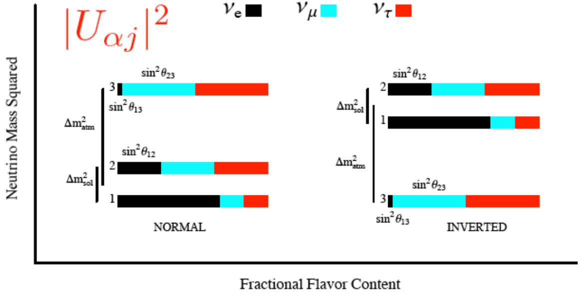
Lecture 2

- critical open experimental questions in neutrino physics
- ‘Portals’
- the neutrino portal

ν Mixing and mass

critical questions

Masses and Mixings



$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$

$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$

$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$

$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03$

$\sin^2\theta_{12} \sim 1/3$

$\sin^2\theta_{23} \sim 1/2$

$\sin^2\theta_{13} < 3\%$

$$\sin^2\theta_{13} \equiv |U_{e3}|^2, \quad \sin^2\theta_{12} \equiv \frac{|U_{e2}|^2}{(1-|U_{e3}|^2)}, \quad \sin^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{(1-|U_{e3}|^2)}$$

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take quiz?

critical question I

- θ_{13}?
  - if $\theta_{13} = 0$, indicates underlying pattern?
  - if $\theta_{13} \neq 0$, CPV possible
  - if $\theta_{13} \neq 0$, matter effects can experimentally determine hierarchy (goal of future longbaseline neutrino oscillation program)

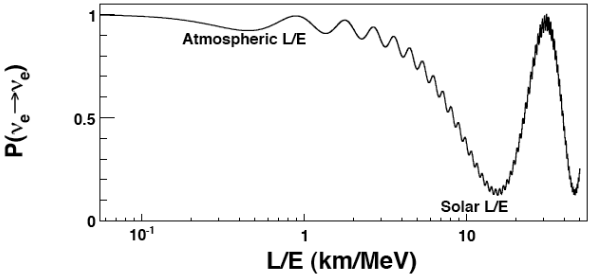
θ_{13} from Reactor Disappearance

kinematic phase:
$\Delta_{ij} \equiv \frac{\delta m^2_{ij} L}{4E}$

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\delta m^2_{ee} L}{4E}\right) - \mathcal{O}(\Delta_{21})^2$$

where $\delta m^2_{ee} = \cos^2\theta_{12}|\delta m^2_{31}| + \sin^2\theta_{12}|\delta m^2_{32}|$

ν_e weight average of $|\delta m^2_{31}|$ and $|\delta m^2_{32}|$



Pure measurement of $\sin^2\theta_{13}$!!!
the ν_e component of ν_3

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take quiz?

critical question II

- δ?
  - if δ, $\theta_{13} \neq 0$, CP is violated in ν oscillations
  - not directly related to leptogenesis, but would be likely in most leptogenesis models

take quiz?

critical question III

- Mass Hierarchy?
  - if $\Delta m^2_{13} > 0$, Hierarchy is "normal" like quark sector
    - ★ heaviest neutrino is mostly heaviest lepton flavor
  - if $\Delta m^2_{13} < 0$, Hierarchy is "inverted" unlike quark sector
    - ★ 2 heaviest neutrinos nearly degenerate, contain large electron flavor fraction
    - ★ clue to underlying symmetry pattern?

take quiz?

critical question IV

- Overall mass scale?
  - Cosmology: upper bound of ~eV
  - mass splittings tiny compared to 1 eV
    - ★ $|\Delta m^2_{13}|=0.0024\ eV^2$
    - ★ $\Delta m^2_{12}=0.00076\ eV2$
  - if ν mass is hierarchical overall scale is ~ 0.05 eV
  - if m_ν >>0.1 eV masses nearly degenerate
    - ★ degeneracy would be clue to underlying symmetry?

take quiz?

critical question V

- Majorana or Dirac?
  - Majorana theoretically/cosmologically favored
    - ★ GUTs
    - ★ leptogenesis/baryogenesis
    - ★ seesaw explanation for tiny masses
    - ★ quantum gravity: no global symmetries
  - Dirac mass would be a surprise! But
    - ★ have no experimental evidence for any Majorana particle
    - ★ have no verified laboratory evidence for lepton or baryon number violation

ββ decay usually conserves lepton number

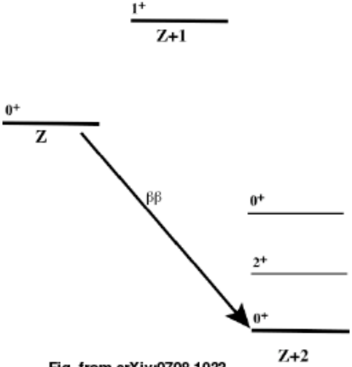
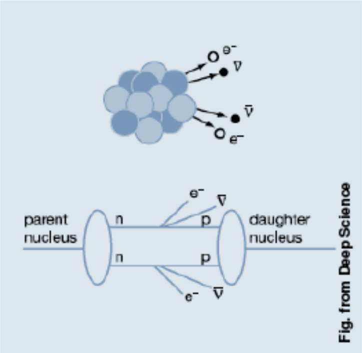


Fig. from arXiv:0708.1033



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ββ , no ν's violates L, tests Majorana nature of ν

insert
m_ν

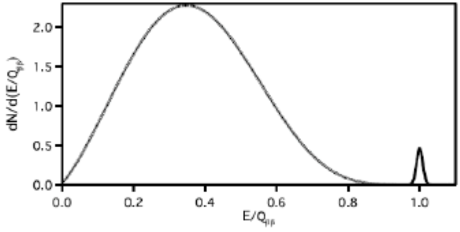
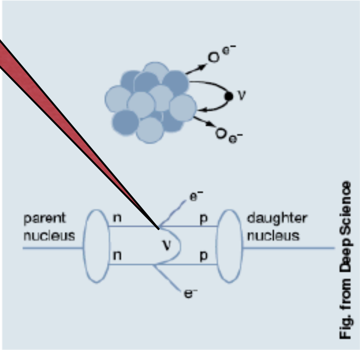


Fig. from arXiv:0708.1033



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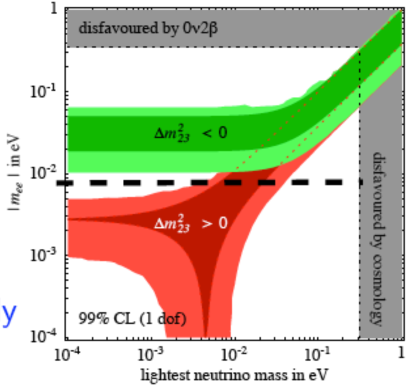
Neutrinoless double beta decay

$$< m >_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$

$$= \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\beta} + m_3 s_{13}^2 e^{2i(\gamma-\delta)} \right|$$

dividing point $m_{\beta\beta} \approx 10 meV$ $\Rightarrow\Rightarrow$



Signal below ∼ 10 meV would imply Majorana and Normal Hierarchy!

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Critical question VI?

Who cares ?

Neutrino mass is physics "beyond the Standard Model", but . . .

we can account for neutrino mass with right handed neutrinos and/or lepton number violating nonrenormalizable interactions in

"the ν Standard Model(s)"

no revision of sacred principles needed either way

Usual reasons to care about Neutrino mass/mixing

- Window into GrandUnifiedTheorieS
- May be related to Leptogenesis/Baryogenesis
- Affects structure formation in Universe
- May affect supernovae dynamics
- Neutrino astronomy affected by mixing
- Use of neutrinos as probe, e.g. geophysical, requires knowledge of mixing parameters

Exotic Physics beyond the ν standard model

- Visible oscillations are affected by tiny GUT scale suppressed operators ('standard' seesaw) and weak force(s)
- Neutrinos can mix with "dark" (sterile) fermions
- Neutrinos can thus experience "dark forces" much more strongly than other known particles
- matter effect on oscillations is sensitive to new forces
- Neutrinos are Special!
  Neutrino physics great place to search for exotica!
  Window on the Dark Sector!

take quiz?

critical question VI

Is the standard picture
of 3 light oscillating neutrinos, interacting via
Standard Model Weak Interactions
correct?

Beyond the ν standard model

"We have a Limited Palette"

-Sidney Coleman, Quantum Field Theory

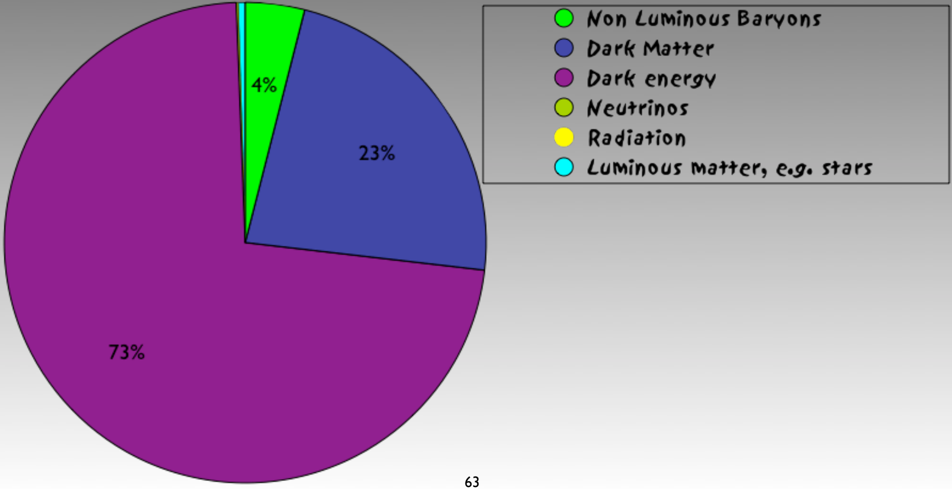
Parameters

- At low energy/long distance Renormalizable (Marginal and Relevant) terms dominate. With Particle/Field content of Standard Model, 19 renormalizable terms are allowed.
    - 6 quark masses, 3 quark mixing angles, 1 CP violating phase, determined by Higgs couplings
    - 3 charged lepton masses
    - 3 gauge couplings, 1 strong CP violating phase
    - 2 parameter Higgs potential gives Higgs vev, Higgs self-coupling (Higgs mass)
- Sufficient for length scales to 10^{-33} cm (if we neglect dark matter, gravity and ν masses), tested to 10^{-17} cm

Gravity and Neutrino mass

- Add (nonrenormalizable) interactions for
  - Gravity-2 more parameters (G_N and Λ)
  - neutrino masses: dimension 5 irrelevant term gives 9 more parameters (3 masses, 3 angles, 3 phases)

Precision Cosmology and The Composition of the Universe



Dark Matter

- Very strong gravitational evidence
- No nongravitational effects seen yet
- Could be almost anything except what we already know
  - Nearly pressureless, collisionless fluid (weakly interacting nonrelativistic particles)
  - No electromagnetic interactions
  - No strong interactions
  - No (suppressed) Standard Model weak interactions
- Most popular and well motivated:
  - (Very) Weakly Interacting Massive Particle
  - Axion

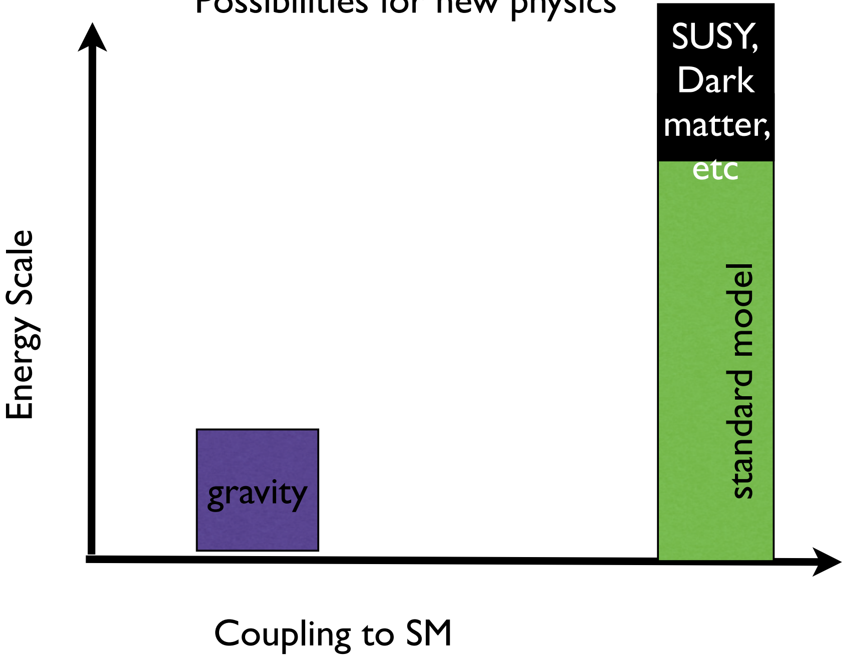
Explain rather than describe?

- historical paradigm-from Fermi theory of weak interactions (nonrenormalizable, “effective theory”, potentially lots of terms) to standard electroweak theory, 2 gauge couplings (plus Higgs mechanism)
- How to repeat?
  - Inspiration? so far lots and lots of speculation
    - Decoupling--Many more models of fundamental physics than low energy parameters, low energy physics always underconstraining

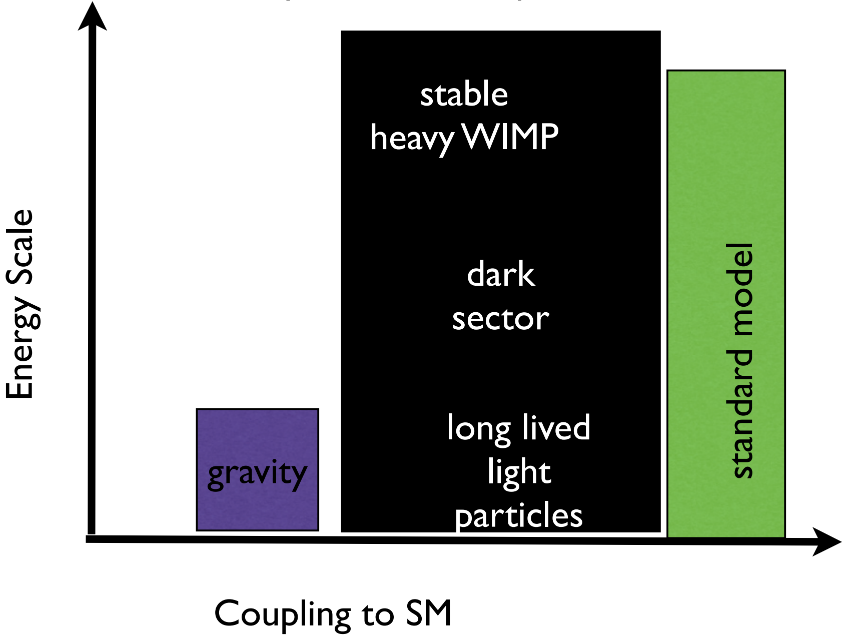
Experimental Guidance

- "High Energy Frontier" (LHC,...)
  - Find new particles! Get lots of information!
- "Intensity Frontier" (low energy rare processes, neutrino physics, precision measurement)
  - only a few parameters to measure
    - Overwhelming theory degeneracy
  - sensitivity to high energy $(1/\text{energy})^n$
    - typically n=4
    - have to improve sensitivity by large factor for modest energy reach

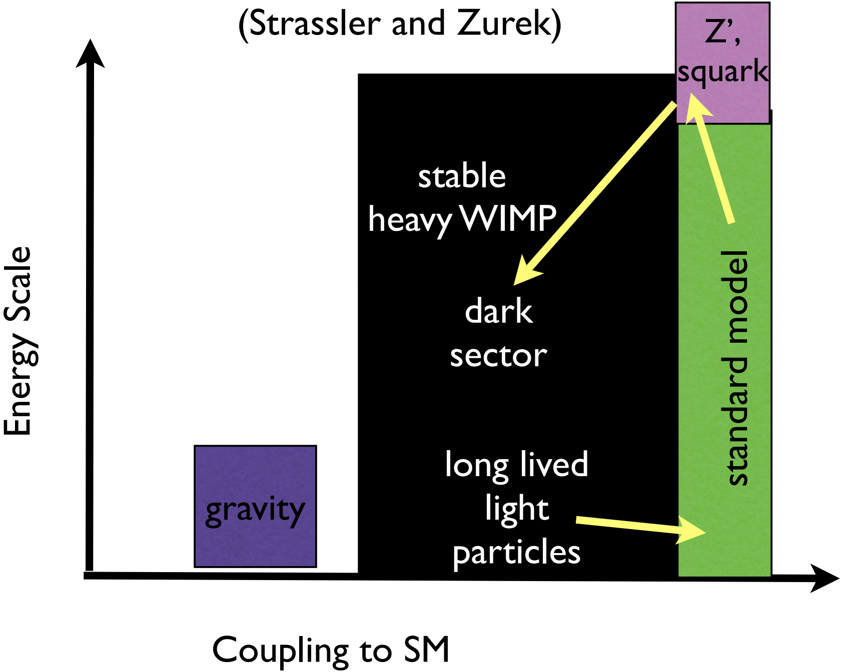
Possibilities for new physics



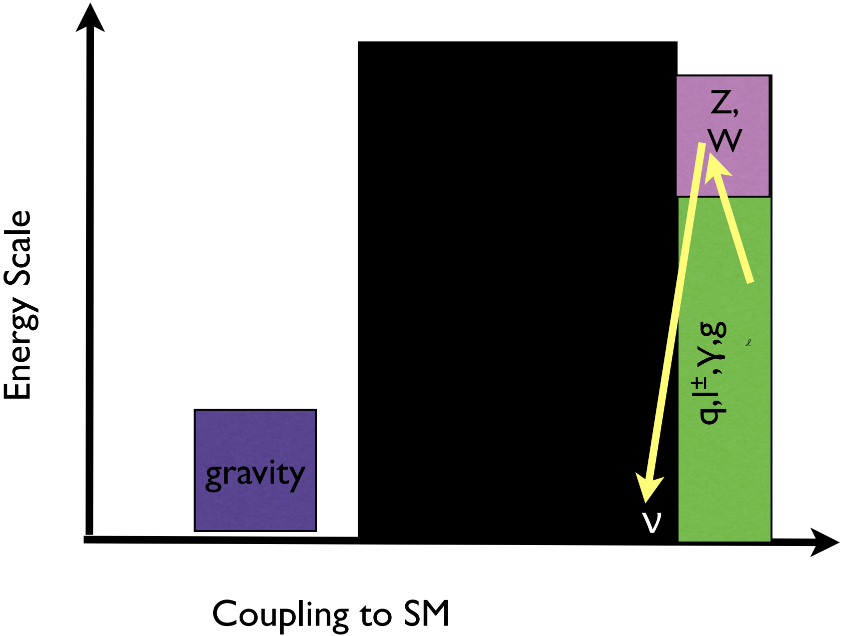
Expanded landscape?



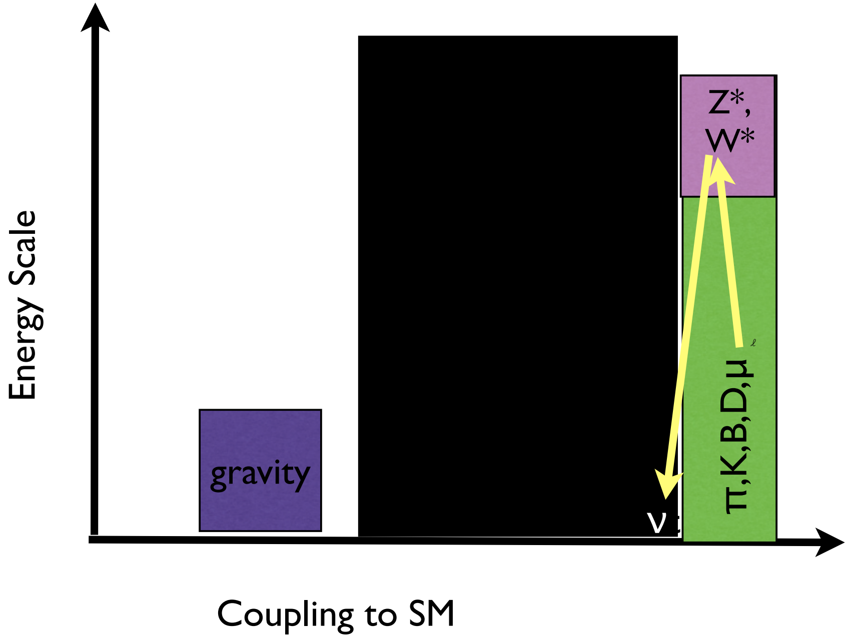
High Energy path to dark sector 'hidden valley' (Strassler and Zurek)

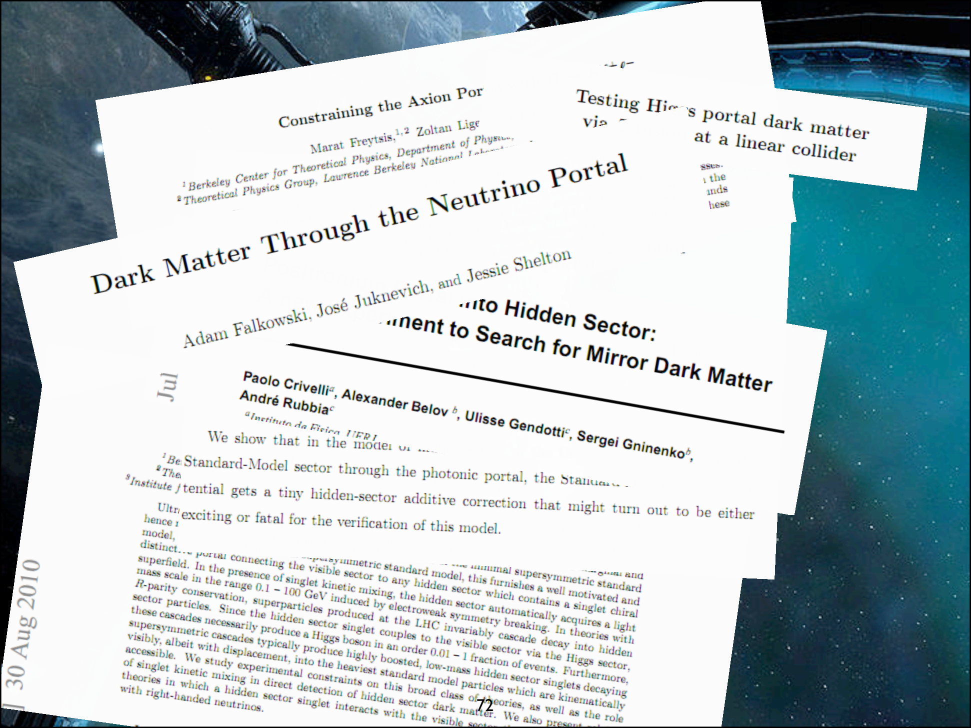


Similar to neutrino access in Standard Model



Low energy portal to neutrinos




Constraining the Axion Por
Marat Freytsis,1,2 Zoltan Lige
1 Berkeley Center for Theoretical Physics, Department of Physics
2 Theoretical Physics Group, Lawrence Berkeley National
Testing Higgs portal dark matter
at a linear collider
Dark Matter Through the Neutrino Portal
Adam Falkowski, José Juknevich, and Jessie Shelton
Hidden Sector:
to Search for Mirror Dark Matter
Paolo Crivelli, Alexander Belov, Ulisse Gendotti, Sergei Gninenko,
André Rubbia
We show that in the model
Standard-Model sector through the photonic portal, the
tential gets a tiny hidden-sector additive correction that might turn out to be either
exciting or fatal for the verification of this model.
Jul
30 Aug 2010
superfield. In the presence of singlet kinetic mixing, the hidden sector which contains a singlet chiral
mass scale in the range 0.1 – 100 GeV induced by electroweak symmetry breaking. In theories with
R-parity conservation, superparticles produced at the LHC invariably cascade decay into hidden
sector particles. Since the hidden sector singlet couples to the visible sector via the Higgs sector,
these cascades necessarily produce a Higgs boson in an order 0.01 – 1 fraction of events. Furthermore,
supersymmetric cascades typically produce highly boosted, low-mass hidden sector singlets decaying
visibly, albeit with displacement, into the heaviest standard model particles which are kinematically
accessible. We study experimental constraints on this broad class of theories, as well as the role
of singlet kinetic mixing in direct detection of hidden sector dark matter. We also present
theories in which a hidden sector singlet interacts with the visible sector
with right-handed neutrinos.

What is a 'portal' ???

- in science fiction and virtual 'reality': a useful short cut to another sector.
- in particle theory???

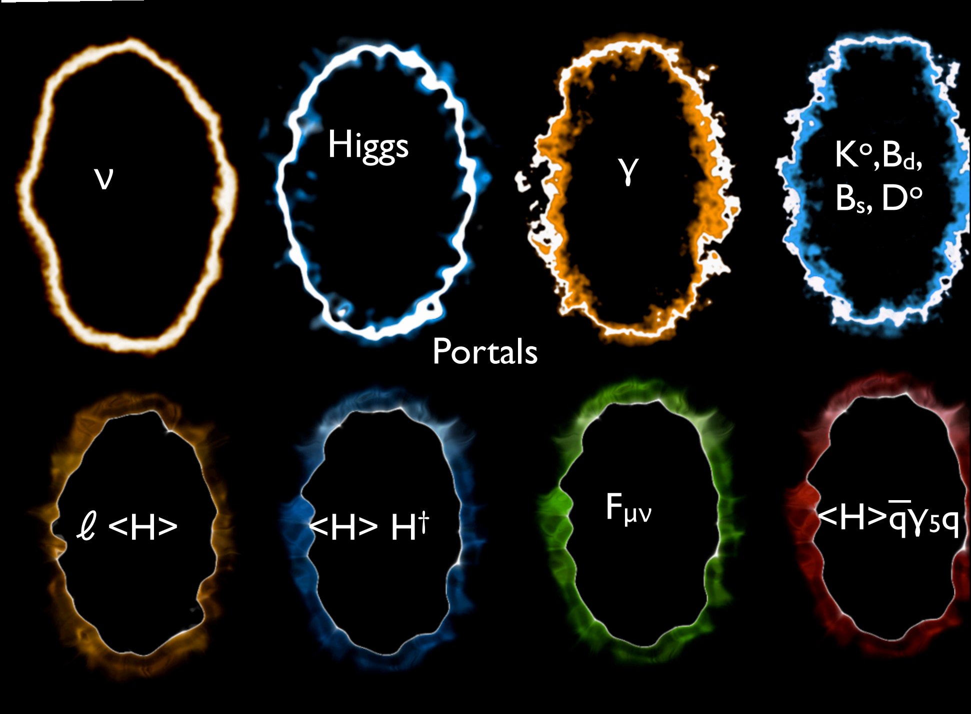
- Two ingredients

1. Dimensional analysis: possibility of a marginal or relevant operator in an effective theory which connects two sectors
2. A long lived particle associated with the operator which can take advantage of the connection to oscillate or decay into the hidden sector

    - Portal is most effective if the long lived particle can mix with a particle of the hidden sector

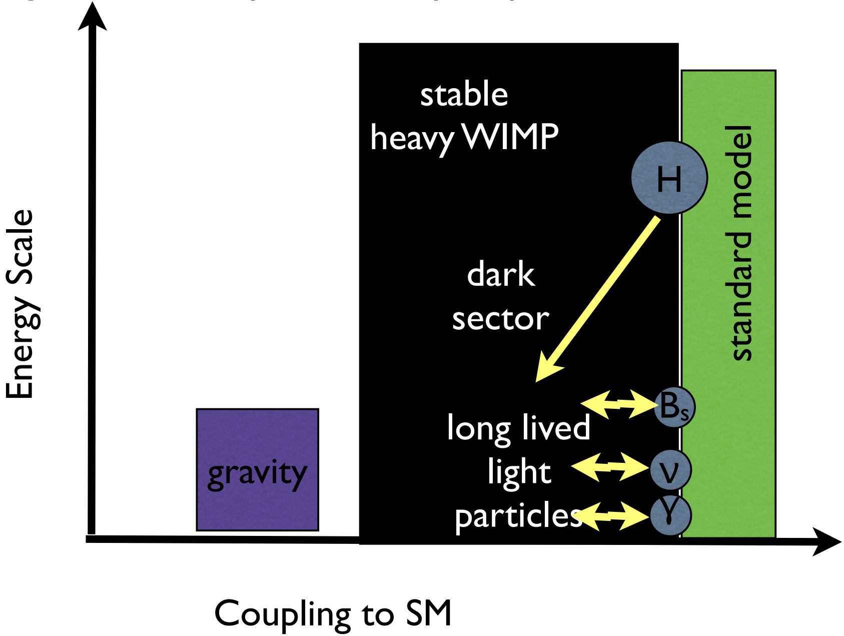
Escaping Decoupling: Mixing of light exotic and Standard particles via renormalizable terms

- Dimensional analysis: at low energy in the effective theory terms “mixing” standard model and light exotic particles are highly relevant
    - either mass or kinetic term can mix the sectors
  - particle eigenstates are linear combination of standard and exotic
  - significant effects on decays/interactions/oscillations of nearly stable and/or weakly coupled particles



ν
Higgs
γ
K°, B_d,
B_s, D°
Portals
ℓ <H>
<H> H†
F_μν
<H>q̄γ_5q

Long lived neutral particles may be portals to dark sector



ν portal

- suppose hidden sector contains a light fermion ψ
- ψ is gauge singlet under standard model gauge interactions
- ψ could have Majorana mass $M\,\psi\,\psi$
- Portal: renormalizable operator $\lambda\, h\, \ell\, \psi$
- λ might be very small, but effects of this operator relevant at low energy
  - origin of neutrino mass? (ψ plays role of ν_R)
  - more interesting if ψ is light.

other effects of ν portal

- ν can mix with exotic neutral fermions
  - sterile neutrinos in oscillations
  - nonunitarity in mixing
  - exotic interactions in oscillations
- Can experience dark forces much more strongly than other particles
- neutrino oscillations phenomenally sensitive to wide variety of exotic, very weakly coupled physics

Exotic Neutral Fermions

- many theories have additional neutral fermions which may mix with neutrinos aka “additional sterile neutrinos”
- in general, mixing need not contribute to neutrino mass, e.g. mixing with Dirac fermion does not give a neutrino mass. Sizable mixing angles with exotic fermions are possible.
- If exotic fermions are heavy, get apparent nonunitarity of light neutrino mixing matrix.
- If exotic fermions are light, called ‘sterile neutrinos’ (no Standard interactions)
- affect neutrino oscillations
- neutrinos can be strongly affected by dark forces

SUMMARY

- 6 critical experimental questions for neutrinos
- neutrino could be portal to a hidden sector of light, weakly coupled (to standard model) new particles
- portals avoid decoupling

Anomalies in ν physics via the ν portal?