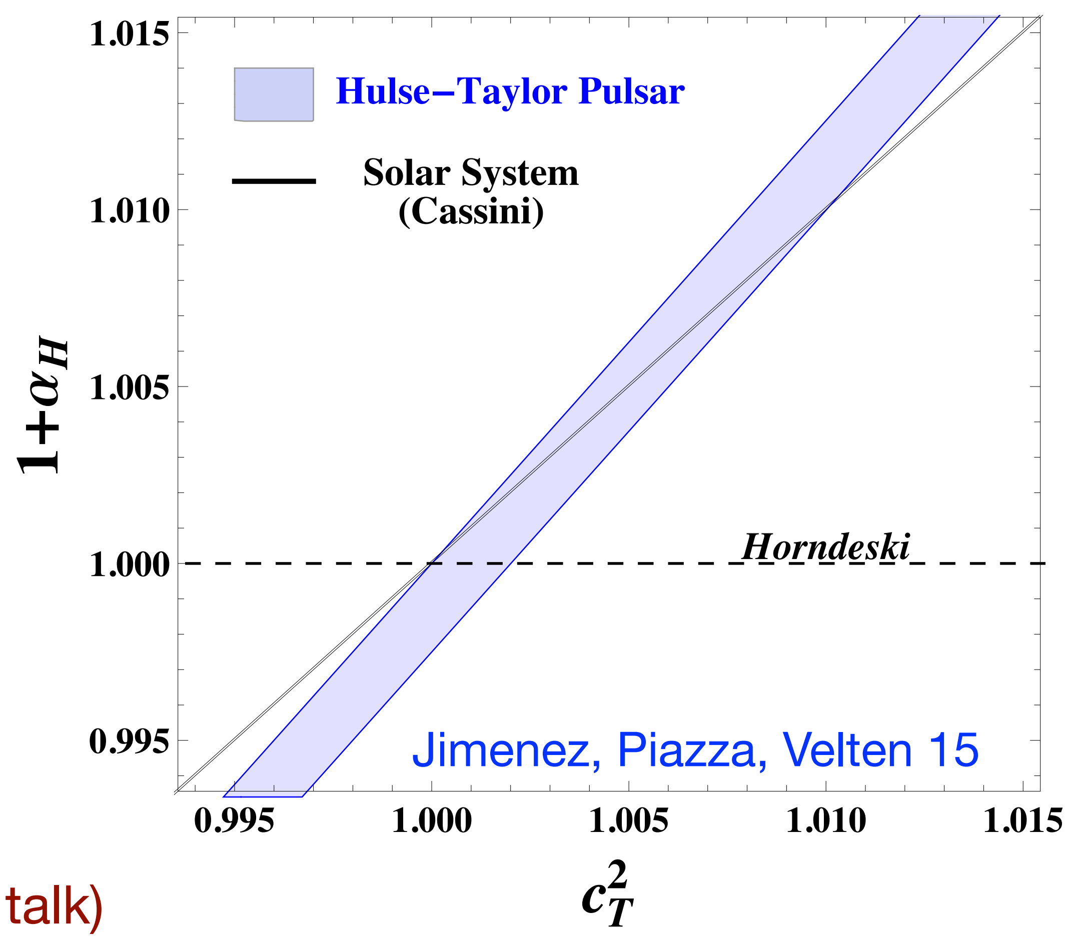

Constraints from black holes and stars (see Sakstein's talk)

Conclusions

❖ Is ΛCDM the ultimate model or simplest approximation given the current precision of data?

❖ Scalar-tensor theories are testable candidate. Have extended beyond Horndeski with higher-order degenerate theories

❖ Unifying description, including higher-order degenerate scalar-tensor theories (and more). Preserves physical principles (locality, causality, unitarity, stability).

❖ Connection with linear observables (Einstein-Boltzmann codes) and GW (partially) worked out