Cosmological Tests of Gravity and links to local tests

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eLiza meeting, Geneva, 16 Apr 2015

Understanding tests of gravity

(T. Baker, D. Psaltis and C.S., Astrophys.J. 802, 63 (2015).

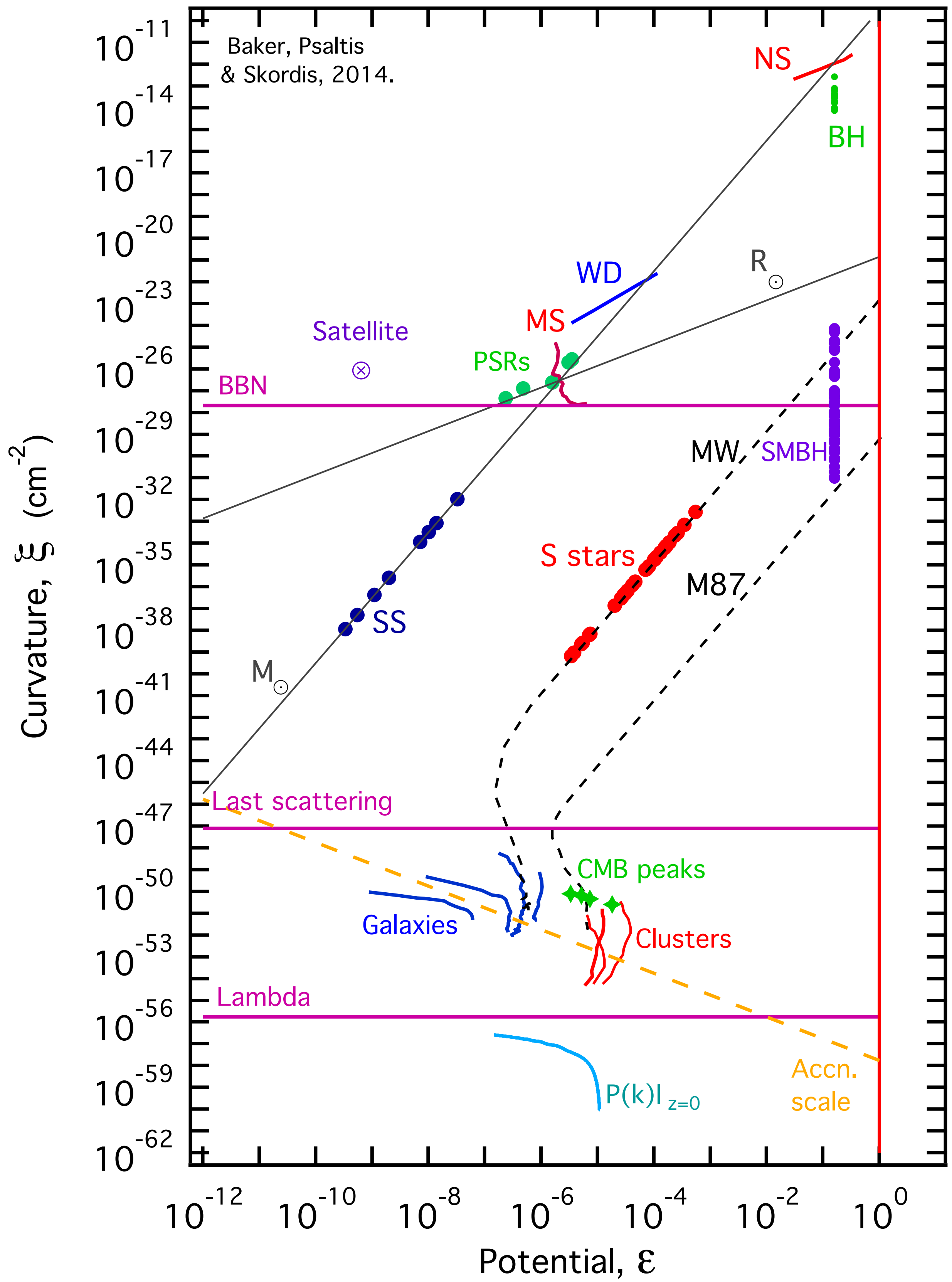
Quantifying gravitational fields:

$g_{\mu\nu} \approx \bar{g}_{\mu\nu} + h_{\mu\nu}$ → "field proxy" $\epsilon = \dfrac{\Phi}{c^2} \sim \dfrac{GM}{c^2 r}$

${R^{\alpha}}_{\beta\mu\nu}$ → "curvature proxy" $\xi = \sqrt{R^{\mu\nu\alpha\beta} R_{\mu\nu\alpha\beta}} \sim \dfrac{GM}{c^2 r^3}$

Surveying the landscape

(T. Baker, D. Psaltis and C.S., Astrophys.J. 802, 63 (2015).



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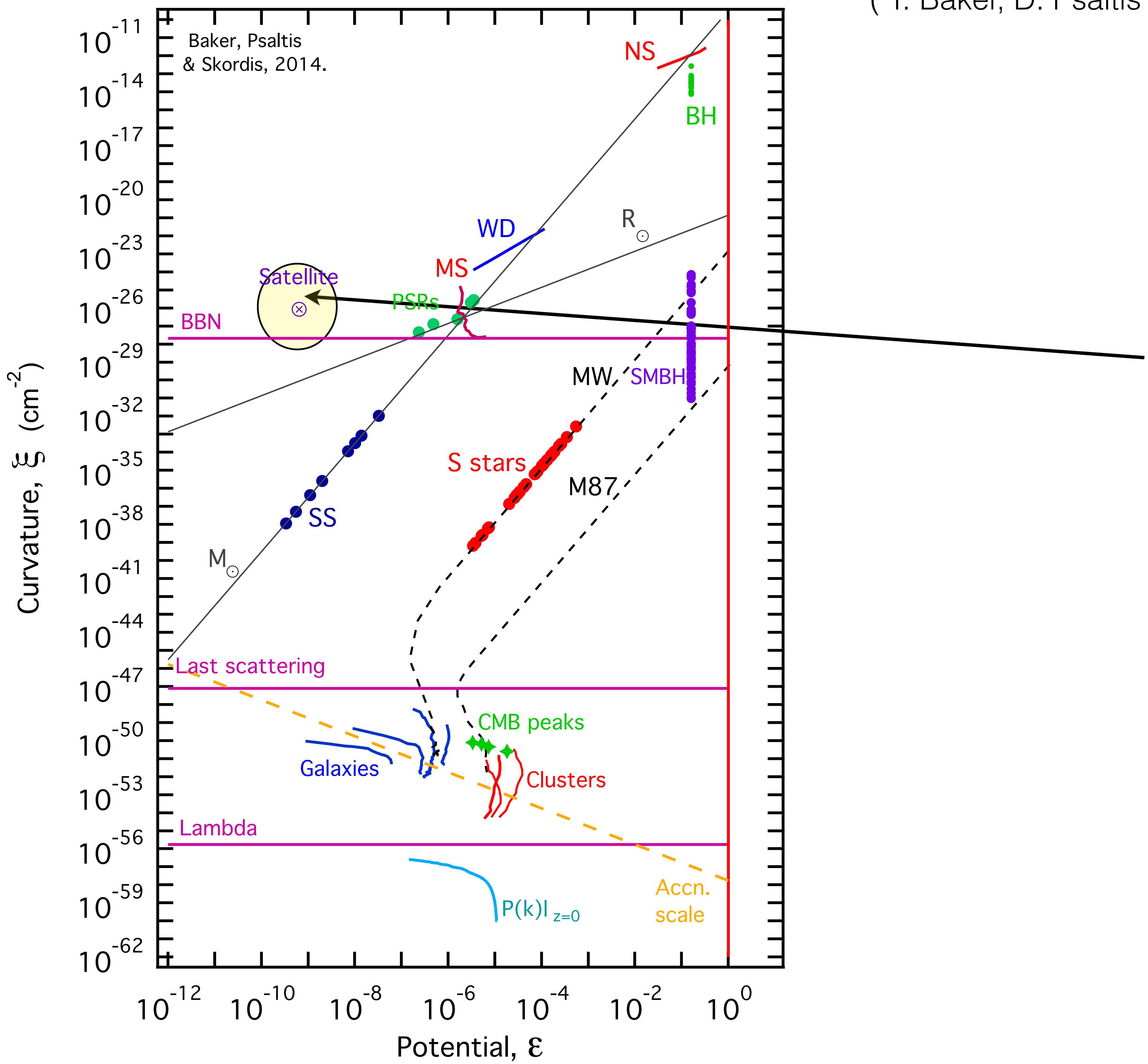

Satellite orbiting the Earth

Surveying the landscape

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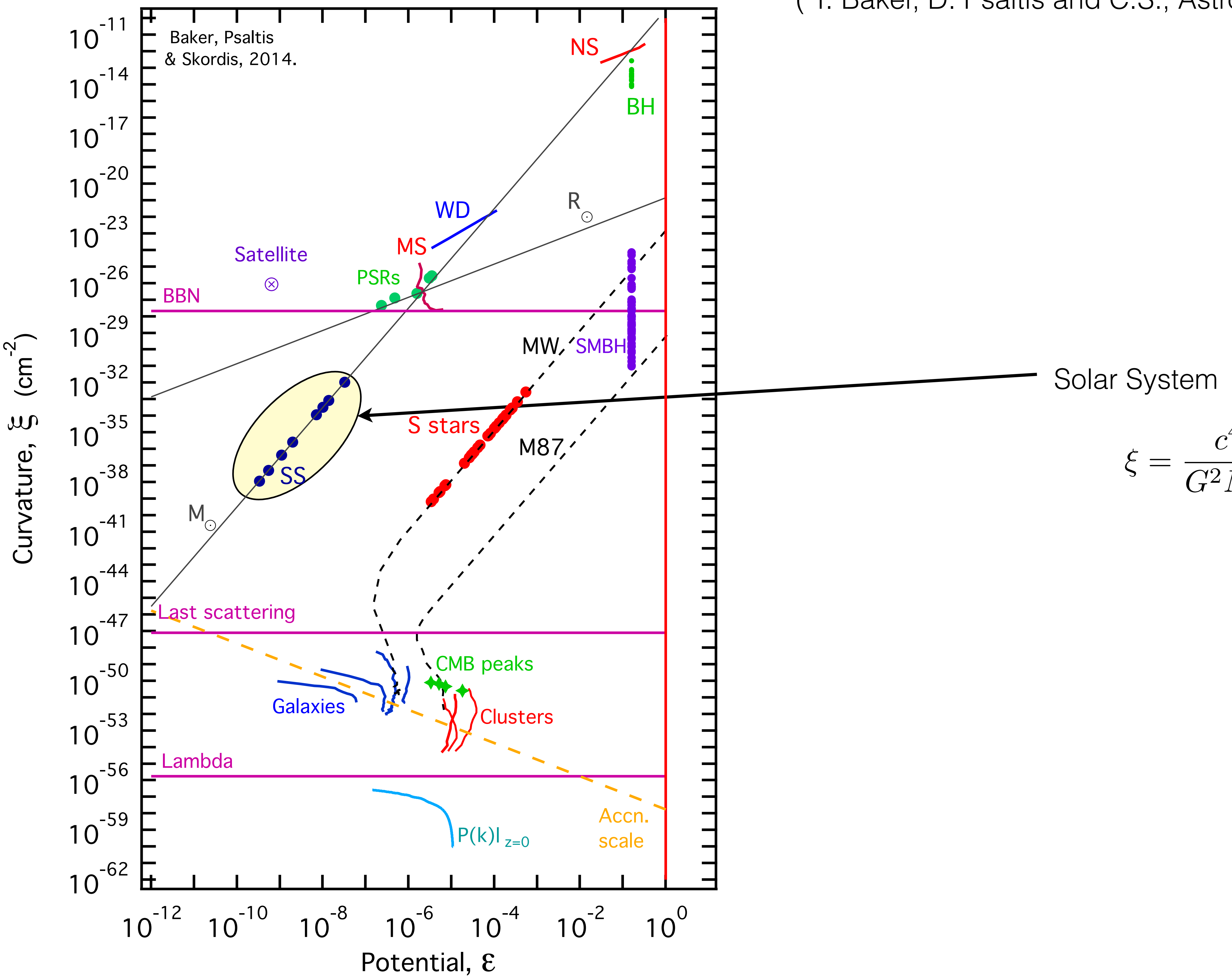

$$\xi = \frac{c^4}{G^2 M^2}\epsilon^3$$

Surveying the landscape

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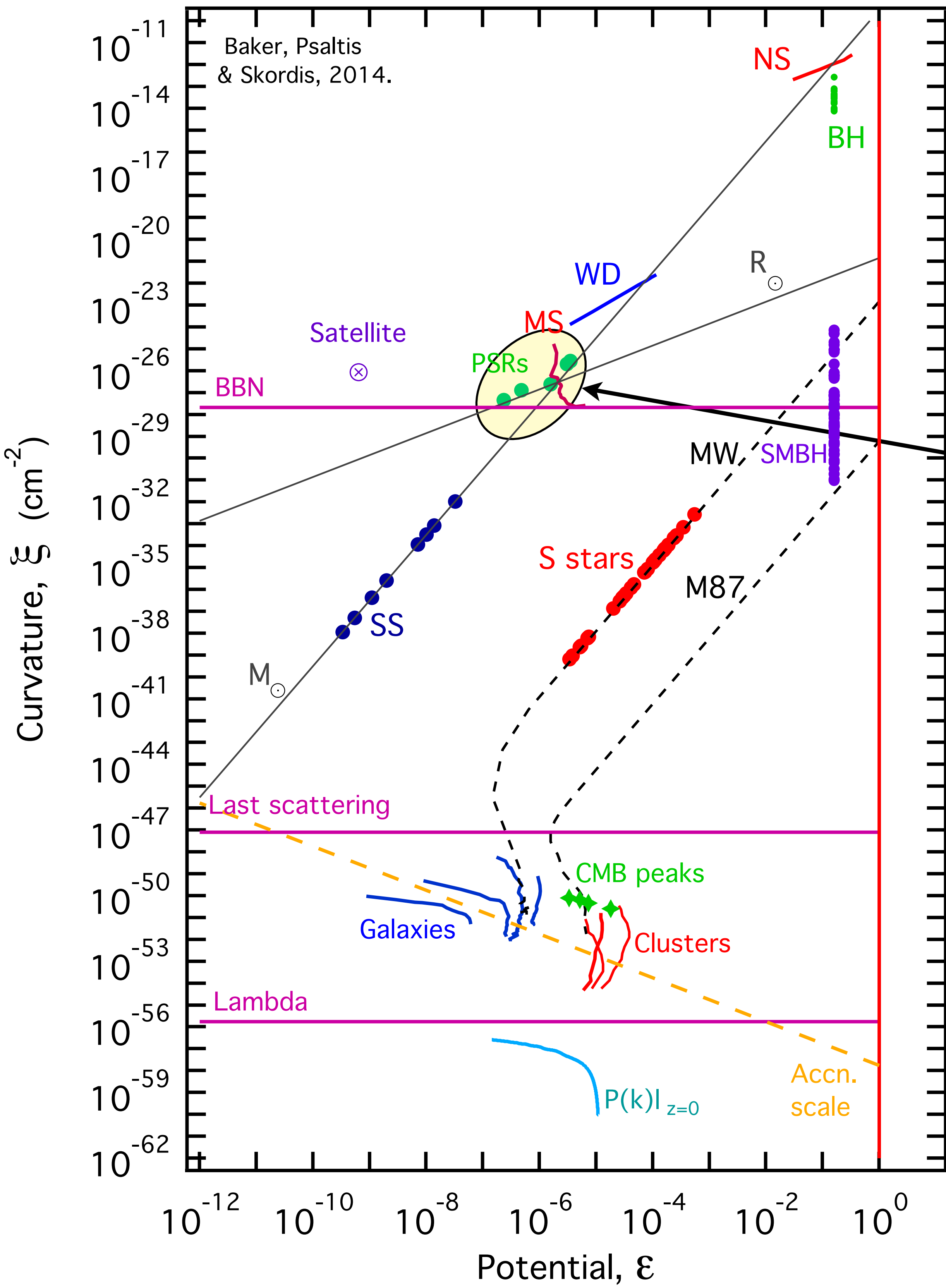
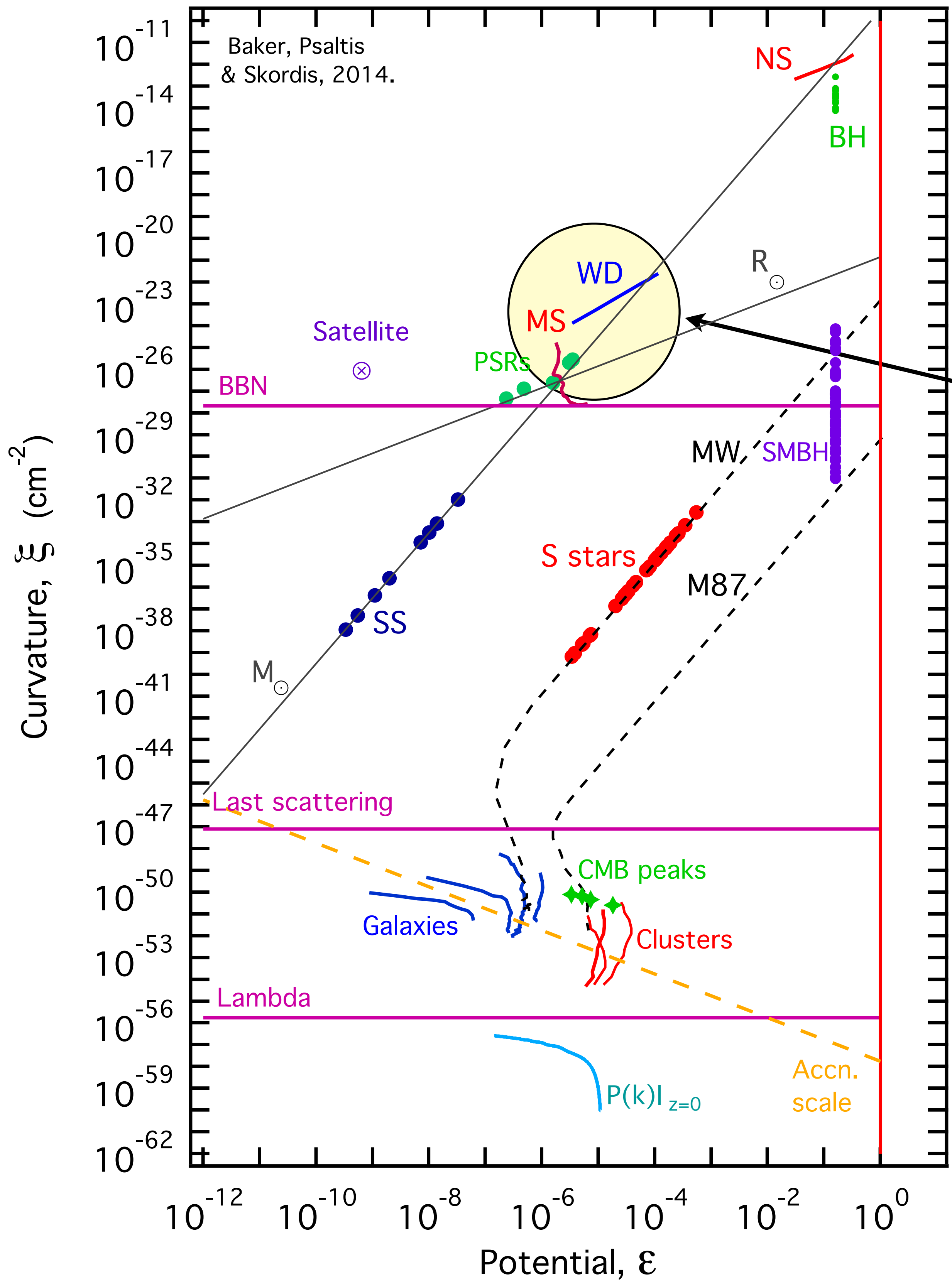


Neutron Star binaries and binary PSRs

Surveying the landscape

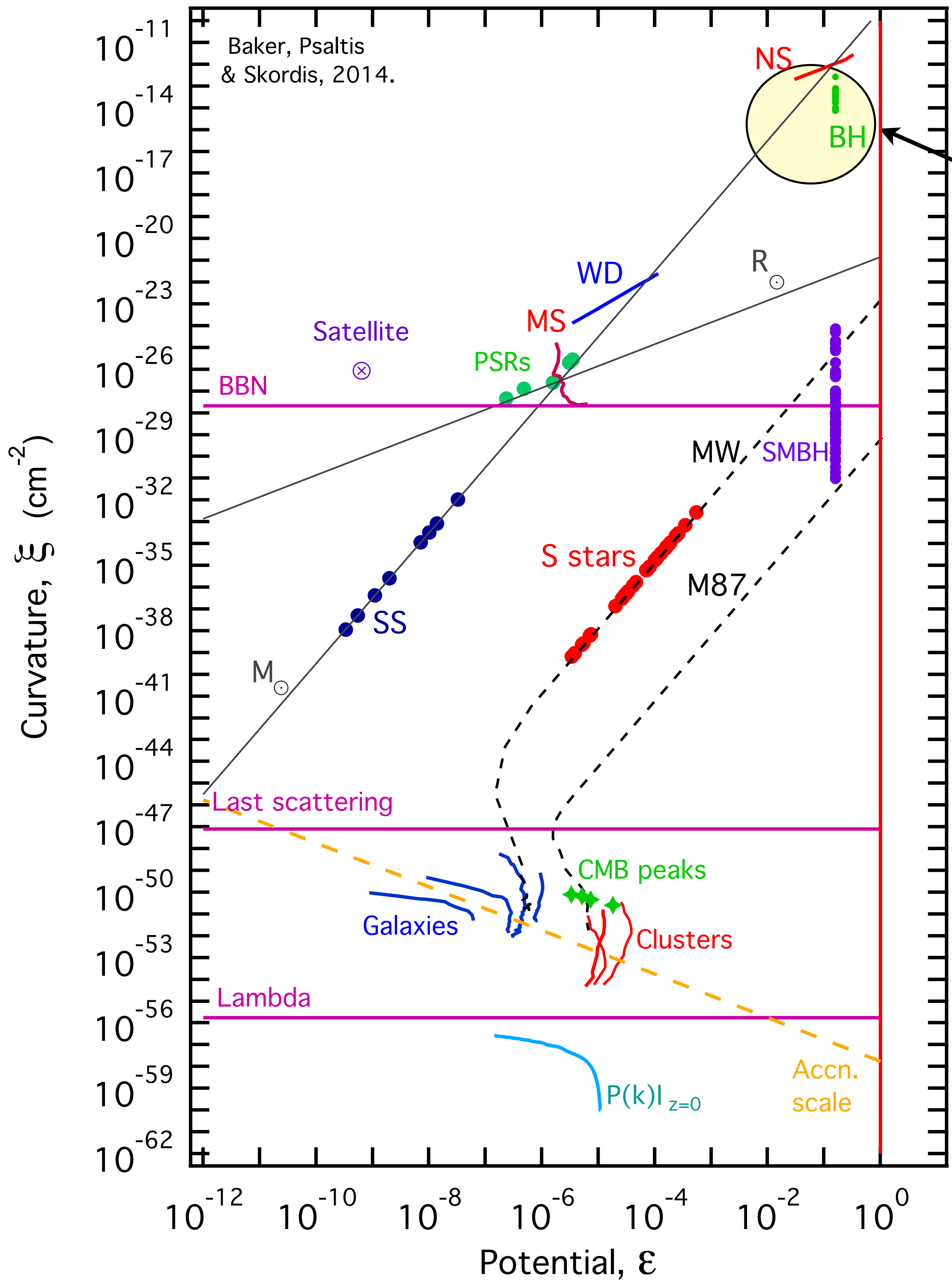
(T. Baker, D. Psaltis and C.S., Astrophys.J. 802, 63 (2015).



Main Sequence stars and White Dwarfs
(evaluated at the surface of the star)

Surveying the landscape

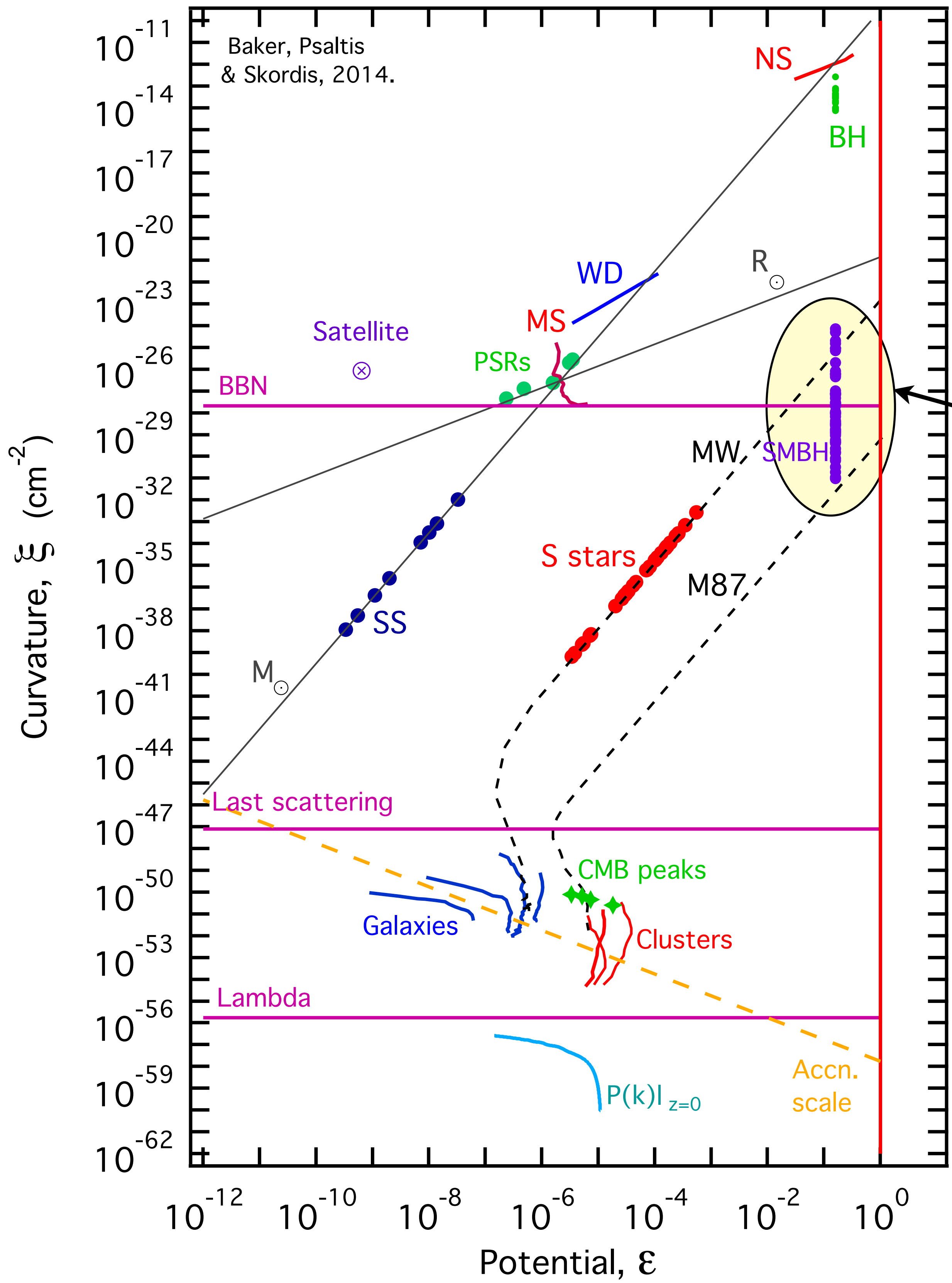
(T. Baker, D. Psaltis and C.S., Astrophys.J. 802, 63 (2015).



Astrophysical BH (evaluated at ISCO)
and Neutron Stars (evaluated at the surface of the star)

Surveying the landscape

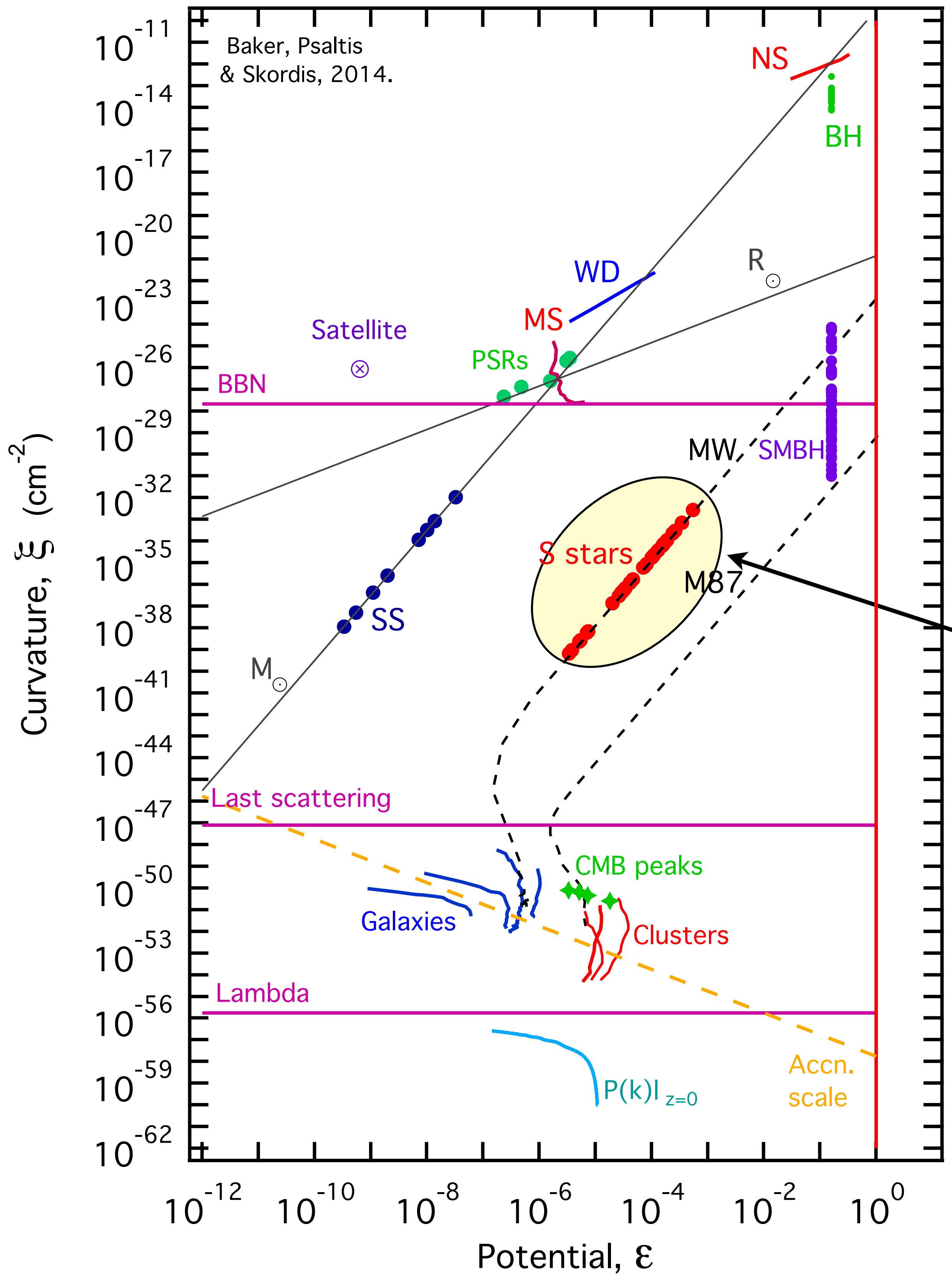
(T. Baker, D. Psaltis and C.S., Astrophys.J. 802, 63 (2015).



Supermassive BH (at ISCO)

Surveying the landscape

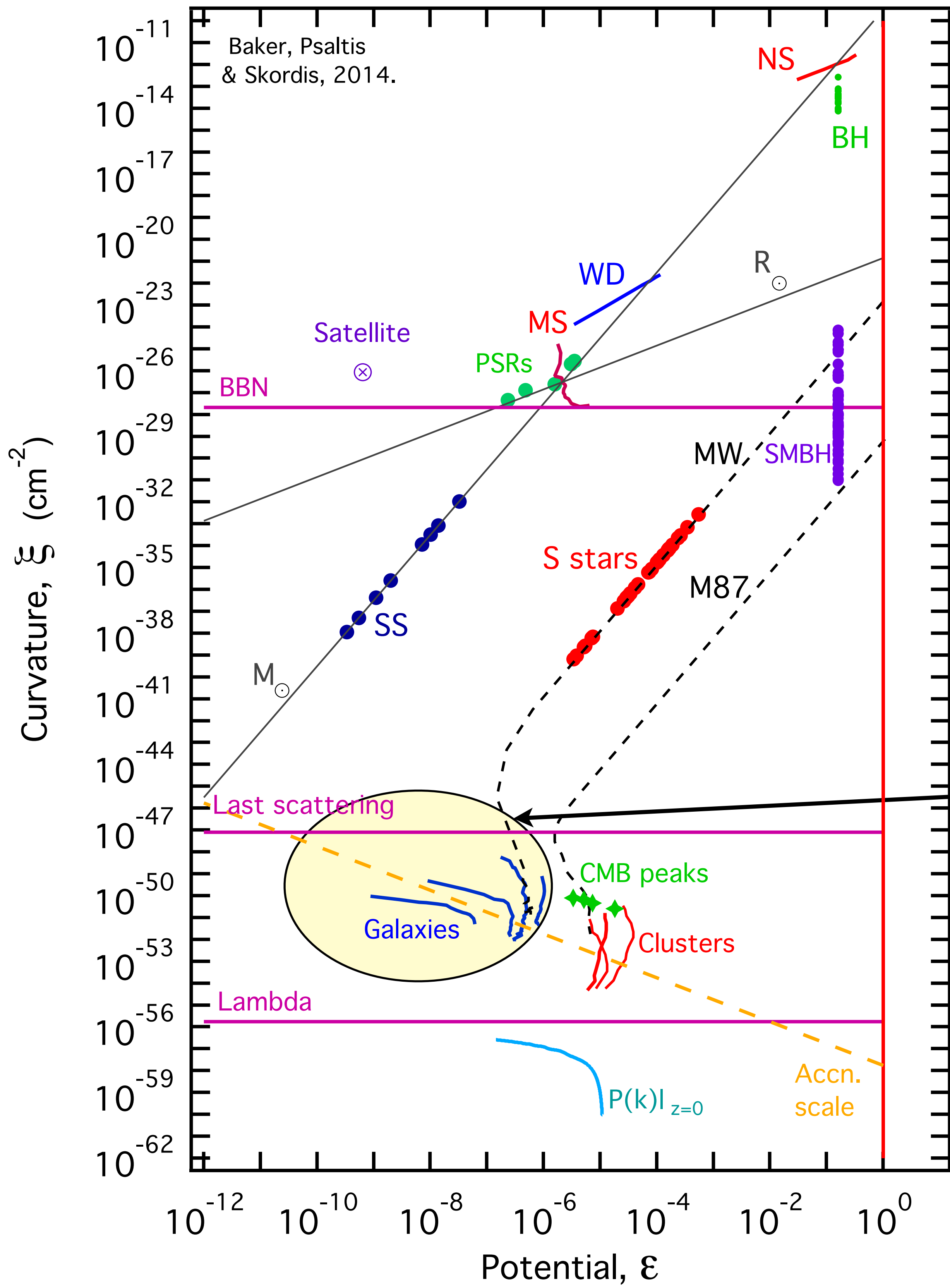
(T. Baker, D. Psaltis and C.S., Astrophys.J. 802, 63 (2015).



S stars orbiting the central BH of the Milky Way

Surveying the landscape

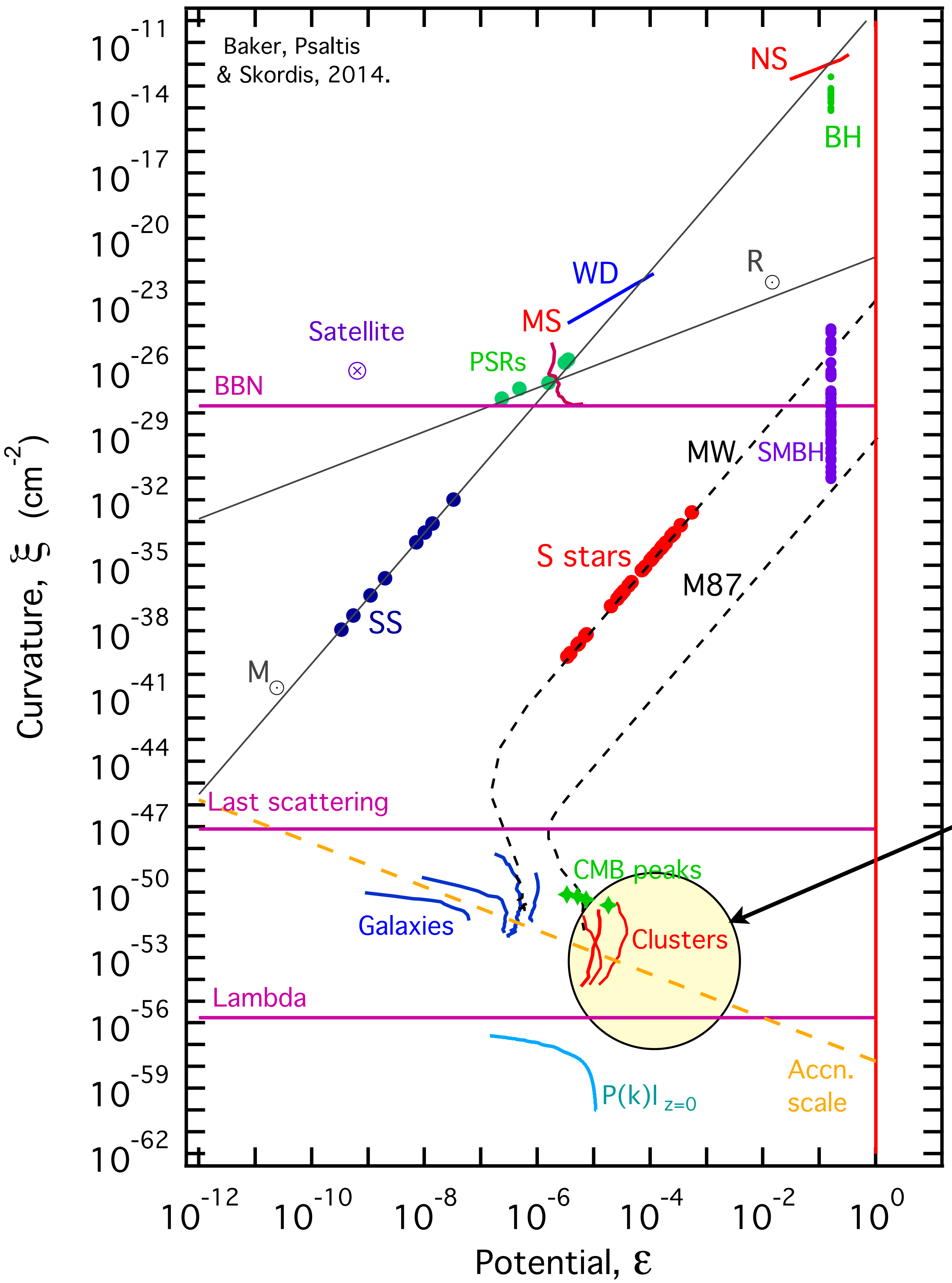
(T. Baker, D. Psaltis and C.S., Astrophys.J. 802, 63 (2015).



Galaxies (evaluated using rotation curve data and $v^2 \sim \Phi \sim \frac{GM}{r}$)

Surveying the landscape

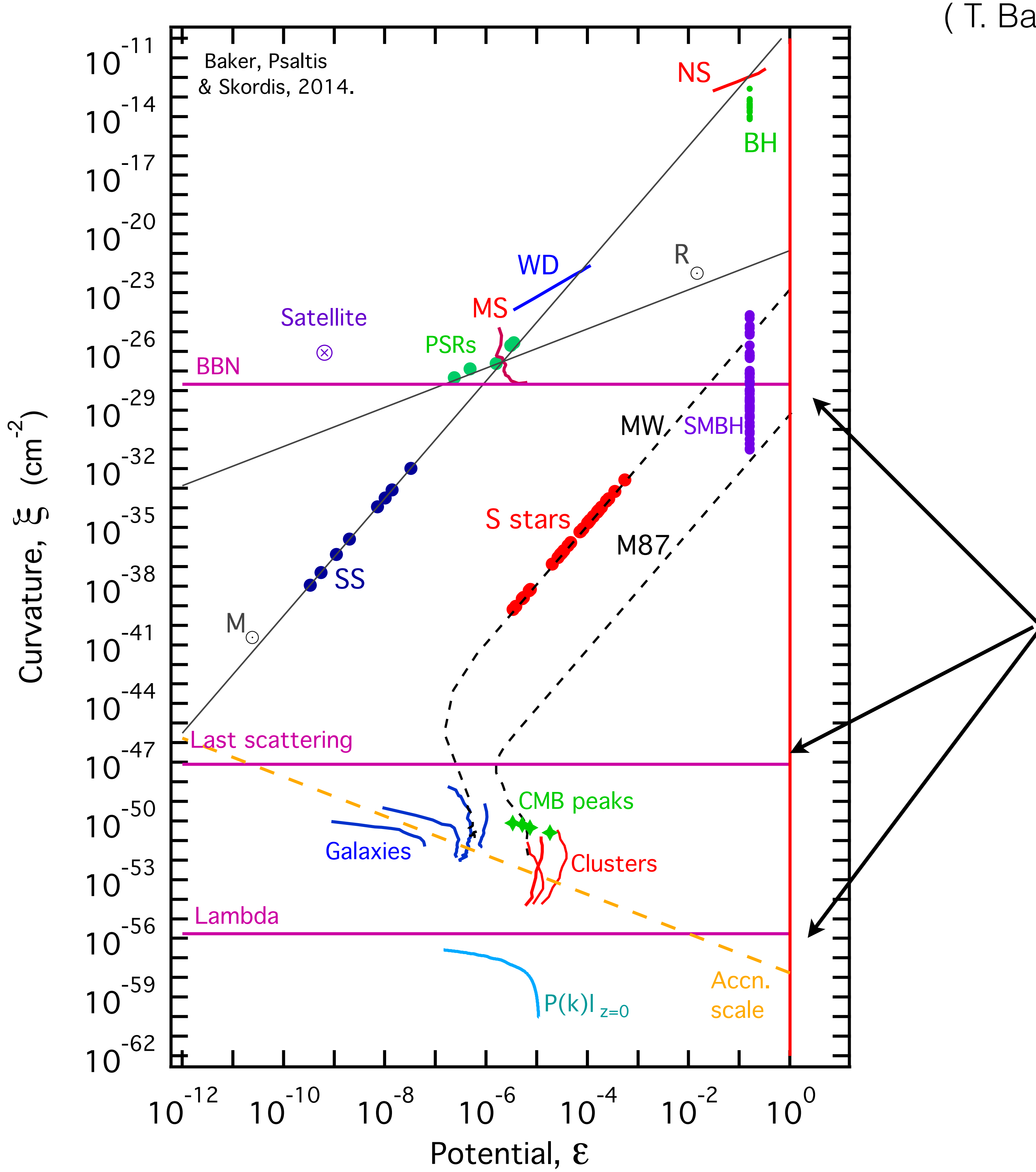
(T. Baker, D. Psaltis and C.S., Astrophys.J. 802, 63 (2015).



Clusters

Surveying the landscape

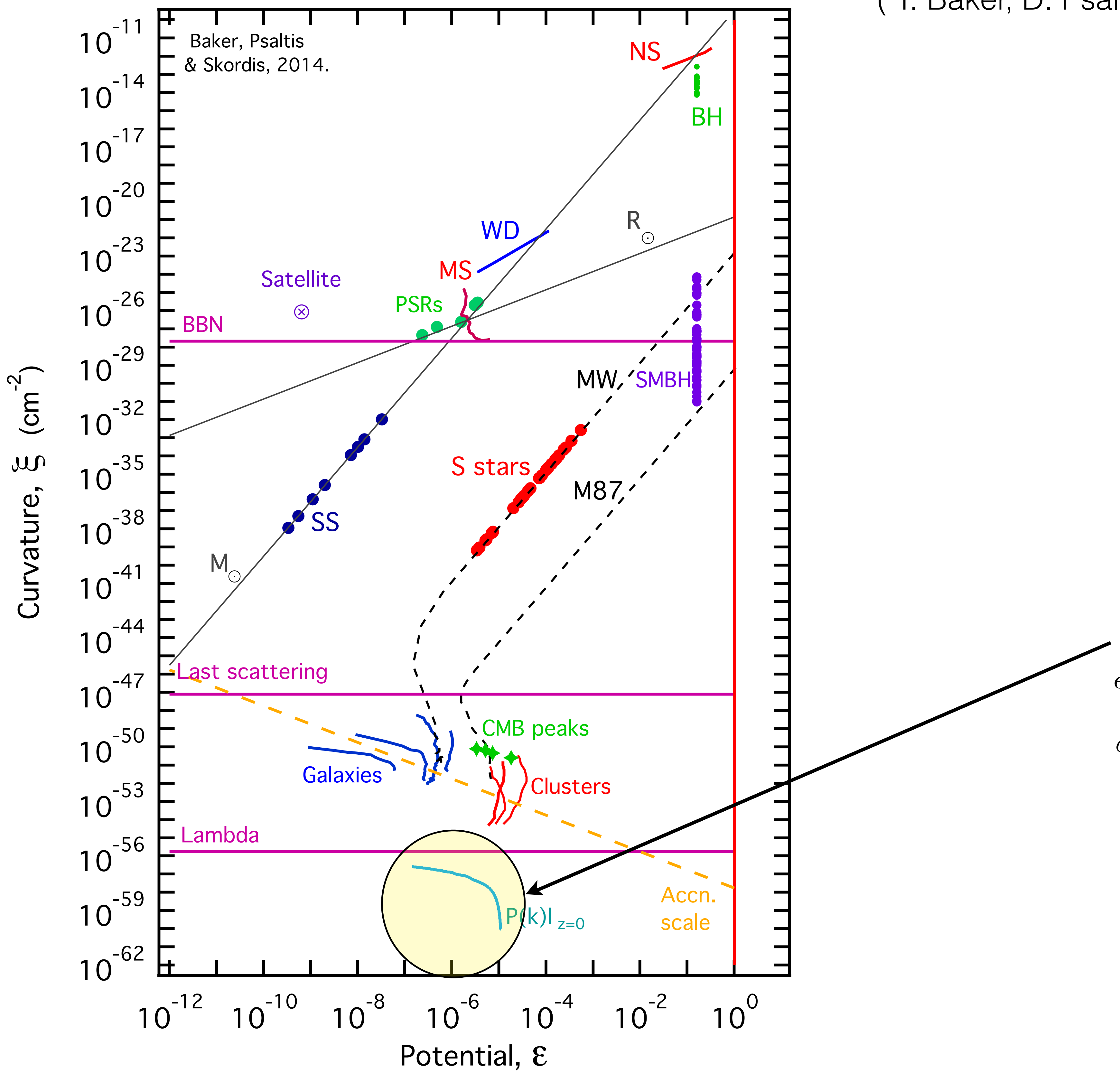
(T. Baker, D. Psaltis and C.S., Astrophys.J. 802, 63 (2015).



$$\xi_0 = \frac{\sqrt{12}}{a^2}\sqrt{\dot{\mathcal{H}}^2 + \mathcal{H}^4}$$

Surveying the landscape

(T. Baker, D. Psaltis and C.S., Astrophys.J. 802, 63 (2015).

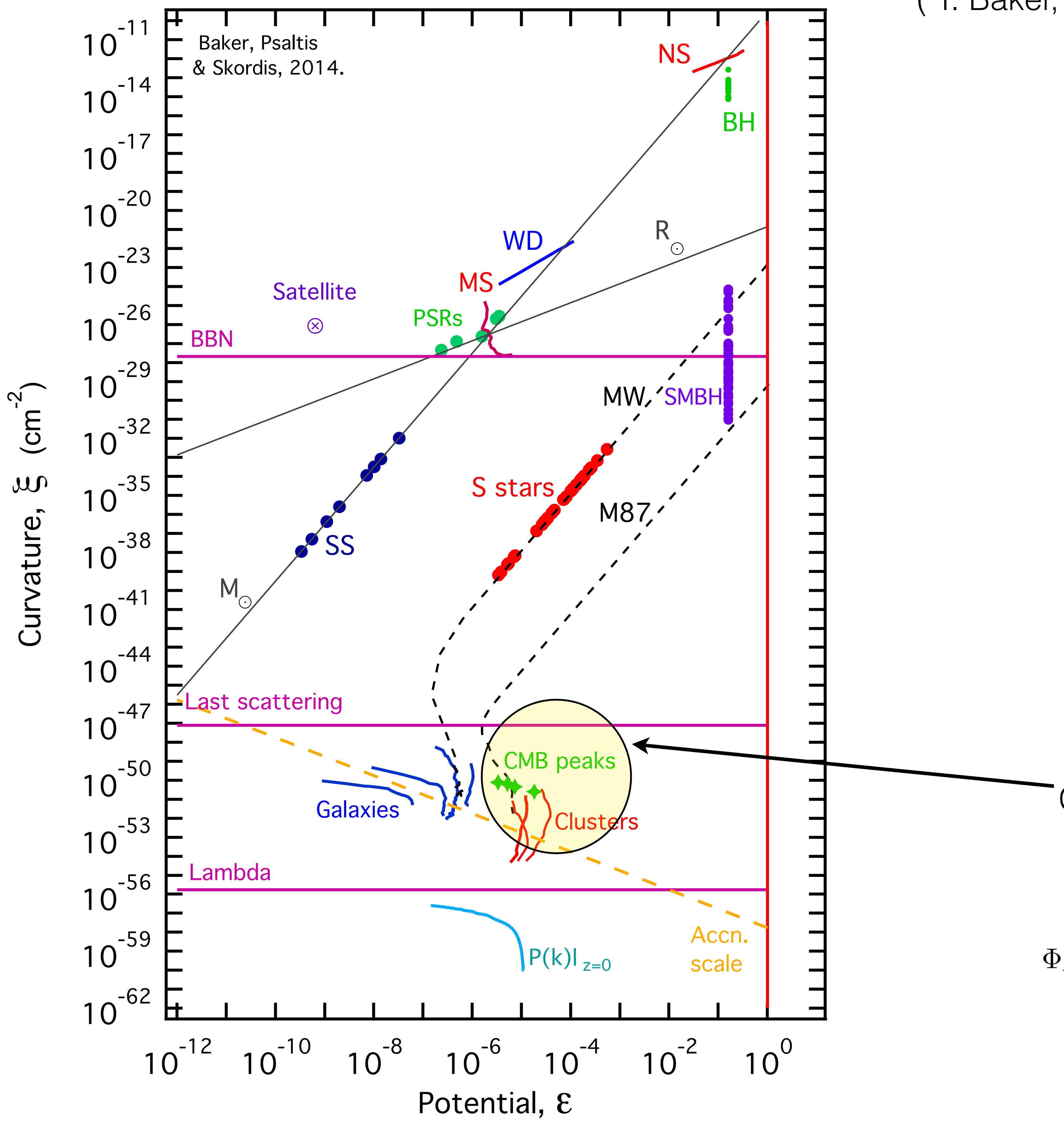


$$\epsilon(t,k) \sim \sqrt{\langle|\Phi(t,\vec{x})|^2\rangle_k}$$

$$\delta\xi(t,k) = \sqrt{\langle|\delta\xi(t,\vec{x})|^2\rangle_k}$$

Surveying the landscape

(T. Baker, D. Psaltis and C.S., Astrophys.J. 802, 63 (2015).

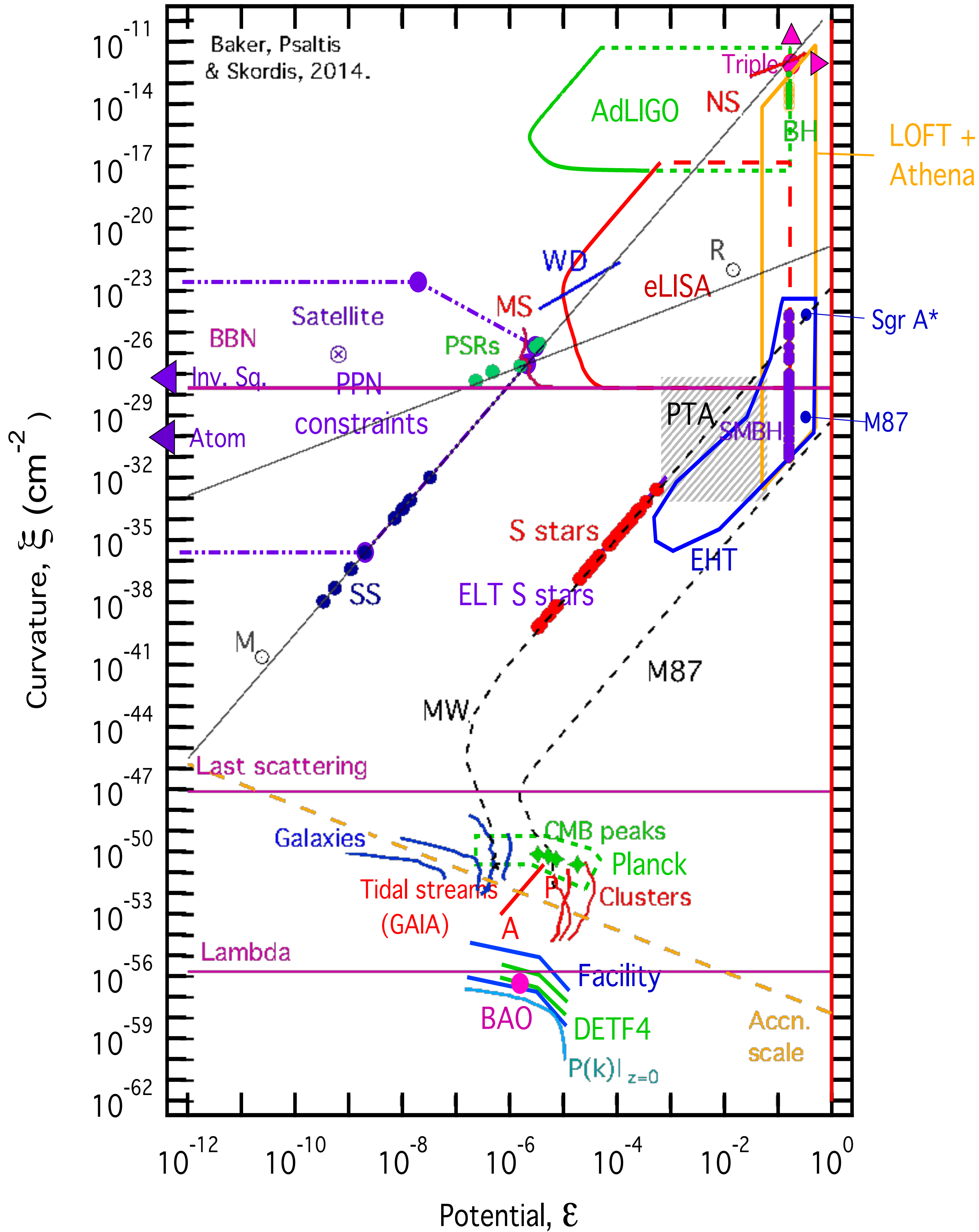


CMB primary anisotropies

$$\epsilon_\ell = \sqrt{\frac{2}{\pi}\int dk k^2 |\Phi_\ell(k)|^2 P_0(k)}$$

$$\Phi_\ell(k) = \int_0^{\eta_0} d\eta j_\ell(k(\eta_0 - \eta)) g_{vis}(\eta)\Phi(\eta, k)$$

What do we know - what will we learn



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What do we know - what will we learn

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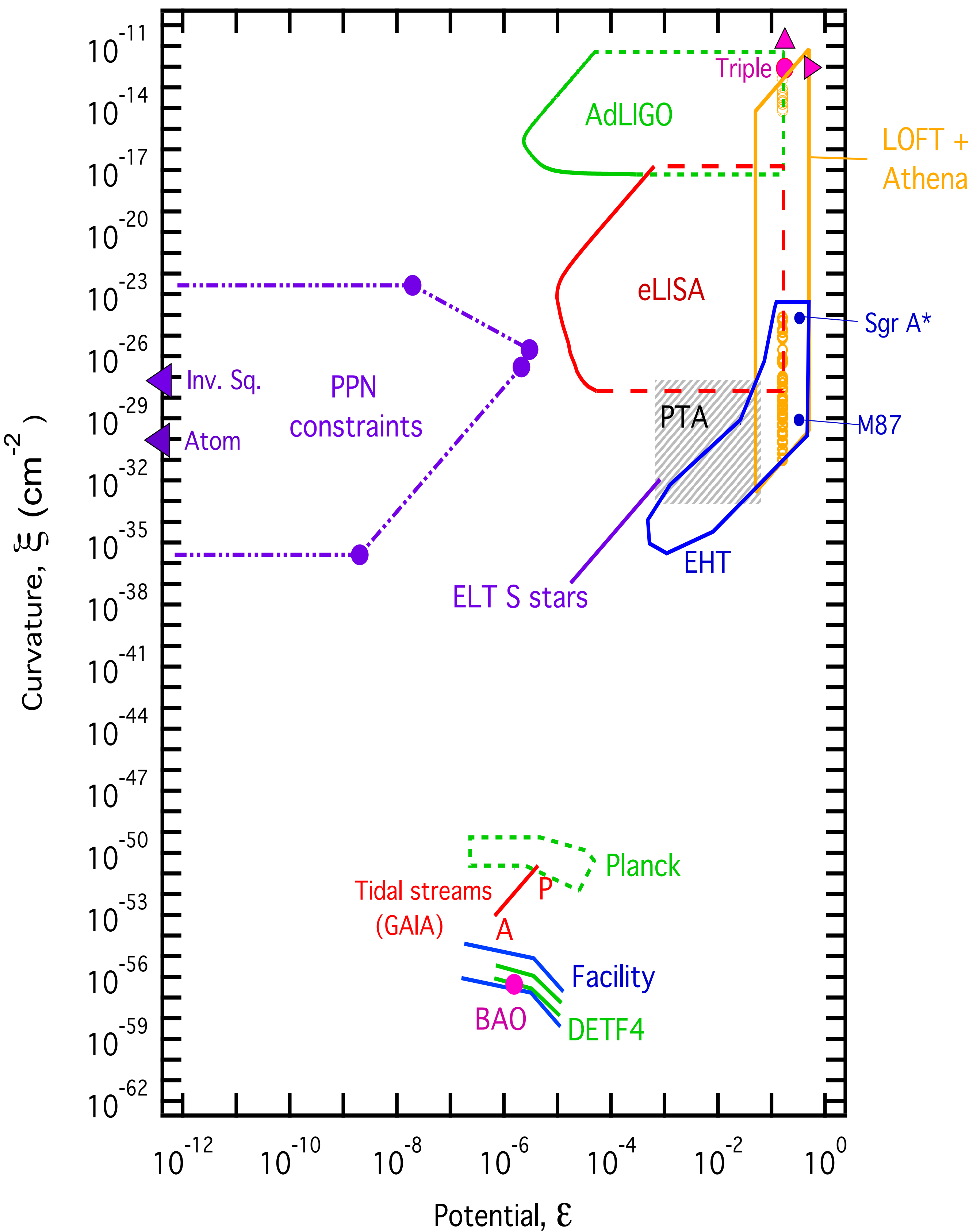
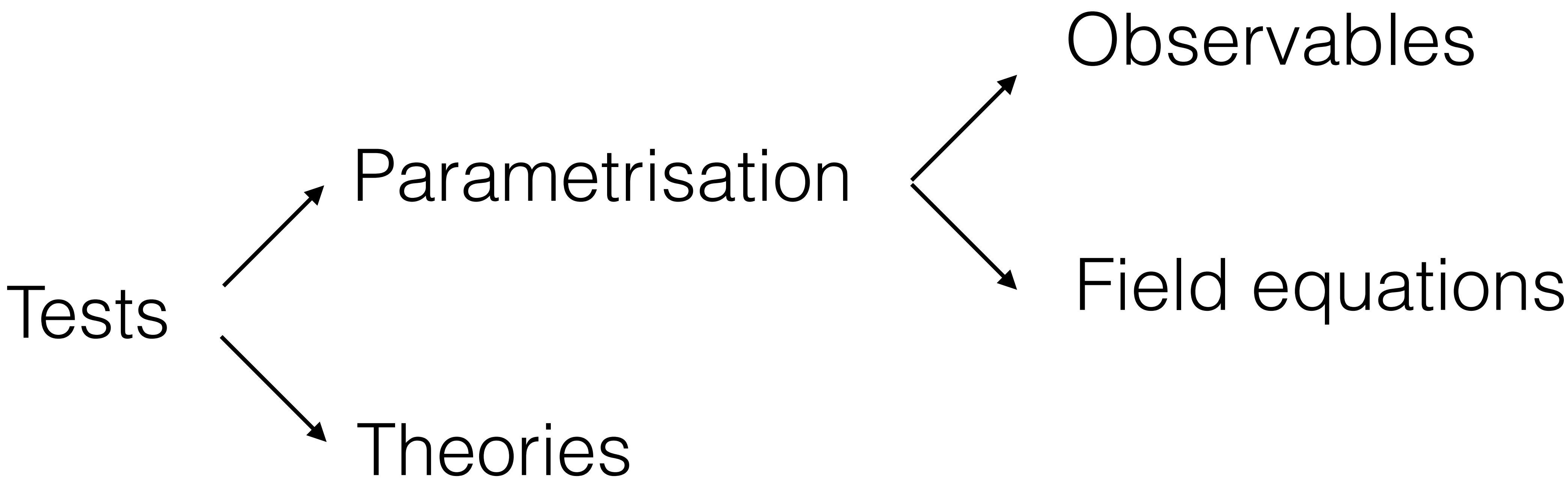


Various methods



Testing the background expansion (e.g. measuring w) does NOT test gravity.

Testing observables — Growth rate

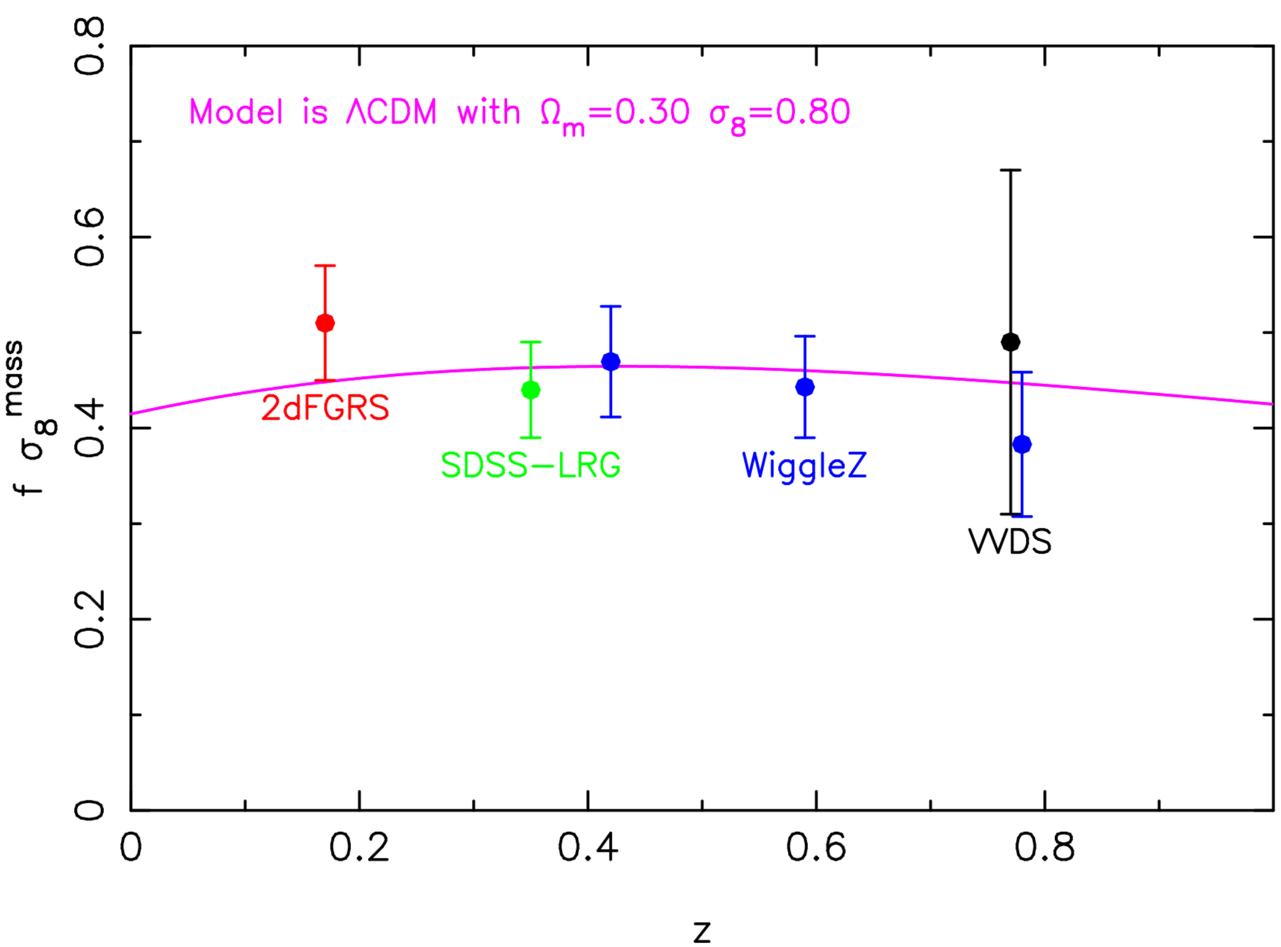
$$f = \frac{d \ln \delta_M}{d \ln a}$$

Parametrise $f = \Omega_M^{\gamma}$ (Linder)

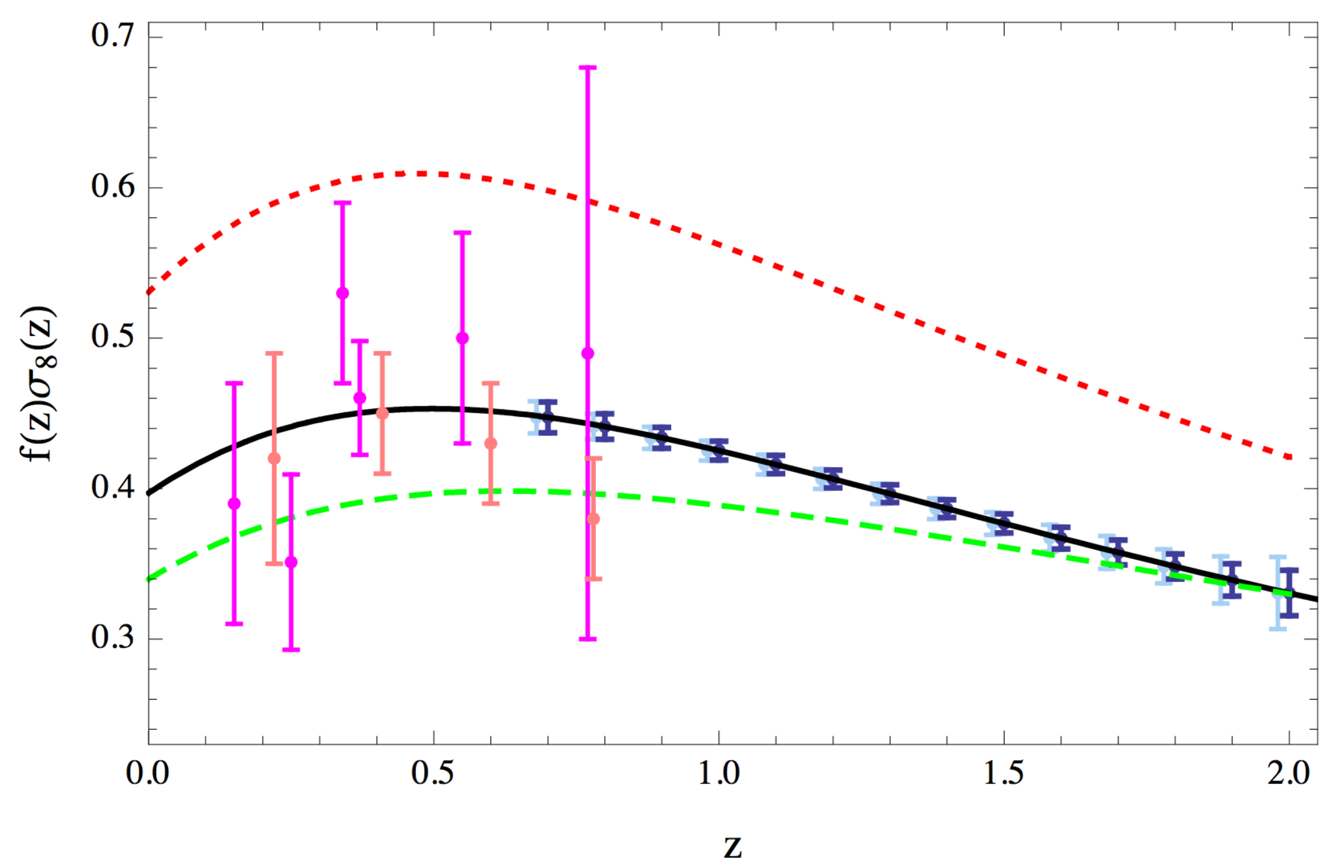
ΛCDM $\gamma = \frac{6}{11} + \ldots$

Caveats:

- MG models may lead to scale-dependent growth
- non-MG dark energy models may also lead to w-dependent growth



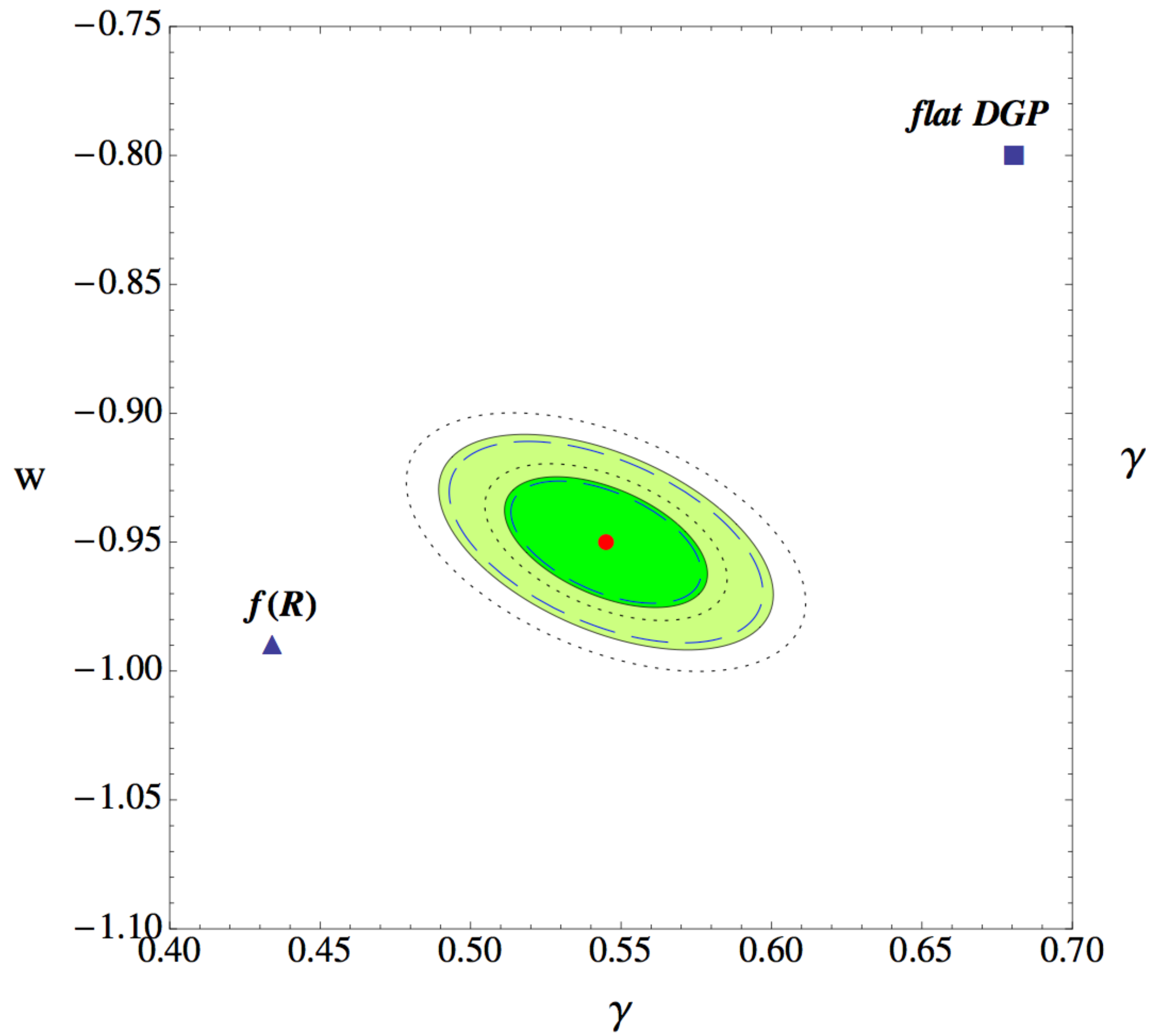
Blake et al, WiggleZ collaboration



EUCLID forecasts: Majerotto et al (2012)

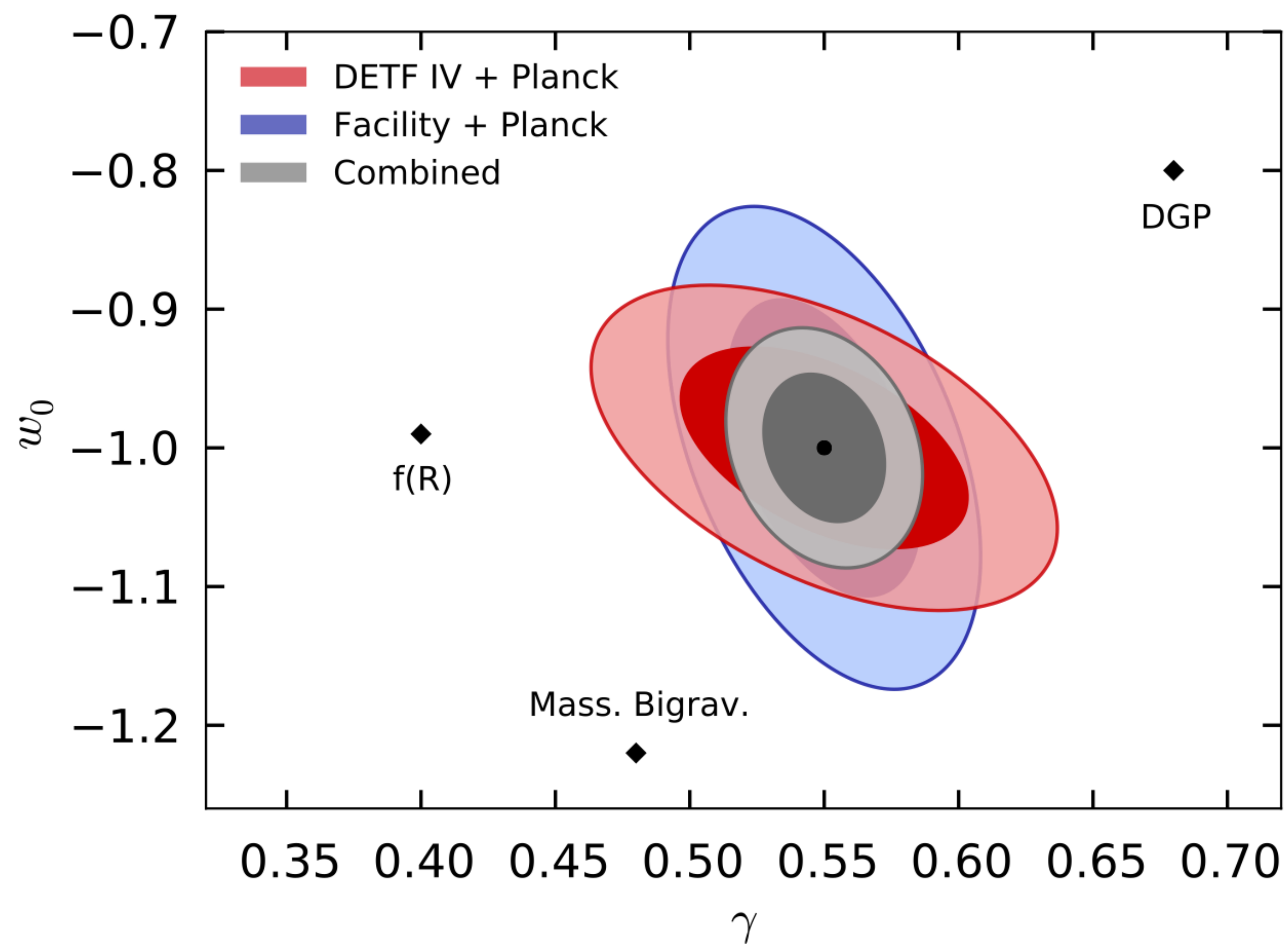
Future constraints: Growth rate

EUCLID, galaxy clustering



Amendola et al, EUCLID theory workgroup collaboration (2013)

21cm Intensity mapping



Bull et al (2014)

Simplified parametrisation

Zhang, Liguori, Bean and Dodelson
Caldwell, Cooray and Melchiorri
Amendola, Kunz and Sapone
Bertschinger and Zukin
Amin, Blandford and Wagoner
Pogosian, Silvestri, Koyama and Zhao
Bean and Tangmatitham

$$-2k^2\Phi = 8\pi G a^2 \rho \delta^{(com)} Q(\tau, k)$$

$$\Phi - \Psi = 8\pi G a^2 (\rho + P)\sigma Q + [1 - R(\tau, k)]\,\Phi$$

further dependent function

$$\Sigma = \frac{1}{2} Q(1+R) \qquad \sim \Phi + \Psi \text{ (Lensing)}$$

$$\Lambda\text{CDM} \quad Q = R = \Sigma = 1$$

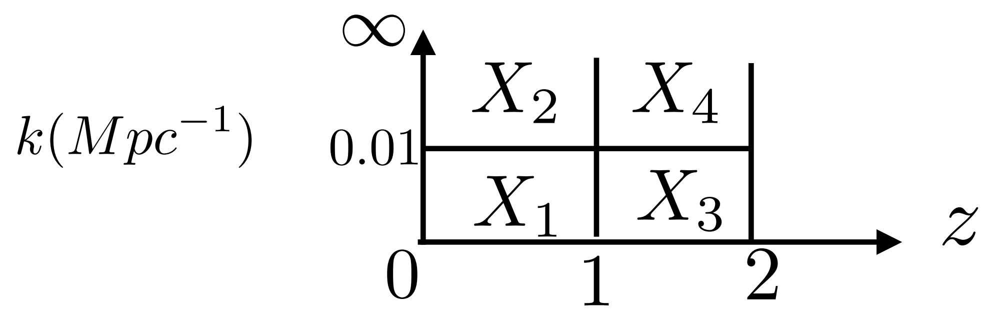
Pros: Simple, Easy to implement

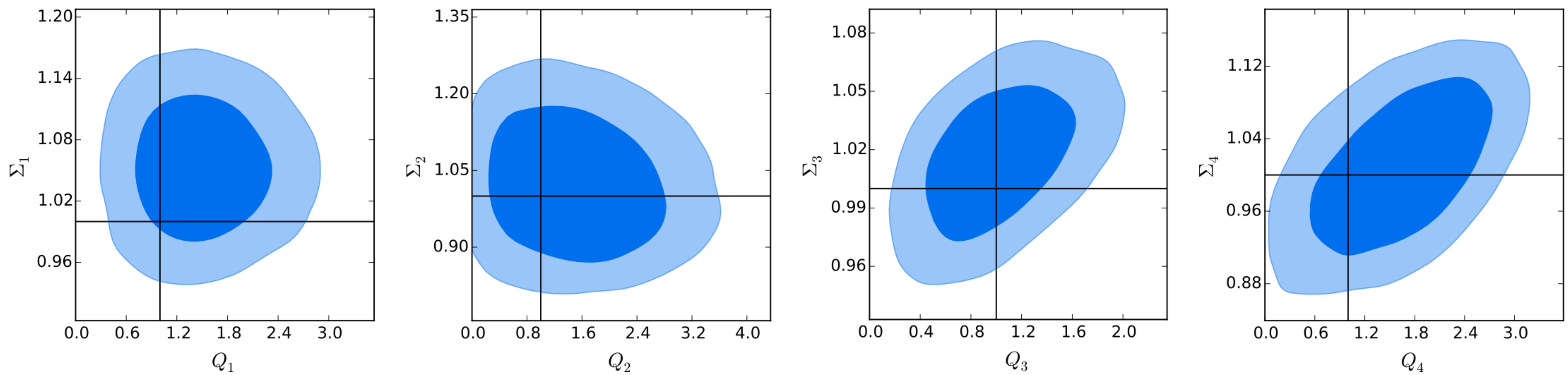
Cons:
- Difficult to associate with theories
- Hard to interpret possible detections beyond LCDM

CFHTLens and Planck

Dossett et al, 2015

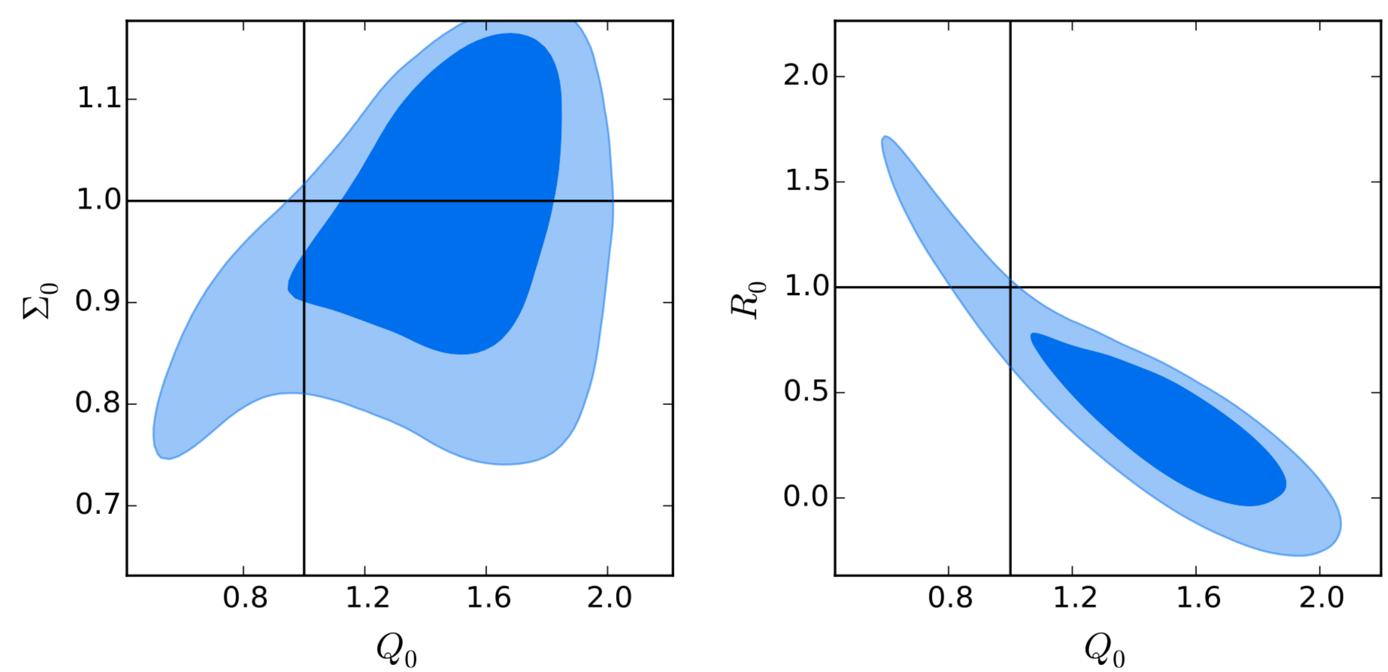
Pixel-method





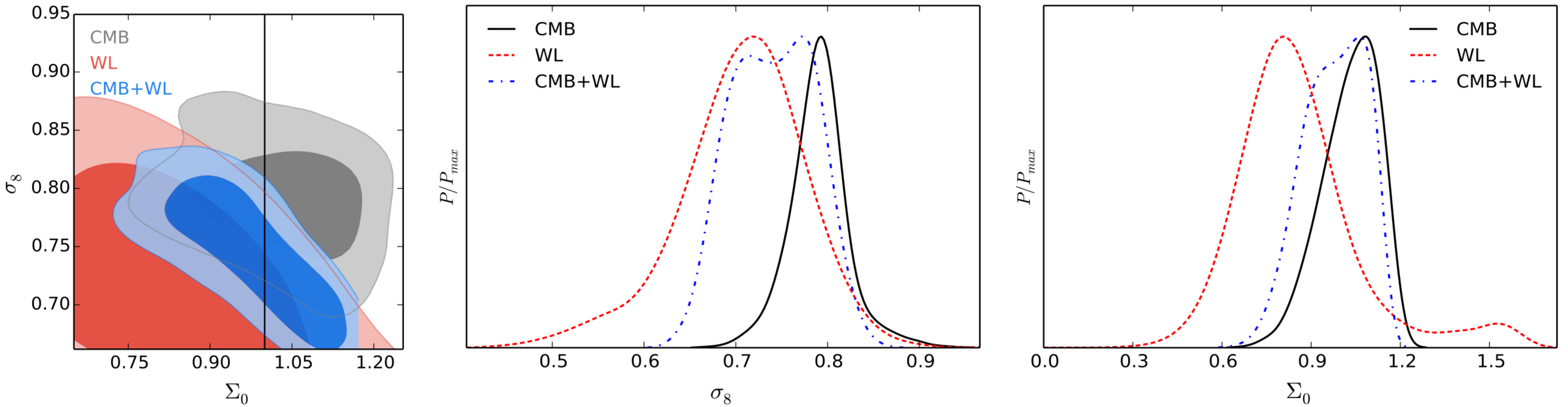
Scale-independent method

$$X = (X_0 - 1)a^s + 1$$



CFHTLens and Planck

Dossett et al, 2015



Tension: Planck with Weak lensing

Effective-field-theory (covariant version)

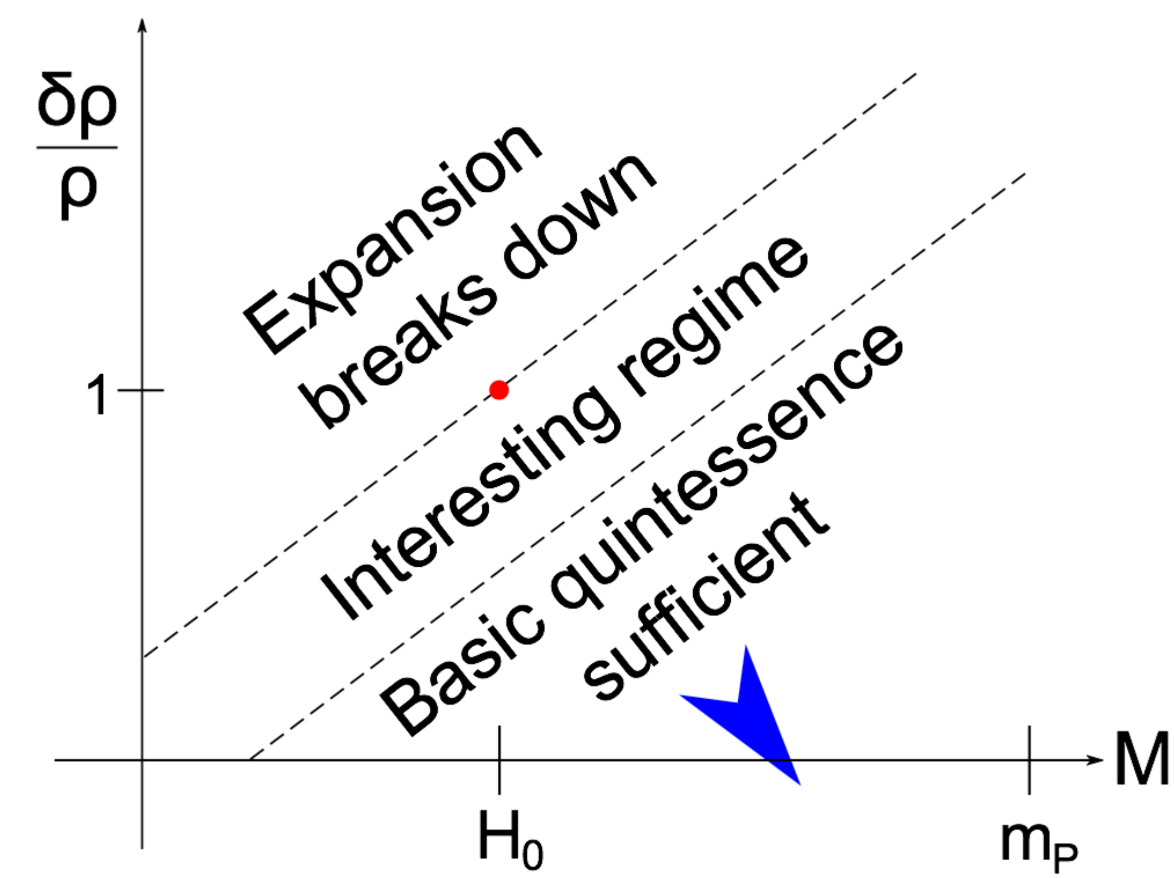
Bloomfield and Flanagan (2011)

$$
\begin{aligned}
S \quad = \quad & S_m[e^{\alpha(\phi)} g, \Psi_A] + \int d^4x \sqrt{-g} \left[\frac{1}{16\pi G} R - \frac{1}{2} (\nabla\phi)^2 - U(\phi) \right] \\
& + \int d^4x \sqrt{-g} \Big[a_1(\phi) (\nabla\phi)^4 + b_2(\phi) T (\nabla\phi)^2 + c_1(\phi) G^{\mu\nu} \nabla_\mu\phi \nabla_\nu\phi \\
& + d_3(\phi) \left(R^2 - 4R^{\mu\nu} R_{\mu\nu} + R^{mu\nu\alpha\beta} R_{\mu\nu\alpha\beta} \right) + d_4(\phi) \epsilon^{\mu\nu\alpha\beta} C_{\mu\nu}{}^{\rho\lambda} C_{\alpha\beta\rho\lambda} + e_1(\phi) T^{\mu\nu} T_{\mu\nu} + e_2(\phi) T^2 \Big]
\end{aligned}
$$

9 free functions of ϕ

- Theory-based
- Background-independent

- Only scalar fields: obsolete by Horndeski(?)
- Background-independent: all functions contribute to both FRW and perturbations



Effective-field-theory (3+1 version)

Gubitosi, Piazza and Vernizzi (2012)
Bloomfield, Flanagan, Park and Watson (2012)

(FRW) Background-dependent

Formulated in the unitary gauge : Scalar field “eaten” by the metric

FRW-only functions

$$
\begin{aligned}
S \;=\; & S_m[g,\Psi_A] + \int d^4x\sqrt{-g}\Big[\frac{1}{16\pi G}f(t)R - \Lambda(t) - c(t)g^{00} \\
& + \frac{1}{2}M_2^4(t)(\delta g^{00})^2 - \frac{1}{2}m_3^2(t)\delta K\delta g^{00} - m_4^2(t)(\delta K^2 - \delta K^{\mu}_{\nu}\delta K^{\nu}_{\mu}) + \frac{1}{2}\tilde{m}_4^2(t)\,{}^{(3)}R\delta g^{00} \\
& - \bar{m}_4^2(t)\delta K^2 + \frac{1}{2}\bar{m}_5(t)\,{}^{(3)}R\delta K + \frac{1}{2}\bar{\lambda}(t)\,{}^{(3)}R^2\Big]
\end{aligned}
$$

perturbations-only functions

higher-spatial derivative perturbations-only functions

10 functions of time

3 background

7 perturbative

Only scalar fields

PPF: Parametrisation of the field equations

C.S. (2009)
Baker, Ferreira and C.S. (2012)

Include all possible terms involving the metric scalar modes and 1 extra scalar mode dof χ

e.g. $-a^2\delta G^0_0 = \kappa a^2 G\,\rho_M\delta_M + A_0 k^2\hat{\Phi} + F_0 k(\dot{\hat{\Phi}} + \mathcal{H}\hat{\Psi}) + \alpha_0 k^2\hat{\chi} + \alpha_1 k\dot{\hat{\chi}} + k^3 M_\Delta(\dot{\nu} + 2\epsilon)$

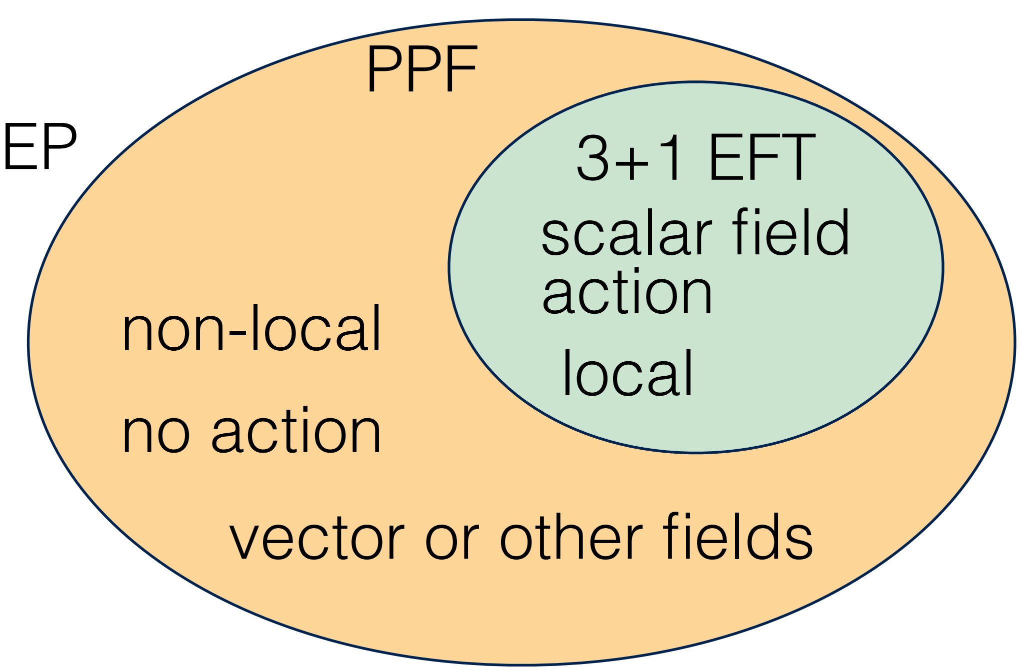
4x4 + 2 = 18 free functions

Bianchi identity + matter stress-energy conservation: 7 constraints

+ 2nd order field equation for χ

11 free functions

- Most general parametrisation compatible with WEP
- Independent of field type (scalar, vector, etc)
- Includes local, non-local, action/no action etc.



Testing theories: New degrees of freedom

GR is unique

(massless spin-2 graviton)

$\Rightarrow$ non-GR theories imply new dof

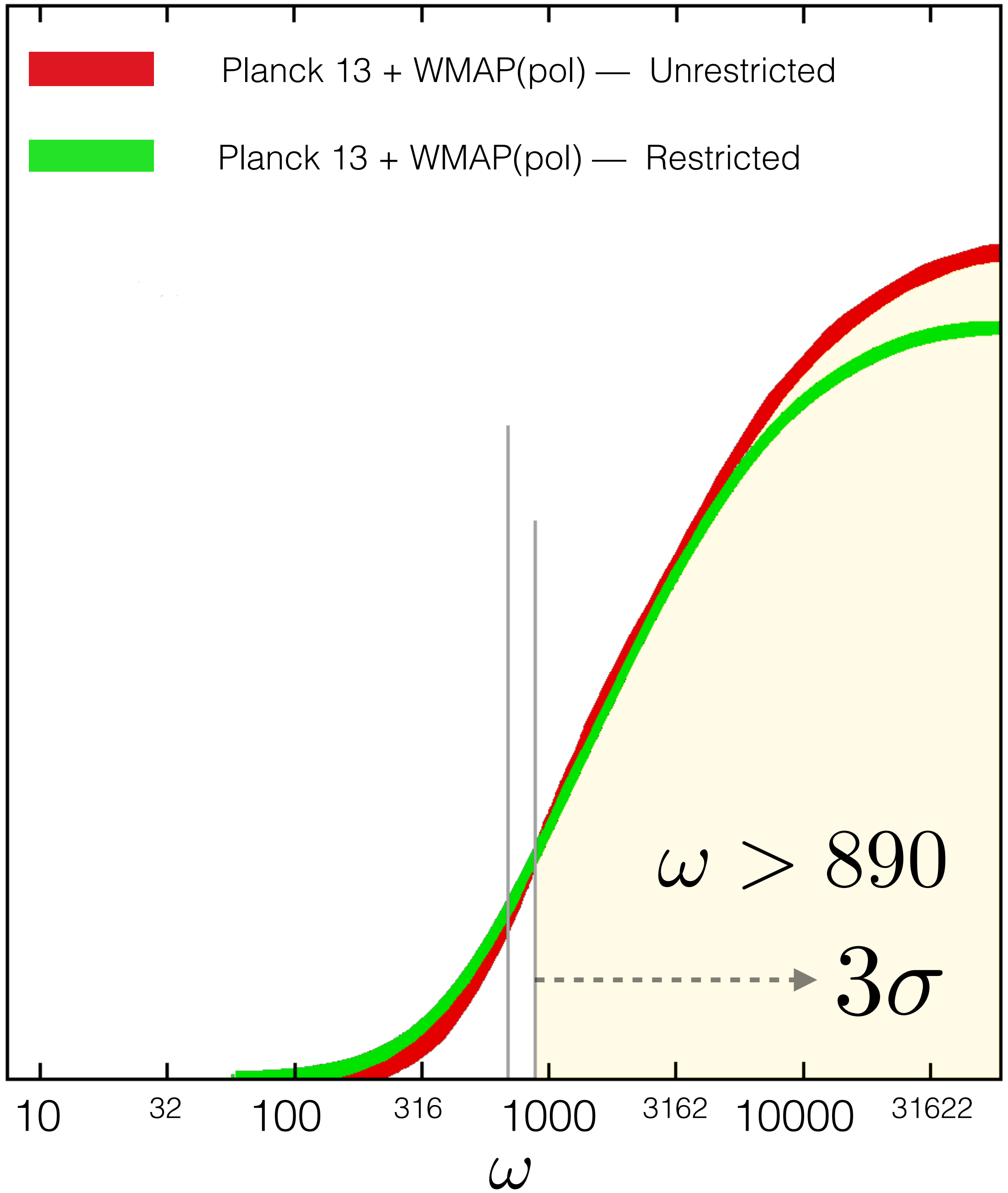
Screening mechanisms (restoration of GR in the solar system)

- Kinetic screening: Vainshtein mechanism
  Derivative couplings become large near massive sources — Vainshtein (1972)
- Chameleon mechanism
  Fields become very massive in dense environments — Khoury & Weltman (2001)
- Symmetron mechanism
  Symmetry restoration in dense environments — Hinterbichler & Khoury (2010)

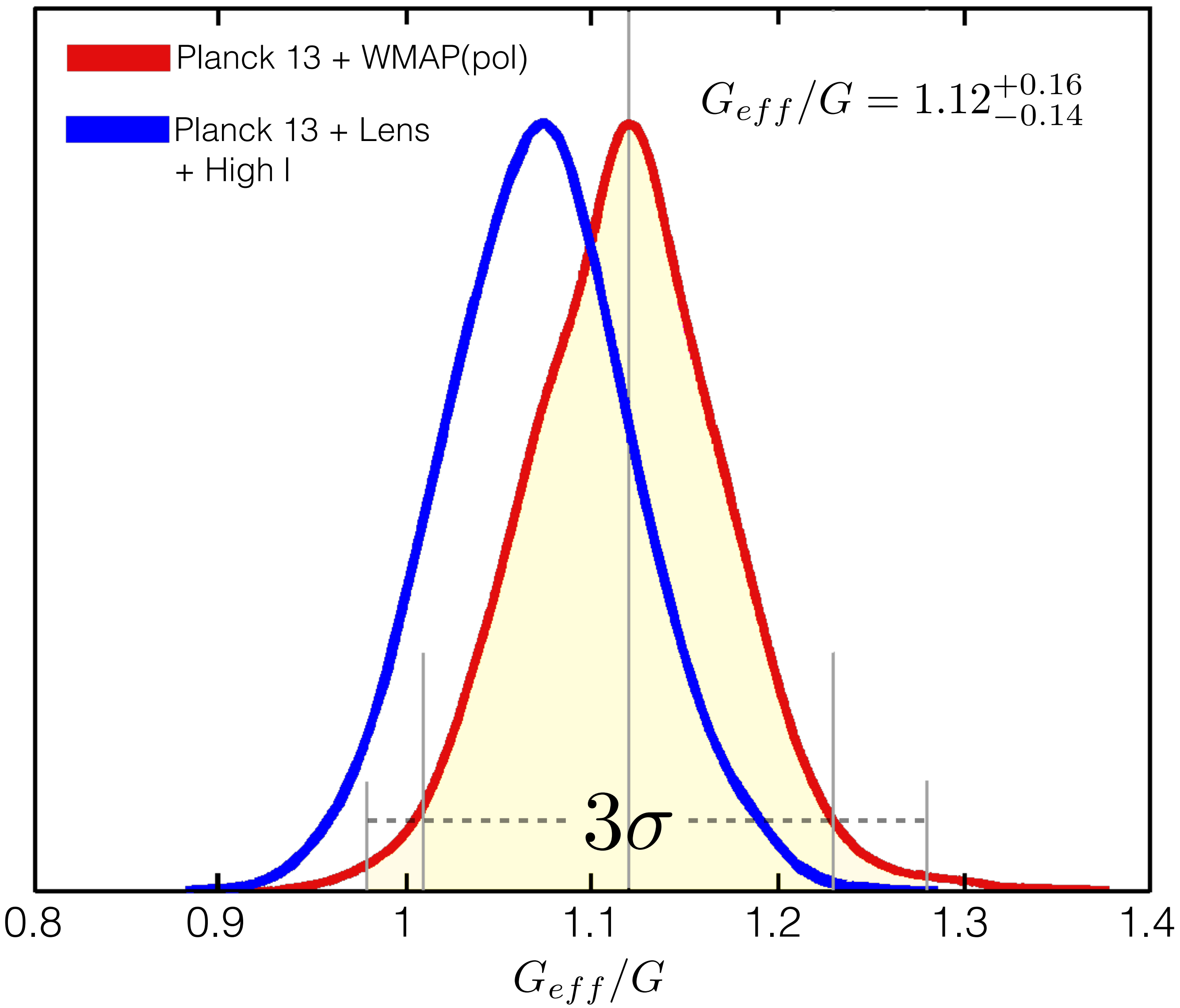
Testing theories: Brans-Dicke

- Simplest alternative to GR
- 1 parameter: ω

Solar system: $\omega > 40000 \ (2\sigma)$



A. Avilez & C.S., PRL 113, 011101 (2013)



Horndeski and Brans-Dicke

Horndeski 1974

$$S[g,\psi] = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\sum_{I=0}^{3} L^{(I)} + S_m$$

$$\begin{aligned}
L^{(0)} &= K^{(0)} \\
L^{(1)} &= K^{(1)}\Box\psi \\
L^{(2)} &= K^{(2)}\,R + K_X^{(2)}\left[(\Box\psi)^2 - (D\psi)^2\right] \\
L^{(3)} &= -6K^{(3)}\,G^{\mu\nu}\nabla_\mu\nabla_\nu\psi + K_X^{(3)}\left[(\Box\psi)^3 - 3(D\psi)^2\Box\psi + 2(D\psi)^3\right]
\end{aligned}$$

[where $D = \nabla\otimes\nabla$ $\quad X = -\frac{1}{2}(\nabla\psi)^2$ $\quad K^{(I)} = K^{(I)}(\psi, X)$]

BD as a limiting case

1. Taylor expand:

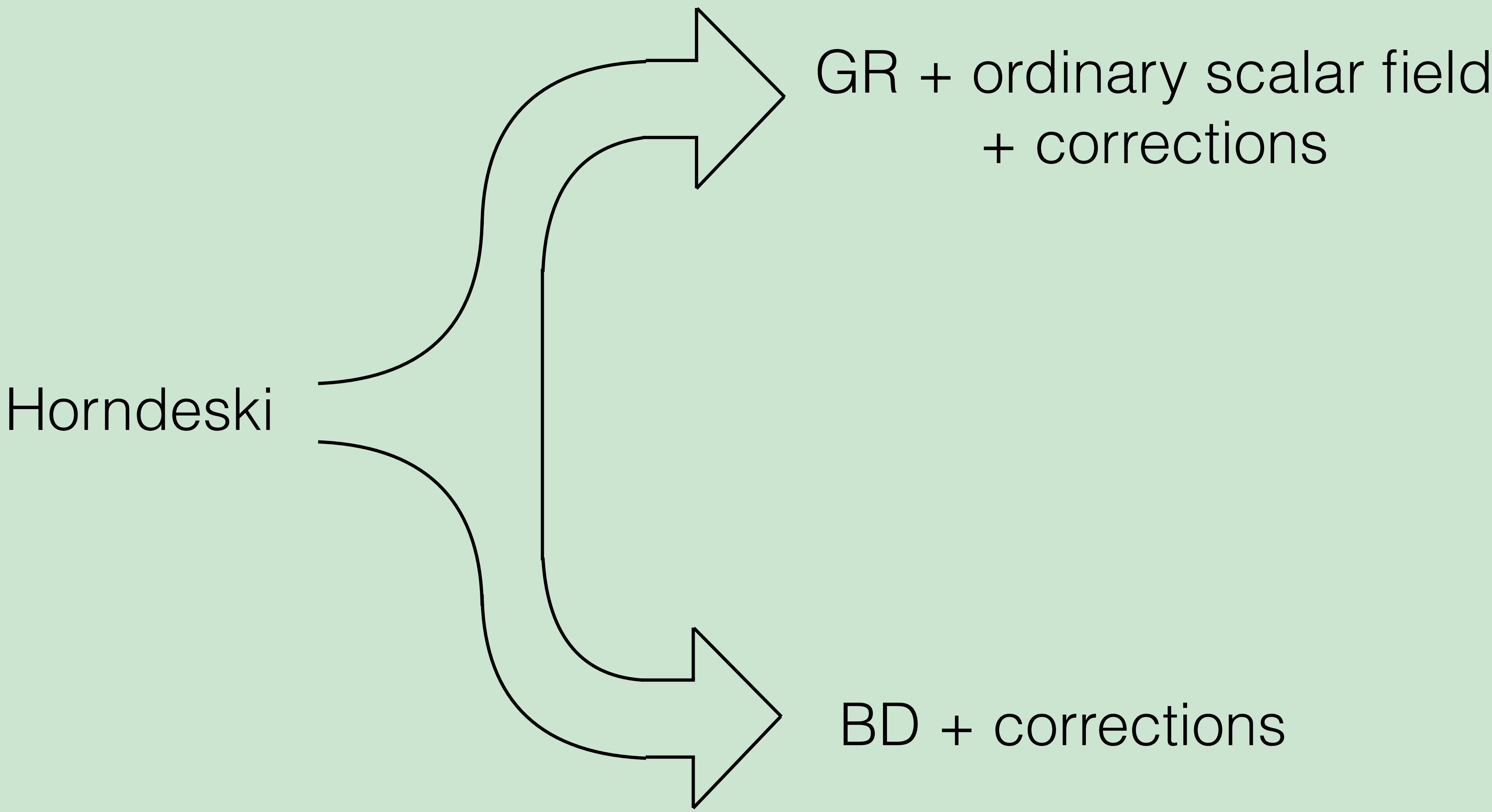
$$\begin{aligned}
K^{(0)} &\approx -2\Lambda + 8\omega X + \epsilon_1\psi^2/\ell_*^2 + \epsilon_2\ell_*^2X^2 \\
K^{(1)} &\approx \epsilon_3\psi^2 + \epsilon_4\ell_*^2X \\
K^{(2)} &\approx \psi^2 + \epsilon_5\psi^4 + \epsilon_6\ell_*^2X \\
K^{(3)} &\approx \epsilon_7\ell_*^2\psi^2 + \epsilon_8\ell_*^4X
\end{aligned}$$

2. Field redefinition: $\phi = \psi^2$

$$\Rightarrow \quad S[g,\phi] = S_{BD} + \sum_{i=1}^{8}\epsilon_i C_i[g,\phi]$$

A. Avilez & C.S., PRL 113, 011101 (2013)

Horndeski and Brans-Dicke



A. Avilez & C.S., PRL 113, 011101 (2013)

The Vainshtein mechanism

A. Vainshtein 1972

Massive gravity

2 x helicity-2 $h_{\mu\nu}$

2 x helicity-1 A_μ

1 x helicity-0 ϕ

vDVZ problem: zero graviton mass limit not GR

The Vainshtein mechanism

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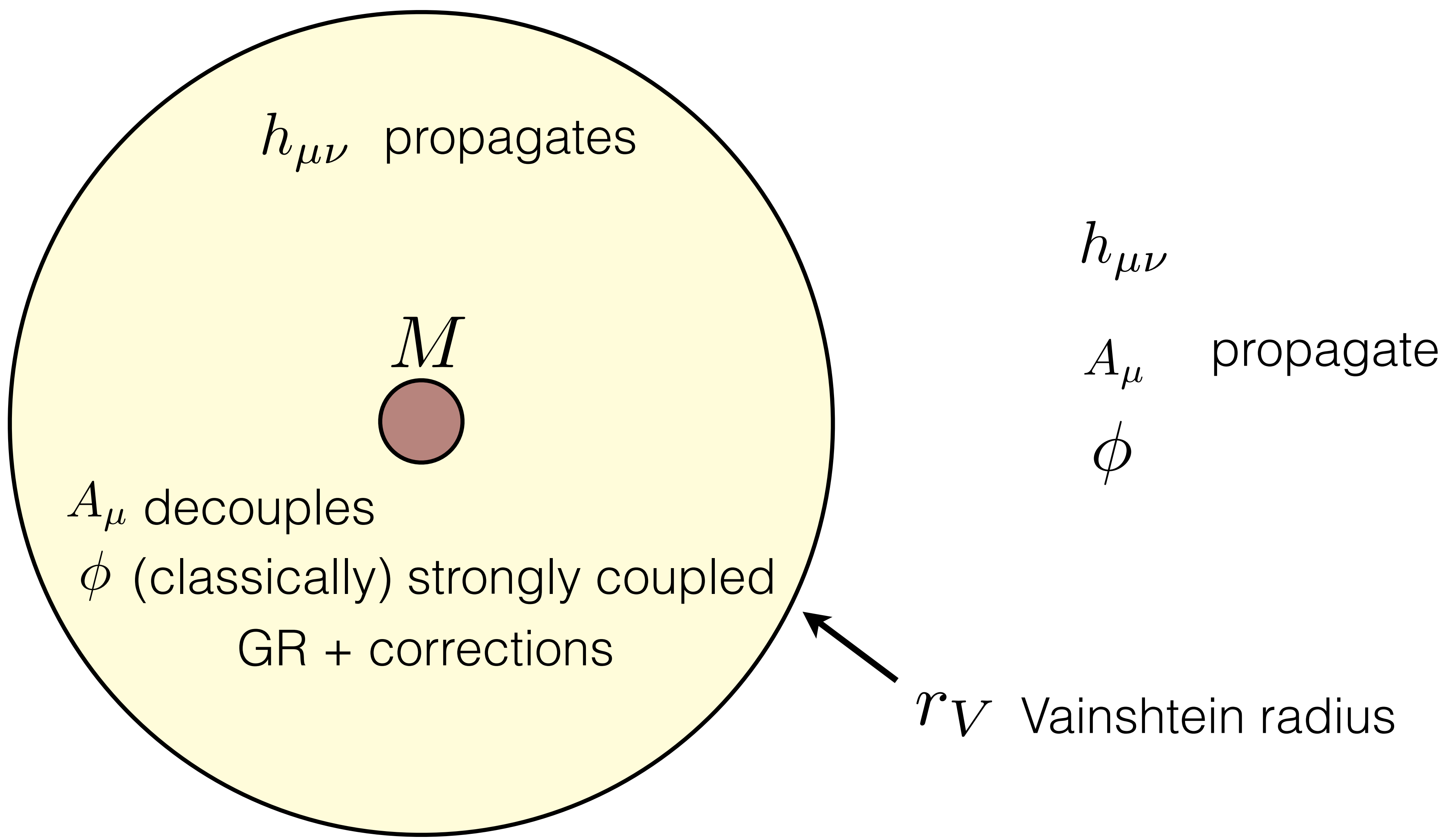
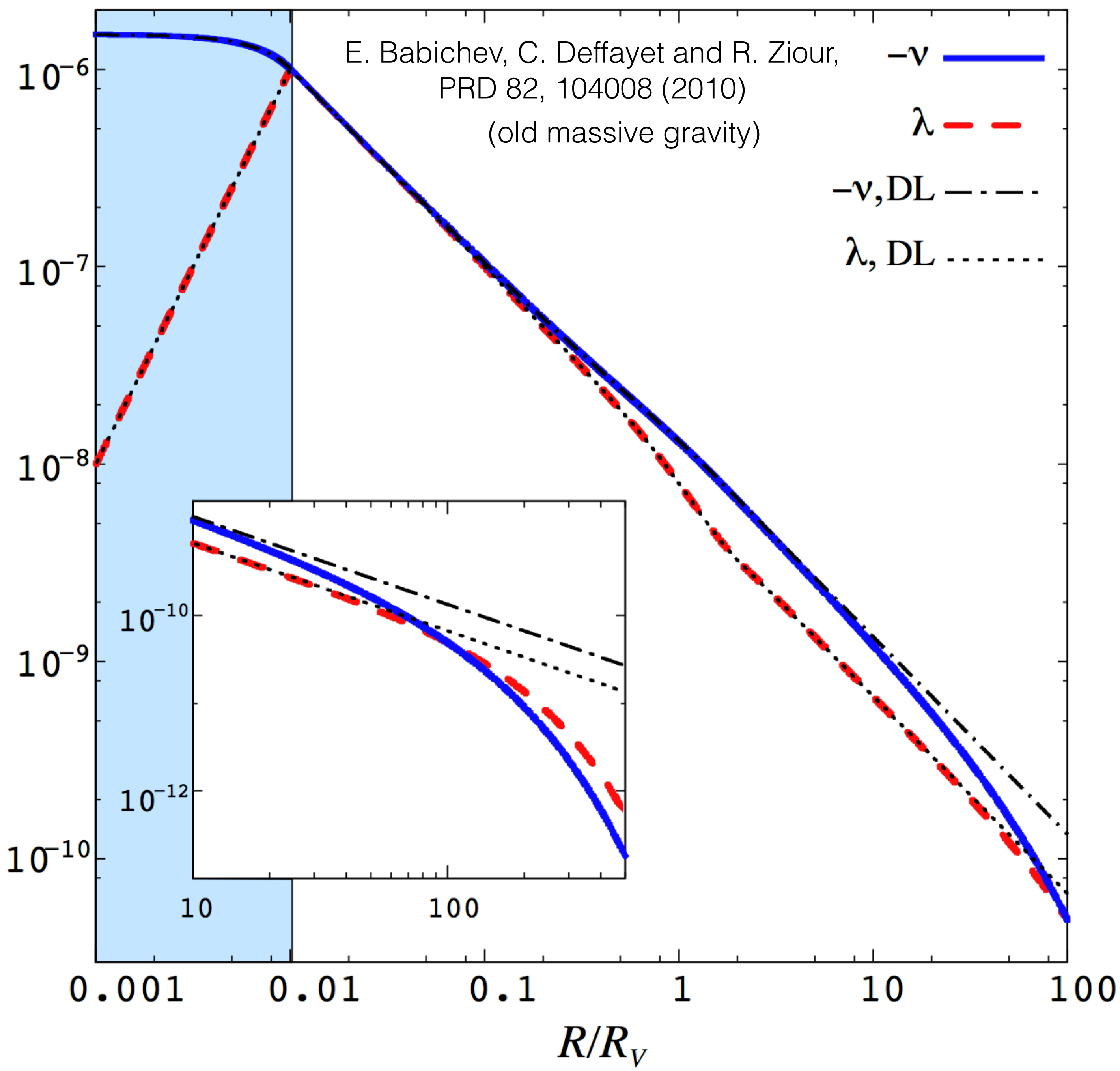


Old massive gravity and Vainshtein



Vainshtein mechanism for Cubic Galileon

Conformal relation $g_{\mu\nu} = e^{2\chi}\tilde{g}_{\mu\nu} \quad \Rightarrow \quad h_{00} = \tilde{h}_{00} - 2\chi = \frac{2GM}{r} - 2\chi$

Point source on Minkowski $\frac{2\omega+3}{r^2}\frac{d}{dr}\left[r^2\chi'\right] + \frac{\alpha}{r^2}\frac{d}{dr}\left[r(\chi')^2\right] = GM\frac{\delta(r)}{r^2}$

$$\Rightarrow \quad \chi' = \frac{2\omega+3}{2\alpha}r\left[-1+\sqrt{1+\frac{4GM\alpha}{(2\omega+3)^2r^3}}\right]$$

two limits

$\alpha \to 0$ $\chi = -\frac{GM}{(2\omega+3)r} + \frac{(GM)^2}{4(2\omega+3)^3}\frac{\alpha}{r^4} + \dots$

$$h_{00} = \frac{\tilde{r}_s}{r}\left[1 - \frac{1}{64\pi(2\omega+3)^2(2+\omega)}\left(\frac{r_V}{r}\right)^3 + \dots\right]$$

$\alpha \to \infty$ $\chi = 2\sqrt{\frac{GM}{\alpha}}r^{1/2} + \dots$

$$h_{00} = \frac{r_s}{r}\left[1 - 4\sqrt{2\pi}\left(\frac{r}{r_V}\right)^{3/2} + \dots\right]$$

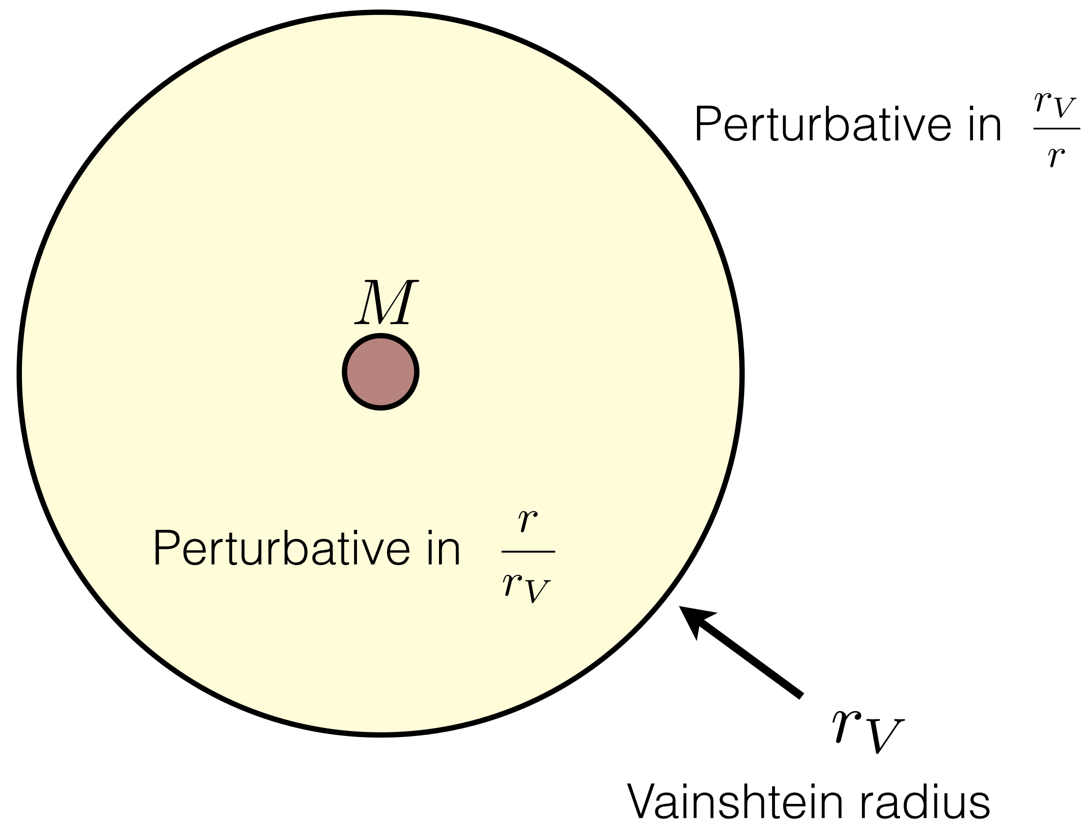
Parametrized Post-Newtonian-Vainshteinian formalism

A. Avilez, A. Padilla, P. Saffin, and C. S. (2015)

New dof give corrections to the PPN potentials, but… two regimes.

2-order expansion:

$$h_{00} = \sum_{n=1}^{\infty} \sum_{m=0}^{\pm\infty} h_{00}^{(2n,m)}$$



Primary order: v (as in PPN)

Secondary order: α The (only) combination of the Schwarzschild radius and the Vainshtein radius which is independent of the source mass

-powers: outside, +powers: inside

Example: Cubic galileon theory — Outside

A. Avilez, A. Padilla, P. Saffin, and C. S. (2015)

$$S[g,\phi] = S_{BD} + \frac{M_p}{8\Lambda^3}\int d^4x\sqrt{-g}\frac{(\nabla\phi)^2}{\phi^3}\Box\phi + S_M[g]$$

Galileon Parameter: $\alpha = \dfrac{M_p}{\Lambda^3}$

Vainshtein radius: $r_V = \dfrac{1}{\Lambda}\left(\dfrac{M}{M_P}\right)^{1/3}$

$$\alpha \sim \frac{r_V^3}{r_s}$$

Expansion to O(2,-2)

$$h_{00} = 2G_C U + 2g_V G_C^3 U_V^{(out)}$$

$$h_{ij} = \left[2\gamma G_C U + \gamma_V G_C^3 U_V^{(out)}\right]\delta_{ij},$$

$$G_C = \frac{4+2\omega}{3+2\omega}\frac{G}{\phi_0^{(out)}}$$

(as BD)

PPN Parameter: $\gamma = \dfrac{1+\omega}{2+\omega}$

new PPNV Parameters: g_V γ_V

new PPNV potential:

$$U_V^{(out)} = \int d^3x' \int d^3x'' \rho(t,\vec{x}')\rho(t,\vec{x}'')\left\{\frac{(\vec{x}-\vec{x}')\cdot(\vec{x}-\vec{x}'')}{|\vec{x}-\vec{x}'|^3|\vec{x}-\vec{x}''|^3} - 2\frac{(\vec{x}-\vec{x}')\cdot(\vec{x}'-\vec{x}'')}{|\vec{x}-\vec{x}'|^3|\vec{x}'-\vec{x}''|^3}\right\}$$

Example: Cubic galileon theory — Inside

Tool: dual theory   Padilla and Saffin (2011)

A. Avilez, A. Padilla, P. Saffin, and C. S. (2015)

auxiliary fields: $A_\mu = \sqrt{\alpha}\nabla_\mu \phi \quad Z = \sqrt{\alpha}\Box\phi$

$$\Rightarrow \quad S_{\rm dual} = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left\{\phi R - \frac{1}{\alpha}\frac{\omega}{\phi}A^2 + \frac{1}{8\phi^3}\left(A^2\Box\phi + 2ZA^\mu\nabla_\mu\phi\right) - \frac{1}{4\sqrt{\alpha}}\frac{1}{\phi^3}ZA^2\right\}$$

$\alpha \to \infty$ possible

Expansion to O(2)

$$h_{00}^{(2)} = 2G_N U + 2\sum_n g_n^{(in)} G_N^{-n} U_n^{(in)}$$

$$h_{ij} = \left(2G_N U + 2\sum_n \gamma_n^{(in)} G_N^{-n} U_n^{(in)}\right)\delta ij$$

new PPNV Parameters: $g_n^{(in)} \quad \gamma_n^{(in)}$

$$\mathcal{L}(u,v) = 2\vec{\nabla}\cdot\left((\vec{\nabla}^2 v)\vec{\nabla}u\right) - \vec{\nabla}^2(\vec{\nabla}u\cdot\vec{\nabla}v) \quad \Rightarrow$$

$$\mathcal{L}(U_0^{(in)}, U_0^{(in)}) = 4\pi\rho$$

$$\mathcal{L}(U_1^{(in)}, U_0^{(in)}) + \mathcal{L}(U_0^{(in)}, U_1^{(in)}) = \nabla^2 U_0^{(in)}$$

$$\cdots$$

Conclusions

- Cosmological tests of gravity are independent of astrophysical and local tests.
- Cosmological tests still not good enough but will be in the future
- Many ways to parametrise gravity for cosmology: pick one depending on what you need to achieve.
- Theories of gravity can morph: screening: PPNV expansion can help!
- Even seemingly innocent theories like Brans-Dicke can hide a lot of complexity when viewed as effective theories.