Cosmic acceleration

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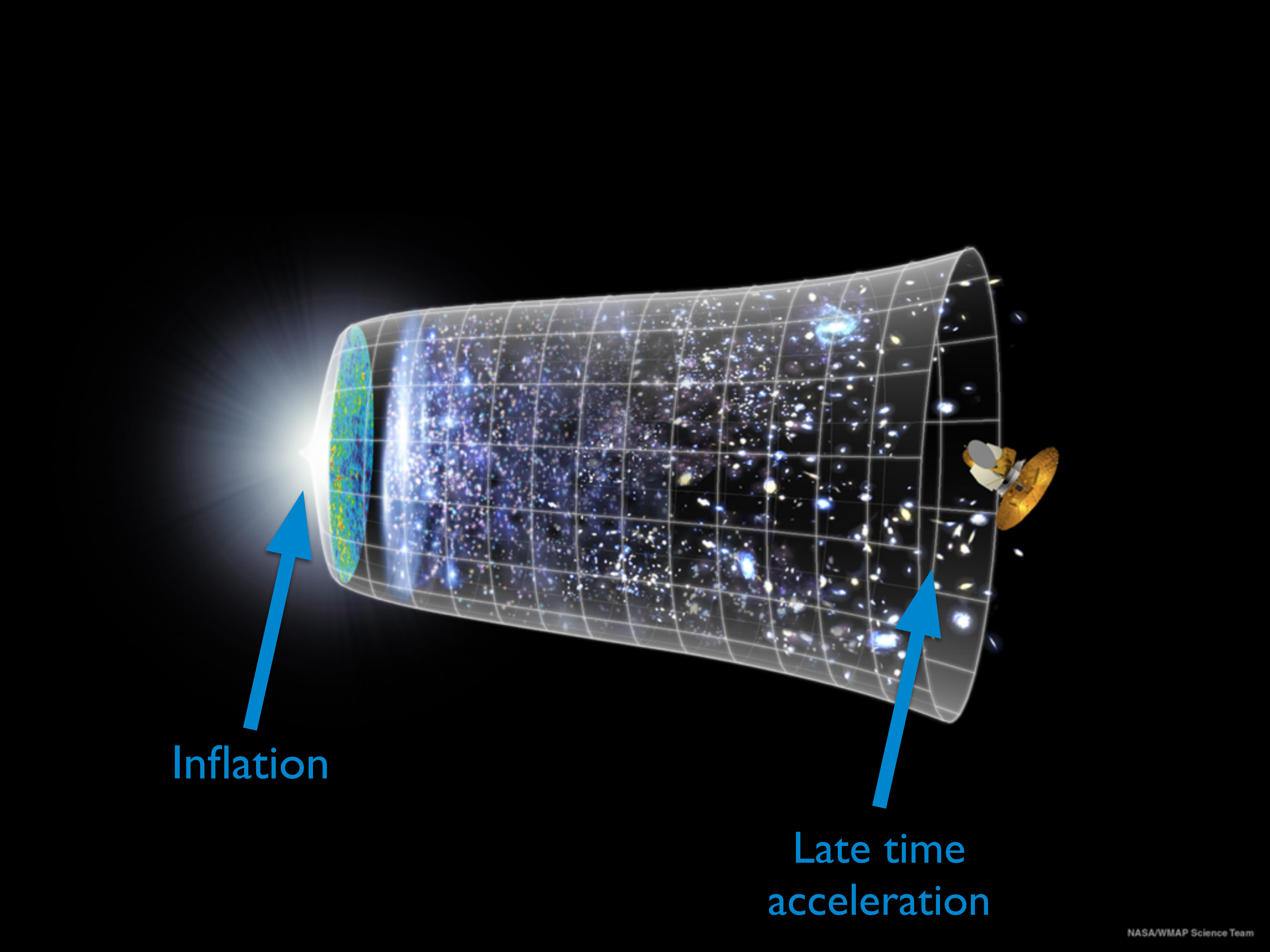
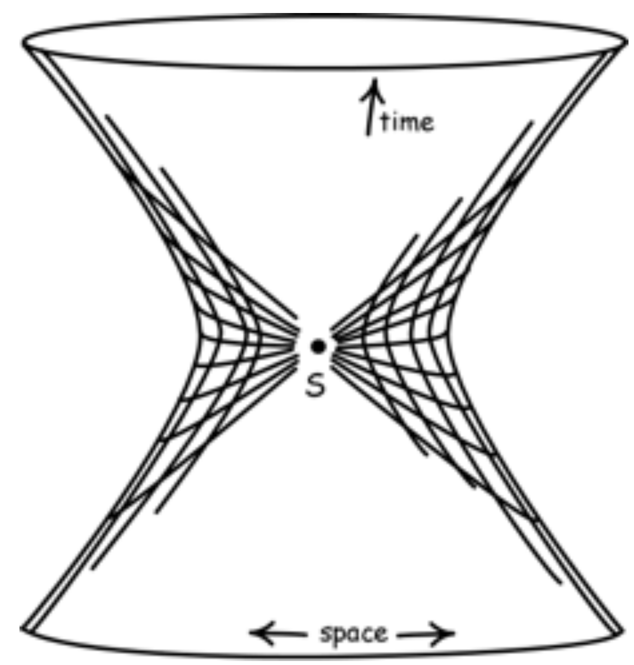

Inflation
Late time acceleration
NASA/WMAP Science Team

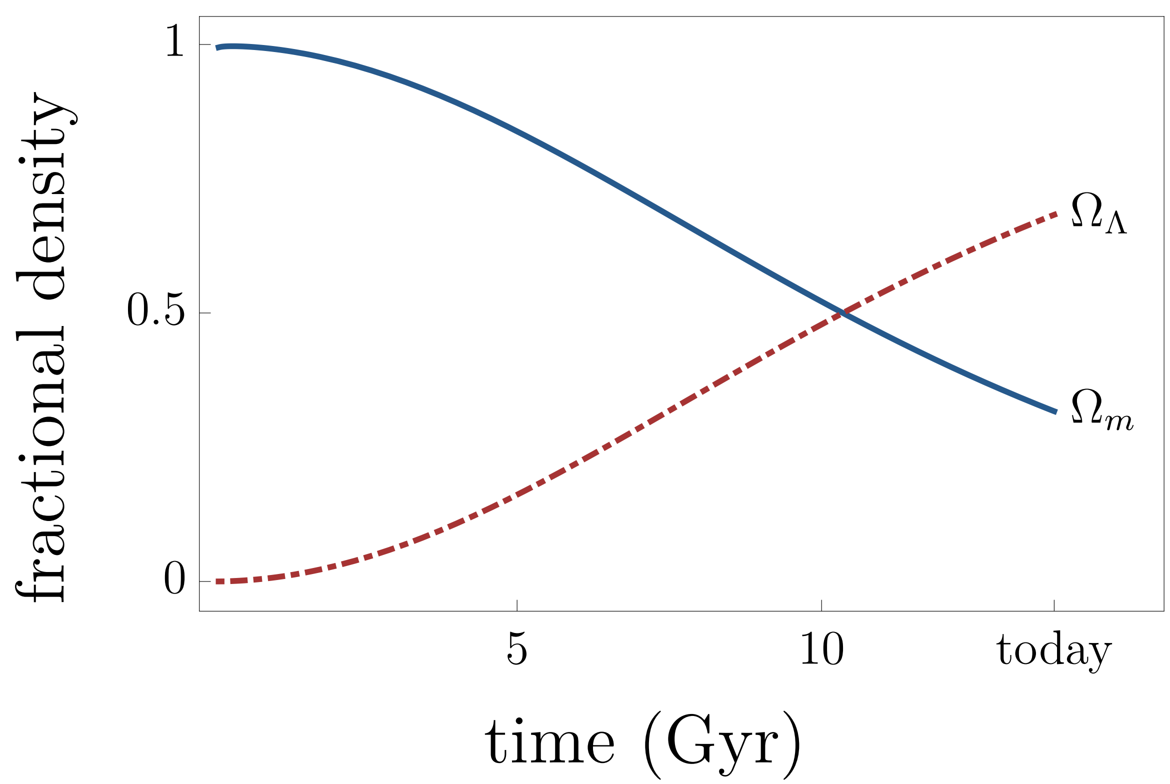
The standard cosmological model

We have a remarkably successful phenomenological model: $\Lambda\mathrm{CDM} \; + \; \mathrm{inflation}$

Involves epochs of accelerated expansion at both ends:



- The early universe went through a phase of quasi-de Sitter expansion



- The present-day universe has recently entered a phase of accelerated expansion

New physics?

These epochs of accelerated expansion can point the way toward new physics

- These phenomena might be difficult to probe otherwise—gravitational sector is a unique handle

Early universe:

- Inflation as a particle collider

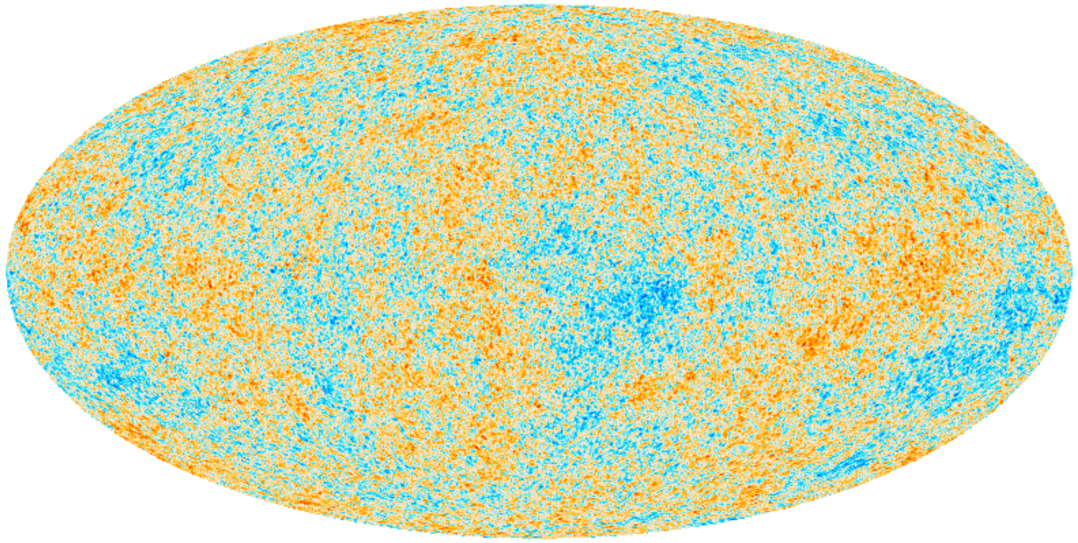
Late universe:

- Light degrees of freedom driving cosmic acceleration

Early-universe acceleration

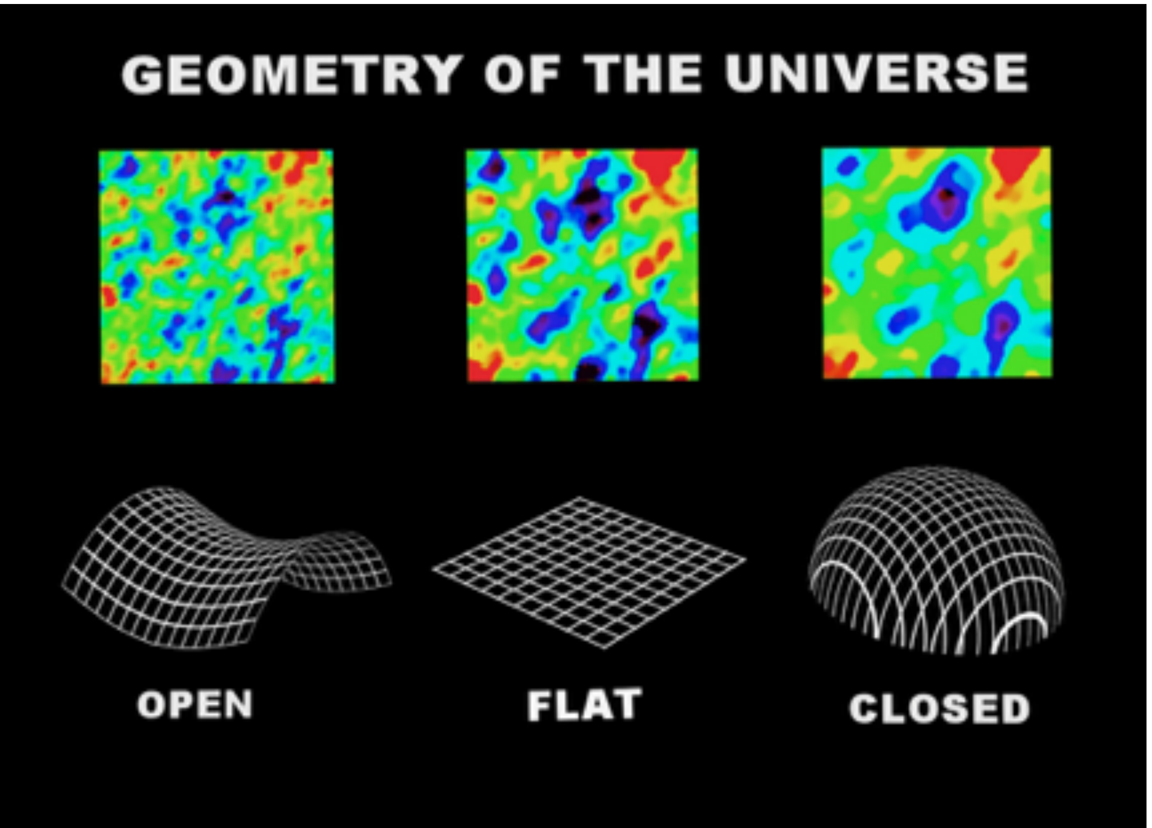
What we see

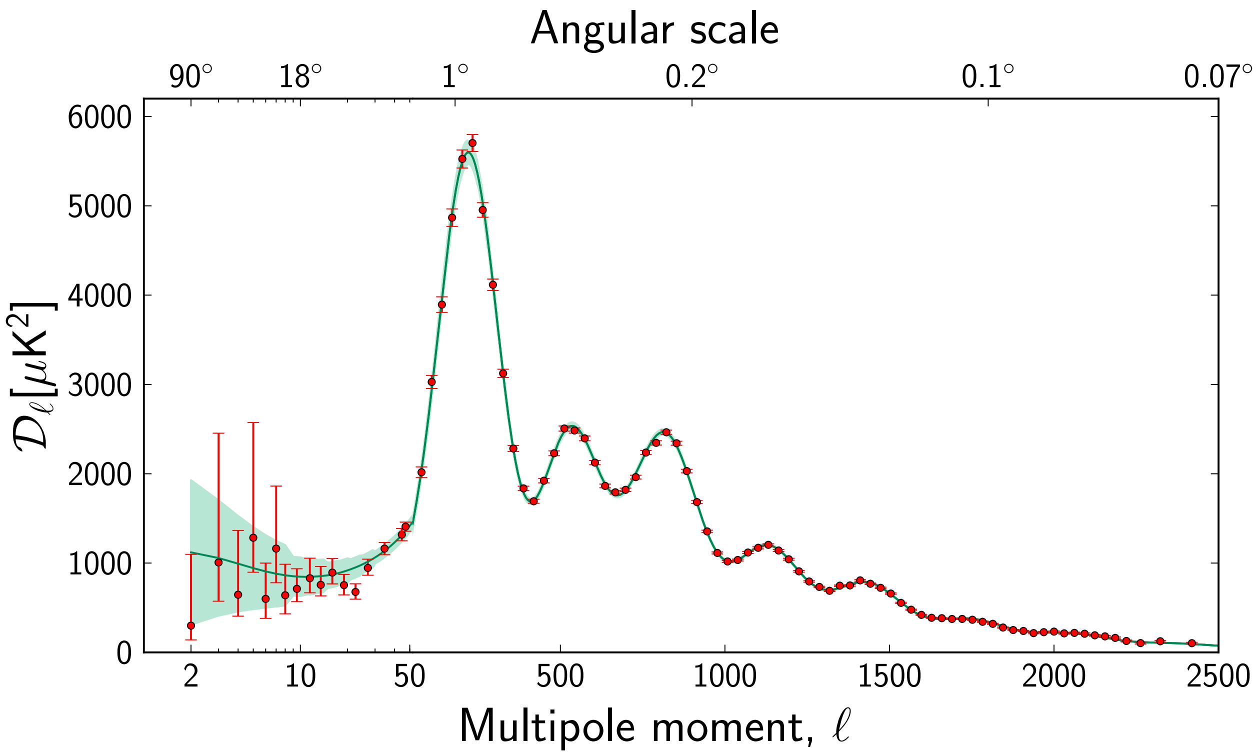
Planck 2013



Temperature of the primordial universe is very uniform, even between regions that nominally *have never been in causal contact*

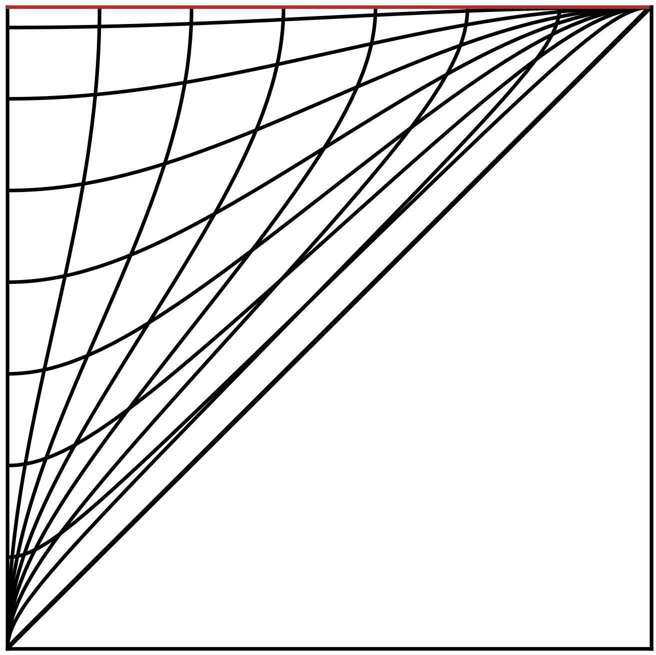
Spatial geometry of the universe is very close to being flat, despite the fact that dynamically the universe should evolve away from flatness





Small tempterature fluctuations (1 part in 10^5) which are correlated and nearly scale-invariant/gaussian

Inflation



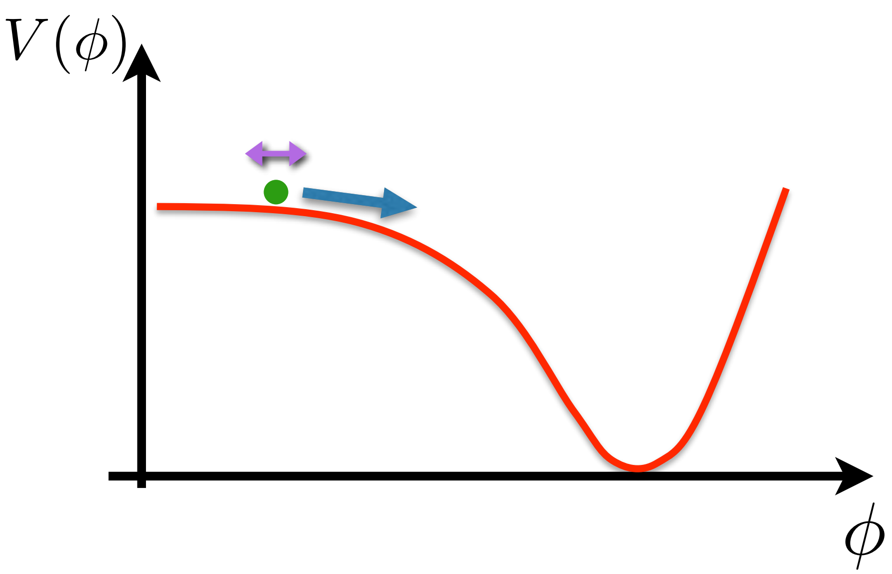
de Sitter

Inflation provides a unified explanation for these observations—posits a phase of nearly de Sitter expansion

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + e^{2Ht}\mathrm{d}\vec{x}^2$$

- Accelerated expansion solves flatness and horizon problems

- Statistics of perturbations controlled by symmetries of de Sitter space



- Simplest incarnation—a field slowly rolling down a fairly flat potential

  Here the dS symmetries only broken proportional to slow-roll parameters

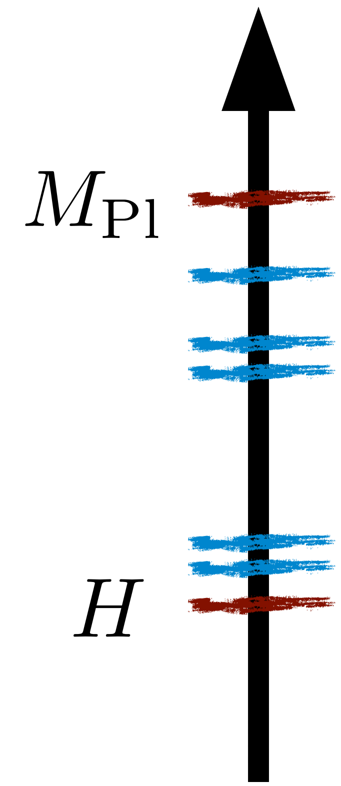
- Inflation is the highest-energy "collider" we have access to

Inflation as a particle accelerator

Chen, Wang 0911.3380
Arkani-Hamed, Maldacena 1503.08043

Particles with masses around Hubble can be excited

$$m^2 \sim H^2 \sim M_{\rm Pl}^{-2} V(\bar{\phi})$$



- Can leave signatures in correlations in the CMB/LSS

- To leading order (in slow-roll), these are controlled by conformal symmetry

- Heavy fields oscillate with a characteristic frequency

$$h \sim \eta^{\frac{3}{2} \pm i\mu} \qquad i\mu = \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$

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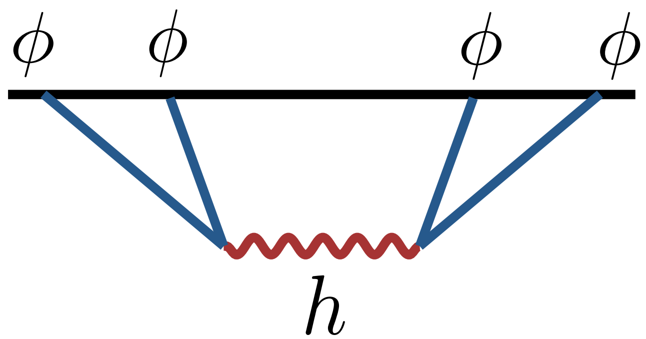
Heavy particles can imprint in correlation functions

- Example: massive spin-*s* particle

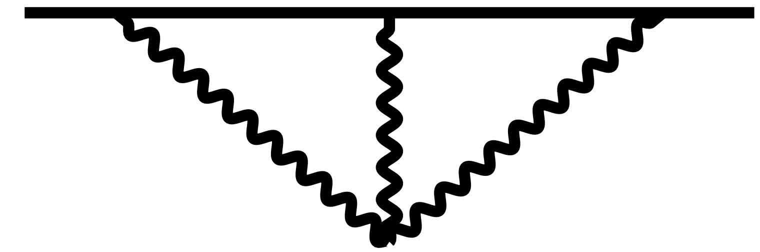


$$\rightarrow \quad \langle \phi\phi\phi\phi \rangle \sim \left[f(\mu, s) \left(\frac{q}{k} \right)^{\frac{3}{2}+i\mu} + \bar{f}(\mu, s) \left(\frac{q}{k} \right)^{\frac{3}{2}-i\mu} \right] P_s(\cos\theta)$$

- Oscillations controlled by particle's mass, angular correlation tell us the spin—like in a collider

- We can also ask what happens for graviton correlation functions

Signatures in spinning correlators



- de Sitter isometries are very constraining: there are only **two** possible "shapes" that the tensor 3pt function can be Maldacena, Pimentel 1104.2846

$$S = \frac{M_{\rm Pl}^2}{2}\int {\rm d}^4x\left[\sqrt{-g}\left(R-6H^2\right)+\frac{1}{\Lambda^4}C^3\right]$$

Imagine letting the graviton mix with a massive spin-2 particle

- There are now two additional shapes that the massive spin-2 can have, can be transmitted to graviton 3pt function Goon, Hinterbichler, AJ, Trodden, in progress

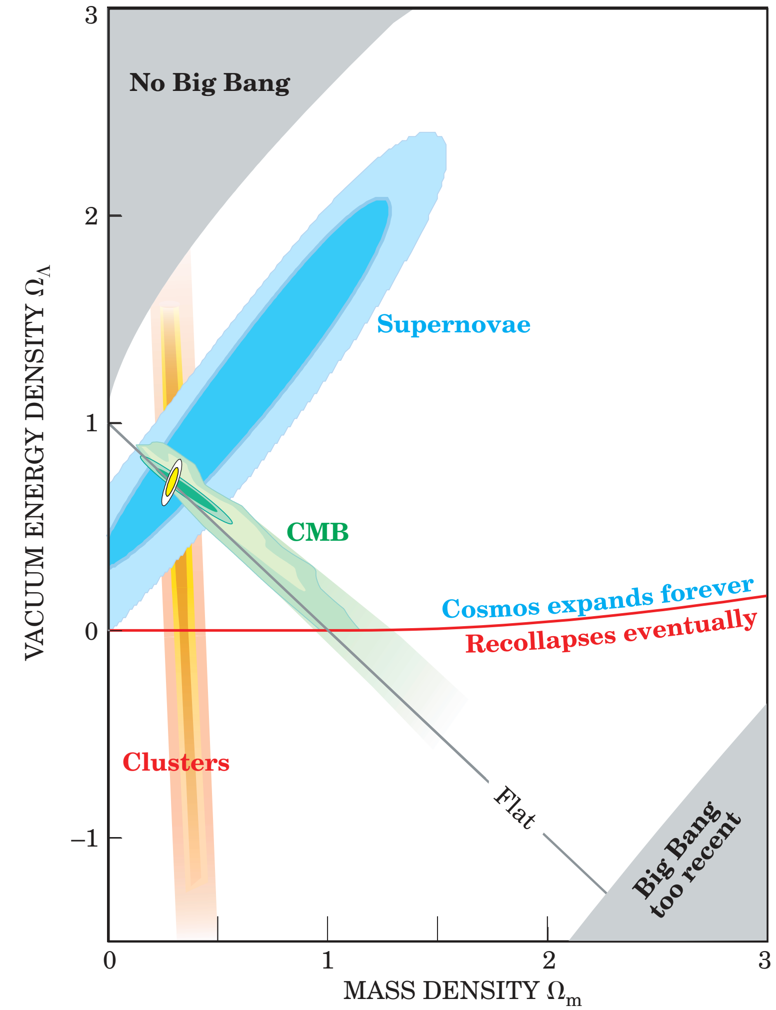
$$S = M_{\rm Pl}^2\int {\rm d}^4x\sqrt{-h}\left(R-6H^2+\frac{1}{\Lambda^4}C^3+m^2h^3+c_h h^2\partial^2 h\right)$$

- Detecting a non Einstein-Hilbert shape would be circumstantial evidence for stringy-type physics, should also expect to see many spinning resonances

Camanho, Edelstein, Maldacena, Zhiboedov 1407.5597
Hinterbichler, AJ, Rosen 1708.05716

Late-time cosmic acceleration

Cosmic acceleration



Perlmutter, *Physics Today* 2003

- On the largest scales the geometry is well-approximated by

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a(t)^2 \mathrm{d}\vec{x}^2$$

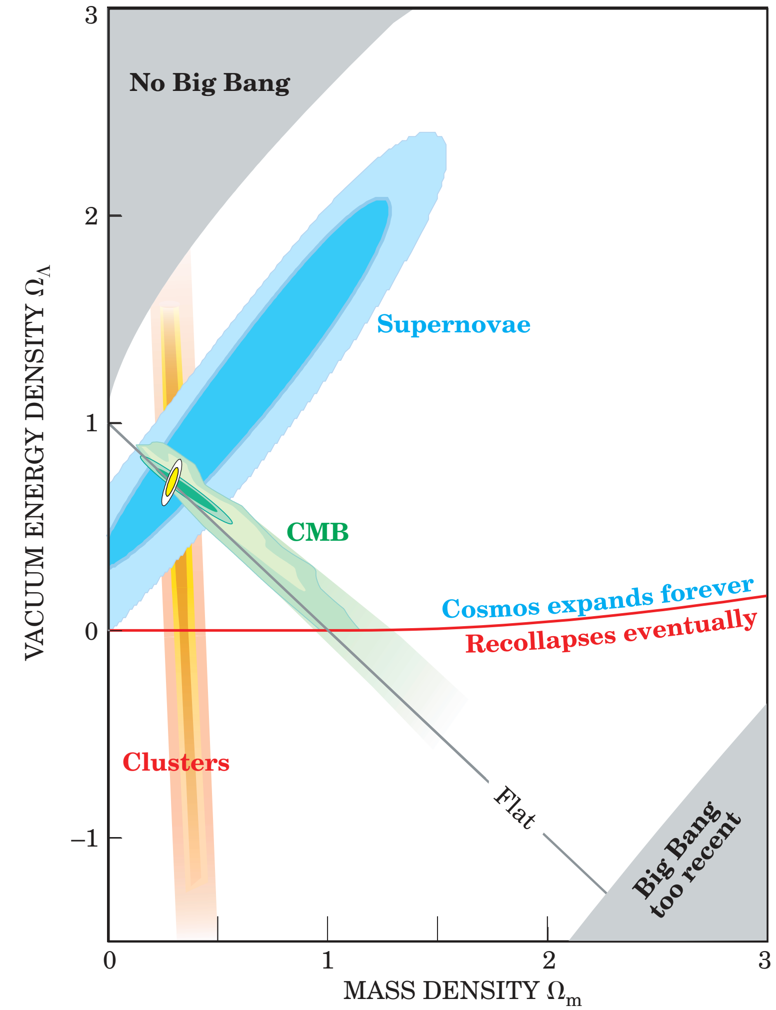
- Background evolution is governed by the Friedmann equations (assuming a perfect fluid drives things)

$$3H^2 = \rho \qquad\qquad 3H^2 + 2\dot{H} = -P$$

- CMB, SN and LSS measurements indicate that the background expansion rate is accelerating $(\ddot{a} > 0)$

- Requires component with $w < -1/3$. In fact, all the data is well-fit by something with $w = -1$ (CC) with $\Lambda_{\mathrm{observed}} \sim (\mathrm{meV})^4$

Cosmic acceleration



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Theoretical expectation: Λ

- Estimate the contribution to the CC from SM fields: $\langle T_{\mu\nu}\rangle \sim -\langle\rho\rangle g_{\mu\nu}$

$$\langle\rho\rangle = \int_0^{\Lambda_{\rm UV}} \frac{\mathrm{d}^3k}{(2\pi)^3}\frac{1}{2}\hbar E_k \sim \int_0^{\Lambda_{\rm UV}} \mathrm{d}k\; k^2\sqrt{k^2+m^2} \sim \Lambda_{\rm UV}^4 + m^2\Lambda_{\rm UV}^2 - \frac{m^4}{2}\log\frac{\Lambda_{\rm UV}}{m}$$

- The contribution from the electron alone, leads to

$$\Lambda_{\rm theory} \sim (10^8\ \mathrm{meV})^4$$

- This is embarrassingly discrepant with the observed value already. Trusting things up to the Planck scale reproduces the famous factor of 10^{120}

- This is a problem of naturalness, the value of the Cosmological Constant is extremely sensitive to the addition of new heavy states

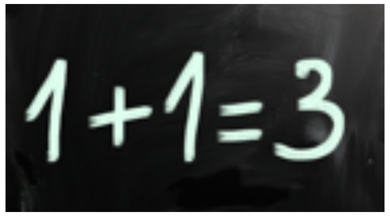
Approaches to understanding this problem

- Maybe naturalness is not a good criterion; maybe things just happen to be tuned.

- Maybe the CC is selected from some distribution and is small for essentially anthropic reasons — larger values of CC would not allow structures to form

- New physics/new degrees of freedom in the gravitational sector?

- Possibly we are calculating something incorrectly — something wrong with our understanding of QFT in curved space?



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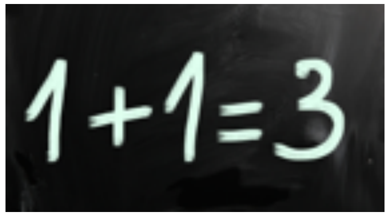

Maybe you don't care about naturalness

Even if you don't care at all about naturalness, thinking about new physics in the gravitational sector is still a reasonable thing to do

- Gravity is well-tested in the lab, in the solar system, in some astrophysical systems (Hulse-Taylor, LIGO,..) and in the CMB
- Moving between these different tests requires a huge extrapolation of scales
- Most of the tests of gravity are in the *weak-field* regime (could have said all until LIGO)
- It is worth mapping out the space of theories which could describe the gravitational sector, and try to understand ways to test these different paradigms

New degrees of freedom

- **Why?** Einstein gravity is remarkably robust: it is essentially the unique theory of a massless spin-2 field*

- Modifications to Einstein gravity almost ubiquitously introduce *new* degrees of freedom—doing this consistently is *hard*

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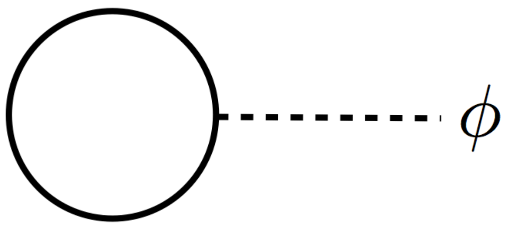
- To neutralize the CC, must couple to SM fields



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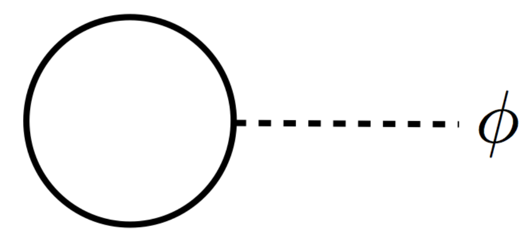
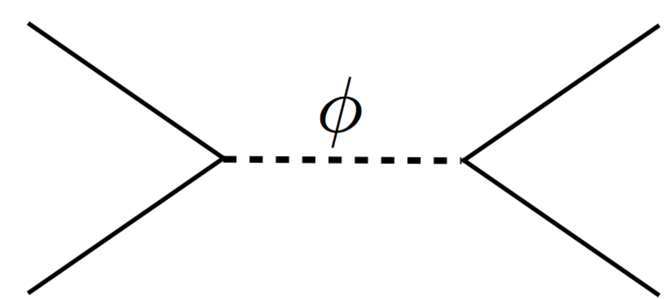
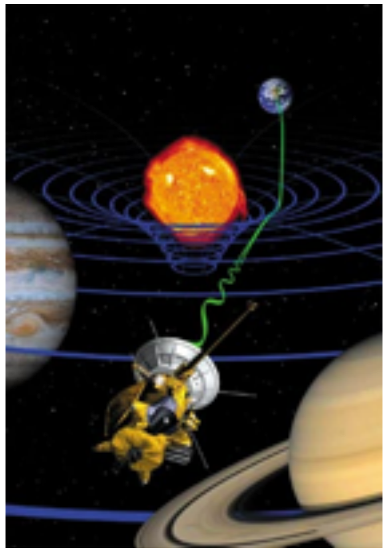


- Unitarity implies that they mediate a force: $\Longrightarrow$



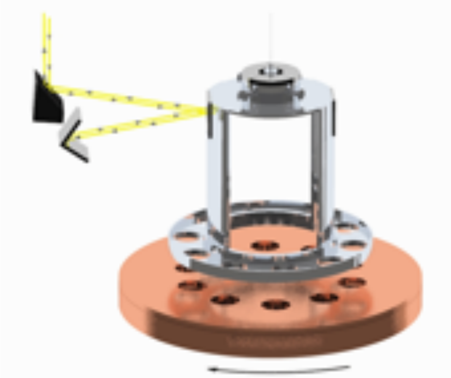
Screening

- Gravity is *extremely* well-tested in the lab & solar system
- No deviations from Einstein gravity—extra degrees of freedom must hide themselves in some way
- Ways in which this can be accomplished are called *screening mechanisms*
- Could also just choose to couple very weakly to everything (dark energy)



Cassini (Shapiro time delay)

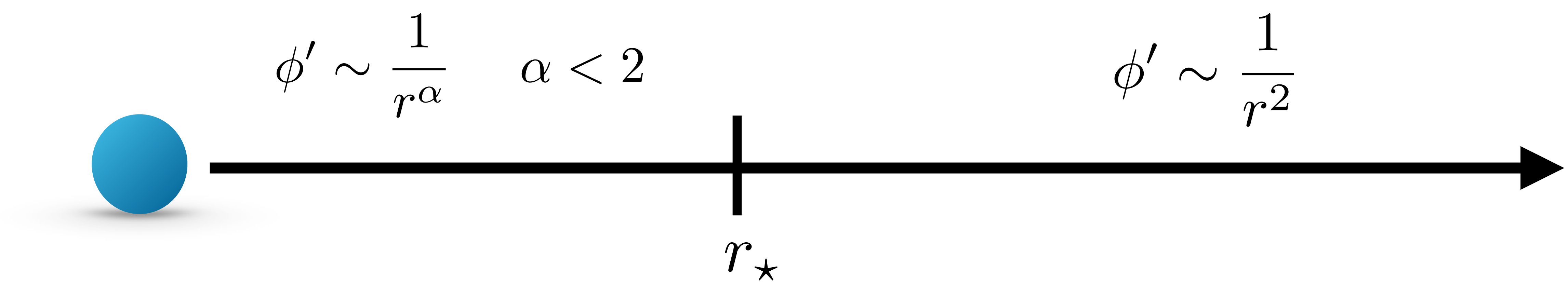
APOLLO (Nordtvedt effect)



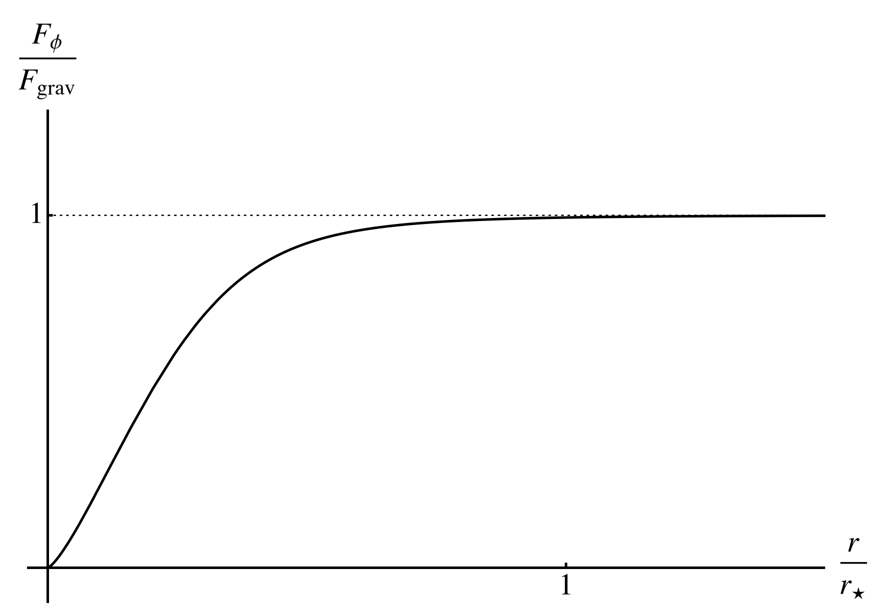
Eöt-Wash (Inverse square law)

Screening fifth forces

- Mechanisms to suppress effects of light degrees of freedom in local environment



- Ratio of fifth force strength to that of gravity drops off sharply



- Various different mechanisms that differ in precise details see, e.g. AJ, Jain, Khoury, Trodden 1407.0059 for more details

Theoretical consistency

Models are also subject to theoretical consistency requirements:

- Theories must be ghost-free (ghosts have wrong-sign kinetic terms)

$$\mathcal{L} = \frac{1}{2}(\partial\chi)^2 - \frac{m^2}{2}\chi^2$$

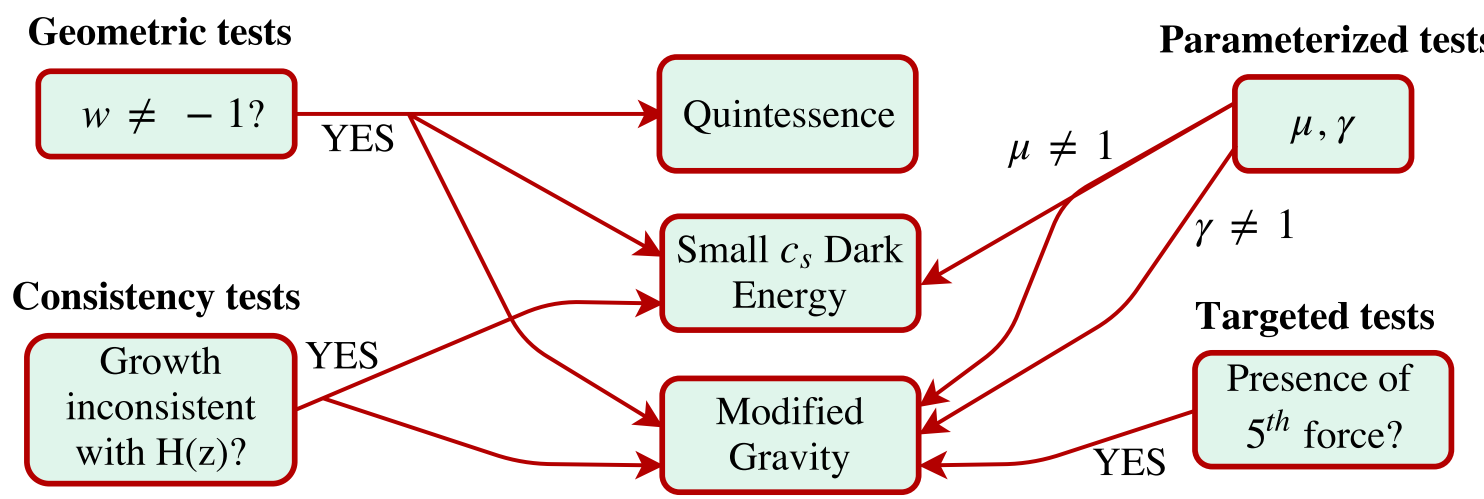
  these fields have *negative* kinetic energy - allows the vacuum to spontaneously decay; often arise from higher-derivative terms (Ostrogradsky)

- Similarly, theories must not possess gradient instabilities (wrong sign spatial gradients)

- A peculiarity—often theories which arise from modifications of gravity possess *superluminality*. Not clear if this is a problem, but would be better if it were absent. (ask me about this if you are curious)

see, e.g. AJ, Lombriser, Schmidt 1601.06133

Cosmological probes?



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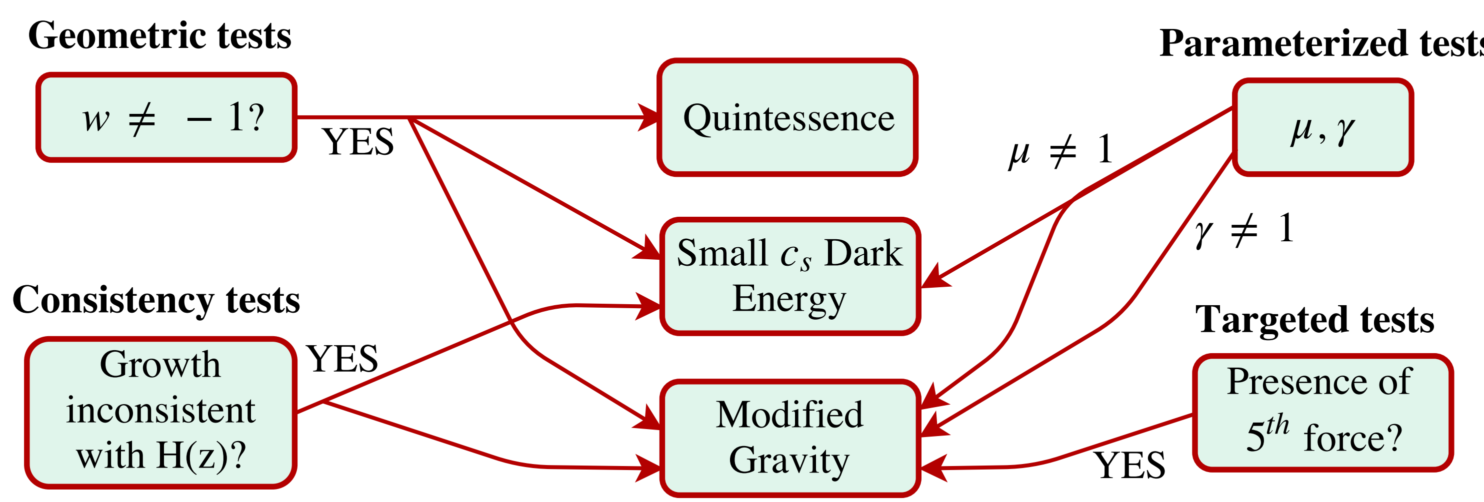

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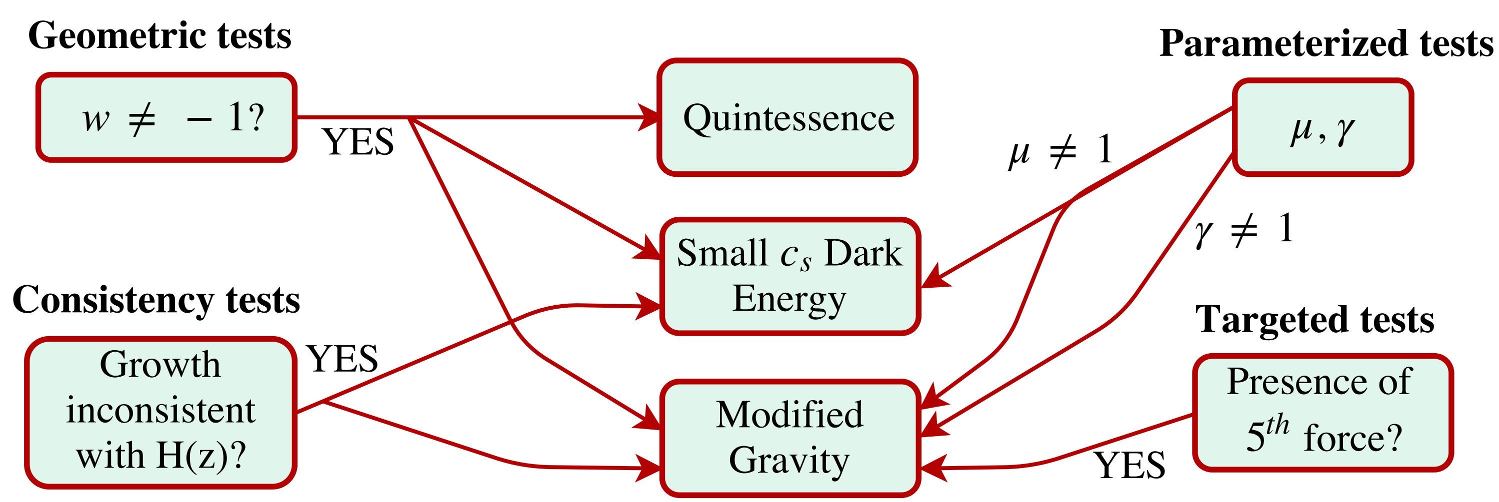

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- Measure both the expansion history and growth of structure: in LCDM or in simple quintessence models, structure formation is fixed by the H(t); deviations from this imply either exotic DE or some kind of MG

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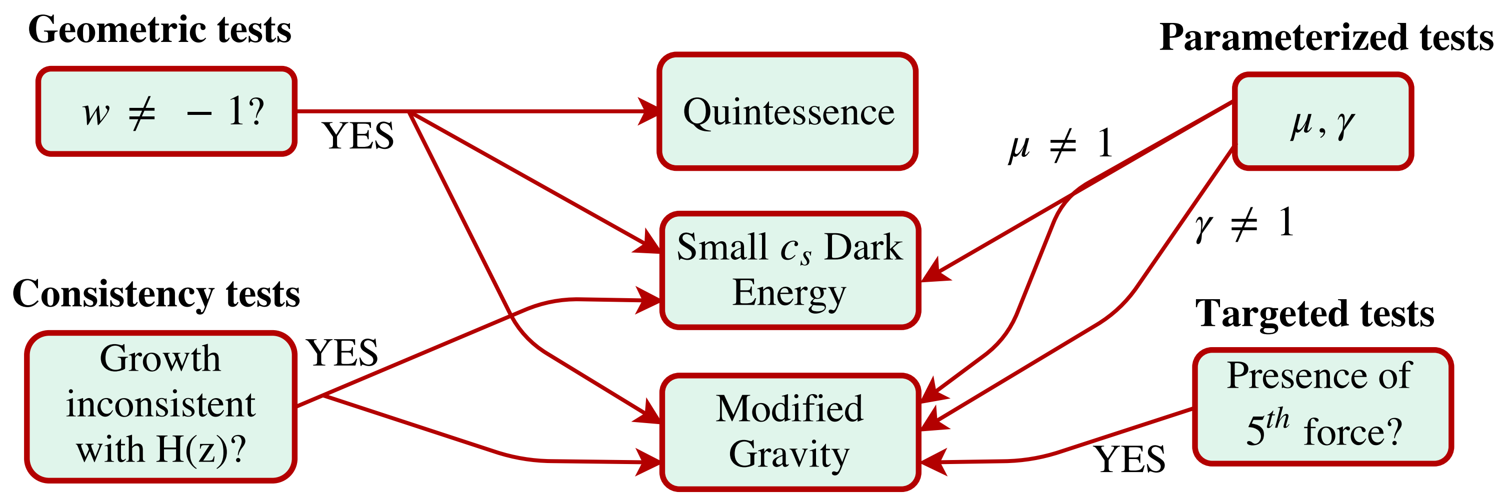

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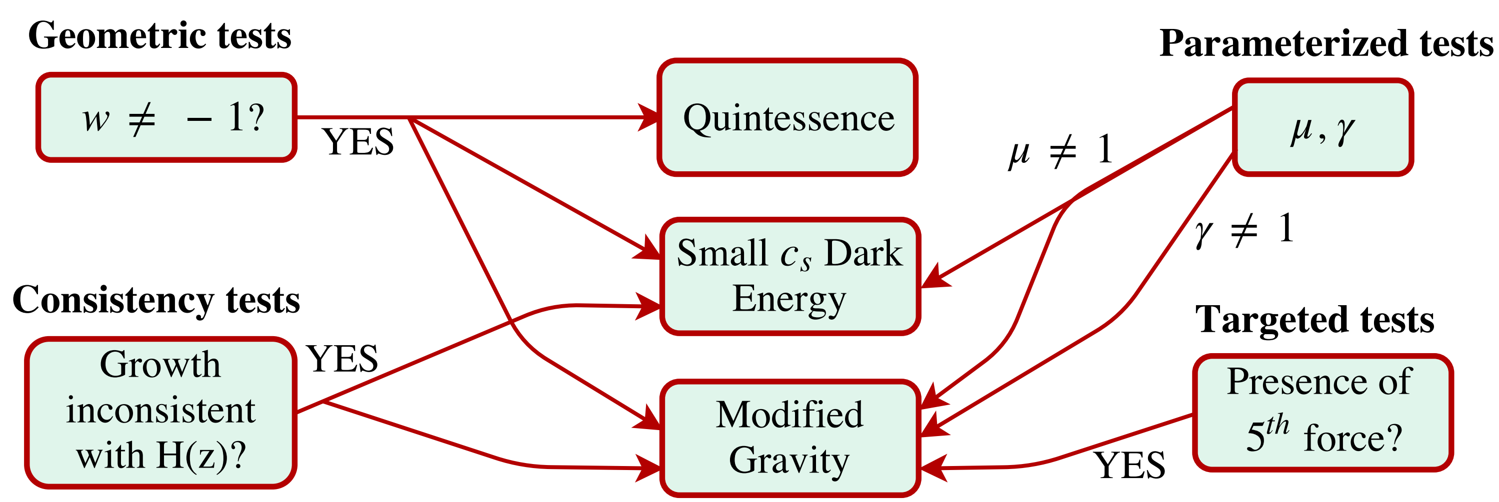

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- Directly parameterize deviations from GR and constrain these parameters (for example by comparing dynamical and lensing masses of objects)
- More targeted tests (lab searches, E_G ,…..)

Conclusions

- The two epochs of accelerated expansion in the standard cosmological model provide unique opportunities to probe physics coupled to the gravitational sector

- Inflation provides a window to physics at extremely high energies—may hope to learn what particles reside there, though measuring this will be challenging

- Late-time cosmic acceleration is still very mysterious, perhaps there is some new physics underlying it