Non-Abelian Dark Forces

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SLAC

Dark Forces Workshop

Sept. 25, 2009

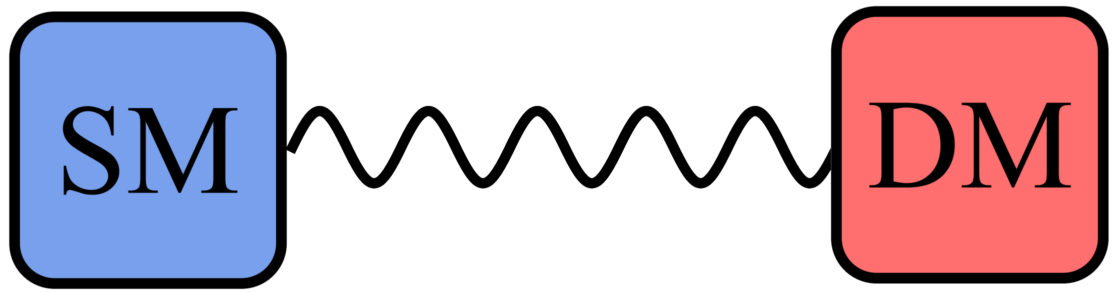
Plan of Talk

- Non-Abelian Dark Sectors & DAMA

Producing Dark Sector

Generic Signatures

Non-Abelian Dark Sectors



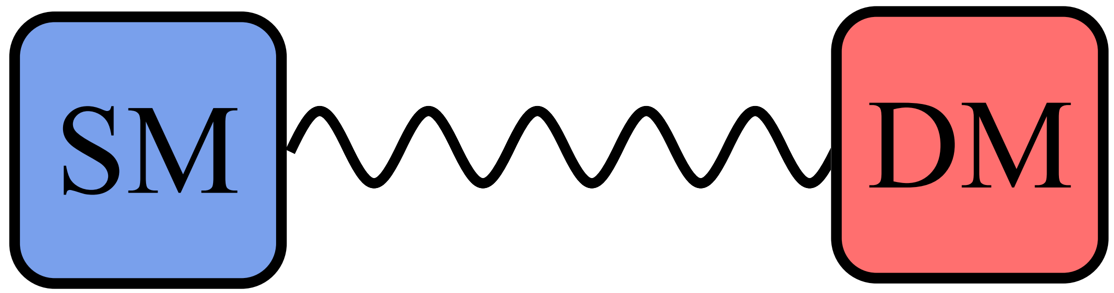
$$\mathcal{L}_{\rm dark} = -\frac{1}{2}{\rm Tr}\ G_{\mu\nu}^2 + \bar{q}\, i\not{D}\, q + m\bar{q}q$$

Confines or is Broken at low energies

$$\Lambda_{\rm dark} \sim \exp\left(-\frac{2\pi}{b_0\alpha_{\rm dark}}\right)$$

Large range of possibilities

Non-Abelian Dark Sectors



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$$\Lambda_{\text{dark}} \sim \exp\left(-\frac{2\pi}{b_0 \alpha_{\text{dark}}}\right)$$

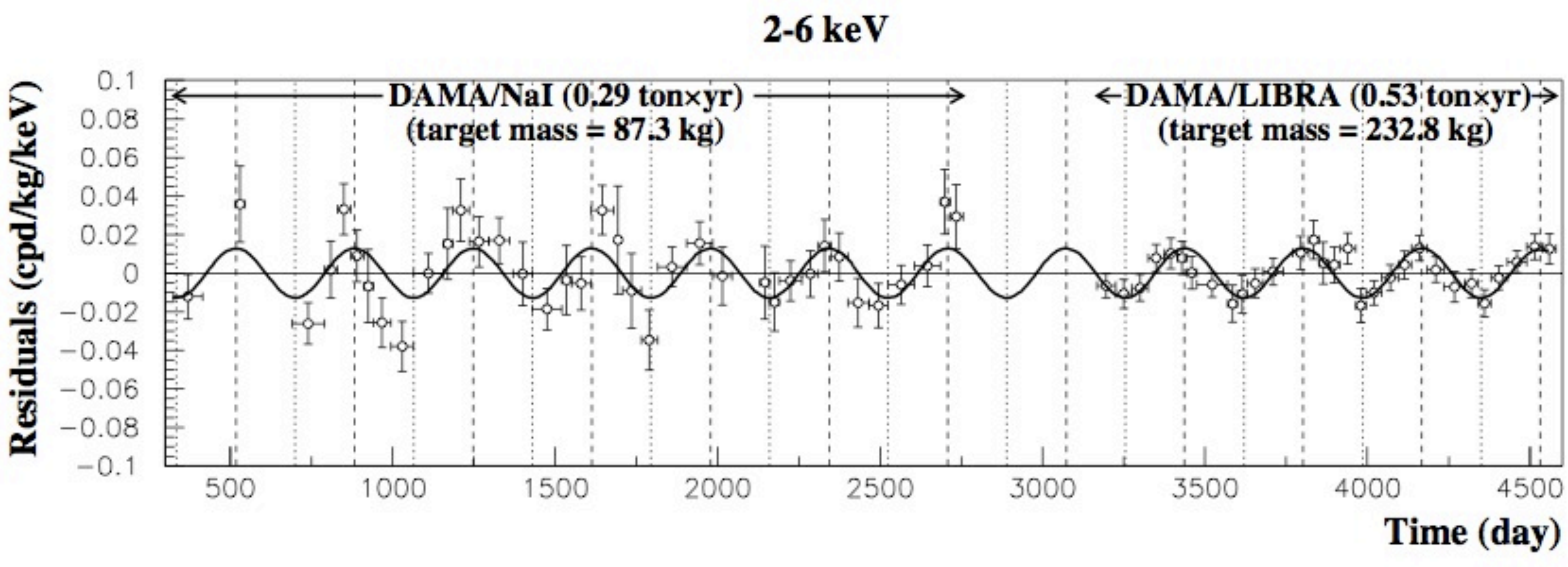
Large range of possibilities

$SU(N_c)$ gauge group

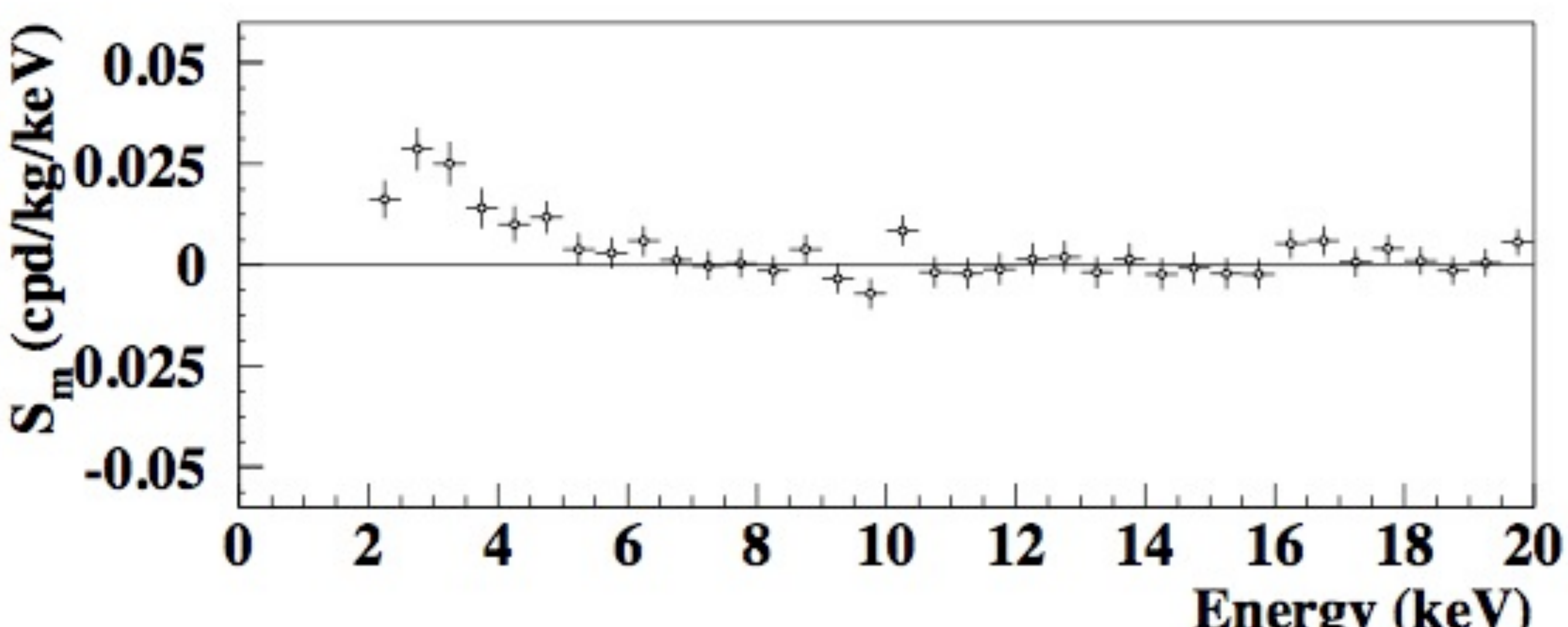
Light flavors

Heavy flavors

11 Years of Oscillation



A distinctive recoil spectrum

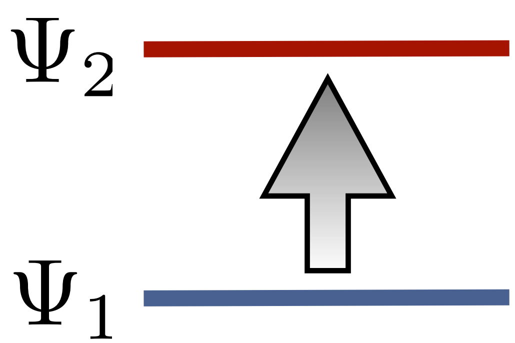


Inelastic Dark Matter

Tucker-Smith & Weiner (2001)

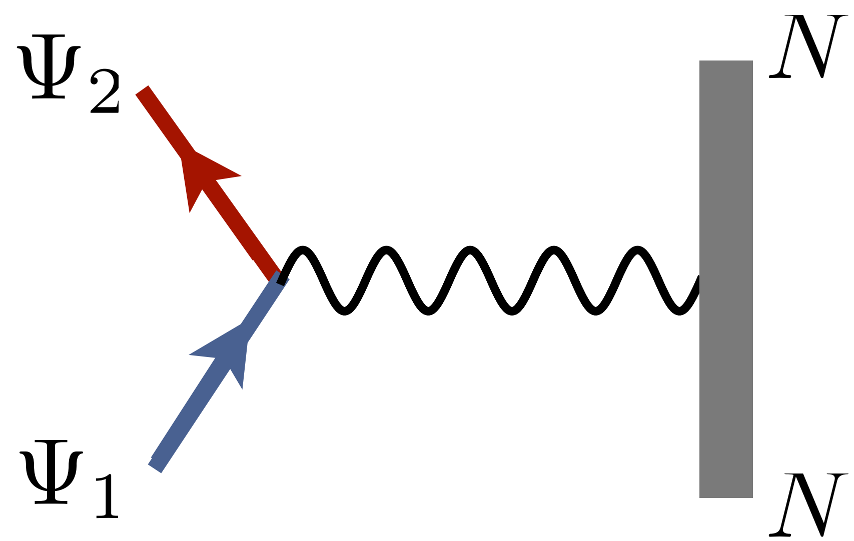
Dark matter has 2 nearly degenerate states

$$\delta m \sim \mathcal{O}(100\ \mathrm{keV})$$



Scattering off the SM is

$$\Psi_1 \longrightarrow \Psi_2$$



3 Consequences:

Scatters off of heavier nuclei (CDMS ineffective)

Large recoil energy (Xe10 & Zep3 didn't look)

Large modulation fraction (Smaller absolute signal)

Inelastic Dark Matter

A new number to explain:

$$\frac{\delta m}{m} \sim 10^{-6}$$

Sign of dark sector dynamics

First of many splittings

New interactions to discover

Changes what questions are interesting

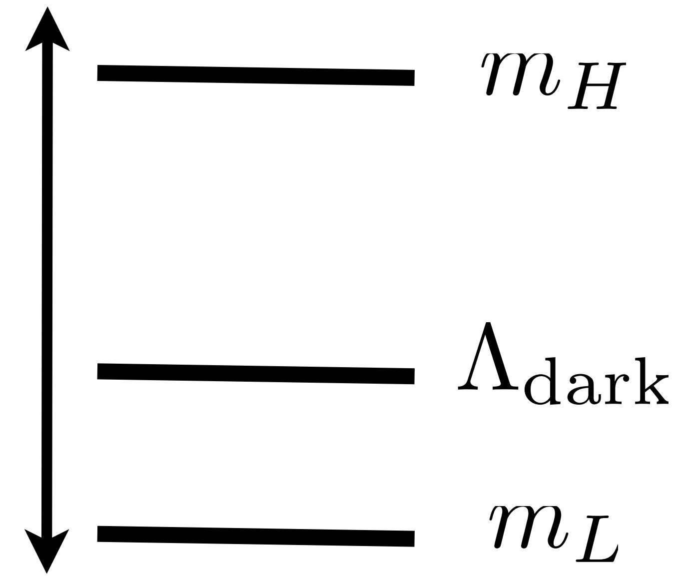
Composite Dark Matter

A new SU(N_c) gauge sector

Confines at Λ_{Dark}

A pair of quarks: q_L $\quad m_L \ll \Lambda_{\mathrm{dark}}$

q_H $\quad m_H \gg \Lambda_{\mathrm{dark}}$



Composite Dark Matter

A new SU(N_c) gauge sector

Confines at $\Lambda_{\rm Dark}$

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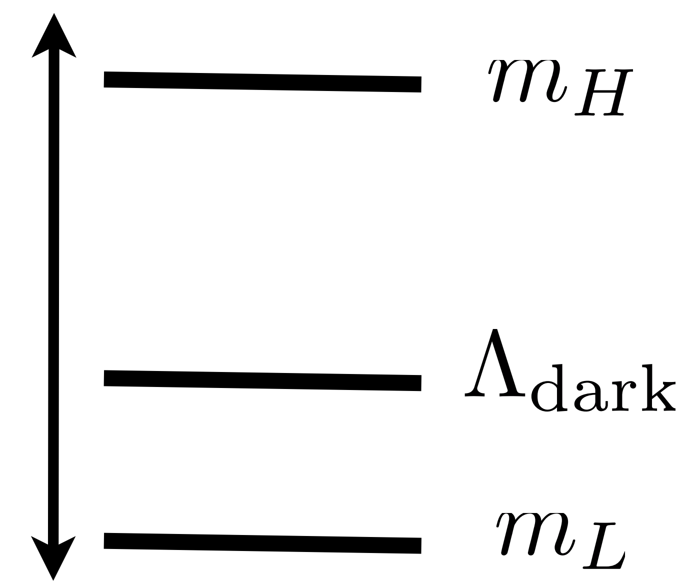


A cosmological asymmetry

$$(n_H - n_{\bar{H}}) = -(n_L - n_{\bar{L}}) \neq 0$$

At $T \ll \Lambda_{\rm Dark}$ DM is in

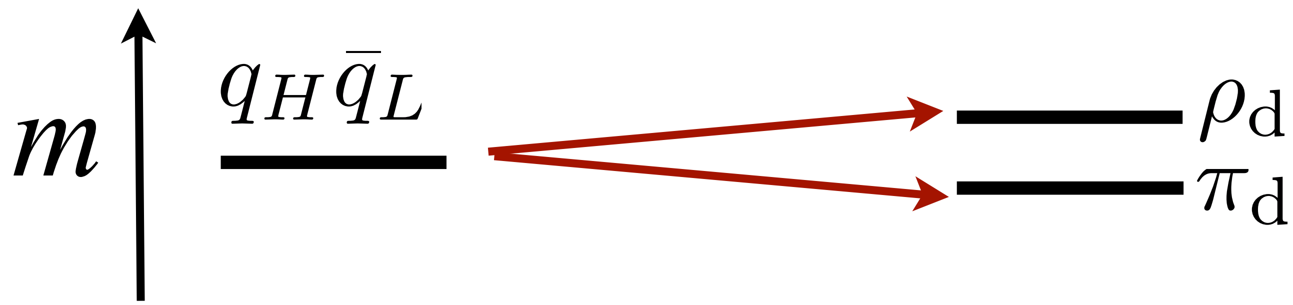
$q_H \bar{q}_L$ bound states

Dark Mesons

Degeneracy of the Ground State

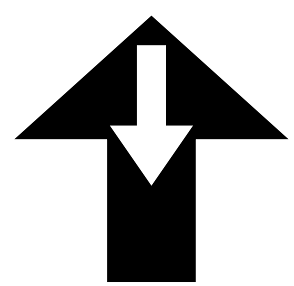
Heavy quark spin preserved in electric interactions

Dark Chromomagnetic interaction breaks spin symmetry



$$\delta H \sim \frac{\vec{\sigma} \cdot \vec{B}}{m_H}$$

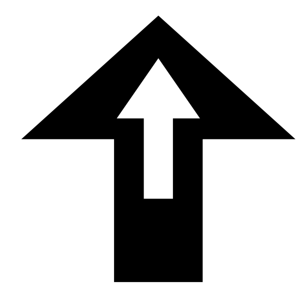
Spin 0



Dark Pion

π_d

Spin 1



Dark Rho

ρ_d

$$m_{\rho_\mathrm{d}} - m_{\pi_\mathrm{d}} \sim \frac{\Lambda^2_\mathrm{Dark}}{m_H}$$

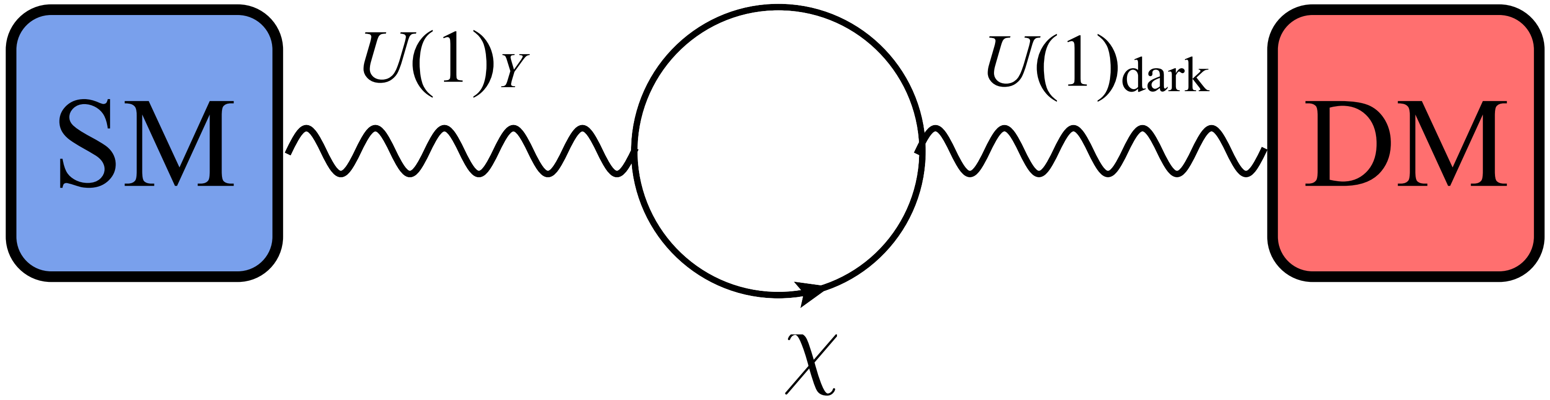
Doesn’t require adding new symmetry and breaking it

Accidental global symmetry from Lorentz Invariance

Coupling to the SM

Kinetically Mix $U(1)_Y$ with $U(1)_{\rm dark}$

$$\mathcal{L}_{\rm mix} = \epsilon\, F^{\mu\nu}_{\rm dark} F_{Y\,\mu\nu}$$



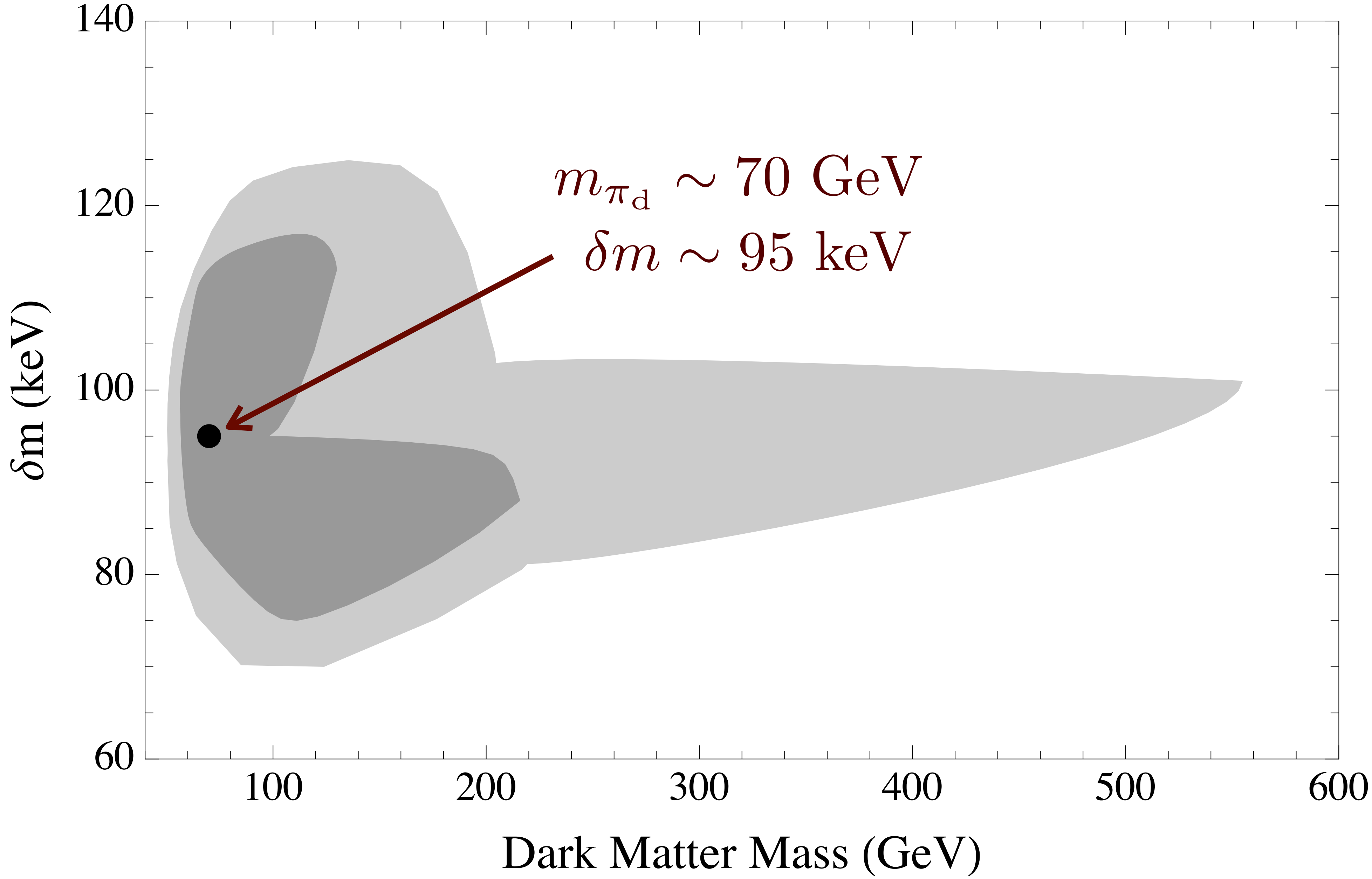
At low energy $\mathcal{L}_{\rm int} = \epsilon\, A^{\mu}_{\rm dark}\, j_{{\rm EM}\,\mu}$

Higgs $U(1)_{\rm dark}$ near EW scale

$$\mathcal{L}_{\rm Higgs} = |D_\mu \phi_{\rm d}|^2 - V(\phi_{\rm d}) \longrightarrow m_{\rm d}^2 A_{\rm d}^2$$

Inelastic Dark Matter

Combining all null experiments with DAMA



$$\Lambda_{dark} \simeq \sqrt{\delta m \, m_{\pi_d}} \simeq 80 \text{ MeV}$$

Beneath Hadronic threshold

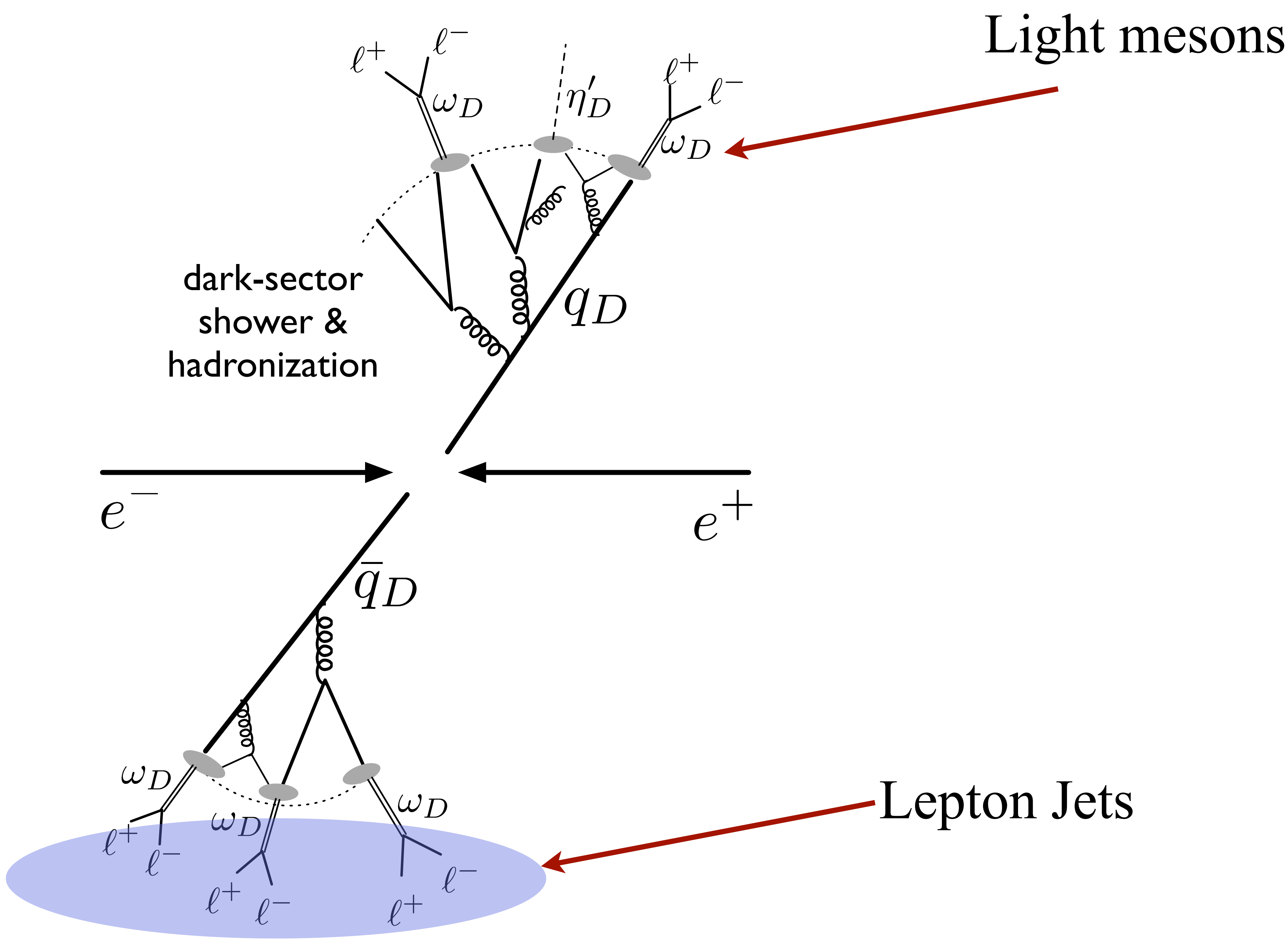
Plan of Talk

Non-Abelian Dark Sectors & DAMA

Producing Dark Sector

Generic Signatures

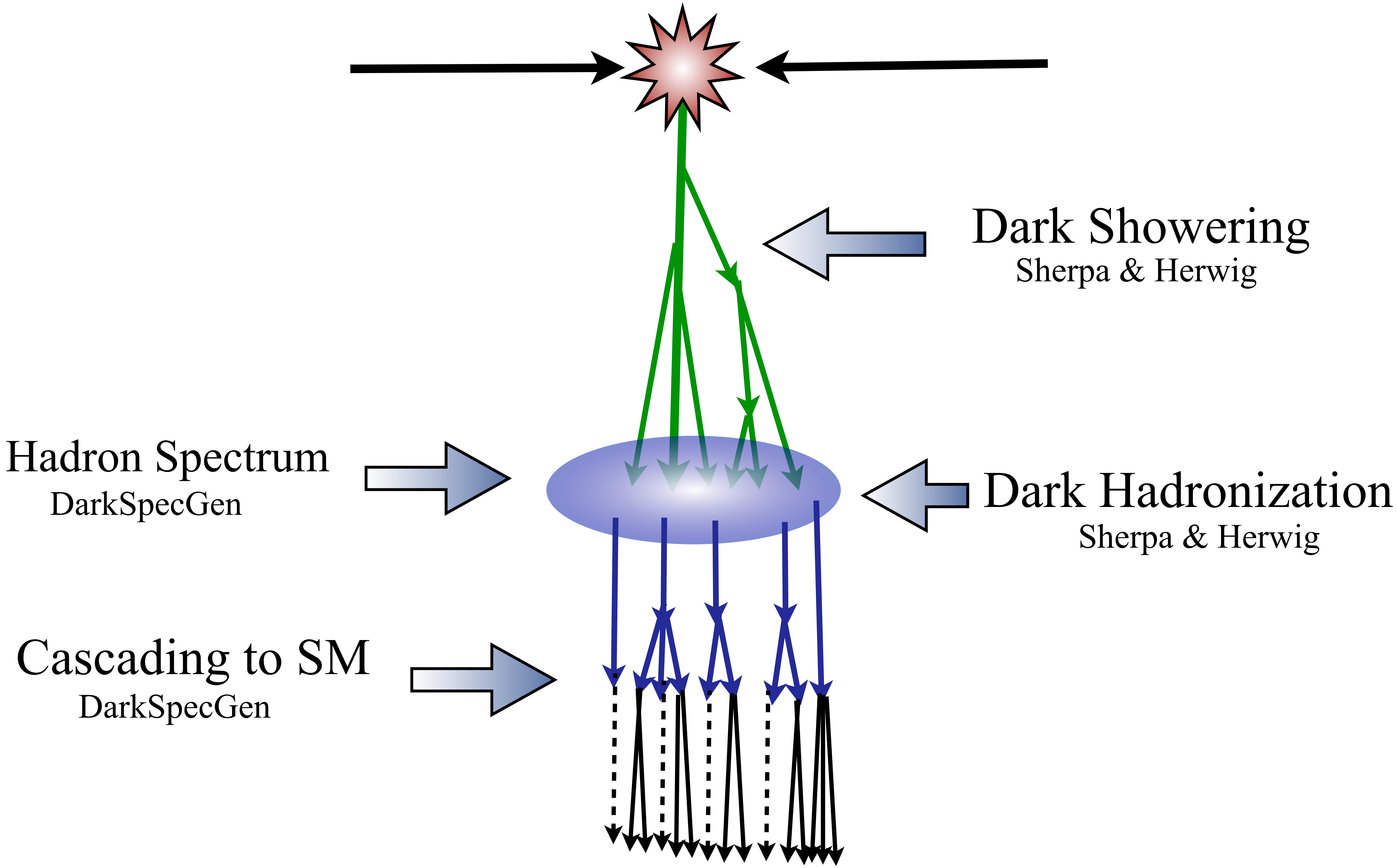
Collider Signatures



New Tools

New Strong Signal Simulation

(J. Wacker w/ S. Schumann, P. Richardson, F. Krauss)



Boosted Physics

When high pT particles
cascade to SM final states
producing collimated final states

“Lepton Jets”

A Challenging Environment

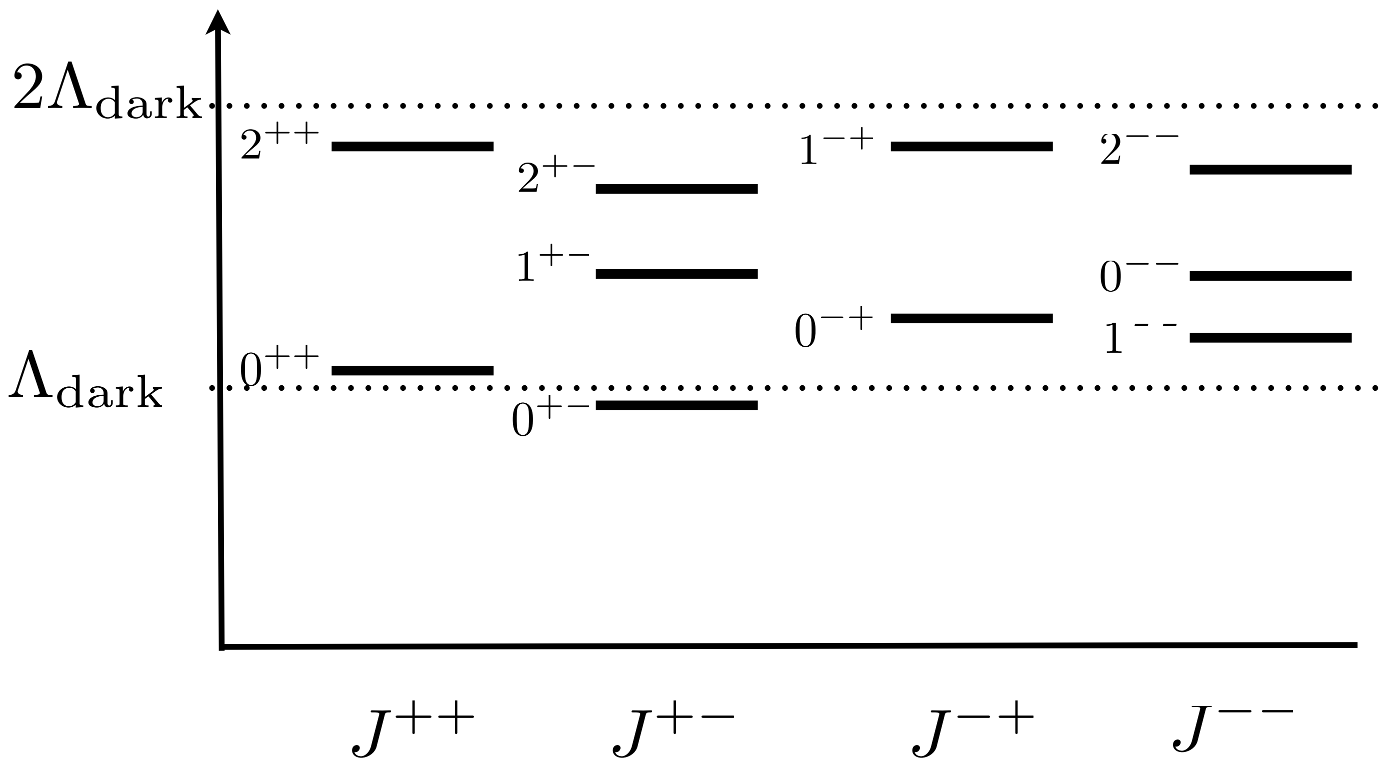
Reconstruction is difficult
Isolation cuts out signal
Cascades produce heterogeneous final states

1 Light Flavor Spectrum

No light pions - Only eta prime

No hadronic decays

~1 dozen quasi stable particles



Only "weak" decays: quasi-stable particles

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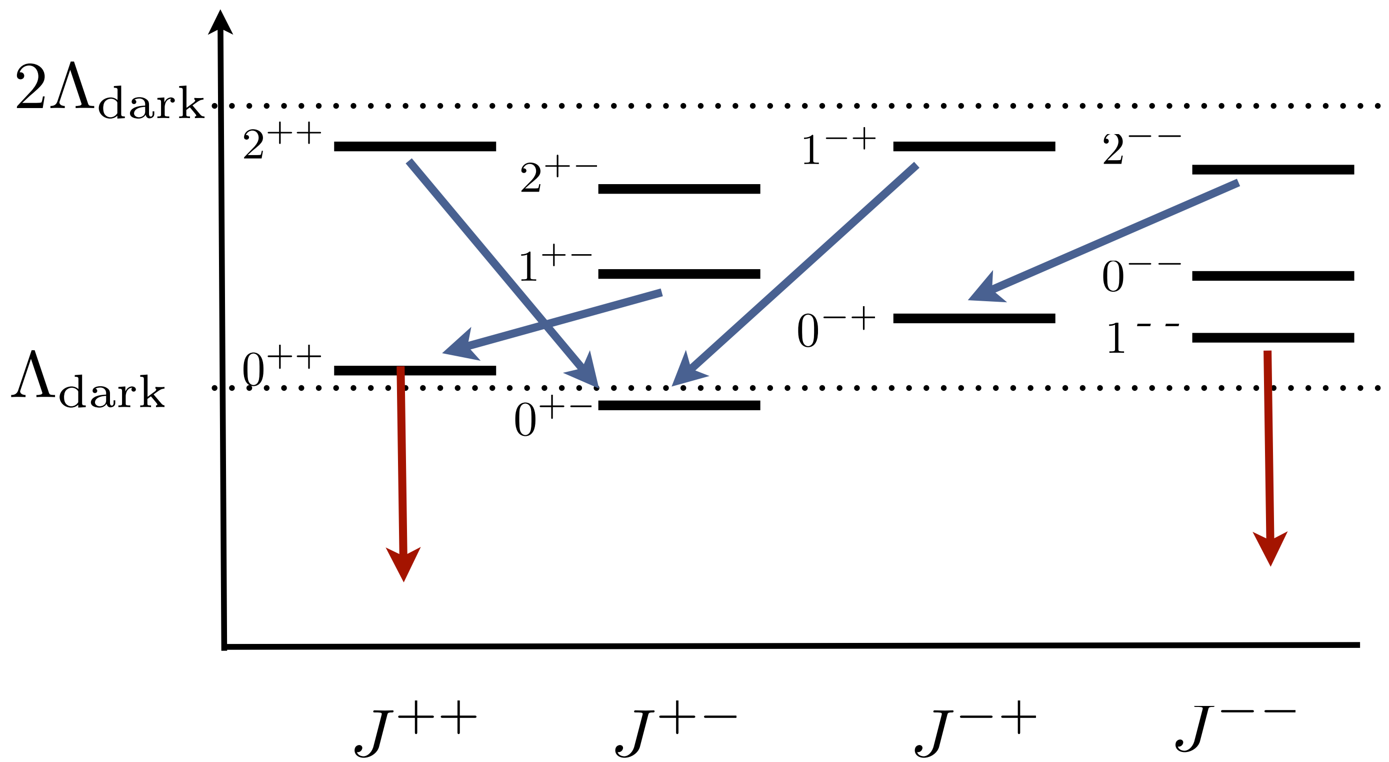

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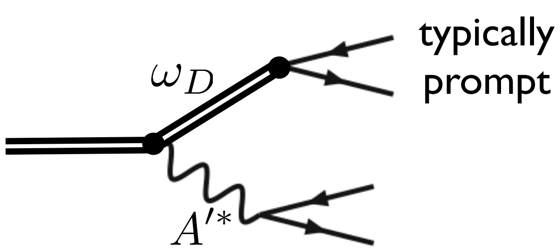

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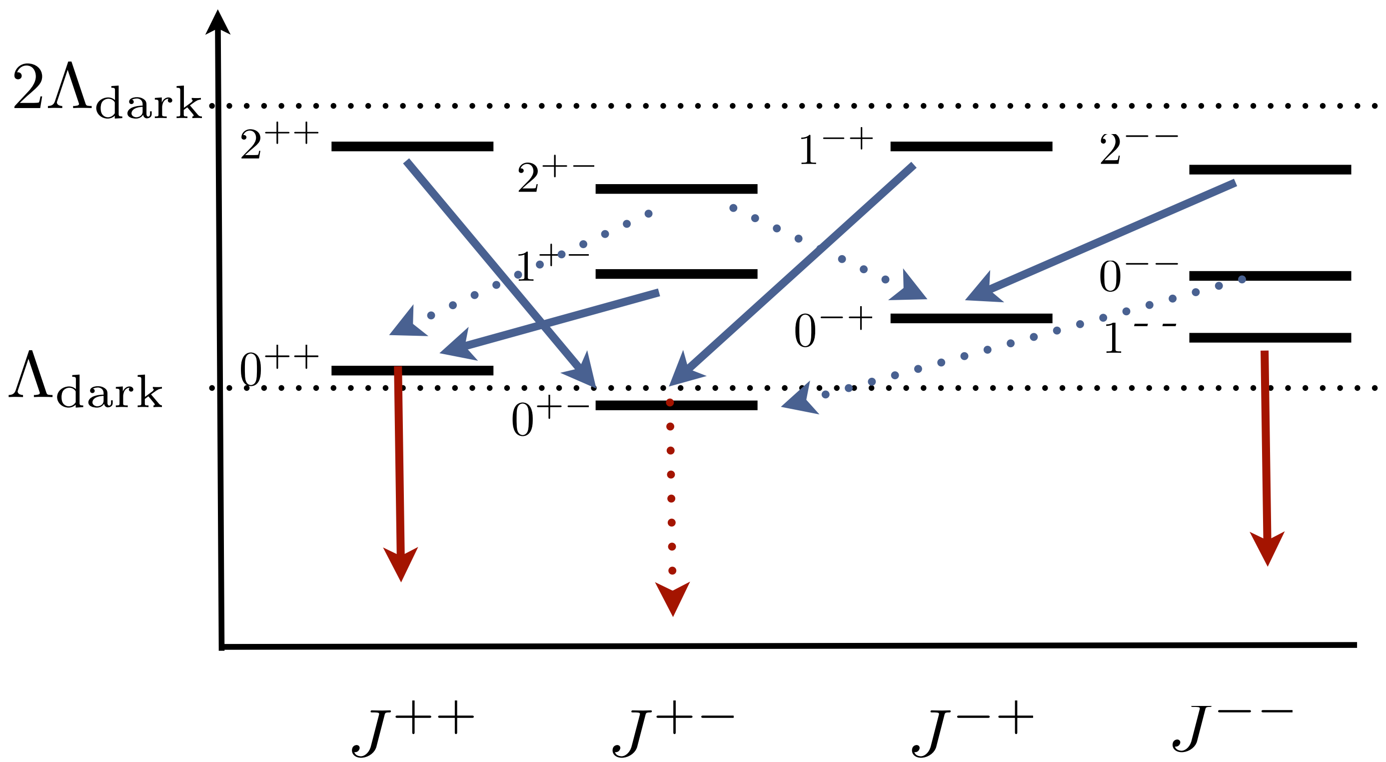

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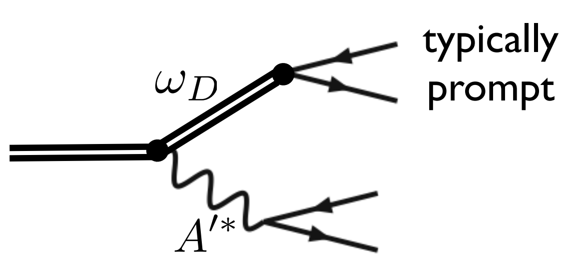

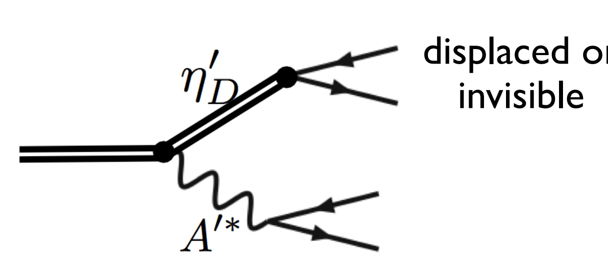

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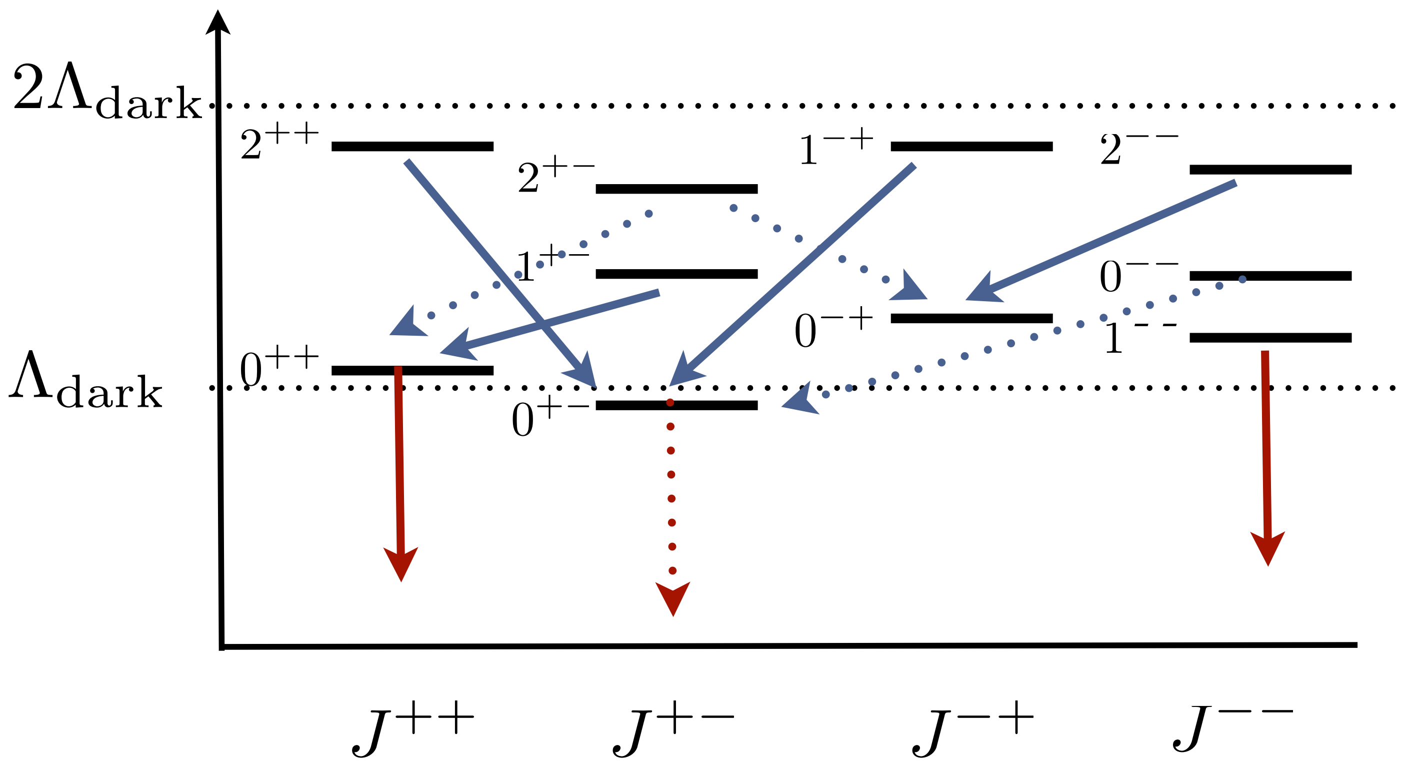

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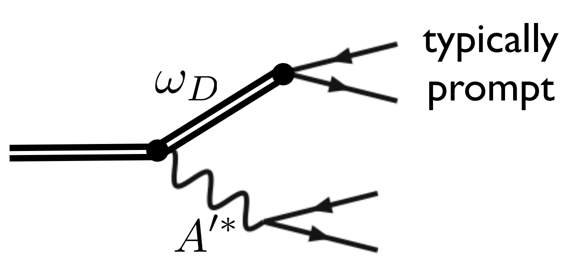
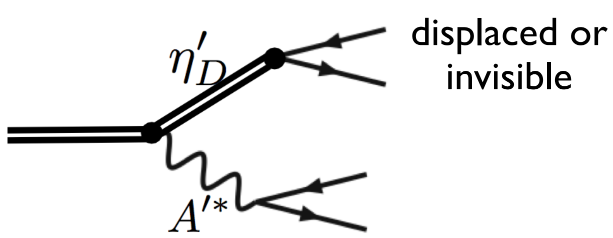




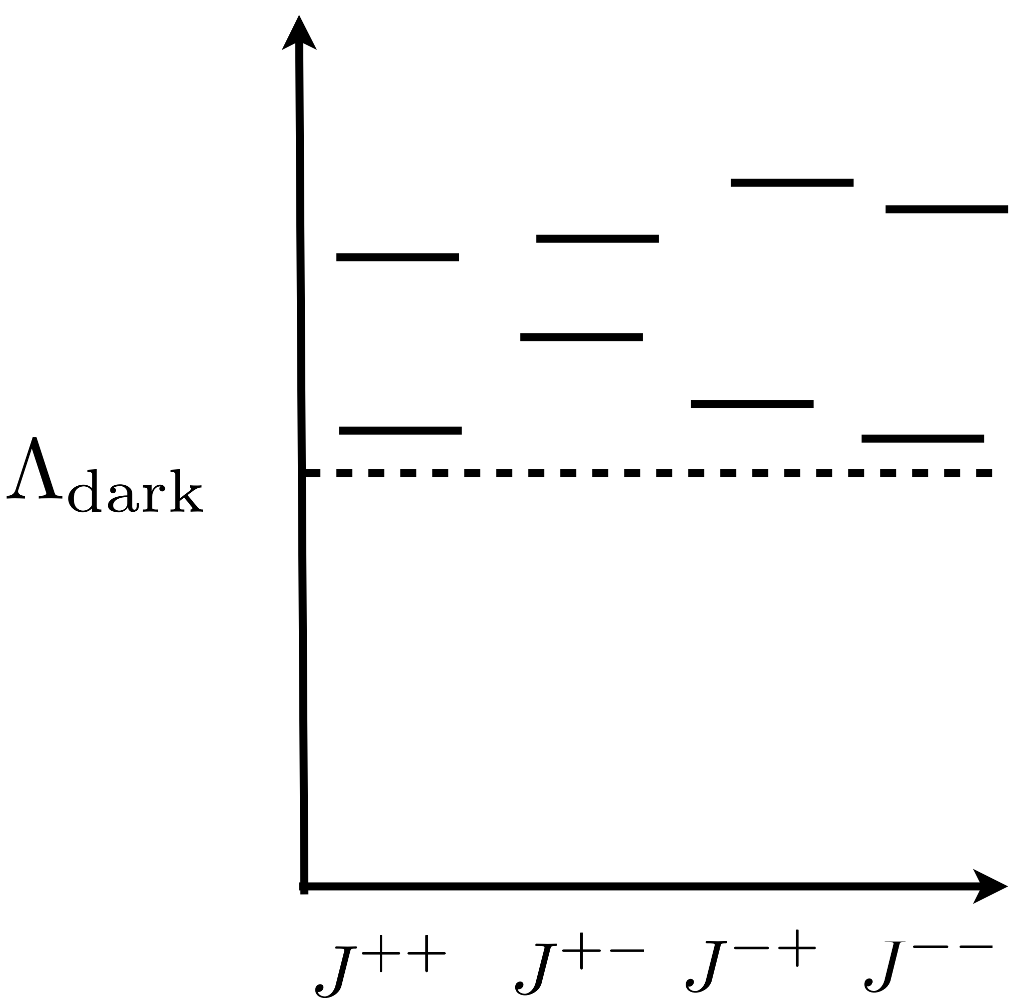
Some short-lived & Some long lived

Lots of visible particles

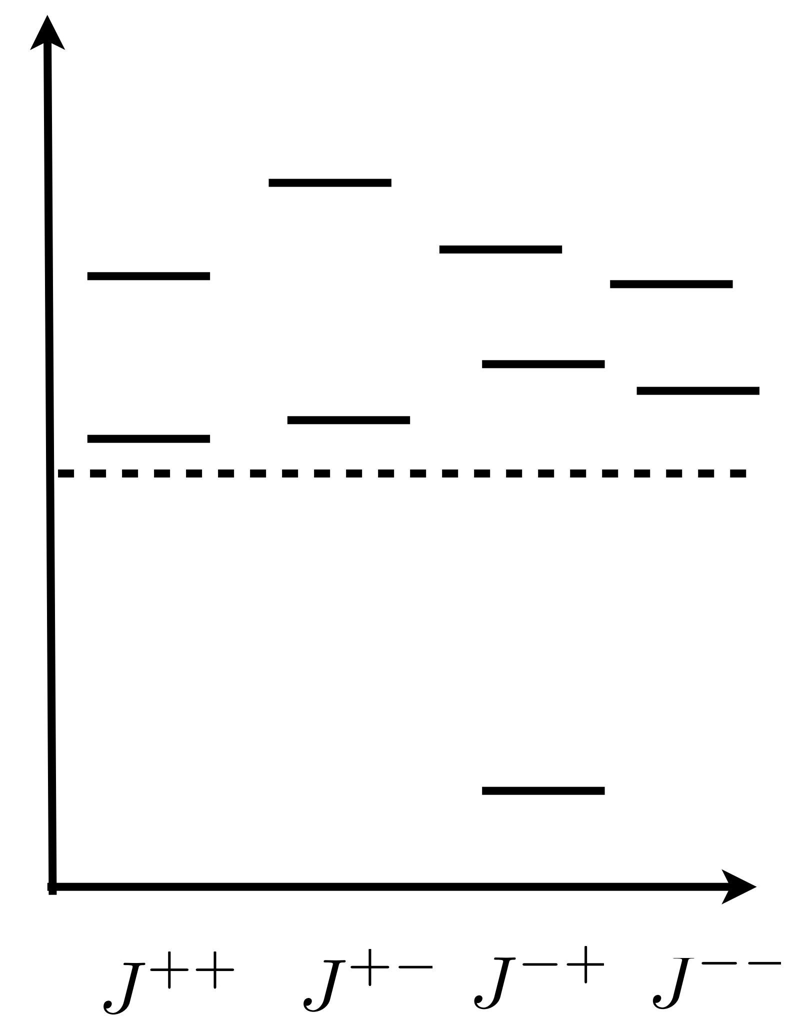
Multiple Light Flavor Spectrum

Light pions $m_\pi = \sqrt{m_q \Lambda_{\rm dark}}$

$I = 0$



$I = 1$



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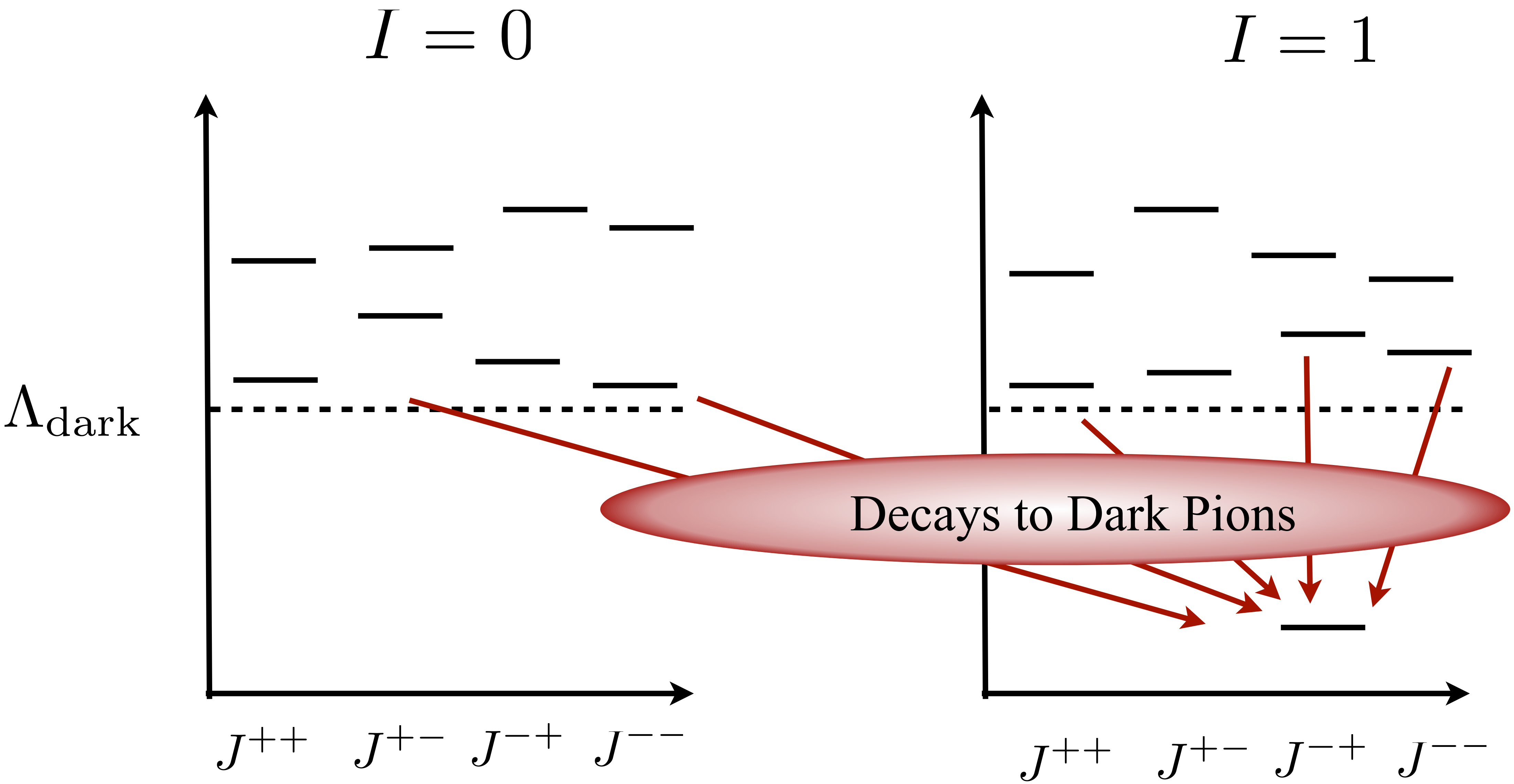

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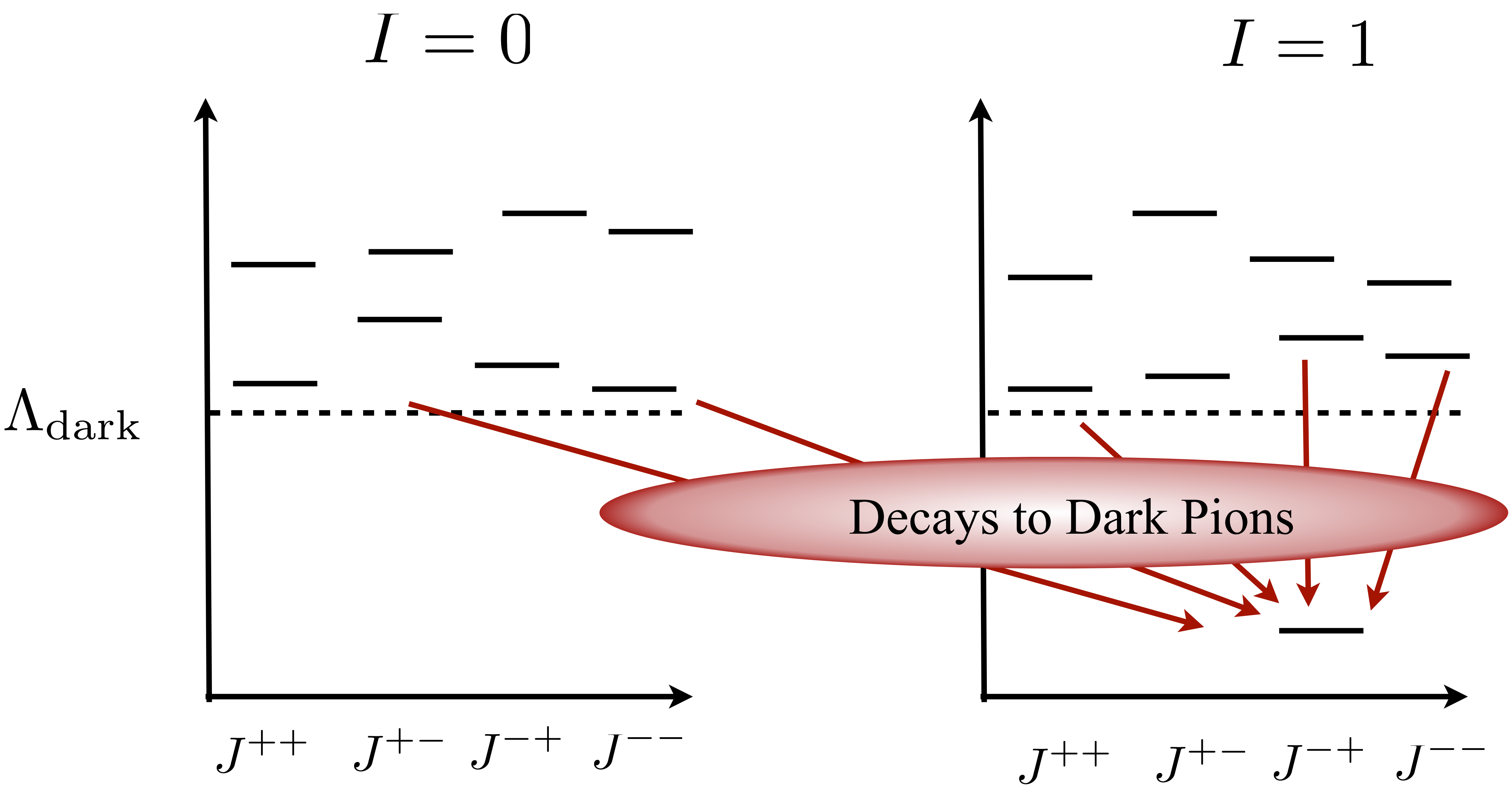

$$\pi \sim \begin{pmatrix} \bar{q}q & \bar{q}q' & \\ \bar{q}'q & \bar{q}'q' & \\ & & \ddots \end{pmatrix}$$

Multiple Light Flavor Spectrum

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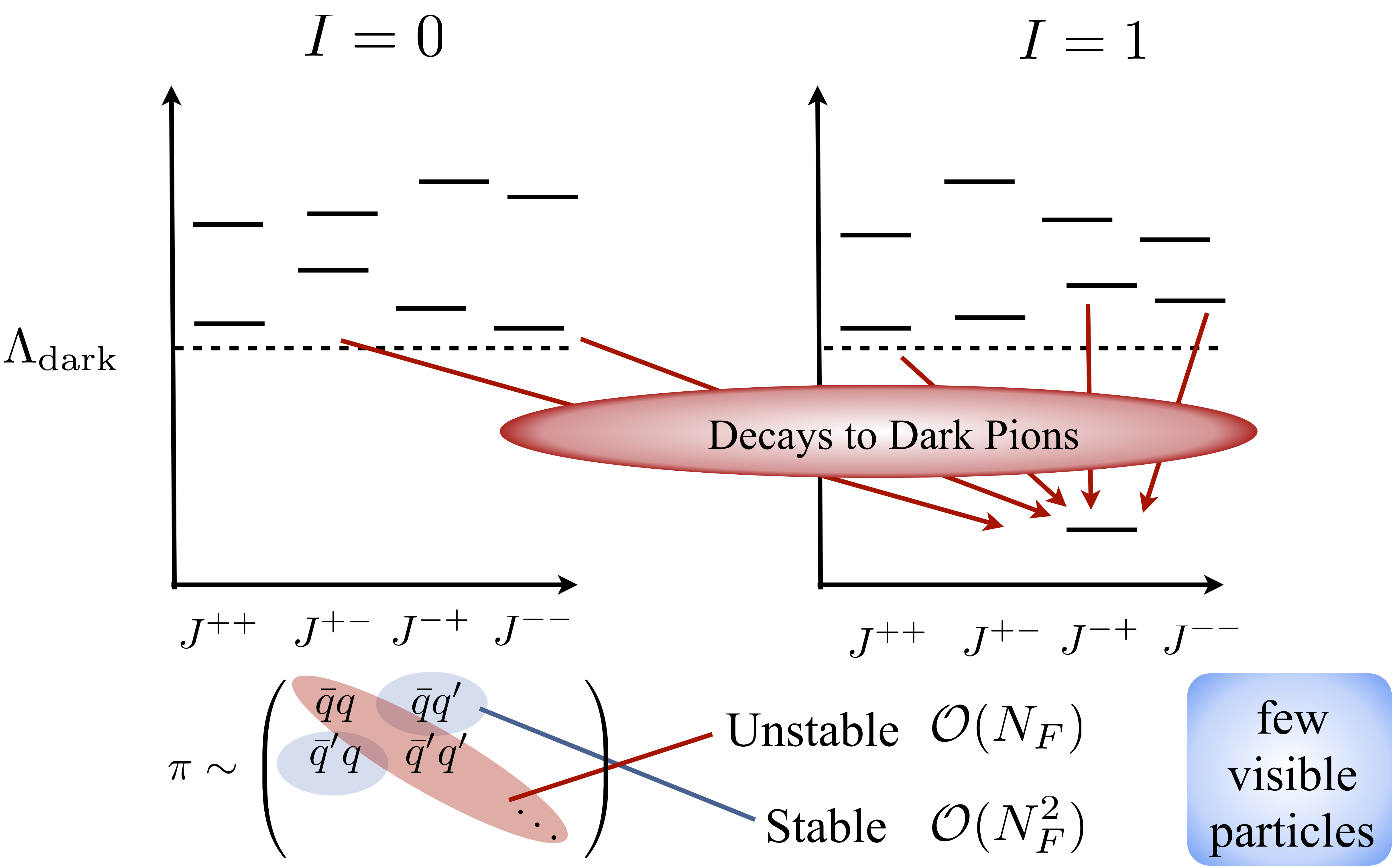


No light flavors

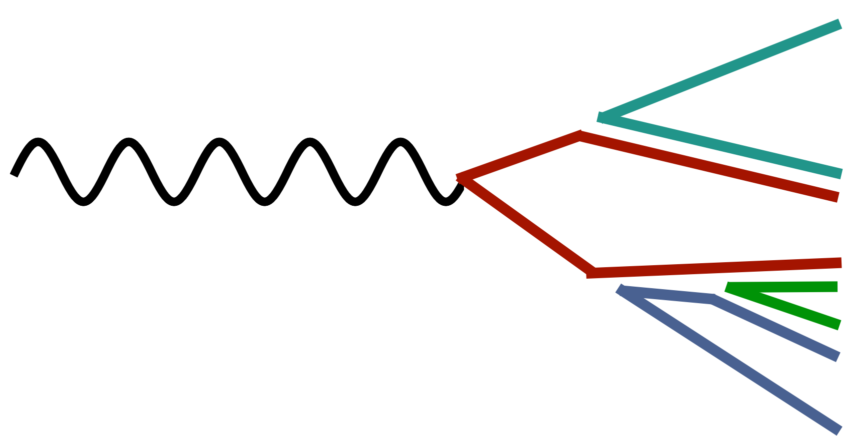
"Quirks" (Luty et al 2008)

Spectra similar to 1 light flavor

(Lattice calculations available)

We don't know how to hadronize

(how to cut color lines)



More theory work necessary

Plan of Talk

Non-Abelian Dark Sectors & DAMA

Producing Dark Sector

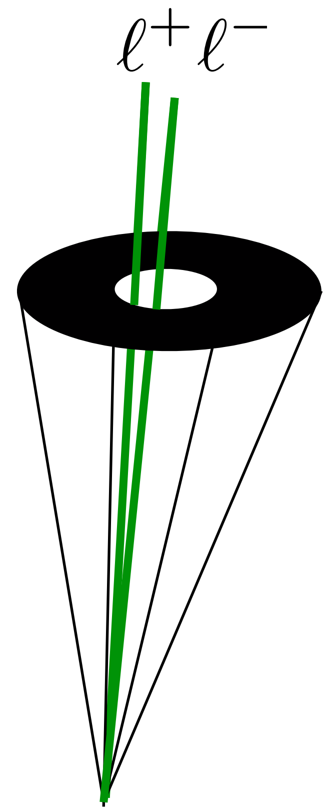
- Generic Signatures

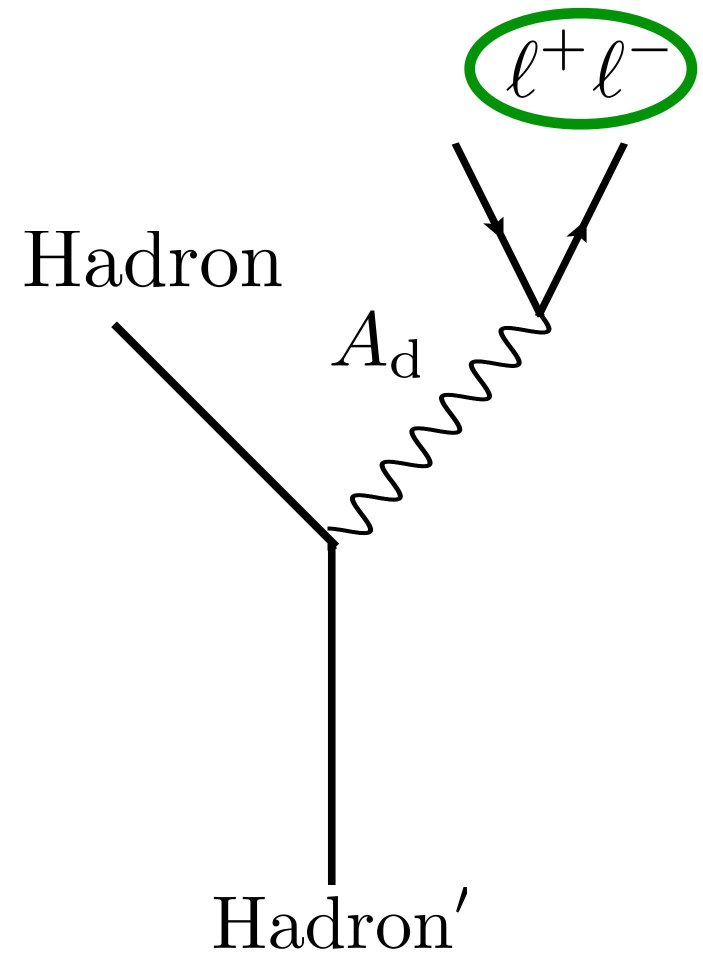
Two-Lepton Lepton Jets

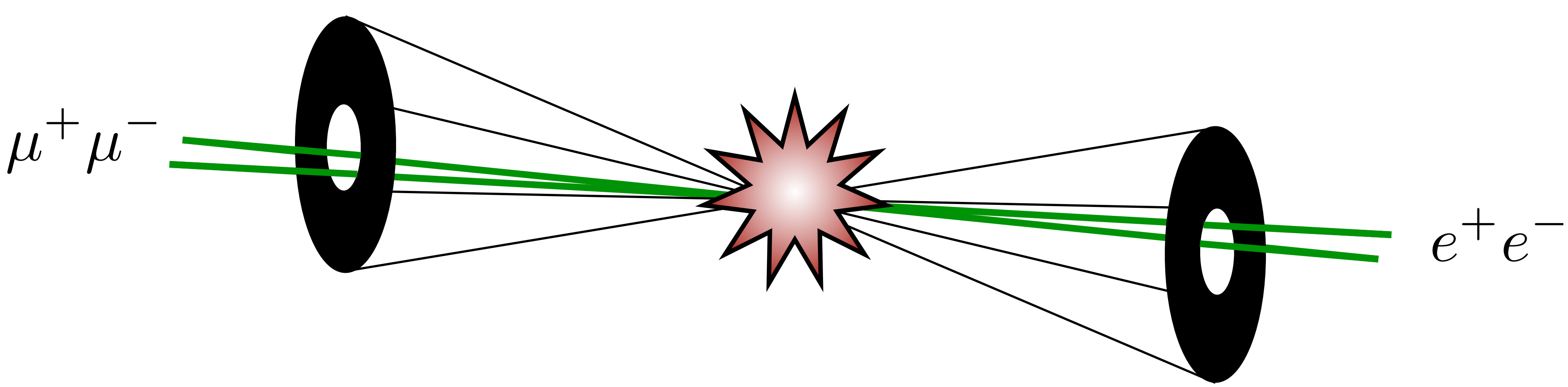
2 oppositely signed leptons in a small cone

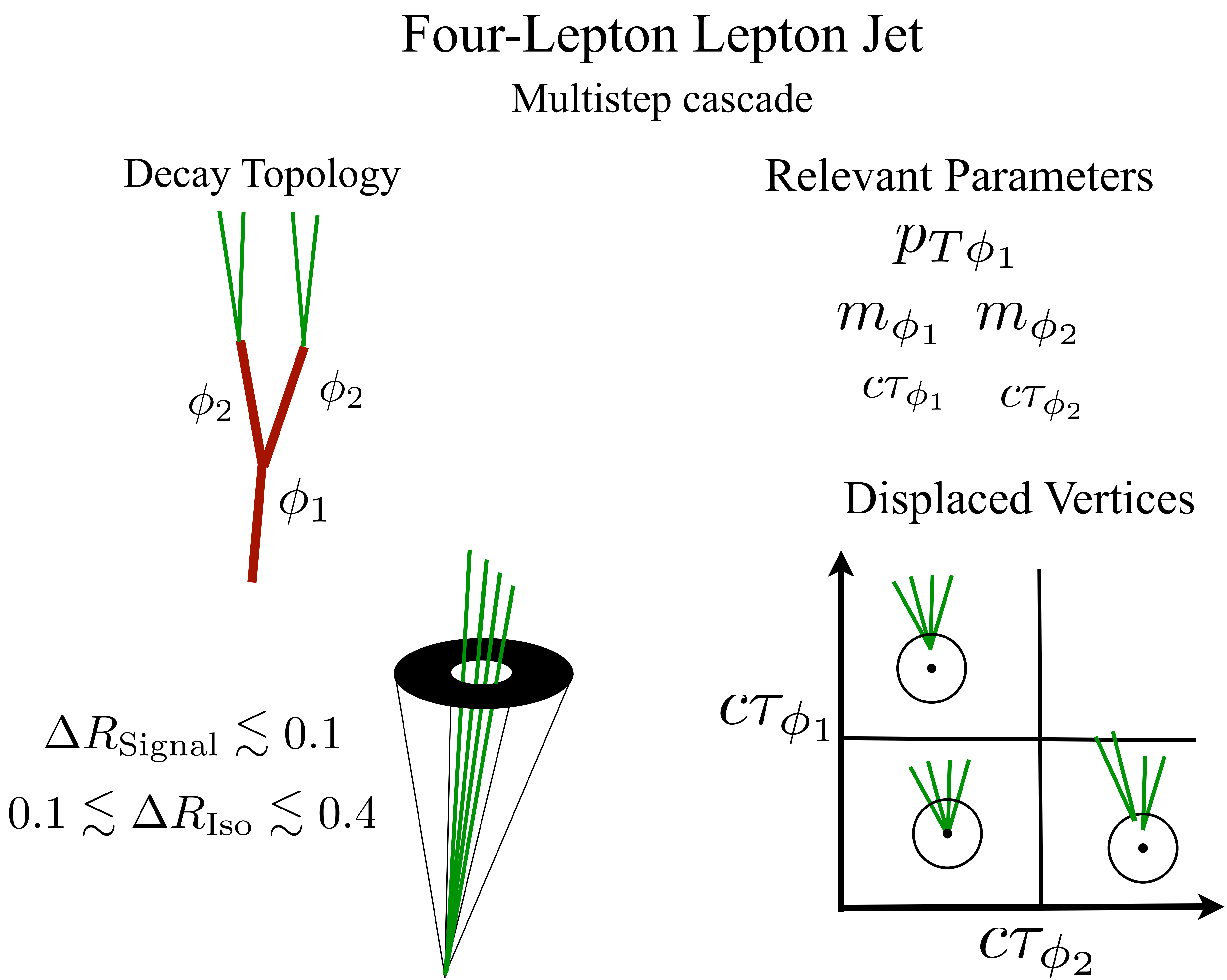
$$\Delta R_{\text{Signal}} \lesssim 0.1$$

$$0.1 \lesssim \Delta R_{\text{Iso}} \lesssim 0.4$$








Four-Lepton Lepton Jet
Multistep cascade
Decay Topology
ϕ_2
ϕ_2
ϕ_1
Relevant Parameters
$p_{T\phi_1}$
m_{ϕ_1} m_{ϕ_2}
$c\tau_{\phi_1}$ $c\tau_{\phi_2}$
Displaced Vertices
$\Delta R_{\mathrm{Signal}} \lesssim 0.1$
$0.1 \lesssim \Delta R_{\mathrm{Iso}} \lesssim 0.4$
$c\tau_{\phi_1}$
$c\tau_{\phi_2}$

Outlook

Non-Abelian Dark Sectors dynamics can explain anomalies

New collider signatures predicted

How to match signals on to theories?

Advances in theory are needed

Hadronization

Hadronic spectrum

Showering

Lots of work in progress...