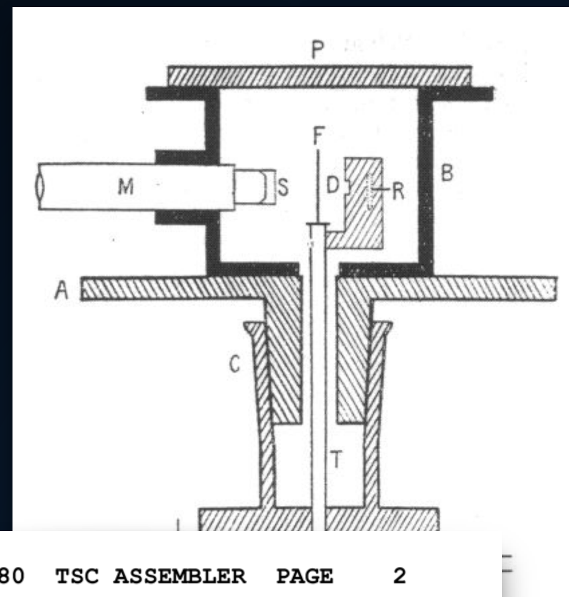
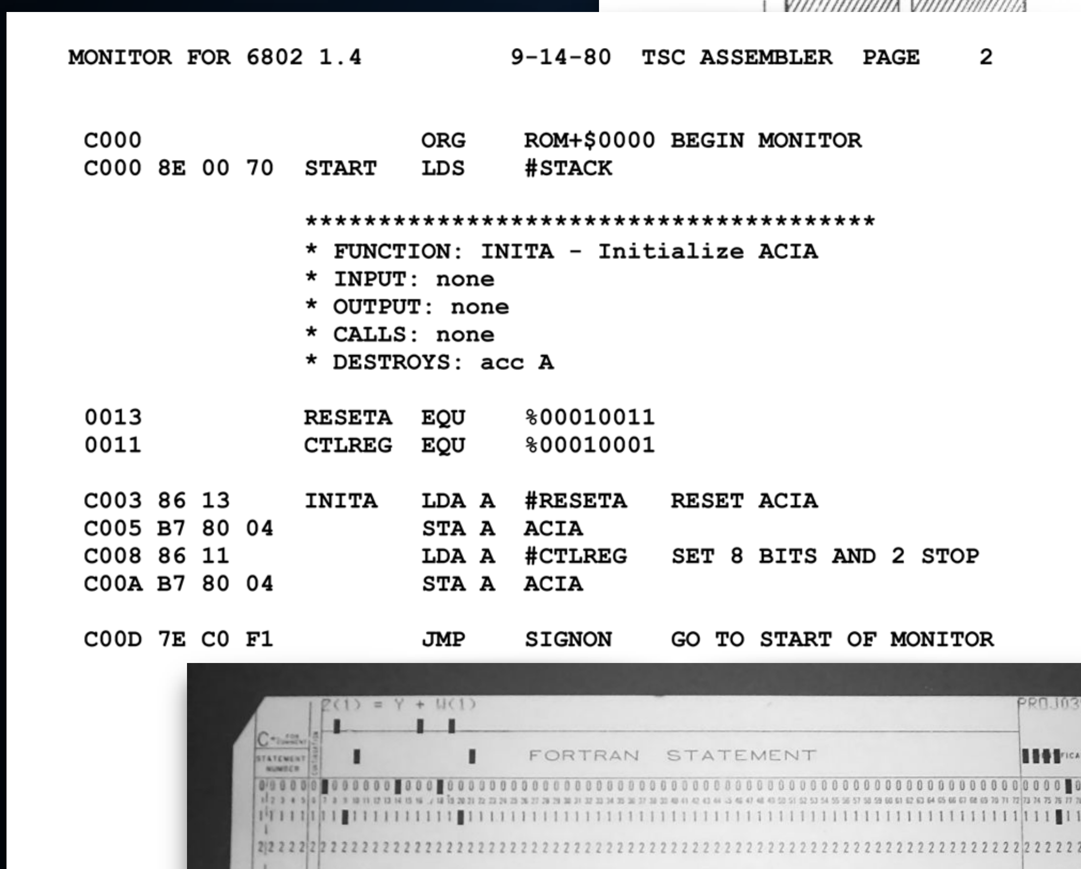
Muon Collider Overview

Lawrence Lee

THE UNIVERSITY OF TENNESSEE KNOXVILLE





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 C008 86 11            LDA A #CTLREG   SET 8 BITS AND 2 STOP
 C00A B7 80 04         STA A ACIA

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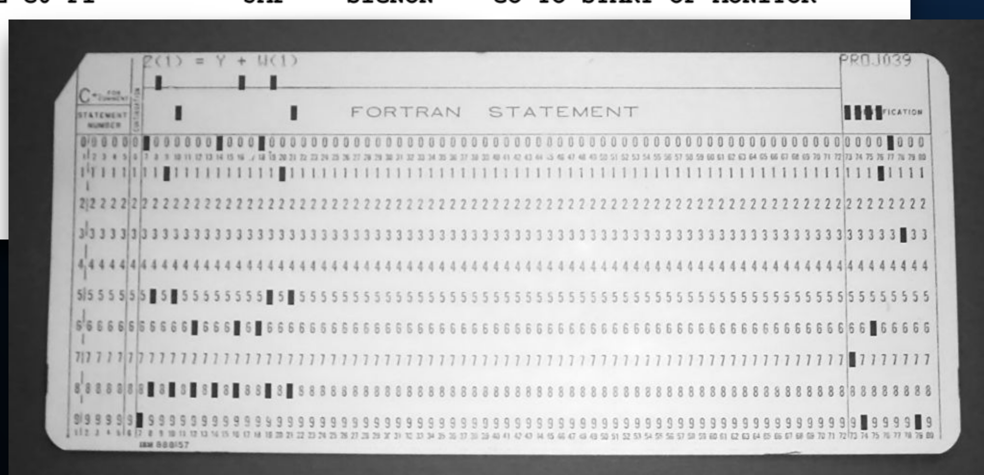

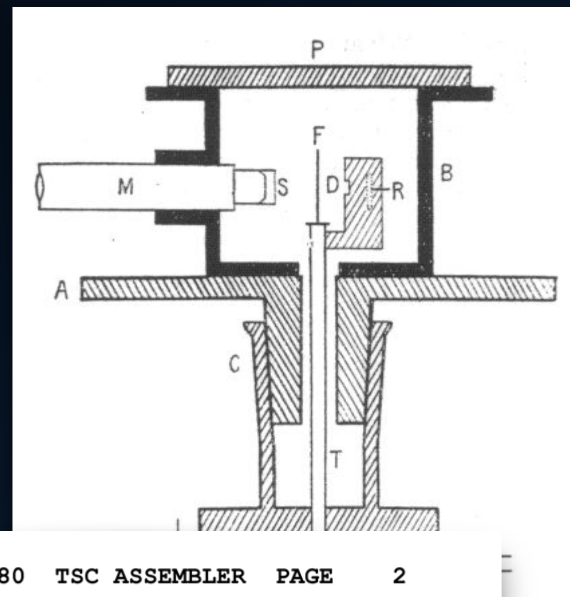


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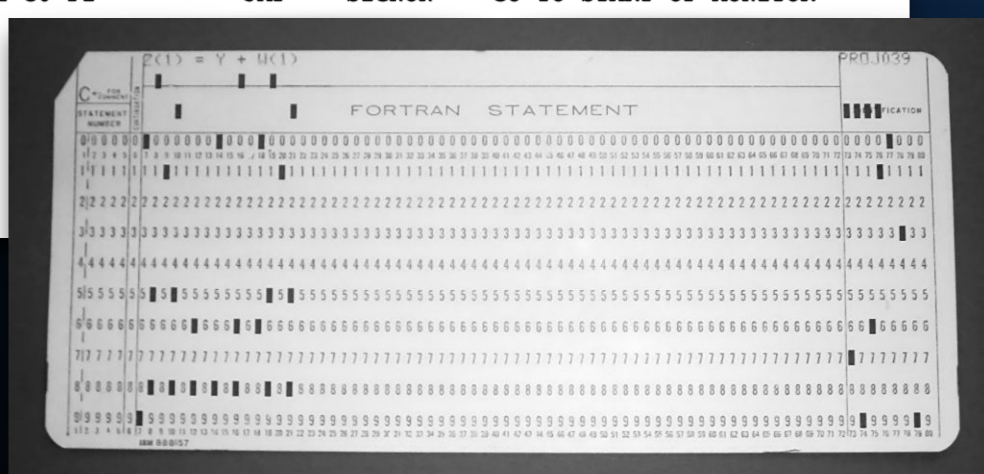

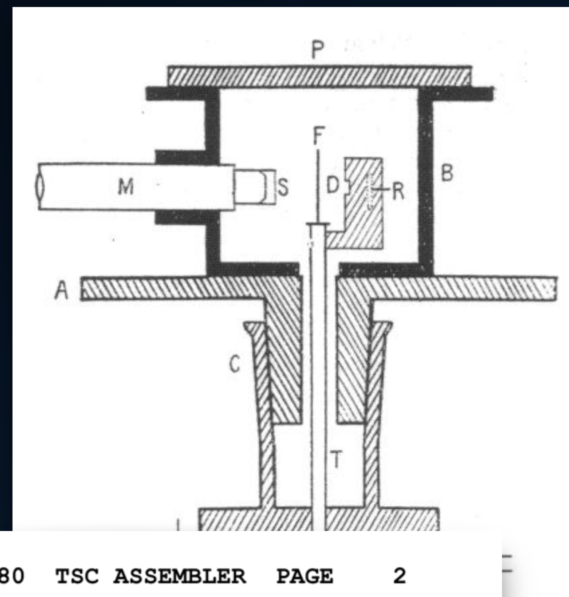


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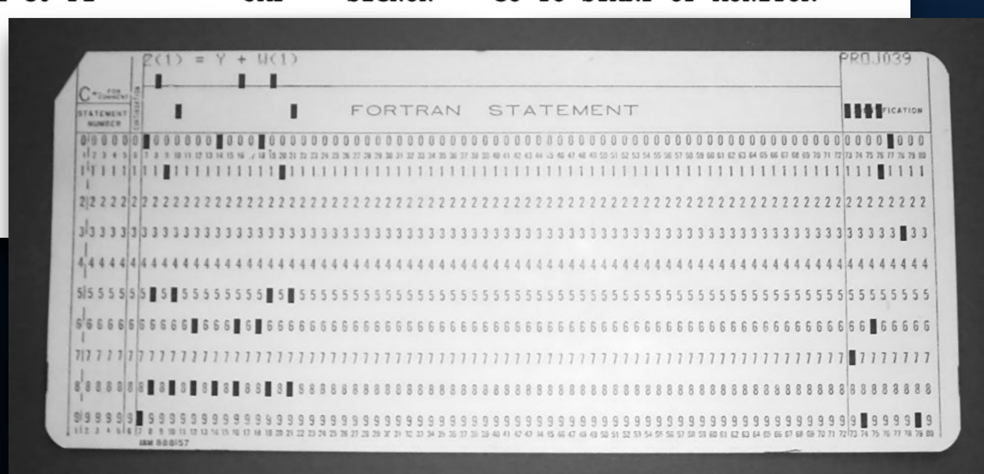
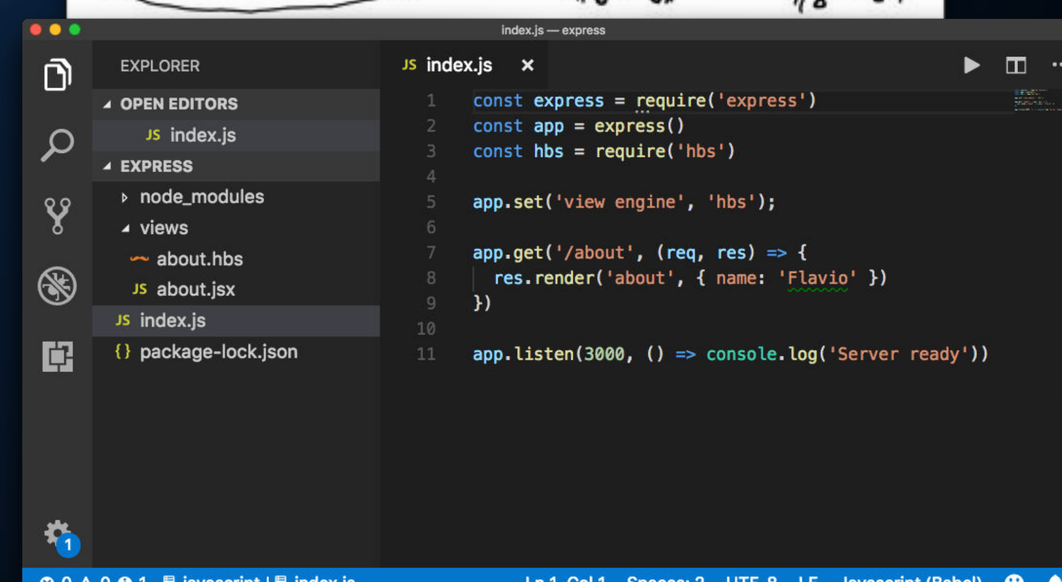
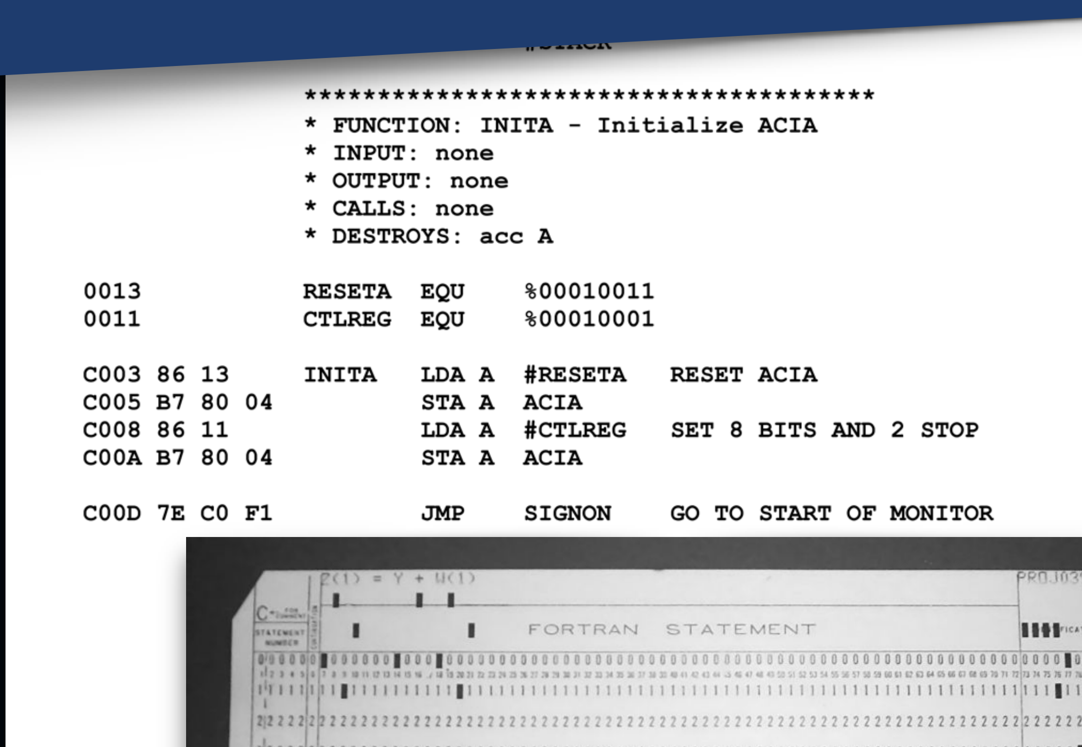




Every physics AI conversation today:

~~“But kids these days won’t know how to X!”~~



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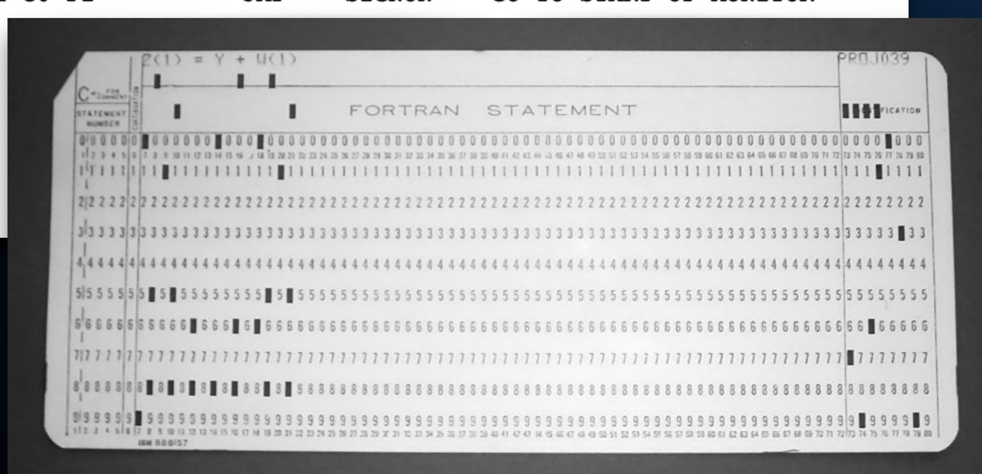

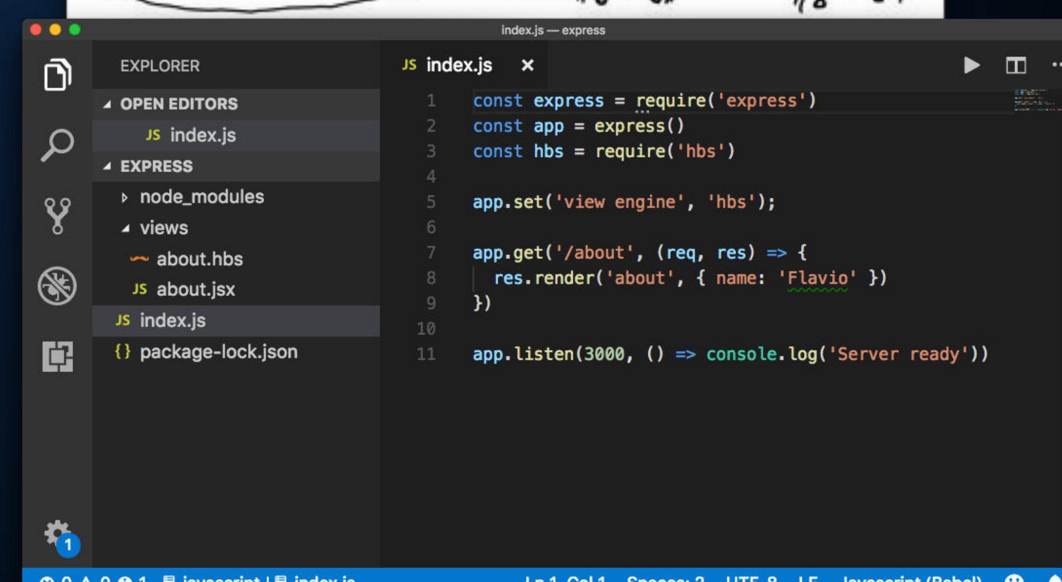

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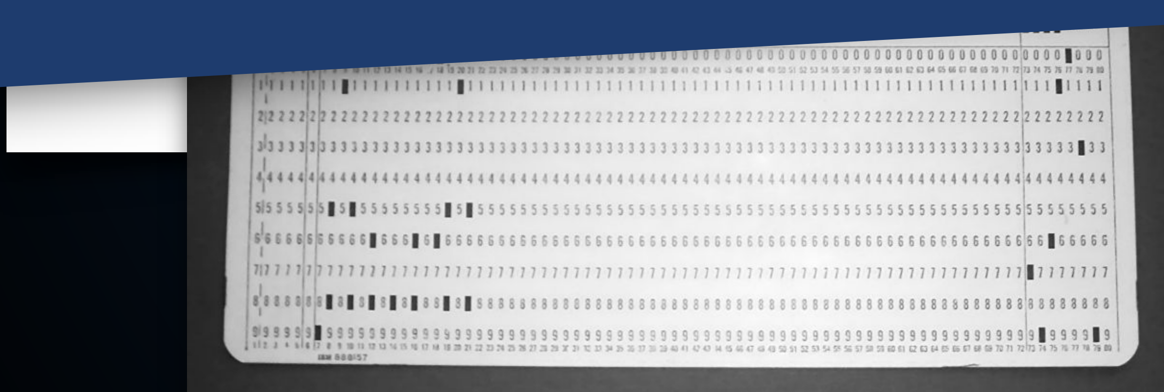
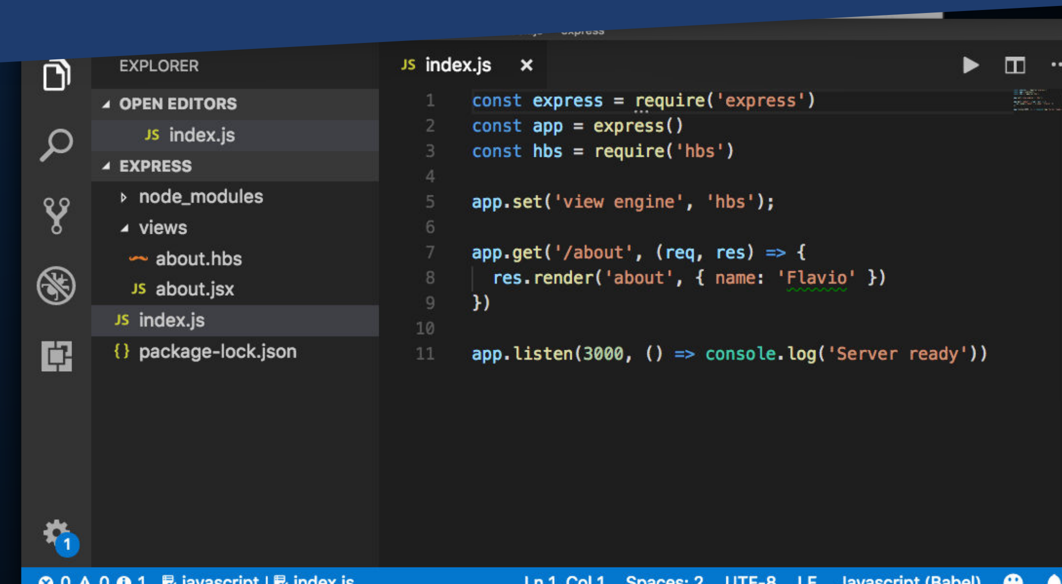
Every step re-centers the physics

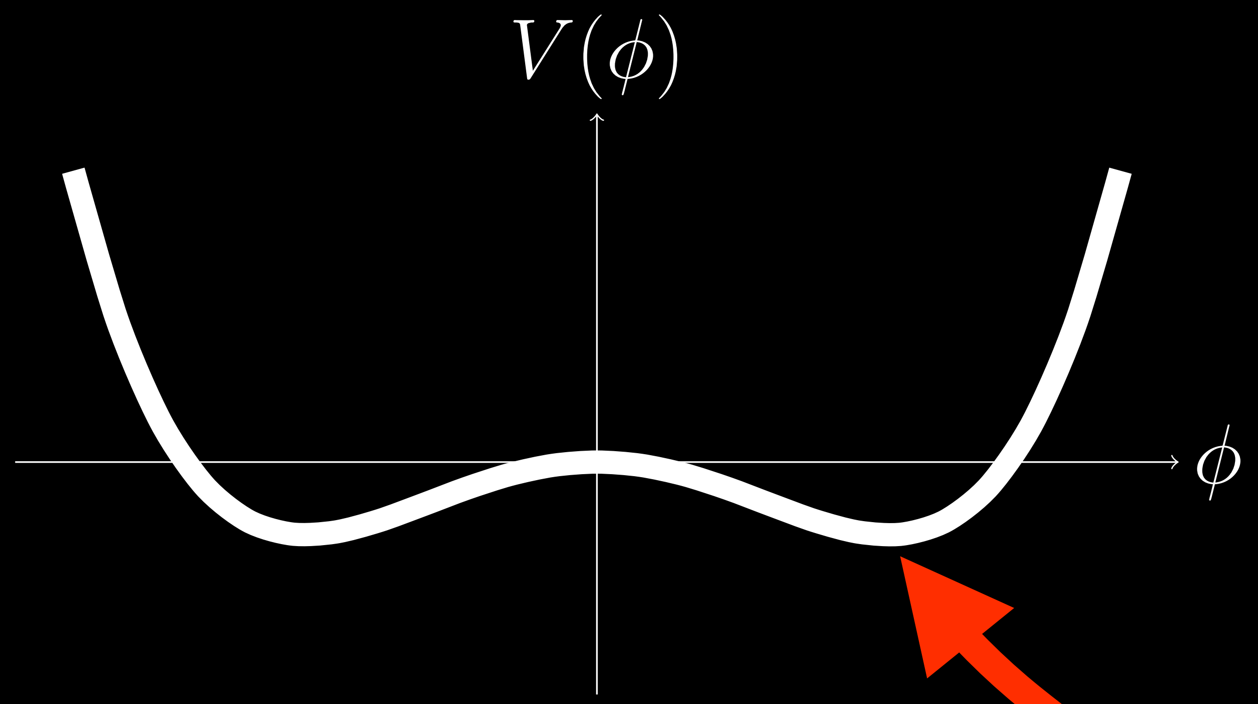
🤖 Effort multiplier qualitatively changes what discoveries are possible





LHC

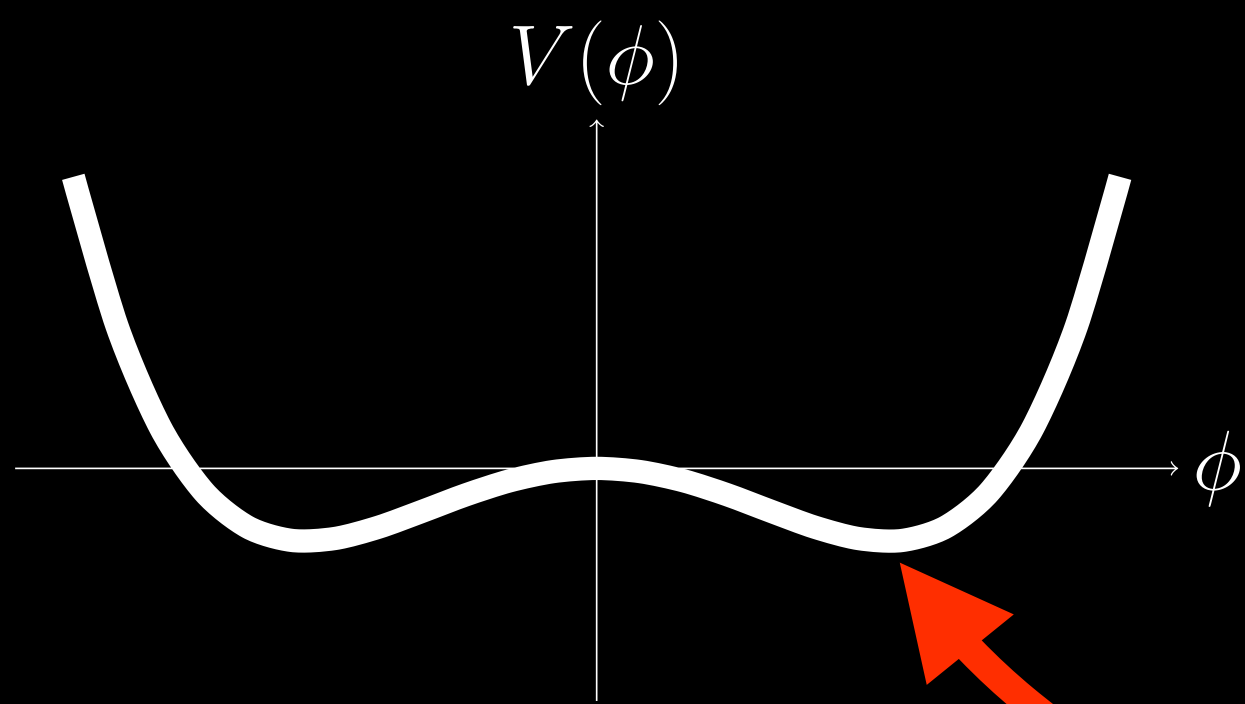
- LHC collides protons at 13-14 TeV
  - Since p is composite, probes interactions scales of ~1 TeV
- But we're **certain that nature hides truths above LHC's reach**
- **Next big step will be to 10 TeV interaction scale**
  - Guaranteed critical physics output from a 10 TeV probe!



The Higgs Boson is the massive radial degree of freedom about the minimum of the Higgs potential

i.e. it takes energy to excite state up wall

Higgs discovery **only confirms there's a minimum** of the Higgs potential



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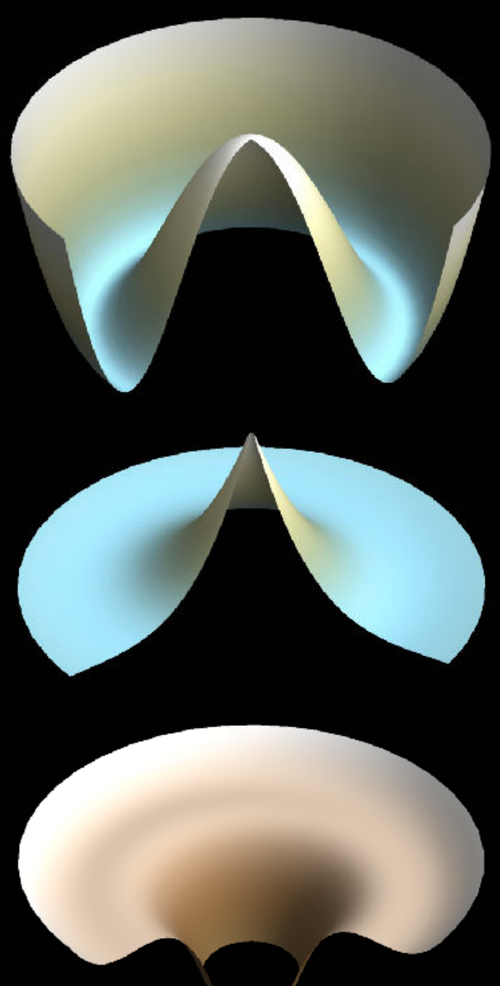
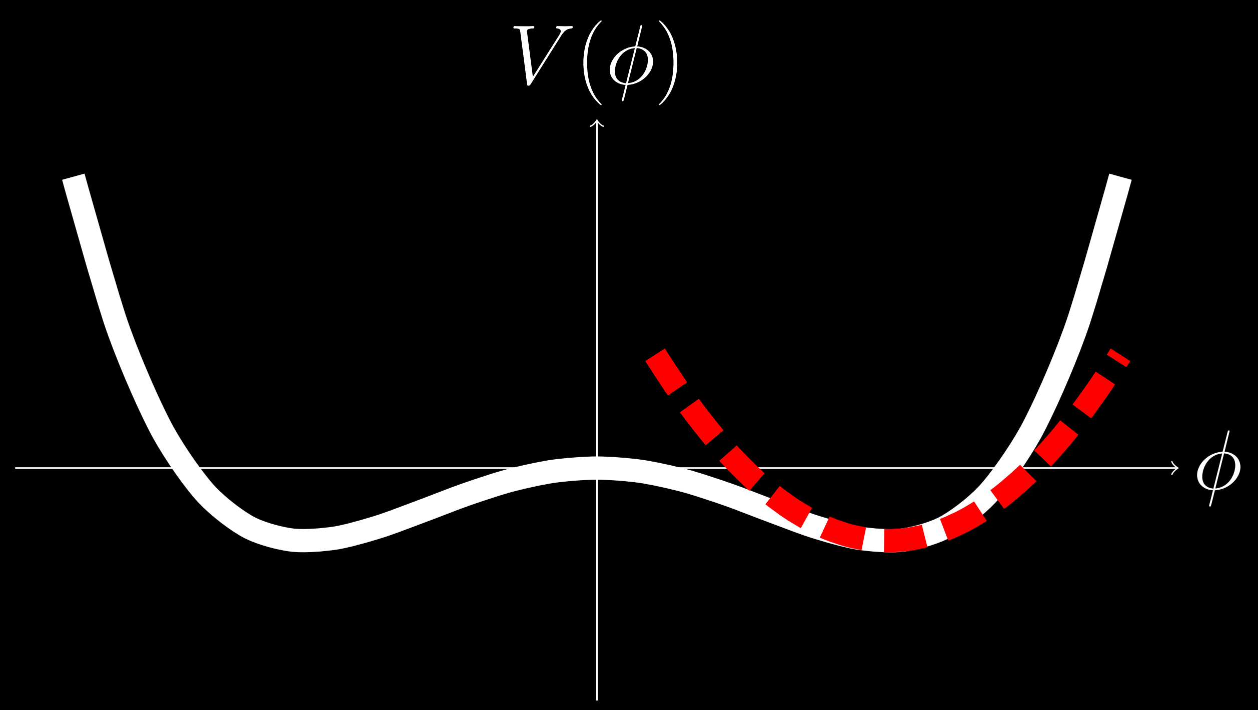
Current knowledge consistent with a wide range of Higgs potential shapes



N Craig & R Petrossian-Byrne

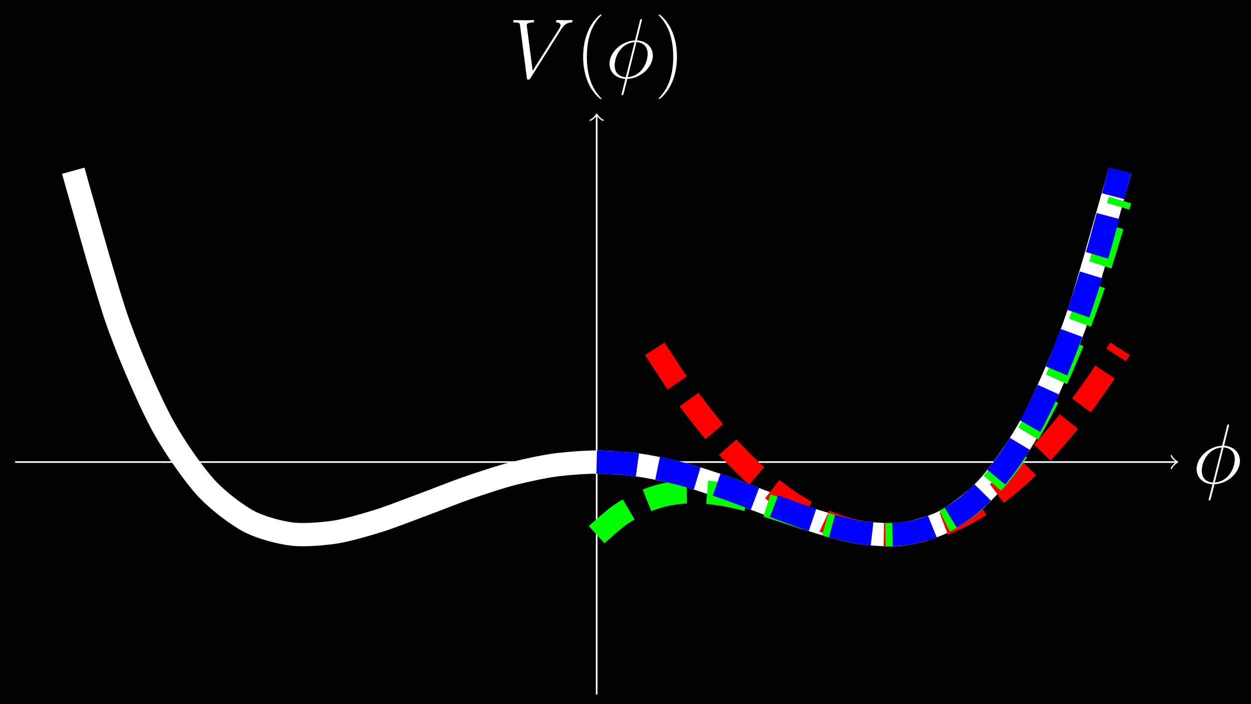


We've only confirmed the Harmonic Oscillator term of Taylor expansion around minimum

To measure full shape of the Higgs potential,

must measure higher order terms
we need multi-Higgs production

$$O(H^2) + O(H^3) + O(H^4)$$



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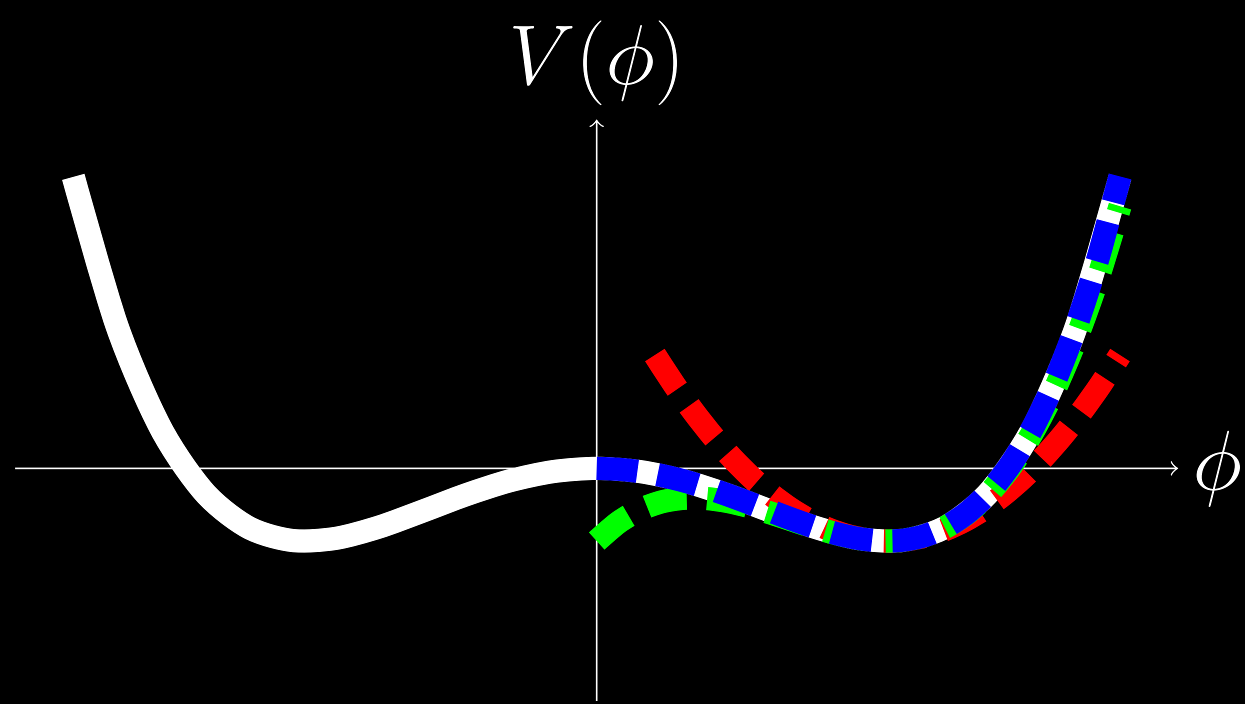

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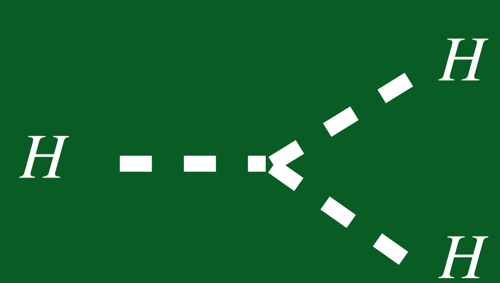
$$O(H^2) + O(H^3) + O(H^4)$$

Trilinear coupling
→ HH production



Quartic coupling
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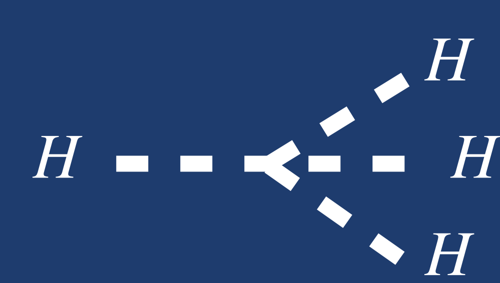
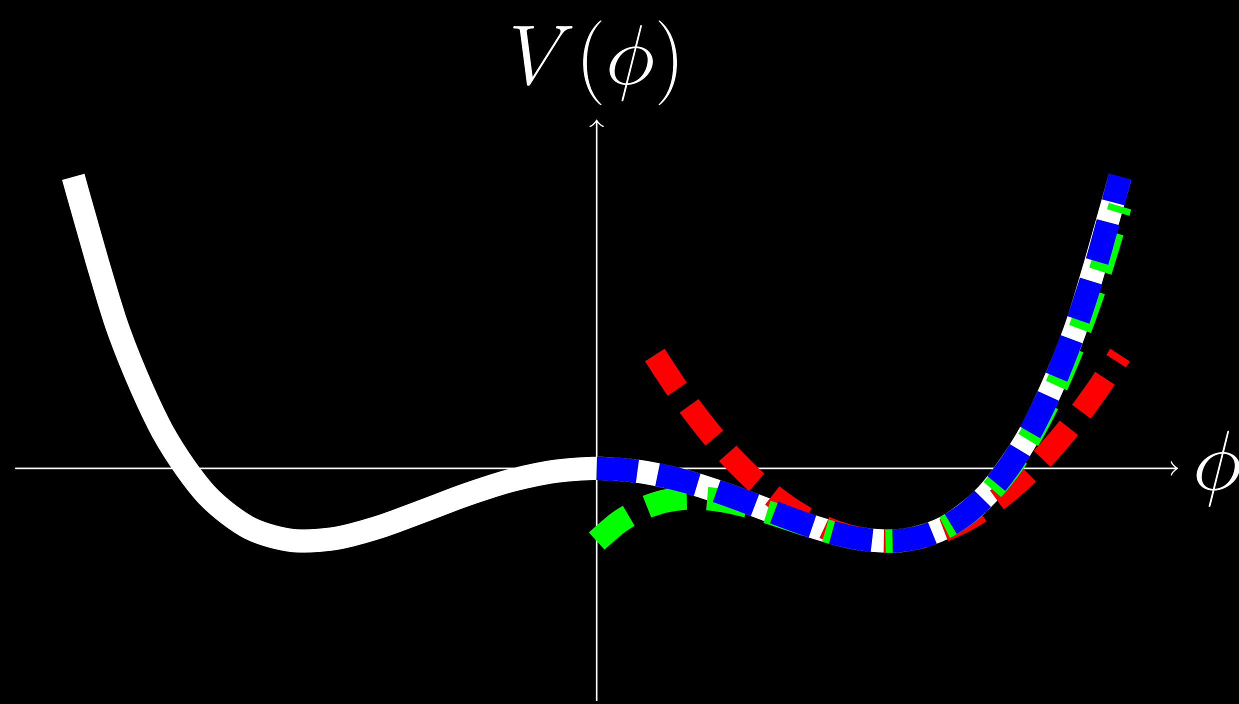


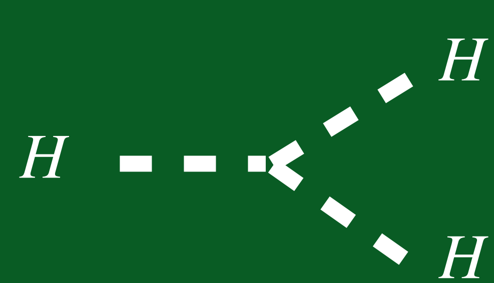


To understand the shape of the Higgs potential, **we need multi-Higgs production**

BSM Contributions?

$$O(H^2) + O(H^3) + O(H^4) + O(H^5) + \ldots$$

Trilinear coupling
→ HH production



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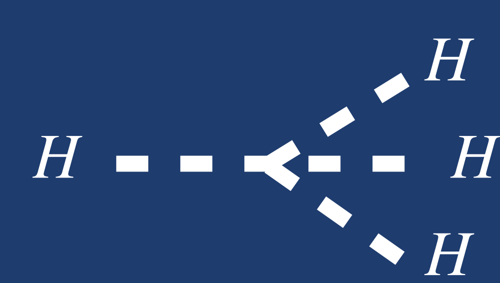
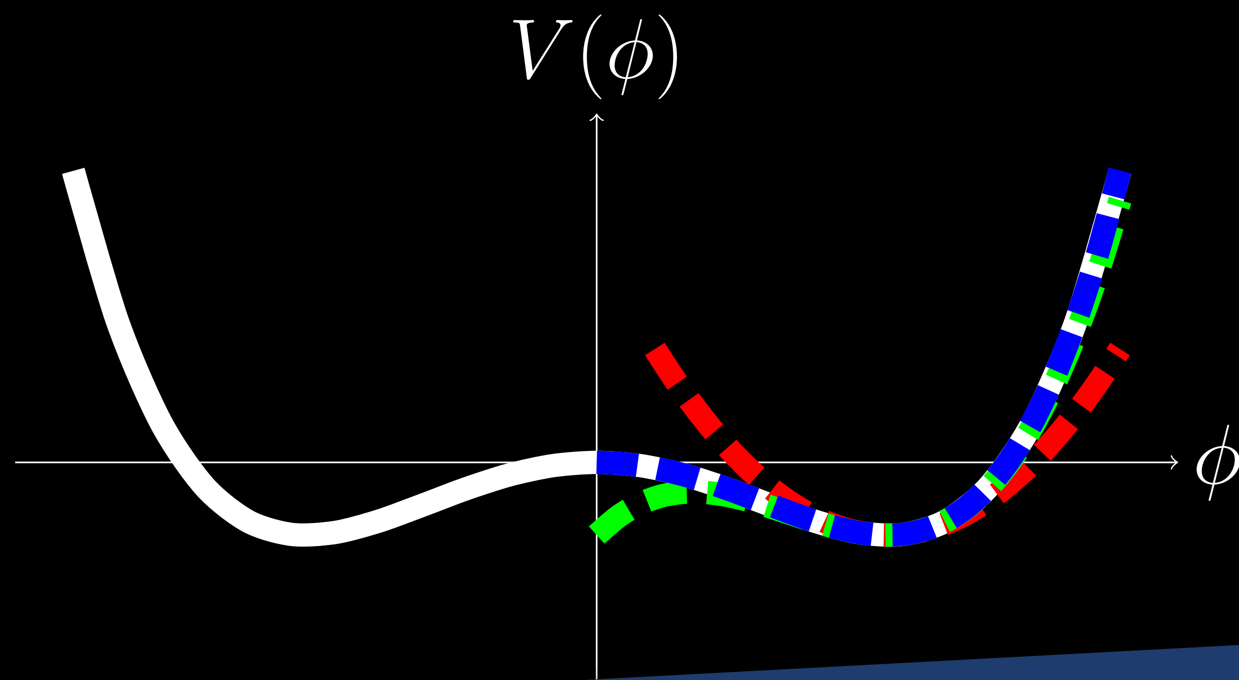




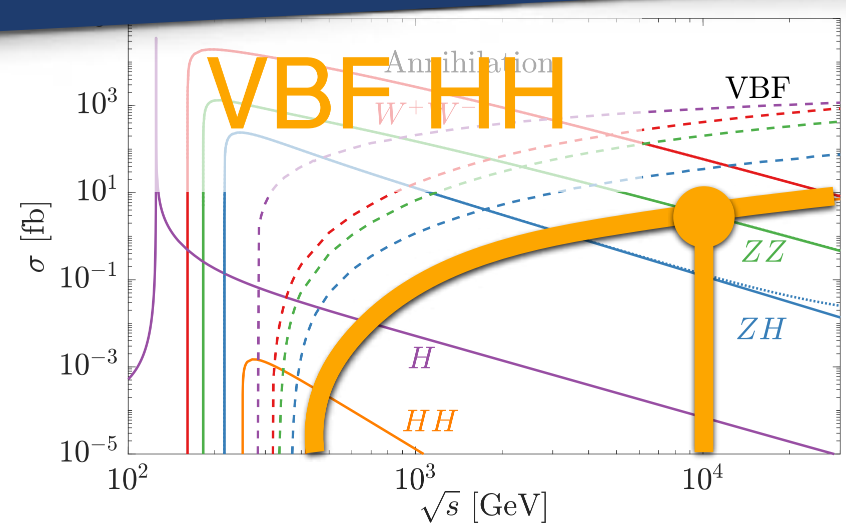
To understand the shape of the Higgs potential, **we need multi-Higgs production**

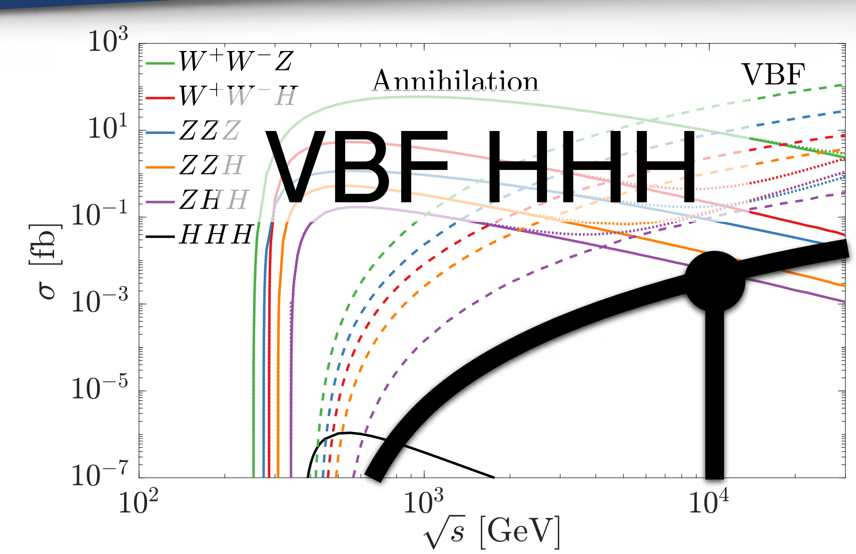
BSM

To map out Higgs potential, need to measure multi-Higgs processes.
To study EWSB, we need EW interactions w/ E ≫ 246 GeV (Higgs VEV)

To study "how"+"why" of the Higgs sector, need a high-luminosity 10-TeV scale collider

Need multi-TeV scale to probe these processes



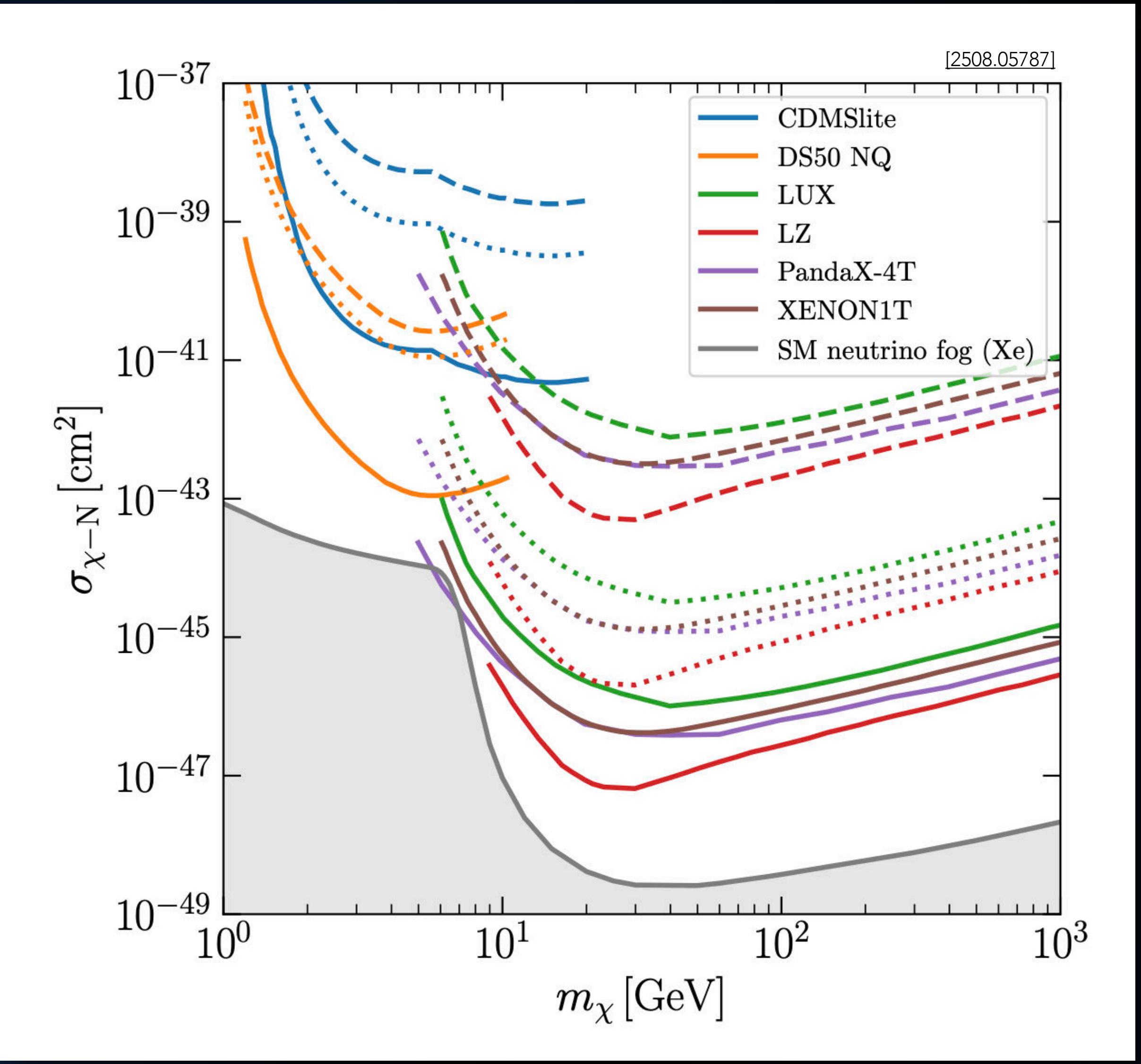


[2212.01323]

A Dark Matter Miracle

- Very convenient coincidence:
  - With Weak couplings, to get thermal relic density correct, **mass needs to be TeV scale!**
  - **Where other SM hints seems to point to…**

- We love WIMPs.
- Direct Detection expt's set limits in mass vs. interaction cross section plane



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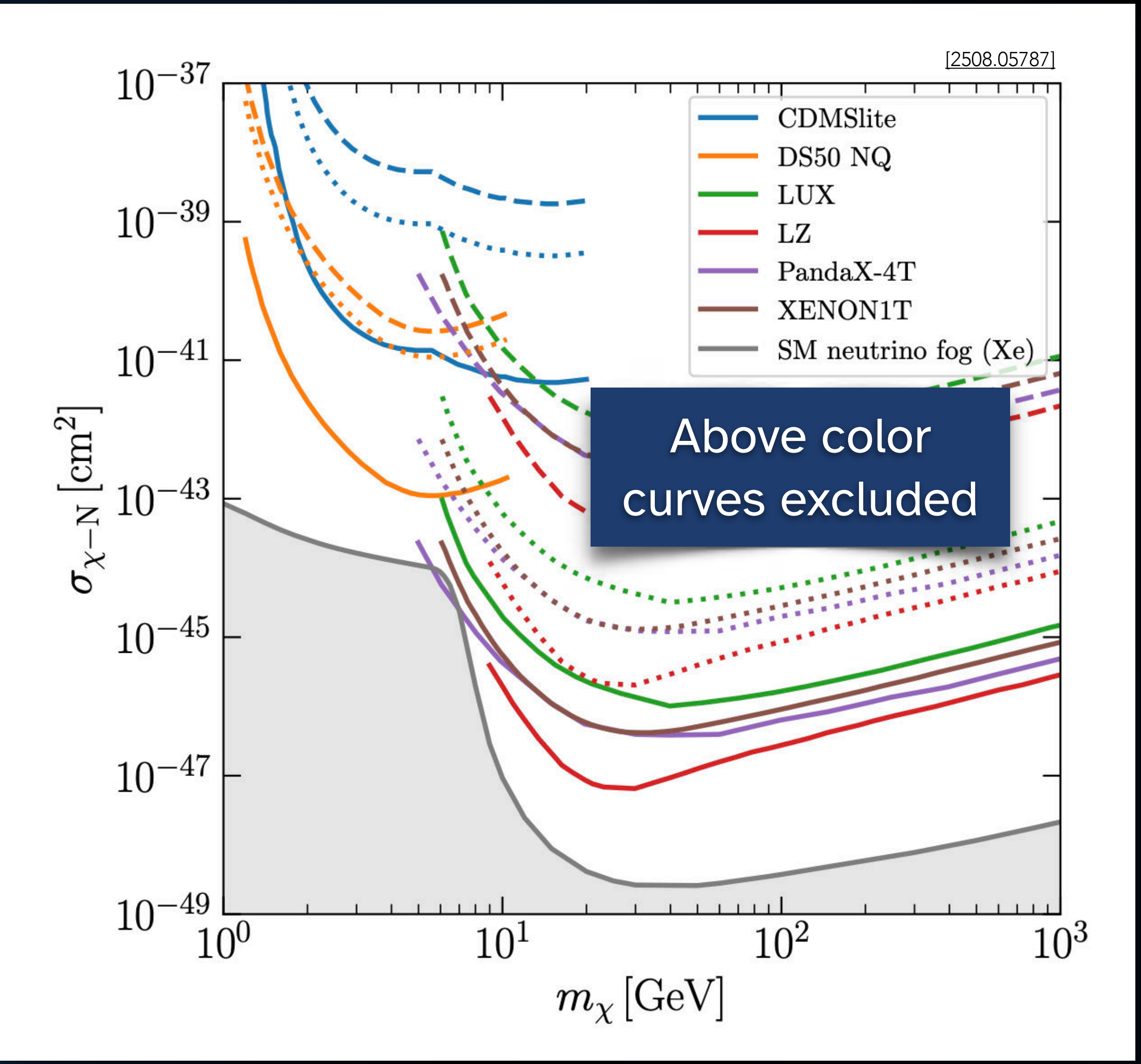

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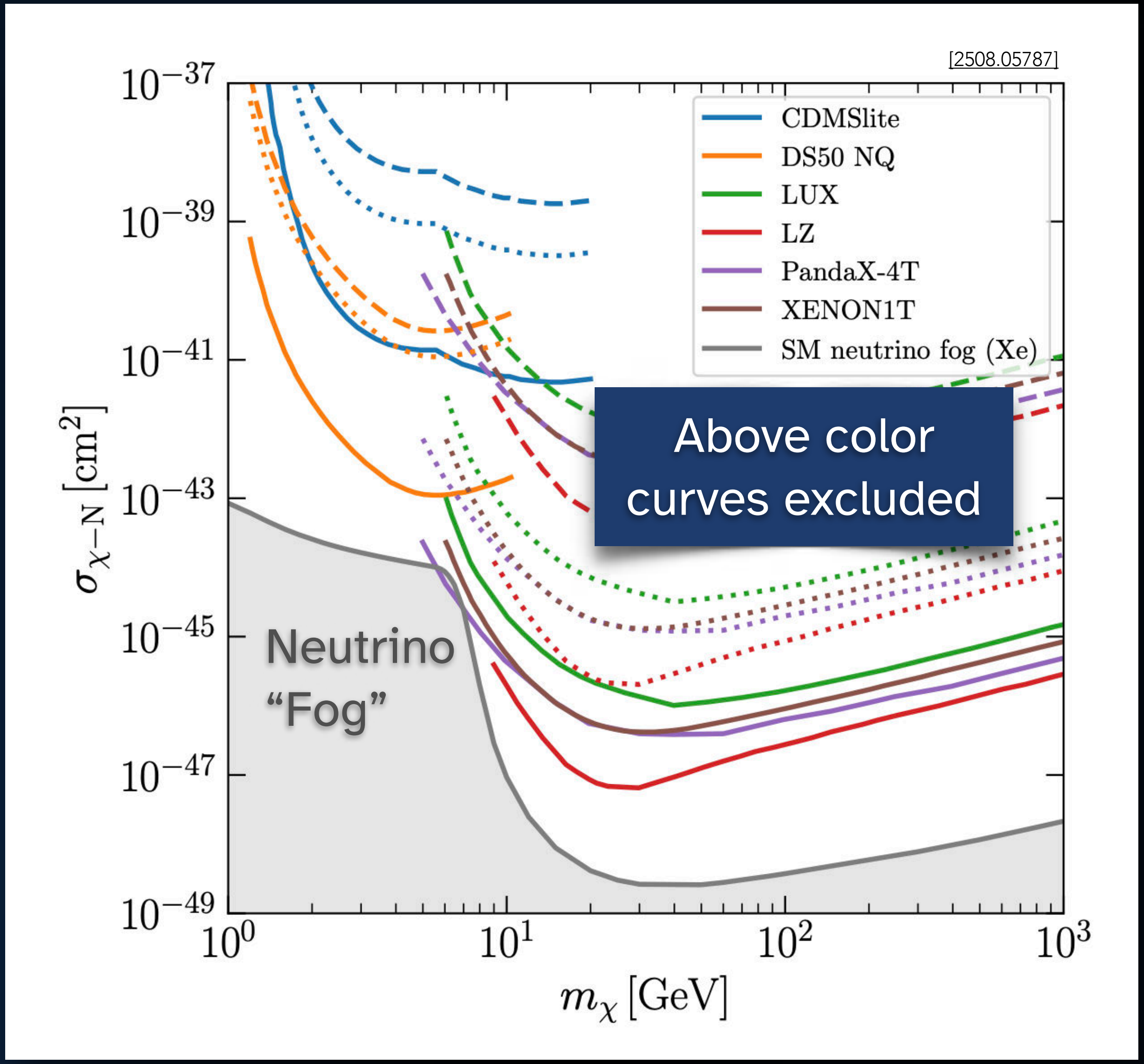

Solar and atmospheric neutrino interactions with experiment give irreducible background

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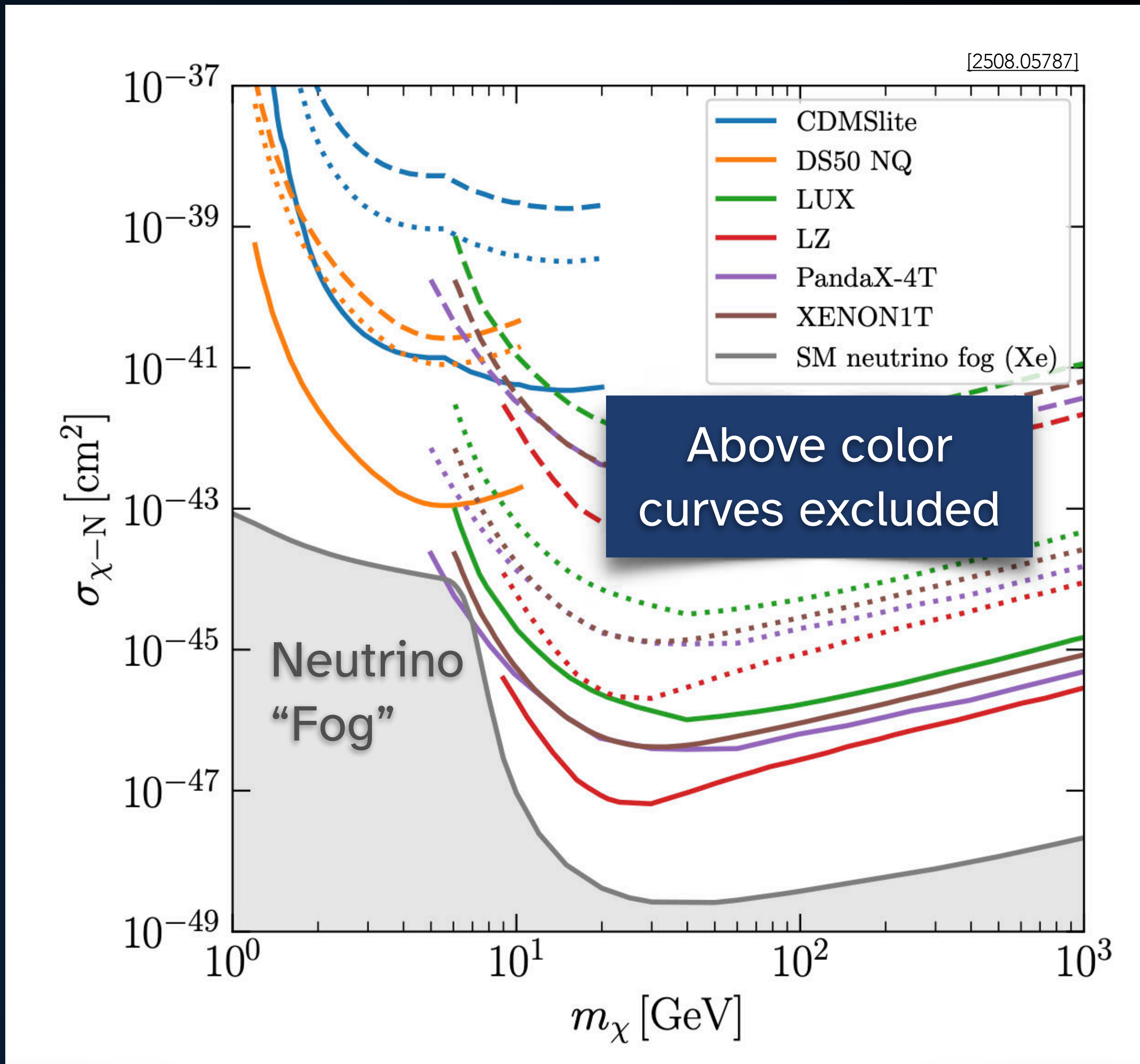
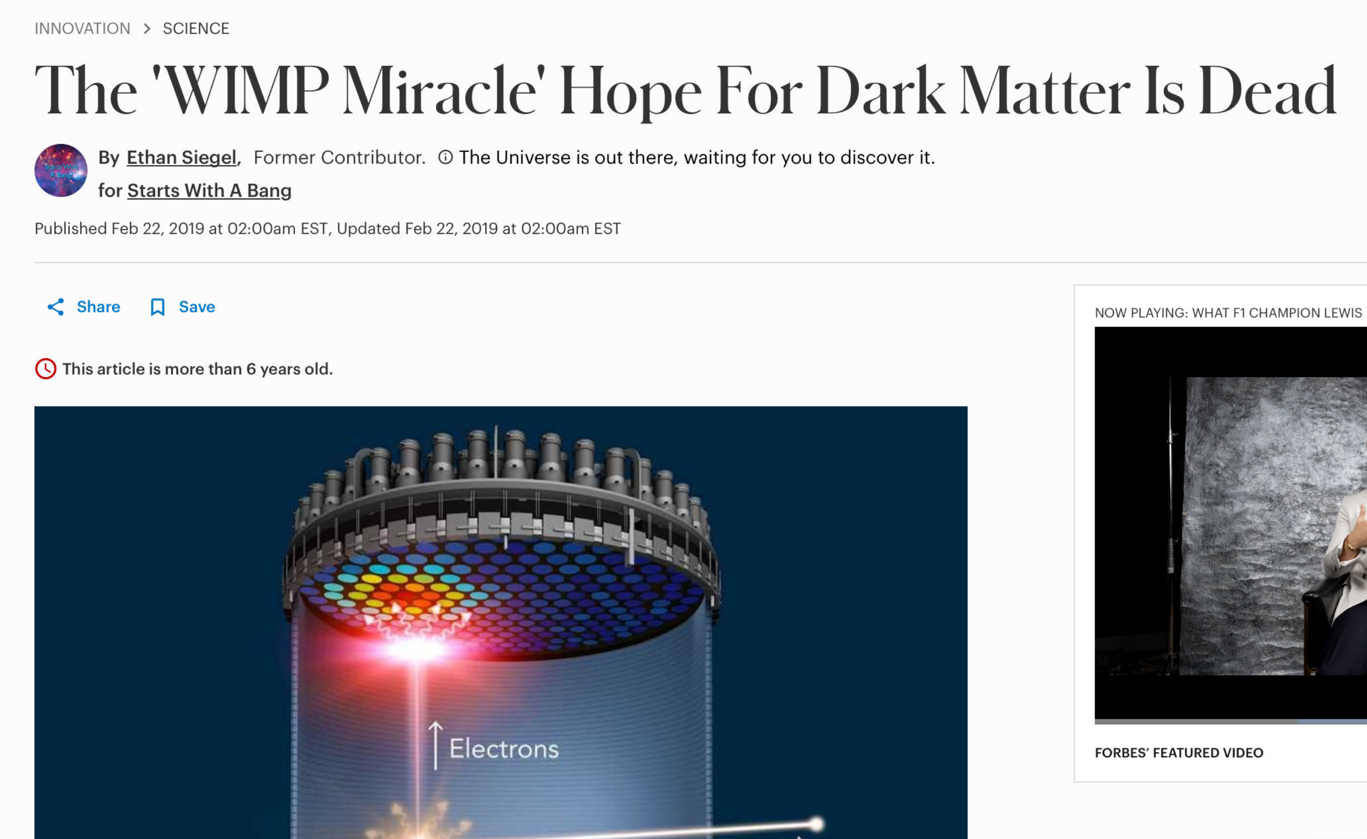


Solar and atmospheric neutrino interactions with experiment give irreducible background

And you may have heard that WIMPs are dead…



INNOVATION > SCIENCE

The 'WIMP Miracle' Hope For Dark Matter Is Dead

By Ethan Siegel, Former Contributor. ⓘ The Universe is out there, waiting for you to discover it.
for Starts With A Bang

Published Feb 22, 2019 at 02:00am EST, Updated Feb 22, 2019 at 02:00am EST

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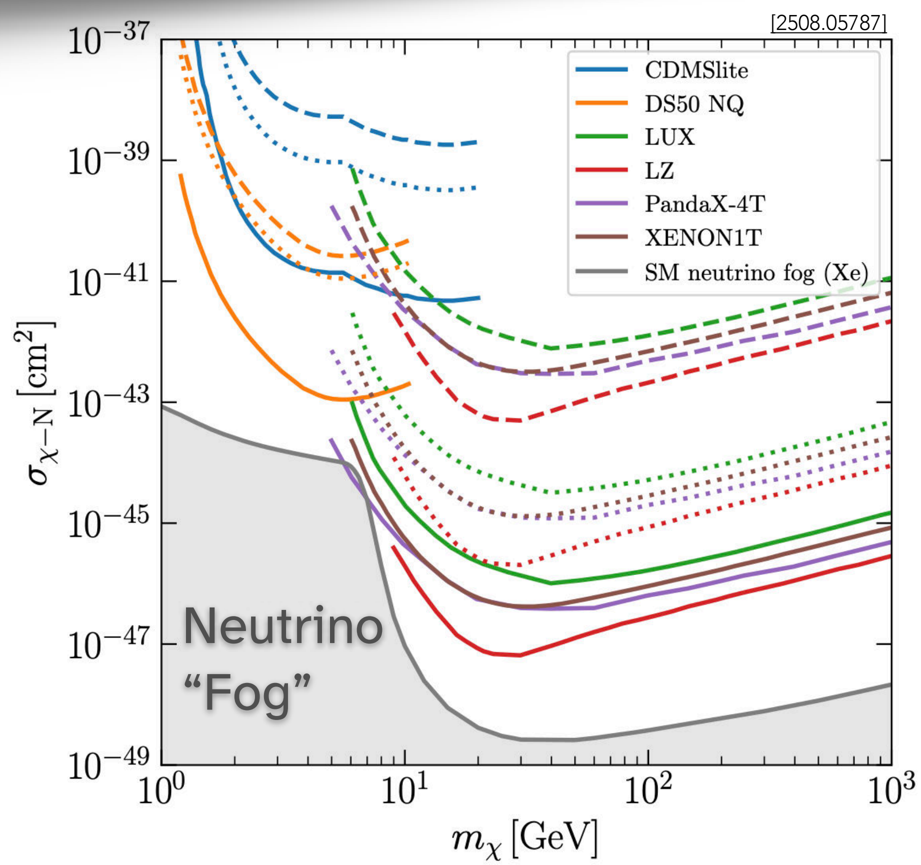
NOW PLAYING: WHAT F1 CHAMPION LEWIS

FORBES' FEATURED VIDEO

Actually WIMPs remain miraculous!
The **simplest** WIMP Dark Matter models **not yet** probed!



Actually…

- Write down **simplest electroweak doublet** addition to SM
- Calculate which mass gives you **observed amount of DM** produced in early universe…

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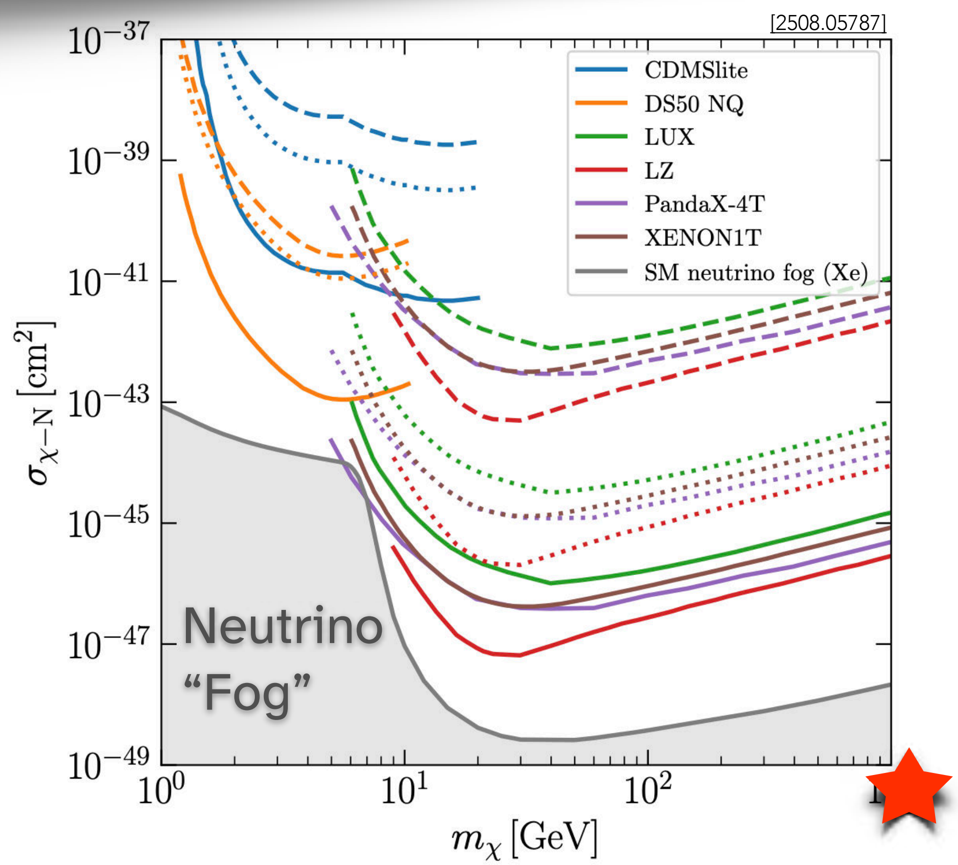

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10^{-49} cm^2, well below **Direct Detection** neutrino floor!
1.1 TeV, well beyond today's **collider** reach (~200 GeV)

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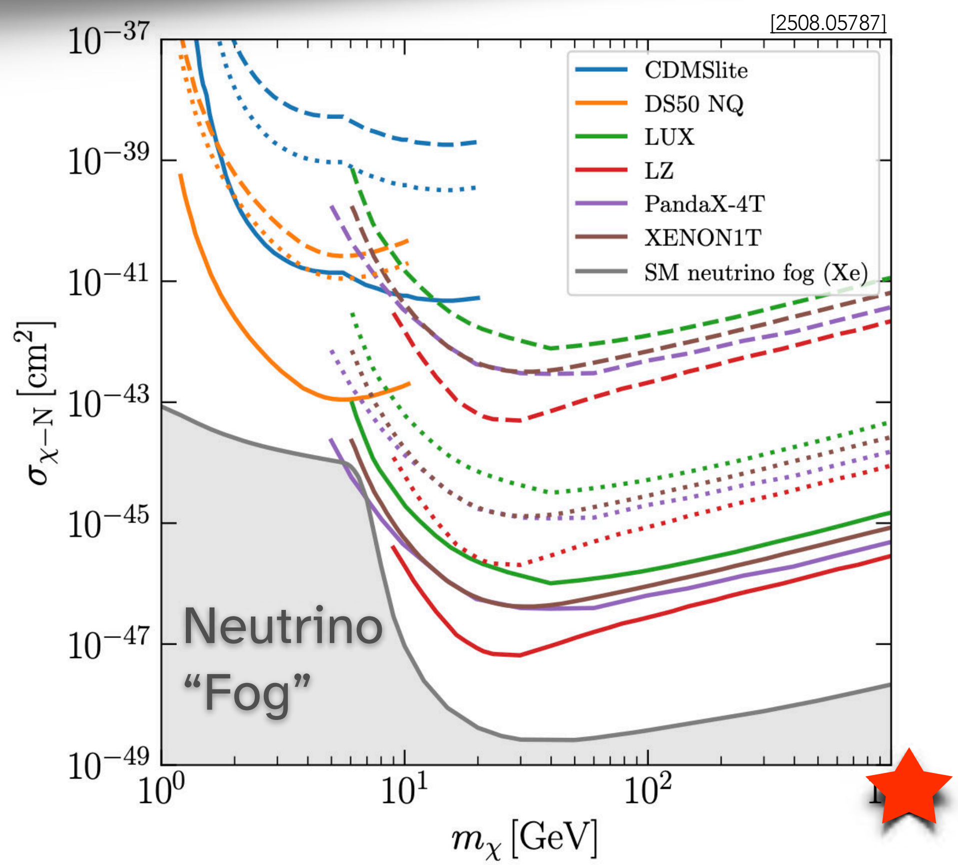

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A multi-TeV-scale collider would be sensitive to these WIMP-y thermal relics for the first time

e.g. 2405.08858
2102.11292
2009.11287
…

Why higher energies?

1) What does the Higgs potential look like + why
2) Are the simplest WIMP DM models are true?

Only the 10-TeV scale will tell us this!

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Motivations for going as high as possible?

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2) Are the simplest WIMP DM models are true?
3) Naturalness 🤫

Only the 10-TeV scale will tell us this!

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2) Are the simplest WIMP DM models are true?

3) Naturalness 🤫

Only the 10-TeV scale will tell us this!

Motivations for going as high as possible?

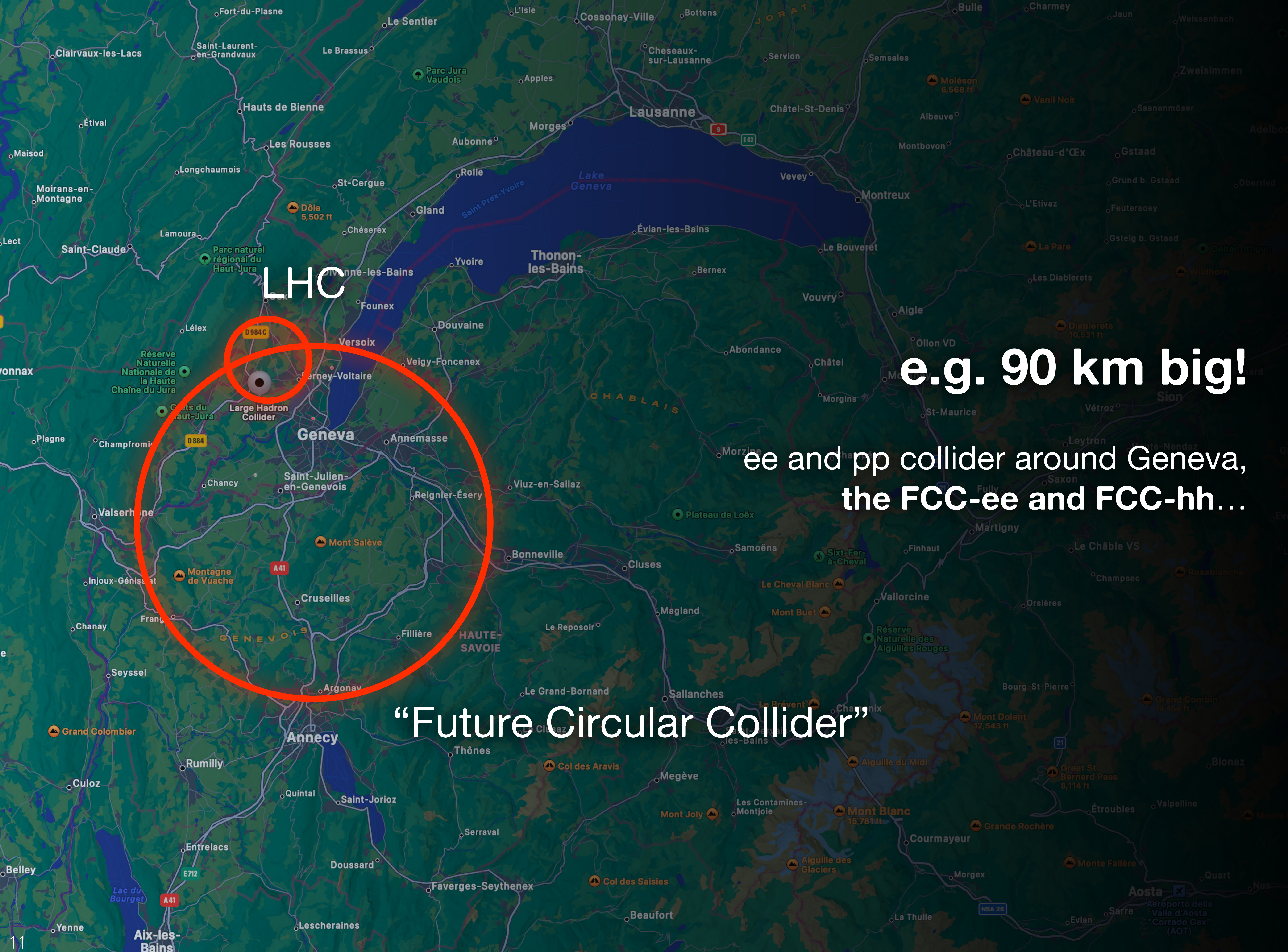
3) The humility to know that there must be something more to discover.

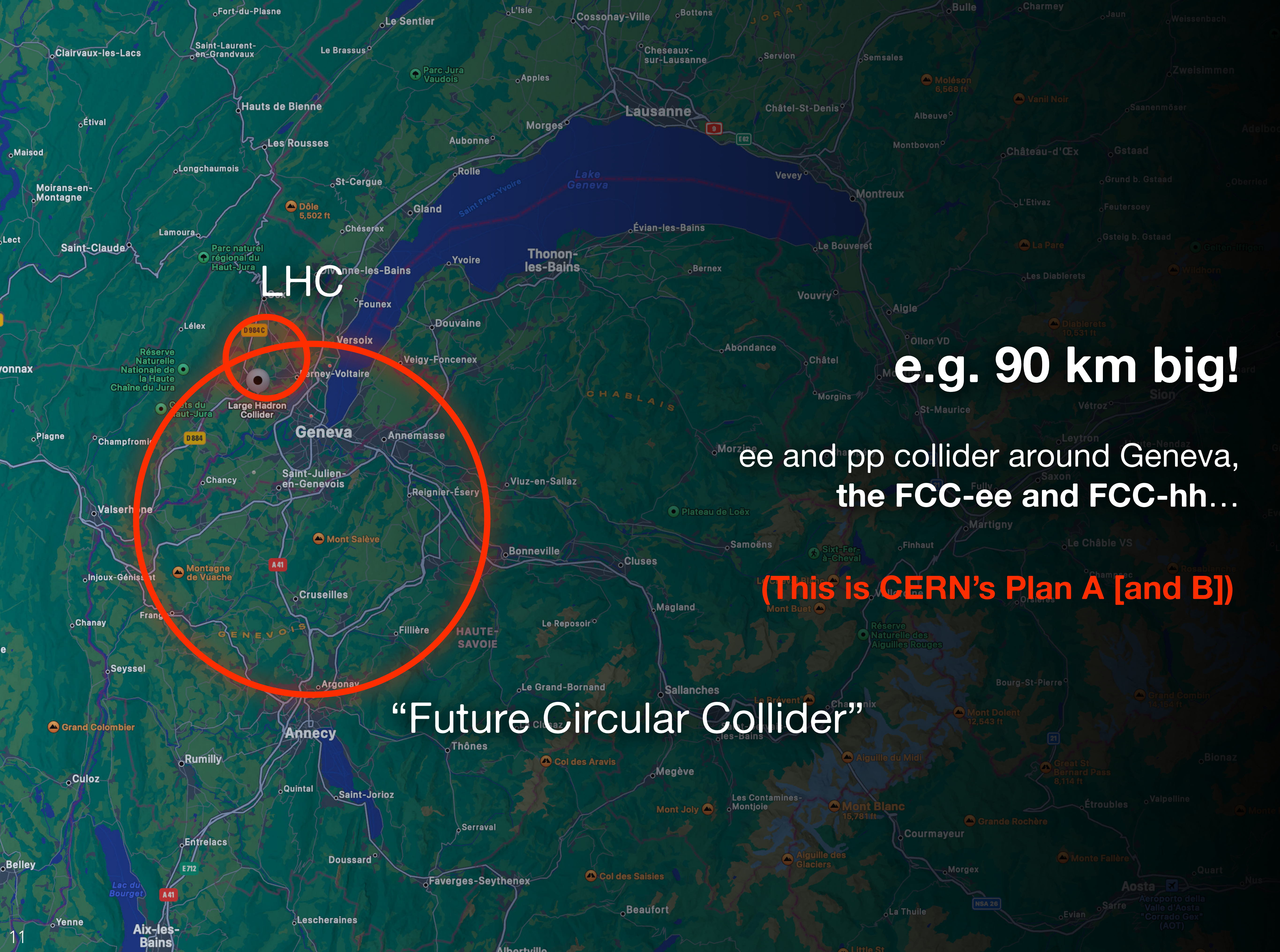
LHC is enormous

LHC is enormous

And we need to get to higher energy…

Temptation is often to “go big”


LHC
Large Hadron Collider
Geneva
e.g. 90 km big!
ee and pp collider around Geneva,
the FCC-ee and FCC-hh…
“Future Circular Collider”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(This is CERN's Plan A [and B])
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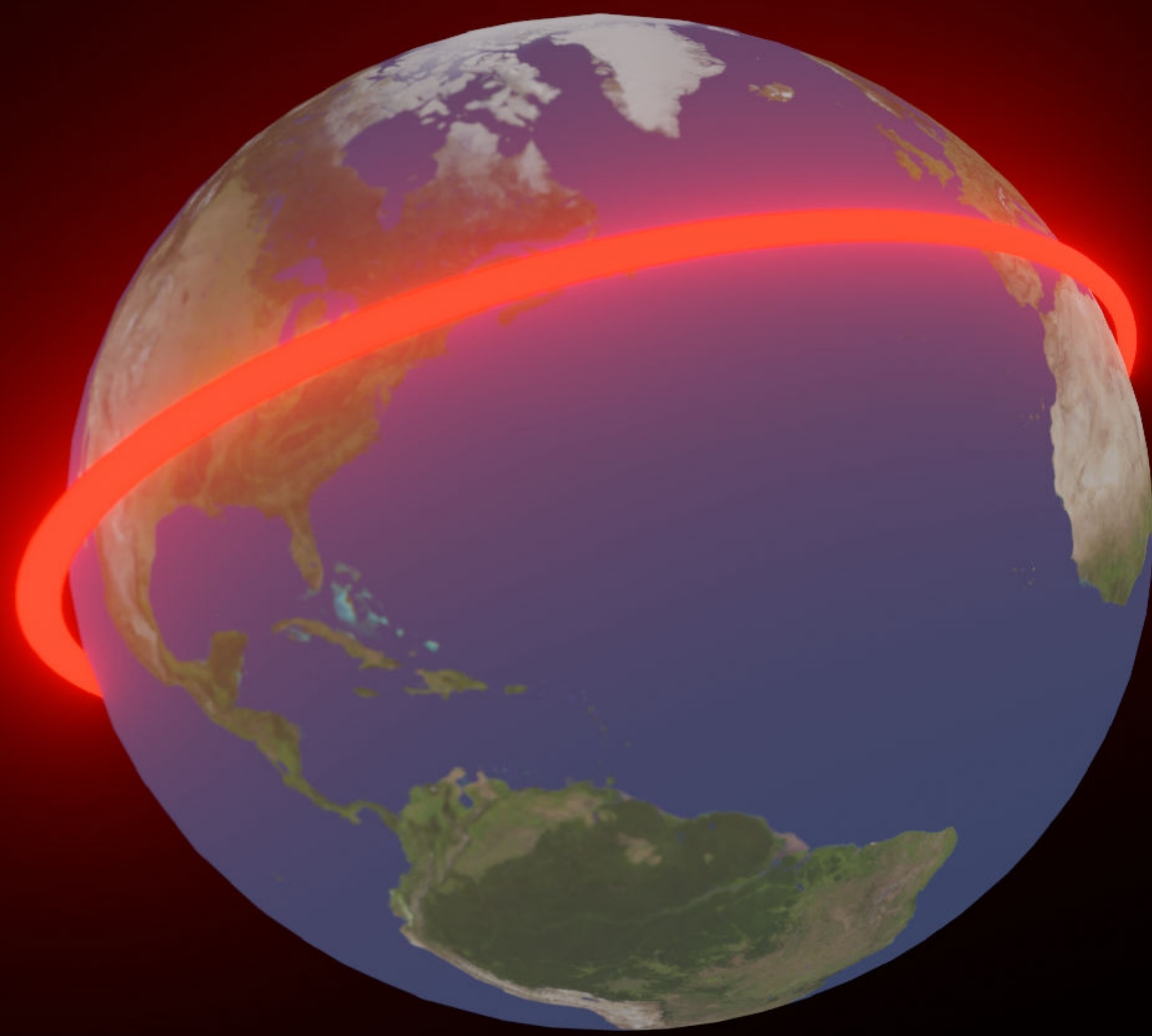
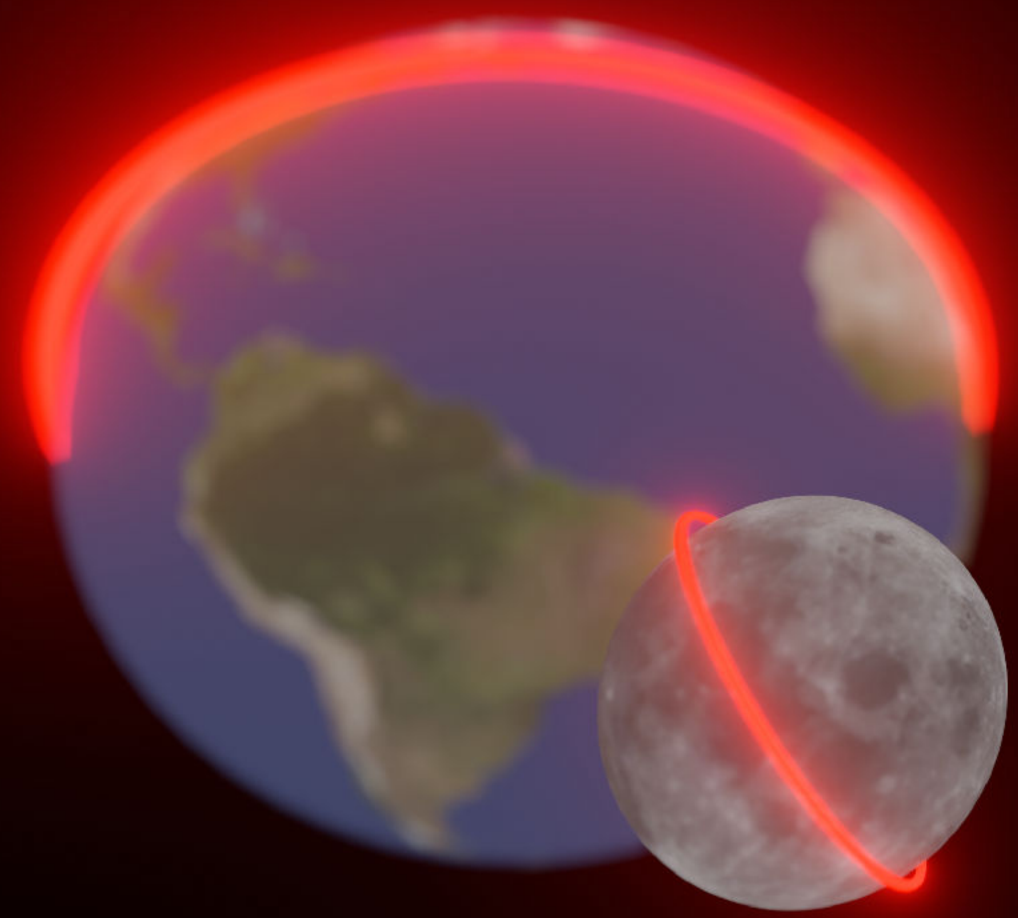


Fermi’s Globatron (1954)

Long history of proposals that are even more “romantic” than a 90 km tunnel.



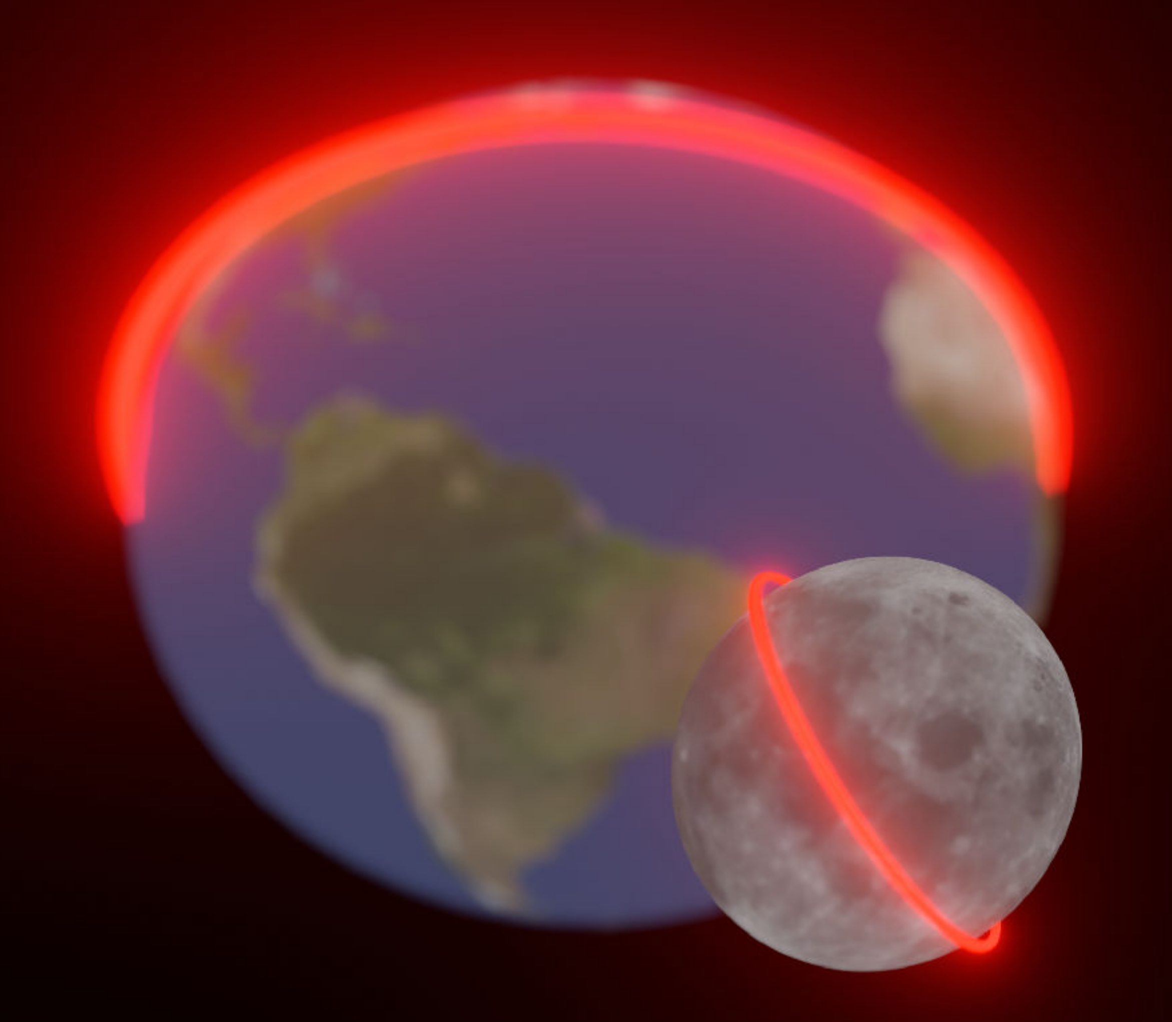
Fermi’s Globatron (1954)

Collider on the moon (2021)
[Again… Seriously… 2106.02048]

Literal Pipe Dreams…

But this is often our natural instinct when we start to dream!

Go Big!



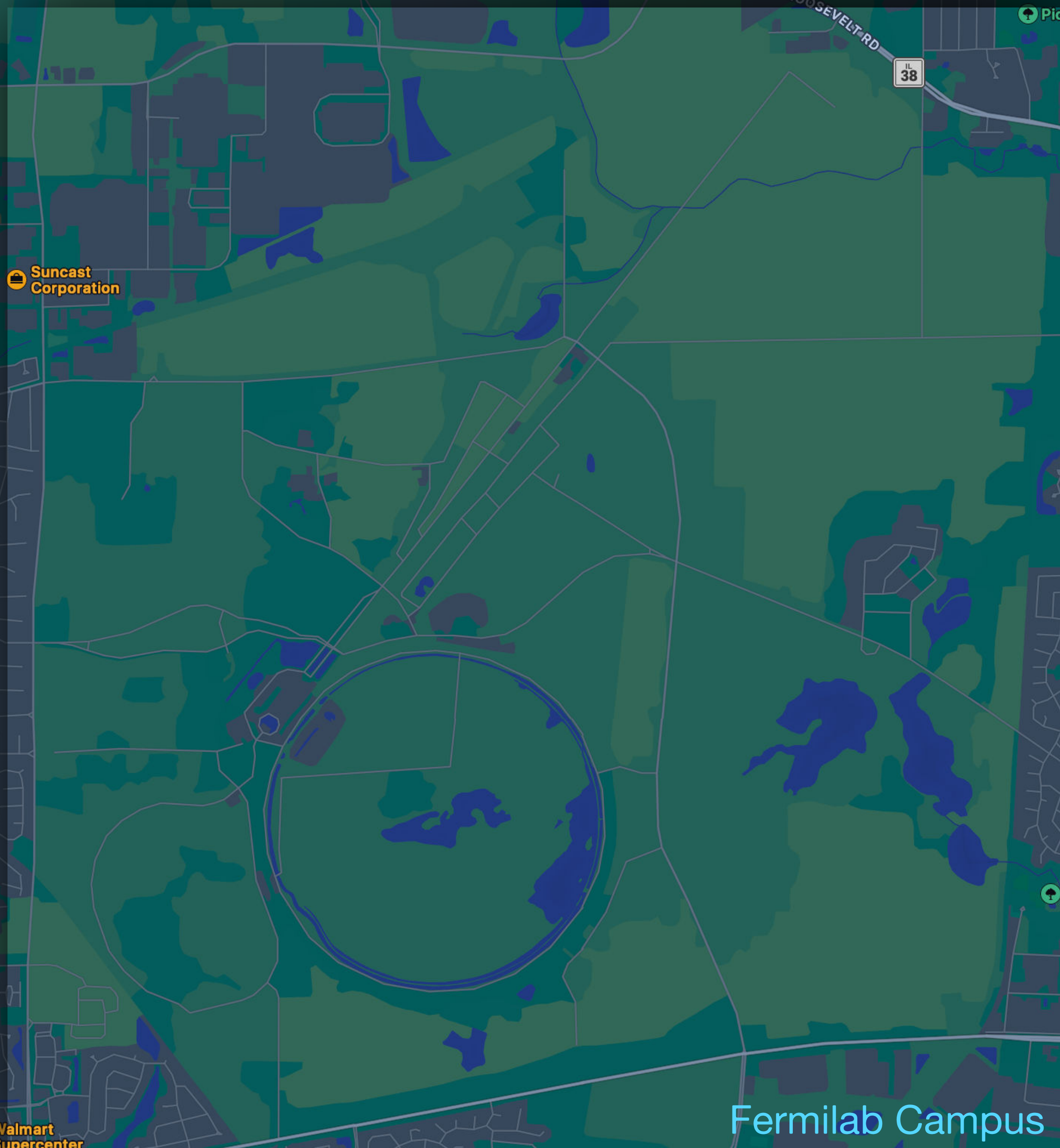
~~Go Big!~~

"Go Home"

Fermilab has a long history of particle physics leadership

Can we bring the highest energies back to US soil?

Fermilab



- **How to reach 10 TeV on American soil?**
- Focus on the electron's heavier cousin, the **muon μ**
- μ's are fundamental → 10 TeV μμ collider comparable w/ 100 TeV pp collider
- Since $m_\mu \gg m_e$, very low synchrotron losses. Get to much higher energies than ee machines
- μ are the only SM particle that can take us to 10 TeV **and beyond**

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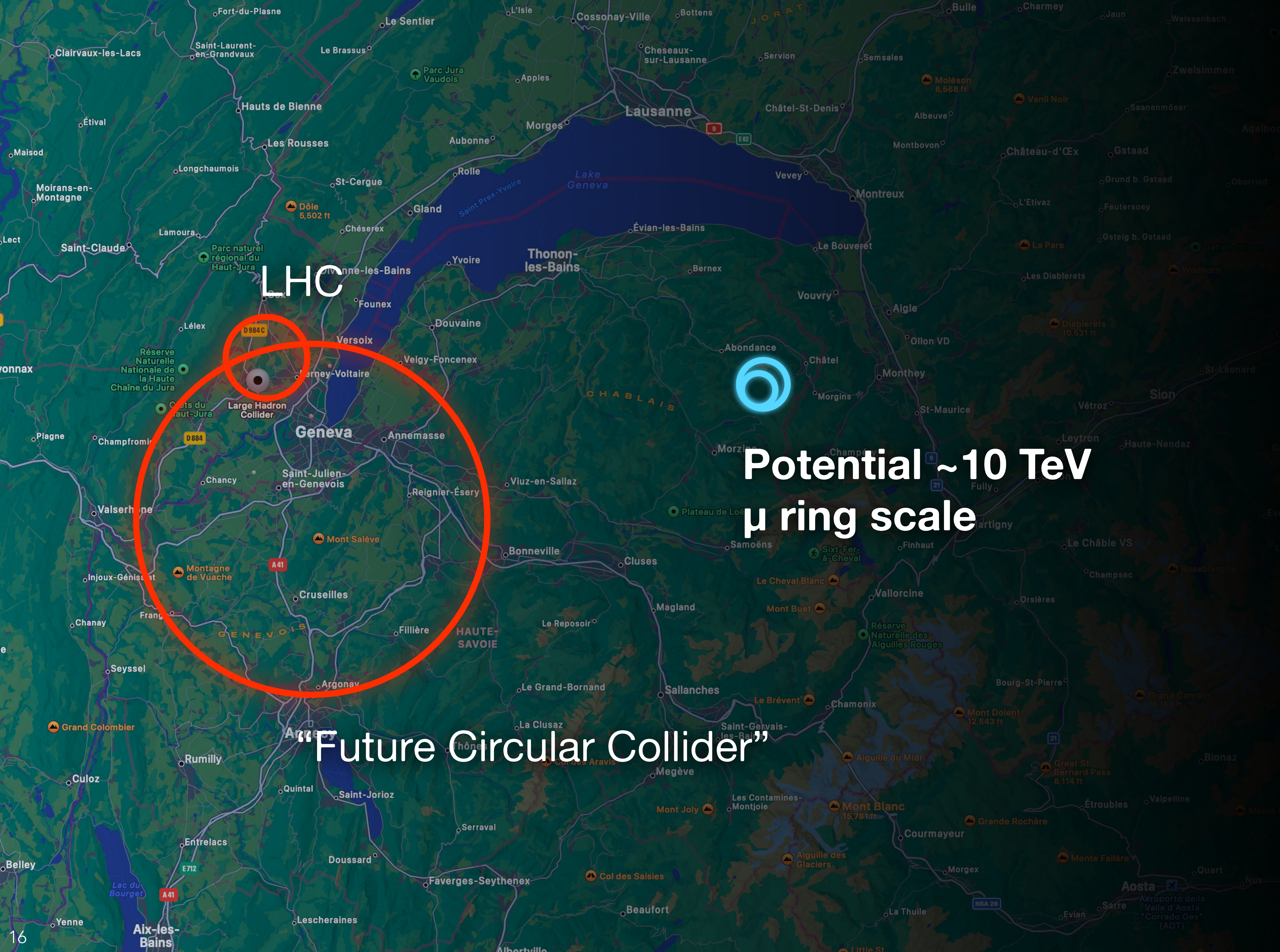
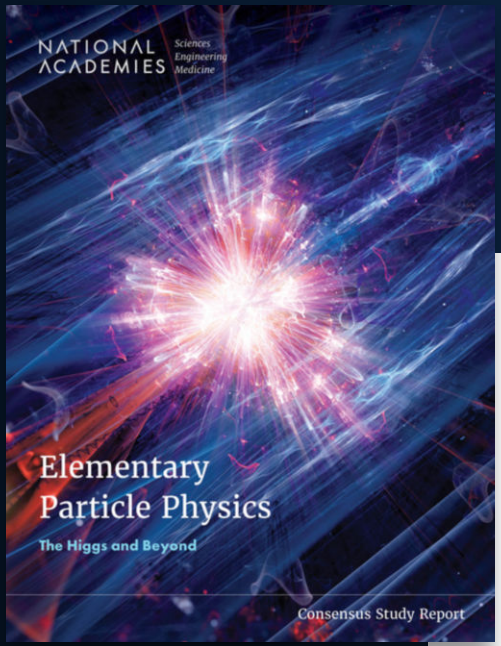
Fermilab campus could fit a ~10 TeV muon collider


LHC
Large Hadron Collider
Potential ~10 TeV
μ ring scale
“Future Circular Collider”
Lausanne
Lake Geneva
Geneva
Annemasse
Thonon-les-Bains
Évian-les-Bains
Montreux
Vevey
Morges
Gland
Nyon
Versoix
Ferney-Voltaire
Saint-Julien-en-Genevois
Mont Salève
Cruseilles
Bonneville
Cluses
Sallanches
Chamonix
Mont Blanc
Megève
Annecy
Aosta
Sion
Aigle
Monthey
HAUTE-SAVOIE
CHABLAIS
GENEVOIS

Strong push from Particle Physics planning exercise (P5, Dec '23)

Although we do not know if a muon collider is ultimately feasible, the road toward it leads from current Fermilab strengths and capabilities to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. This is our Muon Shot.

Exploring the Quantum Universe



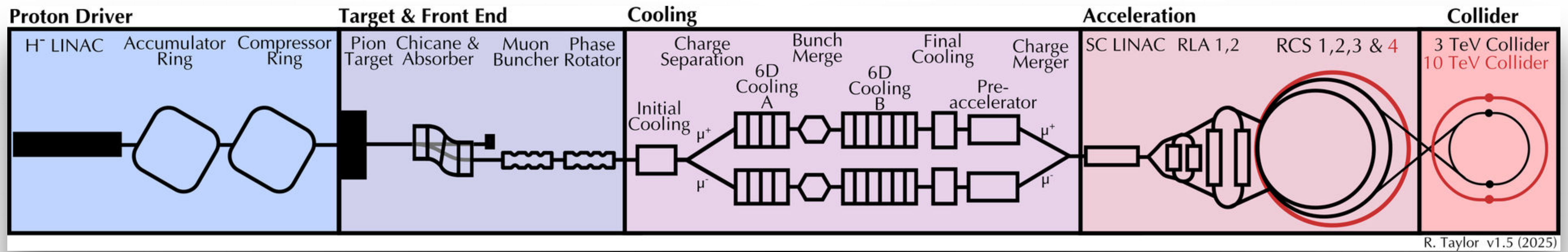
RECOMMENDATIONS

Recommendation 1: The United States should host the world's highest-energy elementary particle collider around the middle of the century. This requires the immediate creation of a national muon collider research and development program to enable the construction of a demonstrator of the key new technologies and their integration.

A collider with approximately 10 times the energy of the Large Hadron Collider (LHC) is crucial for addressing the big questions of particle physics and making discoveries. A 10-TeV muon collider on the Fermi National Accelerator Laboratory (Fermilab) site would have similar discovery reach as a 100-TeV proton collider. A muon collider combines the physics advantages of an electron-positron and a proton-proton collider, with a much smaller size. A machine that collides unstable elementary particles has never been attempted before and requires significant research and development (R&D), international coordination, and a demonstrator project to establish its feasibility. Developing a U.S.-hosted muon collider—an unprecedented machine requiring considerable research, development, and a feasibility demonstrator—would solidify U.S. leadership in particle physics and drive accelerator innovation. The "middle of the century" timeline reflects the project's inherent complexities, which are elaborated in Chapter 2, and underscores the need for global coordination.

And recent NAS panel (June '25)

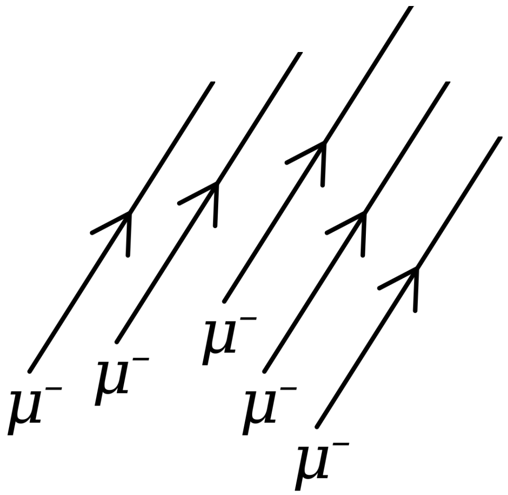
Muon Colliders are a national priority.



Overly simplified:

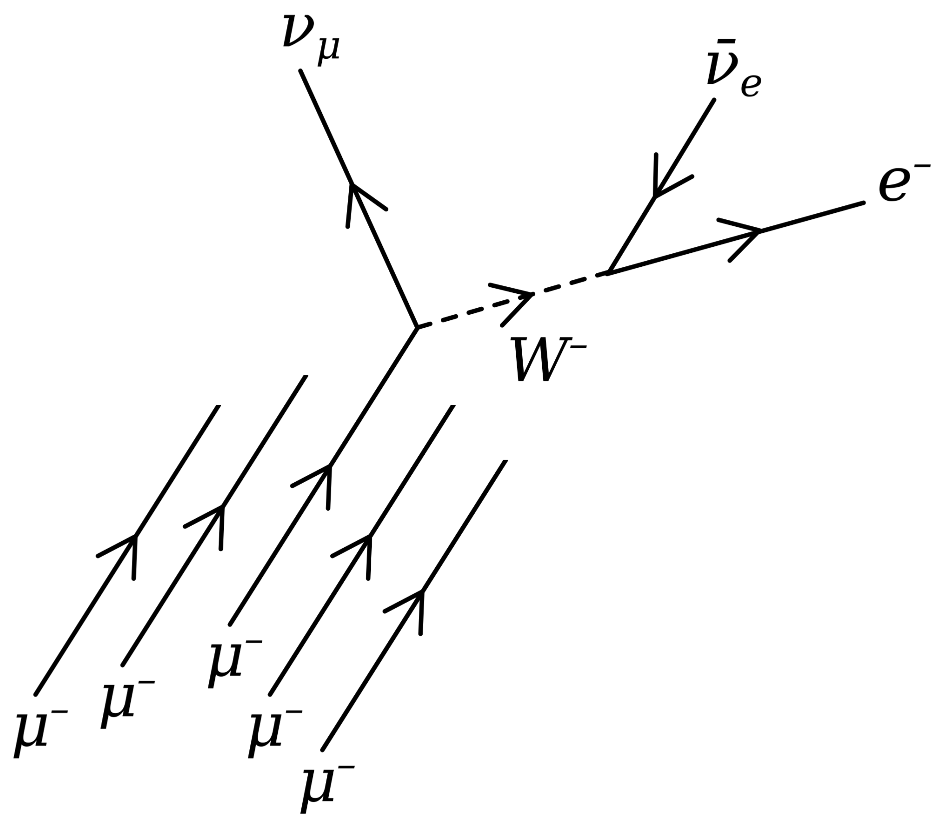
- O(1) **MW** beam of **protons** on **target**
- Intense pion production → **Capture** diffuse muon decay products
- “**Cool**” the muon beam. Reduce phase-space volume of beam
- **Accelerate, Collide, Measure**

Muon Beams



Muon Beams Decay

$\tau_\mu \approx 2\ \mu s$



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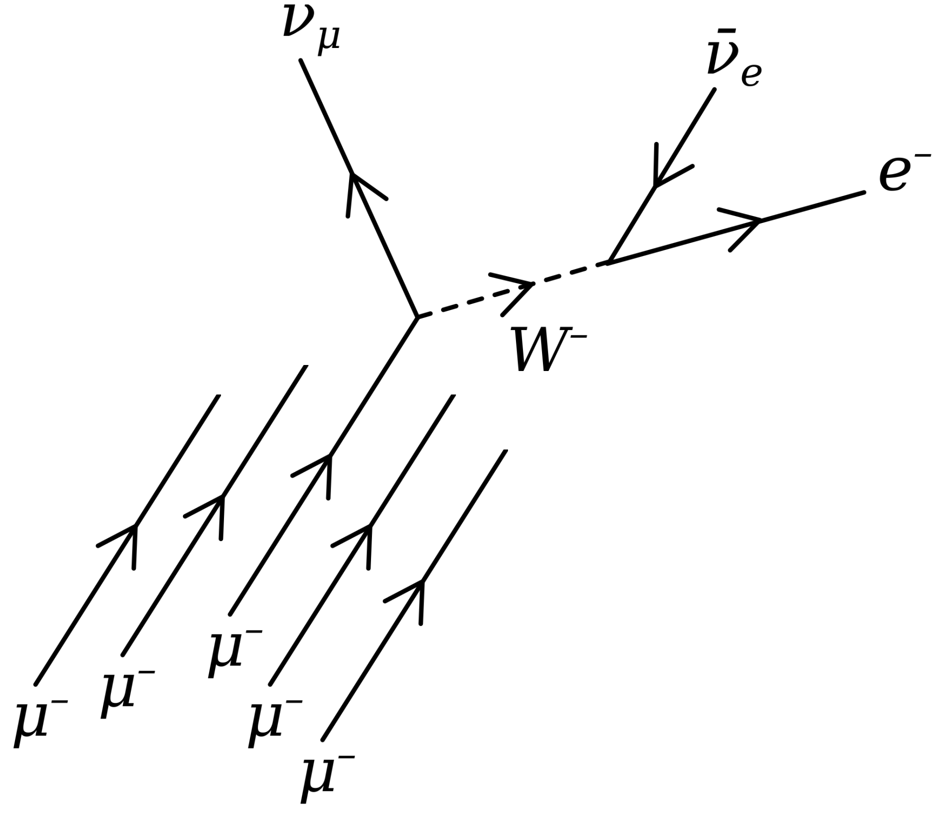
Boost the hell out of them.

At 5 TeV, $\gamma = 50000$,

$\tau_{lab} \approx 100\ ms$



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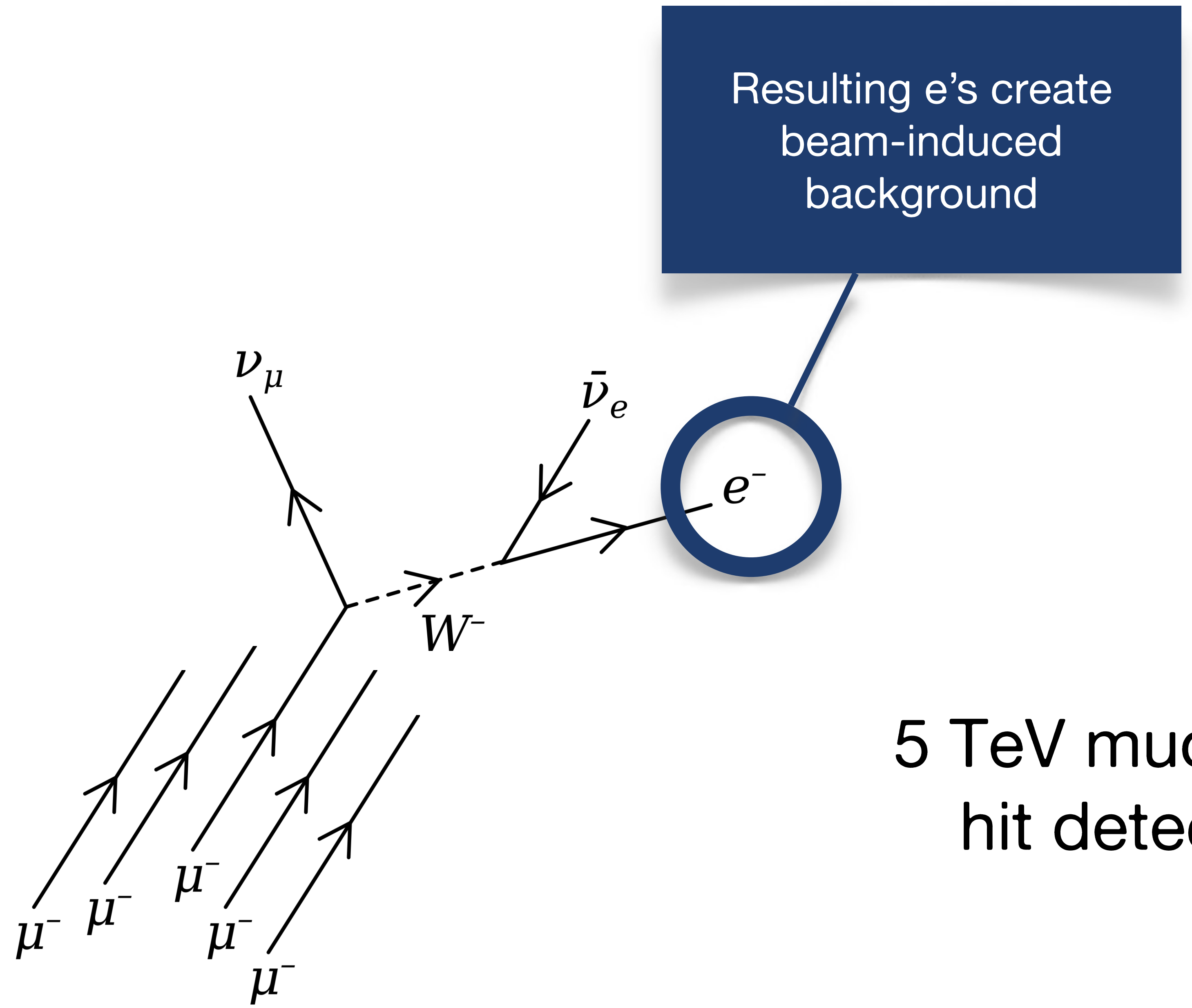

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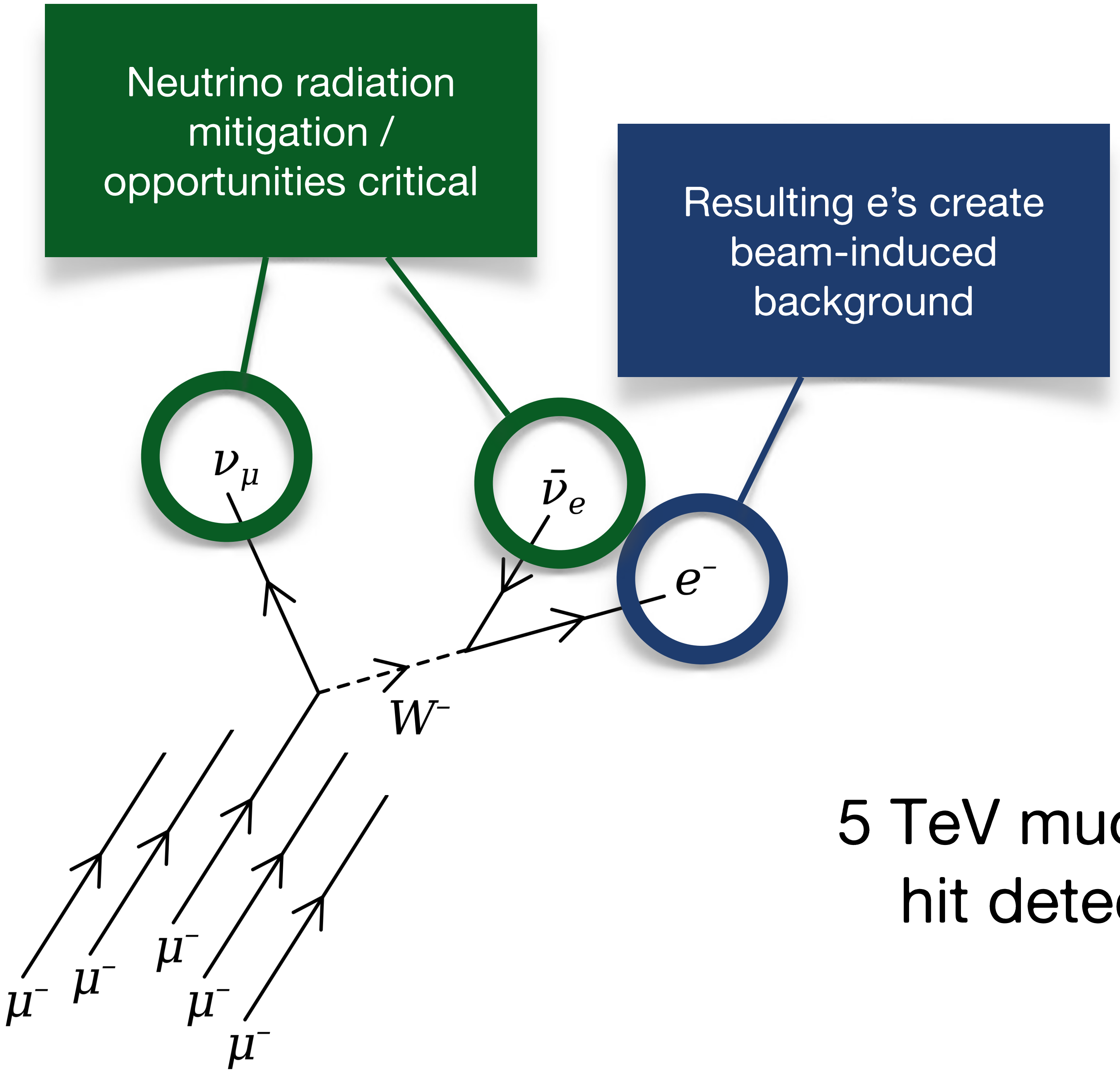

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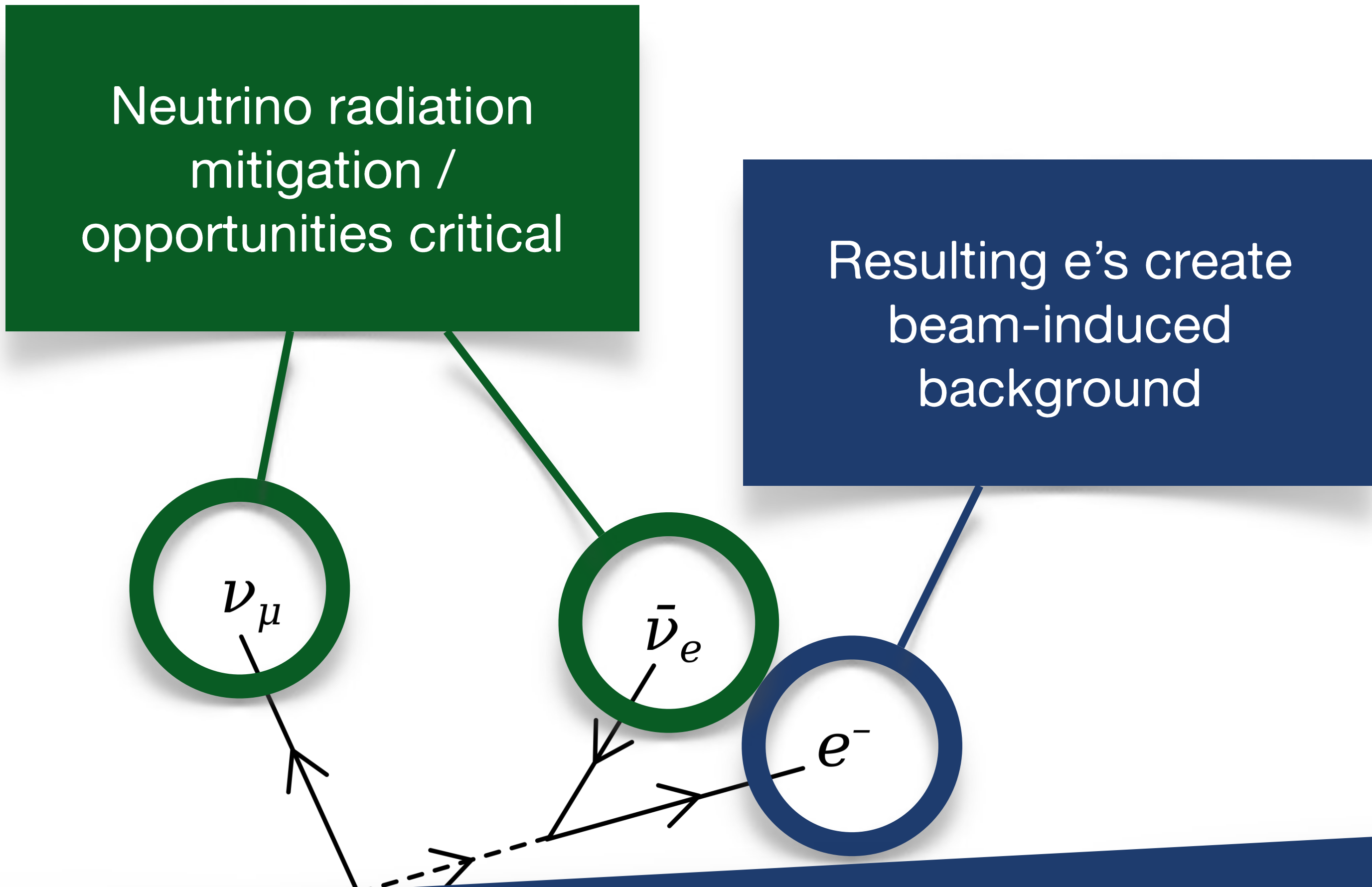

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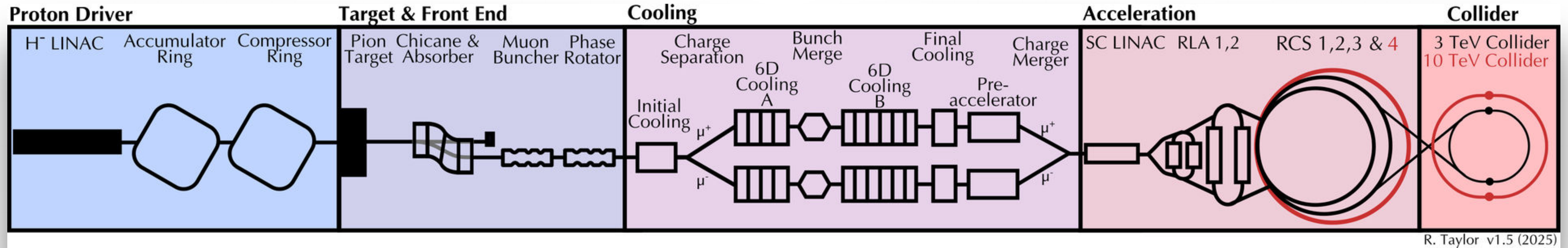
Everything has to be:

Done very quickly
Shielded and radiation hard

Almost all μC challenges are due to this short lifetime



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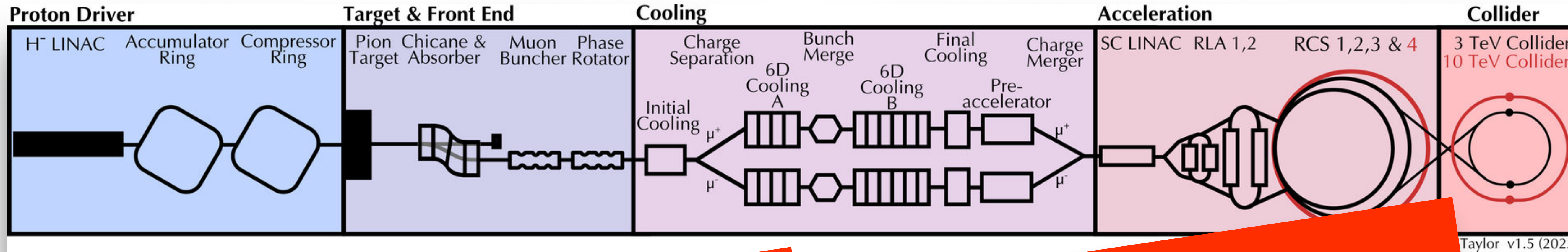

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EXTREME SPACE CHARGE

NEW TARGET TECH NEEDED

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RF IN 20T IN HIGH RADIATION ENV

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WTF 10^{-6} VOLUME REDUCTION

40T MAGNETS!?

!!!!!!

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FAST RAMPING MAGNETS (~10 T/ms)

20T MAGNETS GALORE

LARGE EXP BACKGROUNDS

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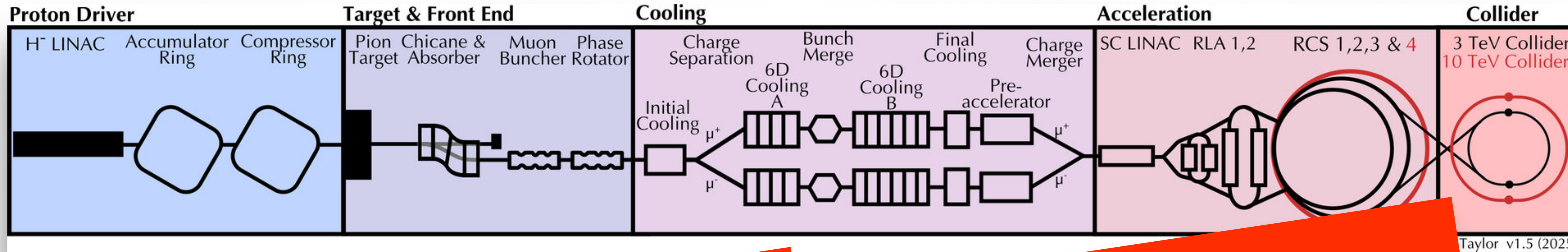

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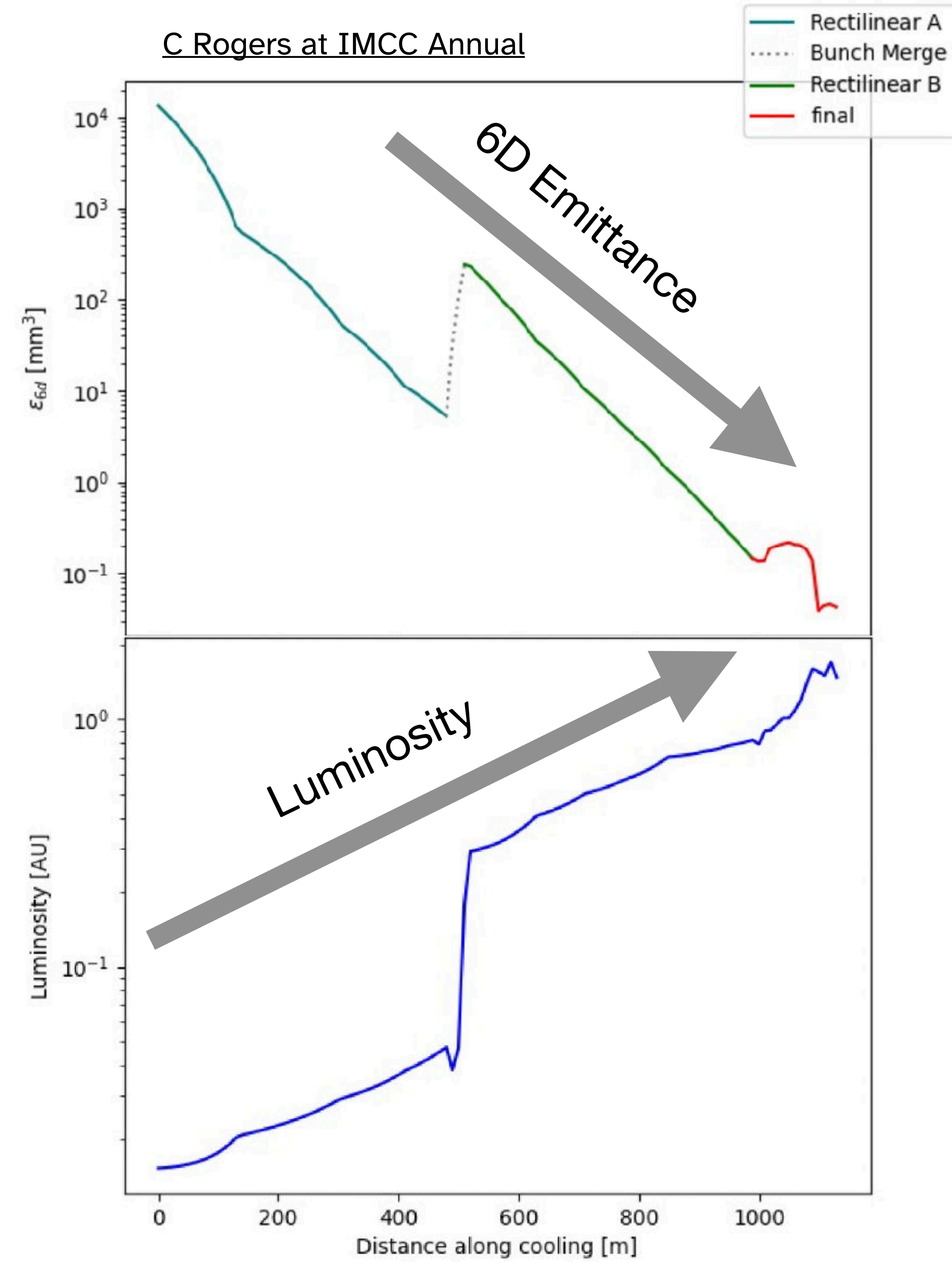
Muon Cooling

- Muons produced this way have **huge phase-space volume,** large 6D "emittance"
- High luminosity requires **emittance reduction of 10^{-6}**
- Liouville's theorem: Reducing phase-space volumes requires **nonconservative process**
    - Remove energy from system → **"Cooling"**



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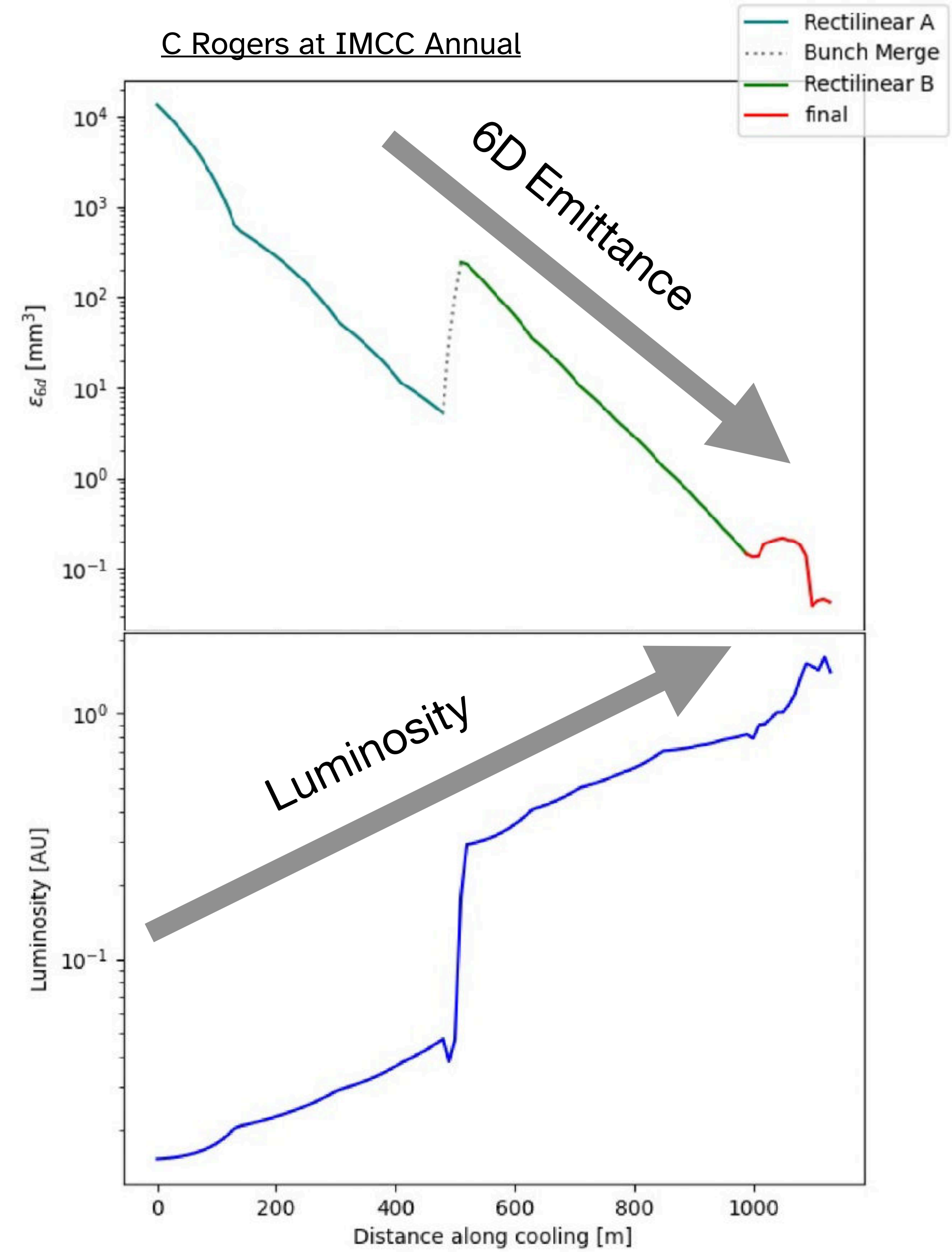
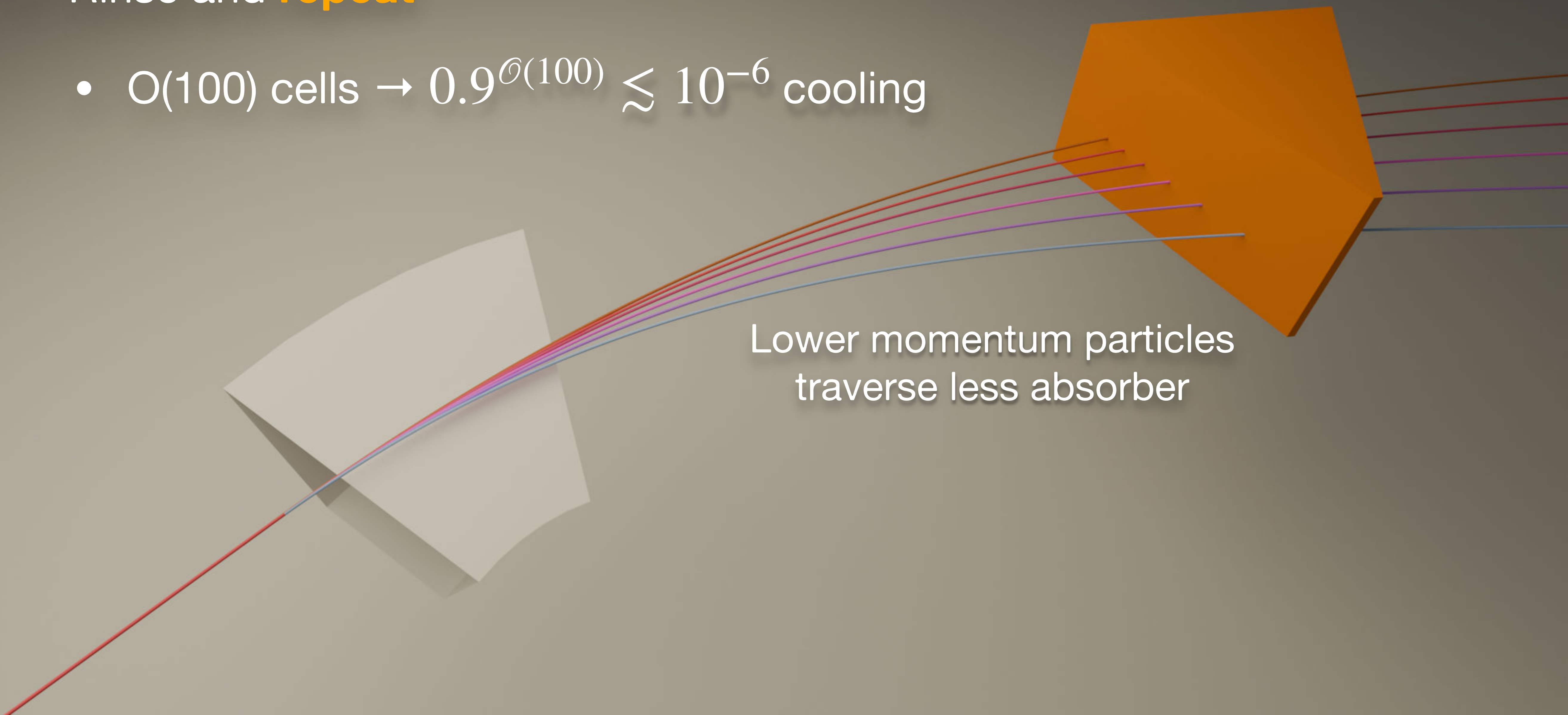
C Rogers at IMCC Annual



- Cool quickly with ionization energy loss in absorbers
- After absorber, beam lower energy w/ **smaller phase-space volume**
  - ~10% emittance reduction per cell
- **RF cavities** restores the **longitudinal** momentum
- Rinse and **repeat**
  - O(100) cells → $0.9^{\mathcal{O}(100)} \lesssim 10^{-6}$ cooling



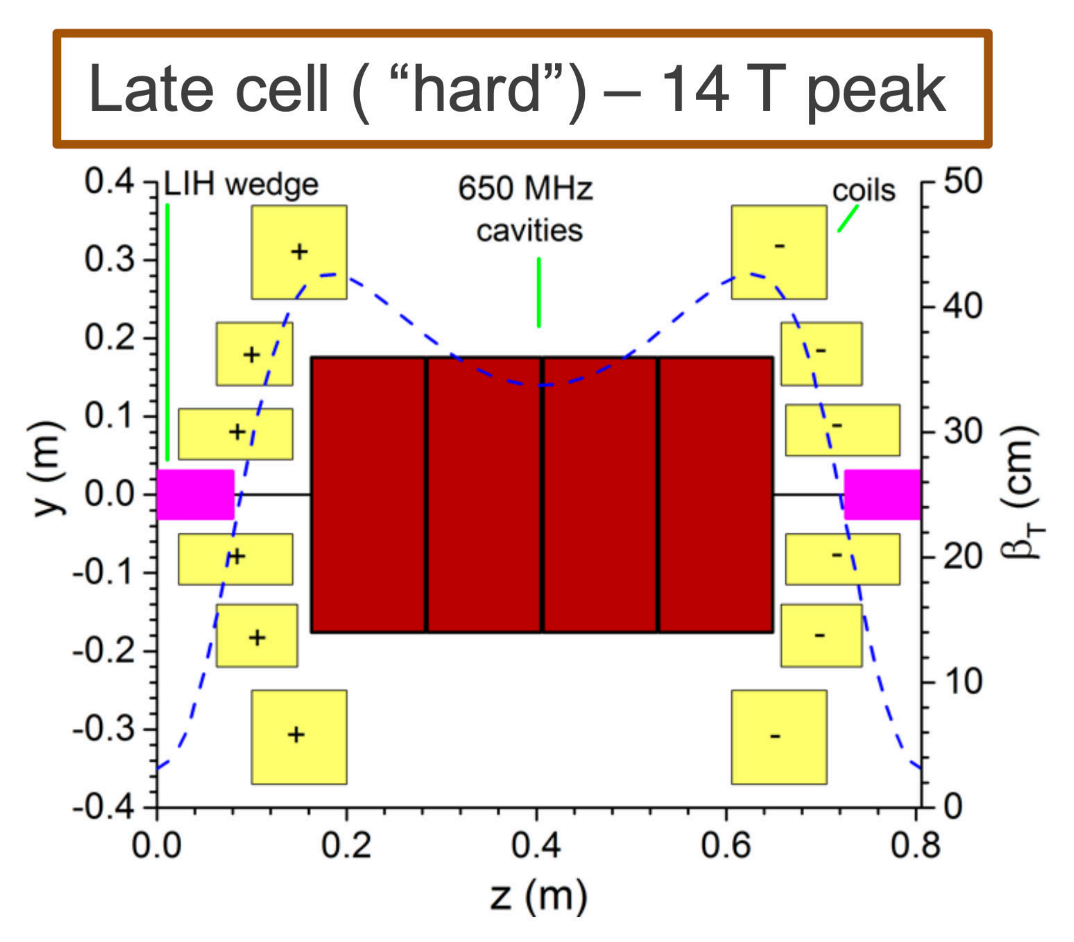
Rinse & Repeat model isn't so simple

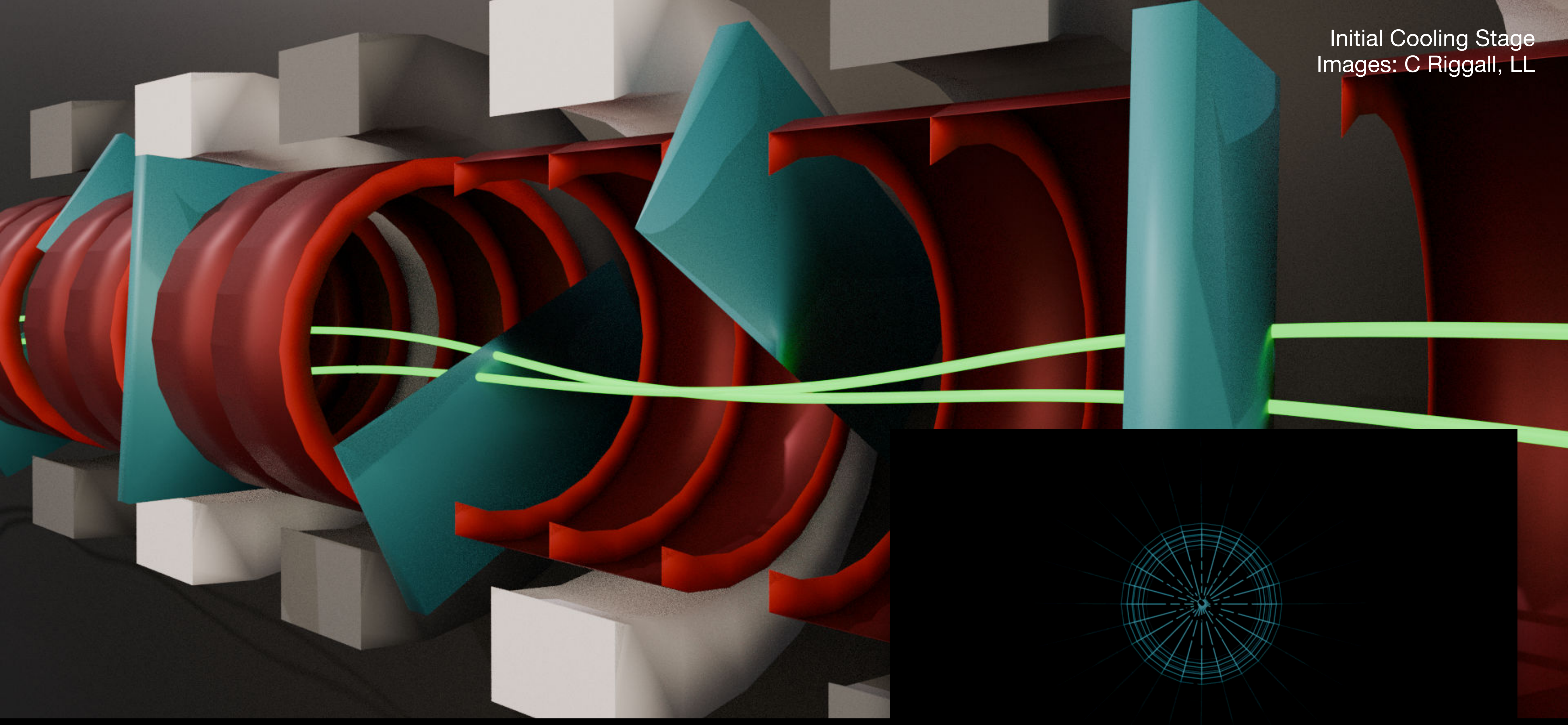
Late stage cooling cells much more challenging to build
(14T, ≥30T, RF)

Don't need a "proof of concept" to believe in ionization energy loss

Need a **"proof of engineering"** demonstration

Need to demonstrate that channel can be physically constructed!



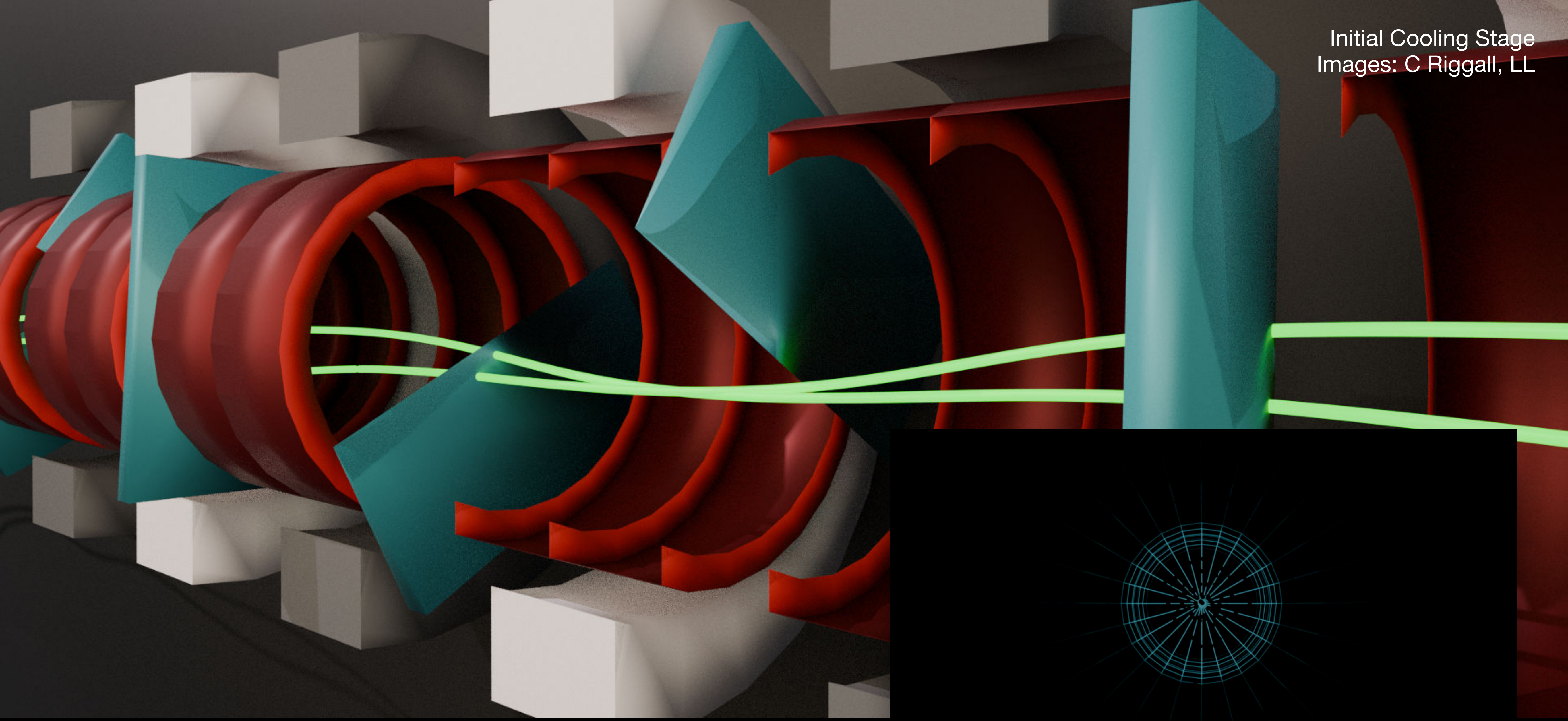


Current initial cooling stage has **900 free parameters**

(Applying strict constraints reduces to “only” ~50 parameters)

Effectively impossible to really optimize by hand.

Ionization processes: Stuck with sampled MC methods?
→ Multiple talks on differentiable methods



Initial Cooling Stage
Images: C Riggall, LL

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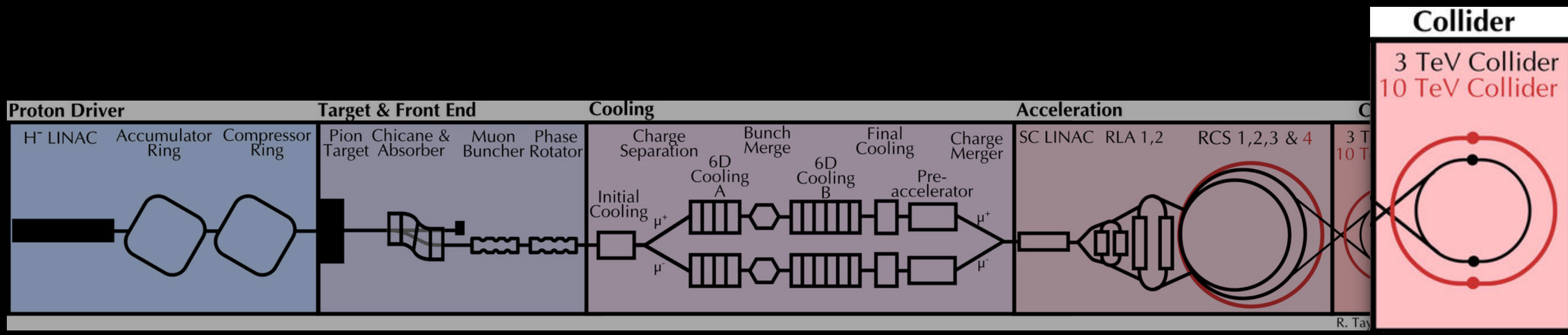
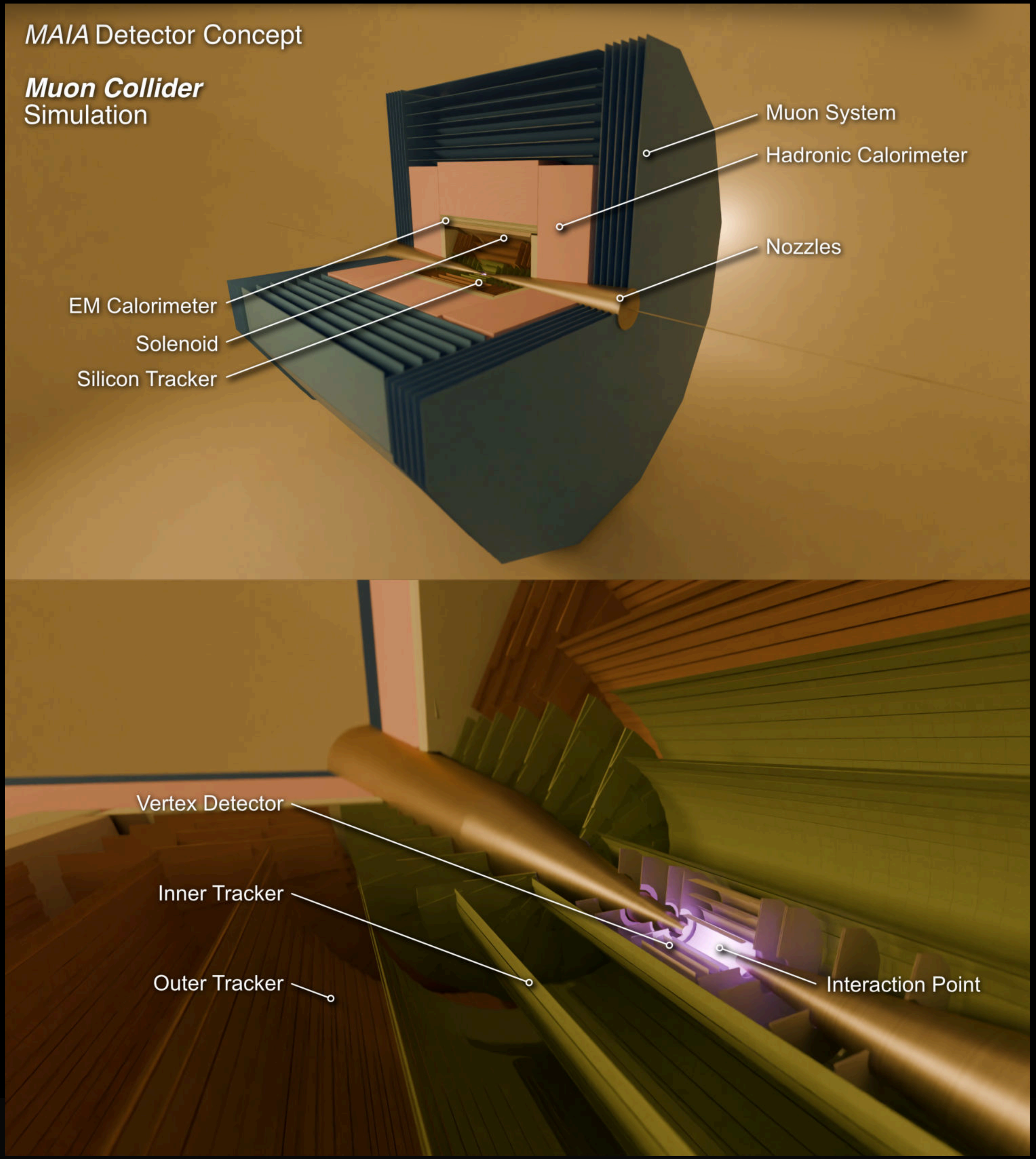


- Ongoing work to characterize the physics performance of **MAIA and MUSIC** detector concepts
- Major challenges:
  - Multi-TeV objects
  - Huge backgrounds from μ decays controlled with
    - Shielding
    - Timing resolution
    - Shape/angle discrimination
- Dense Tungsten Nozzle Shields to protect from TeV-scale electrons from beam μ decays



[2502.00181]

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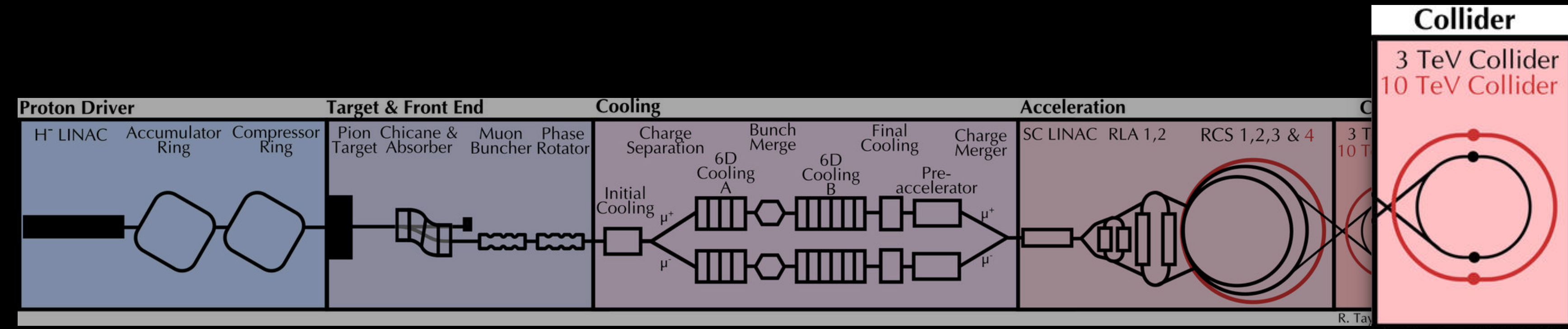

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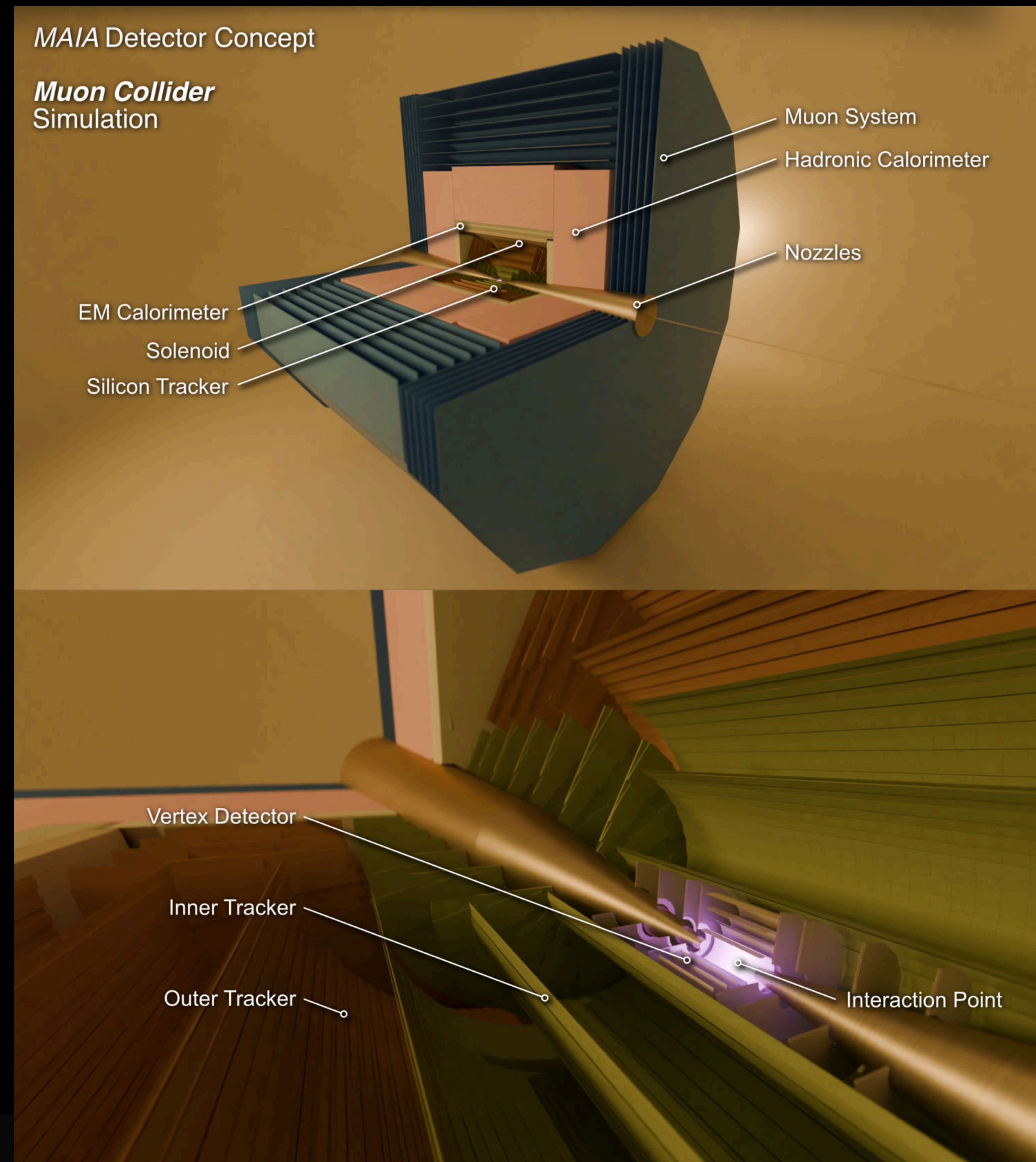

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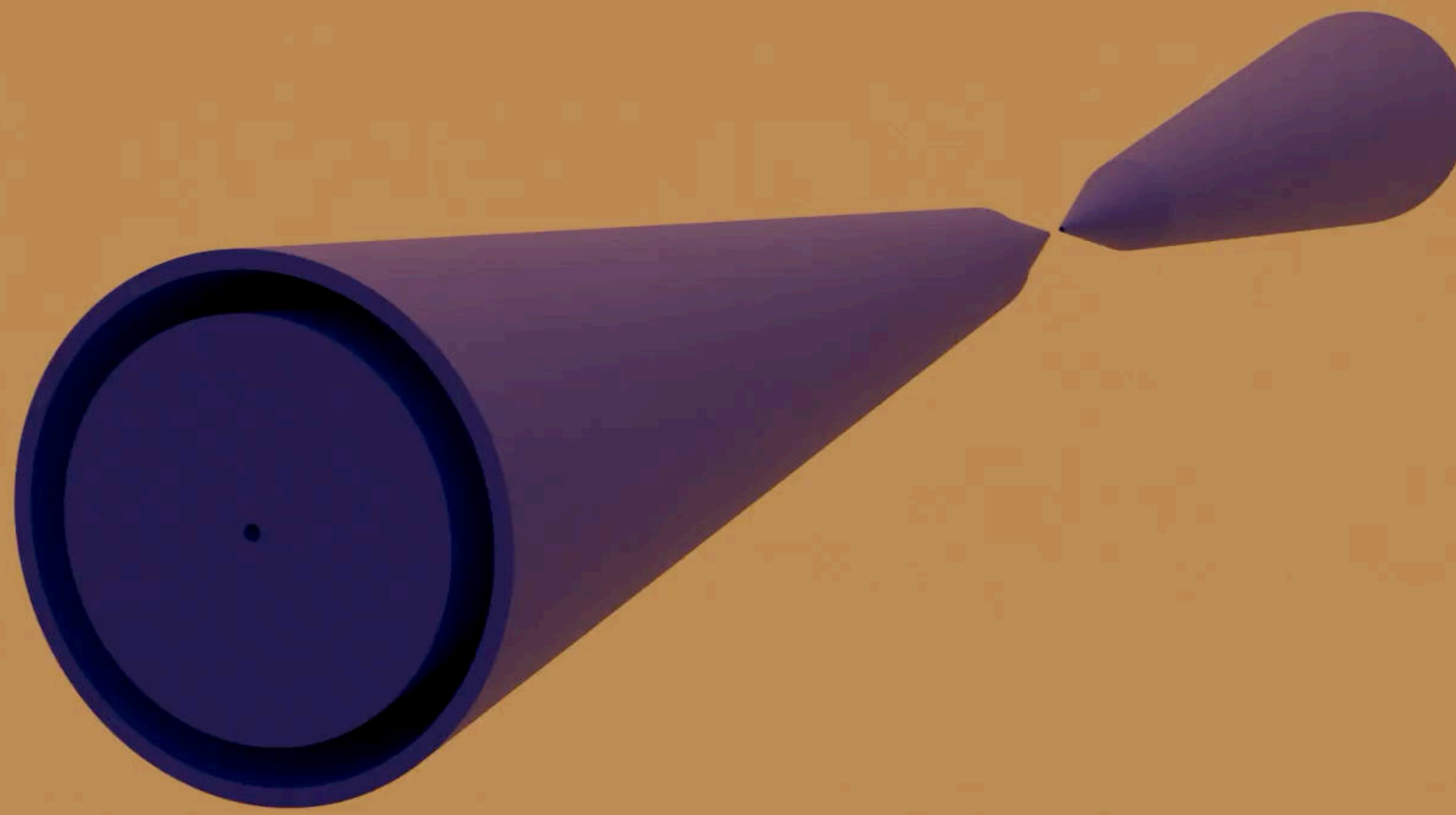
Shielding mostly captures shower!



Blue: 1 TeV incident electron
Yellow: Photons
White: Neutrons

GEANT4/G4TargetPractice
1 TeV electron on μC Tungsten Nozzles

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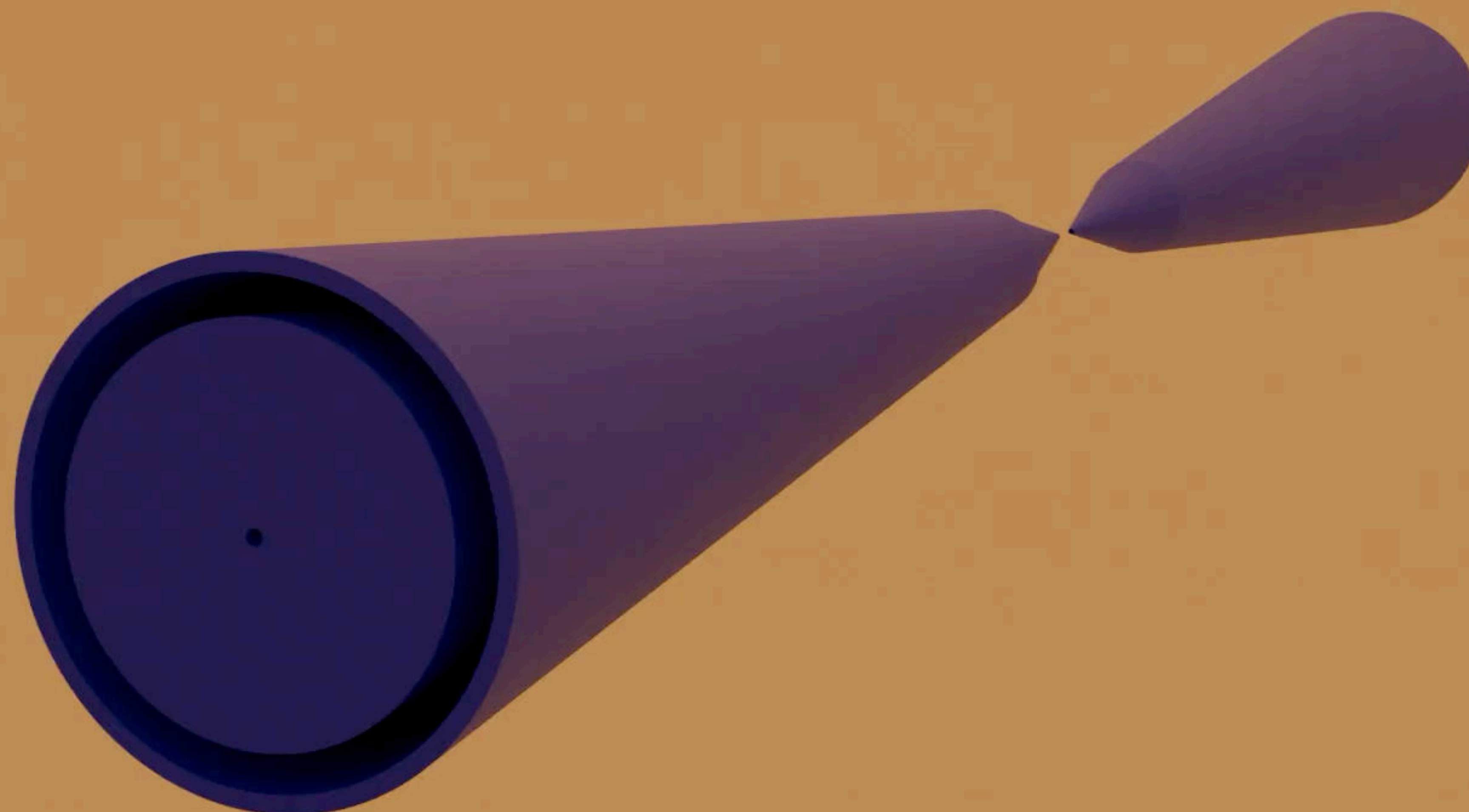

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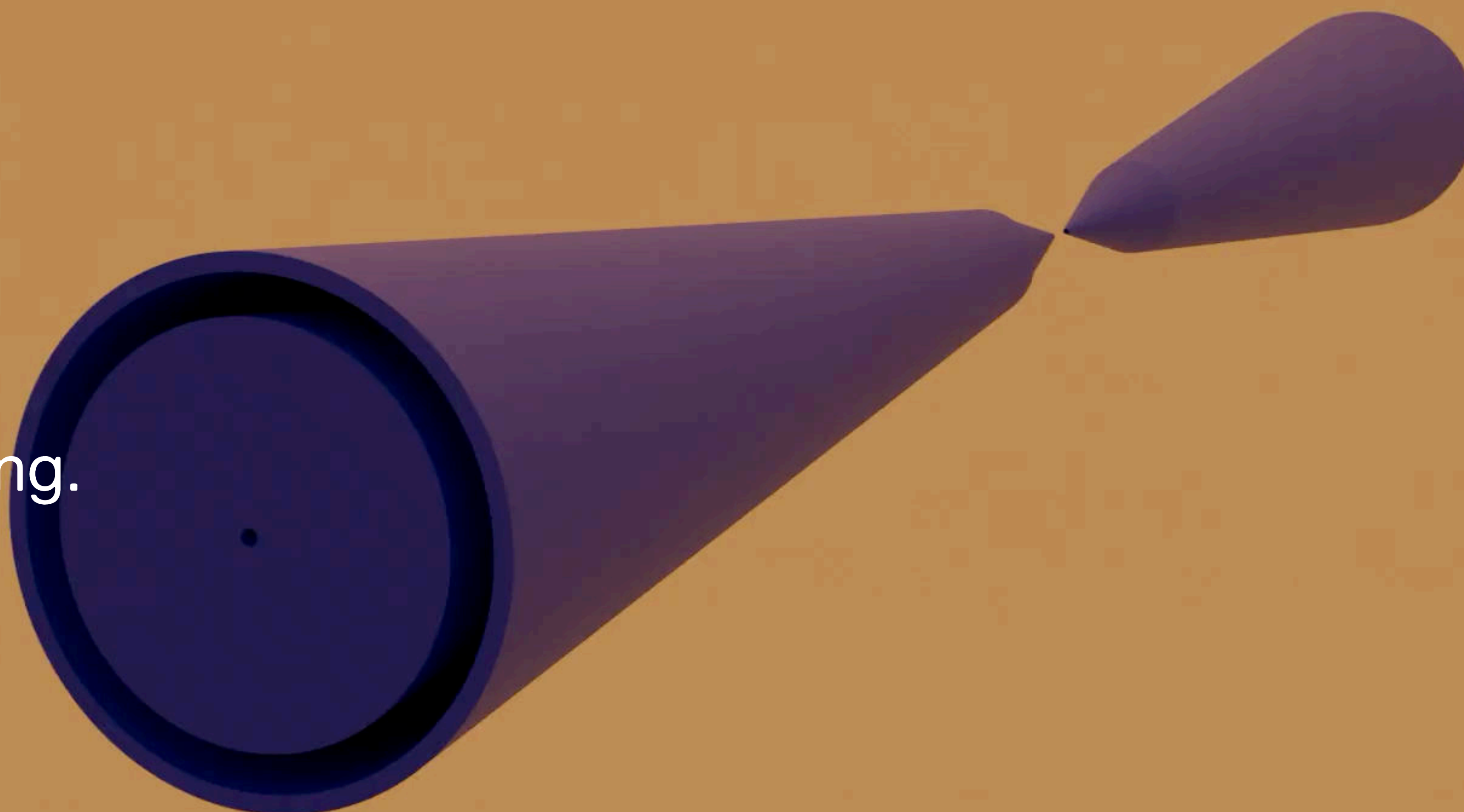

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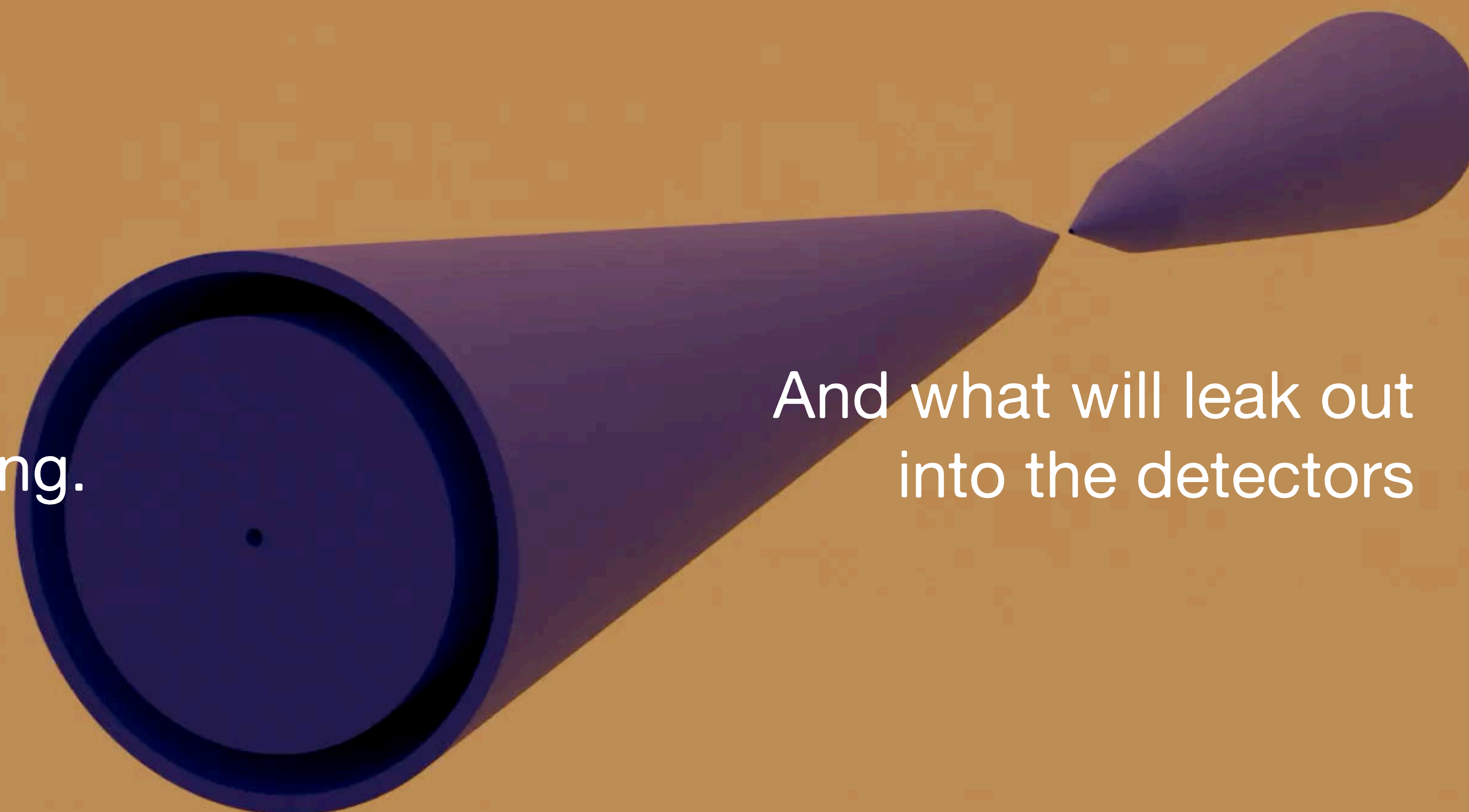

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And what will leak out into the detectors

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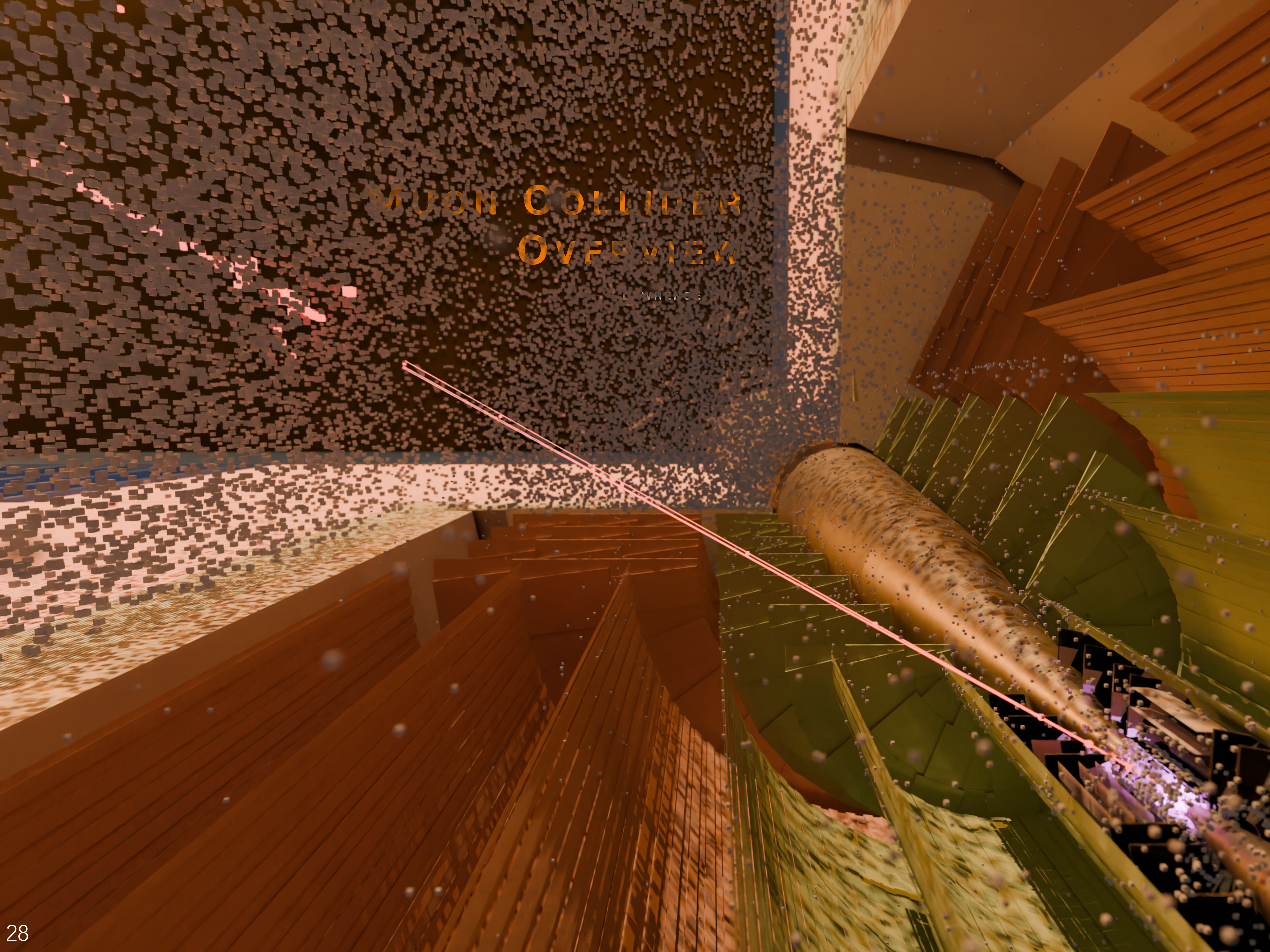
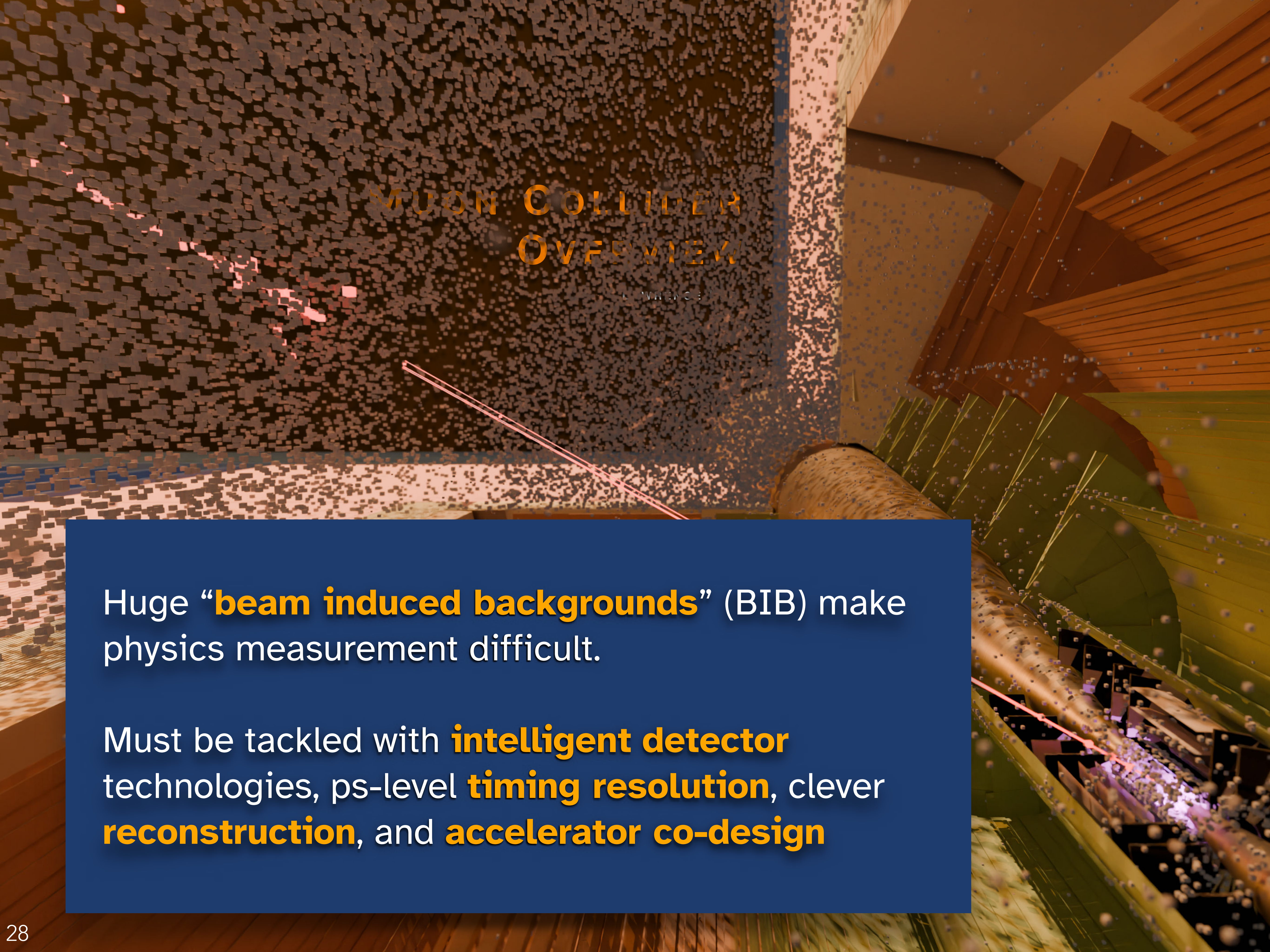
Muon Collider Overview

Lawrence Lee


MUON COLLIDER
OVERVIEW



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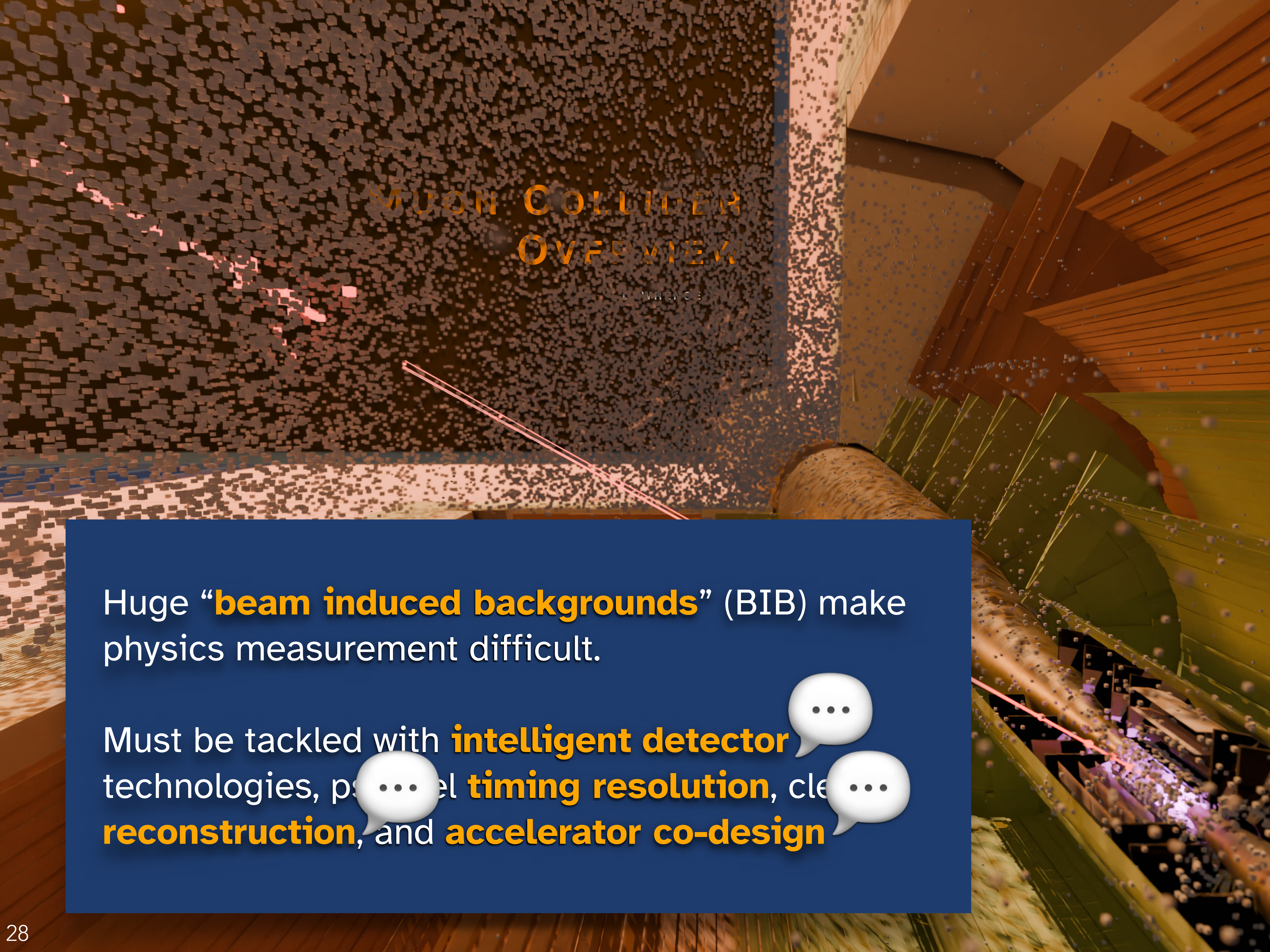
Must be tackled with **intelligent detector** technologies, ps-level **timing resolution**, clever **reconstruction**, and **accelerator co-design**



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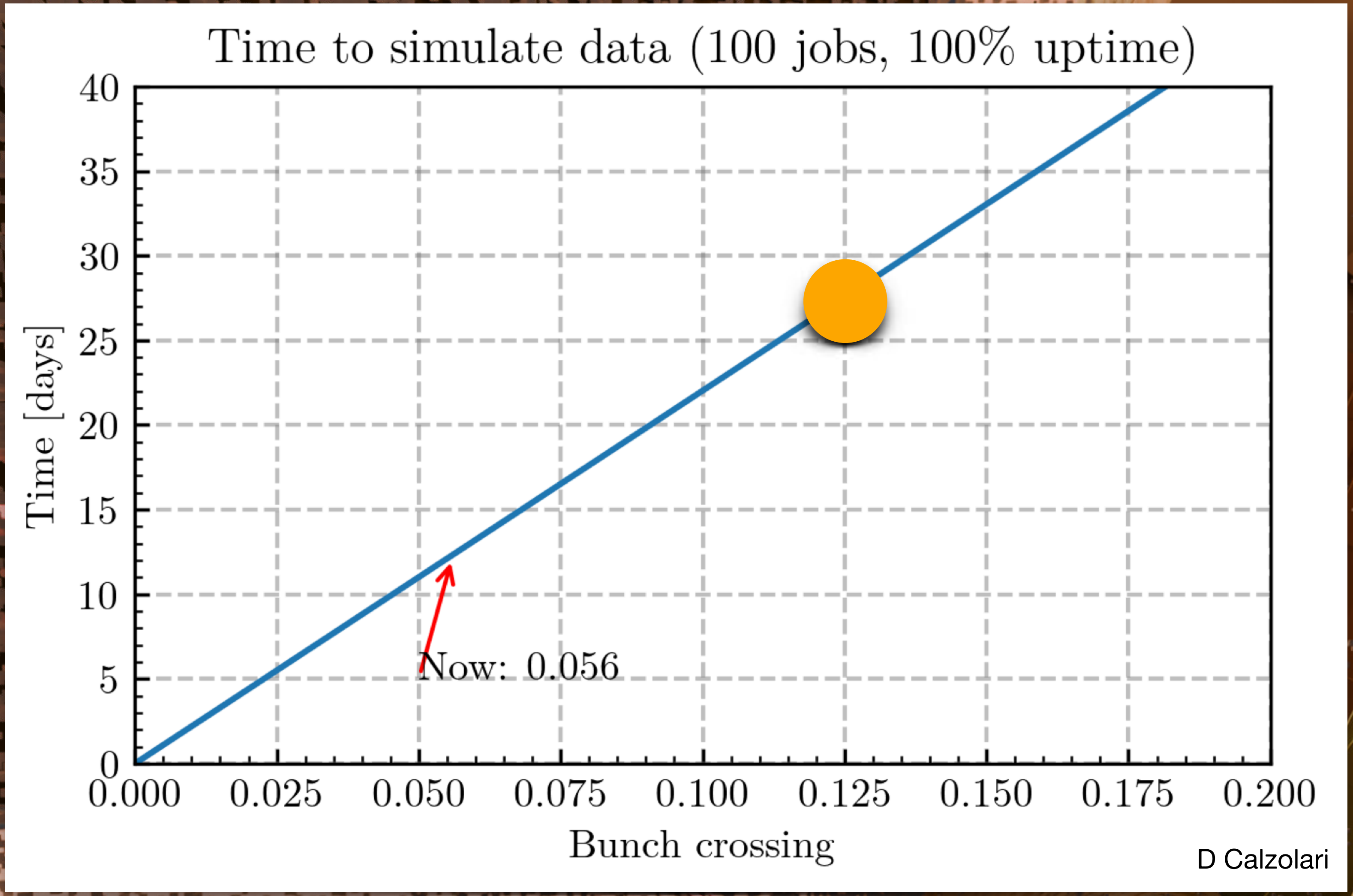
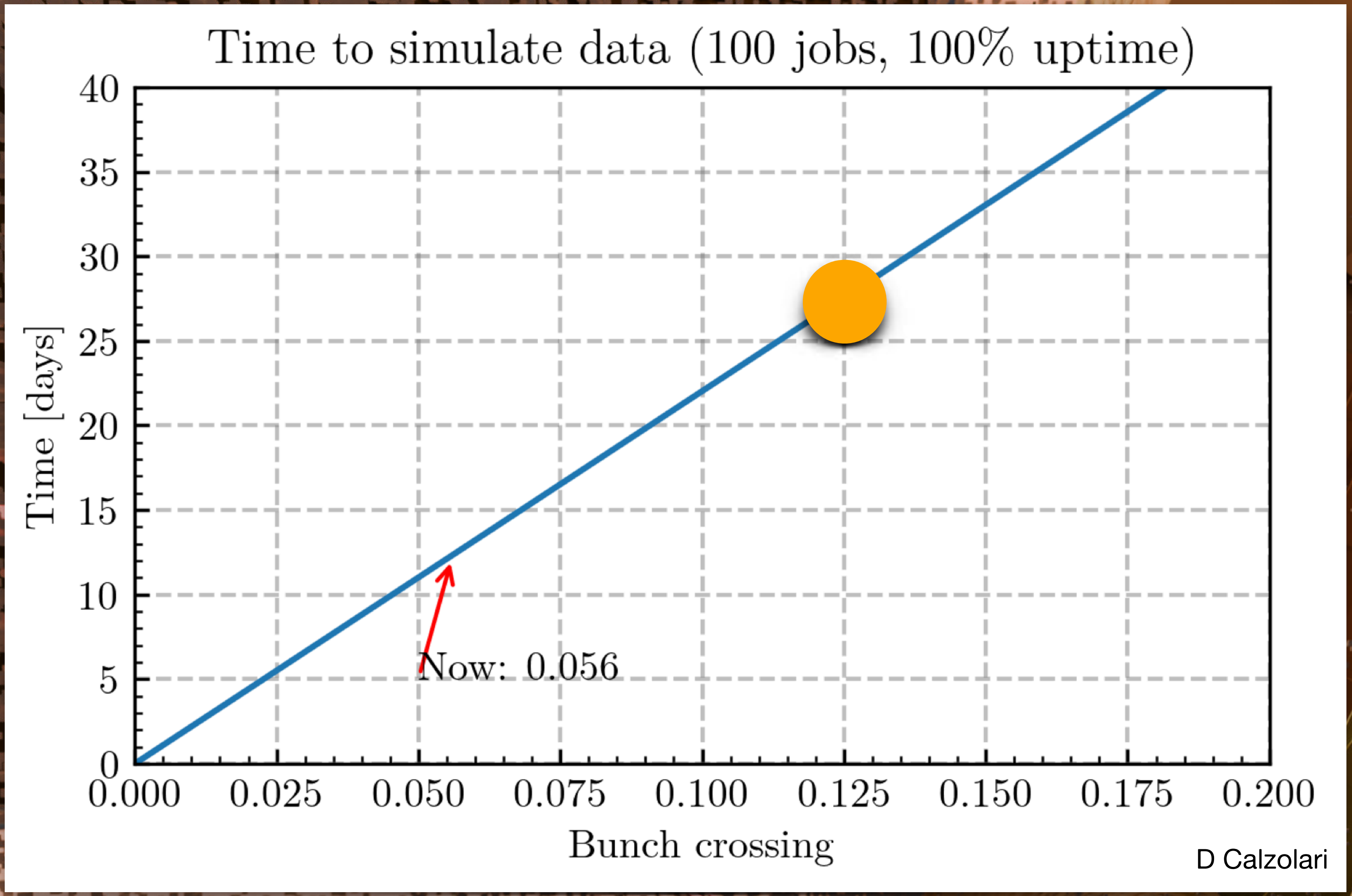


Every BC gets **O(EeV)** of total energy from beam decays into detector region! → Enormous computational challenge!

Simulating in FLUKA for **1 month** of wall time w/ 100x parallelization → **1/8th of an event**

Enormous potential gains from generative networks and new ideas



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- ∃ very difficult challenges to make this work across
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    - Detector R&D
    - Experimental design
    - Machine-detector interface
    - μ cooling design
    - Magnet development
    - Target and proton driver development
    - Simulation challenges
    - Reconstruction algorithms
    - Theory tools
    - …
- **But this requires elbow grease to solve**

Motivating, Inspiring

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— Young-Kee at last year’s USMCC Meeting

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Co-intelligence with physicists deciding what needs to be done.

Inject **human ingenuity** into problem+solution space.

Creativity/Ingenuity

Hard Work

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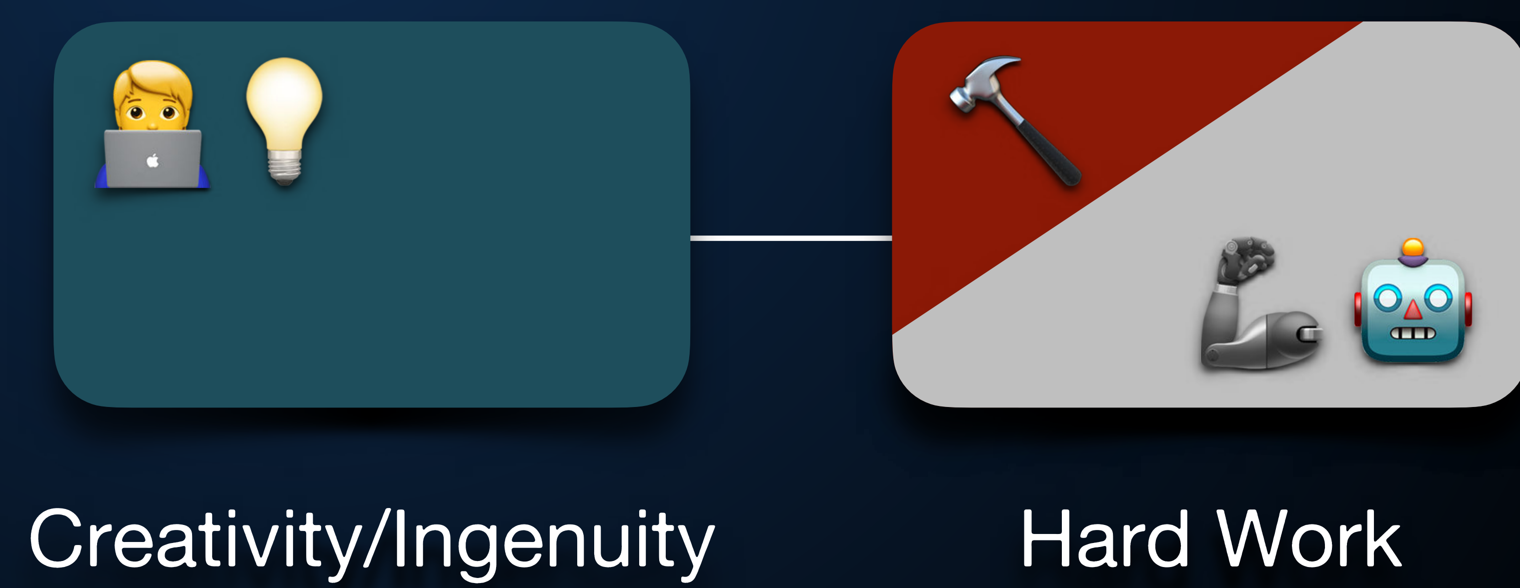

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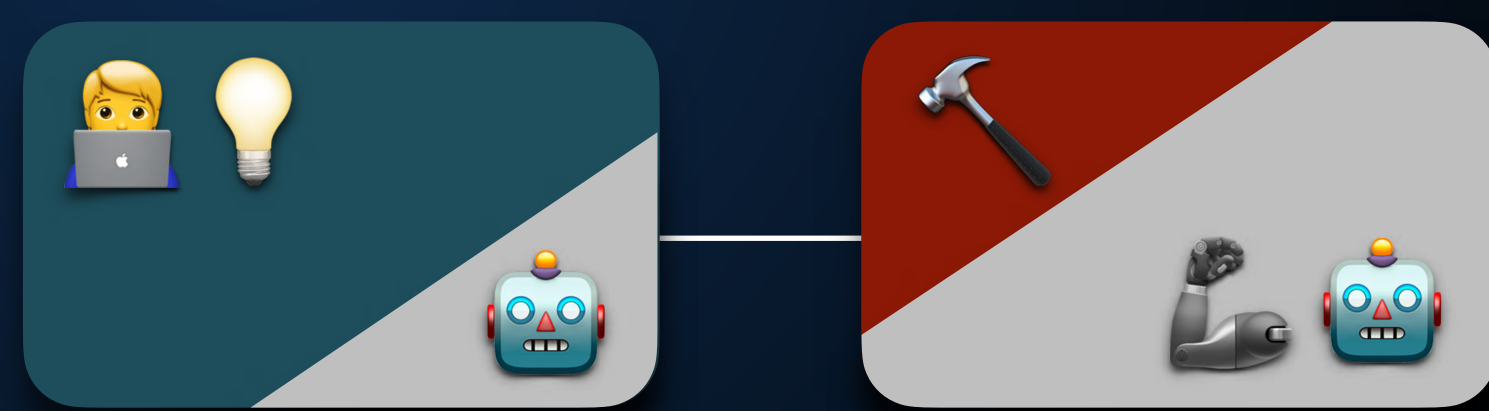

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We remain physicists.

We train physicists.

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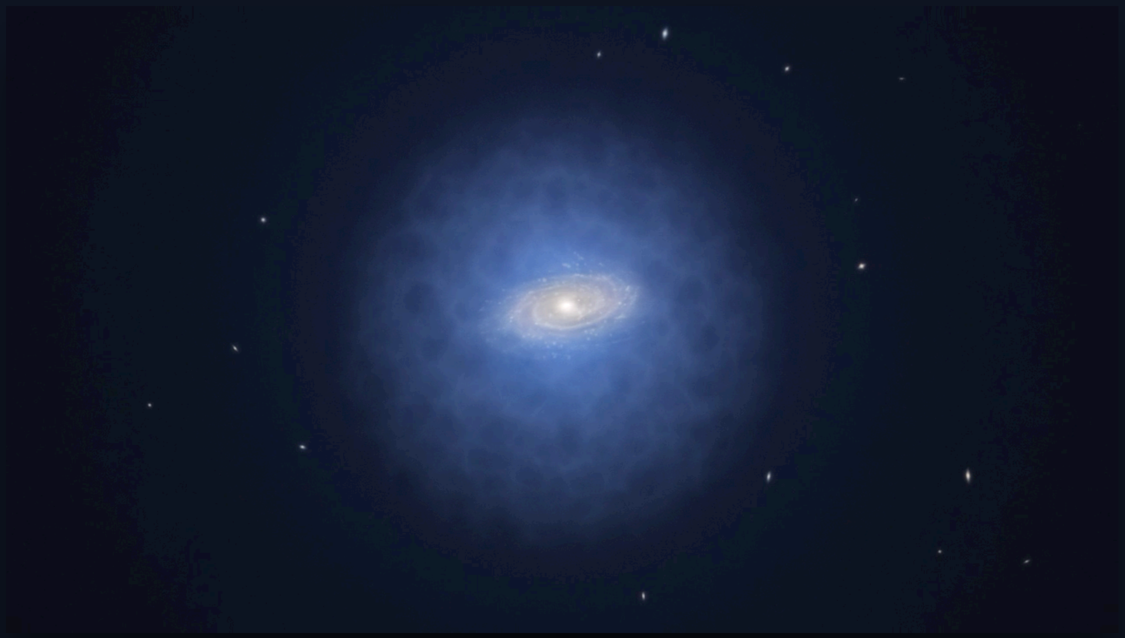
Thanks and enjoy the workshop!

RESEARCH CORPORATION for SCIENCE ADVANCEMENT
NSF
U.S. DEPARTMENT OF ENERGY | Office of Science

Backup

Dark Matter

- Large evidence that most (85%) of the "mass" in the universe is not in SM
  - It's **"Dark"**: Doesn't seem to interact with E&M or our QCD strong force
  - It **does** interact with gravity
  - …and we **hope** it interacts with the Weak force 🤞



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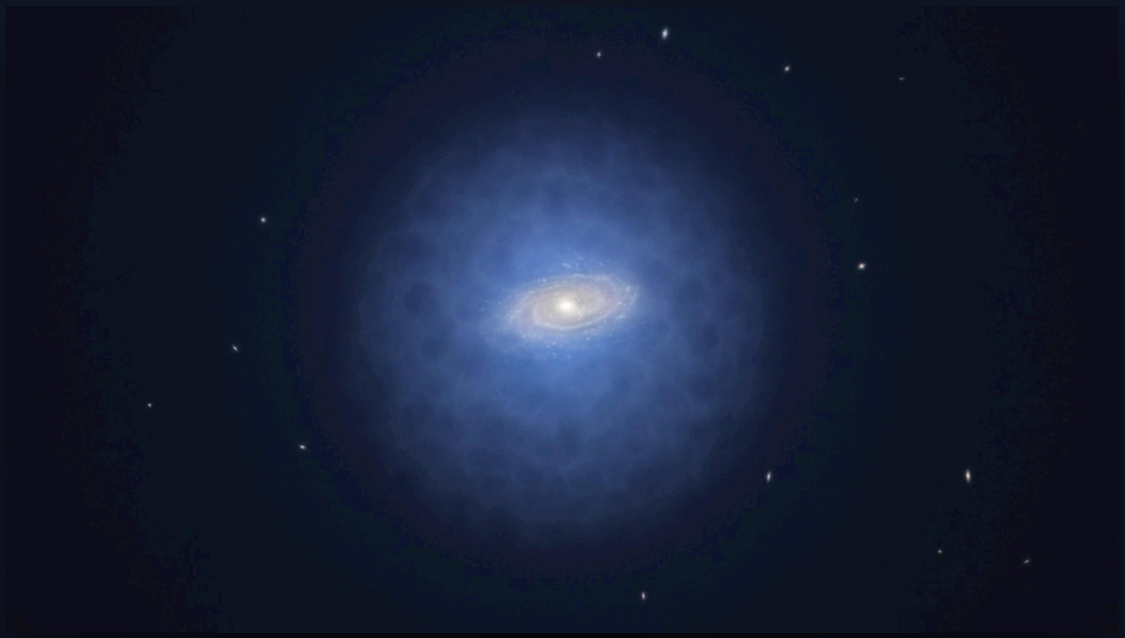

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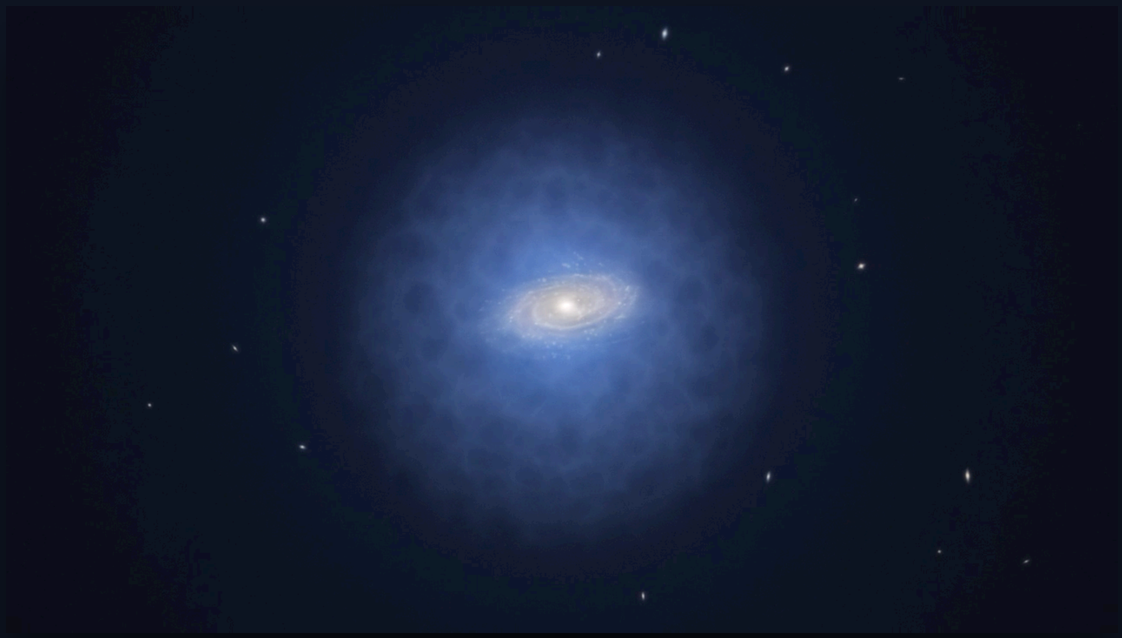

WIMP

(Weakly Interacting Massive Particles)

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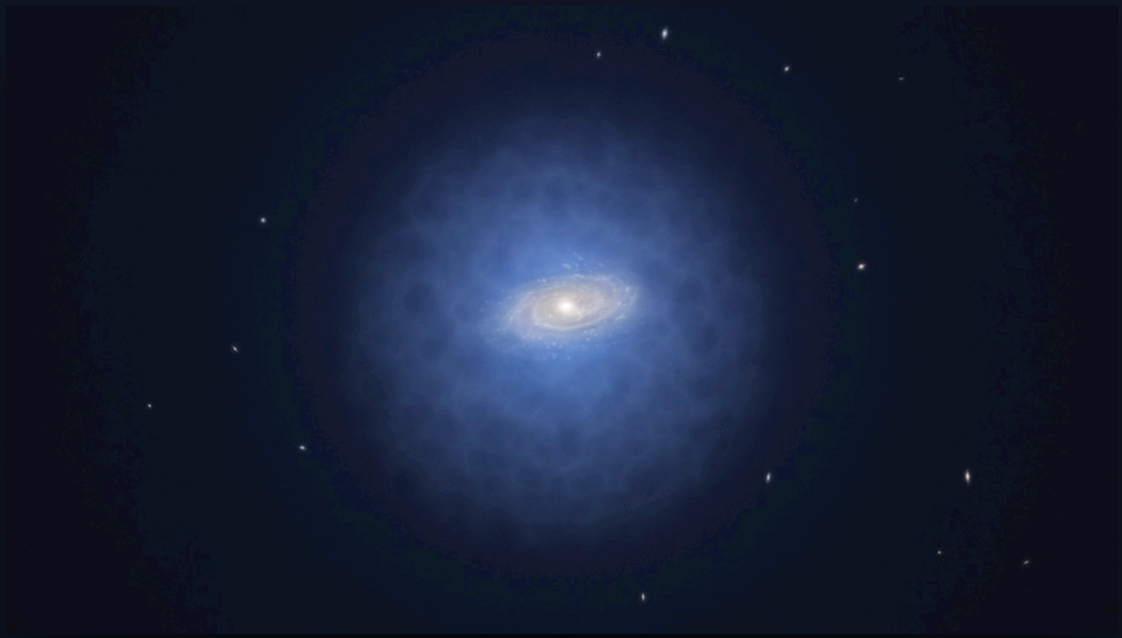
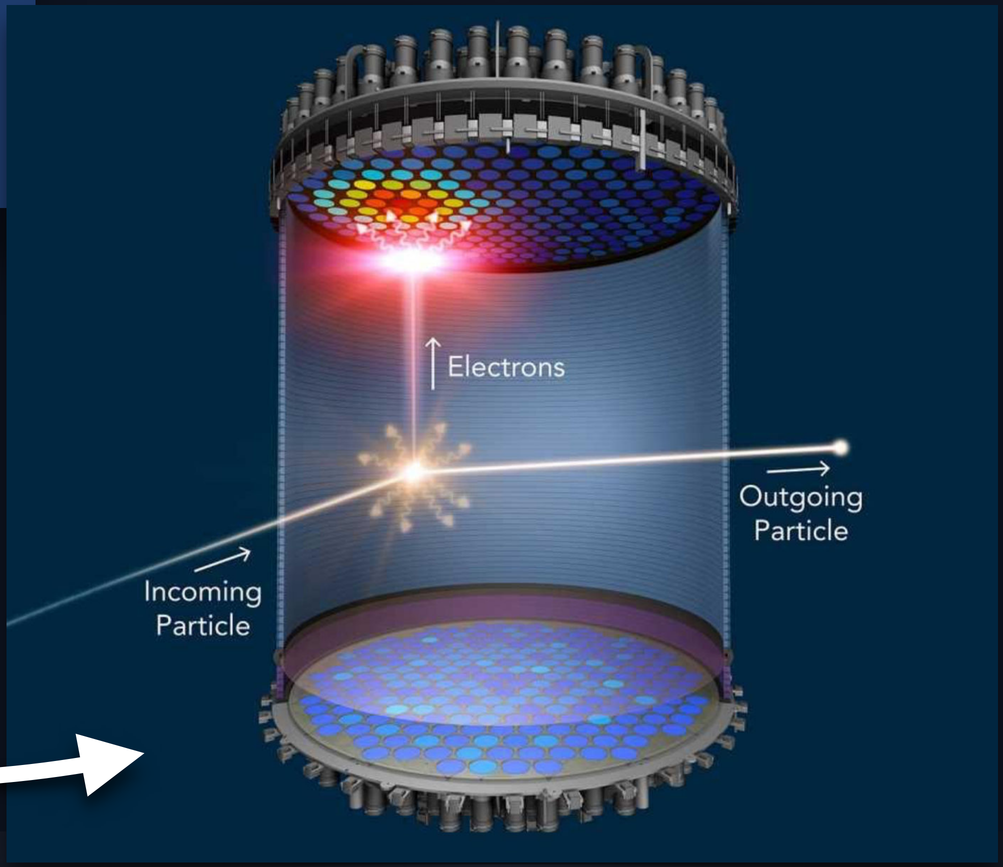
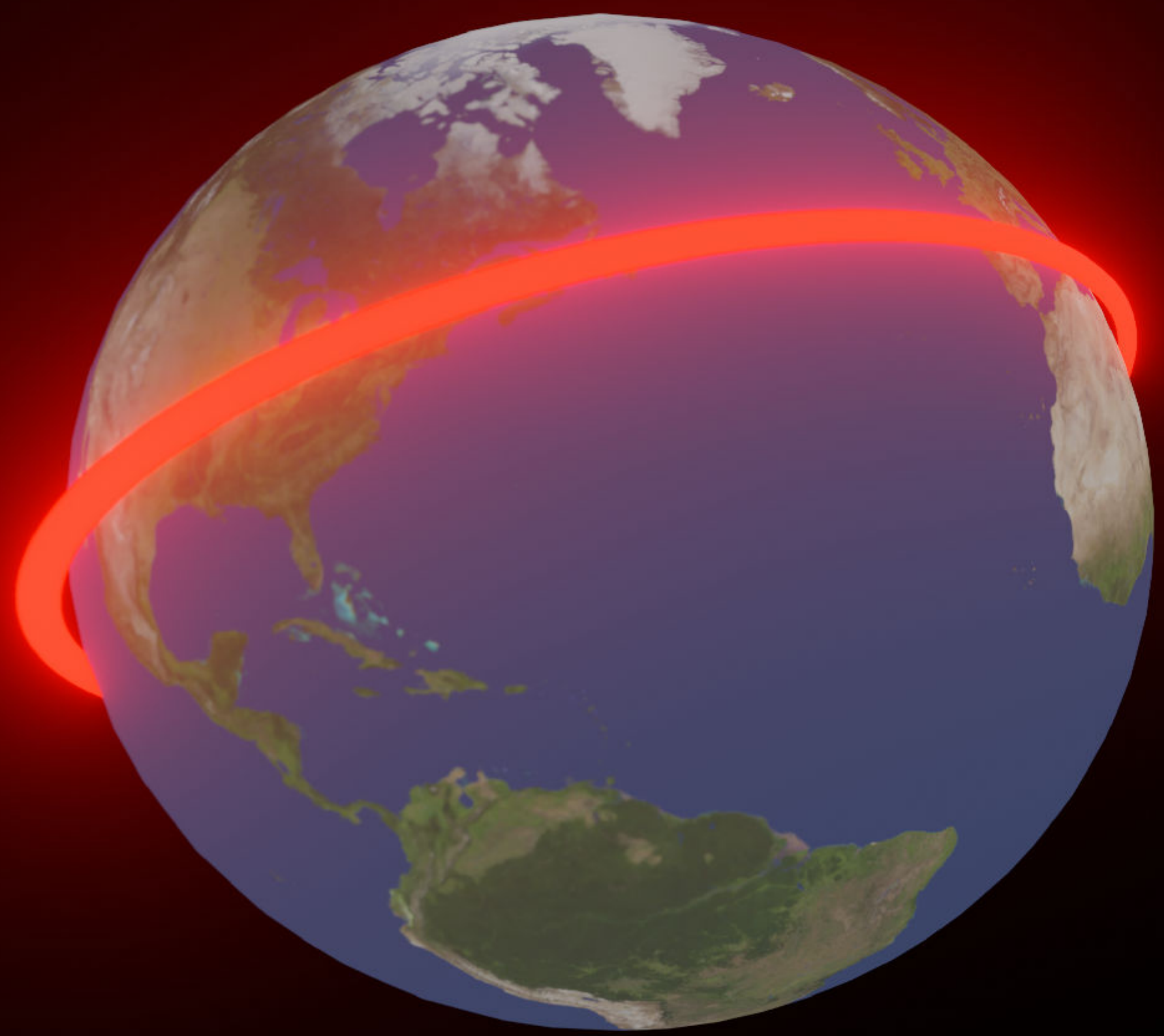


WIMP

(Weakly Interacting Massive Particles)

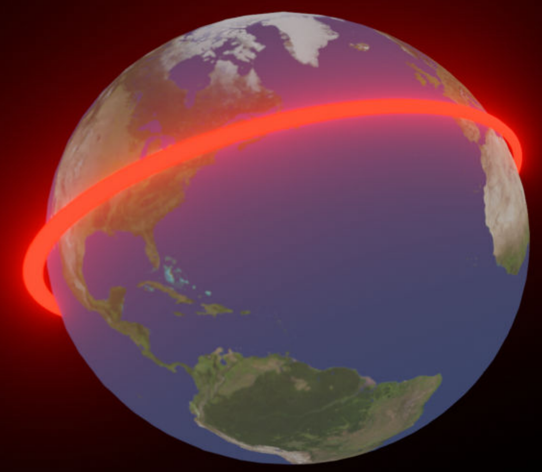
- If DM is "WIMPy", it **couples to SM**!
  - Produce it in the early universe ("Thermal relic")
  - Produce it at colliders
  - See interactions with materials ("direct detection")





Fermi’s Globatron (1954)

40 Years in the Future (1994)
40,000 km



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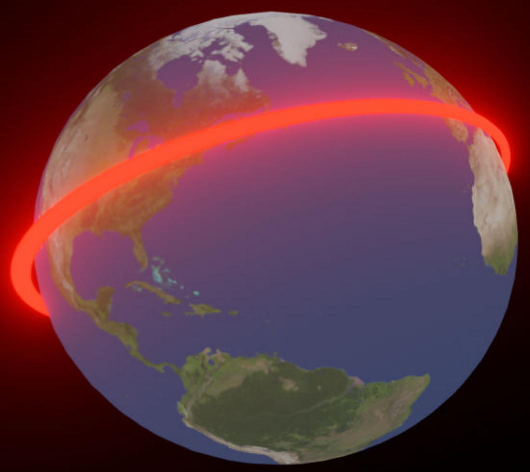
~3 TeV CoM proton collisions
(Fixed target!!!)



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40,000 km
~3 TeV CoM proton collisions
(Fixed target!!!)

Moral:

- Not great at projecting 40 years in the future!
  - We ***did*** reach TeV hadron collisions ***before*** the 90s (at his namesake lab) w/ the Tevatron
  - **But we didn’t need 40,000 km to do it!**

Be **smart, open-minded, and take advantage of new opportunities** to achieve physics goals

Realize seemingly impossible physics
w/ technology, engineering, ingenuity, hard work

I was always told:

"Discovery of new particles is for hadron machines"

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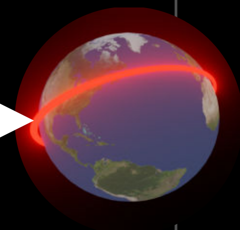
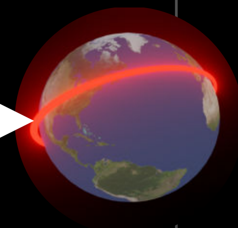
"Discovery of new particles is for hadron machines"

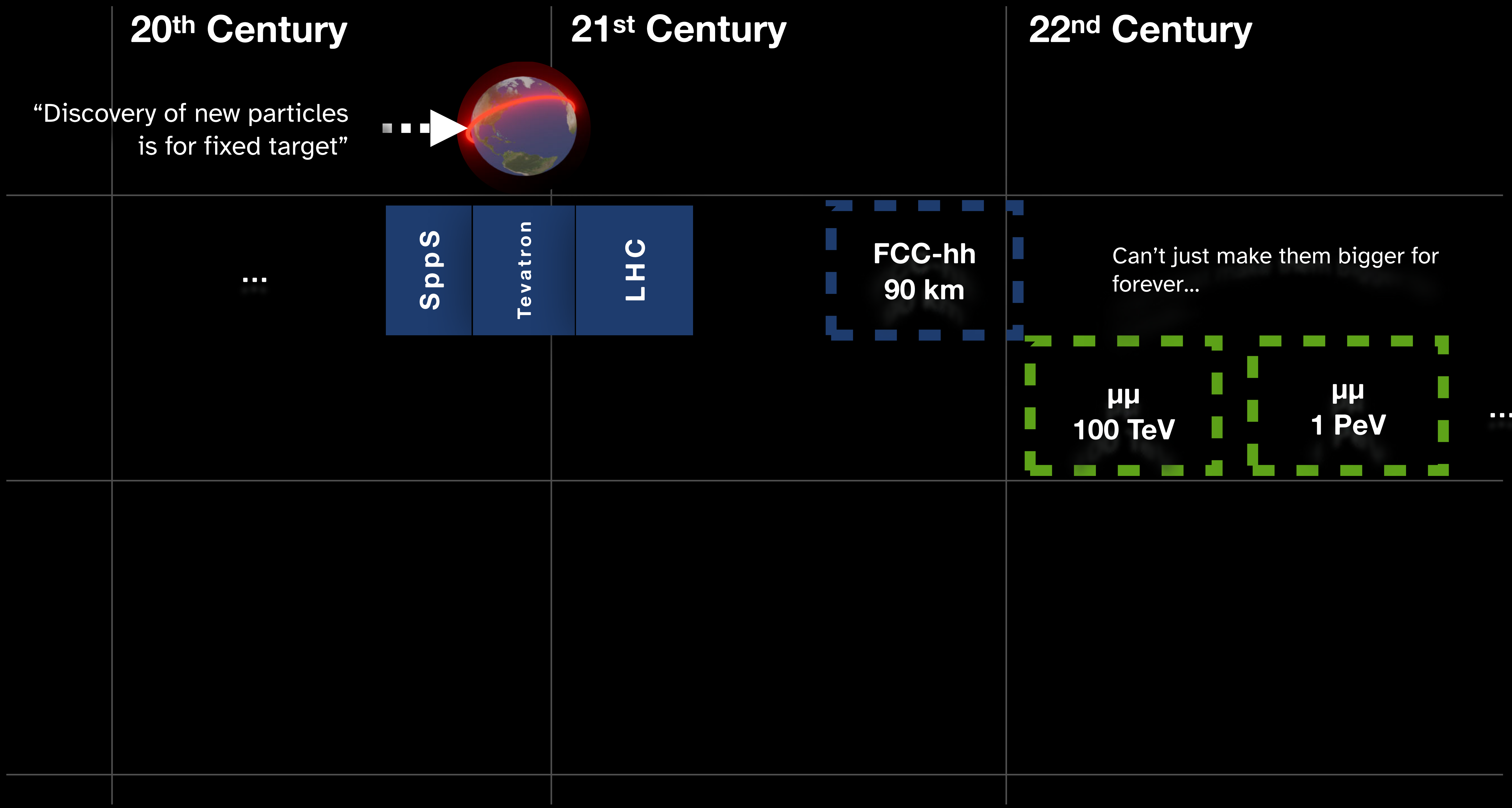
✅ Historically true!

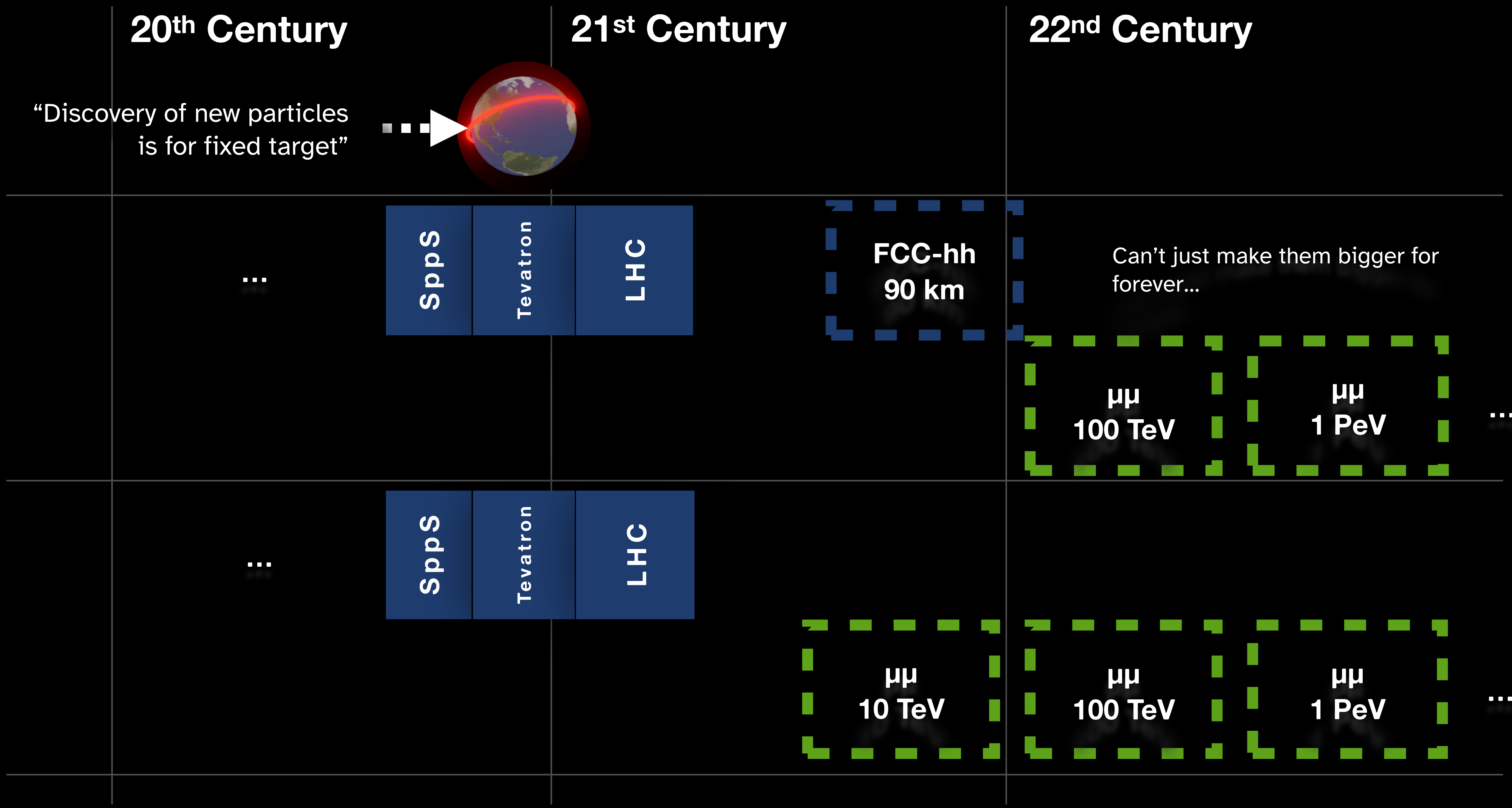
✅ Could keep going with this!

	20th Century	21st Century	22nd Century
	"Discovery of new particles is for fixed target" 		

	20th Century	21st Century	22nd Century
	“Discovery of new particles is for fixed target”		
	… SppS, Tevatron	LHC, FCC-hh 90 km	Can’t just make them bigger for forever…




20th Century
21st Century
22nd Century
“Discovery of new particles is for fixed target”
...
SppS
Tevatron
LHC
FCC-hh
90 km
Can’t just make them bigger for forever...
μμ
100 TeV
μμ
1 PeV
...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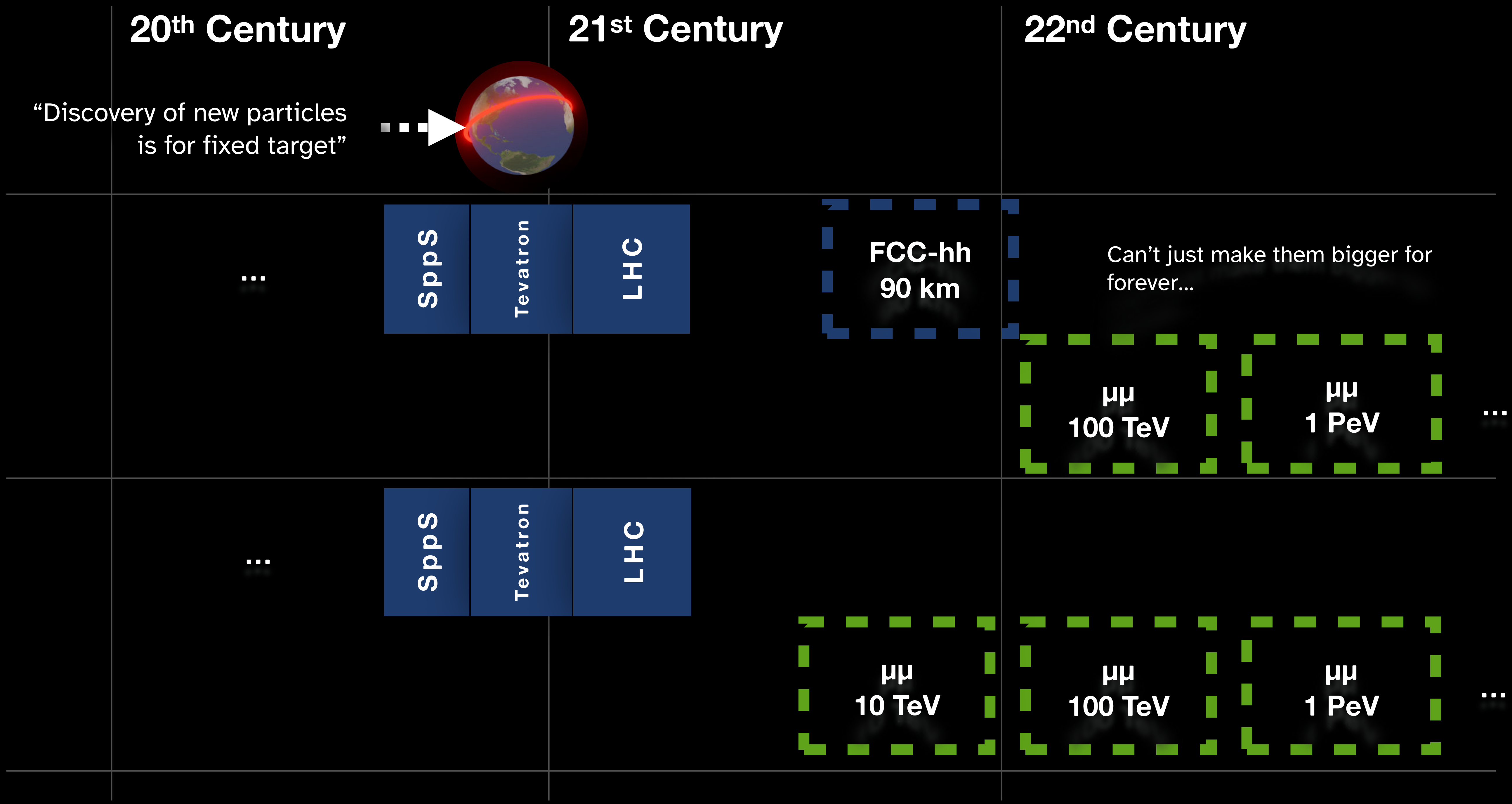
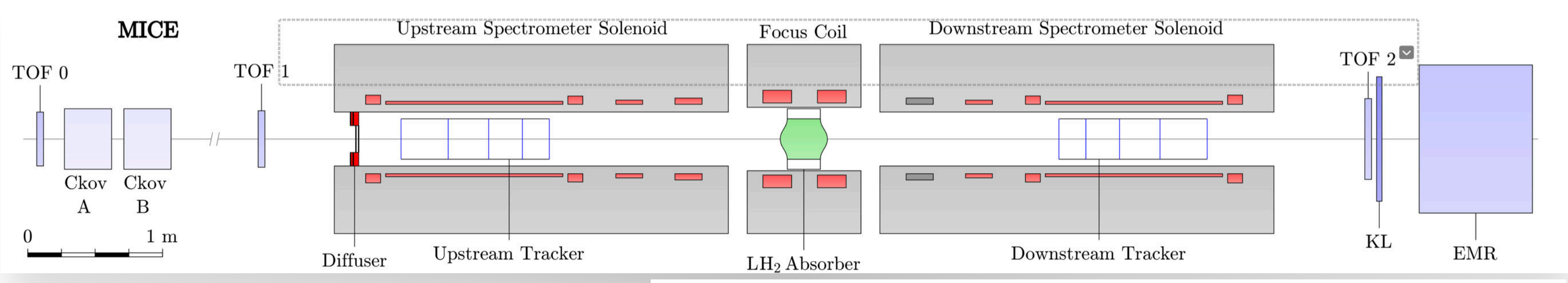


I ask myself:

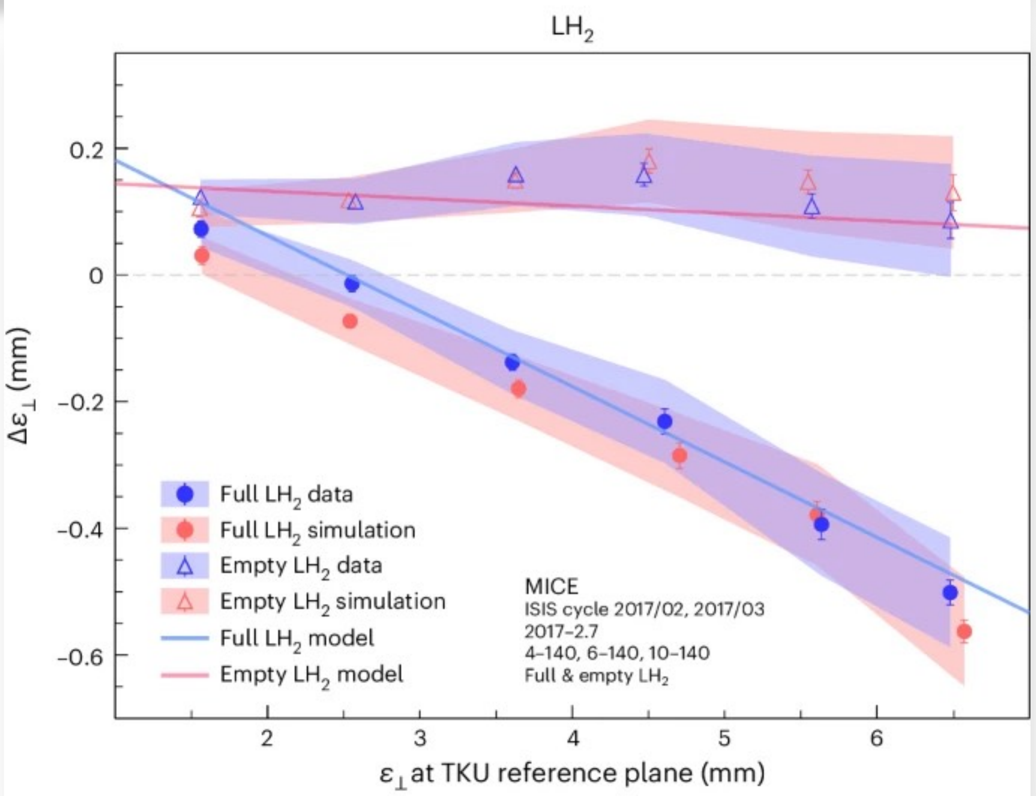
Do I want to work on the last chapter of a 20th c story?
Or start a new discovery program that will continue into the 22nd c?

Ionization Cooling Demonstrations

[2310.05669]



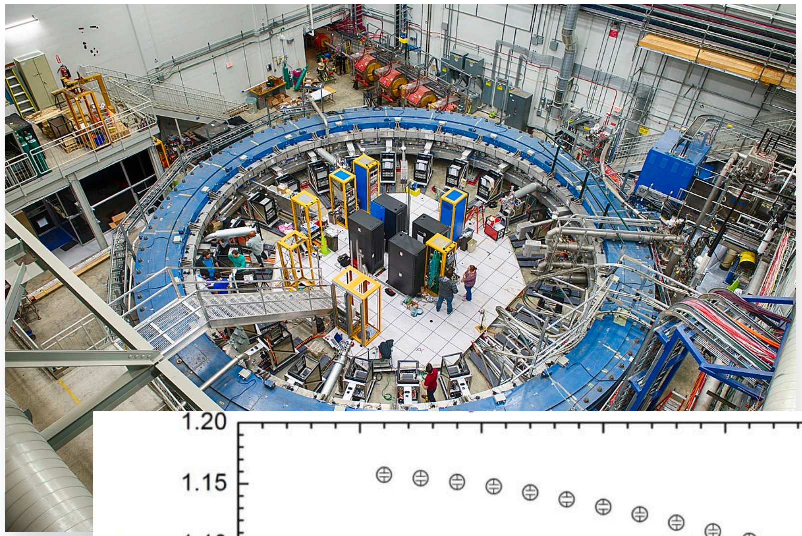
MICE demonstrated 4D cooling in 2020

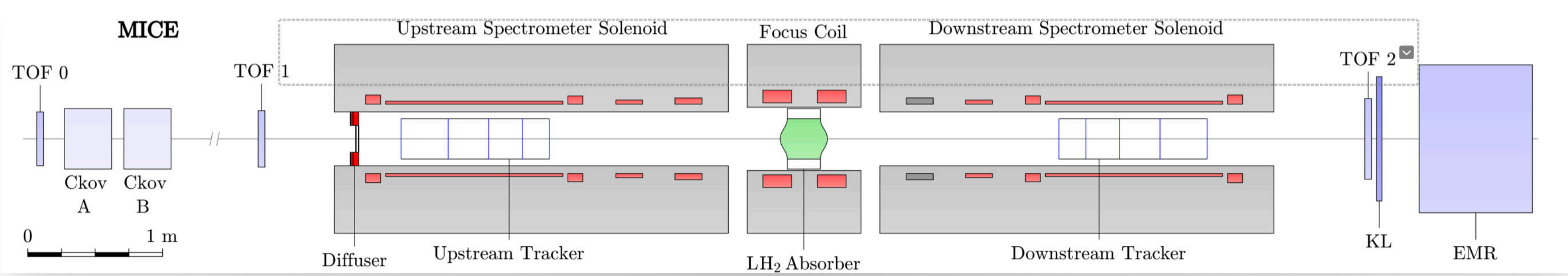


Ionization Cooling Demonstrations

[2310.05669]

[D Stratakis]





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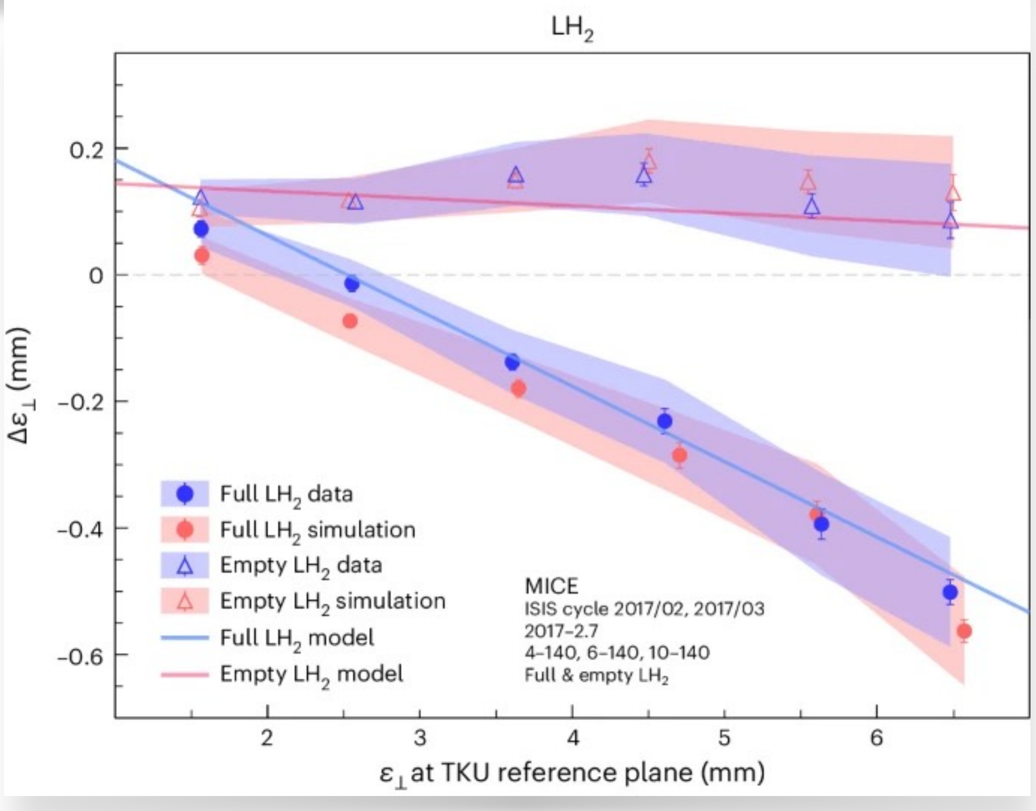

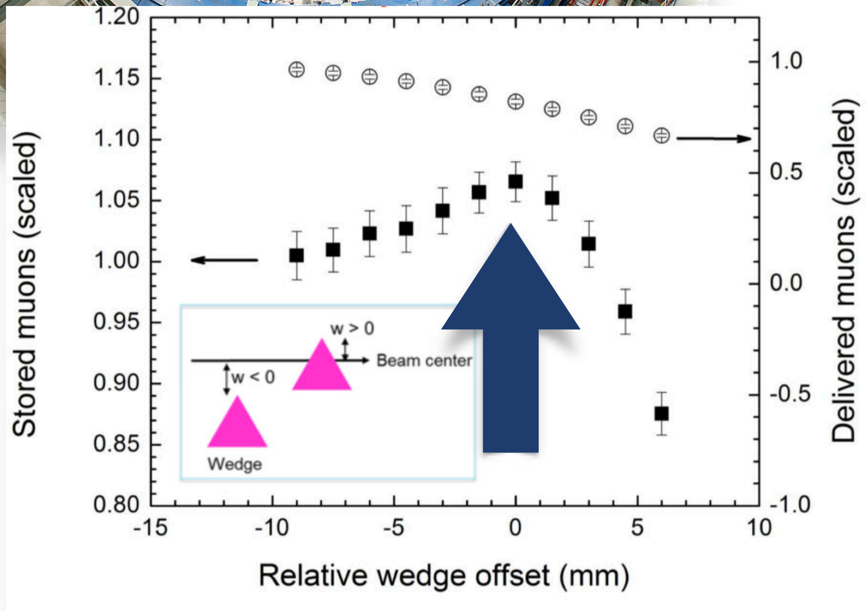

FNAL Muon g-2 demonstrated wedge cooling to increase beam quality

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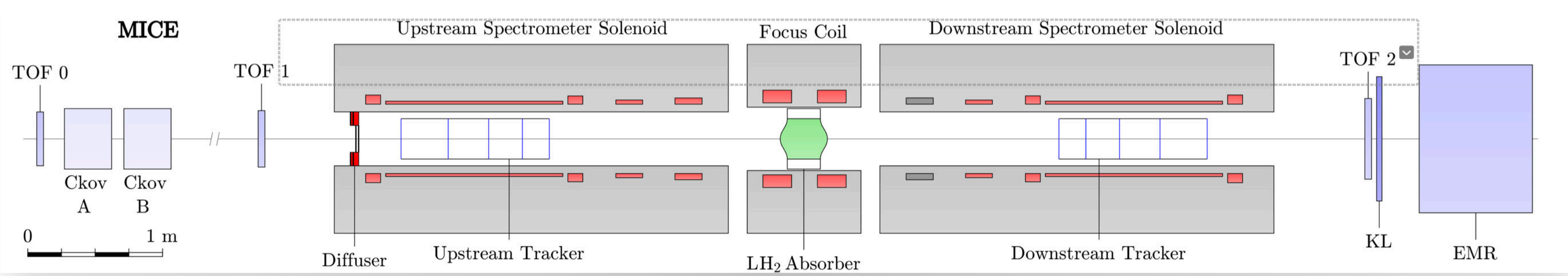

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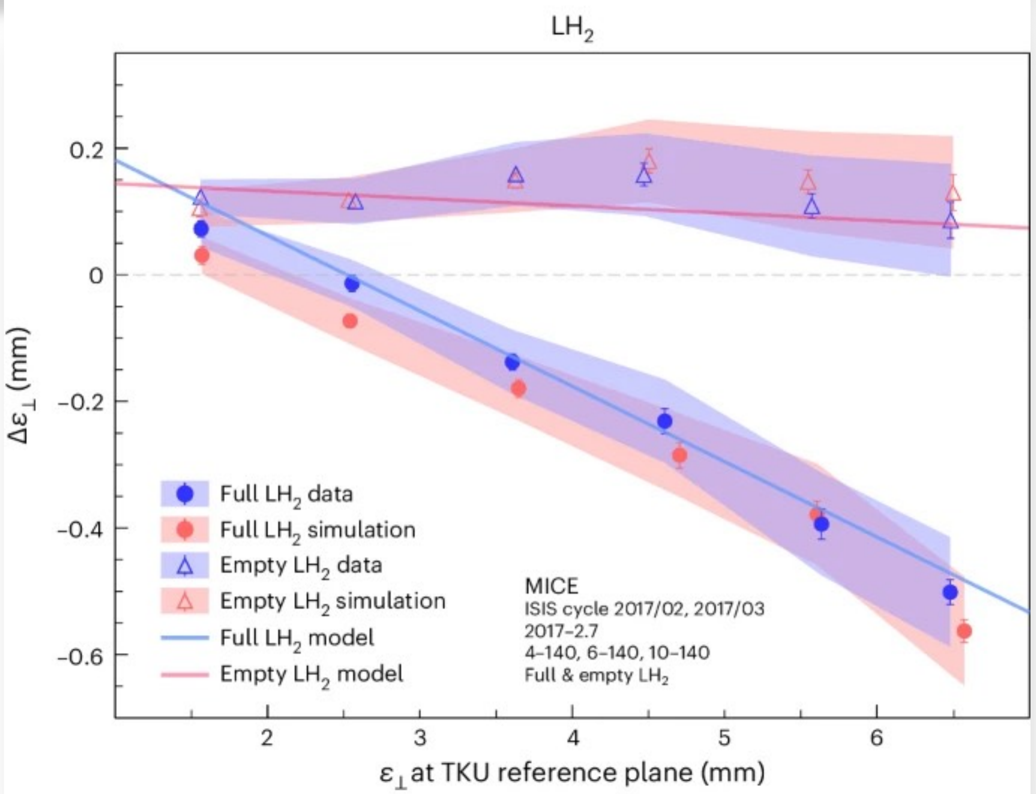

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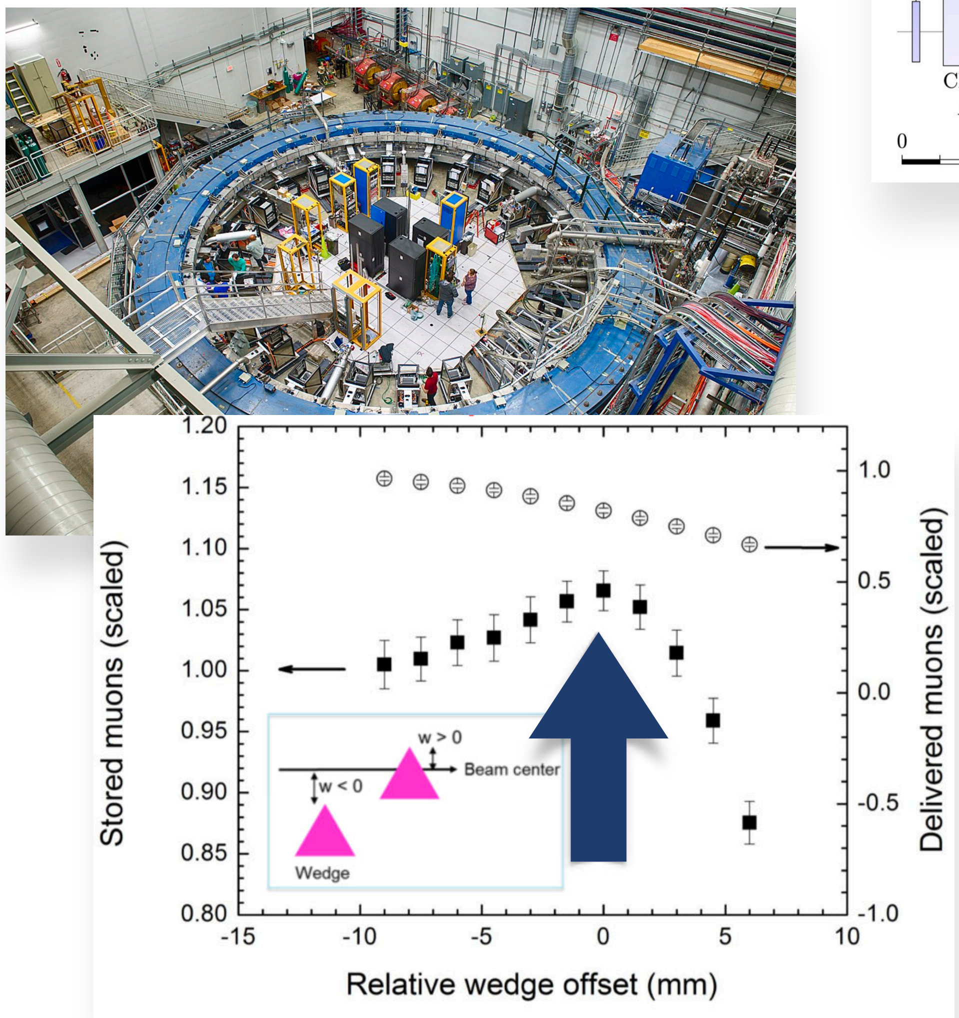

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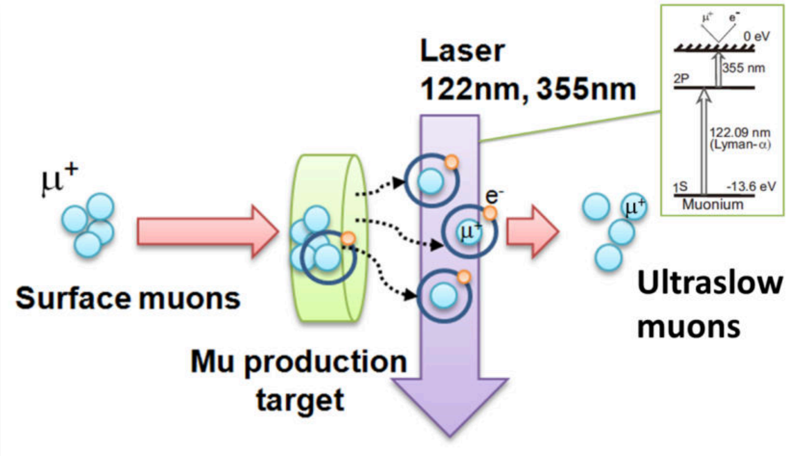
J-PARC created muonium (μ^+e^-)-based **ultra cold muon source** for Muon g-2

(*Not ionization cooling)

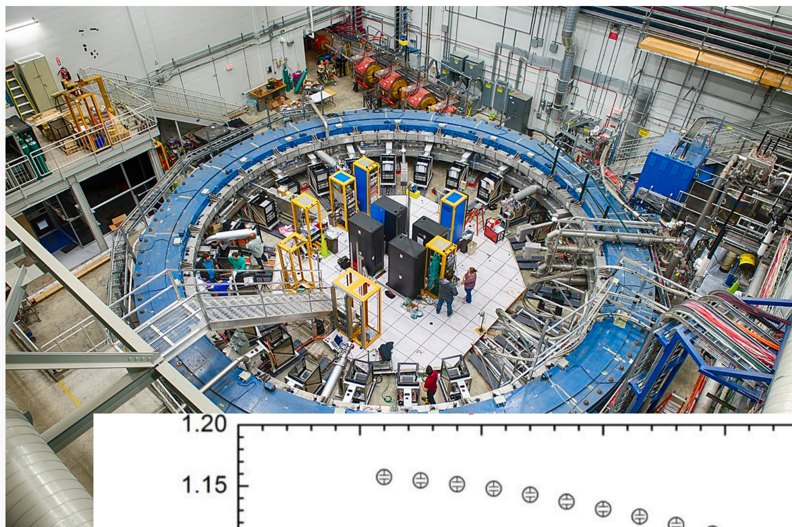


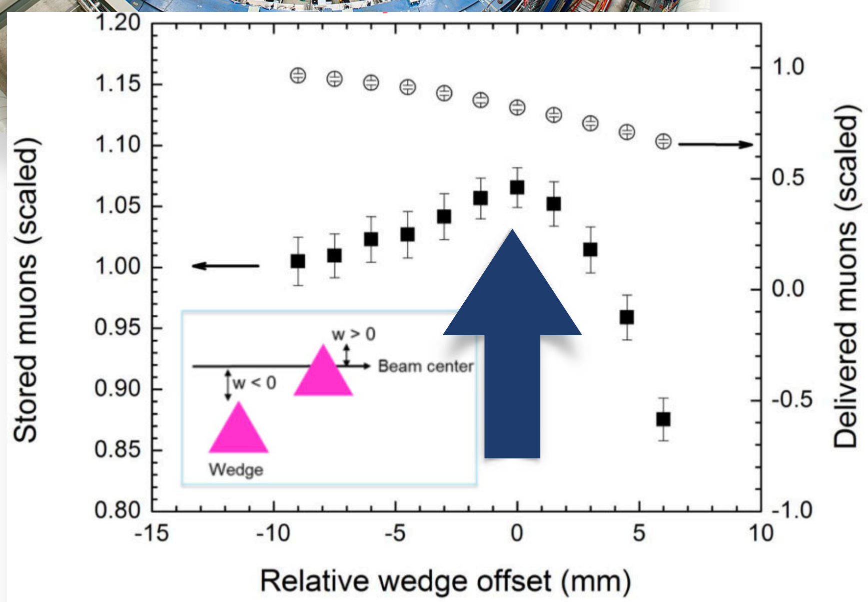
[Kondo, et al]

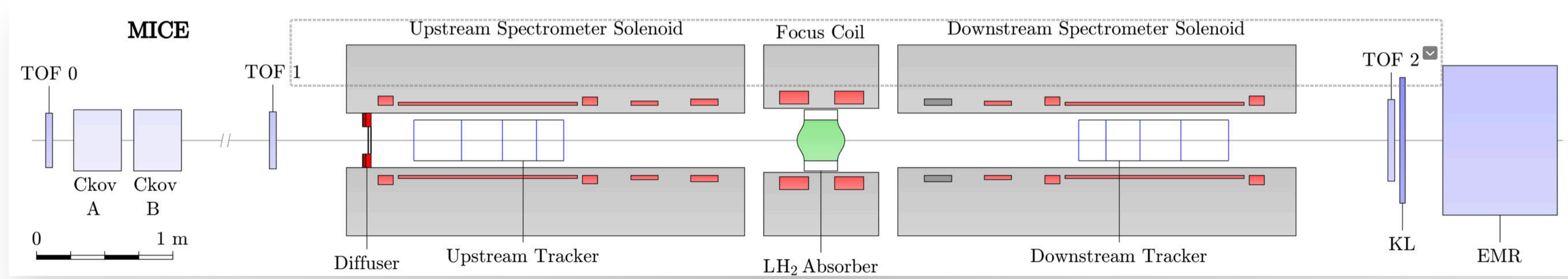
Ionization Cooling Demonstrations

[2310.05669]

[D Stratakis]







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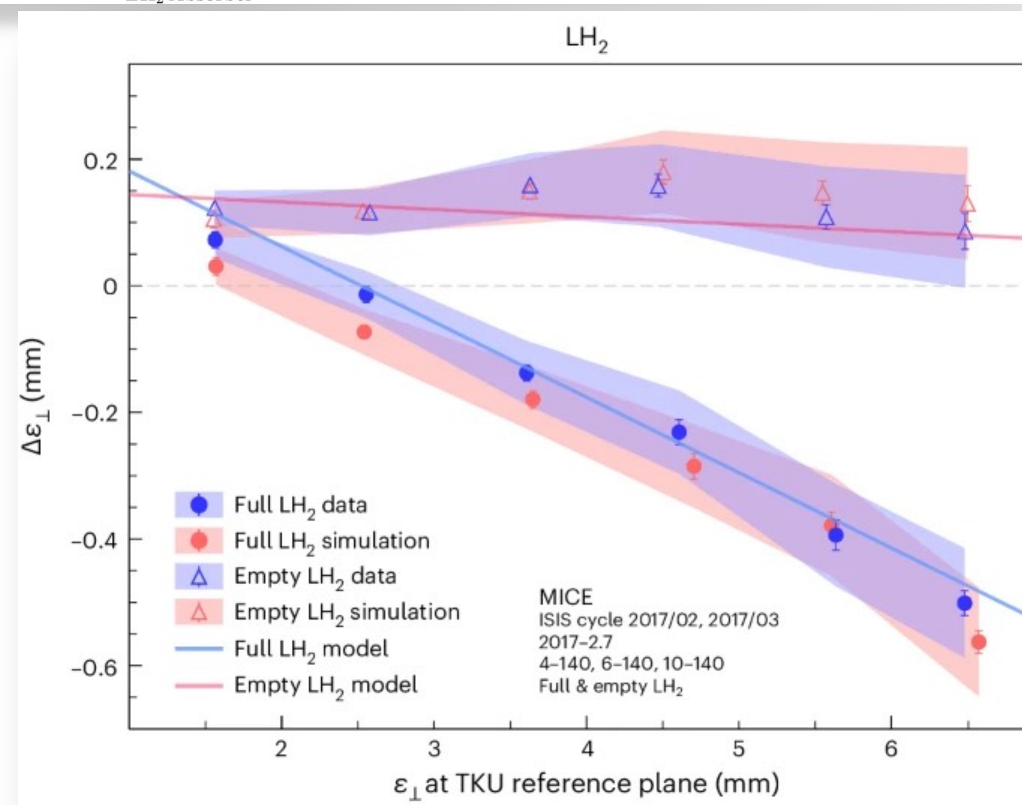

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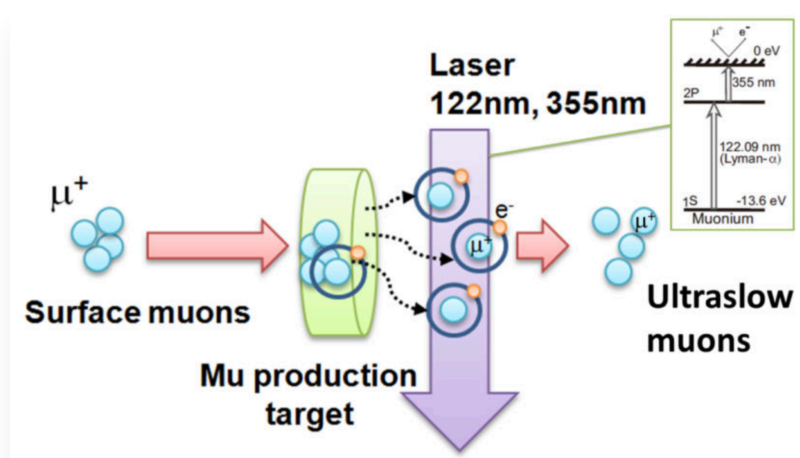
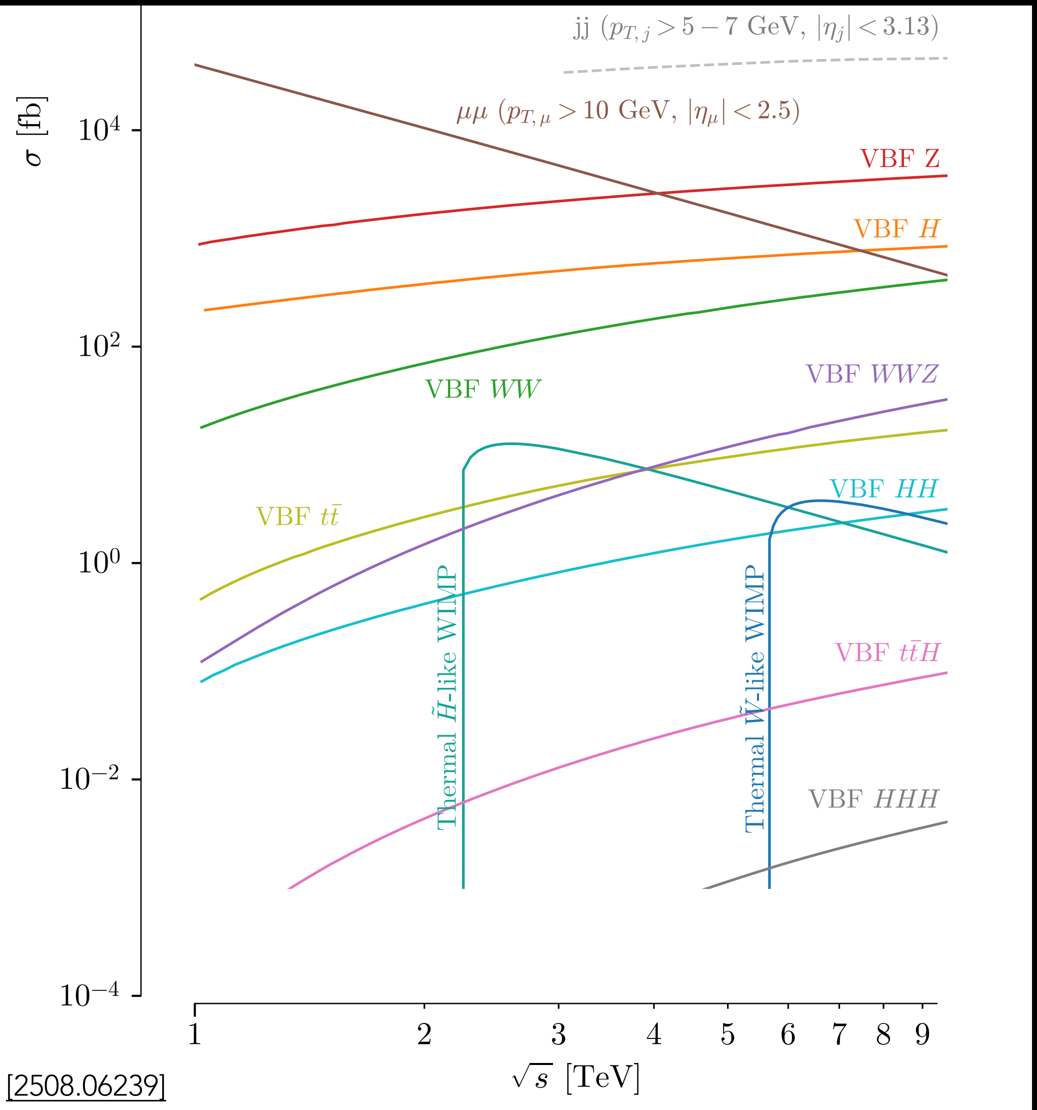


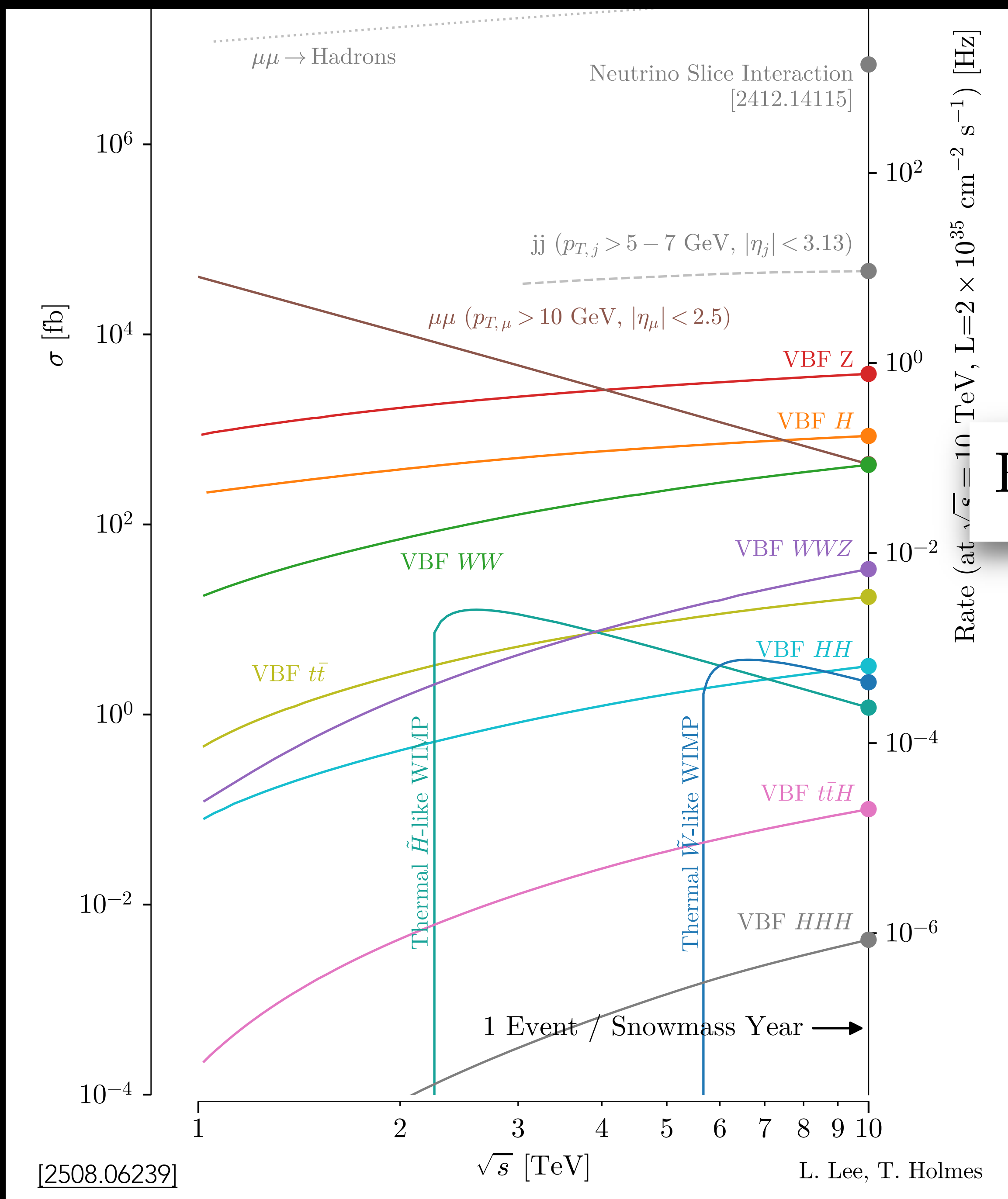
[Kondo, et al]

∃ ways to create cool muon beams!

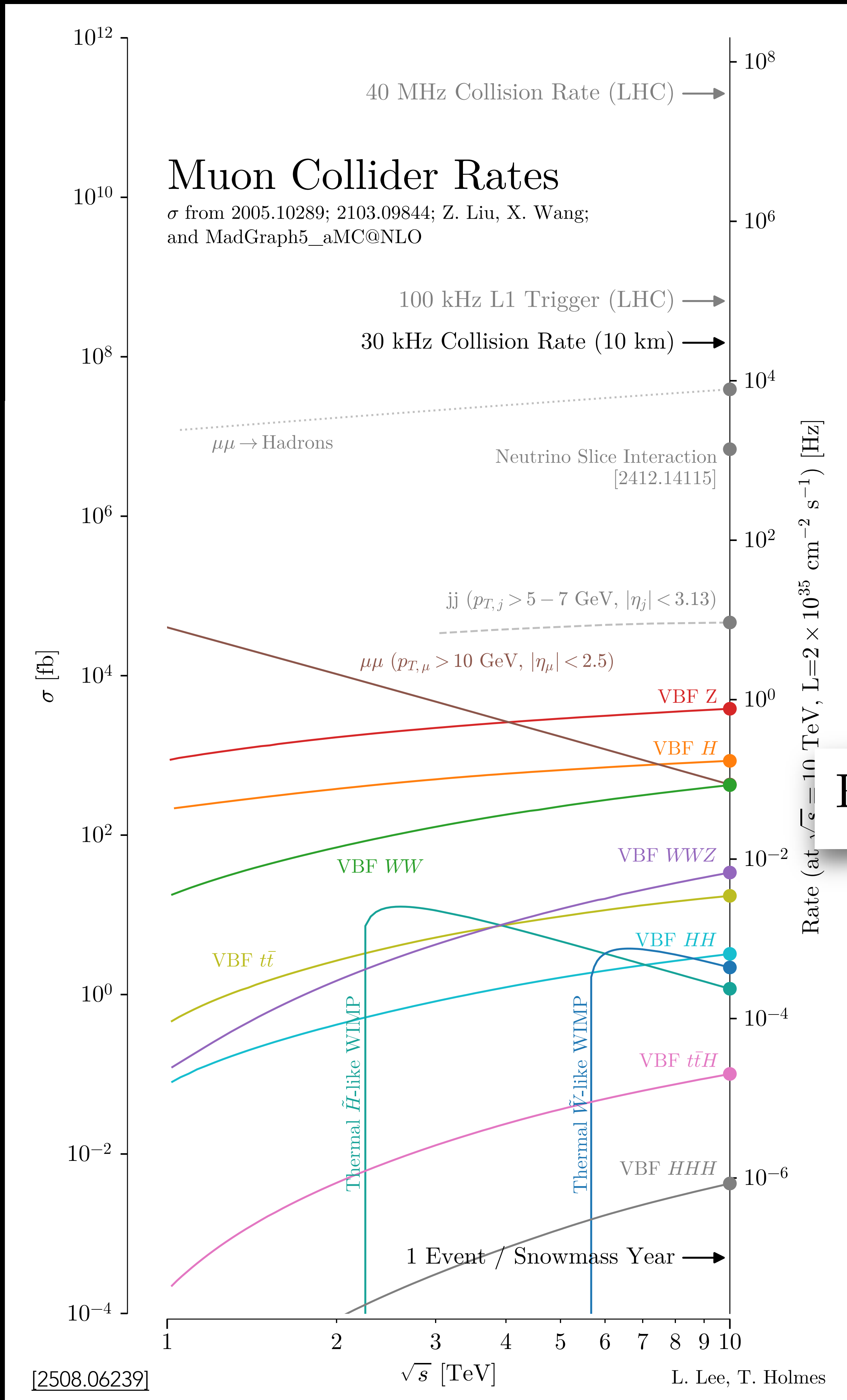
Physics of ionization energy loss is not in dispute.


jj ($p_{T,j} > 5 - 7$ GeV, $|\eta_j| < 3.13$)
$\mu\mu$ ($p_{T,\mu} > 10$ GeV, $|\eta_\mu| < 2.5$)
VBF Z
VBF H
VBF WW
VBF WWZ
VBF $t\bar{t}$
VBF HH
Thermal $\tilde{H}$-like WIMP
Thermal $\tilde{W}$-like WIMP
VBF $t\bar{t}H$
VBF HHH
σ [fb]
10^4
10^2
10^0
10^{-2}
10^{-4}
1
2
3
4
5
6
7
8
9
$\sqrt{s}$ [TeV]

[2508.06239]



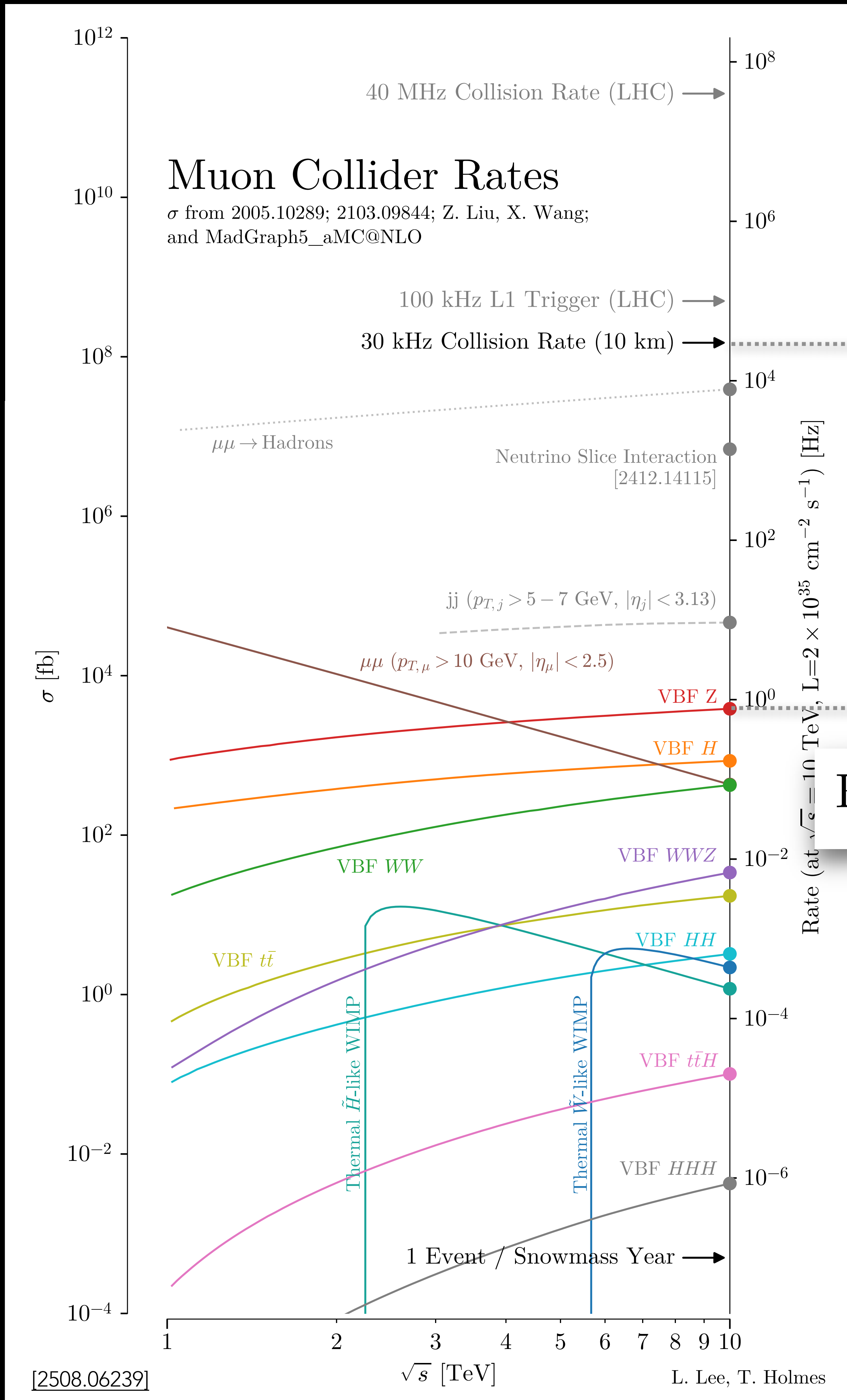
Rate (at $\sqrt{s} = 10$ TeV, L=2×10^{35} cm^{-2} s^{-1}) [Hz]



[2508.06239]

Rate (at $\sqrt{s} = 10$ TeV, L=2×10^{35} cm^{-2} s^{-1}) [Hz]

- Theorist-driven Muon Smasher's Guide's "σ_{tot}" (VBF Z/W) is < 10^{-4} × collision rate!
- Huge implications for detector design in trigger and DAQ



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Swamped by “uninteresting” stuff

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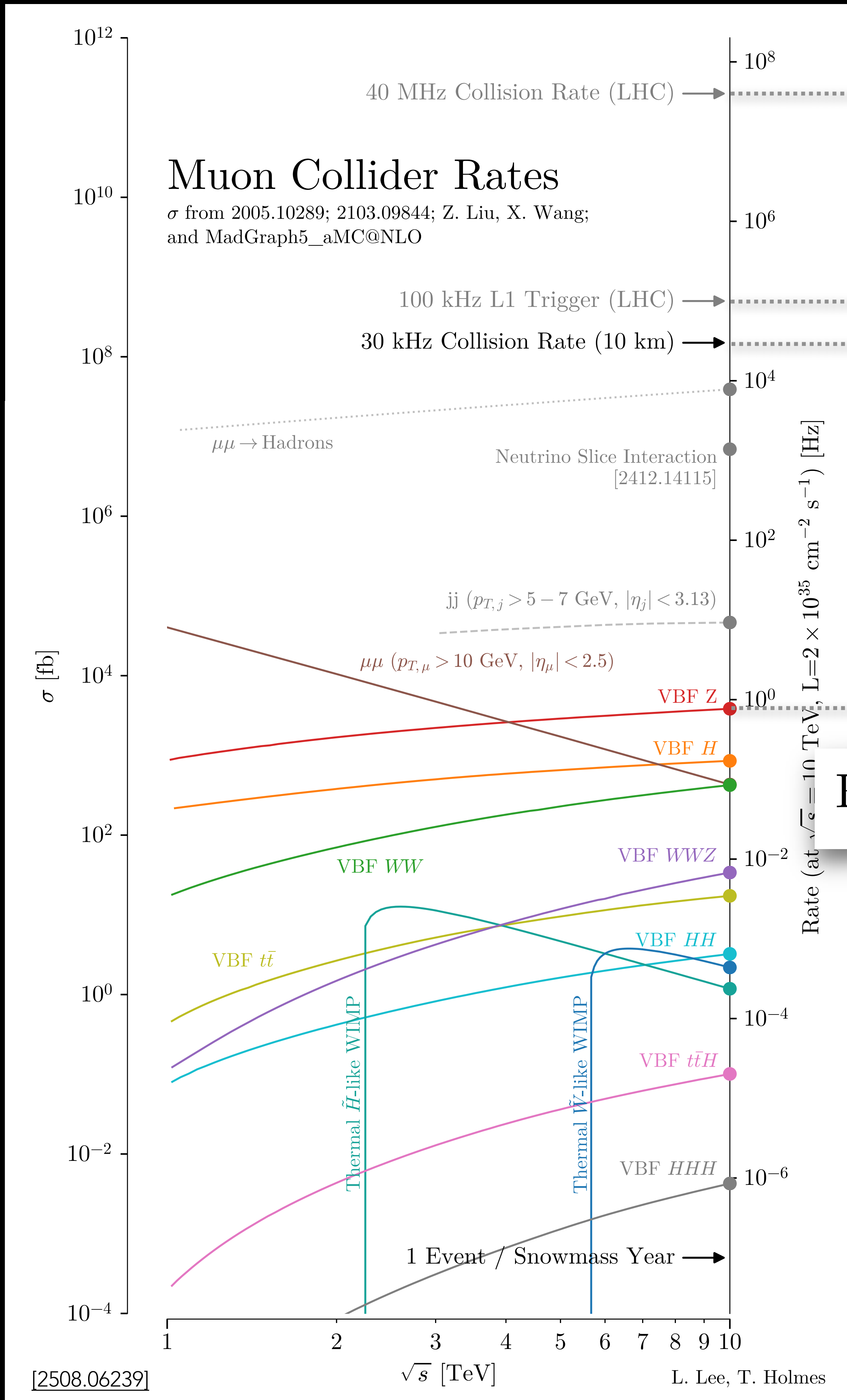

Smaller fraction than LHC throws away at L1!

Swamped by "uninteresting" stuff

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