Title: Beyond the Standard Model â€“ Theory: Introduction and Motivation

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Abstract:


Beyond the Standard Model
I: Introduction and
Motivation
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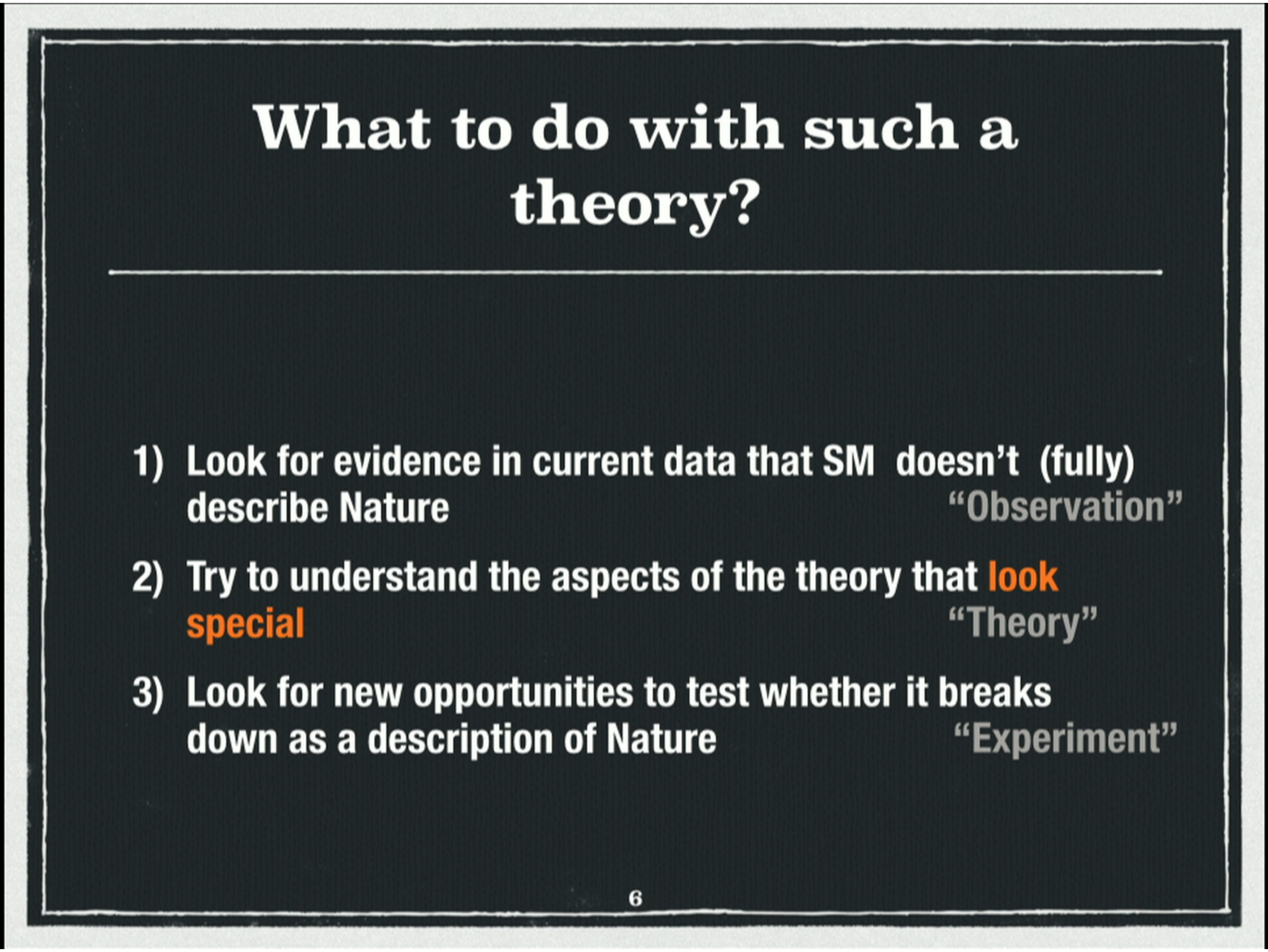
TRISEP 2015

Outline of next 5 lectures

- Today: Introduction
  - More "perspective", fewer calculations
- Tomorrow: Outside the Standard Model
  - Searching for SM-Neutral Physics: Portals to New Physics
  - Dark Matter through the Vector Portal: Theory and Searches
- Friday: Above the Standard Model
  - LHC Phenomenology
  - Status of SUSY


What to do with such a theory?
1) Look for evidence in current data that SM doesn't (fully) describe Nature
"Observation"
2) Try to understand the aspects of the theory that look special
"Theory"
3) Look for new opportunities to test whether it breaks down as a description of Nature
"Experiment"
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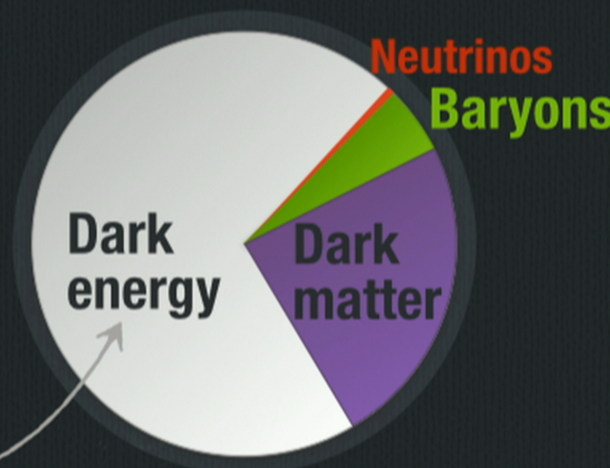
Observation: What's the SM Missing?

2+1 "failures" to account for the larger Universe

- ☐ Baryon Asymmetry
- ☐ Dark Matter
- ☐ [Neutrino masses]



In a sense, SM does "better" on dark energy – which can be fit by an SM parameter (CC) – than on the other components that require additional moving parts

Baryon Asymmetry

- Why are there galaxies but no anti-galaxies?
  - Requires primordial asymmetry of baryons over anti-baryons (1 part in 10^9)

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  - Sakharov: asymmetry production requires 3 condition
    - Baryon No. Violation
    - C- and CP-violation
    - Thermal non-equilibrium

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    - Thermal non-equilibrium
  - SM thermal history has all three, but fails **quantitatively**
  - BSM
    - New scalars coupled to H → 1st order EWPT (non-equililbrium) – sharp & testable (fairly constrained) at colliders!
    - Else need new source for asymmetry – need not be at experimentally accessible energy, but if it is, may be able to test 3 Sakharov conditions

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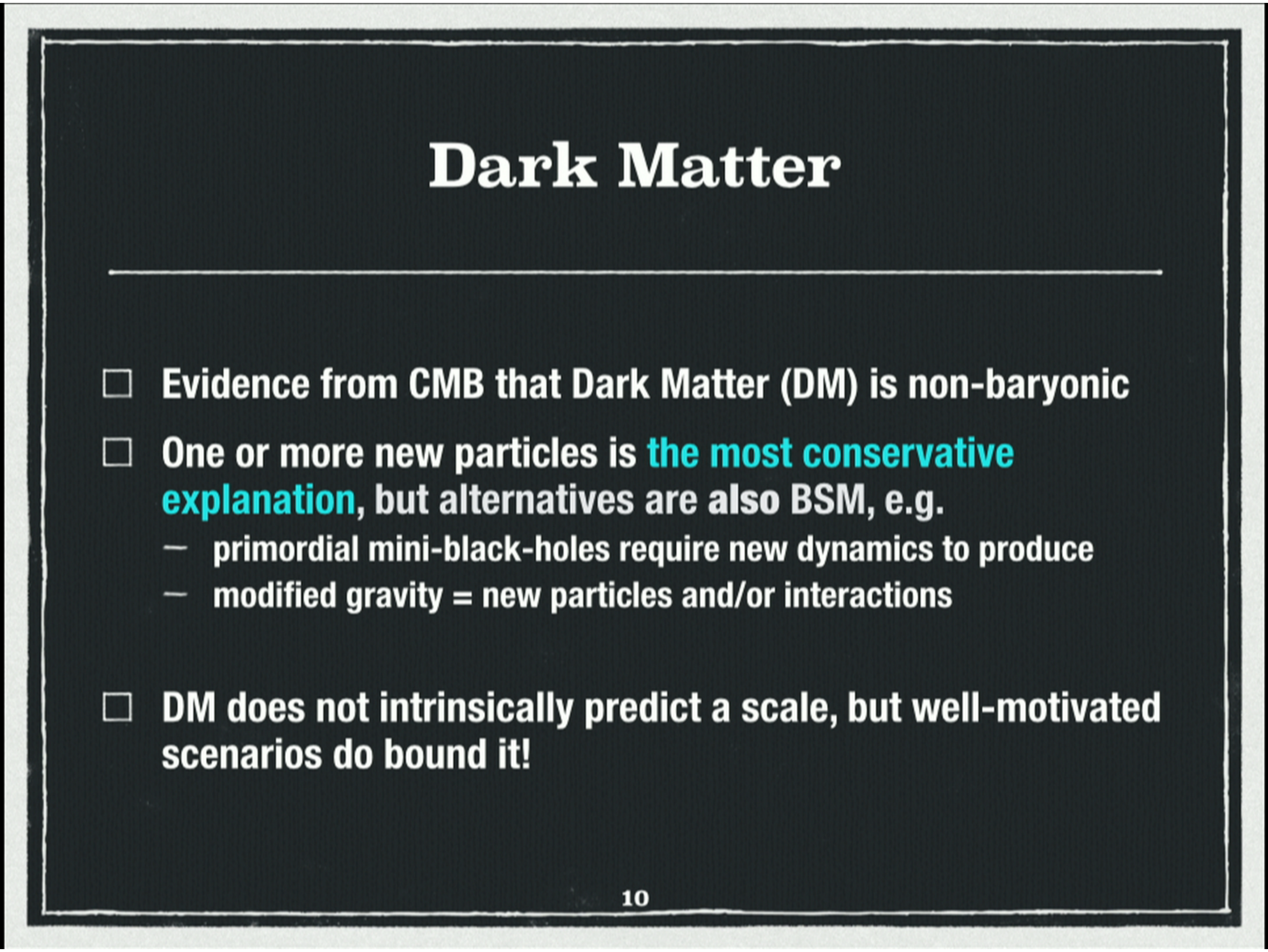
Dark Matter
Evidence from CMB that Dark Matter (DM) is non-baryonic
One or more new particles is the most conservative explanation, but alternatives are also BSM, e.g.
– primordial mini-black-holes require new dynamics to produce
– modified gravity = new particles and/or interactions
DM does not intrinsically predict a scale, but well-motivated scenarios do bound it!
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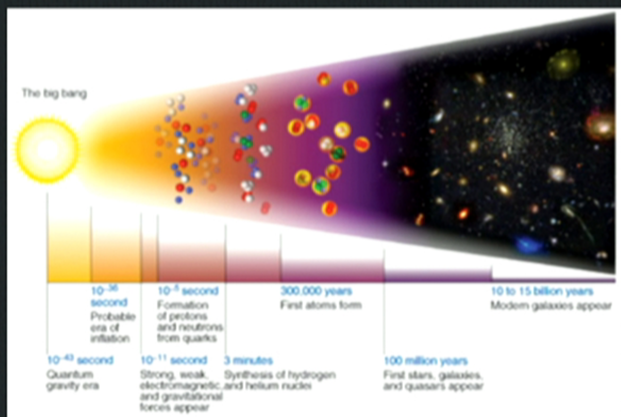
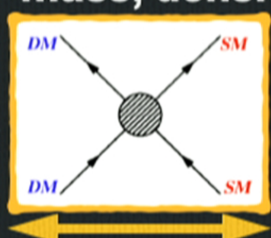
Bounding the Mass of Dark Matter

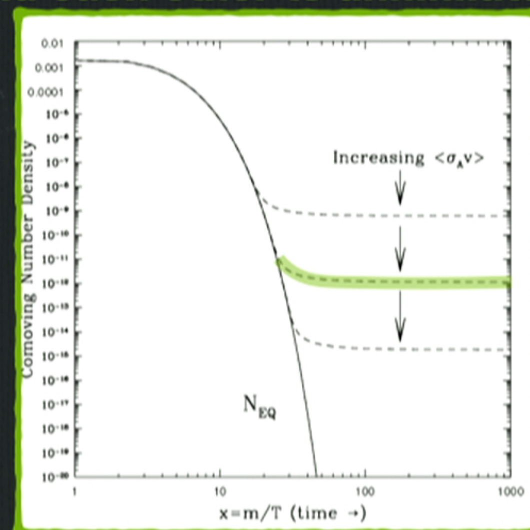


As Universe cools below DM mass, density decreases as $e^{-m/T}$



Dark Matter interacts with SM to stay in equilibrium…

…until dark matter particles can't find each other to annihilate



This transition determines (minimal) DM abundance today

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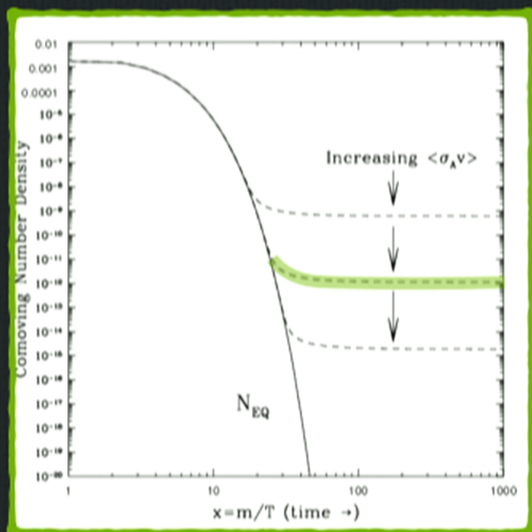

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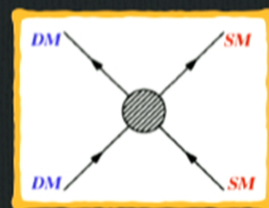

Larger cross-section
⇒ later freeze-out
⇒ lower density

DM density ~ $1/\sigma_{\text{annihiliation}}$
$\gtrsim$ # M^2

⇒ Maximum DM mass*
(even with strong coupling)

*The exception: Dark matter interacting so weakly that it never reaches equilibrium

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Neutrino Masses

- Not really a failure – just a new operator!
  - Dirac? $\lambda_{ia} H L_i N_a$ (N's = singlet Weyl fermions)

    $$m_\nu \sim 0.1\mathrm{eV} \sim \lambda \mathrm{v_{EW}} \to \lambda \sim 10^{-12}$$

    - Implies new (but sterile) field
  - Majorana? $\frac{c_{ij}}{\Lambda}(HL_i)(HL_j)$

    $$m_\nu \sim c v_{EW}^2/\Lambda \to \Lambda \lesssim 10^{15}\mathrm{GeV}$$

    - implies new physical scale & new degree of freedom, but may be out of reach – possible connection to leptogenesis

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Q	3	2	1/6
u	$\bar{3}$	–	-2/3
d	$\bar{3}$	–	1/3
L	–	2	-1/2
e	–	–	1
h	–	2	1/2

×3

All **require** some new physics! It could be

…accessible or inaccessible

…rich or simple

…a hint at new structure, or "just another row on the chart"

But it **must be out there**.

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Theory: What's Funny about the SM?

Parameters include some surprisingly small numbers!

☐ Cosmological Constant	10^{-120}	$M_{Pl}^4 \times 1$
☐ Weak-Planck Hierarchy	10^{-32}	$M_{Pl}^2 \times H^\dagger H$
☐ Strong CP Problem	$<10^{-11}$	$G^{\mu\nu}\tilde{G}_{\mu\nu}$
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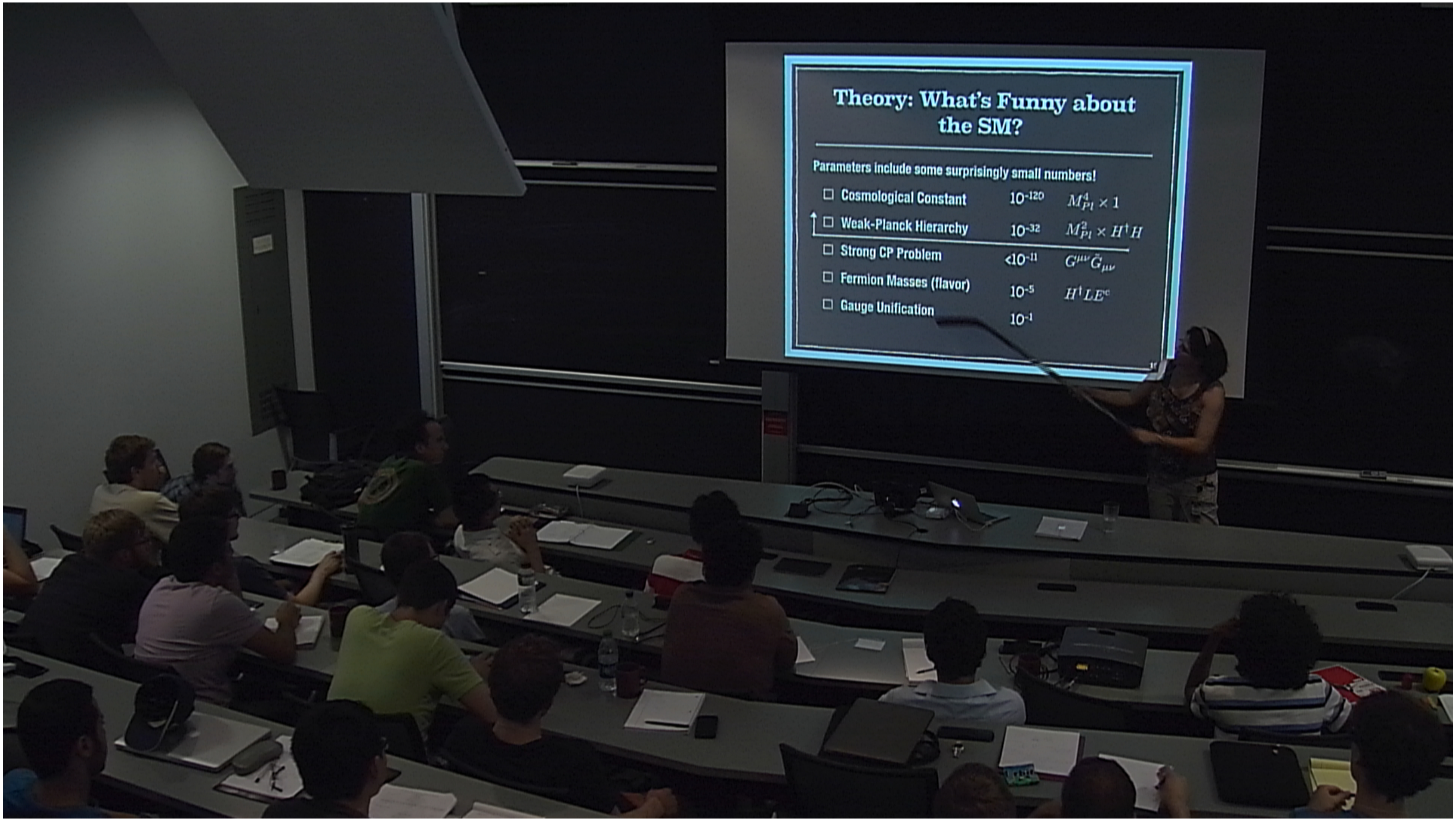
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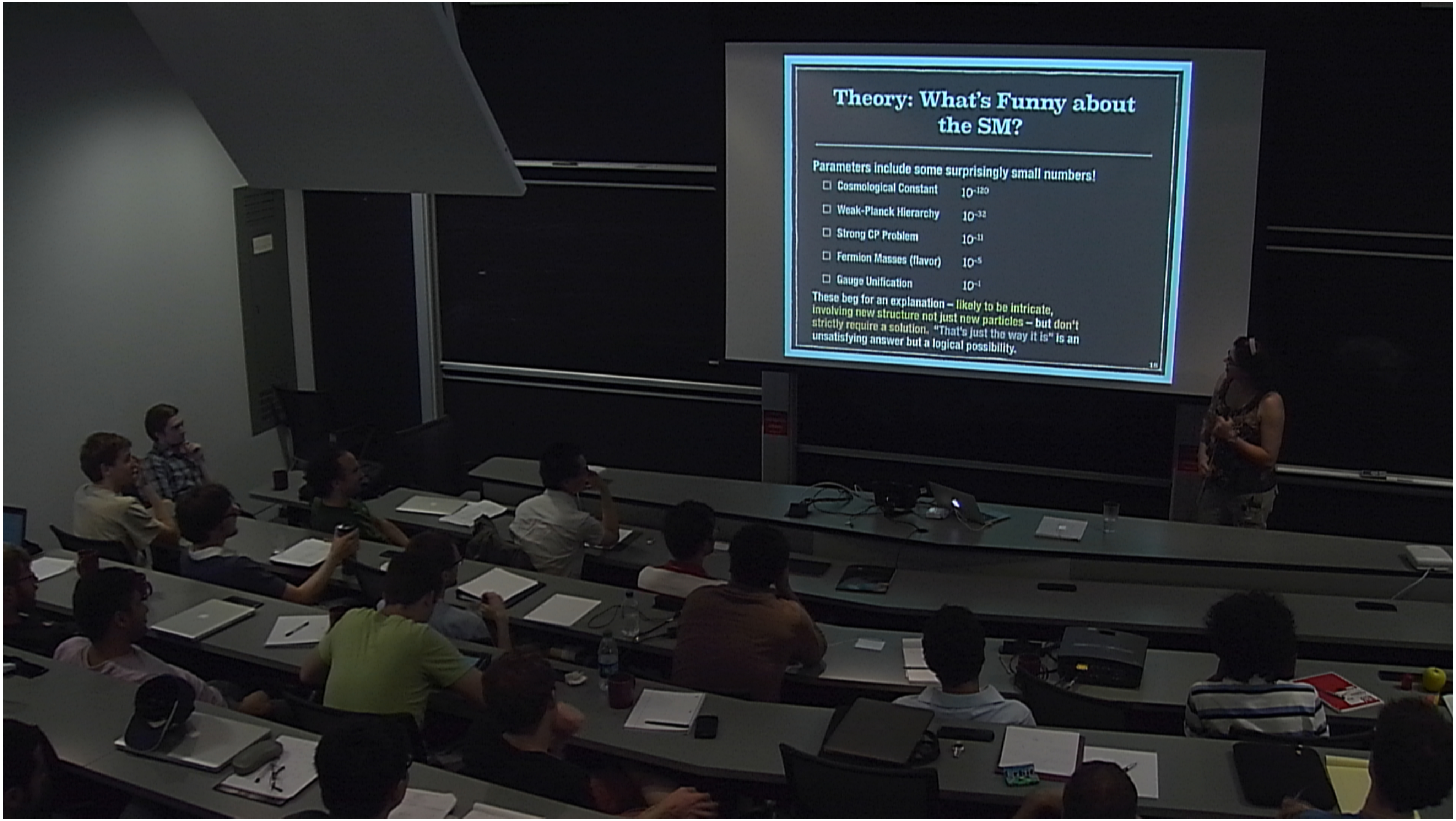
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These beg for an explanation – likely to be intricate, involving new structure not just new particles – but don't strictly require a solution. "That's just the way it is" is an unsatisfying answer but a logical possibility.

Experiment: Finding new ways to test the SM

	SU(3)	SU(2)	U(1)
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d	3	[illegible]	1/3
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x3

New Interactions?

Deeper structure?

New Particles?

Why now?

Too weakly interacting
or too heavy
to have seen before

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Experiment: Finding New Ways to Test the SM

Exploration should be informed by SM problems discussed earlier — both unexplained phenomena and peculiar/unnatural features — but not limited by them!

Not totally obvious: should we really fund "fishing expeditions" alongside "well-motivated experiments"?

I think history of the SM offers a convincing lesson that we should think broadly about what could be found & what hasn't been tested.

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3	5	7	Yes!
7	5	3	No.
0	0	0	No.

You can test another sequence if you want:

Check

When you think you know the rule, describe it in words below and then submit your answer. **Make sure you're right; you won't get a second chance.**

I think I know it

I don't want to play; just tell me the answer.

A Quick Puzzle to Test Yo...

www.nytimes.com/interactive/2015/07/03/upshot/a-quick-puzzle-to-test-your-problem-solv

atlas invisible higgs

THE UPSHOT | A Quick Puzzle to Test Your Problem Solving

MORE

But most people start off with the incorrect assumption that if we're asking them to solve a problem, it must be a somewhat tricky problem. They come up with a theory for what the answer is, like: *Each number is double the previous number*. And then they make a classic psychological mistake.

They don't want to hear the answer "no." In fact, it may not occur to them to ask a question that may yield a no.

Remarkably, 78 percent of people who have played this game so far have guessed the answer without first hearing a single no. A mere 9 percent heard at least three nos — even though there is no penalty or cost for being told no, save the small disappointment that every human being feels when hearing "no."

It's a lot more pleasant to hear "yes." That, in a nutshell, is why so many people struggle with this problem.

What about the Real SM?

- Quantum theory of relativistic particles ⟺ Local QFT
- Structure & interactions of high-spin particles tightly constrained by this assumption
  - SM makes use of all consistent structures: Gravity (spin-2) + Abelian & non-Abelian gauge interactions (spin-1)
- Chiral matter (L and R-handed fermions have different gauge charges)
- All ^except 1 symmetry-allowed couplings (up to dimension 5*) of specified fields are present
  - but with non-generic structure

Framework built on theoretical and experimental surprises!

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Gauge Invariance

PHYSICAL REVIEW VOLUME 138, NUMBER 4B 24 MAY 1965

Photons and Gravitons in Perturbation Theory: Derivation of Maxwell's and Einstein's Equations*

STEVEN WEINBERG†
Department of Physics, University of California, Berkeley, California
(Received 7 January 1965)

Before setting to work, it may be instructive to compare our development with that of other authors who have also tried to derive electrodynamics or general relativity from first principles. Three different previous approaches may be distinguished.

1. Extended Gauge Invariance

We may require the Lagrangian to be invariant under the extended gauge transformation

$$\psi(x) \to e^{iq\Phi(x)}\psi(x) \qquad (1.3)$$

...

The only criticism I can offer to this textbook approach is that no one would ever have dreamed of extended gauge invariance if he did not already know Maxwell's theory. In particular, extended gauge invariance has found no application to the strong or weak interactions, though attempts have not been lacking. In

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Two particles' existence was robustly predicted based on well-established framework: ν_τ, t

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Four more had "solid", widely accepted motivation: ν_μ, h/W/Z

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- → Discovery experiments directly motivated by theory

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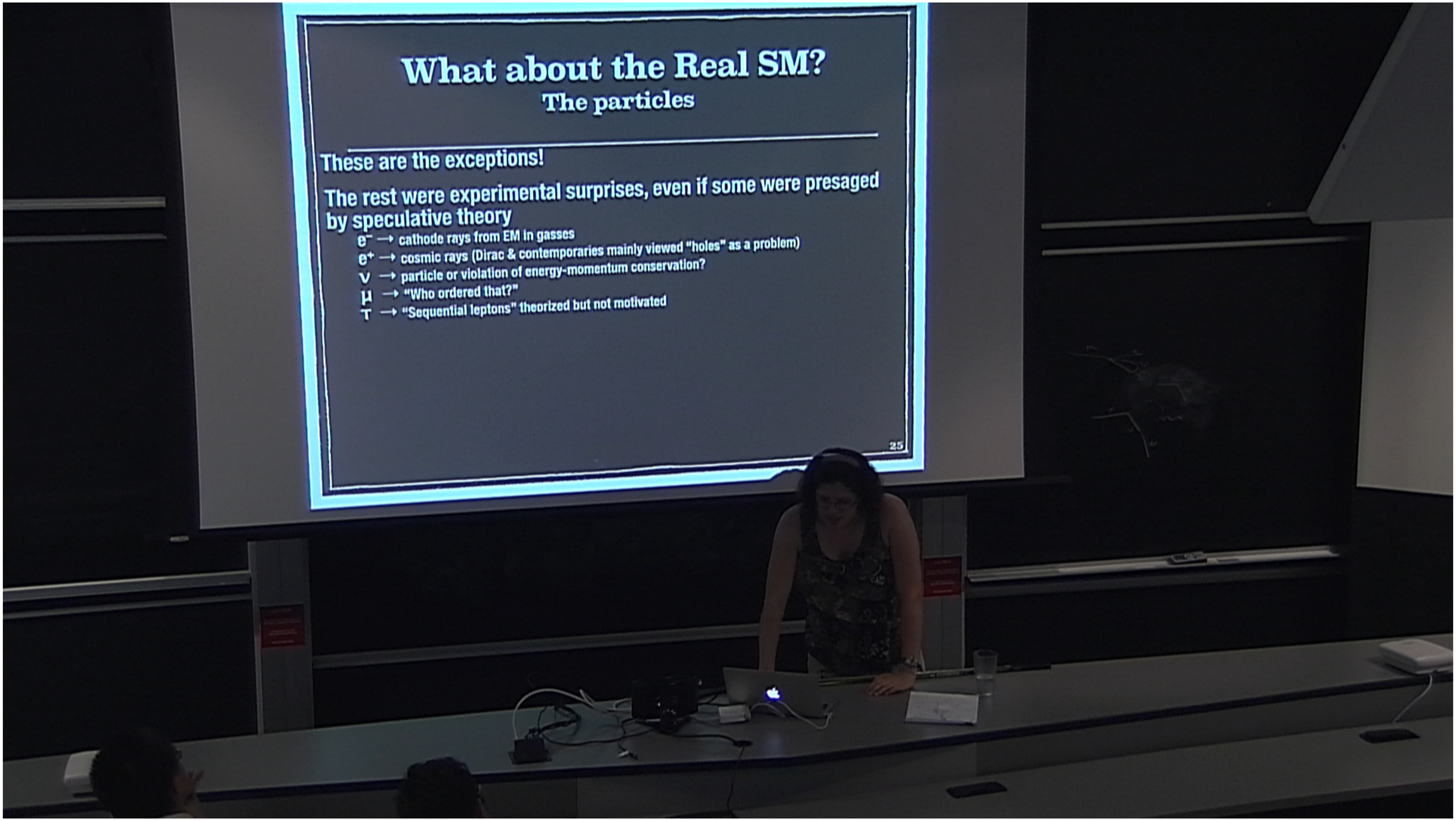
These are the exceptions!

The rest were experimental surprises, even if some were presaged by speculative theory

- e^- → cathode rays from EM in gasses
- e^+ → cosmic rays (Dirac & contemporaries mainly viewed "holes" as a problem)
- ν → particle or violation of energy-momentum conservation?
- μ → "Who ordered that?"
- τ → "Sequential leptons" theorized but not motivated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Moving on to the hadrons/quarks…

- p → Rutherford: totally unexpected
- n → Caused great theoretical confusion
- s → Particle zoo
- b → "Oops"-ilon
- c → Predicted by field theorists, but value of QFT was under serious question at the time

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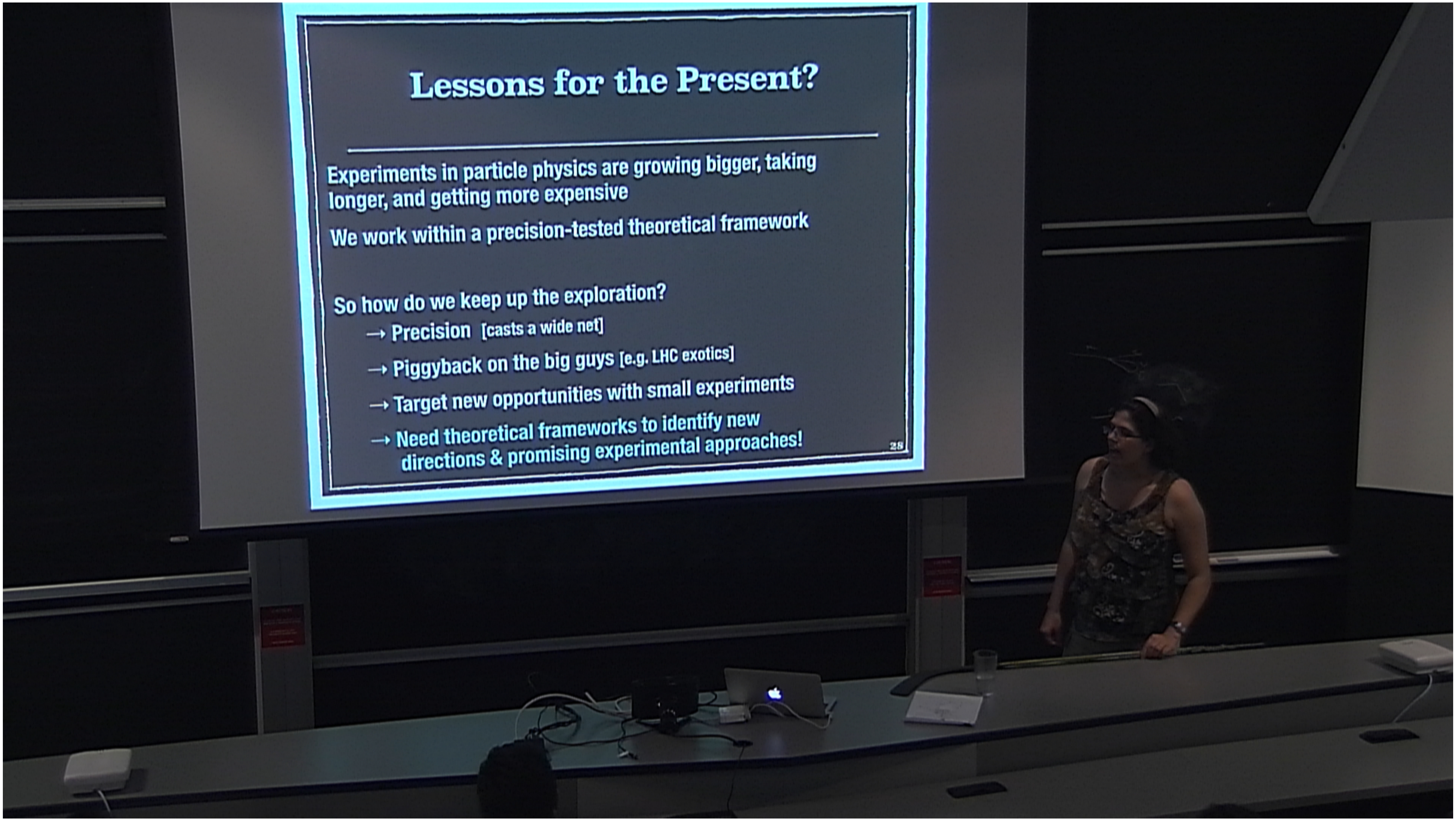
Lessons for the Present?
Experiments in particle physics are growing bigger, taking longer, and getting more expensive
We work within a precision-tested theoretical framework
So how do we keep up the exploration?
→ Precision [casts a wide net]
→ Piggyback on the big guys [e.g. LHC exotics]
→ Target new opportunities with small experiments
→ Need theoretical frameworks to identify new directions & promising experimental approaches!
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Conclusion

- Three facets of physics beyond the Standard Model
  - Basic facts about our Universe that SM alone cannot accommodate
    - Dark Matter, Baryon Asymmetry, (if Majorana) Neutrino Masses
  - Evidence for structure in SM parameters
    - Dark Energy, Weak-Planck hierarchy, Strong CP, (if Dirac) Neutrino Masses, Flavor, gauge unification…
  - Need to push all consistent boundaries of the SM, extend the map of fundamental physics (even if more ocean than land)
    - For high-stakes questions, null results are interesting too

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