LINKING TESTS OF GRAVITY ON ALL SCALES

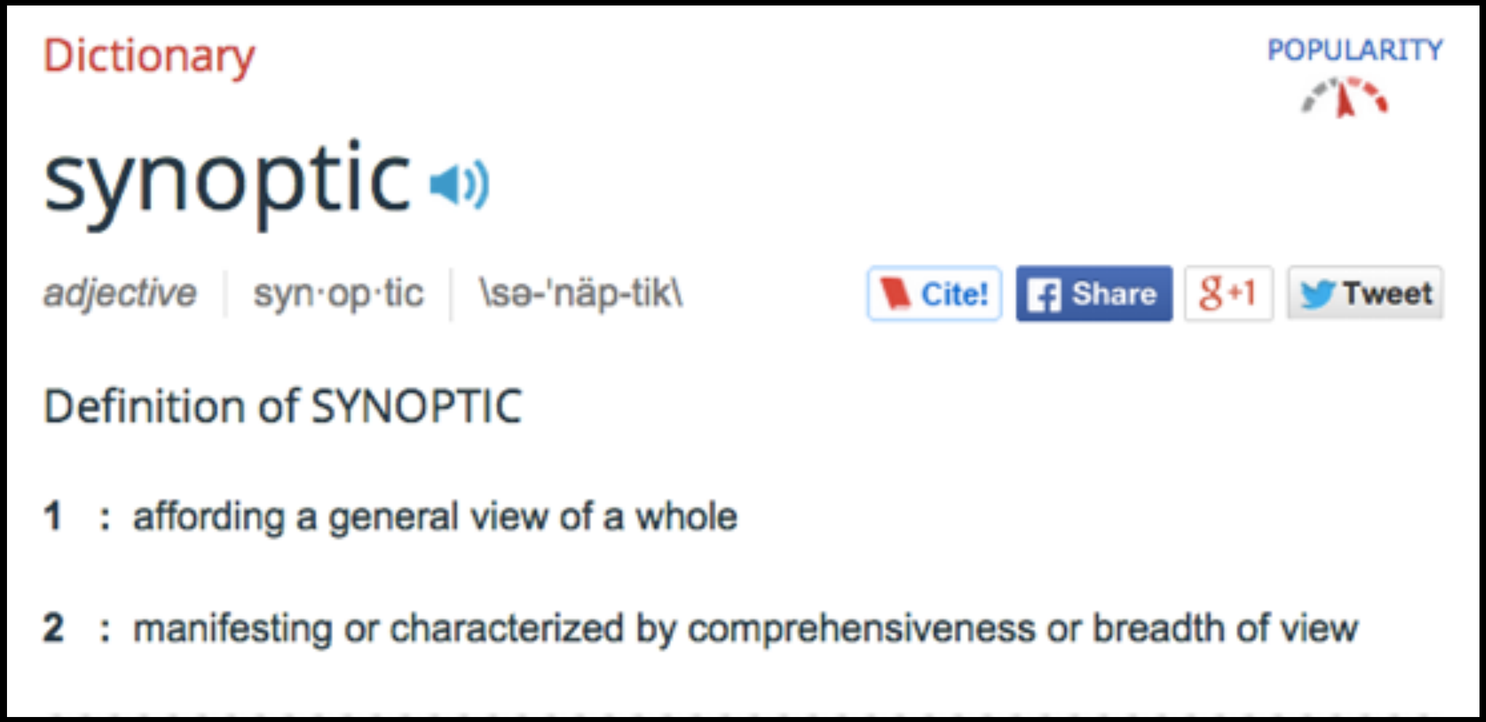
TESSA BAKER

IN COLLABORATION WITH C. SKORDIS & D. PSALTIS.

Oxford Physics

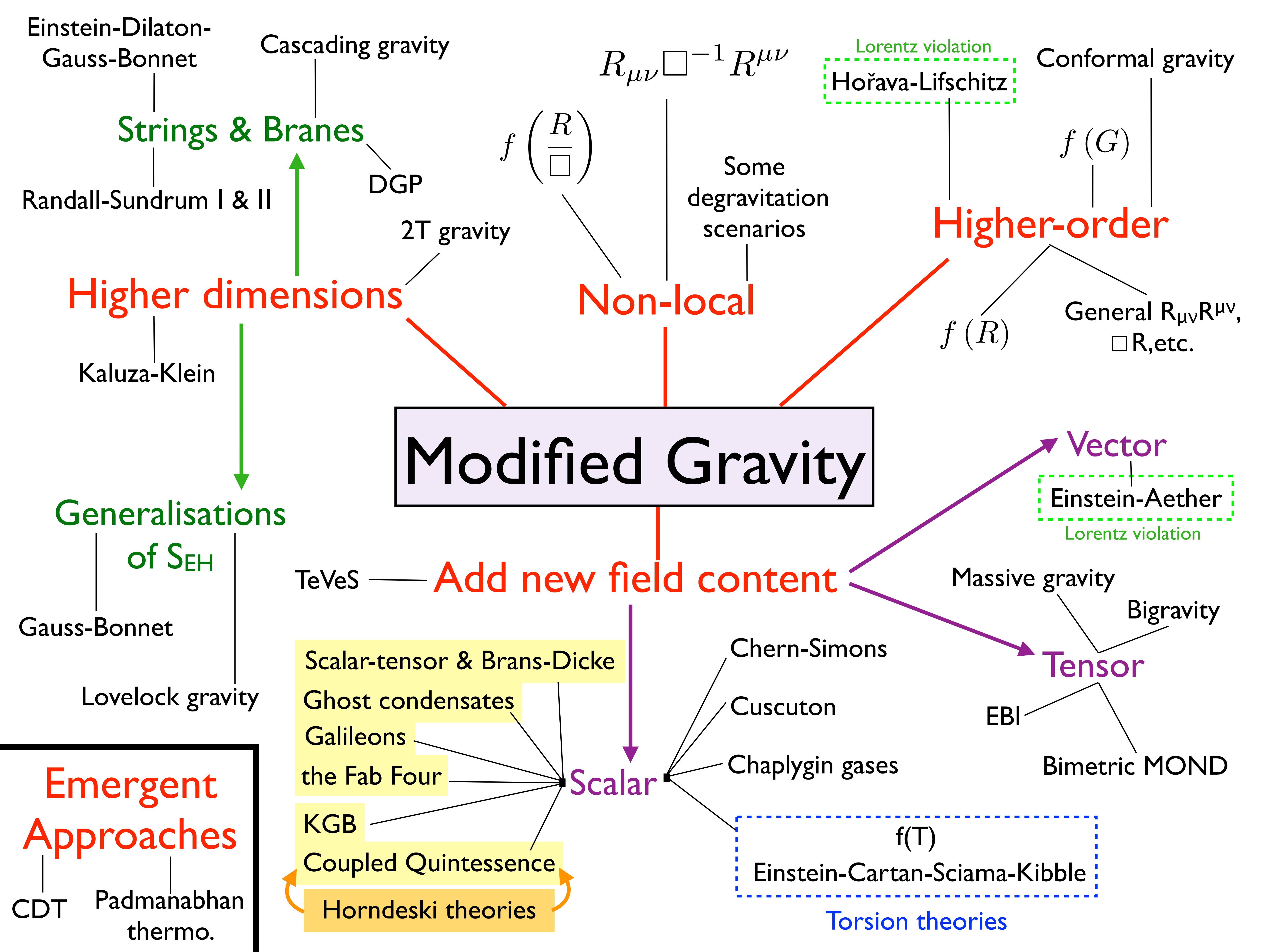
OUTLINE

Theme of this talk: a **synoptic** approach to testing gravity.

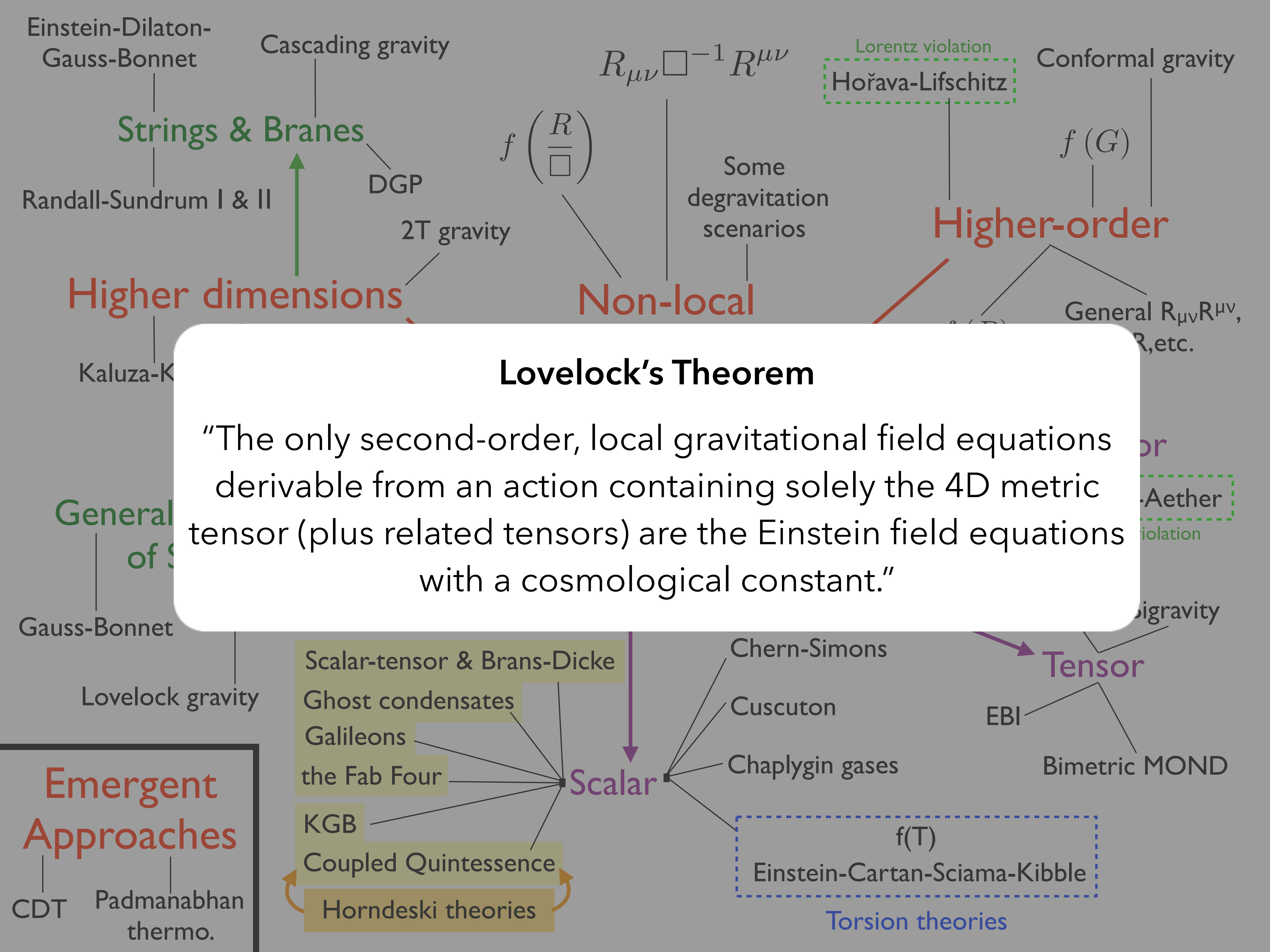


- Model-independent methods for cosmology — status quo.
- A parameter space for tests of gravity:

  How do laboratory, astrophysical and cosmological tests link up?

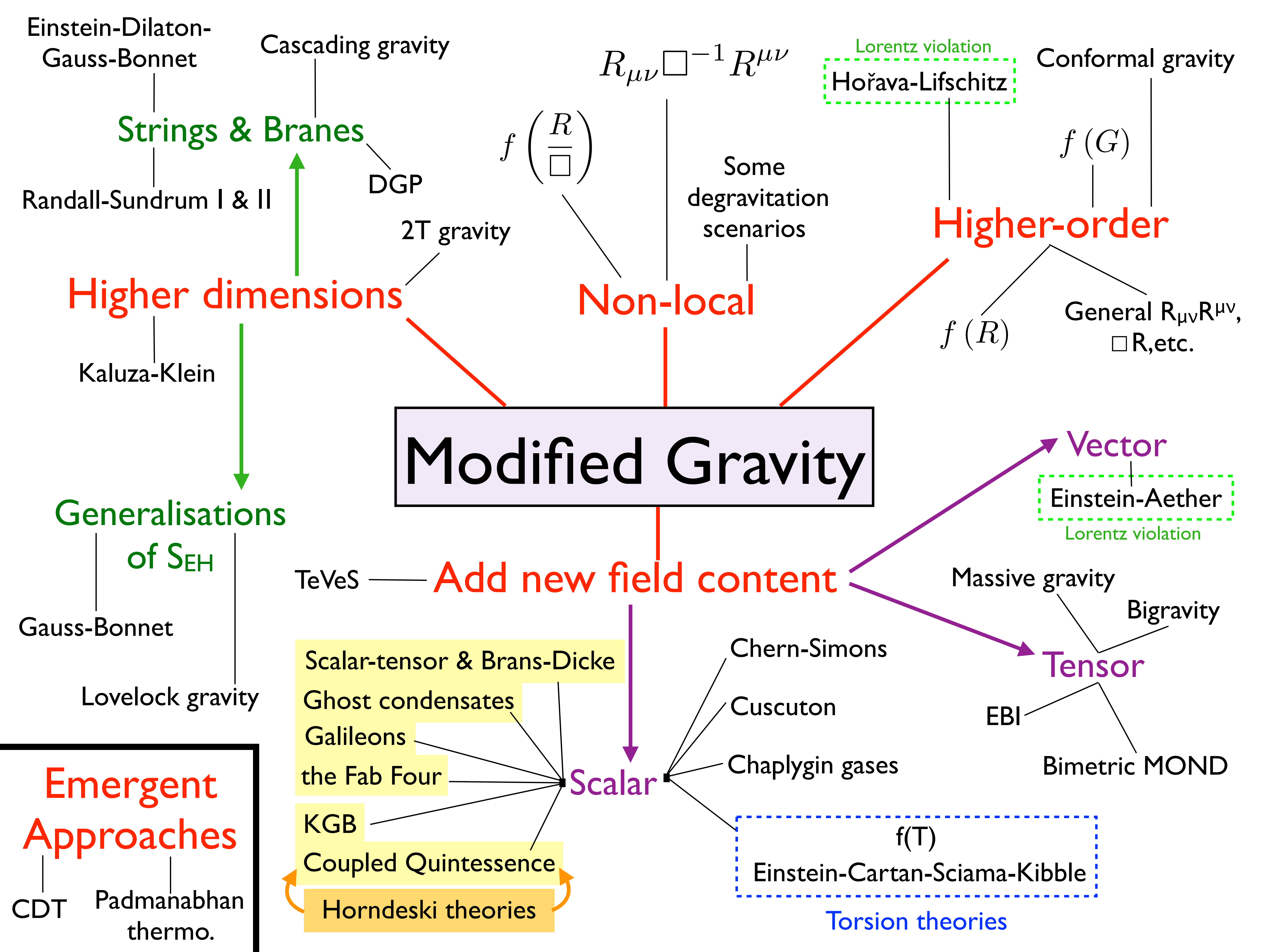


Einstein-Dilaton-Gauss-Bonnet
Cascading gravity
$R_{\mu\nu}\Box^{-1}R^{\mu\nu}$
Lorentz violation
Hořava-Lifschitz
Conformal gravity
Strings & Branes
DGP
$f\left(\frac{R}{\Box}\right)$
Some degravitation scenarios
$f\left(G\right)$
Randall-Sundrum I & II
2T gravity
Higher-order
Higher dimensions
Non-local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



Lovelock's Theorem

"The only second-order, local gravitational field equations derivable from an action containing solely the 4D metric tensor (plus related tensors) are the Einstein field equations with a cosmological constant."



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PARAMETERISED METHODS

- An attempt to step beyond this tangle of models.
- Build a general template for MG, with free `slots'.
- Phenomenological example:

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- Phenomenological example:

$$2\nabla^2\Psi = 8\pi G_N\, \mu\left(a,k\right)\rho_M a^2\Delta_M$$

``G effective”

$$\gamma\left(a,k\right) = \frac{\Phi}{\Psi}$$

``slip”

Constrain these coefficients
(functions of time **and scale**).

(eg. Leonard et al. 1501.03509, many others).

PARAMETERISED METHODS

- An attempt to step beyond this tangle of models.
- Build a general template for MG, with free `slots'.
- Formal example: the EFT of Dark Energy (Gleyzes et al. 1411.3712).

Background expansion.

$$S = \int d\eta d^3x\, N\sqrt{h}\, \Big[\frac{M_P^2}{2} f(\eta) R - \Lambda(\eta) - c(\eta) N$$

$$+ m_1^4 (\delta N)^2 + m_2^3\, \delta N\, \delta K + m_3^2 (\delta K)^2 + m_4^2\, \delta K^\mu_\nu \delta K^\nu_\mu$$

$$+ m_5^2\, {}^{(3)}R\, \delta N + m_6\, {}^{(3)}R\, \delta K + m_7 \left({}^{(3)}R\right)^2 + m_8\, {}^{(3)}R^\mu_\nu\, {}^{(3)}R^\nu_\mu \Big]$$

Perturbations.

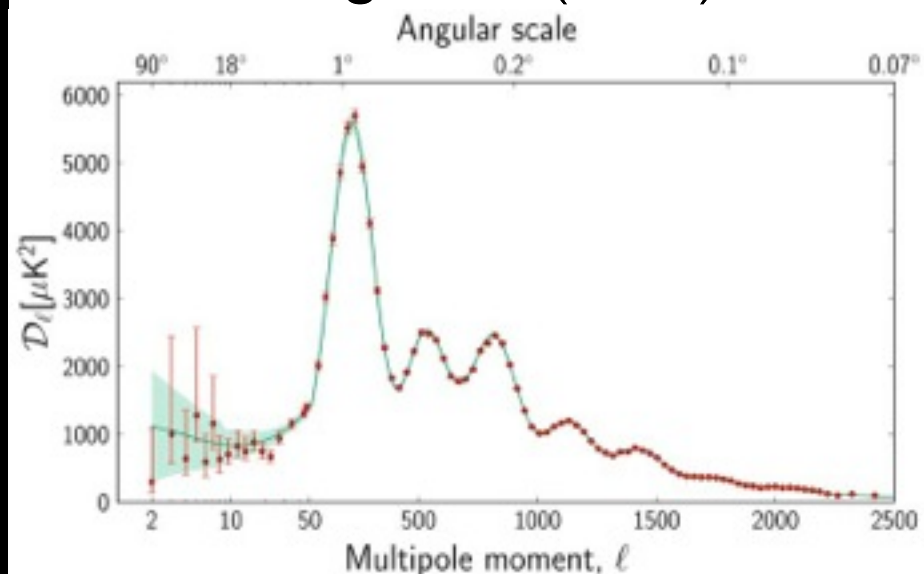
Constrain combinations of these coefficients (functions of time).

PARAMETERISED METHODS

We apply the familiar cosmological datasets:

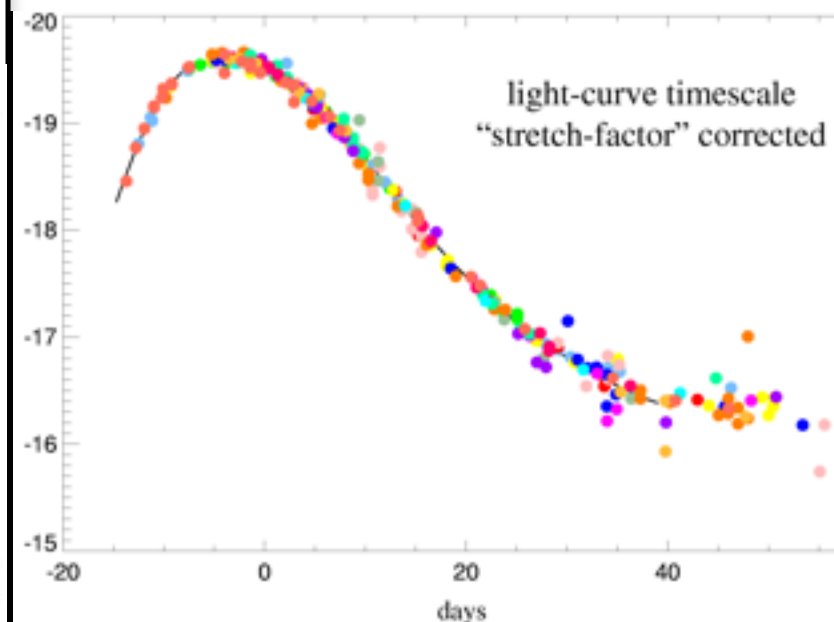
Credit: Planck collaboration.

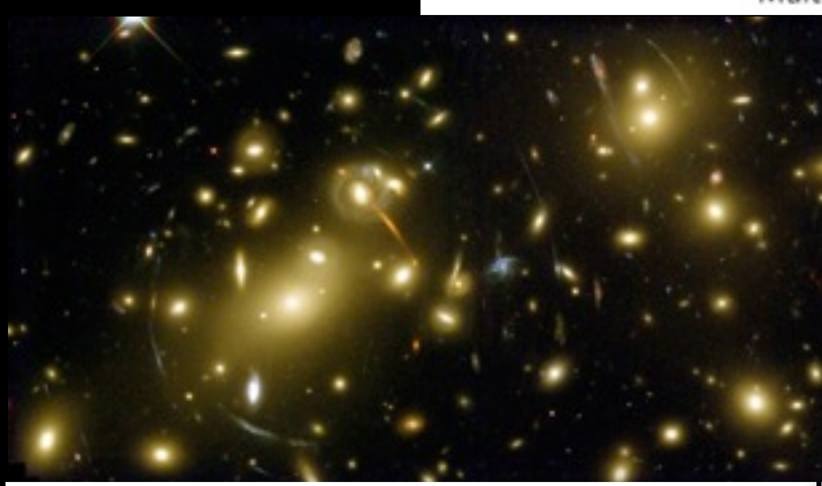
The Cosmic Microwave Background (CMB)



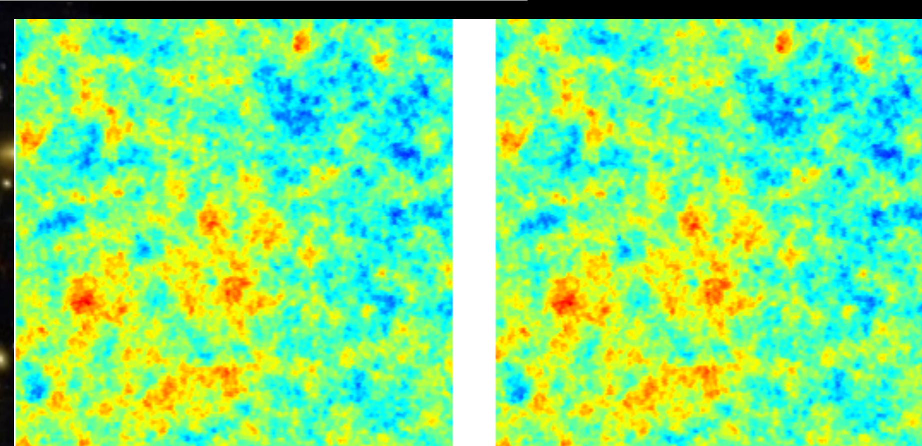
Credit: Kim et al. 1997.

Supernovae 1a





Galaxy weak lensing



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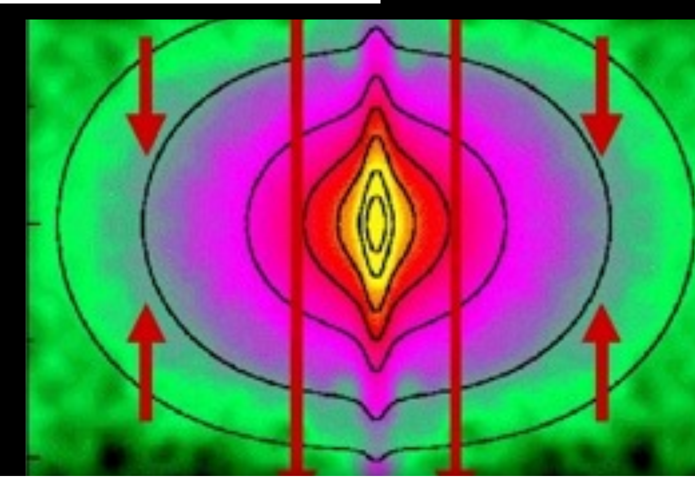
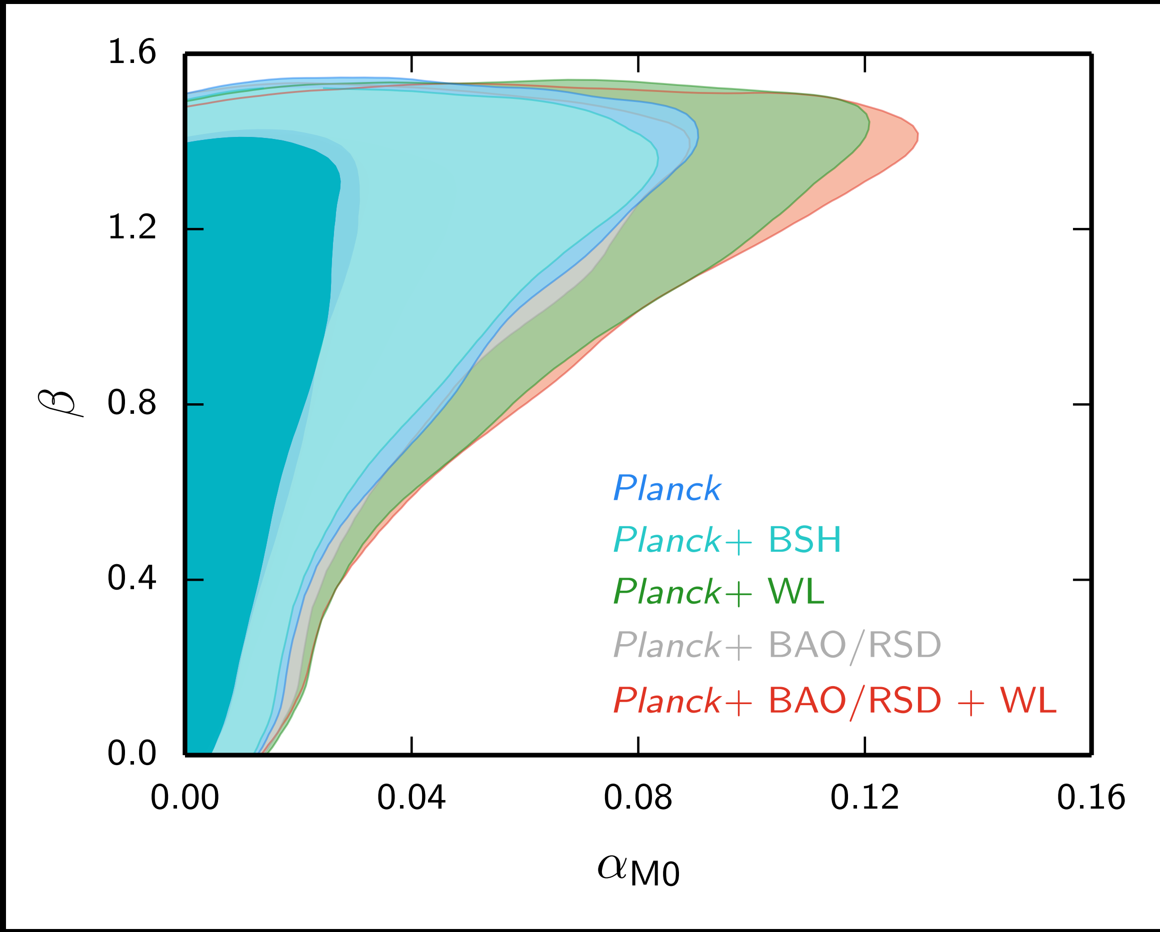


Redshift-space distortions

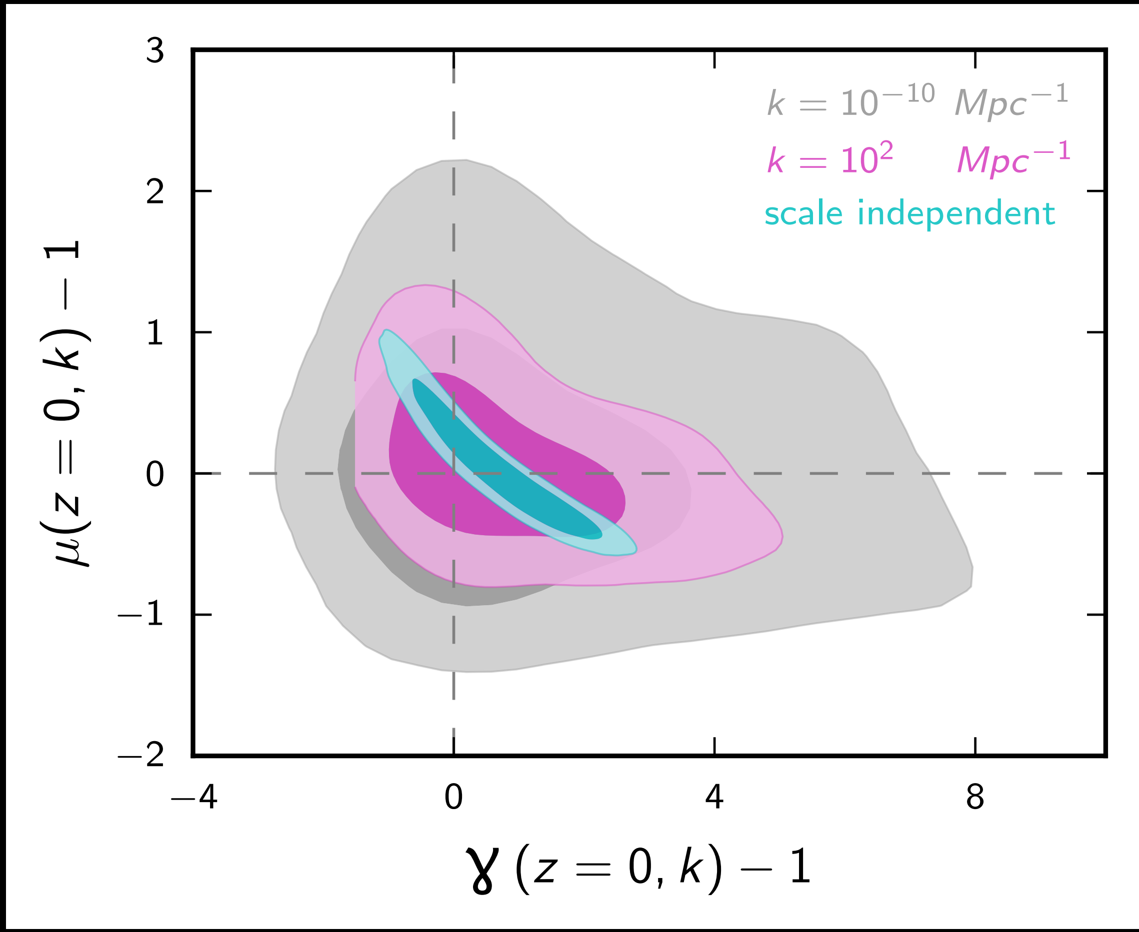
PARAMETERISED METHODS

- An attempt to step beyond this tangle of models.
- Build a general template for MG, with free `slots'.
- Two options: formal or phenomenological.

`Formal'



`Phenomenological'



Planck 2015 results, paper IX.

⇒ The data are not powerfully constraining yet .

THE OBSERVATIONAL TOOLBOX

But this isn't the full story…

Credit: Planck collaboration.

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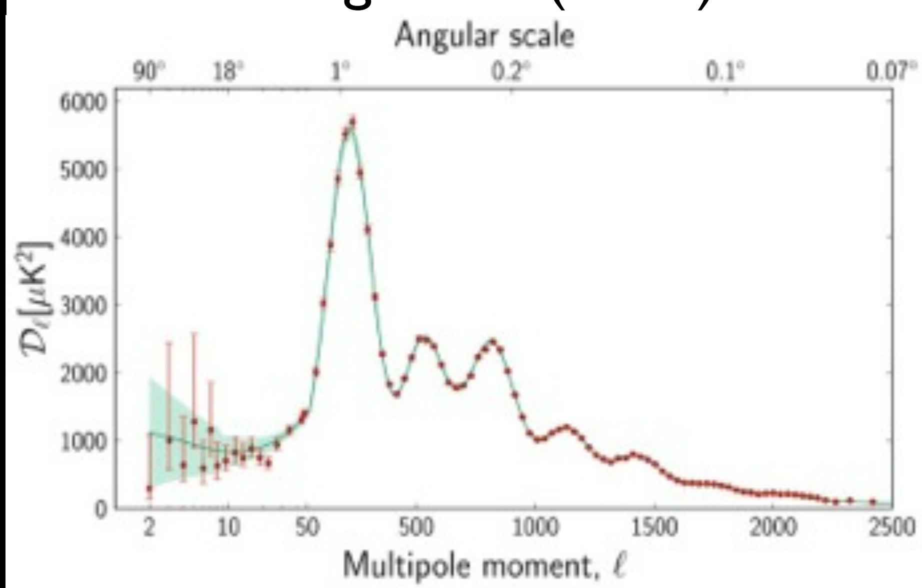

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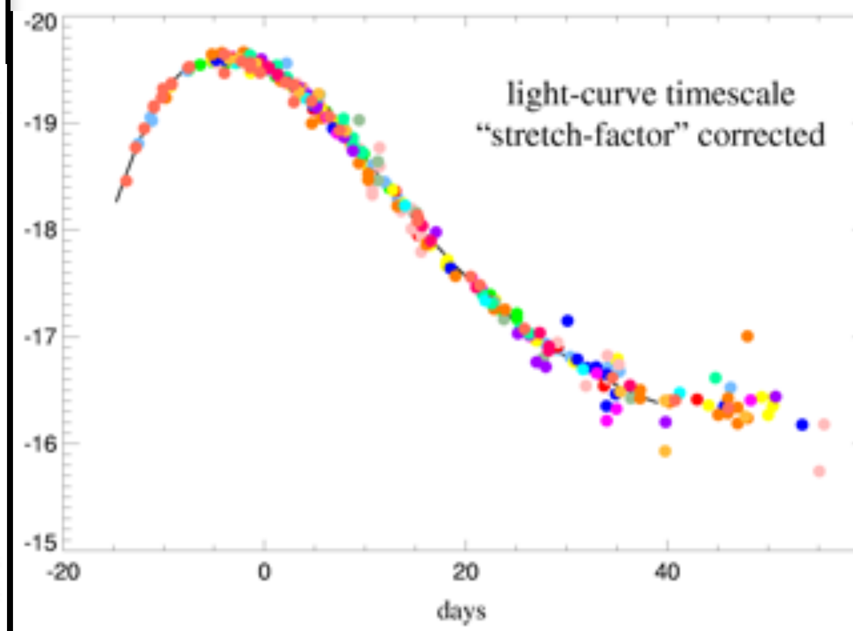

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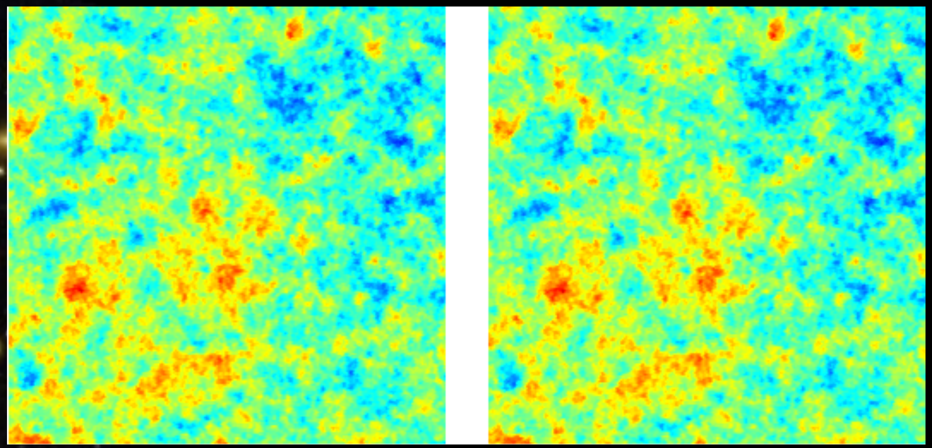

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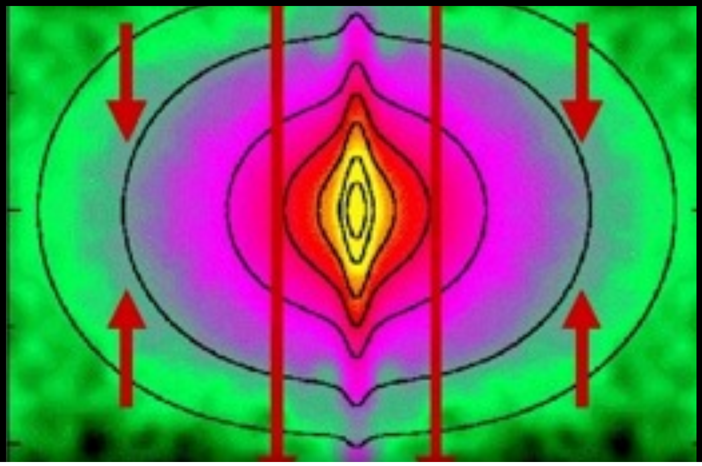

Redshift-space distortions

THE OBSERVATIONAL TOOLBOX

But this isn't the full story…

Cosmological | Astrophysical | Laboratory

What controls whether two tests probe the same `regime' of gravity?

The size of the system?

The gravitational potential?

Spacetime curvature?

The energy scale?

The environmental density?

A PARAMETER SPACE FOR GRAVITY

First, we need a simple way to quantify the gravitational field strengths.

How to describe a gravitational field?

$g_{\alpha\beta}$?　　$R_{\alpha\beta}$?　　R ?　　$R_{\alpha\beta\gamma\delta}$?

Vanishes in vacuum and radiation domination — not helpful.

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How to describe a gravitational field?

$g_{\alpha\beta}$?

$R_{\alpha\beta\gamma\delta}$?

$\delta g_{\alpha\beta} \sim \mathbf{\Phi} \sim v^2/c^2$ ⇒ How Newtonian are you?

$\sqrt{R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}} \sim R \sim G(\rho\text{-}3P)$ ⇒ How curved is your spacetime?

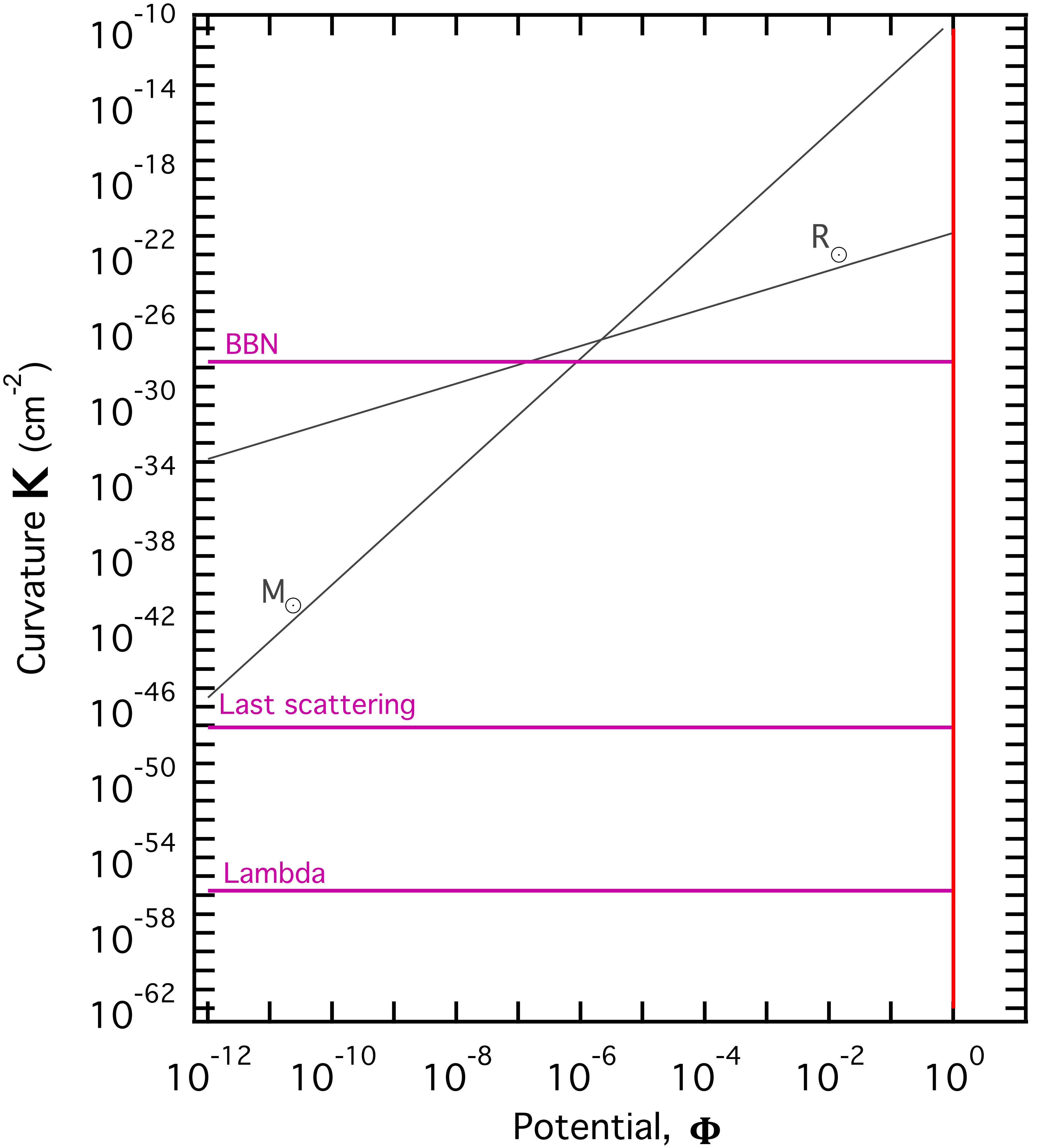
K=Kretschmann scalar.

Unlike $\mathbf{\Phi}$, it is dimensionful. We will use units of cm^{-2}.

For the Schwarzchild metric:

$$\Phi = \frac{GM}{rc^2}$$

$$K = \sqrt{48}\,\frac{GM}{r^3c^2}$$



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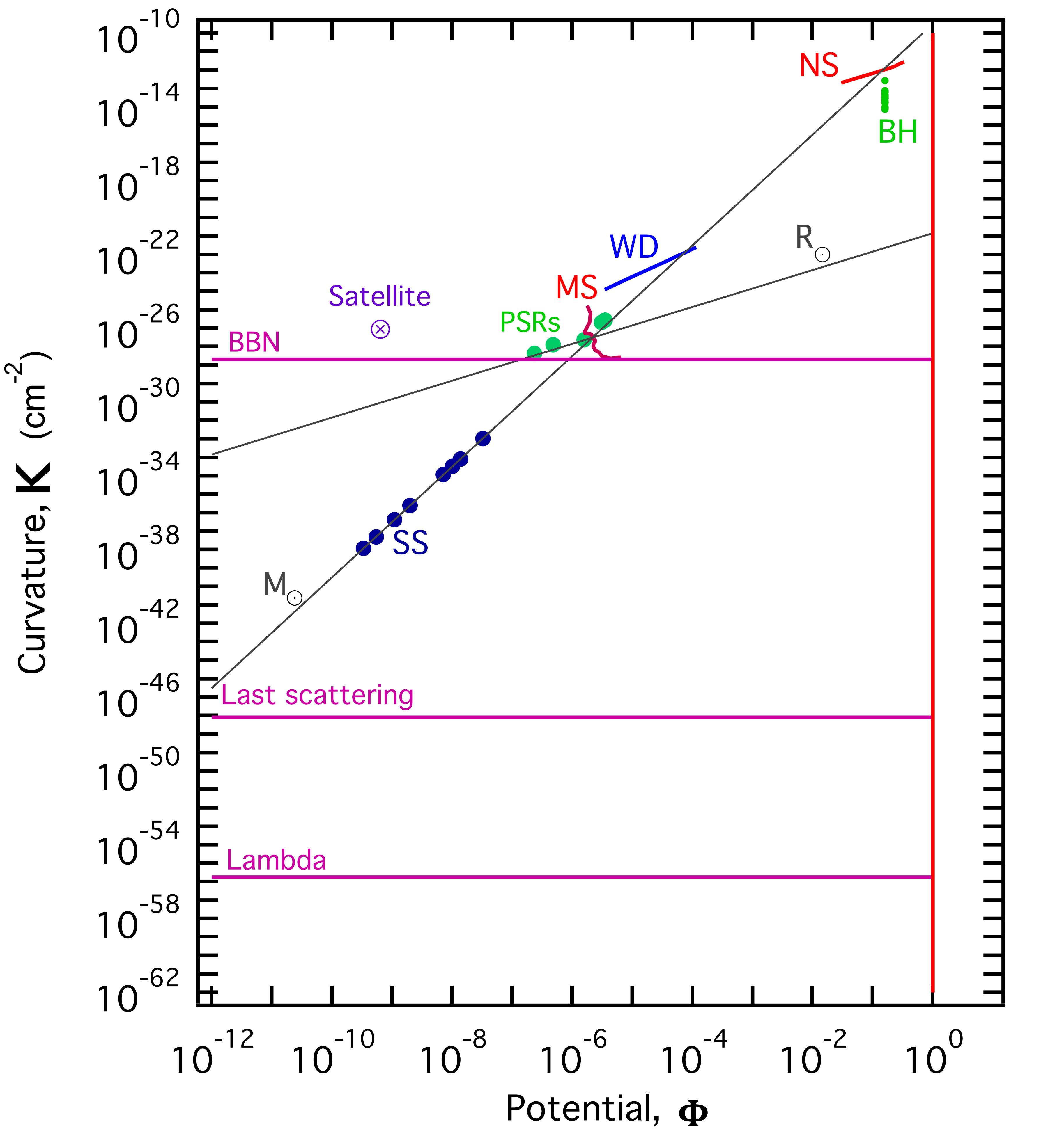

For the Schwarzchild metric:

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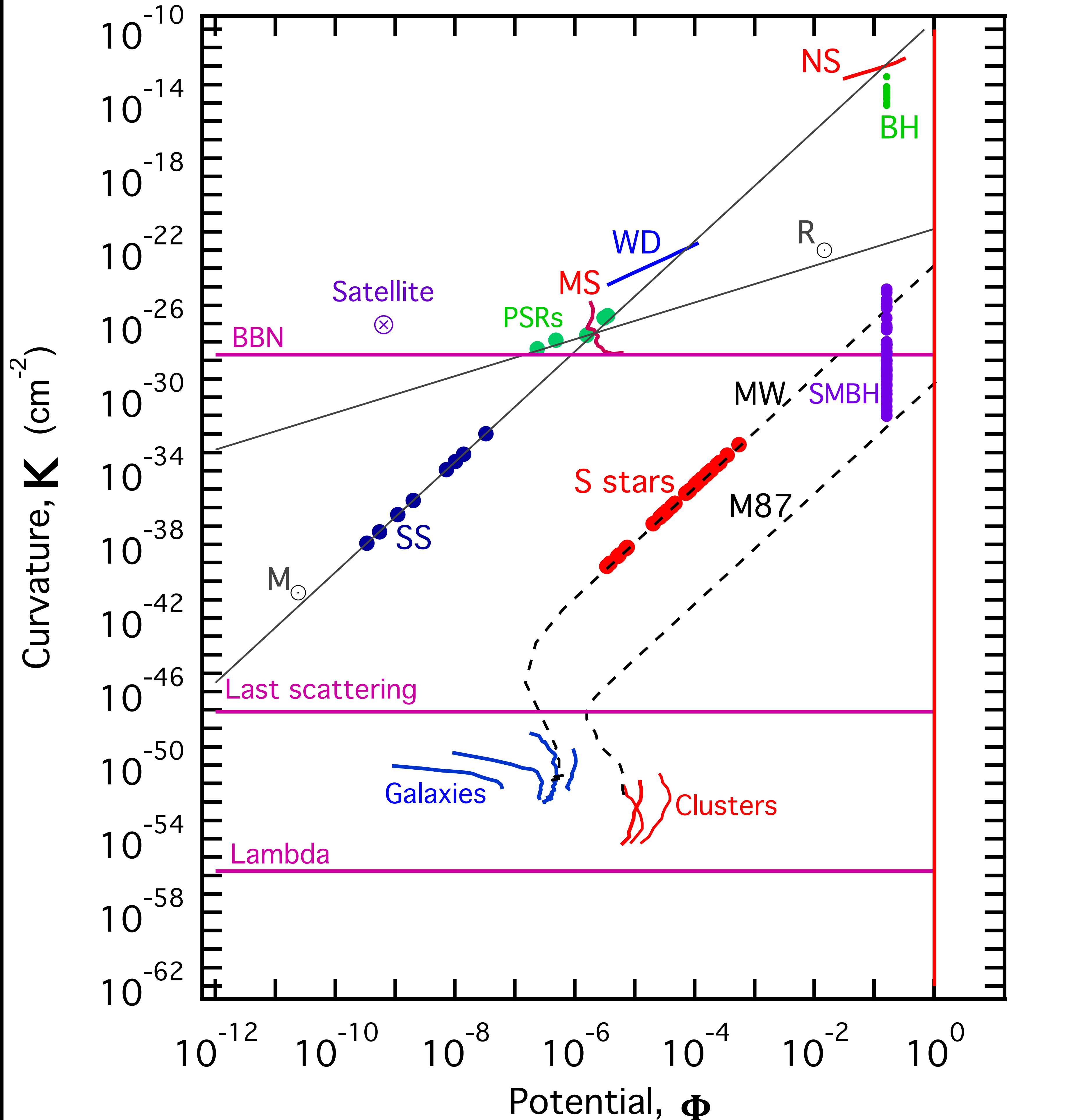
For the FRW metric:

$$K = \frac{\sqrt{12}}{a^2}\left(\dot{\mathcal{H}}^2 + \mathcal{H}^4\right)^{\frac{1}{2}}$$

(in conformal time)



Potential:

$$2\nabla^2\Phi = 3\mathcal{H}^2\Omega_M\Delta_M$$

$$\Delta_M = \delta_M + 3\frac{\mathcal{H}}{k}v_M$$

Kretschmann:

$$\delta K(k,a) = K_{\rm linear}(k,a) - K_0(a)$$

← zeroth-order piece

↓ plug in perturbed FRW metric + LCDM growth approximations

$$\delta K(k,a) = \Phi(k,a)\left[A(a) + k^2 B(a)\right]$$

uninteresting functions of time

Potential:

$$\langle|\Phi(\vec{k},a)|^2\rangle = \left(\frac{3}{2}\frac{H_0^2\Omega_{M0}}{a}\right)^2 \frac{(2\pi)^3}{|k|^4} P_M(k,a)$$

from $\langle\Delta_M(k,a)\Delta_M(k',a)\rangle$

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$$\sqrt{\langle|\delta K(k,a)|^2\rangle} = \frac{3}{2}\frac{H_0^2\Omega_{0M}}{a}\left|A(a)+k^2B(a)\right|\sqrt{\frac{P_M(k,a)}{2\pi^2 k}}$$

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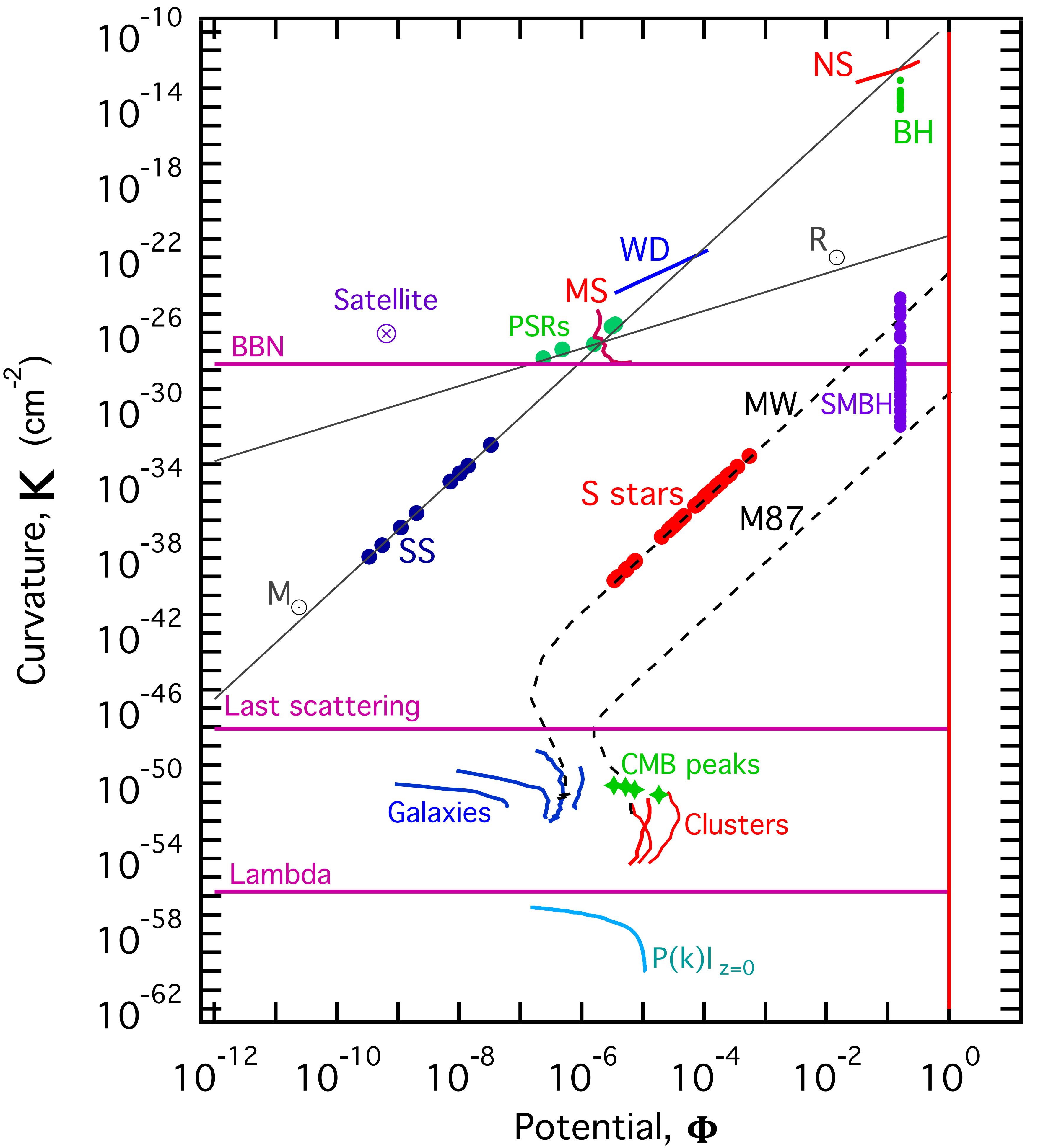


Features:

- Coincident tests.

- Phenomenological acceleration scale:

a* ~ c H

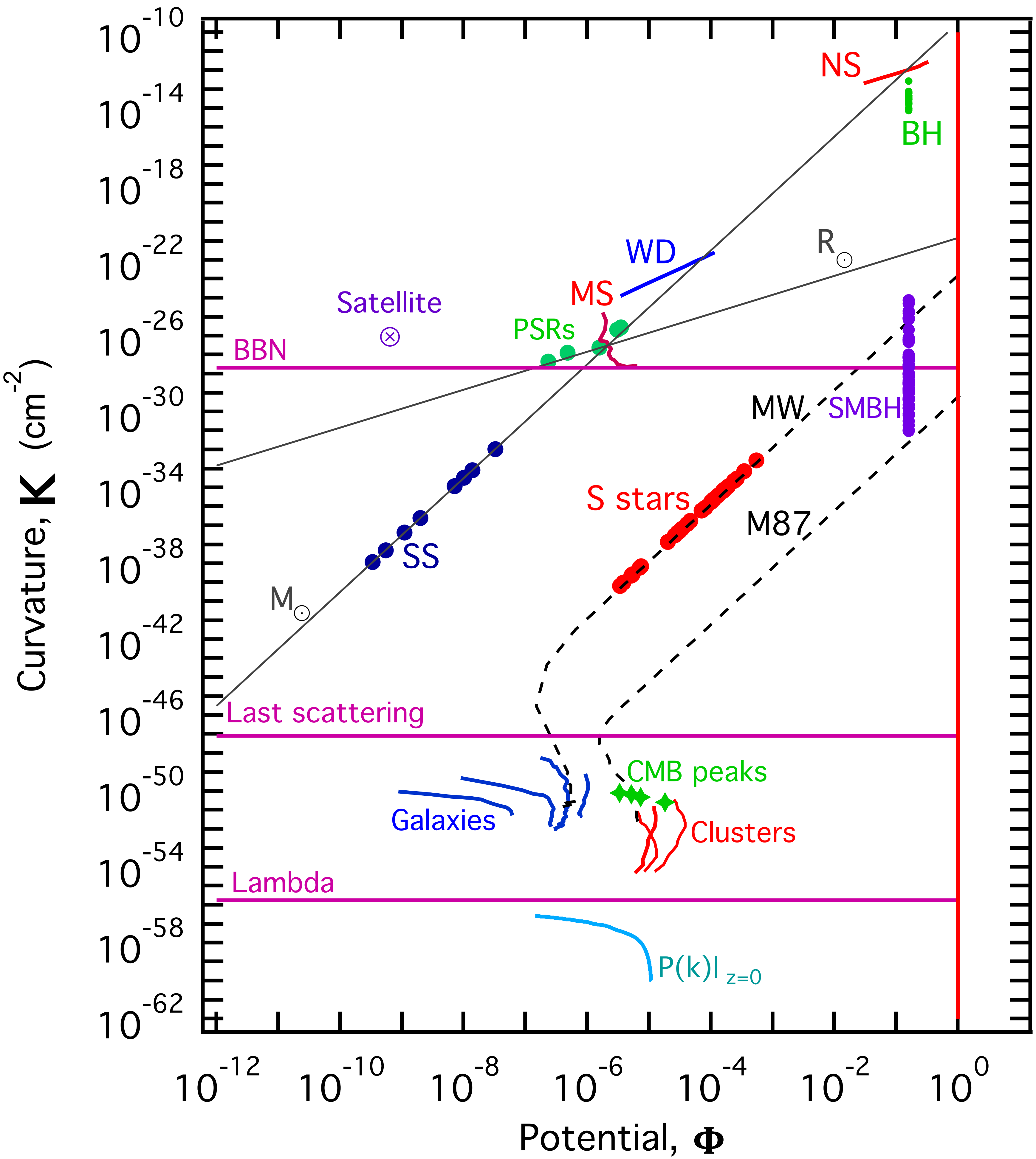
Eg. Schwarzschild case:

$$y = \frac{M}{r^3}, \quad x = \frac{M}{r}$$

$$\text{acceleration, } a \sim \frac{M}{r^2}$$

$$\Rightarrow y \simeq \frac{a^2}{x}$$

⇒ Straight line with negative gradient.



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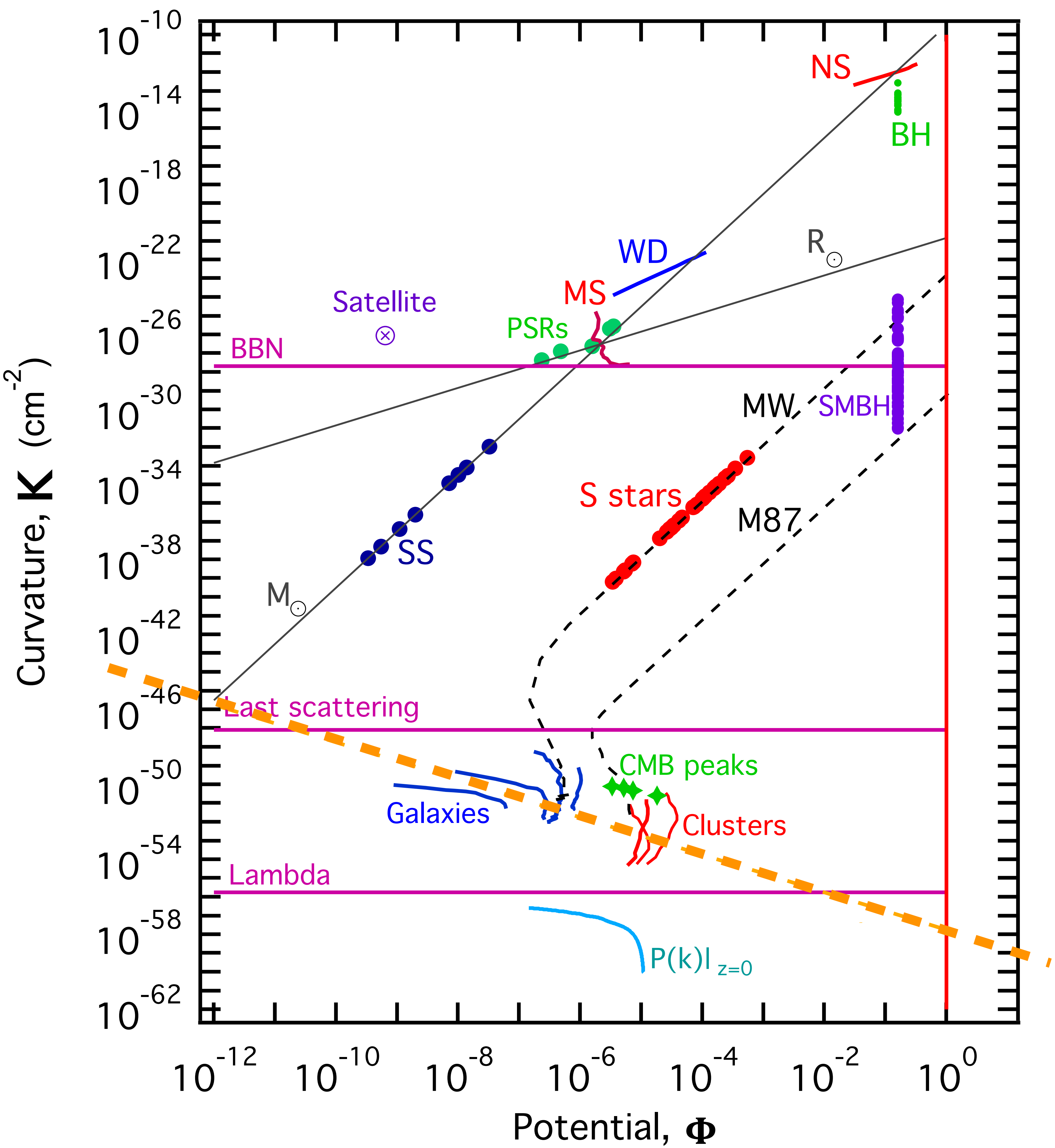
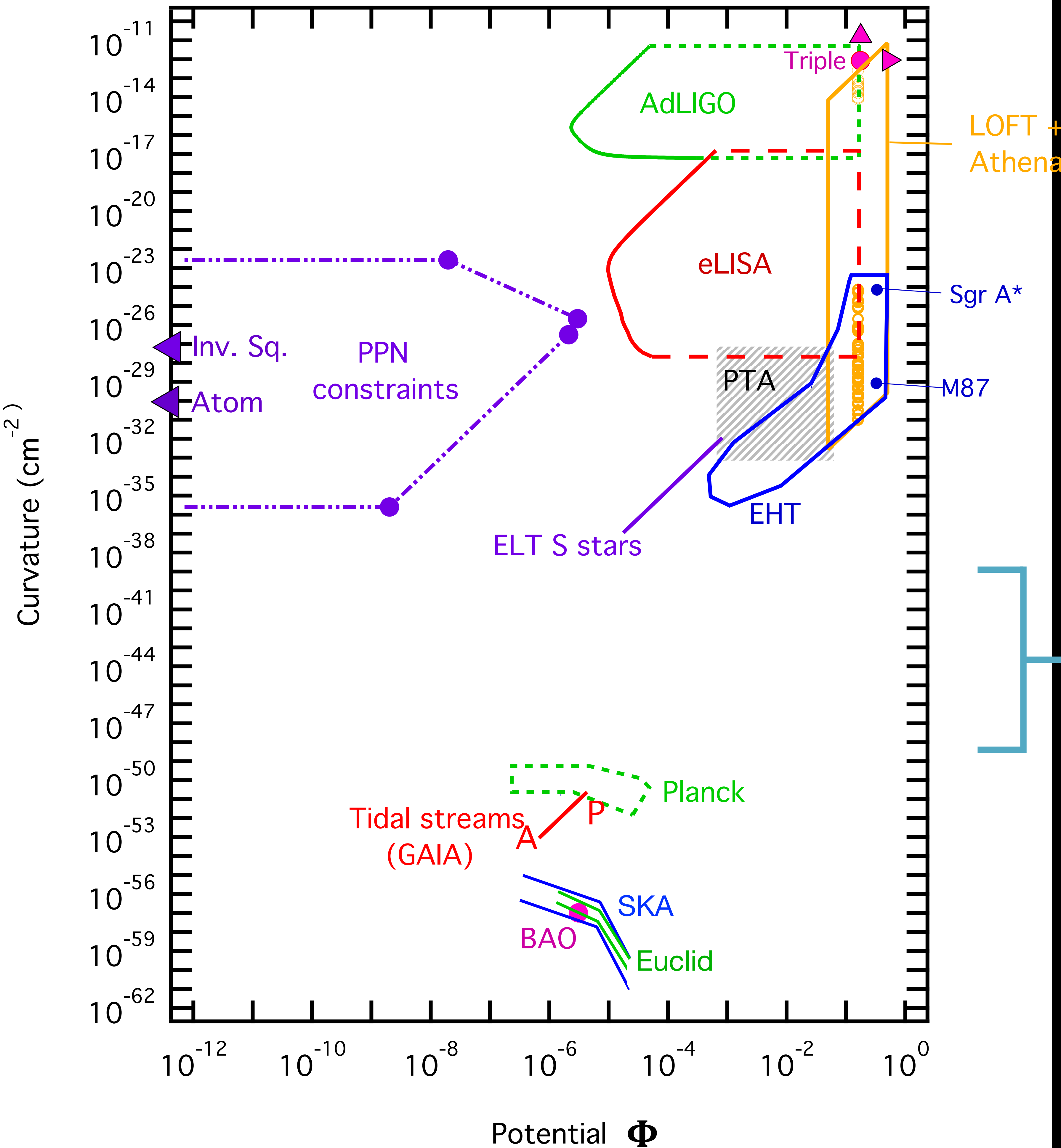
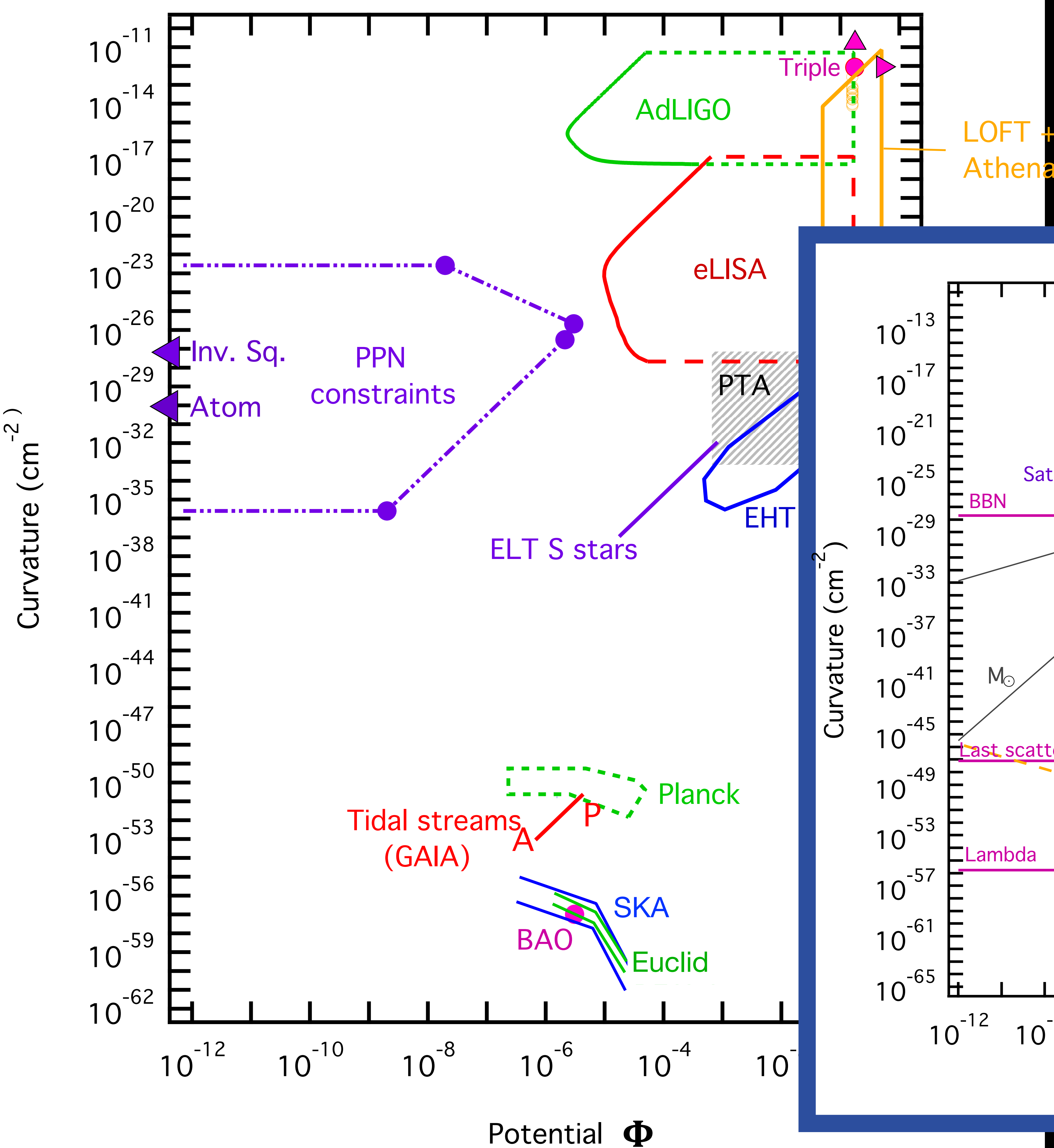


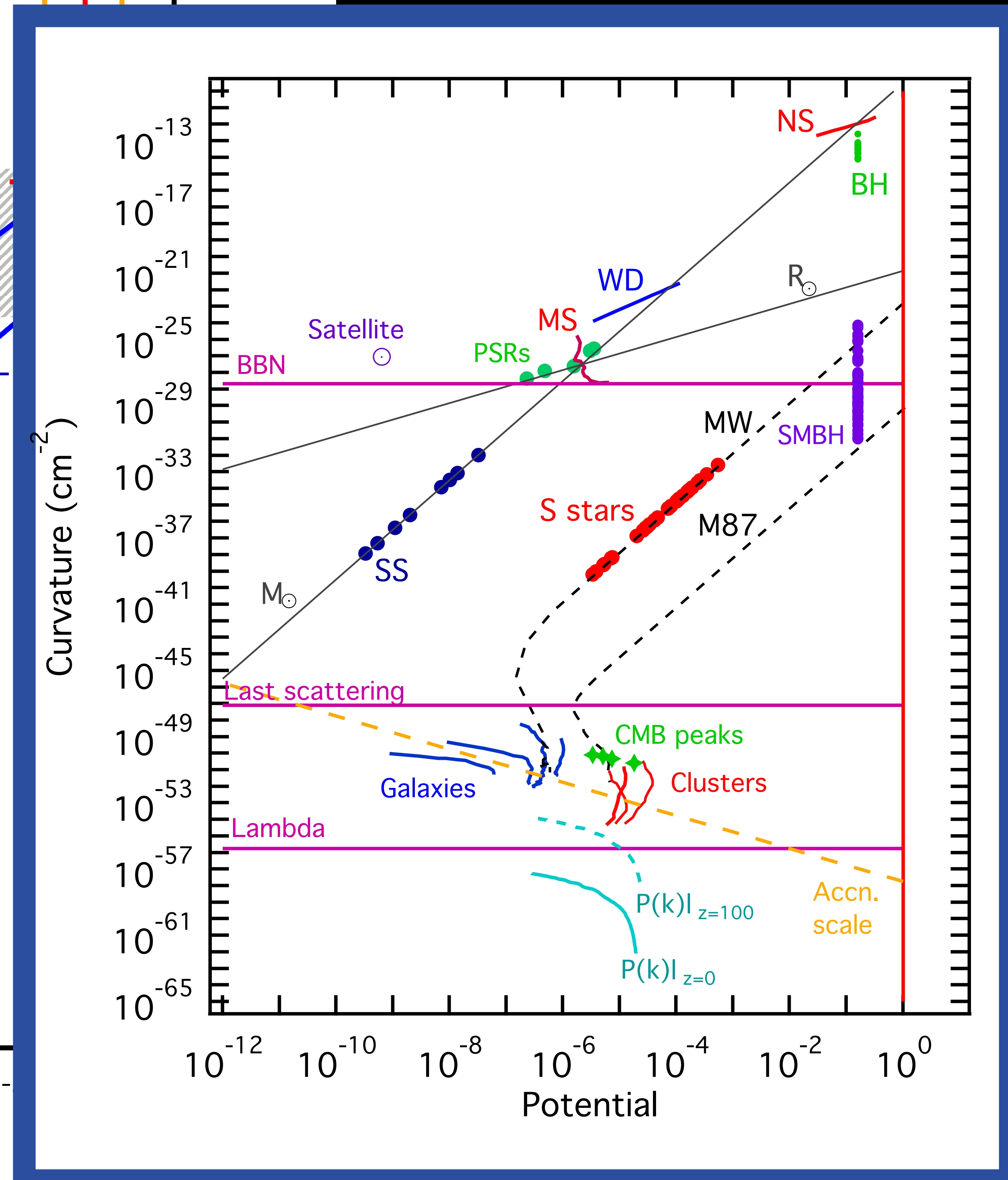


The experiments version.

Desert?

The experiments version.





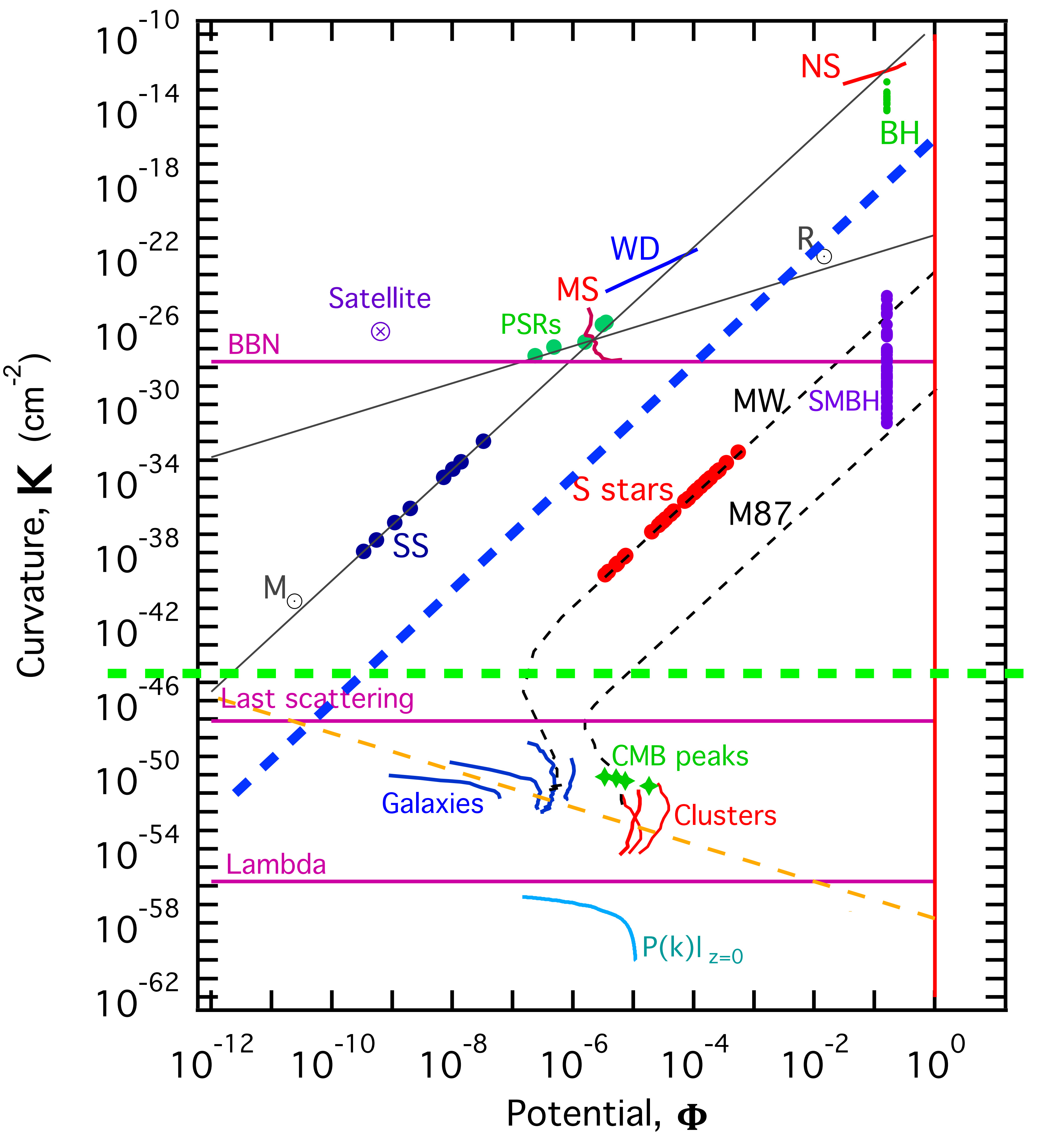
Features:

Choose powers P, Q in:

$$M^P R^Q$$

to build a physical scale (eg. density, acceleration, mass, curvature…).

⇒ lines with different gradients on the diagram.



DISCLAIMER

- Other choices of axes are possible.
- For example:

Observational cosmology	→	Redshift
Strong-field regime	→	Velocity
Screening mechanisms	→	Density

- Maybe one for the discussion session — what would you plot?

CONCLUSIONS

- Two principles of this `synoptic' thinking:
  - Test gravity in a model-independent manner.
  - Use information from **all** scales.
- I’ve presented **one** scheme for quantitatively linking very different gravitational regimes.
- Plenty of data is forthcoming in the strong-field and ultra weak-field regimes. But can we probe the curvature desert?

More details: arXiv 1501.03509.

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A WORD ABOUT SCREENING

MECHANISM	ENVIRONMENTAL CRITERION	'TRIGGER'
Chameleon, dilaton symmetron.	$\Phi > \tilde{\Lambda}$	potential
k-essence, TeVeS-like.	$\|a\| = \|\nabla\Phi\| > \tilde{\Lambda}^2$	acceleration
Vainshstein.	$R \simeq \|\nabla^2\Phi\| > \tilde{\Lambda}^3$	curvature

But most theories do **not** have a known screening mechanism.

→ keep an open mind.

→ are other trigger quantities possible?