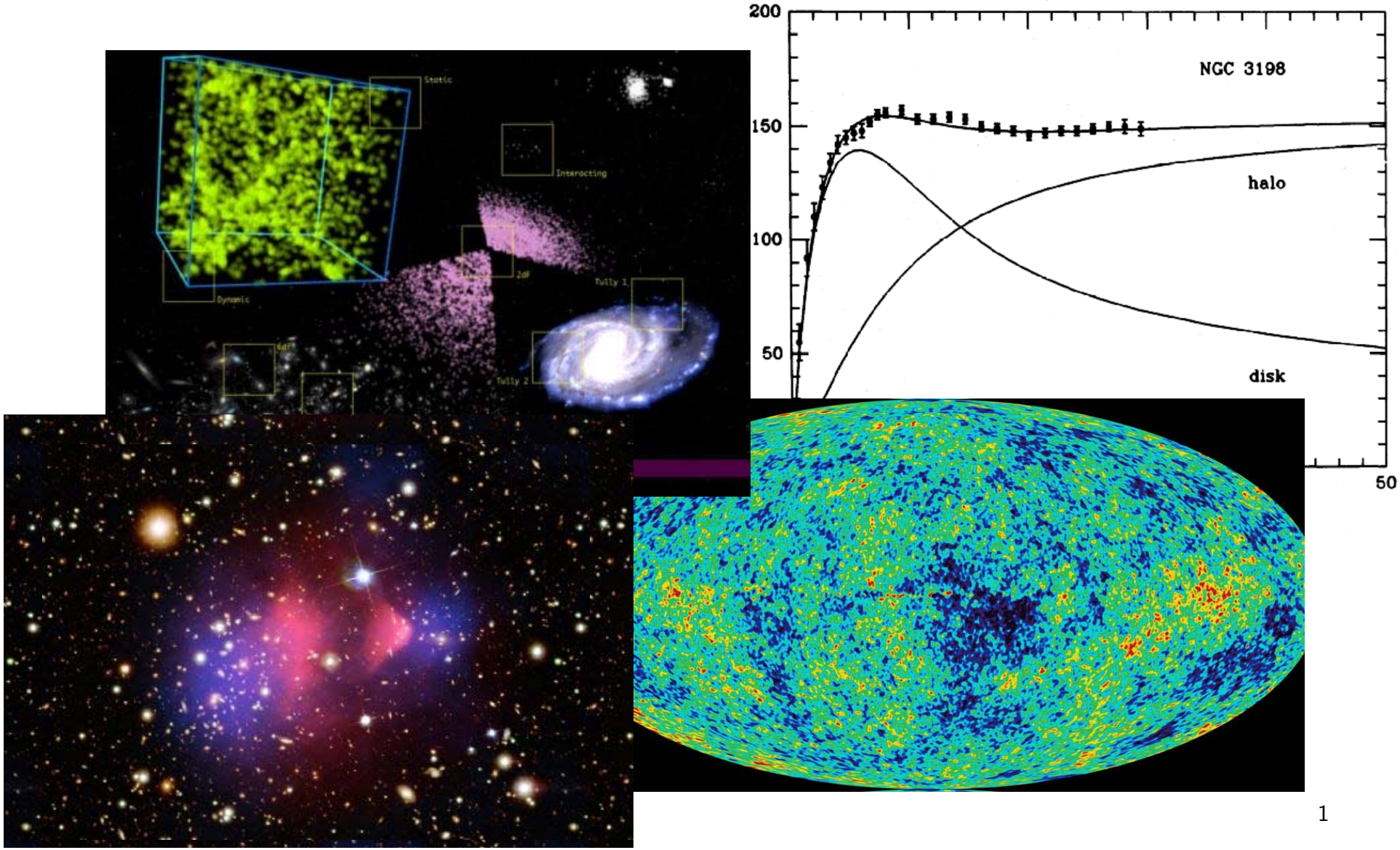
Dark Discrete Gauge Symmetries

Brian Batell

Perimeter Institute

Data inconsistent with the SM + GR



Canonical Dark Matter (WIMP) assumptions:

- Single new elementary particle
- Mass $\sim$ weak scale
- Weakly interacting
- Thermal Relic
- Neutral under color, electromagnetism $\Longrightarrow$ either:
  - DM in $SU(2)_L \times U(1)_Y$ multiplet (such that $Q_{EM} = 0$)
  - DM in the hidden sector $\Longrightarrow$ I will focus on this possibility
- Stable $\Longrightarrow$ Dark symmetry
  - What is the symmetry?

Discrete Z_2 symmetry

- Most common example in literature.
  - R-parity, KK-parity, T-parity, ...

But...

- Ad-hoc
- What is the origin of Z_2 ?
- Why not other symmetries, e.g. Z_N?

Bigger question:

What is the organizing principle for the dark sector?

Gauge Symmetry!

Discrete gauge symmetries

Krauss, Wilczek '90

Prototype model:

- $U(1)_D$ gauge symmetry
- Matter fields χ, with $U(1)_D$ charge $Q_\chi = -1$
- Higgs field ϕ, with charge $Q_\phi = N$
- $U(1)_D$ symmetry breaking: $\langle\phi\rangle = v'/2$

$$\mathcal{L} \supset \phi\chi^N + \text{h.c.} \to v'\chi^N + \text{h.c.}$$

- Remnant Z_N symmetry:

$$\chi \to e^{2\pi i/N}\chi$$

How to talk to the dark sector:

- "Connector" particle - charged under both sectors
- Higher dimensional operators
- Portals

$$B_{\mu\nu}V^{\mu\nu} \qquad \text{U(1) portal} \quad \text{Holdom '86 ,}$$

$$H^\dagger H(AS + BS^2) \qquad \text{Higgs portal ,}$$

$$LHN \qquad \text{Neutrino portal ,}$$

- Focus on $U(1)_D$ symmetry for this talk
  $\Longrightarrow$ vector and Higgs portals available
- Nonabelian DGS DM model + collider

Walker '09; Agashe, Kim, Toharia, Walker '10

Single field models

- Only 3 possibilities at the renormalizable level
  - Scalar

$$Z_2: \quad \Delta\mathcal{L} = \lambda\phi_{(2)}\chi_{(-1)}\chi_{(-1)} + \text{h.c.}$$

$$Z_3: \quad \Delta\mathcal{L} = \lambda\phi_{(3)}\chi_{(-1)}\chi_{(-1)}\chi_{(-1)} + \text{h.c.}$$

  - Fermion

$$Z_2: \quad \Delta\mathcal{L} = \quad -m_D\psi_{(1)}\xi_{(-1)}$$

$$-\lambda_L\phi^\dagger_{(2)}\psi_{(1)}\psi_{(1)} - \lambda_R\phi_{(2)}\xi_{(-1)}\xi_{(-1)} + \text{h.c.}$$

Multi-field models

- Renormalizable Z_N models possible
- Multiple discrete symmetries $\Longrightarrow$ Multi-component DM
  - Example: Z_4 - Higgs $\phi_{(4)}$; Dark matter $\chi_{(-1)}, \chi_{(-2)}$

$$\Delta\mathcal{L} \sim \phi_{(4)}\chi_{(-2)}\chi_{(-2)} + \phi_{(4)}\chi_{(-2)}\chi_{(-1)}\chi_{(-1)}$$

$$+\chi^{\dagger}_{(2)}\chi_{(-1)}\chi_{(-1)} + \text{h.c.}$$

  - Both Z_4 and Z_2 symmetry $(\chi_{(-1)} \to -\chi_{(-1)})$
  - Lightest Z_4 and Z_2 particles stable and DM candidates

Chiral models

- Chiral set: Fermion content chosen so that anomalies cancel and vectorlike mass terms forbidden Batra, Dobrescu, Spivak '05
- One or more Higgsses break $\mathrm{U}(1)_D$ and generate masses
- Example: $\phi_{(5)}, \phi_{(-20)}, \chi_{(2)}, \chi_{(4)}, \chi_{(-7)}, \chi_{(-9)}, \chi_{(10)}, \xi_{(0)}$.

$$\begin{aligned}\Delta\mathcal{L} \;=\; & -\lambda_a \phi_{(5)}\chi_{(2)}\chi_{(-7)} - \lambda_b \phi_{(5)}\chi_{(4)}\chi_{(-9)} \\ & -\lambda_c \phi_{(-20)}\chi_{(10)}\chi_{(10)} - \tfrac{\lambda_d}{\Lambda}\phi^\dagger_{(5)}\phi^\dagger_{(5)}\chi_{(10)}\xi_{(0)} \\ & -\tfrac{1}{2}M\xi_{(0)}\xi_{(0)} + \mathrm{h.c.}\end{aligned}$$

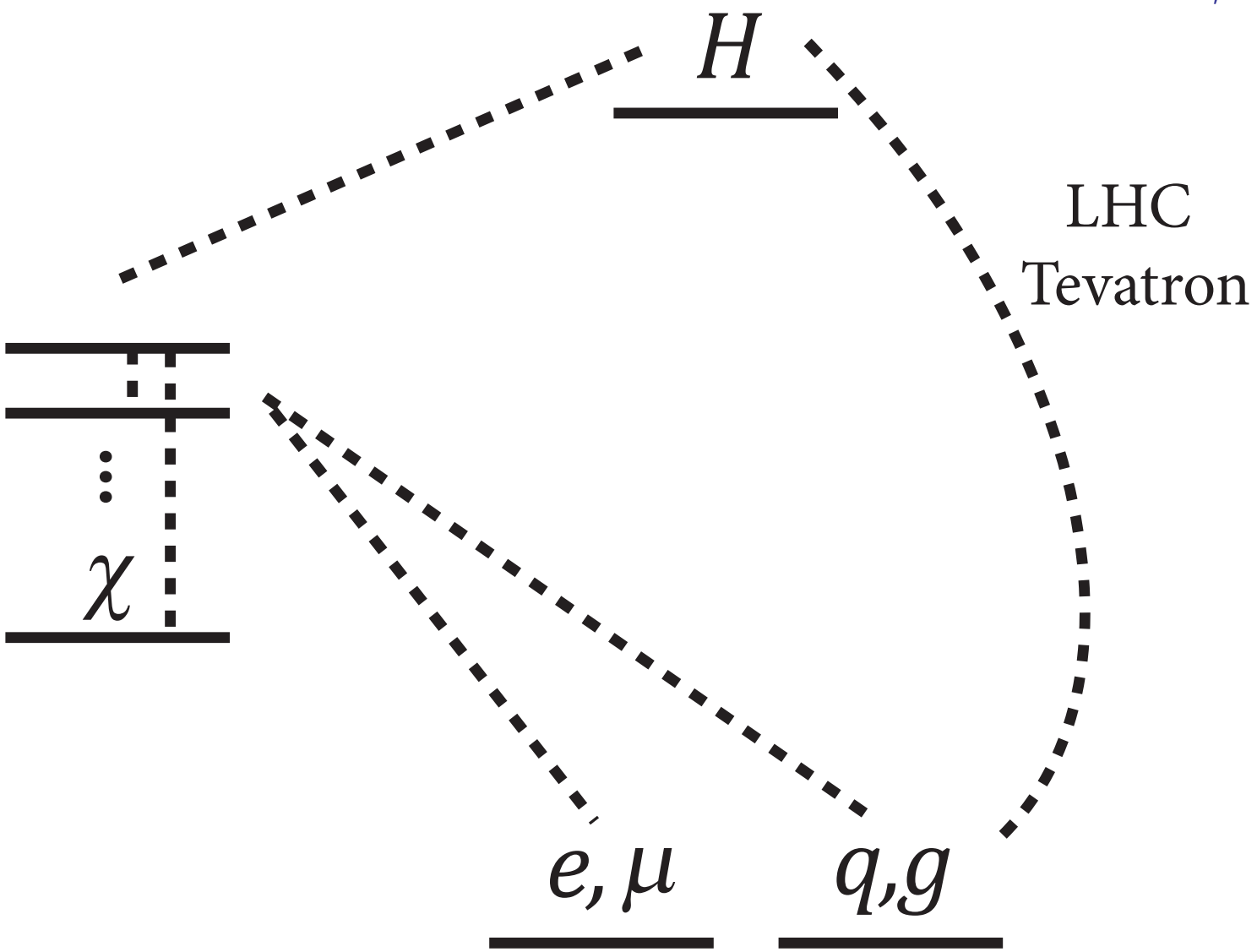
- Both Z_5 and accidental global 'flavor' symmetries stabilize DM (multi-component)

Dark Matter phenomenology

- Relic Abundance:
  - 1) Annihilation into hidden sector: $\chi_j \chi_j \to VV, Vh', hh, \ldots$
  - 2) Annihilation into SM via portals: $\chi\chi \to V^*, h^* \to \overline{\psi}_{SM}\psi_{SM}$
- Direct Detection via portals:
  - Nuclear scattering mediated via kinetic mixing, Higgs portal
  - 'Vanilla' Elastic, Inelastic, Form-factor, Momentum Dependent, light GeV DM, ...
- Indirect detection:
  - Dark Forces, Solar electronic signatures

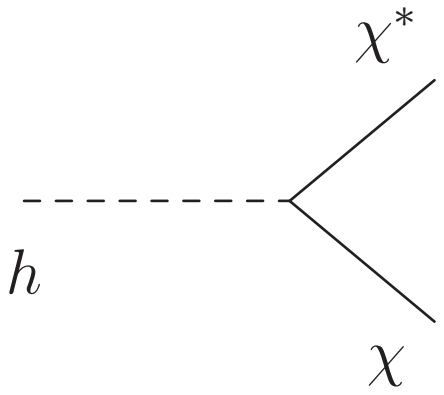
Hidden valley via Higgs

Strassler, Zurek '06



Decays to DM and Z_N partners

$$\Delta\mathcal{L} \supset \lambda_2 (H^\dagger H)(\chi^\dagger \chi)$$

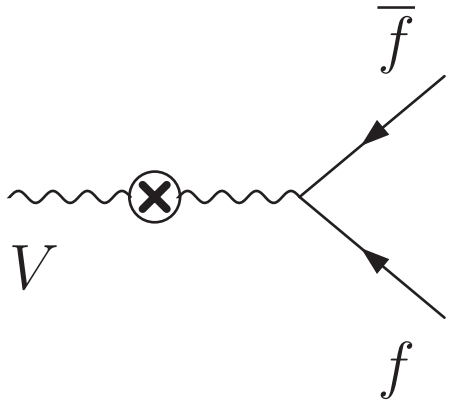


- Compare with $h \to b\bar{b}$:

$$\frac{\Gamma_{\chi^*\chi}}{\Gamma_{b\bar{b}}} \sim \frac{v^2}{m_h^2}\left(\frac{\lambda_2^2}{y_b^2}\right)$$

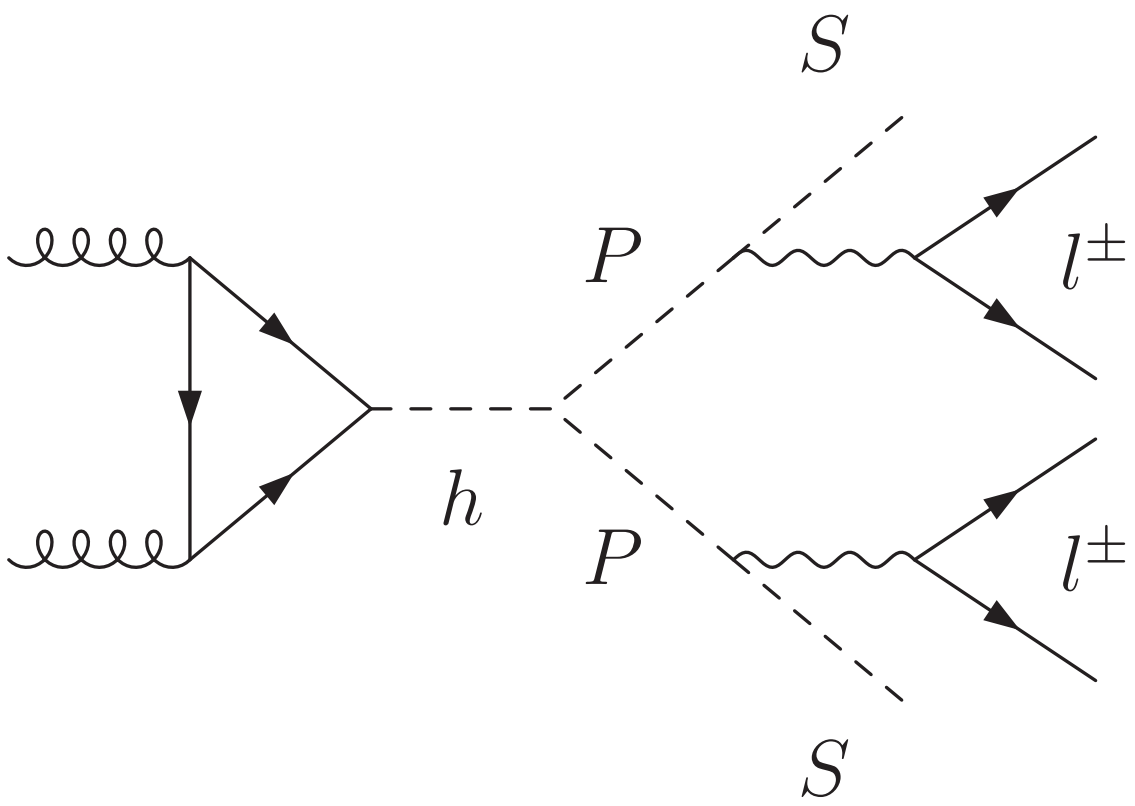
Cascades

$$\mathcal{L} \supset -\frac{\kappa}{2} B_{\mu\nu} V^{\mu\nu}$$



- V can decay to leptons with $O(1)$ branching if $m_V < m_\chi$
- Z_N partners can cascade into V and lighter partner or DM

e.g. Z_2 scalar: $pp \to h \to PP \to 4l^{\pm} + \not{E}_T$



Many possible signatures of the Higgs ...

- $h \to \chi\chi$ Eboli, Zeppenfeld '00
- $h \to VV \to 4l$ Gopalakrishna, Jung, Wells '08
- $h \to h'h' \to 4\chi' \to 8l + 4\chi$
- $h \to$ lepton jets Falkowski, Ruderman, Volansky, Zupan '10
- $h \to \ldots \to \chi_1\chi_2 + nl$ Konar, Kong, Matchev, Park '09

and so on...

Summary

- Discrete symmetries can stabilize dark matter, but ad-hoc
- Discrete gauge symmetry:
  - Remnant subgroup of broken gauge symmetry
  - Exactly conserved owing to its gauge origin
- New states, e.g DM, Z_N partners, V_μ, $h' + \ldots$
- May be multiple symmetries/DM candidates
- $U(1)_D$ sector light $\Longrightarrow$ New Higgs signatures!