Neutrinos, Dark Matter, & the Quest for New Physics

Ian M. Shoemaker

VIRGINIA TECH

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UC SANTA BARBARA
Kavli Institute for Theoretical Physics

Outline

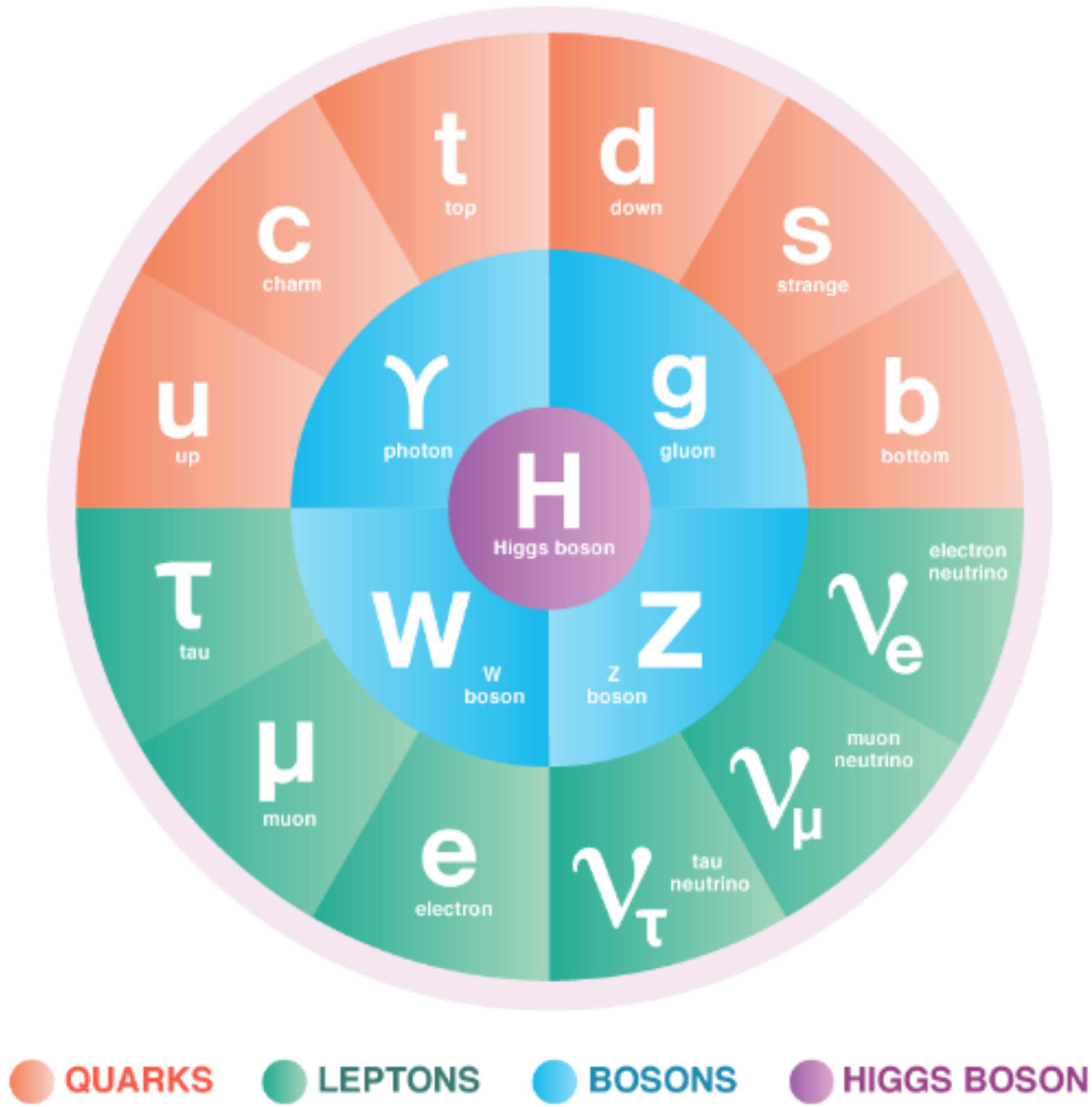
- The Standard Model's successes & limitations.
- The Hunt for New Physics:
  - Dark Matter
  - Neutrinos
  - Complementarity of Experimental Probes.

Landscape of Physics...

Probably most of you are familiar with at least some of the standard model if you just think about some of the building black systems you know about round us, so I’ll start by reviewing some of those.

Introducing the Standard Model

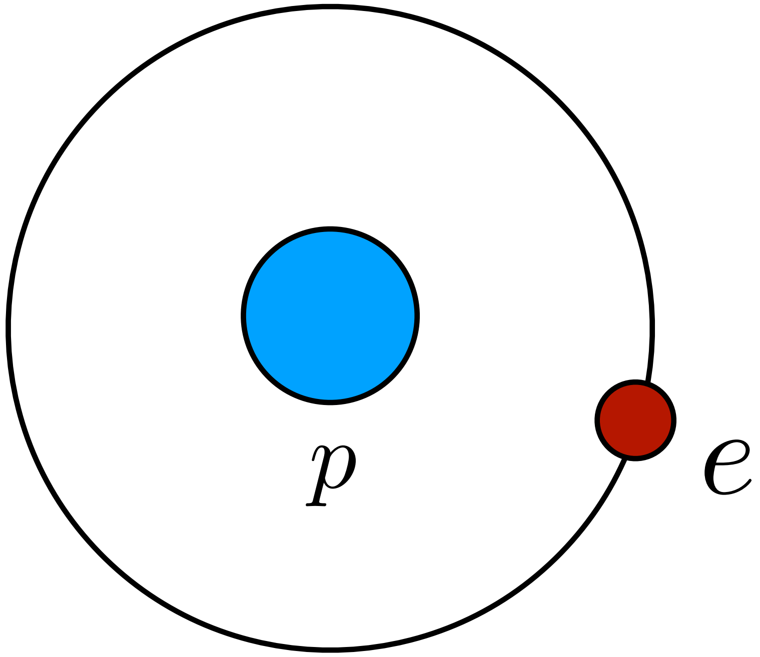
The Standard Model



Matter and Forces

The Standard Model is a theory of matter but also forces.

Representative example: Hydrogen Atom



Matter and Forces

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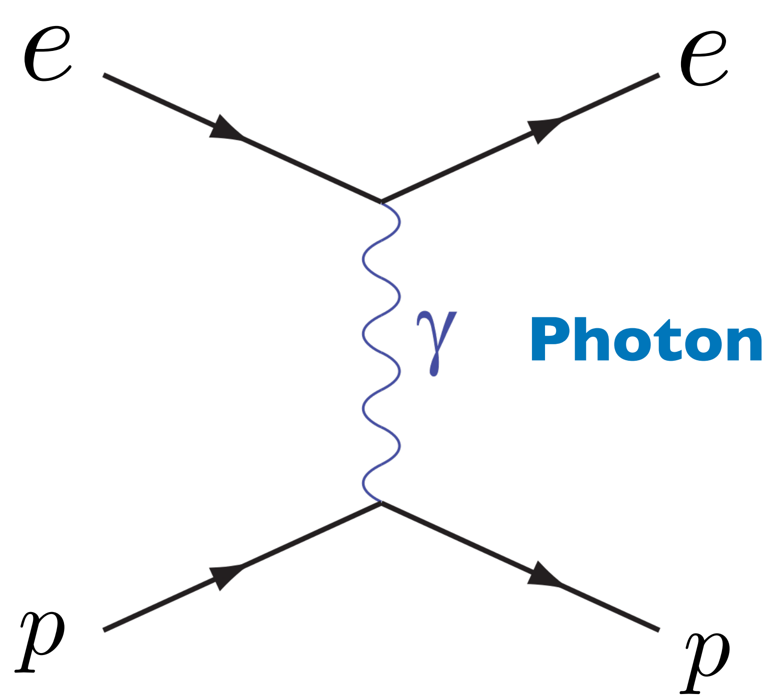
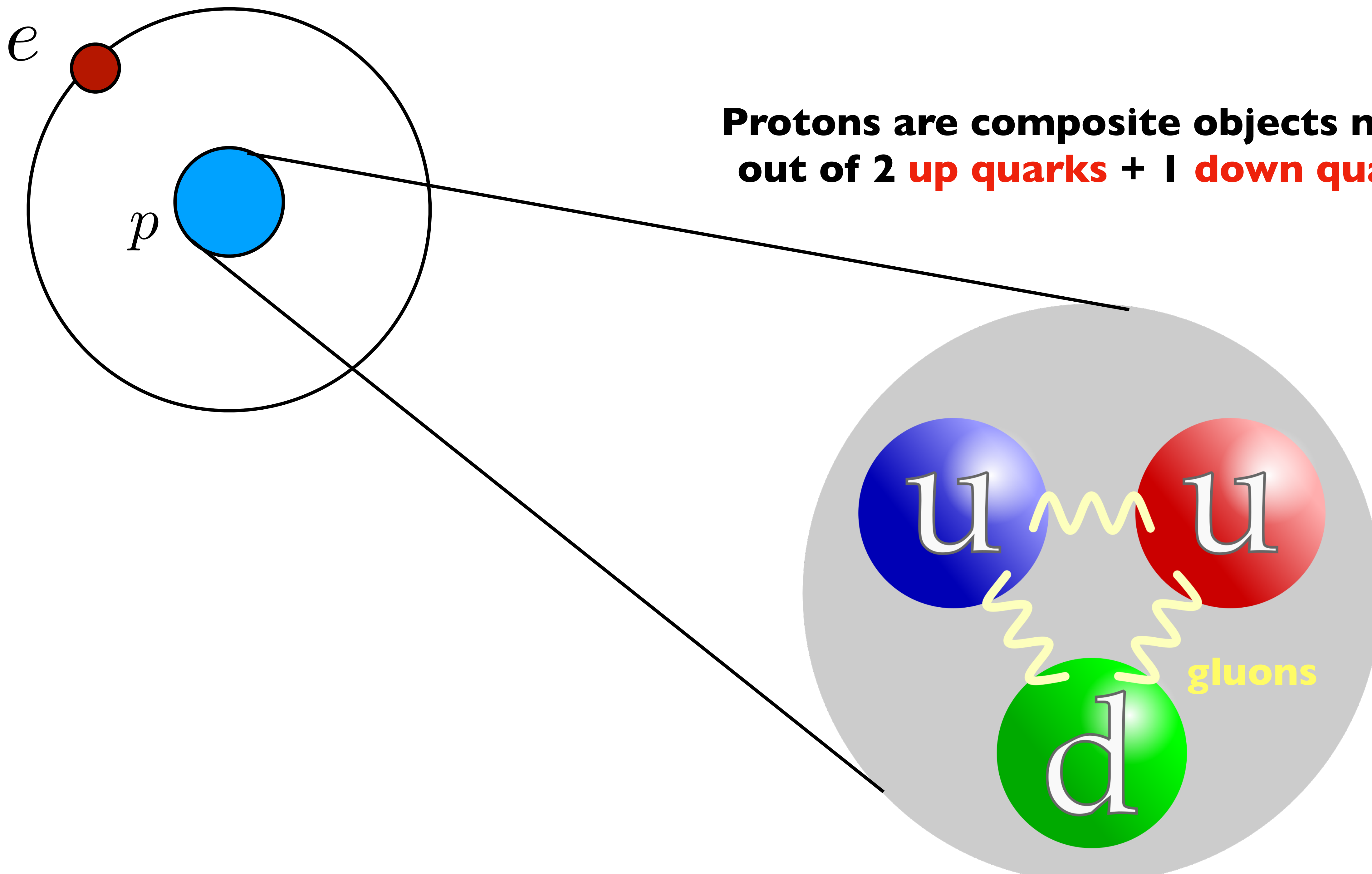
Particle Physicists Picture of an Atom



Electromagnetism is mediated via the exchange of photons.

The Standard Model

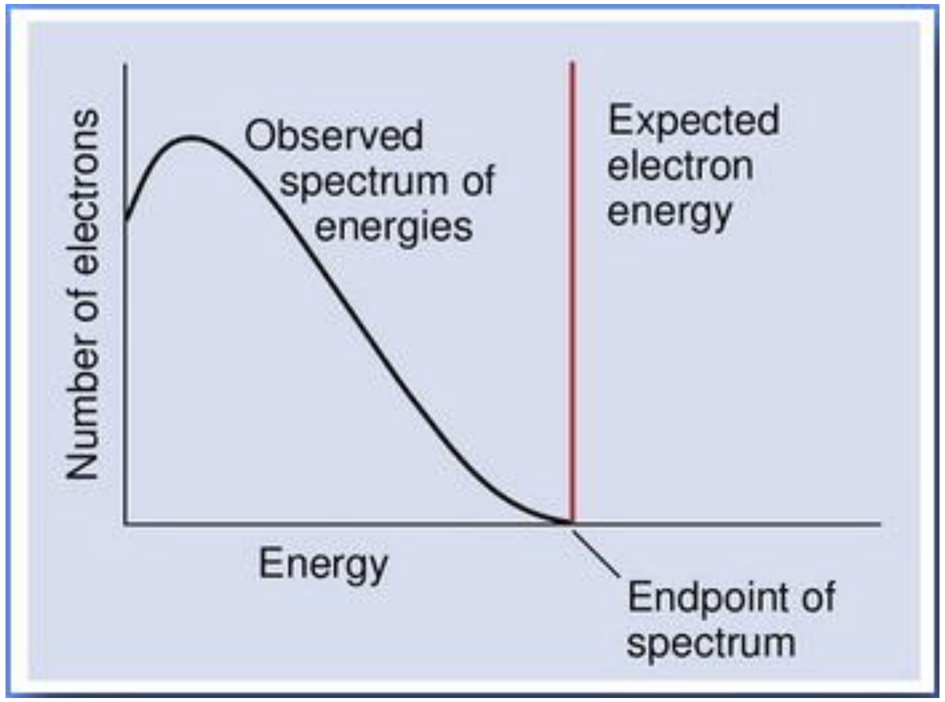
Protons are composite objects made out of 2 up quarks + 1 down quark.



Strong Nuclear Force is mediated via the exchange of gluons.

The Weak Interaction

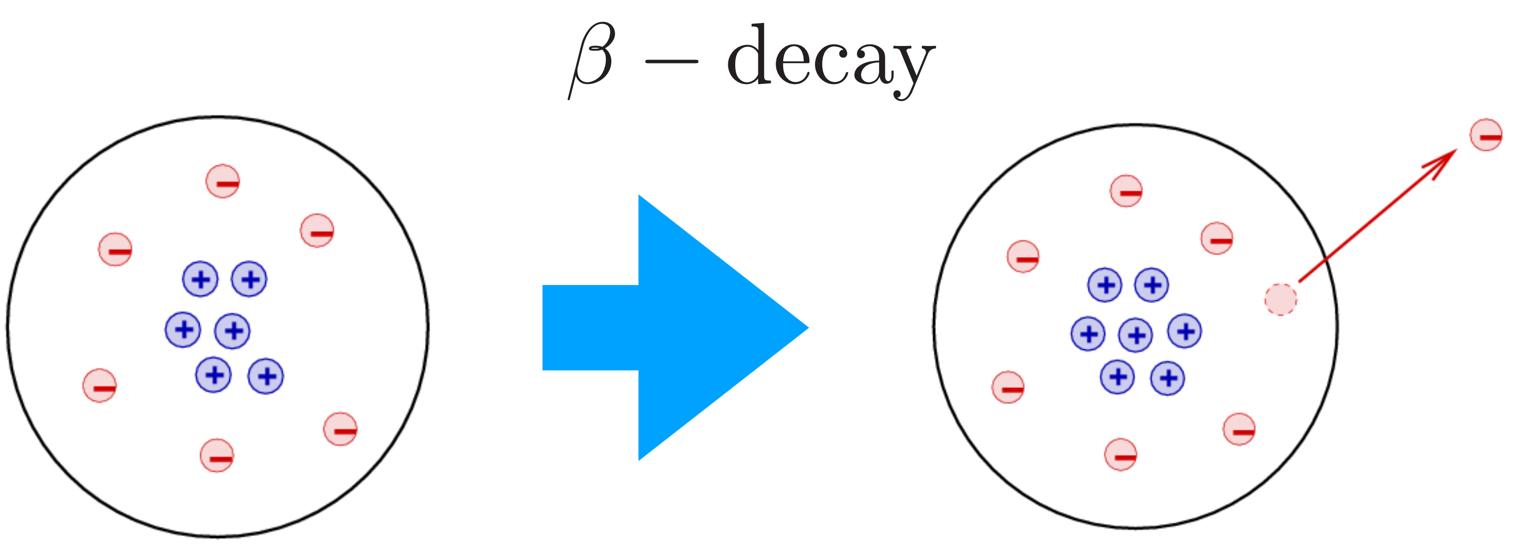
Data:



Apparent violation of energy/momentum!

Wolfgang Pauli proposes

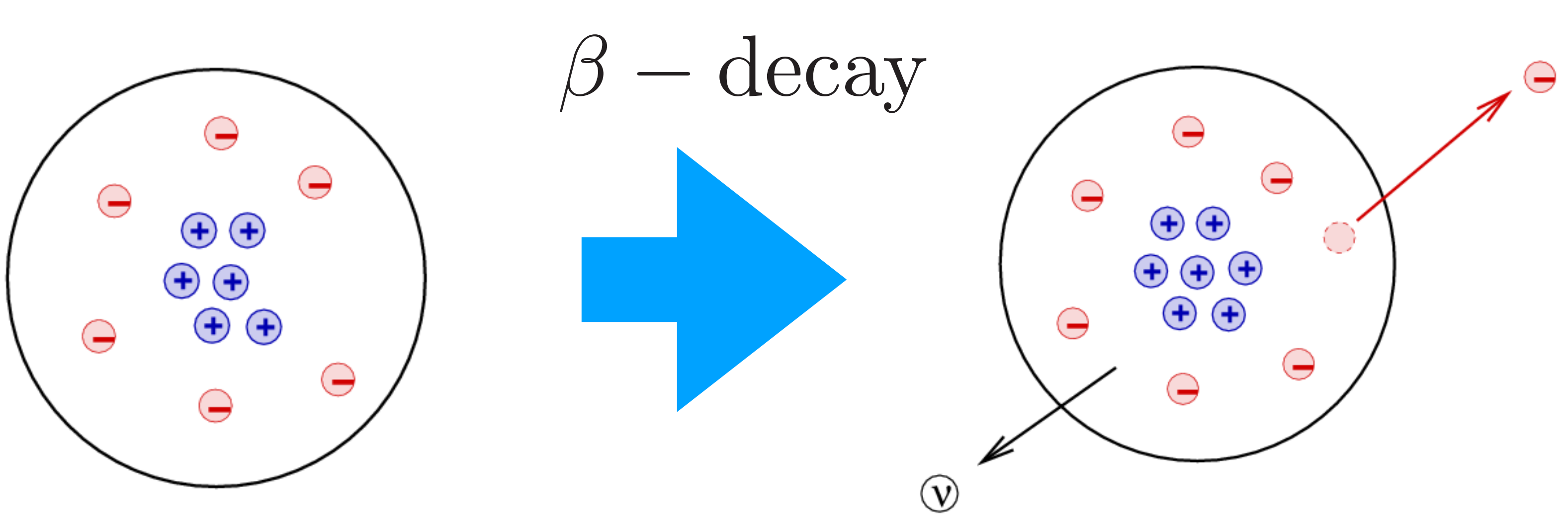
Apparent picture:



Gained a proton & an electron.

Correct picture:

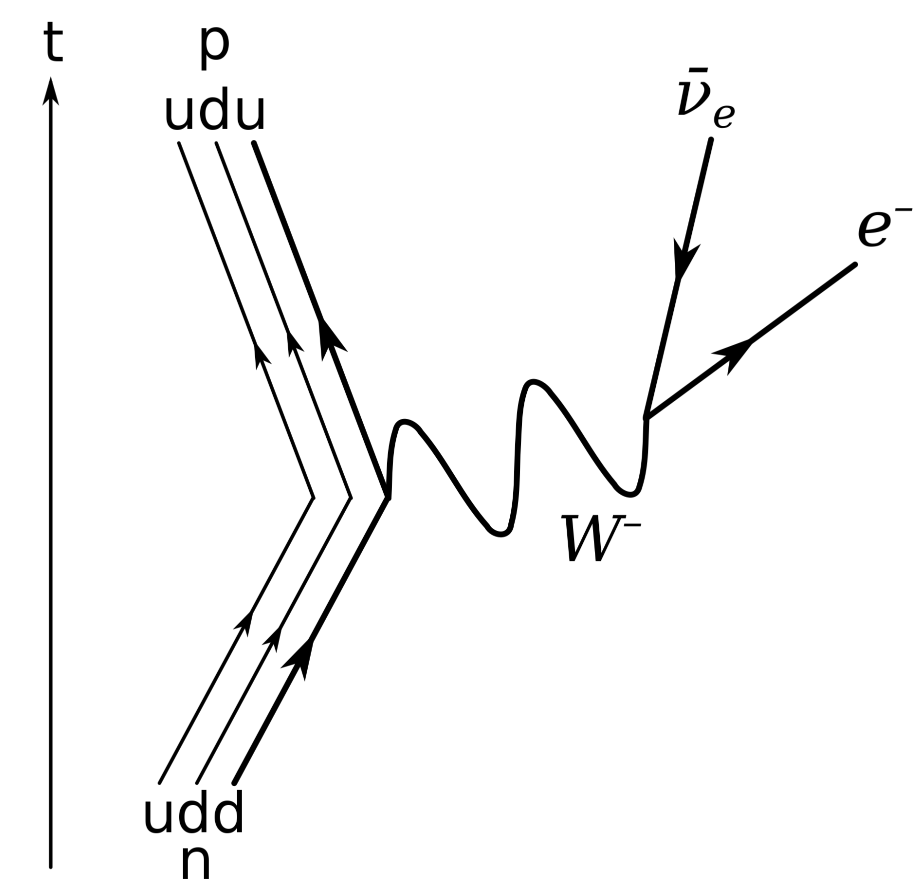
A new light & neutral state carrying away energy/momentum.



The Standard Model

The Weak Force allows neutrons to decay and emit neutrinos.

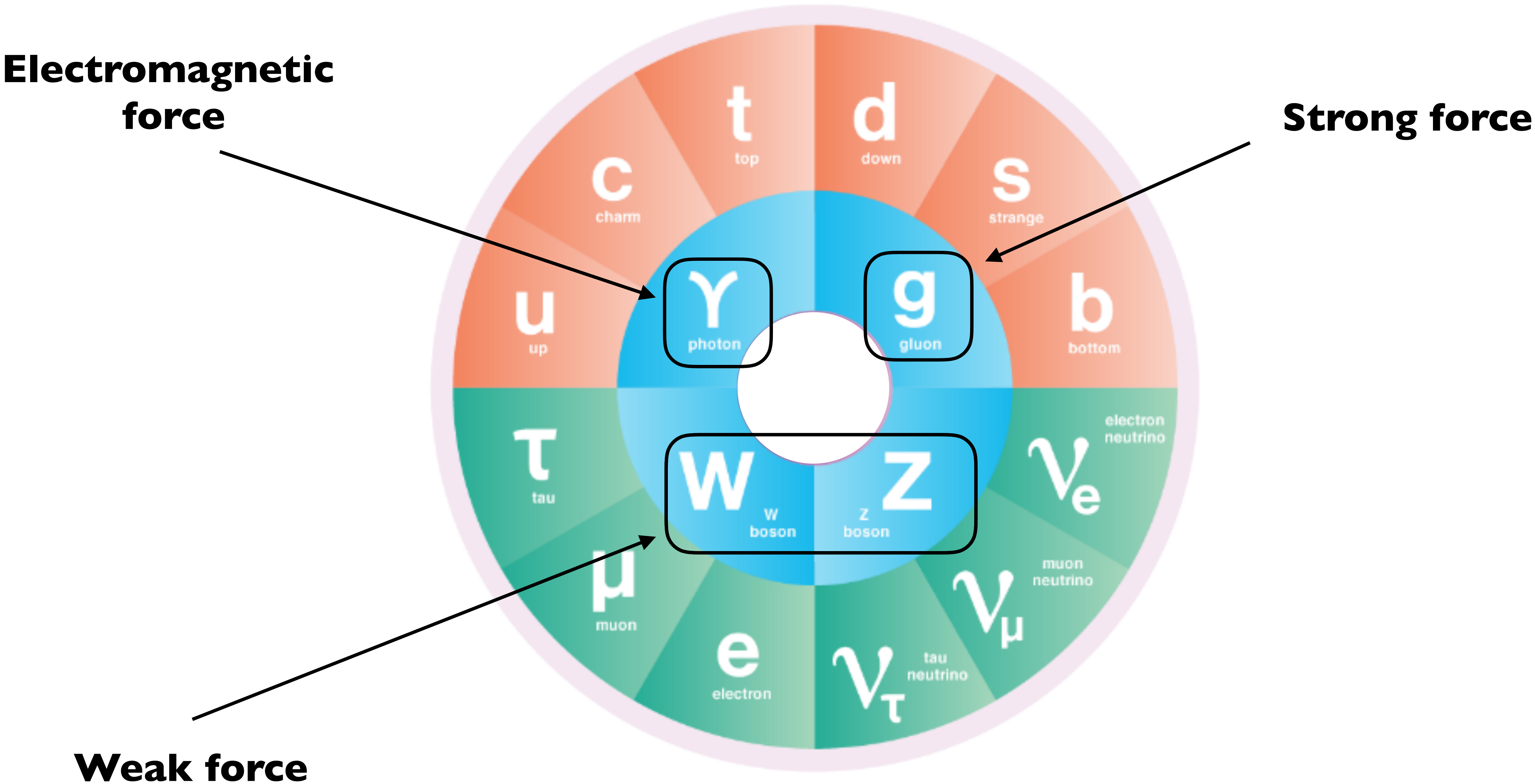
$$\underset{(udd)}{n} \rightarrow \underset{(udu)}{p} + e + \bar{\nu}_e$$



Weak Nuclear Force is mediated via the exchange of W/Z bosons.

the new Periodic Table, but unlike Mendelevye’s table includes not just matter but the force carriers with which matter interacts.

e Standard Model



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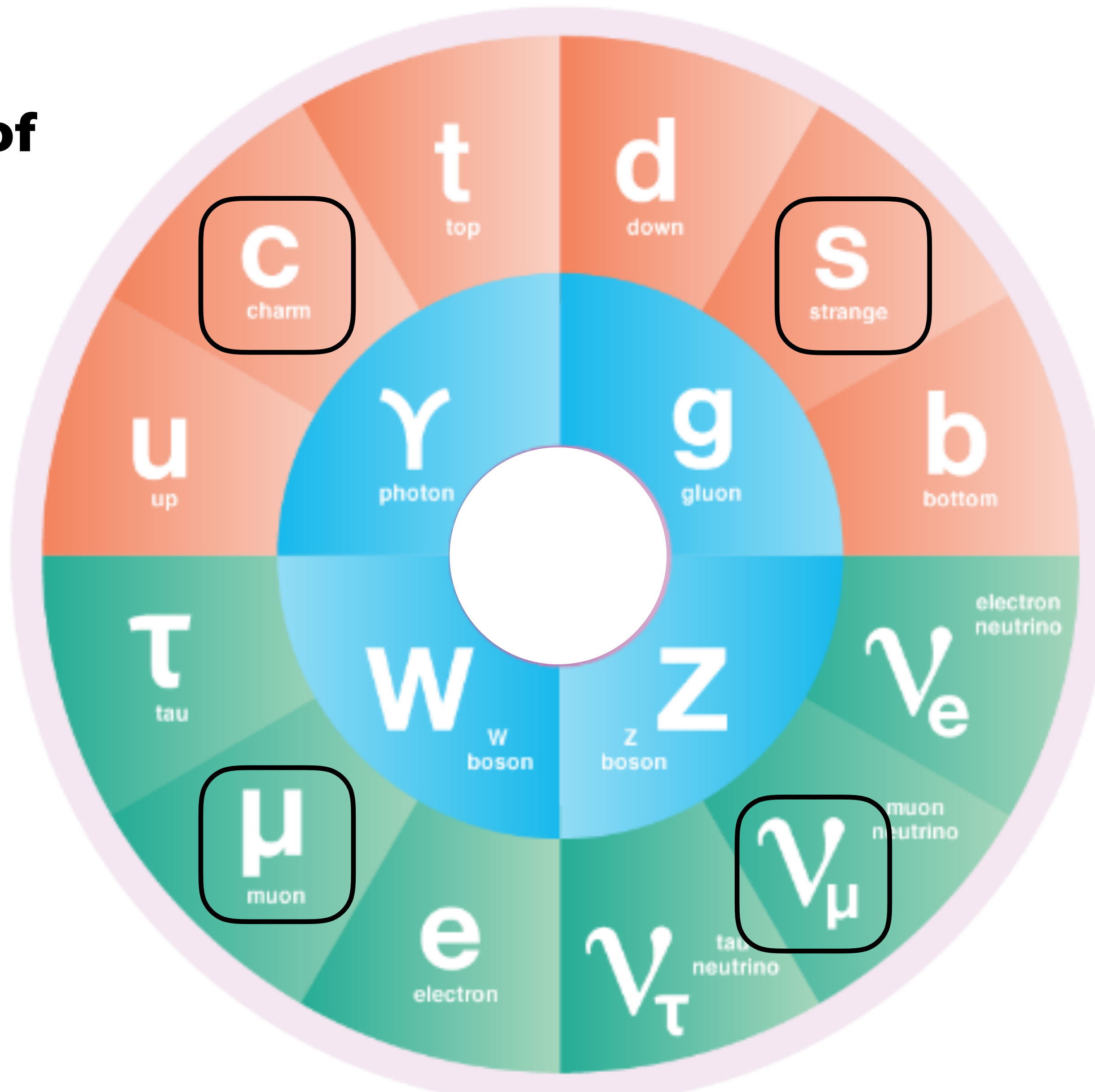
e Standard Model

Atomic Matter
= "1st generation"

the new Periodic Table, but unlike Mendelevye's table includes not just matter but the force carriers with which matter interacts.

e Standard Model

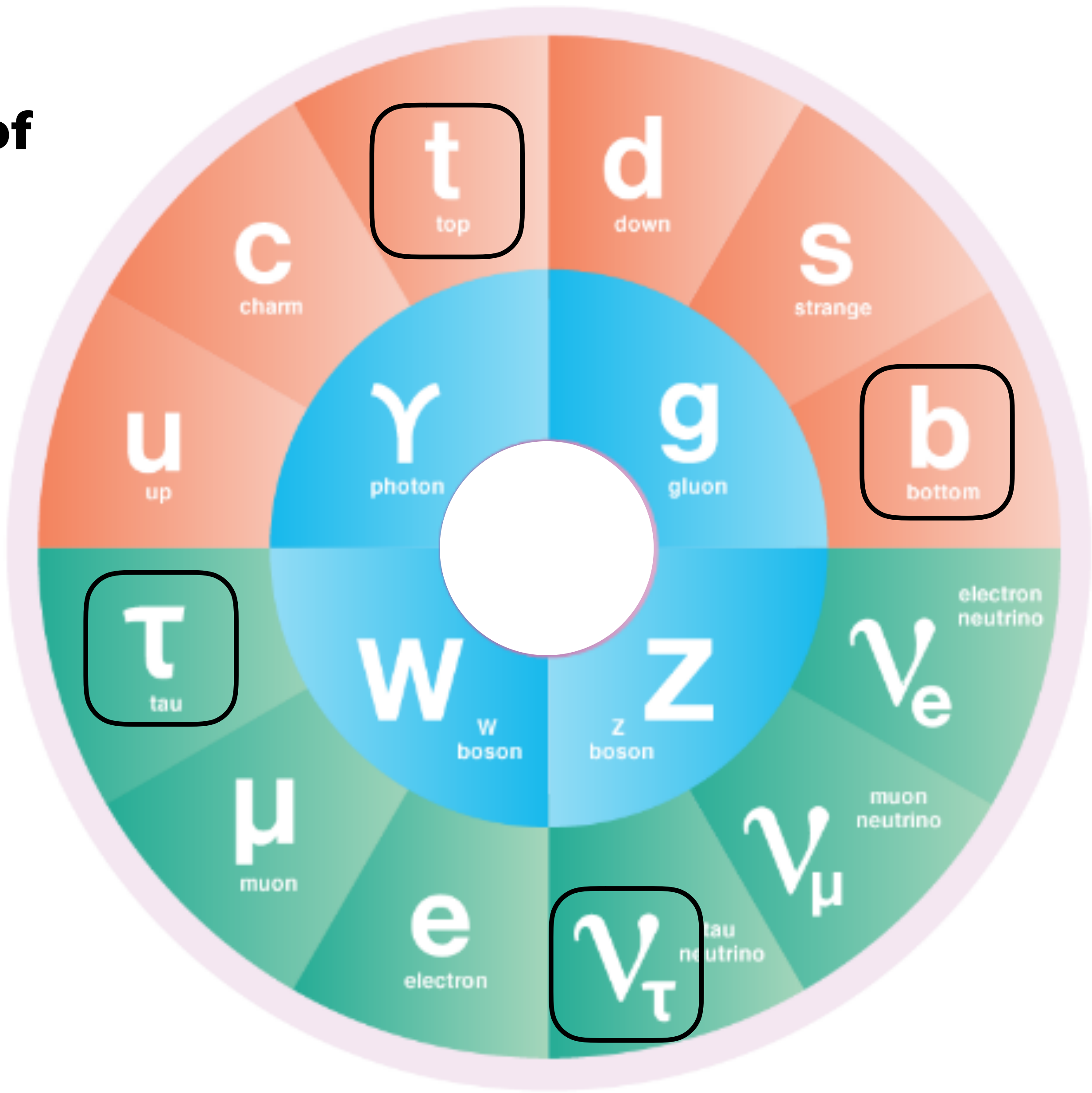
"2nd generation" = heavier version of 1st generation



the new Periodic Table, but unlike Mendelevye's table includes not just matter but the force carriers with which matter interacts.

e Standard Model

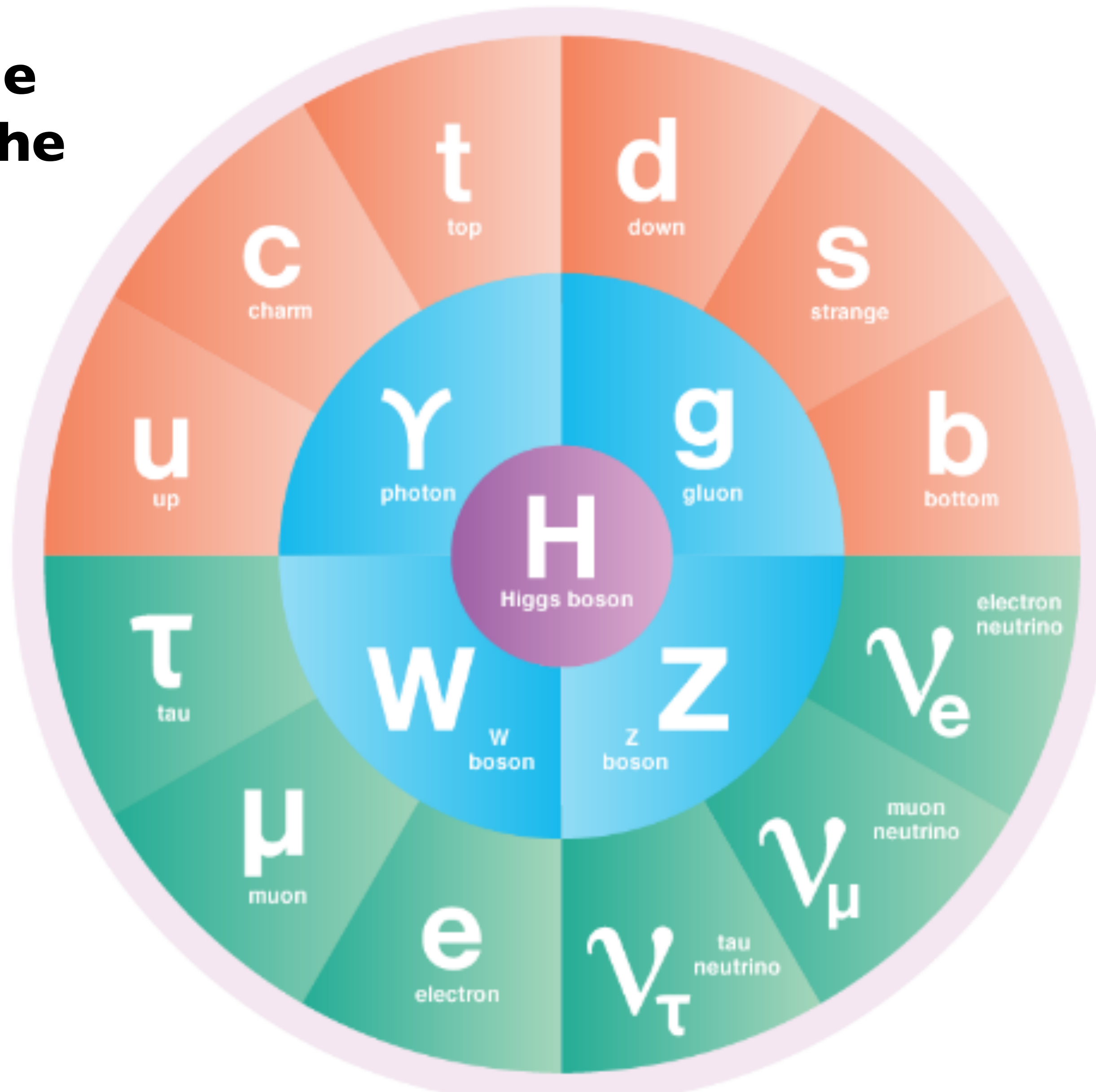
"3rd generation" = heavier version of 2nd generation



the new Periodic Table, but unlike Mendelevye's table includes not just matter but the force carriers with which matter interacts.

e Standard Model

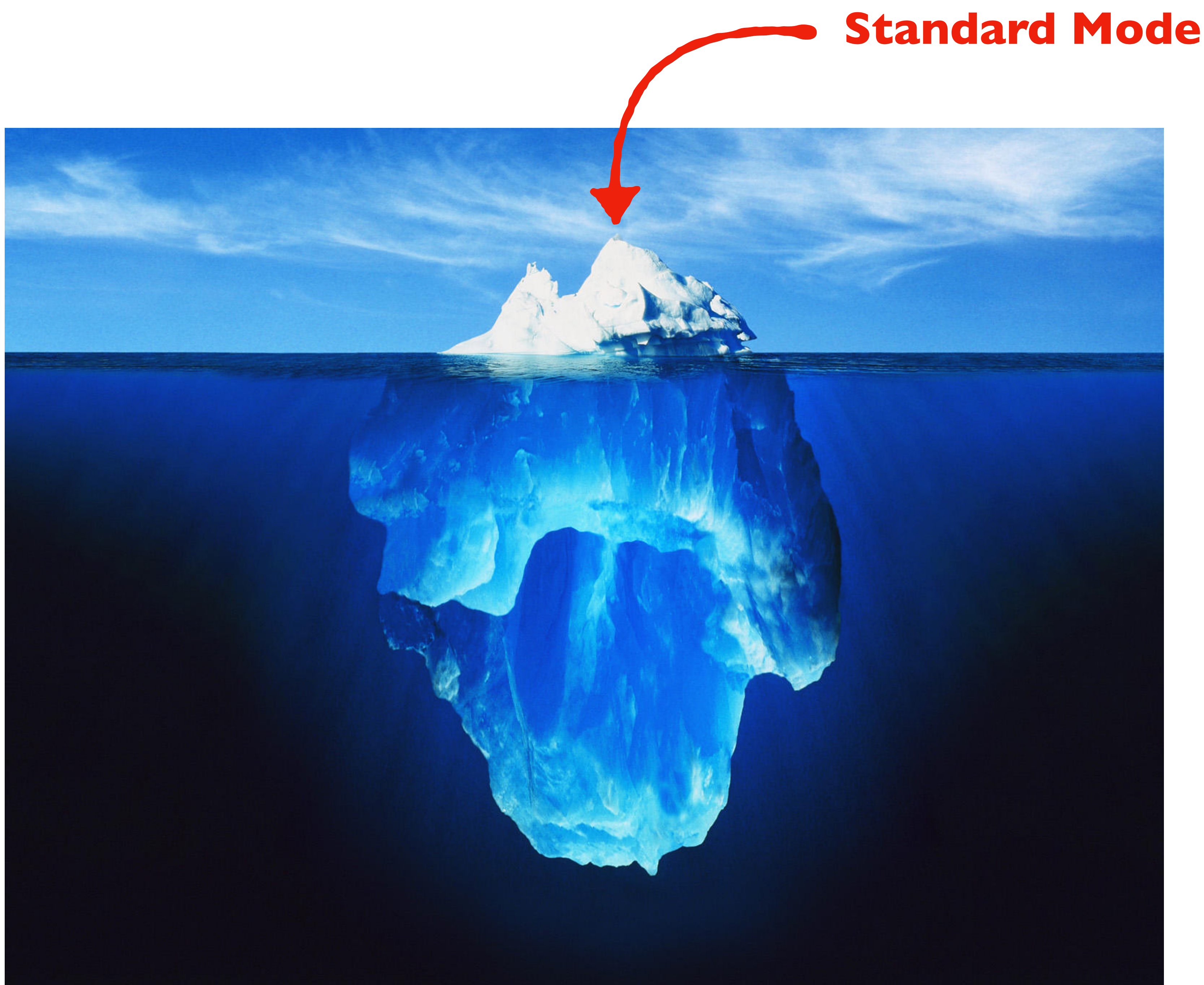
Higgs is responsible for giving mass to the other particles.



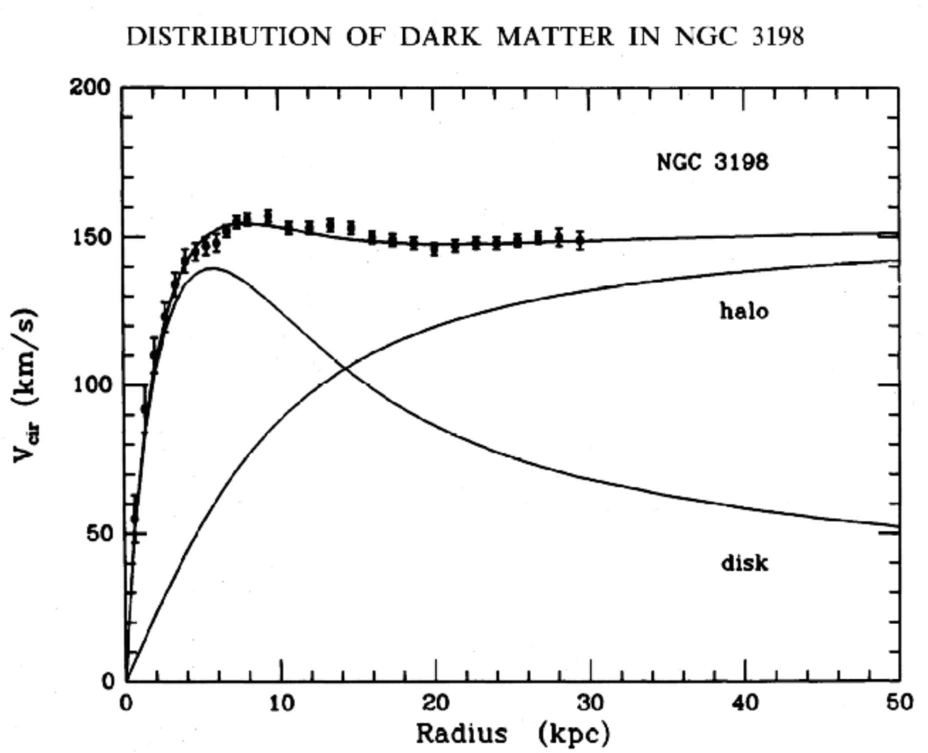
Final Keystone Piece: Higgs!

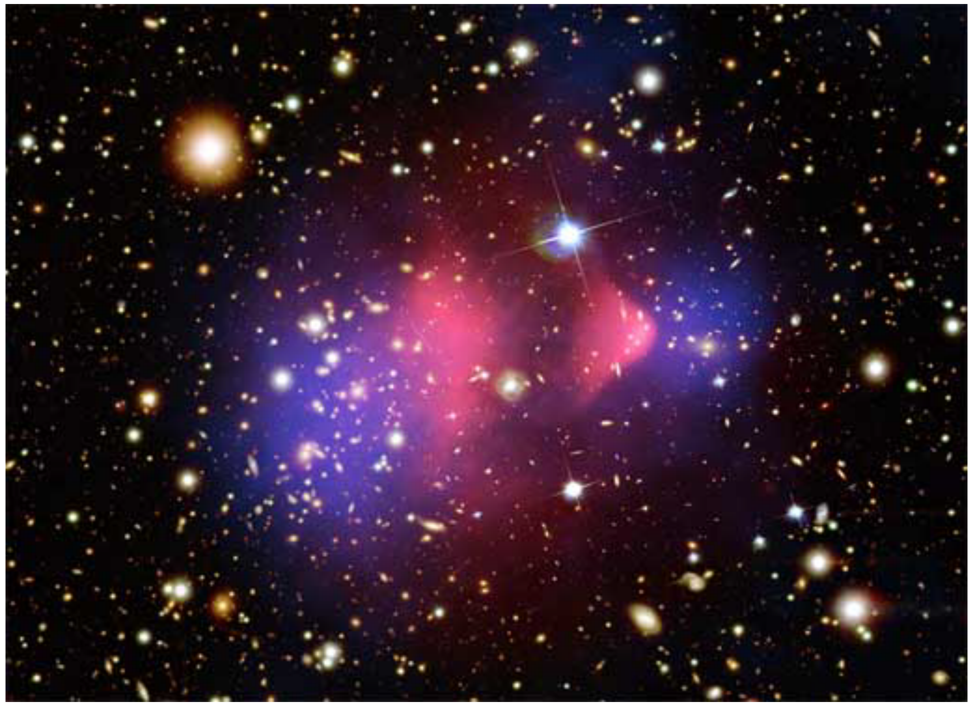
July 4, 2012 at CERN

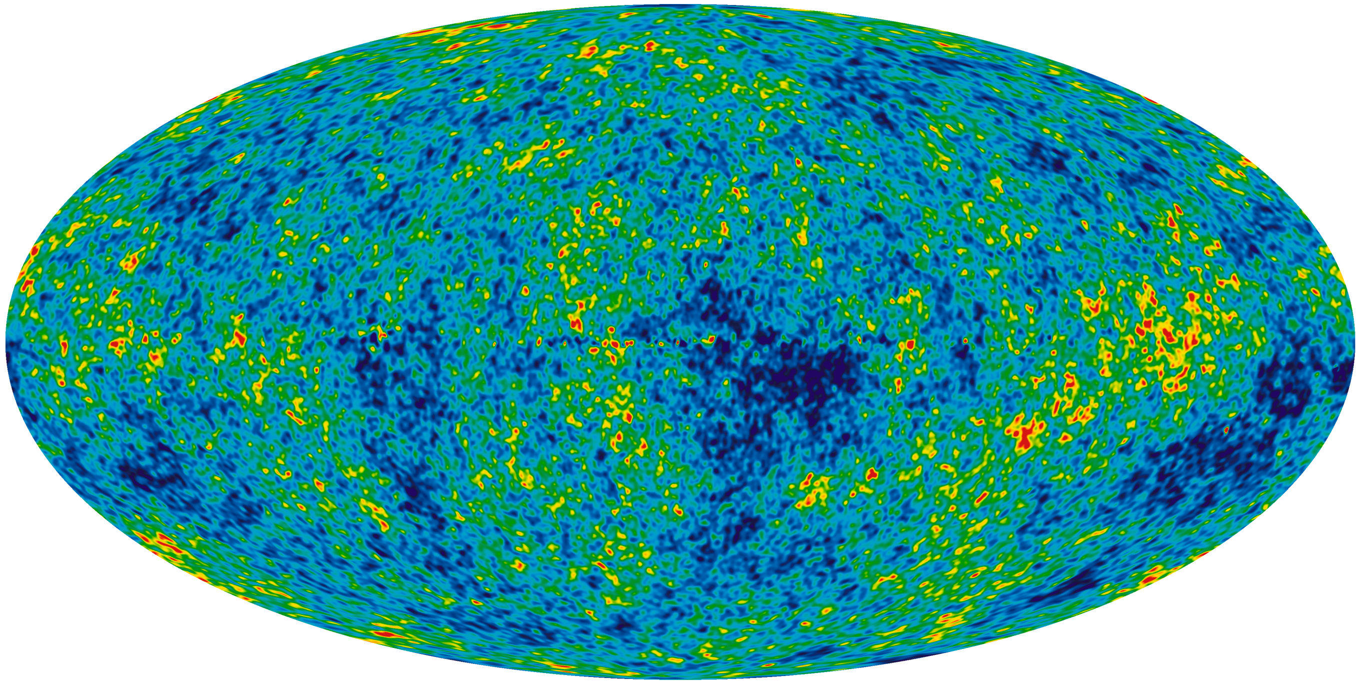
And yet... there's more.

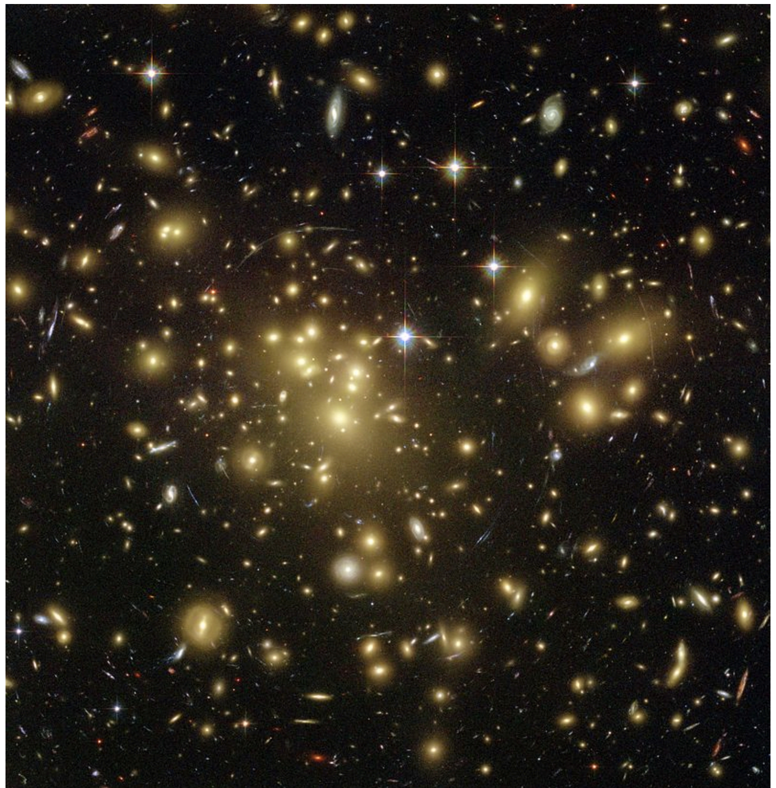


Most of the Universe's Matter is Invisible





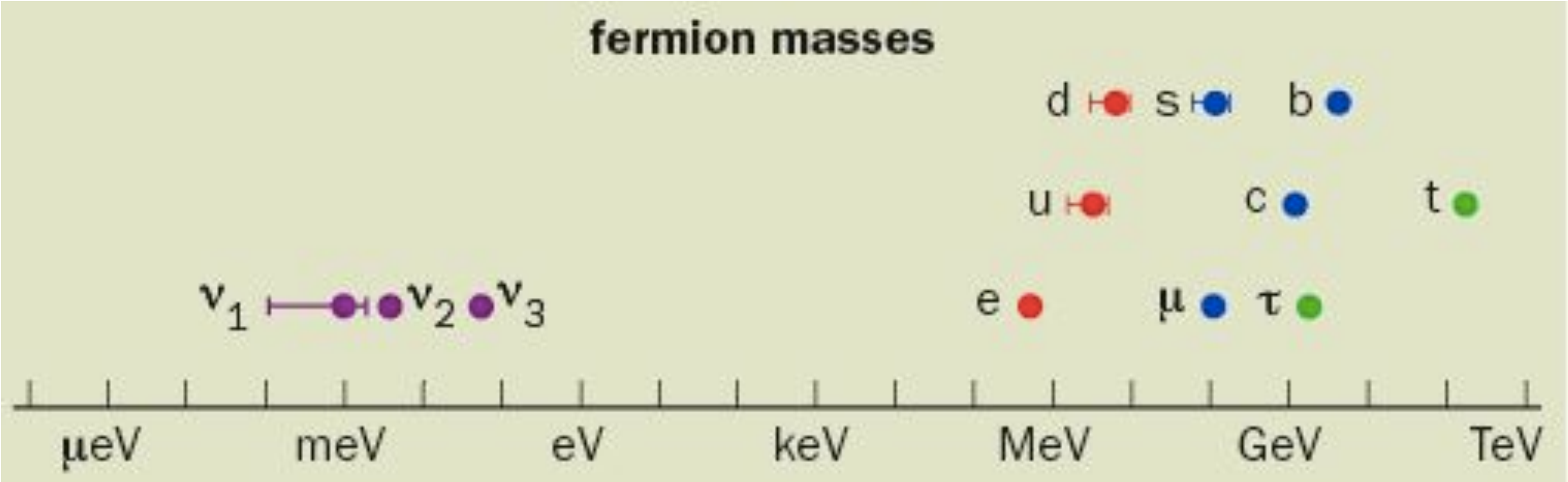




Neutrino Masses Imply New Physics

- **In the Standard Model, masses are forbidden by gauge symmetry.**

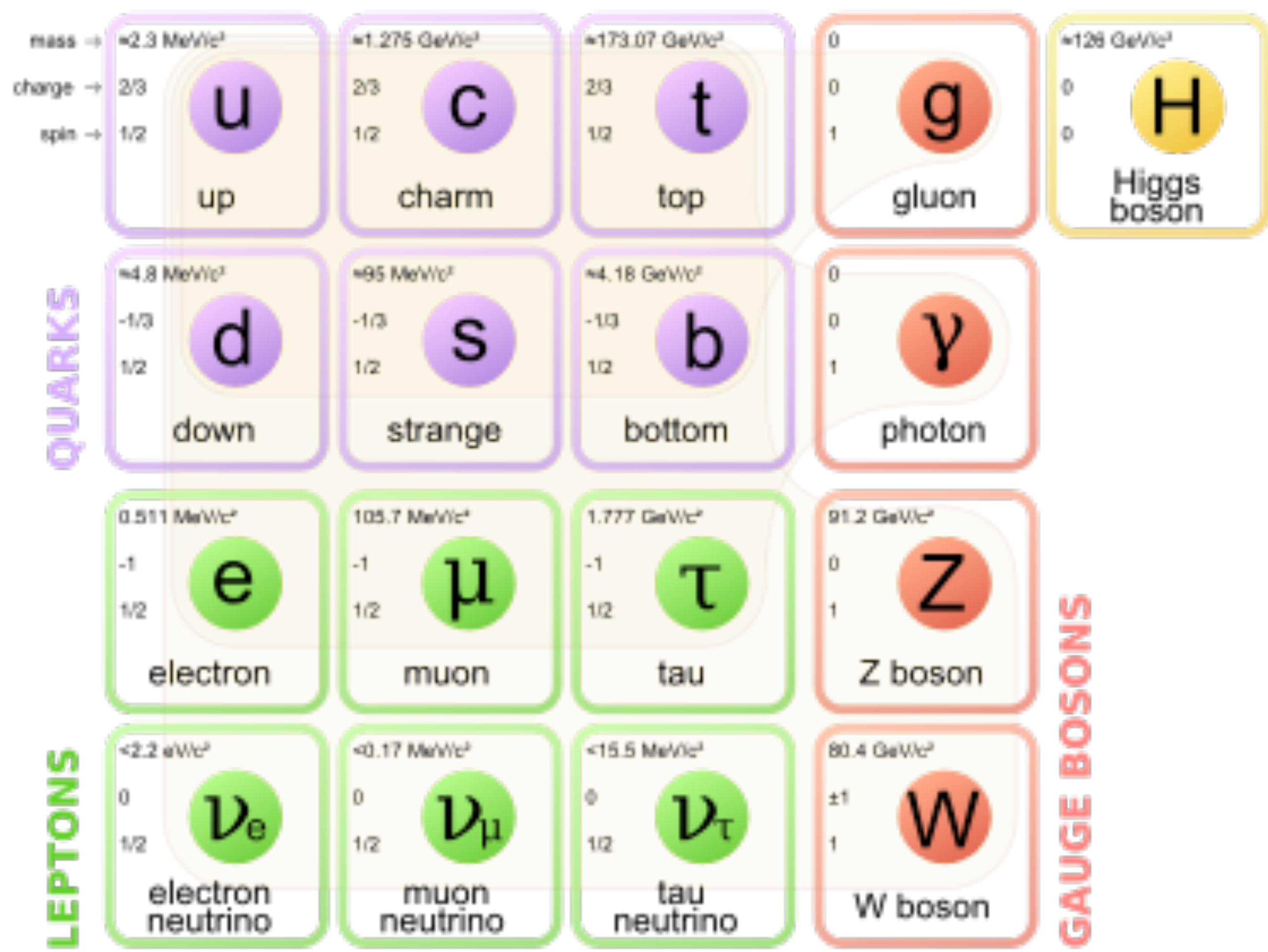
- **However, in the vacuum we live in, the Higgs field has a an expectation value breaking electroweak symmetry**
    - **Gives masses to the SM particles but *not the neutrinos.***
    - **The origin of neutrino masses remains mysterious.**



Dark Matter

Known DM properties

Visible Universe:
The Standard Model (SM)



- Stable or long-lived.
- Not electrically charged ("dark").
- Comprises $\Omega_{DM} \simeq 26\ \%$ of the Universe.
- Based on clustering properties, DM appears **cold** = non-relativistic when gravitational clustering began.

Known DM properties

Visible Universe:
The Standard Model (SM)

- Stable or long-lived.
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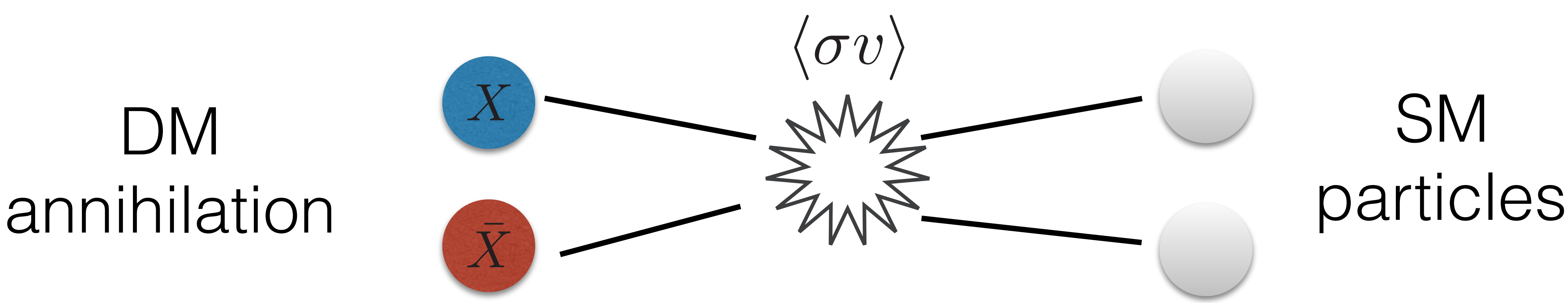
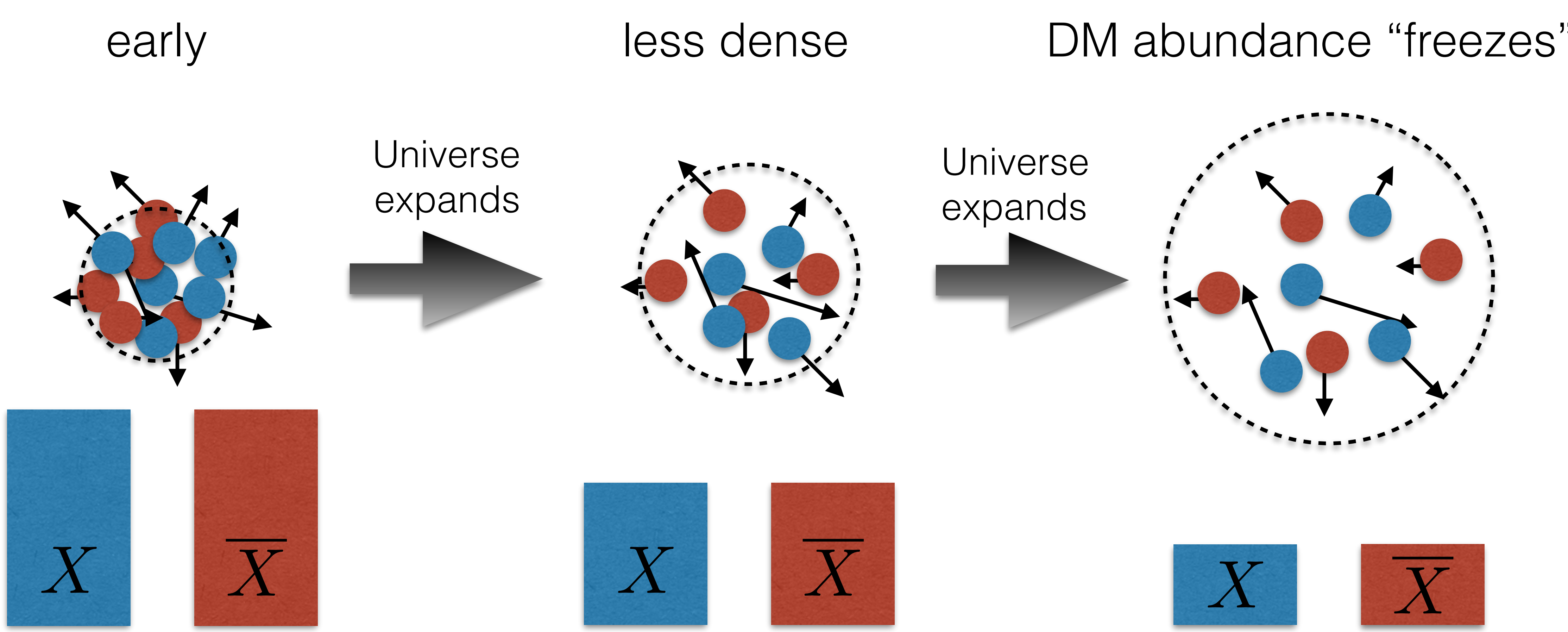
But, many models *beyond* the SM contain particles that can act as a good Dark Matter candidates.

DM as a Thermal Relic

- The early Universe was a hot/dense place.





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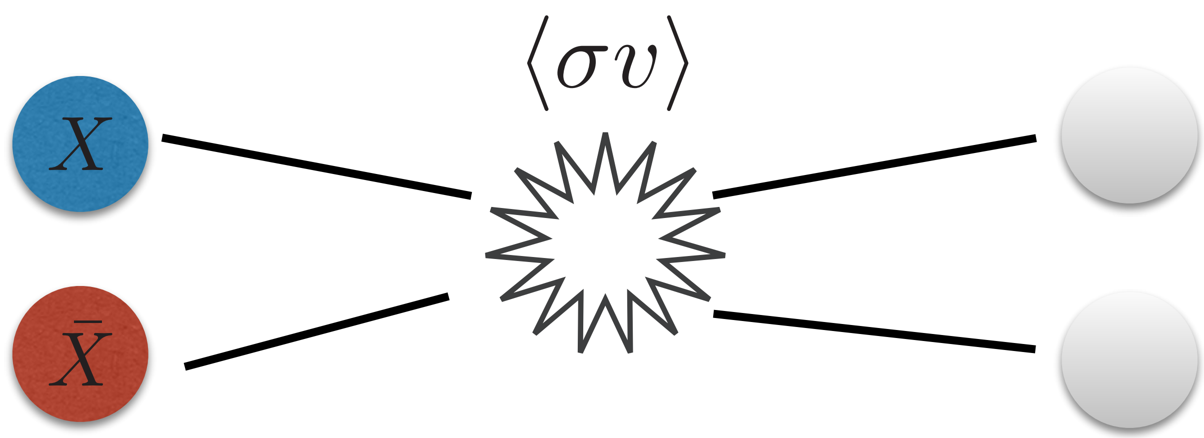
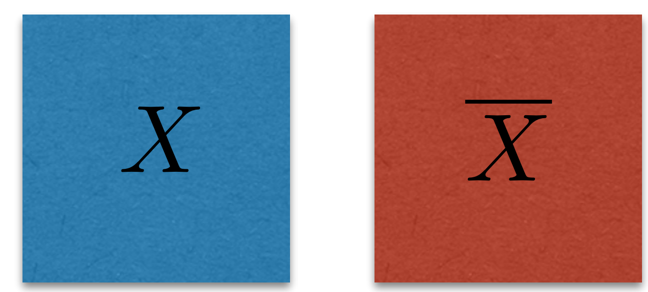


Final "freeze-out" abundance



A thermal relic has the **observed DM abundance** if the **interaction rate** is just right.

An experimental target.

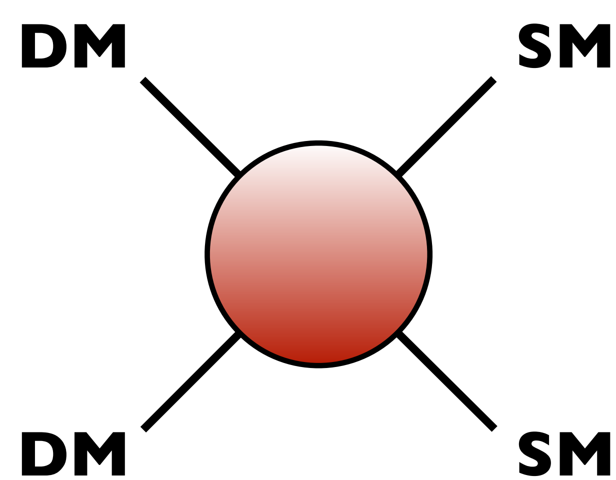
Search Complementarity

"Break it" - Indirect Detection

Search for products of DM annihilation in regions of high DM density.

"Wait for it" Direct Detection

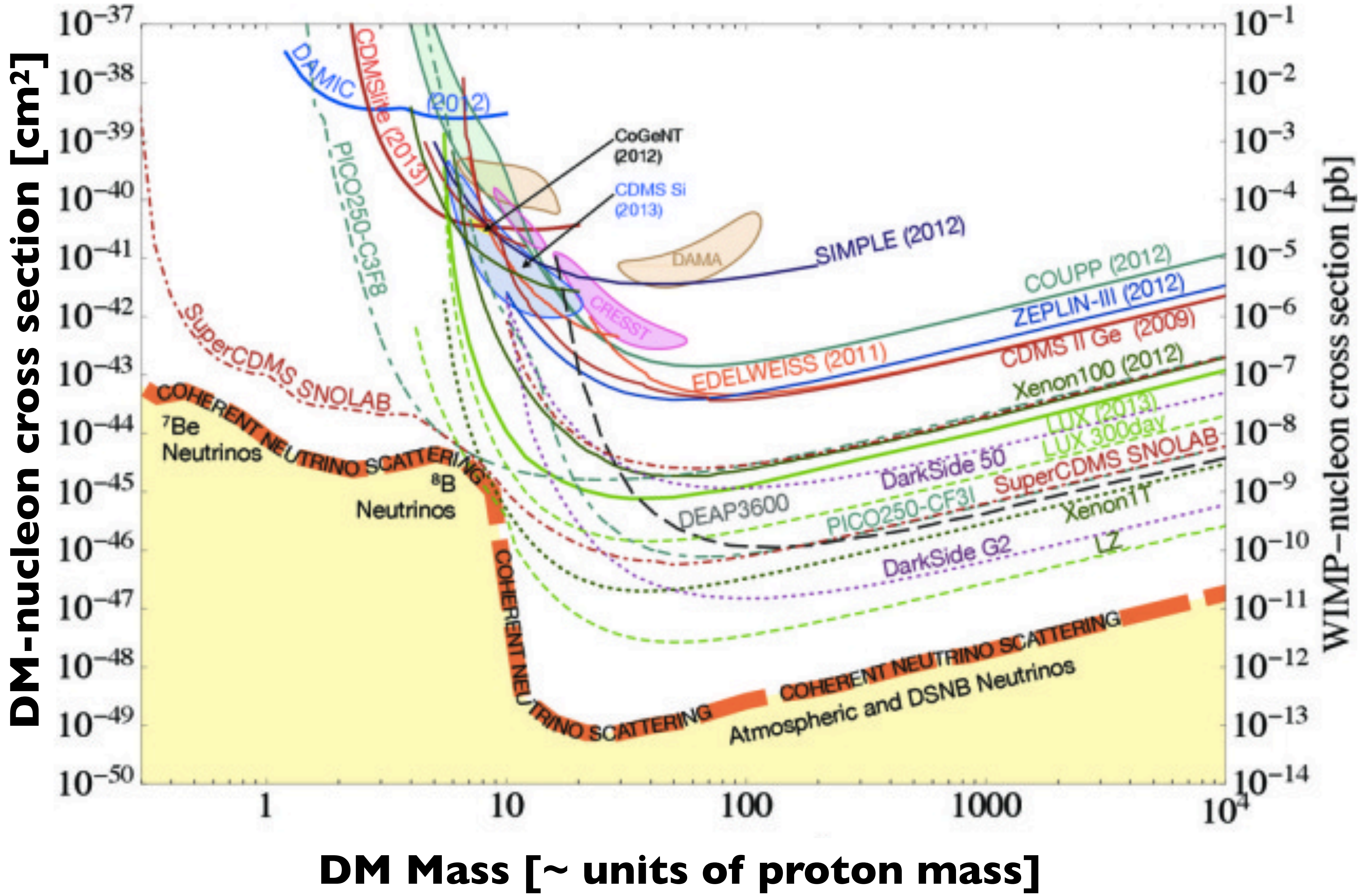
DM-SM scattering in detector



"Make it" - Colliders

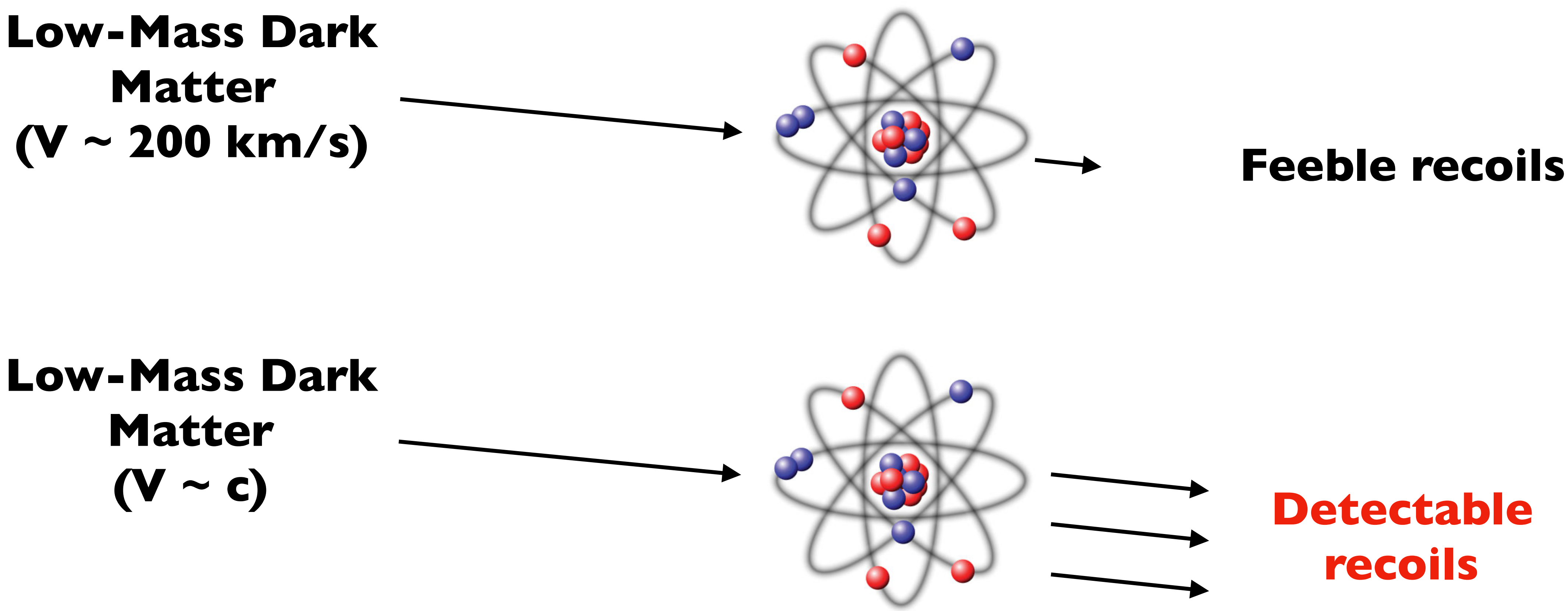
Produce DM and find anomalous missing energy.

DM Direct Detection



Very challenging to probe Dark Matter lighter than a proton mass.

Boosting Light Dark Matter Searches



Some of the ideas being pursued:

- **Dark Matter can get "kicked" to high-speeds by high-energy particles in space: "cosmic-ray boosted Dark Matter."**

- **Dark Matter may be a Dark Sector with an array of new particles/forces able to decay or annihilate to energetic particles.**

Write a script for this part???

Neutrinos as a Signal of New Physics

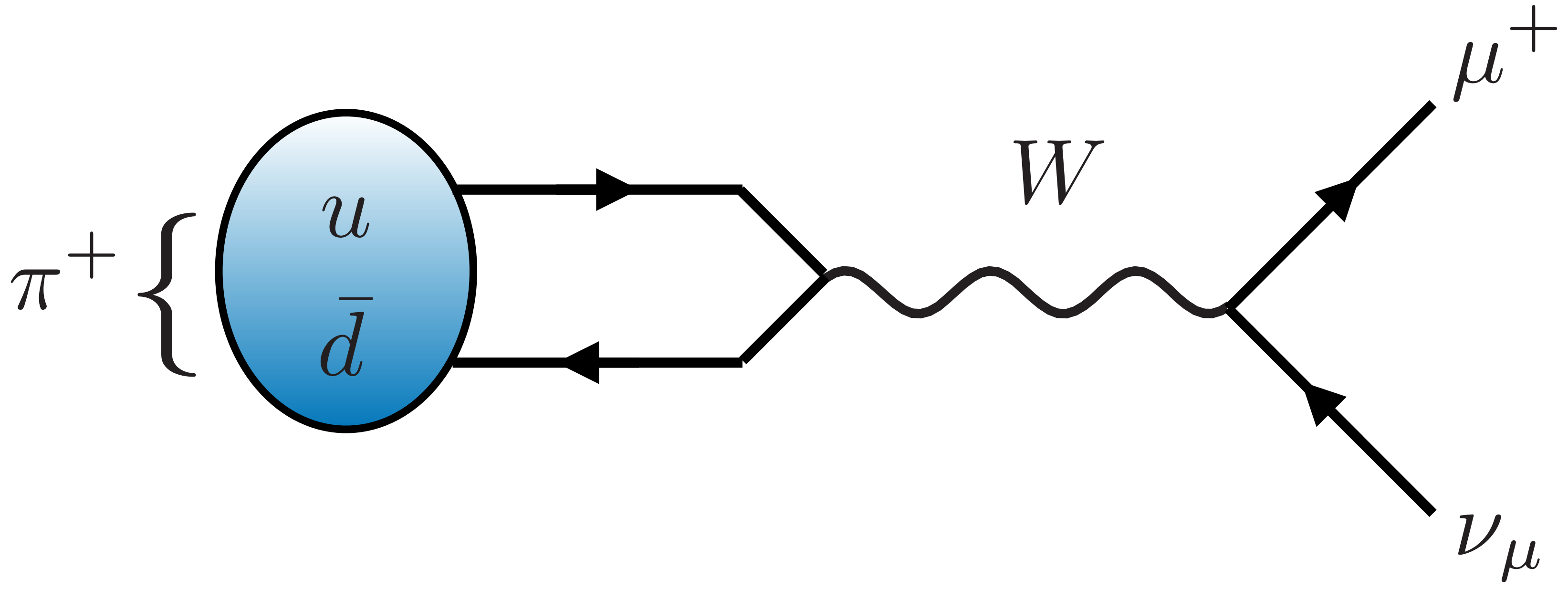
Make Neutrinos

So you want to do some neutrino physics?

<u>Ultra-Minimal</u> steps:

1) **Produce them (interaction eigenstates)**
2) **Detect them**

Produce them (e.g. pion decay)



Pions decay to neutrinos of a definite flavor.

Detect Neutrinos

So you want to do some neutrino physics?

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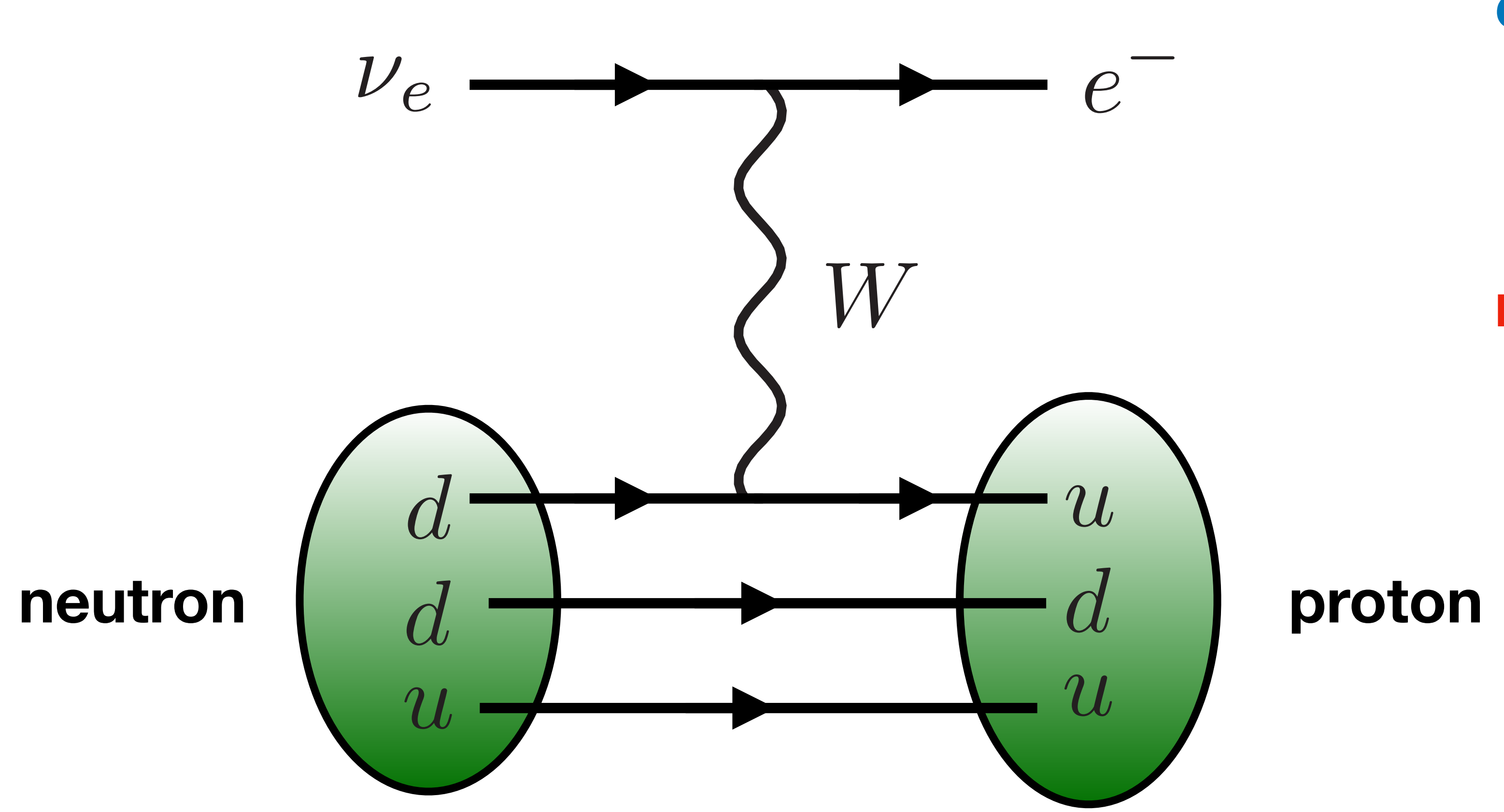
2) **Detect them**

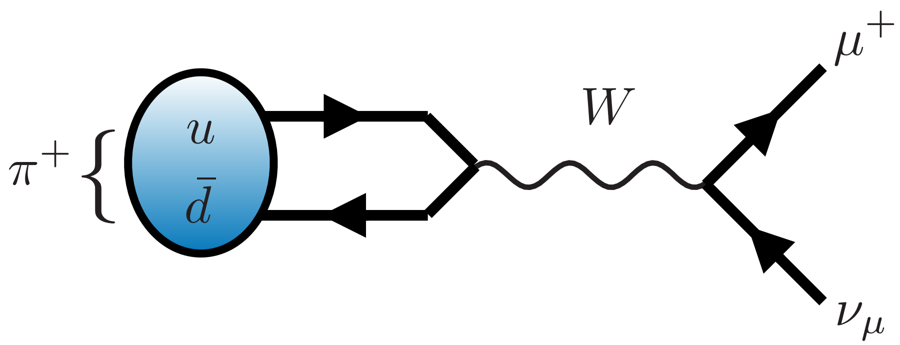
Detect them



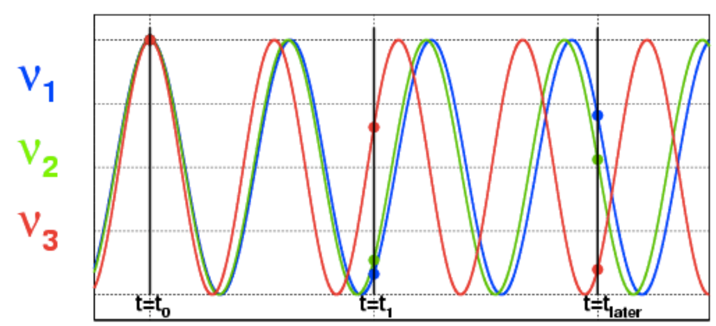
Outgoing charged lepton gives ability to identify incoming neutrino flavor.

Neutrino Flavor Oscillates

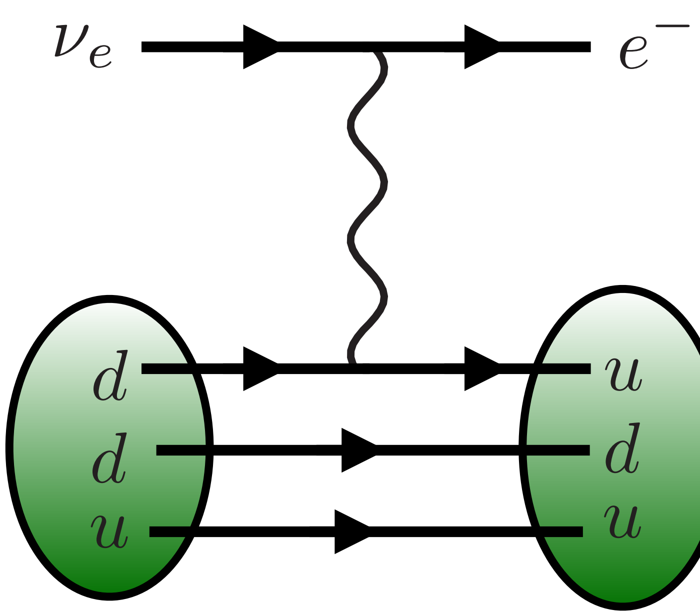
Produce them



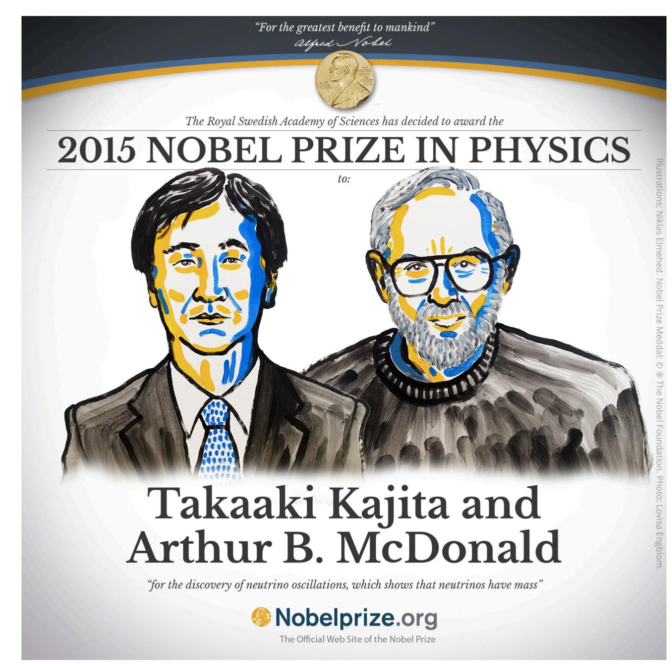
Oscillate



Detect them



Flavor state	$\neq$	energy state



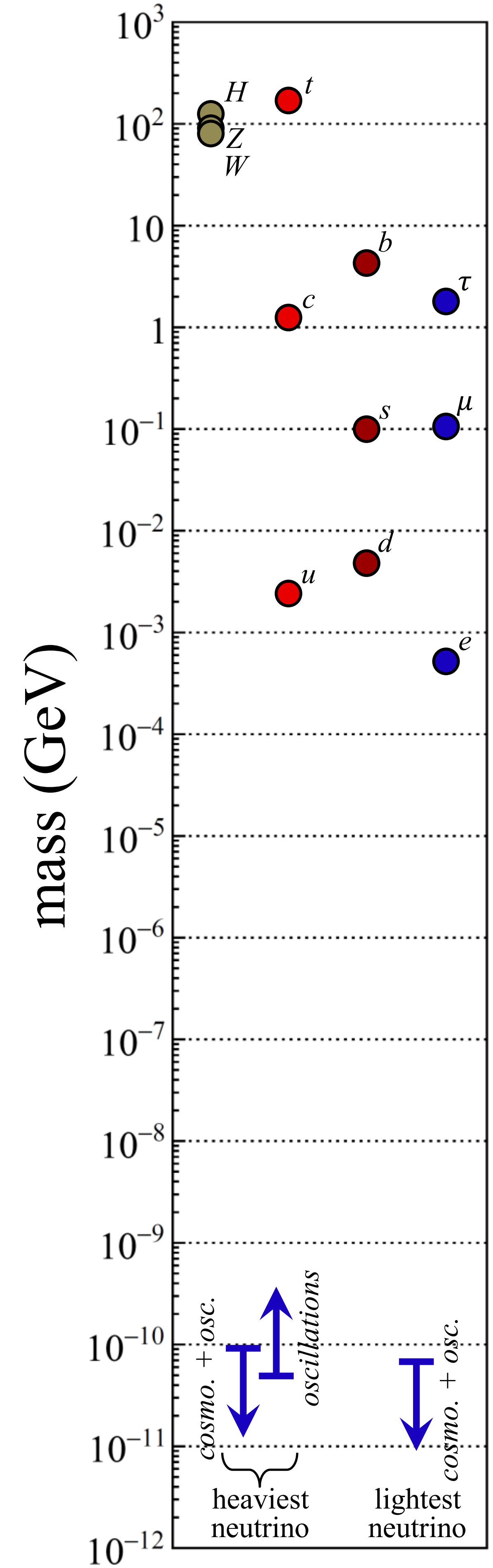
Neutrino masses are nonzero!

The Standard Model cannot explain this.

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Why do neutrinos have mass?

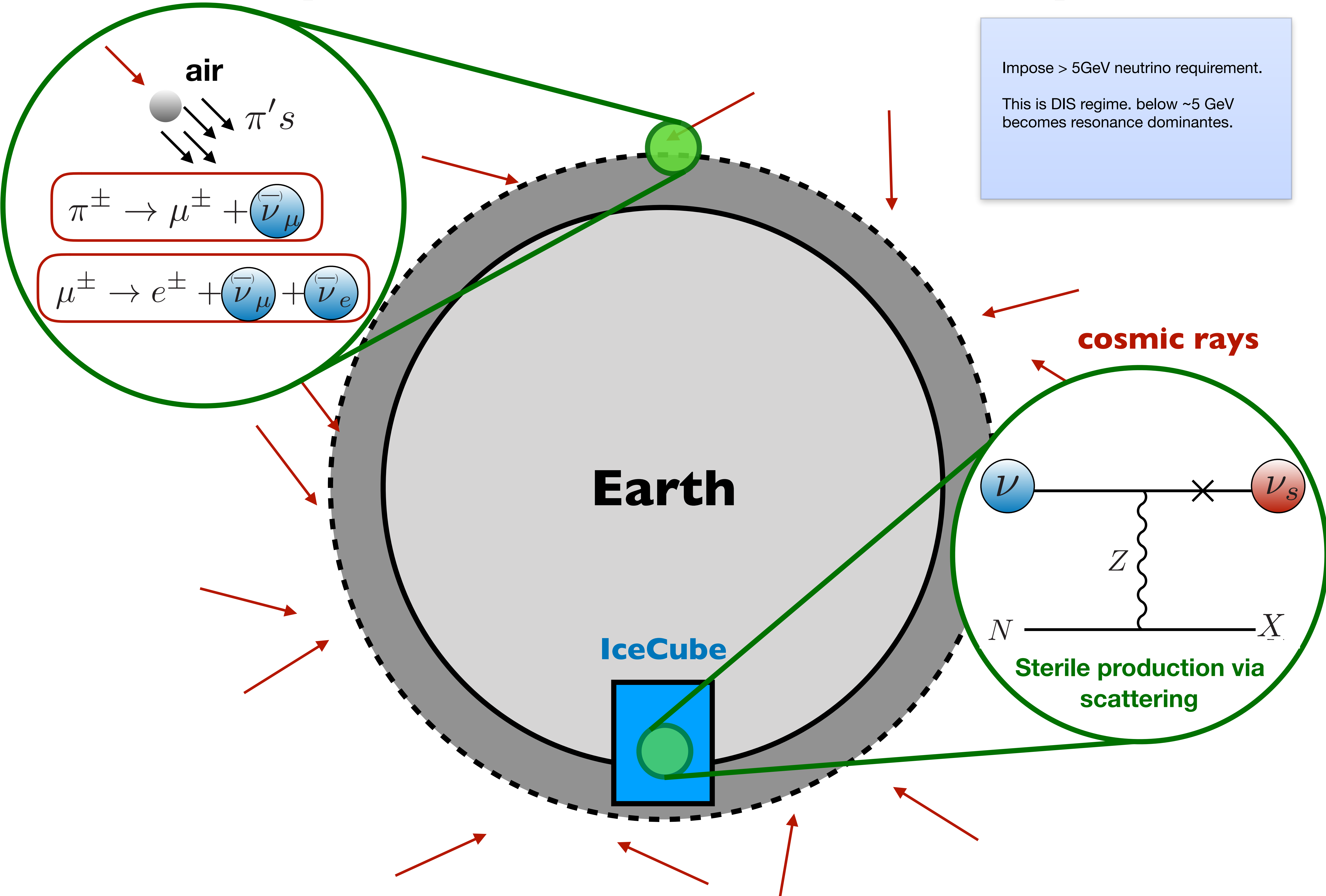
Most popular scenarios involve new particles called sterile neutrinos.



How to detect sterile neutrinos?

-Modified oscillations.
-Rare particle decays.
-Can even play the role of Dark Matter.
-“Up-scattering” in neutrino detectors.

Atmospheric Neutrinos as a BSM probe

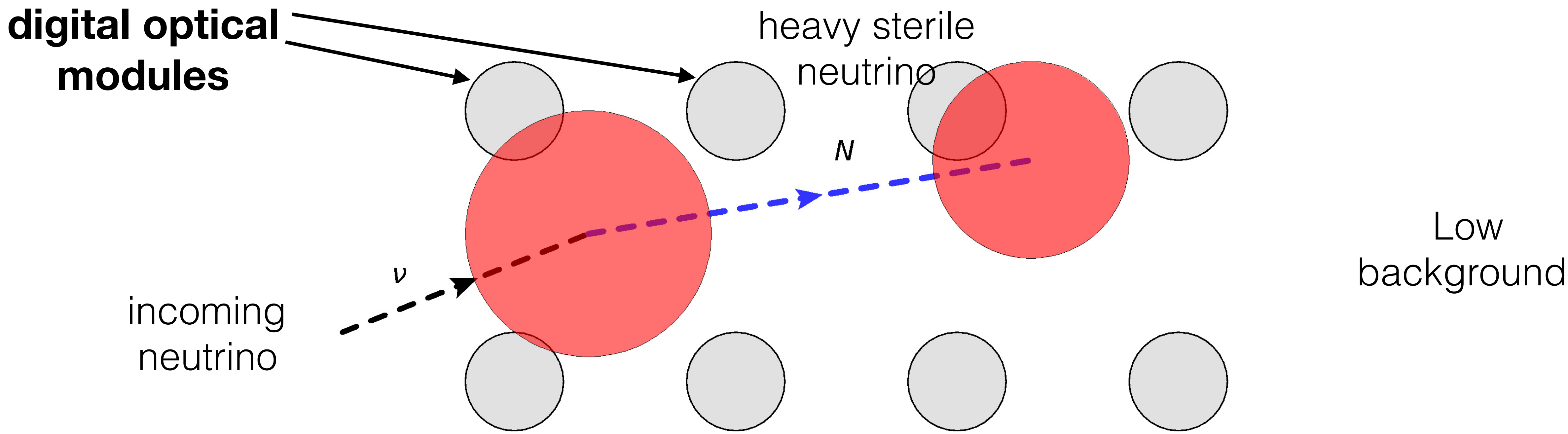


Impose > 5GeV neutrino requirement.

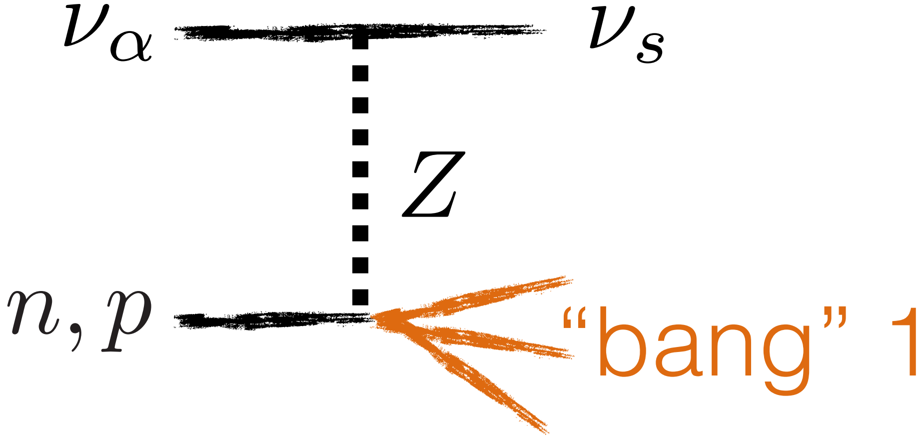
This is DIS regime. below ~5 GeV becomes resonance dominantes.

“Double-bangs” from Sterile Neutrinos

Coloma, Machado, Martinez-Soler, Shoemaker 2017



Step 1: produce Sterile

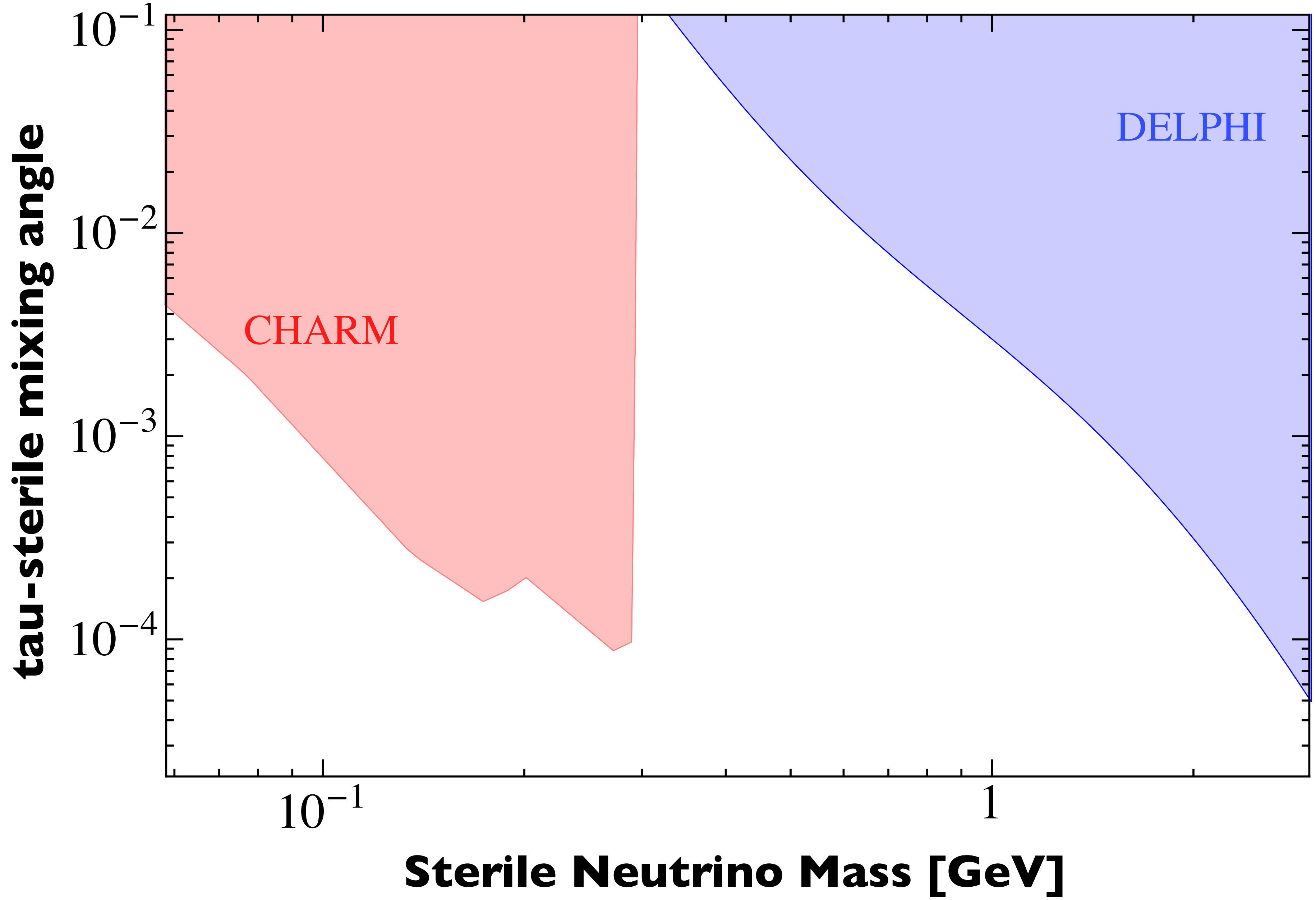


Step 2: Sterile decays

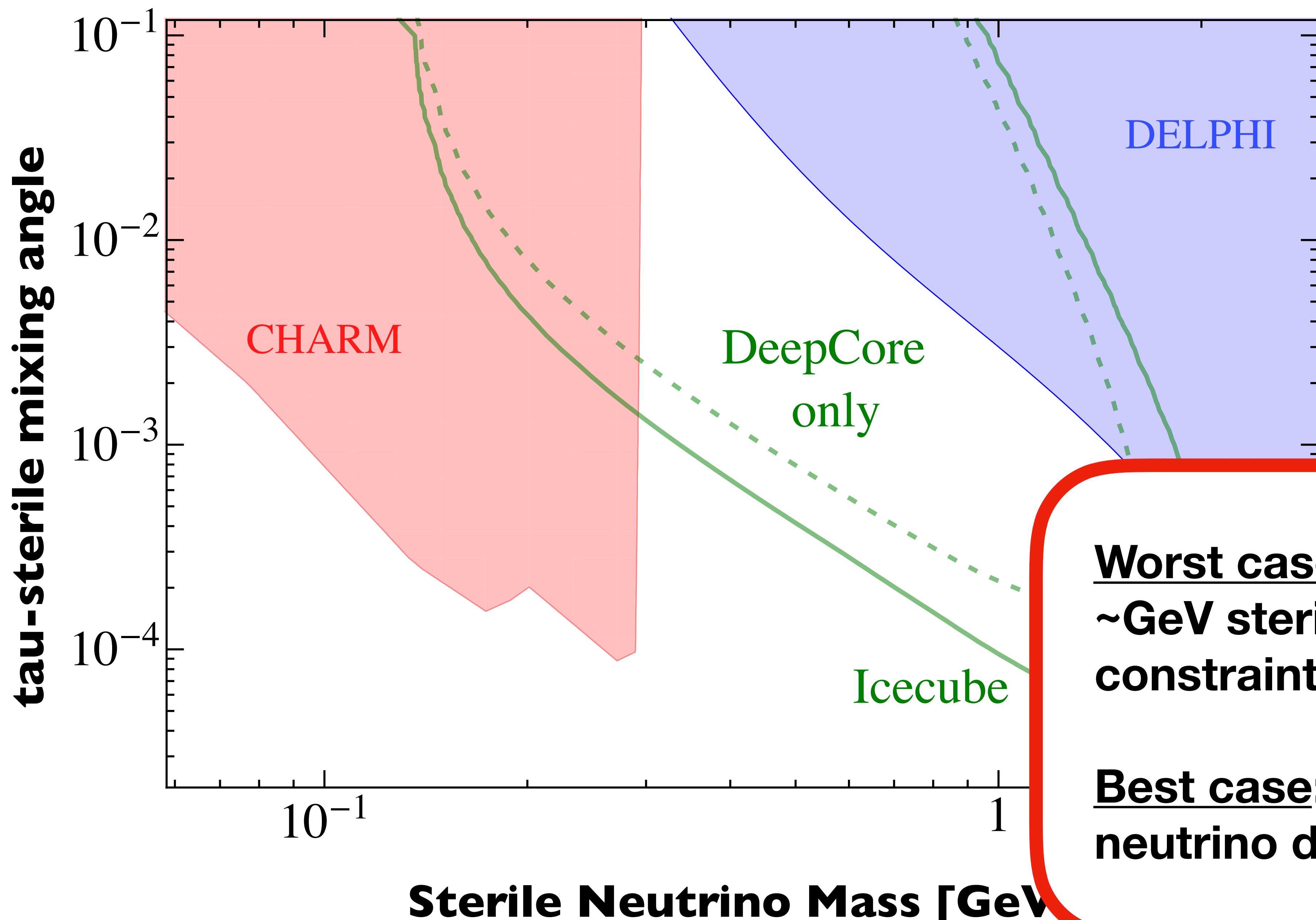
No extra radiation between steps 1 and 2.

nels: rho + nu, eta + nu,
pi +l, K+l

Sterile Neutrinos from the Atmosphere



Sterile Neutrinos from the Atmosphere



<u>Worst case</u>: new ~GeV sterile neutrino constraints.

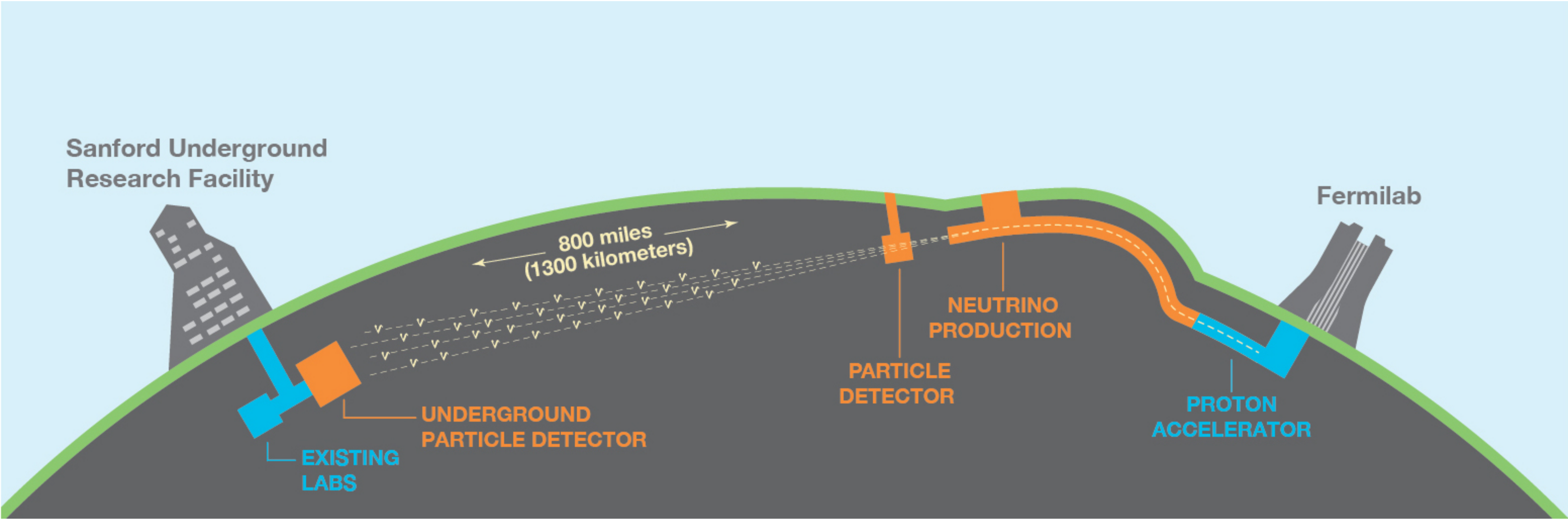
<u>Best case</u>: Sterile neutrino discovery!

Re-purpose existing experiments!

An important lesson:
no need to re-invent the wheel!

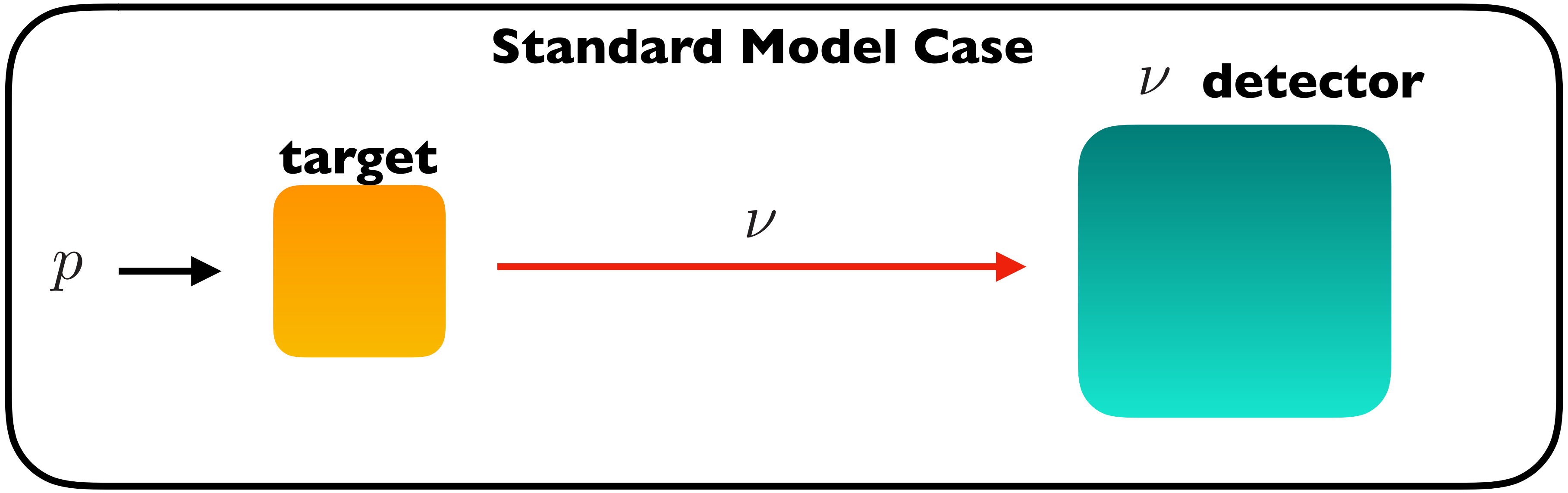
→ **Happy accidents**

DUNE = Deep Underground Neutrino Experiment



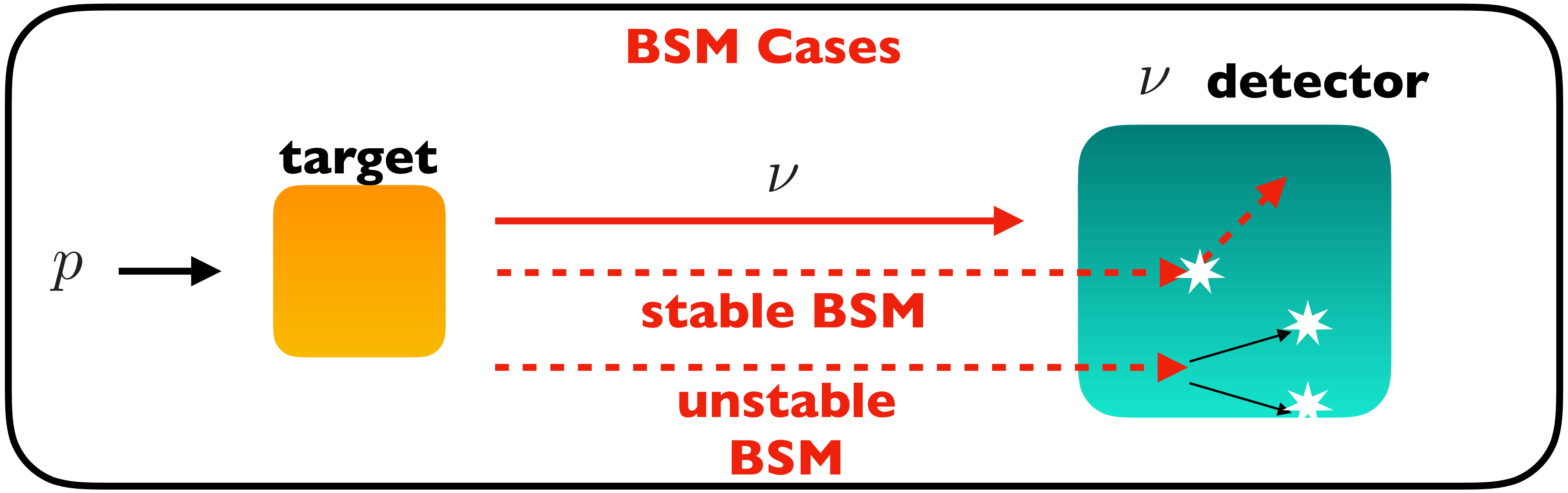
DUNE will pinpoint remaining neutrino oscillation unknowns.

DUNE as a Dark Matter Experiment



1. Proton collisions create unstable mesons.
2. Mesons decay to final states including neutrinos.
3. Neutrinos undergo propagate.
4. Neutrinos interact in detector via “known” SM processes.

DUNE as a Dark Matter Experiment



1. Proton collisions create unstable mesons.
2. Mesons decay to final states including neutrinos. **x** + new particles
3. Neutrinos undergo trivial propagation.
4. Neutrinos interact in detector via “known” SM processes.

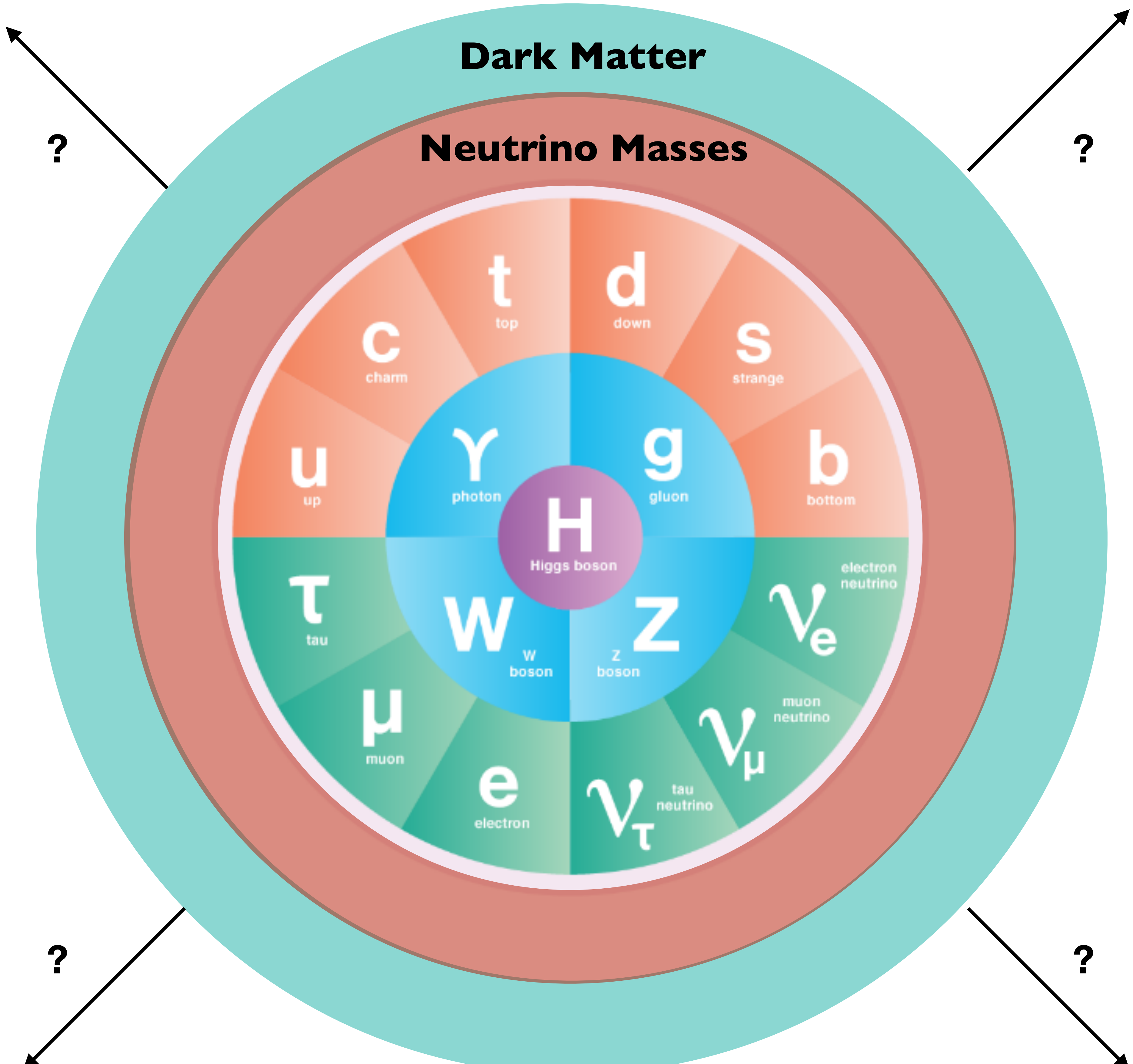
unstable BSM

dark photons,
Sterile neutrinos, ...

stable BSM

Thermal relic
dark matter

The Next Standard Model?



Conclusions and Outlook

- The Standard Model gives us a detailed understanding of the matter and forces at work in the Universe

    - Dark Matter & Neutrino masses indicate that the SM is incomplete.

    - We don't know the full story yet.

- But there is a vigorous pursuit for new phenomena in a broad set of experiments.

- We need to simultaneously expand the theoretical terrain and to widen the experimental search strategies if we are going to uncover the New Standard Model.

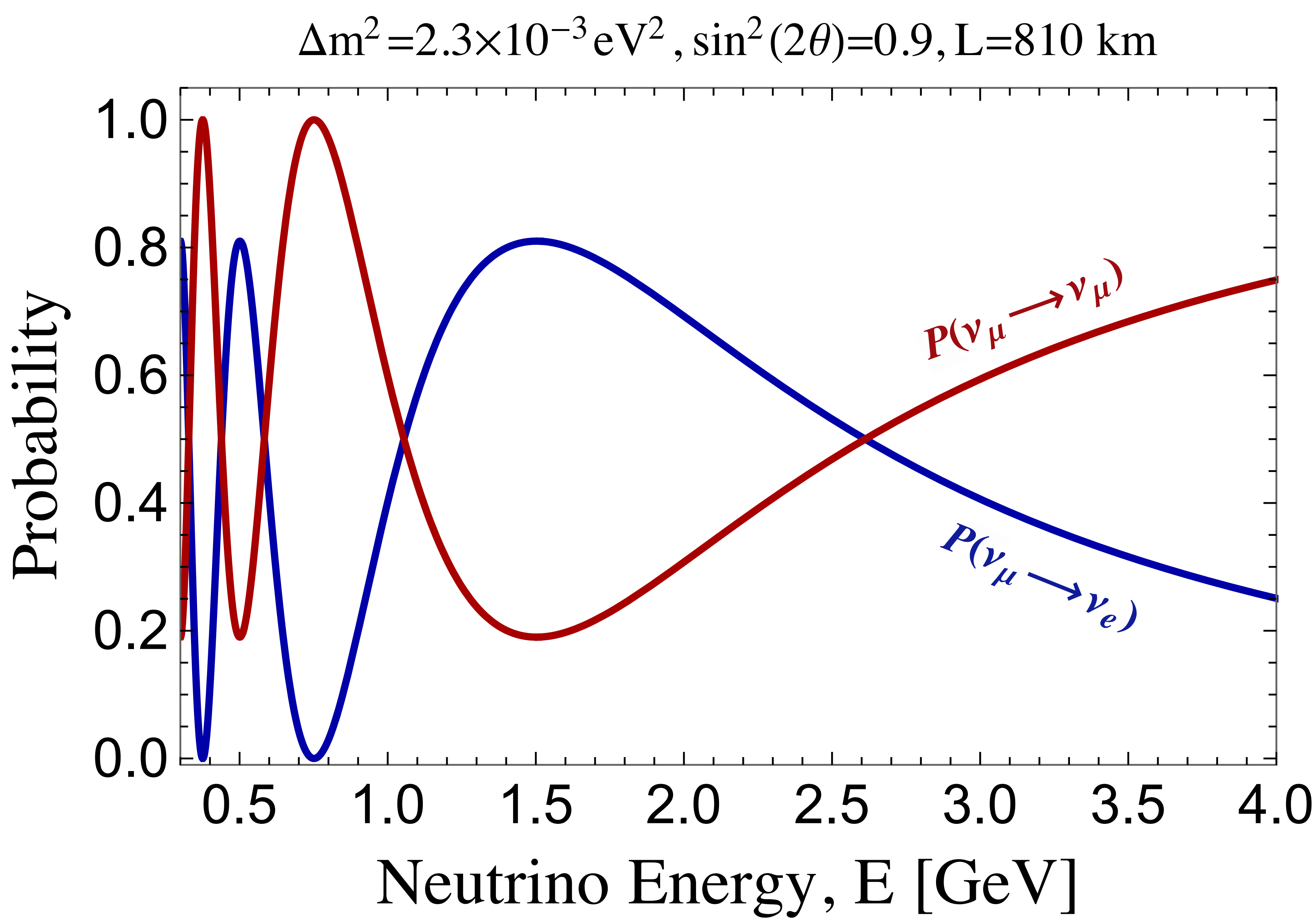
Stay tuned!

Thank you!

Extras

Neutrino Oscillations

Two-flavors: $$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



Magnitude set by:

$$\sin^2(2\theta)$$

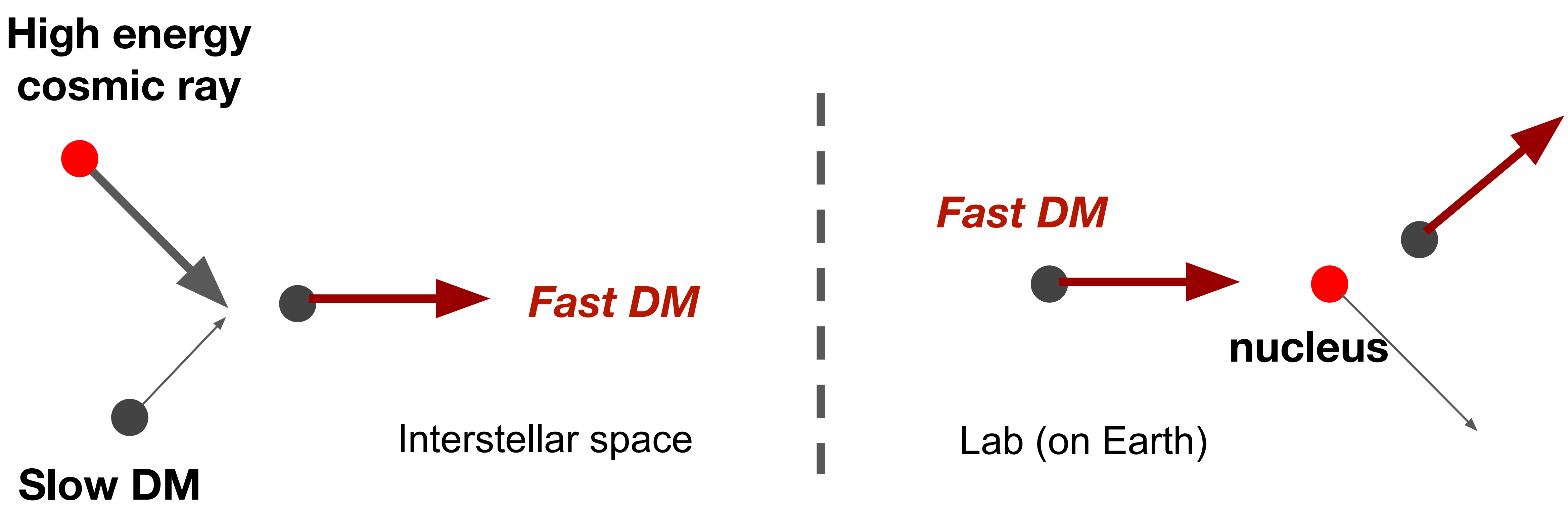
Energy dependence:

$$L_{osc} \equiv \frac{4\pi E}{\Delta m^2}$$

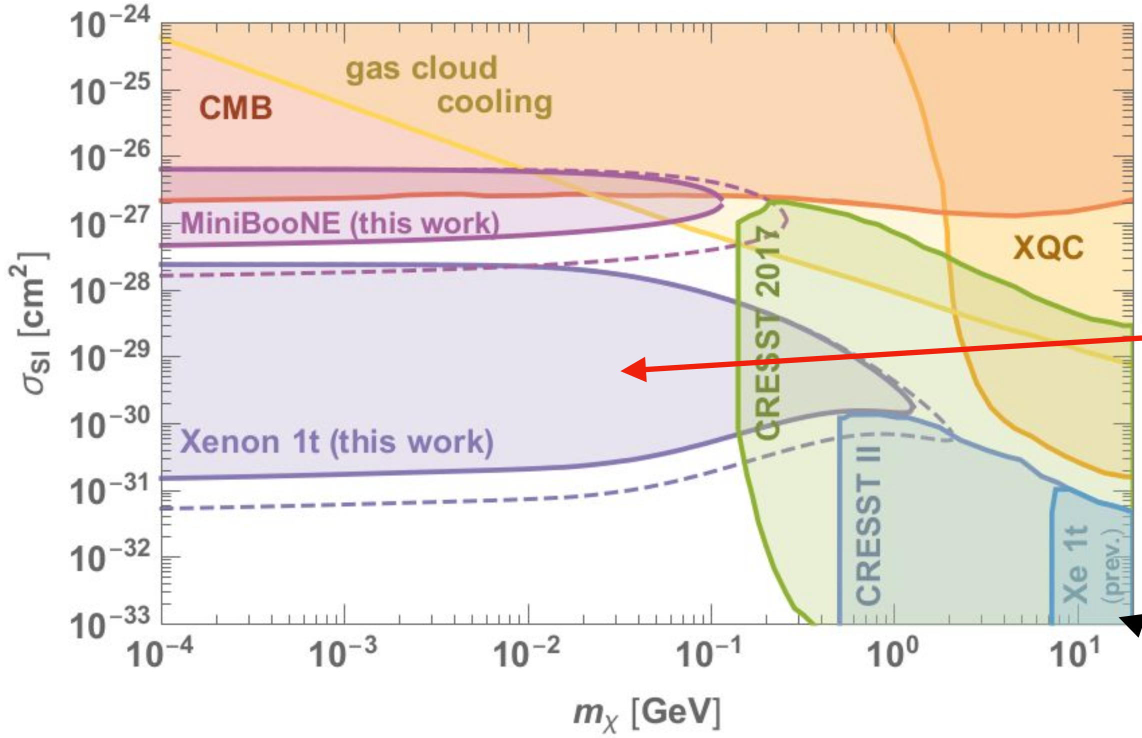
***For now*, only need 3 neutrinos to explain oscillation data.**

Cosmic Ray "Boosted" Dark Matter

- Idea due to Bringmann and Pospelov (PRL, arXiv:1810.10543)
- Direct detection requires/assumes a DM-proton interaction, with no further assumptions we expect cosmic ray-DM collisions



Cosmic Ray “Boosted” Dark Matter



XENON1T search for “boosted Dark Matter”: get access to very low DM masses!

“Standard” XENON1T search for Dark Matter @~200 km/s

<u>Variations:</u>

-Realistic models: Dent, Dutta, Newstead, Shoemaker (2019).

-Dark Matter

- Electron interactions: Dent, Dutta, Newstead, Shoemaker, Tapia Arellano (2020)

-Inelastic Dark Matter: Bell, Dent, Dutta, Newstead, Shoemaker (2021).

Secluded DM

Dark (Hidden) ((Secluded)) Sector Models

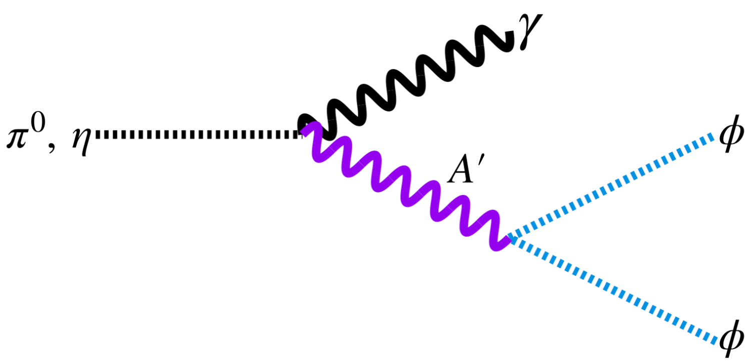
[Batell, Pospelov, Ritz (2009)]

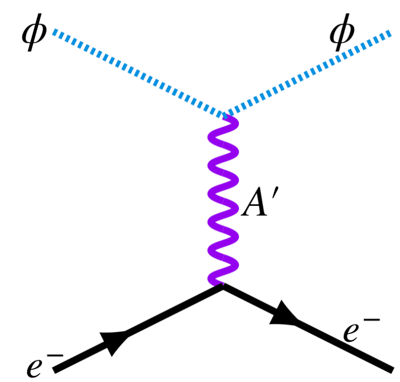
$$\mathscr{L}_{\rm portal} = \begin{cases} \epsilon F_{\mu\nu} F_h^{\prime\mu\nu} & \text{(photon portal)} \\ h|H^2||H_h^2| & \text{(Higgs portal)} \\ y(LH)N & \text{(neutrino portal),} \end{cases}$$

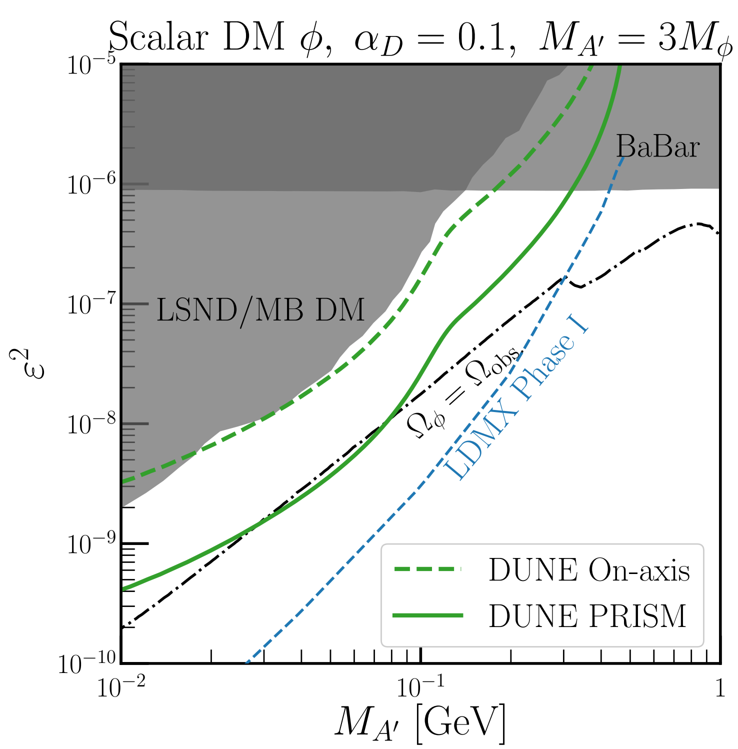
Only 3 renormalizable portals!

Light DM @ DUNE

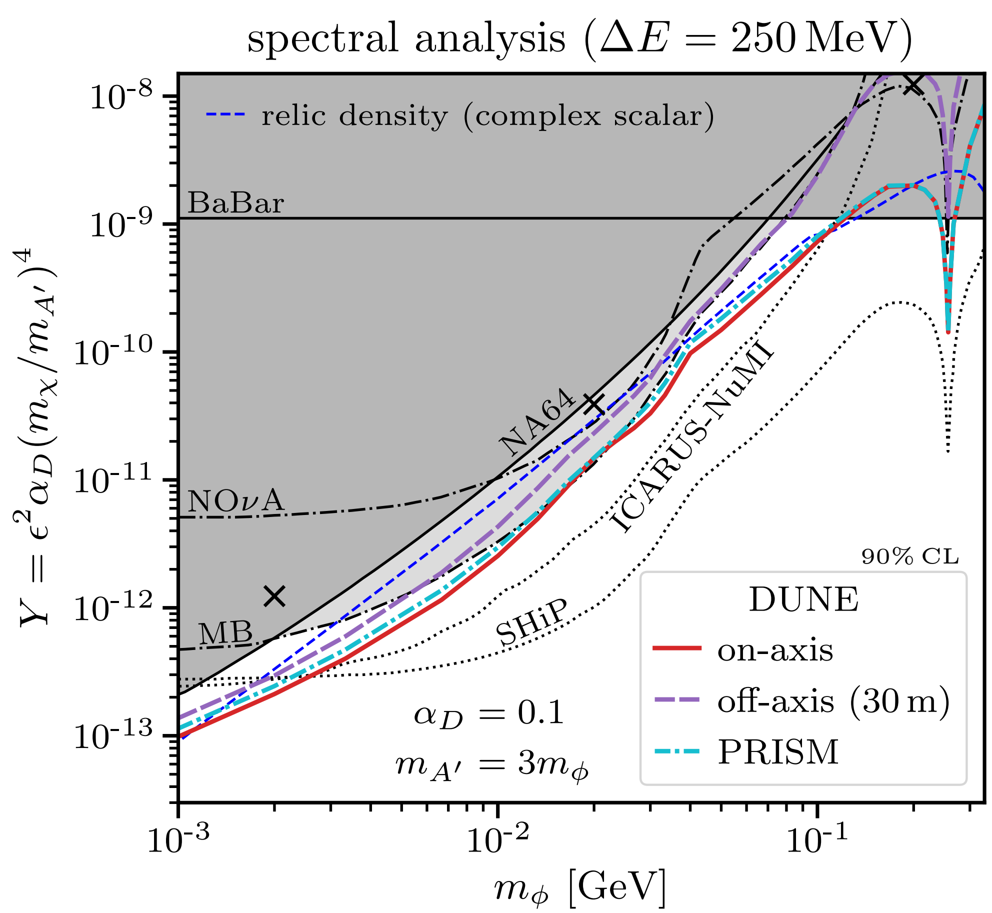
See Also: Coloma, Dobrescu, Frugiuele, Harnik [1512.03852]







De Romeri, Kelly, Machado [1903.10505]



Breitbach, Buonocore, Frugiuele, Kopp, Mittnach [2102.03383]

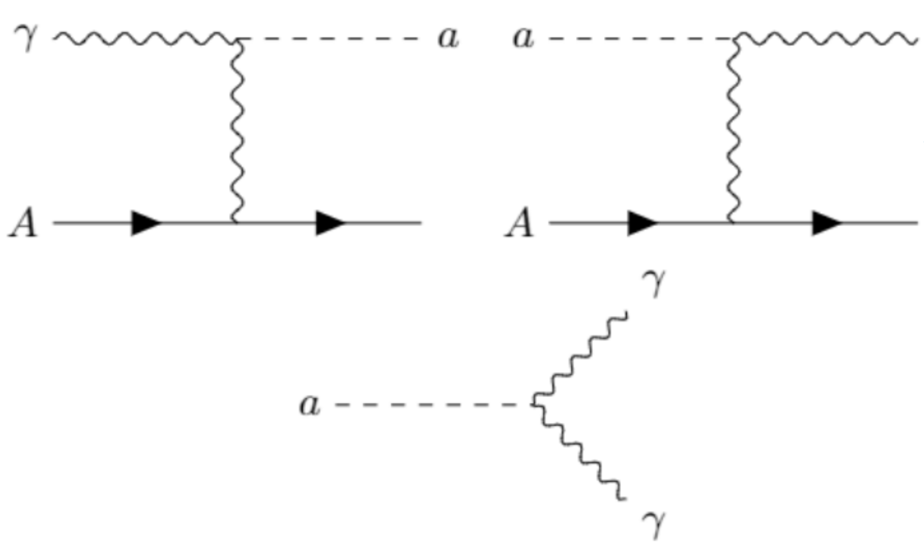
Axions @ DUNE

Axion-like Particles at Future Neutrino Experiments: Closing the "Cosmological Triangle"

Vedran Brdar, Bhaskar Dutta, Wooyoung Jang, Doojin Kim, Ian M. Shoemaker, Zahra Tabrizi, Adrian Thompson, Jaehoon Yu

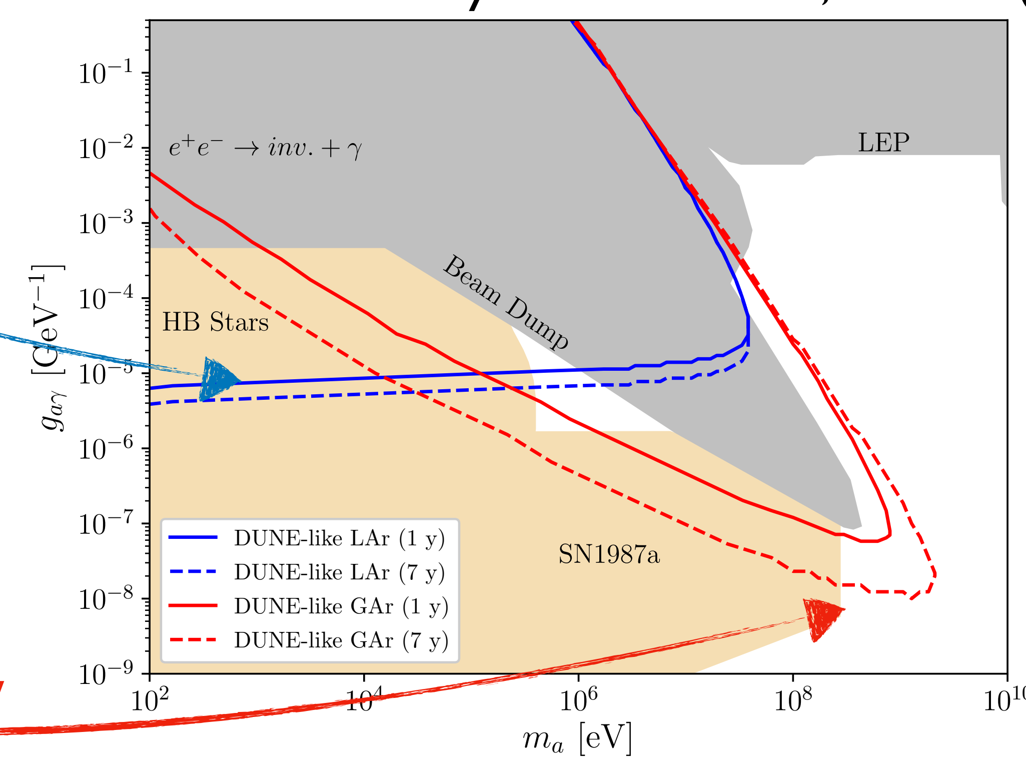
$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Primakoff production



Scattering

Phys. Rev. Lett. 126, 201801 (2021)



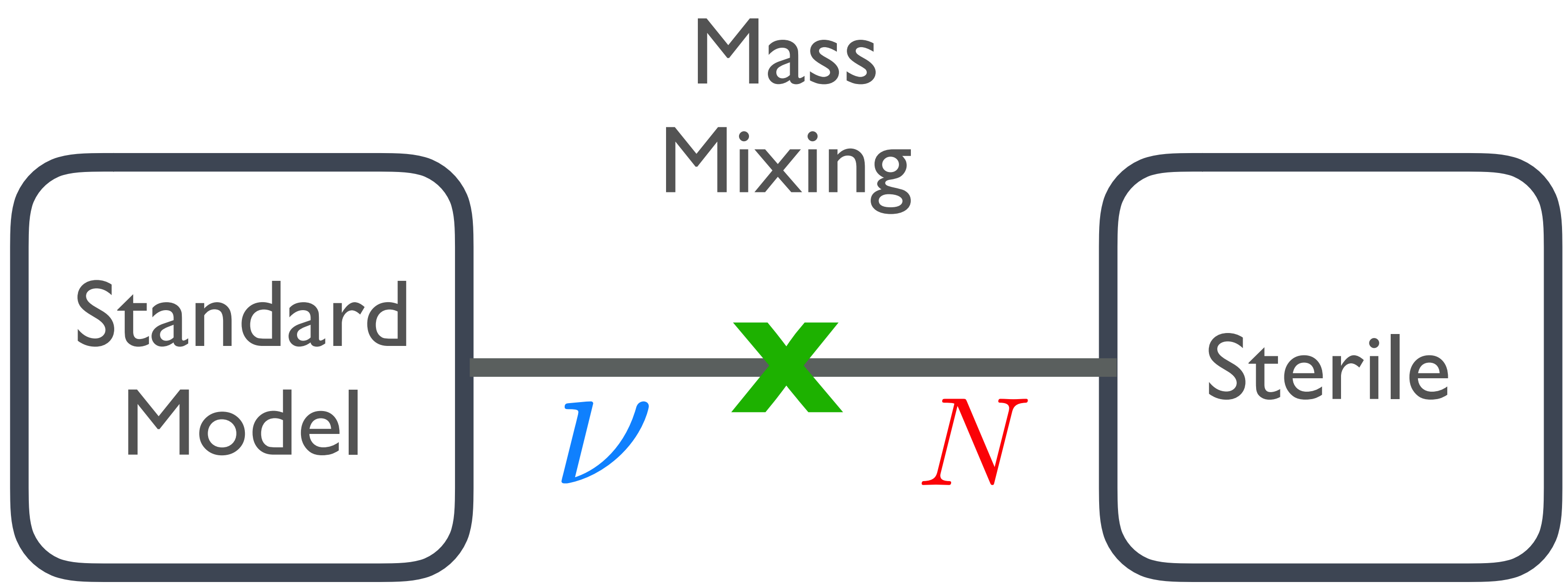
Decay

See also:

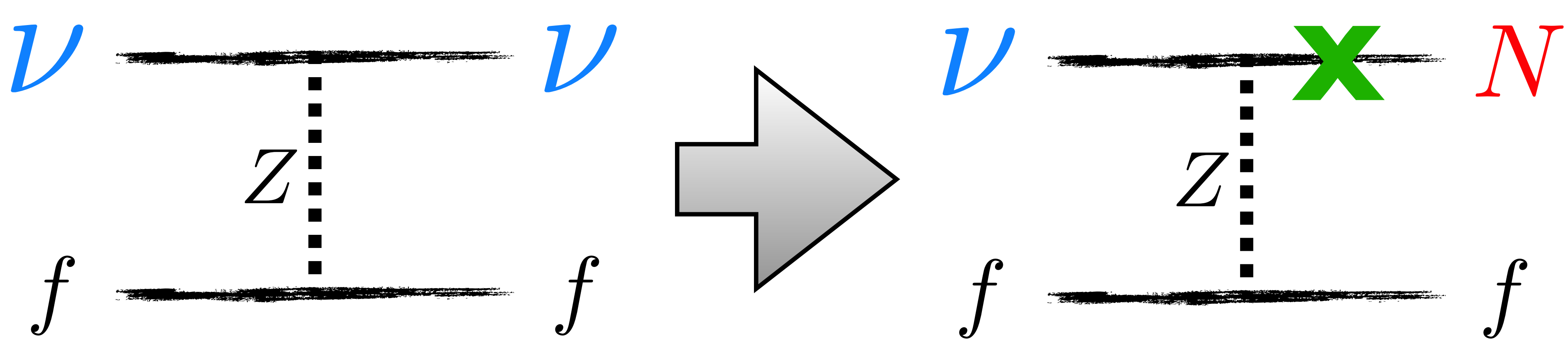
Dent, Dutta, Kim, Liao, Mahapatra, Sinha, Thompson, PRL, 2020

Kelly, Kumar, Liu, 2020

Inheriting Weak Interaction



For example:



$$\sigma_{\nu\to N} \sim \theta^2 \sigma_{\rm SM}$$

DM from Neutrino Scattering

Dodelson, Widrow (1993)

Oscillations + Collisions in expanding Universe:

$$\left(\frac{\partial}{\partial t} - HE\frac{\partial}{\partial E}\right) f_S(E,t) = \left[\frac{1}{2}\sin^2(2\theta_M(E,t))\,\Gamma(E,t)\right] f_A(E,t)$$

Mechanism gives correct DM abundance if:

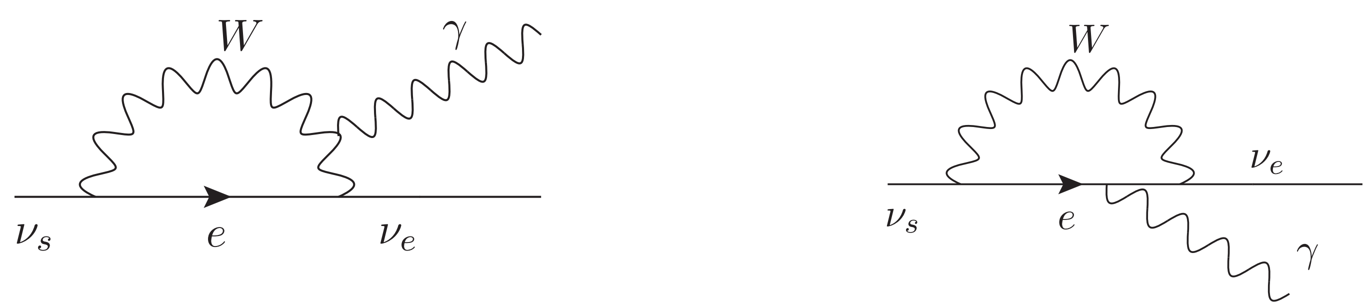
$$\rightarrow \sin^2(2\theta) \simeq 9\times 10^{-10}\left(\frac{g_*(T=100\text{ MeV})}{20}\right)^{1/2}\left(\frac{10\text{ keV}}{m_s}\right)^2$$

Peak production occurs when “collision rate” = “oscillation rate”:

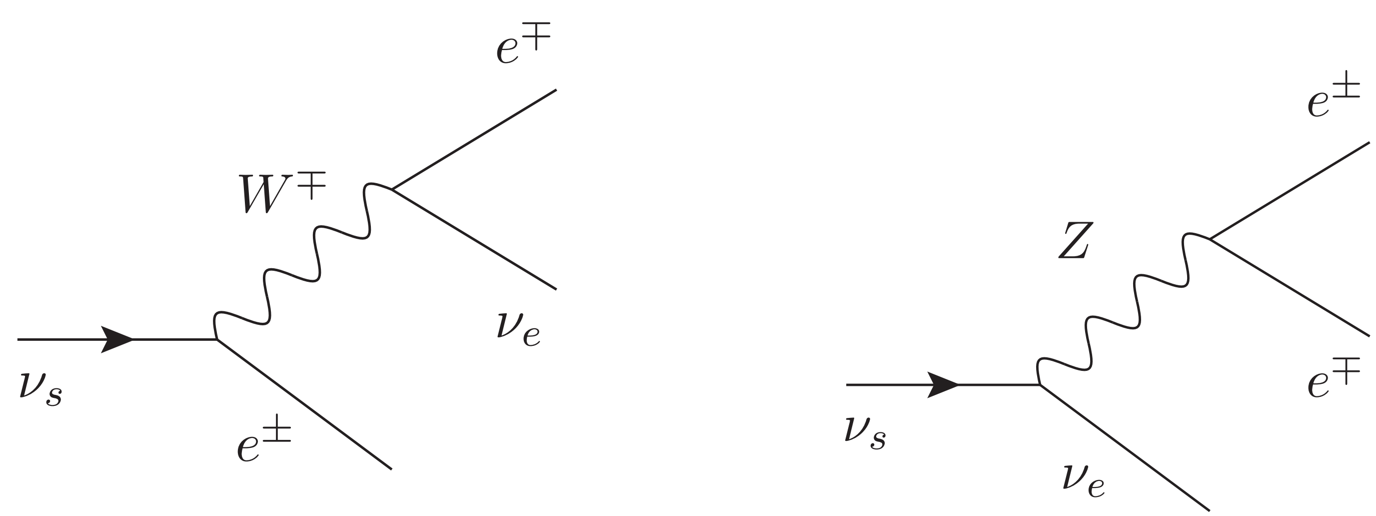
$$T_{\max} \simeq (m_s/G_F)^{1/3} \simeq 200\text{ MeV}\left(\frac{m_s}{\text{keV}}\right)^{1/3}$$

How do you detect it?

Sterile Neutrino DM is unstable



X-ray lines!



gamma spectrum

Sanity check: Stable on universe lifetime scales.

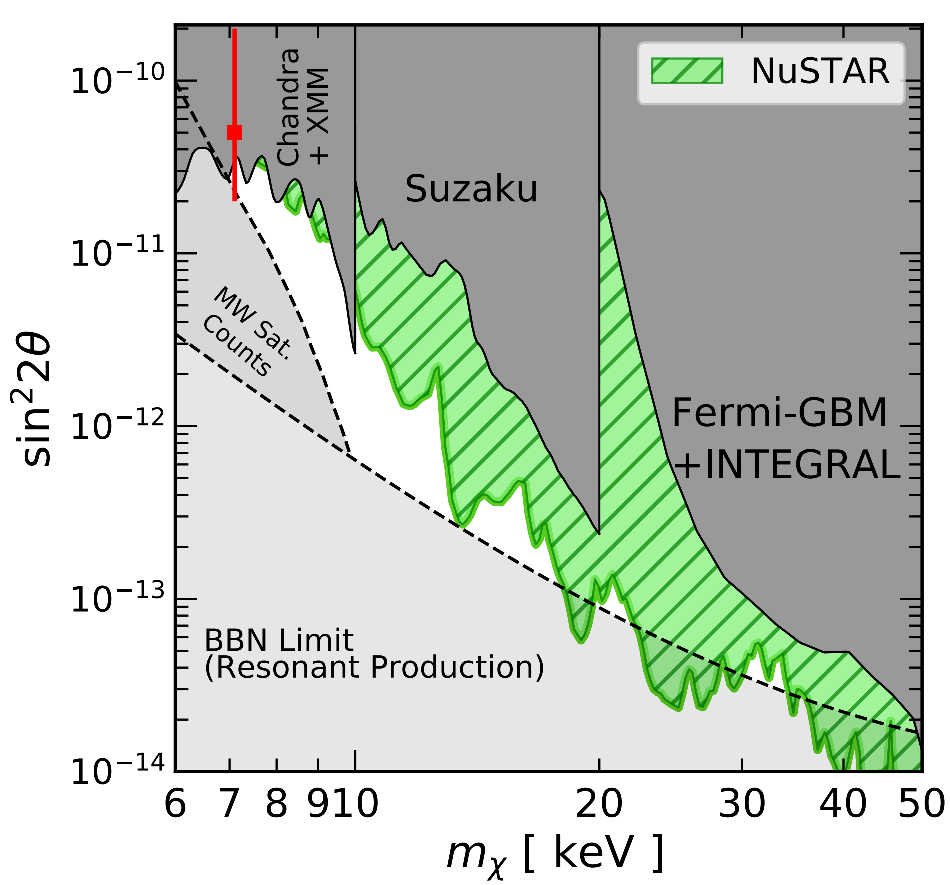
$$\Gamma \sim \sin^2 2\theta G_F^2 m_s^5 \qquad \Rightarrow \sin^2 2\theta \lesssim 0.06 \left(\frac{10\text{ keV}}{m_s}\right)^5$$

Dodelson-Widrow doesn't work for DM above ~700 keV masses.

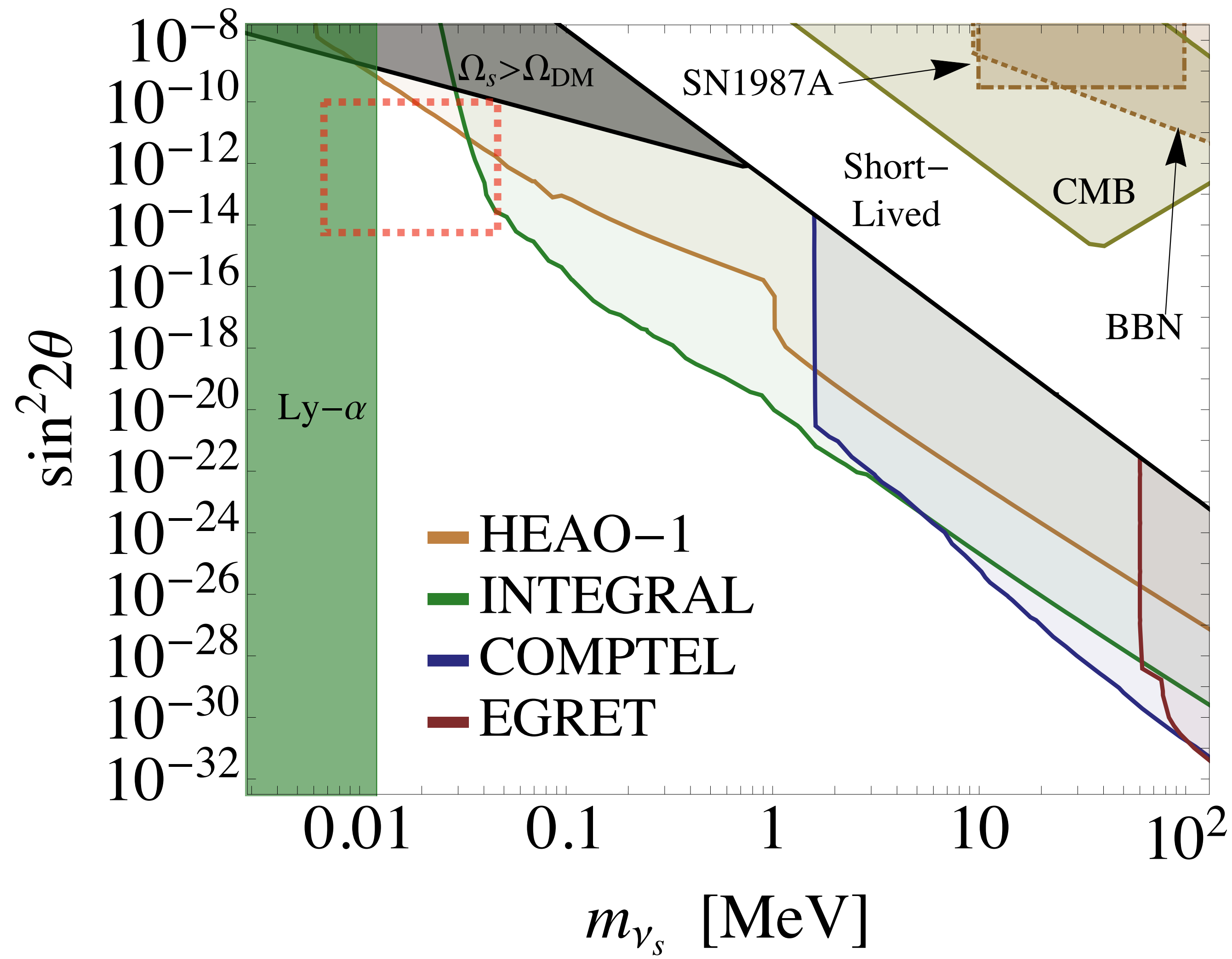
X-ray limits are strong

$$\rightarrow \ \sin^2(2\theta) \simeq 9\times 10^{-10} \ \left(\frac{g_*(T=100\ \mathrm{MeV})}{20}\right)^{1/2} \ \left(\frac{10\ \mathrm{keV}}{m_s}\right)^2$$

Roach et al, [1908.09037]



Essig et al, [1309.4091]



Strongly **excludes minimal DM production mode.**