Early Universe and Cosmology

Mark Trodden
Center for Particle Cosmology
University of Pennsylvania

My Instructions

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No problem!?

Modern Cosmology

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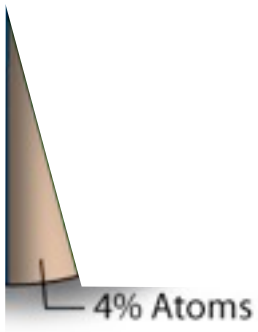

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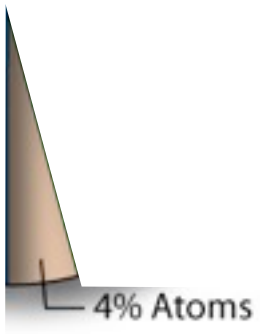

Why is there more
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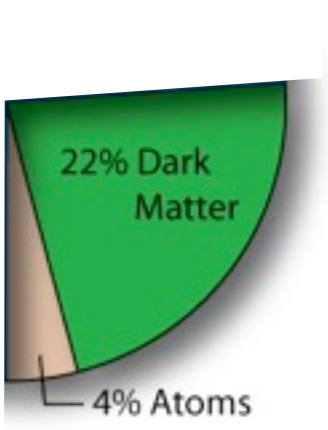

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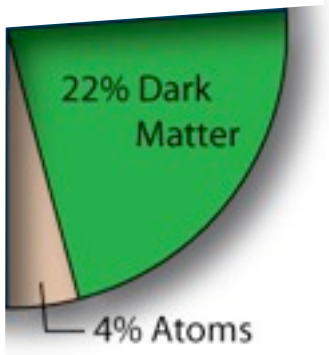

What is the nature of dark matter?

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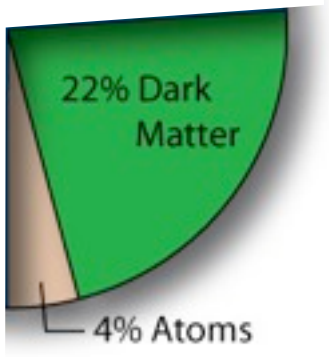

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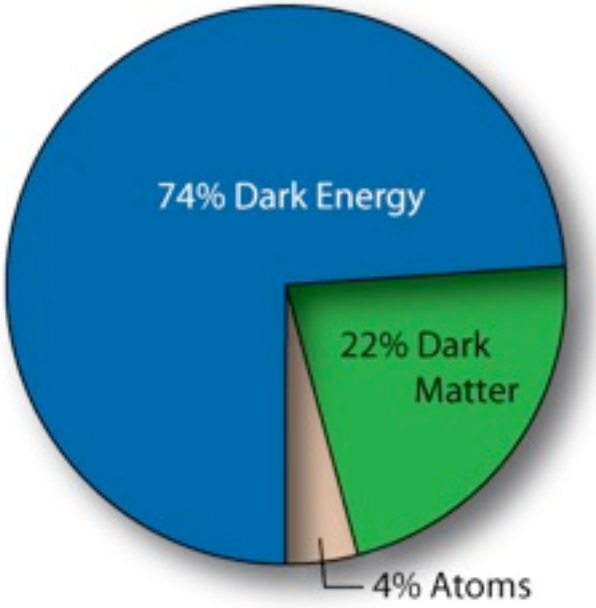

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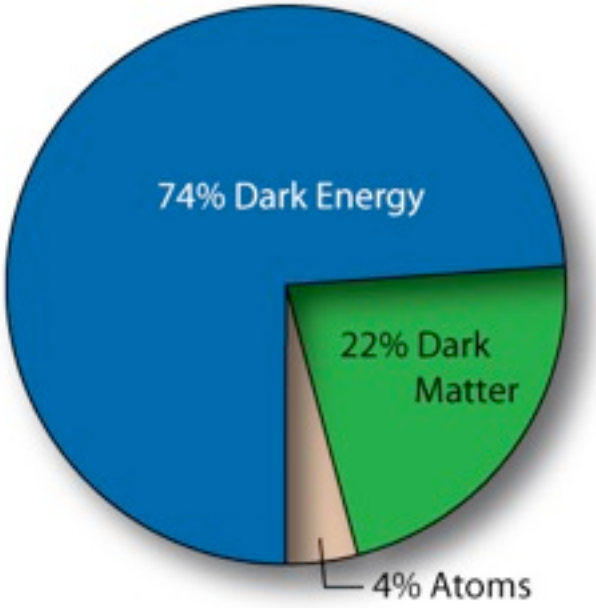

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Why is the cosmological constant so small?

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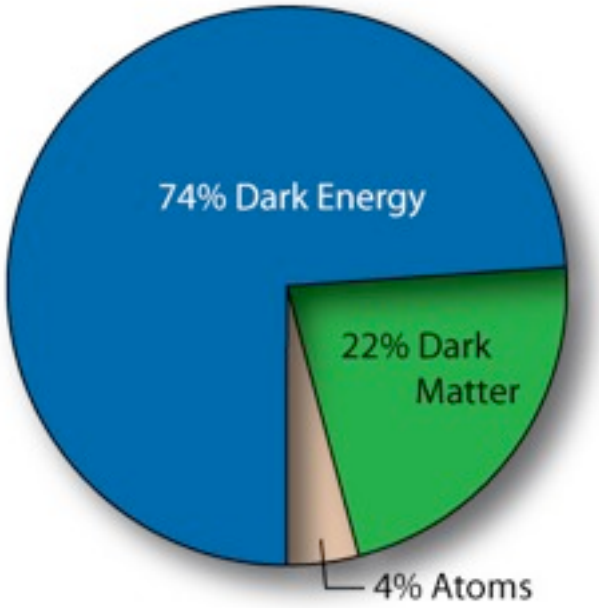

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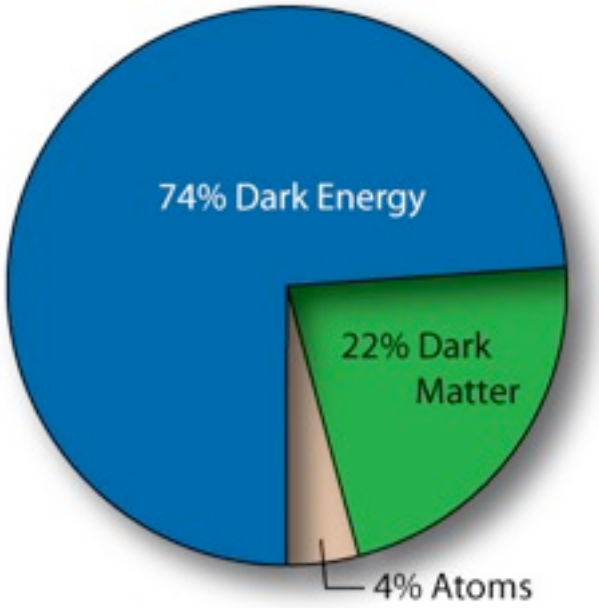

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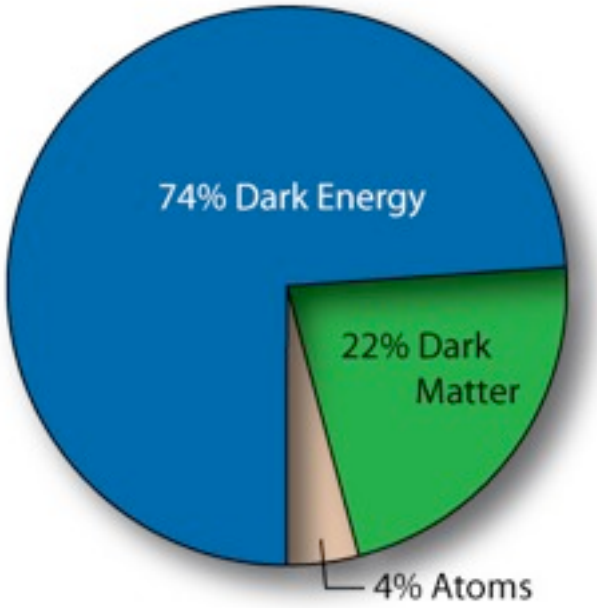

Genesis:

- Why is the universe so flat?
- Why is the universe so homogeneous?
- Why did the universe begin from a low entropy state?
- What resolves the big bang singularity?

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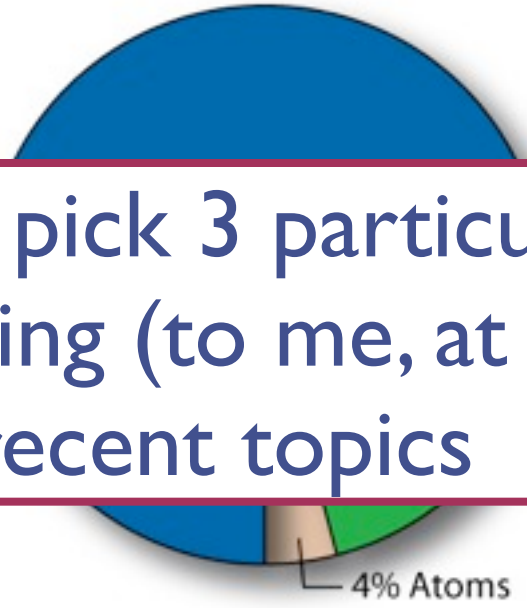

I'll Just pick 3 particularly interesting (to me, at least) recent topics

- Why did the universe begin from a low entropy state?
- What resolves the big bang singularity?

Why is there more matter than antimatter?

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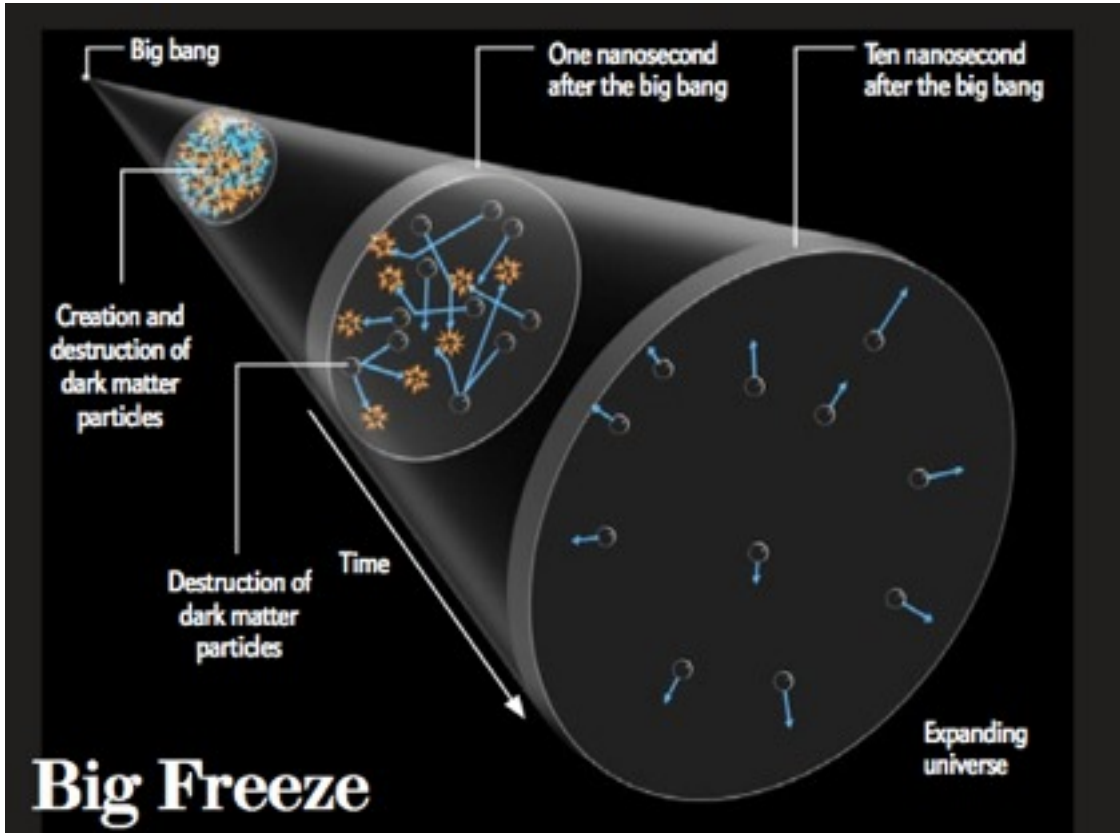
1. Dark Matter

Boltzmann, Expansion & Freeze-out



[J. Feng & M. Trodden, Scientific American, November 2010.]

Boltzmann, Expansion & Freeze-out

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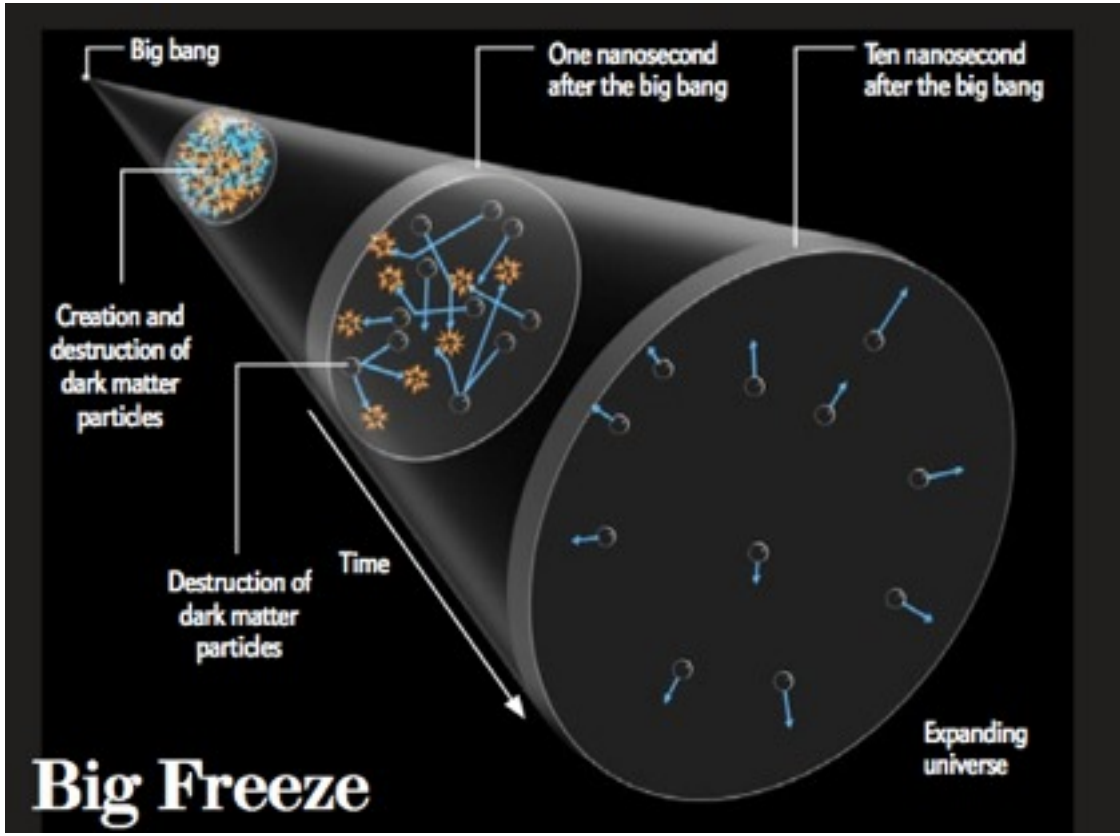

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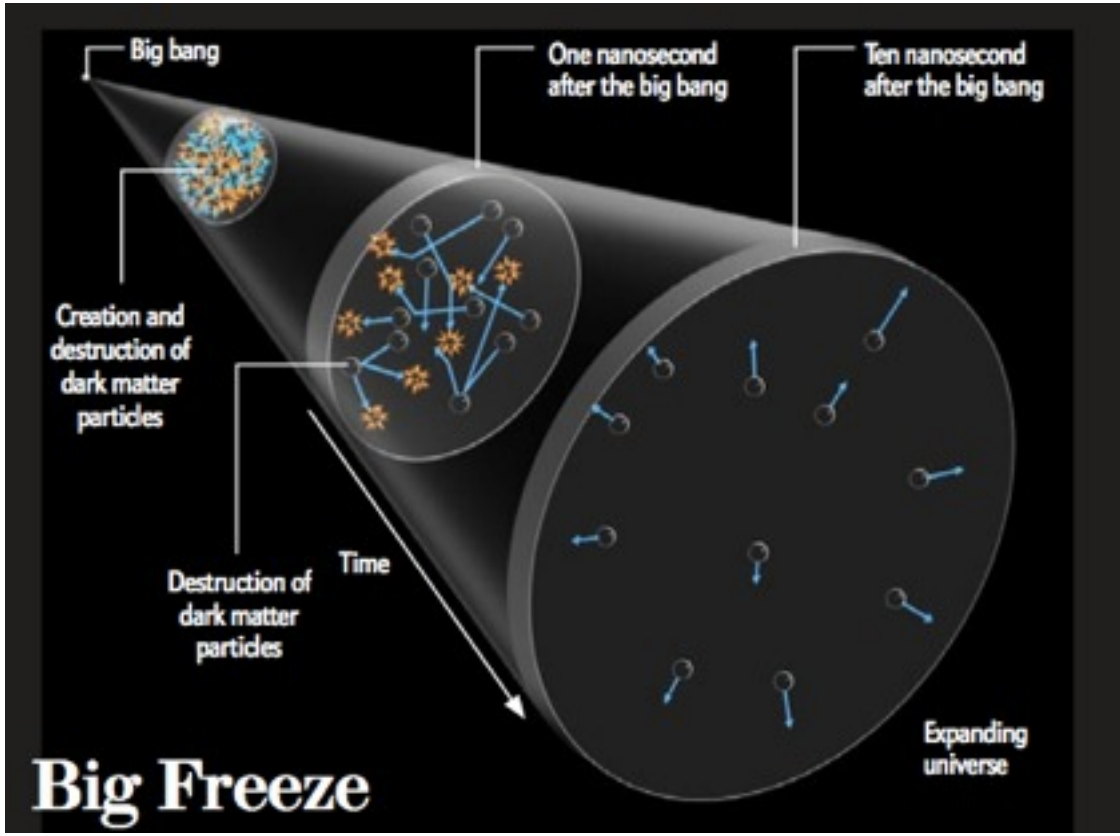
Annihilations



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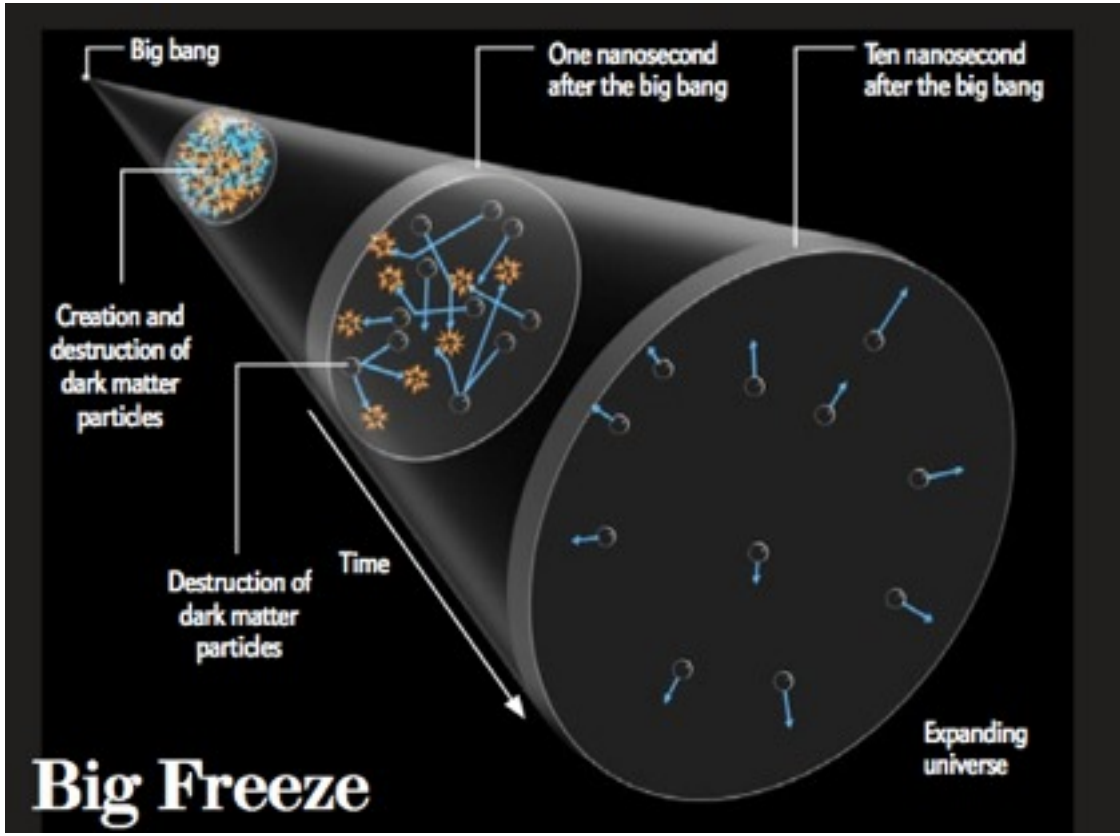

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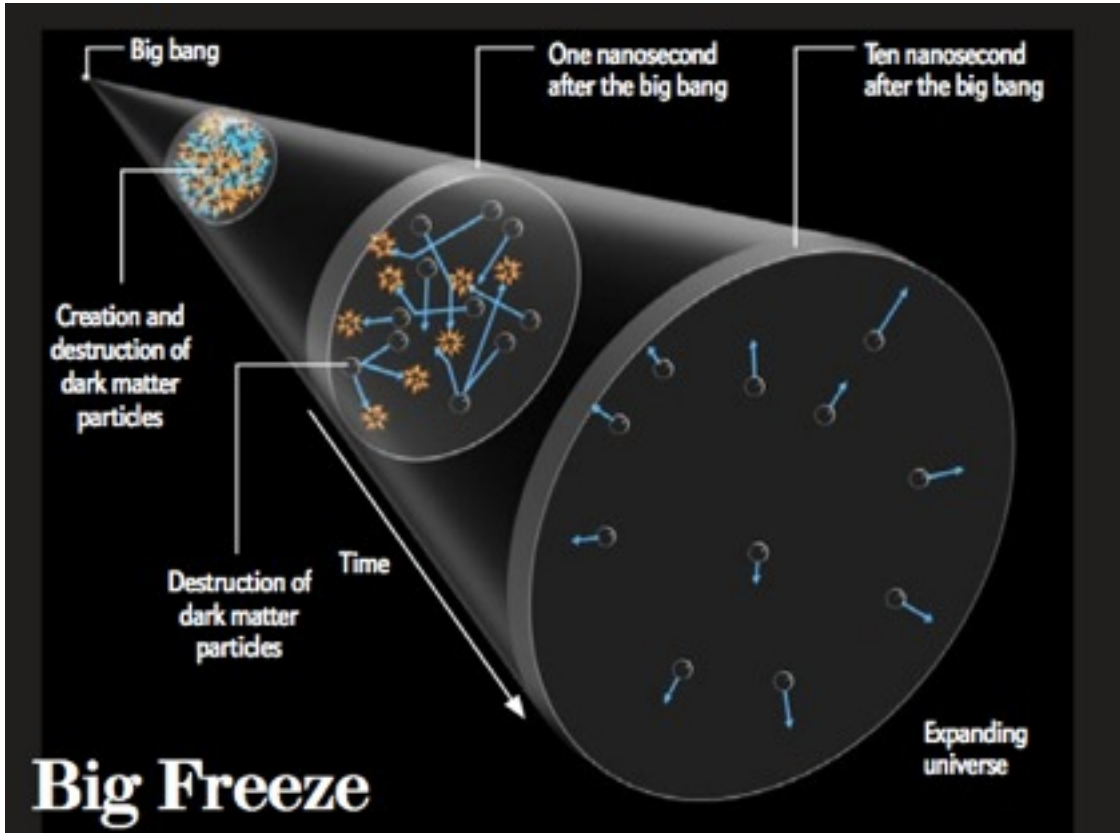

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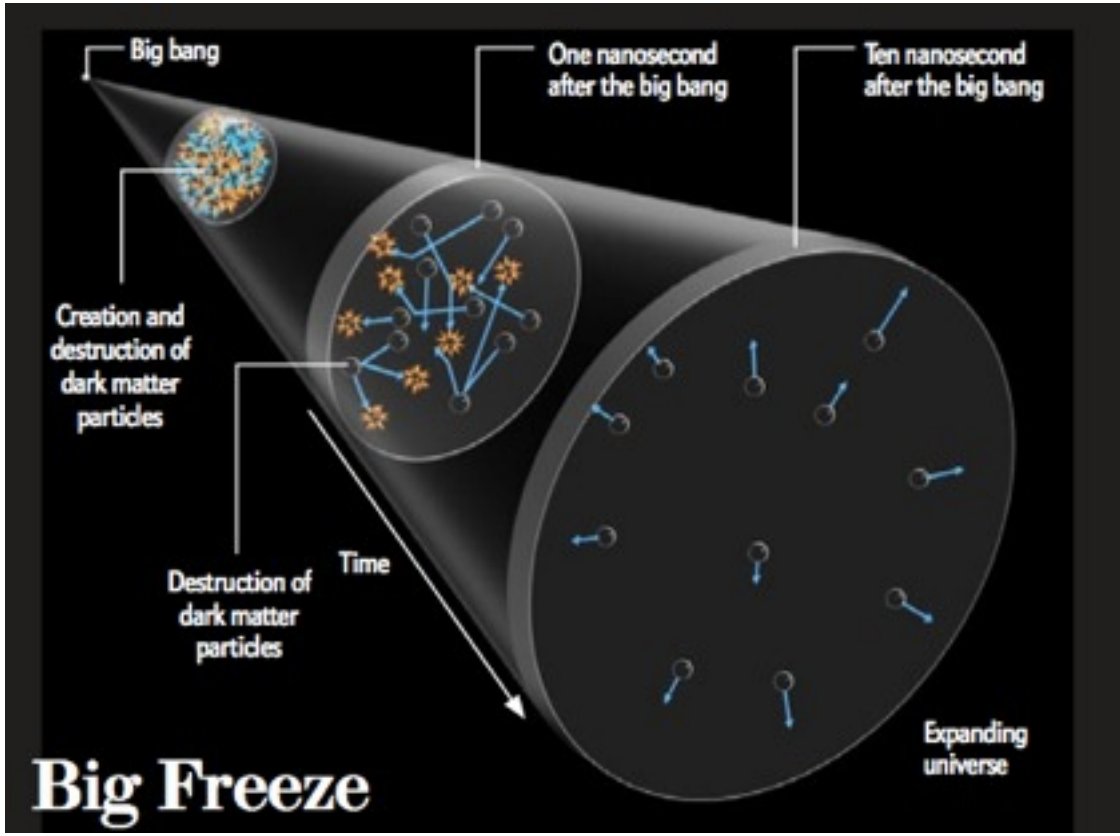

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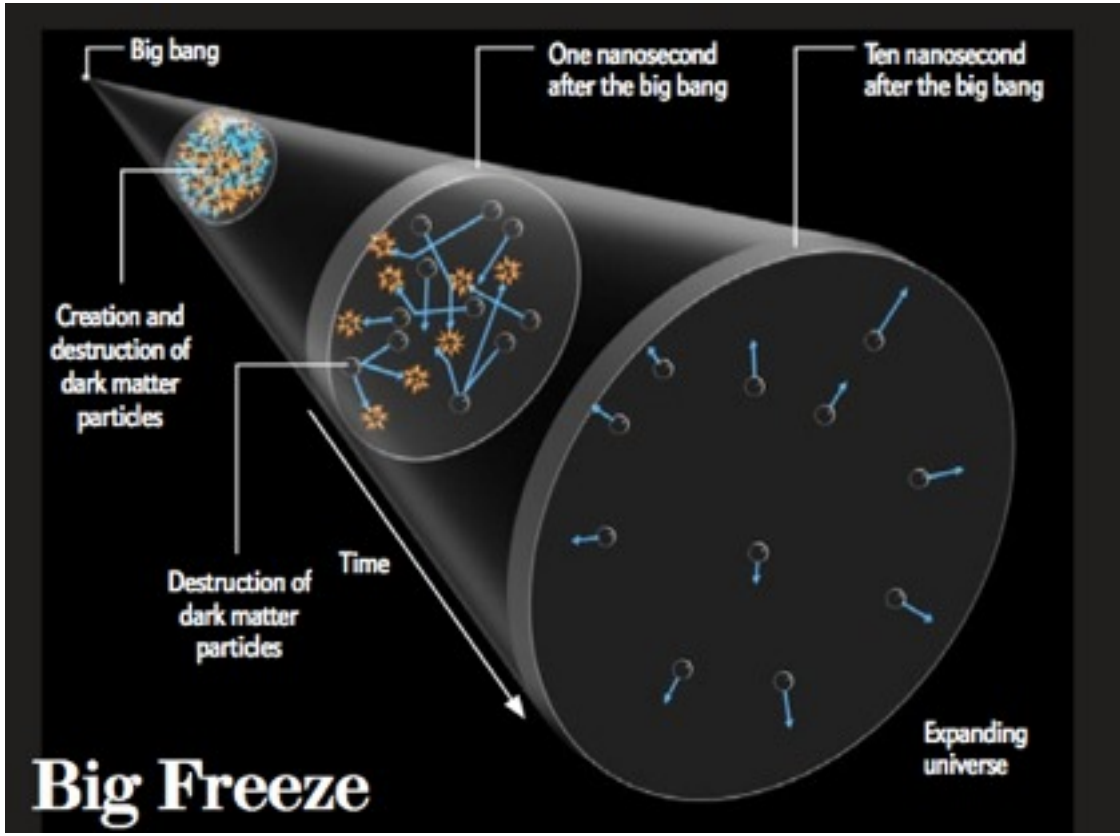

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Amount left over depends on masses and interaction strength.

The Weak Scale emerges

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Different strengths of the interaction lead to different frozen out amounts of dark matter.

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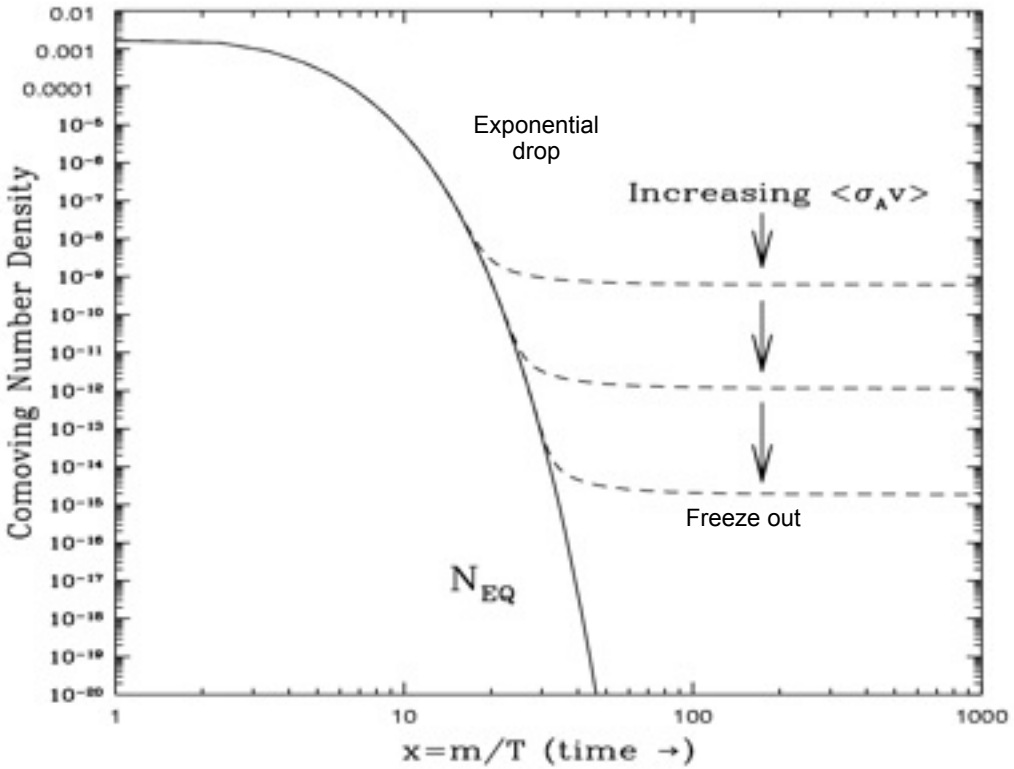

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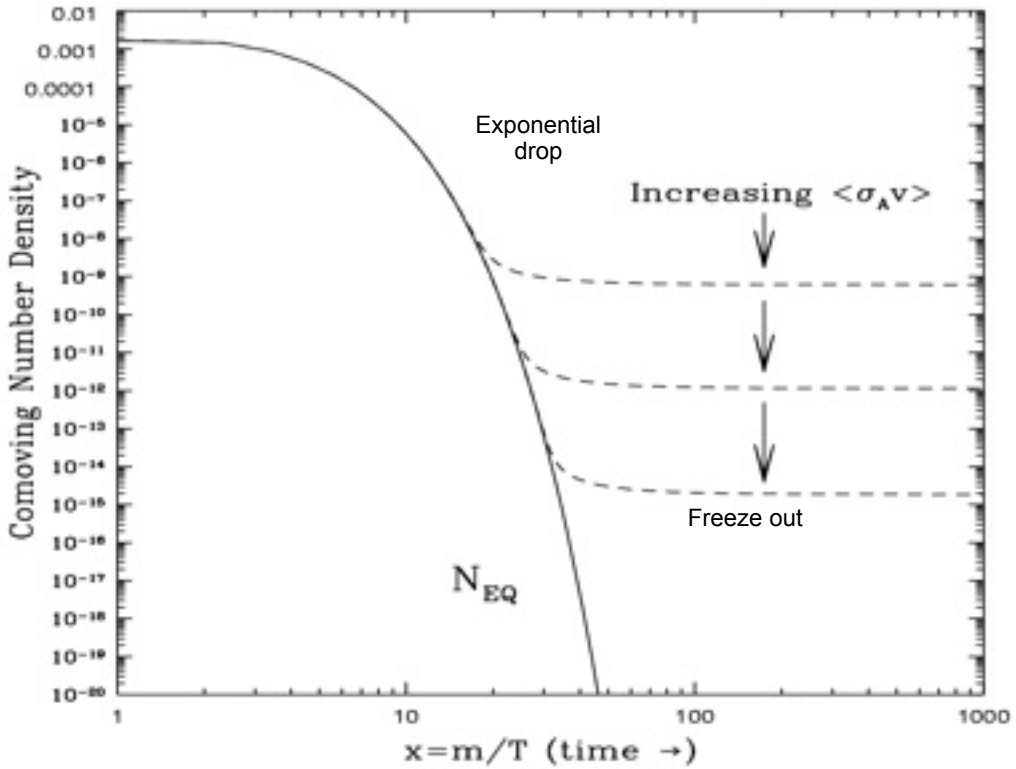

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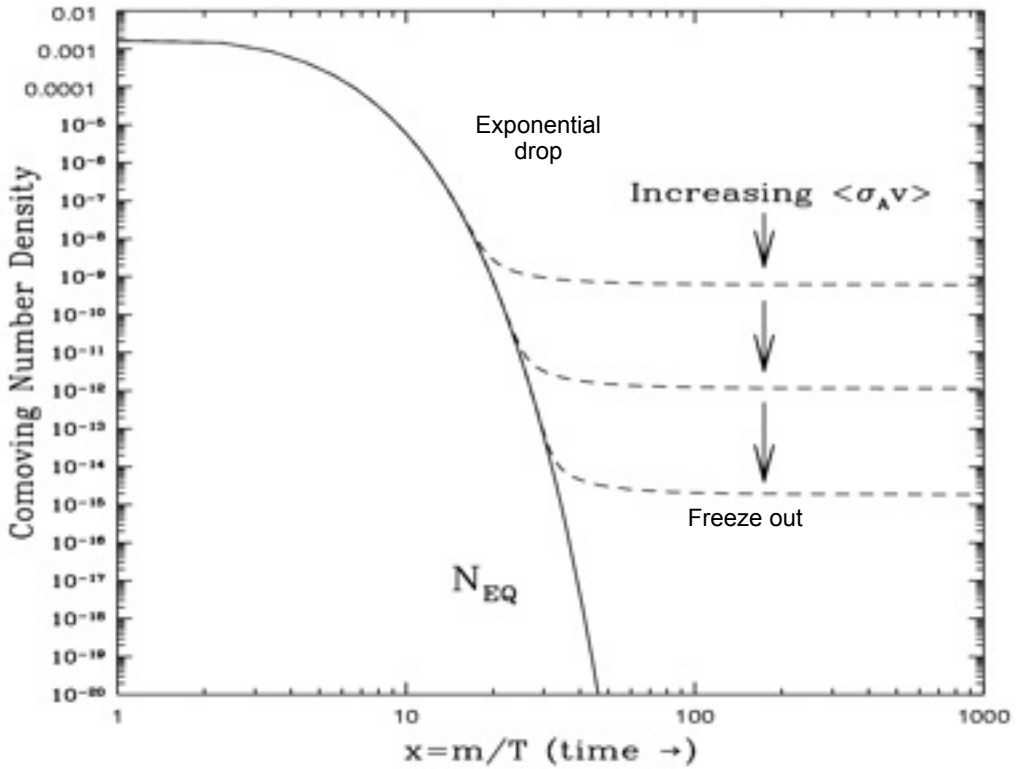

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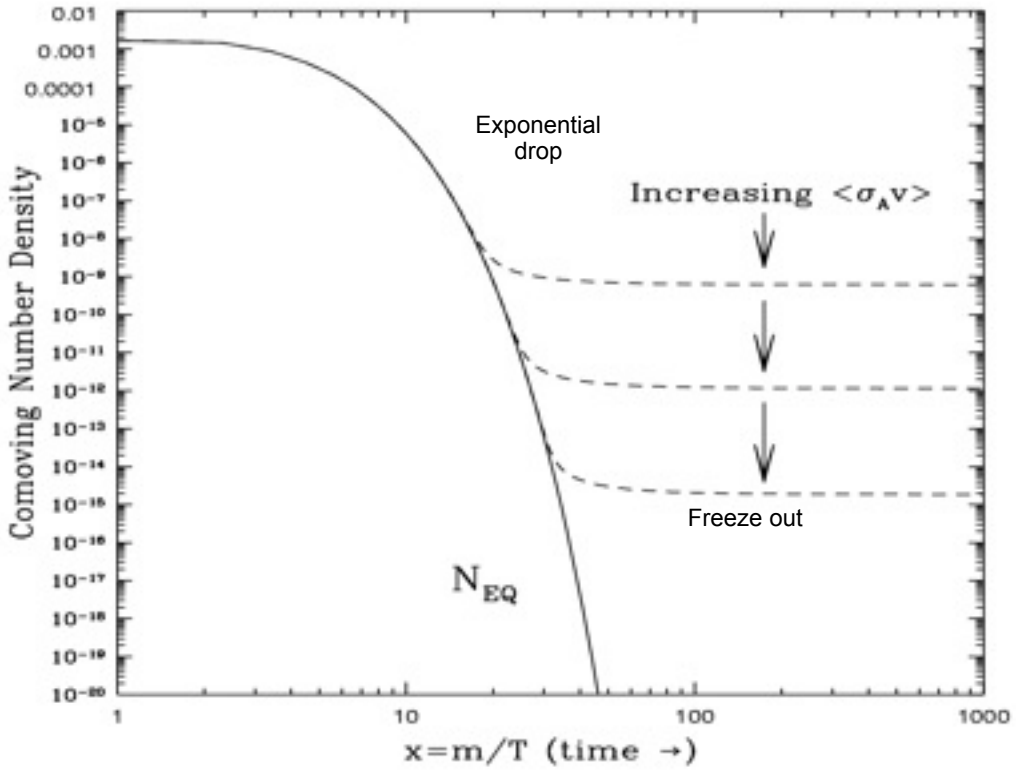

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Remarkably, the observed dark matter abundance is obtained for interactions at the strength of the weak nuclear force!

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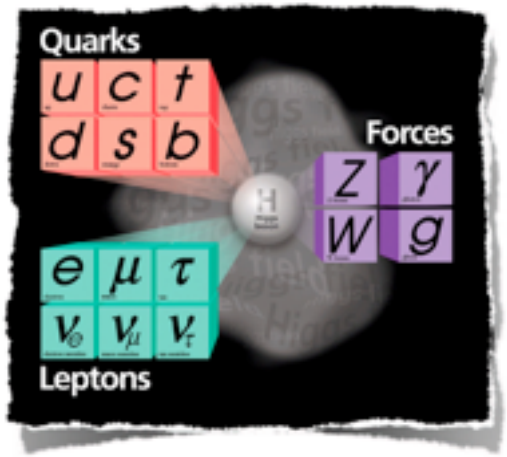

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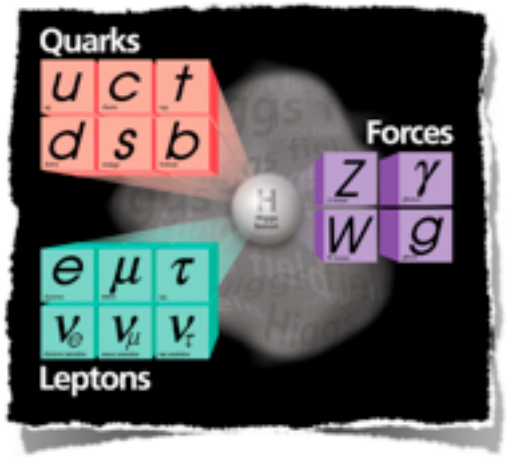

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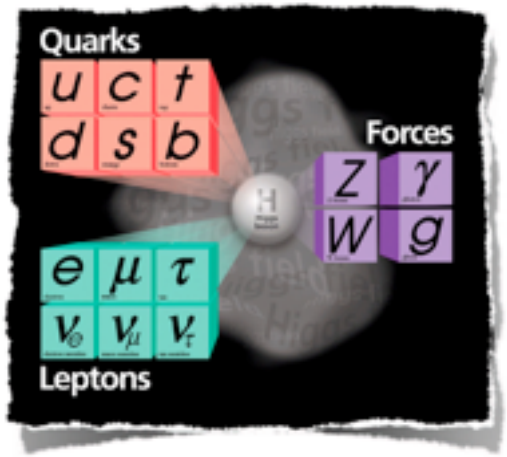

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BUT: the story is, of course, much more compelling than this!

The Hierarchy Problem

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Quantum corrections to the Higgs mass are quadratically divergent

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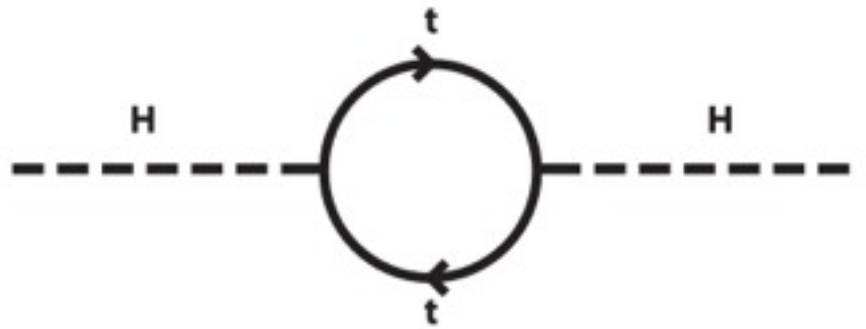

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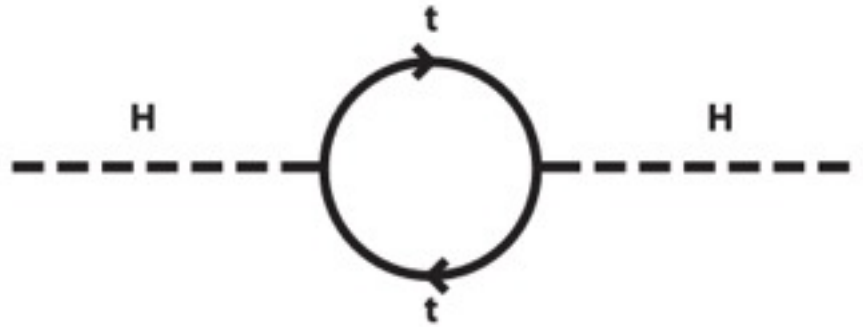

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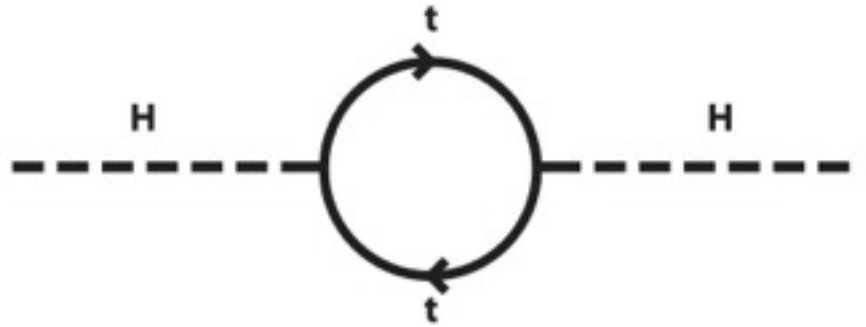

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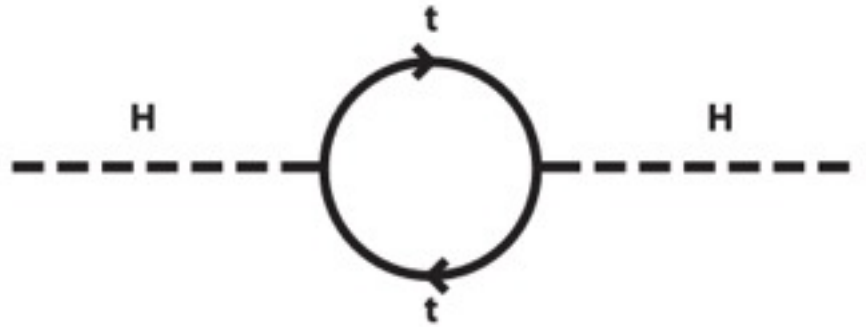

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In which case need to cancel these Planck scale numbers against one another to one part in 10^{15}!

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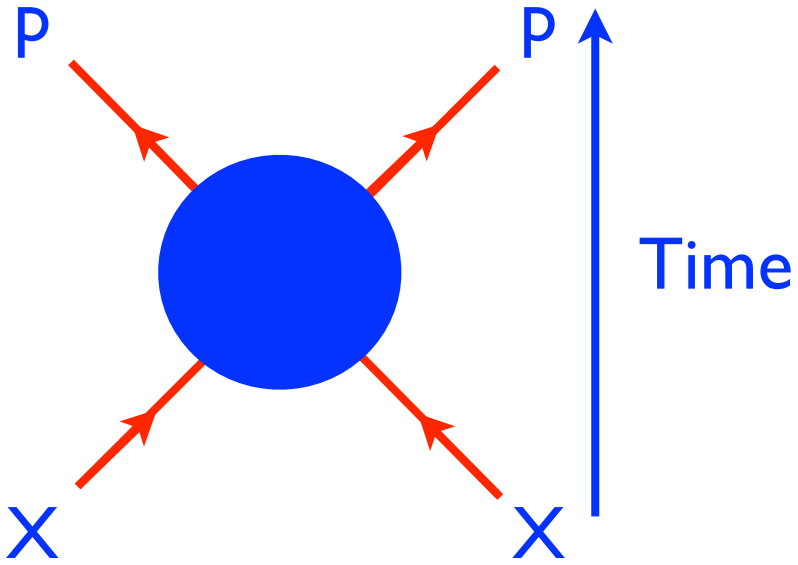
Often, this stable new particle is an ideal WIMP candidate!

Making WIMPs

We know we can have $X + X \rightarrow p + p$



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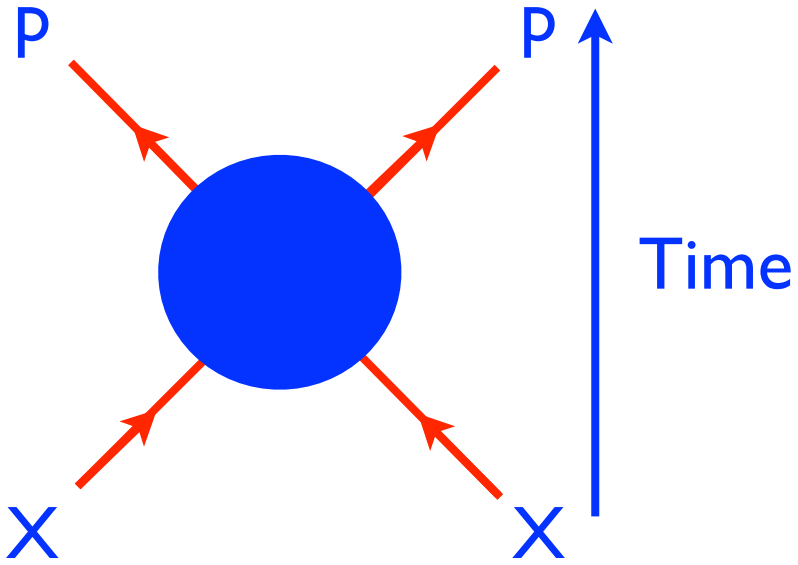

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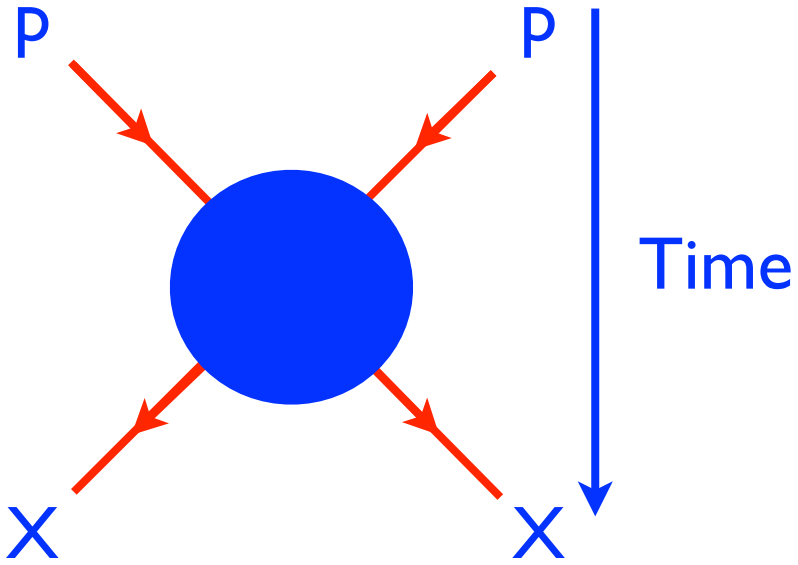

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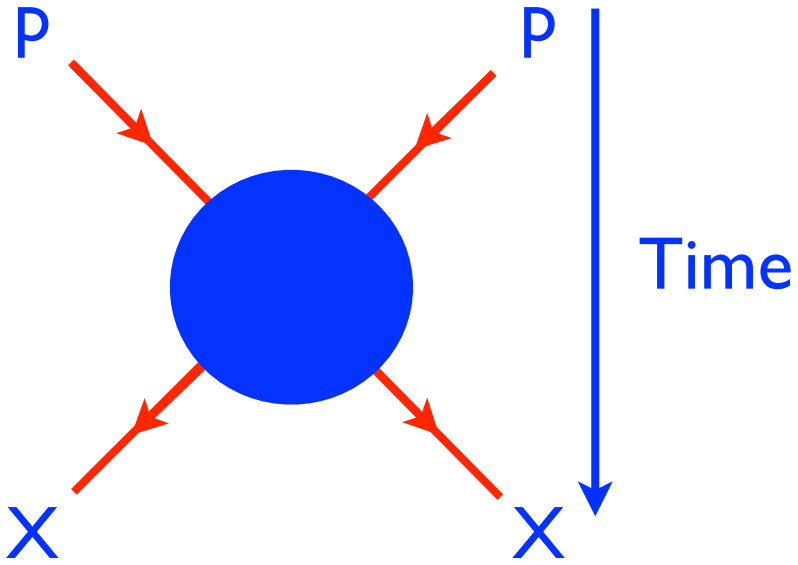

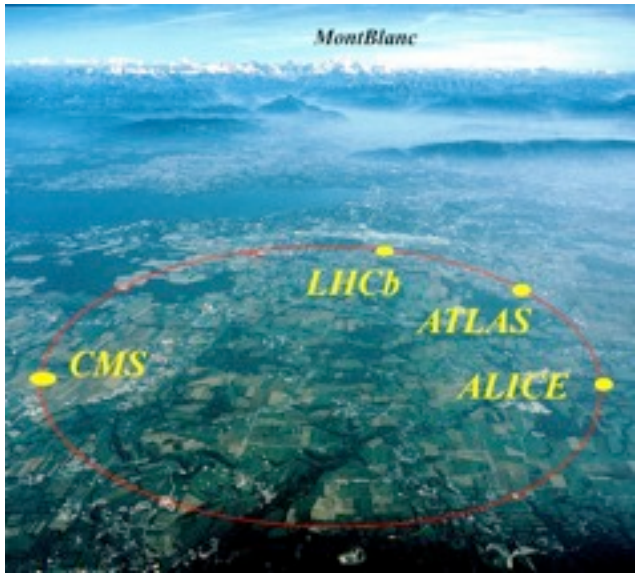

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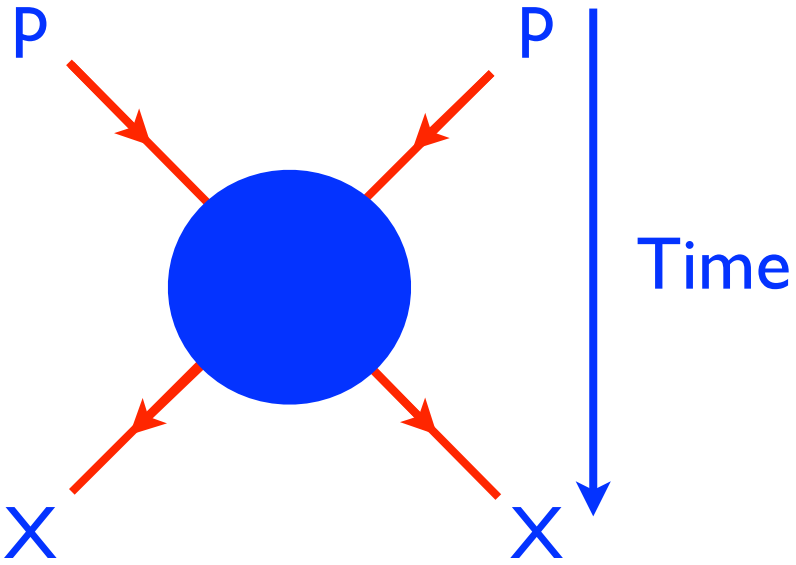

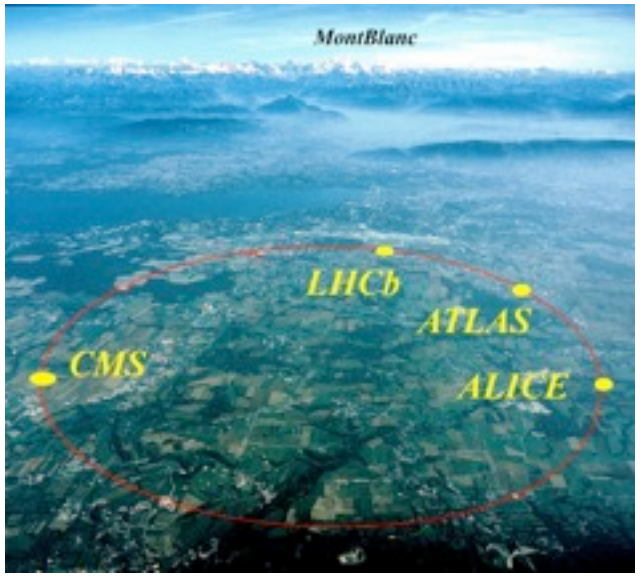

LHC has already begun constraining some models this way (particularly the MSSM, which needs a high cross-section to avoid overproduction)

Direct Detection of WIMPs

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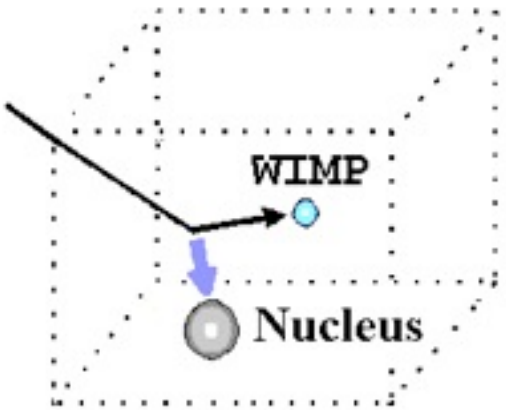

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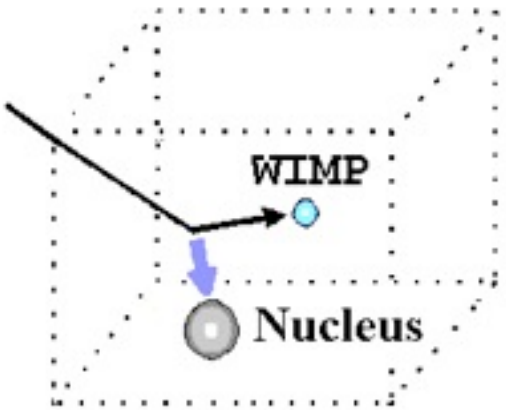

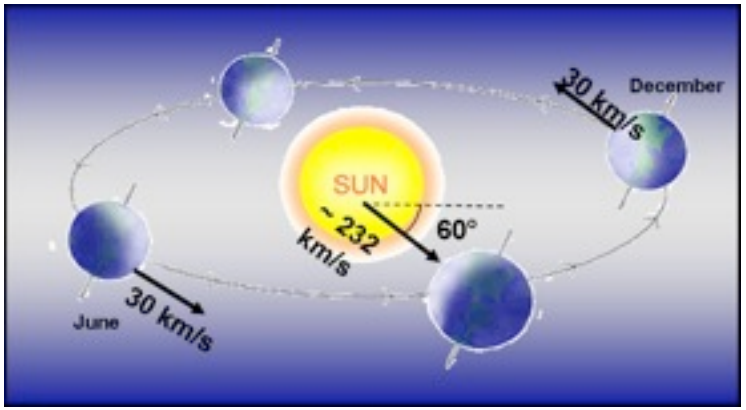

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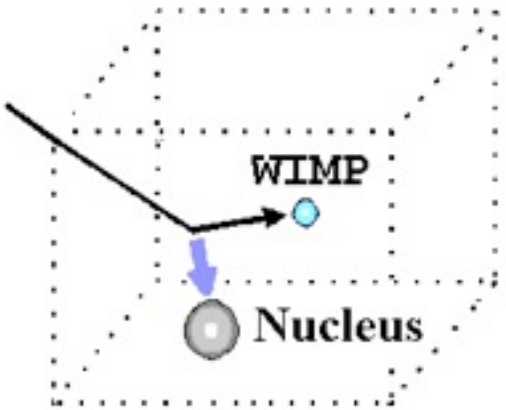

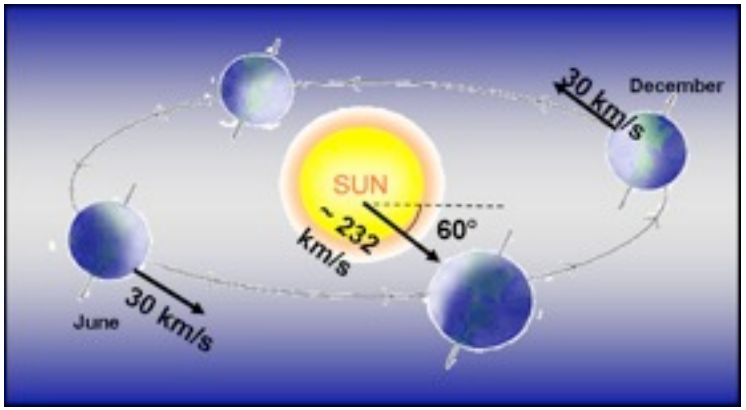

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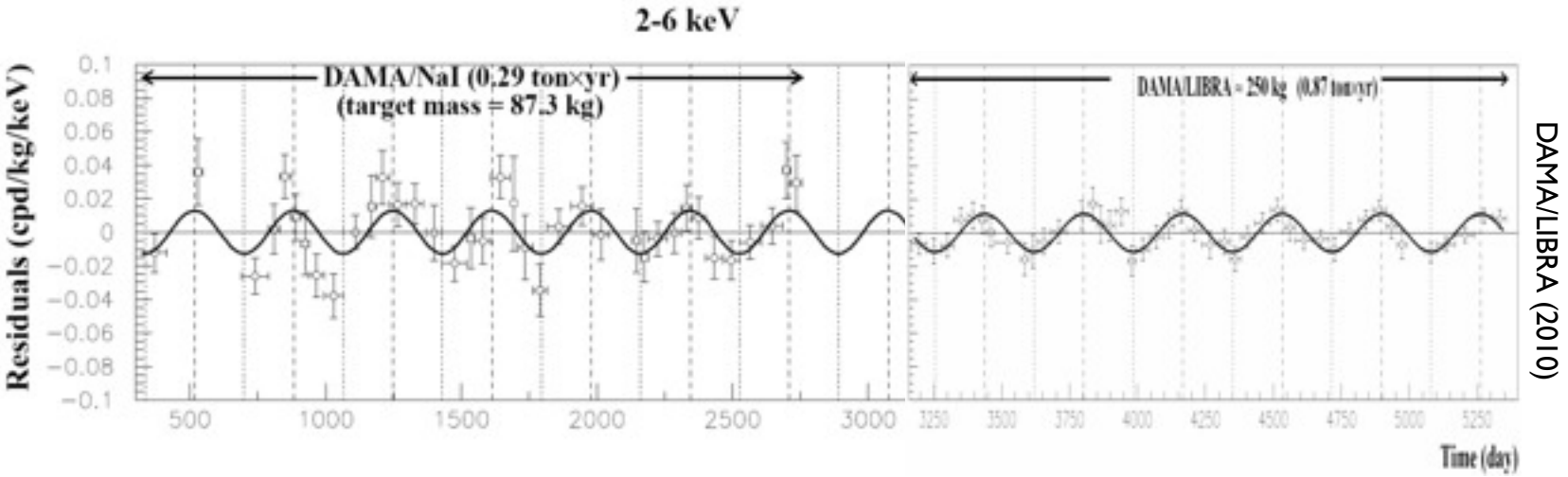

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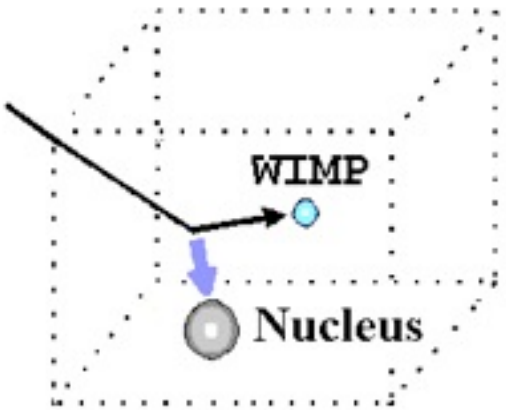

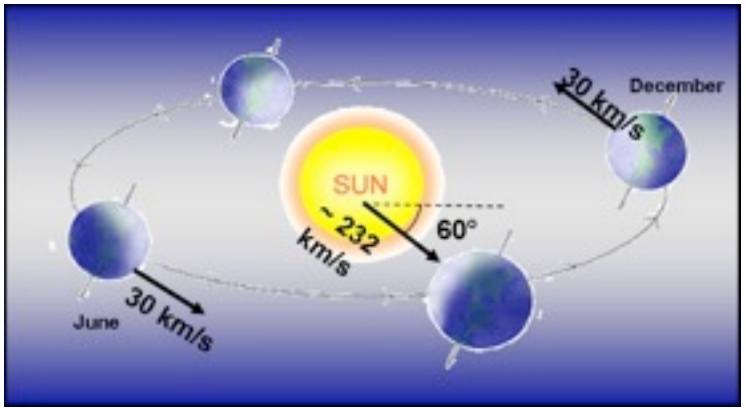

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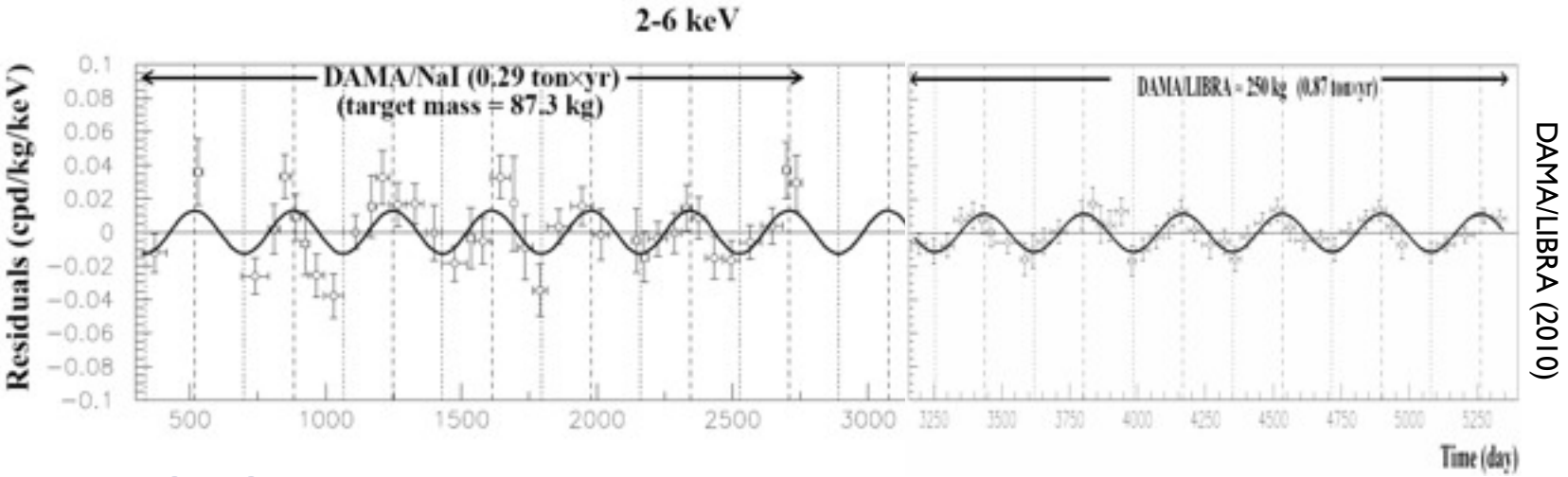
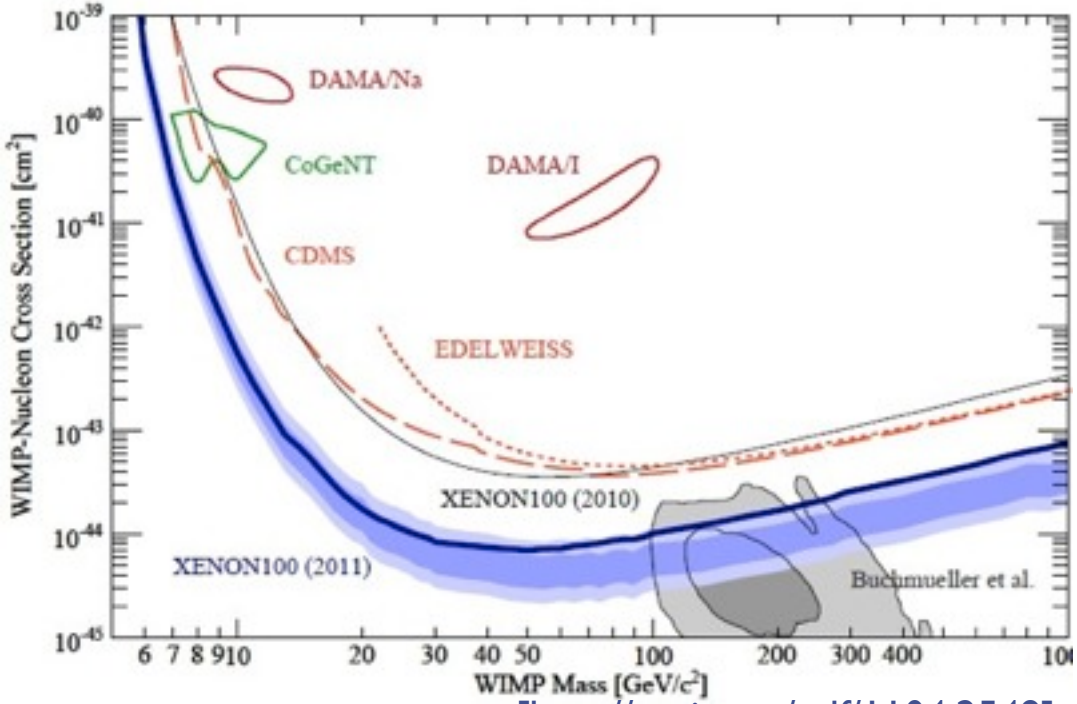


Now CoGeNT has provided additional evidence at low mass

Putting Constraints Together



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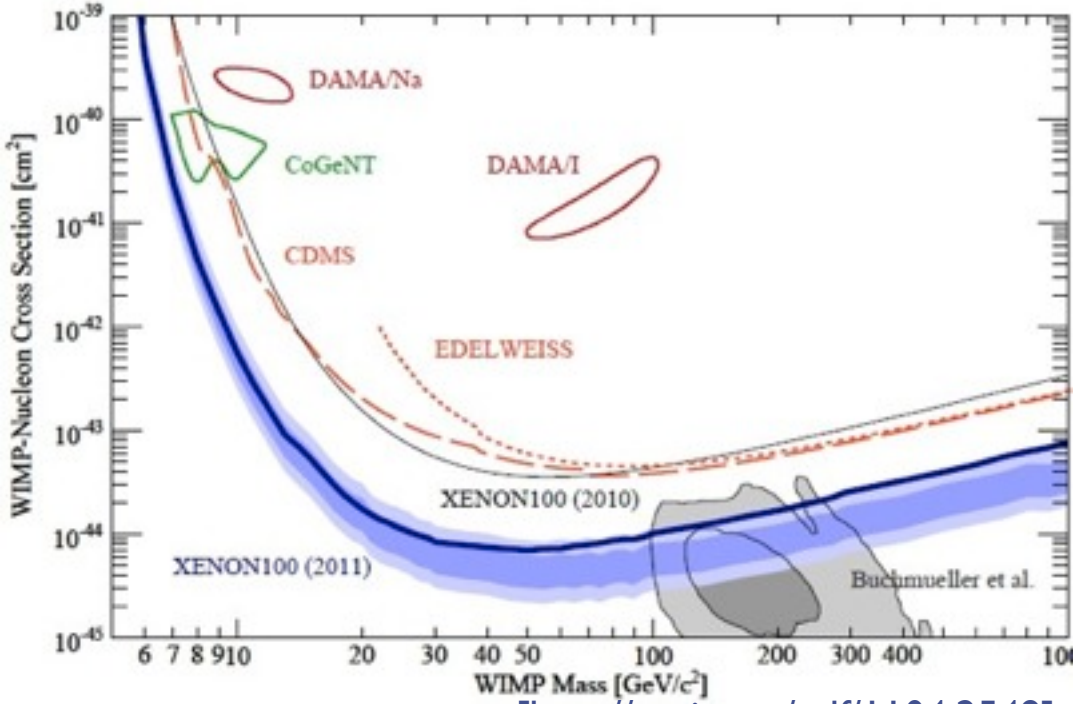

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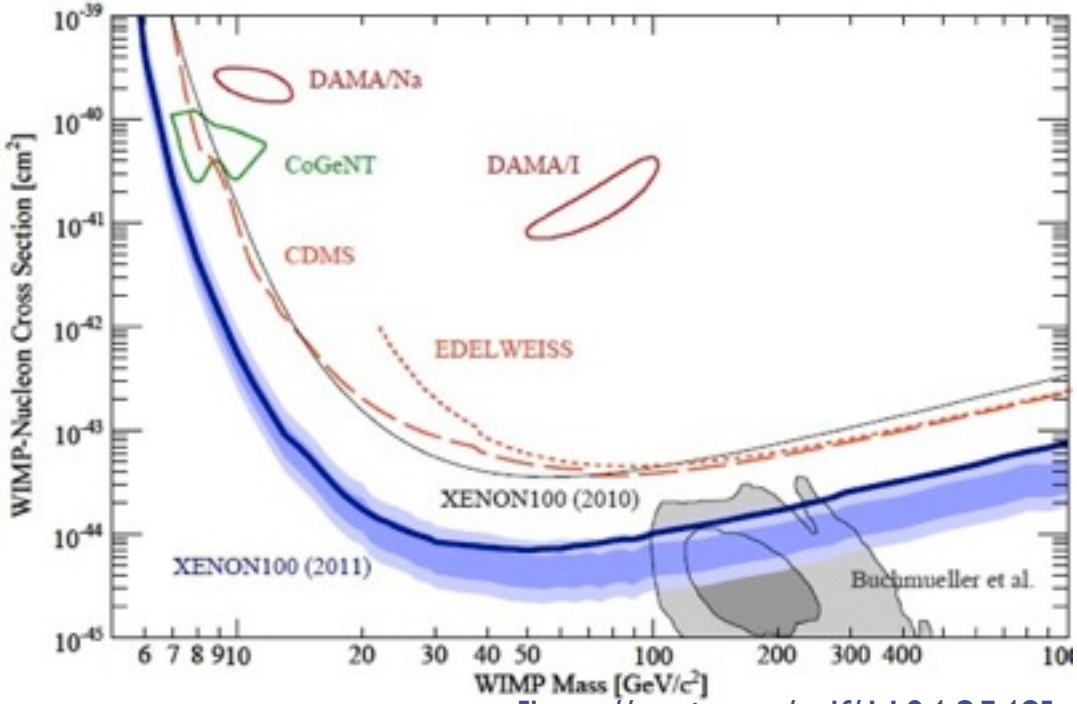

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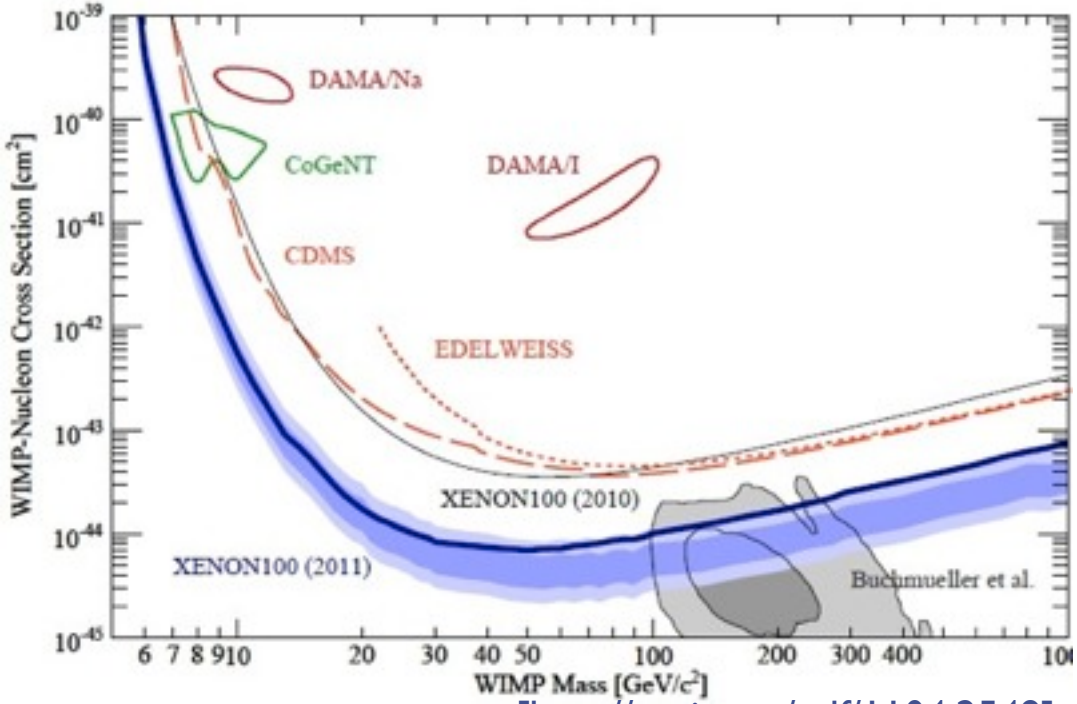

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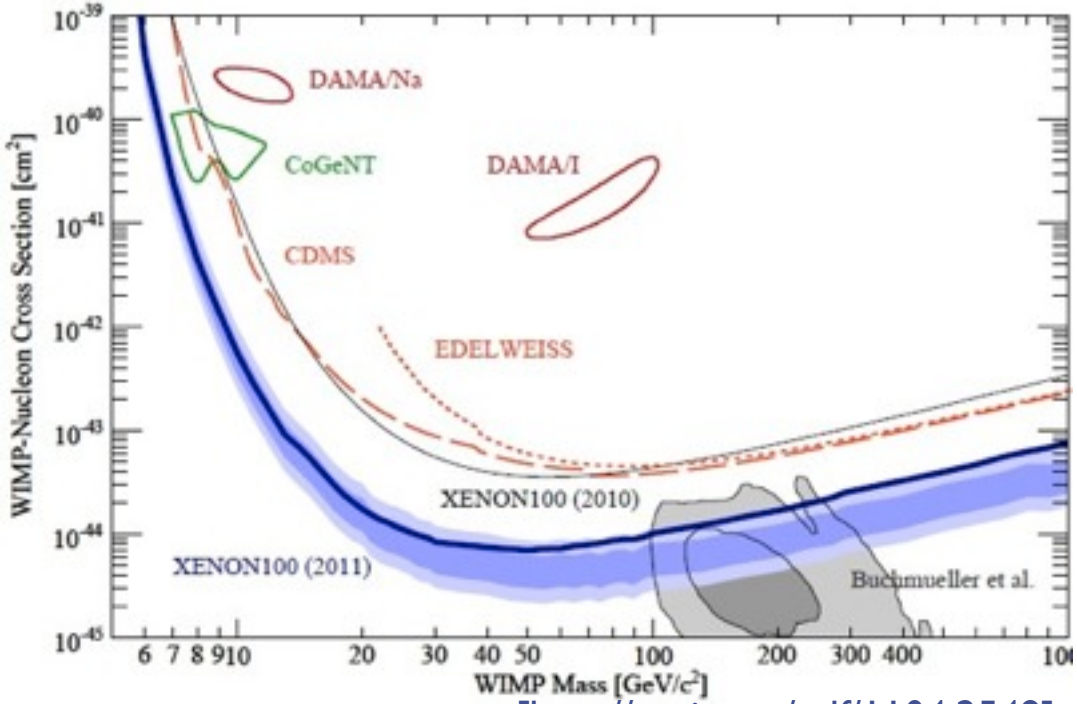

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Need models in high cross-section, low mass regime.

Interestingly, this might also be the kind of particle to address the excess from Fermi, which I won't discuss here, through annihilations of dark matter.

New Model Building

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Examples: Hooper, Collar, Hall, McKinsey (2010); Fitzgerald, Zurek (2010); Fox, Liu, Weiner (2010); Giuliani (2005); Chang, Liu, Pierce, Weiner, Yavin (2010); Feng, Kumar, Marfatia, Sanford (2011); Hooper, Finkbeiner, Dobler (2007); Dobler, Finkbeiner (2008); Alwall, Feng, Kumar, Su (2010); ...

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SEE NEXT TALK - JONGHEE YOO

2. Cosmic Acceleration & New Field Theories

Simple Cosmology - a Reminder

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Evolution of the universe governed by Einstein eqns

$$G_{\mu\nu}(g) = 8\pi G T_{\mu\nu}$$

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When evolution dominated by type i, obtain

$$a(t) \propto t^{2/3(1+w_i)} \qquad \rho(a) \propto a^{-3(1+w_i)} \qquad (w_i \neq -1)$$

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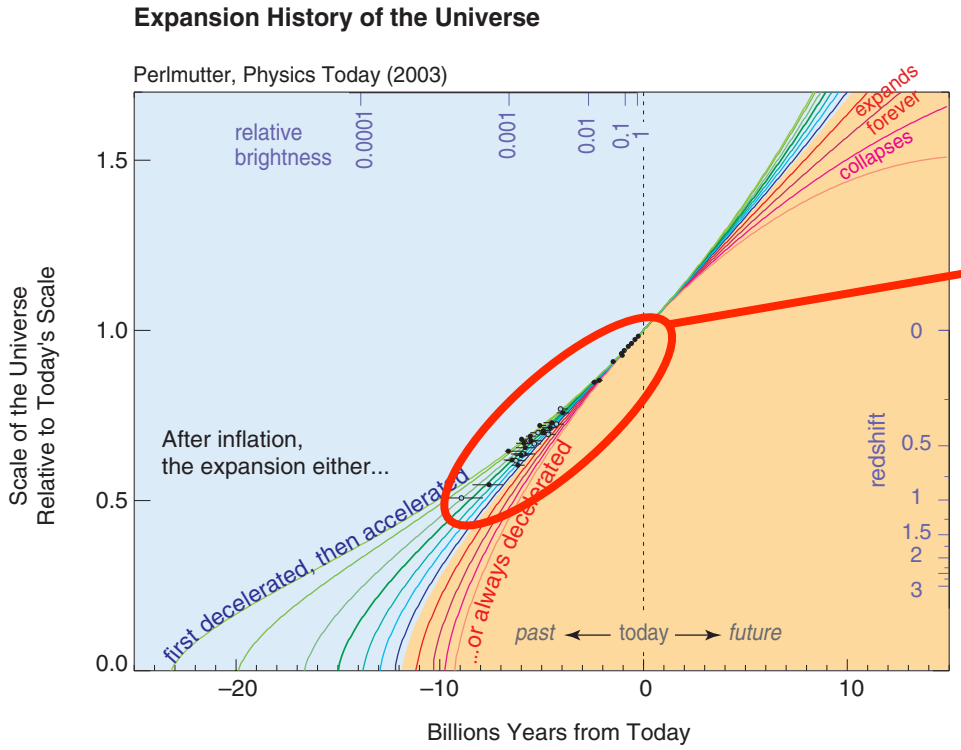

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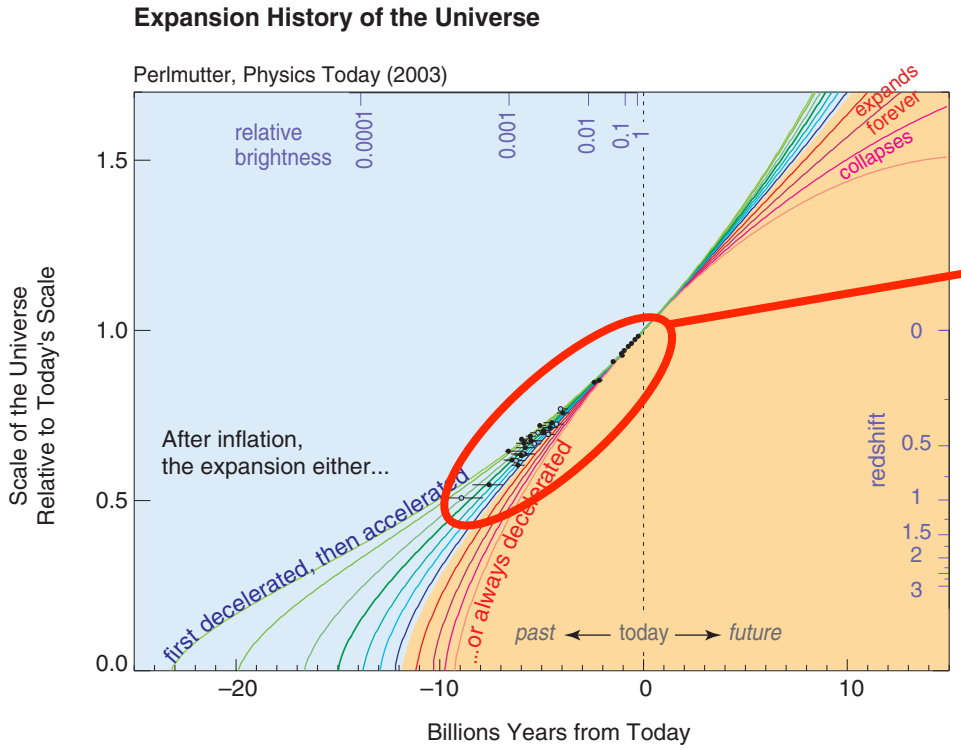

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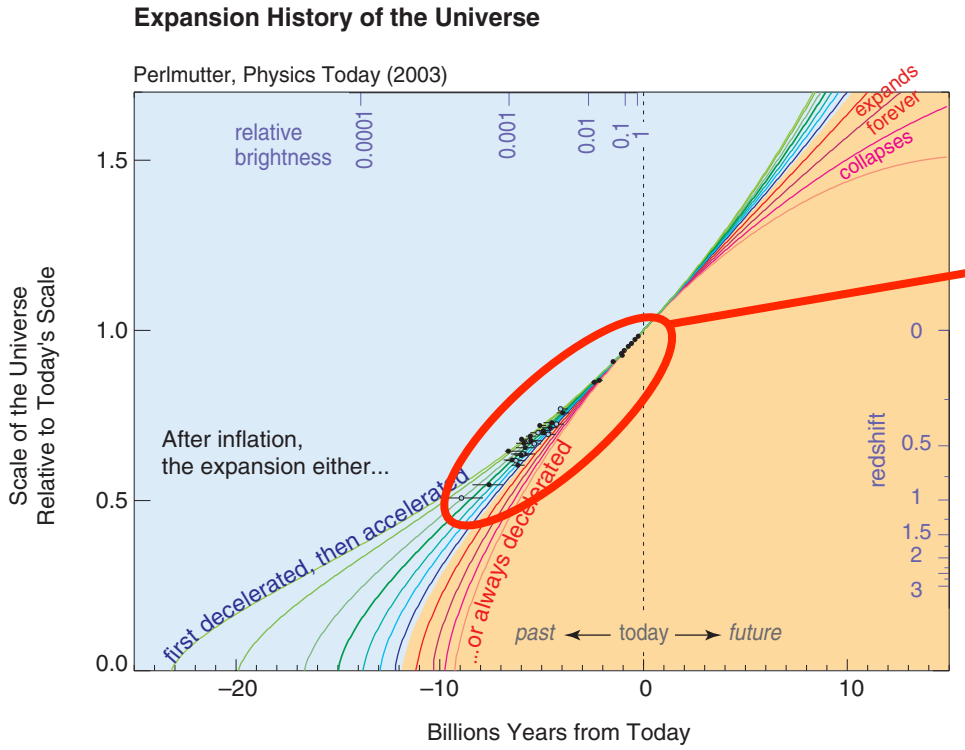

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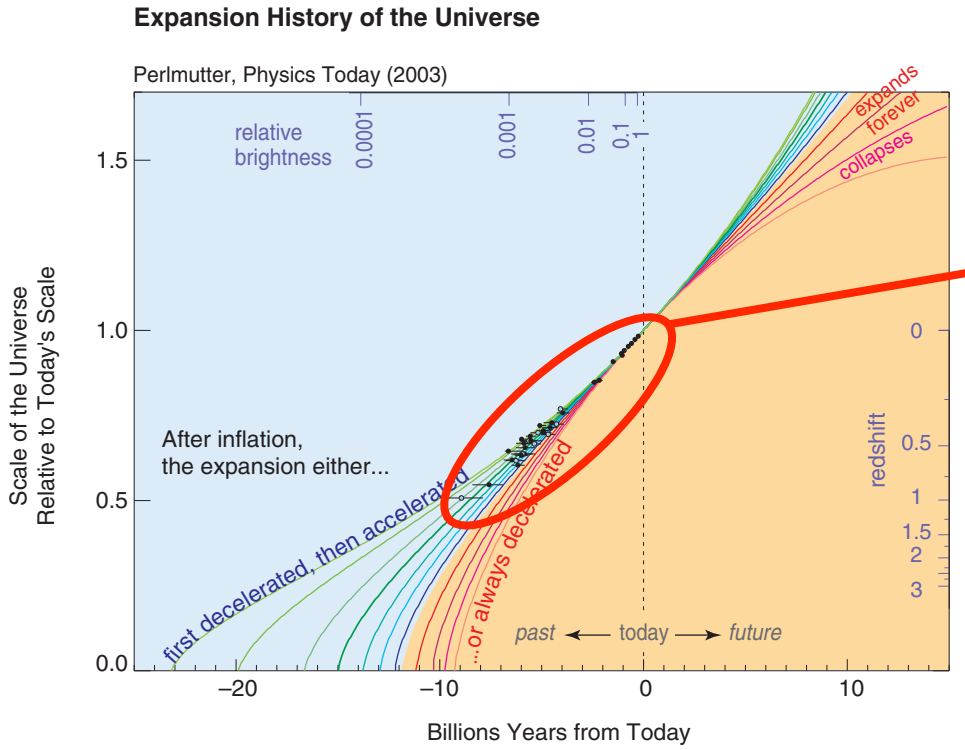

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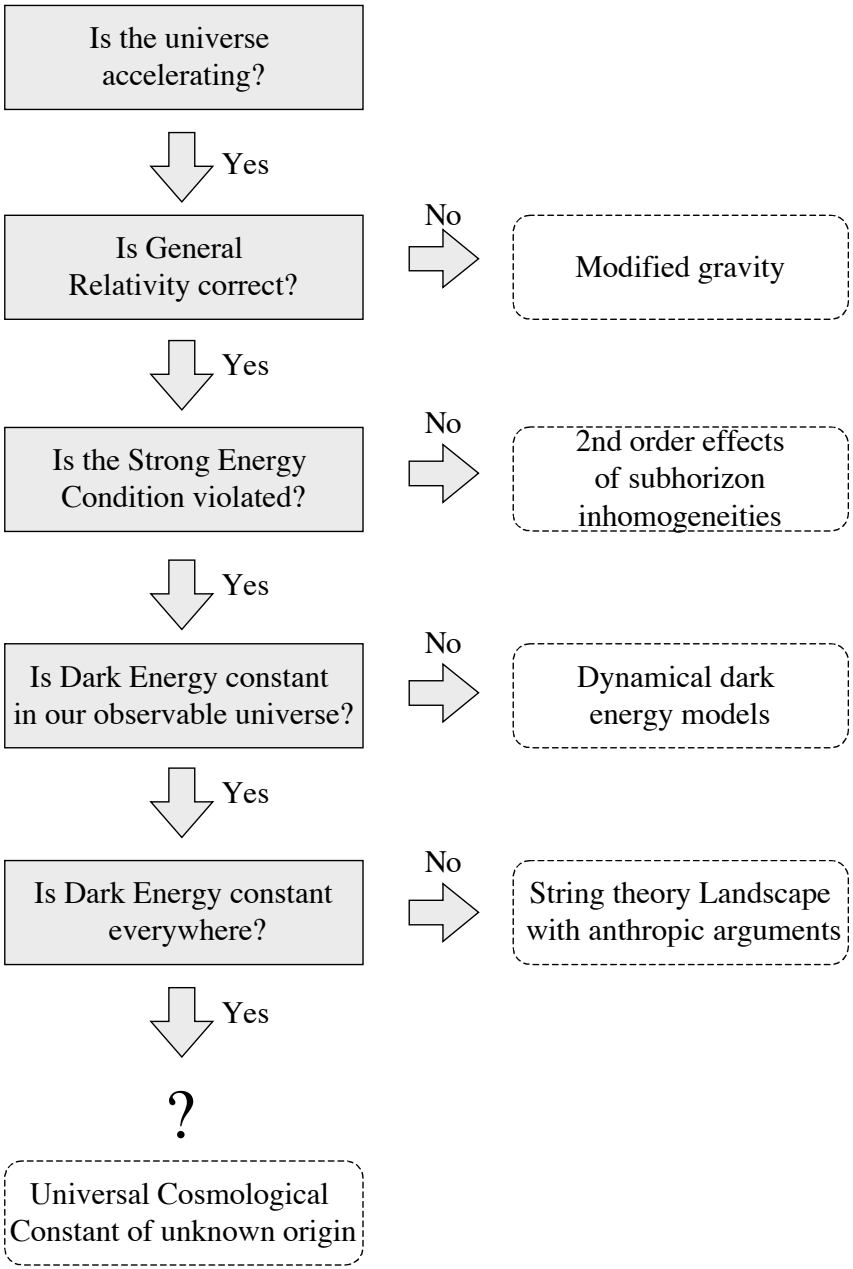
Then we infer that the universe must be dominated by some strange stuff with $p < -\rho/3$. We call this **dark energy!**



(Bean, Carroll & M.T., *DETF White Paper* (2005) [astro-ph/0510059])

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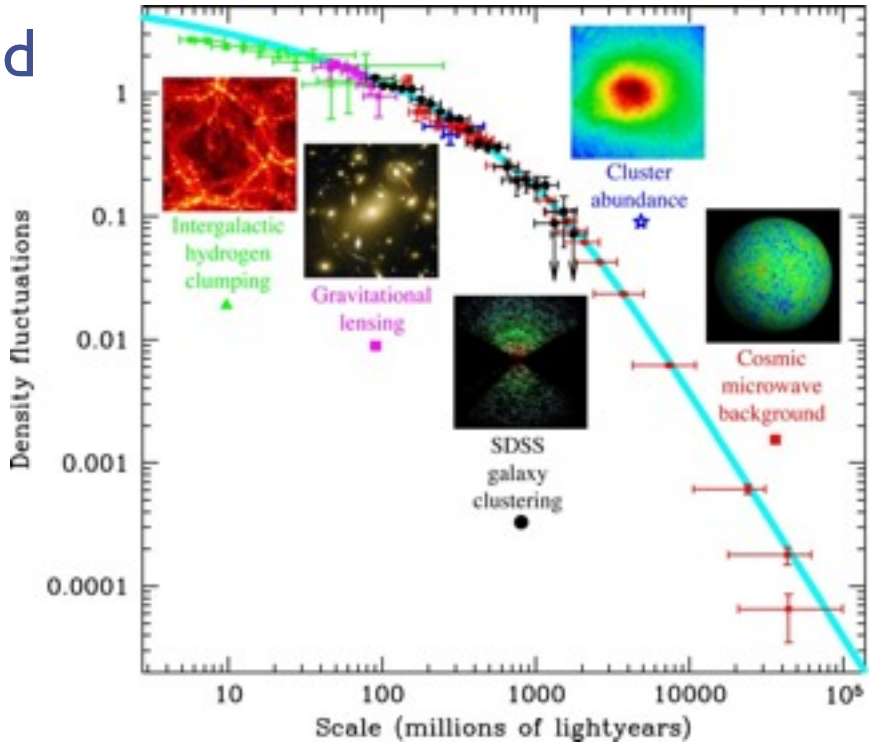

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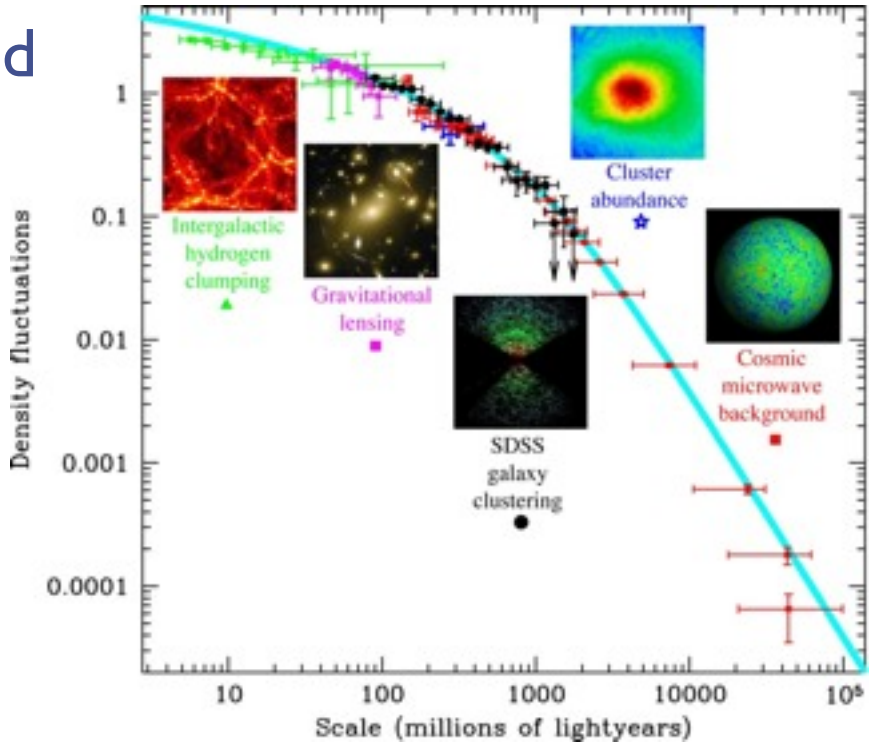
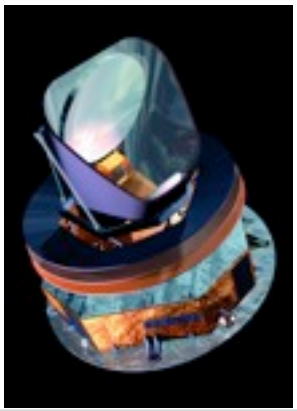


DARK ENERGY SURVEY

LSST Large Synoptic Survey Telescope



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If a dynamical understanding of a small CC is found, it would be hard to accept this.

[Image: SLIM FILMS. Looking for Life in the Multiverse, A. Jenkins & G. Perez, Scientific American, December 2009]

If DE is time or space dependent, would be hard to explain this way.

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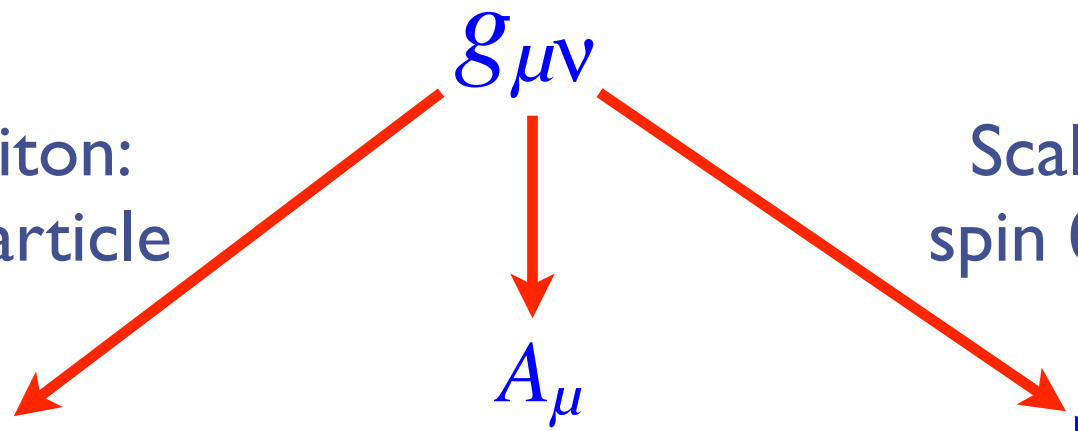

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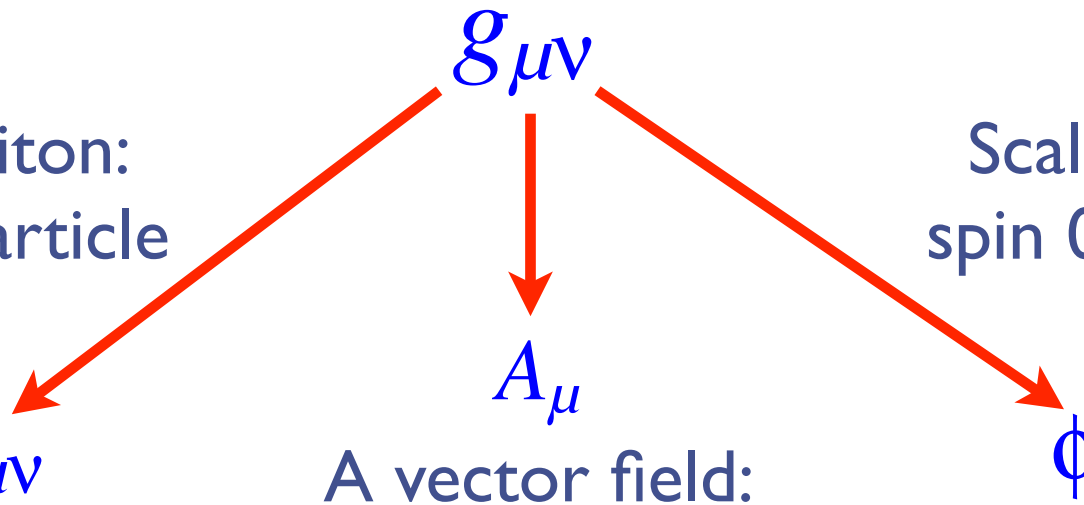

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Almost any other action will free some of them up

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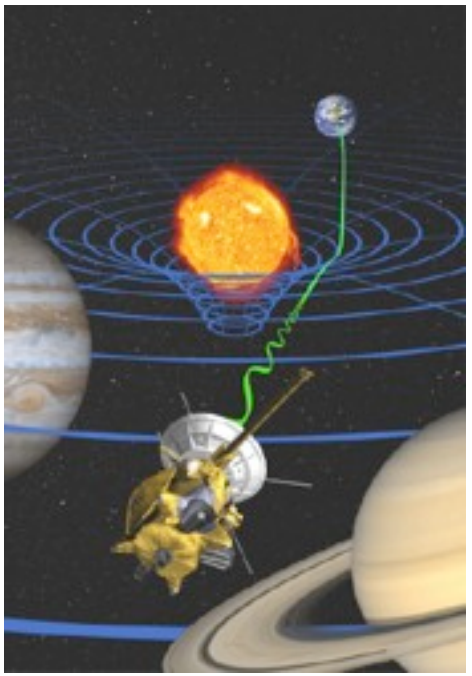

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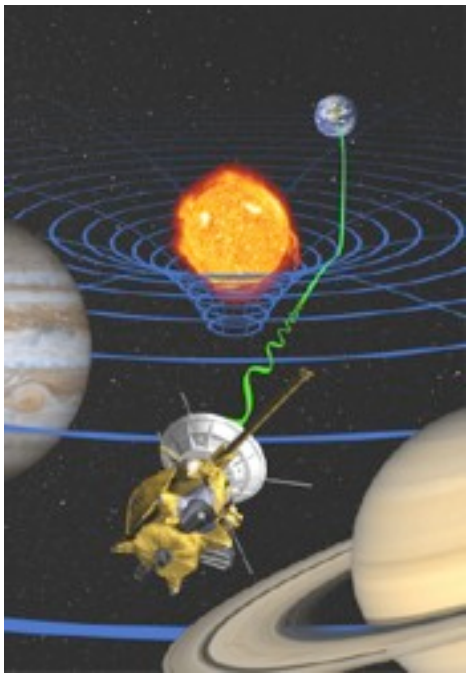

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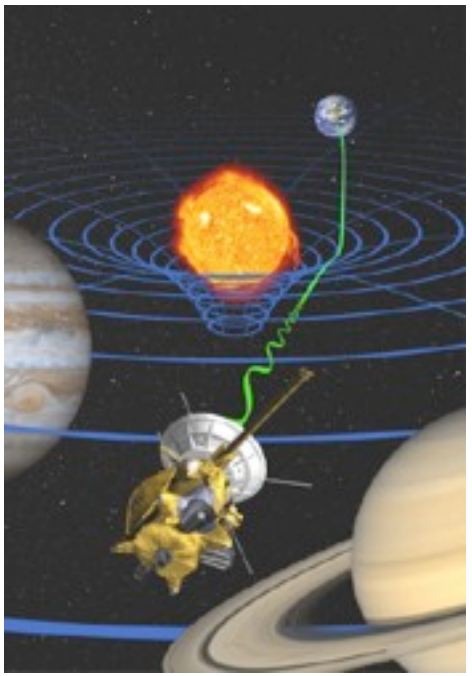

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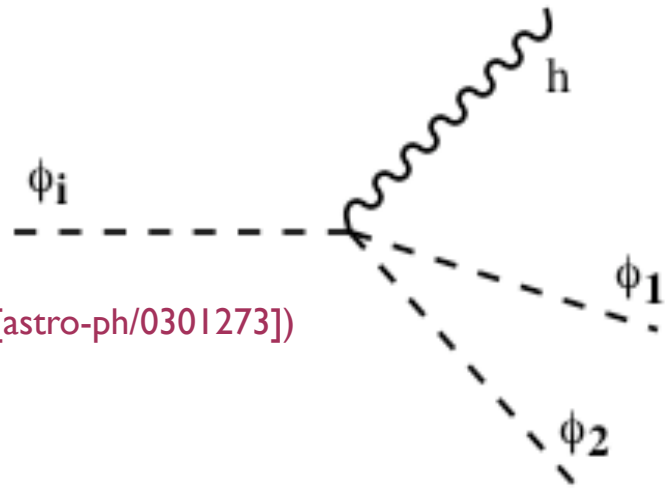
If we were to take these seriously, they'd have negative energy!!

- Ordinary particles could decay into heavier particles plus ghosts



(Carroll, Hoffman & M.T., *Phys.Rev.* **D68:** 023509 (2003) [astro-ph/0301273])

- Vacuum could fragment

(Cline, Jeon & Moore. (2004))

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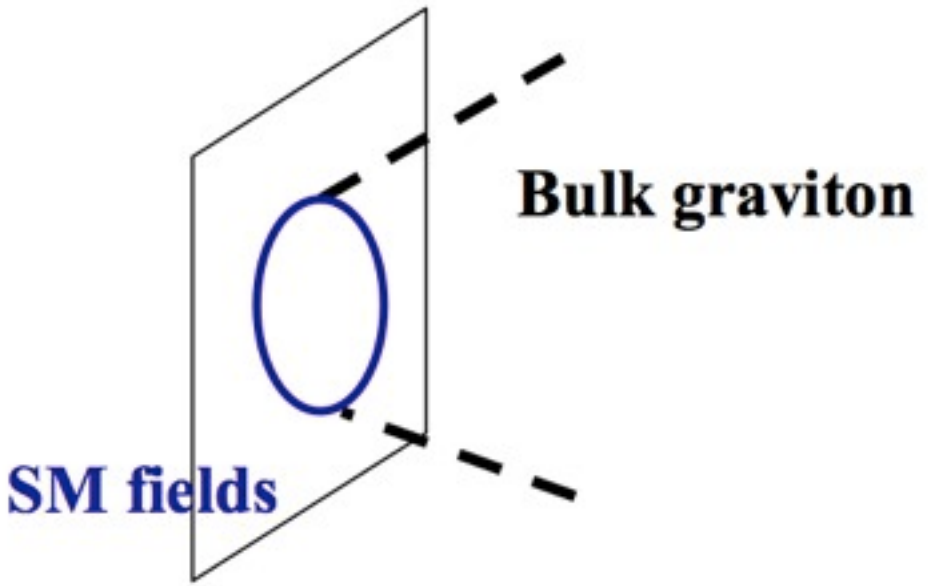

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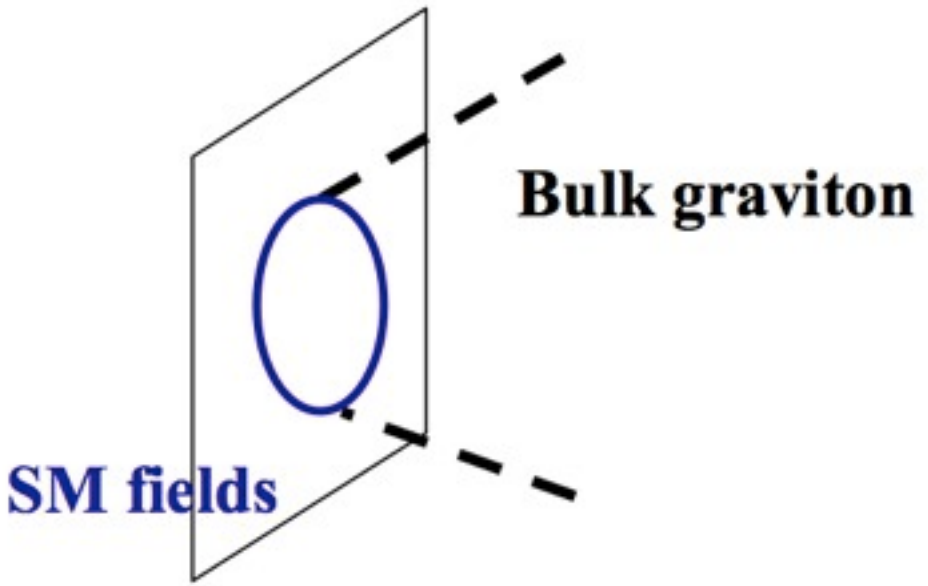

- On *small* scales get 4d gravity
- On *large* scales start to see 5d effects
- Can get acceleration (but comes with problems)

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$$\pi(x) \to \pi(x) + c + b_\mu x^\mu$$

The *Galilean* symmetry!

Galileons

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$$\mathcal{L}_1 = \pi \qquad \mathcal{L}_2 = (\partial\pi)^2 \qquad \mathcal{L}_3 = (\partial\pi)^2 \Box\pi$$

$$\mathcal{L}_4 = \partial_\mu \pi^I \partial_\nu \pi_I \left(\partial^\mu \partial_\rho \pi^J \partial^\nu \partial^\rho \pi_J - \partial^\mu \partial^\nu \pi^J \Box \pi_J \right) + \cdots \qquad \mathcal{L}_5 = \cdots$$

Galileons

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- So can study non-linear classical solutions involving galileon terms, and trust solutions

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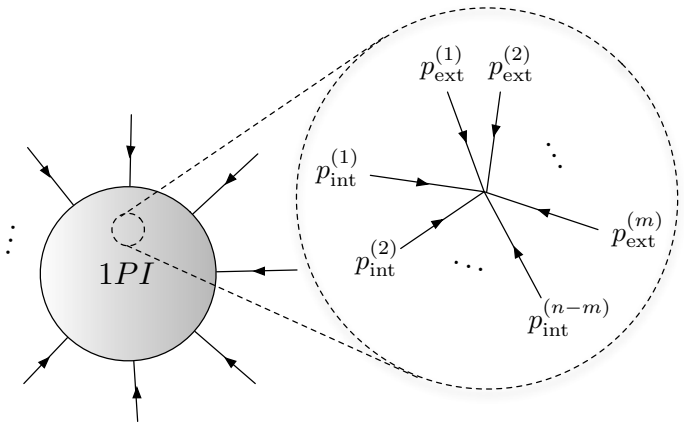

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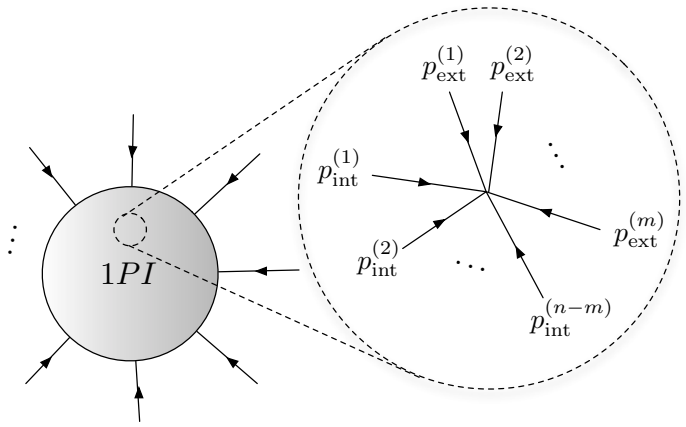

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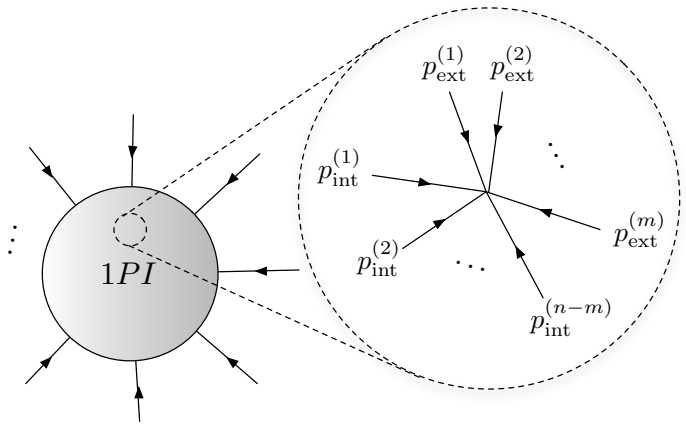

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Have also developed entirely new class of models naturally living in curved space.

(Goon, Hinterbichler & M.T., 2011)

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Connections to massive gravity, higher-dimensional gravity, ...
Interesting to see if this leads anywhere for cosmology in coming year.

3. Inflation and Non-Gaussianity

A Reminder about Inflation

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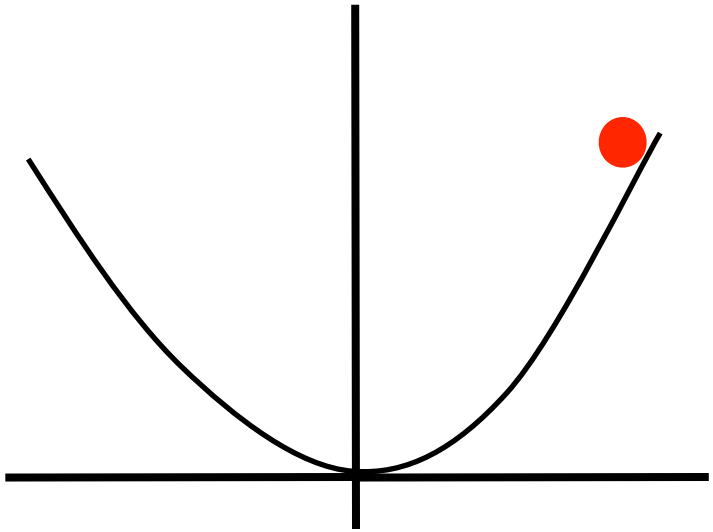

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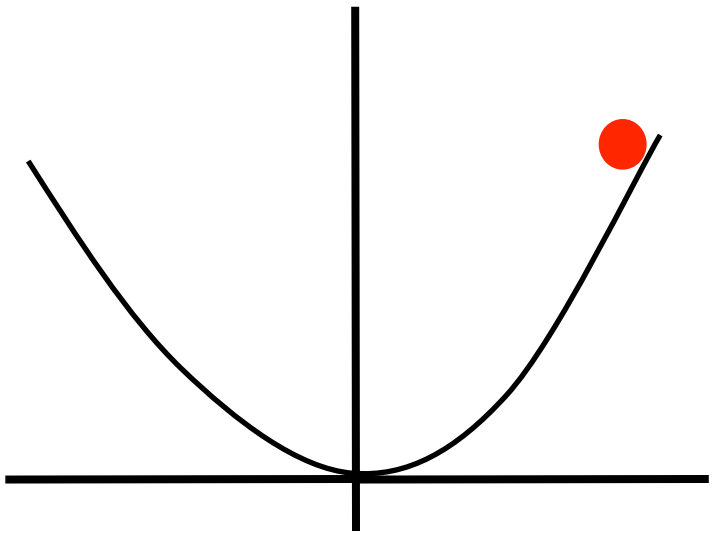

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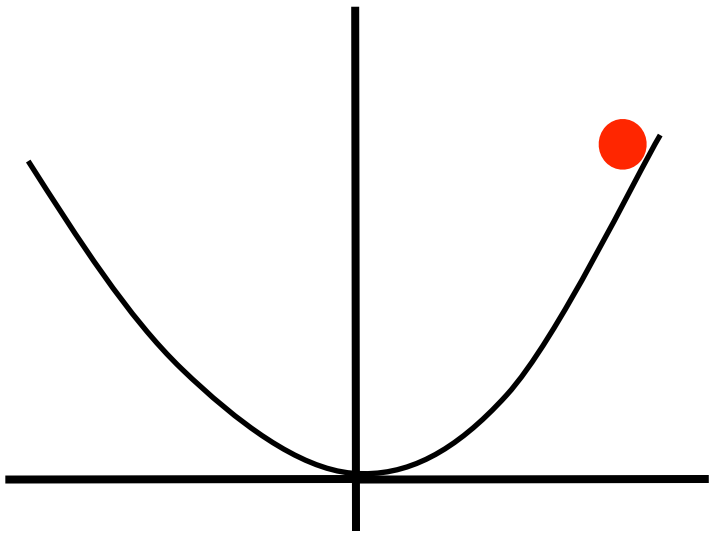

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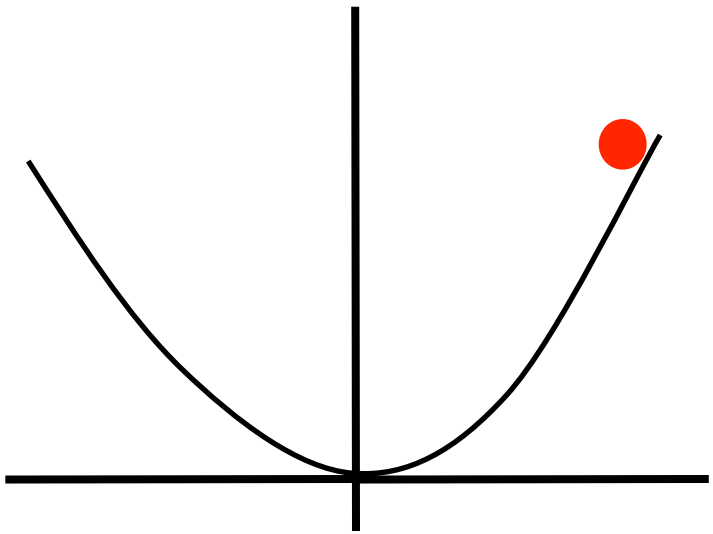

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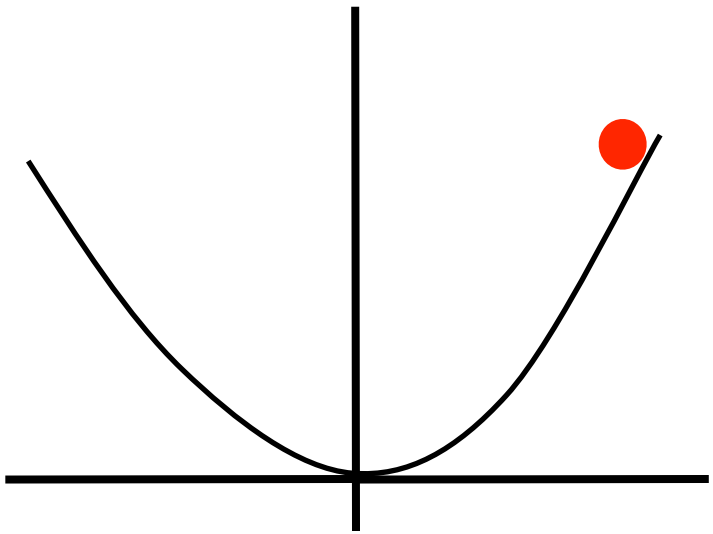

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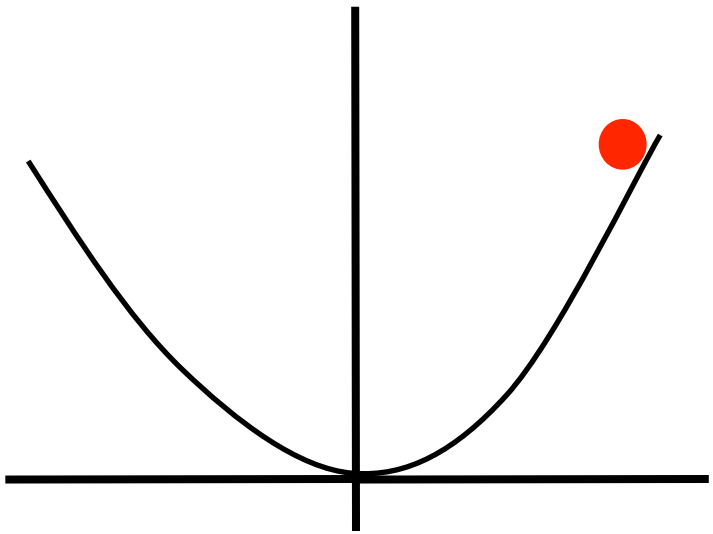

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- The broad predictions of inflation are now beginning to confront observations. We know they require a high-energy density extremely flat potential, but the details of this are now being probed as precision measurements emerge.

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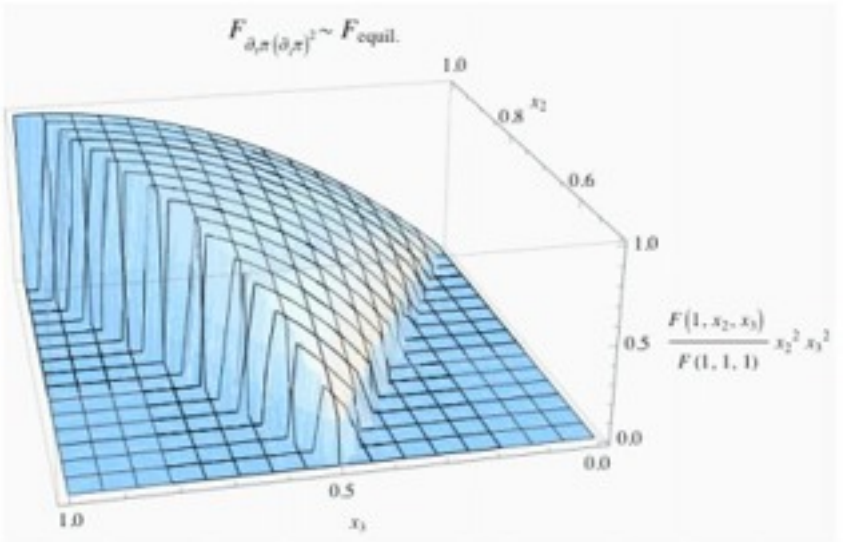
e.g. the *bispectrum*

$$\langle \Phi_{\vec{k}_1} \Phi_{\vec{k}_2} \Phi_{\vec{k}_3} \rangle = 2\pi^{(3)} \delta^3 \left(\sum \vec{k}_i \right) F(k_1, k_2, k_3)$$



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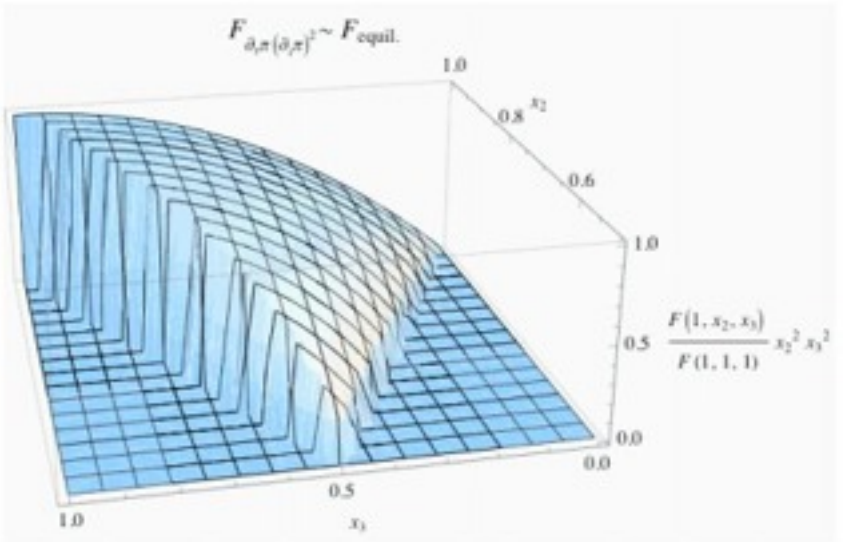
Vanilla inflation typically gives small effect, but some models can give *much* more!



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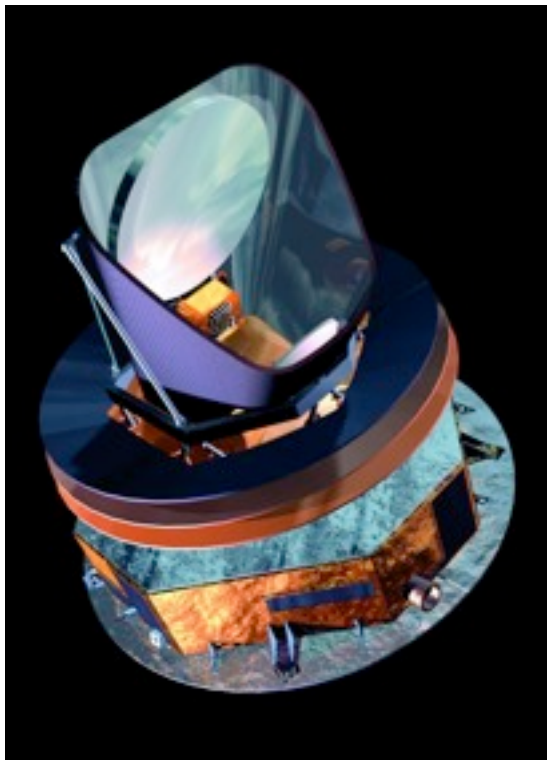

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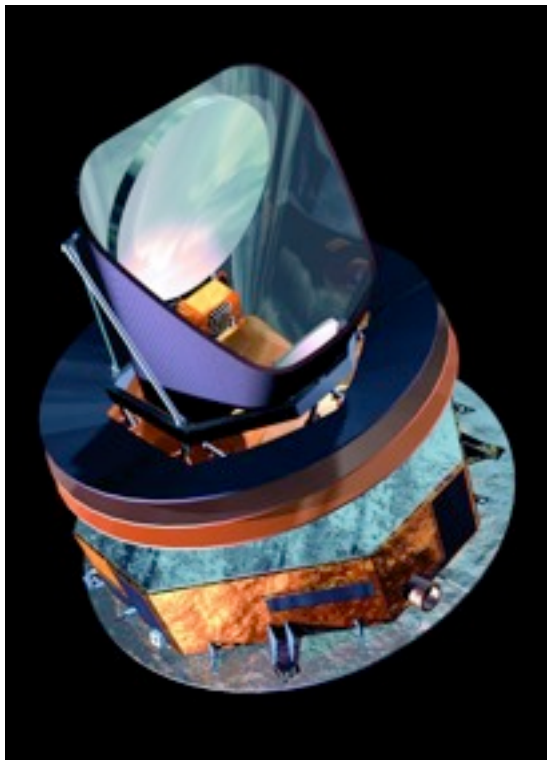

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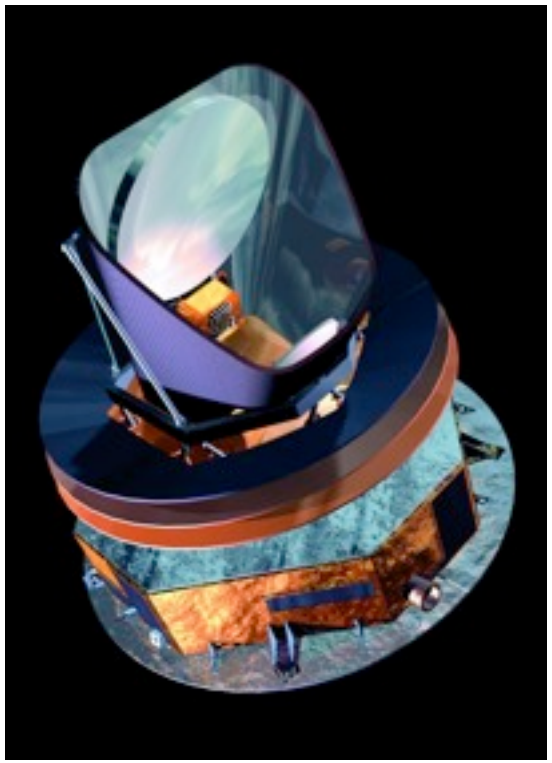
This is the big observational test of many more exotic models of inflation



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