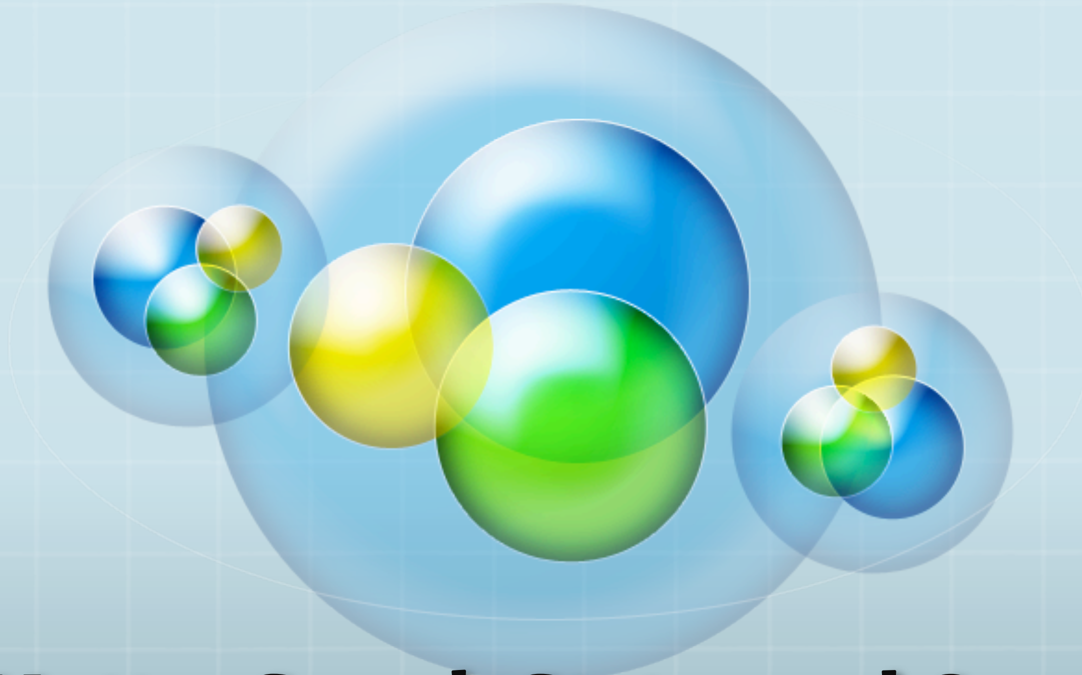

Dark Matter Search Status and Composite Dark Matter

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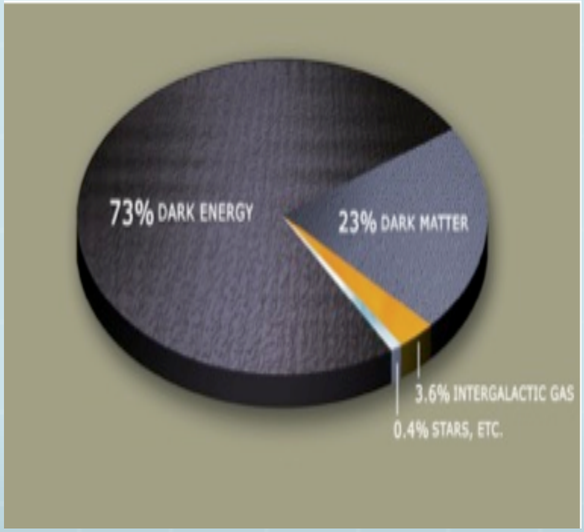
Lattice meets experiments: beyond Standard Model
Oct 26-27, 2012

Outline

- **Overview of dark matter searches**
- **Cosmological history of DM: How to explain the dark matter density?**
- **Composite DM scenarios**

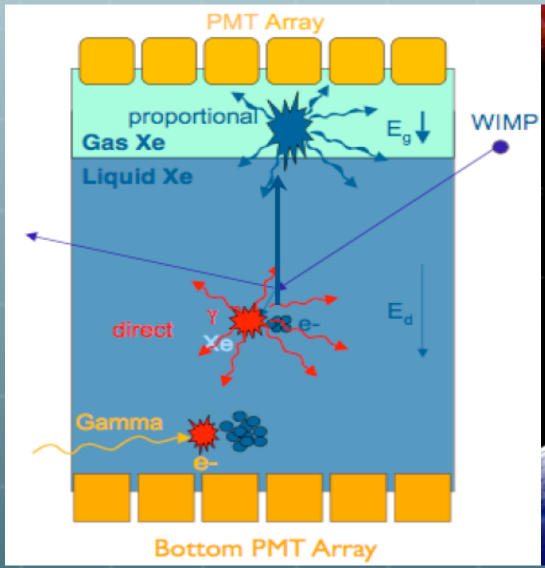
Overview



Measurement from CMB + supernovae +LSS indicates **23% of our universe is composed of DM;**

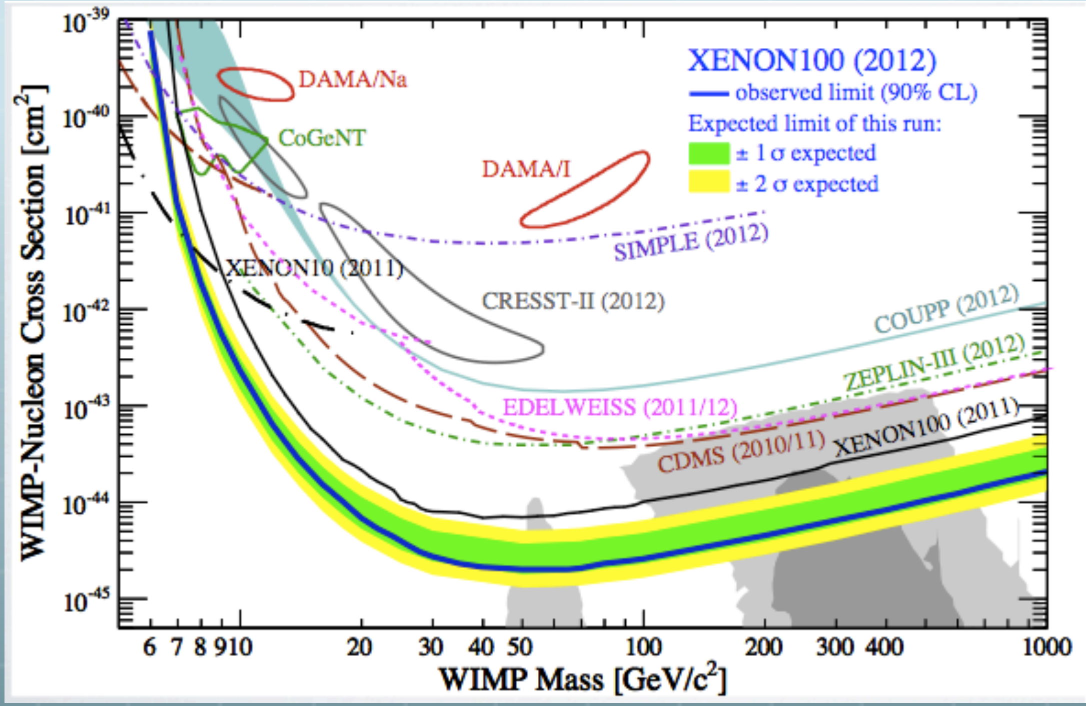
Three ways to detect DM:

Direct detection **Indirect detection** **Collider production**



Direct detection:

XENON 100 rules out DM-nucleon cross section of order 10^{-45} cm^2 for DM mass ~ 100 GeV !



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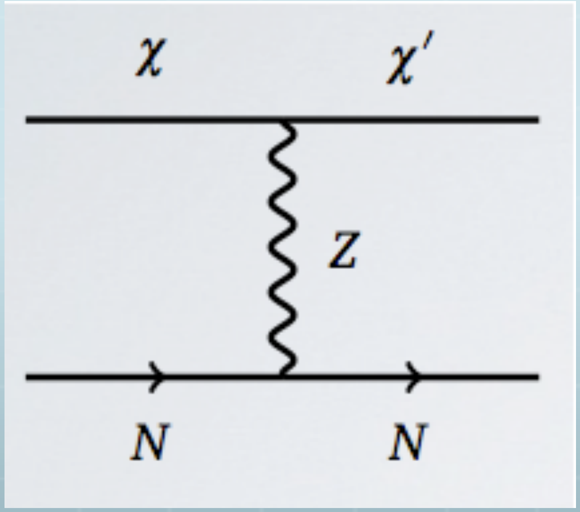
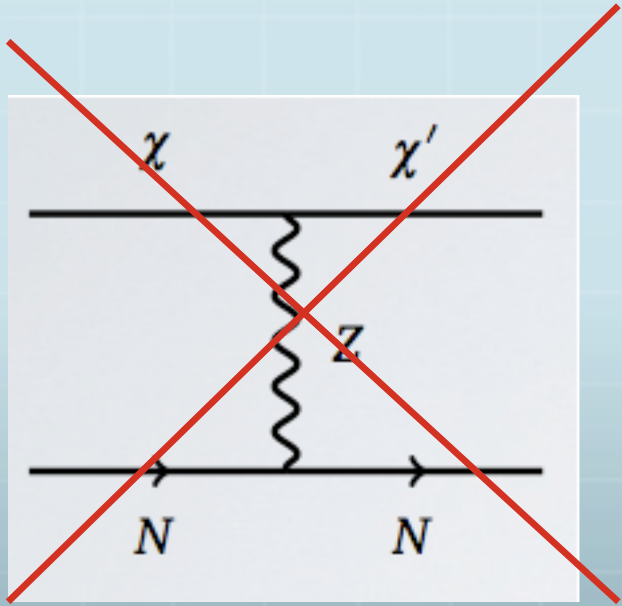
Direct detection implications:



Elastic DM scattering off nucleons through Z-exchange leads to a cross section 10^{-40} cm^2!

Direct detection implications:



Elastic DM scattering off nucleons through Z-exchange leads to a cross section 10^{-40} cm^2!

Unless the elastic scattering is shut off, e.g., due to a mass splitting between χ and χ';
Inelastic DM scenarios

Direct detection implications:

DM scatters off nuclei through Higgs exchange when DM gets part of its mass from the Higgs

For instance, a scalar S with a quartic coupling $\lambda|S|^2|H|^2$

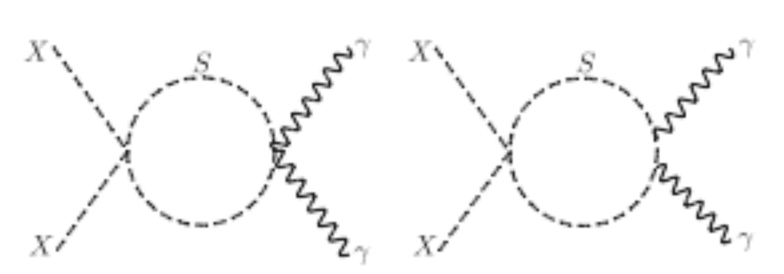
$$\sigma \sim \lambda^2 10^{-44}\mathrm{cm}^2 \left(\frac{100\,\mathrm{GeV}}{m_{DM}}\right)^2$$

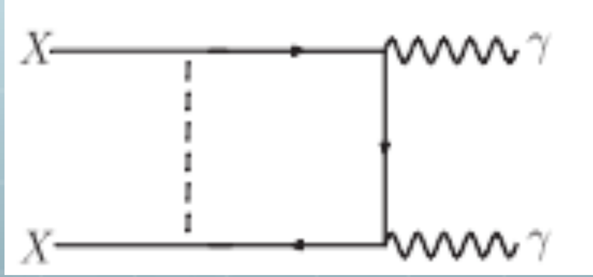
The range current direct detections probe

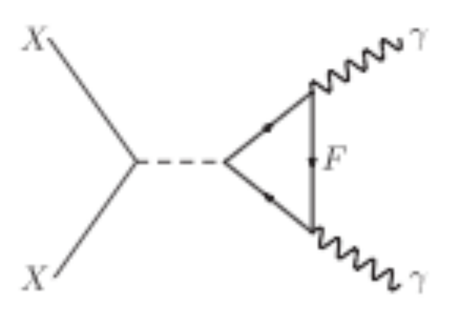
An important quantity for understanding the limits of direction detection is the nucleon form factor which lattice calculations already contribute a lot!
Eg. <N|qq|N> J. Giedt; A. Thomas and R. Young; Toussaint and Freeman '09

- **indirect signal:**

  It was often claimed that: "smoking-gun" signal of annihilating DM would be a monochromatic gamma-ray line (lines) in a region of high DM density, e.g., our Galactic center!







Presently DM is non-relativistic: DM + DM ➔ϒϒ

$$E_\gamma = M_{DM}$$

Recently, an observation of such a line at around 128 GeV is reported: Bringman, Huang, Ibarra, Vogl and Weniger; Weniger;

$$\langle \sigma v \rangle_{DM+DM\rightarrow 2\gamma} \sim 10^{-27}\mathrm{cm}^3/\mathrm{s}$$

Subsequent studies suggest a second line with energy of about 111 GeV: Rajaraman, Tait and Whiteson; Su, Finkbeiner; Consider DM + DM ➔ϒϒ, ϒZ; for DM + DM ➔ϒZ

$$E_\gamma = M_{DM} - \frac{m_Z^2}{4m_{DM}} = 111\mathrm{GeV}$$

It is also reported that both lines show up in unassociated photon sources in the Fermi-LAT catalogue: Su, Finkbeiner

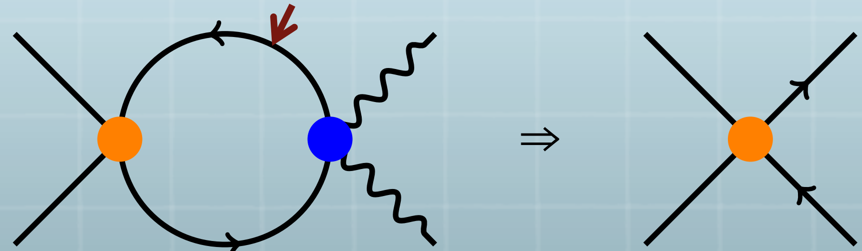
Recently, an observation of such a line at around 128 GeV is reported:

$$\langle \sigma v \rangle_{DM+DM \to 2\gamma} \sim 10^{-27} \mathrm{cm}^3/\mathrm{s}$$

Not easy to explain this line:

a. Continuum constraint; (**almost** rule out MSSM neutralino as an explaination)

charged matter loop (W, ...)



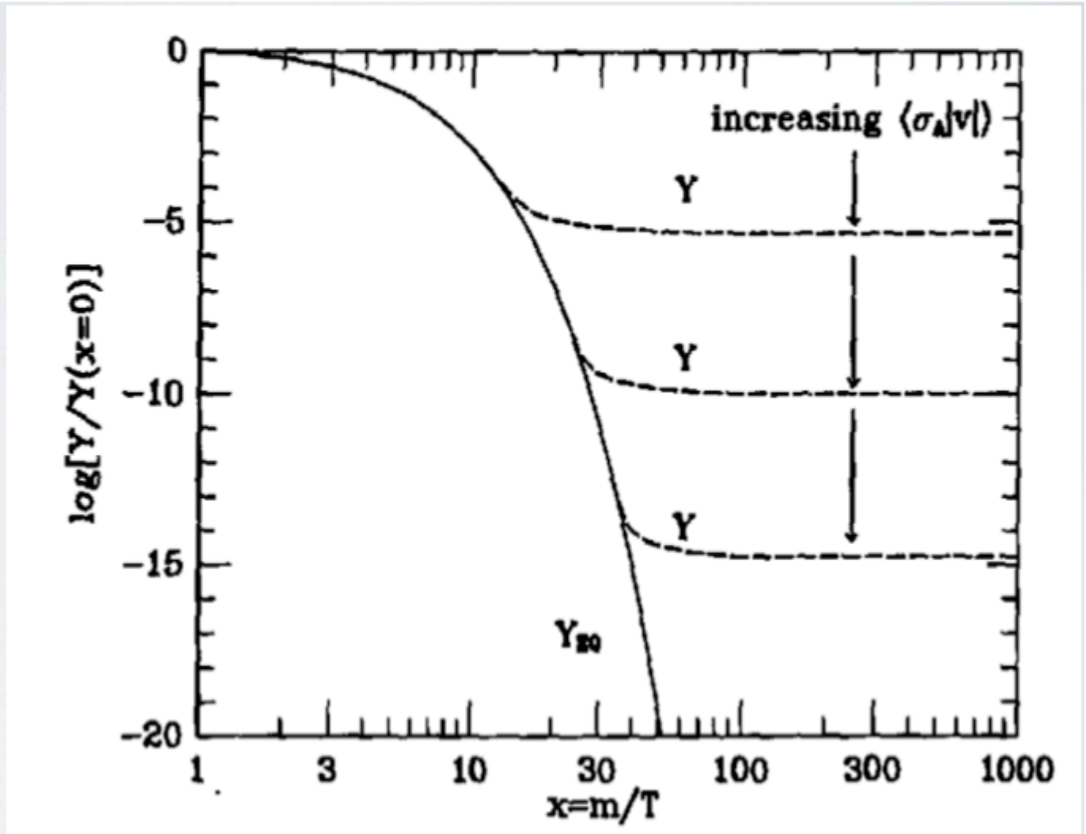
Charged matter can decay to showers of hadrons, π_0

b. Strong couplings and mass coincidences to boost the cross section of the loop process:
large coupling between DM + charged matter running in the loop (e.g, ~10);
charged matter running in the loop has to be light with mass ~ 100 GeV.

Something to watch out: Fermi symposium October 28 - November 2

Cosmological history of DM: How to explain $\Omega h^2 \approx 0.11$

- **Thermal freezeout: DM in thermal equilibrium with the SM until Hubble expansion is faster than the interactions**



$$\Omega h^2 \approx 0.1 \frac{3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

Caution: the annihilation cross section in the early Universe is not necessarily the same as today's.

κ: DM coupling

$$\langle \sigma v \rangle = \frac{1}{8\pi} \frac{\kappa^4}{m_{DM}^2}$$

Only the ratio is fixed to get a right thermal relic

$$m_{DM} \qquad \longleftarrow (100\,GeV - 1\,TeV) \longrightarrow (10 - 100\,TeV)$$

$$\kappa \qquad \longleftarrow (0.1 - 1) \longrightarrow (\sqrt{4\pi} - 4\pi\,)$$

$$WIMP \qquad\qquad ?$$

Thermal history is not the only choice. For example,

- **Asymmetric DM:** Nussinov '85; Barr, Chivukula and Farhi, '90; B. Kaplan '92; E. Kaplan, Luty and Zurek '09…

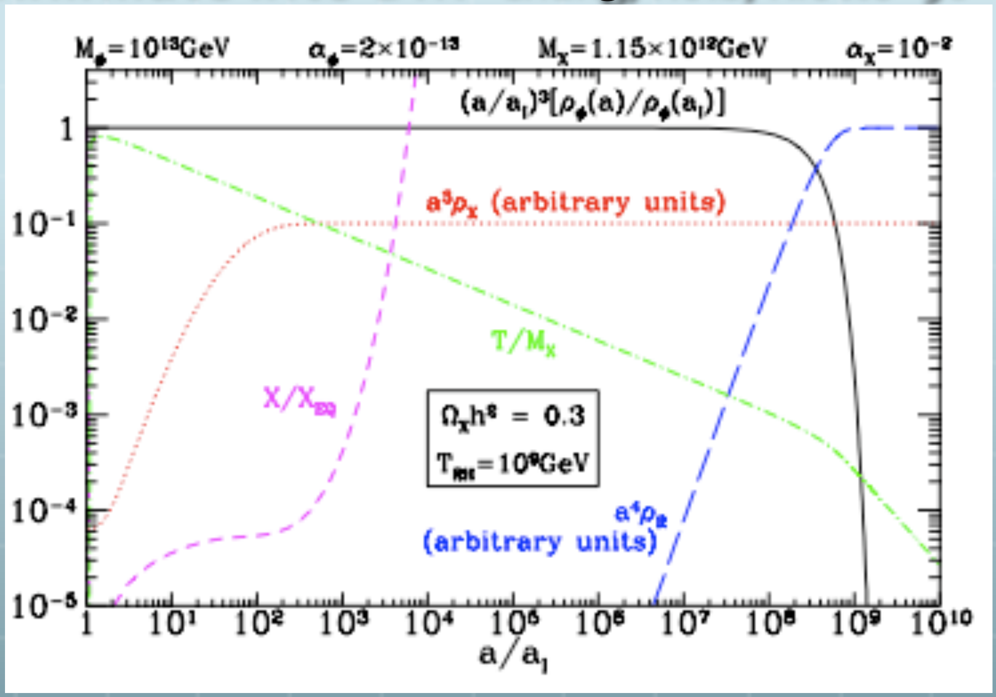
  DM, like ordinary baryons, also has an inherent asymmetry; both asymmetries related by e.g., high-dimensional operators that violate both baryon and DM numbers;

Rough features of original proposals:

$$n_{DM} \sim n_{baryon}, m_{DM} \sim m_{baryon} \rightarrow \rho_{DM} \approx 5\rho_{baryon}$$

- **Non-thermal history e.g: axion DM; more later**

Late-decaying scalar field populates SM radiation, that annihilate into DM Chung, Kolb, Riotto `98



$$\Omega h^2 = M_{DM}^2 \langle \sigma v \rangle \left(\frac{2000 T_{RH}}{M_{DM}} \right)^7$$

DM density is proportional to the annihilation cross section!

Composite DM Theories

- **Thermal composite DM scenarios:** $\langle \sigma v \rangle = \frac{1}{8\pi} \frac{\kappa^4}{m_{DM}^2}$

a. Strongly-interaction heavy DM

saturates the perturbative unitarity bound

$$m_{DM} \qquad \longleftarrow (100\, GeV - 1\, TeV) \longrightarrow (10 - 100\, TeV)$$

$$\kappa \qquad \longleftarrow (0.1 - 1) \longrightarrow (\sqrt{4\pi} - 4\pi\,)$$

$$WIMP \qquad\qquad ?$$

Constraints on self-interaction from dark matter halos and bullet cluster are weak:

$$\frac{\sigma}{m_{DM}} \leq 0.1\,\mathrm{cm}^2/g \approx 500\,\mathrm{GeV}^{-3}$$

In the SUSY context, such composites could naturally reside in dynamical SUSY breaking sector: Dimopoulos, Giudice and Pomarol '98;
Fan, Thaler, Wang (indirect signals) '10.

b. Light thermal DM: pNGB of the flavor group

A confining sector: Λ

$$m_{DM} \ll \Lambda$$

$$f \sim \frac{\Lambda}{4\pi}$$

$$m_{DM}^2 f^2 = m_q \Lambda^3 \rightarrow m_{DM} \sim 4\pi\sqrt{m_q \Lambda}$$

$$\sigma \sim \frac{m_{DM}^2}{4\pi f^4} \sim \frac{(4\pi)^5 m_q}{\Lambda^3}$$

By choosing small explicit flavor symmetry breaking parameter $m_q \ll \Lambda$, one can get the right relic;

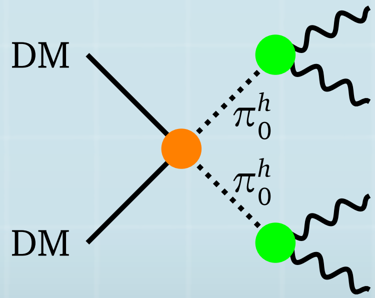
Buckley, Neil '12; In the SUSY context: Ibe, Nakayama, Murayama, Yanagida '09..

- **Asymmetric heavy composite DM scenarios:**
  technibaryon, quirk…

Nussinov '85; Barr, Chivukula and Farhi, '90; Kribs, Roy, Terning and Zurek '09; Del Bobile, Gudnason, Kouvaris, Ryttov and Sannino ;

Non-perturbative effect such as electroweak sphalerons intermix baryon, lepton and the composite DM numbers. The heavy mass of the composite DM also lead to a Boltzmann suppression of their relic $exp[-m_{DM}/T]$, where T is the temperature where sphalerons shut off.

Non-thermal composite DM scenarios: Fan, Reece '12;



$$\frac{1}{2}\left(m_{DM} - \sqrt{m_{DM}^2 - m_\pi^2}\right) < E_\gamma < \frac{1}{2}\left(m_{DM} + \sqrt{m_{DM}^2 - m_\pi^2}\right)$$

The gamma rays are no longer monochromatic but rather box-shaped!

In the limit m_π close to DM mass ~ 260 GeV, the box mimics a line! For example:

$$m_{DM} - m_\pi \approx 50\,\mathrm{MeV}, \delta E_\gamma \approx 5\,\mathrm{GeV}$$

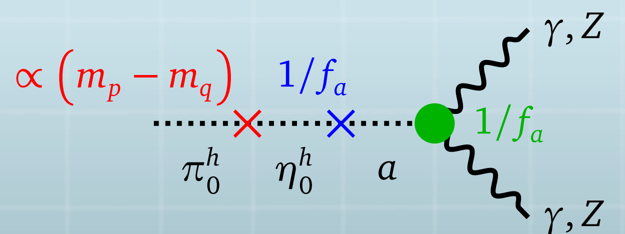
The mass degeneracy could arise from symmetry

Current Fermi resolution is ~ 10 GeV

Simple possibility exists: scale up QCD

$$\pi_+^h \pi_-^h \longrightarrow \pi_0^h \pi_0^h, \qquad \pi_0^h \longrightarrow \gamma\gamma,\ \gamma Z.$$

Doesn't determine relic as it doesn't change the pion numbers



$\sigma v(\pi_+^h \pi_-^h \longrightarrow \pi_0^h a)$ is too small to generate a right thermal relic;

Have to reply on non-thermal history to get the right relic!

Direct detection signal:

a. If composite DM scatters off nucleons through Z/h exchange, the constraints before apply;

b. composite DM itself is SM neutral;
yet if its constituents are charged, it could interact through EM moments such as charge radius and polarizablility.
Pospelov, ter Veldhuis '00

In most models above, two important physical quantities:

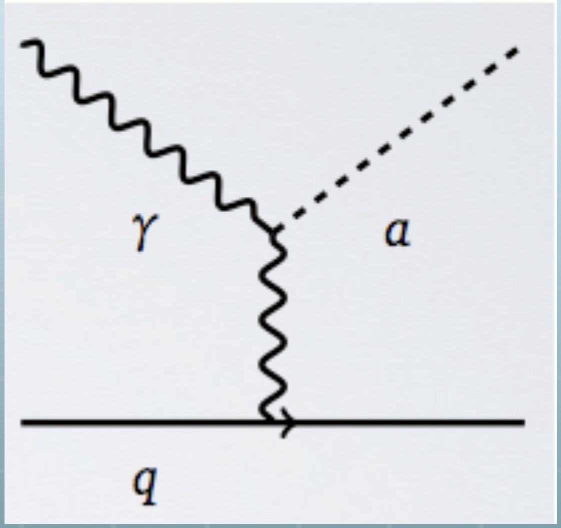
a. Annihilation cross section for determining the relic;
b. Composite DM moments;

They need to be calculated either by χPT or lattice.

- **Axions: solution to the strong CP problem**

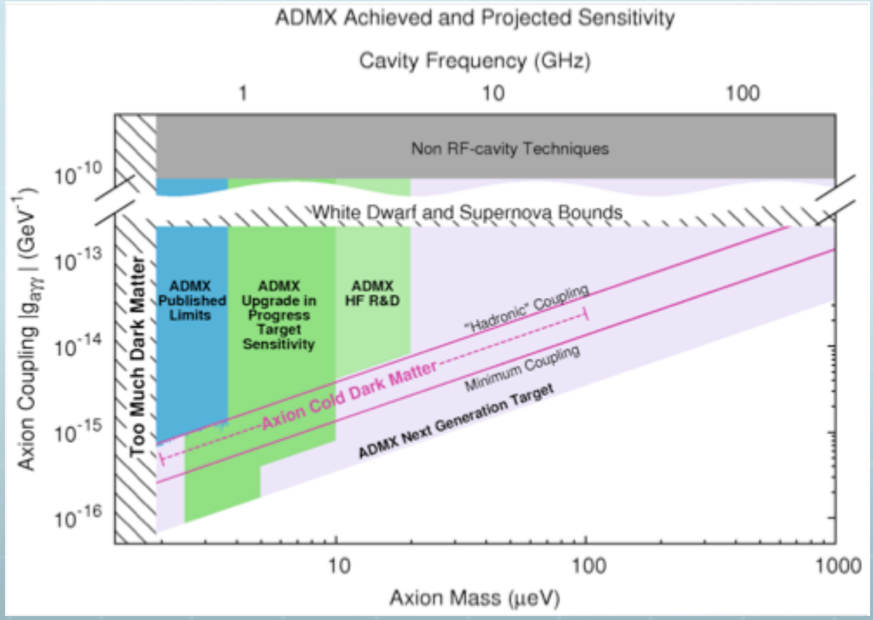
$$10^9\,\mathrm{GeV} \leq f_a \leq 10^{15}\,\mathrm{GeV}$$

Stellar cooling



Relic Abundance:
Allowing late-time decaying particle to dilute the relic
Kawasaki, Moroi, Yanagida '95;

Axion detections:



Lower end of f_a could be probed by ADMX: resonant cavity axion search; looking for axions converting into photons in a magnetic field;

Higher end of f_a could be probed by rapidly time-varying neutron EDM
Graham and Rajedran '11;
The time-dependence (MHz) could be detected by atom-interferometry ..

Conclusion

There have been interesting progresses in DM detections that might give us clues of DM properties;

For composite DM scenarios, the annihilation cross sections and its couplings to SM (through higher order moments) are important quantities for its cosmological history and direct detections.