



## The search for CLFV with the Mu2e Experiment

Kevin Lynch, AD/TSD and Mu2e

FNAL Summer 2023 Lecture Series: STEM at Work

27 July 2023

## What we'll cover...

- Let's start at the beginning
- What is CLFV?
- What is Mu2e and how does it work?
- Summary

# What exactly to physicists think we already now?

- Example: Gravity, or Why Things Fall

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- Example: Gravity, or Why Things Fall



# What exactly do physicists think we already know?

- Example: Gravity, or Why Things Fall



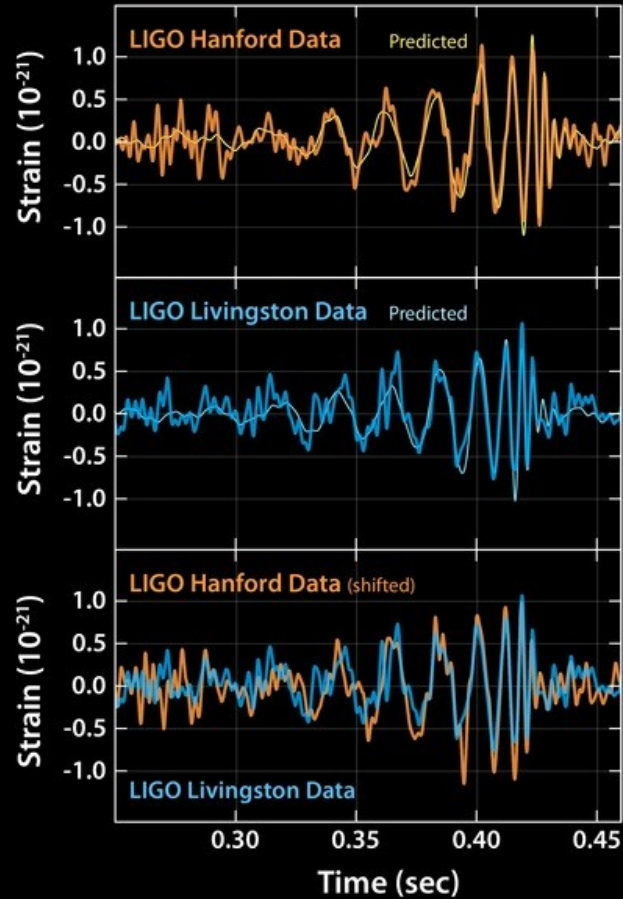
# What exactly do physicists think we already know?

- Example: Gravity, or Why Things Fall



# What exactly do physicists think we already know?

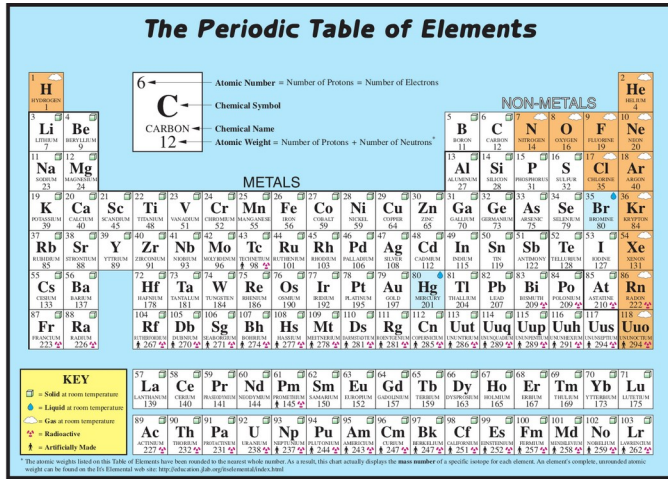
- Example: Gravity



# What else?



# What else?



# What else?

**The Periodic Table of Elements**

Atomic Number = Number of Protons = Number of Electrons  
Chemical Symbol  
Chemical Name  
Atomic Weight = Number of Protons + Number of Neutrons

**NON-METALS**

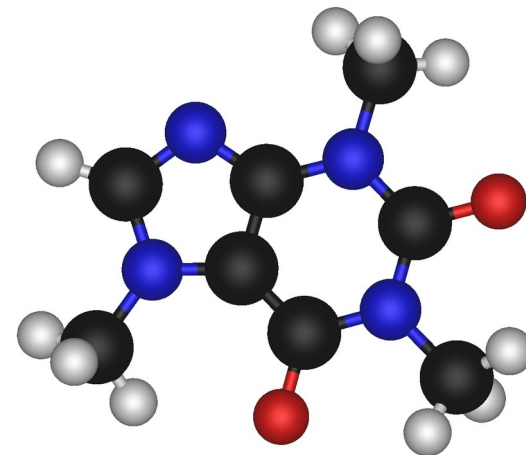
**METALS**

1	2																	10
H	He																	Ne
Li	Be											B	C	N	O	F	Ne	
Na	Mg											Al	Si	P	S	Cl	Ar	
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	
Cs	Ba																	Rn
Fr	Ra																	Uuo

**KEY**

- ☐ = Solid at room temperature
- ☉ = Liquid at room temperature
- ☁ = Gas at room temperature
- ☛ = Radioactive
- ☛ = Artificially Made

This periodic table is based on the Table of Elements that were included in the periodic table of 1911. As a result, this table actually displays the mass number of a specific isotope for each element. An element's complete, unabbreviated name, weight can be found on the IUPAC website: <http://iupac-chemistry.com/elements/index.html>



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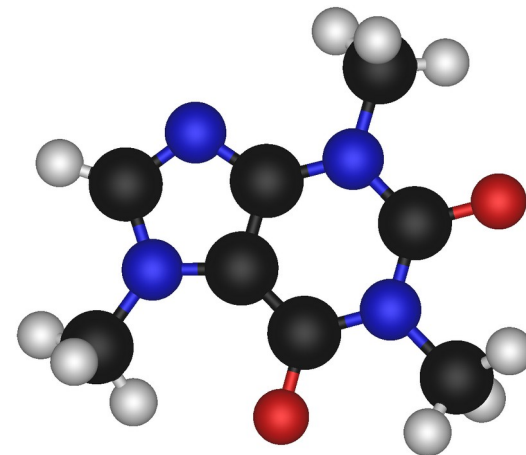
METALS

1	2																	10	11		
H	He																	Ne	Ar		
Li	Be											B	C	N	O	F	Ne	Ar	Kr	Xe	Rn
Na	Mg											Al	Si	P	S	Cl	Ar	Kr	Xe	Rn	
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	Xe	Rn		
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	Rn			
Cs	Ba	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn					
Fr	Ra	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Uuq	Uup								

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This periodic table is based on the Table of Elements from the Lawrence Livermore National Laboratory. As a result, this table actually displays the mass number of a specific isotope for each element. A weight can be found on the IUPAC website: <http://education.jlab.org/elemental/index.html>



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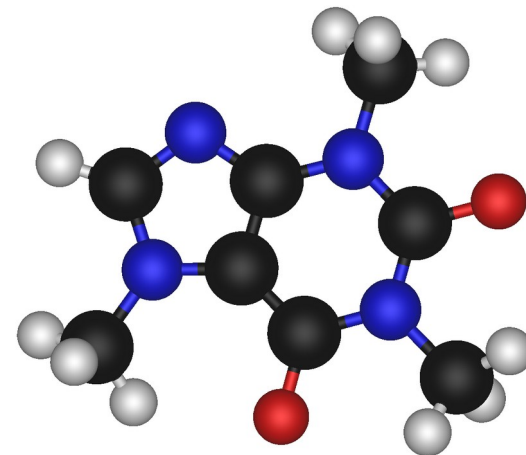
**METALS**

1 H Hydrogen	2 He Helium																	10 Ne Neon	11 Na Sodium	12 Mg Magnesium											18 Ar Argon				
3 Li Lithium	4 Be Beryllium																	19 K Potassium	20 Ca Calcium											36 Kr Krypton					
5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon																	37 Rb Rubidium	38 Sr Strontium											54 Xe Xenon	
13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon																	55 Cs Cesium	56 Ba Barium											86 Rn Radon	
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton	37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon				
87 Fr Francium	88 Ra Radium	89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 Nh Nihonium	103 Fl Flerovium	104 Mc Moscovium	105 Lv Livermorium	106 Ts Tennessine	107 Og Oganesson	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovium	116 Lv Livermorium	117 Ts Tennessine	118 Og Oganesson				

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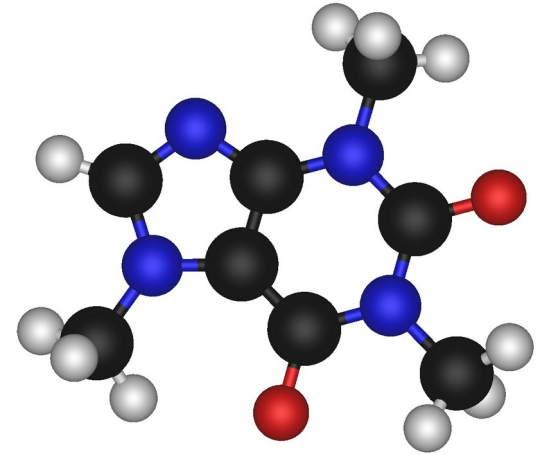
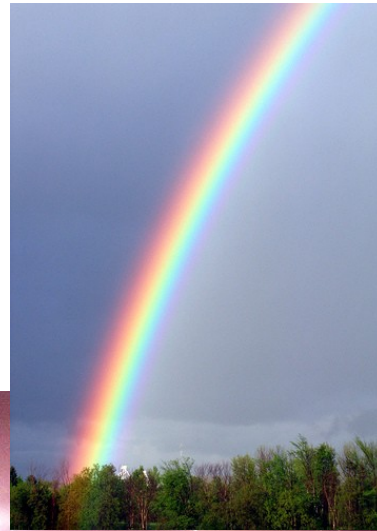
**METALS**

1	H	2	He	3	Li	4	Be	5	B	6	C	7	N	8	O	9	F	10	Ne																
11	Na	12	Mg	13	Al	14	Si	15	P	16	S	17	Cl	18	Ar																				
19	K	20	Ca	21	Sc	22	Ti	23	V	24	Cr	25	Mn	26	Fe	27	Co	28	Ni	29	Cu	30	Zn	31	Ga	32	Ge	33	As	34	Se	35	Br	36	Kr
37	Rb	38	Sr	39	Y	40	Zr	41	Nb	42	Mo	43	Tc	44	Ru	45	Rh	46	Pd	47	Ag	48	Cd	49	In	50	Sn	51	Sb	52	Te	53	I	54	Xe
55	Cs	56	Ba	57	La	58	Ce	59	Pr	60	Nd	61	Pm	62	Sm	63	Eu	64	Gd	65	Tb	66	Dy	67	Ho	68	Er								
87	Fr	88	Ra	89	Rf	90	Th	91	Pa	92	U	93	Np	94	Pu	95	Am	96	Cm	97	Bk	98	Cf	99	Es	100	Fm								

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# What else?

**The Periodic Table of Elements**

6 ← Atomic Number = Number of Protons = Number of Electrons  
C ← Chemical Symbol  
CARBON-12 ← Atomic Weight = Number of Protons + Number of Neutrons

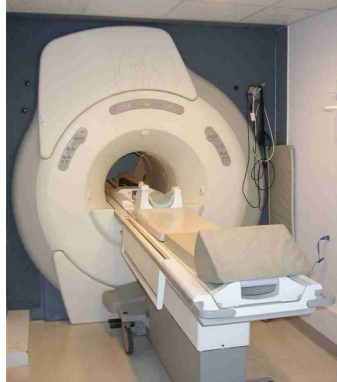
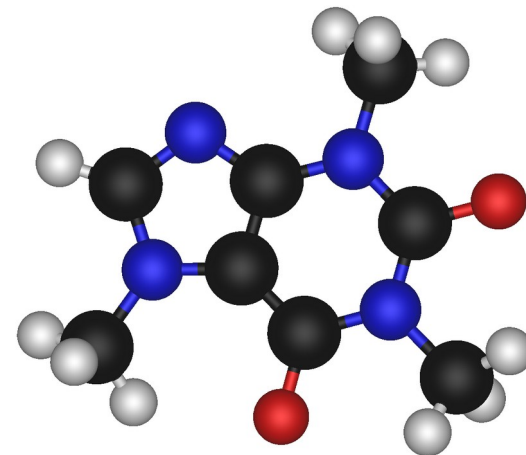
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1	2																	10																																																															
H	He																	Ne																																																															
Li	Be	B	C	N	O	F	Ne	Na	Mg	Al	Si	P	S	Cl	Ar	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr																																																
3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40																																												
Na	Mg	Al	Si	P	S	Cl	Ar	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe																																						
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	Cs	Ba	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	W	Re	Os	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn																																	
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100																		
Cs	Ba	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	W	Re	Os	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn	Fr	Ra	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Uuq	Uup																																					
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**6** ←  
**C**  
←  
**CARBON**  
←  
**12**

NON-METALS

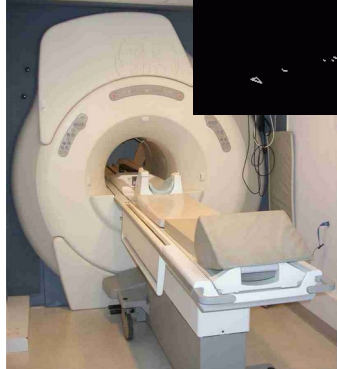
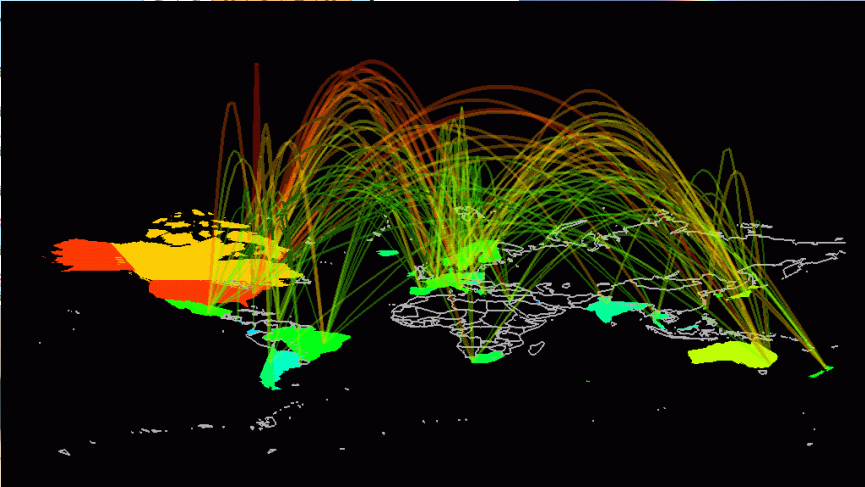
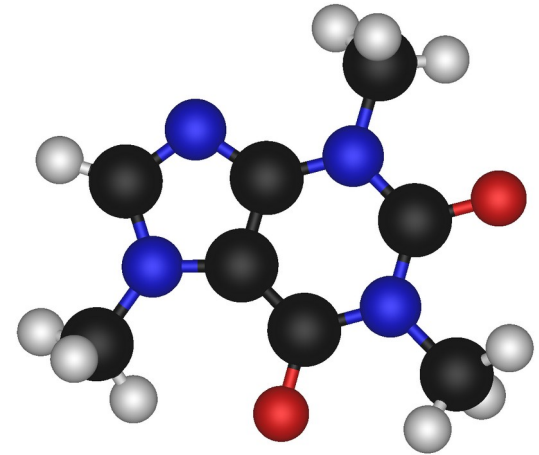
METALS

1	2											3	4				
H	He											Li	Be				
3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
Li	Be	B	C	N	O	F	Ne	Na	Mg	Al	Si	P	S	Cl	Ar		
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
Cs	Ba	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf
87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104
Fr	Ra	Ac	Th	Pa	U	Np	Pu	A	B	C	D	E	F	G	H	I	J
85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102
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- Why are there so many forces?

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- Why are there so many forces?

We have theories and models that we think can describe most of these - but we don't really understand all the "whys" and "whats" and "hows" – and there are things we know we don't know!

# *Quantum Field Theory and the Standard Model* quantify what we know

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## Matter

# *Quantum Field Theory* and the *Standard Model* quantify what we know

Matter

Forces

# Quantum Field Theory and the Standard Model quantify what we know

Matter

2,4 MeV $\frac{2}{3}$ $\frac{1}{2}$ <b>u</b> up	1,27 GeV $\frac{2}{3}$ $\frac{1}{2}$ <b>c</b> charm	171,2 GeV $\frac{2}{3}$ $\frac{1}{2}$ <b>t</b> top	0 0 1 <b>γ</b> photon
4,8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ <b>d</b> down	104 MeV $-\frac{1}{3}$ $\frac{1}{2}$ <b>s</b> strange	4,2 GeV $-\frac{1}{3}$ $\frac{1}{2}$ <b>b</b> bottom	0 0 1 <b>g</b> gluon
<2,2 eV 0 $\frac{1}{2}$ <b>ν<sub>e</sub></b> electron neutrino	<0,17 MeV 0 $\frac{1}{2}$ <b>ν<sub>μ</sub></b> muon neutrino	<15,5 MeV 0 $\frac{1}{2}$ <b>ν<sub>τ</sub></b> tau neutrino	91,2 GeV 0 1 <b>Z<sup>0</sup></b> weak force
0,511 MeV -1 $\frac{1}{2}$ <b>e</b> electron	105,7 MeV -1 $\frac{1}{2}$ <b>μ</b> muon	1,777 GeV -1 $\frac{1}{2}$ <b>τ</b> Tau	80,4 GeV ±1 1 <b>W<sup>±</sup></b> weak force

Forces

# Quantum Field Theory and the Standard Model quantify what we know

Matter

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<2,2 eV 0 $\frac{1}{2}$ <b><math>\nu_e</math></b> electron neutrino	<0,17 MeV 0 $\frac{1}{2}$ <b><math>\nu_\mu</math></b> muon neutrino	<15,5 MeV 0 $\frac{1}{2}$ <b><math>\nu_\tau</math></b> tau neutrino	91,2 GeV 0 1 <b><math>Z^0</math></b> weak force
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0,511 MeV -1 $\frac{1}{2}$ <b>e</b> electron	105,7 MeV -1 $\frac{1}{2}$ <b><math>\mu</math></b> muon	1,777 GeV -1 $\frac{1}{2}$ <b><math>\tau</math></b> Tau	80,4 GeV $\pm 1$ 1 <b><math>W^\pm</math></b> weak force

Forces



# Quantum Field Theory and the Standard Model quantify what we know

Quarks  
Matter

2,4 MeV $\frac{2}{3}$ $\frac{1}{2}$ <b>u</b> up	1,27 GeV $\frac{2}{3}$ $\frac{1}{2}$ <b>c</b> charm	171,2 GeV $\frac{2}{3}$ $\frac{1}{2}$ <b>t</b> top	0 0 <b><math>\gamma</math></b> 1 photon
4,8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ <b>d</b> down	104 MeV $-\frac{1}{3}$ $\frac{1}{2}$ <b>s</b> strange	4,2 GeV $-\frac{1}{3}$ $\frac{1}{2}$ <b>b</b> bottom	0 0 <b>g</b> 1 gluon
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0,511 MeV -1 $\frac{1}{2}$ <b>e</b> electron	105,7 MeV -1 $\frac{1}{2}$ <b><math>\mu</math></b> muon	1,777 GeV -1 $\frac{1}{2}$ <b><math>\tau</math></b> Tau	80,4 GeV $\pm 1$ 1 <b><math>W^\pm</math></b> 1 weak force

Forces

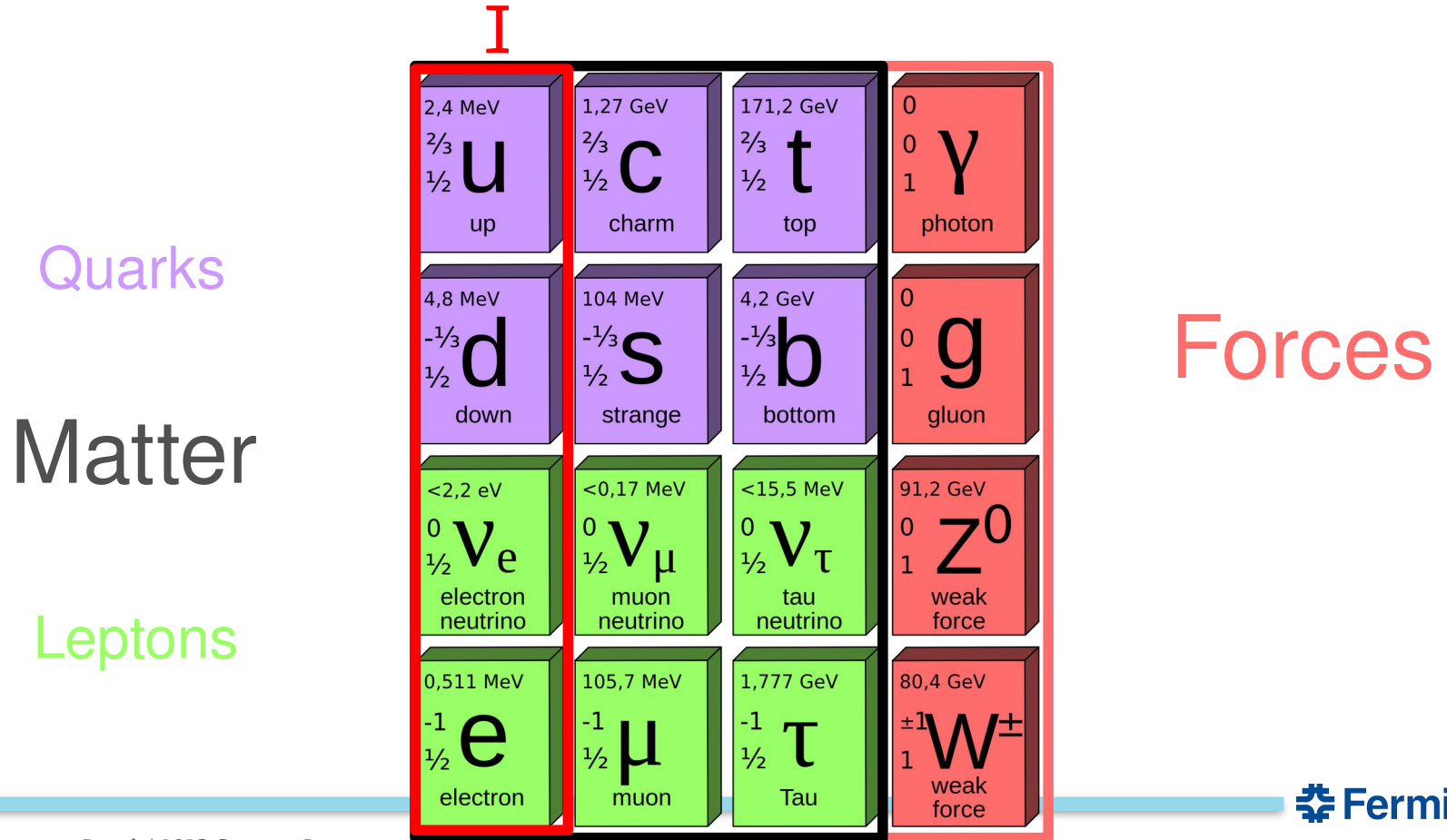
# Quantum Field Theory and the Standard Model quantify what we know

Quarks  
Matter  
Leptons

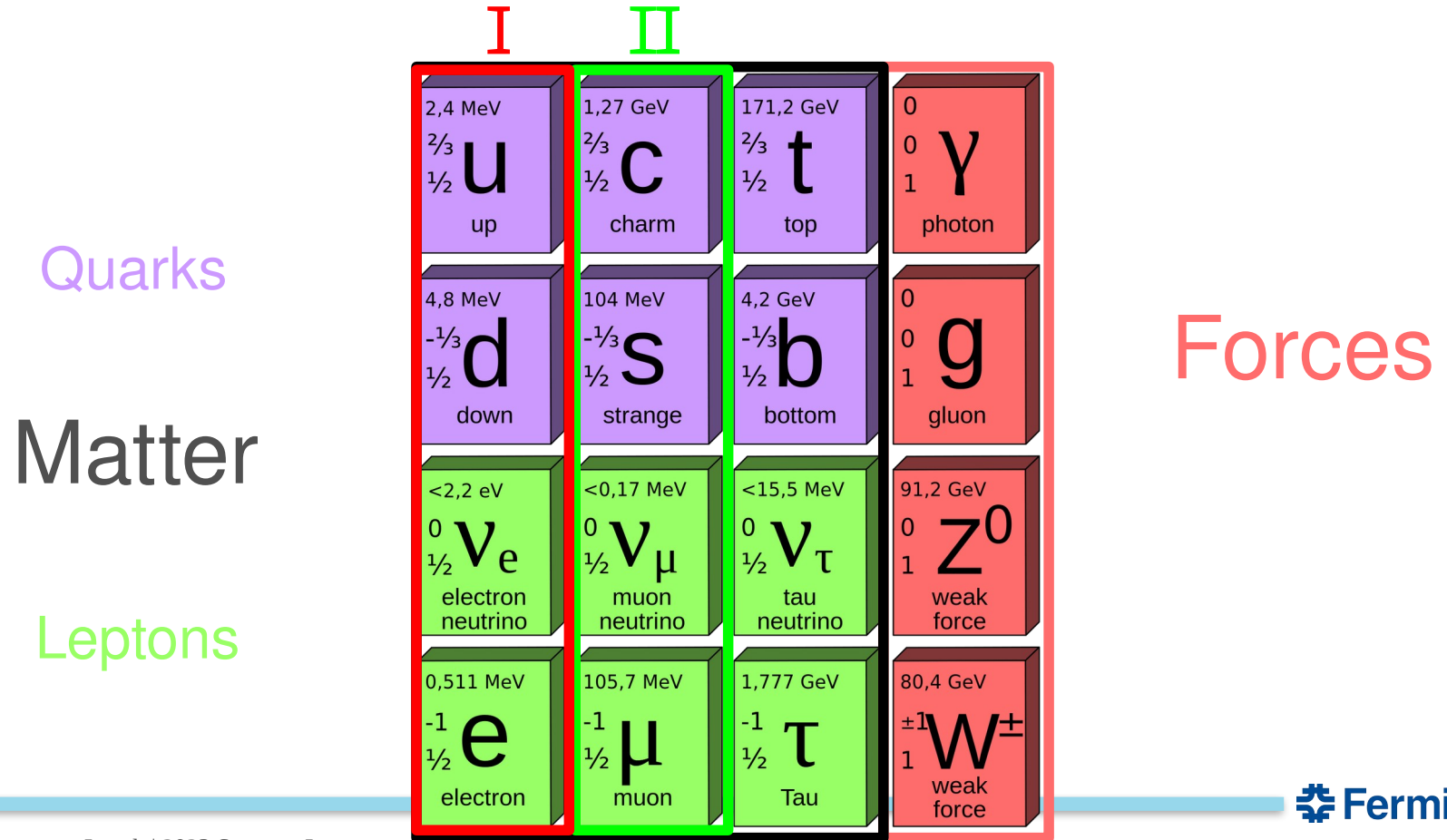
2,4 MeV $\frac{2}{3}$ $\frac{1}{2}$ <b>u</b> up	1,27 GeV $\frac{2}{3}$ $\frac{1}{2}$ <b>c</b> charm	171,2 GeV $\frac{2}{3}$ $\frac{1}{2}$ <b>t</b> top	0 0 <b>γ</b> 1 photon
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0,511 MeV -1 $\frac{1}{2}$ <b>e</b> electron	105,7 MeV -1 $\frac{1}{2}$ <b>μ</b> muon	1,777 GeV -1 $\frac{1}{2}$ <b>τ</b> Tau	80,4 GeV ±1 1 <b>W<sup>±</sup></b> 1 weak force

Forces

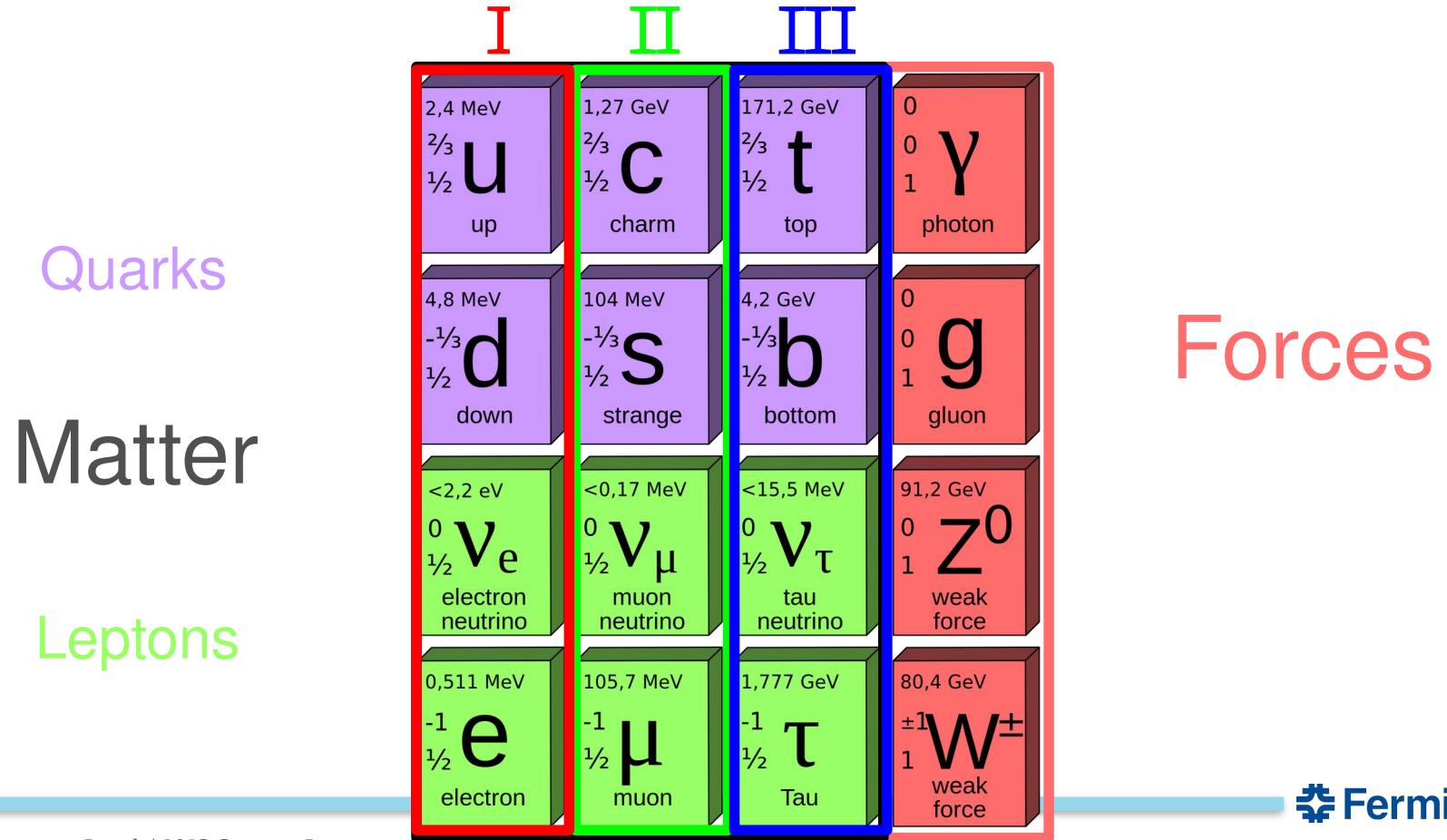
# Quantum Field Theory and the Standard Model quantify what we know



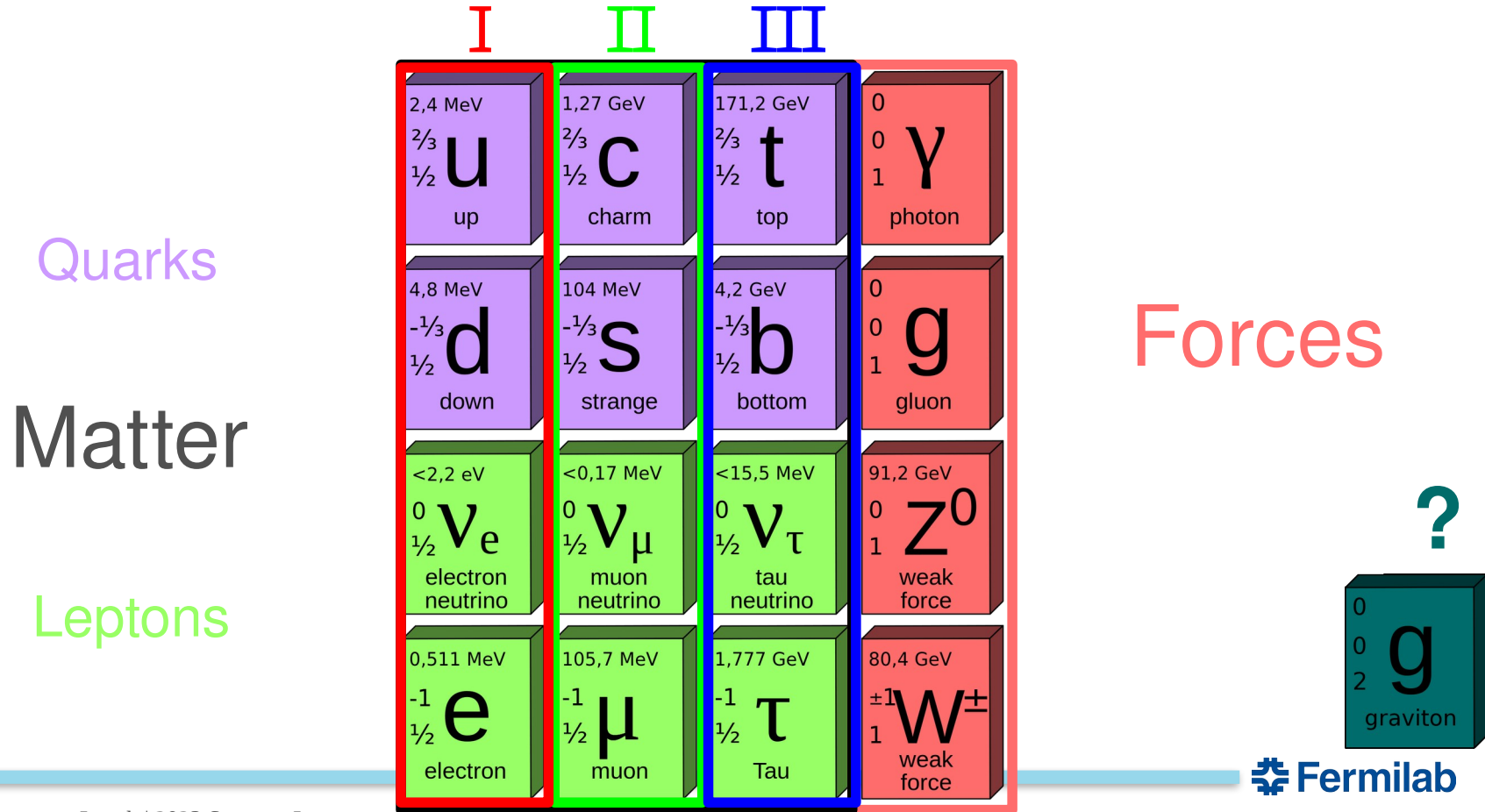
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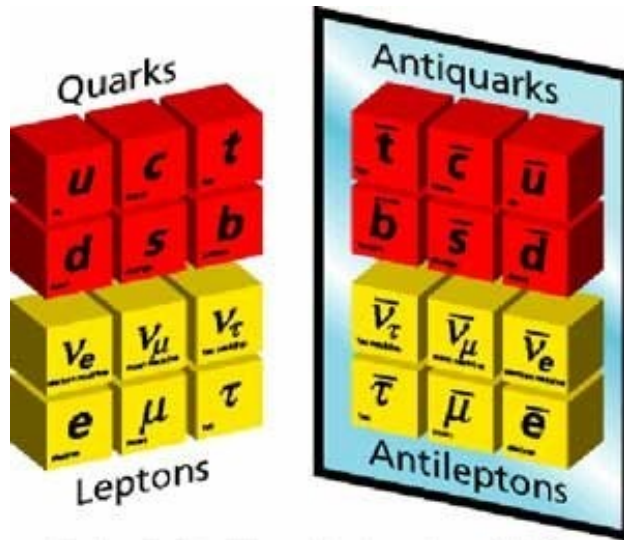
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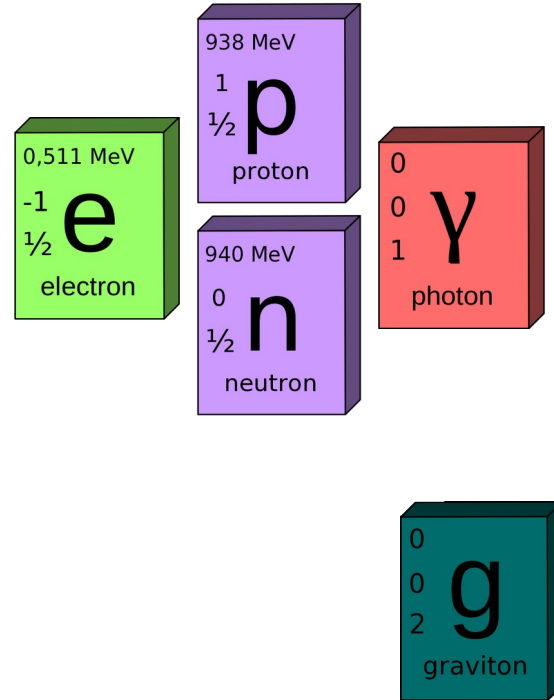


And there's a mirror world of "antimatter"

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# It is the *Standard Model* that quantifies what we know

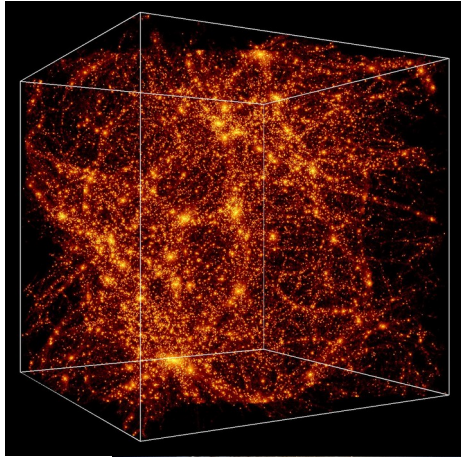
But we don't see all this complexity in our everyday existence!





# There are no experiments in conflict\* with the Standard Model ...

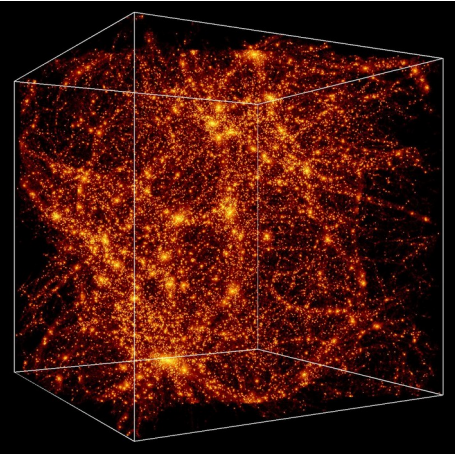
# There are no experiments in conflict\* with the Standard Model ...



From the very  
largest known  
structures...



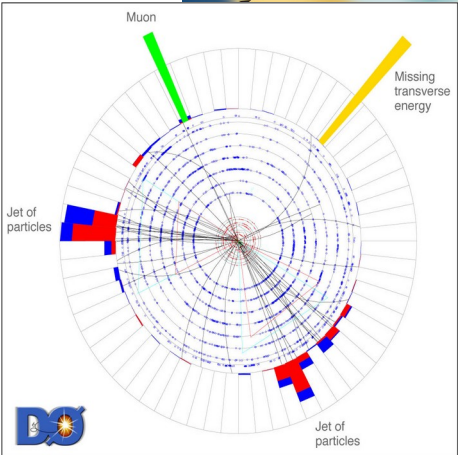
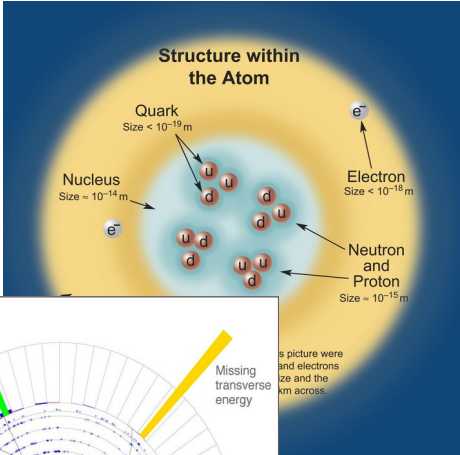
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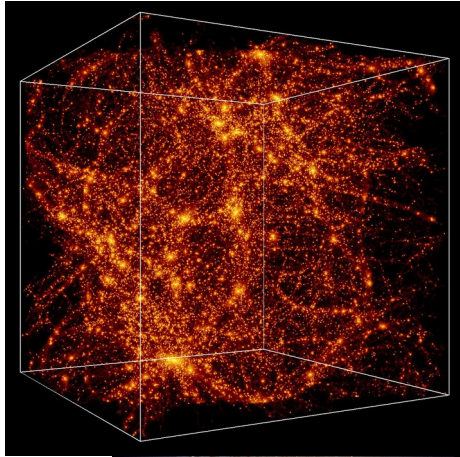


... to the very smallest!



This picture were and electrons size and the km across.

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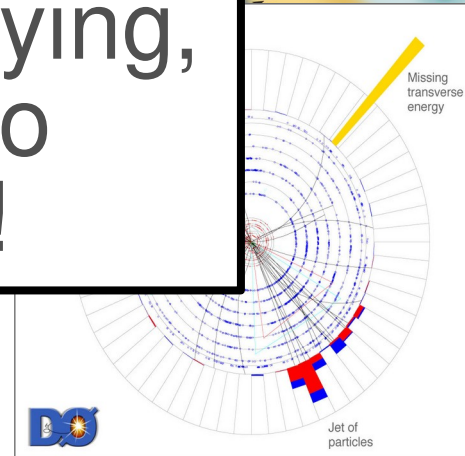
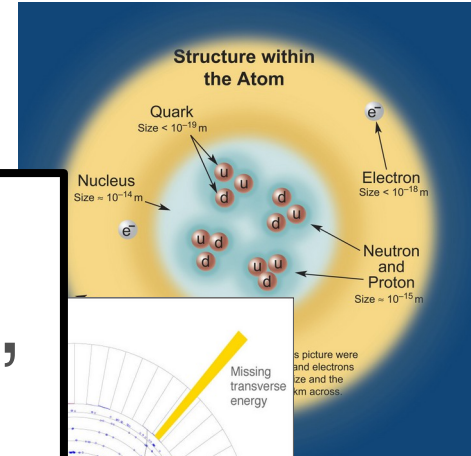


From the very largest known

This is extremely frustrating, annoying, and difficult to understand!



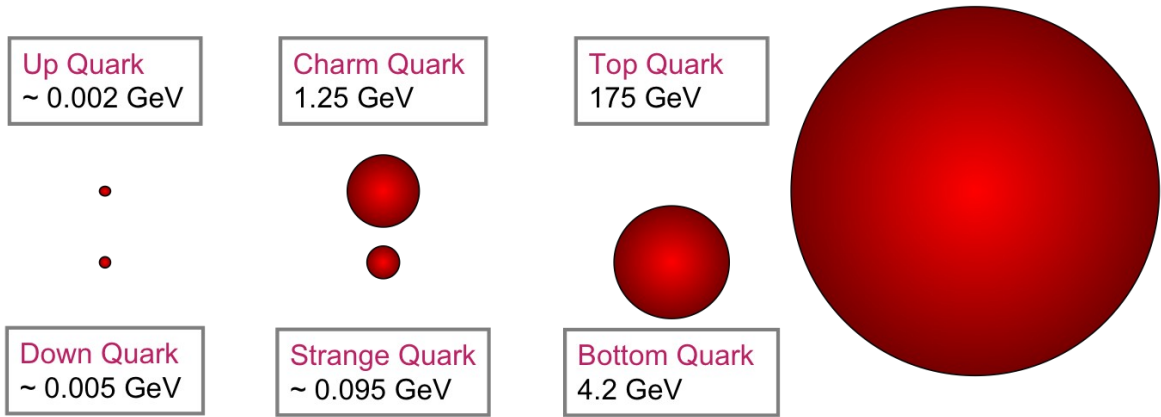
very smallest!



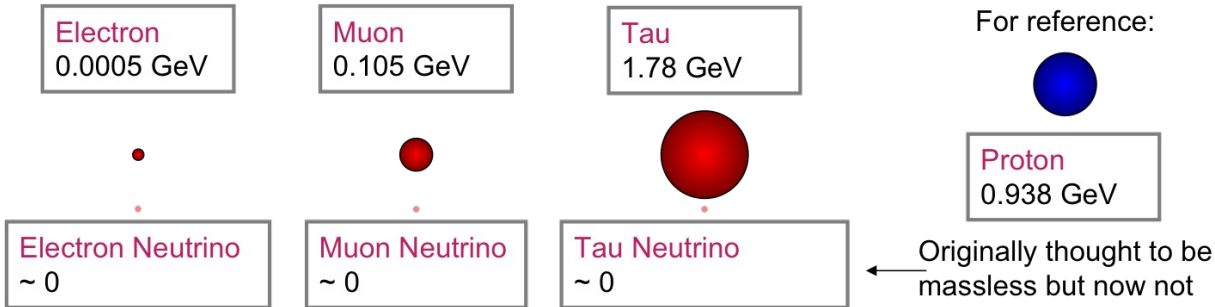
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# But all is not well: The flavor problem – Or, why are things heavy?

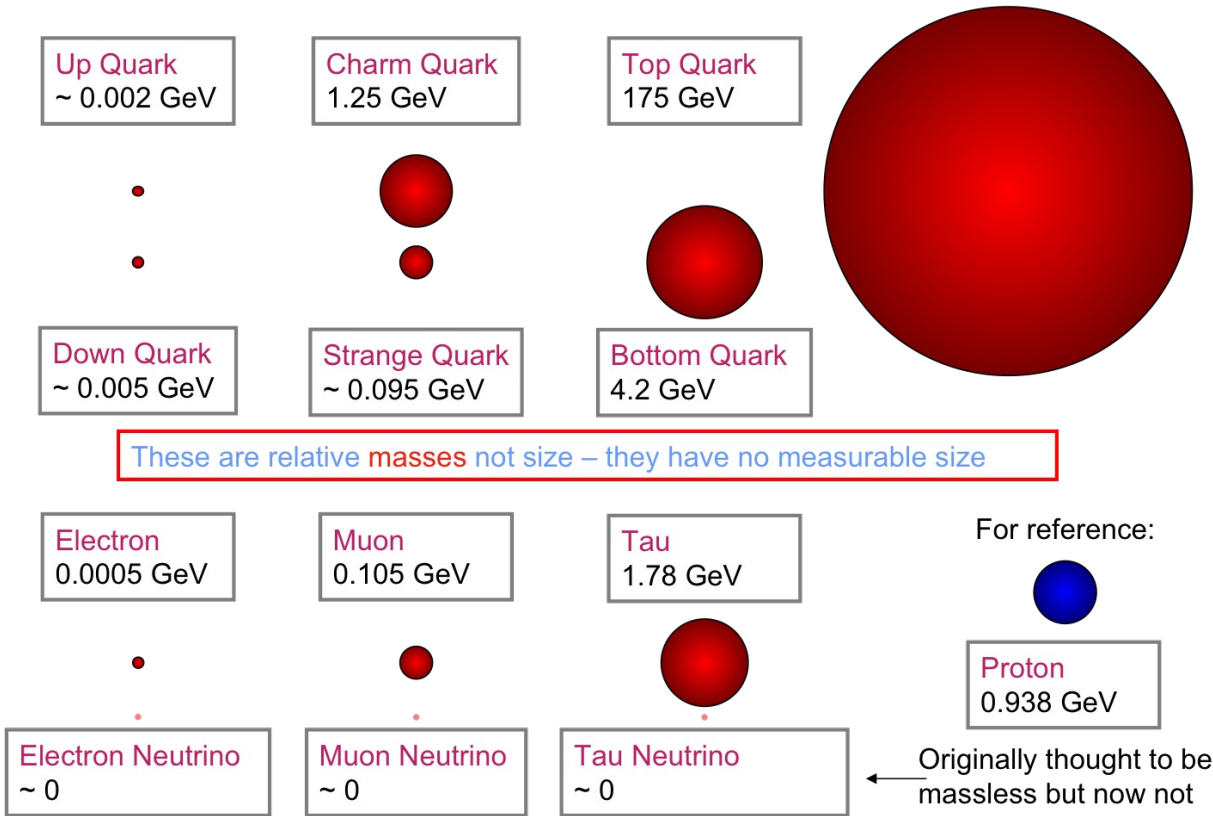
# But all is not well: The flavor problem – Or, why are things heavy?



These are relative masses not size – they have no measurable size



# But all is not well: The flavor problem – Or, why are things heavy?



We have a descriptive – but not explanatory! - solution: the Higgs Boson

# Some other minor issues: what's the rest of the universe?

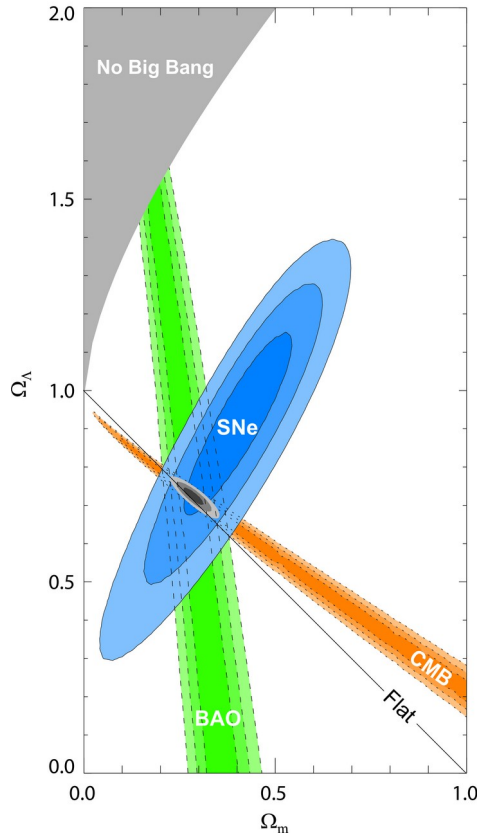


## Some other minor issues: what's the rest of the universe?

96% of the universe is *not* the stuff I've told you about! And we have no idea what that other stuff is!

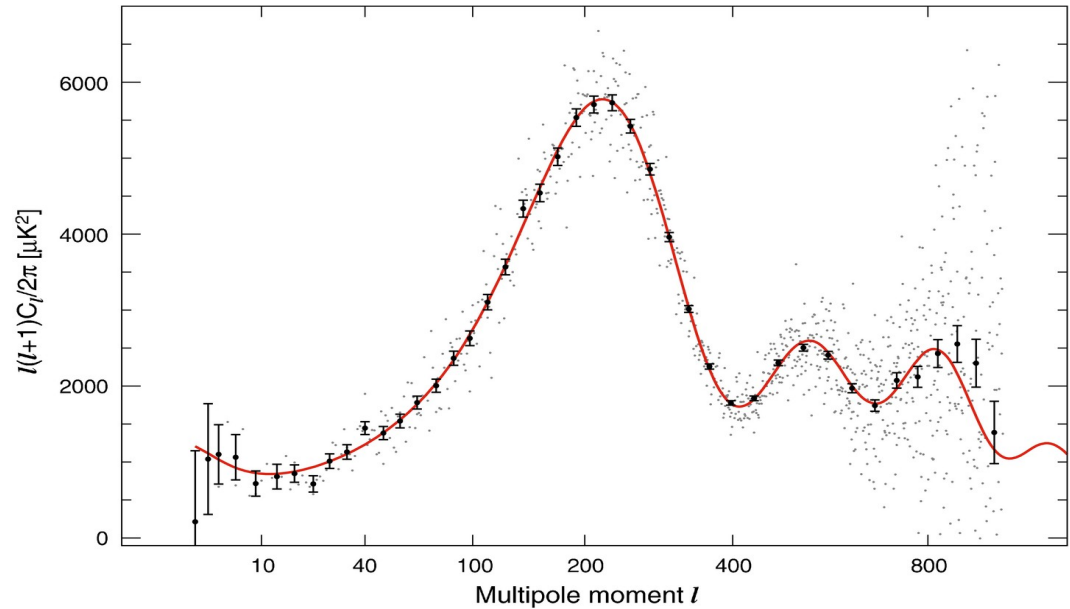
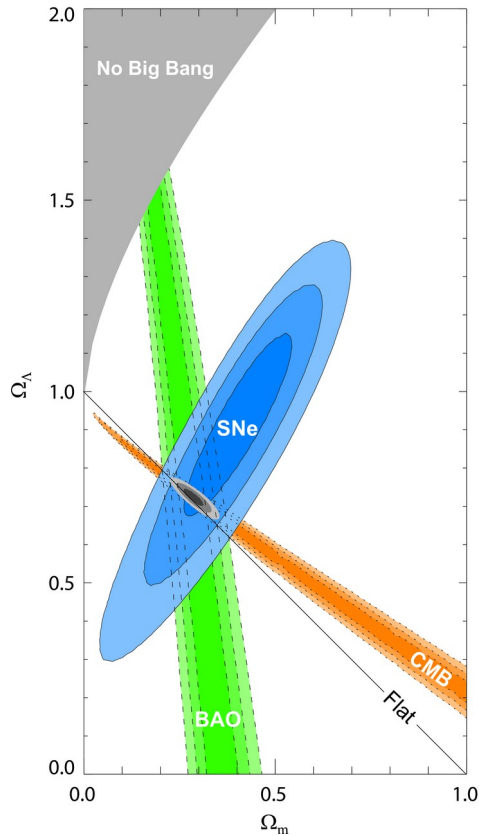
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- Modified gravity
- Extra dimensions to the universe
  - Both small and large varieties
- Add new particles
  - Supersymmetry
- Add new forces
  - Strongly and weakly interacting
- And lots of others!

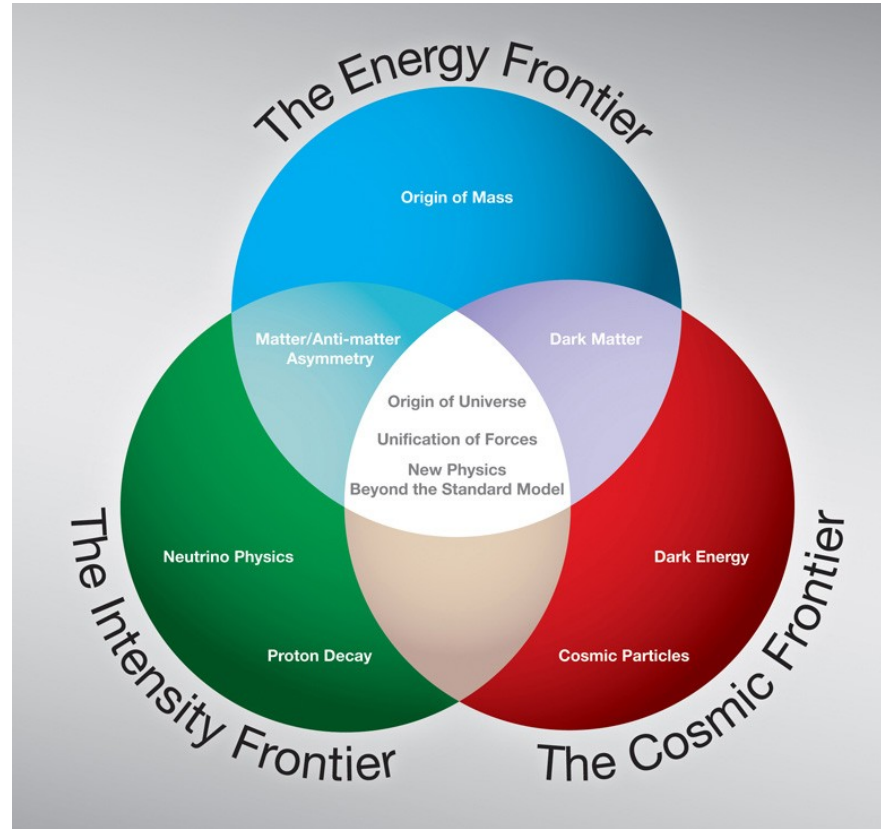
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None of these scenarios (yet) provide a complete, consistent solution ... and they never will, in the absence of guidance from *experiments*.

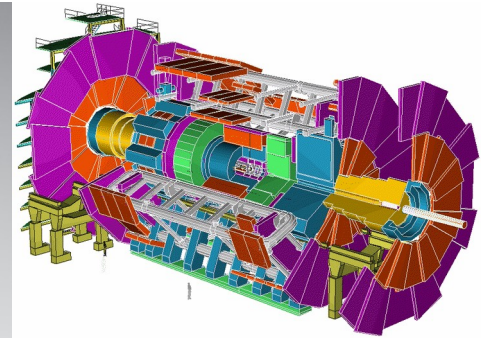
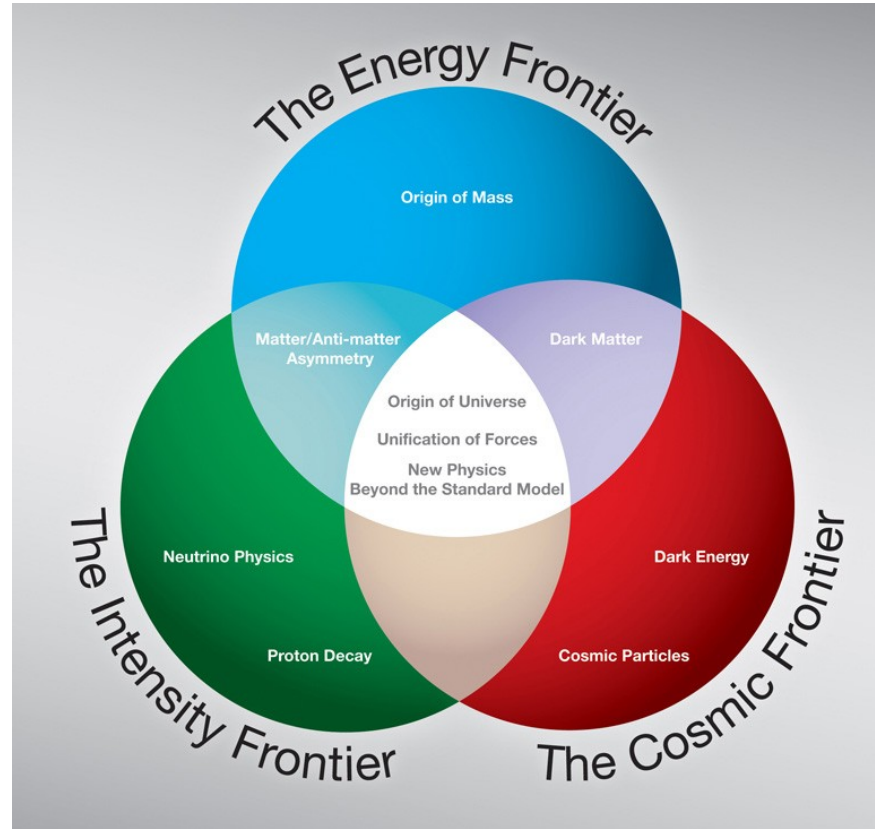
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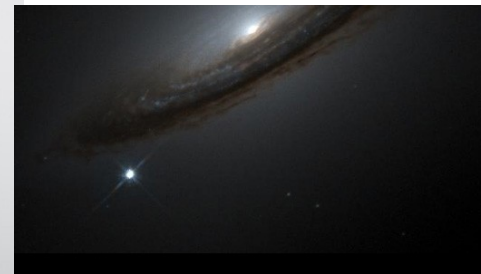
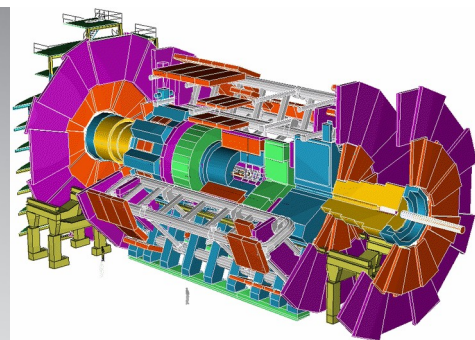
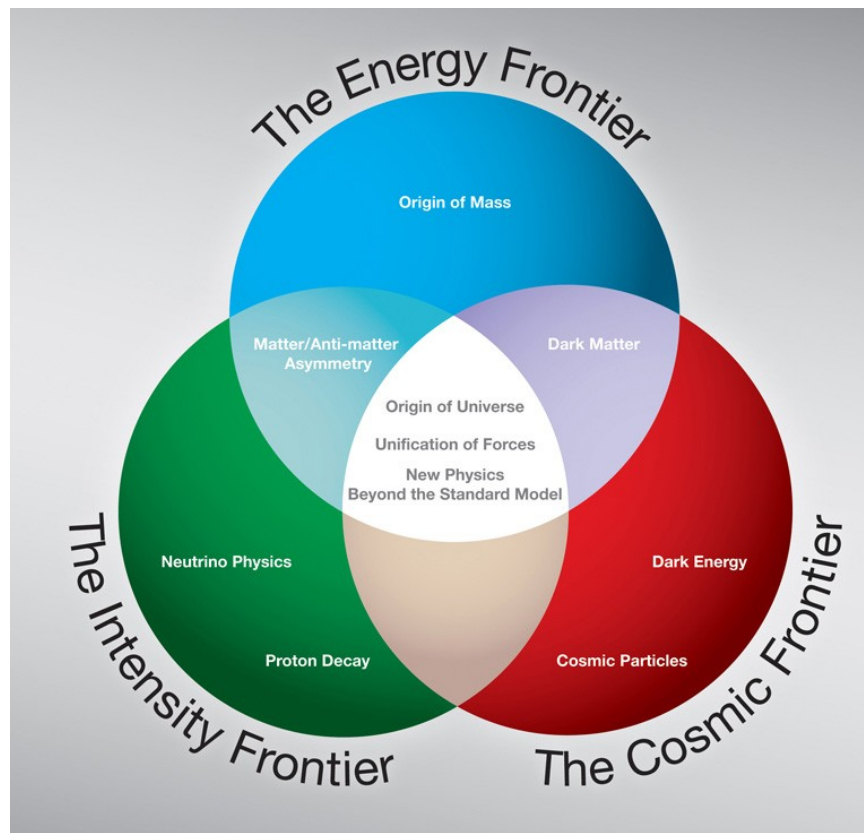




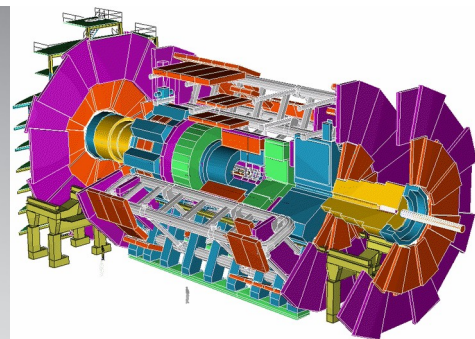
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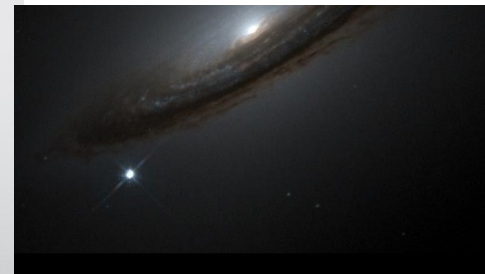
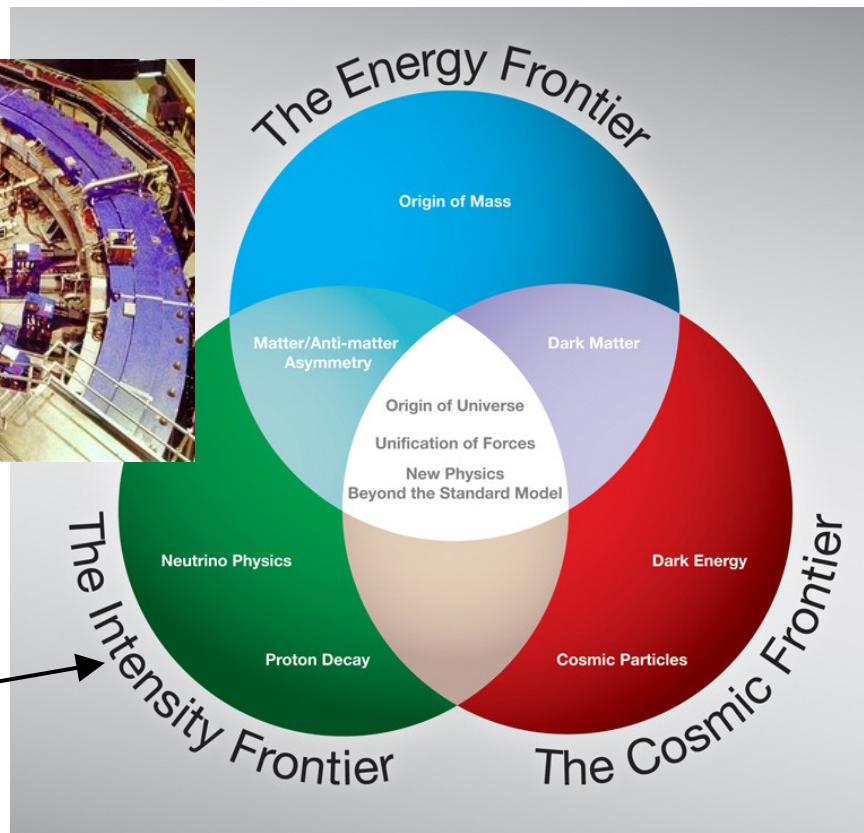
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Mu2e lives here!

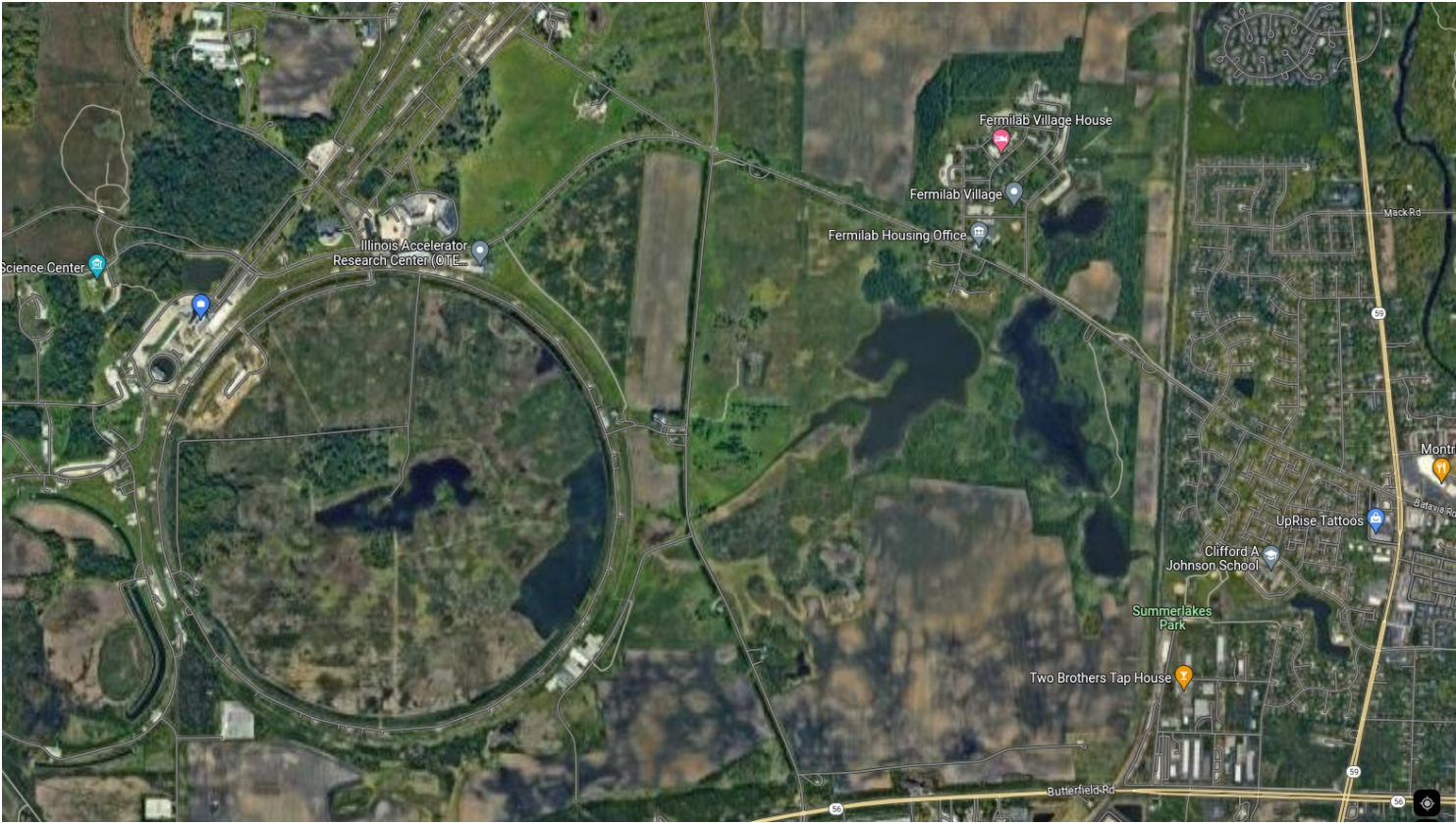


# Intensity Frontier experiments are further split into two classes

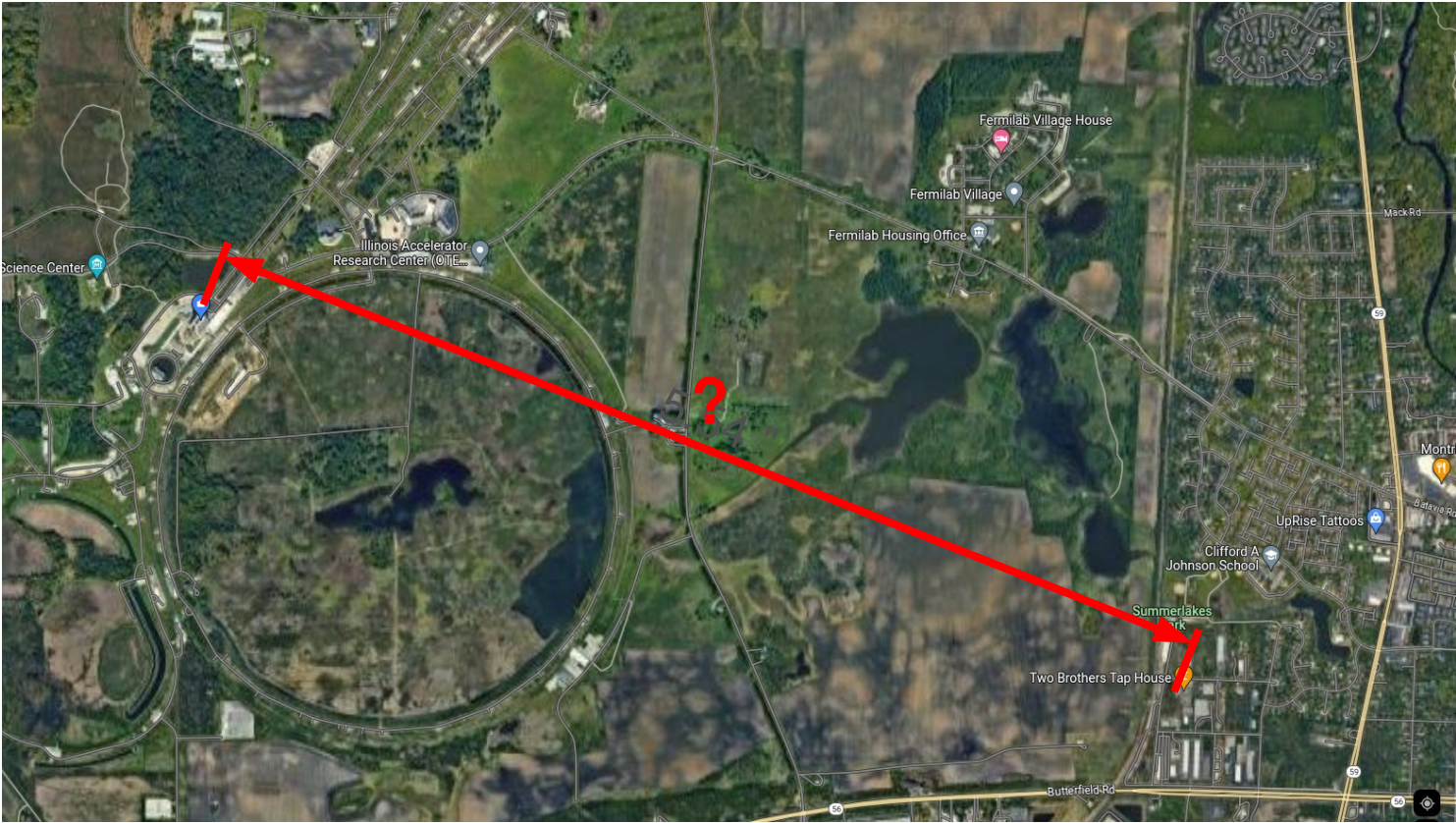
- Precision Measurements
  - Try to measure specific parameters with ridiculously high precision
    - Eg: Muon  $g-2$
- Rare and Forbidden Process Searches
  - We look in huge piles of data for
    - Events the Standard Model predicts are extremely rare, in the hopes they occur more/less often, or
    - Events the Standard Model predicts don't happen at all, in the hopes that they occur more often than that
    - Eg:  $\text{Mu}2e$

# Precision Measurements: How far to Two Brothers?

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# Rare Searches: what is the natural frequency of people with blue hair?



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Oh, and, make sure you aren't fooled by people who *dye* their hair blue ... and then lie about it!

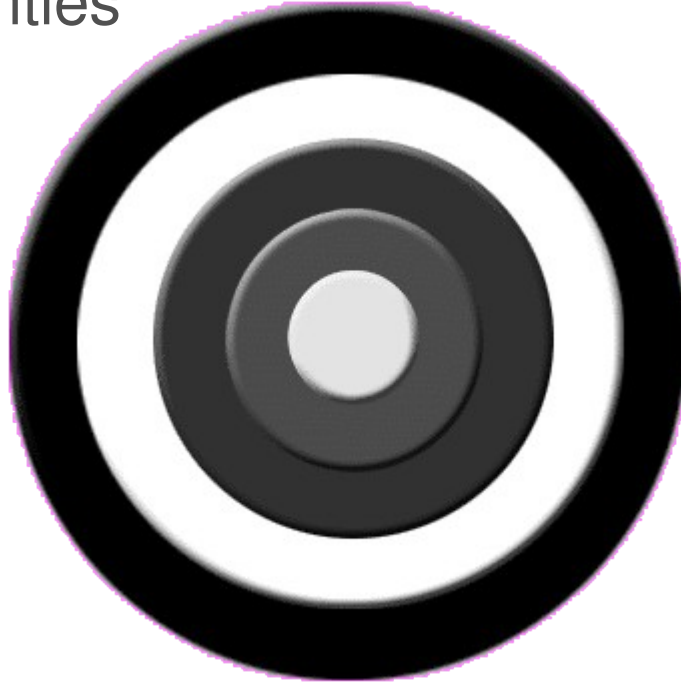
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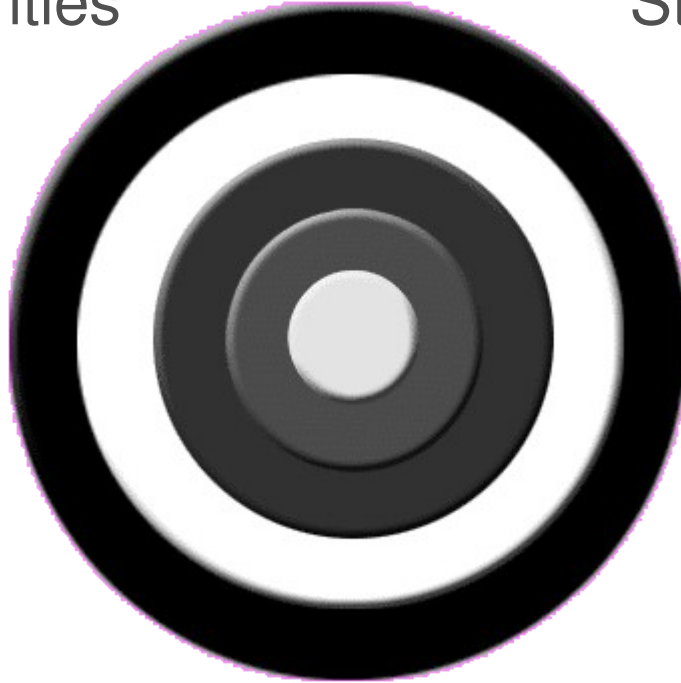
Systematic Uncertainties



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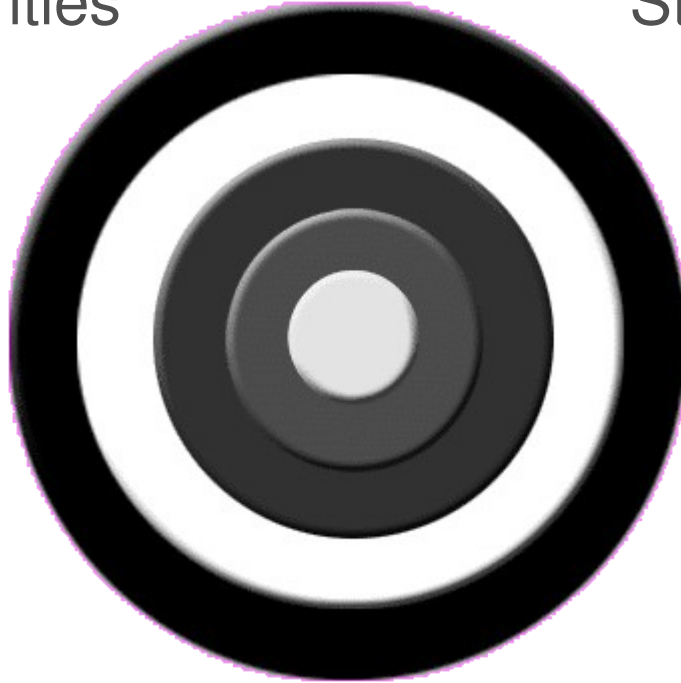
Statistical Uncertainties



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## Systematic Uncertainties

Systematics is about removing or accounting for effects that shift or scale your measurements from underlying physics.



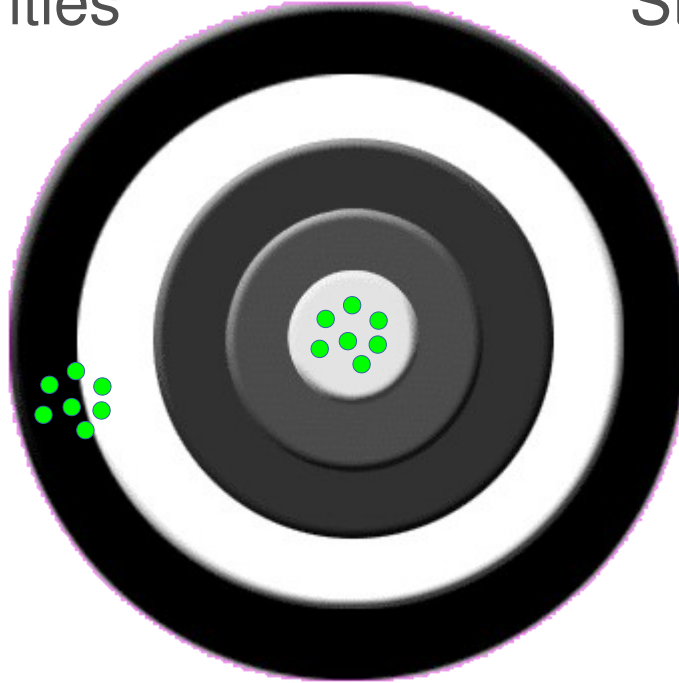
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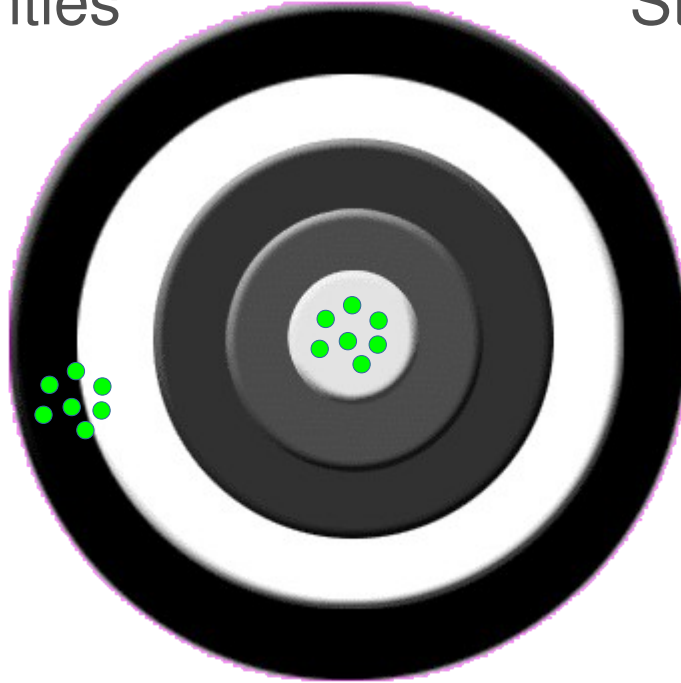




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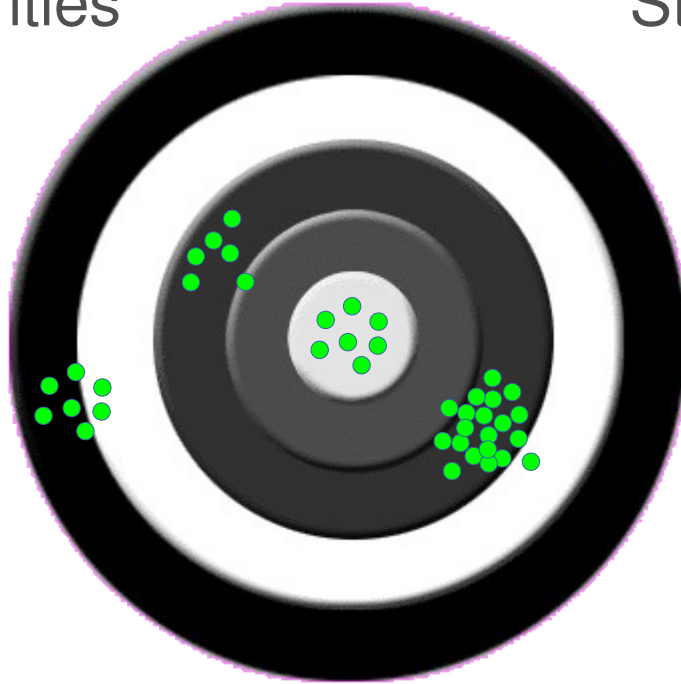
Statistics is about making *lots* of measurements to overcome Poisson.

$$\frac{\delta\tau}{\tau} \propto \frac{1}{\sqrt{N}}$$

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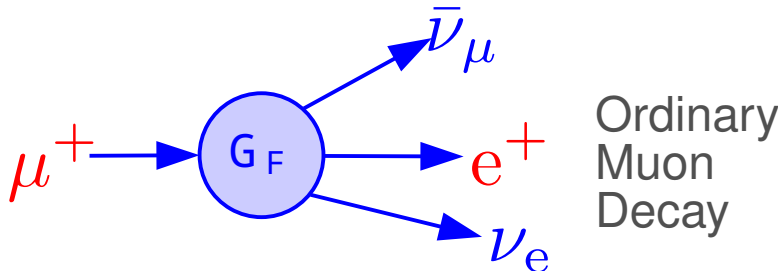
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I.I.Rabi: "Who ordered that?"

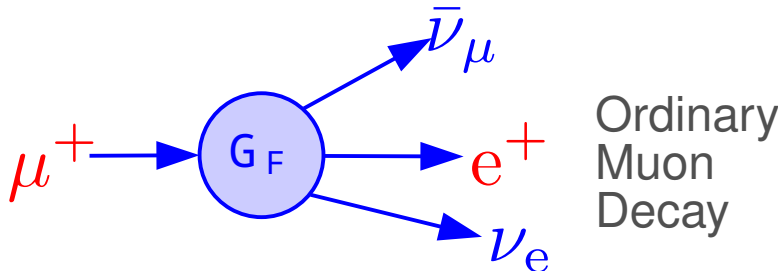
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**But we do know lots of things *about* muons!**

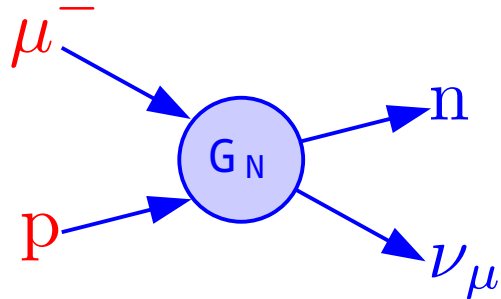
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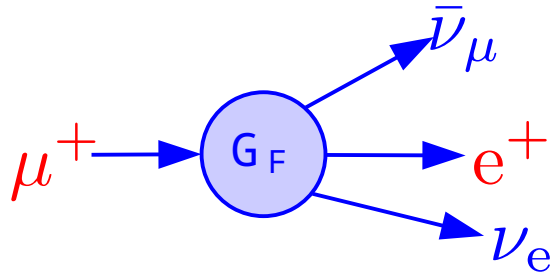


Ordinary  
Muon  
Decay

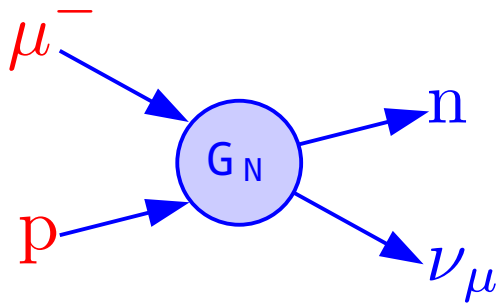


Muon  
Nuclear  
Capture

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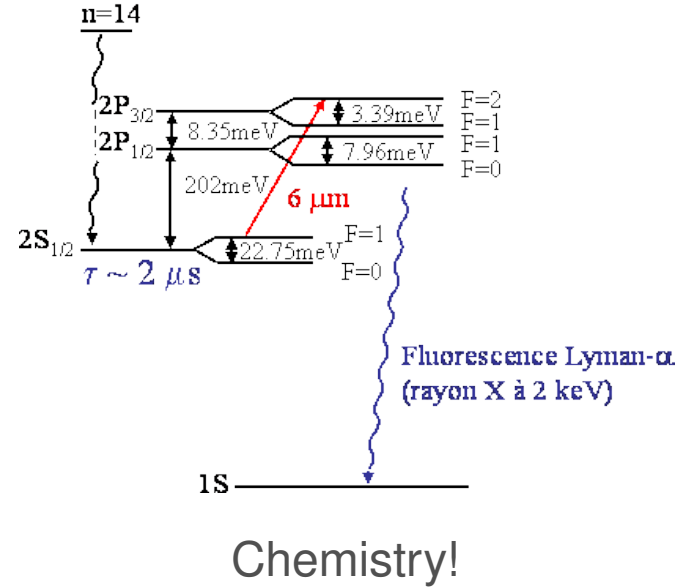


Ordinary  
Muon  
Decay



Muon  
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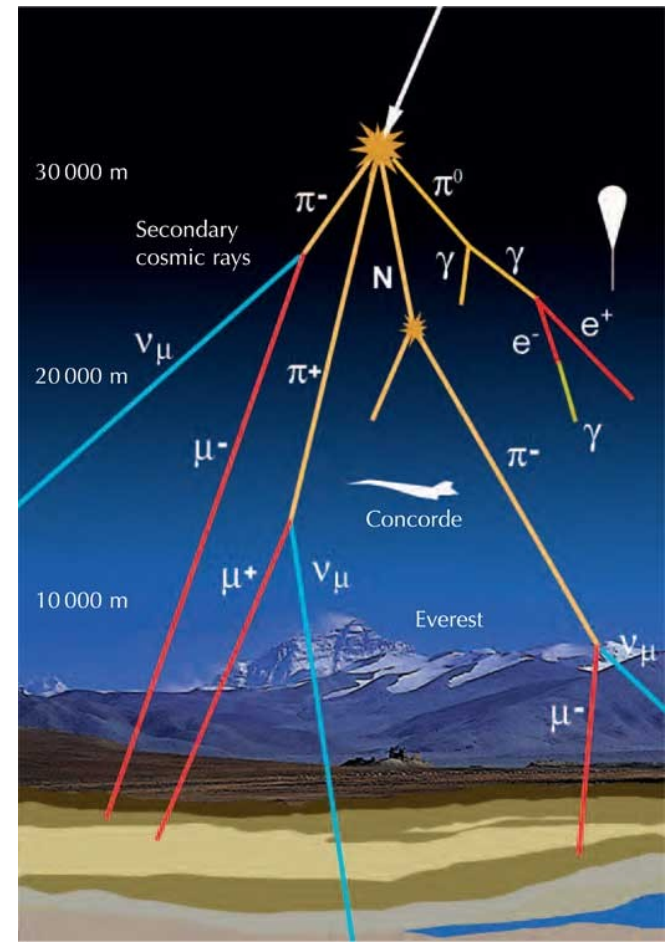
Collisions :  $\mu^- + H_2 \rightarrow [\mu, p^+]$  ( $n=14$ )



# Making muons is easy!

You bathe in cosmic ray muons every second of your life!

- ~1 per square centimeter per minute at sea level
- 10,000 will pass through you during this talk!

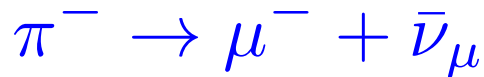
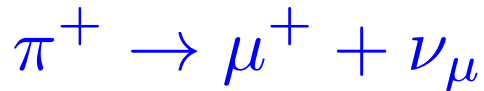


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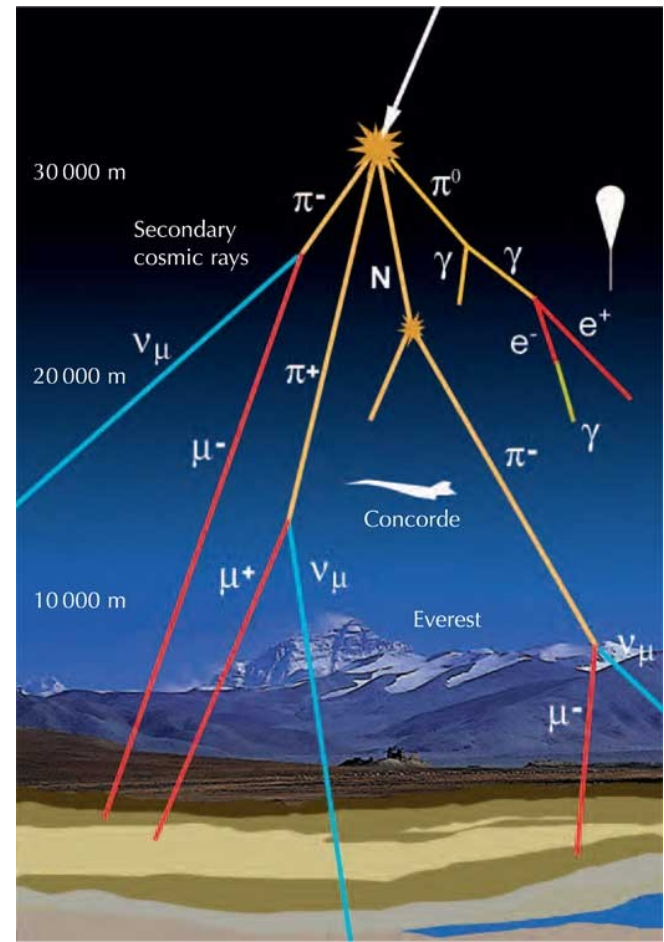
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Protons + nucleii  $\rightarrow$  “junk” + pions



99.99%



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- That is, lepton flavor (and number!) are *conserved*



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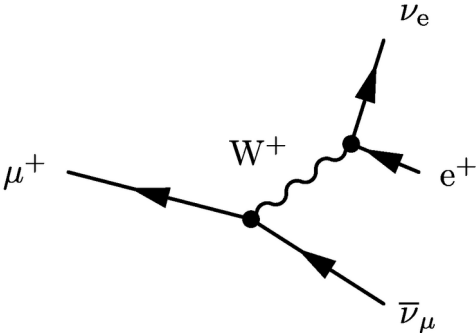
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<p>&lt;2,2 eV</p> <p>0 <math>\nu_e</math></p> <p><math>\frac{1}{2}</math></p> <p>electron neutrino</p>	<p>&lt;0,17 MeV</p> <p>0 <math>\nu_\mu</math></p> <p><math>\frac{1}{2}</math></p> <p>muon neutrino</p>	<p>&lt;15,5 MeV</p> <p>0 <math>\nu_\tau</math></p> <p><math>\frac{1}{2}</math></p> <p>tau neutrino</p>
<p>0,511 MeV</p> <p>-1 <math>e</math></p> <p><math>\frac{1}{2}</math></p> <p>electron</p>	<p>105,7 MeV</p> <p>-1 <math>\mu</math></p> <p><math>\frac{1}{2}</math></p> <p>muon</p>	<p>1,777 GeV</p> <p>-1 <math>\tau</math></p> <p><math>\frac{1}{2}</math></p> <p>Tau</p>

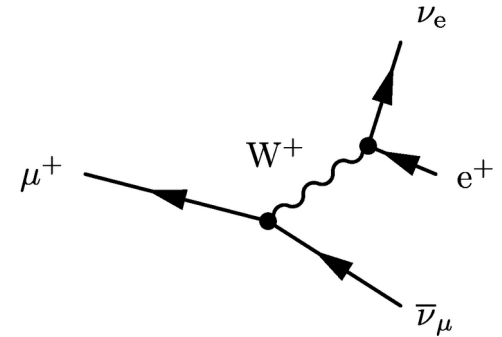


This is *allowed*

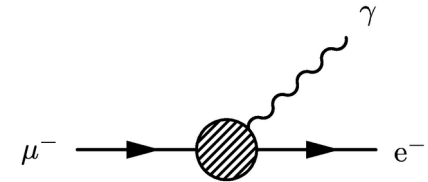
# In the Standard Model\*, once a muon always a muon

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$< 2,2 \text{ eV}$ $0$ $\nu_e$ $1/2$ electron neutrino	$< 0,17 \text{ MeV}$ $0$ $\nu_\mu$ $1/2$ muon neutrino	$< 15,5 \text{ MeV}$ $0$ $\nu_\tau$ $1/2$ tau neutrino
$0,511 \text{ MeV}$ $-1$ $e$ $1/2$ electron	$105,7 \text{ MeV}$ $-1$ $\mu$ $1/2$ muon	$1,777 \text{ GeV}$ $-1$ $\tau$ $1/2$ Tau



This is *allowed*

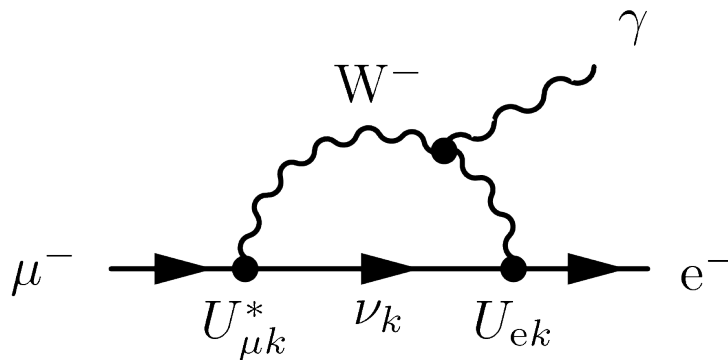


This is *forbidden*

# Mu2e (and our competitor COMET) are searches for charged lepton flavor violation with discovery potential

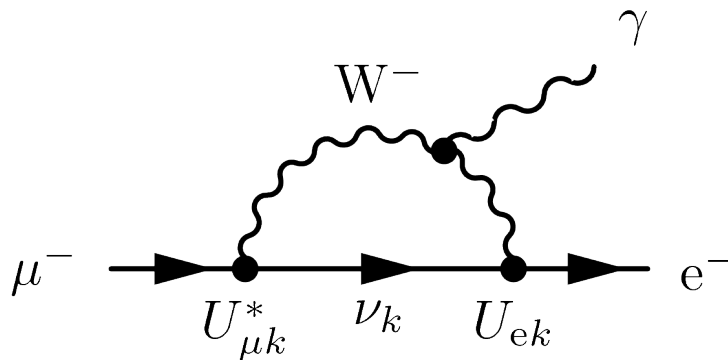
# Mu2e (and our competitor COMET) are searches for charged lepton flavor violation with discovery potential

Although it has never been observed, we know that CLFV **must** occur, *even in the Standard Model*, through neutrino loop effects.



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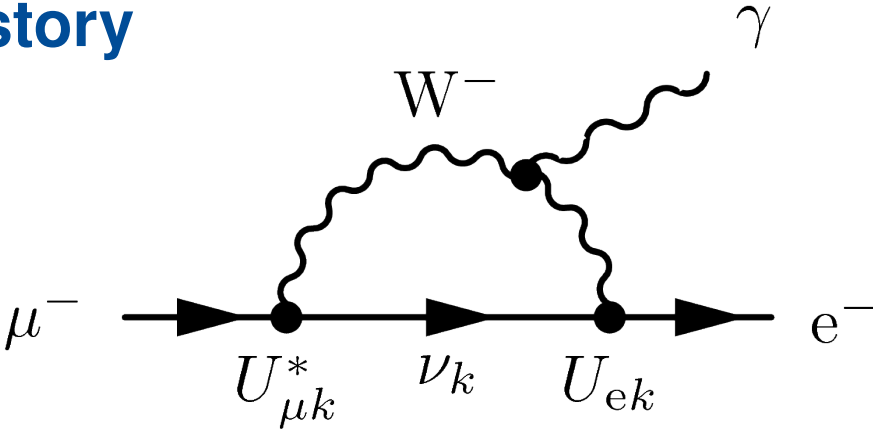
Although it has never been observed, we know that CLFV **must** occur, *even in the Standard Model*, through neutrino loop effects.



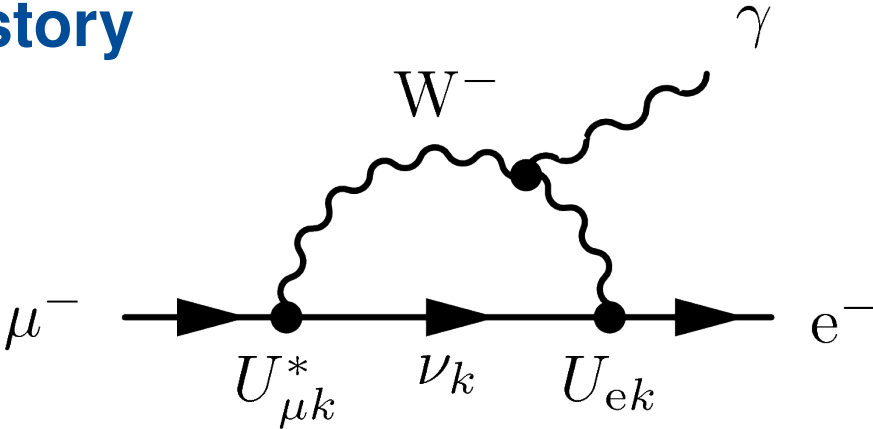
However, the predicted SM rates are unobservably small:

$$\text{Br}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{k=2,3} U_{\mu k}^* U_{ek} \frac{\Delta m_{1k}^2}{M_W^2} \right|^2 < 10^{-54}$$

# This is a good news/bad news story



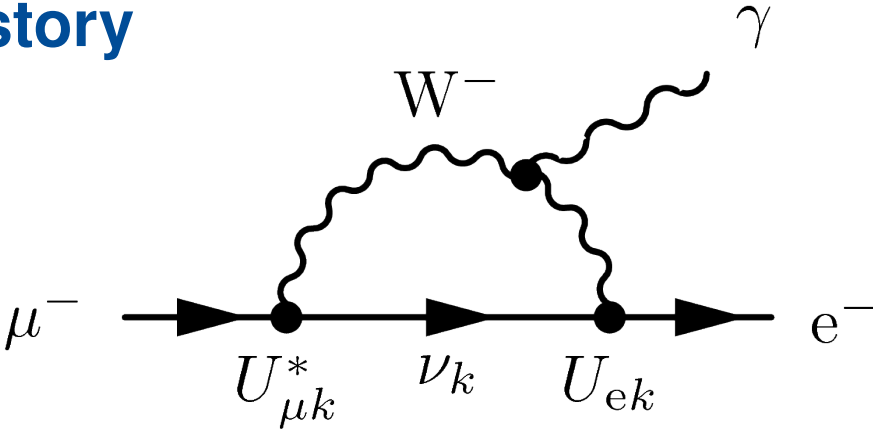
# This is a good news/bad news story





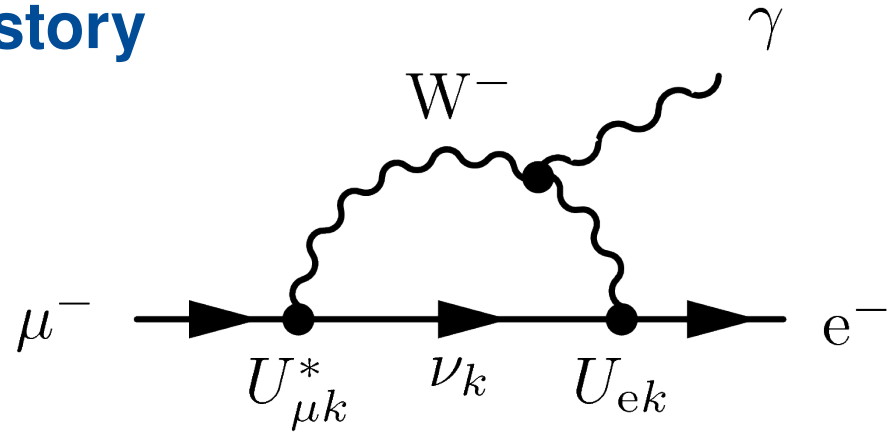
# This is a good news/bad news story

First, the bad news: we'll never observe this!



# This is a good news/bad news story

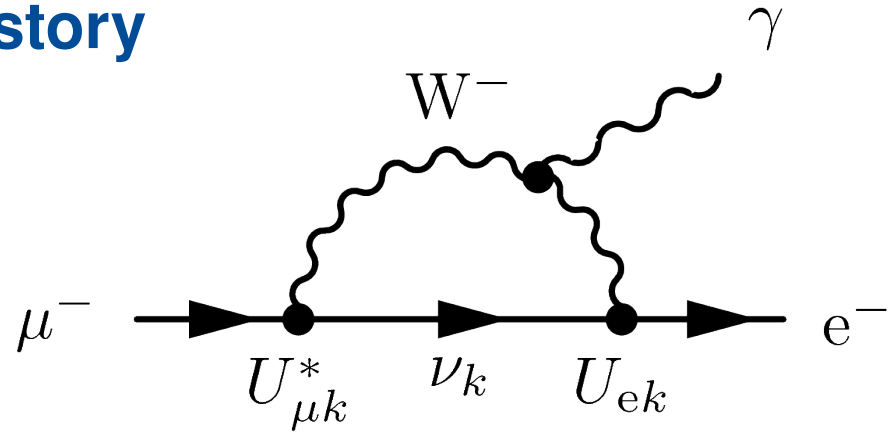
First, the bad news: we'll never observe this!



Now, the good news: we'll never observe this!

# This is a good news/bad news story

First, the bad news: we'll never observe this!



Now, the good news: we'll never observe this!

*Any signal of CLFV is unambiguous evidence for physics beyond the Standard Model!*

# There are many potential signatures of CLFV physics in the muon sector

Surface muon beams

$$\mu^+ \rightarrow e^+ \gamma$$

$$\mu^+ \rightarrow e^+ e^+ e^-$$

$$\mu^+ e^- \leftrightarrow \mu^- e^+$$

Double CLFV!

“High” energy beams

$$\mu^- A(Z, N) \rightarrow e^- A(Z, N)$$

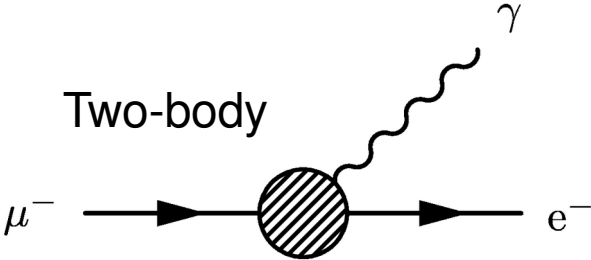
$$\mu^- A(Z, N) \rightarrow e^+ A(Z - 2, N)$$

CLFV and LNV!

There are a large number of experiments proposed to further address these channels; I apologize for only mentioning those I'm involved with.

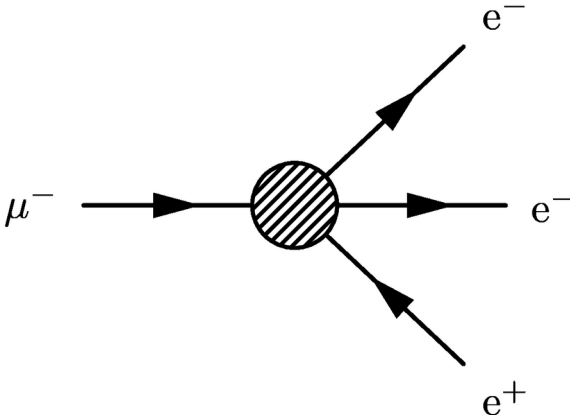
# The most powerful signatures are being actively pursued

$$\mu^+ \rightarrow e^+ \gamma$$



MEG/MEG-II at PSI

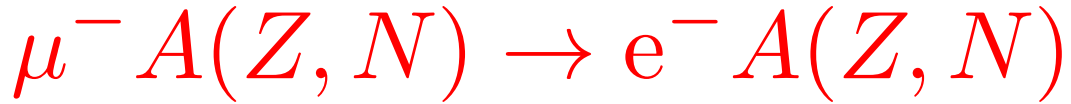
$$\mu^+ \rightarrow e^+ e^+ e^-$$



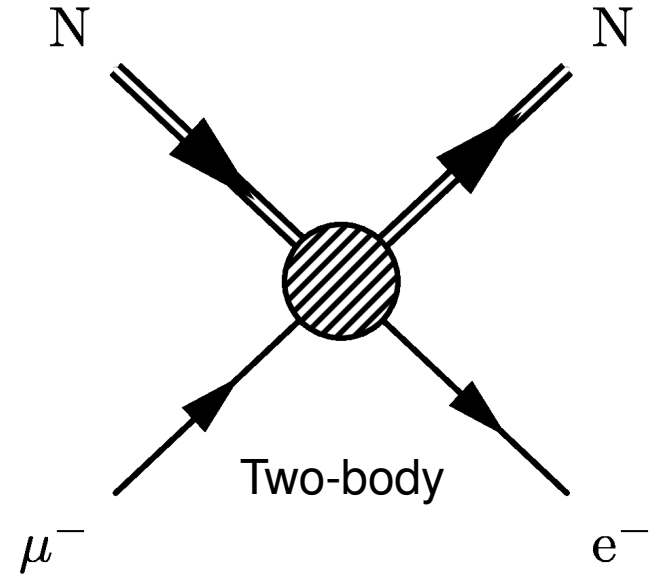
Mu3e at PSI

# Coherent neutrinoless conversion is the Mu2e program

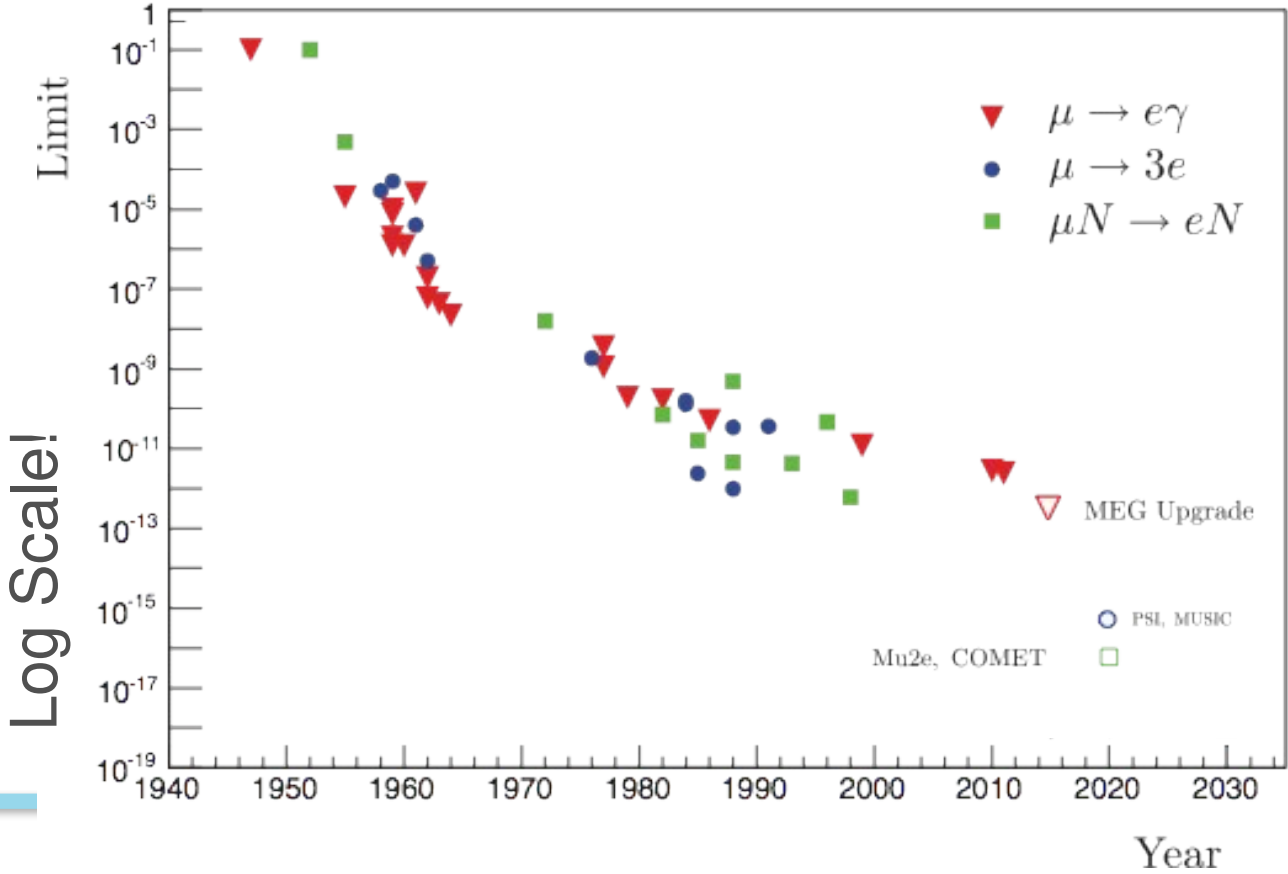
Mu2e and COMET will search for Coherent Conversion



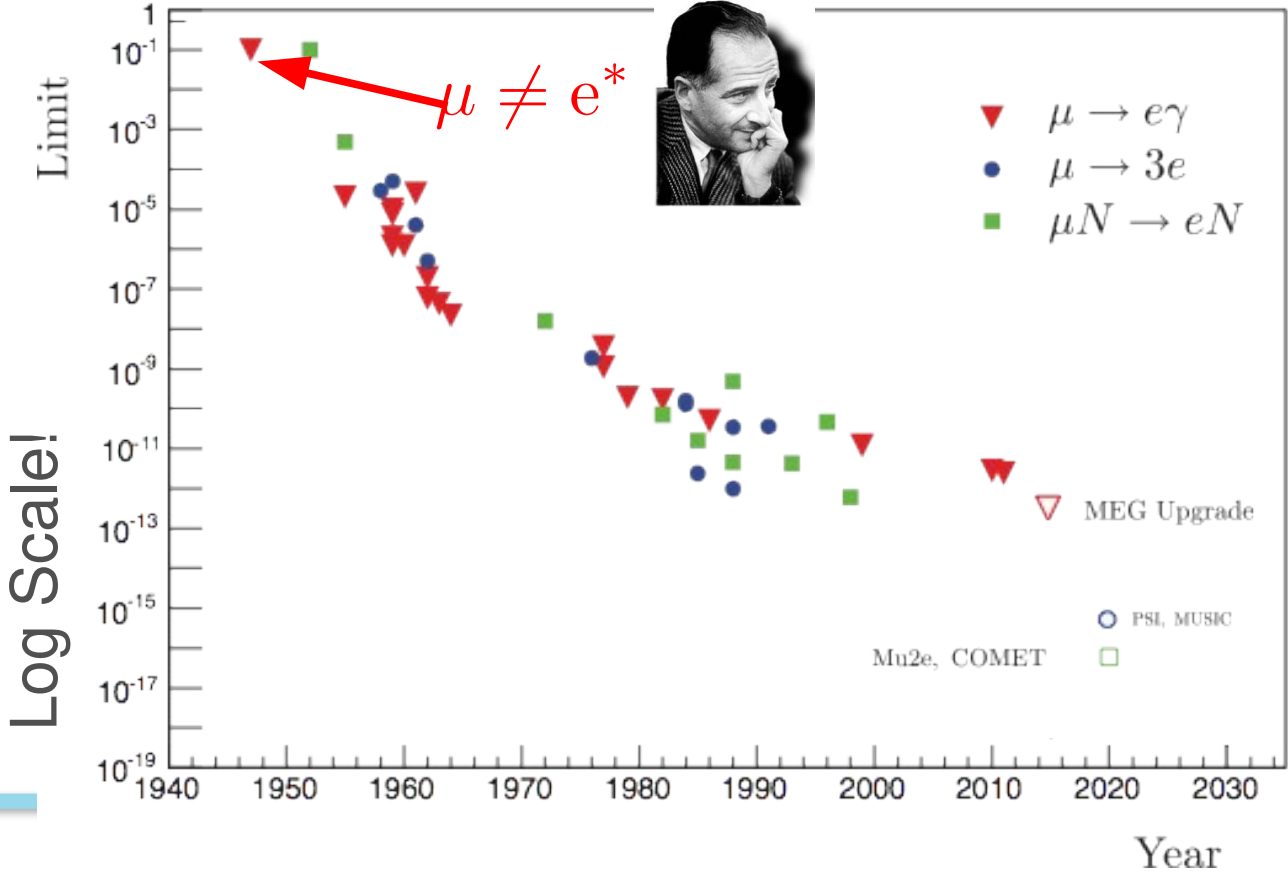
$$R_{\mu e} = \frac{\Gamma(\mu^- A \rightarrow e^- A)}{\Gamma(\mu^- A \rightarrow \nu_\mu A')}$$



# We're extending a long line of experiments designed to understand the mystery of muon flavor

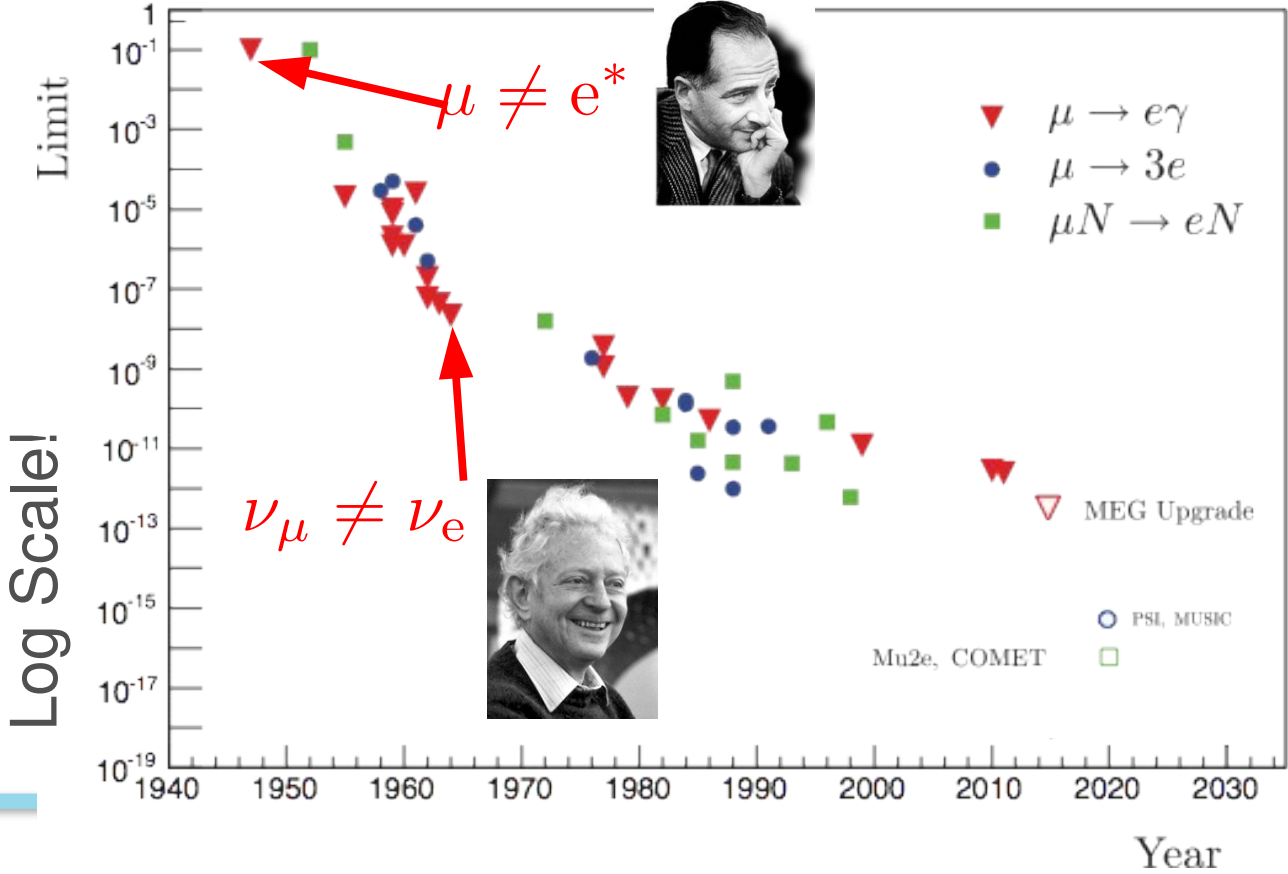


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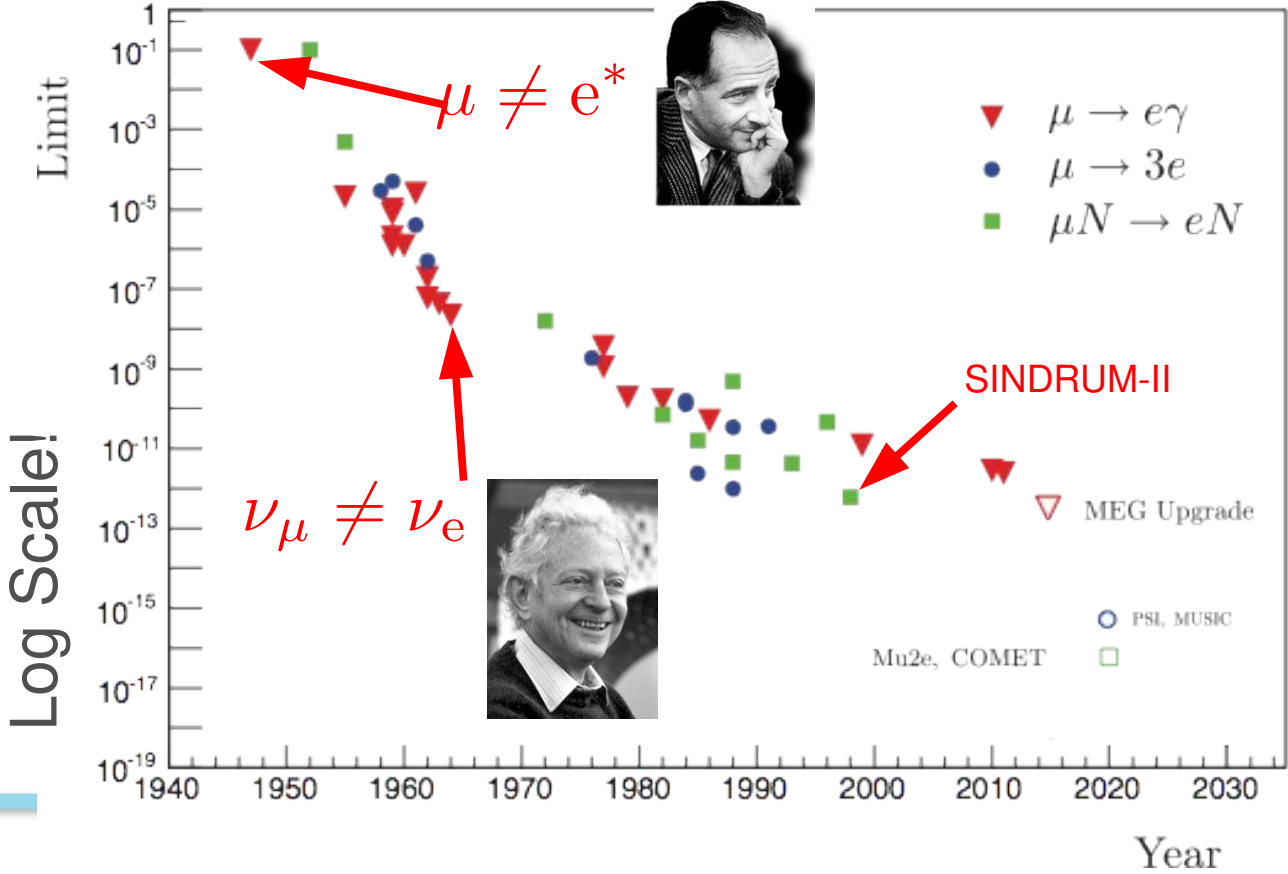




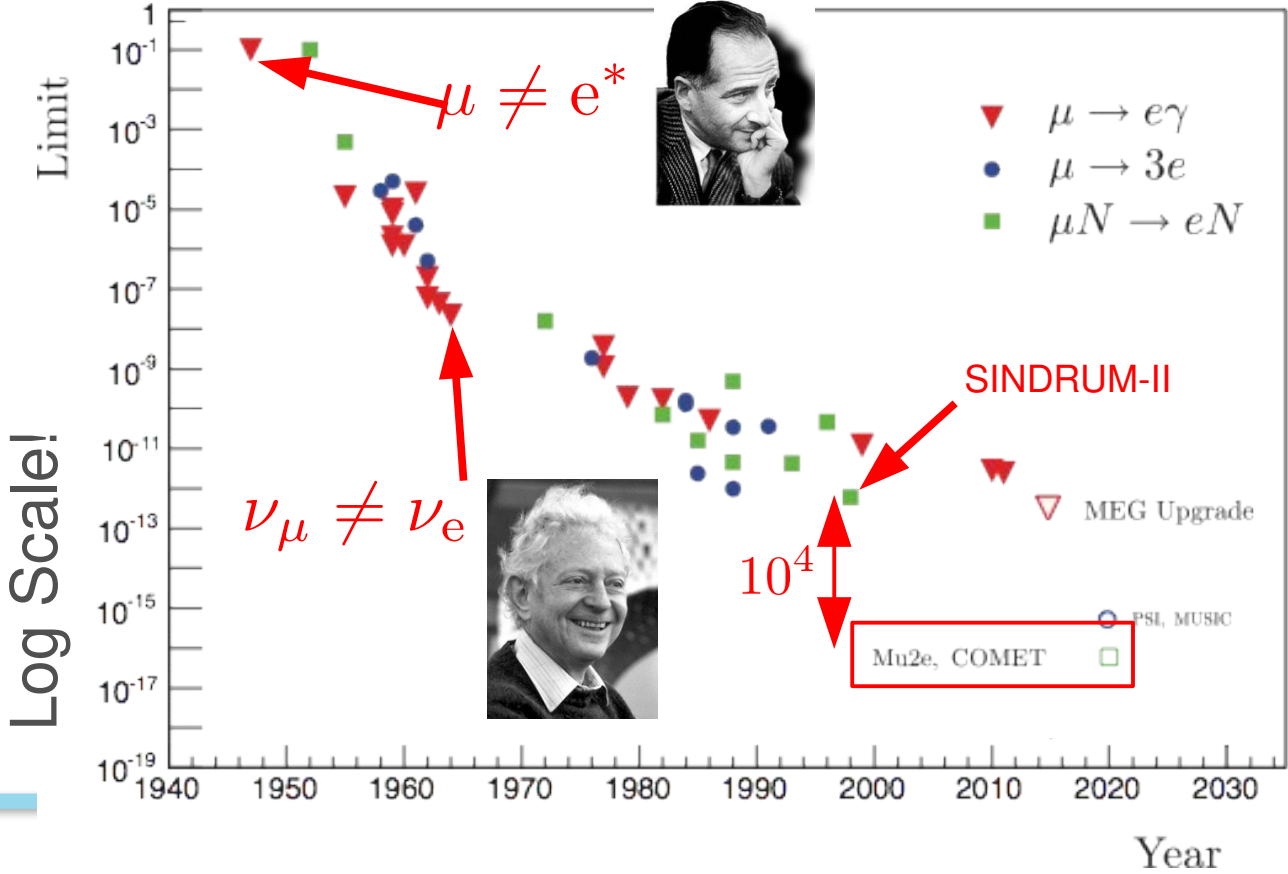
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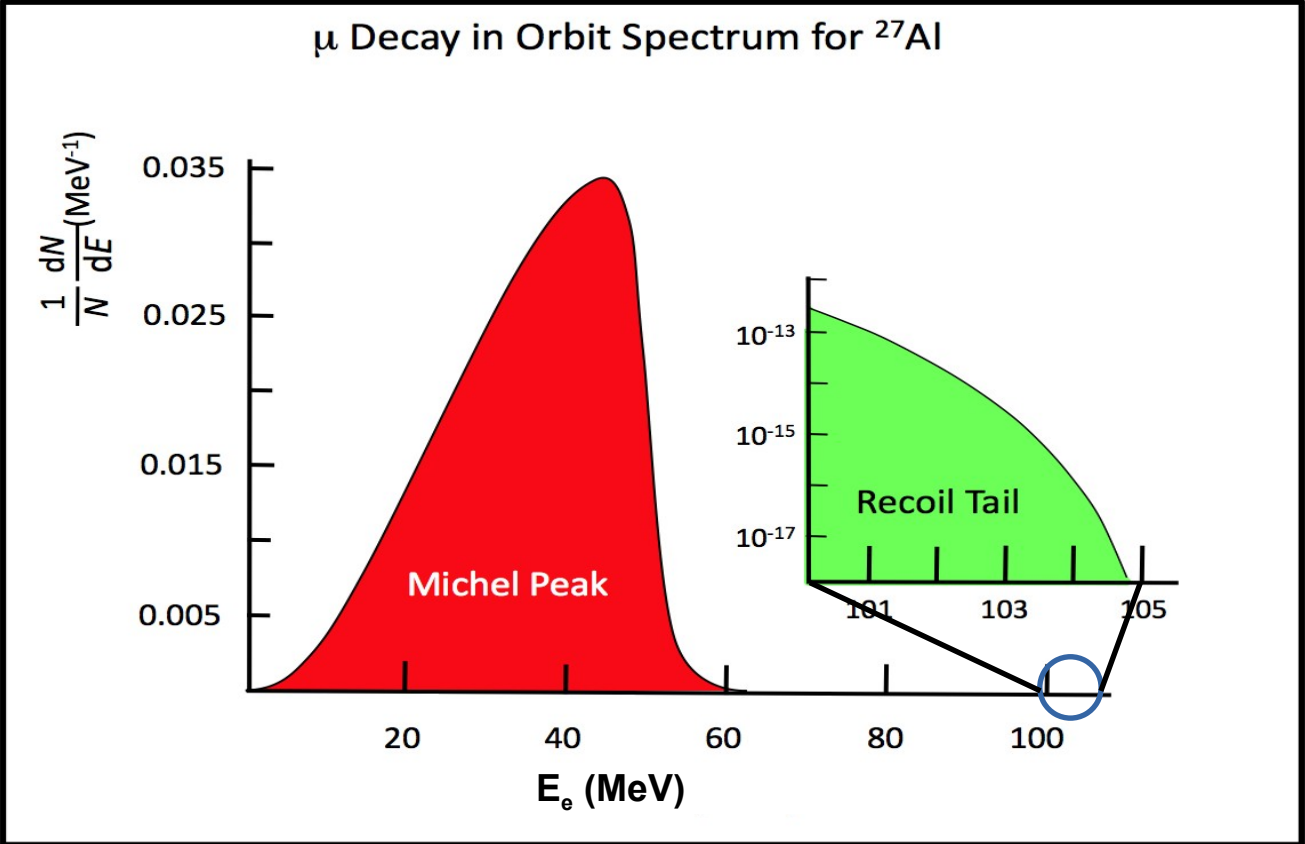


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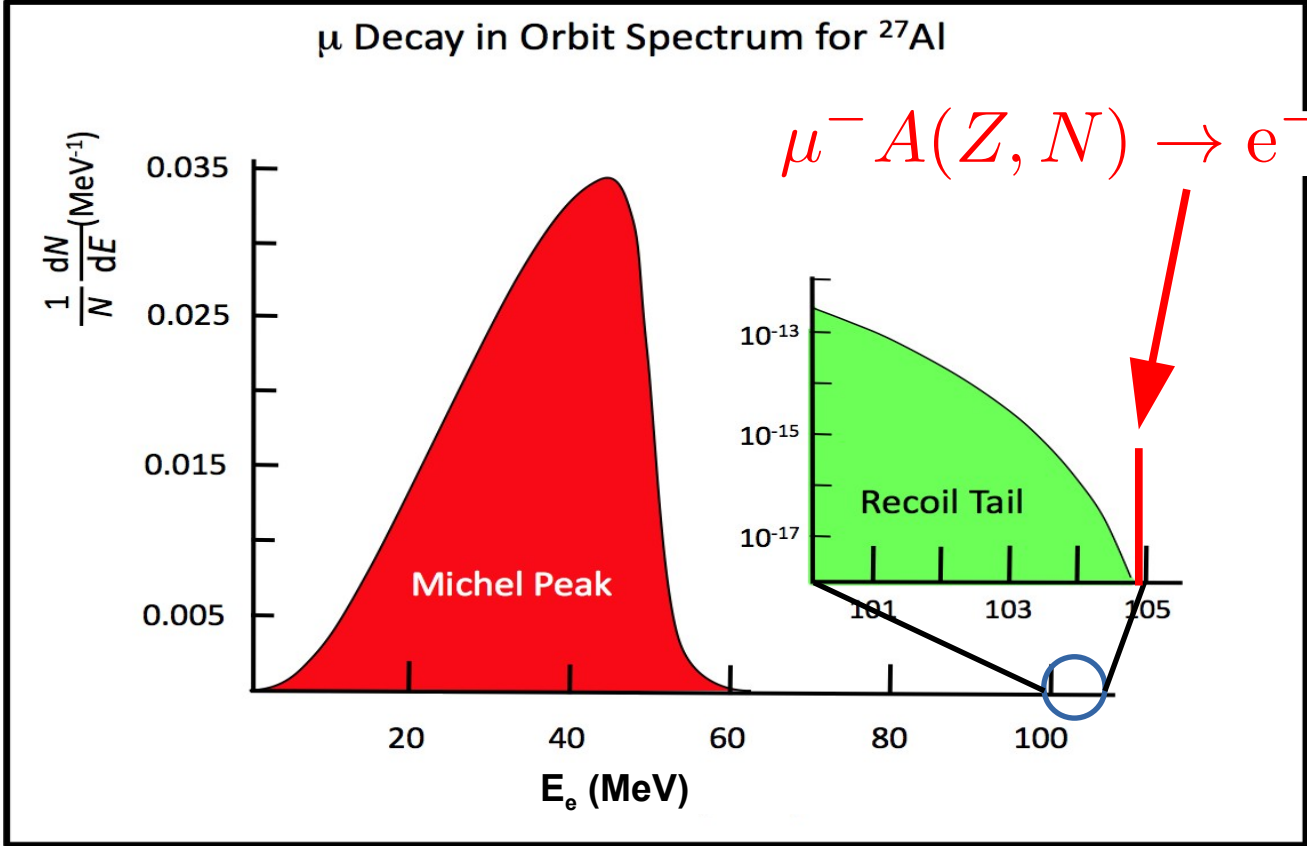


# Our key advantage: conversion is kinematically distinct from the background muon decay spectrum

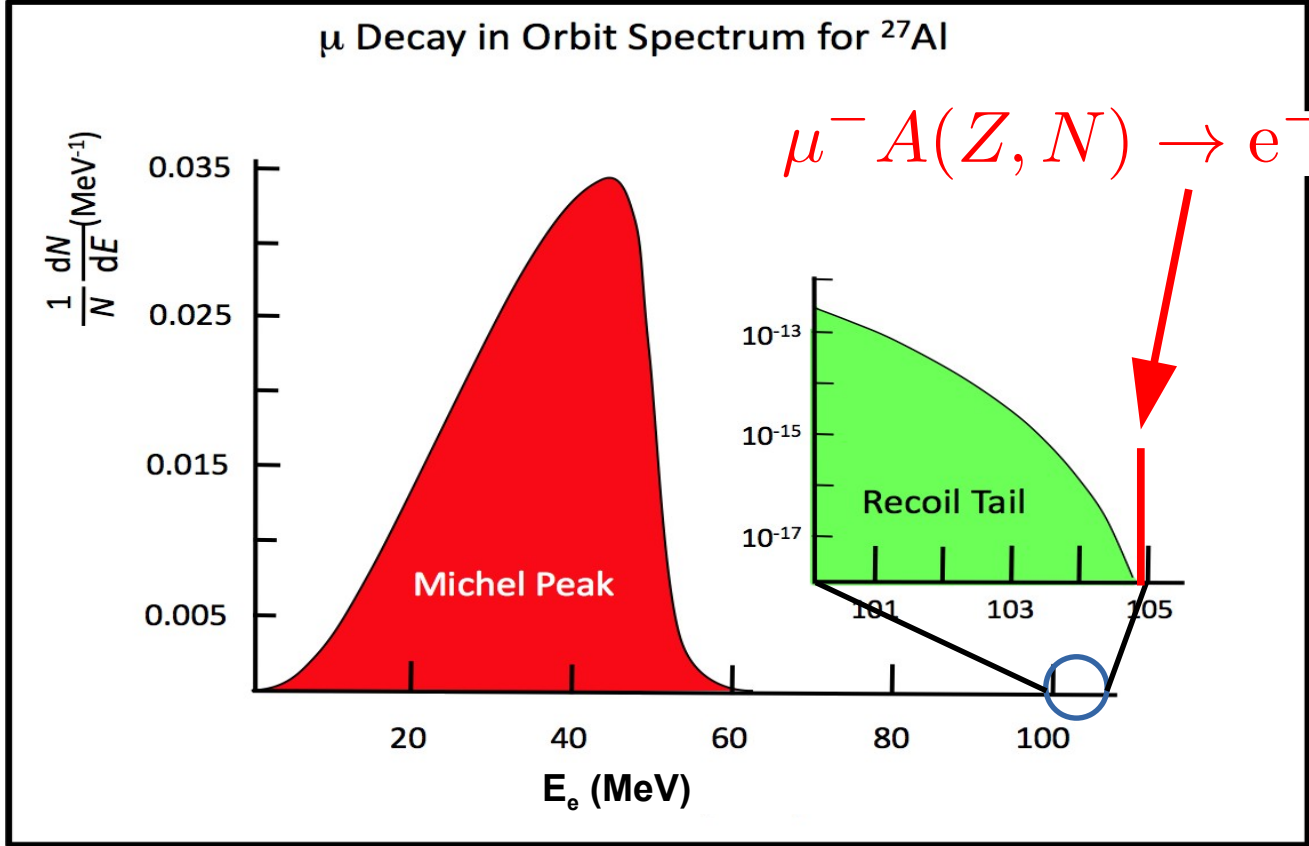
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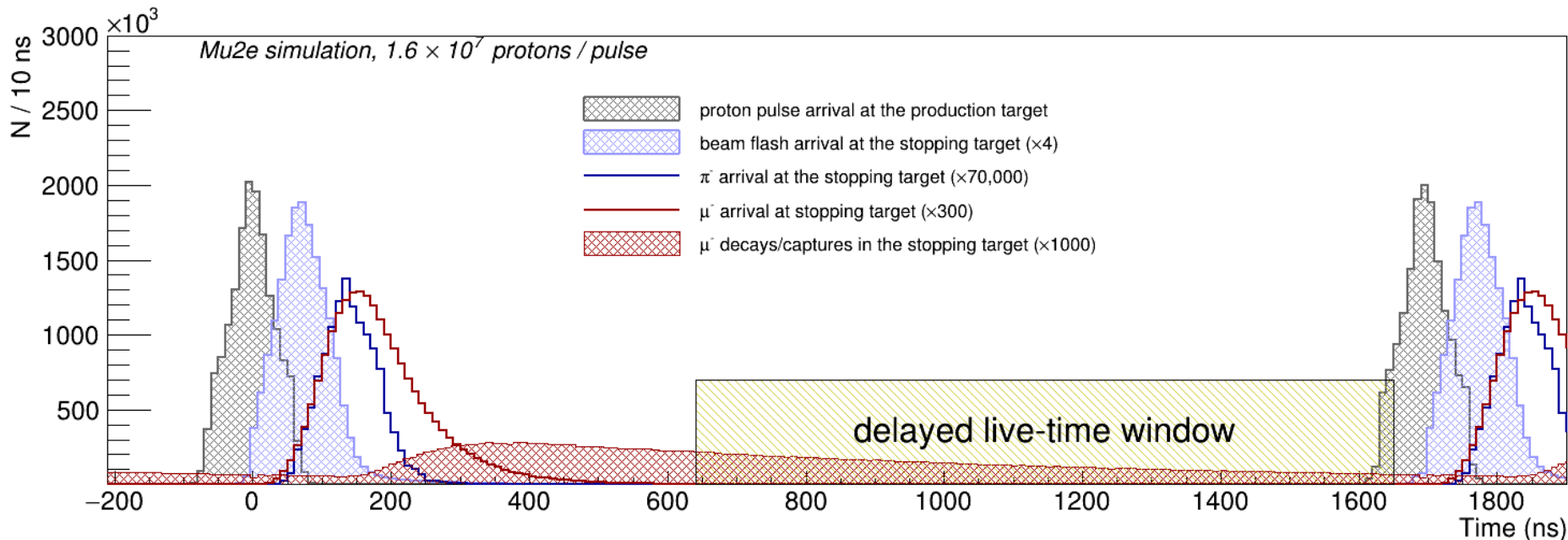


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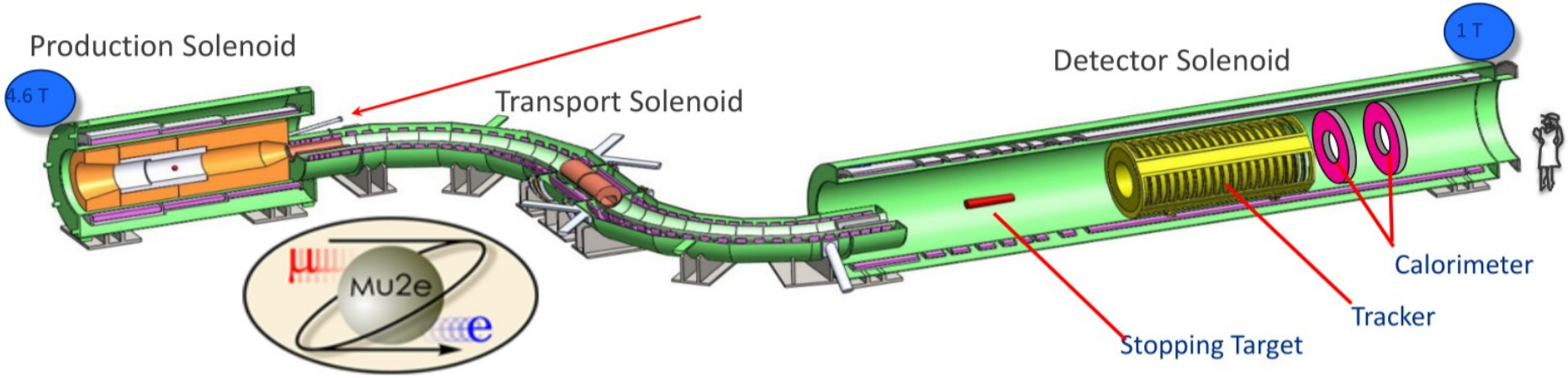
Our signal is a mono-energetic electron at 105 MeV, above the background tail!

# Beam induced backgrounds can be reduced by using a pulsed beam source ... which we can generate at Fermilab





# Let's first explore how Mu2e will tackle this challenge

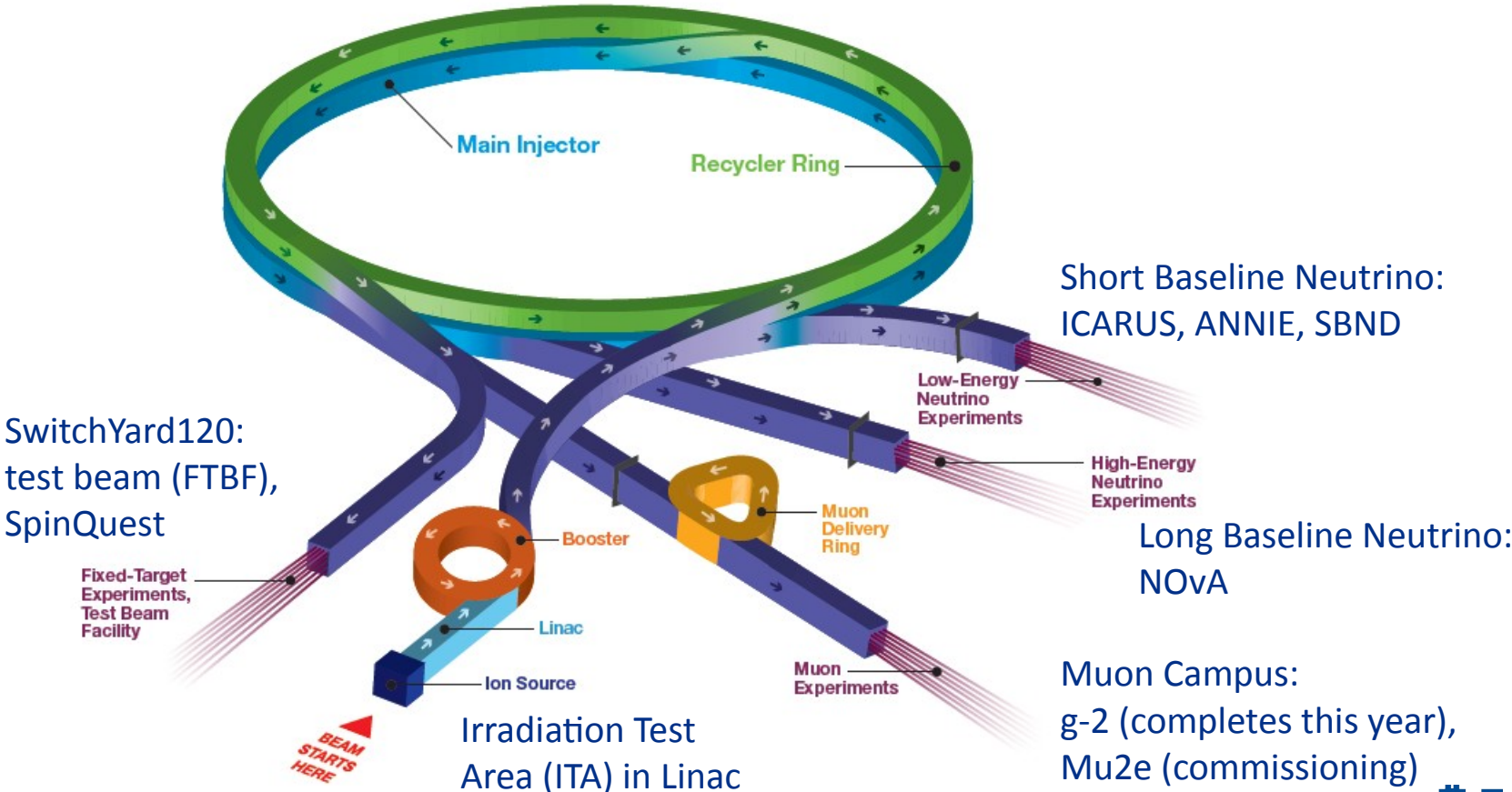


**Where do our protons come from? Keep this constraint in mind:**

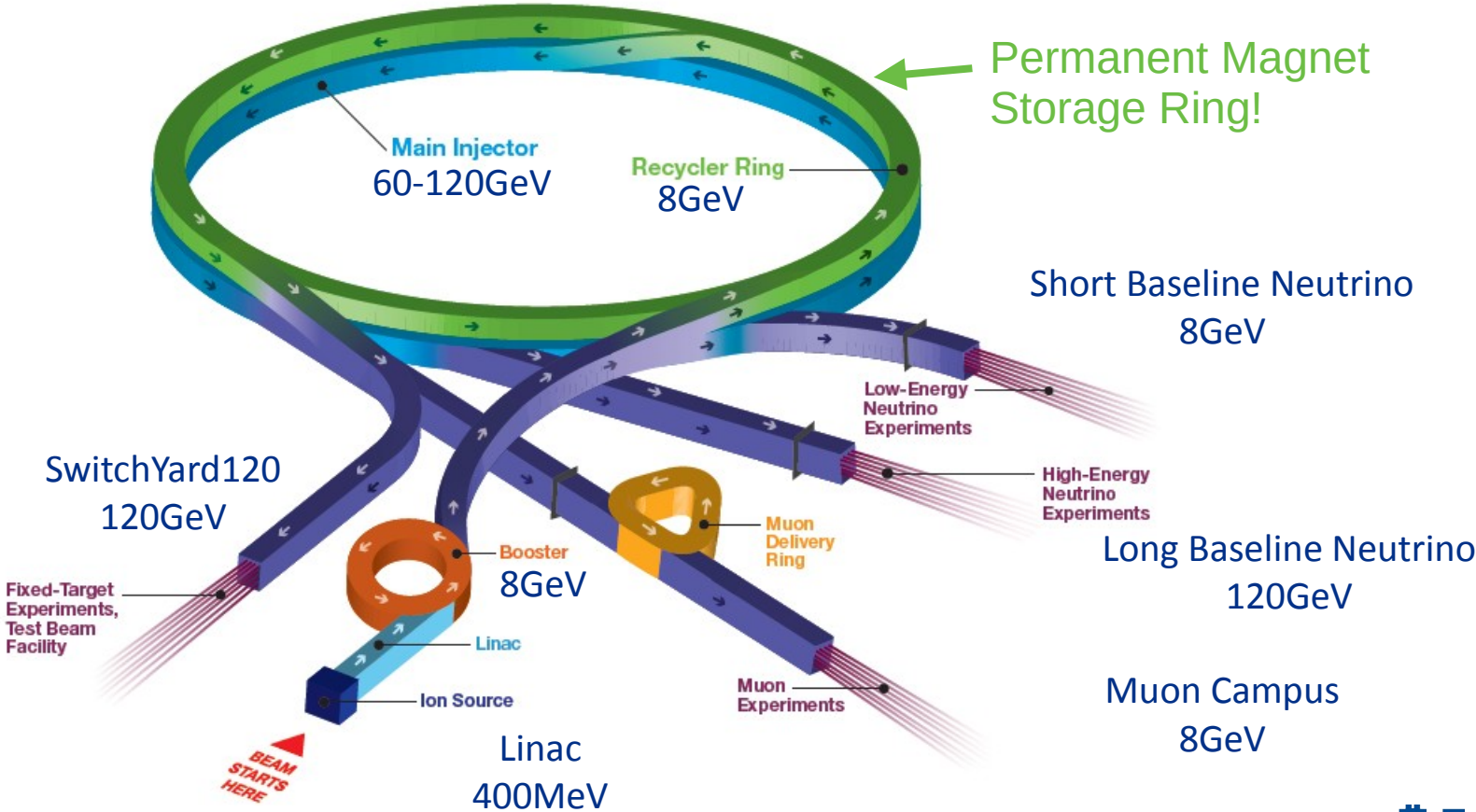
## Where do our protons come from? Keep this constraint in mind:

Since the end of Tevatron running, *neutrino physics* has driven the proton economics at Fermilab, and that *will* remain the key driver for the next 30+ years!

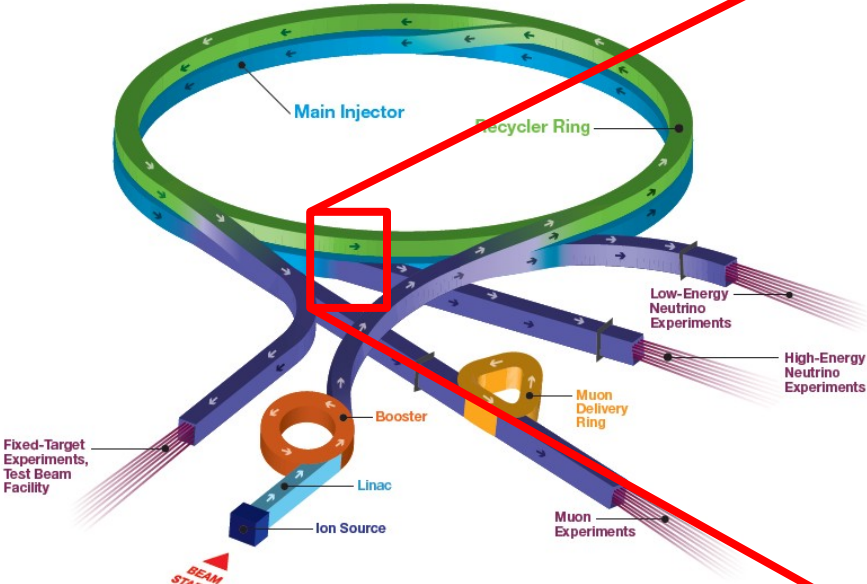
# Cartoon of the current accelerator complex



# Cartoon of the current accelerator complex



# Reminder that these cartoons hide a wealth of complex and interesting science and engineering



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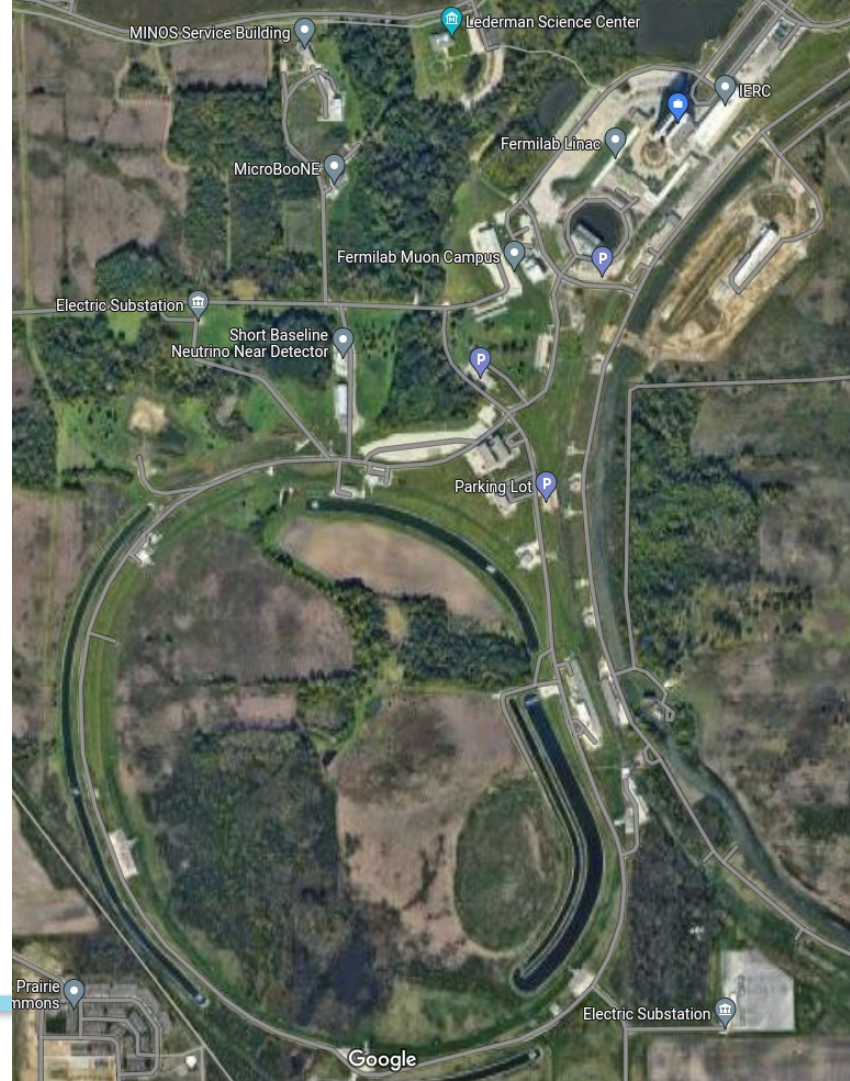
Recycler Ring

NuMI Extraction Line

Main Injector



They also hide a vast hierarchy of scales!



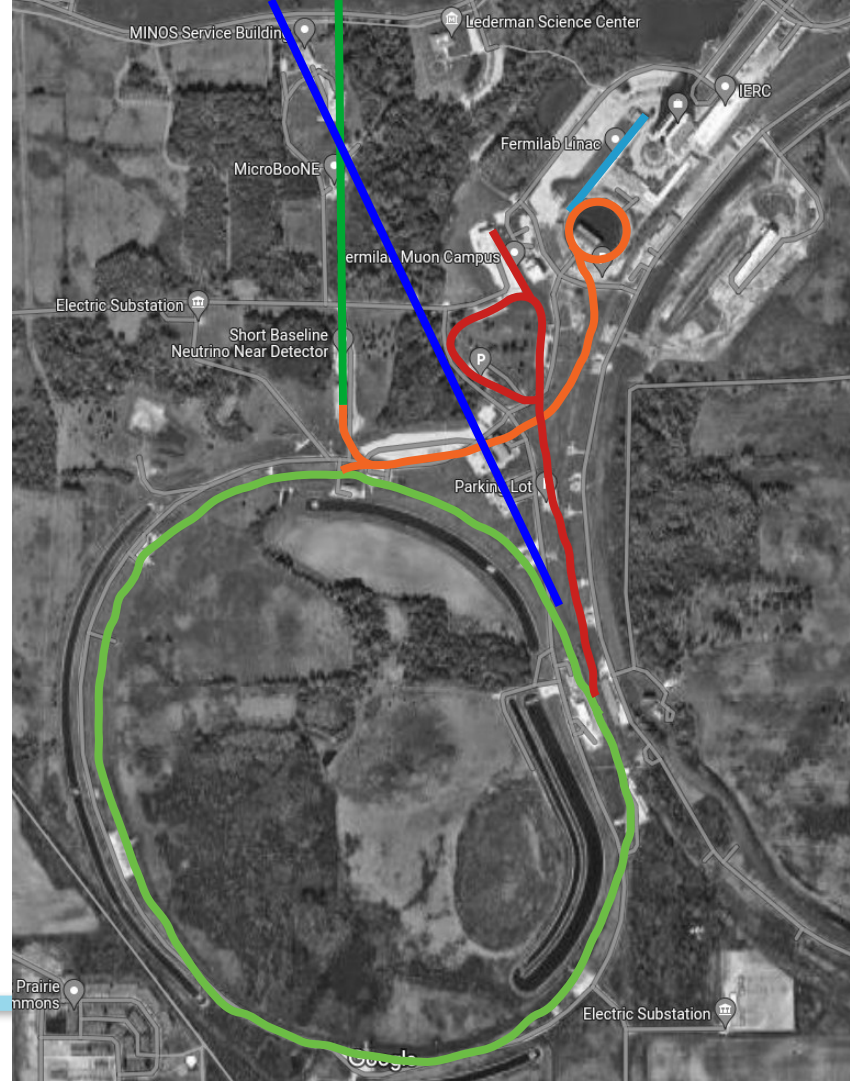


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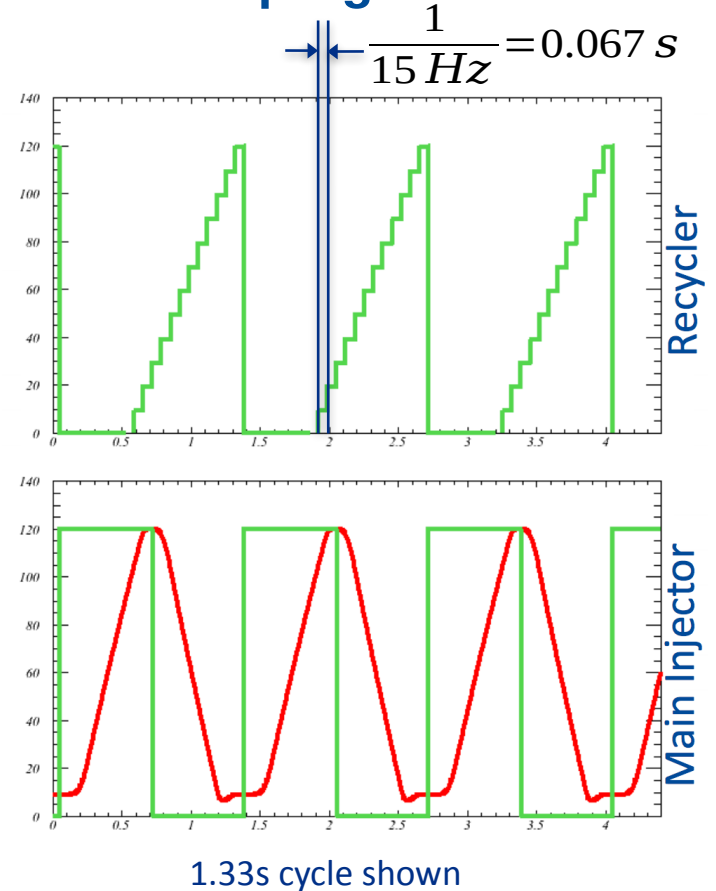
# They also hide a vast hierarchy of scales!

- Linac (400MeV)
- Booster (8GeV)
- RR/MI (8GeV/120GeV)
- Muon Campus (3.094GeV/8GeV)
- BNB (8GeV)
- NuMI (120GeV)



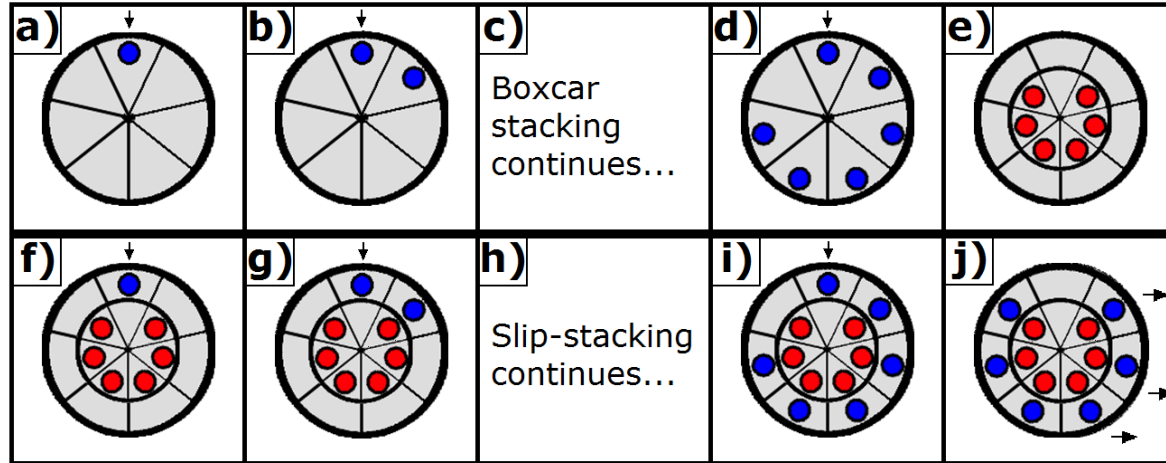
# The accelerator timeline is organized around the NuMI program

- H<sup>-</sup> linac (1970, 1993, 2012)
  - 400 MeV linac ~20mA
- Booster synchrotron (1970)
  - H<sup>-</sup> stripping injection (1978)
    - 16 turns to  $\sim 4.7 \times 10^{12}$  p per pulse
  - Resonant Ramp from 0.4 to 8 GeV at 15 Hz
- Recycler (1998)
  - 3.3 km permanent magnet 8 GeV ring
  - Slip-stacking 12 Booster batches,  $\sim 56 \times 10^{12}$  p
  - Also re-bunches beam for Muon Campus
- Main Injector (1998, but!)
  - 8 to 120 GeV ramp, cycle time 1.133\*-1.4 s



# Stacking beam in the Recycler is the key timeline constraint

- Slip stacking is a method of injecting multiple beams at different momenta into the same circular machine.
  - We combine slip stacking with boxcar stacking to stuff beam into the Recycler



7x as many  
53MHz RF  
buckets in RR/MI  
as in Booster  
(588/84) ... 81  
filled buckets per  
transfer

- These manipulations require 13 ticks of the Booster clock
  - 12 for injection, one for extraction

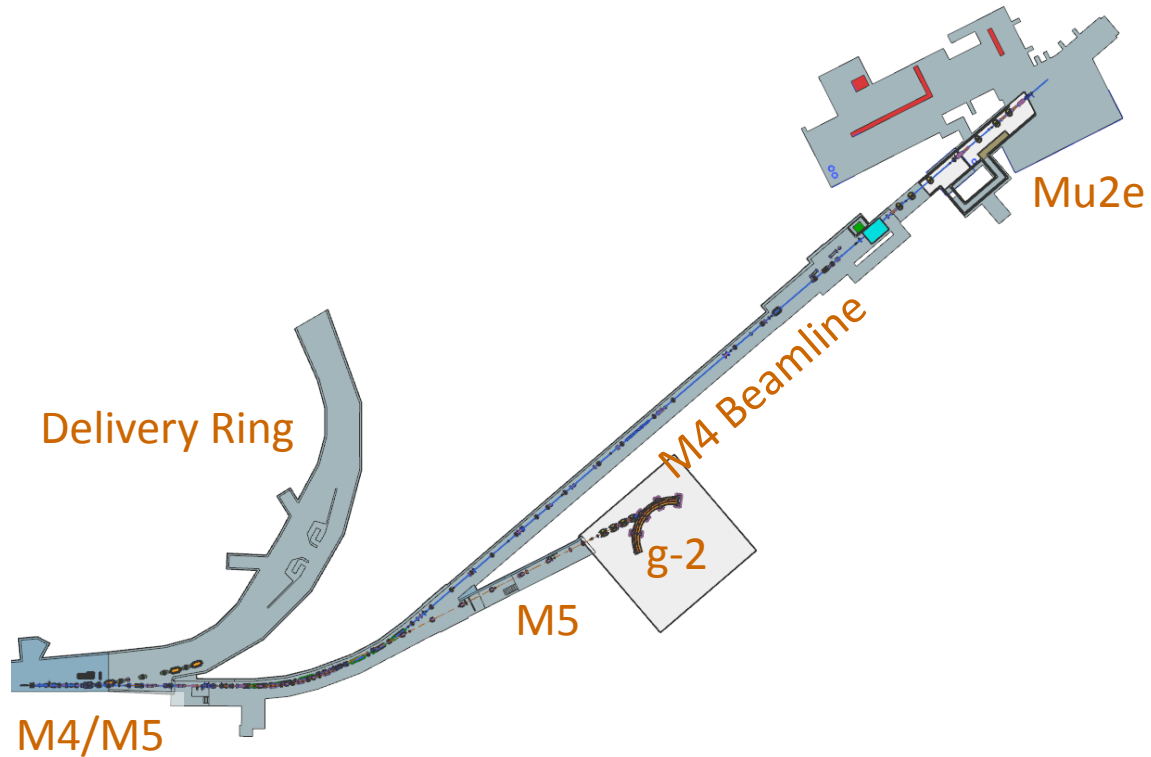
# We want to take those spare protons and move them to Mu2e

- Each Booster batch is rebunched from  $81 \times 53\text{MHz}$  to  $4 \times 2.5\text{MHz}$
- The rebunched beam pulses are extracted one at a time from the RR
- These pulses are injected into the  $2.36\text{MHz}$  DR
- Those protons are then slowly extracted to the experiment



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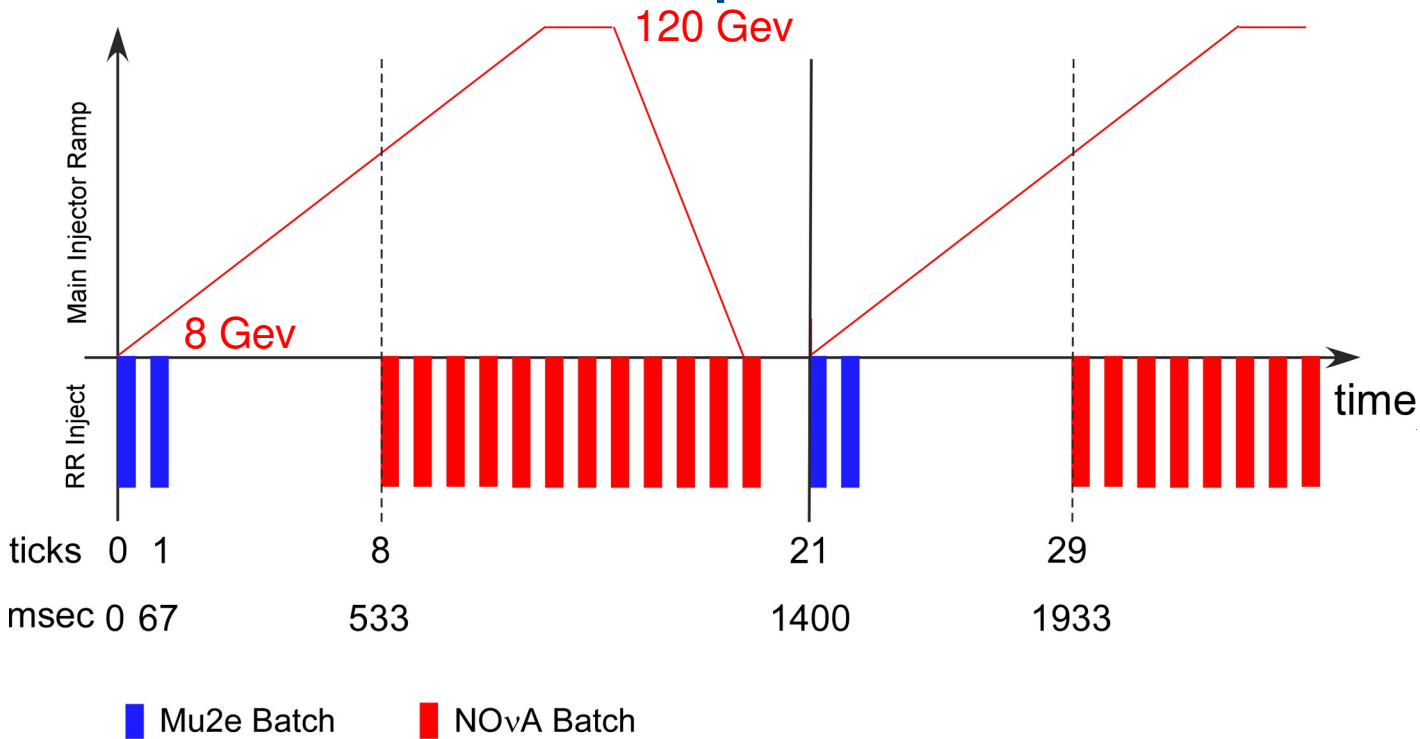
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M4/M5

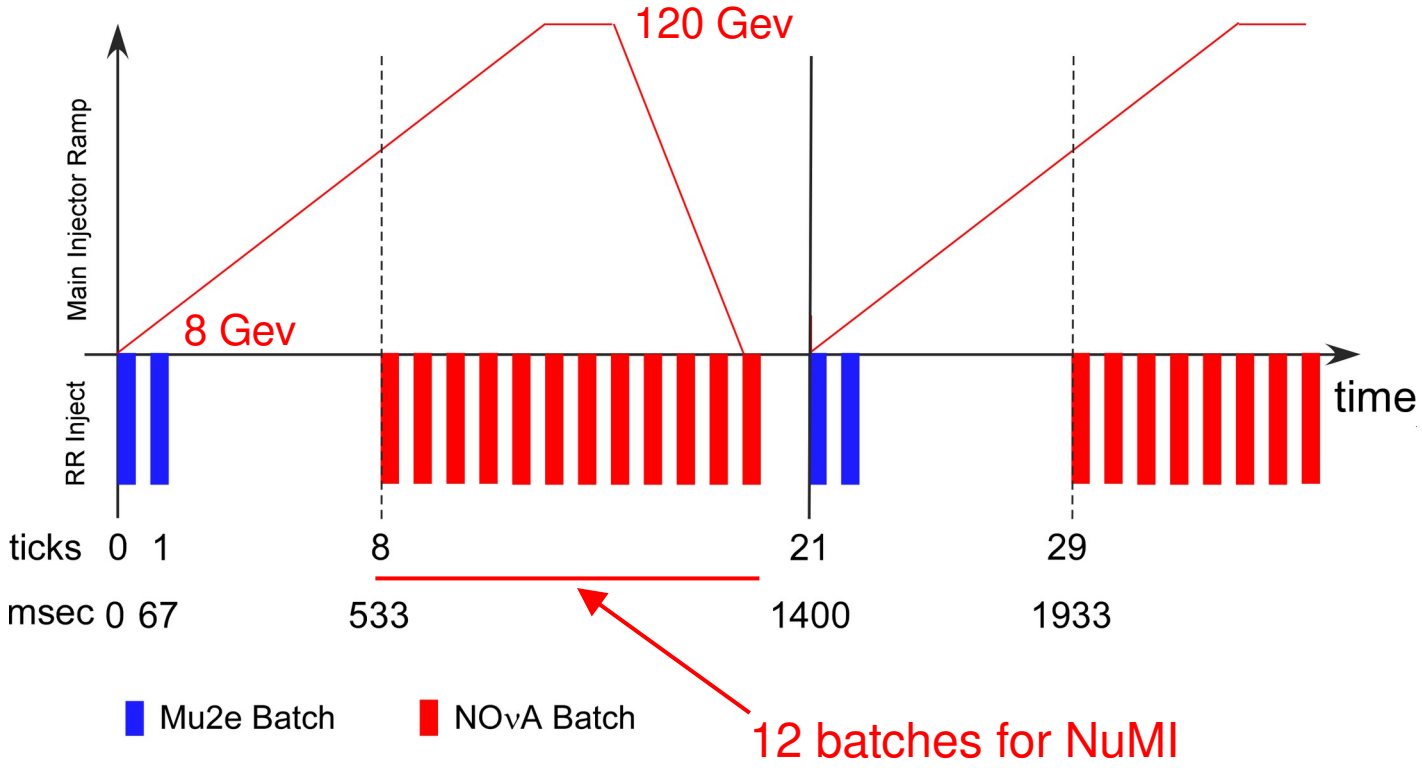
# All our machine timelines are built around moving 12 successive Booster batches to the MI – how does this impact muons?



1 tick = 1/15 sec

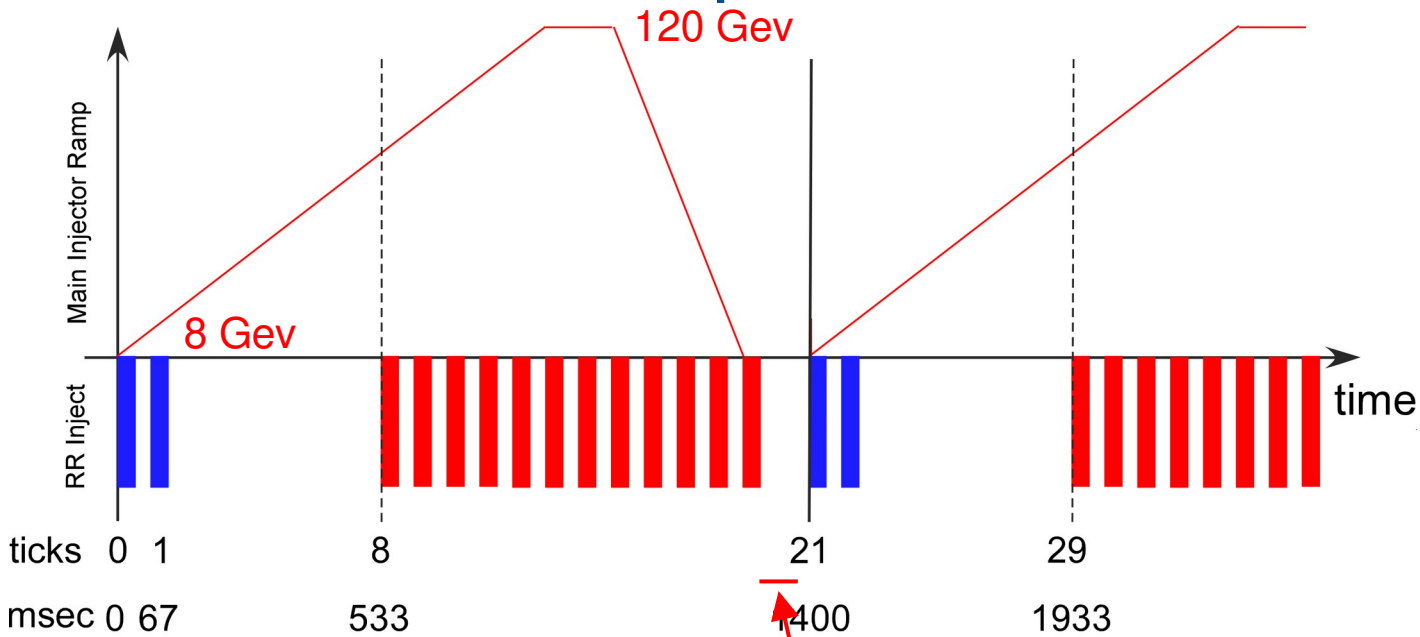


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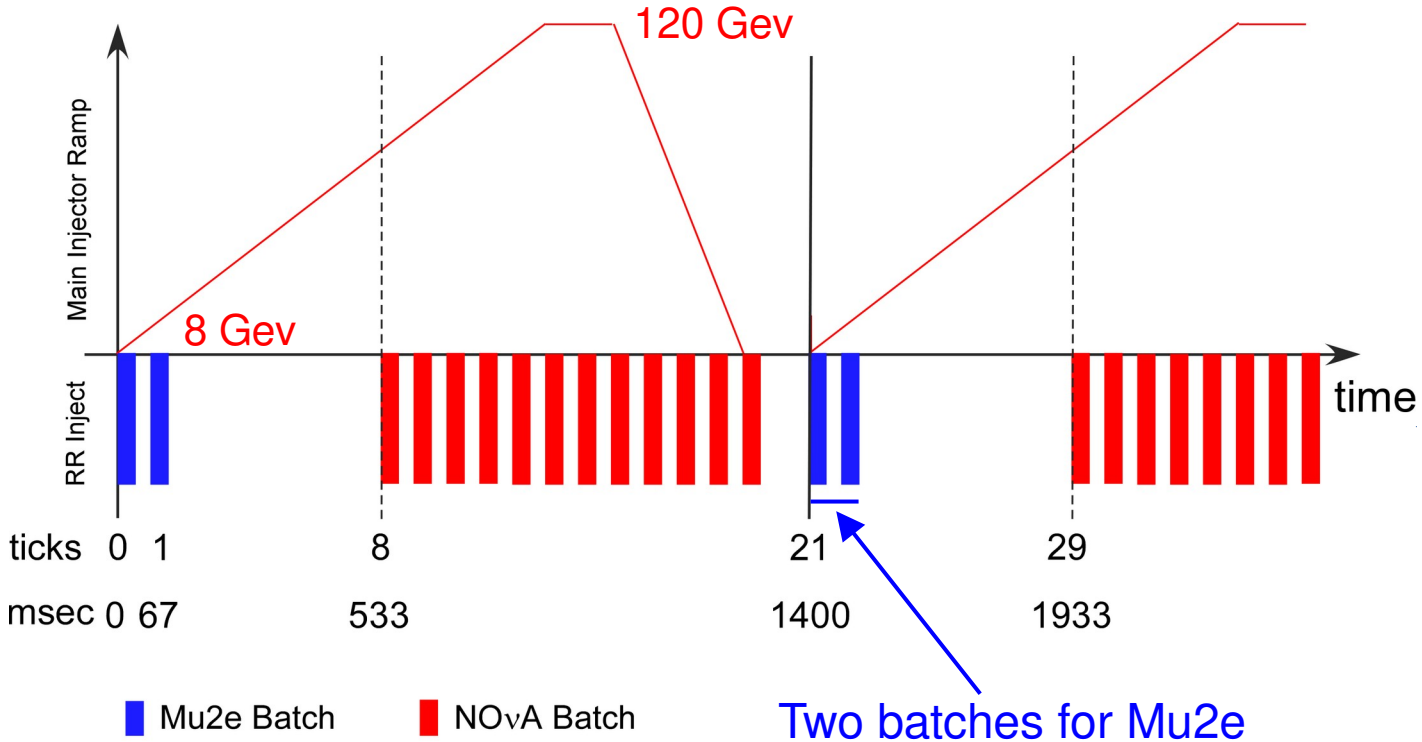
■ Mu2e Batch

■ NOvA Batch

1 tick = 1/15 sec

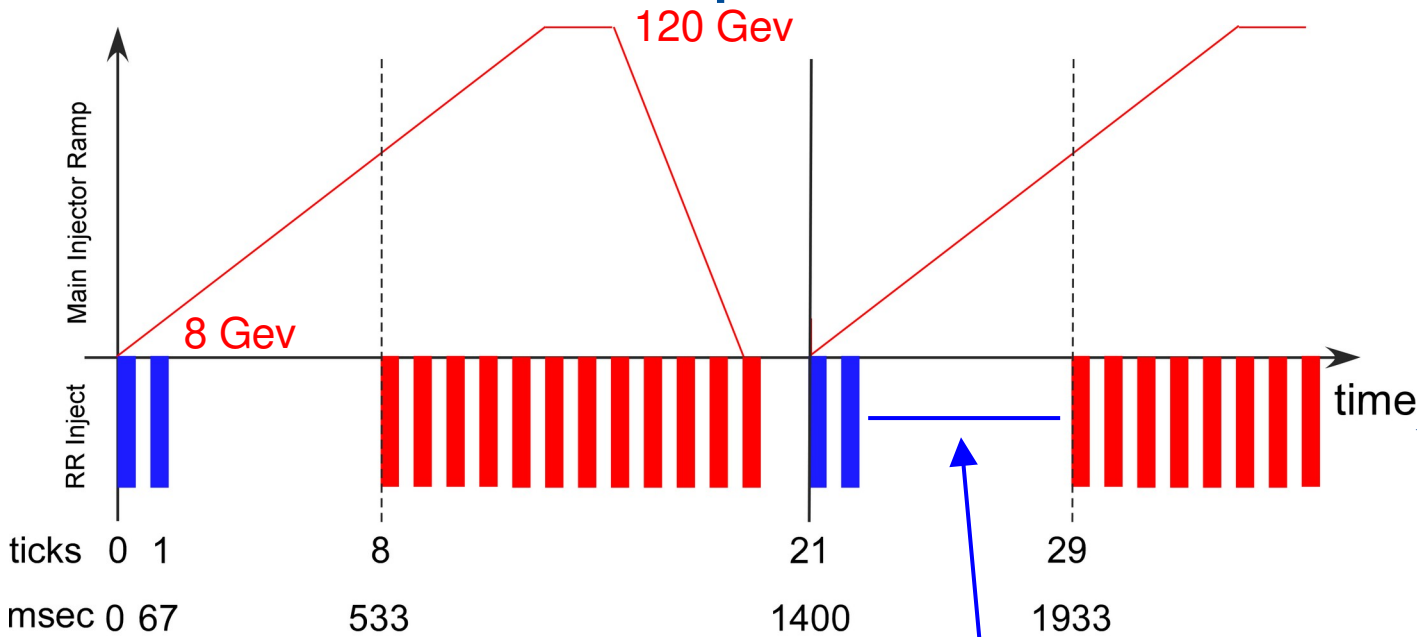
One tick for RR → MI transfer

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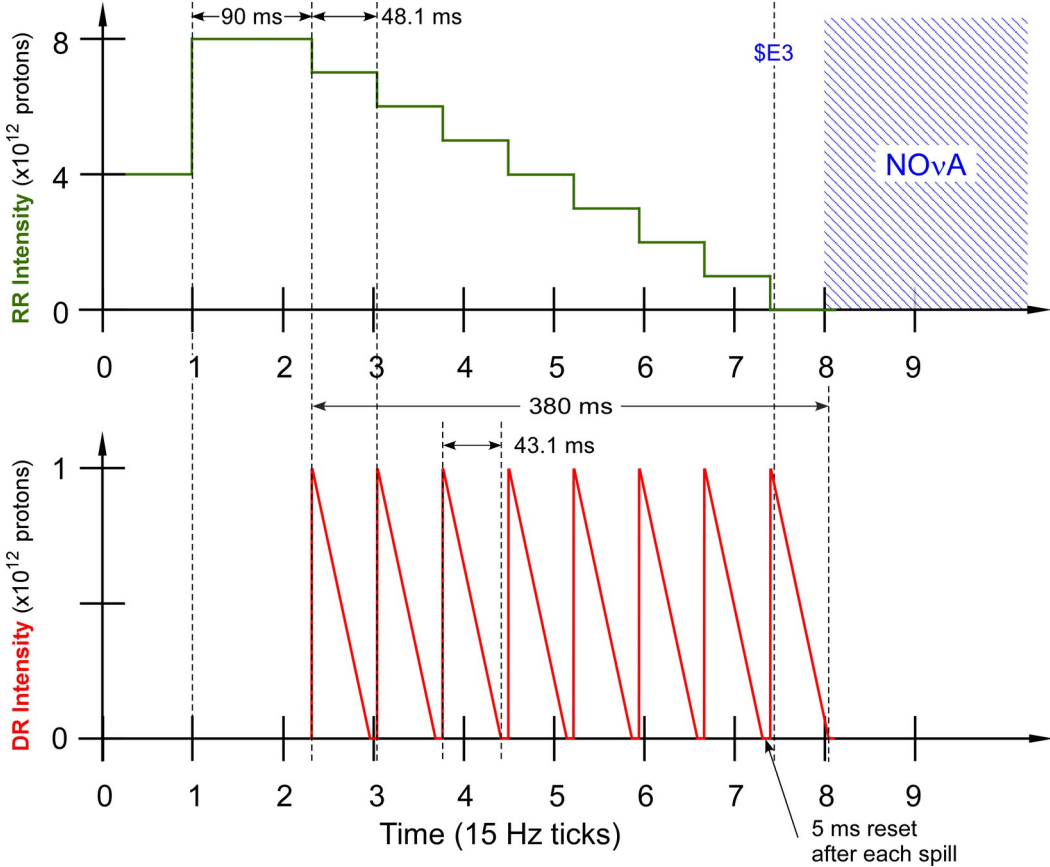


■ Mu2e Batch    ■ NOvA Batch

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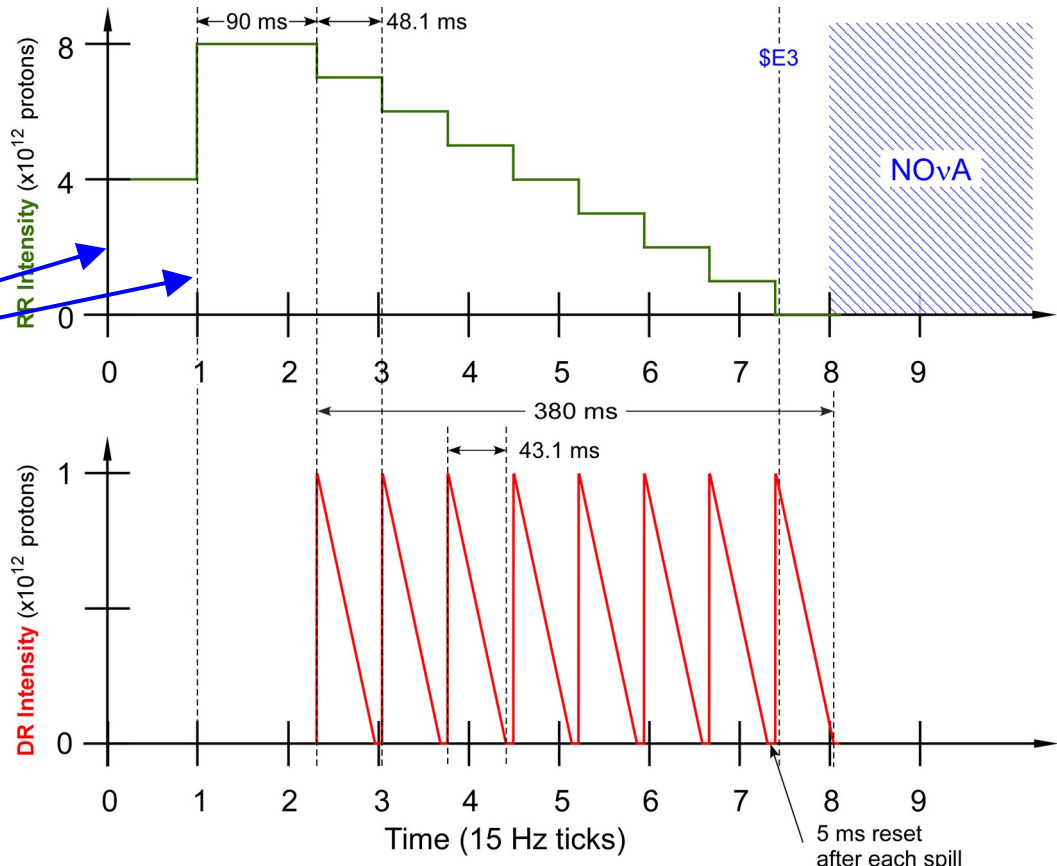
Rebunching and transfer to DR  
81x2 53MHz → 1x8 2.5MHz

# Beam to Mu2e is resonantly extracted from the DR over 8 ticks



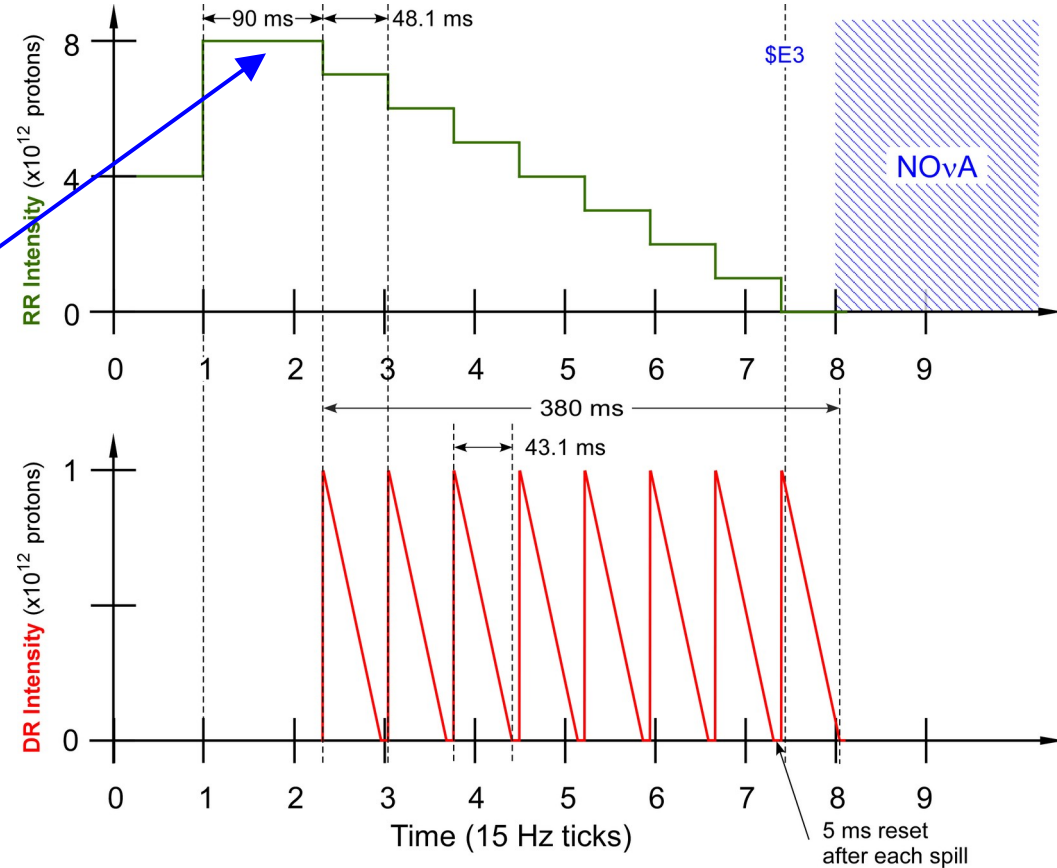
# Beam to Mu2e is resonantly extracted from the DR over 8 ticks

Two batches from Booster

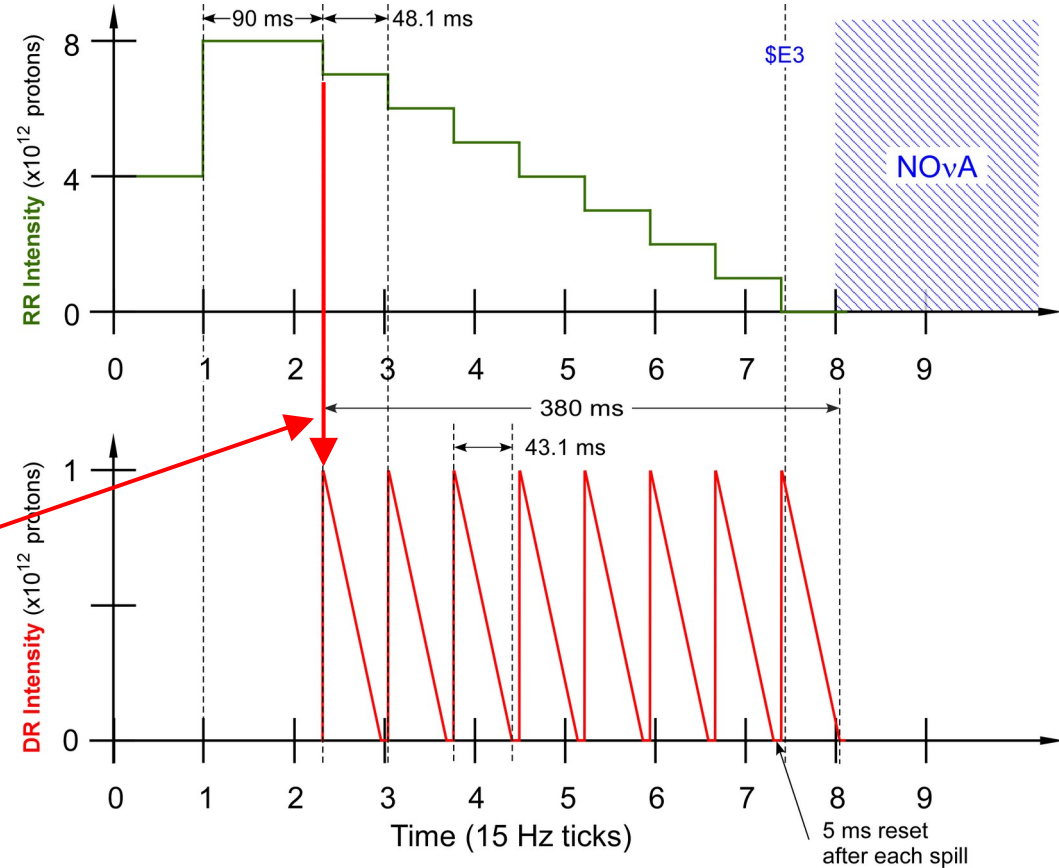


# Beam to Mu2e is resonantly extracted from the DR over 8 ticks

Rebatching takes >1 15Hz tick!!!



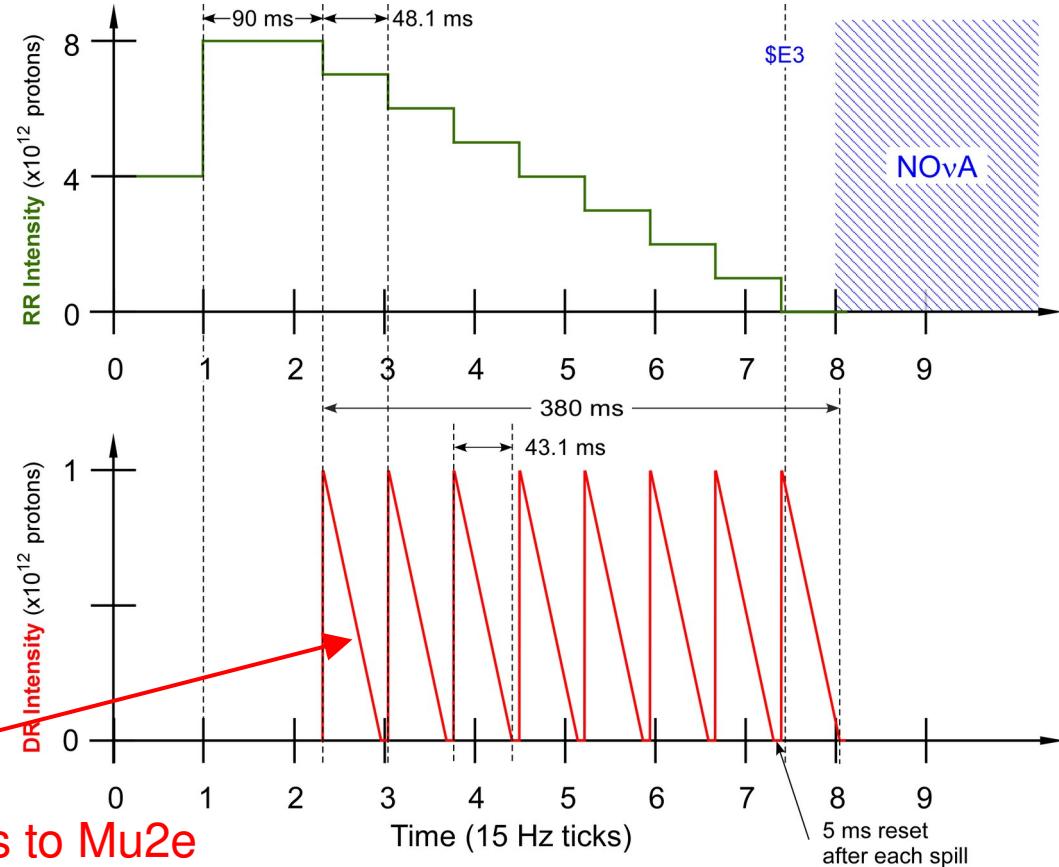
# Beam to Mu2e is resonantly extracted from the DR over 8 ticks



Move one of the new batches to DR  
2.5MHz  $\rightarrow$  2.36MHz!



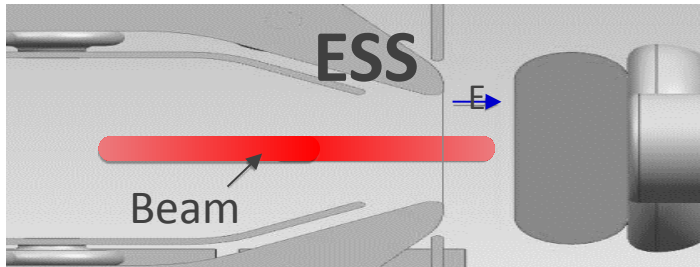
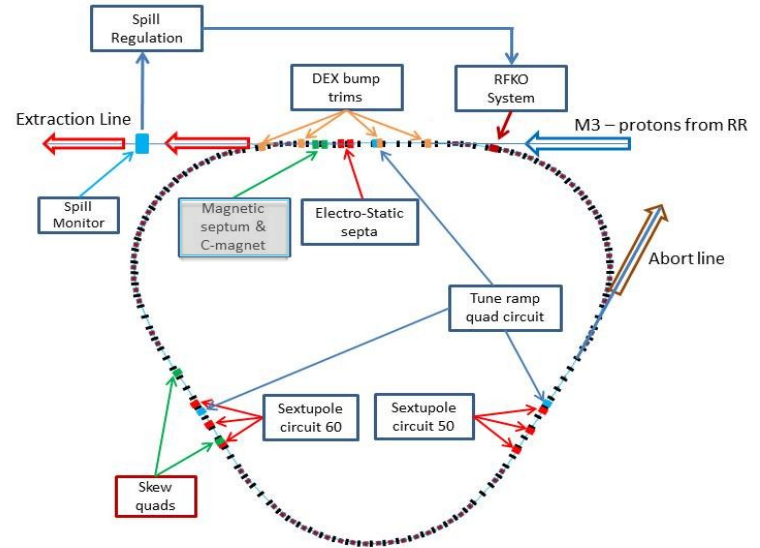
# Beam to Mu2e is resonantly extracted from the DR over 8 ticks



Resonant extraction ~25-30k pulses to Mu2e

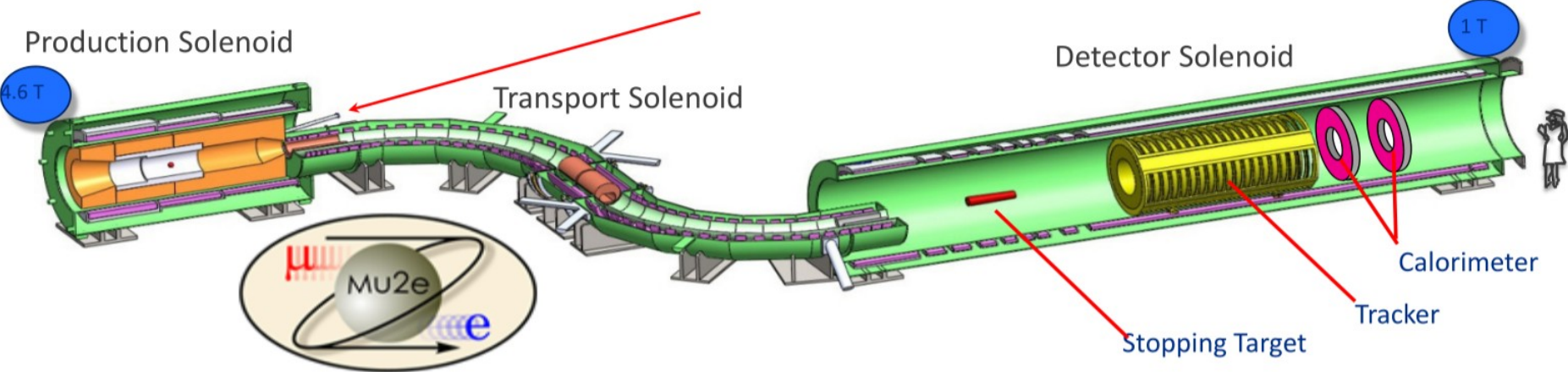
# Mu2e resonantly extracts from the delivery ring

- Quadrupoles intentionally drive a  $1/3$  integer resonance in the horizontal tune.
- Sextupoles induce a controlled beam instability.
- Septum foils peel off a bunch each turn.
- Dynamic spill regulation control is accomplished by tune corrections and RFKO.
- Full extraction occurs over  $\sim 25\text{-}30\text{k}$  turns.
- Remaining beam is dumped, and the cycle starts again.

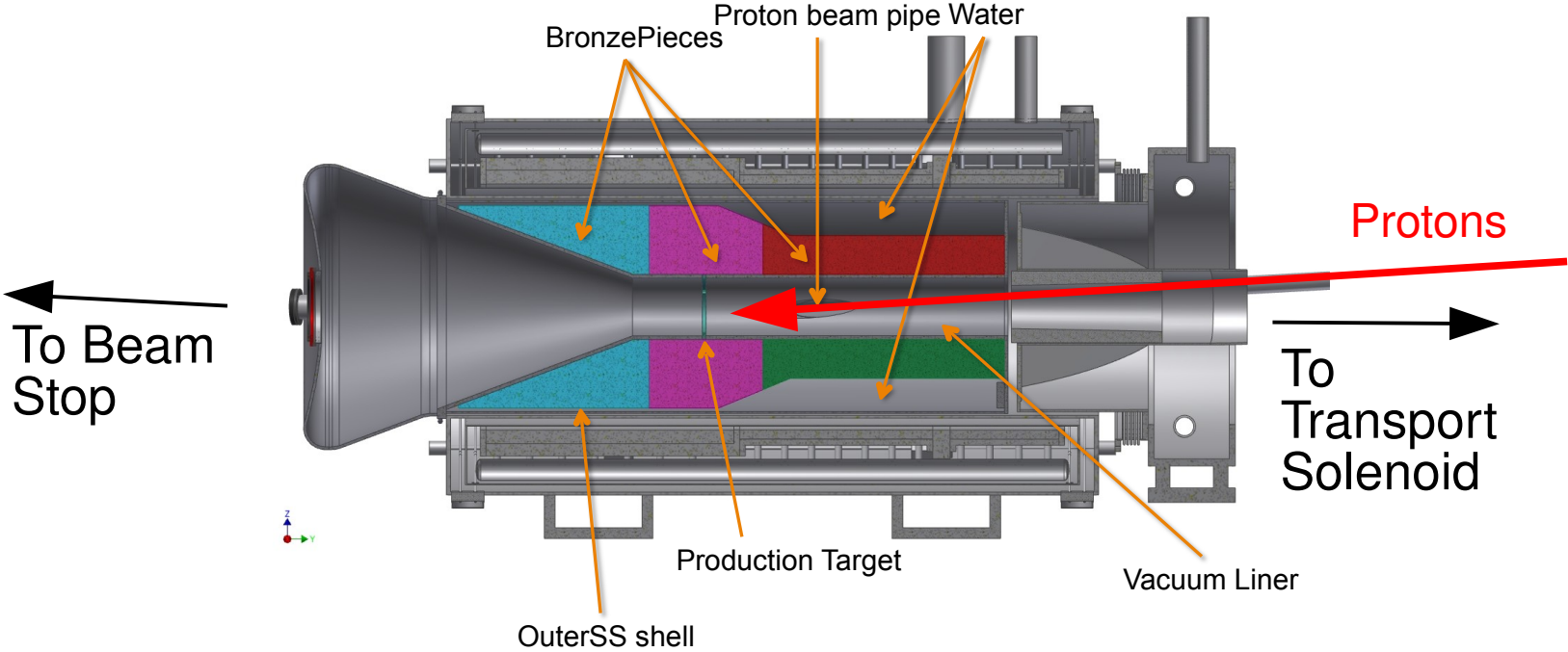


The delivery ring orbital period –  $1695\text{ns}$  – drives the interpulse spacing in Mu2e, and is a nearly ideal match to the muonic aluminum lifetime of  $864\text{ns}$ .

# Twenty slides ago, I showed you this picture

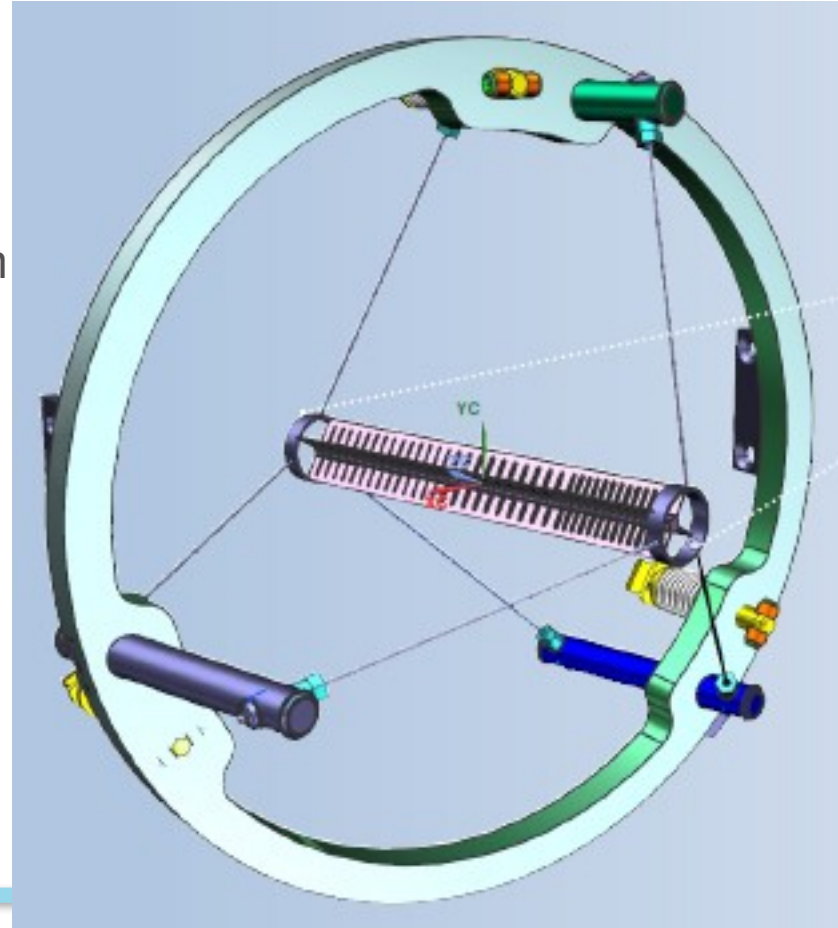


# The production target is mounted inside a high field Production Solenoid, and we capture and transport backward muons



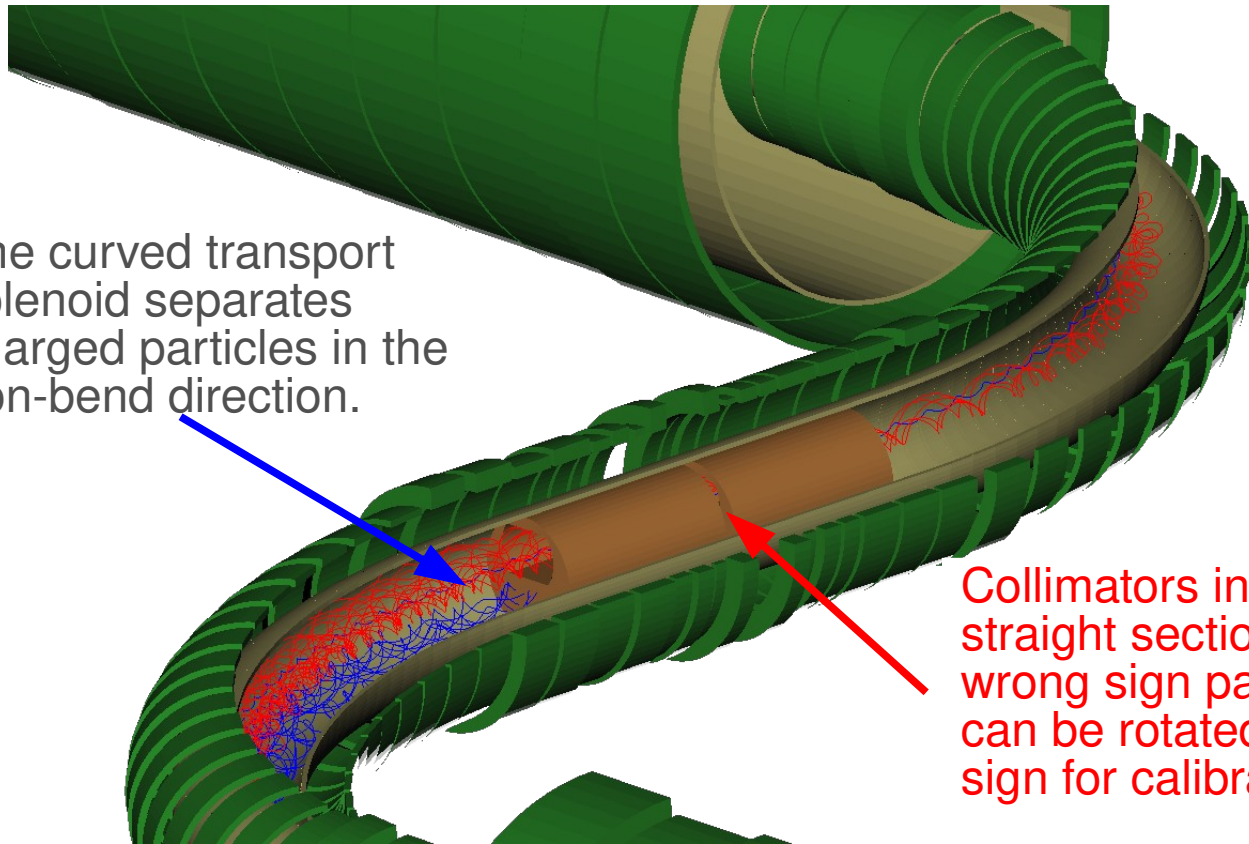
# The production target is a radiatively cooled tungsten structure

- Bicycle wheel support
- LaO<sub>2</sub>-doped Tungsten, core is EDMed from single rod
- Longitudinally segmented cylinder (**stress management**):
  - 3.15 mm radius, 160+60 mm length
- Longitudinal fins (**structure and thermal management**)
- 1mm tungsten spokes
- ~ 700 W power absorption
- ~ 1500 K temperature



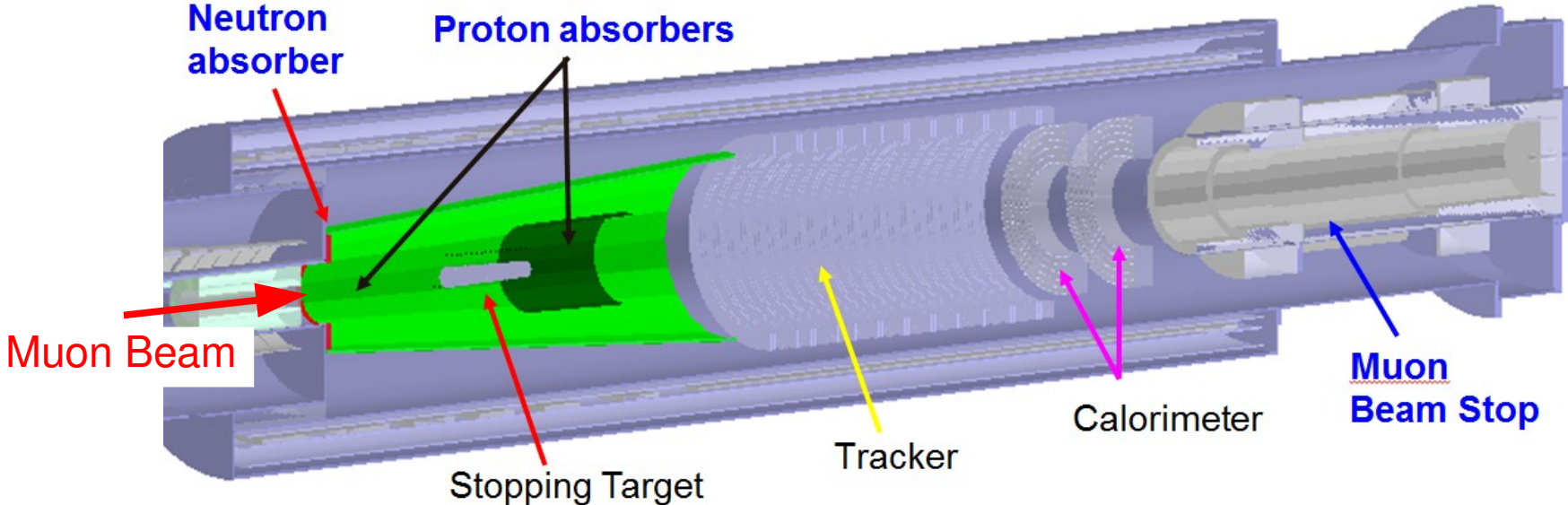
# The Transport Solenoid sign-selects with a collimator

The curved transport solenoid separates charged particles in the non-bend direction.

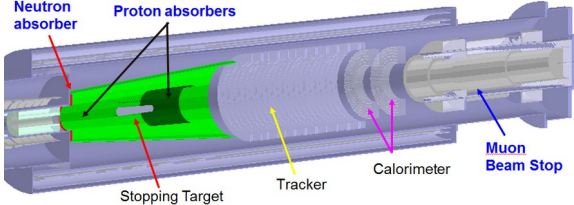
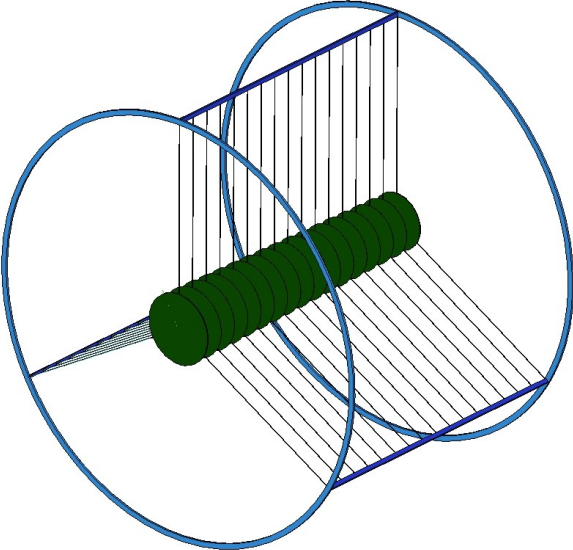


Collimators in the central straight section reject most wrong sign particles, and can be rotated to change sign for calibration runs.

# The Detector Solenoid is the heart of the experiment



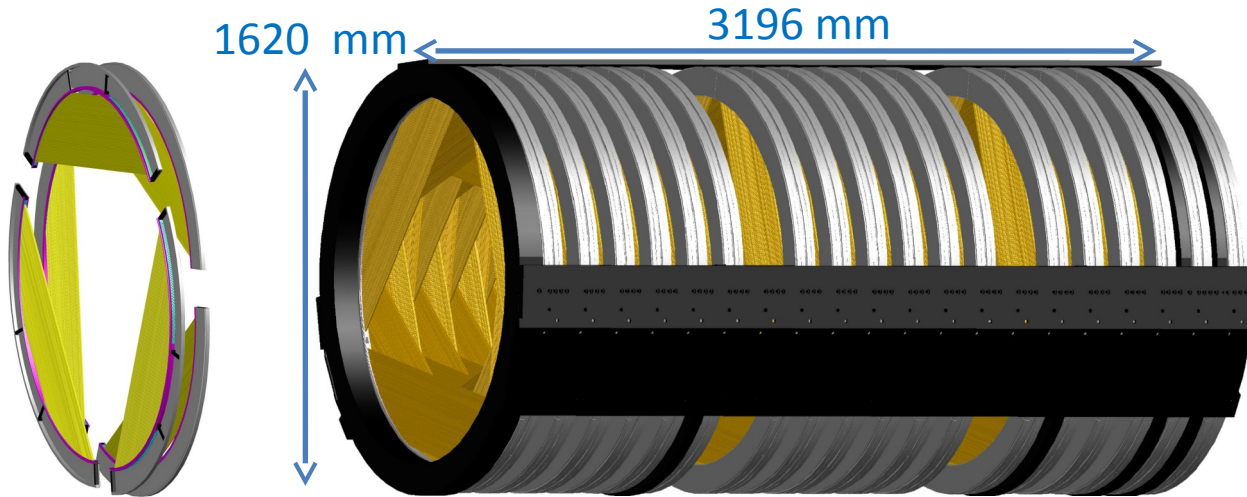
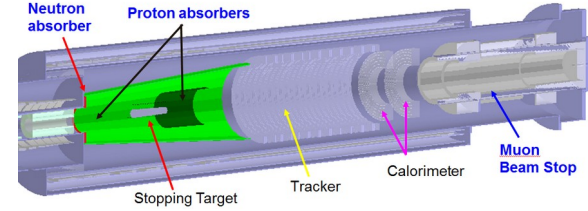
# The Detector Solenoid is the heart of the experiment



The stopping target is 17 Al foils to intercept and stop the secondary beam



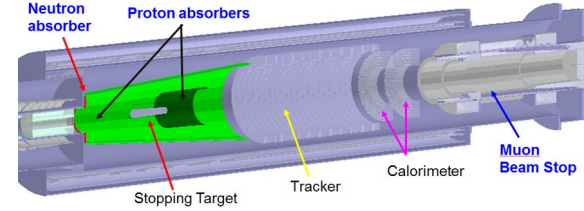
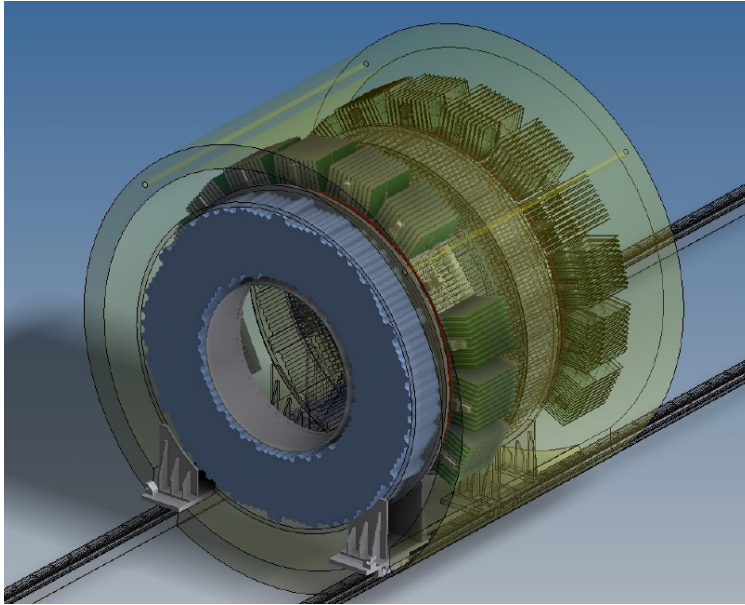
# The Detector Solenoid is the heart of the experiment



The electron tracker is a low mass straw tube design with 18 stations of tubes transverse to the secondary beam, with 21,000 straws in total.

It provides precision momentum measurement.

# The Detector Solenoid is the heart of the experiment

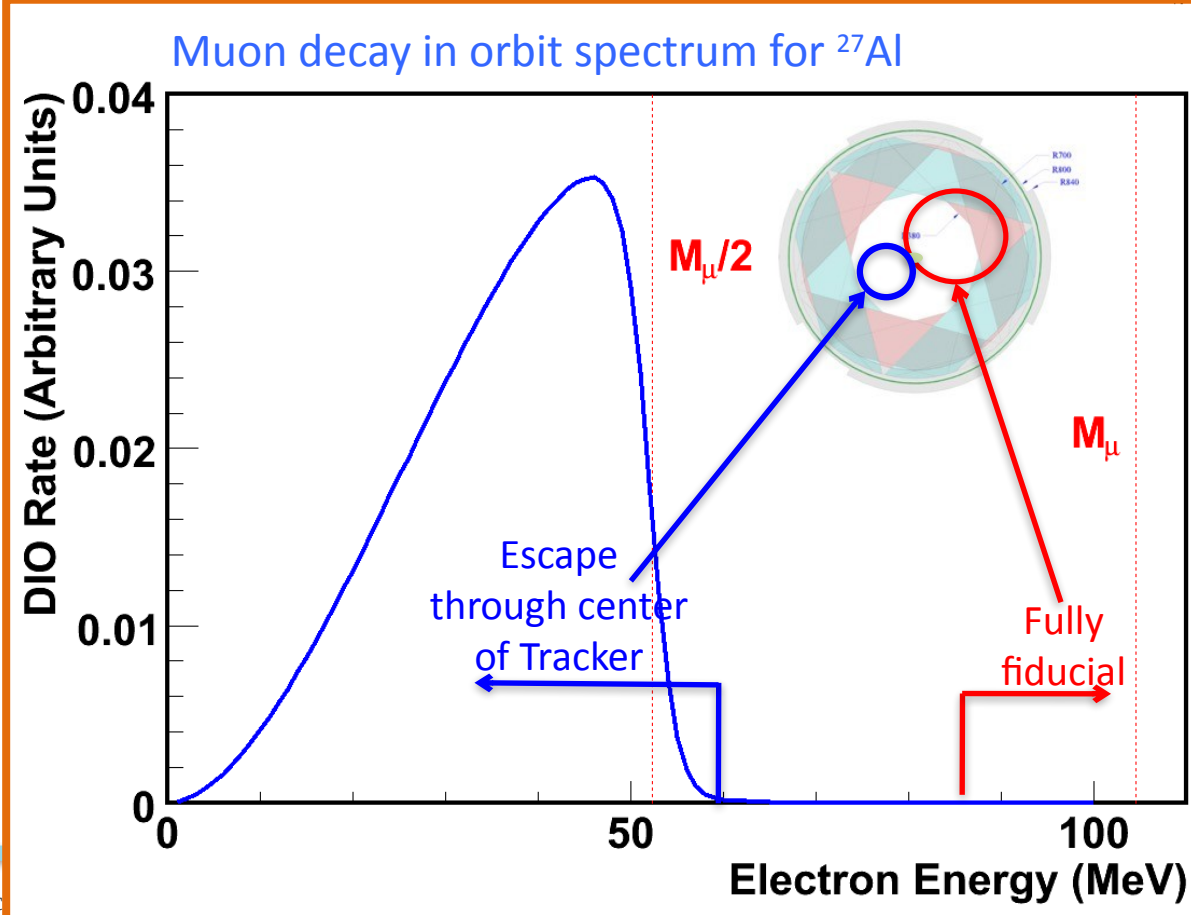


The calorimeter is a two layer, annular, undoped CsI crystal calorimeter.

It provides precision timing and particle ID

# Detectors are uninstrumented along the axis of the solenoid

The vast majority of remnant beam, brehmstrahlung, and muon decay products escape down this central hole and are captured in a muon beam stop designed to prevent “back splash”



# Mu2e running will be split by the LBNF shutdown

Construction should complete in 2025, with commissioning and Run 1 physics data in 2026-2027.

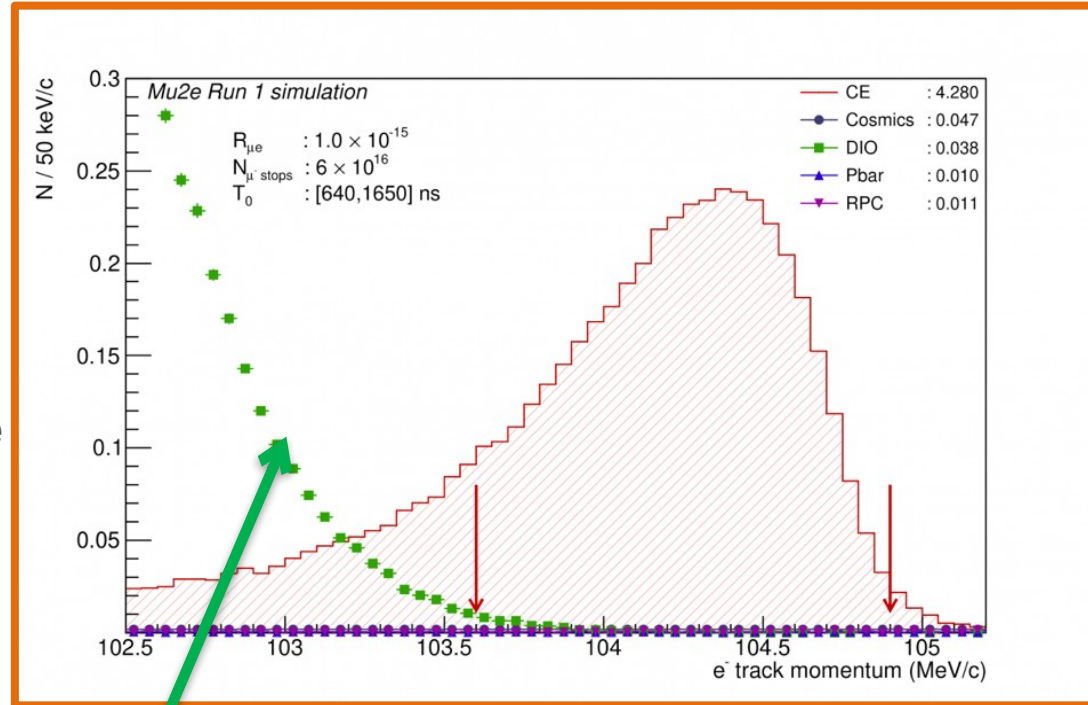
Recently completed a sensitivity estimate for Run 1:

- $5\sigma$  discovery  $R = 1.1 \times 10^{-15}$
- 90% CL  $R < 5.9 \times 10^{-16}$
- 1000x better than SINDRUM-II
- Paper to be submitted to Universe

Run 2 will commence in 2029 with a goal to improve the measurement to 10000x better than SINDRUM-II.

For the full dataset, our expected sensitivity

- 90% CL  $R < \text{few} \times 10^{-17}$

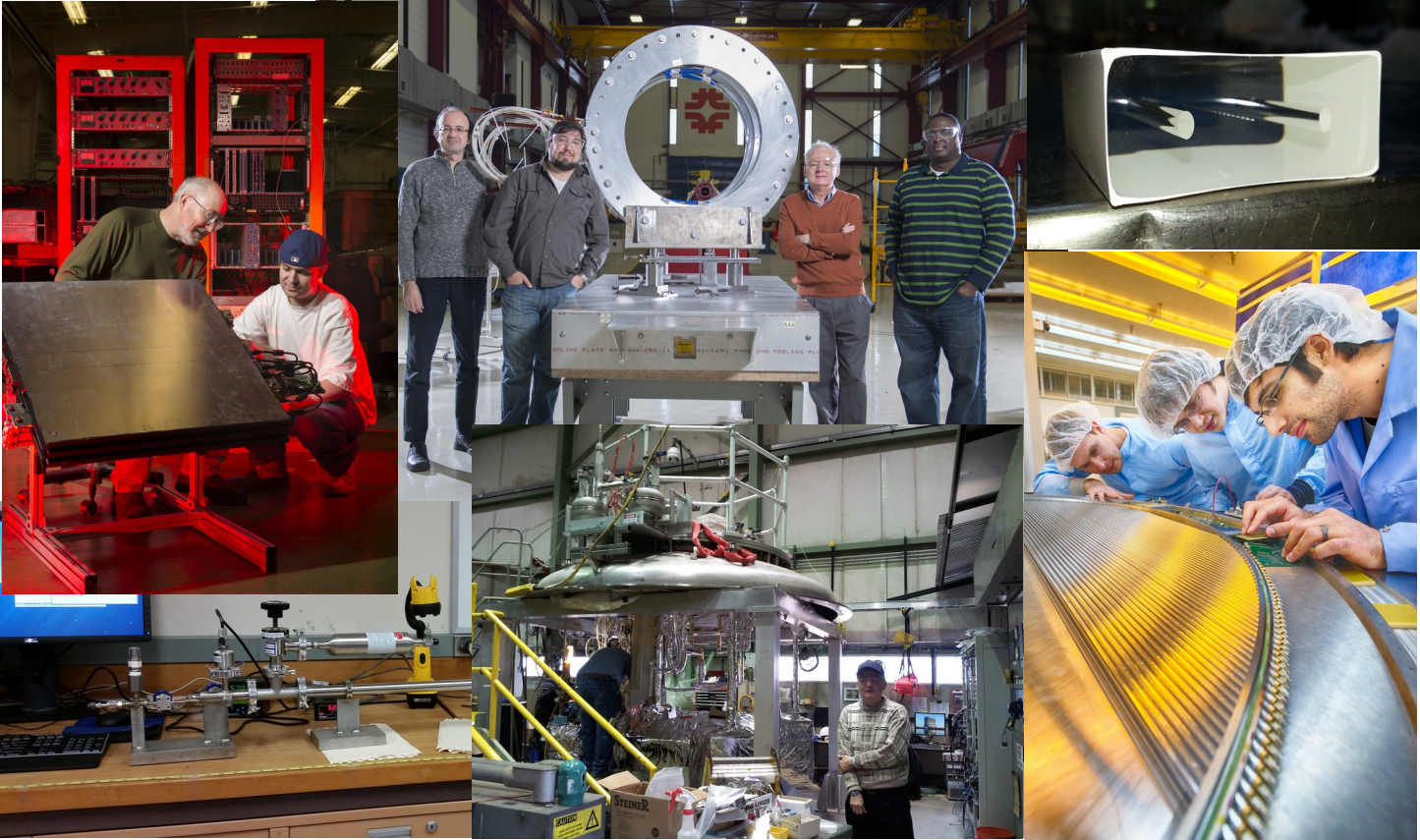


Long DIO tail due to nuclear recoil

## To summarize...

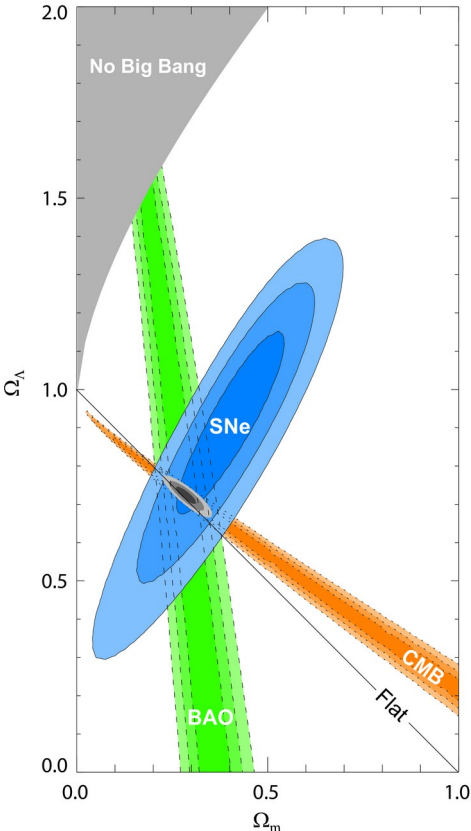
- Fundamental muon physics today is focused on CLFV searches
  - $\mu \rightarrow e \gamma$
  - $\mu \rightarrow eee$
  - $\mu N \rightarrow e N$
- Mu2e and COMET are friendly competition in the conversion search with much shared DNA
  - Both aim for a 10,000x improvement over SINDRUM-II
- We're either going to discover new physics in the next few years, or we'll provide a nearly unprecedented improvement in sensitivity, either of which beg for a next generation experiment
  - Although I couldn't talk about them today, there are ideas to gain an additional 2-3 orders of magnitude with future searches in these and other channels

# Thanks for your interest and attention!





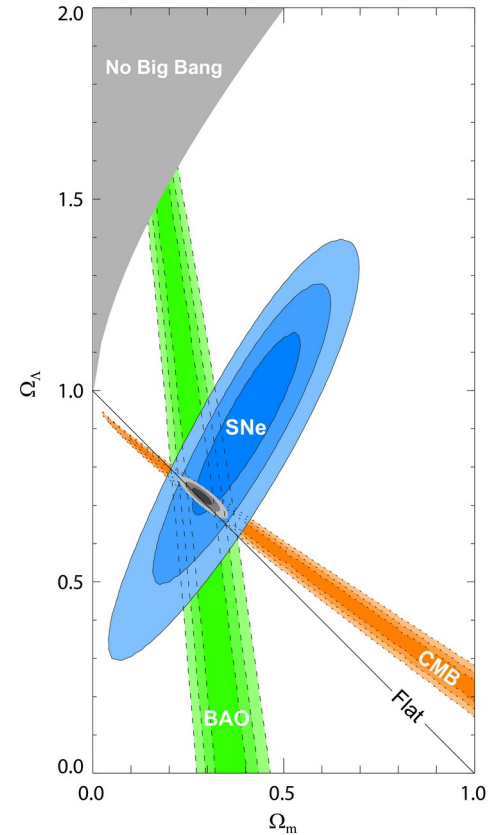
# But it gets even worse: the vacuum energy problem





## But it gets even worse: the vacuum energy problem

Some of that stuff - aka the *dark energy* - controls the ultimate fate of the universe!

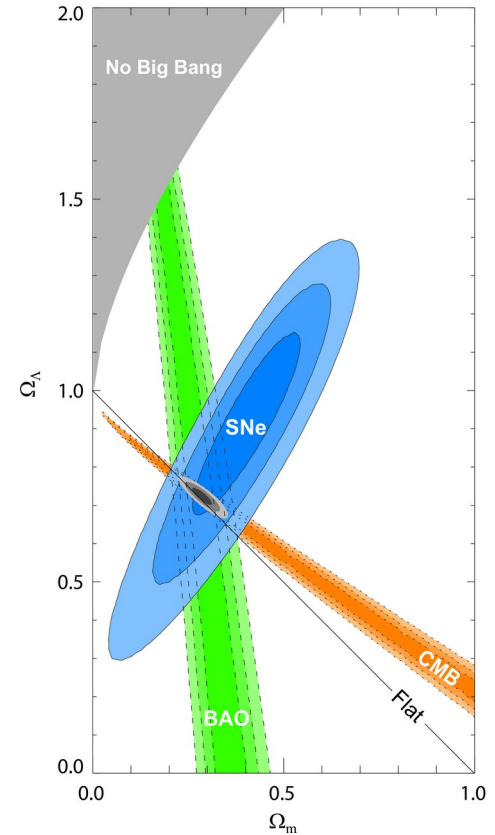


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Measured Cosmological Constant

$$\Lambda_{\text{CDM}} = 10^{-47} \text{ GeV}^4$$



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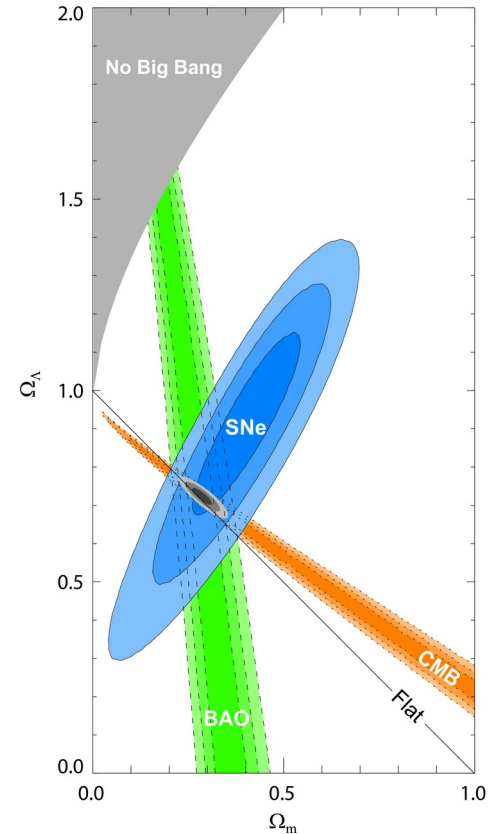
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