Dark Energy: Theory

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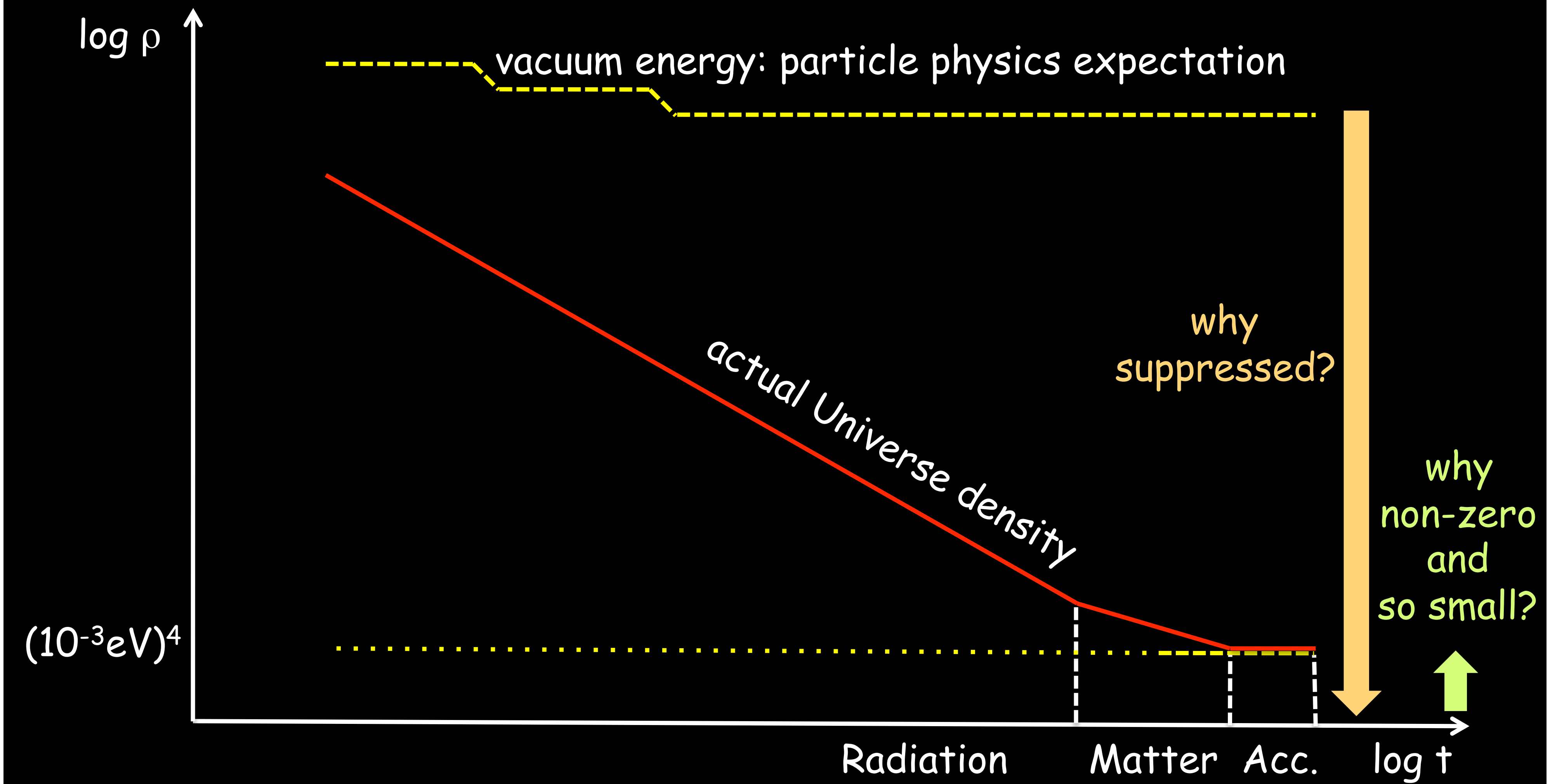
The problem

- Current acceleration, if described by FLRW, requires to add $(10^{-3}eV)^4$ term to Friedmann:

$$3m_P^2\,(H^2 \pm a^2/k) = \rho$$

- Particle physics predicts
  - $\rho \sim m_P^4 \sim (10^{28}eV)^4$ or m_{susy}^4 or $m_{EW}^4 \sim (10^{11}eV)^4$ from radiative corrections to vacuum energy
  - $\Delta\rho \sim m_{EW}^4 \sim (10^{11}eV)^4$ or $m_{QCD}^4 \sim (10^8eV)^4$ variations of vacuum energy during phase transitions

Why so small / Why now?



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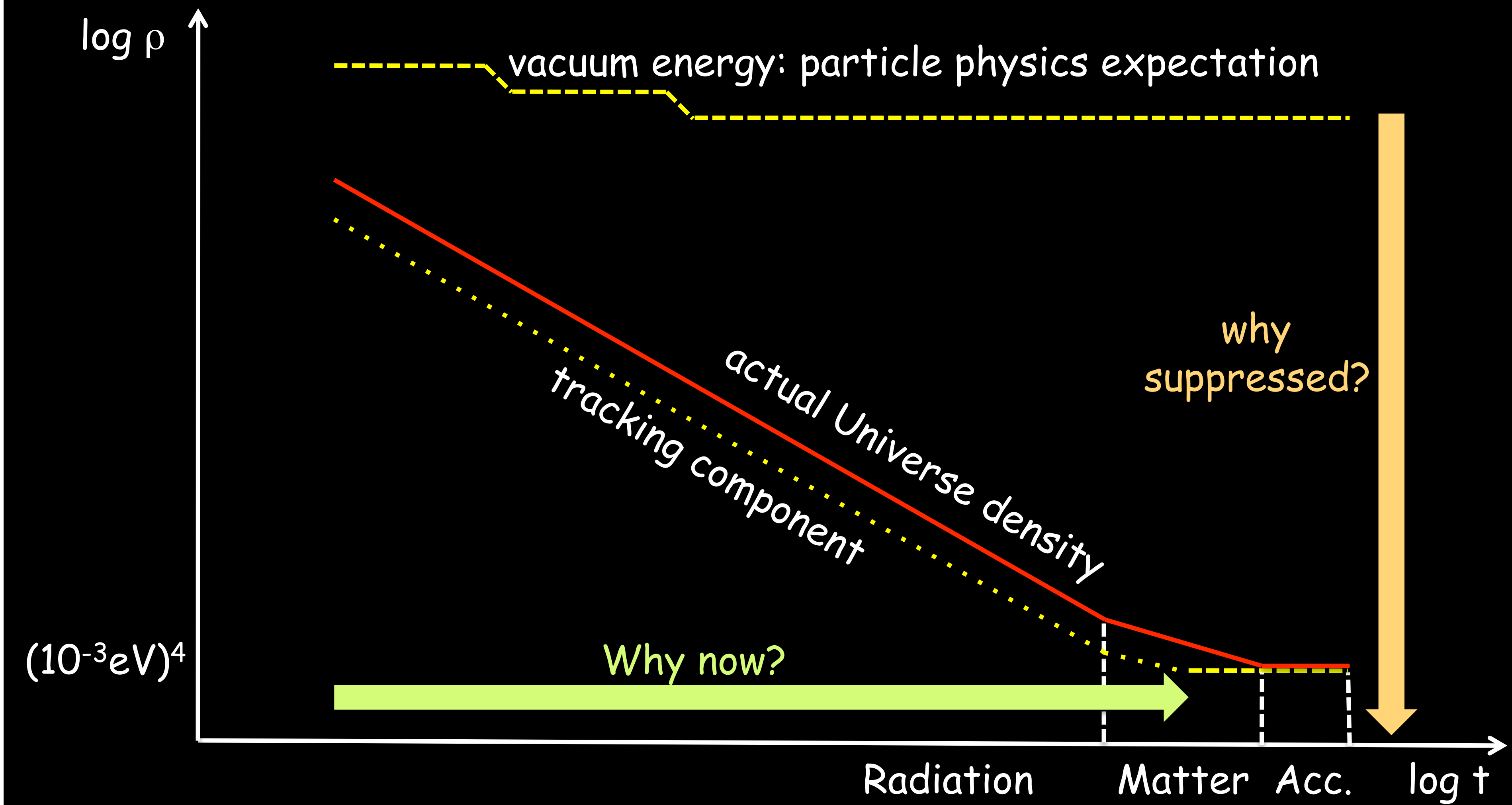


Difficulty to make predictive theory

- introduce one theory/model for explaining a single phenomenon: apparent acceleration of the universe (described so far by single number Λ)
- difficult to discriminate between models… and nature does not comply necessarily with « minimal model »
- A bit of hope: 
  - may measure more observables in future, see end of talk… but not guaranteed!
  - some models may lead to independent predictions… but actual explanation need not be connected with anything else !

… possible everlasting frustration …

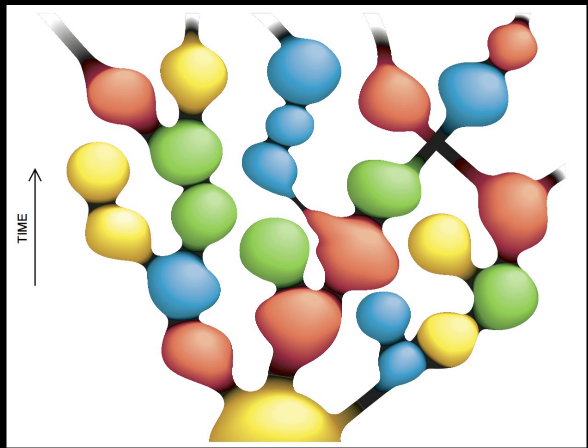
Λ

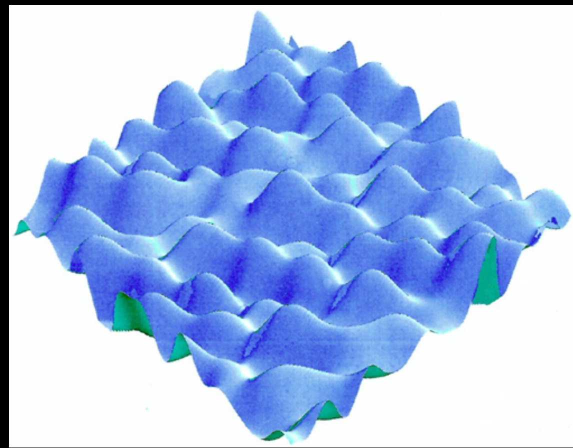
- Ideal from Occam's razor point of view, but not satisfactory… (especially, argument of phase transitions)

OCCAM'S RAZOR
Your theory is too complex

Λ

- Anthropic way: eternal inflation, string landscape

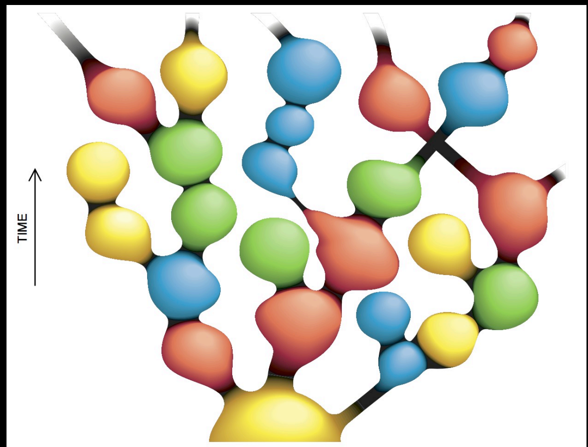


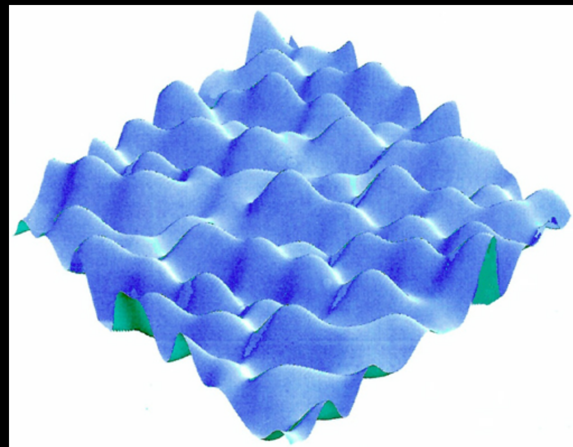


  - not against for philosophical reason
  - but practical issue: no lower bound, so likelihood impossible to evaluate:

Λ

- Anthropic way: eternal inflation, string landscape





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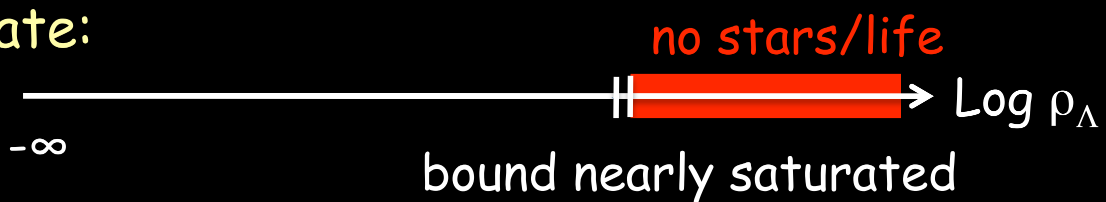


Beyond Λ

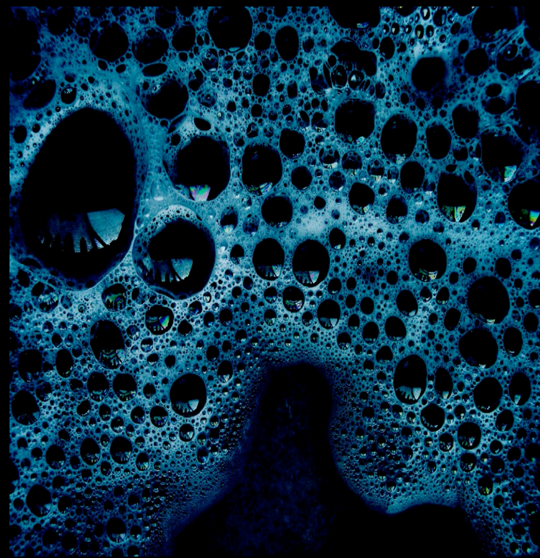
FLRW	Ordinary matter (b,γ,ν,dm particles)	Einstein Gravity	
			averaging effects
			inhomogeneous cosmology
			dark energy models
			modified gravity models

Averaging effects

- background expansion described by average of Einstein Equation (EE), not by EE applied to average quantities.
- non-linear structure formation: « effective contributions » to Friedmann, from averaged squared fluctuations
  Buchert; Rasanen; …
- Very difficult to compute, but effect seems to be tiny, and more like radiation enhancement Green & Wald 11

Inhomogeneous cosmology

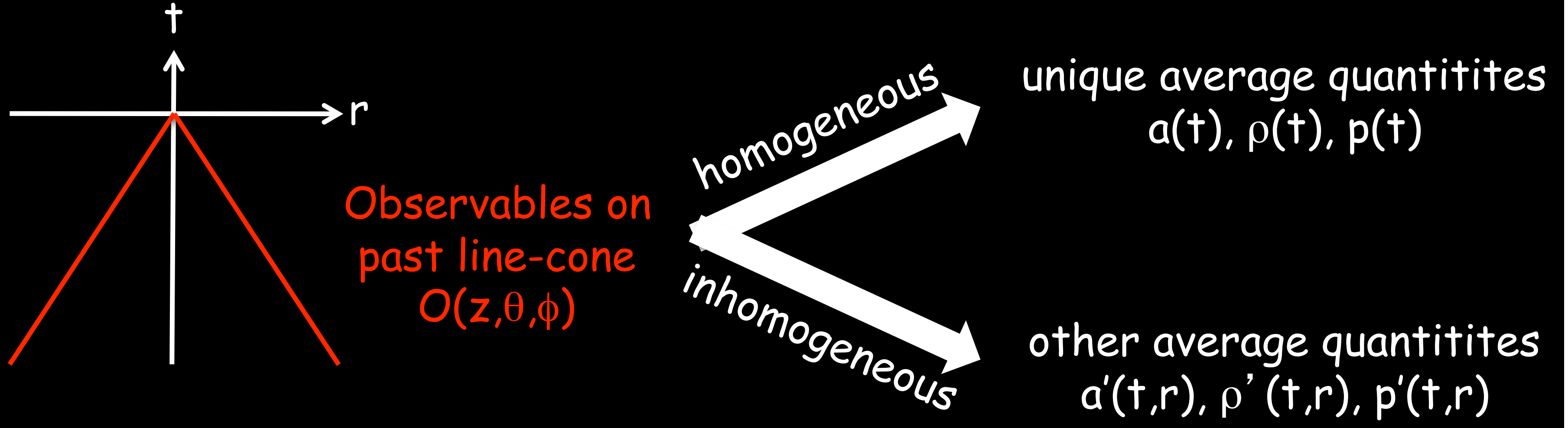
- non-linear inhomogeneities (with only dust) may impact $d_L(z)$ and dim supernovae
  - isotropy without homogeneity:
    big non-linear bubble nearly centred on us
    ~~(Copernician principle)~~
    Célerier 99; Tomita 00; + many…
  - many non-linear bubbles all around us
    Kantowski 69; Weinberg 76; + many…



- toy models built e.g. by sewing FLRW + Tolman-Bondi

Inhomogeneous cosmology

- Case of a big bubble: a formal degeneracy



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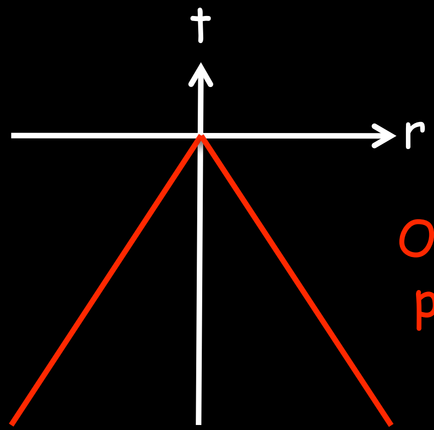

Observables on past line-cone $O(z,\theta,\phi)$

homogeneous → unique average quantitites $a(t)$, $\rho(t)$, $p(t)$

inhomogeneous → other average quantitites $a'(t)$, $\rho'(t)$, $p'(t)$

- background level::

$\boxed{\text{accelerated homogeneous universe}} \Longleftrightarrow \boxed{\text{decelerated inhomogeneous universe}}$

Inhomogeneous cosmology

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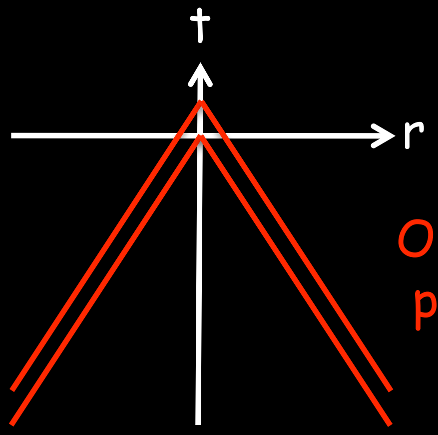

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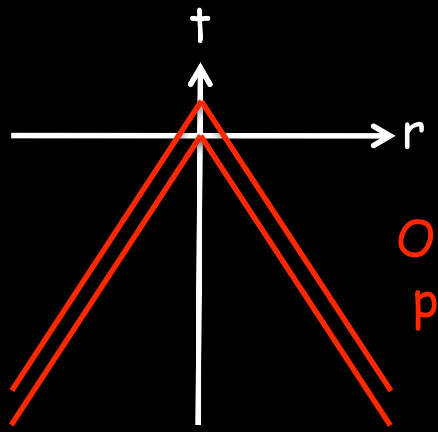

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Inhomogeneous cosmology

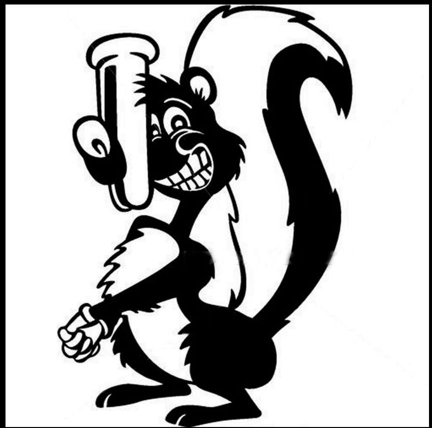
- Assuming sCDM + bubble(s), difficulty to explain simultaneously
  - luminosity distance probed by SNIa
  - primary CMB anisotropy spectrum
  - no strong anisotropic ISW / Rees-Sciama effect
  - Large Scale Structure power spectrum

  … in currently studies with toy models, no good fit to the data with Λ=0

  Brouzakis et al. 08; Valkenburg 09; Biswas et al. 10; …

- Need theory to predict bubble(s) (phase transitions?)

Dark Energy: quintessence

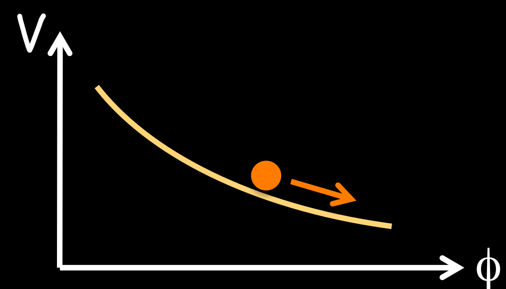


- canonical scalar fields / quintessence models never taken too seriously by theorists because they just replace one fine-tuning by another one (next slide)

- but popular due to their freedom (in scalar potential): might be effective description of some more fundamental theory (not even true, see end of the talk)

Dark Energy: quintessence

- Acceleration → slow-roll: $m_p^2 V''/V \ll 1$
- $m_{eff}^2 = V'' \ll (10^{-33}\text{eV})^2$: triggers 5th force unless uncoupled to other species; unstable against radiative correction unless invoking symmetry (e.g. shift symmetry): then, back to Λ…
- solution (1): run-away potential.
  But why should the field have the correct VEV today?
  Answer: with a tracking potential. But:
  - Perfect tracking: $V=e^{-\alpha\phi}$
    … no fine-tuned parameter but no mechanism for DE domination
  - Imperfect tracking: $V=\lambda(\phi/m_p)^{-\alpha}$
    … DE takes over if λ fine-tuned as much as m_{eff}^2



Copeland et a. 97; …

Dark Energy: quintessence

- Acceleration → slow-roll: $m_p^2 V''/V \ll 1$
- $m_{eff}^2 = V'' \ll (10^{-33}\text{eV})^2$: triggers 5^{th} force unless uncoupled to other species; unstable against radiative correction unless invoking symmetry (e.g. shift symmetry): then, back to Λ…
- solution (2): non-canonical kinetic term (K-essence).
  Tracking behavior until matter/radiation equality.
  But still some fine-tuning in initial conditions…
  Armendariz-Picon & Mukhanov 00; Malquarti 03; …
- solution (3): chameleon (mass depends on local matter density)
  Khoury & Weltman; Davies, Brax et al.;…

Dark Energy: coupled quintessence

- more predictive: DE domination can be triggered by known sector of particle physics through coupling with DM or ν's

- MaVaNs:
  - $\mathcal{L} \sim f(\phi)\nu\nu$: DE behaviour triggered by non-relativistic transition: $\rho \sim (10^{-3}\mathrm{eV})^4$ comes from $m_\nu \sim 10^{-2}\mathrm{eV}$
  - predictive: neutrino masses varies with time/position
  - coupling can be reformulated as fifth force which may lead to instabilities (ν clumps). Model of Fardon et al. 04 excluded, model of Wetterich et al. requires non-trivial investigation.

Dark Energy: others

- topological defect network? $w < -\frac{1}{3}$ but too large.
- bose condensation of a species (of DM) ? Bassett et al. 02
- thermodynamical effect (no ad hoc term in Lagragian, but collective effect of interactions)
  - postulate equation of state for unified dark energy/dark matter: Chaplygin gas Kamenshchik et al. 01
  - postulate an equation for bulk viscosity effects in a weakly-self-interacting fluid Colistete et al. 07; Li & Barrow 09

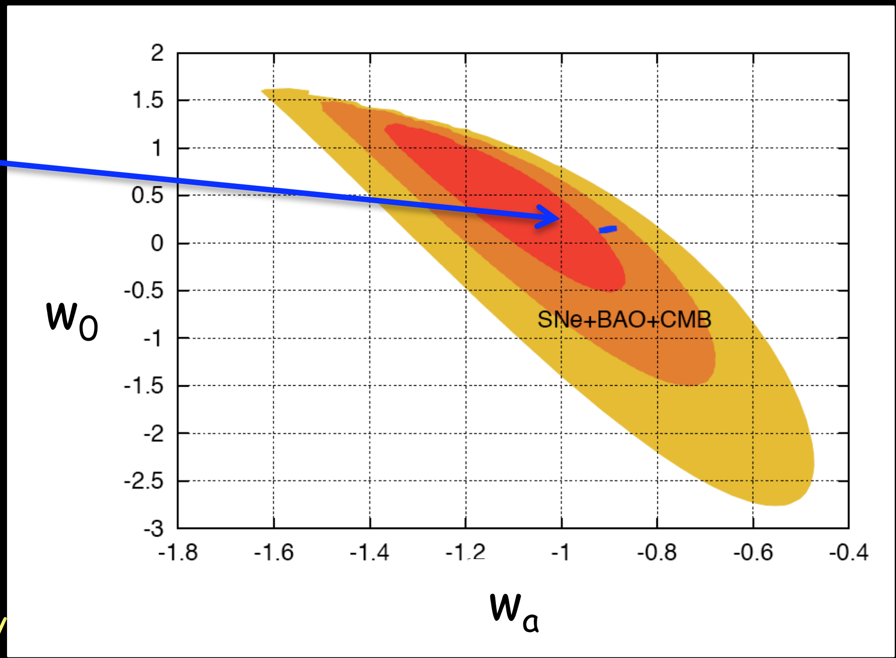
… need to fine-tune parameters as in initial problem, plus generic issues of instabilities, requiring some amount of extra fine-tuning

Dark Goo

- first DE model based on microscopic calculation of bulk viscosity effects Gagnon & Lesgourgues 11
  - fluid made of massive spin-0 particles, decoupling from rest of plasma at arbitrary temperature, remaining self-coupled through $\lambda\phi^4$ interactions: two temperatures T_γ and T_x
  - when self-interaction fail to establish equilibrium pressure instantaneously when fluid expands, bulk viscosity: $p_{eff}=p-3H\xi$
  - expression of $\rho(T)$, $p(T)$, $\xi(T)$ from QFT at finite T Jeon 95

Dark Goo

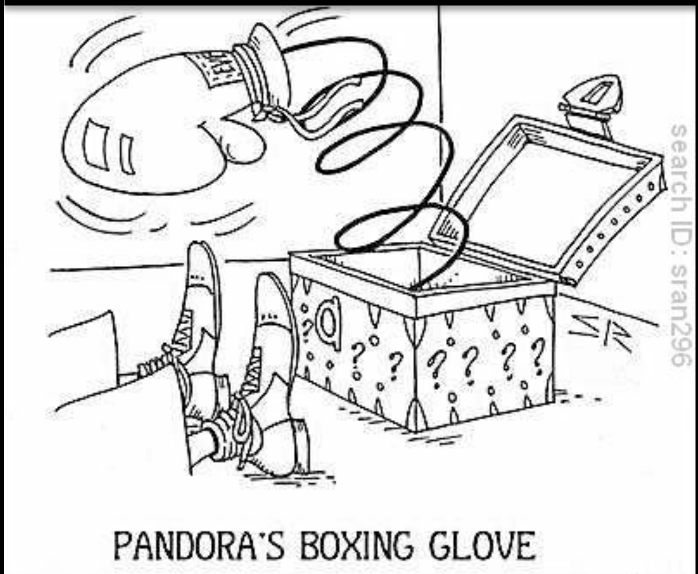
- Dark Goo: first DE model based on microscopic calculation of bulk viscosity effects Gagnon & Lesgourgues 11
  - works for m ~ [0.01 - 2] eV, λ ~[2.10^{-5} - 1]
  - model equivalent to DE with w_0~-0.9, w_a~0.1, negligible DE perturbations



Modified Gravity

- Pandora's box:

Clifton et al. 11



- extra fields: scalar-tensor, Enstein-Aether, bimetric, massive, tensor-vector-scalar …
- higher derivatives and non-local: f(R), Horava-Lifshitz, Galileons …
- extra dimensions: braneworld with bulk gravity (DGP, degravitation,…), Einstein-Gauss-Bonnet …

Modified Gravity

- Goal: modify gravity in infrared, but extra light scalar fields with universal coupling to all matter: fifth force, clash with solar system tests; mechanism to prevent this: e.g. chameleon-like
- other problems: ghosts, instabilities, super-luminal propagation…
- technical issue: difficulty to compute perturbation evolution… should get almost same CMB/LSS spectrum as in ΛCDM

DE/MG equivalence

- Modification of $G_{\mu\nu} = 8\pi \mathcal{G}\, T_{\mu\nu}$ can be put on both sides: formal equivalence between DE/MG
- But if many observables can be predicted/measured, one of the two can appear as much more natural
- Geometry of flat FLRW with linear perturbations:
  - background: one function of time $H(t)$
  - perturbations: two functions of time and wavenumber $\phi(t,k)$, $\psi(t,k)$

Perturbations as smoking guns

- Independent measurement of $\{\phi(t,k)\ ,\ \psi(t,k)\}$ (growth of structure + weak lensing)
- sCDM : $\phi(t,k) - \psi(t,k) \Leftrightarrow$ anisotropic pressure $\sigma(t,k)$ of b + dm = 0

  $\psi(t,k) \Leftrightarrow \delta\rho(t,k)$ of b + dm (Poisson)
- MG + ordinary matter : modification of these two relations
- GR + dark energy : same relation but extra source of density and anisotropic pressure perturbations; using $T_{\mu\nu}$ conservation, everything specified in terms of $\{\delta p, \sigma\}$; DE model provides relations [e.g. quintessence: $\delta p(t,k)=c^2\delta\rho(t,k)$ and $\sigma(t,k)=0$]
- One-to-one correspondence
- If deviations are detected : may look like natural prediction for MG and crazy model for DE, or vice-versa

Conclusion : future of the field completly uncertain !

- Deviations from Λ ?
- Non-trivial perturbation effect ?
- Model complying with observations AND providing non-trivial predictions testable in the lab or in astrophysics ?