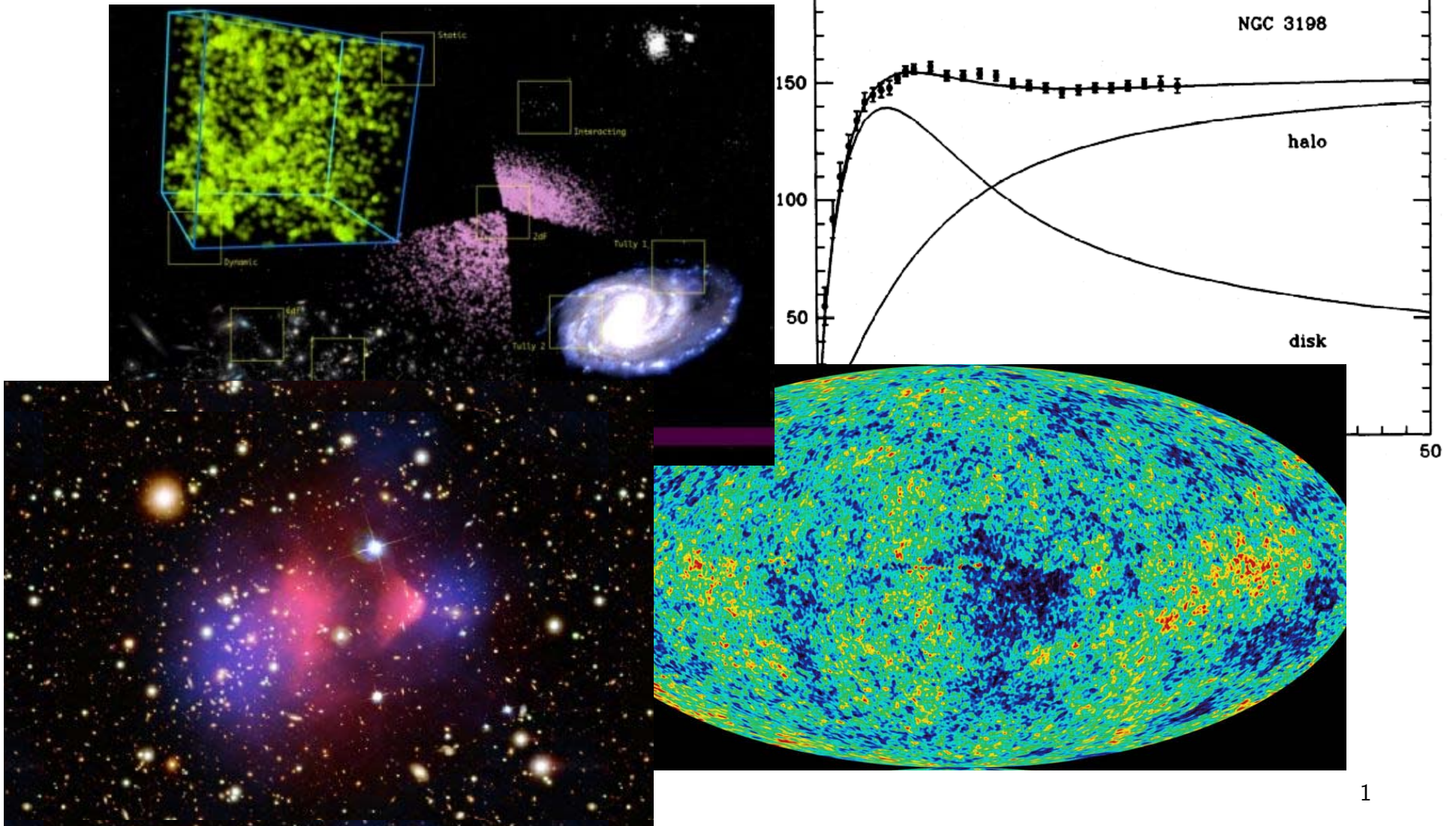


Dark Discrete Gauge Symmetries

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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 \implies either:
 - DM in $SU(2)_L \times U(1)_Y$ multiplet (such that $Q_{EM} = 0$)
 - DM in the hidden sector \implies I will focus on this possibility
- Stable \implies 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

Model ingredients:

- $U(1)_D$ 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: $\langle \phi \rangle = v'/2$

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

- Descendant Z_N symmetry:

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

Single field models

- 3 possibilities at the renormalizable level

- Scalar

$$Z_2 : \phi_{(2)} \chi_{(-1)} \chi_{(-1)} + \text{h.c.}$$

$$Z_3 : \phi_{(3)} \chi_{(-1)} \chi_{(-1)} \chi_{(-1)} + \text{h.c.}$$

- Fermion

$$Z_2 : \phi_{(2)}^\dagger \psi_{(1)} \psi_{(1)} + \phi_{(2)} \xi_{(-1)} \xi_{(-1)} + \text{h.c.}$$

- Multi-field models \implies many more possibilities!

Multi-field models

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

$$\begin{aligned}\Delta\mathcal{L} \sim & \phi_{(4)}\chi_{(-2)}\chi_{(-2)} + \phi_{(4)}\chi_{(-2)}\chi_{(-1)}\chi_{(-1)} \\ & + \chi_{(2)}^\dagger\chi_{(-1)}\chi_{(-1)} + \text{h.c.}\end{aligned}$$

- Both Z_4 and Z_2 symmetry ($\chi_{(-1)} \rightarrow -\chi_{(-1)}$)
- 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 Higgses break $U(1)_D$ and generate masses
- Example: $\phi_{(5)}, \phi_{(-20)}, \chi_{(2)}, \chi_{(4)}, \chi_{(-7)}, \chi_{(-9)}, \chi_{(10)}, \xi_{(0)}$.

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

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

How to talk to the dark sector:

- “Connector” particle - charged under both sectors
- Higher dimensional operators
- Portals

| | |
|--------------------------|-------------------|
| $B_{\mu\nu}V^{\mu\nu}$ | U(1) portal , |
| $H^\dagger H(AS + BS^2)$ | Higgs portal , |
| LHN | Neutrino portal , |

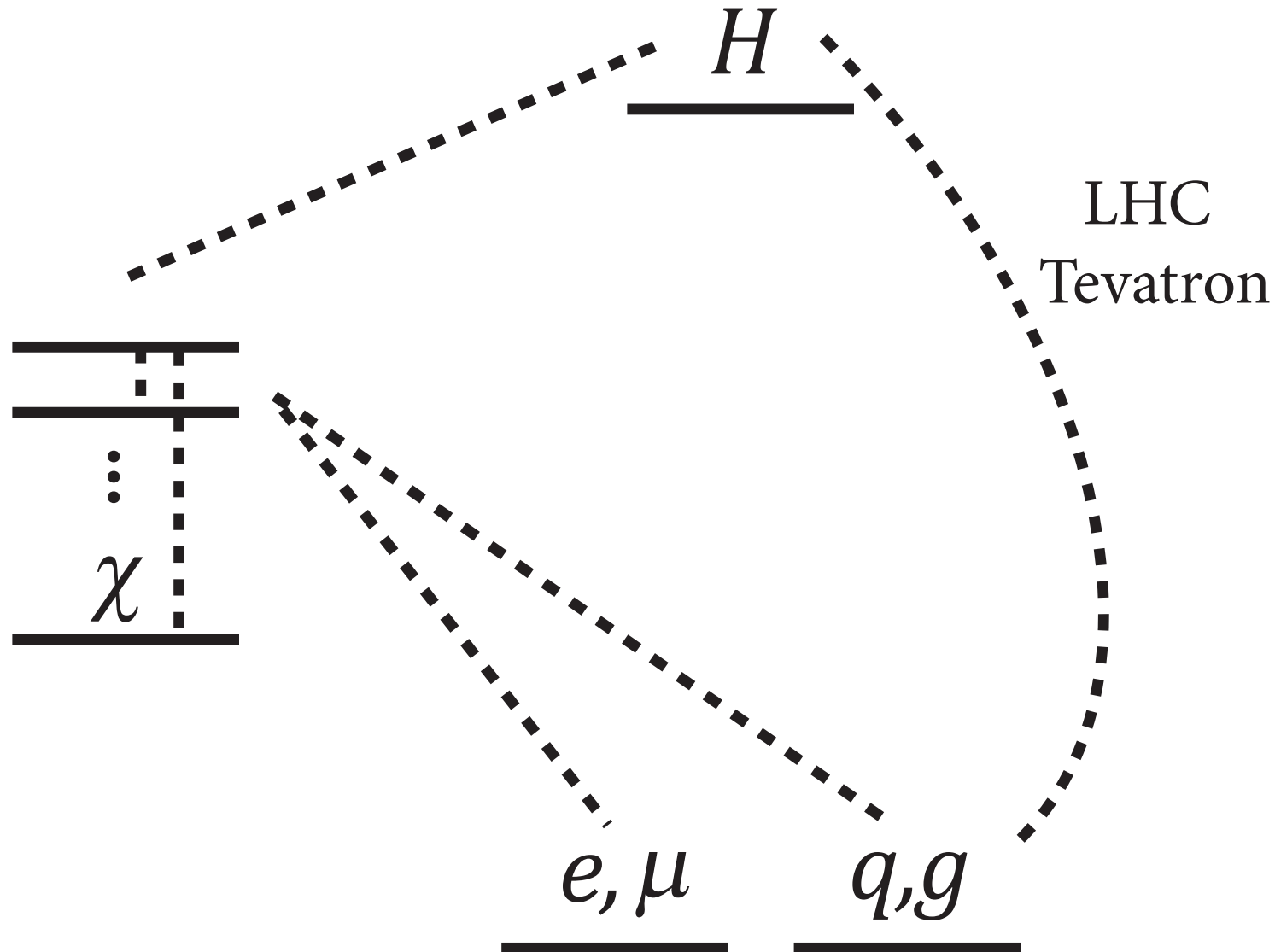
- $U(1)_D$ symmetry \implies vector and Higgs portals available!

Dark Matter phenomenology

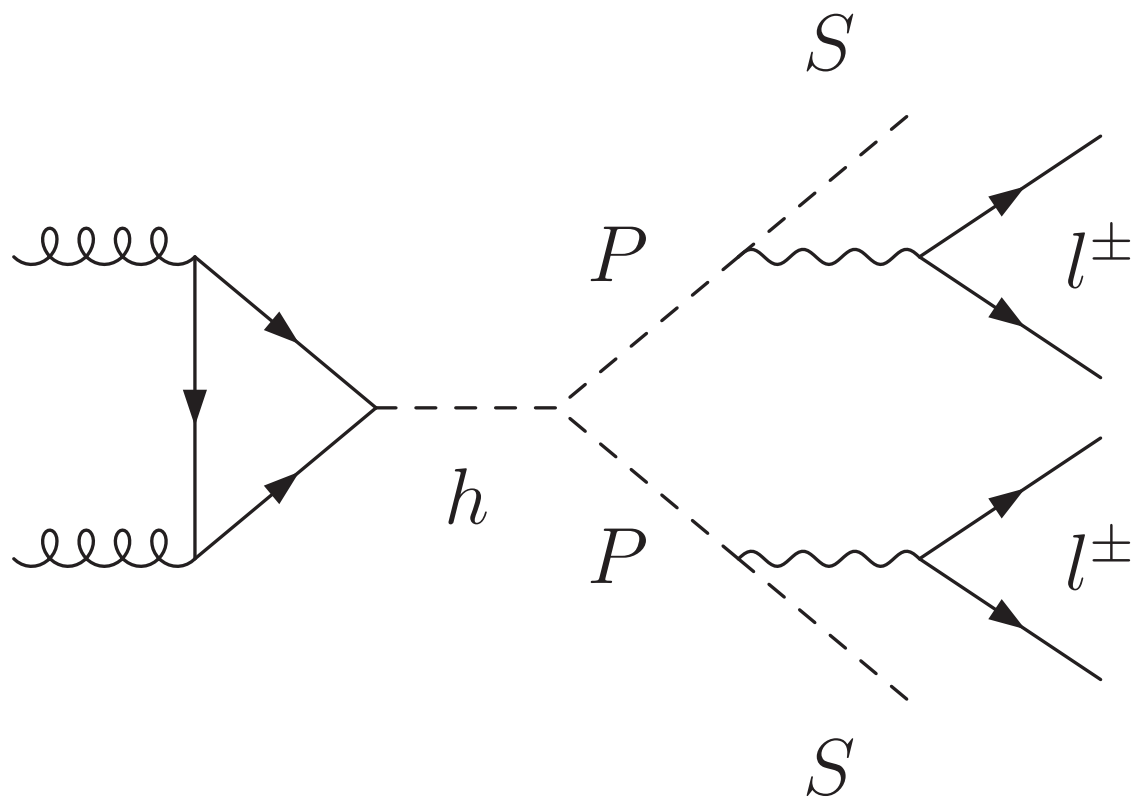
- Relic Abundance:
 - Annihilation either into hidden sector, V_μ, h', \dots , or into SM via portals - 'Secluded DM'
- Direct Detection via portals:
 - 'Vanilla' Elastic, Inelastic, Form-factor, Momentum Dependent, light GeV DM, Exothermic ...
- Indirect Detection:
 - MeV DM, Dark Forces ...

Hidden valley via Higgs

Strassler, Zurek '06



e.g. Z_2 scalar: $pp \rightarrow h \rightarrow PP \rightarrow 4l^\pm + \cancel{E}_T$



Many more possible signatures of the Higgs ...

- $h \rightarrow \chi\chi$

Eboli, Zeppenfeld '00

- $h \rightarrow VV \rightarrow 4l$

Gopalakrishna, Jung, Wells '08

- $h \rightarrow h'h' \rightarrow 4\chi' \rightarrow 8l + 4\chi$

- $h \rightarrow$ lepton jets

Falkowski, Ruderman, Volansky, Zupan '10

- $h \rightarrow \dots \rightarrow \chi_1\chi_2 + nl$

Konar, Kong, Matchev, Park '09

and so on...

Summary

- Z_N symmetry derived from gauge symmetry
- New states, e.g DM, Z_N partners, V_μ , $h' + \dots$
- May be multiple symmetries/DM candidates
- $U(1)_D$ sector light \implies **New Higgs signatures!**