Small Seminar, Large Lectures!

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Small Seminar

- Tricky name!
- Speaker not scheduled
- First lesson: I have <u>NOT</u> nailed that subject !

1990's

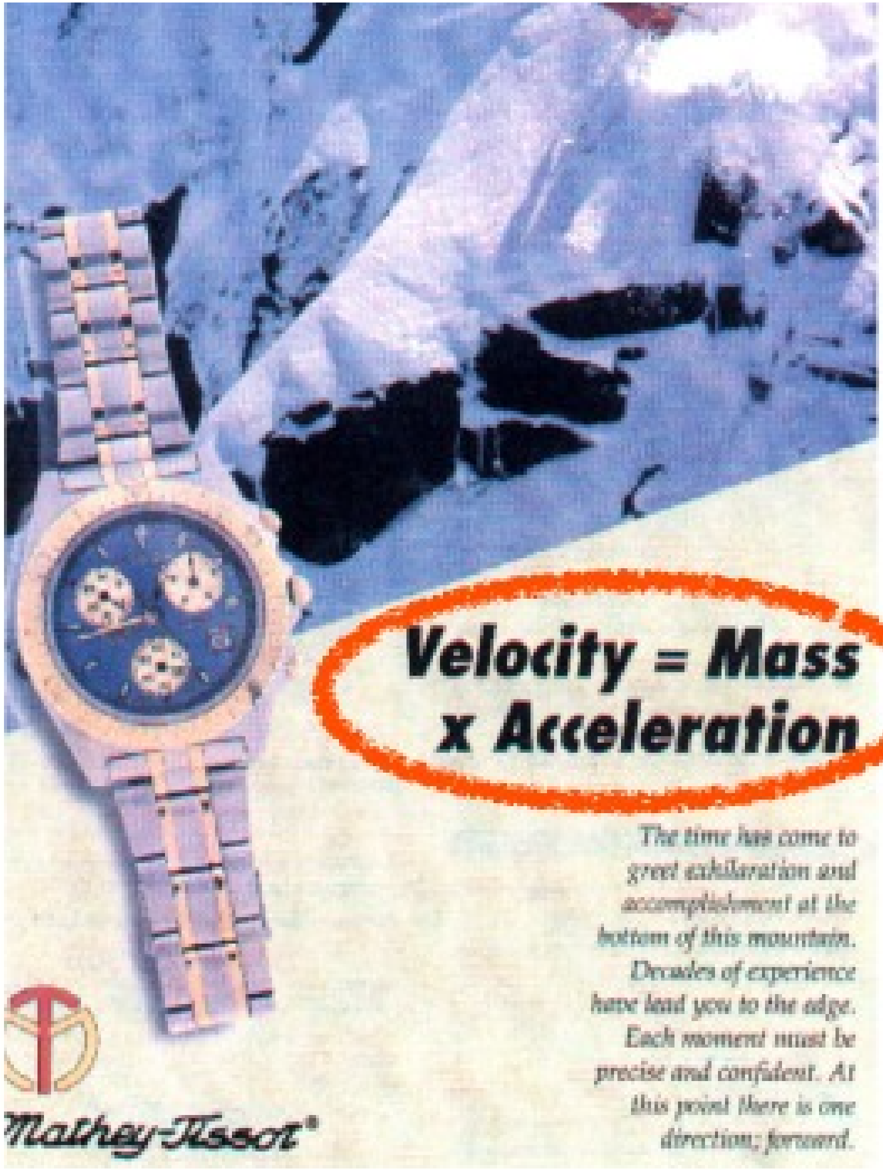
- Marios' Student (Msc candidate)
- My fisrt BSCG: 1993
  - Isolation & immersion (1980's: island!)

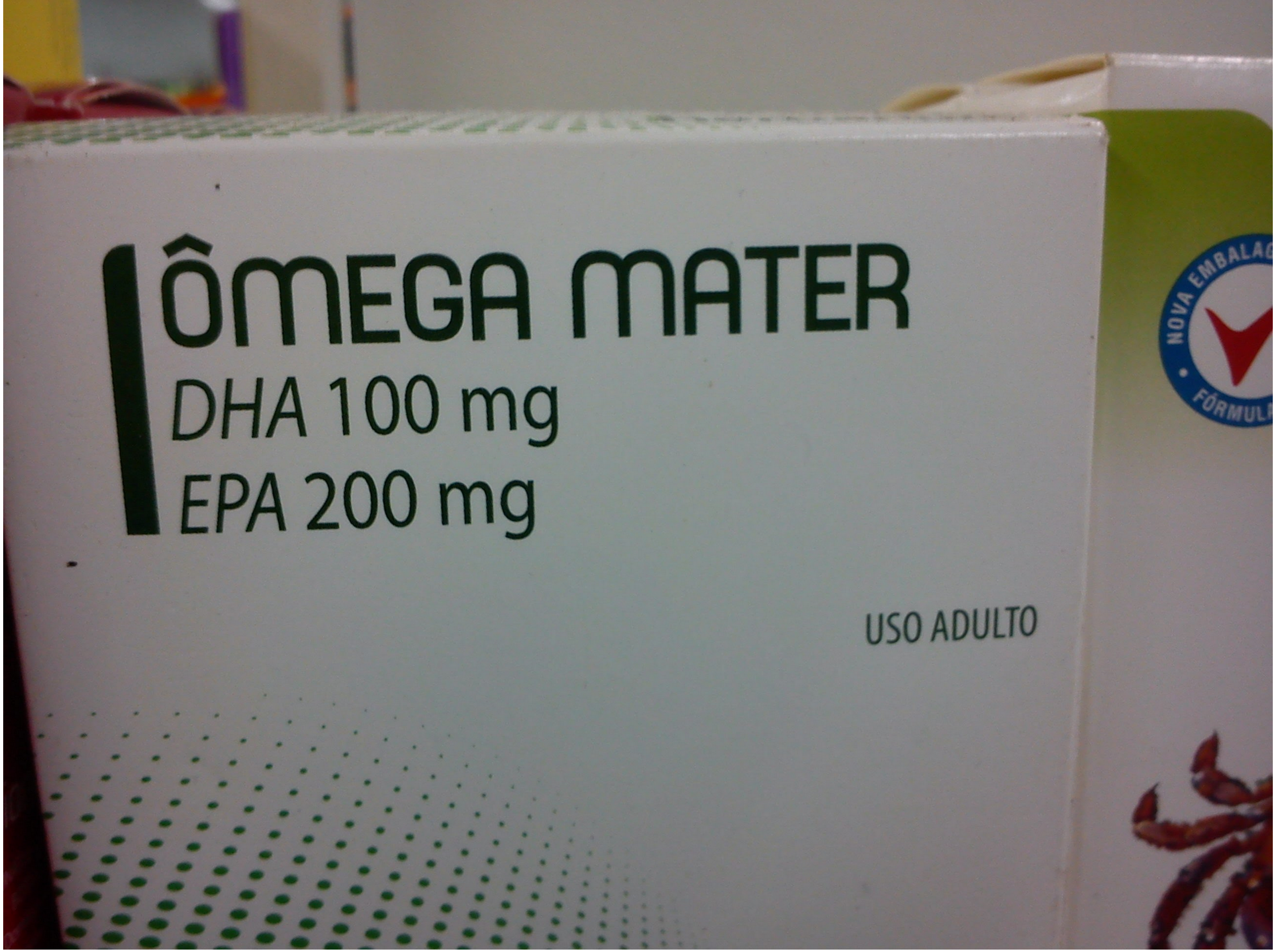
1993 – VII BSCG

1995 – VIII BSCG

A lot has happenned since then…


Quintessence
Ventoux – Rhône Valley Vineyards
CHÂTEAU
PESQUIÉ


Velocity = Mass
x Acceleration
The time has come to
greet exhilaration and
accomplishment at the
bottom of this mountain.
Decades of experience
have lead you to the edge.
Each moment must be
precise and confident. At
this point there is one
direction; forward.
Mathey-Tissot®


ÔMEGA MATER
DHA 100 mg
EPA 200 mg
USO ADULTO

$(\mathcal{N})$ BSCG

- Still, the beach was no match for the lectures!
- Immersion really works
  - Les Houches
  - Swieca Schools
  - ...

MSc

- 2nd subject !
- Cosmological Perturbations
  - Mario
  - Salim
  - Martha
  - Klippert

Growth of Perturbations in Modified Theories of Gravity

- Inflation
  - Accelerated expansion
  - Starobinsky's model
- Long wavelength Perturbations: growth!
  - Mukhanov, Feldman, Brandenberger, Phys. Rep. 215, 5-6 (1992)
  - Carloni, Dunsby and Troisi, PRD 77, 024024 (2008)

Modified Theories of Gravity

$$S = \int \sqrt{-g}\, f(R)\, d^4x$$

$$f_R \equiv \frac{df}{dR}$$

$$\begin{aligned} f_R\left(R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R\right) &= \\ &= \frac{1}{2}g_{\mu\nu}\left(f - Rf_R\right) + \nabla_\mu\nabla_\nu f_R - \\ &- g_{\mu\nu}\nabla_\alpha\nabla^\alpha f_R \end{aligned}$$

$$3\Box f_R(R) + R\cdot f_R(R) - 2f(R) = 0$$

Conformal transformation to the Einstein frame:

$$\tilde{g}_{\mu\nu} \equiv \chi g_{\mu\nu}$$

$$\chi \equiv f' = \exp\left[\sqrt{\frac{2}{3}}\phi\right]$$

$$S = \int d^4x \sqrt{-g} \frac{1}{2} \left[\tilde{R} - \tilde{g}^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - 2V(\phi)\right]$$

Jordan frame

$$S = \int \sqrt{-g}\, f(R)\, d^4x$$

$$\tilde{g}_{\mu\nu} \equiv \chi g_{\mu\nu}$$

$$\chi \equiv f_R = \exp\left[\sqrt{\frac{2}{3}}\phi\right]$$

$$V(\tilde{\chi}) \equiv \frac{Rf' - f}{2(f')^2}$$

Einstein frame

$$S = \int d^4x \sqrt{-g}\frac{1}{2}\left[\tilde{R} - \tilde{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - 2V(\phi)\right]$$

Jordan frame ?

$$S = \int \sqrt{-g}\, f(R)\, d^4x$$

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Einstein frame

$$S = \int d^4x \sqrt{-g}\frac{1}{2}\left[\tilde{R} - \tilde{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - 2V(\phi)\right]$$

Guido Magnano and Leszek M. Sokokowski,
Phys. Rev. D50 (8), 5039 (1994)

$$f(\phi) = \mathrm{e}^{2\beta\phi} \left[2V_E(\phi) + 2\beta^{-1} \frac{\mathrm{d}V_E(\phi)}{d\phi} \right]$$

$$R(\phi) = \mathrm{e}^{\beta\phi} \left[4V_E(\phi) + 2\beta^{-1} \frac{\mathrm{d}V_E(\phi)}{d\phi} \right]$$

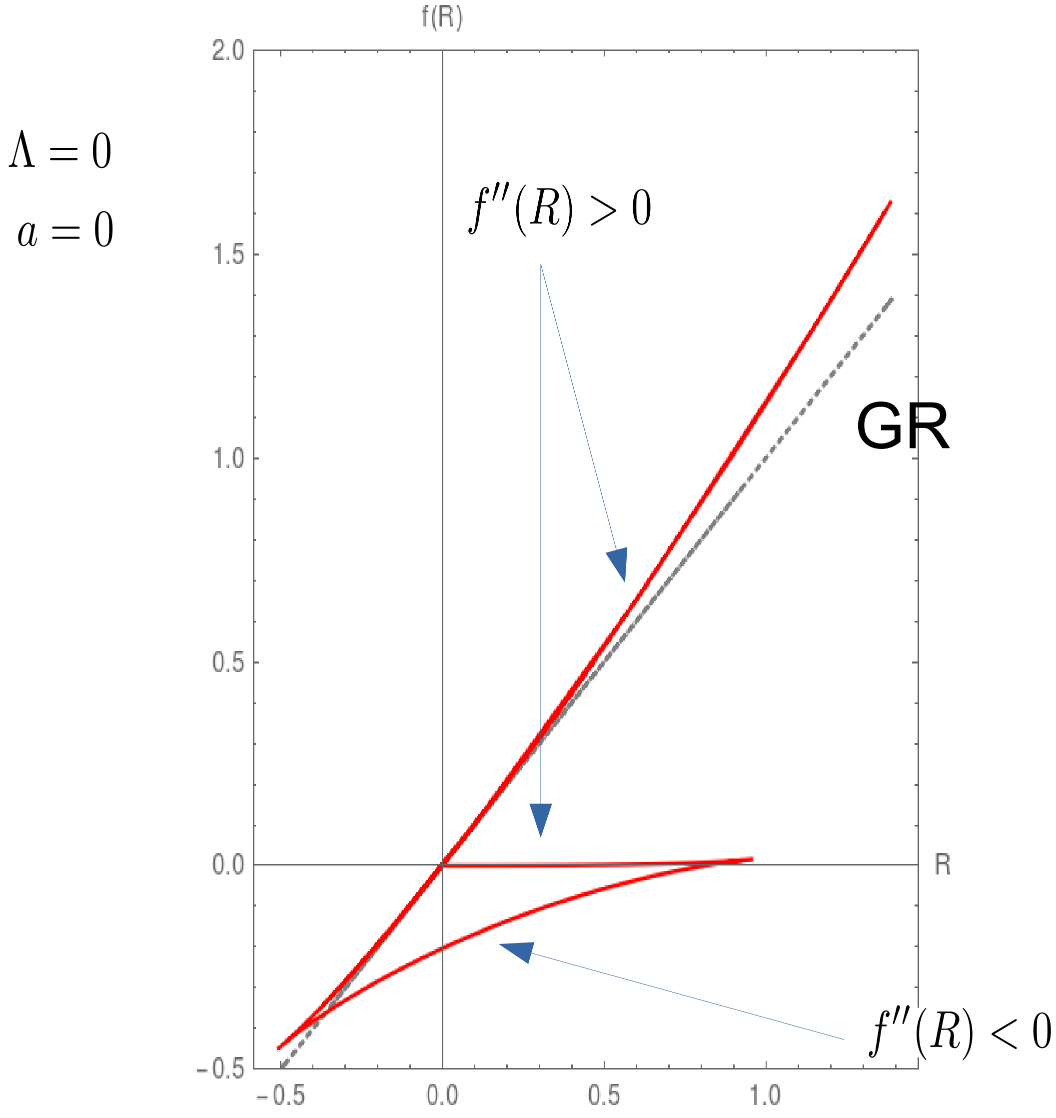
$$\beta = \sqrt{\frac{2}{3}}$$

$$V(\phi) = \frac{1}{2}m^2(\phi - a)^2 + \Lambda$$

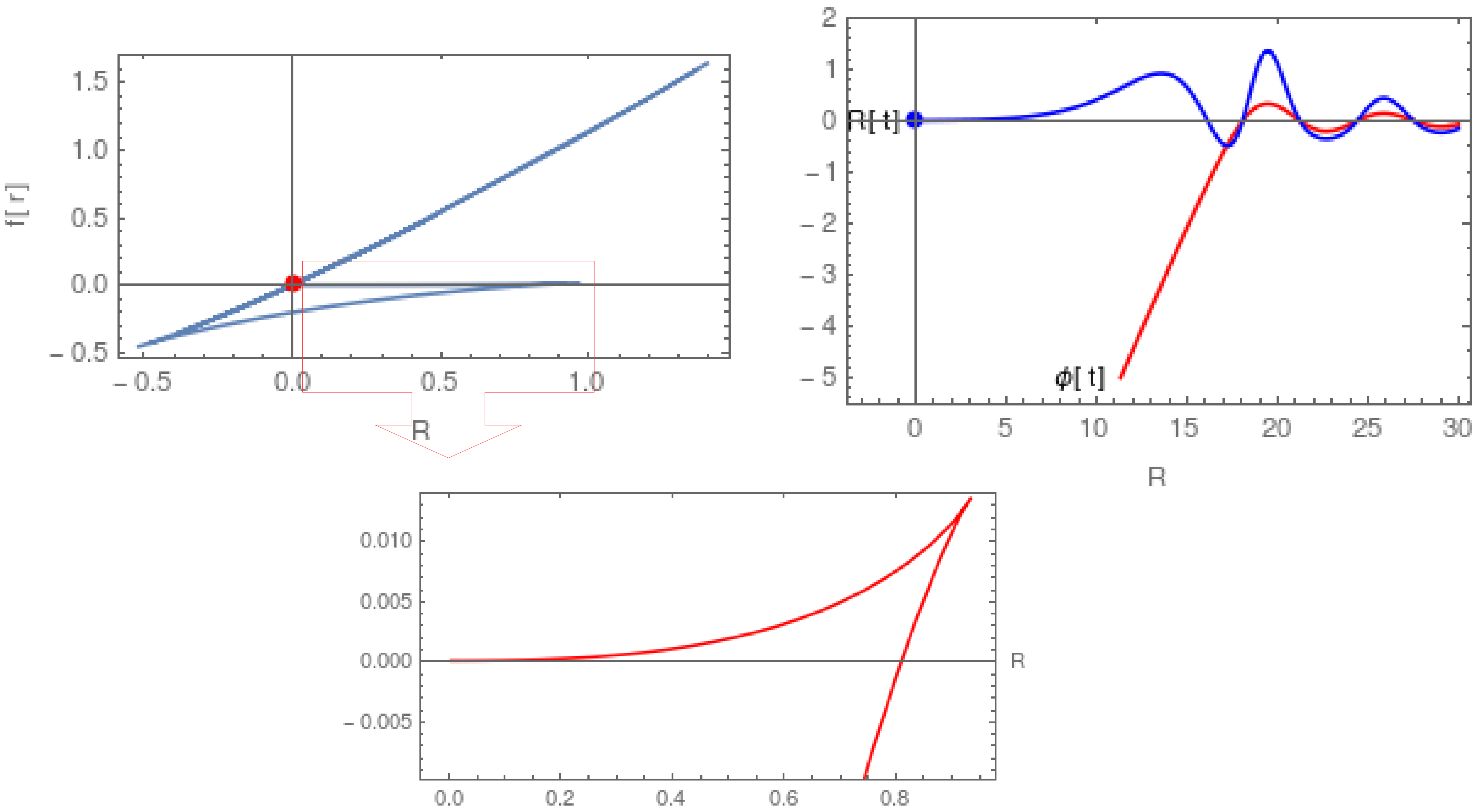
- Simplest potential
- Similar (but different!) from Starobinsky's
- Initial Conditions:
  - In the Einstein Frame
  - Suitable for inflation (in both frames)

  => $R_J(t_i) \rightarrow 0$ (but $\rho \rightarrow \infty$!)

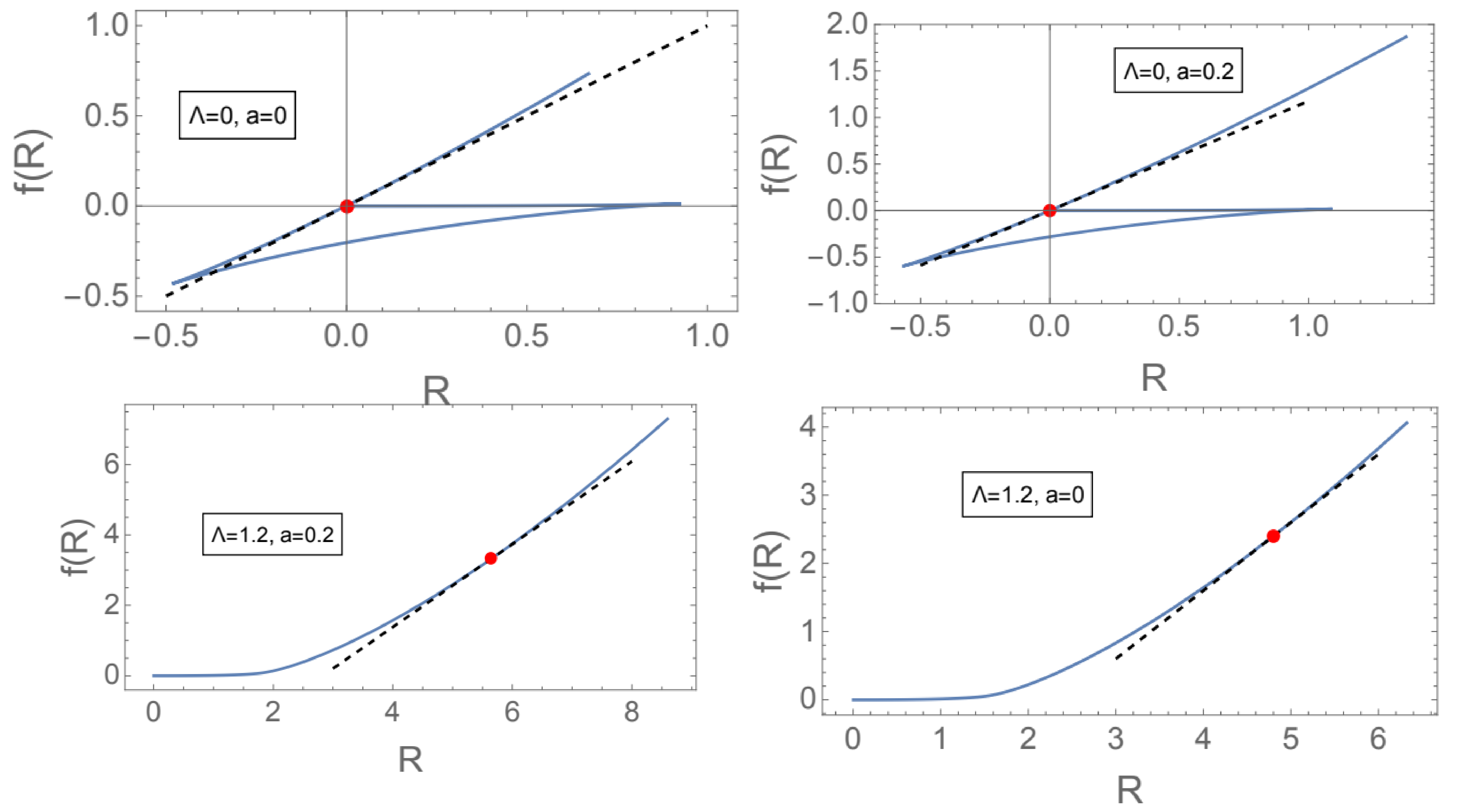
"Thermodynamics of f(R) theories of gravity", JCAP June (2020), C.D. Peralta and S.E. Jorás



$\Lambda = 0$
$a = 0$
f(R)
$f''(R) > 0$
GR
$f''(R) < 0$
R
2.0
1.5
1.0
0.5
0.0
-0.5
-0.5
0.0
0.5
1.0



f[r]
1.5
1.0
0.5
0.0
– 0.5
– 0.5
0.0
0.5
1.0
R
2
1
0
R[t]
– 1
– 2
– 3
– 4
– 5
ϕ[t]
0
5
10
15
20
25
30
R
0.010
0.005
0.000
– 0.005
R
0.0
0.2
0.4
0.6
0.8



Λ=0, a=0
f(R)
R
Λ=0, a=0.2
f(R)
R
Λ=1.2, a=0.2
f(R)
R
Λ=1.2, a=0
f(R)
R

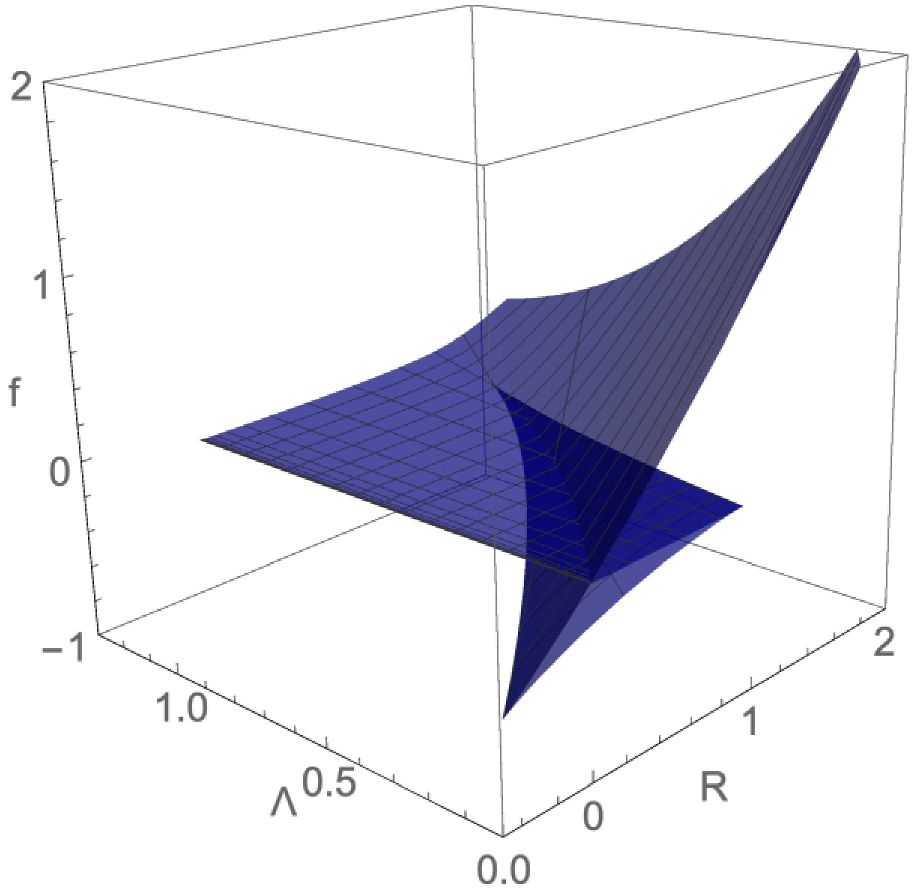
Physical meaning of a :

$$f(R)\Big|_{\mathrm{RG}} = \frac{1}{16\pi G_N} R$$

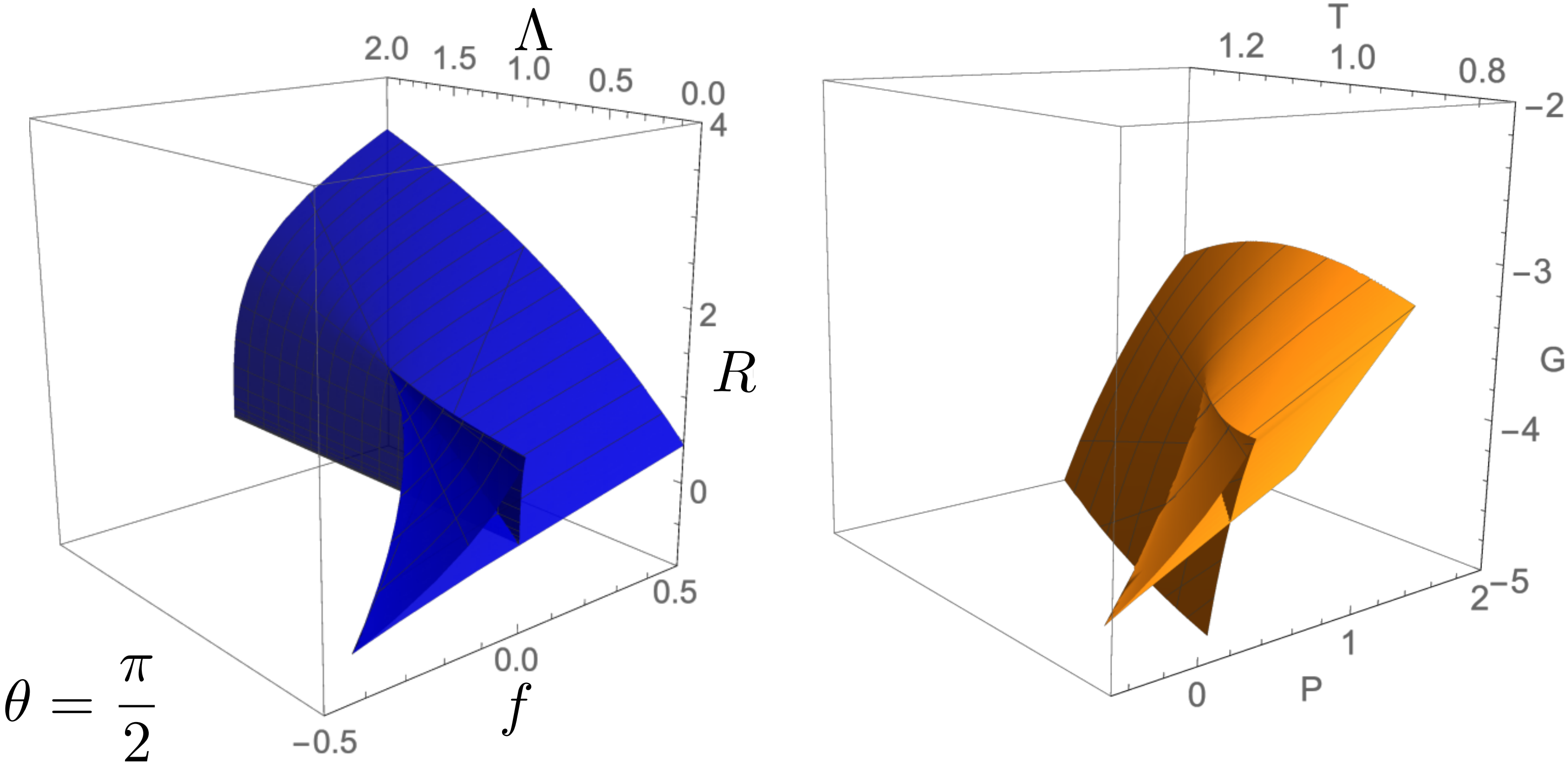
$$f'(R)\Big|_{R=0} = \frac{1}{16\pi G_N} \exp(\beta\, a) = \frac{1}{16\pi \tilde{G}_N}$$

$$\mathcal{L}_{\mathcal{J}} = f(R) \approx f(0) + f'(R)\cdot R \approx \mathrm{e}^{\beta a} R - 2\Lambda \exp(2\beta a)$$

Physical meaning of Λ:



$$\begin{pmatrix} -G \\ P \end{pmatrix} \equiv \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} f \\ R \end{pmatrix}$$

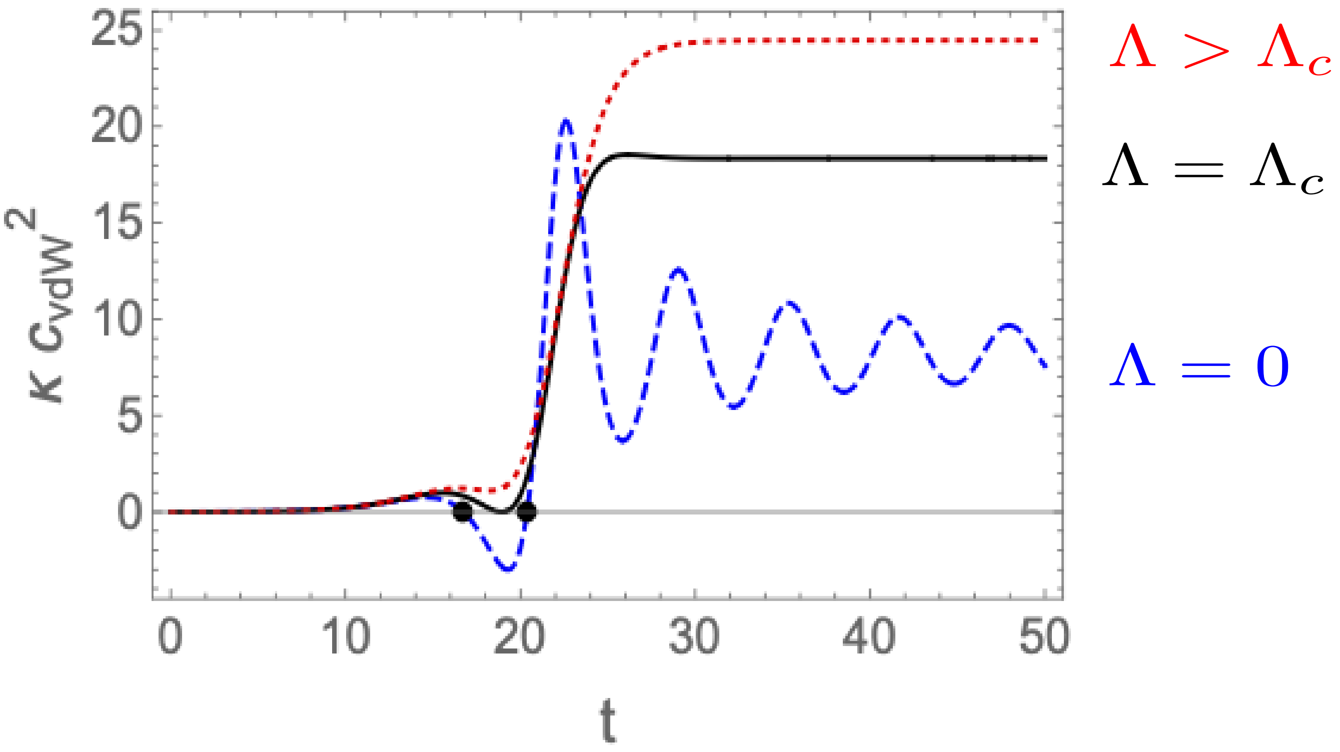


van der Waals

vdw

$$\rho =: \kappa/V$$

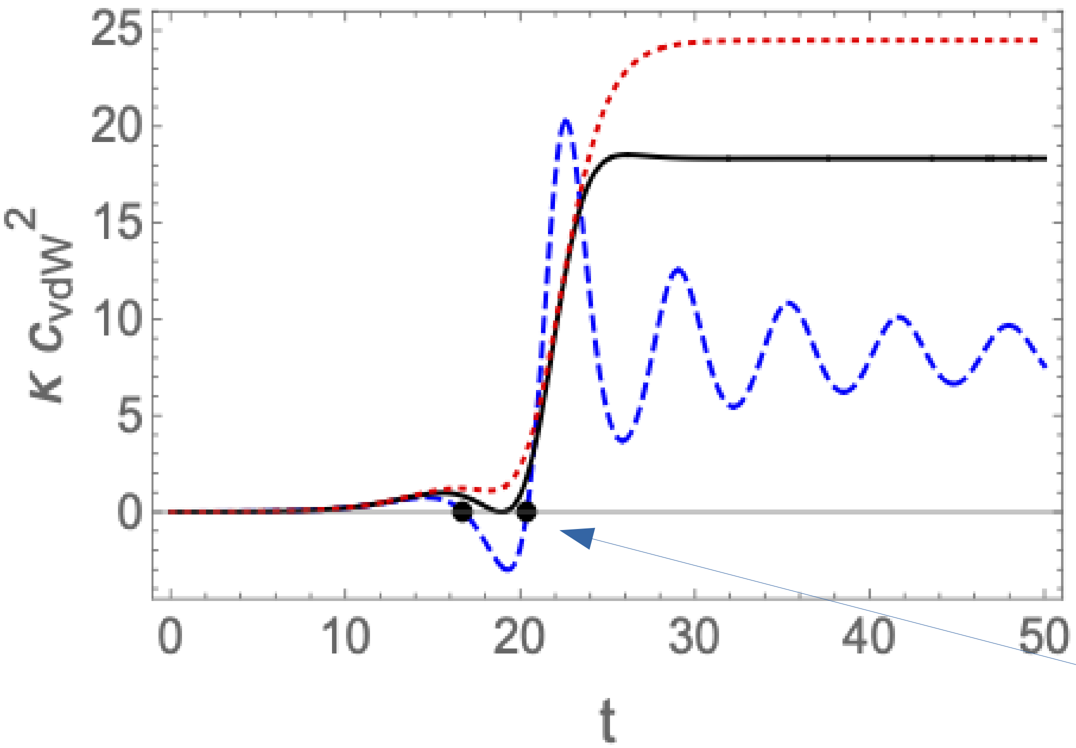
$$c^2_{\mathrm{vdW}} \equiv \dot{P}/\dot{\rho} = -(V^2/\kappa)\dot{P}/\dot{V}$$

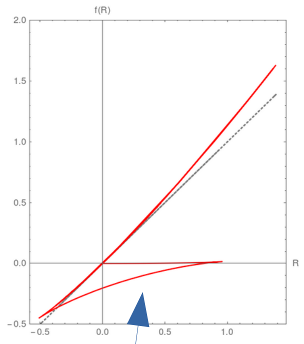


vdw

$$\rho =: \kappa/V$$

$$c_{\text{vdW}}^2 \equiv \dot{P}/\dot{\rho} = -(V^2/\kappa)\dot{P}/\dot{V}$$

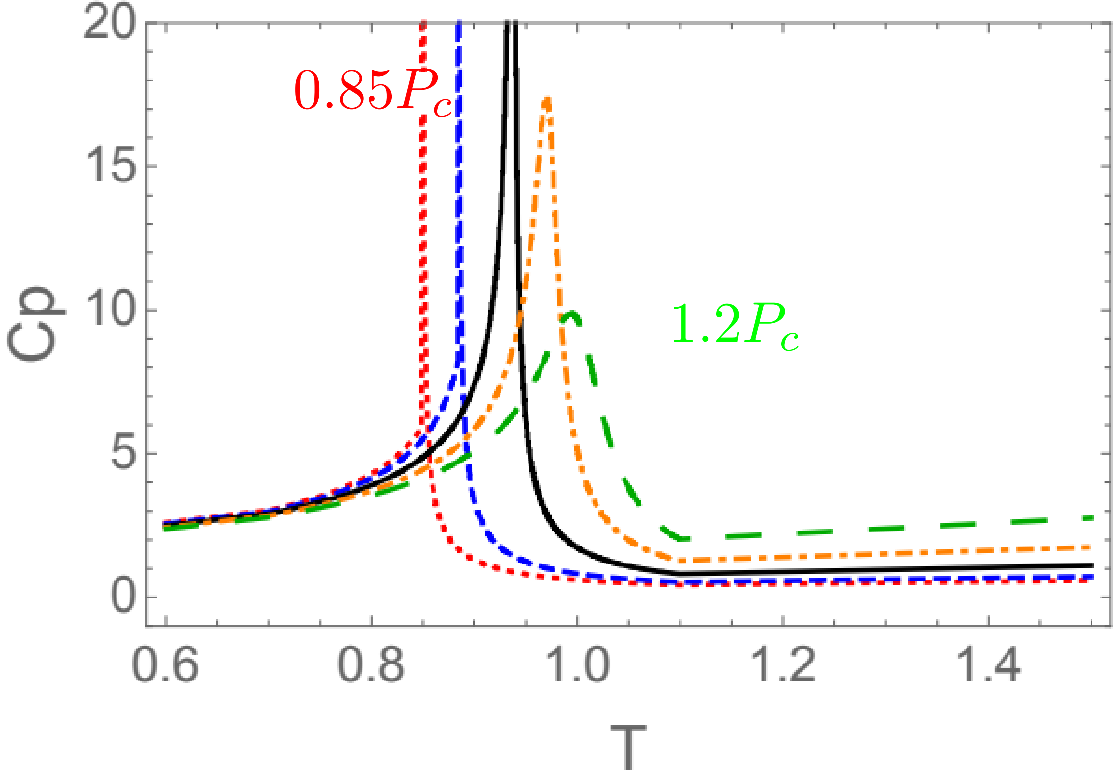




$$f''(R) < 0$$

Specific Heat at Constant Pressure

$$C_P|_{P_c} \sim [(T_c - T)/T_c]^{\alpha} \qquad \alpha \approx 1.00$$



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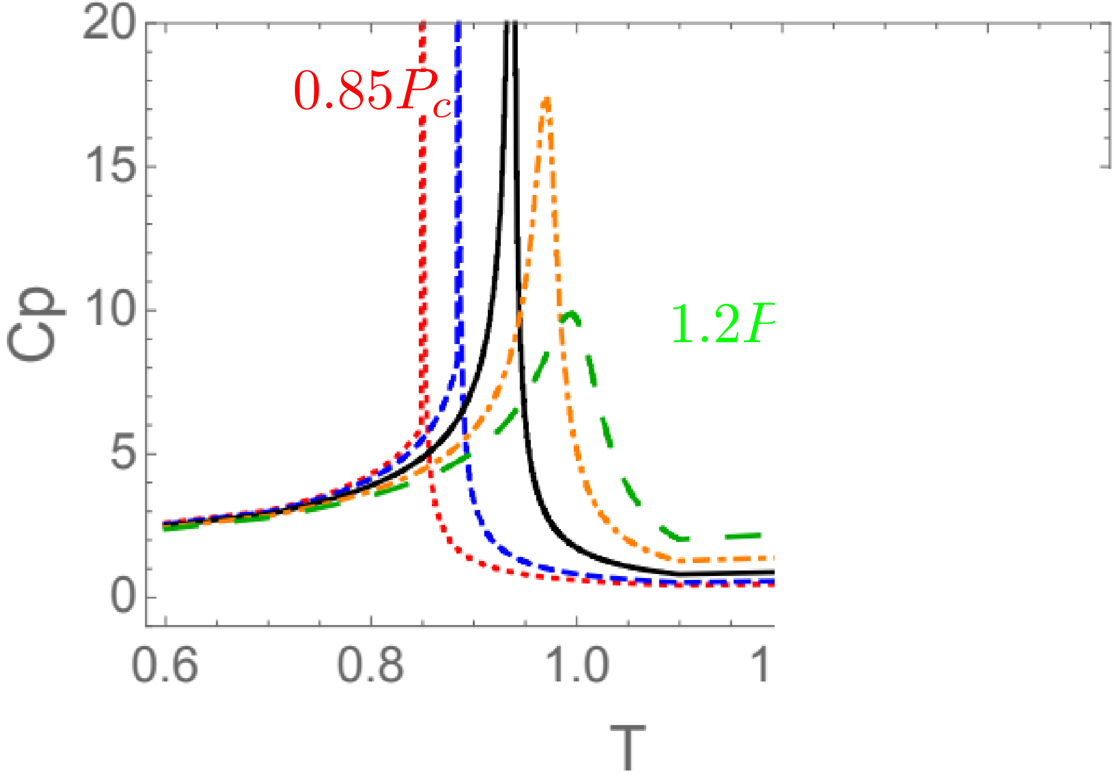

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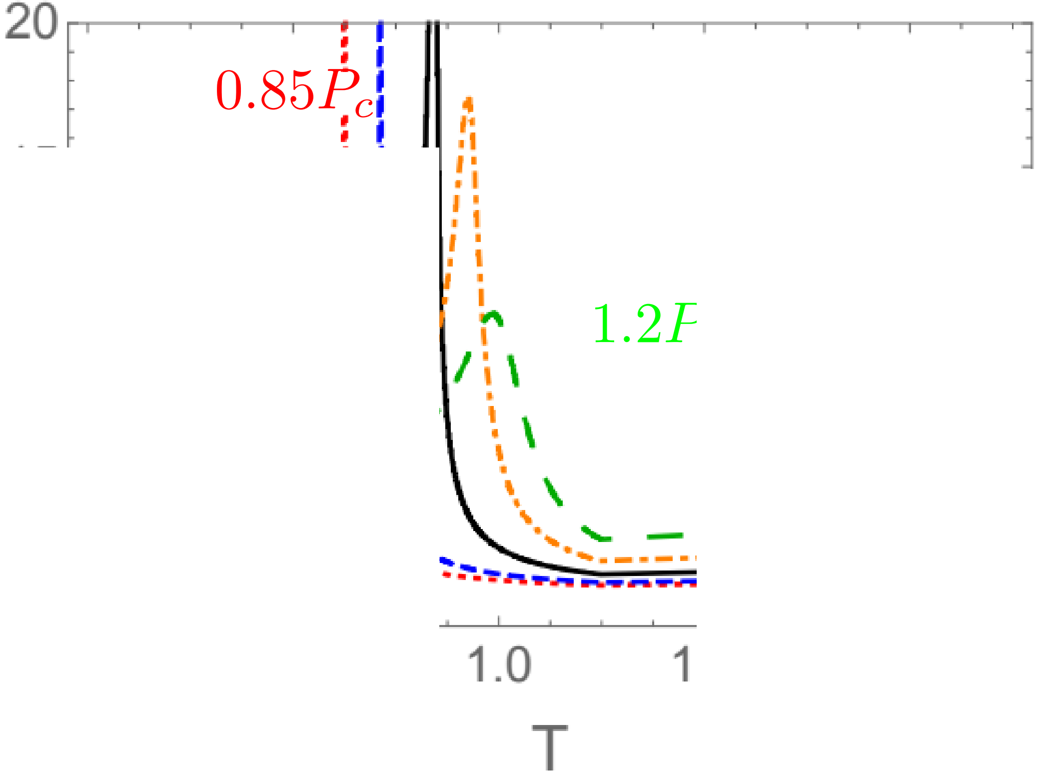
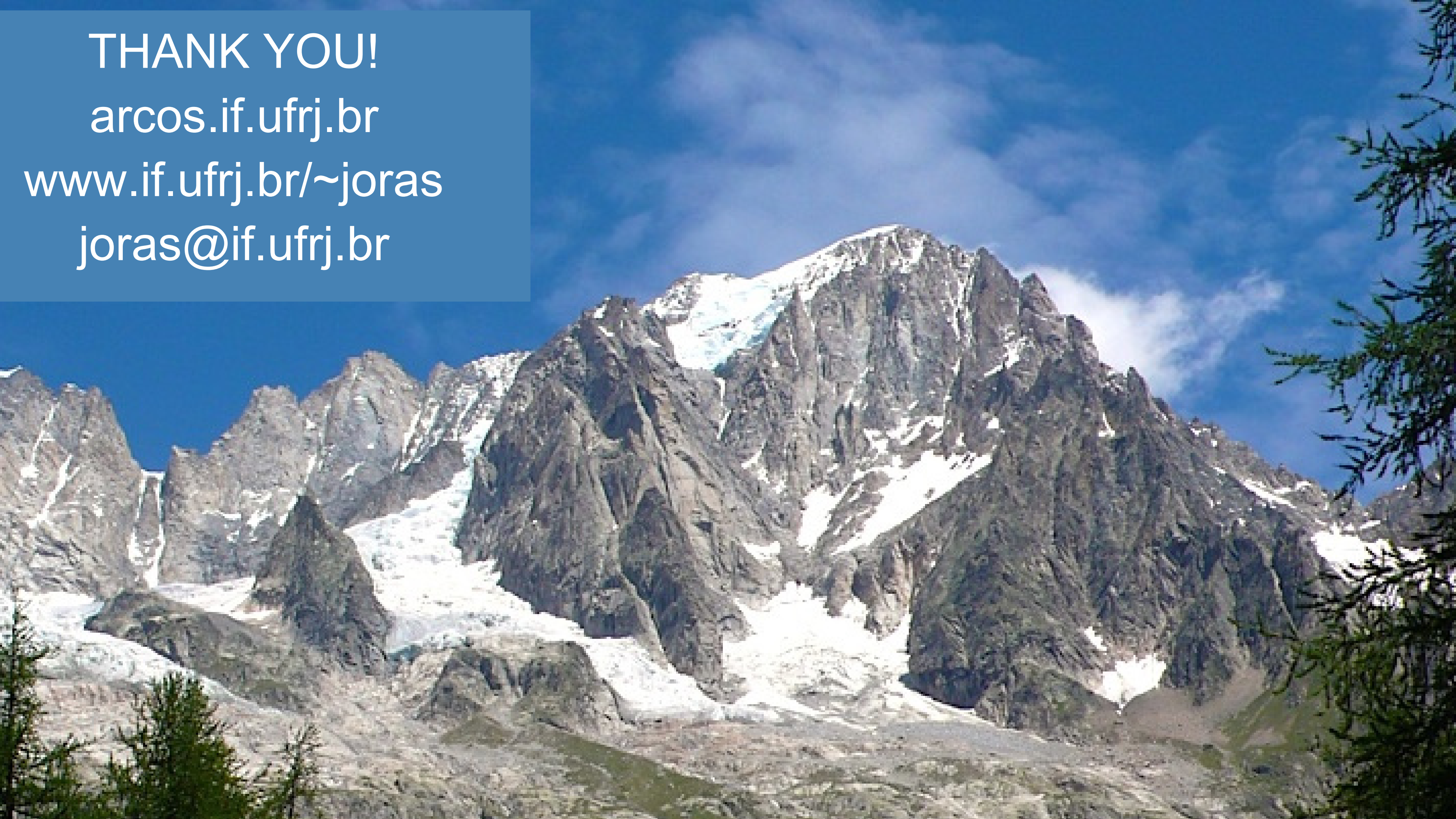


Instability:

- Growth of "curvature" perturbations?
  - Saikat Chakraborty (North- West University, South Africa)
  - Previous results: $f(R) = R + \alpha R^2$
    - Growth of super-Hubble modes in the accelerating phase?

With matter:

- Coupled growth (curvature + matter) ?
- In the final stage: parametric resonance?
- César Peralta (Universidad Antonio Nariño, Colombia)


THANK YOU!
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WARNING
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ALERT


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