The dark side of the Universe

Francesco Pace

Physics Department, Unito & INFN

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Outline

1. Introduction and motivation

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   - The cosmological constant

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   - Horndeski models
3. Linear perturbations
   - EFT
4. Nonlinear perturbations

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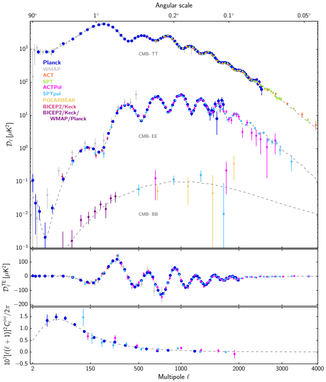
   - Spherical collapse model
5. Conclusions

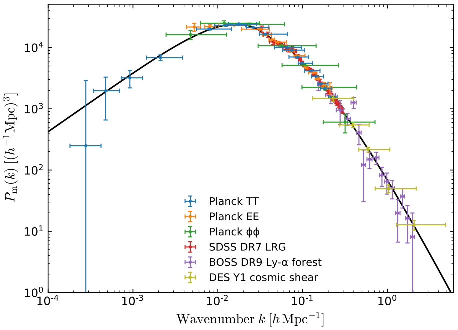
The three pillars of cosmology

- Background: no perturbations, very simple
- Linear perturbations: small amplitudes, important for large scales
- Nonlinear perturbations: very difficult to treat analytically, mainly done with approximate methods or N-body simulations. It's the "holy grail" of theoretical cosmology

Outline

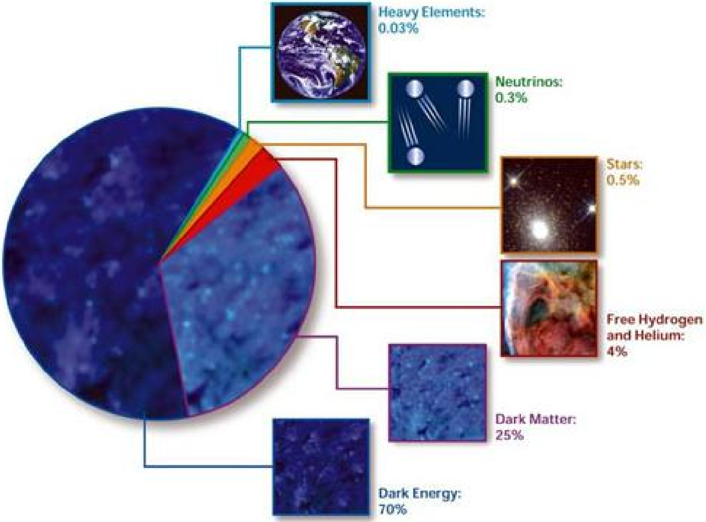
What do different probes tell us? ΛCDM





Courtesy of https://www.cosmos.esa.int, Planck2018 results

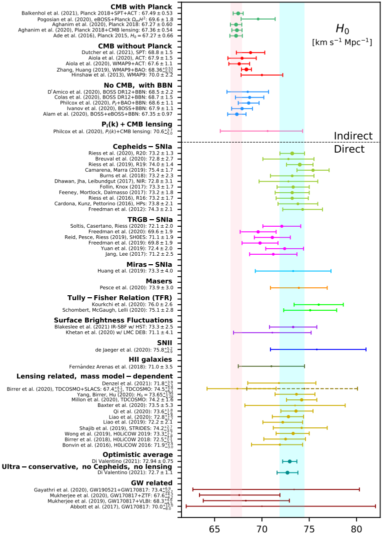
What's the Universe made of?



Outline

But there are problems

- Naturalness: why is the value of Λ so small?
- Coincidence: why is it important now?
- Tensions between low- and high-z probes (H_0, σ_8, $A_{\rm lens}$)



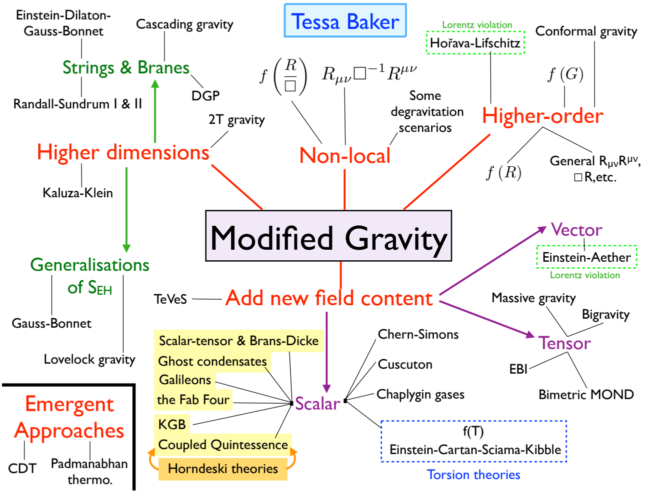
Solutions

1. It is the cosmological constant (anthropic principle, string landscape) - it agrees with data, but unsatisfactory
2. Supernova data are wrong (distance-duality relation) - unlikely
3. Violation of the Copernican principle (LTB models) or problems with GR (backreaction) - unlikely
4. Scalar field evolving (dark energy)
5. GR is wrong (modified gravity)

What do dark energy and modified gravity do?

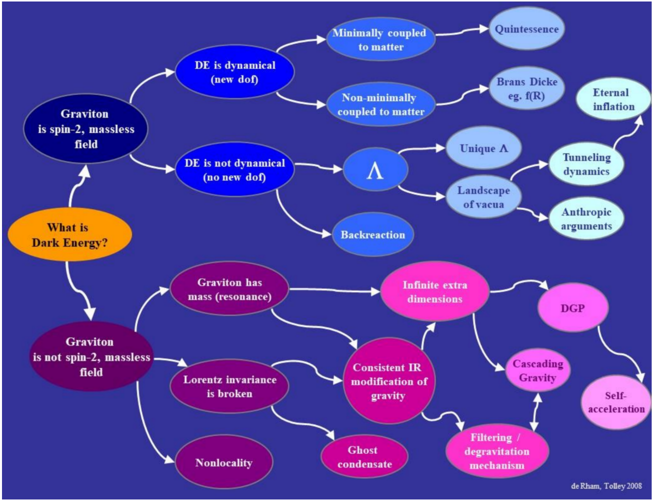
- Determine structure formation and evolution
- Change background evolution
- Modify linear perturbations
- Strongly affect nonlinear perturbations
- May help to resolve cosmological anomalies?
- Most importantly, they help us to better understand gravity

Some examples of modified gravity



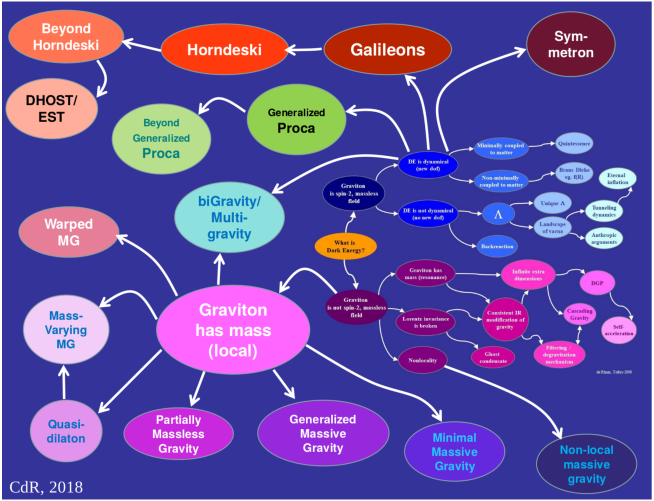
Courtesy of Tessa Baker

Modified gravity in 2008 . . .



Courtesy of Claudia de Rham

. . . and now



Courtesy of Claudia de Rham

Outline

Horndeski models

$$\begin{aligned}
\mathcal{L}_2 &= G_2(\phi, X) \\
\mathcal{L}_3 &= G_3(\phi, X)\Box\phi \\
\mathcal{L}_4 &= G_4(\phi, X)R + G_{4,X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla^\nu\phi)\right] \\
\mathcal{L}_5 &= G_5(\phi, X)R(\nabla^\mu\nabla^\nu\phi) - \frac{1}{6}G_{5,X}\left[(\Box\phi)^3 - 3\Box\phi(\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla^\nu\phi)\right. \\
&\quad \left. +2(\nabla^\mu\nabla_\alpha\phi)(\nabla^\alpha\nabla_\beta\phi)(\nabla^\beta\nabla_\mu\phi)\right]
\end{aligned}$$

- Most general theory with 2$^{\rm nd}$ order e.o.m.
- It encompasses many models studied in the literature
- Perturbations described by H plus 4 free functions of time, $\alpha_{\rm K}$, $\alpha_{\rm B}$, $\alpha_{\rm M}$, $\alpha_{\rm T}$
- Linear combinations of G_i and their derivatives
- Physical meaning, possibility of constraining them with observations
- GW constraint implies $\alpha_{\rm T} \approx 0$. This rules out a large number of Horndeski models [$G_5 \approx$ constant and $G_4 = G_4(\phi)$]

Outline

Effective Field Theory (EFT) of dark energy (DE)

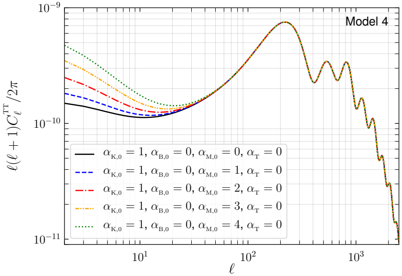
- Similar approach to particle physics
- Valid only on the scales of interest
- Ignores degrees of freedom on smaller scales
- It requires a separation of scales
- There are different, but equivalent approaches
- Use 3+1 split (uniform scalar field hypersurfaces)
- Geometry described by ${}^3R_{\mu\nu}$, extrinsic curvature $K_{\mu\nu}$, g^{00} or lapse N

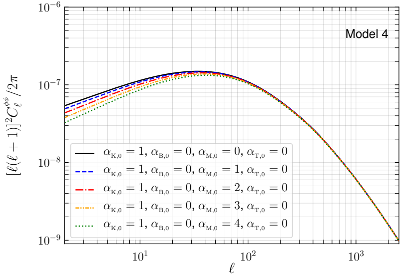
EFT d.o.f.

- $H(t)$ [$w_{\rm ds}(t)$]: background evolution
- $\alpha_{\rm K}(t)$: "kineticity" - kinetic energy, large $\alpha_{\rm K} \rightarrow$ small $c_{\rm s}^2$
- $\alpha_{\rm B}(t)$: "braiding" - mixing of kinetic terms and metric, contributes to DE clustering
- $\alpha_{\rm M}(t)$: "running rate of the Planck mass" $M^2(t)$ - $H\alpha_{\rm M} = {\rm d}\ln M^2/{\rm d}t$, contributes to anisotropic stress
- $\alpha_{\rm T}(t)$: "tensor speed excess" - $c_{\rm gw}^2/c^2 = 1 + \alpha_{\rm T}$, contributes to anisotropic stress
- $\alpha_{\rm H}(t)$: "beyond Horndeski" - higher order term that cancels in e.o.m.
- Stability conditions: $c_{\rm s}^2 > 0$, $c_{\rm T}^2 > 0$, $\alpha = \alpha_{\rm K} + 6\alpha_{\rm B}^2 > 0$

Bellini & Sawicki, 2014; Gleyzes et al., 2014, 2015

CMB spectra for α_K and α_M non zero





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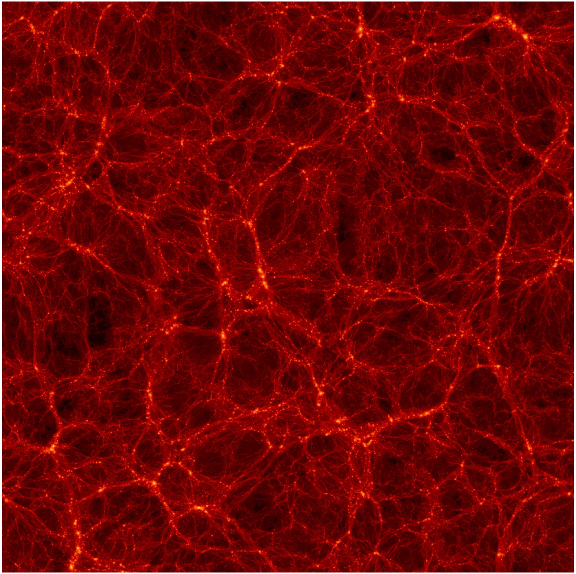
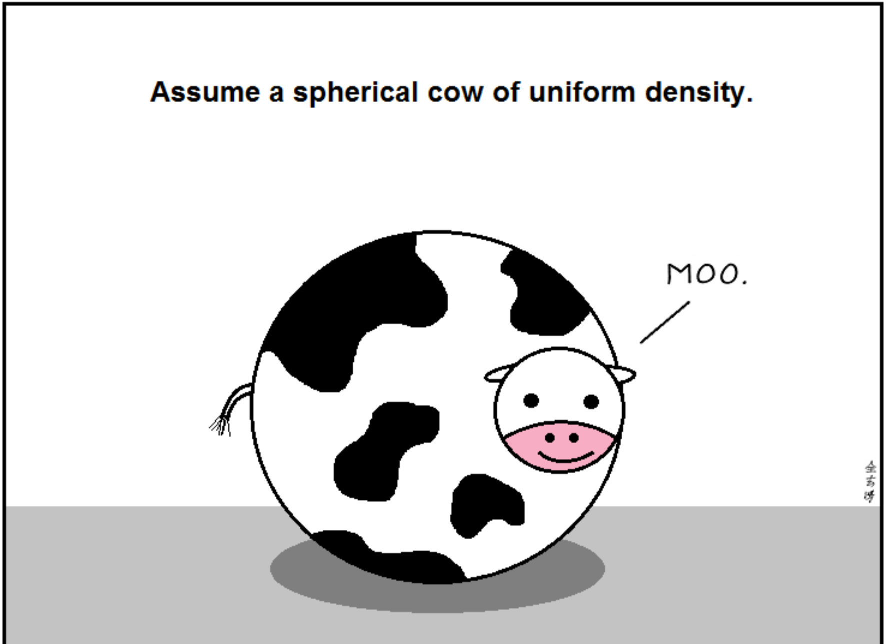
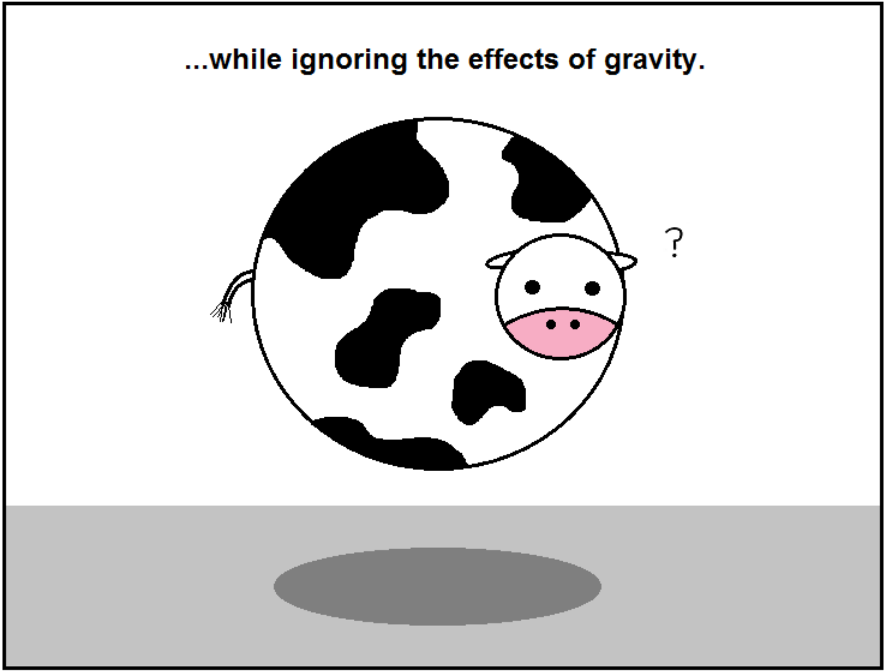
The Universe today

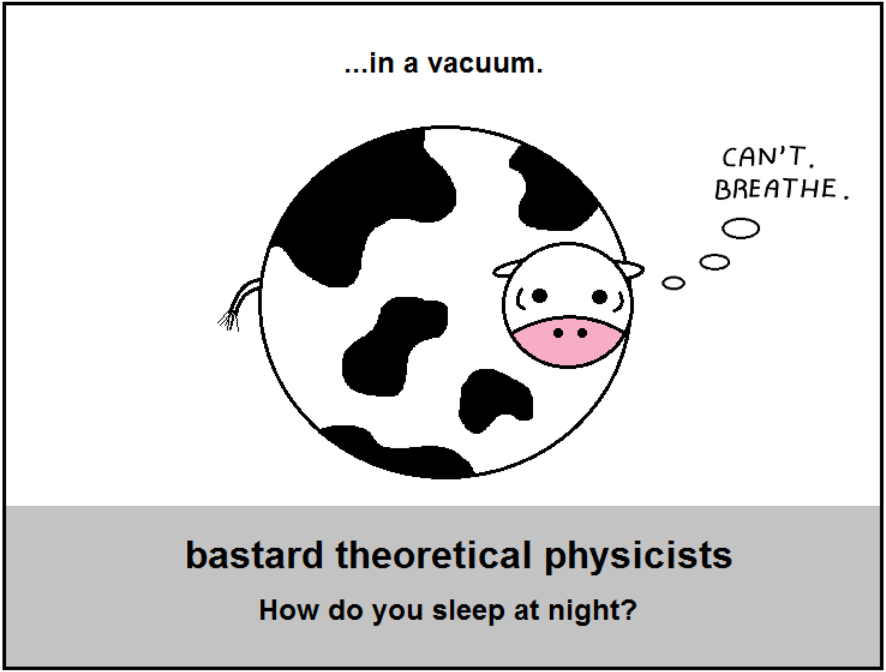


Spherical collapse model (SCM)

- Describes the evolution of perturbations on non-linear scales
- Based on the fluid approach
- Main assumptions
  1. Sphericity
  2. Isolated perturbations
  3. Top-hat density profile
- Easy to use for DE, more complications for MG
- Provides physical quantities related to the halo mass function


Assume a spherical cow of uniform density.
MOO.


...while ignoring the effects of gravity.
?

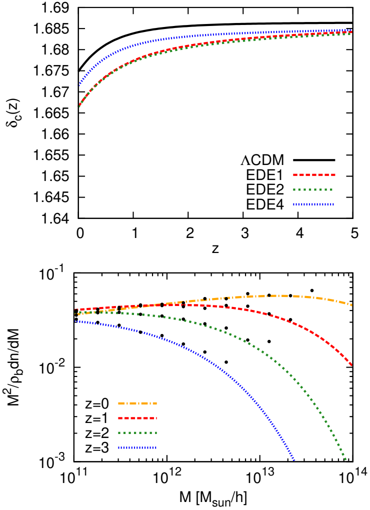

...in a vacuum.
CAN'T. BREATHE.
bastard theoretical physicists
How do you sleep at night?

Fisica

Physics of the SCM

1. Initial perturbation expands following the Hubble flow
2. Overdense regions slow down and reach a maximum size
3. Perturbation recollapses to a (mathematical) point
4. Virialization not native in the formalism
5. Physical quantities returned: $z_{\rm ta}$, $\zeta = 1 + \delta^{\rm NL}(z_{\rm ta})$, $z_{\rm vir}$, $R_{\rm vir}/R_{\rm ta}$, $\Delta_{\rm V}$

Theoretical results and comparison with simulations



Fisica Torino

FP et al., 2010

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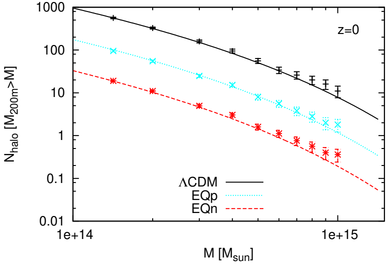

FP et al., 2014

Conclusions and future directions

- Current data compatible with ΛCDM, but future ones can constrain DE and MG models
- Discrepancies between early and late time (large and small scales)
- SCM in good agreement with simulations
- Long-term goal: Self-consistent numerical library to be used in cosmology