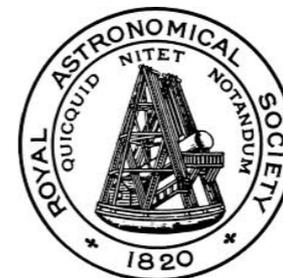
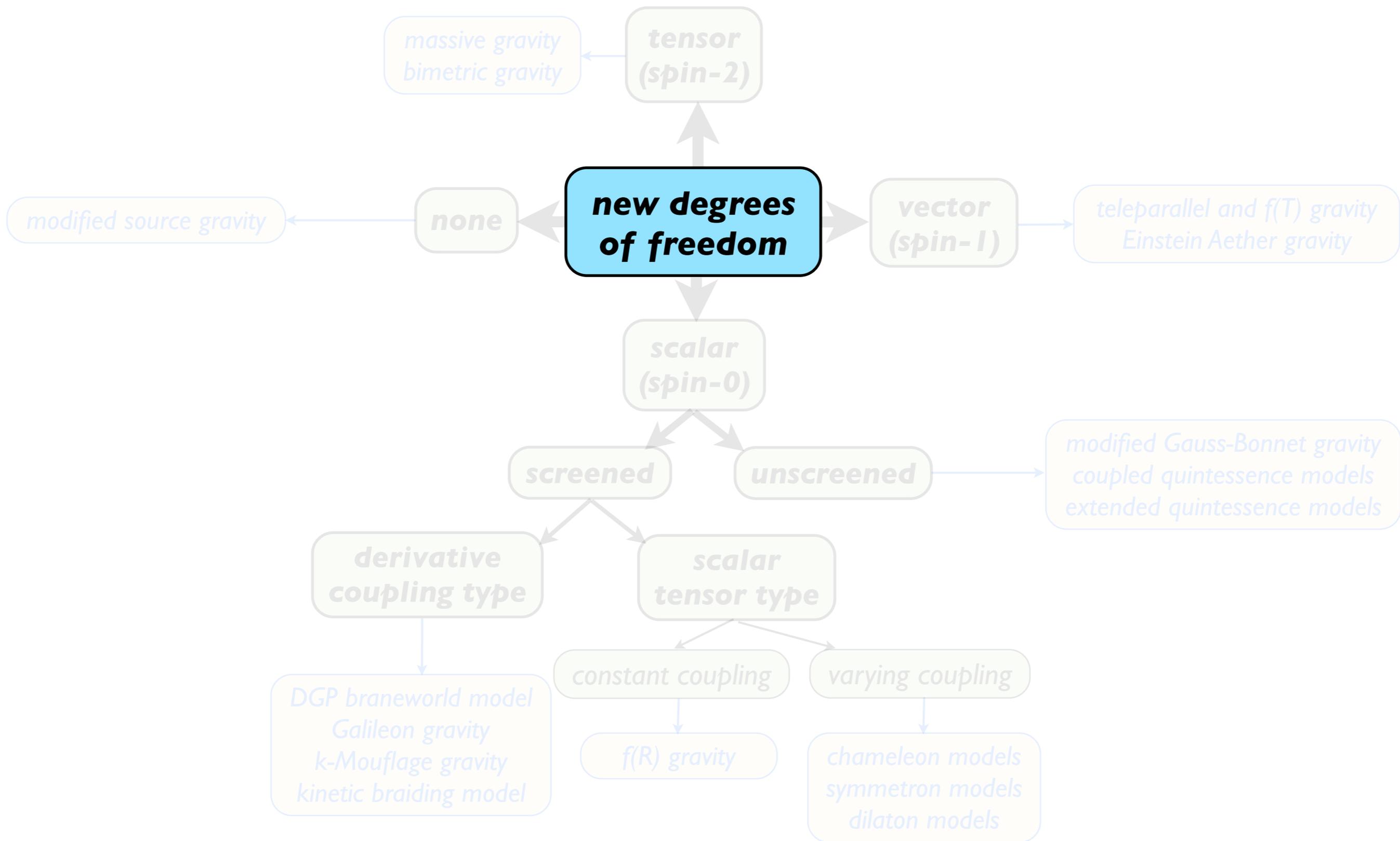


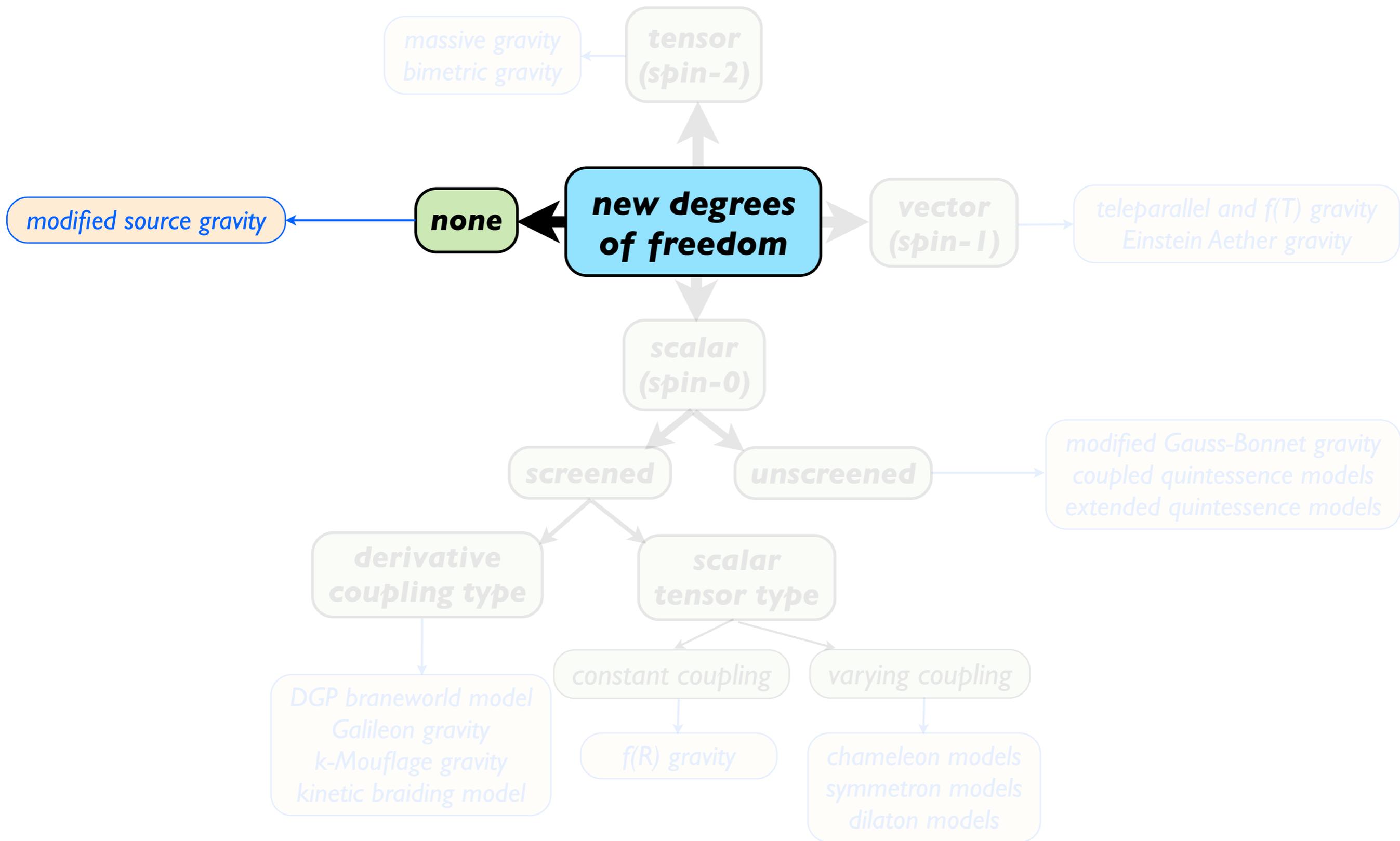
# *modified gravity at crossroad*

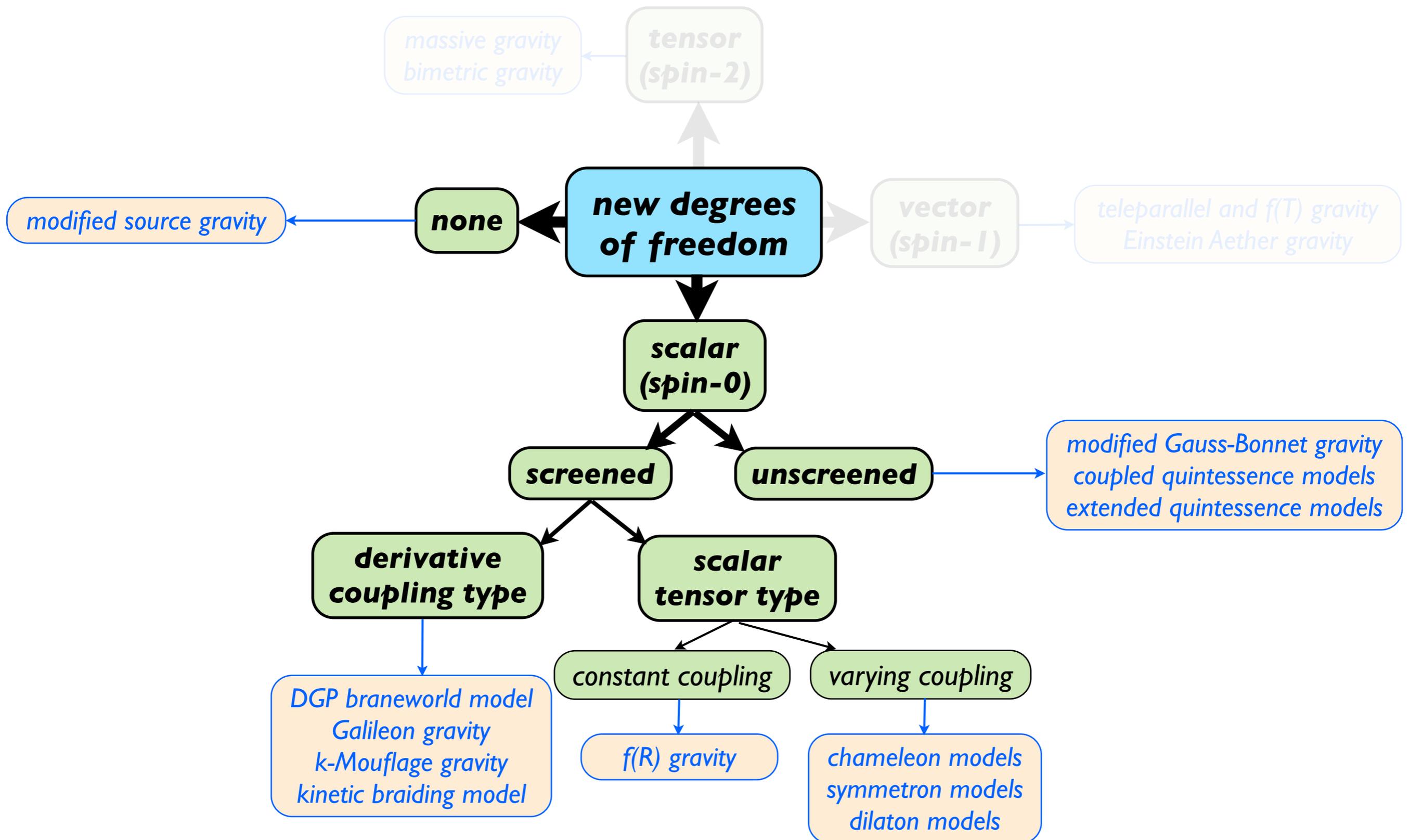
*PONT 17/04/2014 @ Avignon*

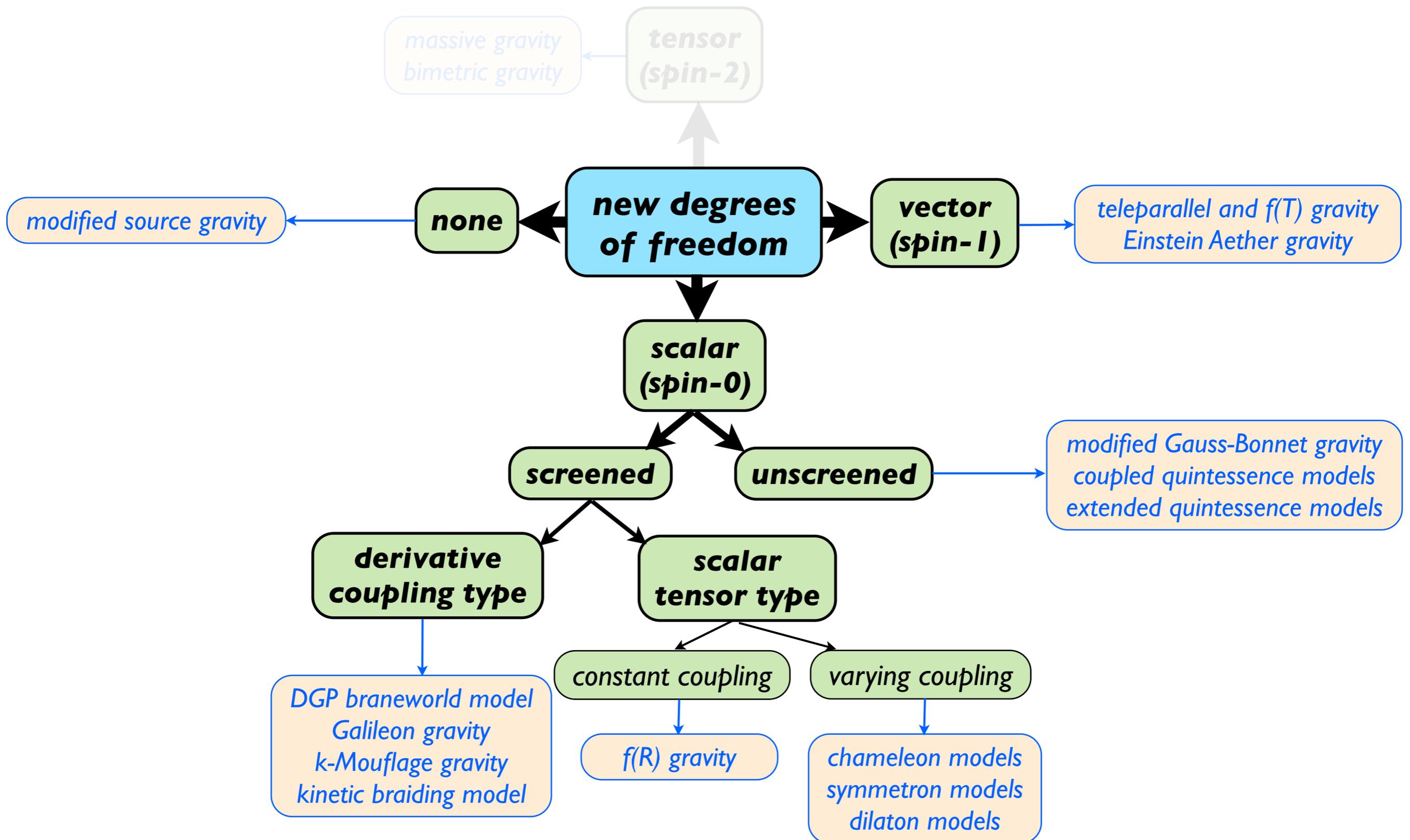
*Baojiu Li*

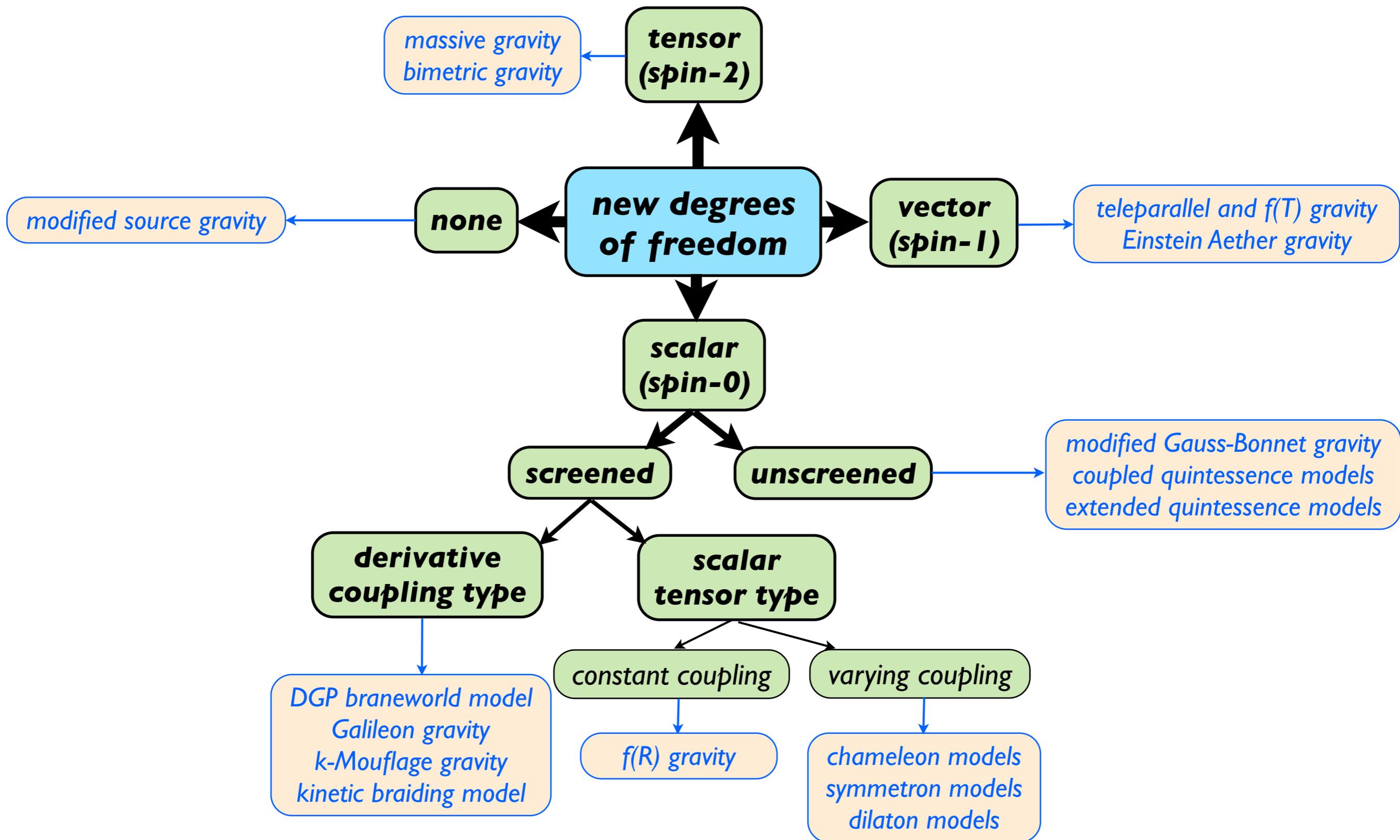












<i>critera</i>		<i>description</i>
<i>essential</i>	<i>E1</i>	
	<i>E2</i>	
	<i>E3</i>	
<i>desired</i>	<i>D1</i>	
	<i>D2</i>	
<i>extra</i>	<i>X1</i>	
	<i>X2</i>	

<i>critera</i>		<i>description</i>
<i>essential</i>	<i>E1</i>	<i>must not be in conflict with terrestrial and solar system tests of gravity</i>
	<i>E2</i>	
	<i>E3</i>	
<i>desired</i>	<i>D1</i>	
	<i>D2</i>	
<i>extra</i>	<i>X1</i>	
	<i>X2</i>	

<i>critera</i>		<i>description</i>
<i>essential</i>	<i>E1</i>	<i>must not be in conflict with terrestrial and solar system tests of gravity</i>
	<i>E2</i>	<i>must fit current large-scale cosmological data, e.g., CMB, CMB lensing</i>
	<i>E3</i>	
<i>desired</i>	<i>D1</i>	
	<i>D2</i>	
<i>extra</i>	<i>X1</i>	
	<i>X2</i>	

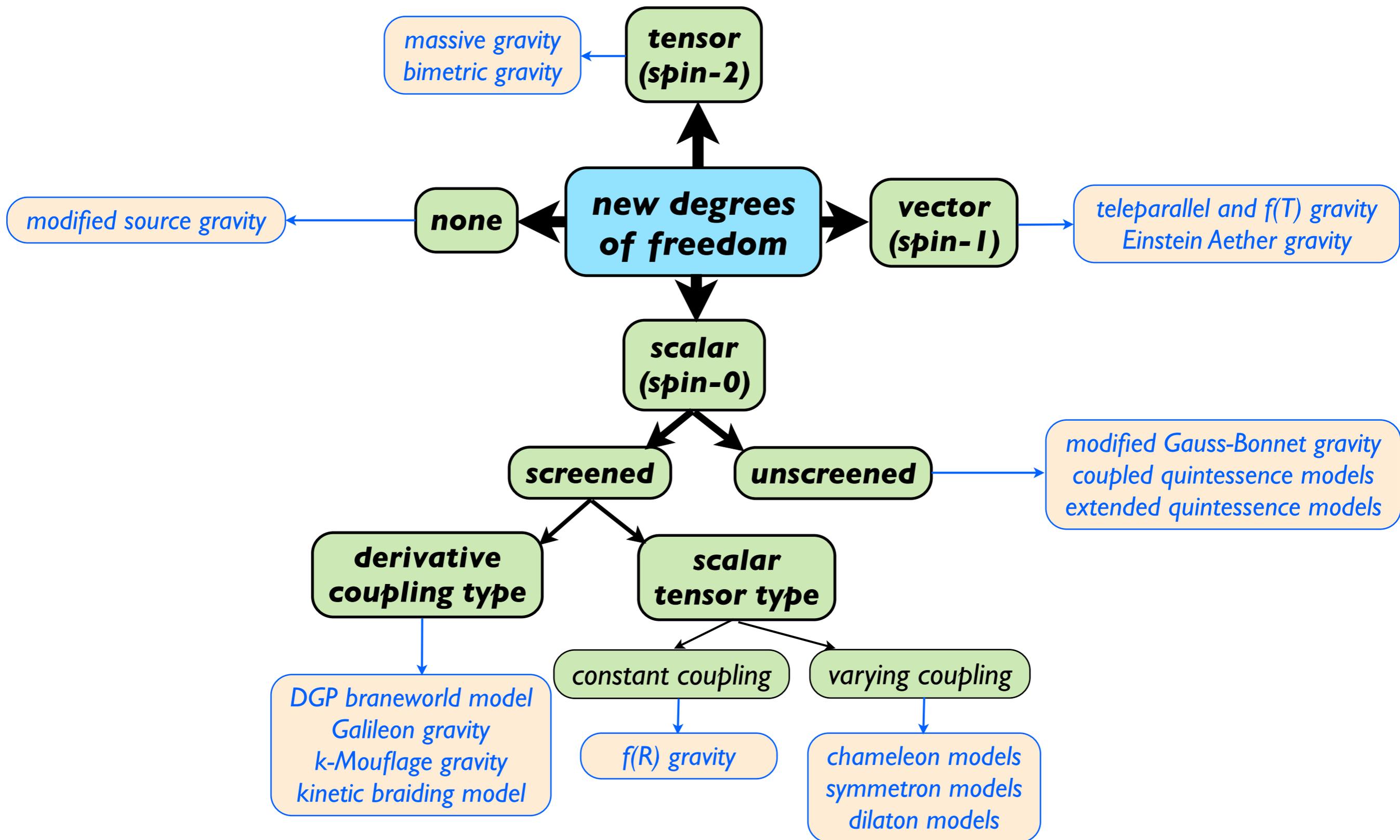
<i>critera</i>		<i>description</i>
<i>essential</i>	<i>E1</i>	<i>must not be in conflict with terrestrial and solar system tests of gravity</i>
	<i>E2</i>	<i>must fit current large-scale cosmological data, e.g., CMB, CMB lensing</i>
	<i>E3</i>	<i>must fit other cosmological data from supervoid to galactic scales</i>
<i>desired</i>	<i>D1</i>	
	<i>D2</i>	
<i>extra</i>	<i>X1</i>	
	<i>X2</i>	

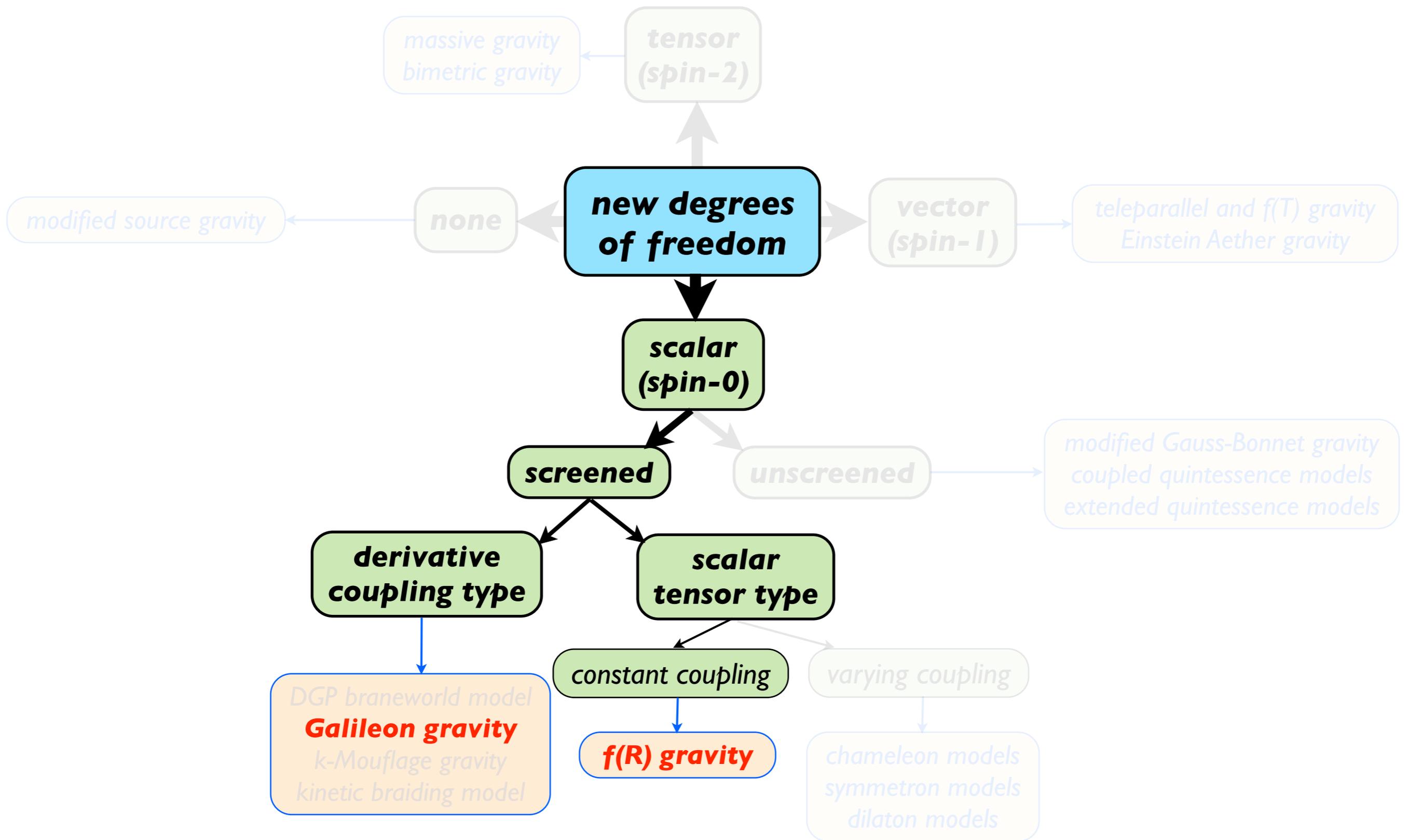
<i>critterion</i>		<i>description</i>
<i>essential</i>	<i>E1</i>	<i>must</i> not be in conflict with terrestrial and solar system tests of gravity
	<i>E2</i>	<i>must</i> fit current large-scale cosmological data, e.g., CMB, CMB lensing
	<i>E3</i>	<i>must</i> fit other cosmological data from supervoid to galactic scales
<i>desired</i>	<i>D1</i>	<i>should</i> be simple, without too many free parameters or free functions
	<i>D2</i>	
<i>extra</i>	<i>X1</i>	
	<i>X2</i>	

<i>critterion</i>		<i>description</i>
<i>essential</i>	<i>E1</i>	<i>must</i> not be in conflict with terrestrial and solar system tests of gravity
	<i>E2</i>	<i>must</i> fit current large-scale cosmological data, e.g., CMB, CMB lensing
	<i>E3</i>	<i>must</i> fit other cosmological data from supervoid to galactic scales
<i>desired</i>	<i>D1</i>	<i>should</i> be simple, without too many free parameters or free functions
	<i>D2</i>	<i>should</i> not involve too much fine tuning of parameters
<i>extra</i>	<i>X1</i>	
	<i>X2</i>	

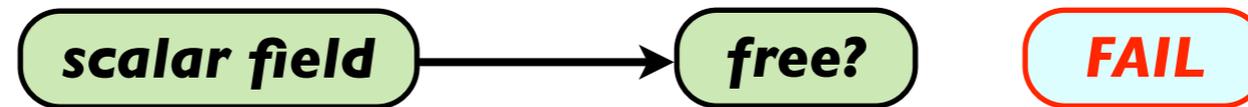
<i>critterion</i>		<i>description</i>
<i>essential</i>	<i>E1</i>	<i>must</i> not be in conflict with terrestrial and solar system tests of gravity
	<i>E2</i>	<i>must</i> fit current large-scale cosmological data, e.g., CMB, CMB lensing
	<i>E3</i>	<i>must</i> fit other cosmological data from supervoid to galactic scales
<i>desired</i>	<i>D1</i>	<i>should</i> be simple, without too many free parameters or free functions
	<i>D2</i>	<i>should</i> not involve too much fine tuning of parameters
<i>extra</i>	<i>X1</i>	<i>hope</i> to be testable by terrestrial particle or gravity experiments
	<i>X2</i>	

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<i>essential</i>	<i>E1</i>	<i>must</i> not be in conflict with terrestrial and solar system tests of gravity
	<i>E2</i>	<i>must</i> fit current large-scale cosmological data, e.g., CMB, CMB lensing
	<i>E3</i>	<i>must</i> fit other cosmological data from supervoid to galactic scales
<i>desired</i>	<i>D1</i>	<i>should</i> be simple, without too many free parameters or free functions
	<i>D2</i>	<i>should</i> not involve too much fine tuning of parameters
<i>extra</i>	<i>X1</i>	<i>hope</i> to be testable by terrestrial particle or gravity experiments
	<i>X2</i>	<i>hope</i> to be distinguishable from the standard LCDM paradigm

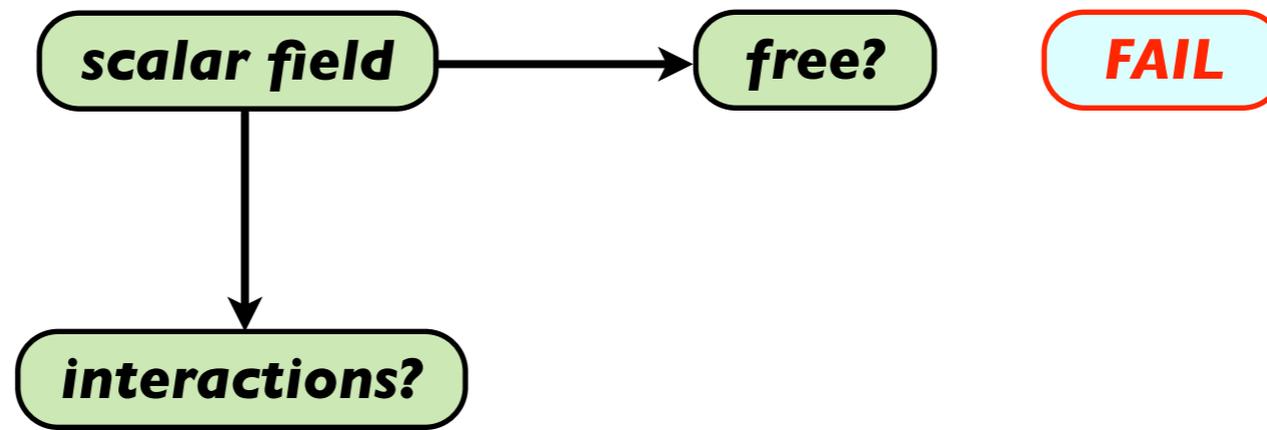




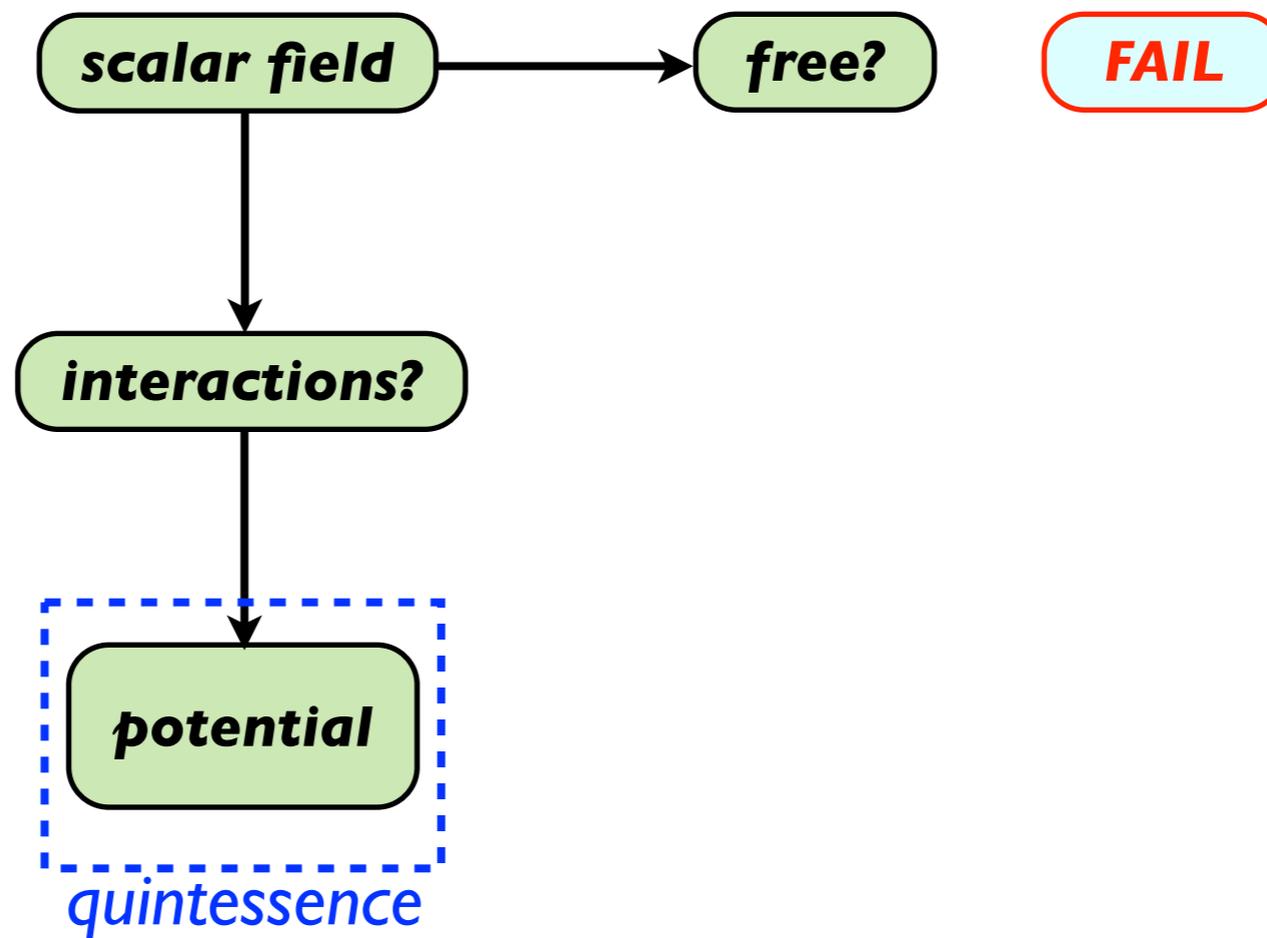
# MOTIVATING MODIFIED GRAVITY



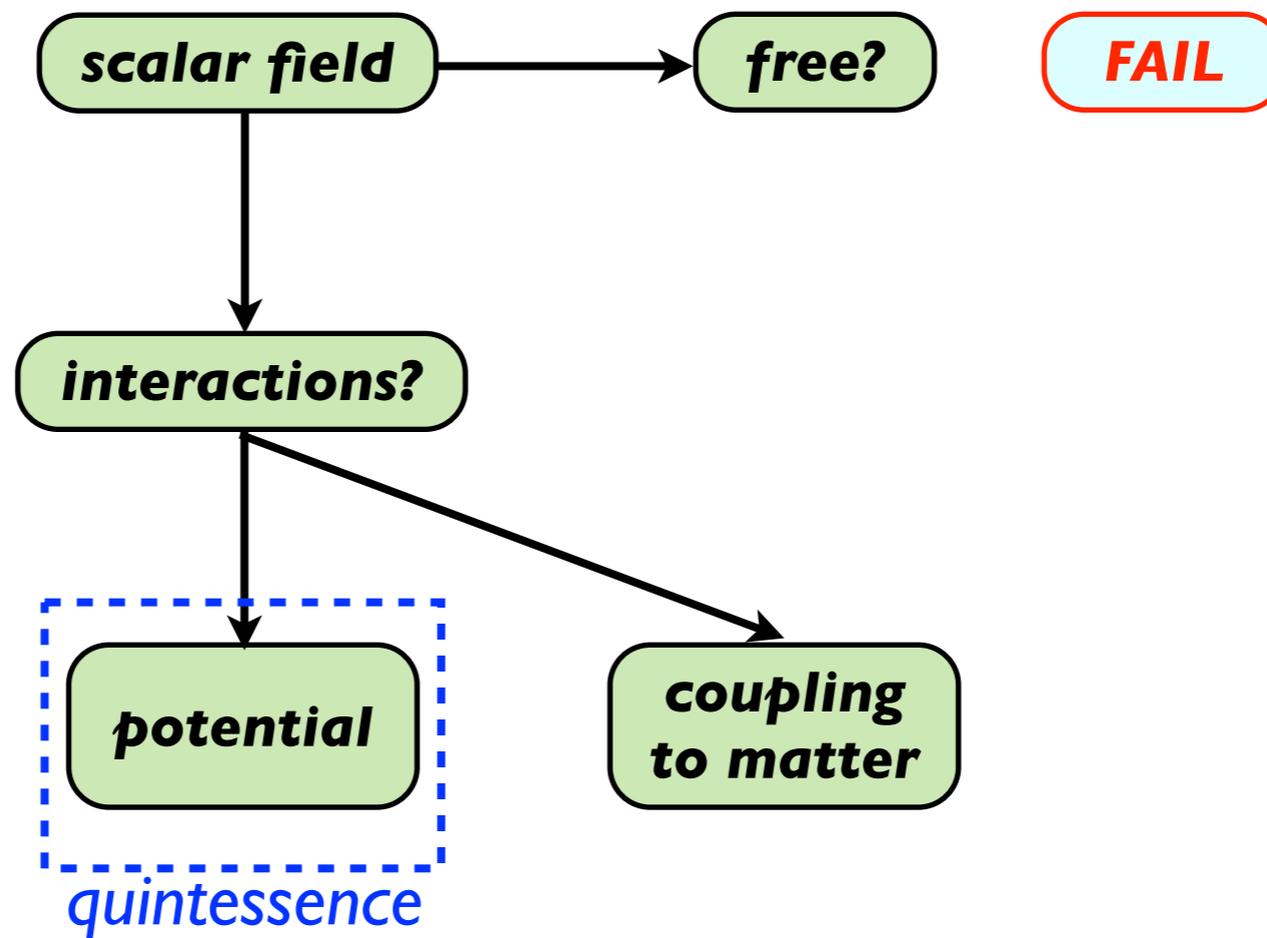
# MOTIVATING MODIFIED GRAVITY



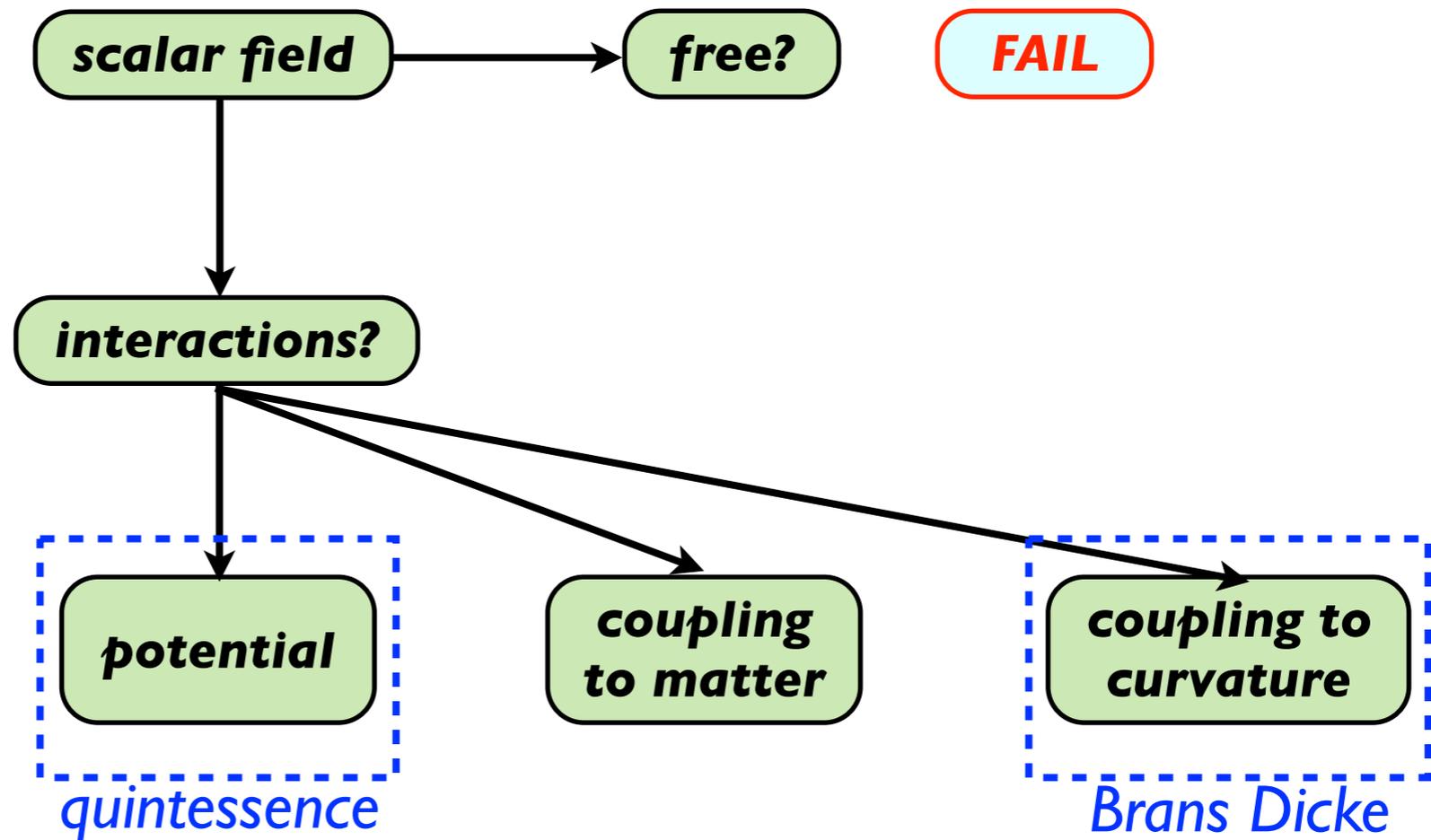
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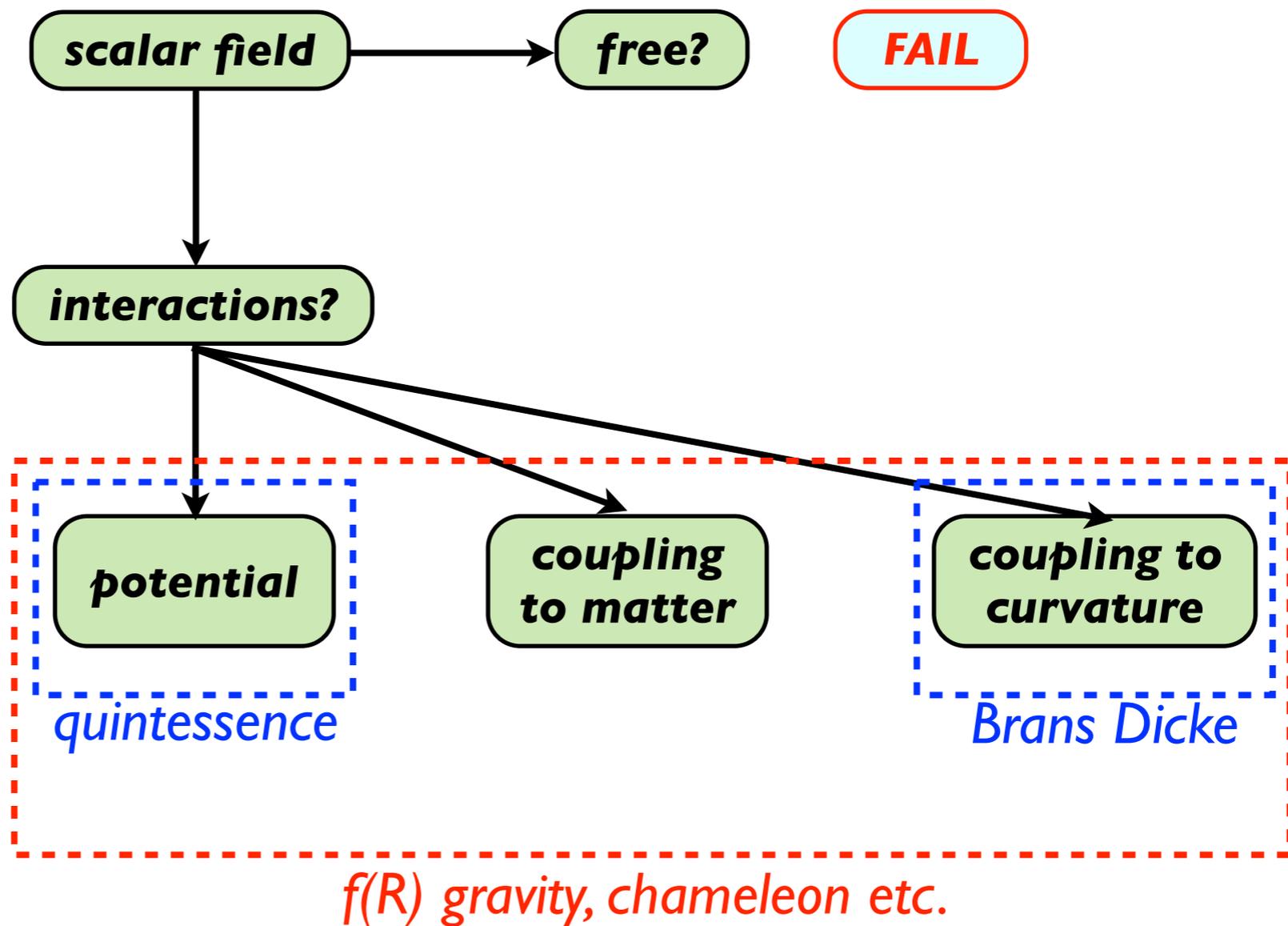
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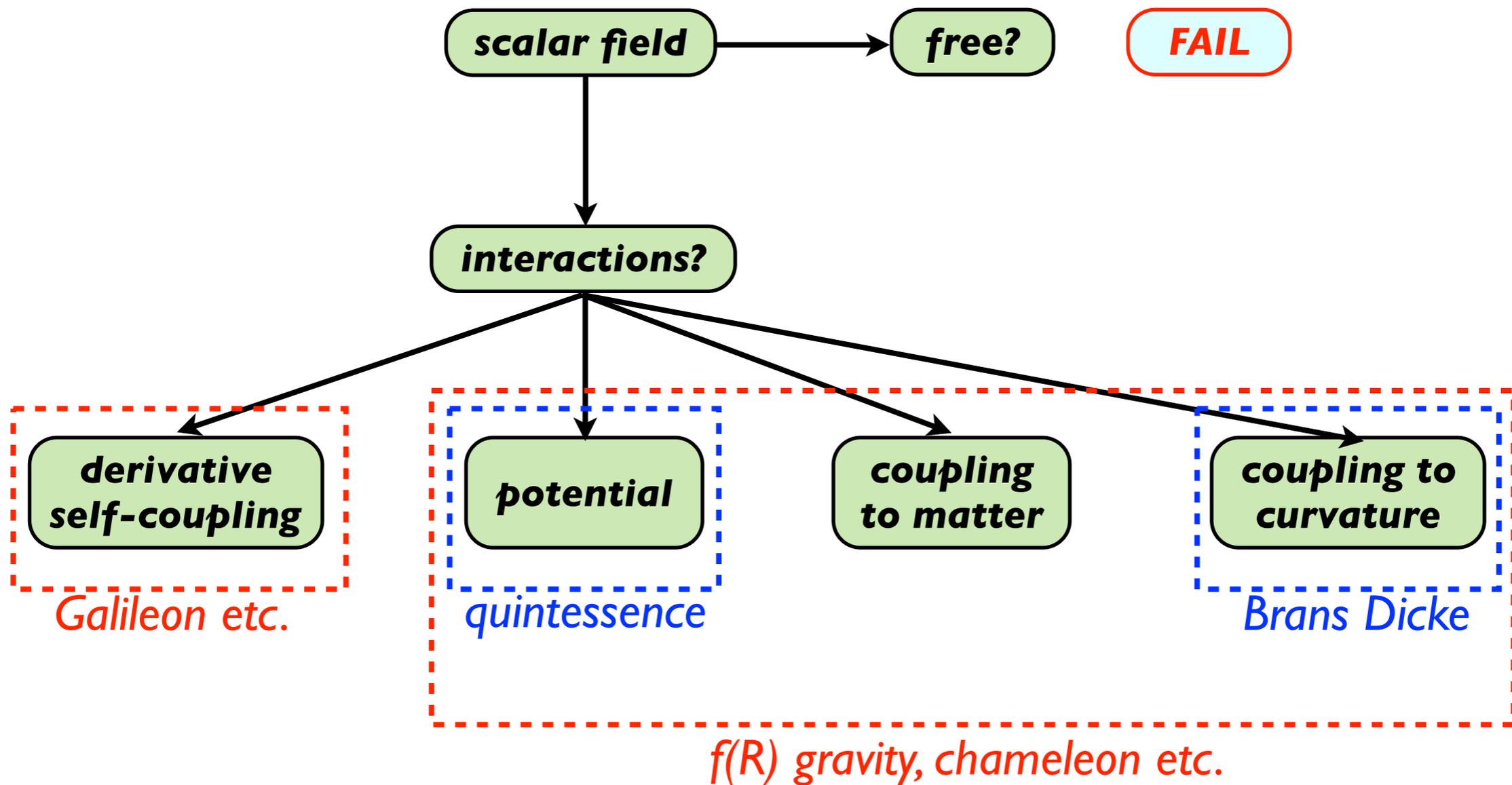
# MOTIVATING MODIFIED GRAVITY



# MOTIVATING MODIFIED GRAVITY



# MOTIVATING MODIFIED GRAVITY



# **F(R) GRAVITY**

$$R - 2\Lambda$$

*Einstein-Hilbert action  
with a cosmological constant*

# **F(R) GRAVITY**

*Einstein-Hilbert  
action for  $f(R)$*

$$R - 2\Lambda \rightarrow R + f(R)$$

*Einstein-Hilbert action  
with a cosmological constant*

# F(R) GRAVITY

*Einstein-Hilbert  
action for  $f(R)$*

$$R - 2\Lambda \rightarrow R + f(R) \sim R - 2\Lambda - 10|f_{R0}| \frac{\Lambda^2}{R}$$

*Einstein-Hilbert action  
with a cosmological constant*

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*Einstein-Hilbert  
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$f_{R0} \equiv \frac{df(R)}{dR} \ll 1$



*Einstein-Hilbert action  
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*Einstein-Hilbert  
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$$\underbrace{R - 2\Lambda}_{\text{dashed green circle}} \rightarrow R + f(R) \sim \underbrace{R - 2\Lambda}_{\text{dashed green circle}} - 10 |f_{R0}| \frac{\Lambda^2}{R}$$

$f_{R0} \equiv \frac{df(R)}{dR} \ll 1$

$\uparrow$

*Einstein-Hilbert action  
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*Einstein-Hilbert action  
with a cosmological constant*

*it is this additional term that  
people have been studying*

# GALILEON GRAVITY

$$\mathcal{L}_{\text{Galileon}} = \sum_{i=2}^5 \frac{(-)^i}{i!} \frac{c_i}{M_{\text{Pl}}^{i-2} \Lambda^{i-2}} \mathcal{L}_i$$

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$$\mathcal{L}_{\text{Galileon}} = \sum_{i=2}^5 \frac{(-)^i}{i!} \frac{c_i}{M_{\text{Pl}}^{i-2} \Lambda^{i-2}} \mathcal{L}_i$$

$$\mathcal{L}_2 = (\nabla^\mu \varphi \nabla_\mu \varphi) \text{ standard kinetic term}$$

# GALILEON GRAVITY

$$\mathcal{L}_{\text{Galileon}} = \sum_{i=2}^5 \frac{(-)^i}{i!} \frac{c_i}{M_{\text{Pl}}^{i-2} \Lambda^{i-2}} \mathcal{L}_i$$

$$\mathcal{L}_2 = (\nabla^\mu \varphi \nabla_\mu \varphi)$$

$$\mathcal{L}_3 = (\nabla^\mu \varphi \nabla_\mu \varphi) \square \varphi$$

*cubic Galileon*

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$$\mathcal{L}_{\text{Galileon}} = \sum_{i=2}^5 \frac{(-)^i}{i!} \frac{c_i}{M_{\text{Pl}}^{i-2} \Lambda^{i-2}} \mathcal{L}_i$$

$$\mathcal{L}_2 = (\nabla^\mu \varphi \nabla_\mu \varphi)$$

$$\mathcal{L}_3 = (\nabla^\mu \varphi \nabla_\mu \varphi) \square \varphi$$

$$\mathcal{L}_4 = (\nabla^\mu \varphi \nabla_\mu \varphi) \left[ 2 (\square \varphi)^2 - 2 \nabla^\alpha \nabla^\beta \varphi \nabla_\alpha \nabla_\beta \varphi - \frac{1}{2} R \nabla^\lambda \nabla_\lambda \varphi \right]$$

*quartic Galileon*

# GALILEON GRAVITY

$$\mathcal{L}_{\text{Galileon}} = \sum_{i=2}^5 \frac{(-)^i}{i!} \frac{c_i}{M_{\text{Pl}}^{i-2} \Lambda^{i-2}} \mathcal{L}_i$$

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$$\mathcal{L}_5 = (\nabla^\mu \varphi \nabla_\mu \varphi) \left[ (\square \varphi)^3 - 3 \square \varphi \nabla^\alpha \nabla^\beta \varphi \nabla_\alpha \nabla_\beta \varphi + 2 \nabla^\alpha \nabla_\beta \varphi \nabla^\beta \nabla_\gamma \varphi \nabla^\gamma \nabla_\alpha \varphi - 6 G_{\alpha\beta} \nabla^\beta \varphi \nabla_\lambda \varphi \nabla^\alpha \nabla^\lambda \varphi \right]$$

quintic (full) Galileon

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>							
<i>Galileon</i>							

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>							
<i>Galileon</i>							

<i>screening</i>	<i>description</i>
<i>chameleon</i>	
<i>Vainshtein</i>	

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>							
<i>Galileon</i>							

<i>screening</i>	<i>description</i>
<i>chameleon</i>	<i>deviation from GR suppressed in regions with deep Newtonian potential</i>
<i>Vainshtein</i>	

$$R - 2\Lambda \rightarrow R + f(R) \sim R - 2\Lambda - 10|f_{R0}|\frac{\Lambda^2}{R}$$

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>							
<i>Galileon</i>							

<i>screening</i>	<i>description</i>
<i>chameleon</i>	<i>deviation from GR suppressed in regions with deep Newtonian potential</i>
<i>Vainshtein</i>	<i>deviation from GR suppressed inside or around very massive bodies</i>

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$$\mathcal{L}_{\text{Galileon}} = \frac{1}{2!}c_2 \nabla^\mu \varphi \nabla_\mu \varphi - \frac{1}{3!}c_3 \frac{1}{M_{\text{Pl}}\Lambda} \square \varphi \nabla^\mu \varphi \nabla_\mu \varphi$$

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>							
<i>Galileon</i>							

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<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>							
<i>Galileon</i>							

<i>screening</i>	<i>deviates from GR on</i>	<i>environmental dependence</i>	<i>nonlinearity</i>
<i>chameleon</i>			
<i>Vainshtein</i>			

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<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>							
<i>Galileon</i>							

<i>screening</i>	<i>deviates from GR on</i>	<i>environmental dependence</i>	<i>nonlinearity</i>
<i>chameleon</i>	<i>small scales</i>		
<i>Vainshtein</i>	<i>large scales</i>		

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<i>f(R) gravity</i>							
<i>Galileon</i>							

<i>screening</i>	<i>deviates from GR on</i>	<i>environmental dependence</i>	<i>nonlinearity</i>
<i>chameleon</i>	<i>small scales</i>	<i>strong</i>	
<i>Vainshtein</i>	<i>large scales</i>	<i>weaker</i>	

$$R - 2\Lambda \rightarrow R + f(R) \sim R - 2\Lambda - 10|f_{R0}|\frac{\Lambda^2}{R}$$

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<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>							
<i>Galileon</i>							

<i>screening</i>	<i>deviates from GR on</i>	<i>environmental dependence</i>	<i>nonlinearity</i>
<i>chameleon</i>	<i>small scales</i>	<i>strong</i>	<i>pure &amp; strong</i>
<i>Vainshtein</i>	<i>large scales</i>	<i>weaker</i>	<i>pure &amp; strong</i>

$$R - 2\Lambda \rightarrow R + f(R) \sim R - 2\Lambda - 10|f_{R0}|\frac{\Lambda^2}{R}$$

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<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●						
<i>Galileon</i>							

<i>screening</i>	<i>deviates from GR on</i>	<i>environmental dependence</i>	<i>nonlinearity</i>
<i>chameleon</i>	<i>small scales</i>	<i>strong</i>	<i>pure &amp; strong</i>
<i>Vainshtein</i>	<i>large scales</i>	<i>weaker</i>	<i>pure &amp; strong</i>

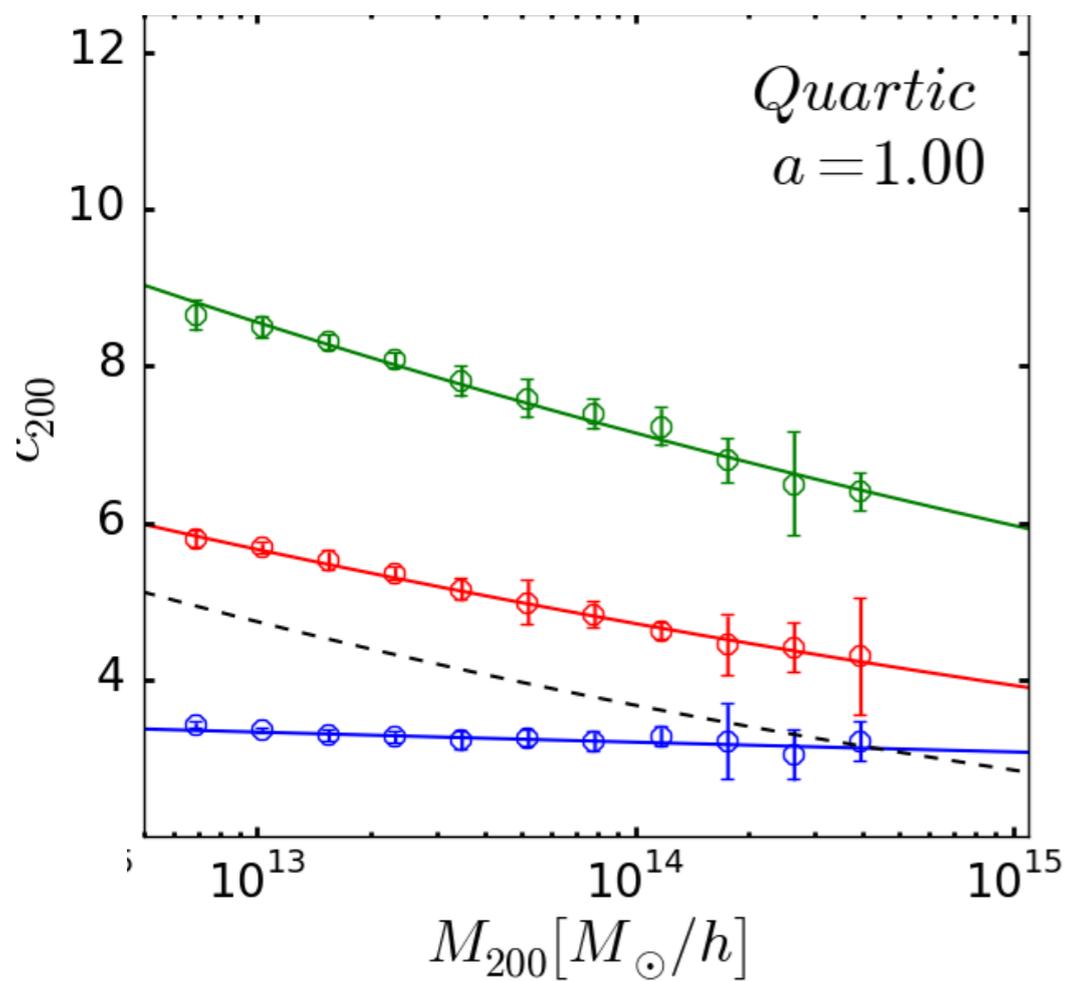
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<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●						
<i>Galileon</i>							

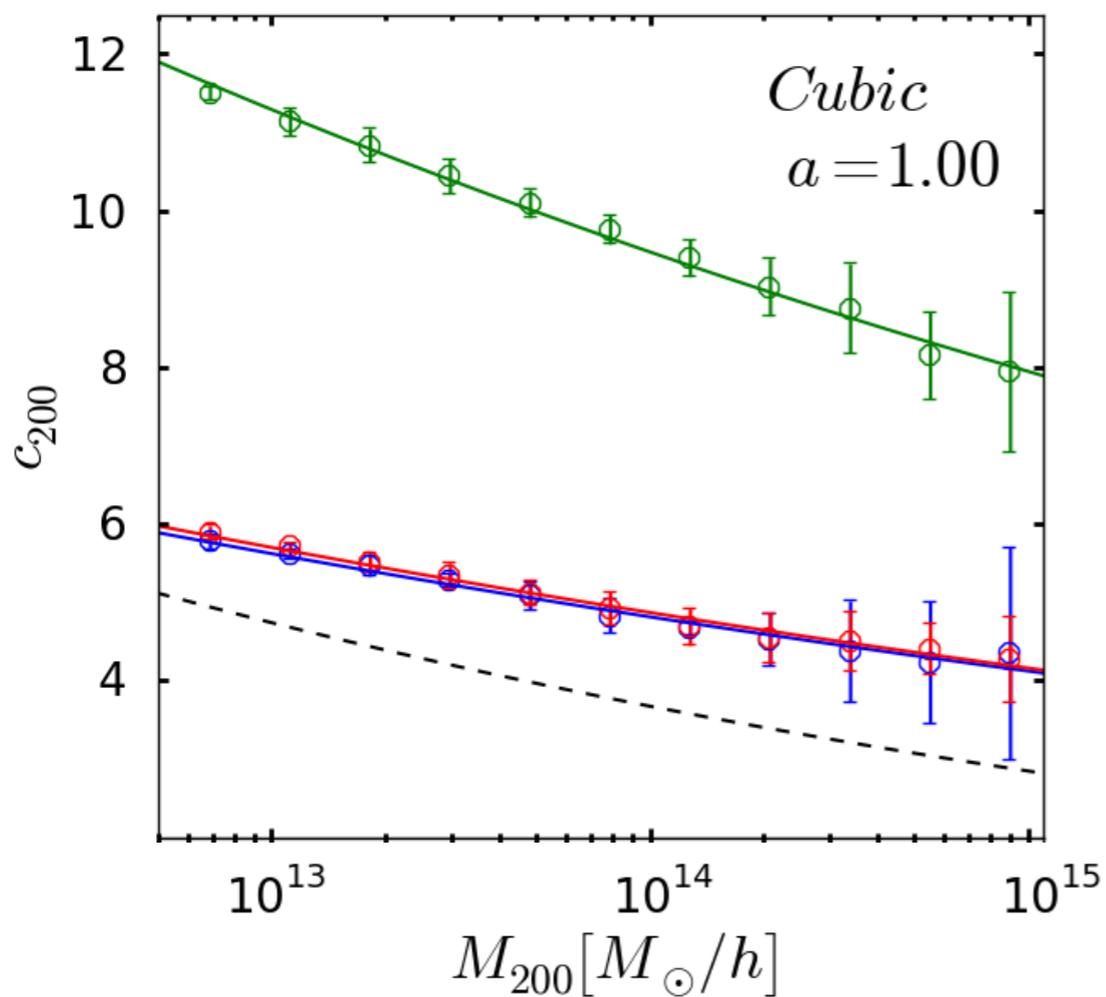
	<i>expansion history</i>	<i>force law</i>
<i>red</i>	<i>Galileon</i>	<i>GR</i>
<i>green</i>	<i>Galileon</i>	<i>linear Galileon</i>
<i>blue</i>	<i>Galileon</i>	<i>screened Galileon</i>

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●						
<i>Galileon</i>							



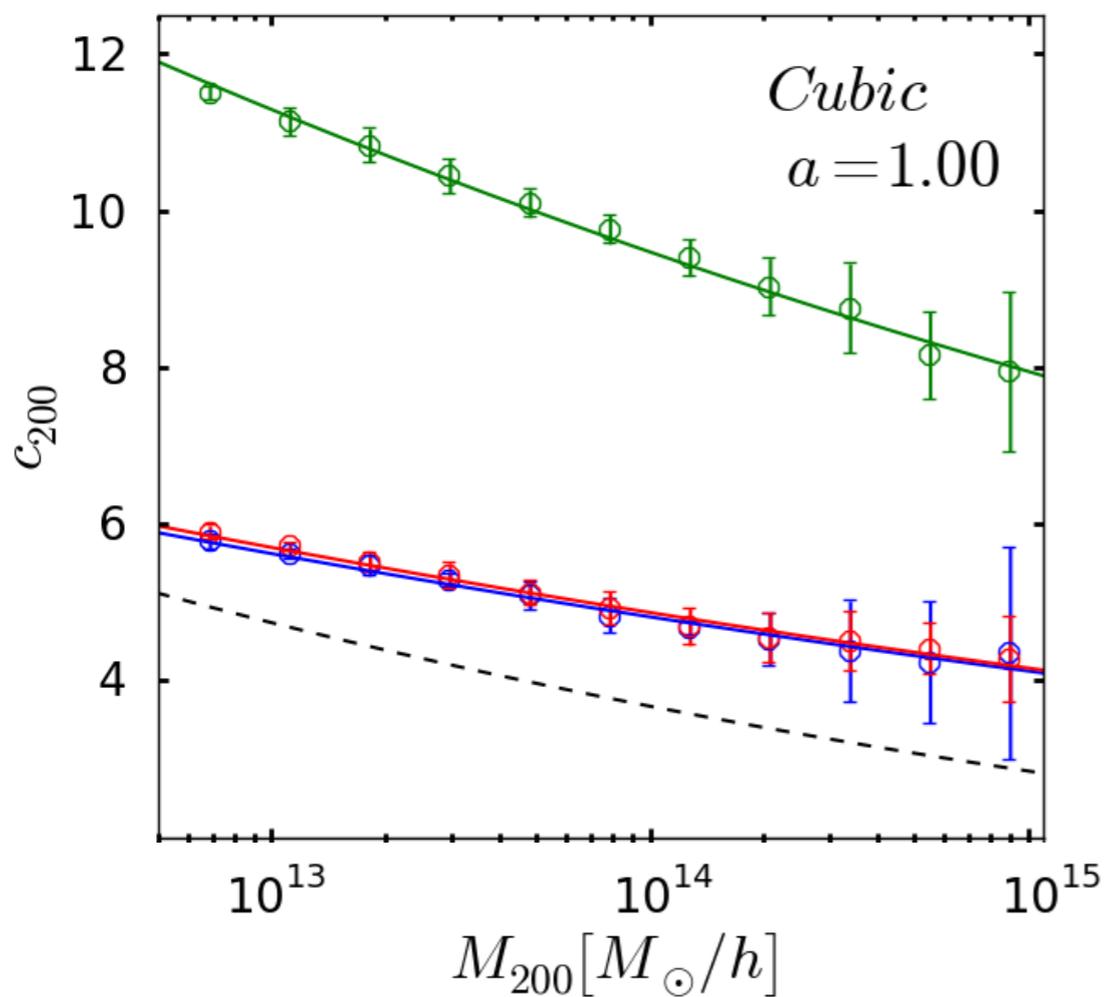
	<i>expansion history</i>	<i>force law</i>
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<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●						
<i>Galileon</i>							



	<i>expansion history</i>	<i>force law</i>
<i>red</i>	<i>Galileon</i>	<i>GR</i>
<i>green</i>	<i>Galileon</i>	<i>linear Galileon</i>
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<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●						
<i>Galileon</i>	●						



	<i>expansion history</i>	<i>force law</i>
<i>red</i>	<i>Galileon</i>	<i>GR</i>
<i>green</i>	<i>Galileon</i>	<i>linear Galileon</i>
<i>blue</i>	<i>Galileon</i>	<i>screened Galileon</i>

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●						
<i>Galileon</i>	●						

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●						
<i>Galileon</i>	●						

<i>screening</i>	<i>deviates from GR on</i>	<i>environmental dependence</i>	<i>nonlinearity</i>
<i>chameleon</i>	<i>small scales</i>	<i>strong</i>	<i>pure &amp; strong</i>
<i>Vainshtein</i>	<i>large scales</i>	<i>weaker</i>	<i>pure &amp; strong</i>

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●						
<i>Galileon</i>	●						

<i>screening</i>	<i>deviates from GR on</i>	<i>environmental dependence</i>	<i>nonlinearity</i>
<i>chameleon</i>	<i>small scales</i>	<i>strong</i>	<i>pure &amp; strong</i>
<i>Vainshtein</i>	<i>large scales</i>	<i>weaker</i>	<i>pure &amp; strong</i>

*for realistic  $f(R)$  models,  $|f_{R0}|$  is so small that essentially no deviation can be felt on very large scales, e.g, in CMB*

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●						

<i>screening</i>	<i>deviates from GR on</i>	<i>environmental dependence</i>	<i>nonlinearity</i>
<i>chameleon</i>	<i>small scales</i>	<i>strong</i>	<i>pure &amp; strong</i>
<i>Vainshtein</i>	<i>large scales</i>	<i>weaker</i>	<i>pure &amp; strong</i>

*for realistic  $f(R)$  models,  $|f_{R0}|$  is so small that essentially no deviation can be felt on very large scales, e.g, in CMB*

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●						

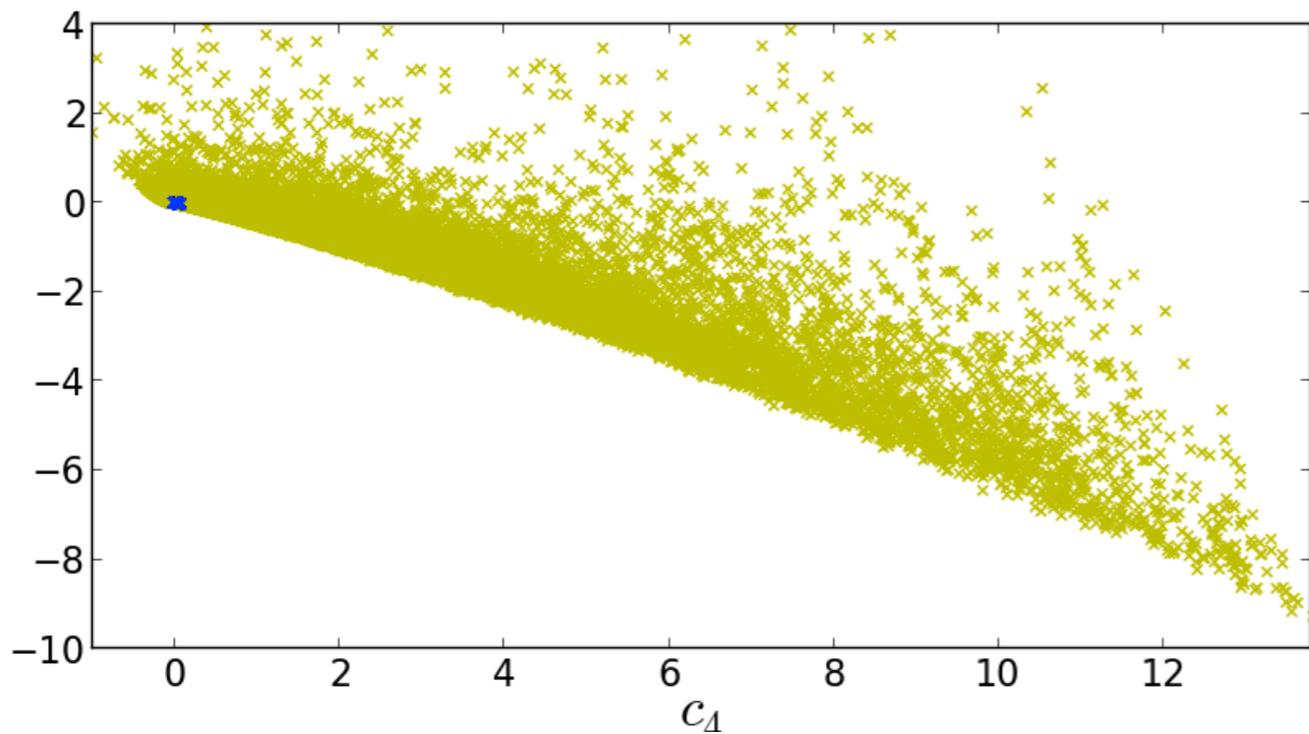
<i>screening</i>	<i>deviates from GR on</i>	<i>environmental dependence</i>	<i>nonlinearity</i>
<i>chameleon</i>	<i>small scales</i>	<i>strong</i>	<i>pure &amp; strong</i>
<i>Vainshtein</i>	<i>large scales</i>	<i>weaker</i>	<i>pure &amp; strong</i>

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●						

<i>screening</i>	<i>deviates from GR on</i>	<i>environmental dependence</i>	<i>nonlinearity</i>
<i>chameleon</i>	<i>small scales</i>	<i>strong</i>	<i>pure &amp; strong</i>
<i>Vainshtein</i>	<i>large scales</i>	<i>weaker</i>	<i>pure &amp; strong</i>

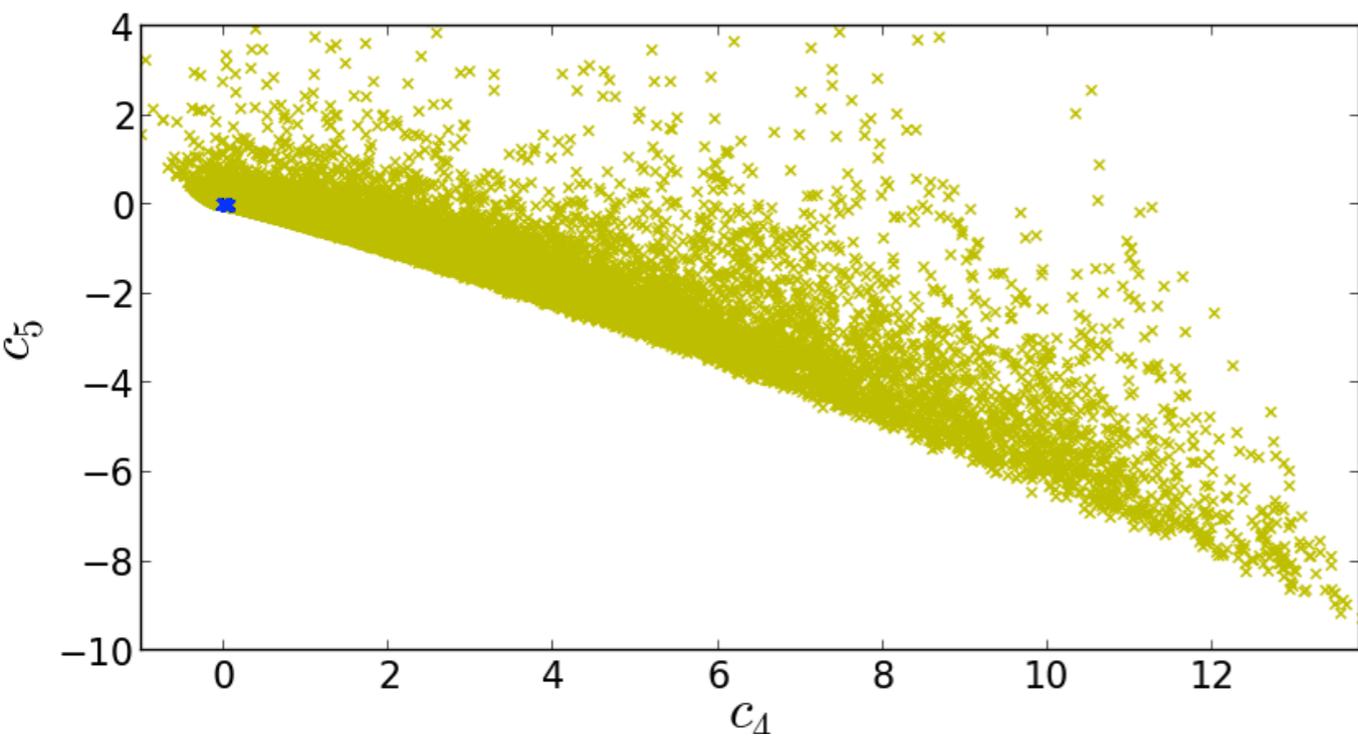
*CMB (mainly the integrated Sachs Wolfe effect) will see implications of the Galileon field*

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●						

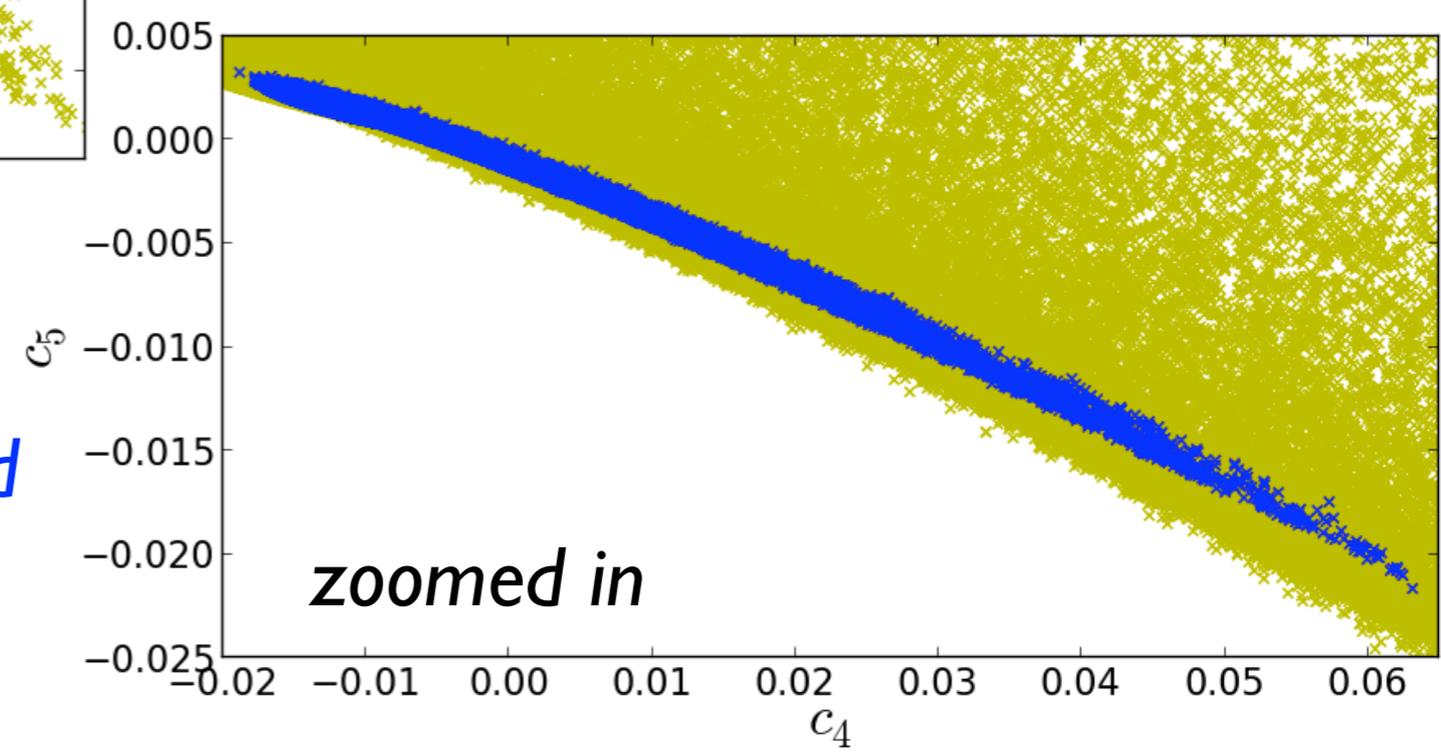


*yellow points: expansion data only*  
*blue points: Planck CMB data added*

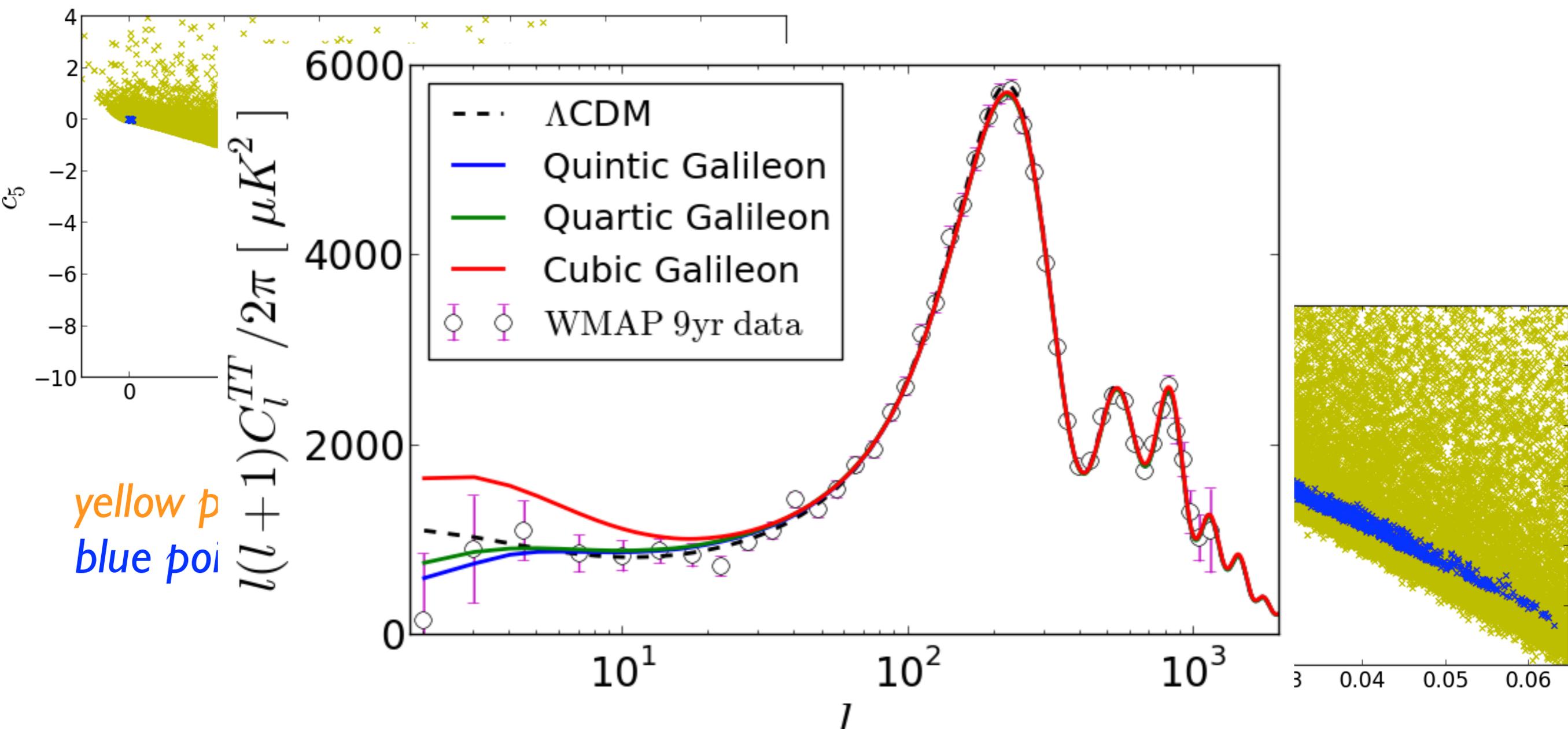
<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●						



*yellow points: expansion data only*  
*blue points: Planck CMB data added*



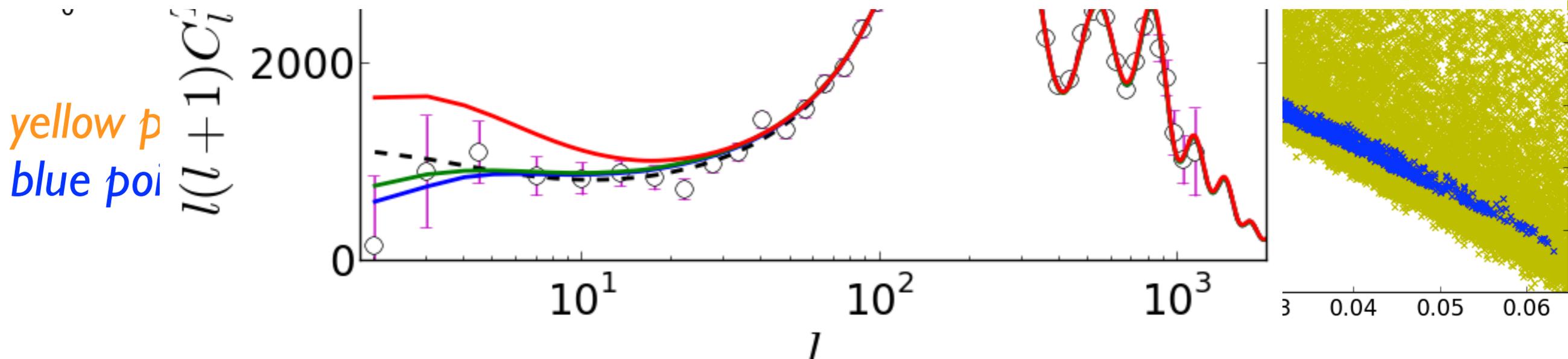
<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●						



model	E1	E2	E3	D1	D2	X1	X2
<i>f</i> (R) gravity	●	●					
Galileon	●						

*cubic* Galileon disfavoured by low-*l* CMB data  
*quartic/quintic* Galileon have other problems

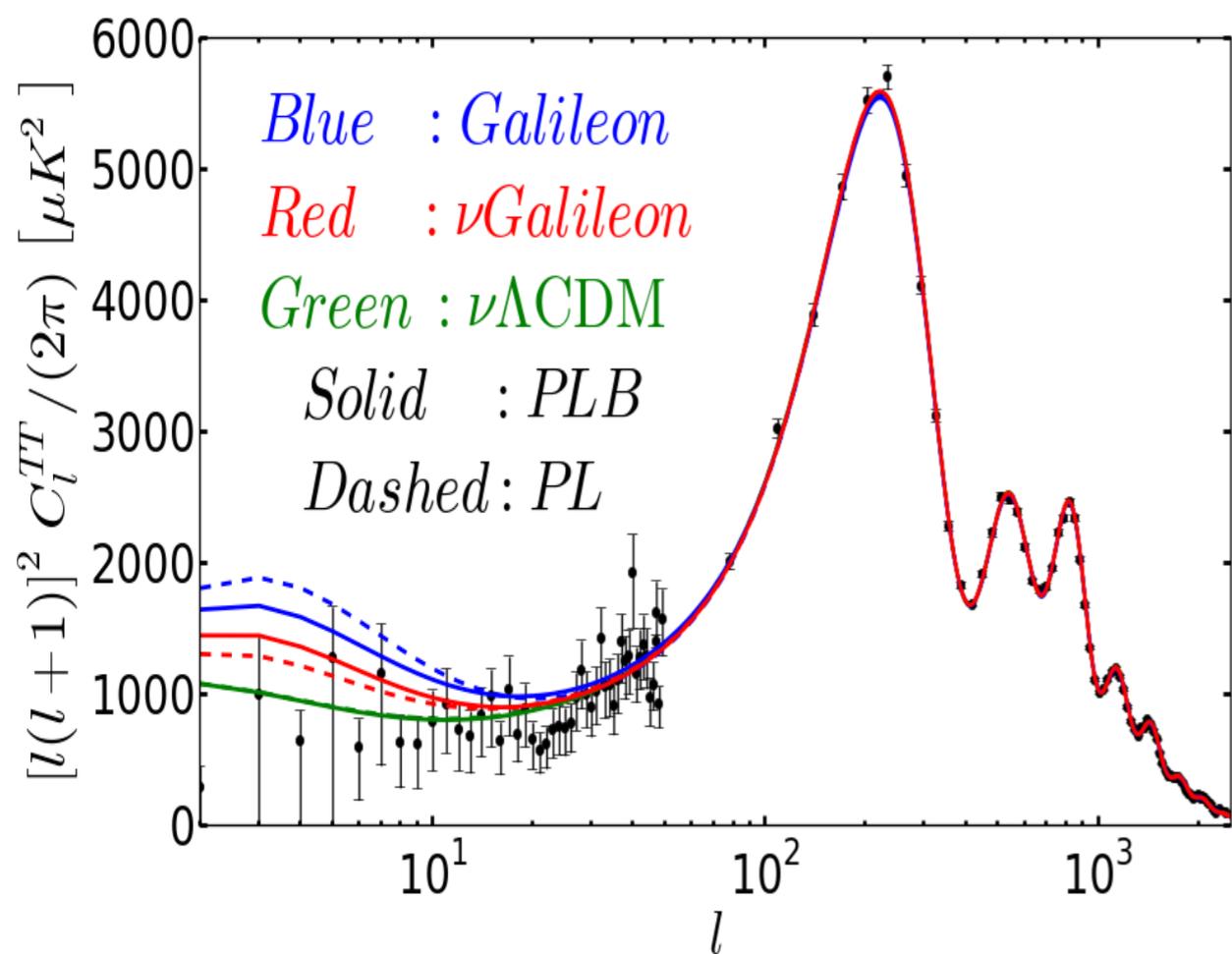
Galileon model ruled out?



<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●						

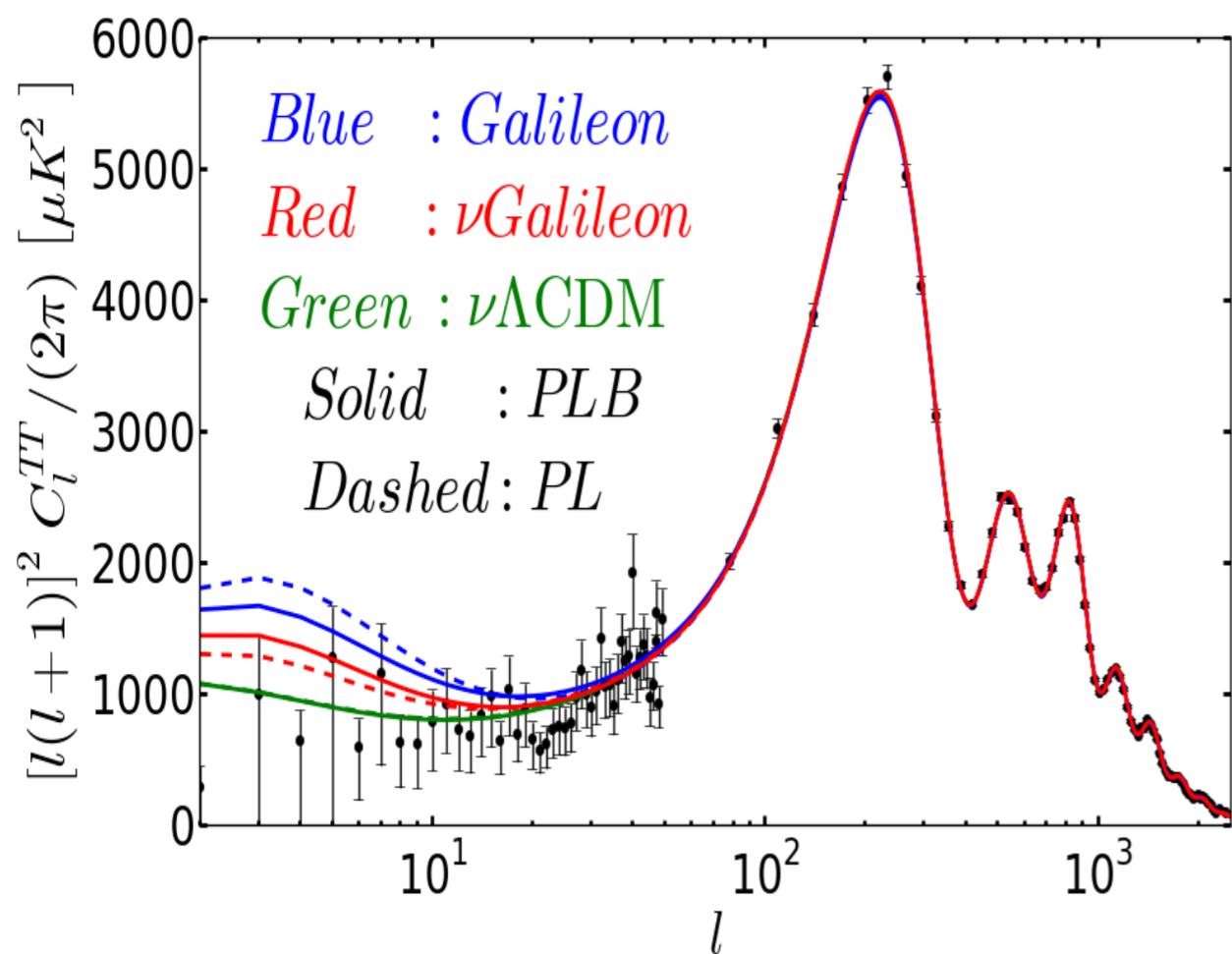
	<i>ΛCDM</i>	<i>Galileon</i>	$\Delta\chi^2$
<i>CMB</i>			
+ <i>CMB lensing</i>			
+ <i>BAO</i>			
+ $H_0$			
+ $\sigma_8(\Omega_m/0.25)^{0.47}$			

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●						



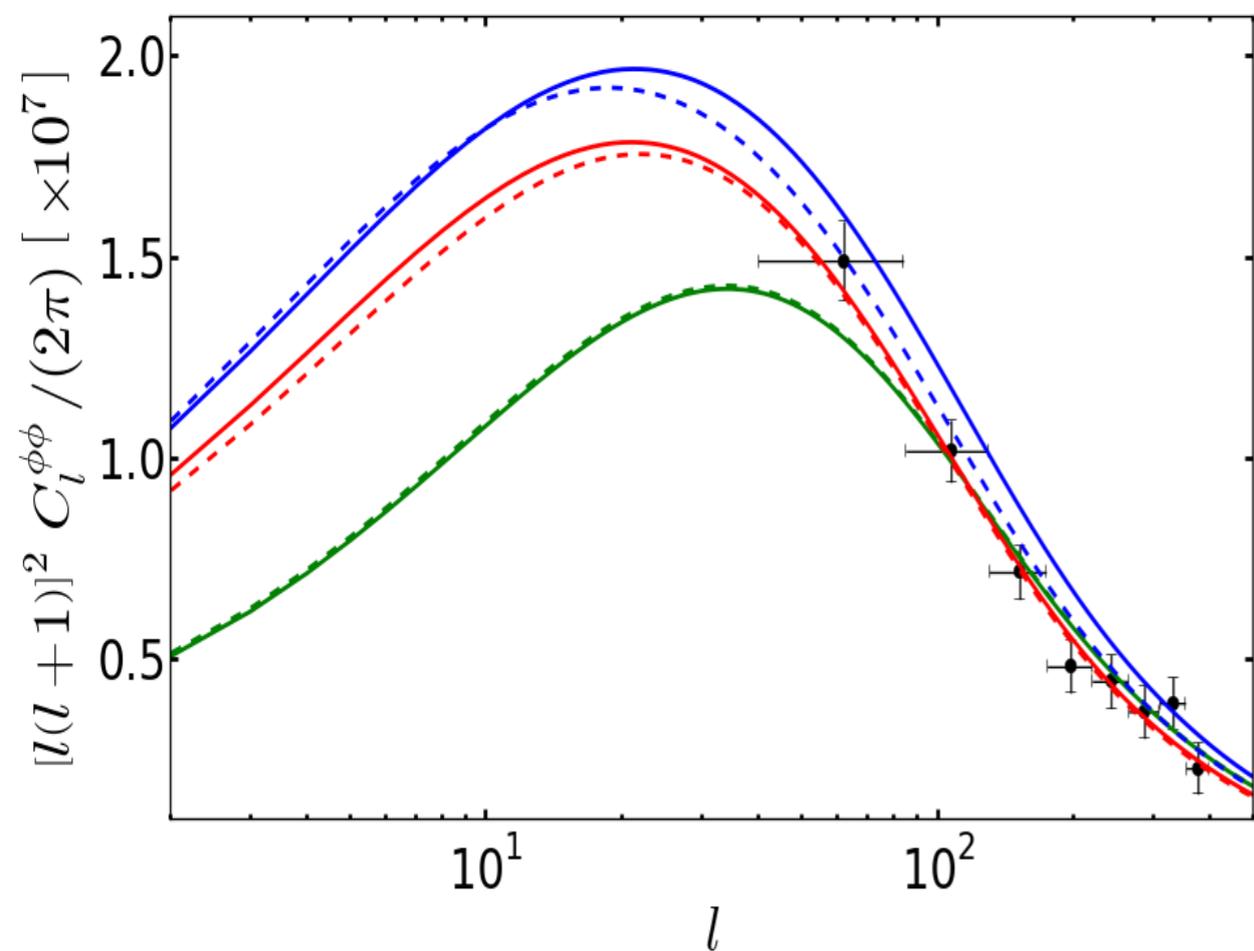
	<i>LCDM</i>	<i>Galileon</i>	$\Delta\chi^2$
<i>CMB</i>			
+ <i>CMB lensing</i>			
+ <i>BAO</i>			
+ <i>H<sub>0</sub></i>			
+ $\sigma_8(\Omega_m/0.25)^{0.47}$			

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●						



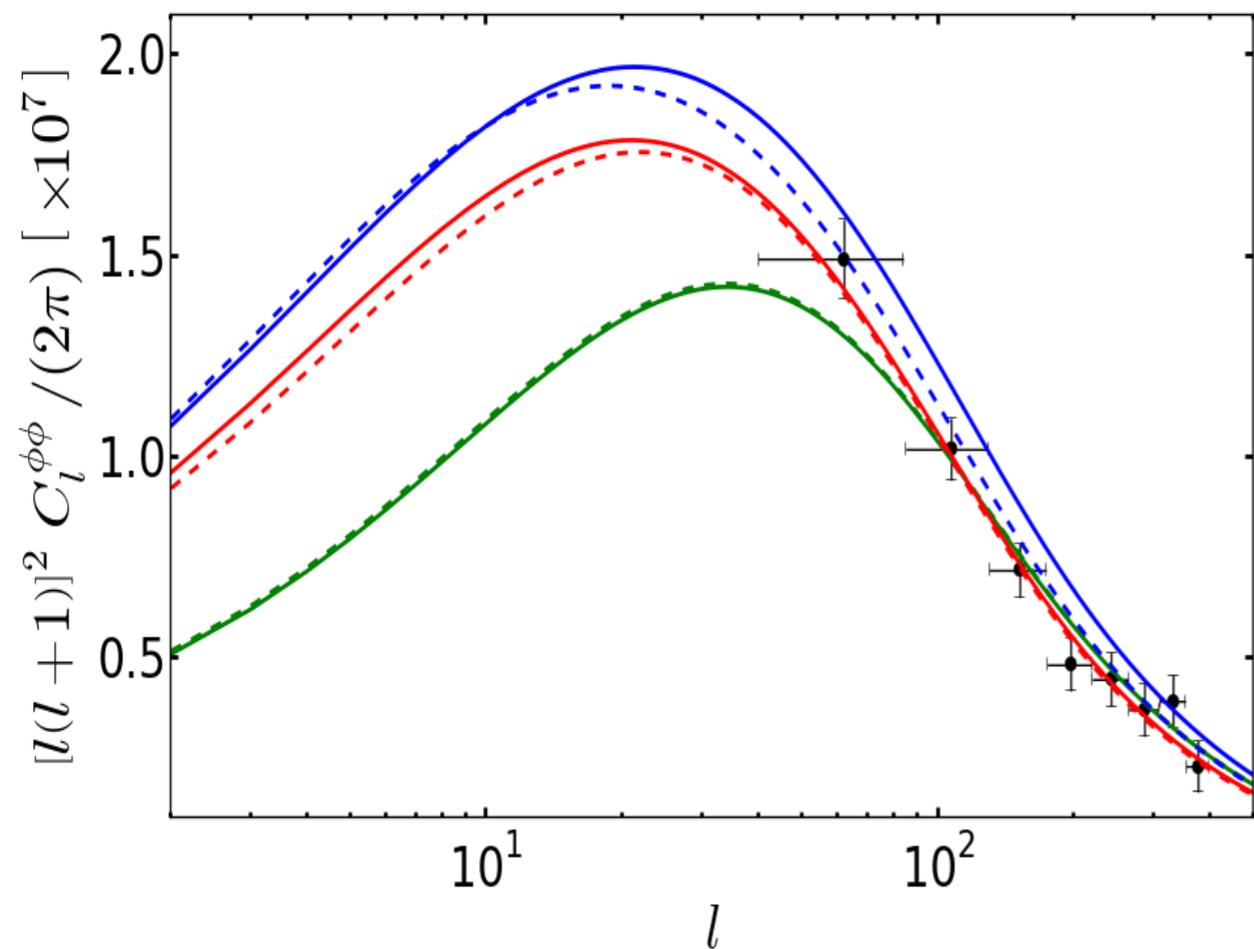
	<i>LCDM</i>	<i>Galileon</i>	$\Delta\chi^2$
<i>CMB</i>	9805.5	9811.5	<b>+6.0</b>
+ <i>CMB lensing</i>			
+ <i>BAO</i>			
+ <i>H<sub>0</sub></i>			
+ $\sigma_8(\Omega_m/0.25)^{0.47}$			

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●						



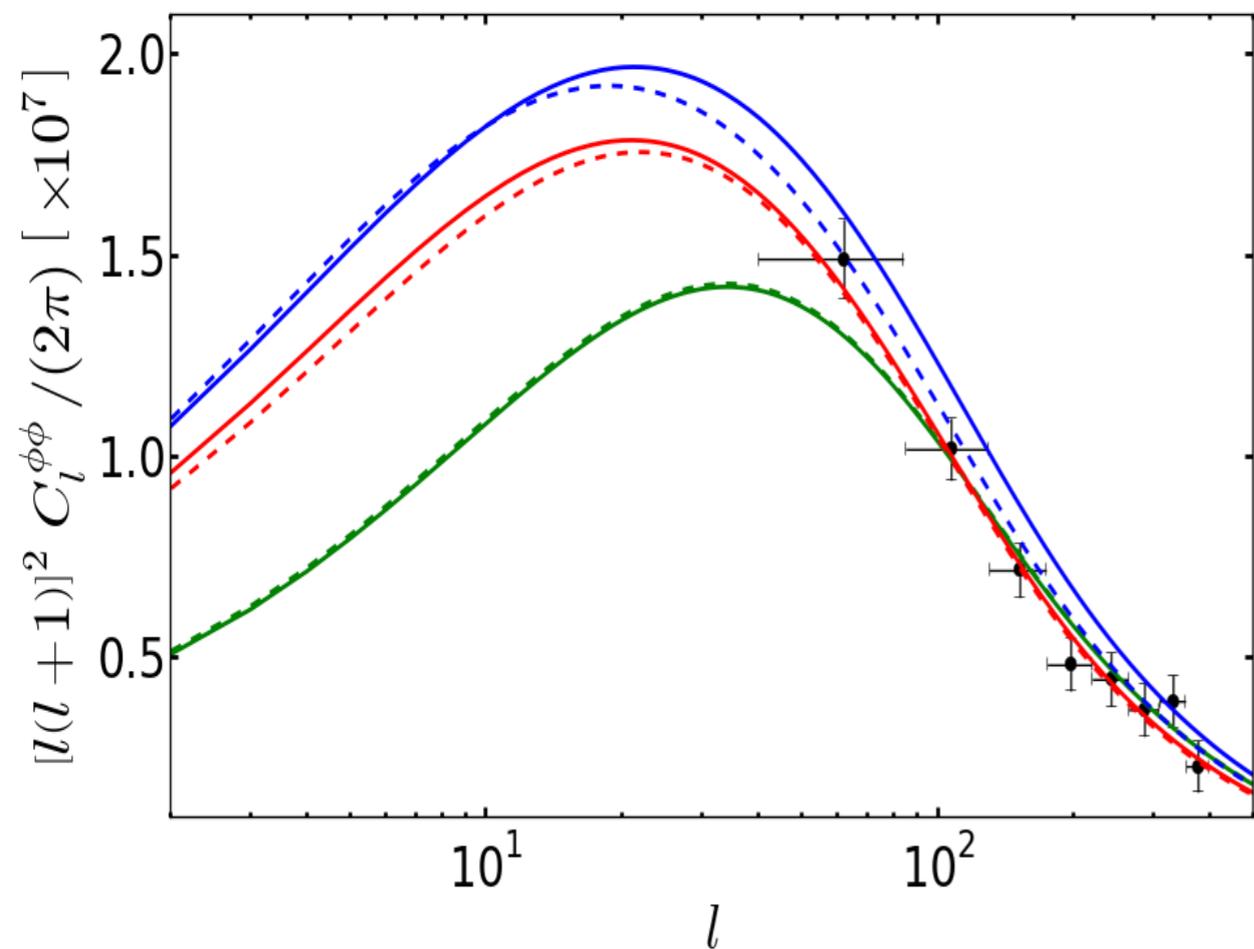
	<i>ΛCDM</i>	<i>Galileon</i>	$\Delta\chi^2$
<i>CMB</i>	9805.5	9811.5	<b>+6.0</b>
+ <i>CMB lensing</i>			
+ <i>BAO</i>			
+ $H_0$			
+ $\sigma_8(\Omega_m/0.25)^{0.47}$			

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●						



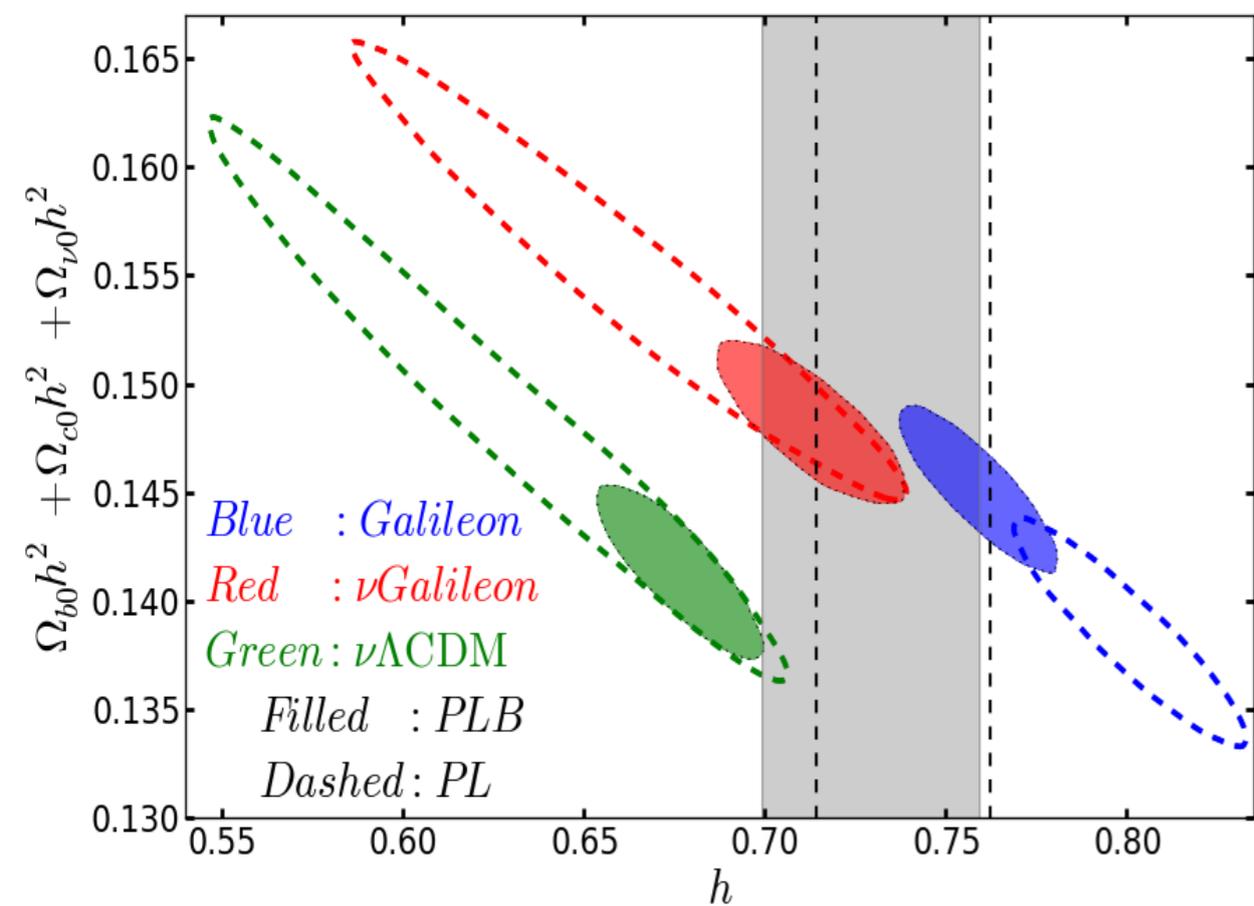
	<i>LCDM</i>	<i>Galileon</i>	$\Delta\chi^2$
<i>CMB</i>	9805.5	9811.5	+6.0
+ <i>CMB lensing</i>	9814.1	9816.0	+1.9
+ <i>BAO</i>			
+ <i>H<sub>0</sub></i>			
+ $\sigma_8(\Omega_m/0.25)^{0.47}$			

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●						



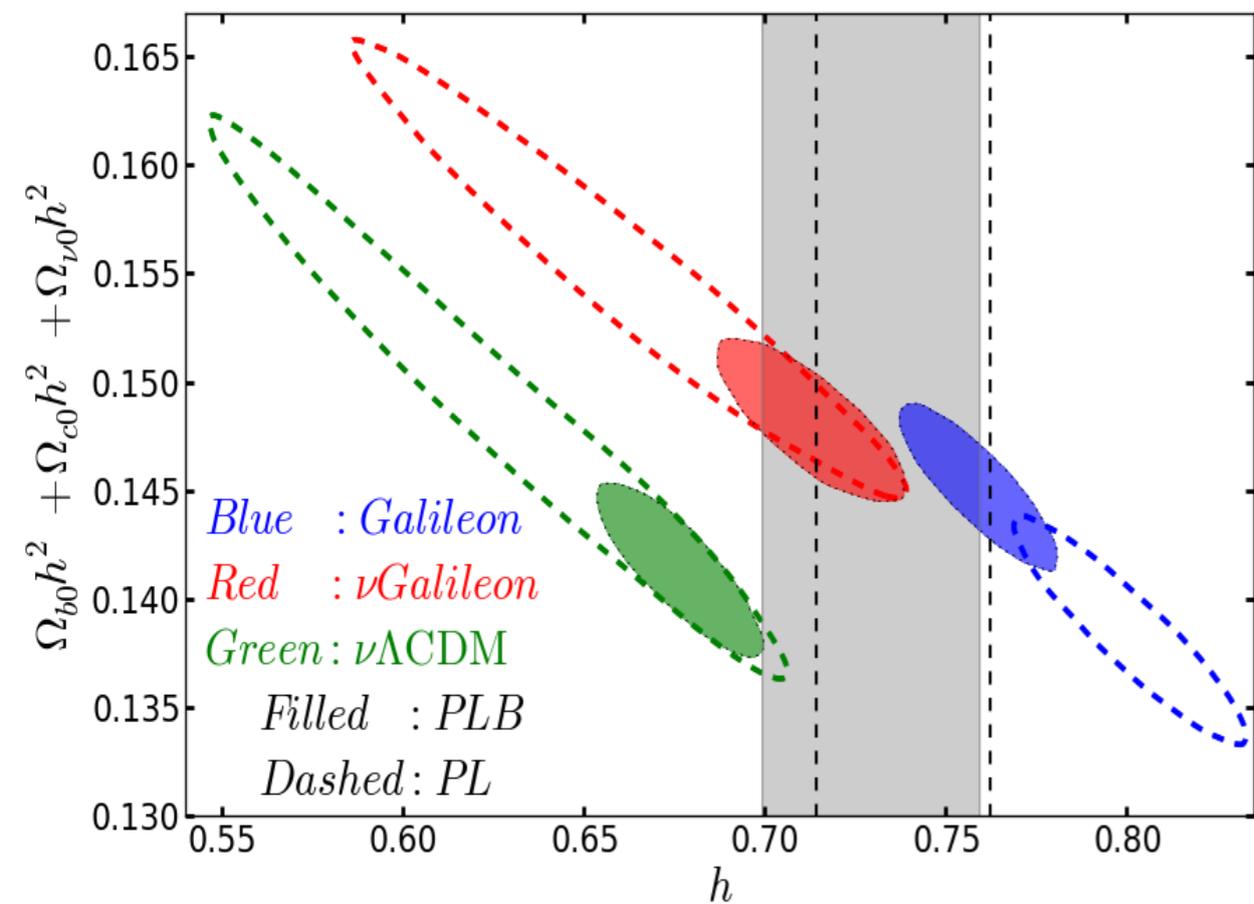
	<i>LCDM</i>	<i>Galileon</i>	$\Delta\chi^2$
<i>CMB</i>	9805.5	9811.5	+6.0
+ <i>CMB lensing</i>	9814.1	9816.0	+1.9
+ <i>BAO</i>	9815.5	9819.0	+3.5
+ <i>H<sub>0</sub></i>			
+ $\sigma_8(\Omega_m/0.25)^{0.47}$			

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●						



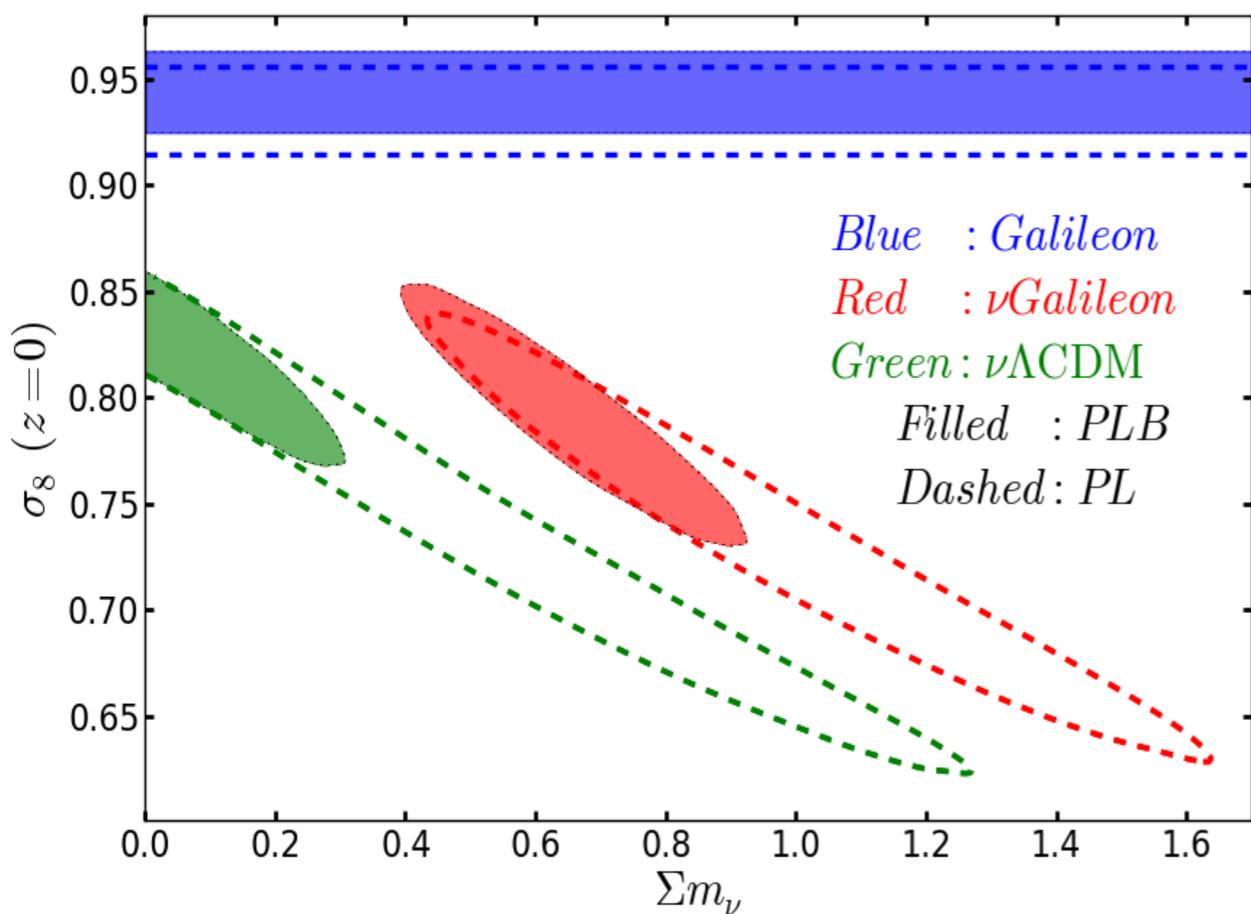
	<i>LCDM</i>	<i>Galileon</i>	$\Delta\chi^2$
<i>CMB</i>	9805.5	9811.5	+6.0
+ <i>CMB lensing</i>	9814.1	9816.0	+1.9
+ <i>BAO</i>	9815.5	9819.0	+3.5
+ <i>H<sub>0</sub></i>			
+ $\sigma_8(\Omega_m/0.25)^{0.47}$			

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●						



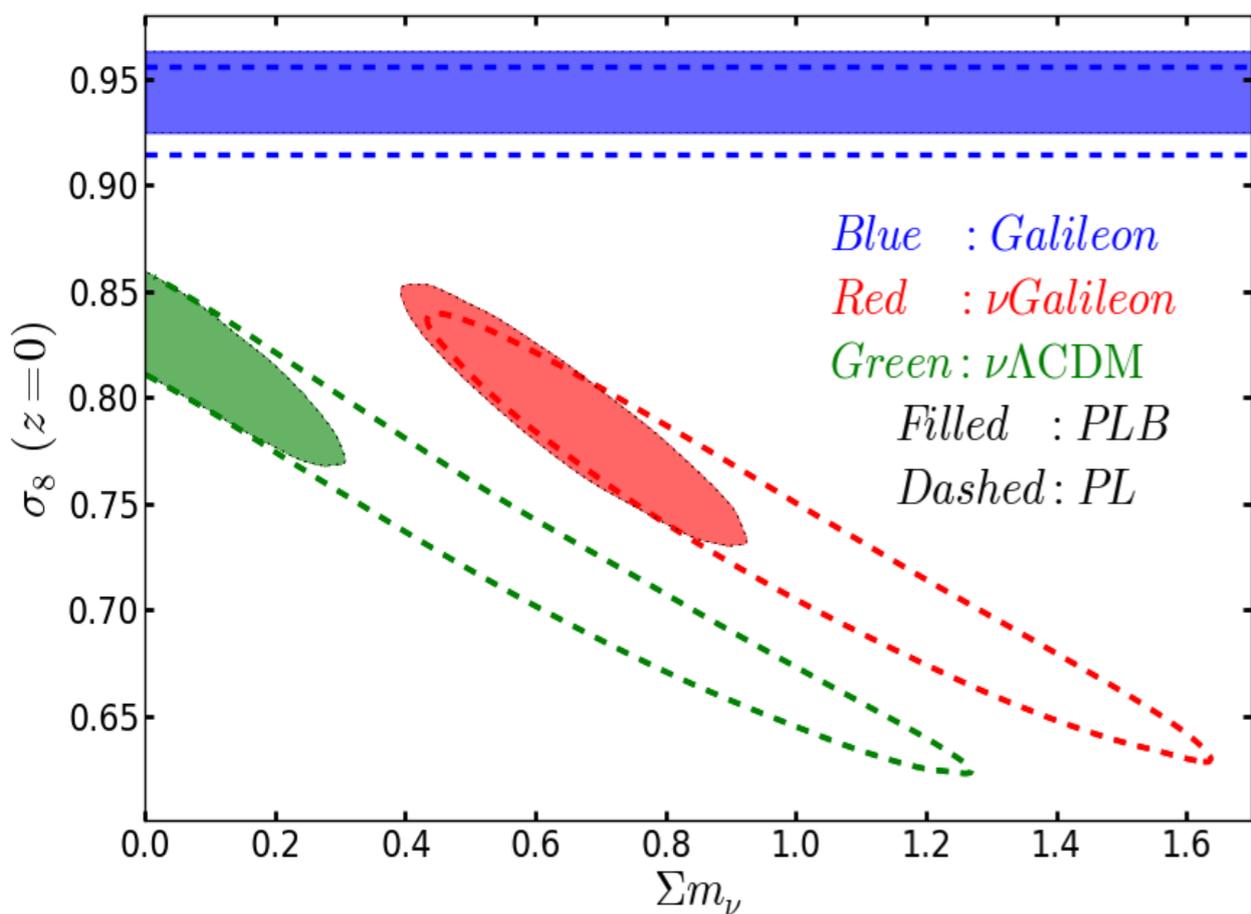
	<i>ΛCDM</i>	<i>Galileon</i>	$\Delta\chi^2$
<i>CMB</i>	9805.5	9811.5	+6.0
+ <i>CMB lensing</i>	9814.1	9816.0	+1.9
+ <i>BAO</i>	9815.5	9819.0	+3.5
+ <i>H<sub>0</sub></i>	9822.0	9820.2	-1.8
+ $\sigma_8(\Omega_m/0.25)^{0.47}$			

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●						



	<i>ΛCDM</i>	<i>Galileon</i>	$\Delta\chi^2$
<i>CMB</i>	9805.5	9811.5	+6.0
+ <i>CMB lensing</i>	9814.1	9816.0	+1.9
+ <i>BAO</i>	9815.5	9819.0	+3.5
+ <i>H<sub>0</sub></i>	9822.0	9820.2	-1.8
+ $\sigma_8(\Omega_m/0.25)^{0.47}$			

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●						



	<i>LCDM</i>	<i>Galileon</i>	$\Delta\chi^2$
<i>CMB</i>	9805.5	9811.5	<b>+6.0</b>
<b>+ <i>CMB lensing</i></b>	9814.1	9816.0	<b>+1.9</b>
<b>+ <i>BAO</i></b>	9815.5	9819.0	<b>+3.5</b>
<b>+ <i>H<sub>0</sub></i></b>	9822.0	9820.2	<b>-1.8</b>
<b>+ <math>\sigma_8(\Omega_m/0.25)^{0.47}</math></b>	9845.5	9821.5	<b>-24.0</b>

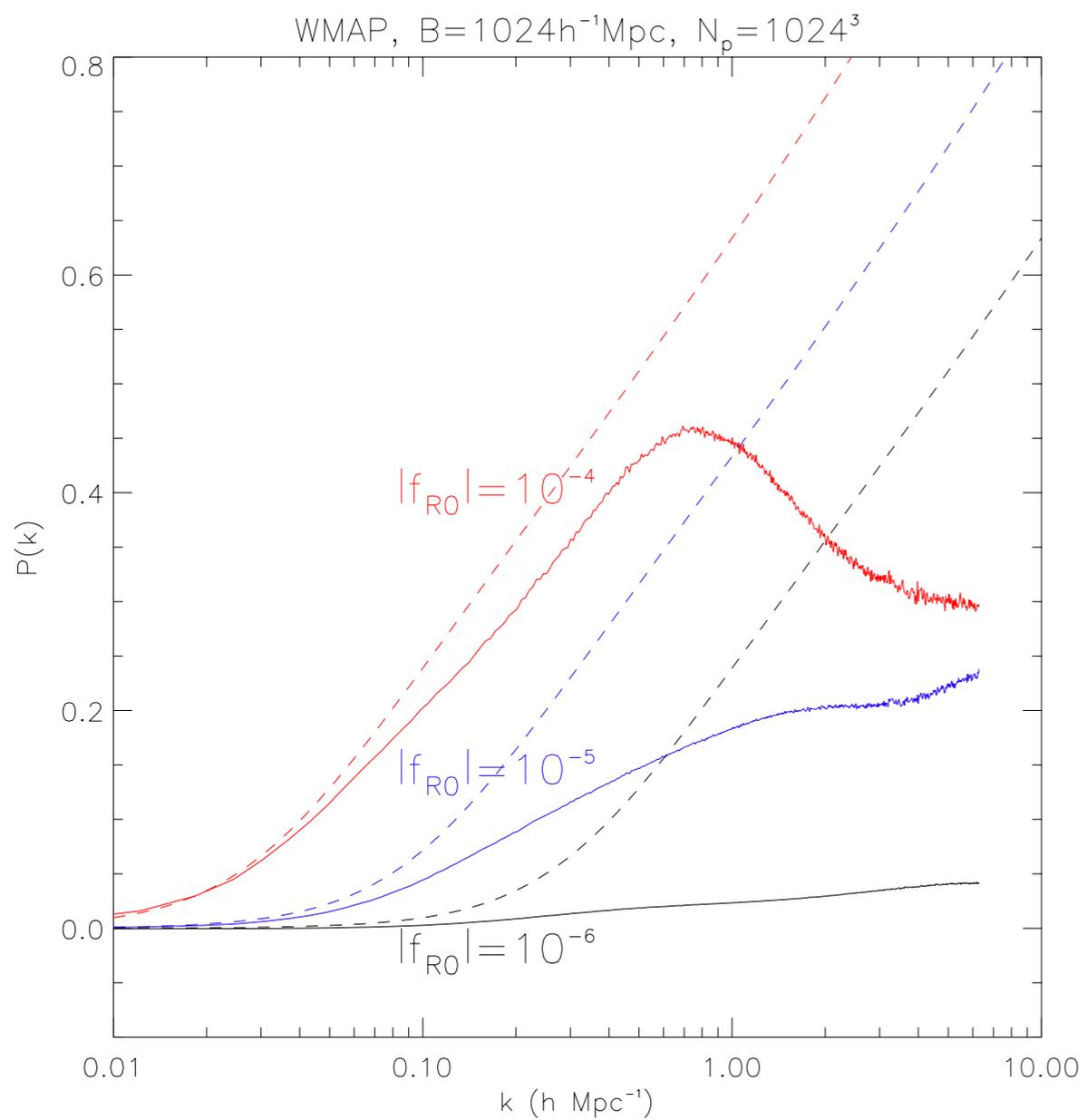
<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●	●					

	<i>ΛCDM</i>	<i>Galileon</i>	$\Delta\chi^2$
<i>CMB</i>	9805.5	9811.5	+6.0
+ <i>CMB lensing</i>	9814.1	9816.0	+1.9
+ <i>BAO</i>	9815.5	9819.0	+3.5
+ <i>H<sub>0</sub></i>	9822.0	9820.2	-1.8
+ $\sigma_8(\Omega_m/0.25)^{0.47}$	9845.5	9821.5	-24.0

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●	●					

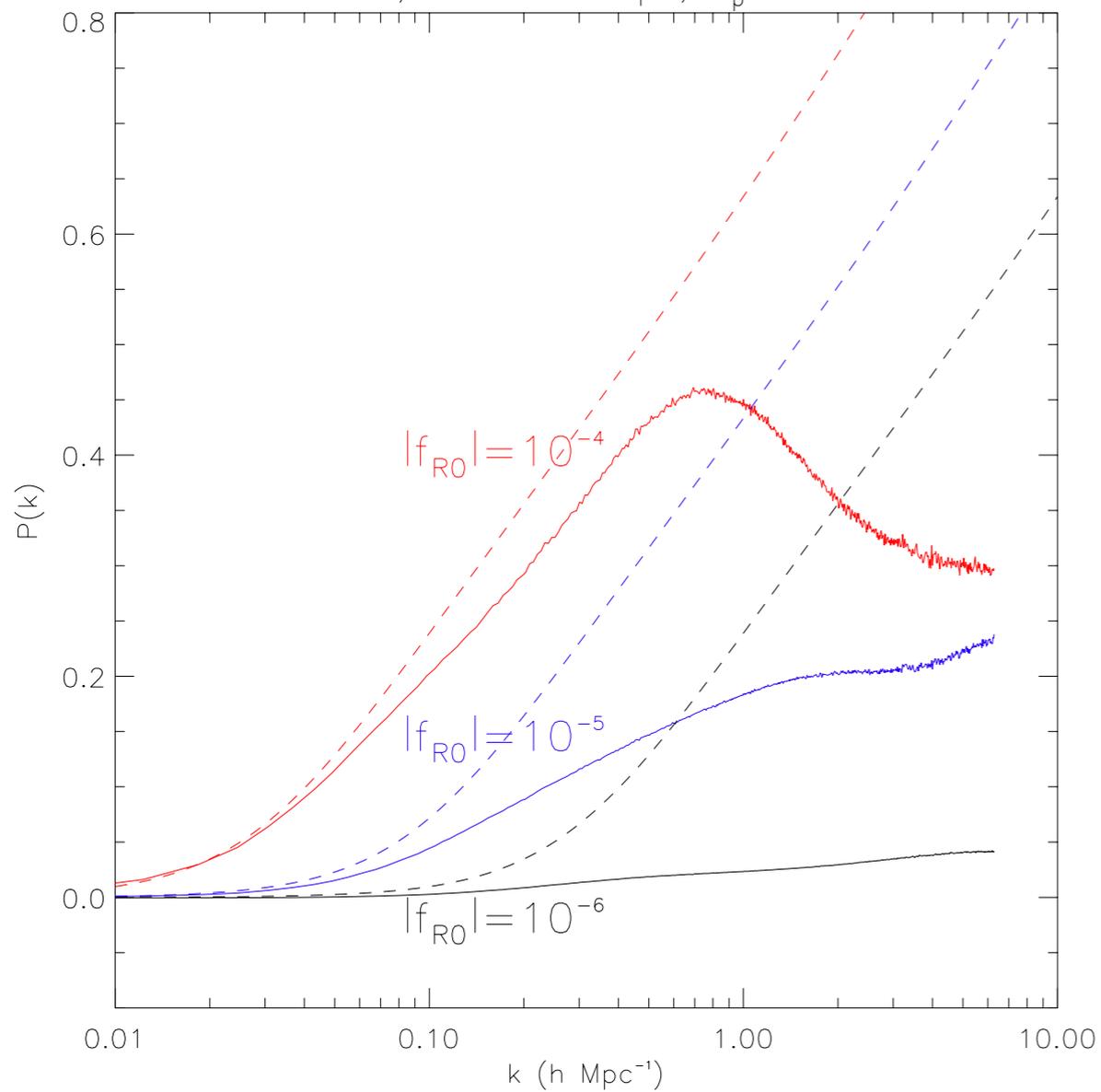
<i>screening</i>	<i>deviates from GR on</i>	<i>environmental dependence</i>	<i>nonlinearity</i>
<i>chameleon</i>	<i>small scales</i>	<i>strong</i>	<i>pure &amp; strong</i>
<i>Vainshtein</i>	<i>large scales</i>	<i>weaker</i>	<i>pure &amp; strong</i>

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●	●					



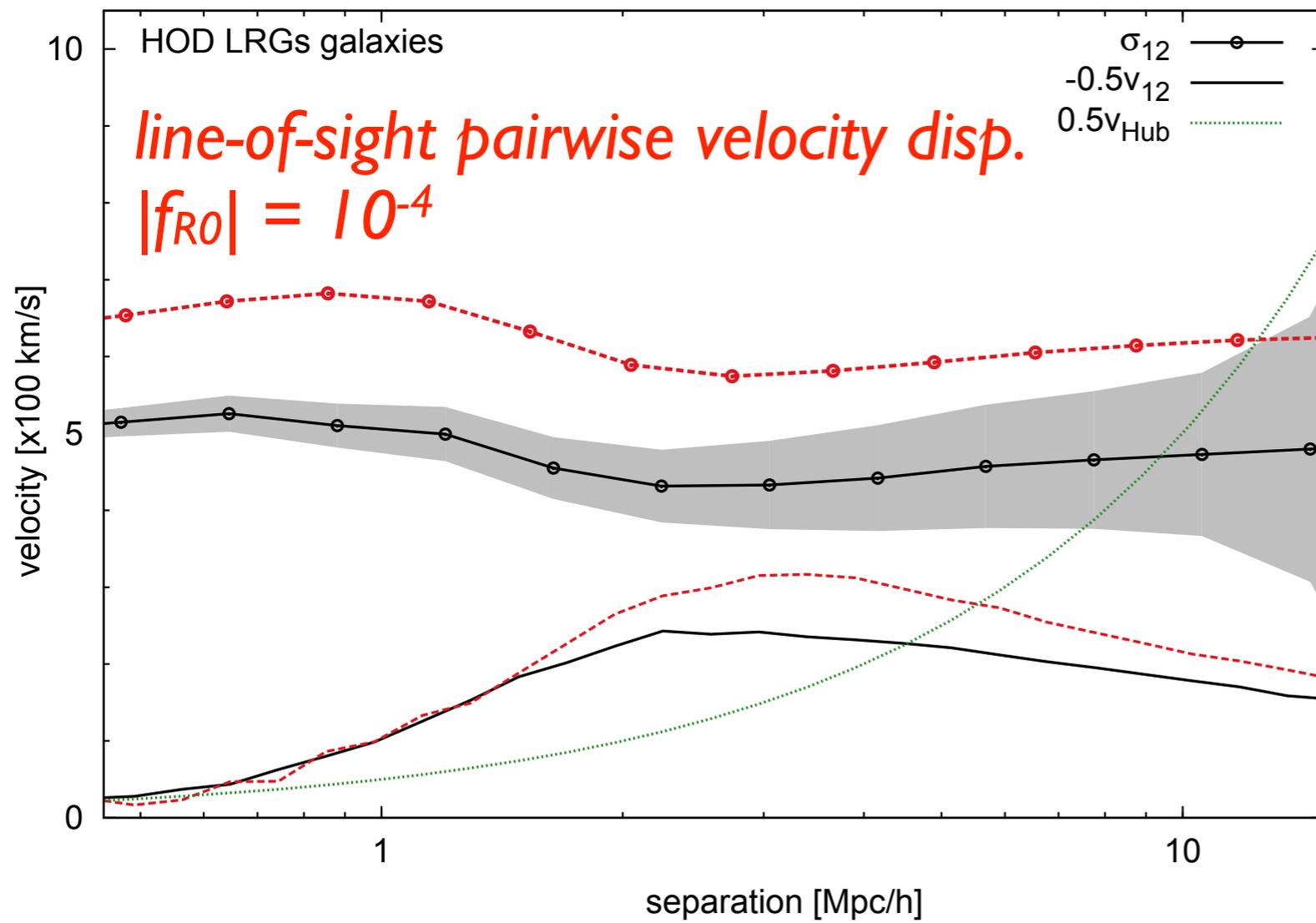
<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●	●					

WMAP,  $B=1024h^{-1}\text{Mpc}$ ,  $N_p=1024^3$

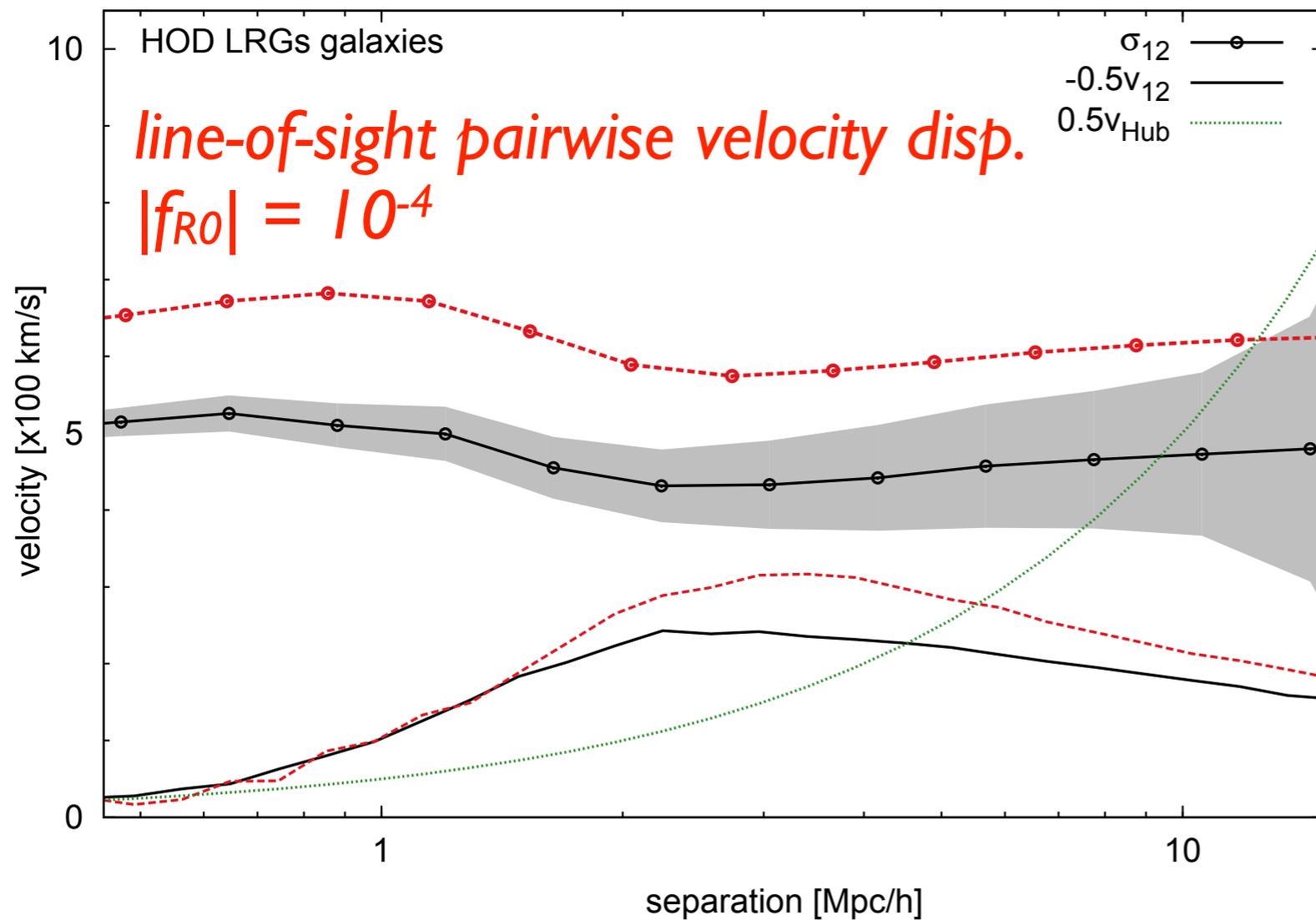


*linear theory fails wherever it predicts a deviation from GR due to the nonlinearity in the chameleon mechanism*

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●	●					

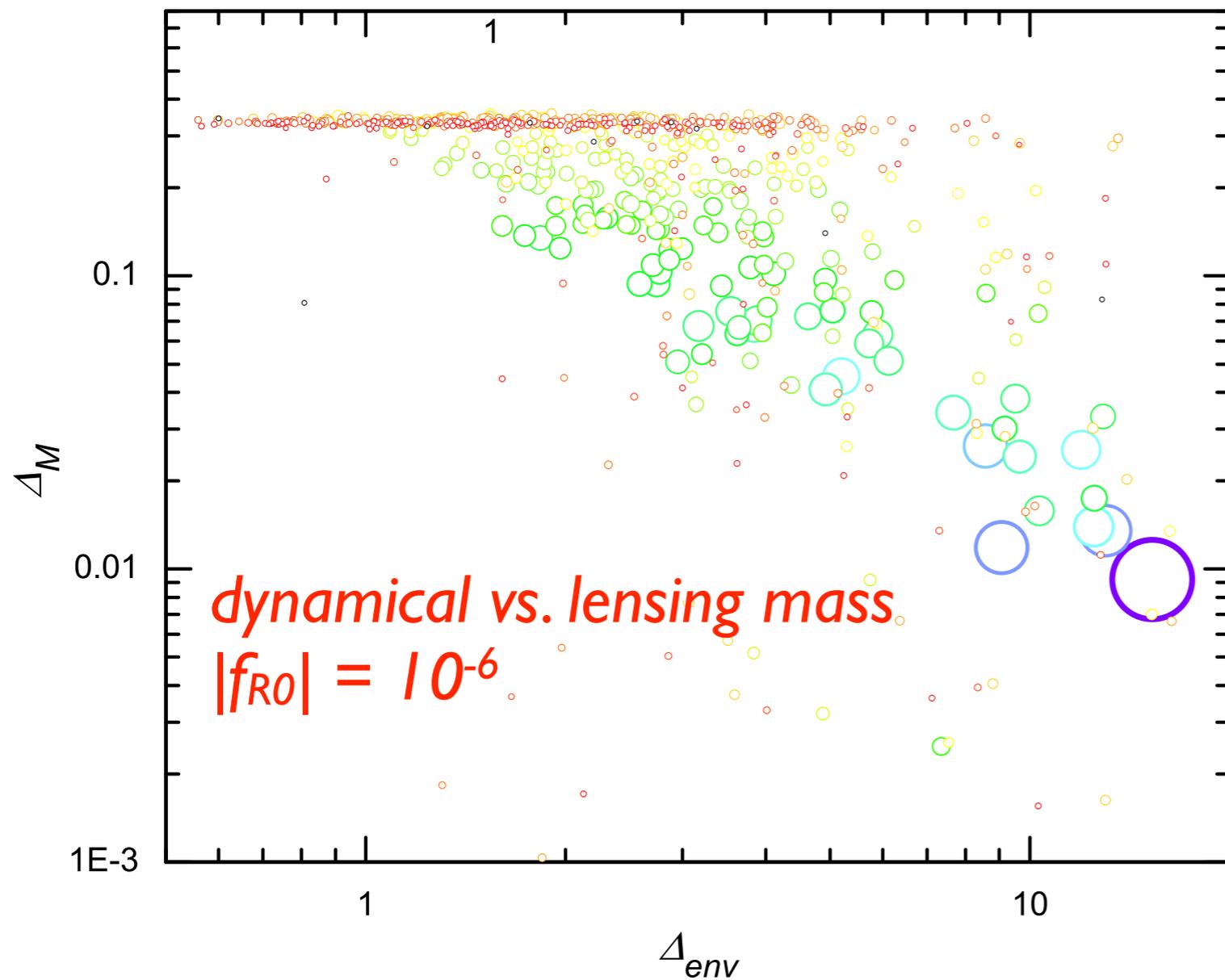


<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●	●					



*most cosmological observations are capable of constraining the parameter to  $|f_{R0}| = 10^{-5} \sim 10^{-4}$*

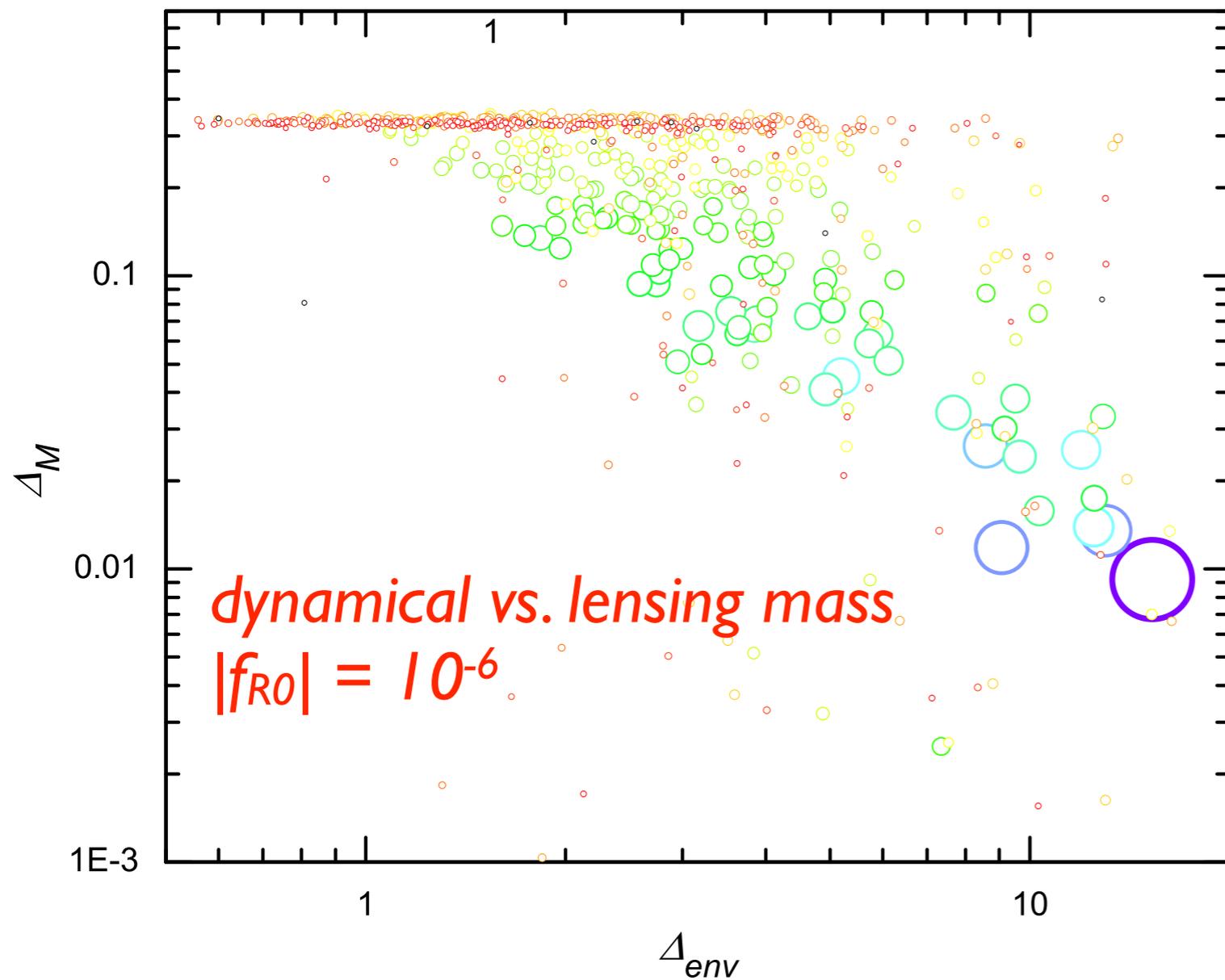
<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●					
<i>Galileon</i>	●	●					



*most cosmological observations are capable of constraining the parameter to  $|f_{R0}| = 10^{-5} \sim 10^{-4}$*

*further constraints, e.g, to  $10^{-6}$ , depends on the quality of data*

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●				
<i>Galileon</i>	●	●					



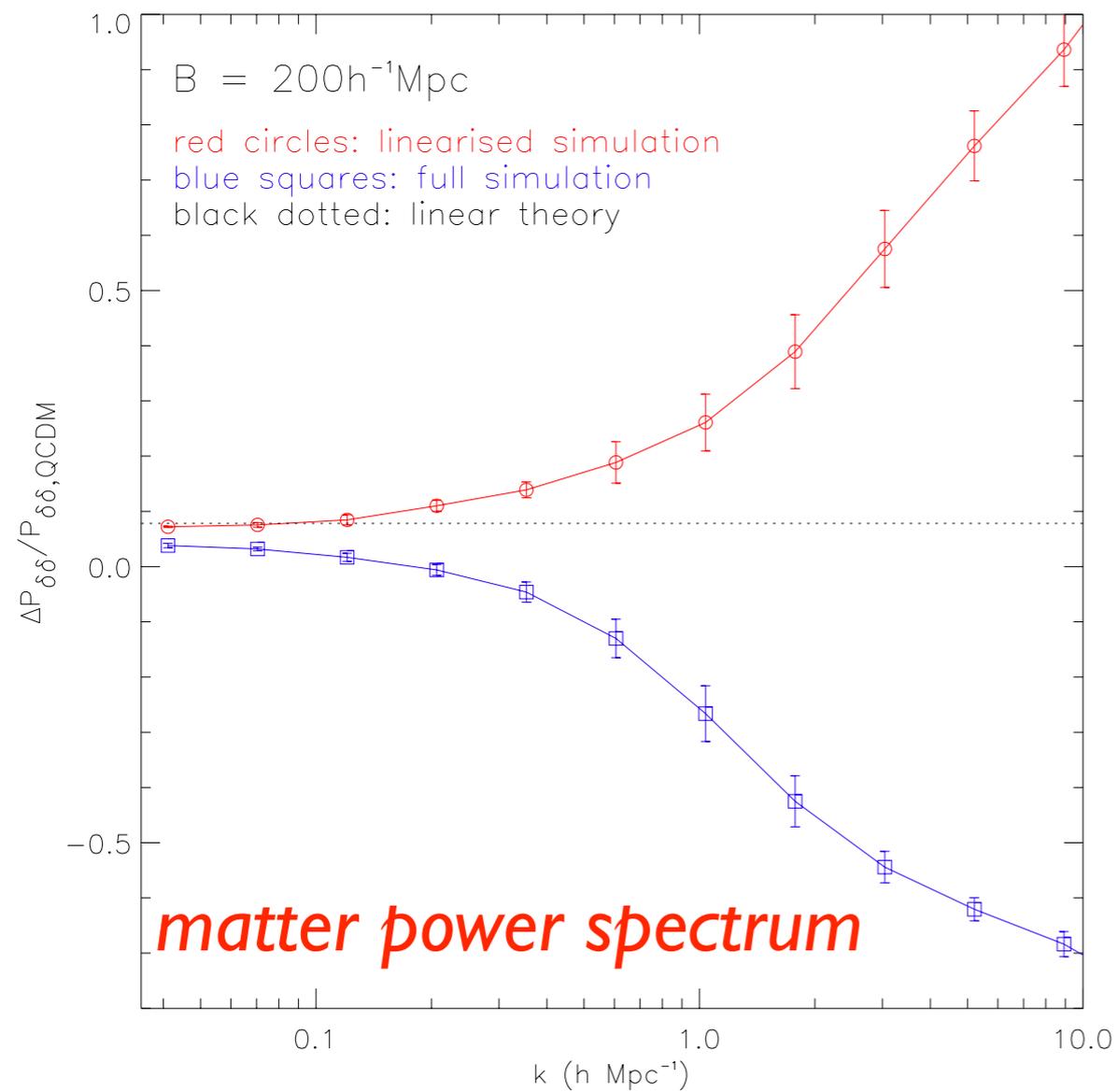
*most cosmological observations are capable of constraining the parameter to  $|f_{R0}| = 10^{-5} \sim 10^{-4}$*

*further constraints, e.g, to  $10^{-6}$ , depends on the quality of data*

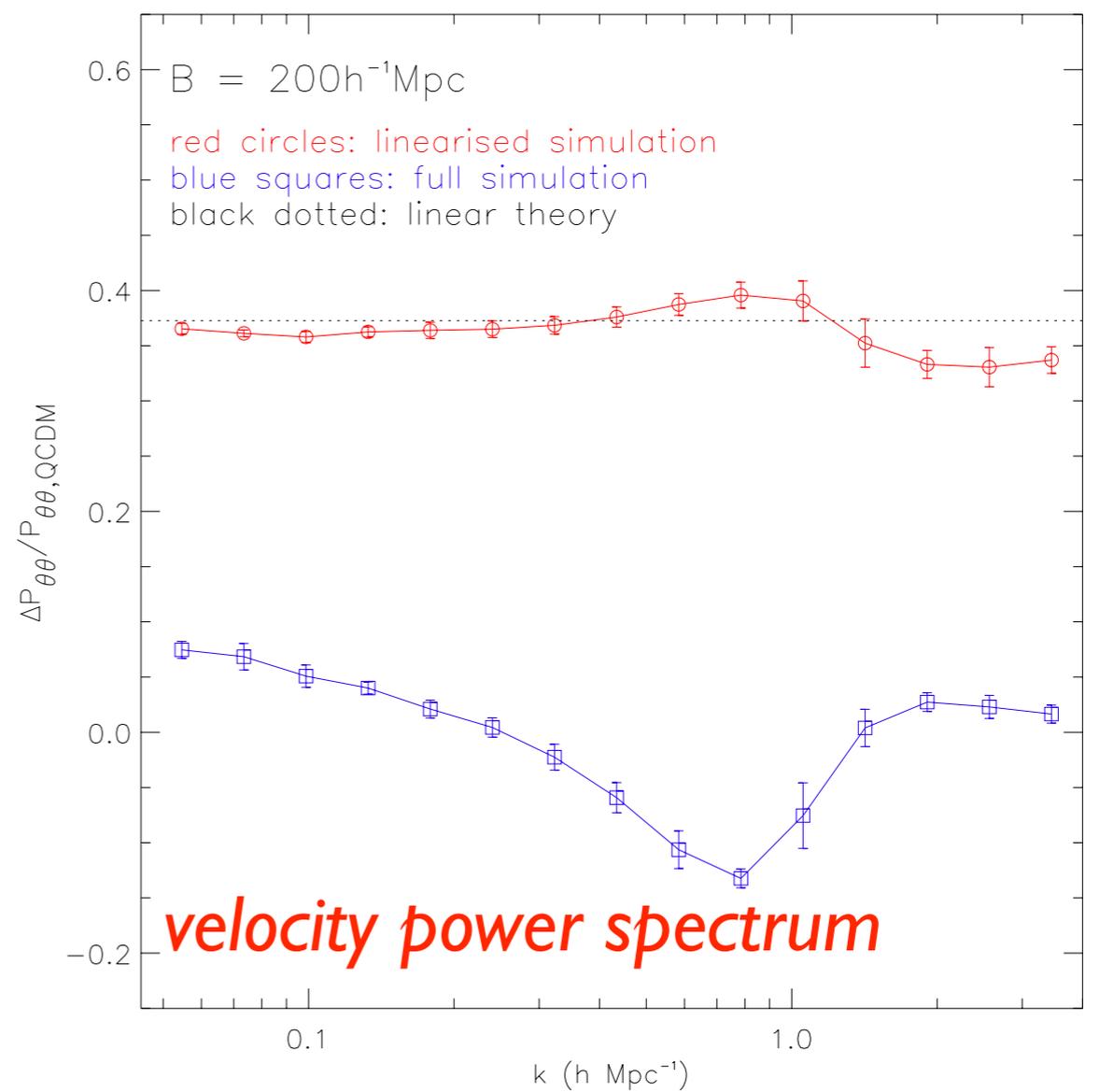
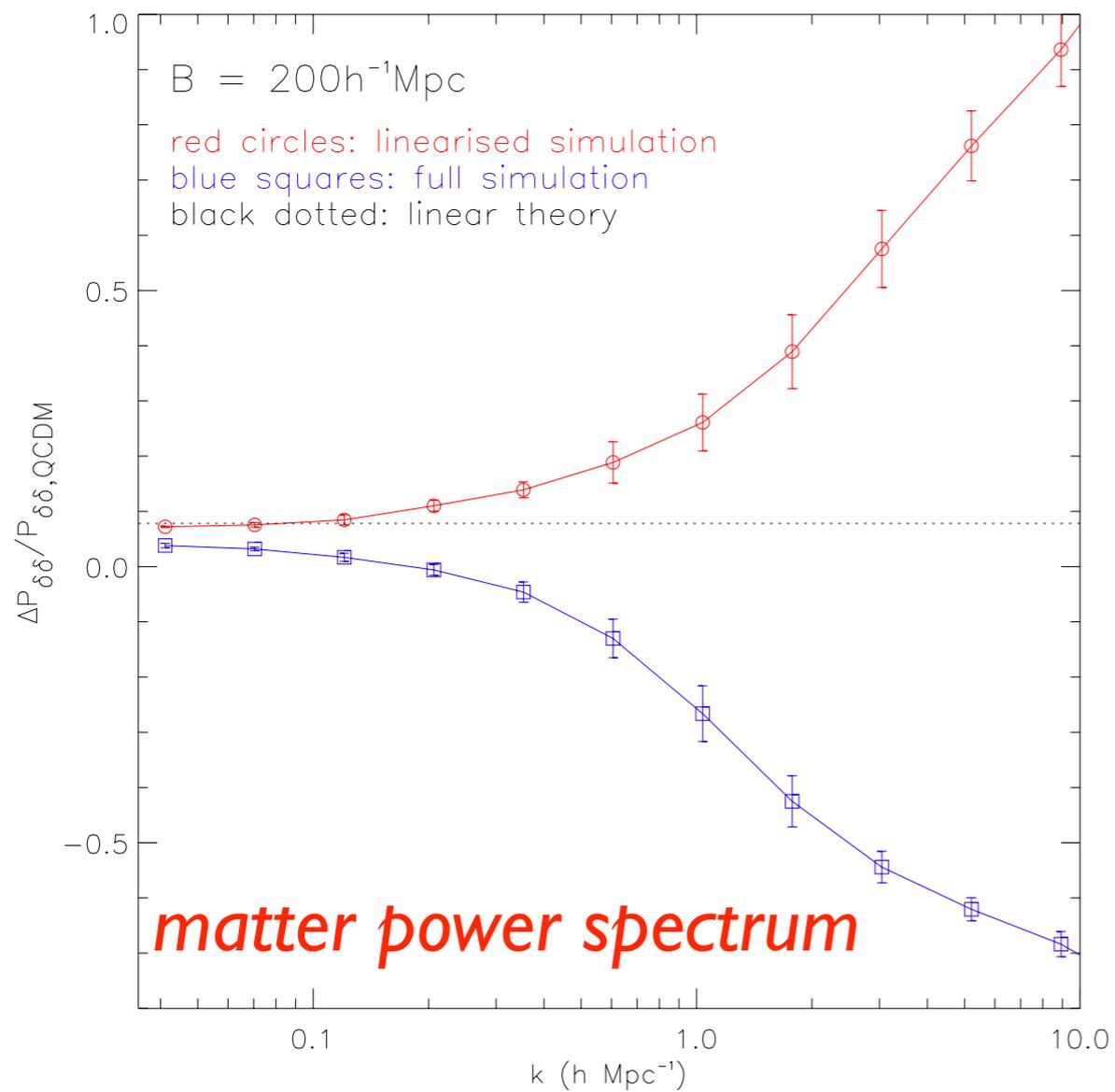
<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●				
<i>Galileon</i>	●	●					

<i>screening</i>	<i>deviates from GR on</i>	<i>environmental dependence</i>	<i>nonlinearity</i>
<i>chameleon</i>	<i>small scales</i>	<i>strong</i>	<i>pure &amp; strong</i>
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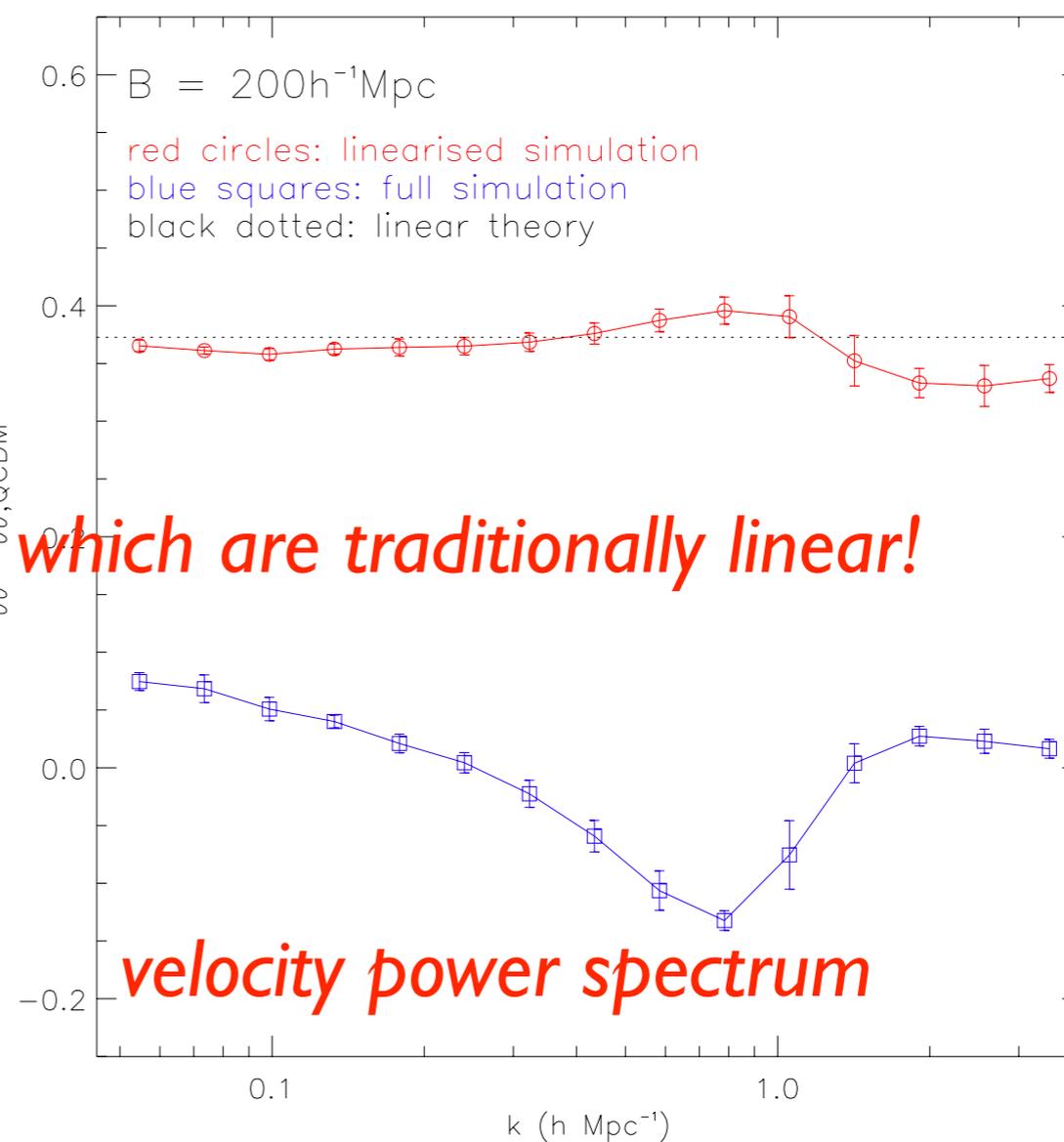
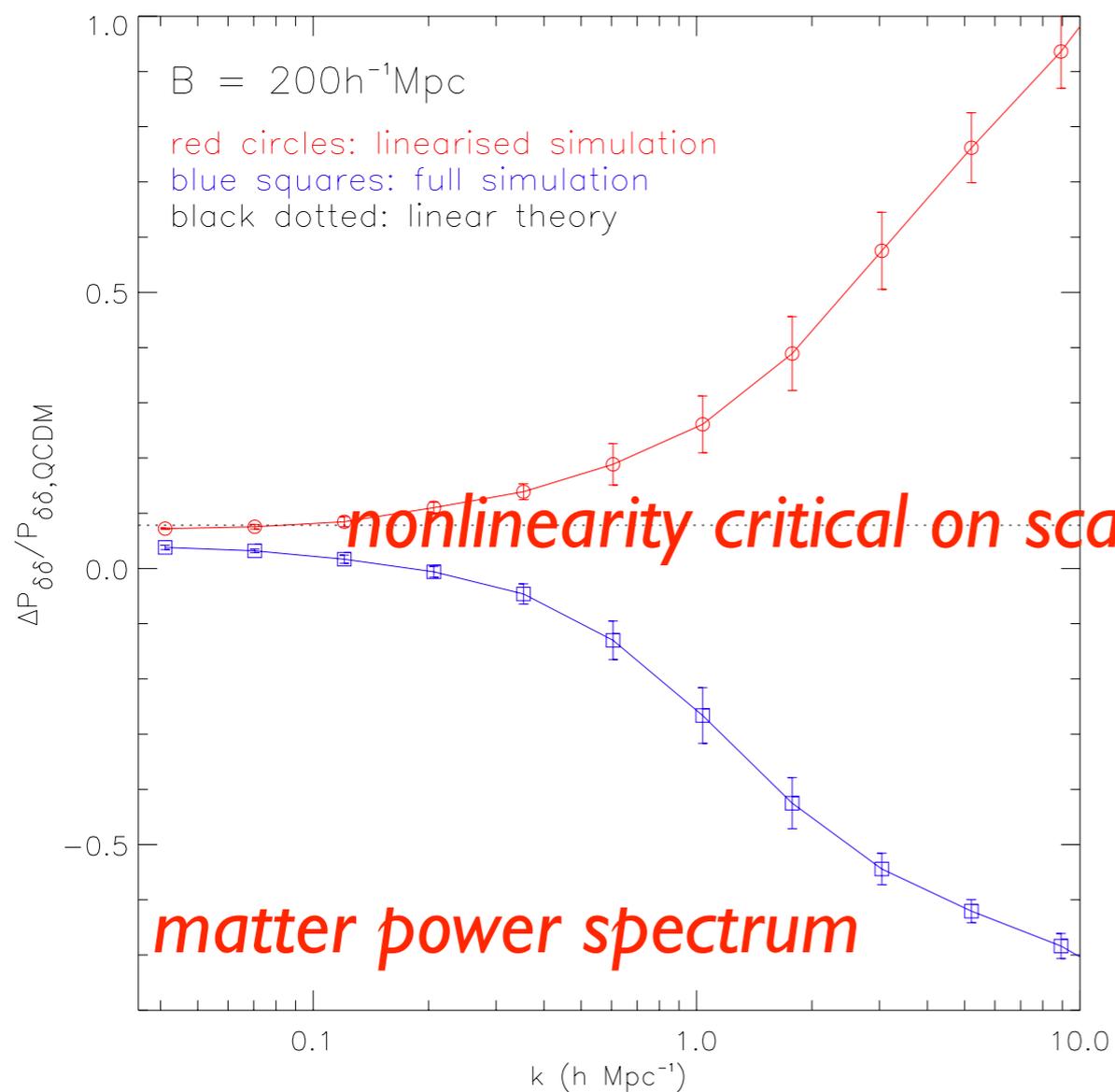
<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●				
<i>Galileon</i>	●	●					



<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●				
<i>Galileon</i>	●	●					



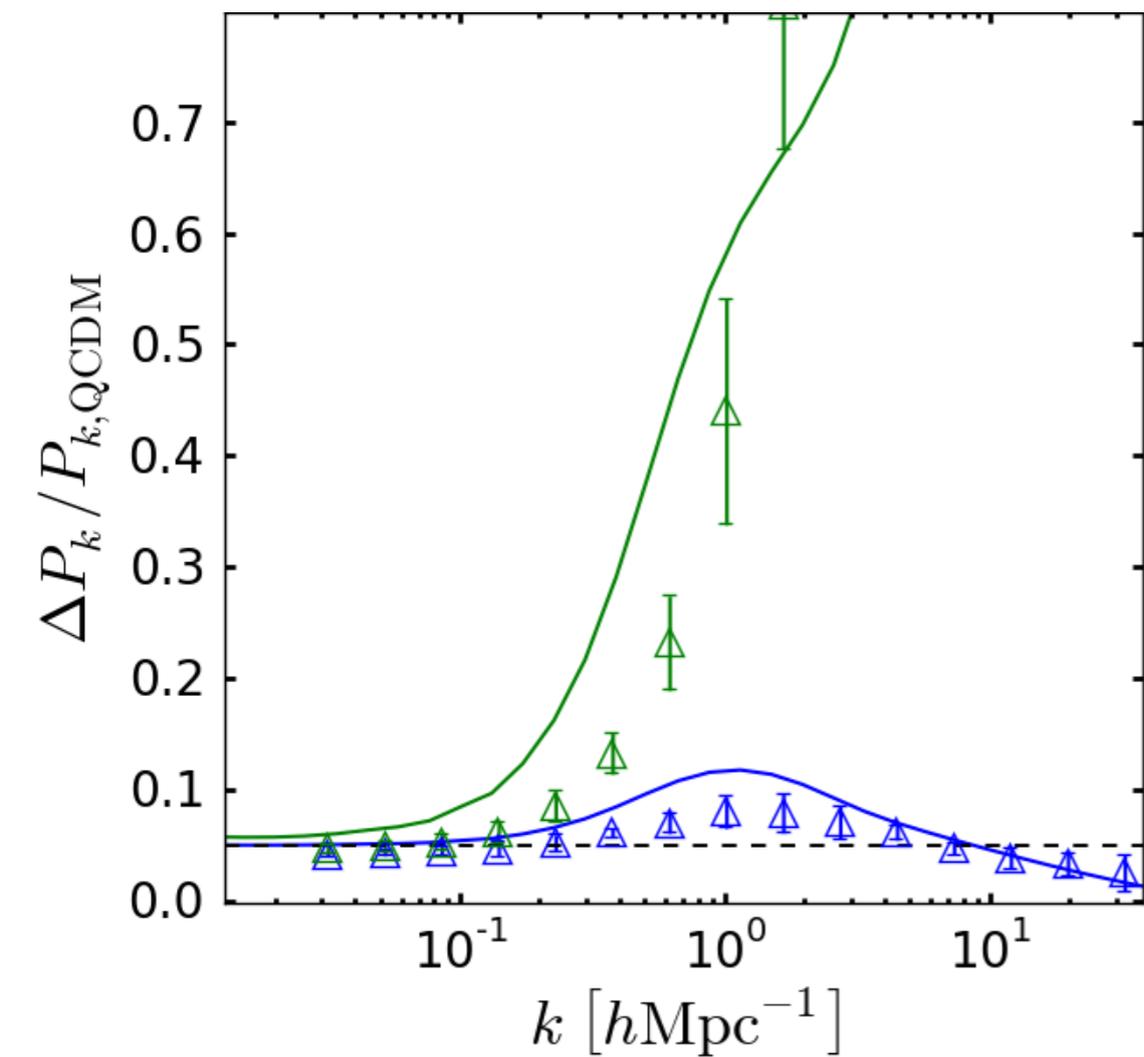
model	E1	E2	E3	D1	D2	X1	X2
<i>f(R) gravity</i>	●	●	●				
<i>Galileon</i>	●	●					



<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●				
<i>Galileon</i>	●	●					

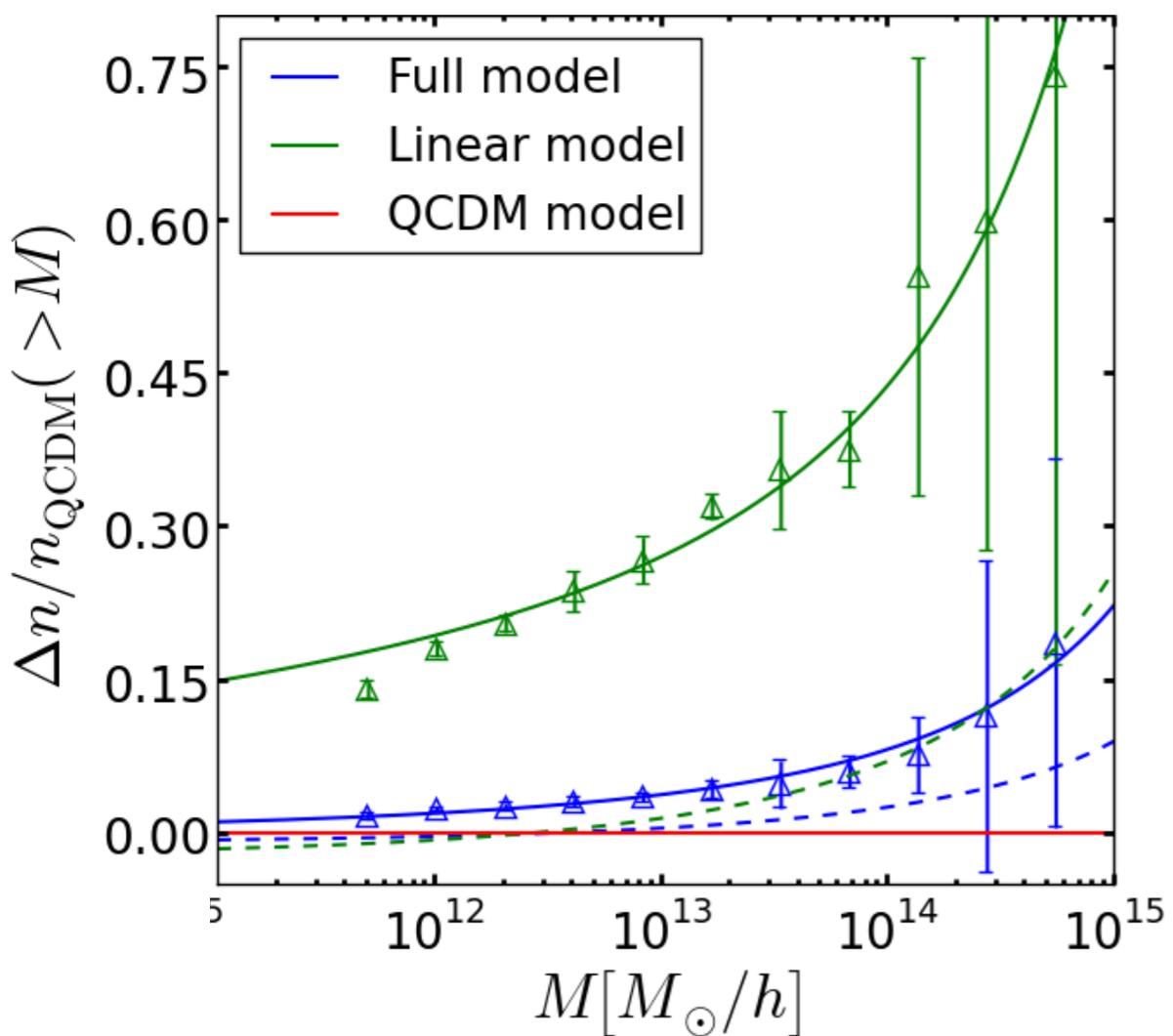
	<i>expansion history</i>	<i>force law</i>
<i>red</i>	<i>Galileon</i>	<i>GR</i>
<i>green</i>	<i>Galileon</i>	<i>linear Galileon</i>
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<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●				
<i>Galileon</i>	●	●					



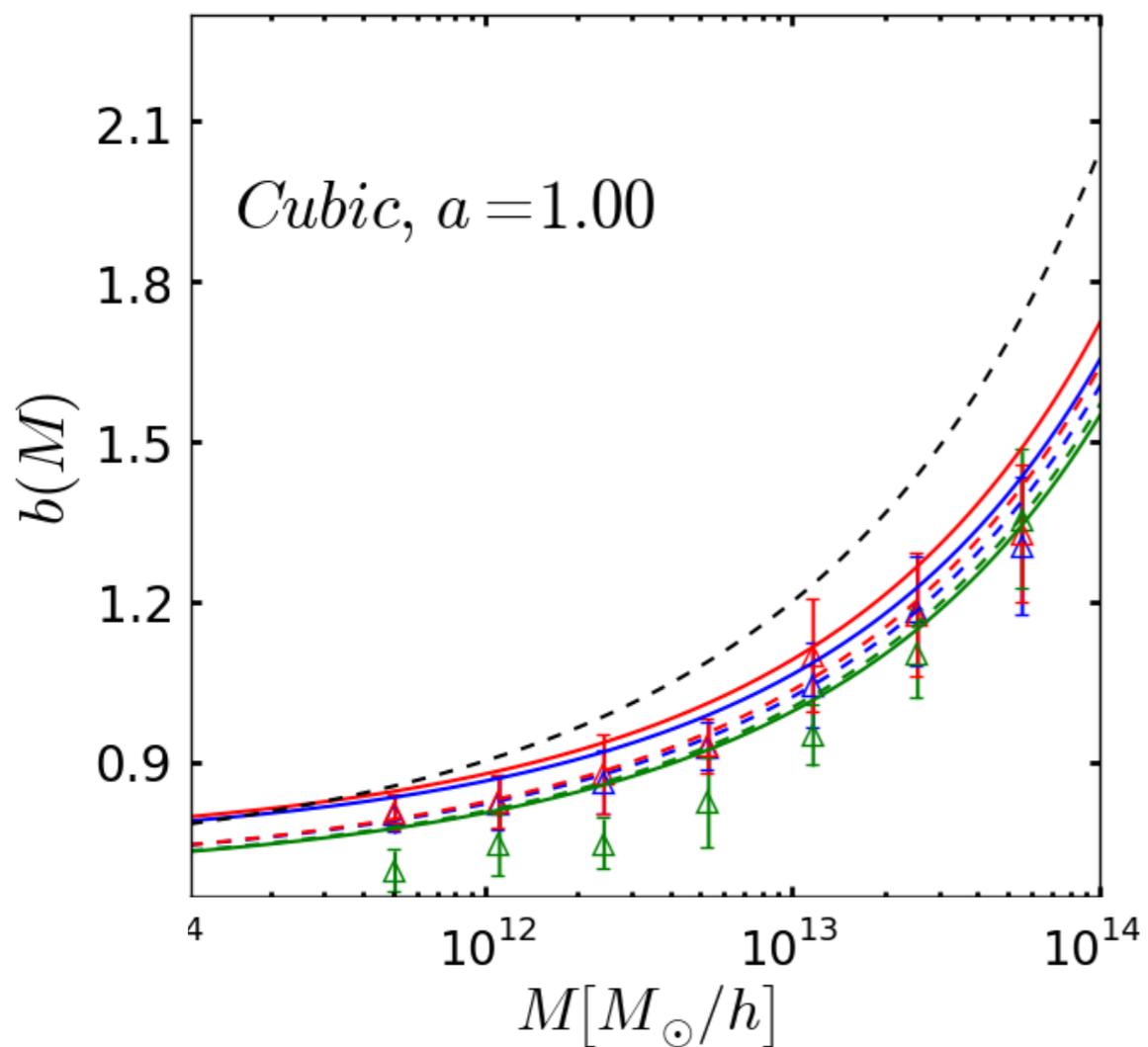
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<i>Galileon</i>	●	●					



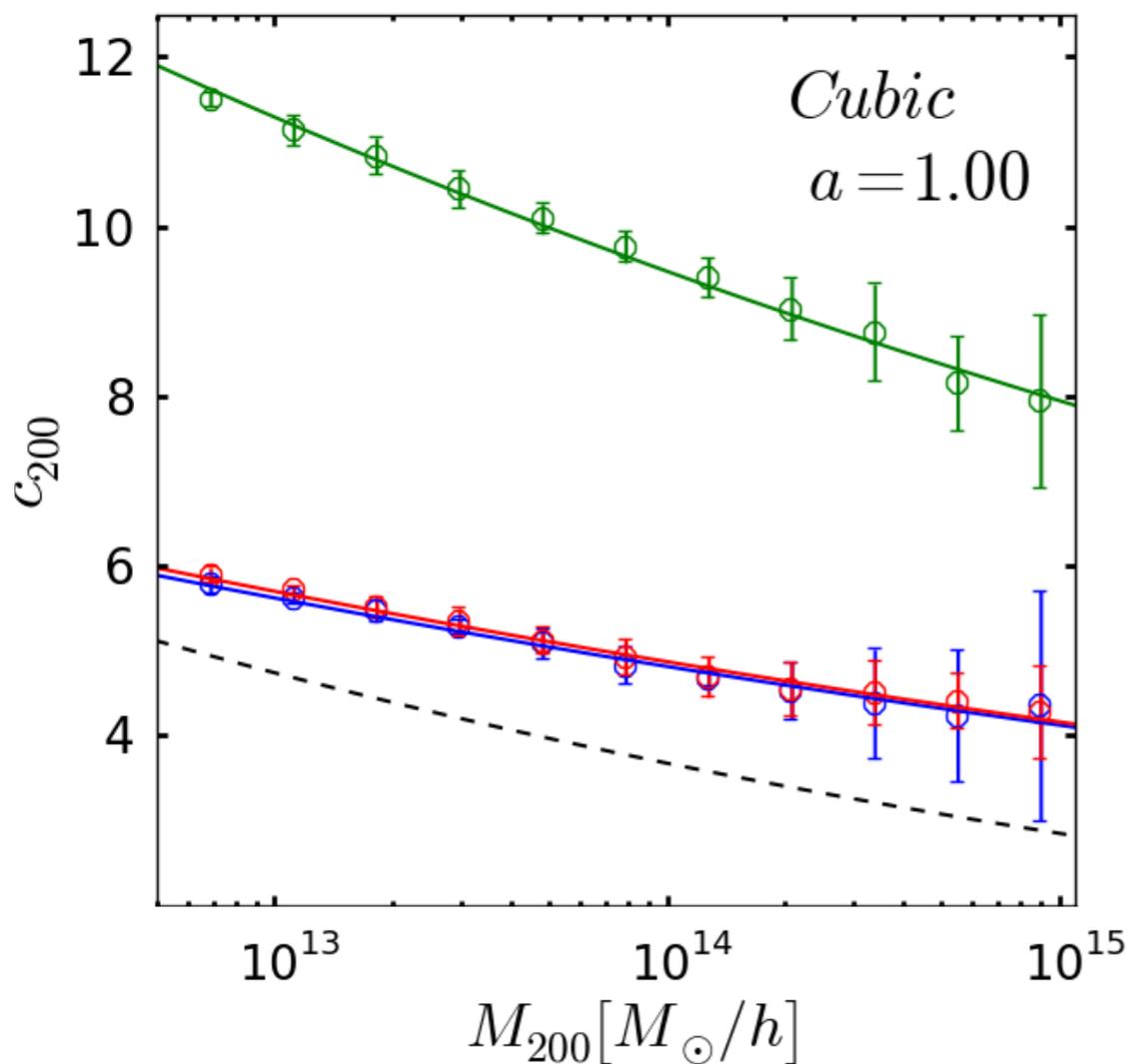
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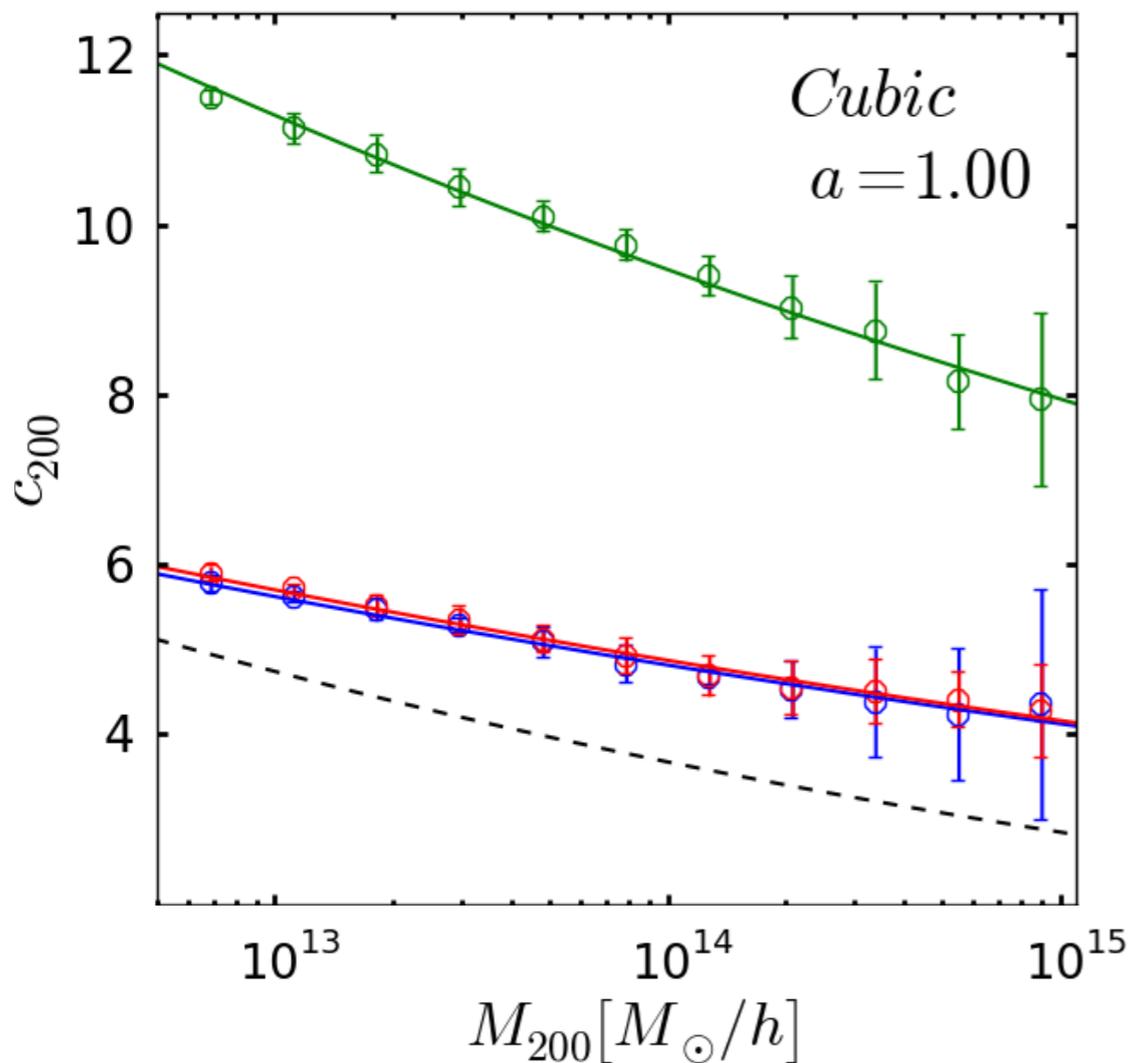
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<i>f(R) gravity</i>	●	●	●				
<i>Galileon</i>	●	●					



	<i>expansion history</i>	<i>force law</i>
<i>red</i>	<i>Galileon</i>	<i>GR</i>
<i>green</i>	<i>Galileon</i>	<i>linear Galileon</i>
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<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●				
<i>Galileon</i>	●	●	●				



	<i>expansion history</i>	<i>force law</i>
<i>red</i>	<i>Galileon</i>	<i>GR</i>
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<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●				
<i>Galileon</i>	●	●	●				

$$R - 2\Lambda \rightarrow R + f(R) \sim R - 2\Lambda - 10|f_{R0}|\frac{\Lambda^2}{R}$$

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<i>Galileon</i>	●	●	●				

*great freedom in choosing the functional form*

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<i>f(R) gravity</i>	●	●	●				
<i>Galileon</i>	●	●	●				

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*smaller than  $10^{-6} \sim 10^{-5}$  by cosmological data  
 $10^{-7}$  or smaller by astrophysical considerations*

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<i>f(R) gravity</i>	●	●	●	●	●		
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<i>f(R) gravity</i>	●	●	●	●	●		
<i>Galileon</i>	●	●	●				

$$\mathcal{L}_{\text{Galileon}} = \frac{1}{2!} c_2 \nabla^\mu \varphi \nabla_\mu \varphi$$

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<i>f(R) gravity</i>	●	●	●	●	●		
<i>Galileon</i>	●	●	●				

$$\mathcal{L}_{\text{Galileon}} = \frac{1}{2!} c_2 \nabla^\mu \varphi \nabla_\mu \varphi - \frac{1}{3!} c_3 \frac{1}{M_{\text{Pl}} \Lambda} \square \varphi \nabla^\mu \varphi \nabla_\mu \varphi$$

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<i>f(R) gravity</i>	●	●	●	●	●		
<i>Galileon</i>	●	●	●				

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Once we decide to have derivative interactions of the scalar field, this is the simplest and first possibility to write down, just like  $R$  is the most natural curvature invariant.

model	E1	E2	E3	D1	D2	X1	X2
<i>f(R) gravity</i>	●	●	●	●	●		
<i>Galileon</i>	●	●	●				

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Other possible terms will

- (i) involve new free functions to be tuned, and/or
- (ii) not solve more problems with the additional complexity, and/or
- (iii) cause new problems

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●	●	●		
<i>Galileon</i>	●	●	●				

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<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●	●	●		
<i>Galileon</i>	●	●	●	●			

$$\mathcal{L}_{\text{Galileon}} = \frac{1}{2!} c_2 \nabla^\mu \varphi \nabla_\mu \varphi - \frac{1}{3!} c_3 \frac{1}{M_{\text{Pl}} \Lambda} \square \varphi \nabla^\mu \varphi \nabla_\mu \varphi$$

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<i>f(R) gravity</i>	●	●	●	●	●		
<i>Galileon</i>	●	●	●	●			

$$\mathcal{L}_{\text{Galileon}} = \frac{1}{2!} \nabla^\mu \varphi \nabla_\mu \varphi - \frac{1}{3!} \sqrt{\frac{3}{2} \Omega_\Lambda} \frac{1}{M_{\text{Pl}} \Lambda} \square \varphi \nabla^\mu \varphi \nabla_\mu \varphi$$

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<i>f(R) gravity</i>	●	●	●	●	●		
<i>Galileon</i>	●	●	●	●			

*0.99~1.03 depending on data sets;*

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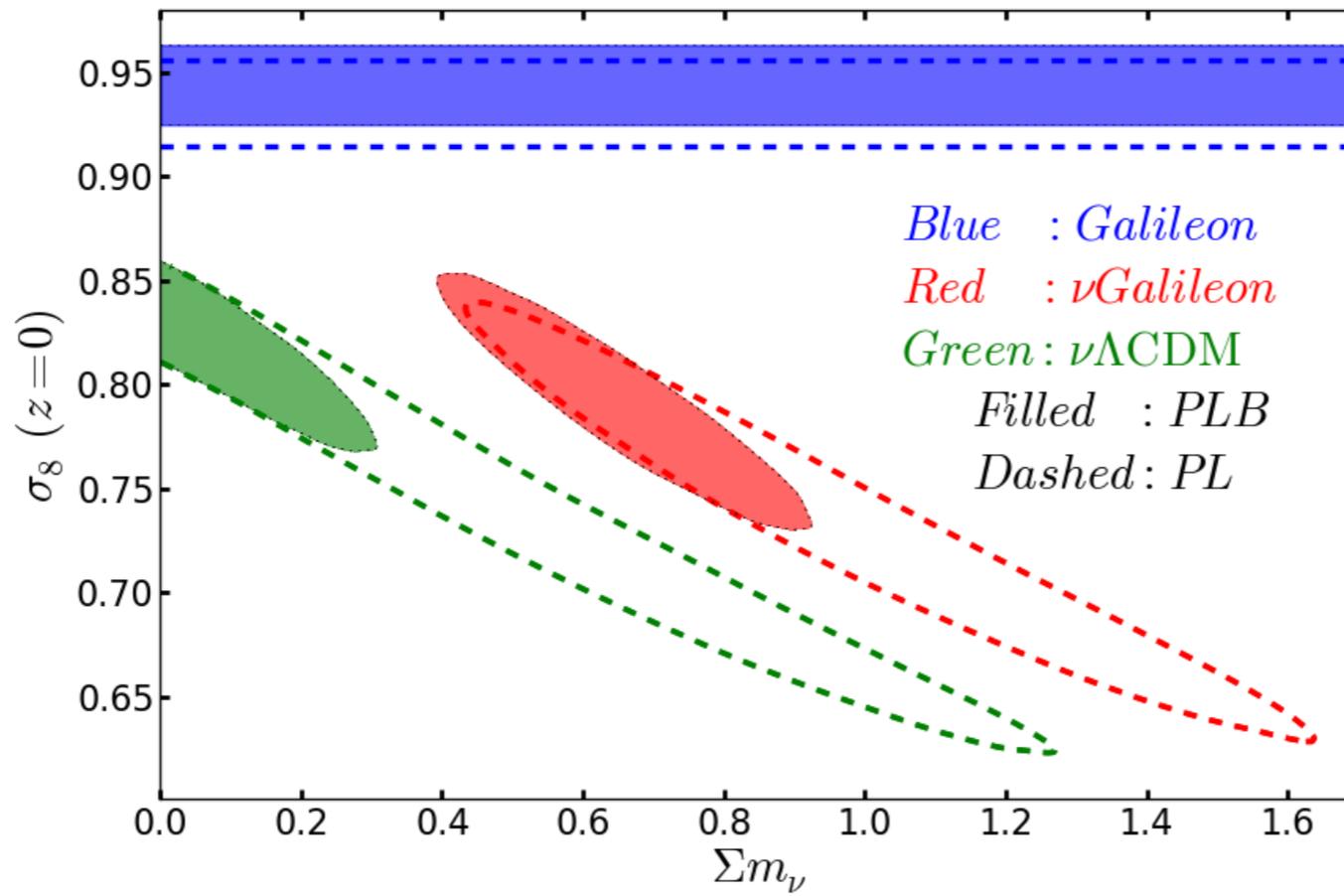
<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●	●	●	●	
<i>Galileon</i>	●	●	●	●	●		

*in equivalent formulae with a scalar field coupled to matter, possible constraints can be obtained from energy shifts in atomic levels*

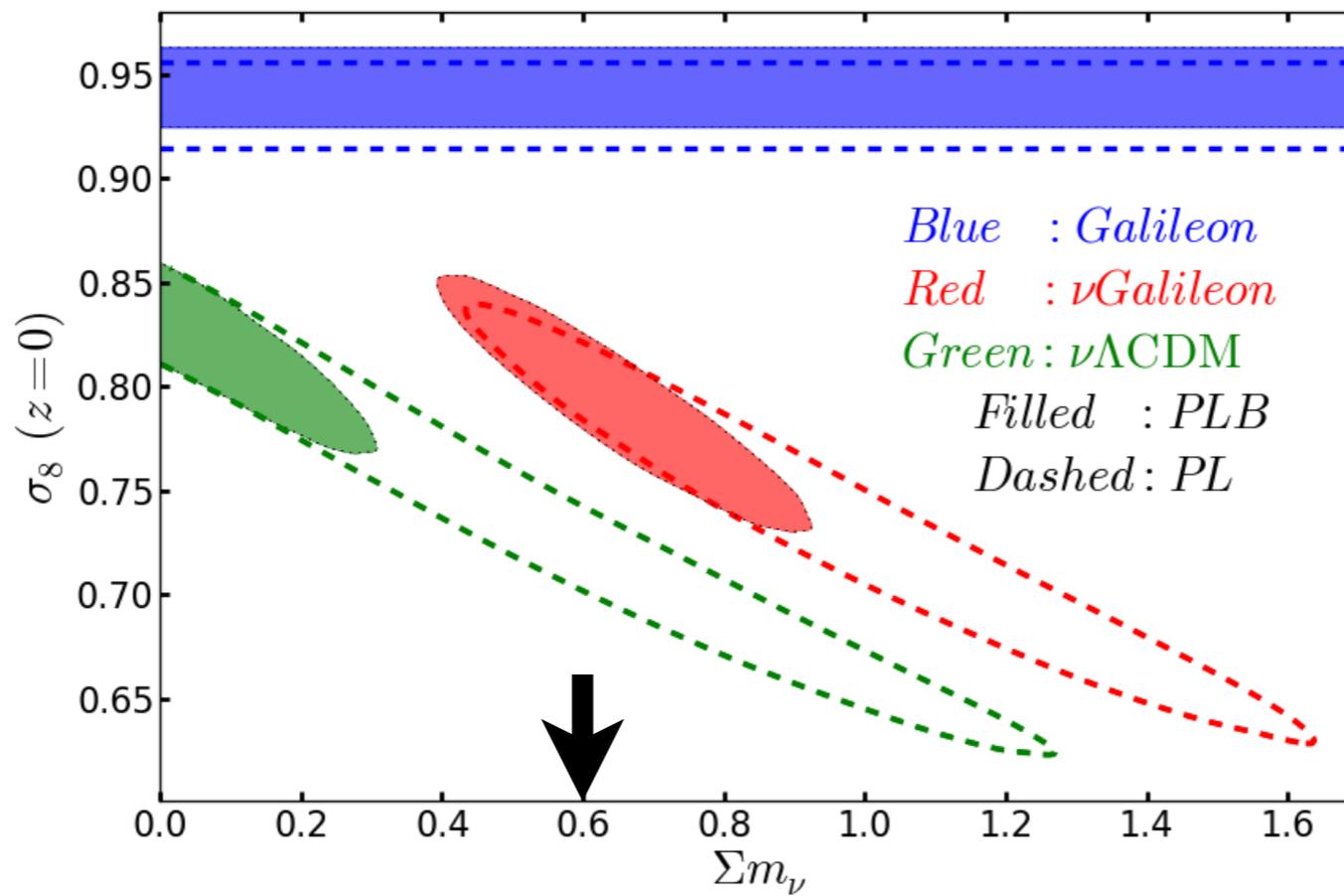
<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●	●	●	●	●
<i>Galileon</i>	●	●	●	●	●		

*for a model which can pass local gravity tests, cosmology is practically not distinguishable from LCDM*

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●	●	●	●	●
<i>Galileon</i>	●	●	●	●	●		

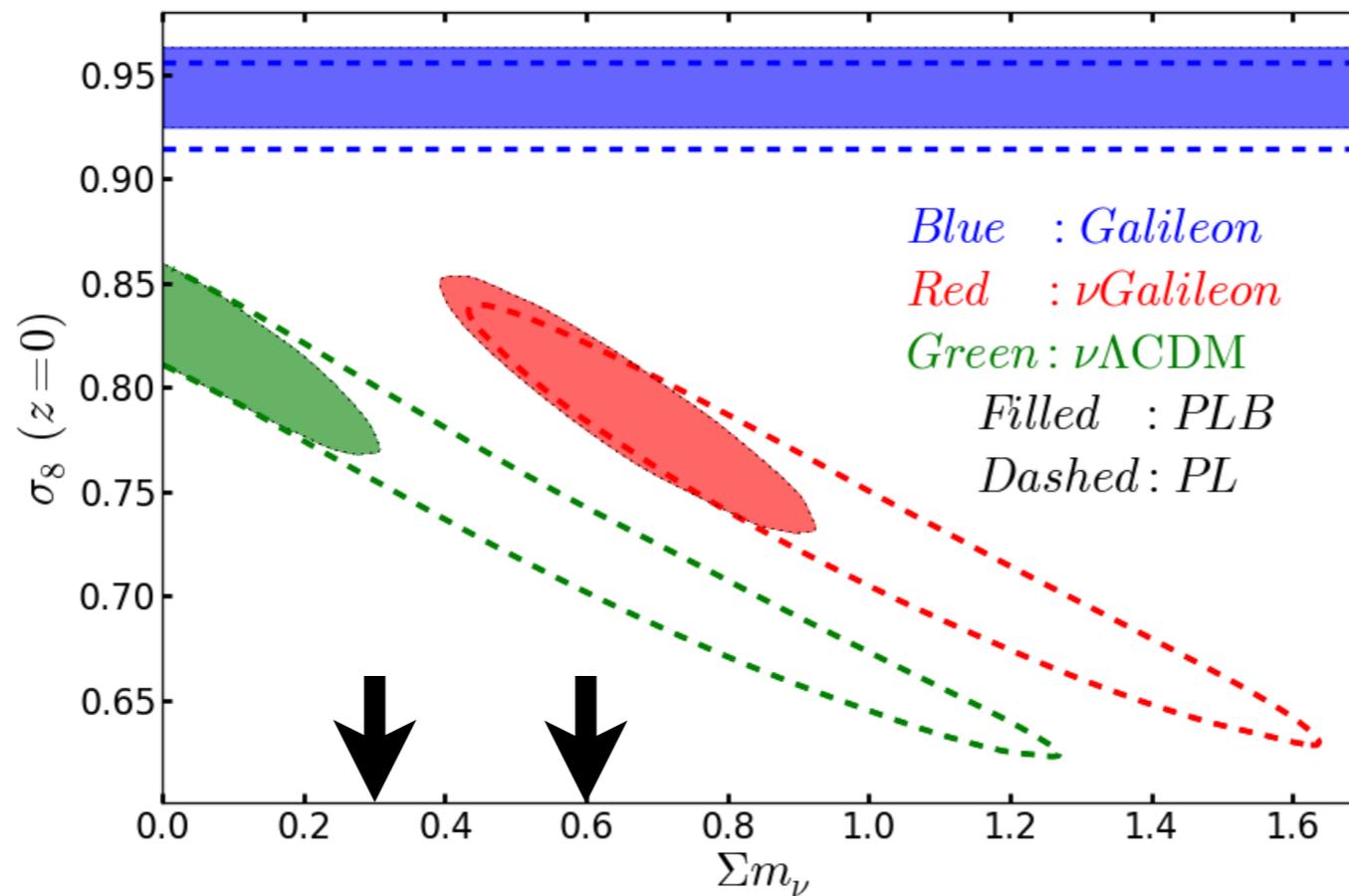


<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
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*Tritium beta decay*  
*e.g., KATRIN*

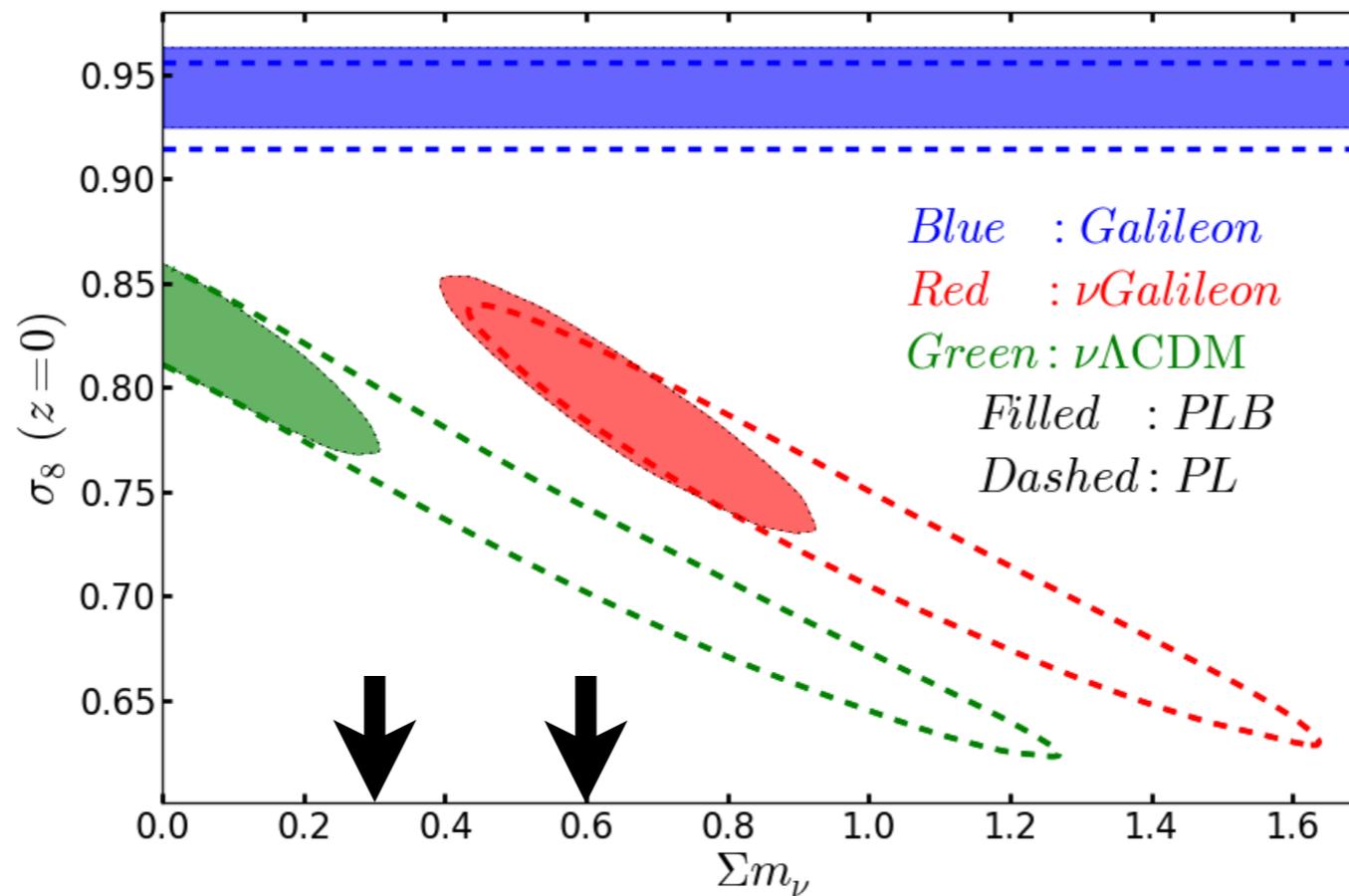
<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●	●	●	●	●
<i>Galileon</i>	●	●	●	●	●		



*neutrinoless double beta decay, e.g., GERDA*

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<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●	●	●	●	●
<i>Galileon</i>	●	●	●	●	●	●	



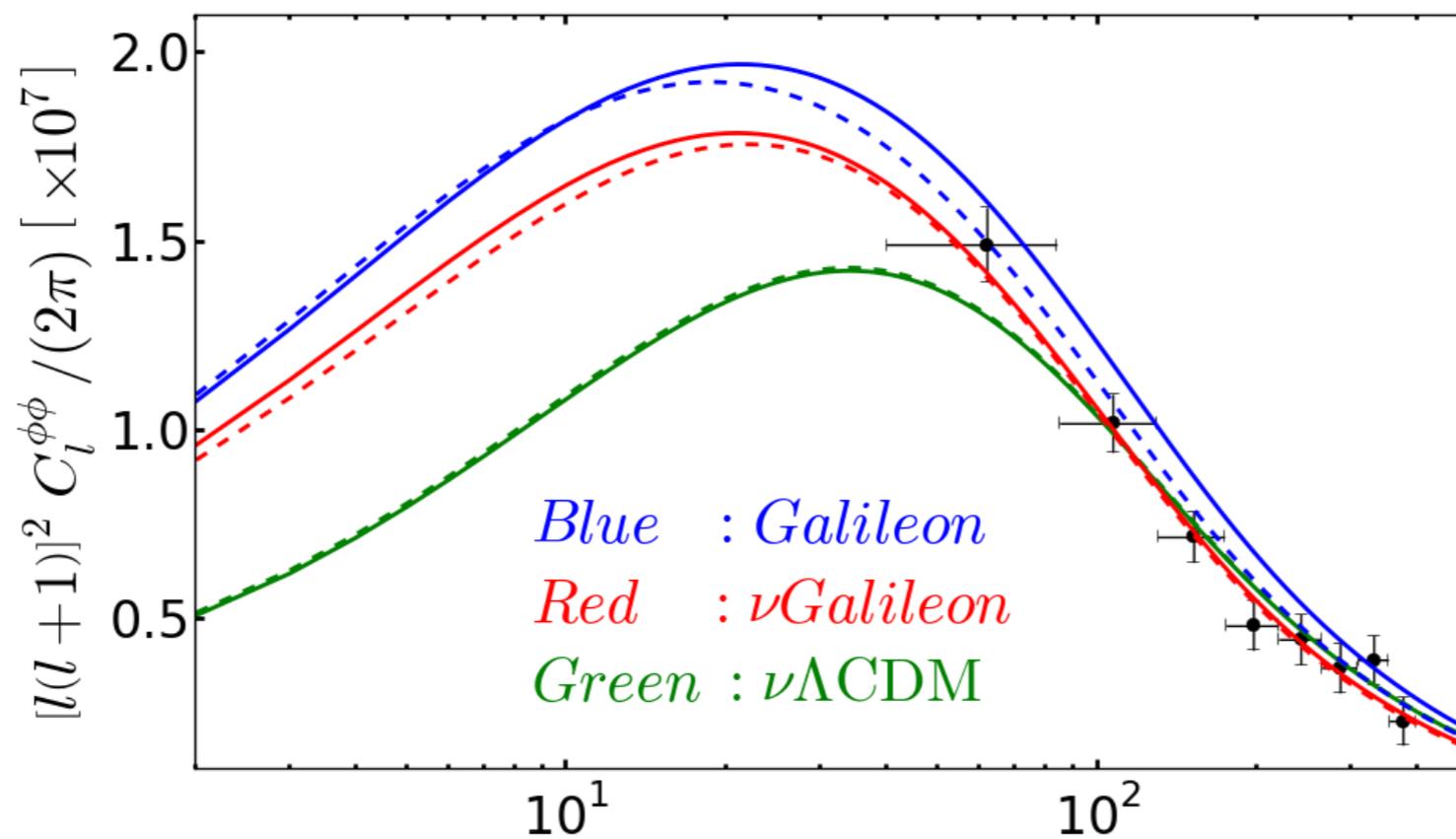
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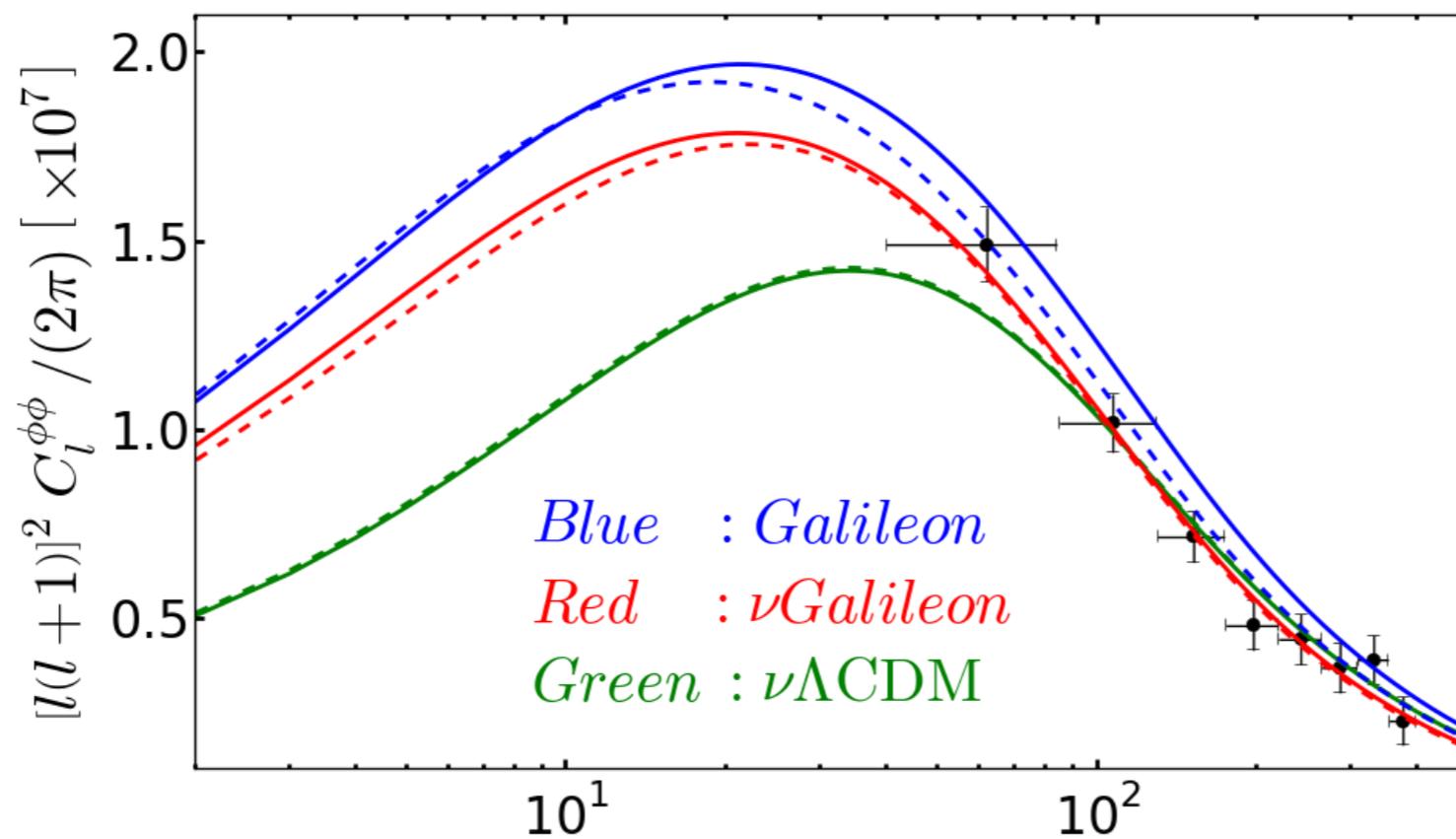
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<i>f(R) gravity</i>	●	●	●	●	●	●	●
<i>Galileon</i>	●	●	●	●	●	●	

*difference in background expansion history*

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●	●	●	●	●
<i>Galileon</i>	●	●	●	●	●	●	

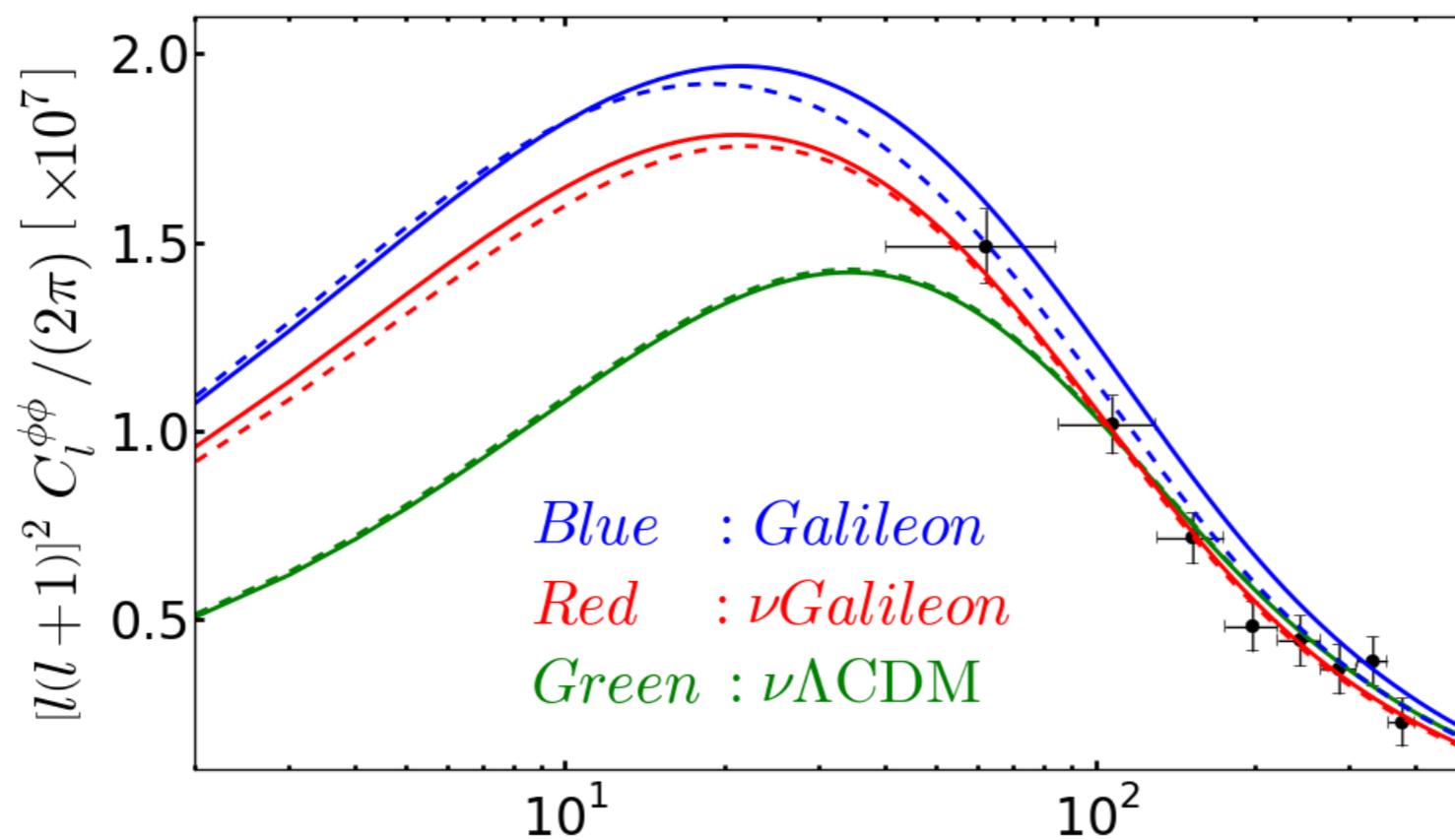


<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●	●	●	●	●
<i>Galileon</i>	●	●	●	●	●	●	



*data points:*  
*Planck CMB lensing*

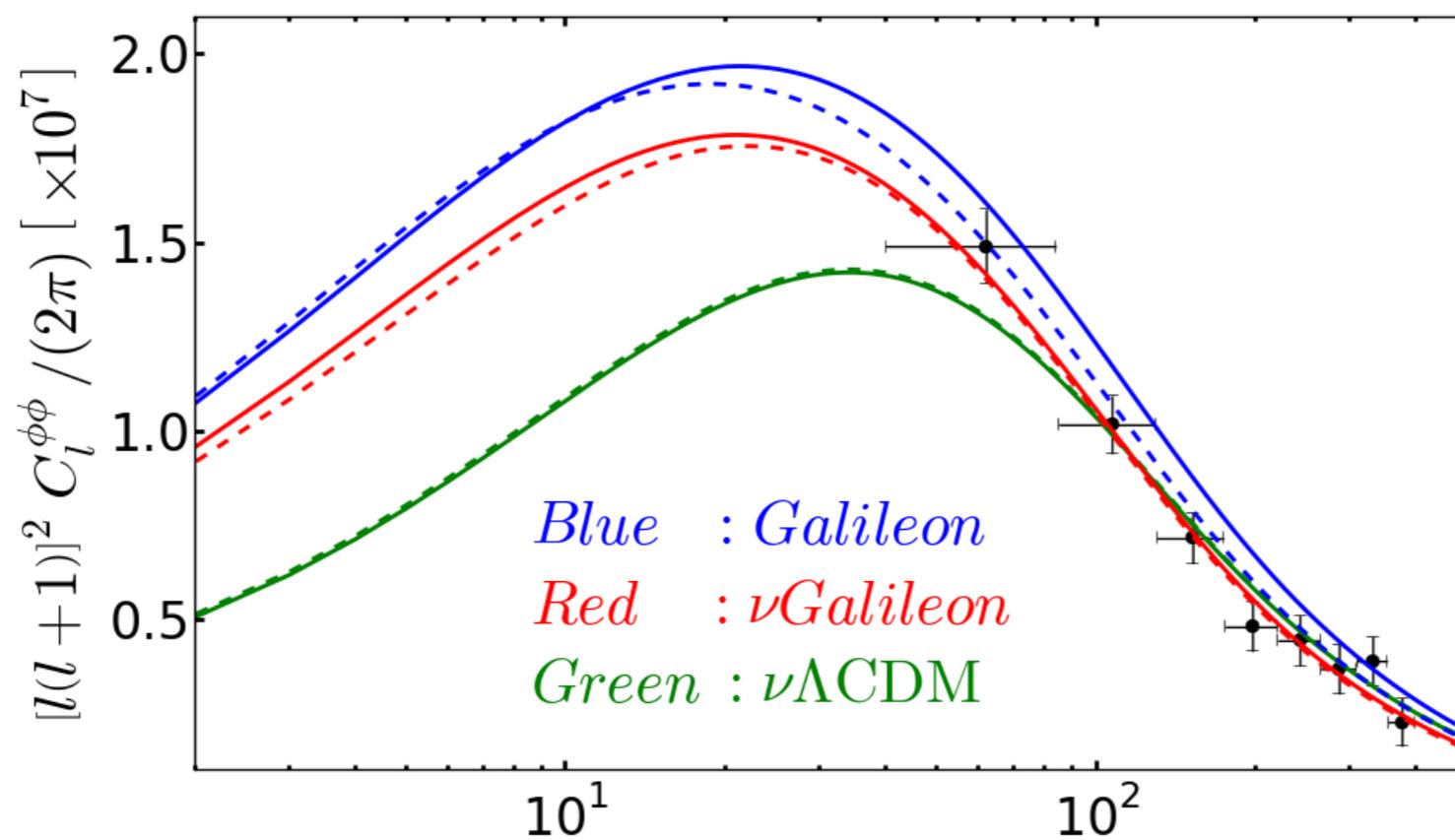
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<i>f(R) gravity</i>	●	●	●	●	●	●	●
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*substantial difference in CMB lensing potential at large angular scales*

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
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<i>Galileon</i>	●	●	●	●	●	●	●



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<i>f(R) gravity</i>	●	●	●	●	●	●	●
<i>Galileon</i>	●	●	●	●	●	●	●

*other possible tests: ISW-galaxy cross correlation*

<i>model</i>	<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>D1</i>	<i>D2</i>	<i>X1</i>	<i>X2</i>
<i>f(R) gravity</i>	●	●	●	●	●	●	●
<i>Galileon</i>	●	●	●	●	●	●	●

*other possible tests: ISW-galaxy cross correlation*

*complications:*

*(i) controversy in observational data*

*(ii) nonlinearity of screening kicks in on large scales*

# **SUMMARY**

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- ✘  *$f(R)$  gravity: a cosmological model that cannot be tested in cosmology*
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- ✘ *other possibilities: k-mouflage, kinetic gravity braiding, massive gravity, non-local gravity etc.*

# SUMMARY

- ✘ *modified gravity theories are proposed as alternatives to dark energy, but some are indeed dark energy plus modified gravity*
- ✘ *viable modified gravity theories need screening mechanisms and therefore generically strongly nonlinear*
- ✘ *care needs to be taken when using linear perturbation theory: growth rate, redshift space distortions, even the ISW effect*
- ✘ *numerical simulation codes have recently been developed to study such theories, e.g., ECOSMOG, MG-Gadget, ISIS*
- ✘  *$f(R)$  gravity: a cosmological model that cannot be tested in cosmology*
- ✘ *Galileon gravity: potential strong future constraints, but need full simulations to assess these constraints; also uniquely testable by neutrino experiments*
- ✘ *other possibilities: k-mouflage, kinetic gravity braiding, massive gravity, non-local gravity etc.*
- ✘ *no outstanding candidate yet*