New Physics at the TeV Scale

Matt Reece
Harvard University
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Summary

This talk has two parts:

- **The hierarchy problem:** as important as ever. [Review / reminder]

- **A few interesting examples of TeV-scale physics** [Largely advertising the work of others]
  - Novel event-shape tools for exploring hidden sectors and unusual events at colliders
  - Electron electric dipole moment as a rapidly progressing probe of TeV-to-PeV scale new physics
  - The Fermi-LAT Galactic Center Excess and CP violation

About the Hierarchy Problem

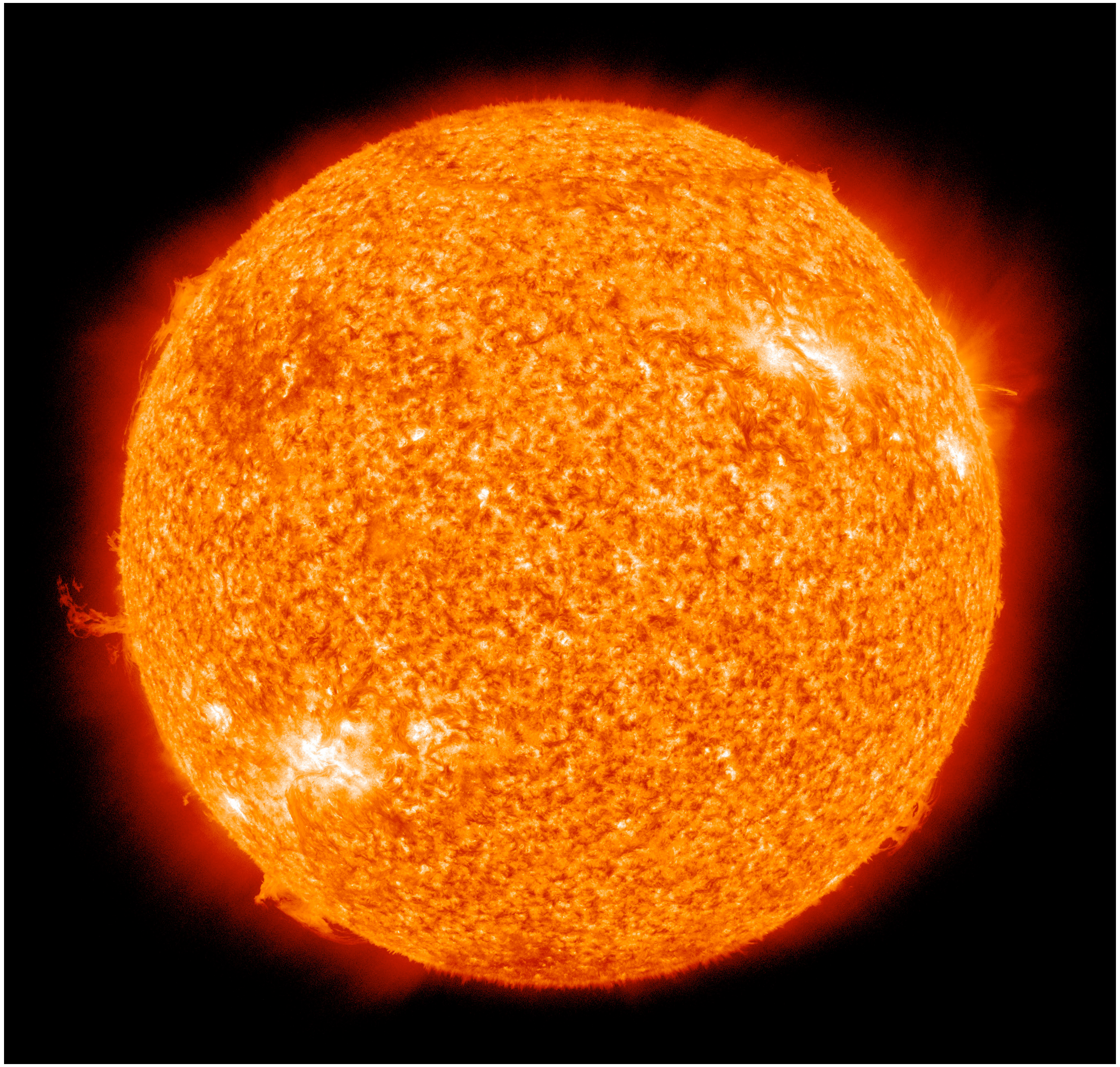
Some big questions about small numbers

- Hierarchy problem: why is $m_W^2/M_{\rm Pl}^2 \approx 10^{-33}$?
- Strong CP problem: why is $|\bar{\theta}| \lesssim 10^{-10}$?
- Flavor: why the wide range of Yukawa couplings and of mixings, e.g. $y_e \approx 3 \times 10^{-6}$ but $y_t \approx 0.95$?
- Neutrino masses: why so small? $m_\nu \sim \dfrac{v^2}{10^{15}\ \text{GeV}}$ or $m_\nu \sim 10^{-13} v$?
- Cosmological constant problem: why $\rho_\Lambda \sim 10^{-120} M_{\rm Pl}^4$?
- Matter/antimatter asymmetry: why $(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-9}$?
- Dark matter abundance: why $n_{\rm DM}/n_\gamma \sim 10^{-12} m_{\rm DM}/\text{TeV}$?
- Primordial density perturbations: why $\delta\rho/\rho \sim 10^{-5}$?

Common theme: when we see small numbers, we're not satisfied until we can *explain* them in terms of some underlying mechanism.

The electroweak hierarchy and our world

The mysterious number that best motivates new colliders is the electroweak hierarchy. We should not lose sight of how important it is to understand.



The electroweak hierarchy is not just an obscure fact about high-energy physics. It is crucial for the existence of large objects like stars and planets.

$$M_\odot \approx 2 \times 10^{30}\ \mathrm{kg}$$

$$\approx 1.1 \times 10^{57}\ \mathrm{GeV}$$

$$\approx 0.6 \left(\frac{M_{\mathrm{Pl,unred}}}{m_{\mathrm{proton}}}\right)^3 m_{\mathrm{proton}}$$

The electroweak hierarchy and our world

It's possible to do a more detailed estimate of both the minimum and maximum size of an ordinary star. A star should be hot enough for nuclear fusion to happen in its core.

$$P_{\text{fuse}}(E) \sim \exp(-E/T - \mathcal{O}(\alpha)\sqrt{m_p/E})$$

Boltzmann ↗ ↖ Gamow (WKB)

The rate peaks at $E_g \sim \alpha^{2/3} m_p^{1/3} T^{2/3}$. In order to not have too much suppression, we need

$$T \gtrsim E_g \quad \Rightarrow \quad T \gtrsim \alpha^2 m_p$$

We need thermal pressure to balance gravitational attraction, and for the star *not* to be so compact that electron degeneracy pressure is important. Putting the pieces together gives a bound on stellar mass.

[Details: V. Weisskopf, *Science* **187**(4177):605–612 (1975); Burrows and Ostriker, *PNAS* 111 (7):2409-2416 (2014).]

The electroweak hierarchy and our world

The detailed estimate, assuming a ball of hydrogen gas that is hot enough for nuclear fusion to work despite Coulomb repulsion, leads to a scaling like:

$$\frac{M_{\text{star}}}{m_{\text{proton}}} \gtrsim \left(\frac{M_{\text{Pl}}}{m_{\text{proton}}}\right)^3 \left(\frac{m_{\text{proton}}}{m_{\text{electron}}}\right)^{3/4} \alpha^{3/2}$$

In fact, a star also cannot be too much heavier than this without collapsing.

Similar reasoning reveals that the maximum mass of a rocky planet scales like

$$\frac{M_{\text{rocky planet}}}{m_{\text{proton}}} \lesssim \left(\frac{M_{\text{Pl}}}{m_{\text{proton}}}\right)^3 \alpha^{3/2}$$

If the Higgs VEV were near the Planck scale, the Universe would be a very different place!

[Details: V. Weisskopf, *Science* **187**(4177):605–612 (1975); Burrows and Ostriker, *PNAS* 111 (7):2409-2416 (2014).]

What is the hierarchy problem?

A good solution to the hierarchy problem should leave us feeling like we *understand* the origin of a scale in terms of some more fundamental physics.

A good example comes from QCD: we can ***compute*** the QCD scale from the gauge coupling measured at some higher energy, and it comes out exponentially small in a robust manner:

$$\Lambda_{\mathrm{QCD}} \sim M\,\mathrm{e}^{-8\pi^2/(bg(M)^2)}$$

Or BCS superconductivity: Cooper pairing from similar running of marginal interaction. (Shankar, Polchinski)

We want something similar for the EW hierarchy. Not literally the same, but same qualitative character of allowing us to compute the scale from something more microscopic.

What is the hierarchy problem?

A further remark about the QCD scale:

$$\Lambda_{\mathrm{QCD}} \sim M\,\mathrm{e}^{-8\pi^2/(bg(M)^2)}$$

By some simple fine-tuning measures, this is “fine-tuned”; e.g. Barbieri-Giudice,

$$\frac{\partial \log \Lambda_{\mathrm{QCD}}}{\partial \log g} = 2\log\left|\frac{\Lambda_{\mathrm{QCD}}}{M}\right| \sim 100$$

This doesn’t bother me. Shouldn’t be too quick to dismiss a theory because of moderate sensitivity to an underlying parameter.

What is the hierarchy problem?

At the most fundamental level, the question we want to ask is really:

where did the weak scale come from?

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where did the weak scale come from?

Various refinements of this question, or related questions, are:

- Can we *explain* or *compute* the weak scale in terms of a more fundamental theory beyond the Standard Model?
- Are there microscopic *dynamics* that tell us why electroweak symmetry breaking happened, or that make it more likely?
- What is the shape of the Higgs potential? (Strong motivation for measuring the Higgs self-coupling.)
- Is the Higgs boson a fundamental particle, or is it composite?
- What would happen if we heated up the universe above the weak scale?

What is the hierarchy problem NOT?

The question is ***NOT***

how do I regulate a loop diagram?

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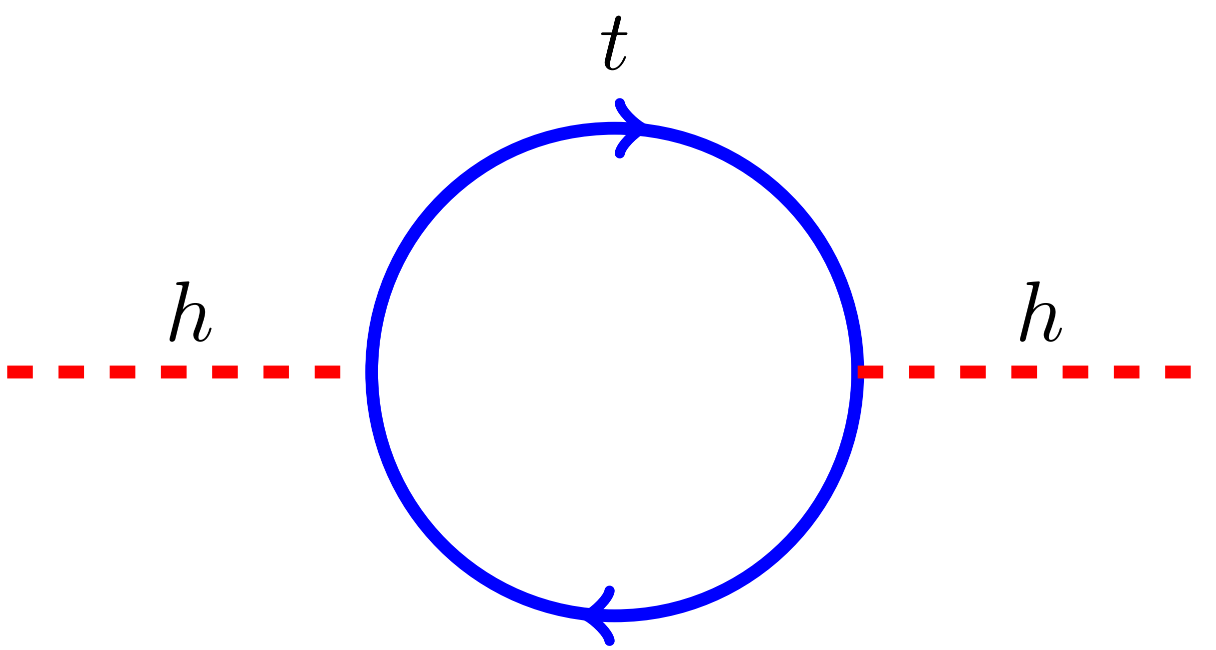
how do I regulate a loop diagram?

- The problem will *not* go away just because you like to use dimensional regularization, which has no power divergences.
- The problem will *not* go away simply because you like a different choice of "fine-tuning measure."
- The fact that you can measure Standard Model parameters and do calculations to high precision that match data at the weak scale does *not* mean there is nothing to explain.

What not to say

Like many other people, I have given talks where, due to lack of time or wanting to focus on other points, I have just said things like:



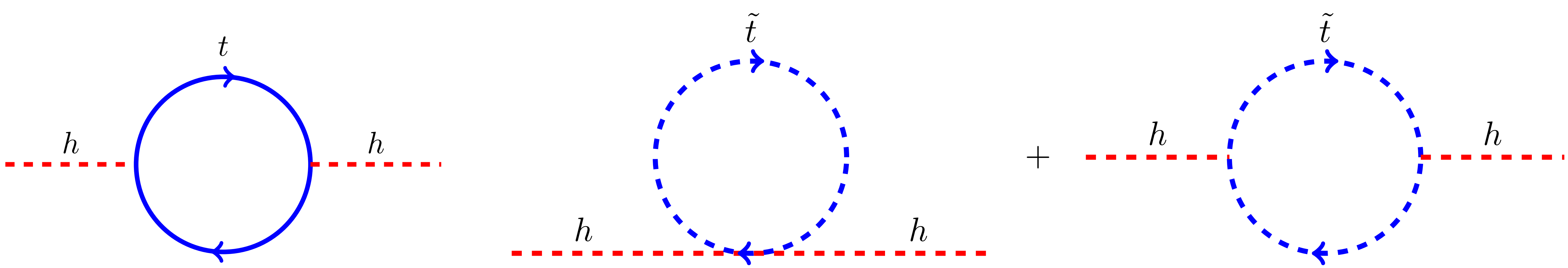
$$\delta m_H^2 \sim \frac{y_t^2}{16\pi^2}\Lambda_{\rm UV}^2$$

This diagram is quadratically divergent, so the weak scale is quadratically sensitive to UV scales. We need a low cutoff or a cancelation of this divergence.

Because then…

Some people respond "power divergences are unphysical" or "when you use the renormalized mass in a calculation, there is no problem" or any number of other things you've probably heard before.

Or maybe we are a little more careful and we say something like:

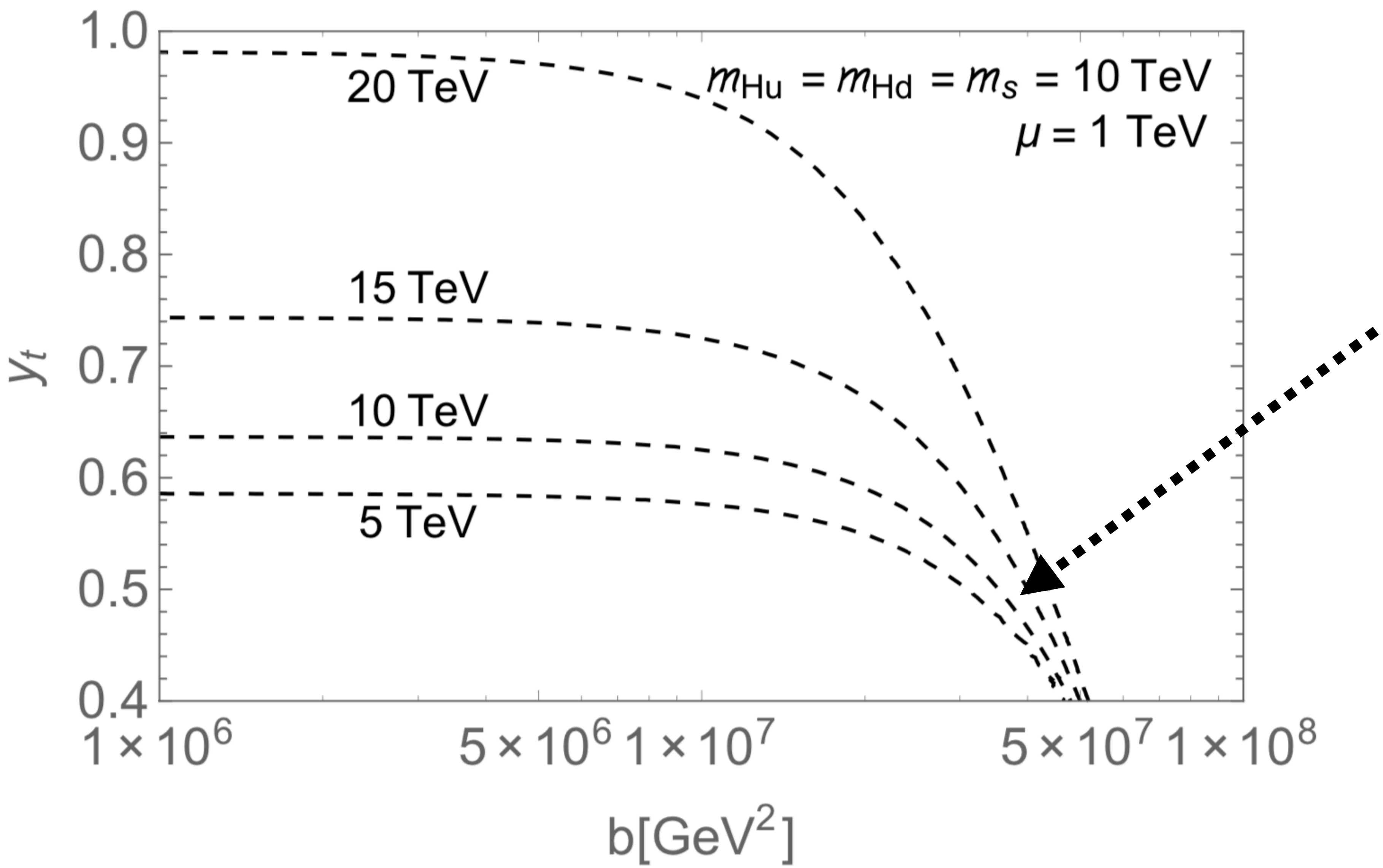


$$\delta m^2_{H_u} = -\frac{3}{8\pi^2} y_t^2 \left(m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} + |A_t|^2 \right) \log \frac{\Lambda}{\mathrm{TeV}}.$$

What we have is *quadratic sensitivity* to *physical scales*.

What does a solution look like?

When we say that weak-scale SUSY solves the hierarchy problem, we mean something simple:



fine-tuning would be relevant if we lived here

The weak scale can be ***computed*** from input parameters, and is *typically* of order* the SUSY breaking parameters.

* leaves room for small accidents

Don’t overrely on technical naturalness

A theory in which the hierarchy becomes “technically natural”—that is, in which you can compute radiative corrections and don’t find dramatic changes—*might or might not* solve the hierarchy problem.

If the theory introduces a tiny number by hand, from my viewpoint it hasn’t solved the problem, even if that number is stable. But it has, perhaps, *made the problem more tractable*.

Putting too much emphasis on radiative stability would discard other problems, like the Strong CP problem, which in my mind are every bit as important as the hierarchy problem.

Indeed, tiny technically natural couplings seem to be problematic in UV-complete gravitational theories (this is a whole other talk, about the Weak Gravity Conjecture).

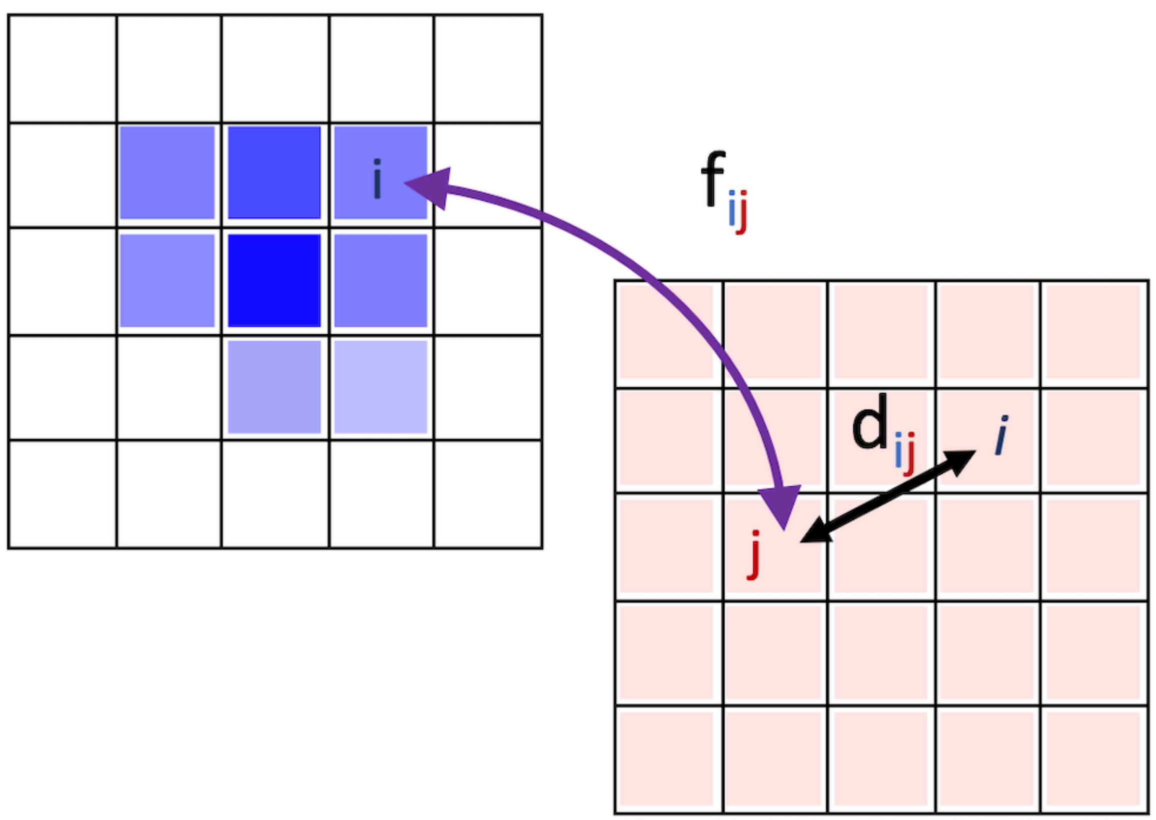
Searching for New Physics at the TeV Scale and Beyond

Novel Event-Shape Variables

Event Isotropy from Energy-Mover Distance

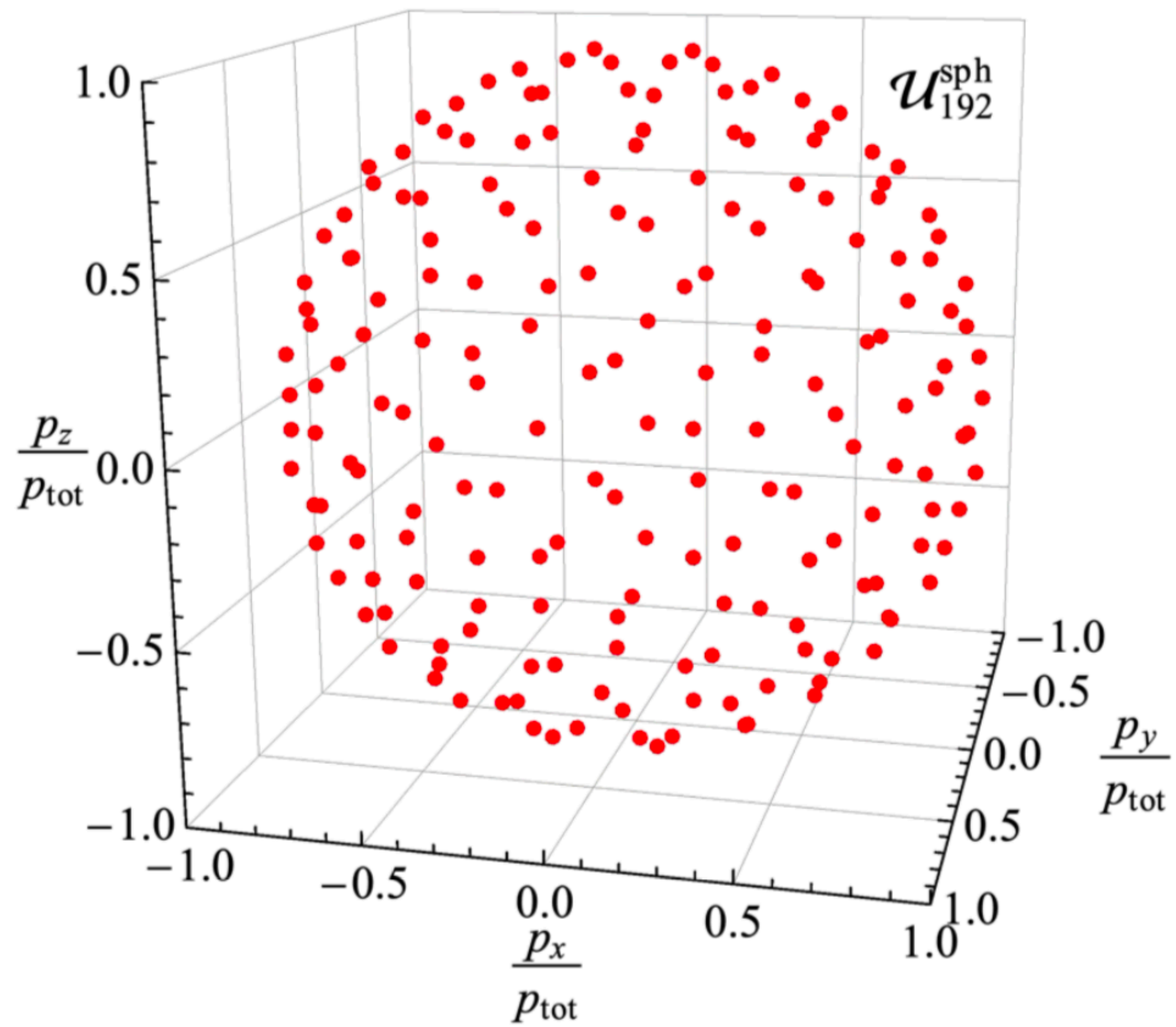
Cari Cesarotti and Jesse Thaler, 2004.06125

[see Cari Cesarotti's parallel talk slides from Monday]



EMD: sum of weight f_{ij} (energy) times distance d_{ij}

Event Isotropy: EMD to reference spherical event. 0 for sphere, 1 for dijet



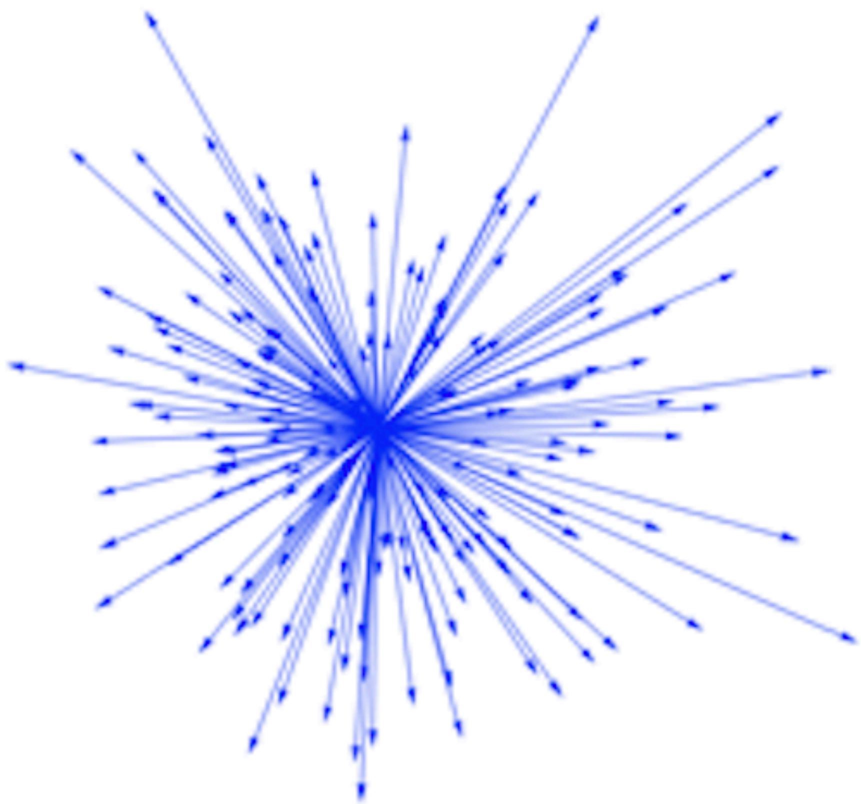
[building on EMD as metric on events: Komiske, Metodiev, Thaler 1902.02346]

Simplified Models from 5D for Exotic Events

It's useful to have a way to generate sample events with a wide range of unusual, non-QCD-like event shapes.

CFTs at large 't Hooft coupling are known to produce **spherical event shapes** (Strassler '08, Hofman/Maldacena '08).

A discrete analogue is **cascade decays (1→2) of KK modes in a slice of a 5D space**. (Csaki, MR, Terning '08)

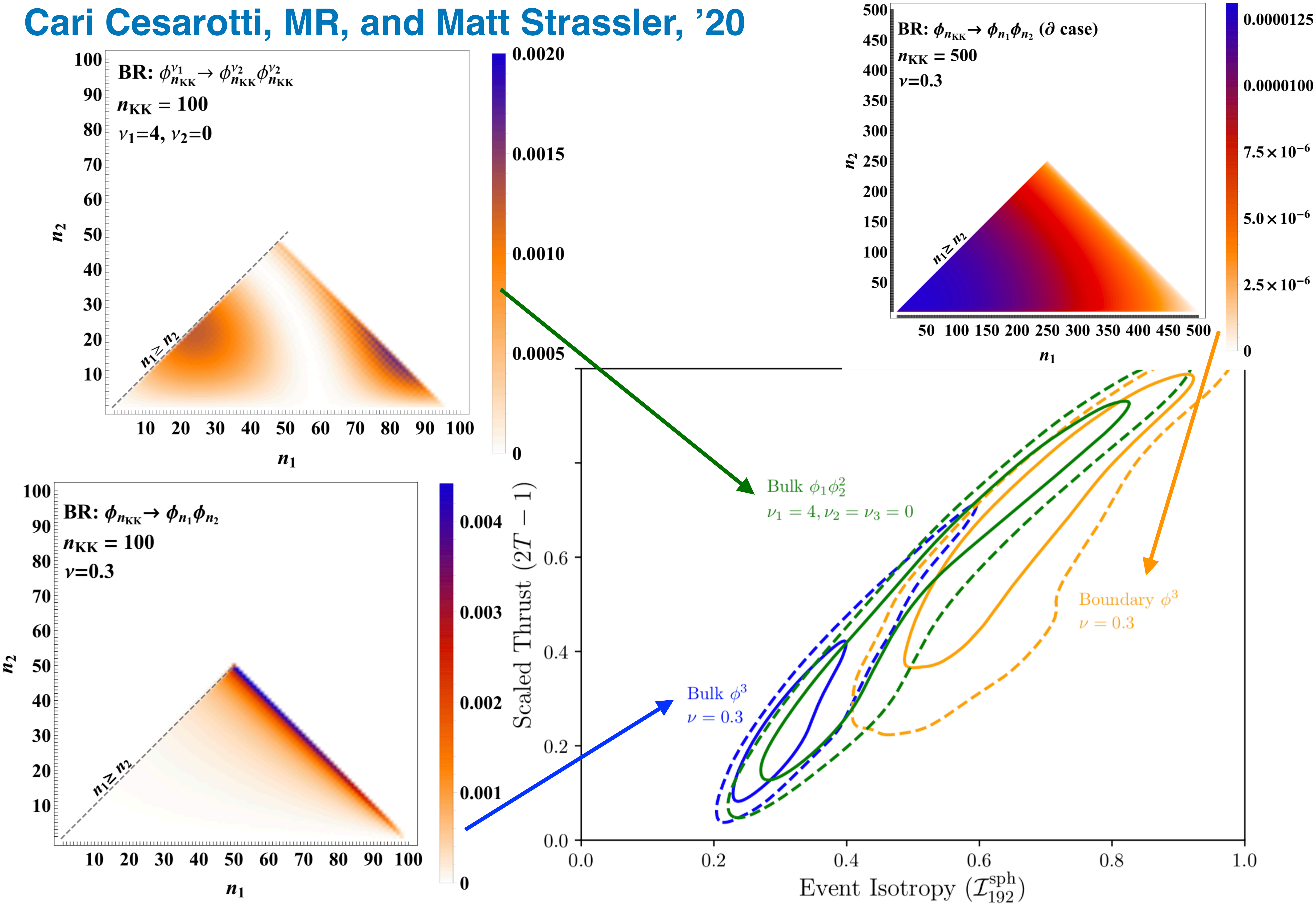


Use 5D cascades (toy dual of Hidden Valley) as a **simplified model for generating many-particle events** with novel shapes.

Test case for event isotropy. (Cesarotti, MR, Strassler to appear)

Event Isotropy and RS Hidden Valleys

Cari Cesarotti, MR, and Matt Strassler, '20



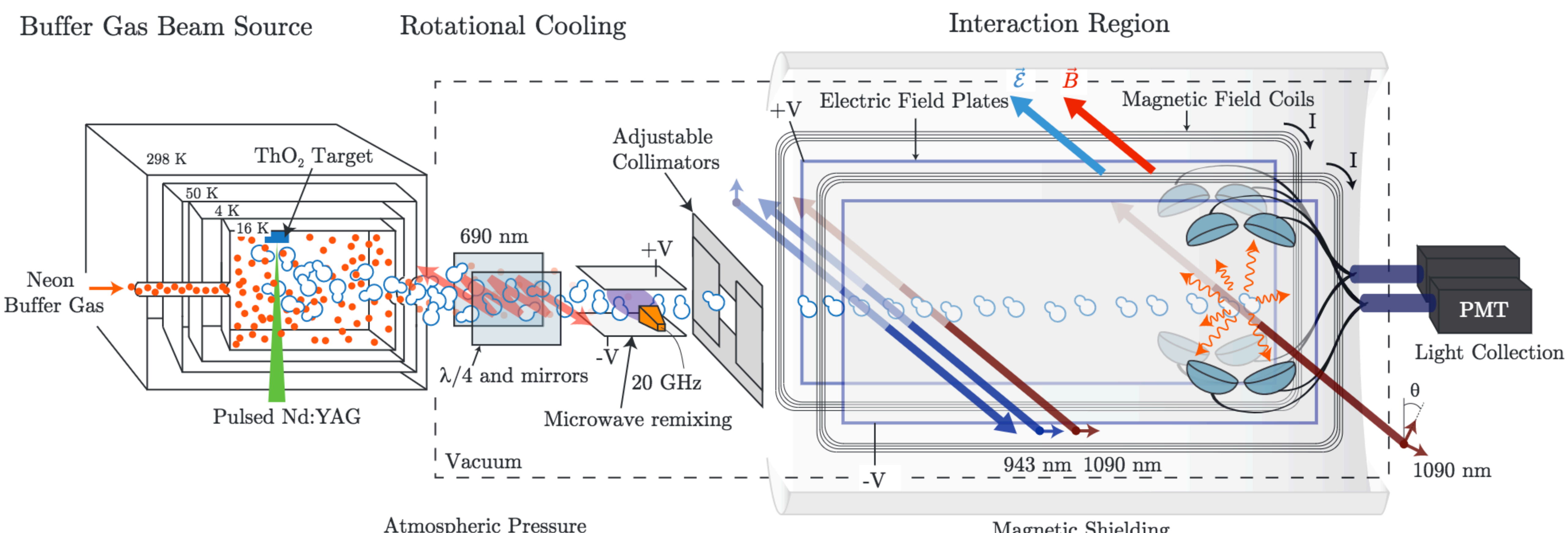
Searches for CP Violation

Atomic Physics Testing the Standard Model

Colliders may not be our first sign of new physics!

Recent dramatic progress in AMO physics: searches for the electron EDM.

ACME 2 (source: electronedm.org) DeMille, Doyle, Gabrielse and collaborators. New result in 2018.



Electron EDM

The 2018 bound from ACME is: $|d_e| \lesssim 1.1 \times 10^{-29}\, e\,\text{cm}$

This improves on the previous, 2013, ACME bound by about an order of magnitude.

EDMs violate chirality, so putting in the electron mass a spurion, we expect an effect of order:

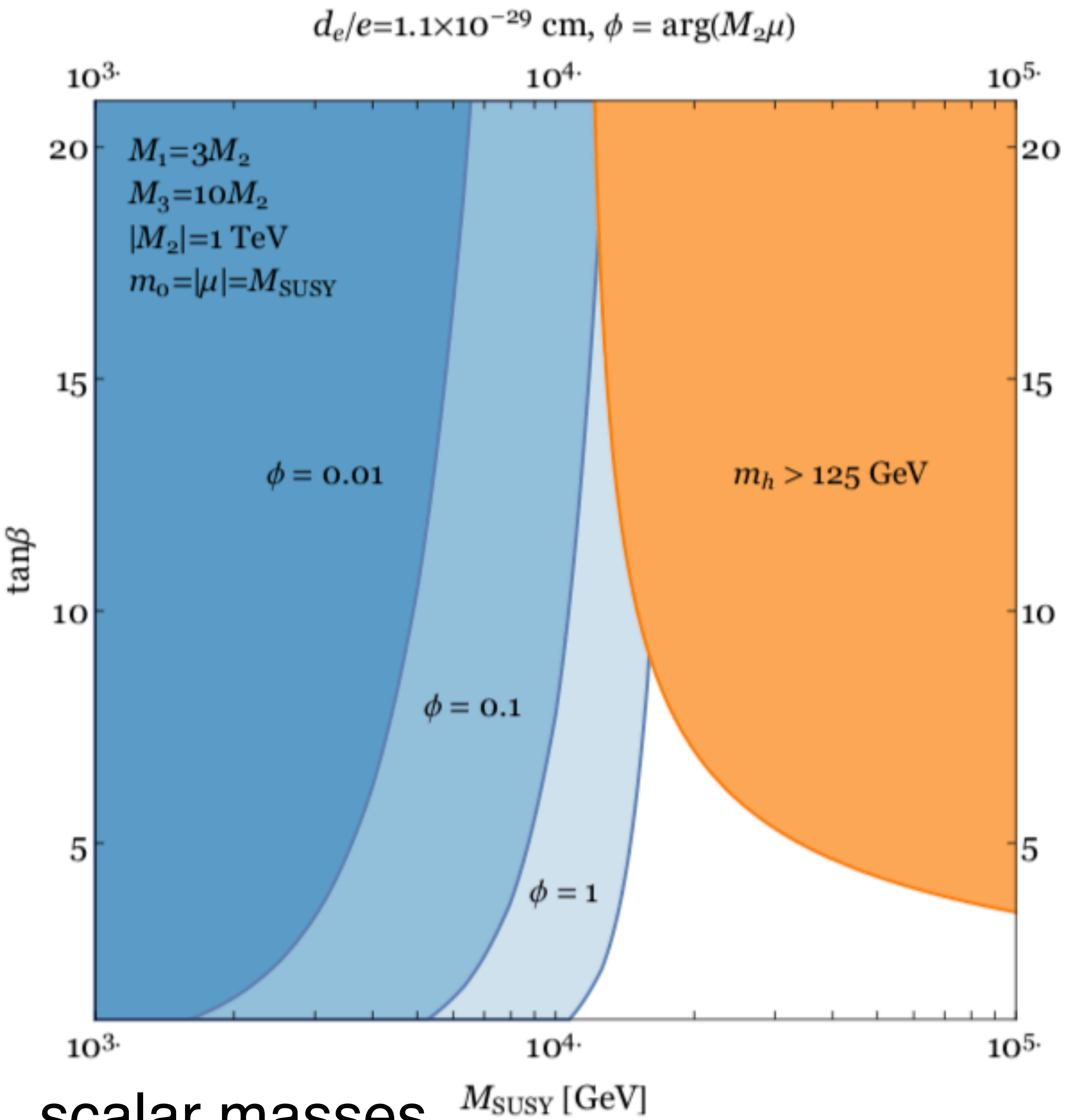
$$d_e \sim \delta_{\text{CPV}} \left(\frac{\lambda}{16\pi^2} \right)^k \frac{m_e}{M^2}$$

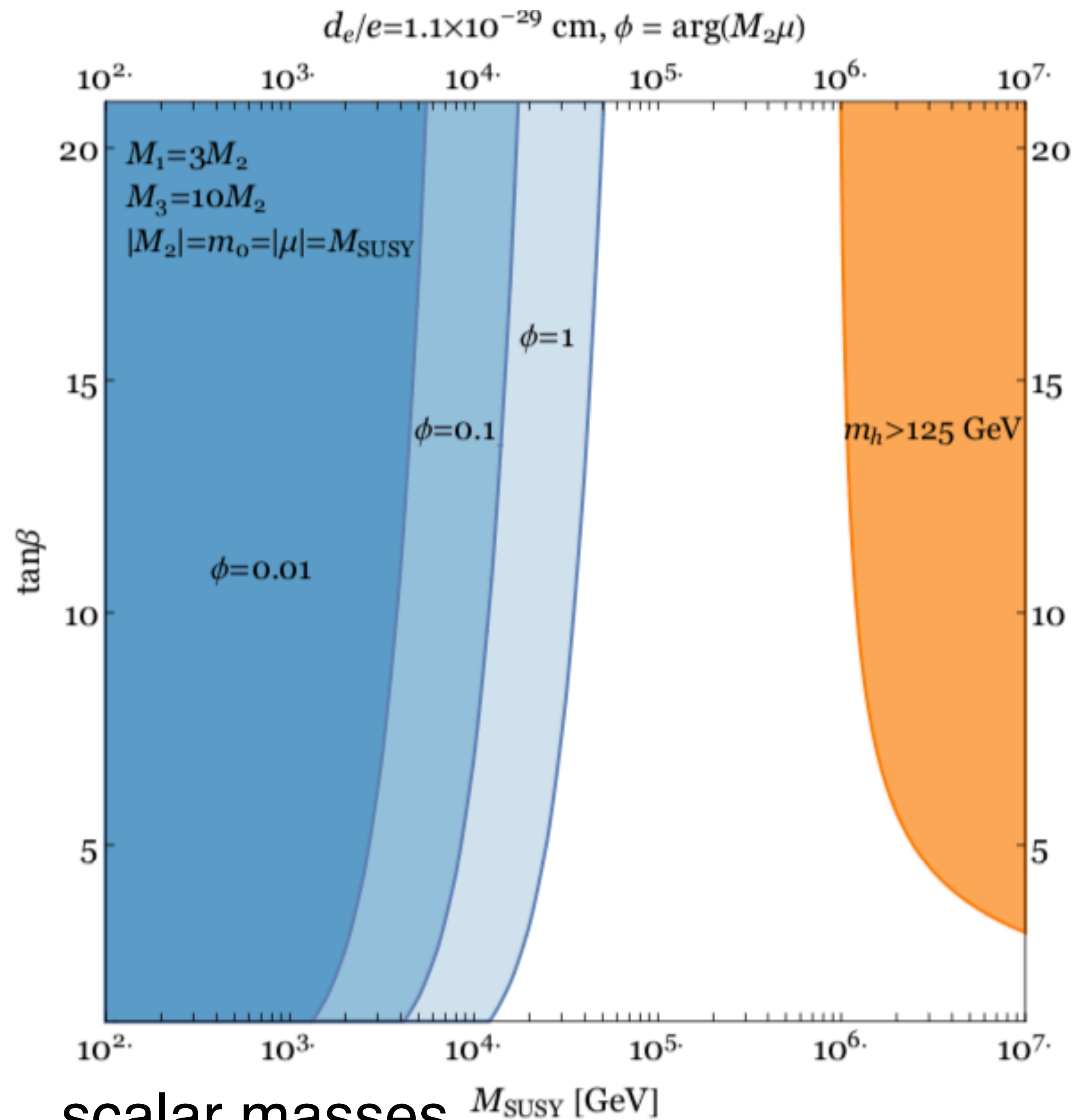
Then dimensional analysis tells us that the experiment probes masses

0-loop	1-loop	2-loop
1000 TeV	50 TeV	3 TeV

for order-one CPV phases this often exceeds LHC reach!

Electron EDM vs. MSSM





scalar masses

Split SUSY

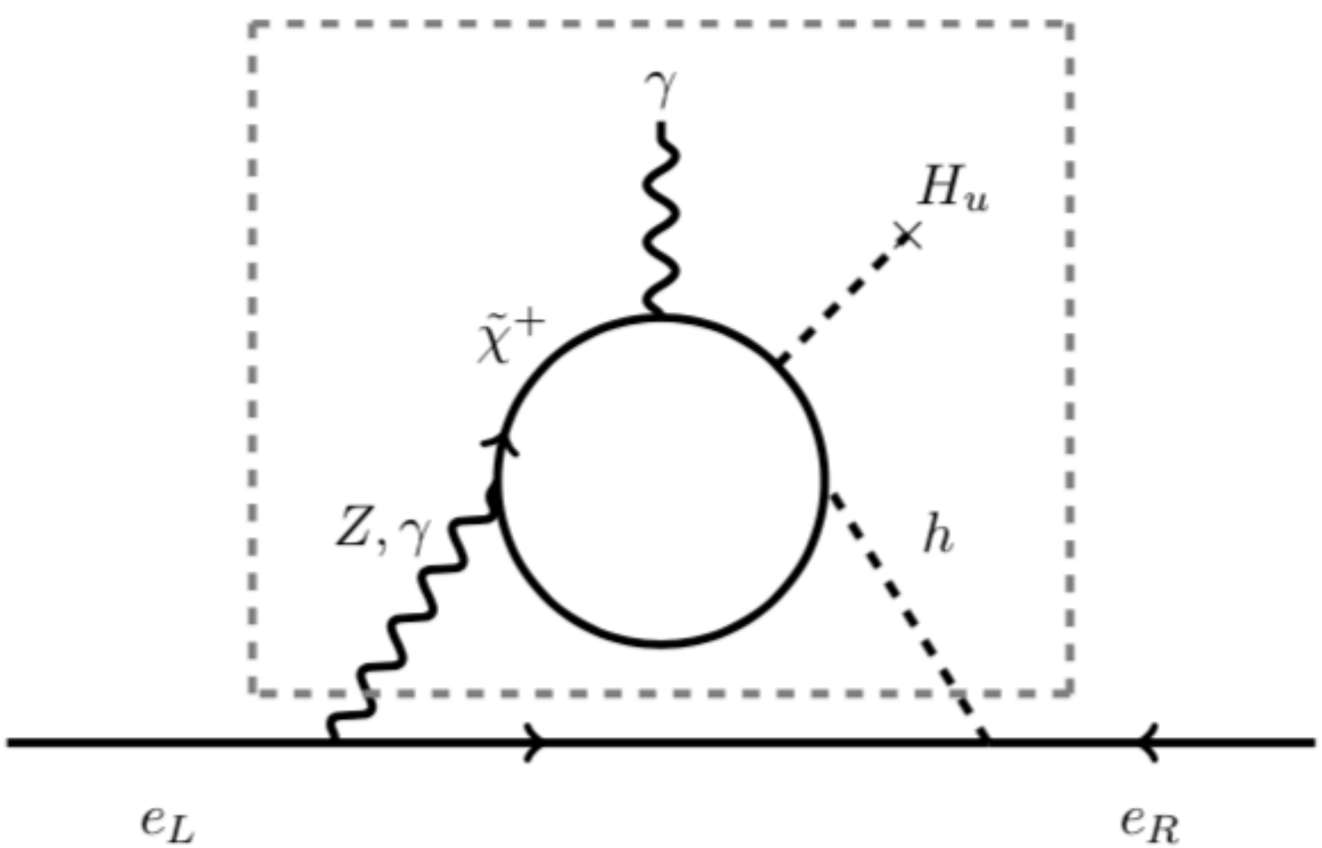
scalar masses

High-Scale SUSY

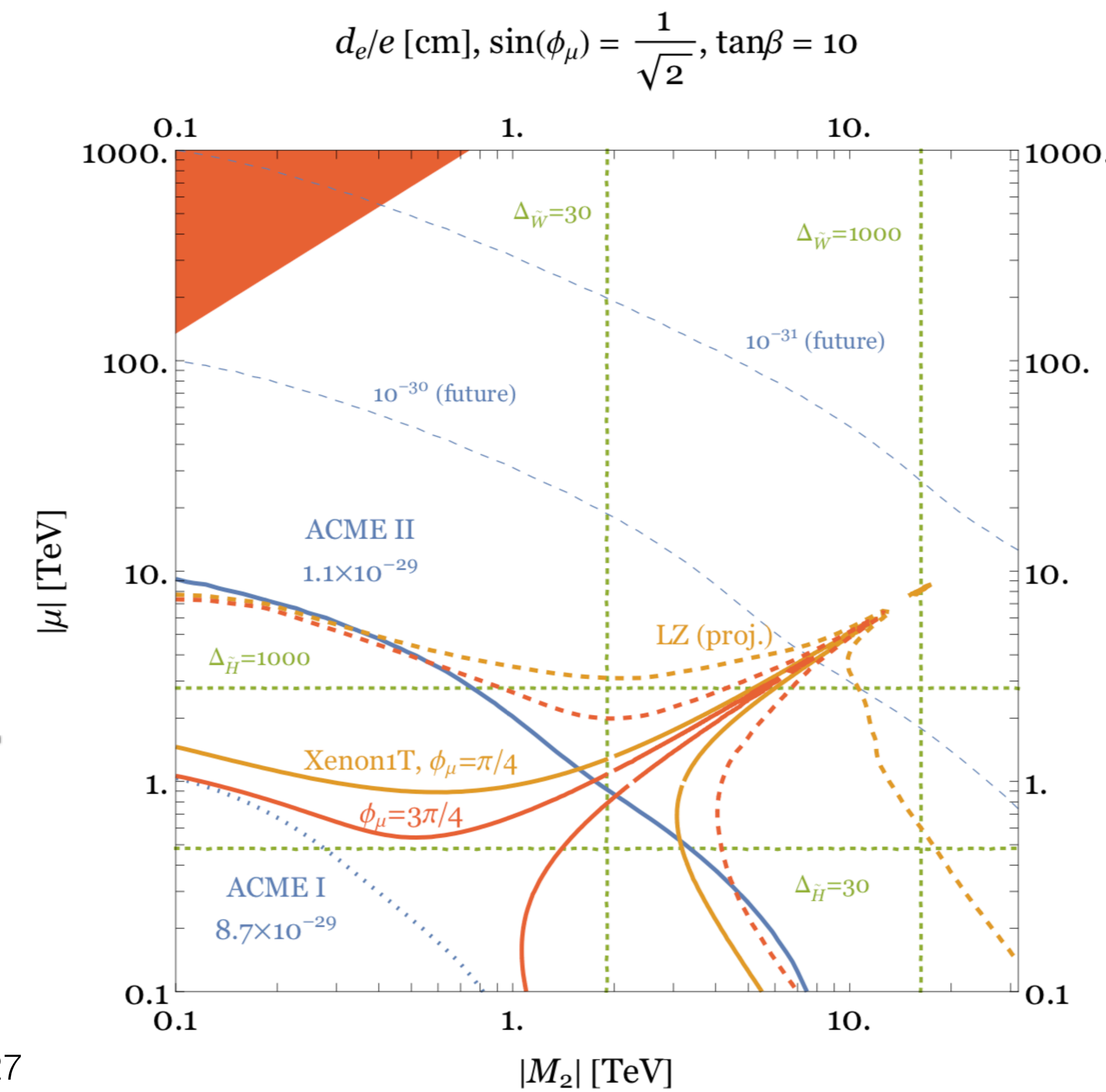
One-loop effects: Cari Cesarotti, Qianshu Lu, Yuichiro Nakai, Aditya Parikh, MR, '18

Electron EDM vs. Electroweak Physics

Quite generally, electroweak new physics coupling to the Higgs boson gives rise to an electron EDM (Barr-Zee).



Powerful split SUSY electroweakino constraints from ACME 2!



[Cesarotti, Lu, Nakai, Parikh, MR, ’18]

Future EDM experiments

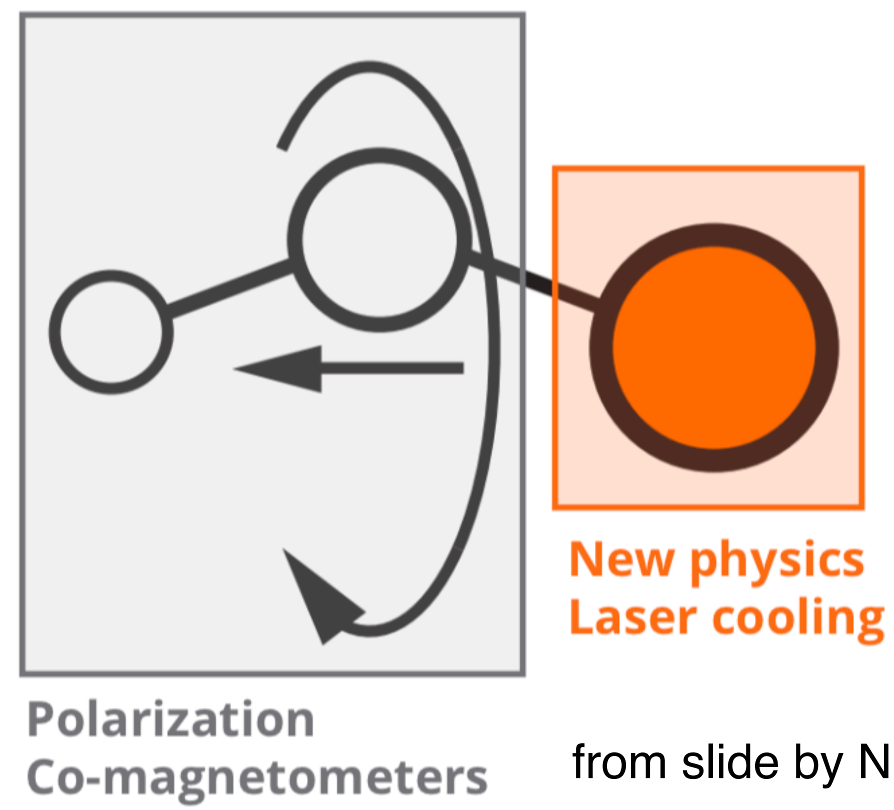
To improve, need more molecules, longer coherence times. Need special molecules:

Laser cooling can produce many slow-moving molecules to study. Avoid exciting molecular rotational, vibrational modes.

EDM systematics need "internal co-magnetometer."

Hutzler & Kozyryev 2017: **polyatomic molecules can give both! (ex: YbOH)**

Polyatomic EDM



from slide by N. Hutzler

Time scale of 5-10 years:

$$|d_e| \lesssim 10^{-32}\, e\,\mathrm{cm}$$

1-loop, PeV scale sensitivity

Other planned experiments: trapped molecular ions (Cornell, Ye, JILA), YbF (Hinds, Imperial), EDM^3 (Vutha, Horbatsch, Hessels, Toronto/York), …

Galactic Center GeV Excess

The Galactic Center Excess [GCE]

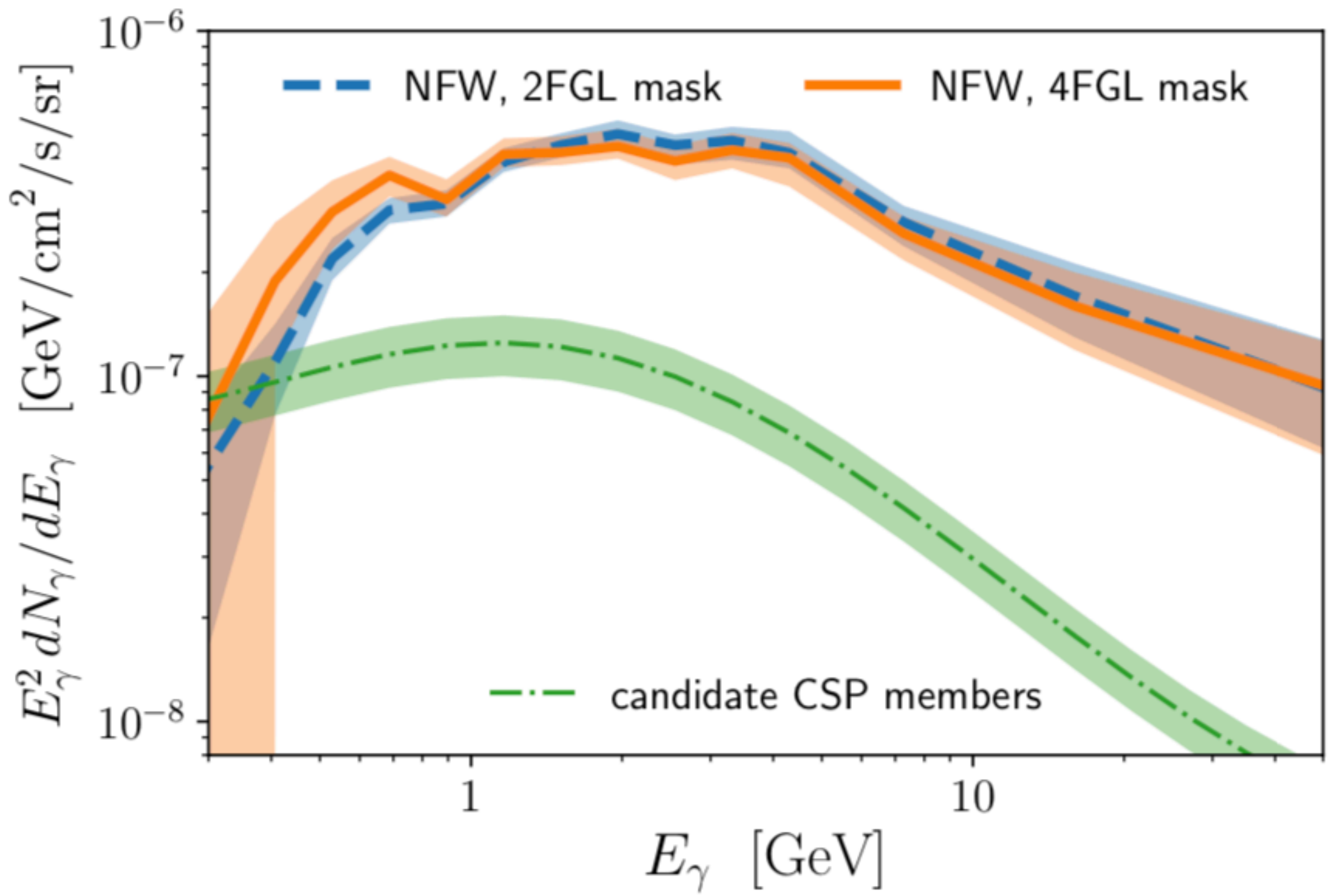
Goodenough & Hooper ’09, ’10

follow-ups by Abazajian, Bartels, Calore, Canac, Cholis, Coleman, Crocker, Daylan, Finkbeiner, Gordon, Horiuchi, Kaplinghat, Karwin, Krishnamurthy, Kwa, Lee, Linden, Lisanti, Macias, McCabe, Murgia, Paterson, Pohl, Porter, Portillo, Rodd, Safdi, Slatyer, Tait, Tanedo, Weniger, Xue, Fermi-LAT collab, many others….

Annihilating dark matter, or astrophysics?

Ongoing debate, see, e.g.:
Leane & Slatyer ’19
Zhong, McDermott, Cholis, Fox ’19
Buschmann, Rodd, Safdi, Chang, Mishra-Sharma, Lisanti, Macias ’20
Abazajian, Horiuchi, Kaplinghat, Keeley, Macias ’20

Less general sentiment that it’s point sources than circa 2015

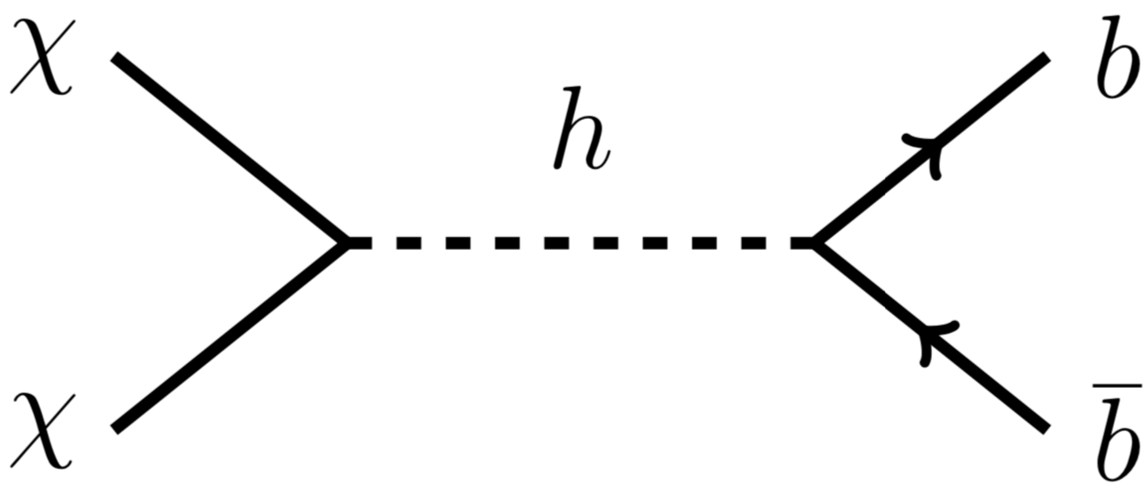


Zhong, McDermott, Cholis, Fox ’19

The GCE: Higgs or Not?

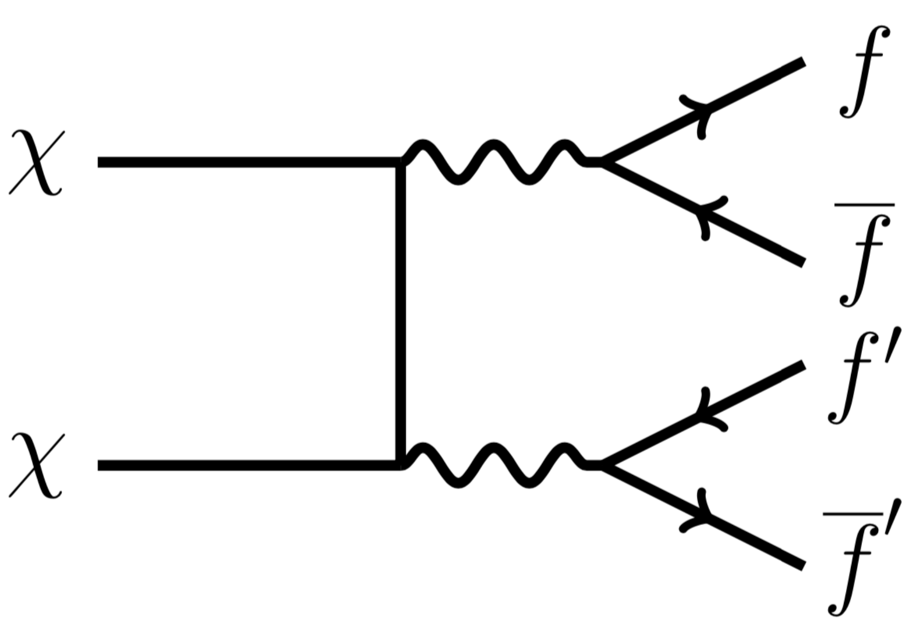
For a GCE model [too many refs to cite here], two very different scenarios:

Direct annihilation to SM final states, through the Higgs?



- reasonable spectral shape
- could lie near resonance
- velocity-suppressed if CP-conserving
- EDM constraint if CP-violating?

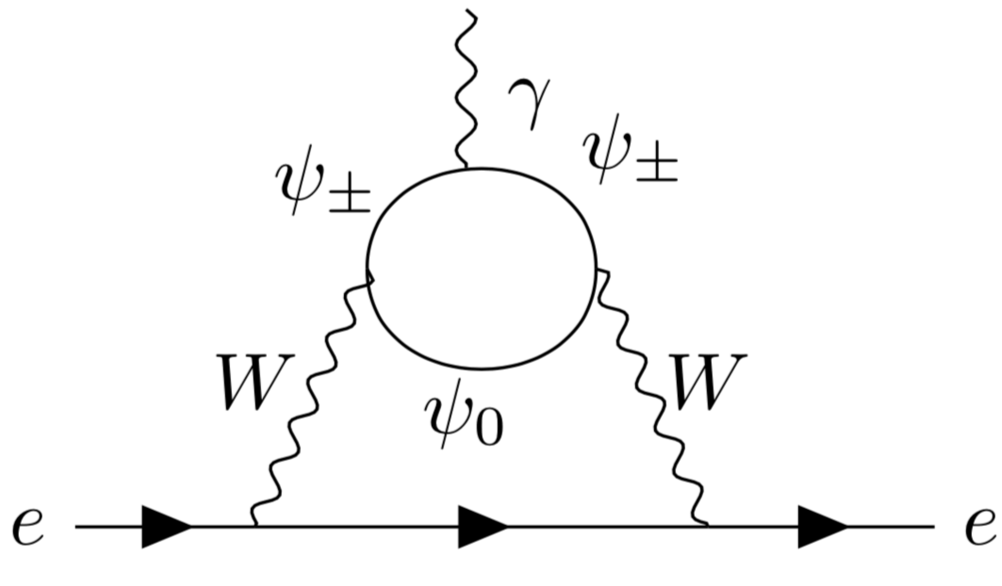
Annihilation through a mediator: "hidden-sector models"



- on-shell mediator decouples annihilation rate from SM coupling
- easy to evade constraints from terrestrial experiments
- various models fit shape

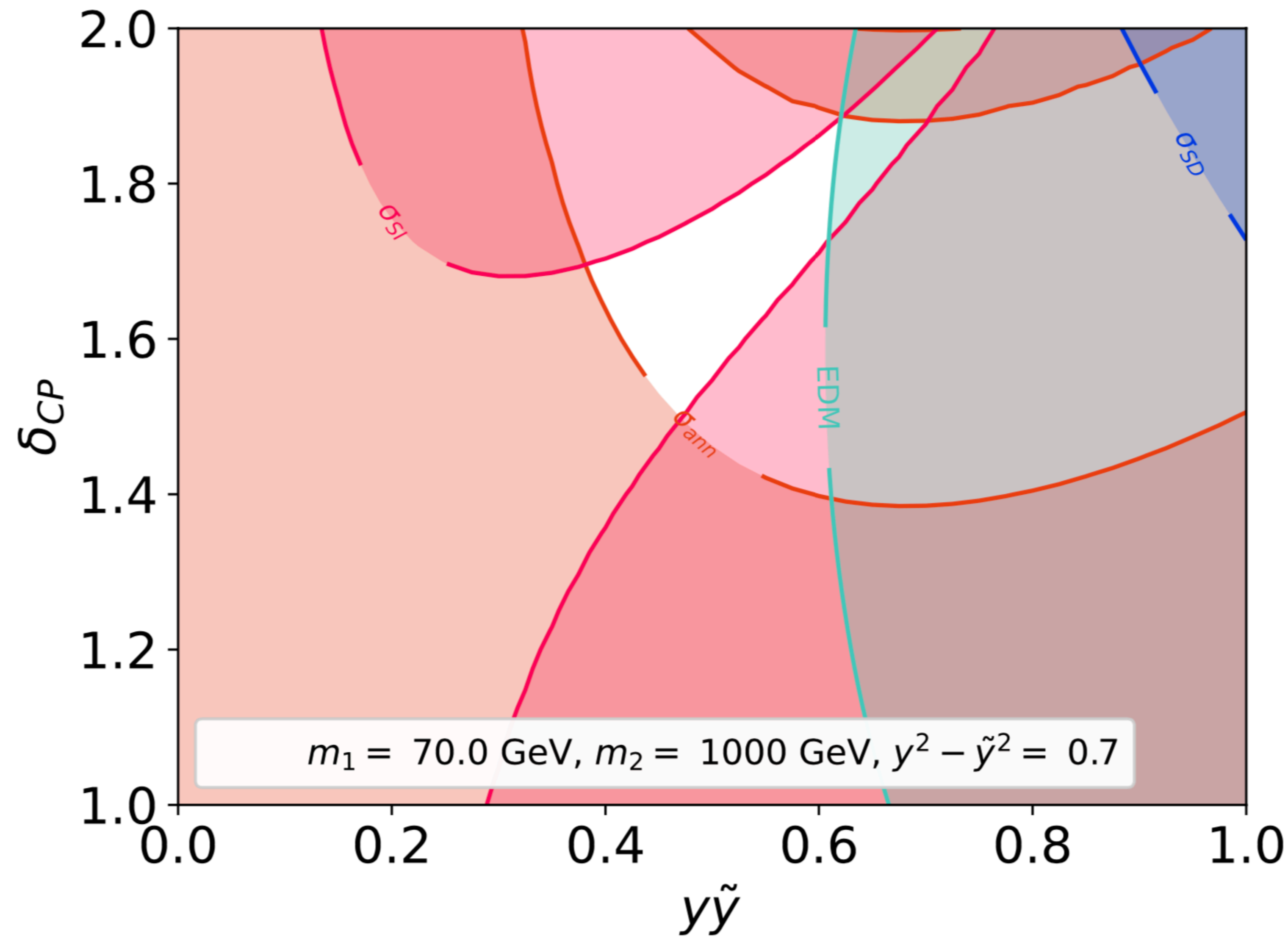
CPV Higgs-DM Couplings and the GCE

Possible in a **singlet-doublet** model. The 2-loop diagram with **two W bosons,** rather than one Higgs and one photon, is **less constrained**.



Katie Fraser, Aditya Parikh, Linda Xu, to appear '20
[see Linda Xu parallel talk slides from Monday]

also: Carena, Osborne, Shah, Wagner '19



$$-m_2\tilde{\psi}_2\psi_2 - \frac{m_1}{2}\psi_1\psi_1 + y_{DM}\psi_1 H^\dagger \psi_2 - \tilde{y}_{DM}\psi_1 H \cdot \tilde{\psi}_2$$

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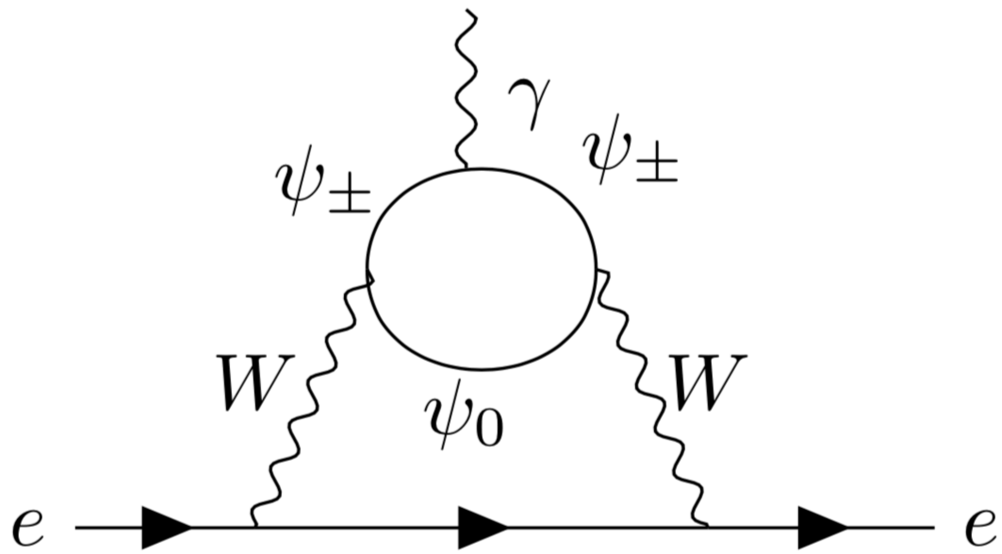

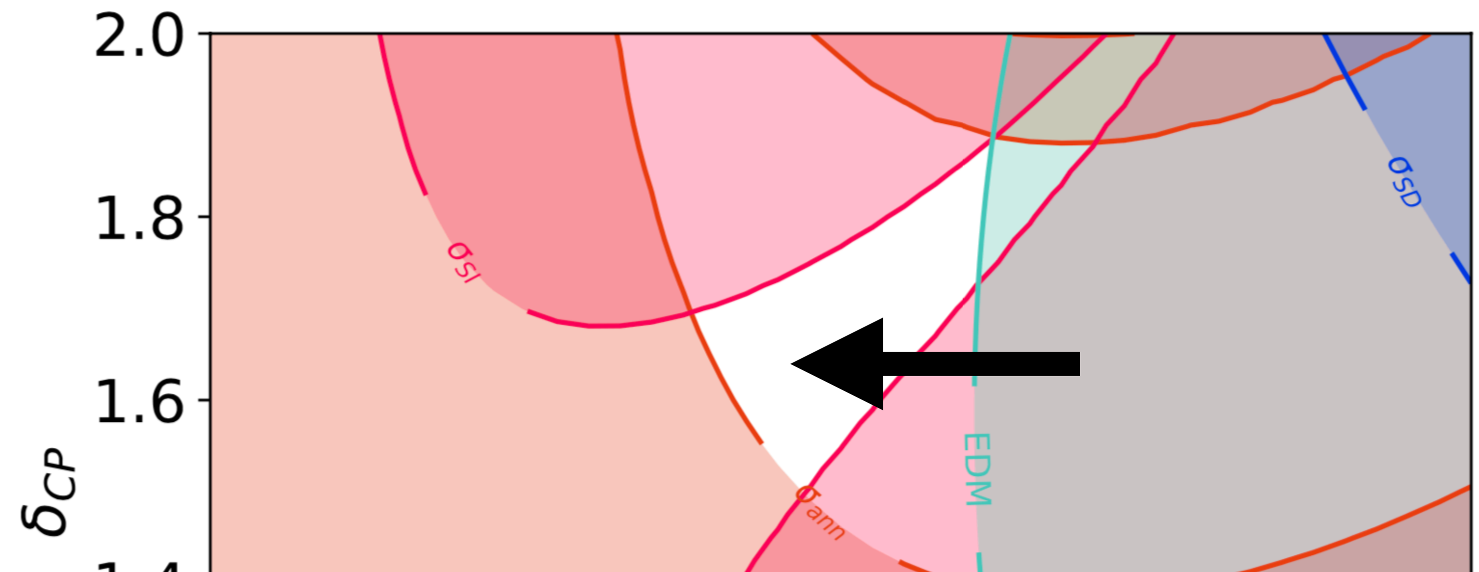

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[see Linda Xu parallel talk slides from Monday]

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Provides further, strong motivation for improving the electron EDM bound in the near future!

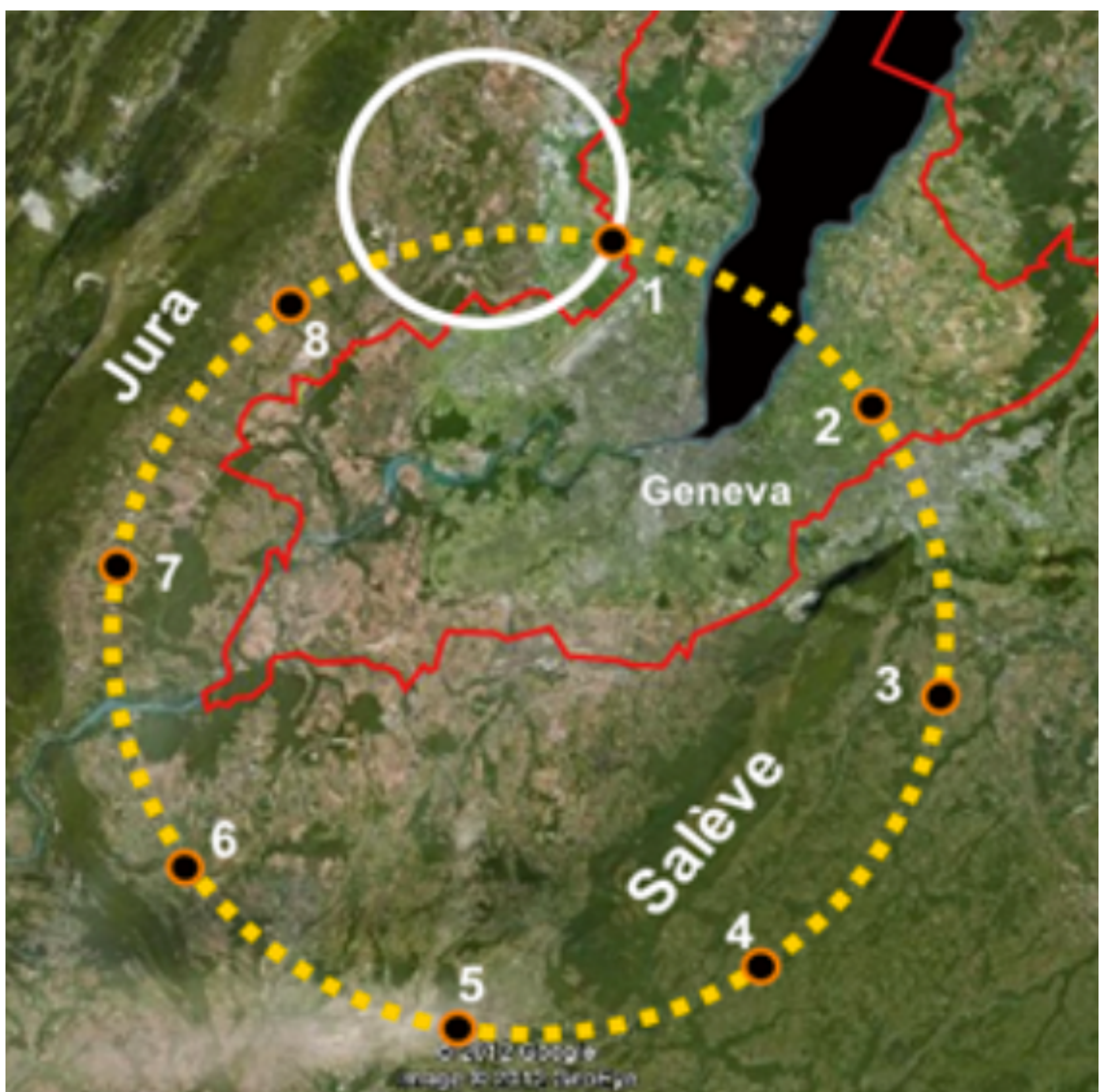
Closing Comments

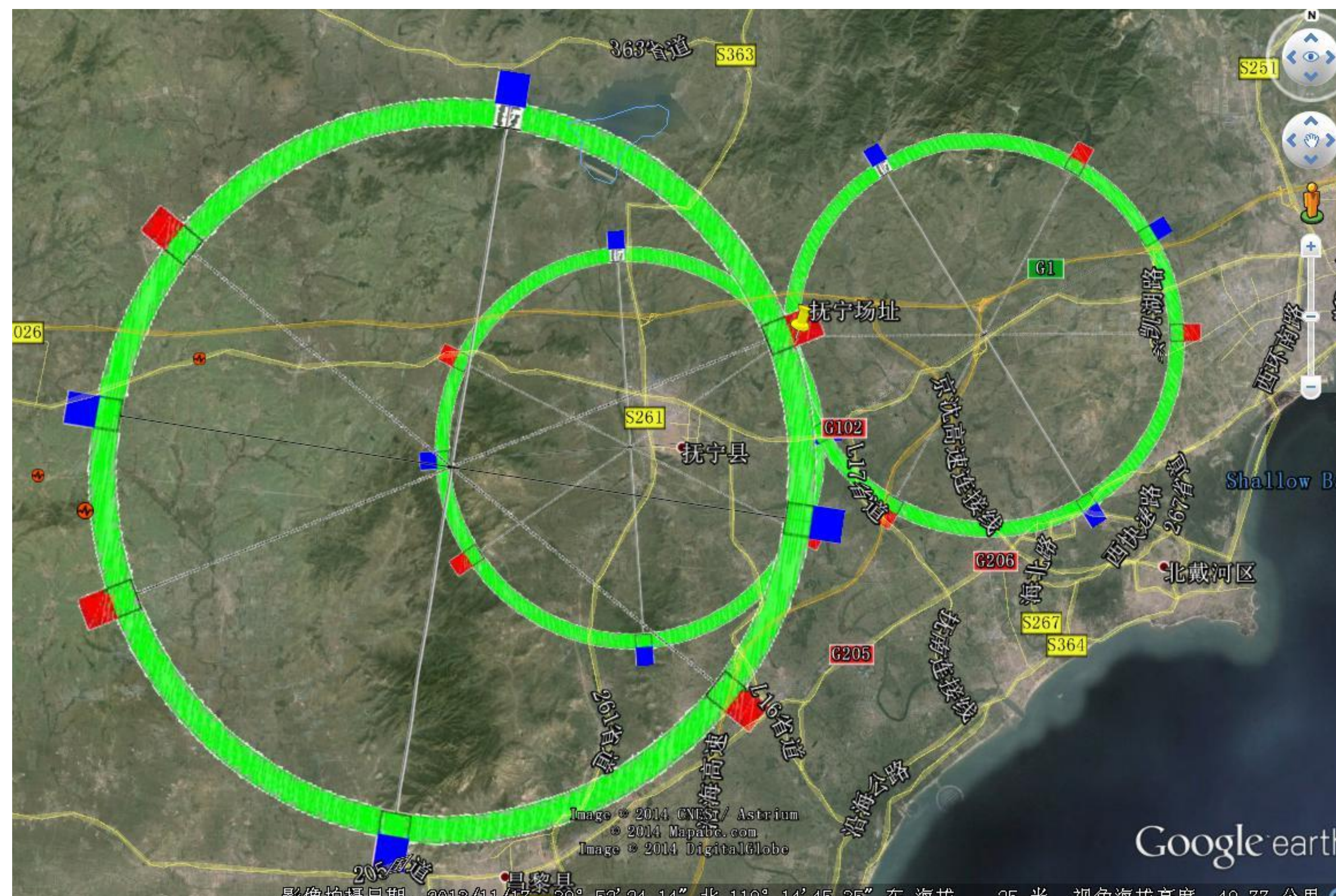
Big Tunnels: The Future of Our Field

New physics could be decisively ***discovered*** by an EDM experiment.

New physics can be thoroughly ***understood*** at a collider.

Whether near Geneva, Qinhuangdao, or somewhere else entirely, this is what we need for our future:





Summary

The LHC found what looks like an elementary spin-0 Higgs boson. Still, ***we do not understand the weak scale***.

We need to make good use of the LHC, but also plan for the future. ***Important to emphasize the big-picture questions.***

Keep an eye out for important discoveries from beyond the world of colliders, like **EDM searches** or dark matter.

However, to really ***understand*** new physics:

Particle physics needs new energy-frontier colliders!