New dark forces hidden in low-energy QCD

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References:
ST. PRD [arXiv:1404.4370]
Kaplinghat, ST, Yu. PRL [arXiv:1508.03339]

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Outline

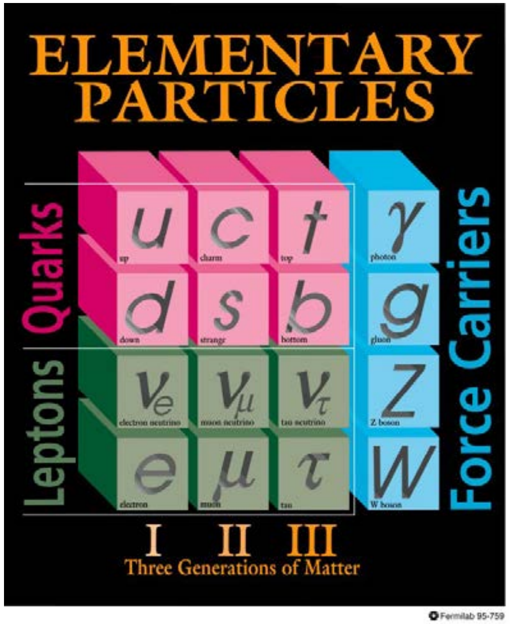
- Motivations from the dark sector
  - Astrophysical hints from small scale structure
  - Self-interacting dark matter

- Blind spot for new force searches:
  - Leptophobic gauge bosons

Searching for new forces

SM based on $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry.

Are there any additional gauge symmetries? Look for new gauge bosons.



Motivations:

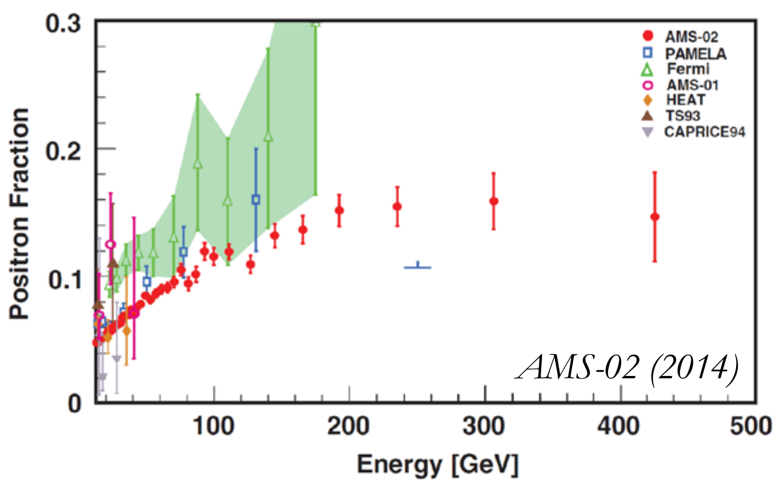
1. **Grand unified theories:** Generically have additional gauge bosons, but typically very heavy (10^{16} GeV).
2. **Dark matter:** Stability of dark matter related to new gauge symmetry?

   Can also give the right relic density.

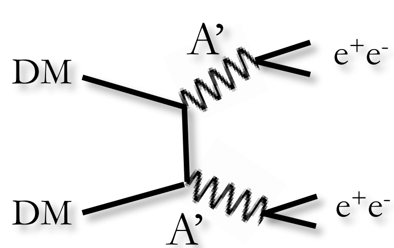
Motivations for new GeV-scale forces

Dark matter indirect detection anomalies
e.g. Pamela/AMS-02 positron excess

Pospelov & Ritz (2008); Arkani-Hamed et al (2008)

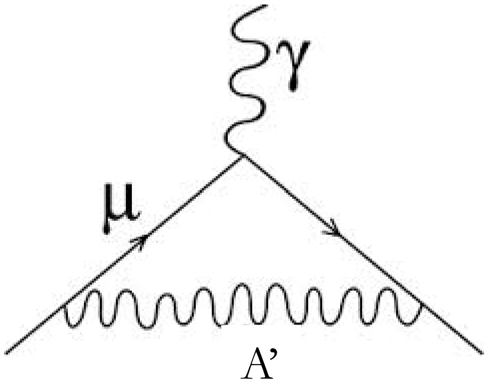


Dark matter annihilation



$(g\text{-}2)_\mu$ anomaly

Pospelov (2008)



Dark matter and structure of galaxies

Core/cusp problem: Galaxies and clusters are less dense than cold dark matter (WIMPs) predictions

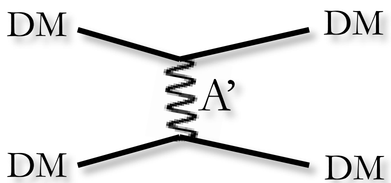
Moore (1994), Flores & Primack (1994)

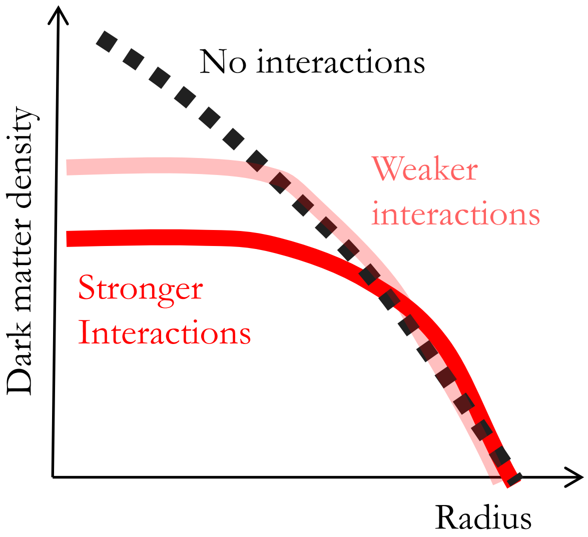
Self-interacting dark matter

Spergel & Steinhardt (2000)

MeV–GeV scale dark force

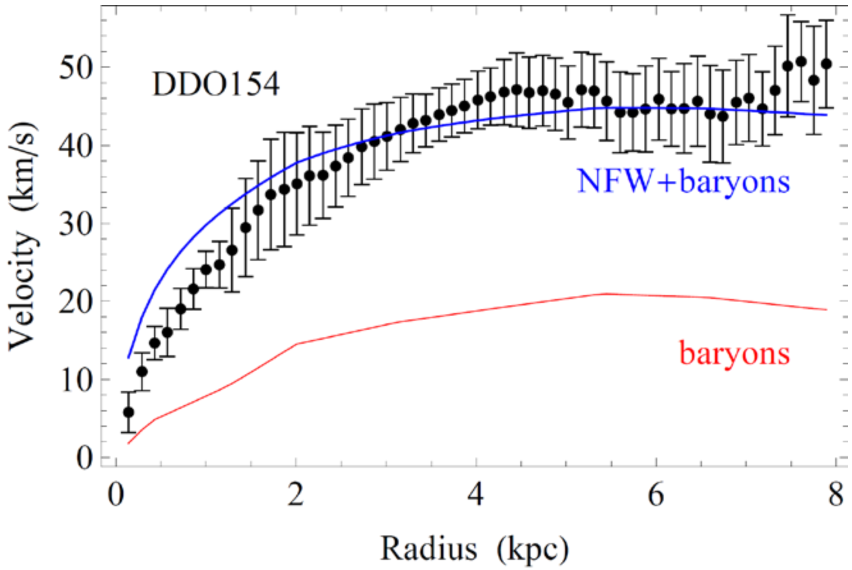
ST, Yu, Zurek (2013)

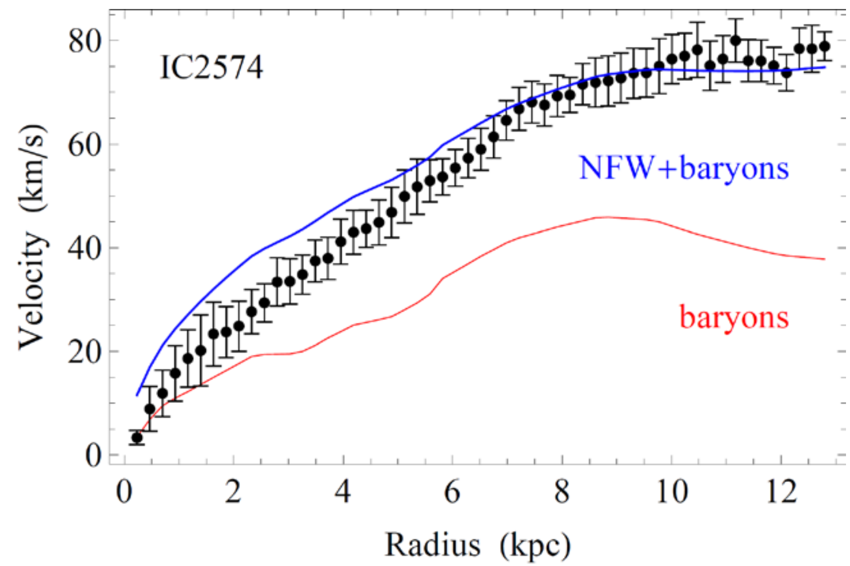




Cores in field galaxies

THINGS (dwarf galaxy survey) - Oh et al. (2011)



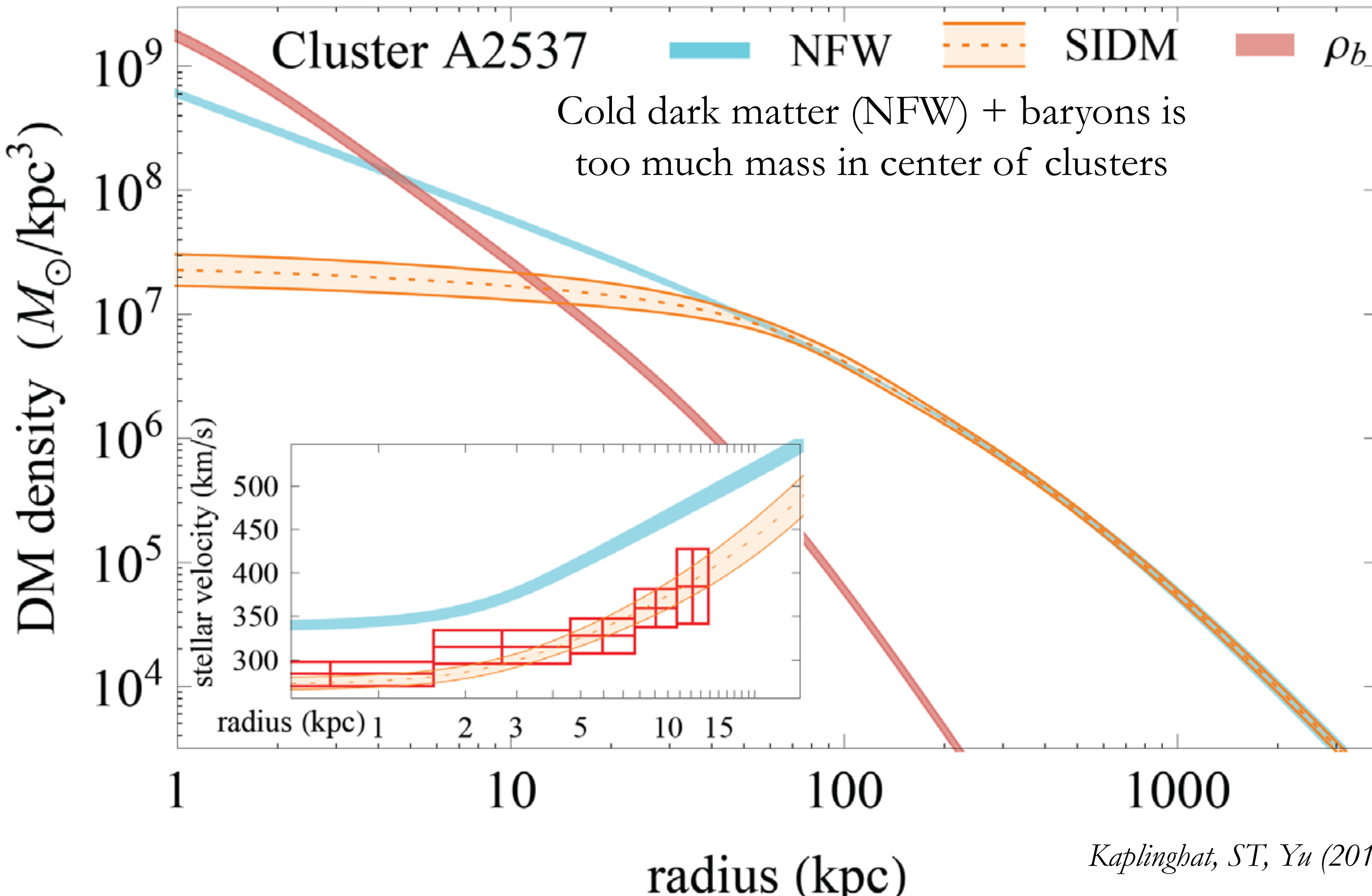


Core/cusp problem: Cold dark matter halo (NFW profile) + baryons predict too much mass in centers of galaxies

Cores in galaxy clusters

Stellar kinematics within brightest central elliptical galaxy

Strong and weak gravitational lensing



Kaplinghat, ST, Yu (2013)

Self-interacting Dark Matter

Unknown if core/cusp is solved by DM physics or baryonic astrophysics
If DM is responsible, what are the particle physics implications?

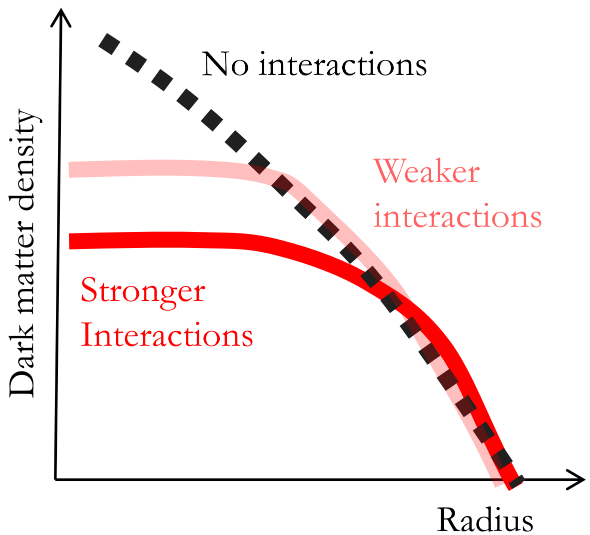


Figure of merit:
Velocity-weighted cross section per DM mass

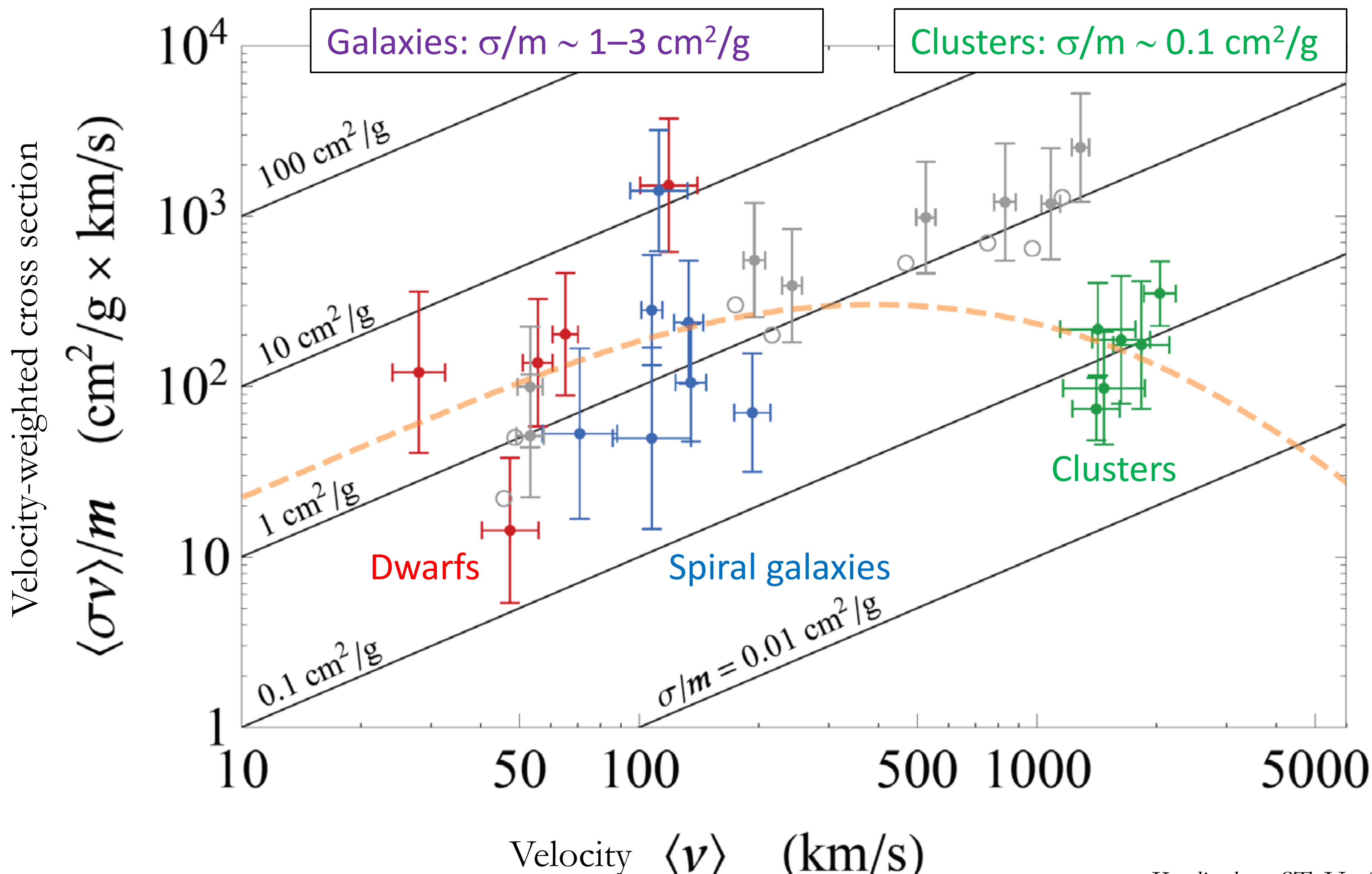
$$\text{rate} = \frac{\langle \sigma v \rangle}{m} \rho_{\text{dm}}$$

Dwarf and spiral galaxies:
velocity ~ 30-200 km/s

Clusters: velocity ~ 1500 km/s

Can all observations be fit by a simple particle physics model?

Fits to dwarfs, LSBs, and clusters



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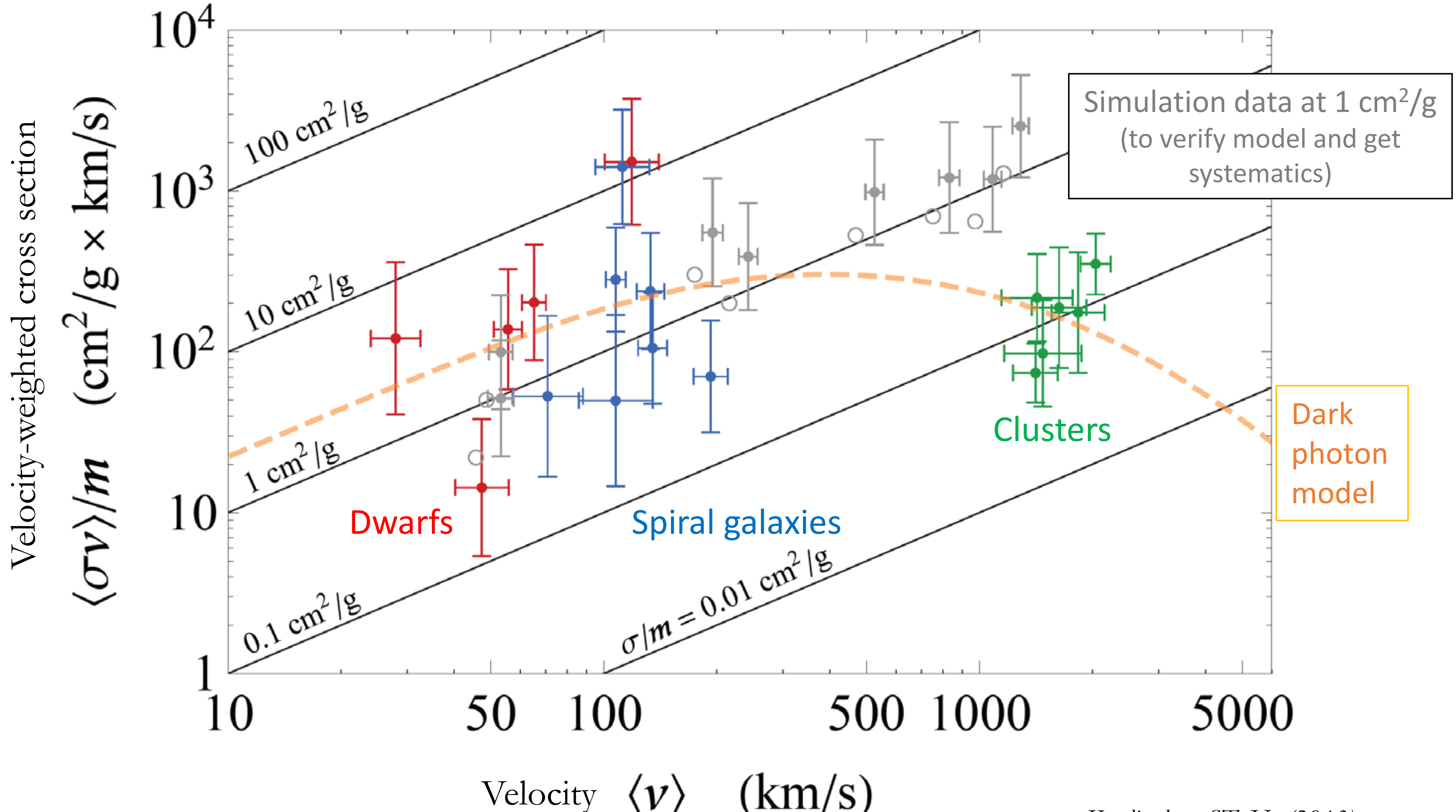
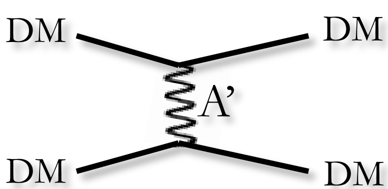
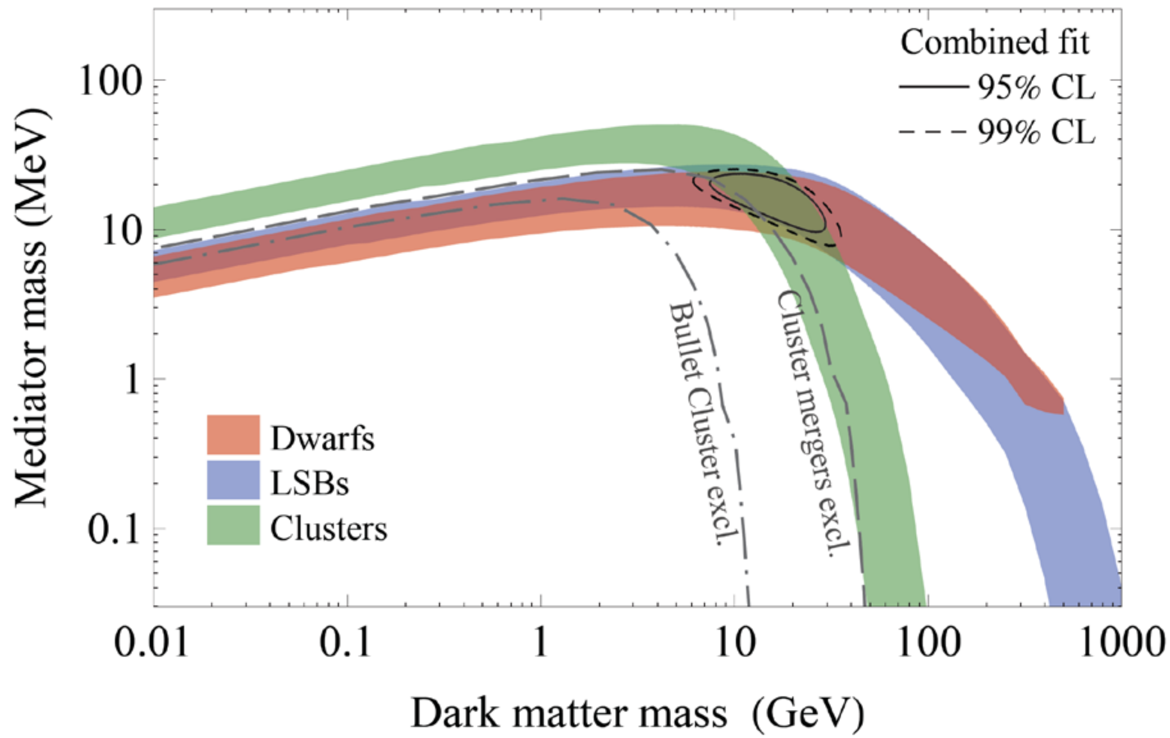


Kaplinghat, ST, Yu (2013)

Dark matter with dark photon

Self-interactions via gauge boson mediator



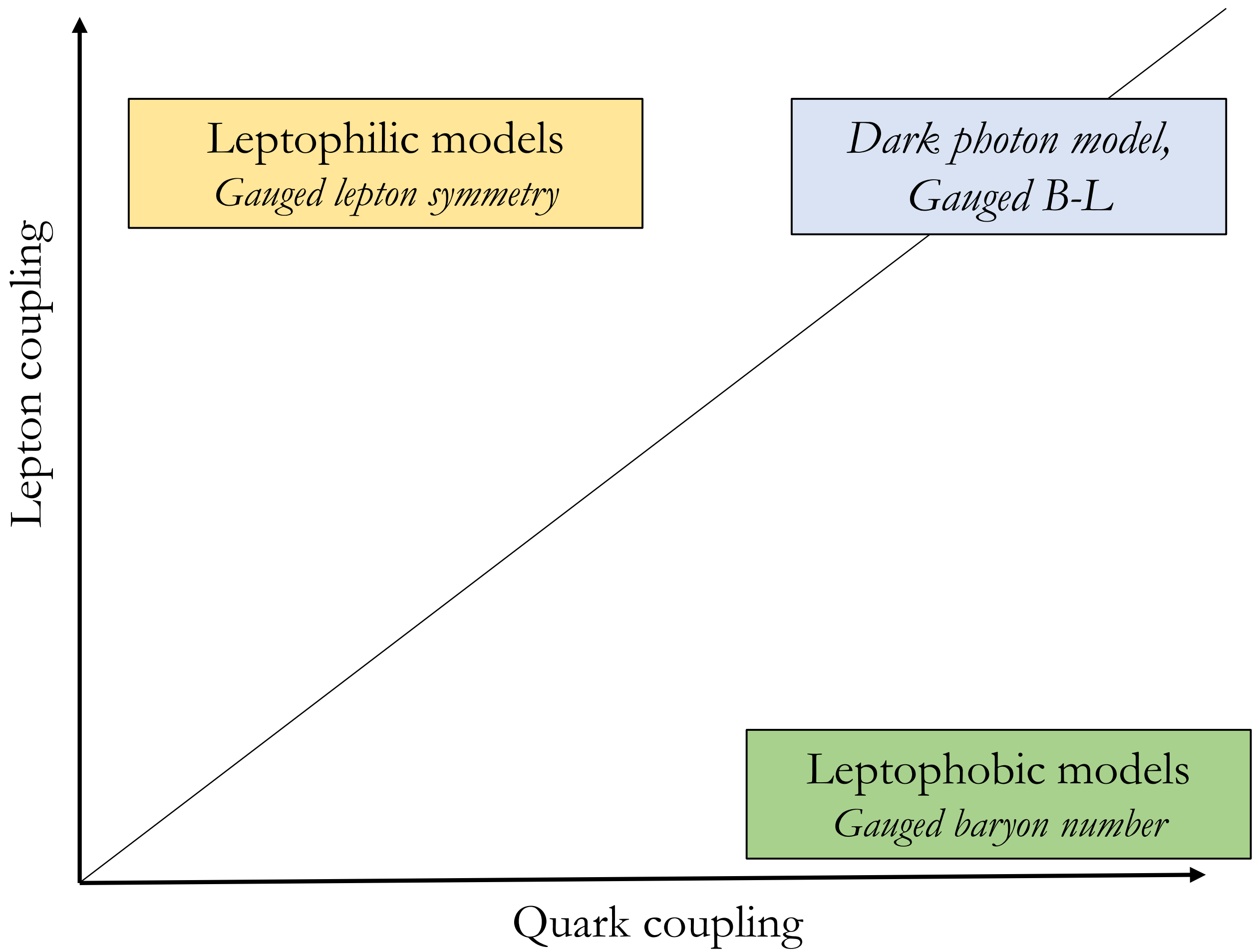


Kaplinghat, ST, Yu (2013)

Model-dependent: Dark sector parameters can be fit from astrophysical data.
Not fixed how dark photon couples to Standard Model (kinetic mixing unknown)

Model-independent: Dark sector particles below GeV scale to get large enough cross section

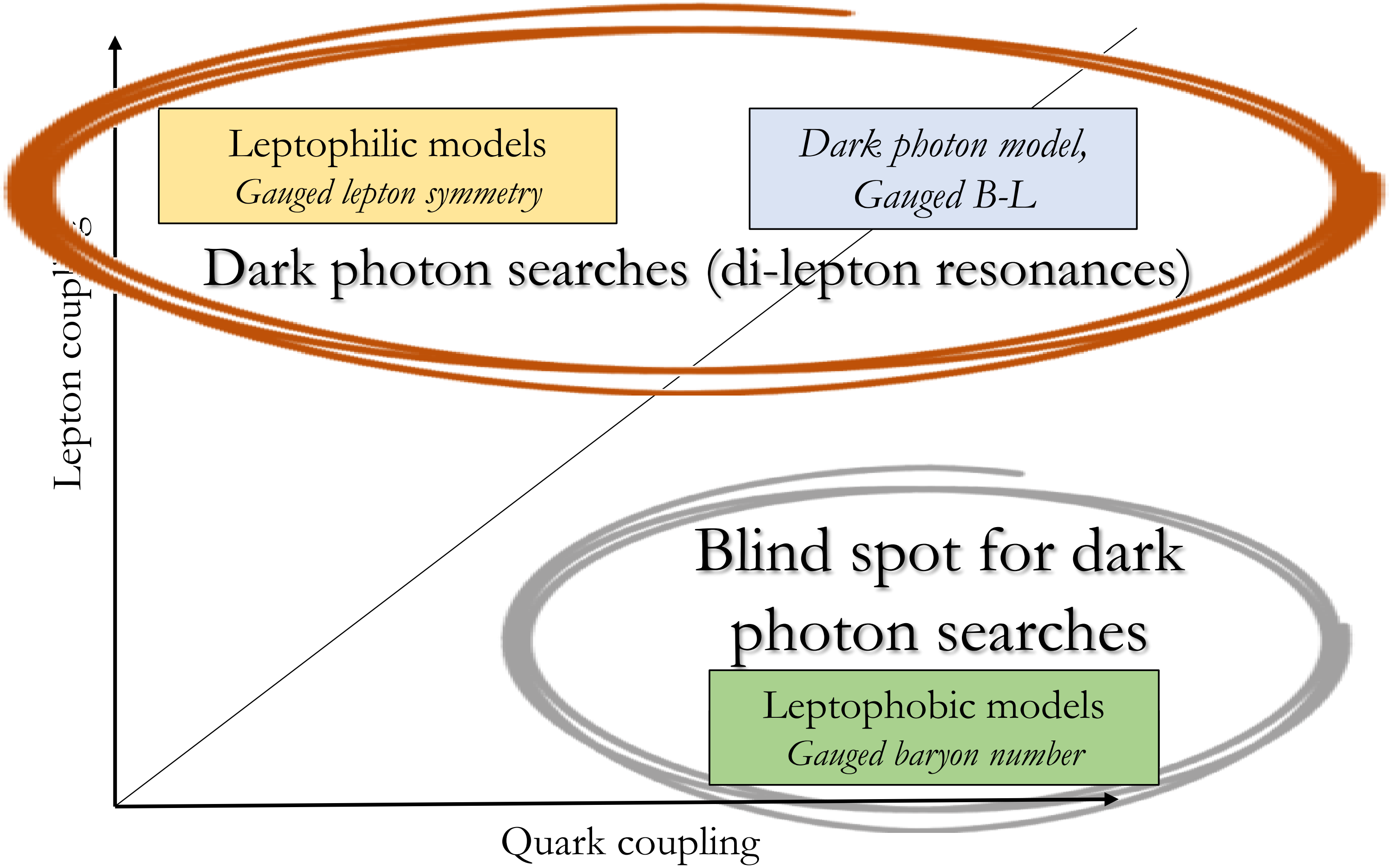
Beyond dark photons



Also a third axis: decays to invisible states (neutrinos, light dark matter)

Davoudiasl et al (2012), Batell et al (2009), deNiverville et al (2011,2012)

Beyond dark photons



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New force coupling to quarks

Most dark photon searches are for A' coupling to leptons (or invisible states)

What if a new force couples mainly to quarks?

Old idea: *Radjoot (1989), Foot et al (1989), Nelson & Tetradis (1989), He & Rajpoot (1990), Carone & Murayama (1995), Bailey & Davidson (1995), Aranda & Carone (1998), Fileviez Perez & Wise (2010), Graesser et al (2011), Dobrescu & Frugiule (2014), Batell et al (2014), …*

Simplest model: $U(1)_B$ gauge boson coupled to baryon number

$$\mathscr{L} = \frac{g_B}{3}\,\bar{q}\gamma^\mu q B_\mu$$

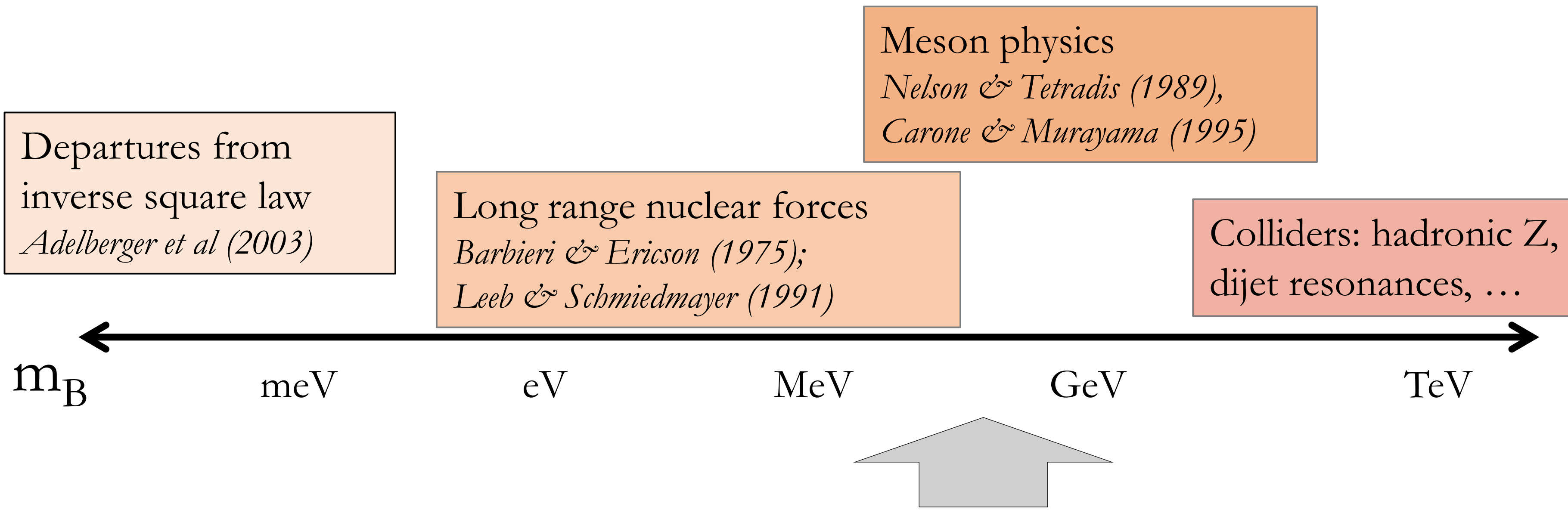
Flavor-universal charge g_B coupling to all quarks

Also known as: "leptophobic *Z'*" or " baryonic photon γ_B " or " Z'_B " or "*B* boson"

New force coupling to quarks

B boson = gauge boson coupled to baryon number

Discovery signals depend on the *B* mass



Is it possible to discover light weakly-coupled forces hiding in nonperturbative QCD regime?

Theoretical constraints from anomalies

- $U(1)_B$ gauge symmetry is anomalous. Requires new fermions with electroweak quantum numbers.

- Absence of new fermions at colliders (mass > 100 GeV) implies new baryonic force must have very small coupling

$$g_B \lesssim 10^{-2} \times (m_B/100 \text{ MeV})$$

$$\alpha_B = \frac{g_B^2}{4\pi} \lesssim 10^{-5} \times (m_B/100\,\text{MeV})^2$$

Detecting the *B* boson

- Can a weakly-coupling force ($g_B << 1$) be detected in the nonperturbative regime of QCD?

- B boson preserves the symmetries of QCD
  - Charge conjugation, parity, and isospin or $SU(3)_{flavor}$

- Previous lore: *Nelson & Tetradis (1989)*
  - Above $2m_\pi$, decay dominated by $B \rightarrow \pi\pi$
  - B boson buried under huge $\rho \rightarrow \pi\pi$ background

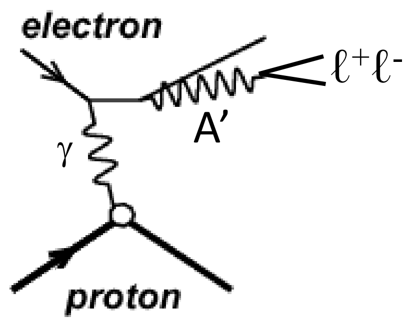
Baryonic force at the QCD scale

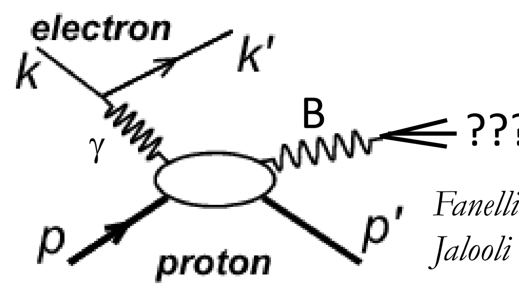
- How are the gauge bosons produced?
- What are the experimental signatures?

Dark photon

B boson

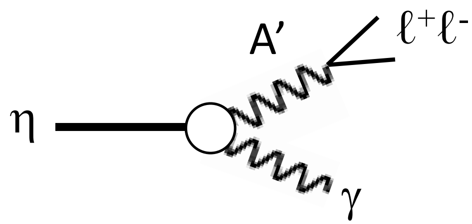
Direct production:

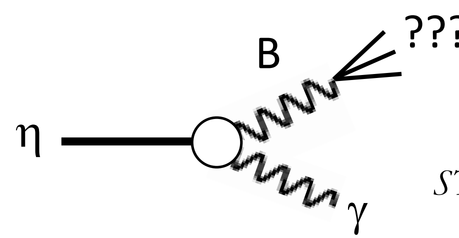




Fanelli & Williams (2016); Jalooli & ST (in prep)

Meson decays:





ST (2014)

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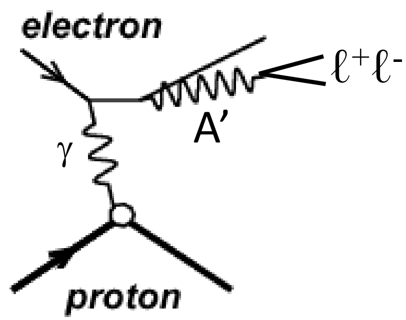

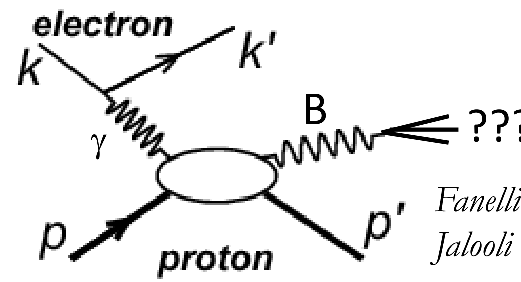

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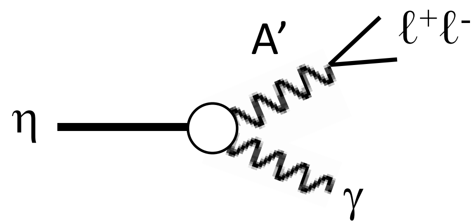
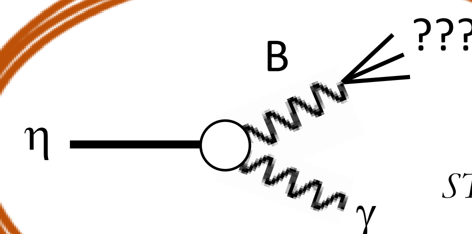


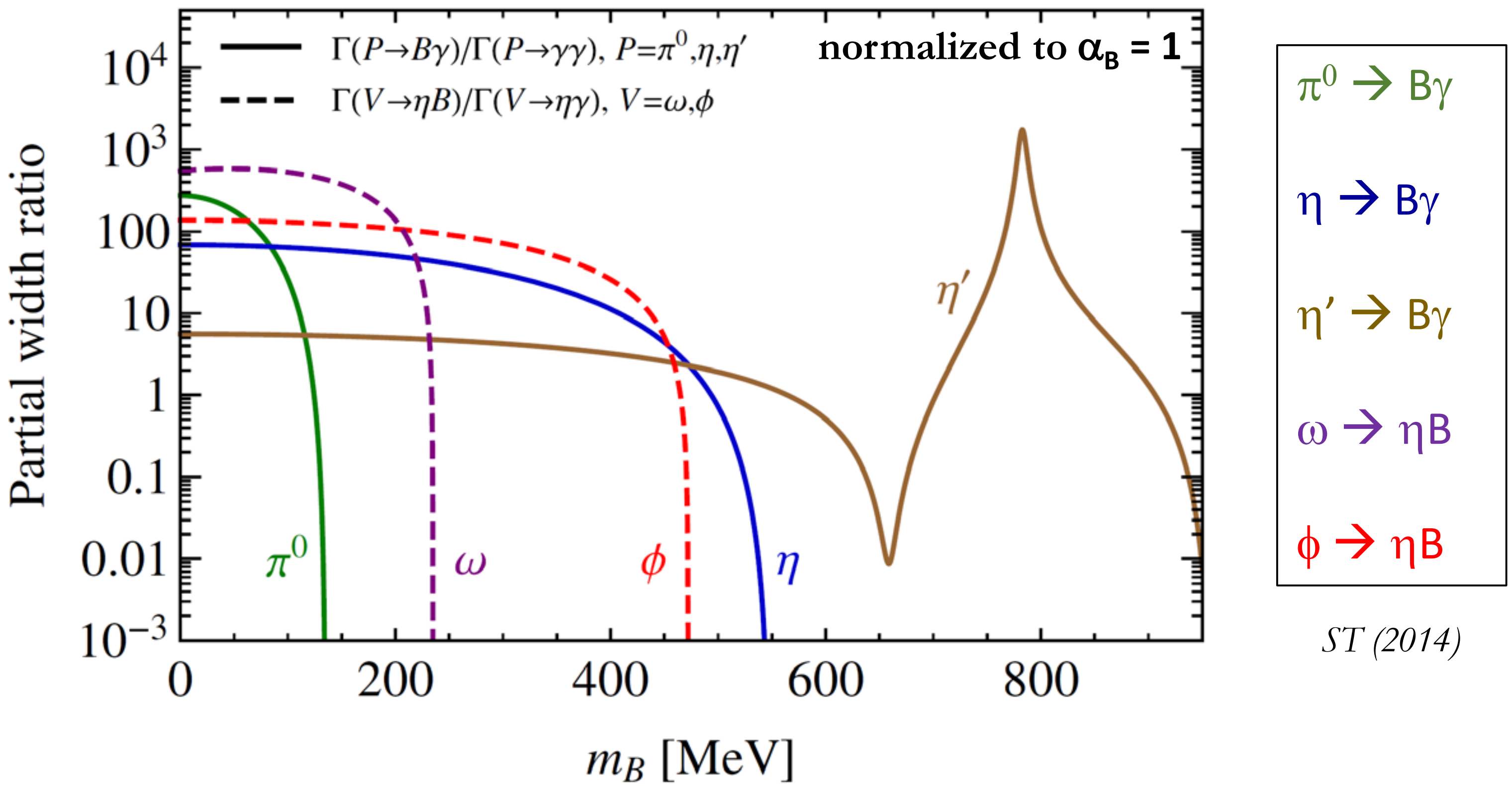


ST (2014)

B bosons production

Meson decays: $\pi^0 \to B\gamma, \quad \eta \to B\gamma, \quad \eta' \to B\gamma, \quad \omega \to \eta B, \quad \phi \to \eta B$

Like SM decays: $\pi^0 \to \gamma\gamma, \quad \eta \to \gamma\gamma, \quad \eta' \to \gamma\gamma, \quad \omega \to \eta\gamma, \quad \phi \to \eta\gamma$



ST (2014)

B boson decay

How does B decay? Worry: B → ππ is hopeless.

Recall the original Lagrangian: $\mathscr{L} = \frac{g_B}{3}\,\bar{q}\gamma^\mu q B_\mu$

The quantum numbers for B:

- $J = 1$
- $P = C = -$
- $I = 0$
- G = –

B boson decay

B has same quantum numbers as the **ω** meson

Particle Data Book

$\omega(782)$

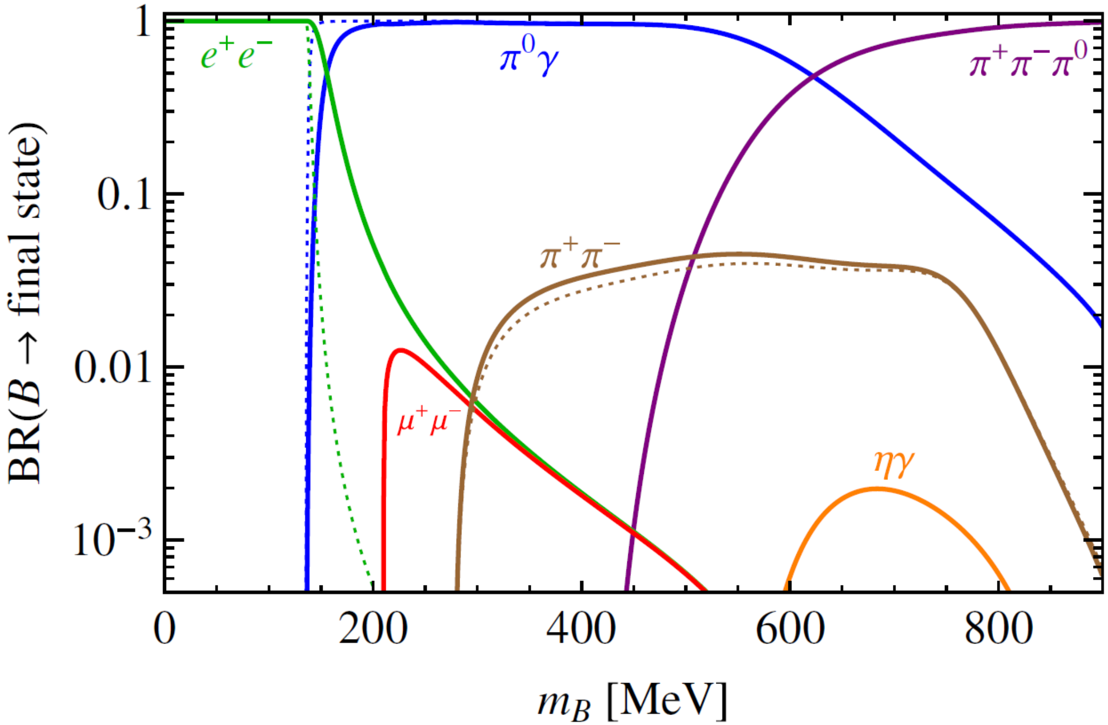
$I^G(J^{PC}) = 0^-(1^{--})$

$\omega(782)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi^+\pi^-\pi^0$	(89.2 ± 0.7) %	
Γ_2	$\pi^0\gamma$	(8.28 ± 0.28) %	S=2.1
Γ_3	$\pi^+\pi^-$	$(1.53^{+0.11}_{-0.13})$ %	S=1.2
Γ_9	e^+e^-	$(7.28 \pm 0.14) \times 10^{-5}$	S=1.3
Γ_{15}	$\mu^+\mu^-$	$(9.0 \pm 3.1) \times 10^{-5}$	
Γ_{16}	3γ	$< 1.9 \times 10^{-4}$	CL=95%

ω → ππ forbidden by G-parity
(Isospin-violating ρ–ω mixing)

B boson decay branching ratios



Computed using vector meson dominance

Subleading lepton couplings arise by B-γ mixing

Solid: $\varepsilon = e g_B/16\pi^2$
Dotted: $\varepsilon = 0.1\, e g_B/16\pi^2$

New signatures not covered in dark photon searches: $B \to \pi^0\gamma,\ \pi^+\pi^-\pi^0$

B boson signal channels

Decay $\rightarrow$ Production $\downarrow$	$B \rightarrow e^+e^-$ $m_B \sim 1-140$ MeV	$B \rightarrow \pi^0\gamma$ 140–620 MeV	$B \rightarrow \pi^+\pi^-\pi^0$ 620–1000 MeV	$B \rightarrow \eta\gamma$
$\pi^0 \rightarrow B\gamma$	$\pi^0 \rightarrow e^+e^-\gamma$	$\cdots$	$\cdots$	$\cdots$
$\eta \rightarrow B\gamma$	$\eta \rightarrow e^+e^-\gamma$	$\eta \rightarrow \pi^0\gamma\gamma$	$\cdots$	$\cdots$
$\eta' \rightarrow B\gamma$	$\eta' \rightarrow e^+e^-\gamma$	$\eta' \rightarrow \pi^0\gamma\gamma$	$\eta' \rightarrow \pi^+\pi^-\pi^0\gamma$	$\eta' \rightarrow \eta\gamma\gamma$
$\omega \rightarrow \eta B$	$\omega \rightarrow \eta e^+e^-$	$\omega \rightarrow \eta\pi^0\gamma$	$\cdots$	$\cdots$
$\phi \rightarrow \eta B$	$\phi \rightarrow \eta e^+e^-$	$\phi \rightarrow \eta\pi^0\gamma$	$\cdots$	

Covered by dark photon searches
Limits are more model dependent

New signals not being covered in dark photon searches

A new type of signature for meson factories:

$\pi^0\gamma$ resonances in rare decays

B boson signal channels

Decay $\rightarrow$ Production $\downarrow$	$B \rightarrow e^+e^-$ $m_B \sim 1 - 140$ MeV	$B \rightarrow \pi^0\gamma$ 140–620 MeV	$B \rightarrow \pi^+\pi^-\pi^0$ 620–1000 MeV	$B \rightarrow \eta\gamma$
$\pi^0 \rightarrow B\gamma$	$\pi^0 \rightarrow e^+e^-\gamma$	$\cdots$	$\cdots$	$\cdots$
$\eta \rightarrow B\gamma$	$\eta \rightarrow e^+e^-\gamma$	$\eta \rightarrow \pi^0\gamma\gamma$	$\cdots$	$\cdots$
$\eta' \rightarrow B\gamma$	$\eta' \rightarrow e^+e^-\gamma$	$\eta' \rightarrow \pi^0\gamma\gamma$	$\eta' \rightarrow \pi^+\pi^-\pi^0\gamma$	$\eta' \rightarrow \eta\gamma\gamma$
$\omega \rightarrow \eta B$	$\omega \rightarrow \eta e^+e^-$	$\omega \rightarrow \eta\pi^0\gamma$	$\cdots$	$\cdots$
$\phi \rightarrow \eta B$	$\phi \rightarrow \eta e^+e^-$	$\phi \rightarrow \eta\pi^0\gamma$	$\cdots$	

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A new type of signature for meson factories:

$\pi^0\gamma$ resonances in rare decays

$\eta \to \pi^0\gamma\gamma$

Particle Data Book

η $\quad I^G(J^{PC}) = 0^+(0^{-+})$

η DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Neutral modes		
Γ_1	neutral modes	(72.12 ± 0.34) %	S=1.2
Γ_2	2γ	(39.41 ± 0.20) %	S=1.1
Γ_3	$3\pi^0$	(32.68 ± 0.23) %	S=1.1
Γ_4	$\pi^0 2\gamma$	$(2.7\pm0.5)\times10^{-4}$	S=1.1

B boson signature:
$\eta \to B\gamma \to \pi^0\gamma\gamma$

Mimics the rare SM decay $\eta \to \pi^0\gamma\gamma$

Nelson & Tetradis (1989)

Total rate constraint:

$$\frac{\Gamma(\eta\to B\gamma)}{\Gamma(\eta\to\gamma\gamma)} = 2\frac{\alpha_B}{\alpha_{em}}\left(1-\frac{m_B^2}{m_\eta^2}\right)^3 \times O(1) < \frac{\Gamma(\eta\to\pi^0\gamma\gamma)}{\Gamma(\eta\to\gamma\gamma)} \sim 10^{-3}$$

Requires $\alpha_B < 10^{-5} << \alpha_{em}$

Boost sensitivity by searching for $\pi^0\gamma$ resonance in $\eta \to \pi^0\gamma\gamma$

Proposal by Jefferson Eta Factory (JLab)

$\phi \rightarrow \eta\pi^0\gamma$

$\phi(1020)$	$I^G(J^{PC}) = 0^-(1^{--})$
Mode	**Fraction (Γ_i/Γ)**
Γ_6 $\eta\gamma$	(1.309 ± 0.024) %
Γ_{22} $\pi^0\eta\gamma$	$(7.27 \pm 0.30) \times 10^{-5}$

B boson signature:
$\phi \rightarrow \eta B \rightarrow \eta\pi^0\gamma$

Mimics the rare SM decay $\phi \rightarrow \eta\pi^0\gamma$

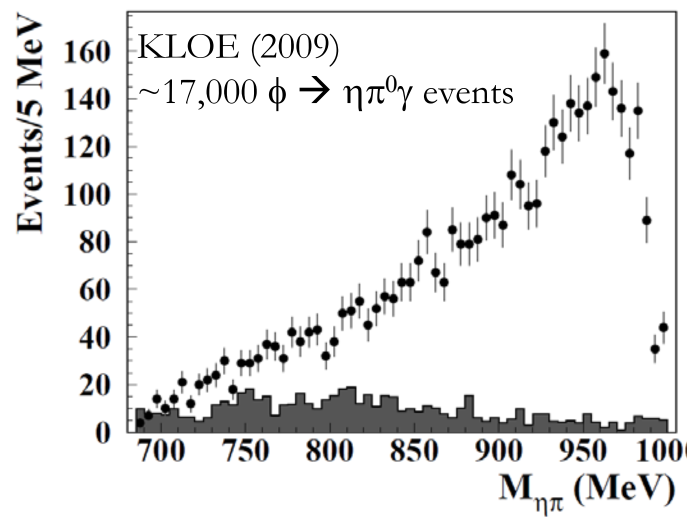
SM decay target for understanding scalar resonance in QCD

$\phi \rightarrow a_0(980)^*\gamma \rightarrow \eta\pi^0\gamma$

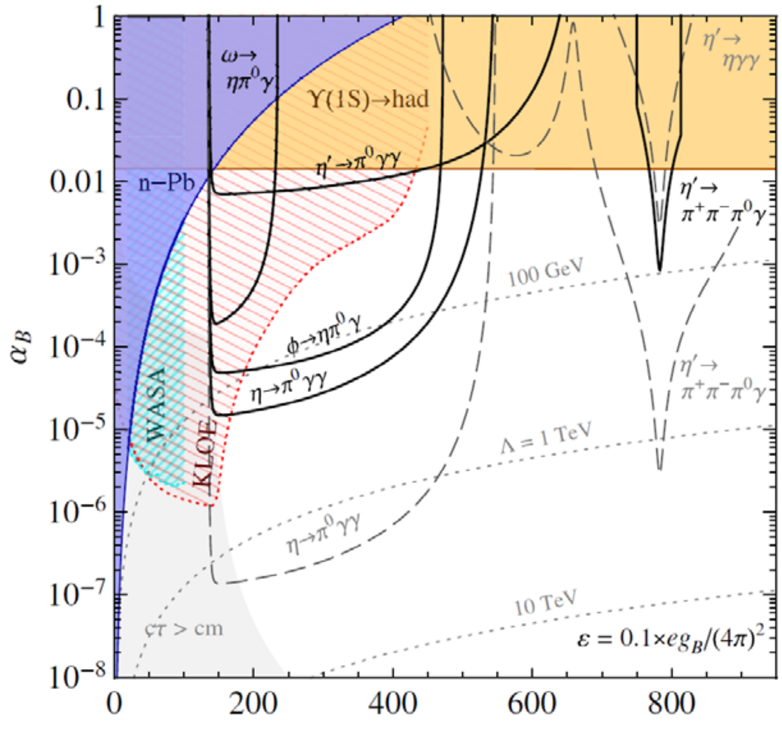
Achasov & Ivanchenko (1989)

B boson signature: $\pi^0\gamma$ invariant mass peak

Total rate constraint: $\alpha_B < 5\text{x}10^{-5} << \alpha_{em}$



Constraints on *B* boson



ST (2014)

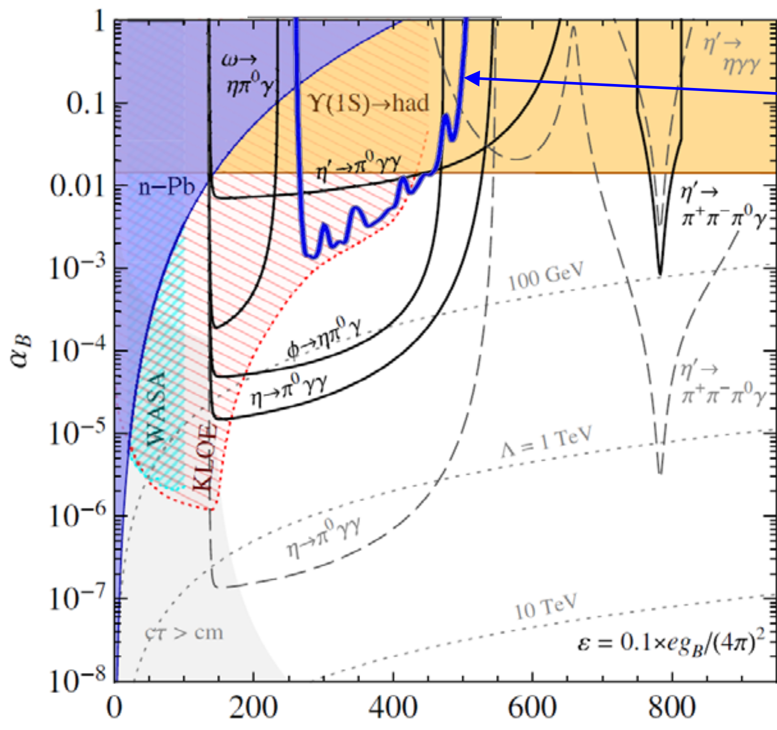
Black lines = rare meson decays (based on total rate)

Blue = low-energy neutron scattering

Orange = U→hadrons

Red/**Blue** hatched = Dark photon searches (model-dependent)

Constraints on B boson



ST (2014)

First official B boson search
Won et al [Belle] (2016)

Search for $\pi^+\pi^-$ resonance in
$\eta \rightarrow B\gamma \rightarrow \pi^+\pi^-\gamma$

Conclusions

- New forces beyond the Standard Model:
  - Motivated by dark matter
  - Would be a game-changing particle physics discovery

- GeV-scale leptophobic forces
  - Blind spot to dark photon searches
  - Even very small couplings can be discovered (10^5x smaller than EM)
  - Smoking gun signature: a $\pi^0\gamma$ resonance in rare meson decays.
  - No bump hunt done (with potential for discovery)