Non-Standard WIMPs

HEAP 2009

Patrick Fox

Fermilab

Plan

- Dark Matter mini-review
- Standard WIMP story
  - Collider, direct and indirect detection implications
- Non-standard WIMPs
  - Motivation to "think outside the box"
  - Some examples
  - Implications for experiments
- Conclusions

Dark Matter

Lots of evidence for non-baryonic matter:

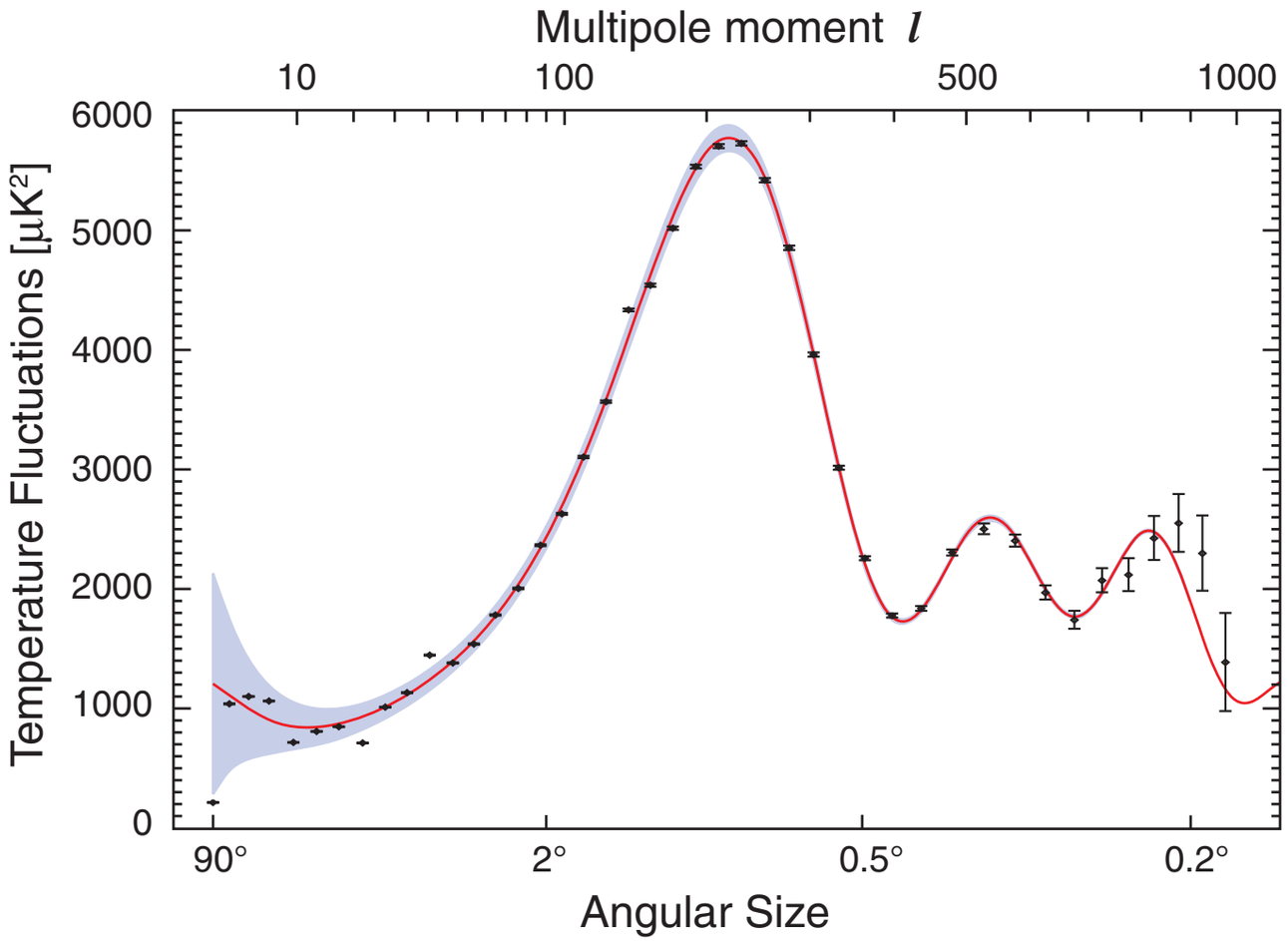
Dark Matter

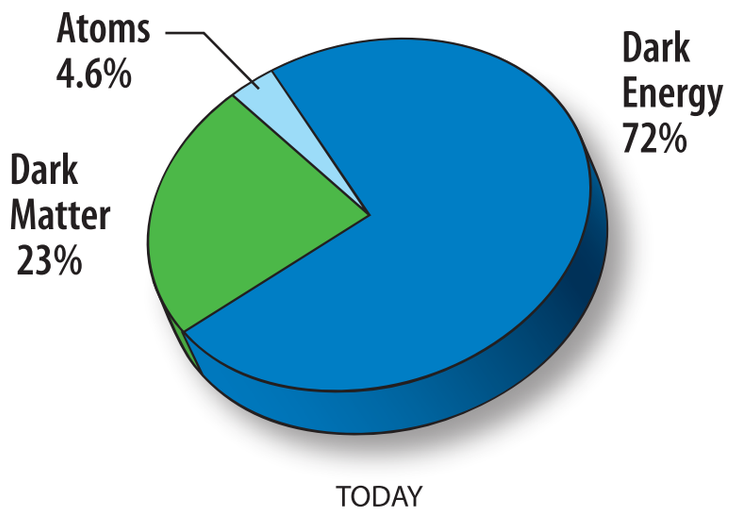
Lots of evidence for non-baryonic matter:

Unfortunately almost all gravitational in nature

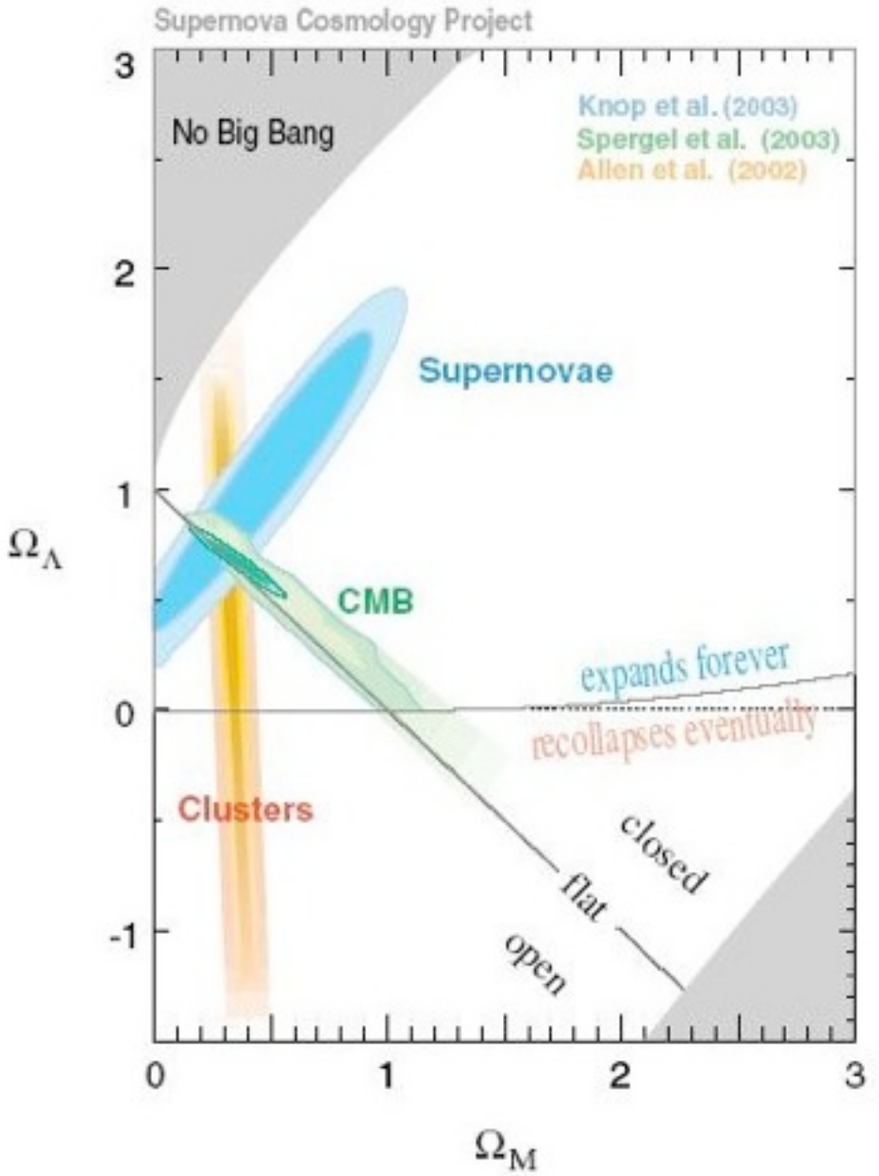
Dark Matter

The era of precision cosmology





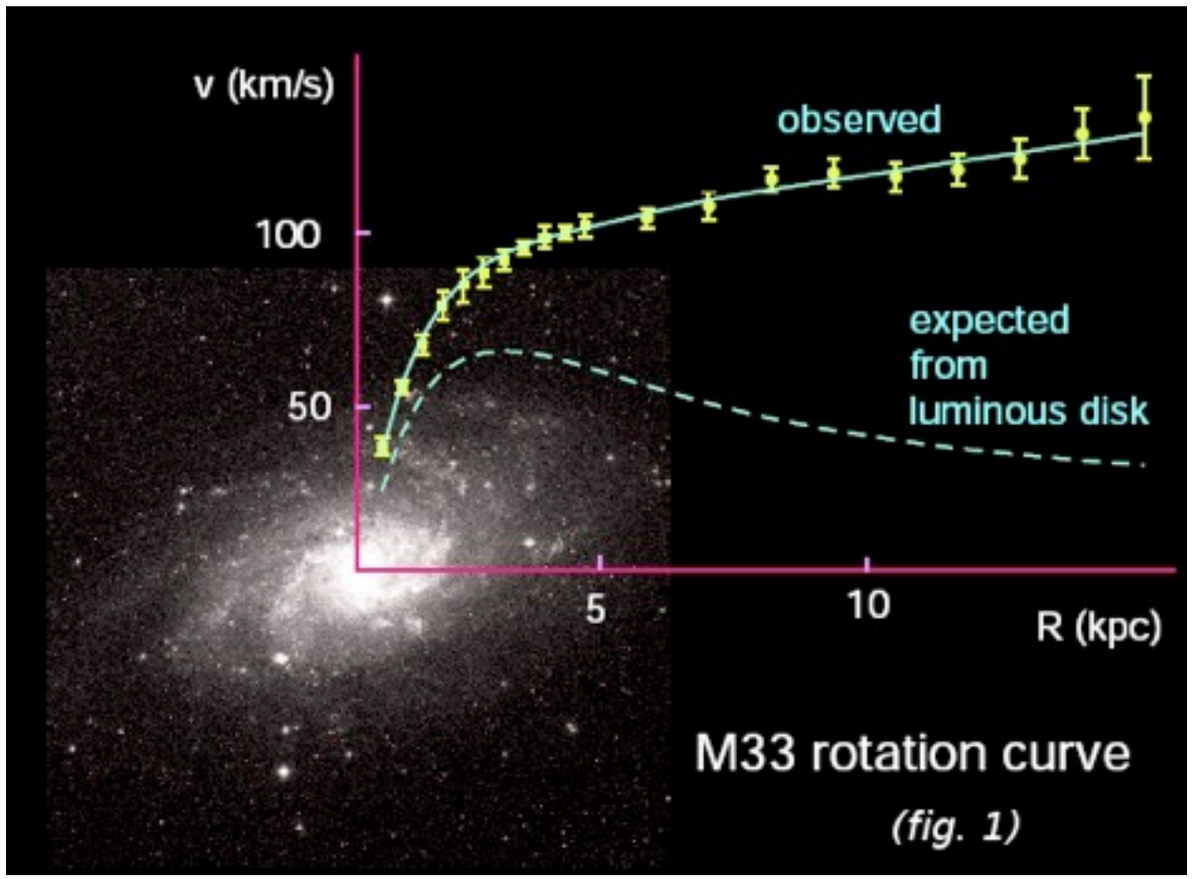
TODAY



Cosmological abundance

$$\Omega_{DM} \sim 0.2$$

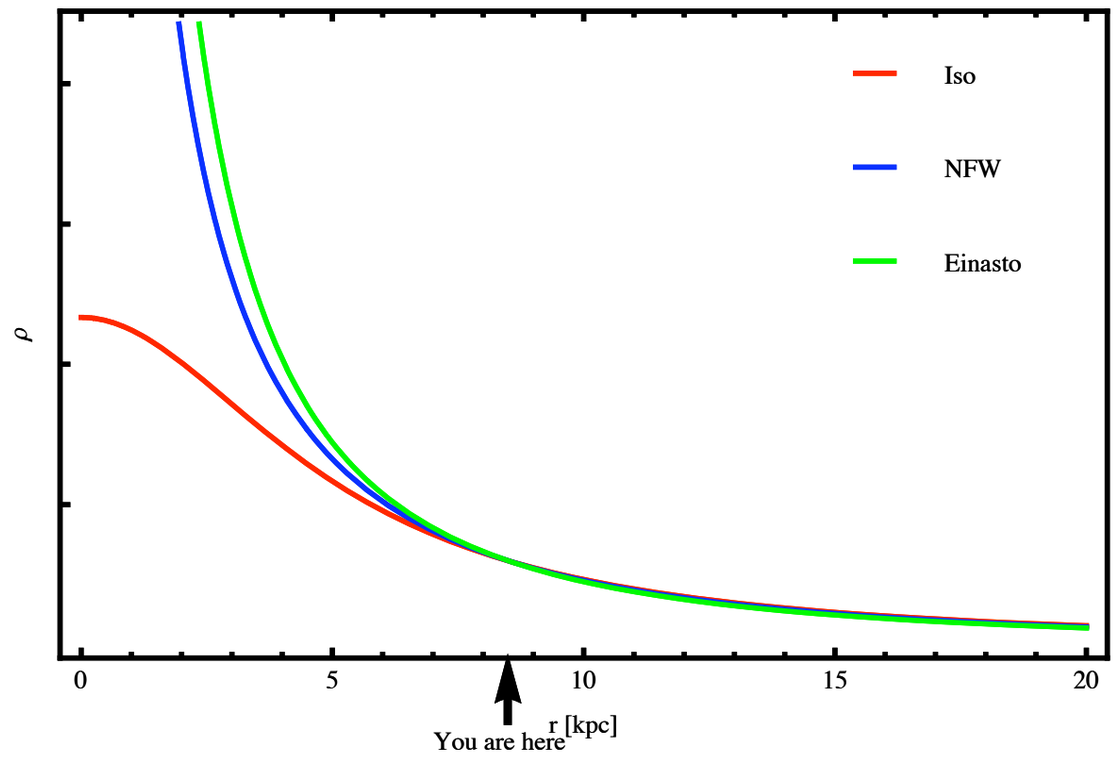
Dark Matter



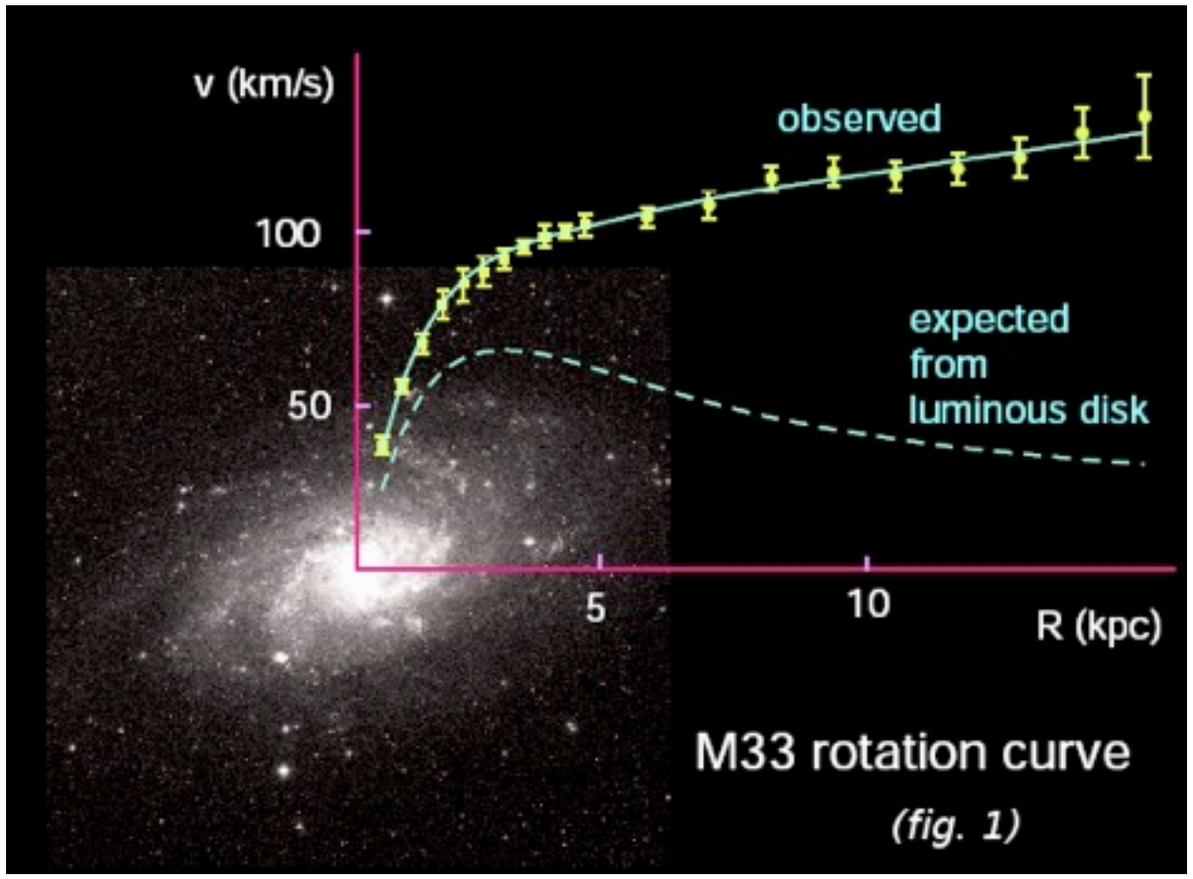
Local properties

$\rho_{DM} \sim 0.3 \text{ GeV cm}^{-3}$

$v \sim 200 \text{ km/s}$ Maxwell-Boltzmann?



Dark Matter



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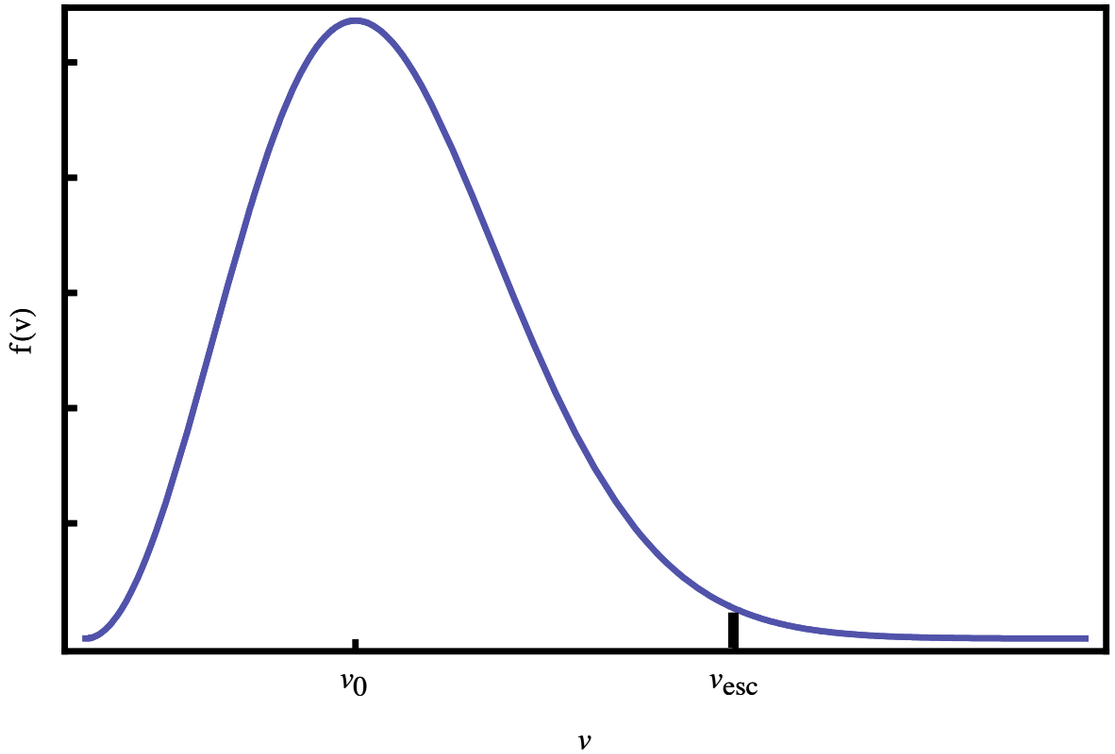
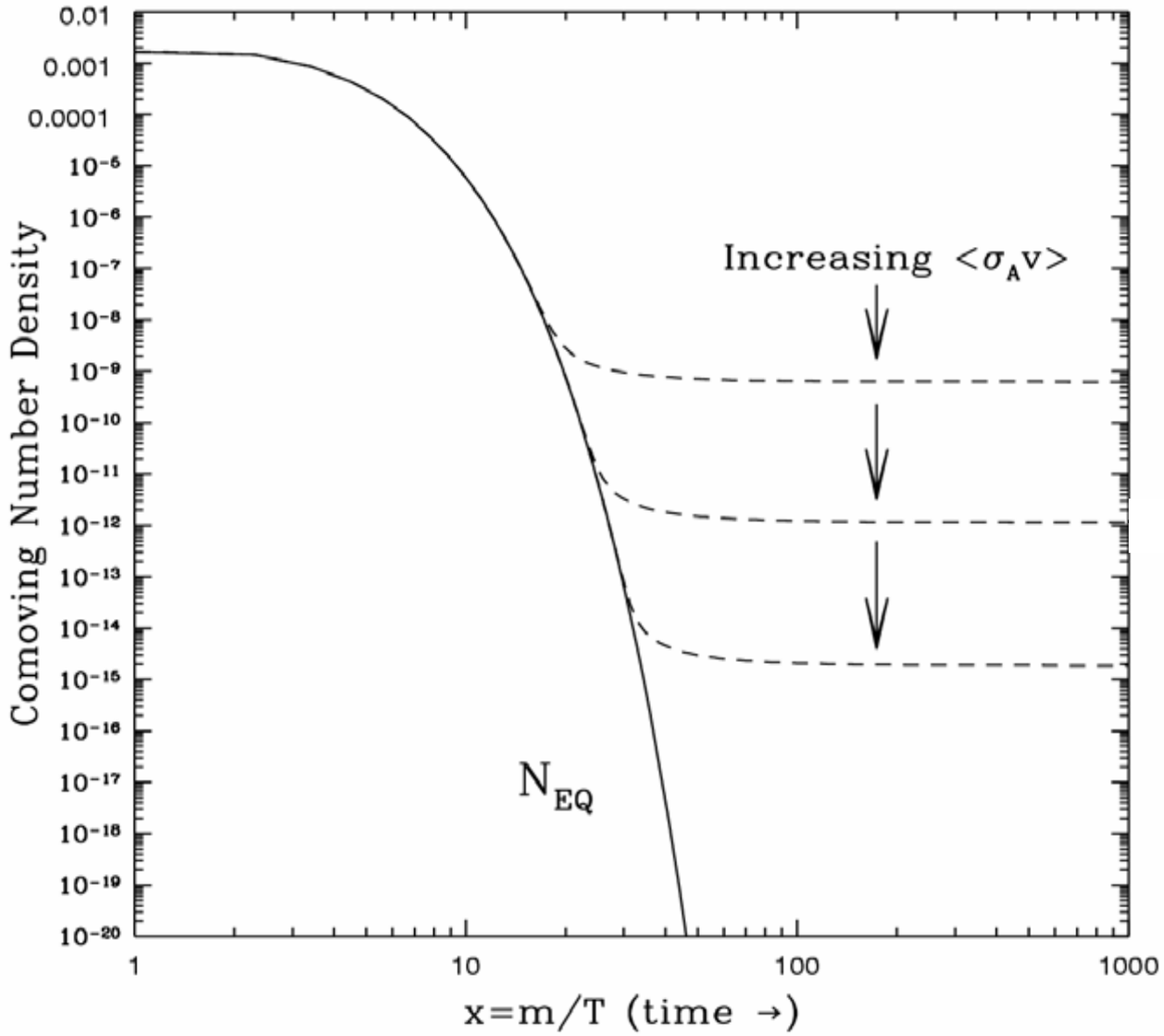


Freeze Out

"The weak shall inherit the Universe"

The WIMP as a thermal relic



$$n_{eq} = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$$

$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle\left(n^2 - n_{eq}^2\right)$$

$$\Omega h^2 \approx 0.1\left(\frac{m/T}{20}\right)\left(\frac{g_*}{80}\right)^{-1}\left(\frac{3\times 10^{-26}\mathrm{cm}^2\mathrm{s}^{-1}}{\sigma v}\right)$$

WIMPs

Amazing (misleading?) fact:

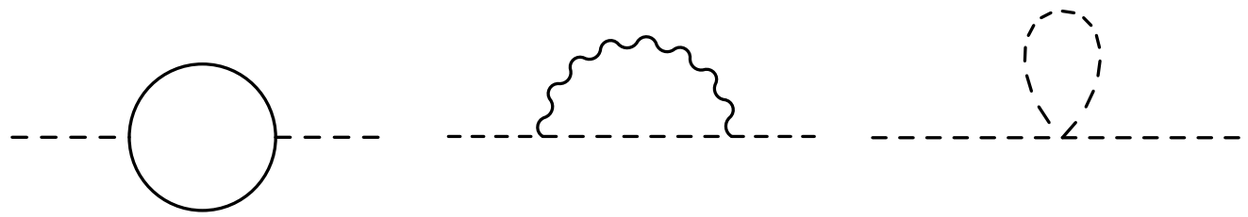
[Feng and Kumar]

$$\langle \sigma v \rangle \sim \frac{\alpha_W^2}{M_W^2} \sim 1\,\mathrm{pb} \sim 3 \times 10^{-26} \mathrm{cm}^2 \mathrm{s}^{-1}$$

and $m/T \sim 20$, $m \sim \mathrm{TeV}$

Thermal WIMP is a great DM candidate.
Many examples exist in particle physics.
LPOPs e.g. LSP, LKP, LTP

The LPOP's

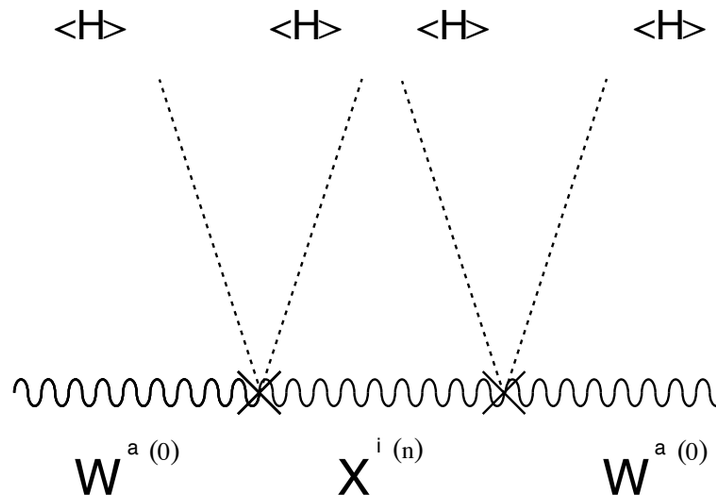


The SM hierarchy problem:

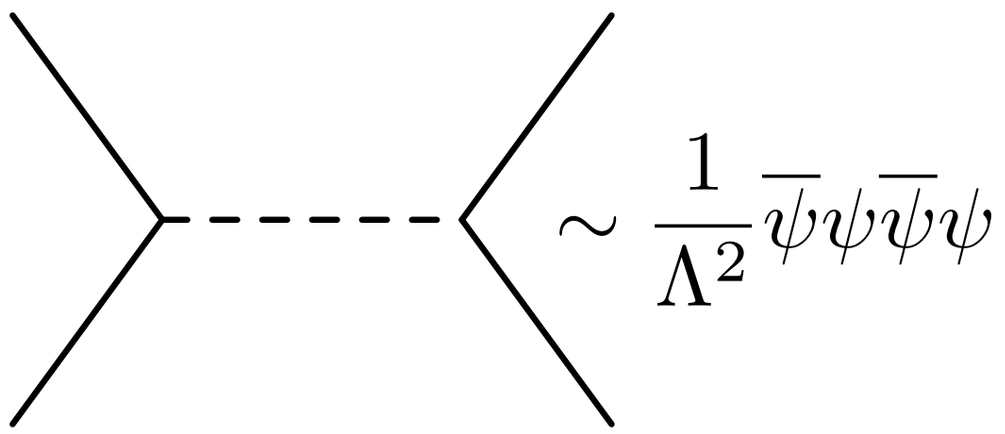
$$\Delta m_H^2 \sim \frac{g^2}{16\pi^2}\Lambda^2$$

Many solutions exist: Supersymmetry, Technicolor, Little Higgs, Composite Higgs, Extra-dimensions, ...

New weak scale states coupled to SM

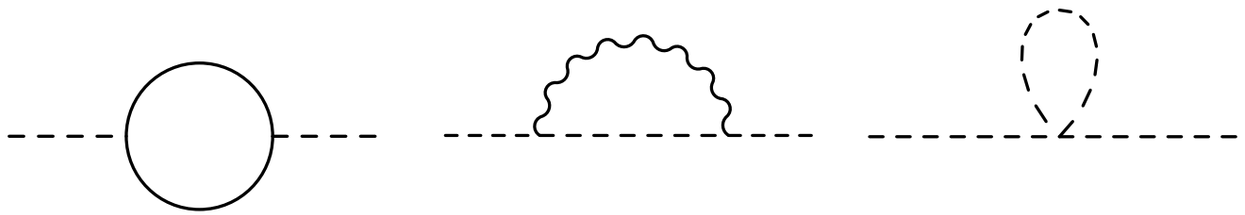


Precision tests of electroweak observables and searches for FCNCs place strong constraints on new particle masses



$$\sim \frac{1}{\Lambda^2}\overline{\psi}\psi\overline{\psi}\psi$$

The LPOP's



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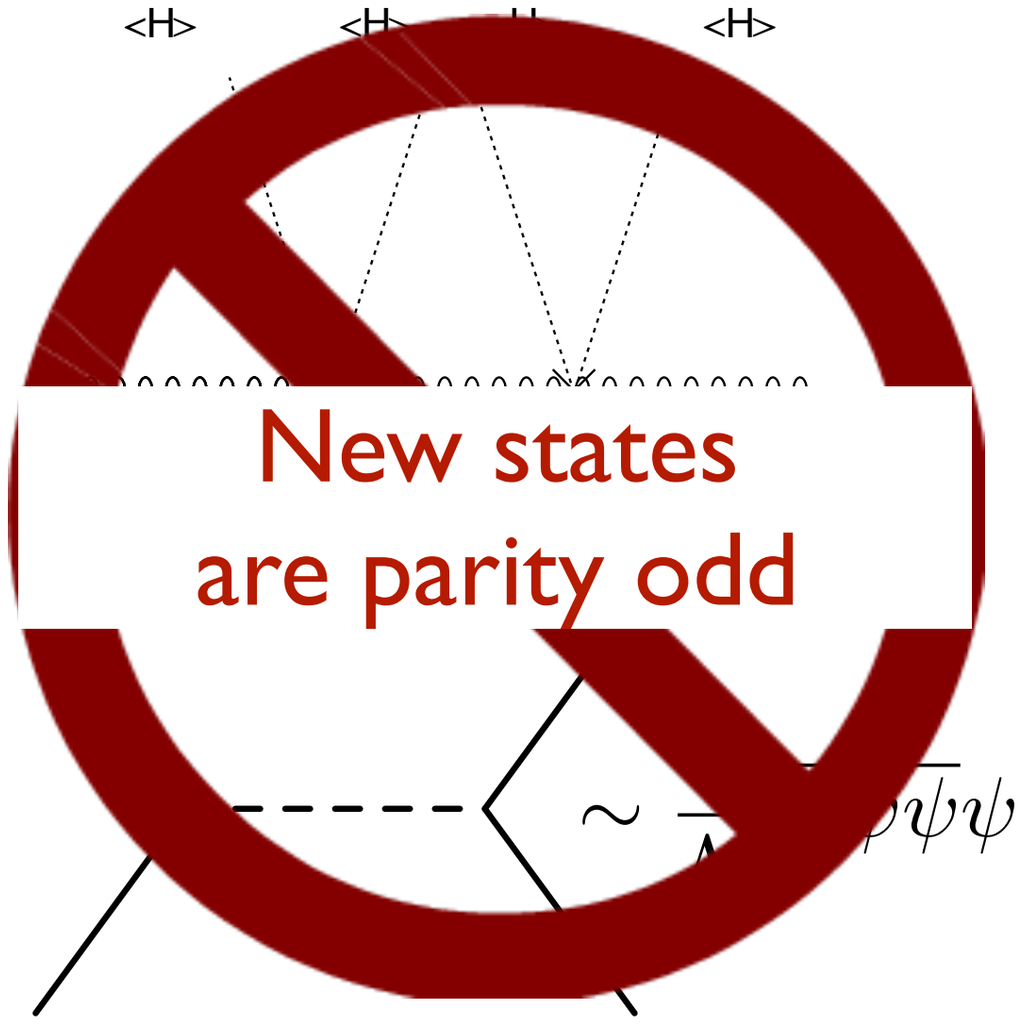
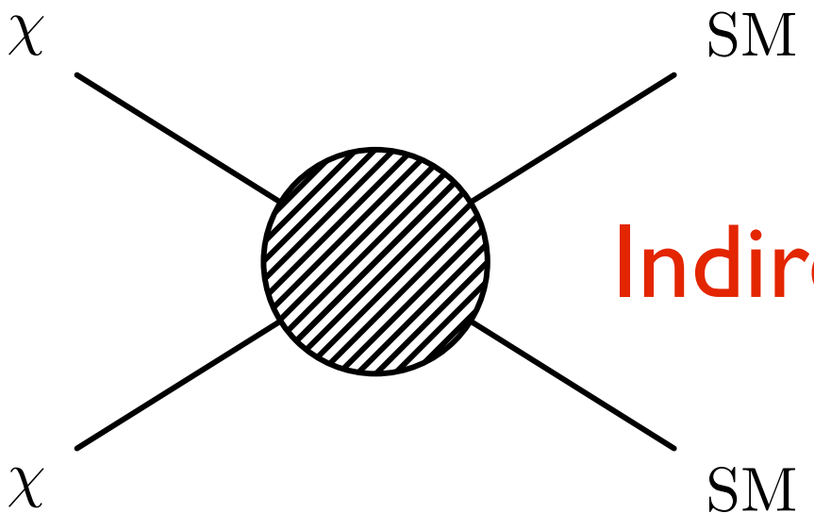


Standard WIMPs

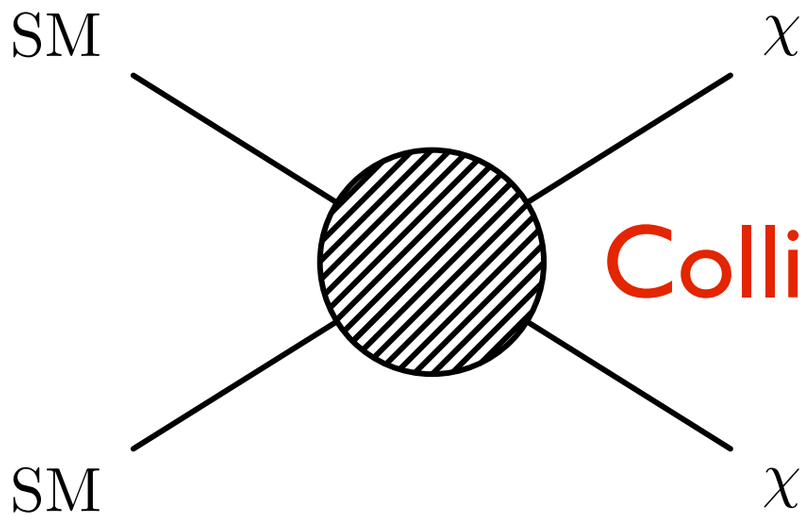
- WIMP is the lightest parity odd particle,
- Connected to the BSM physics that solves the hierarchy problem
- Thermally produced in early universe
- Weak scale in mass and annihilation cross section
- Local abundance is ~0.3 GeV/cm^3
- Can be searched for in various ways

Searching for WIMPs

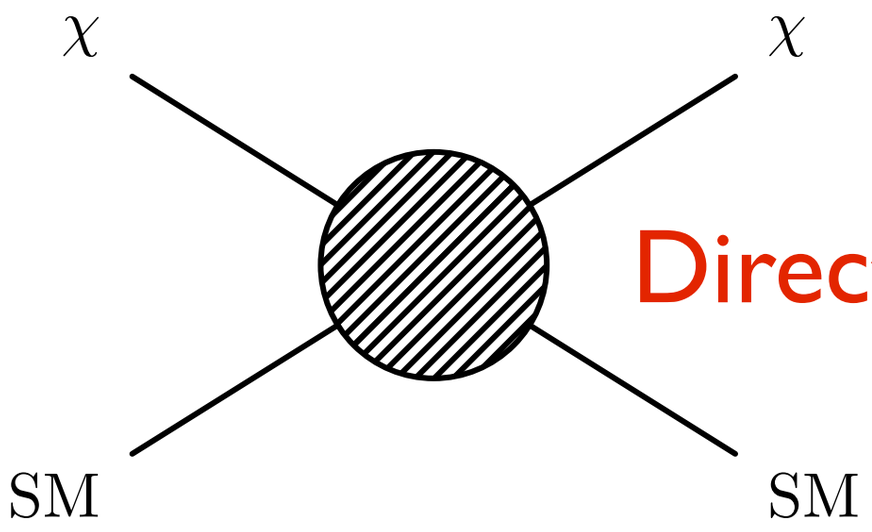
In a given model there are correlated observables



Indirect detection

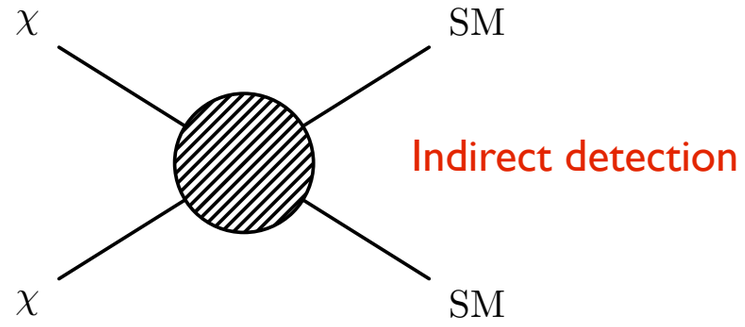


Collider searches



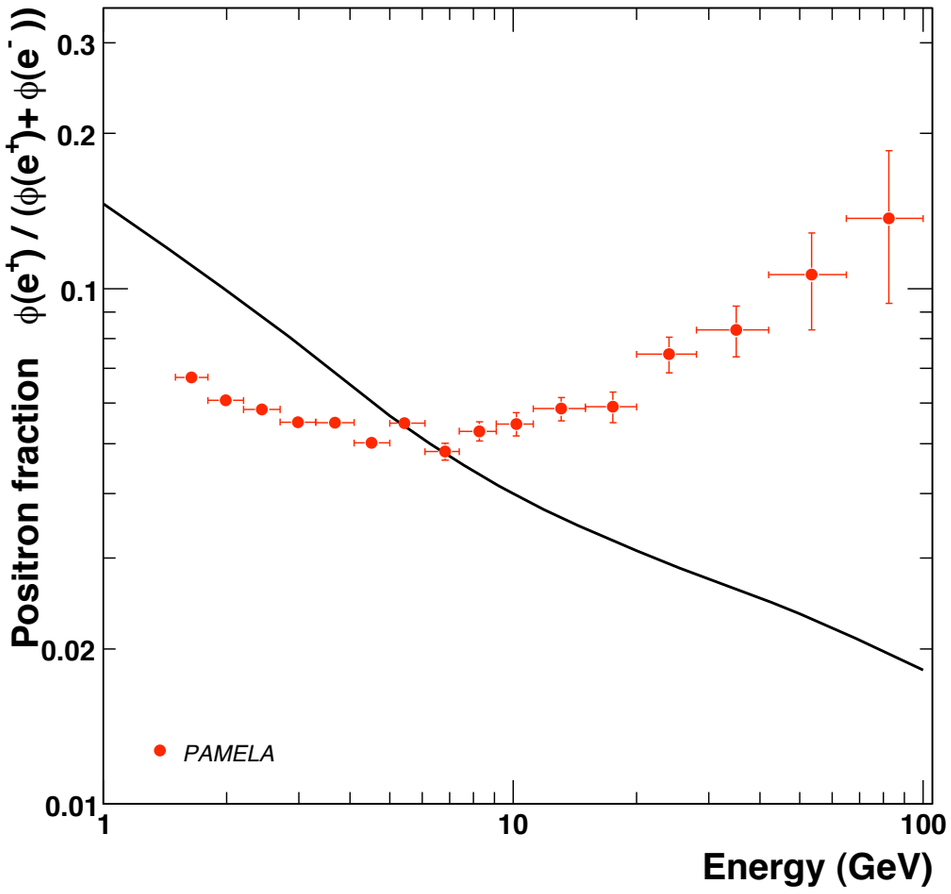
Direct detection

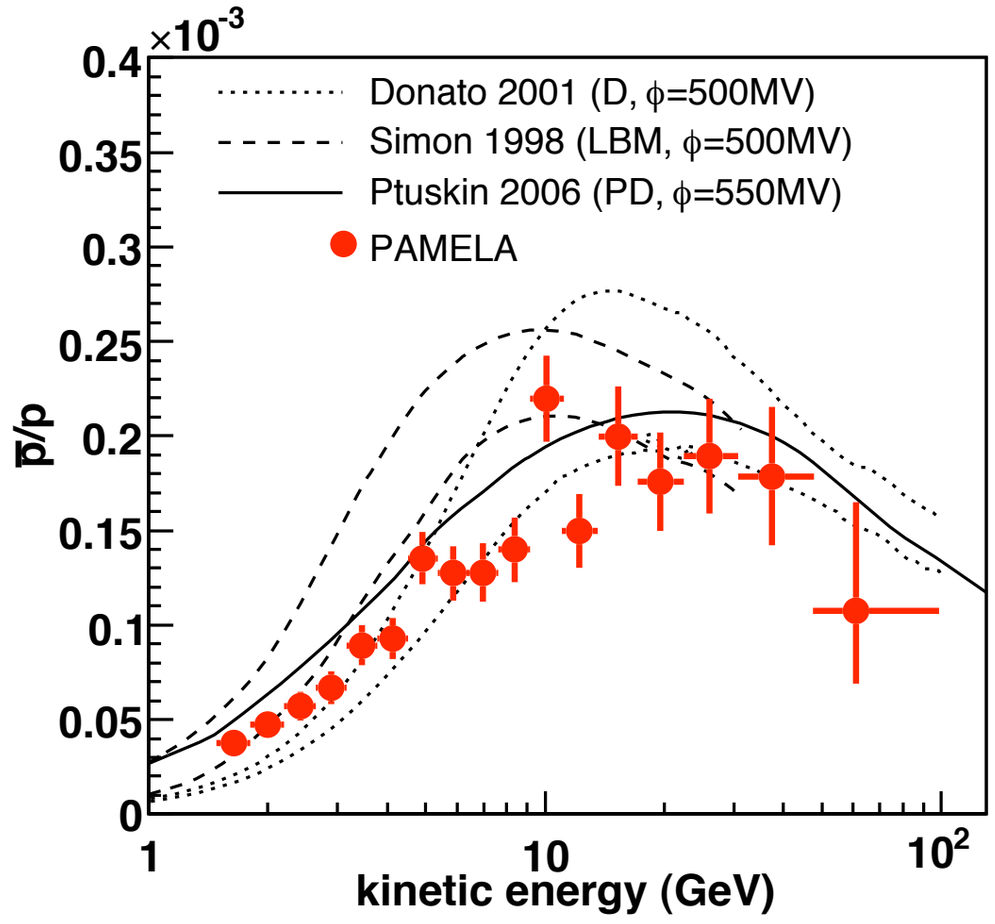
Motivation for non-standard WIMPs



Indirect detection

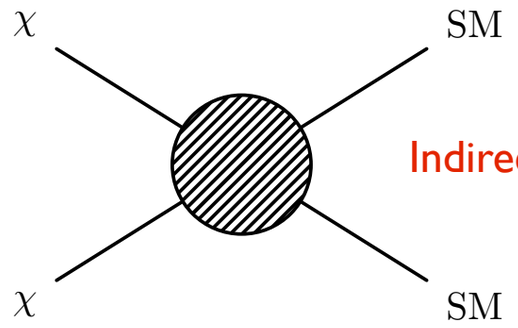
PAMELA





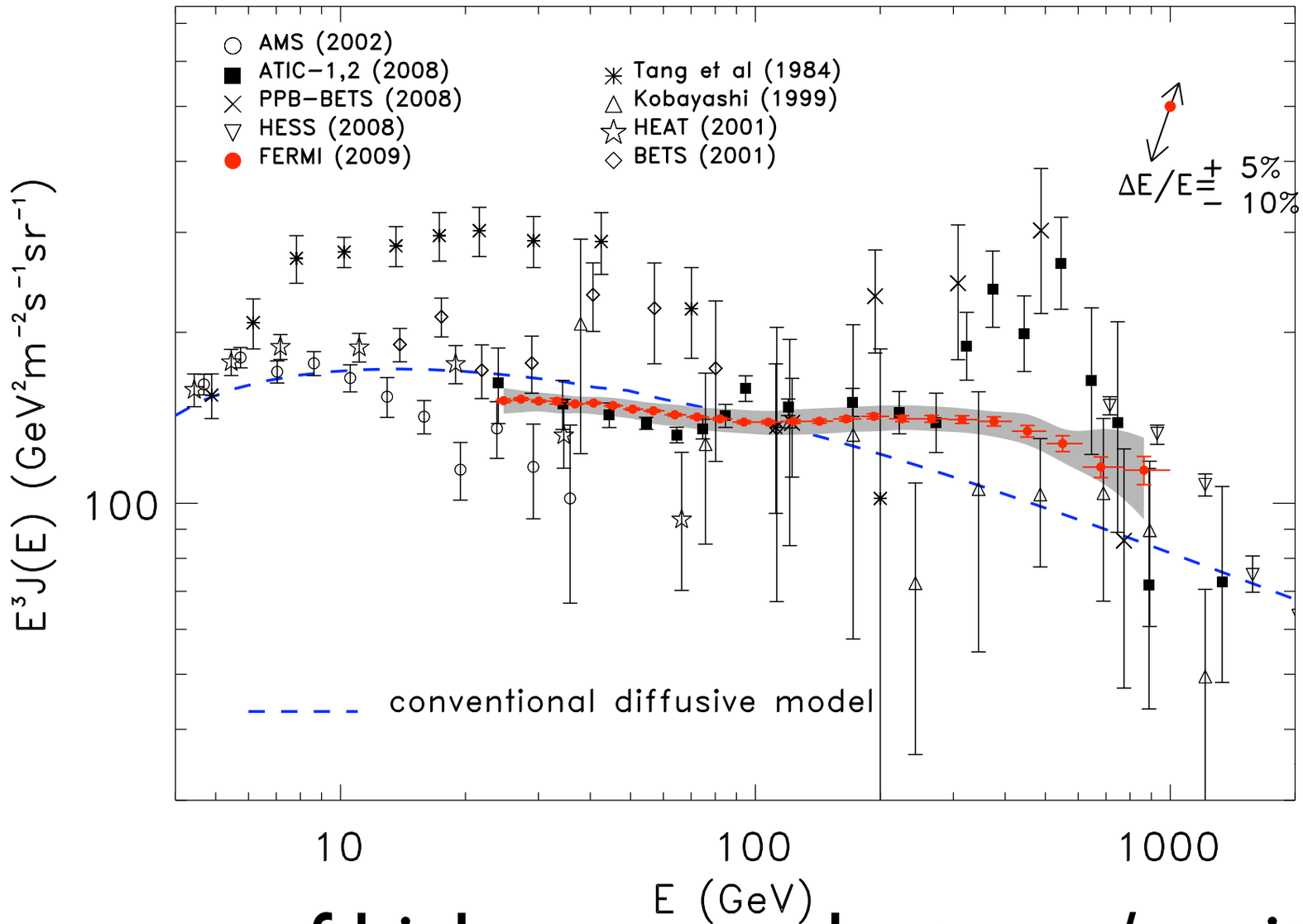
New source of high energy positrons, no anti-protons

Motivation for non-standard WIMPs



Indirect detection

FERMI



New source of high energy electrons/positrons, no noticeable features below ~1 TeV

Interpretation

- Nearby, young pulsar
- Incorrect modeling of propagation of cosmic-rays
- Lepton rich dark matter decay/annihilation products

Rate is ~(100-1000)x higher than expected for thermal DM relic.

Mass (>800 GeV) is also far larger than "normal" weak scale models of DM

$$\Gamma \sim \int \rho^2 \langle \sigma v \rangle dV$$

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Particle physics

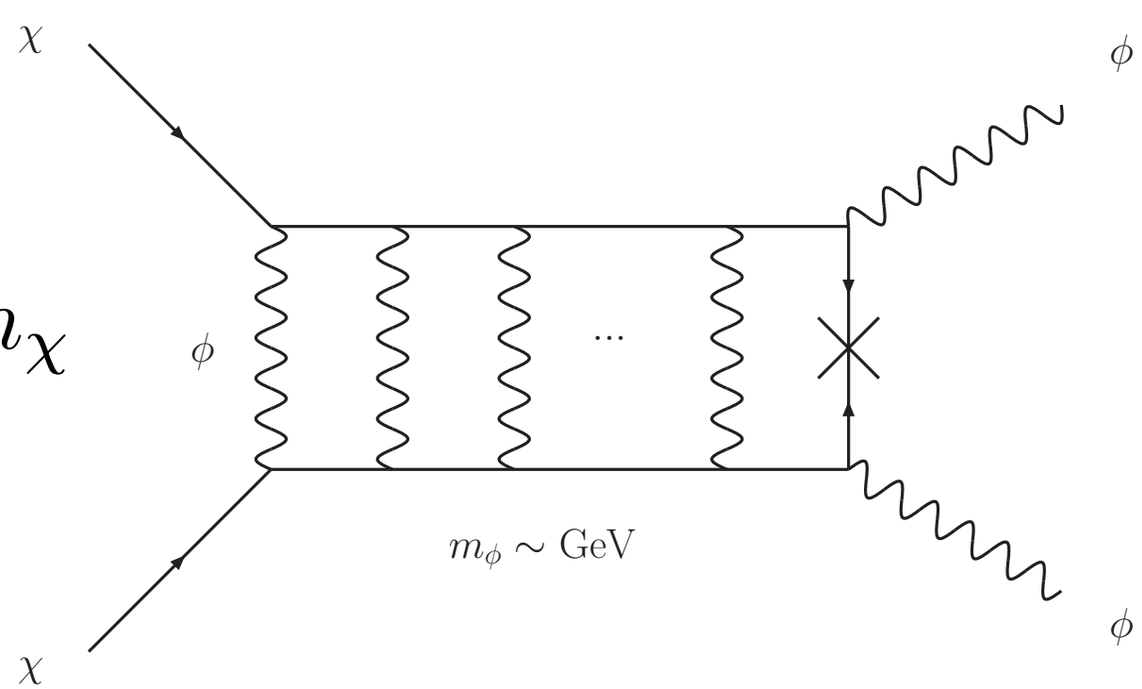
$$\langle \sigma v \rangle_{freeze\ out} \neq \langle \sigma v \rangle_{now}$$

Dark Forces

Velocity dependent enhancement to annihilation cross section from Sommerfeld enhancement [Hisano, Matsumoto, Nojiri, Saito] [Arkani-Hamed, Finkbeiner, Slatyer, Weiner]

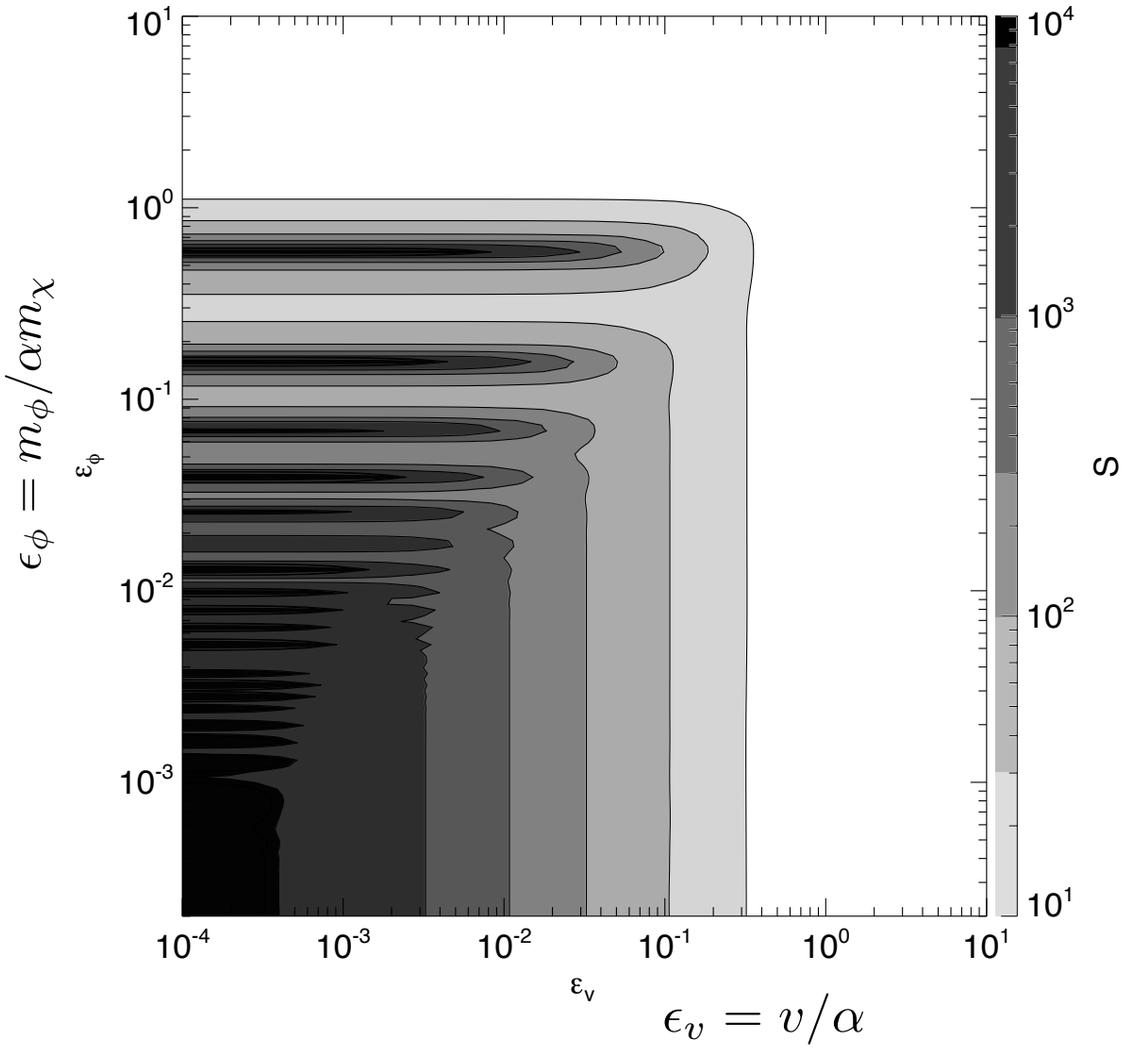
$$\sigma v \sim |\psi(0)|^2$$

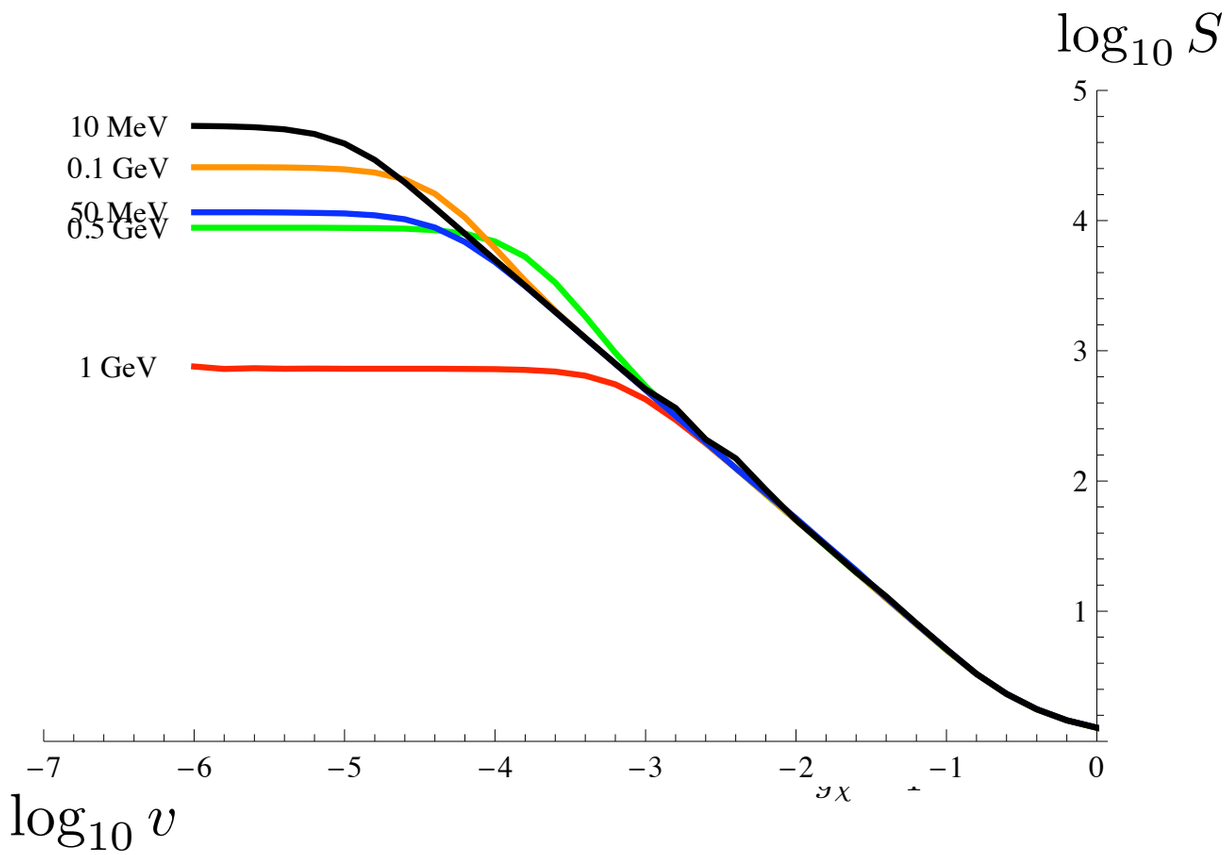
$$m_\phi \lesssim \alpha\, m_\chi$$



$$\Rightarrow \sigma v \sim \frac{1}{v}$$

Dark Forces





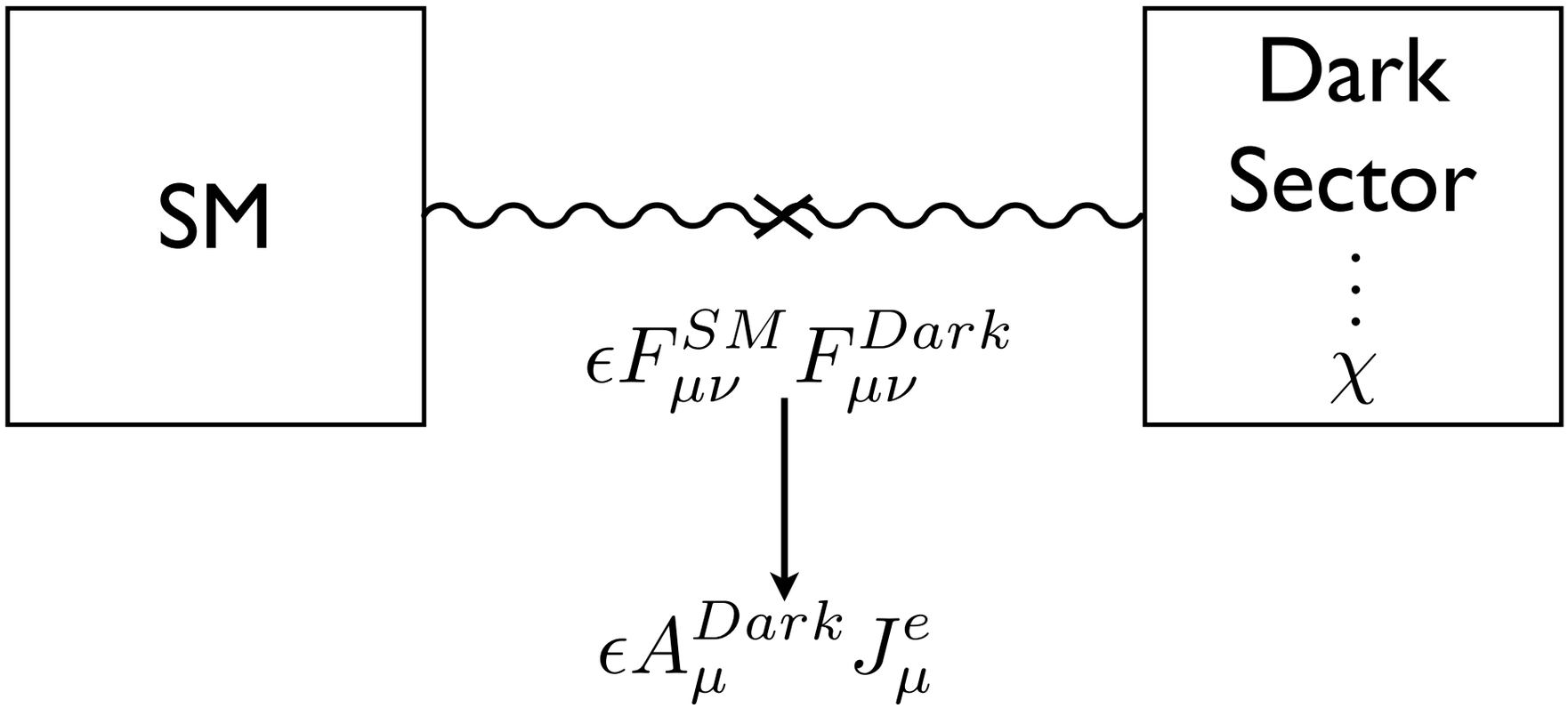
A new light state coupled to the DM, can also explain lepton rich final states

- A symmetry forbids hadrons $m_\phi \lesssim 20\ \mathrm{GeV}$ [PJF and Poppitz]
- Kinematics forbids hadrons $m_\phi \lesssim 500\ \mathrm{MeV}$

[Arkani-Hamed, Finkbeiner, Slatyer, Weiner]

Kinetic Mixing

[Holdom; Arkani-Hamed, Finkbeiner, Slatyer, Weiner]



- Dark gauge boson is massive, m<proton mass
- Dark sector cascades, hidden valleys [Strassler and Zurek]
- Displaced vertices
- High multiplicity, lepton rich events
- Missing energy

Bounds on light gauge bosons

Anomalous magnetic moments $\Delta(g-2)_l \sim \frac{g_l^2}{4\pi^2}\frac{m_l^2}{M_U^2}$

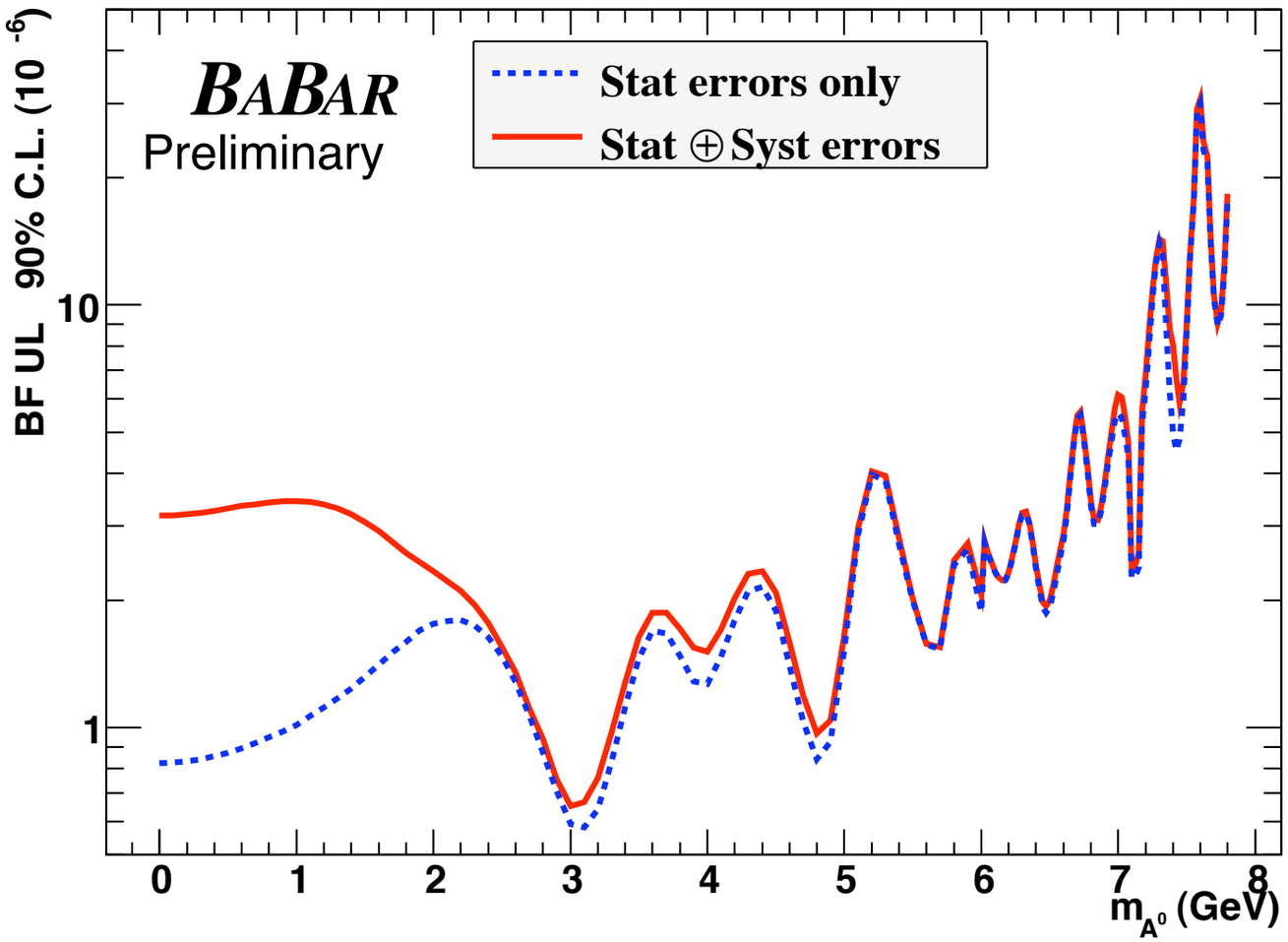
$$g_e \lesssim 4\times 10^{-2}\frac{M_U}{\mathrm{GeV}},\ g_\mu \lesssim 2\times 10^{-3}\frac{M_U}{\mathrm{GeV}},\ g_\tau \lesssim 0.4\frac{M_U}{\mathrm{GeV}}$$

U-boson couples to neutrinos influences $\nu - e$ scattering

$$g_e \lesssim 3\times 10^{-3}\frac{M_U}{\mathrm{GeV}}$$

Bounds on light gauge boson

B-factory constraints on $e^+e^- \to \gamma + \not{E}_T$

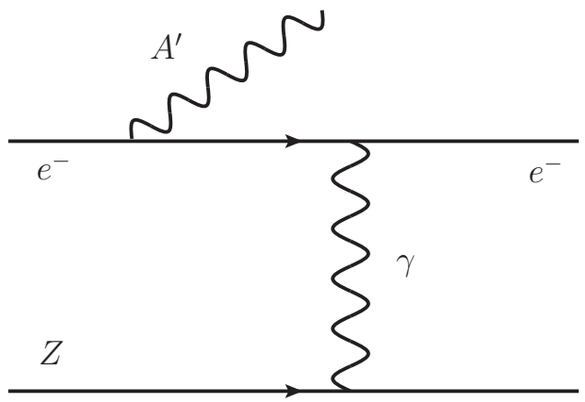


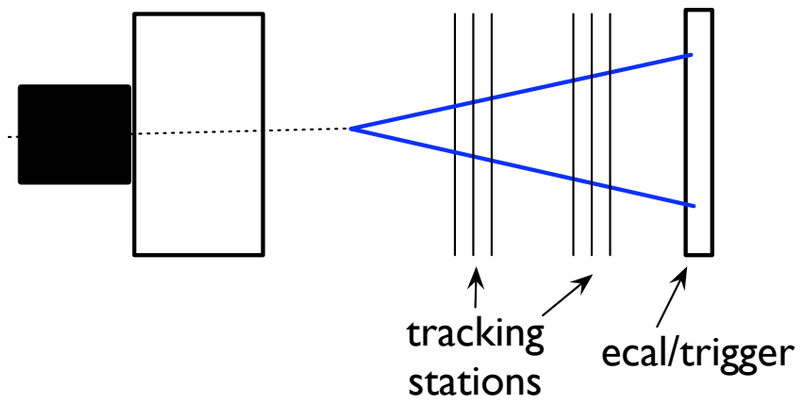
Translates to

$$g_e \lesssim 10^{-3}$$

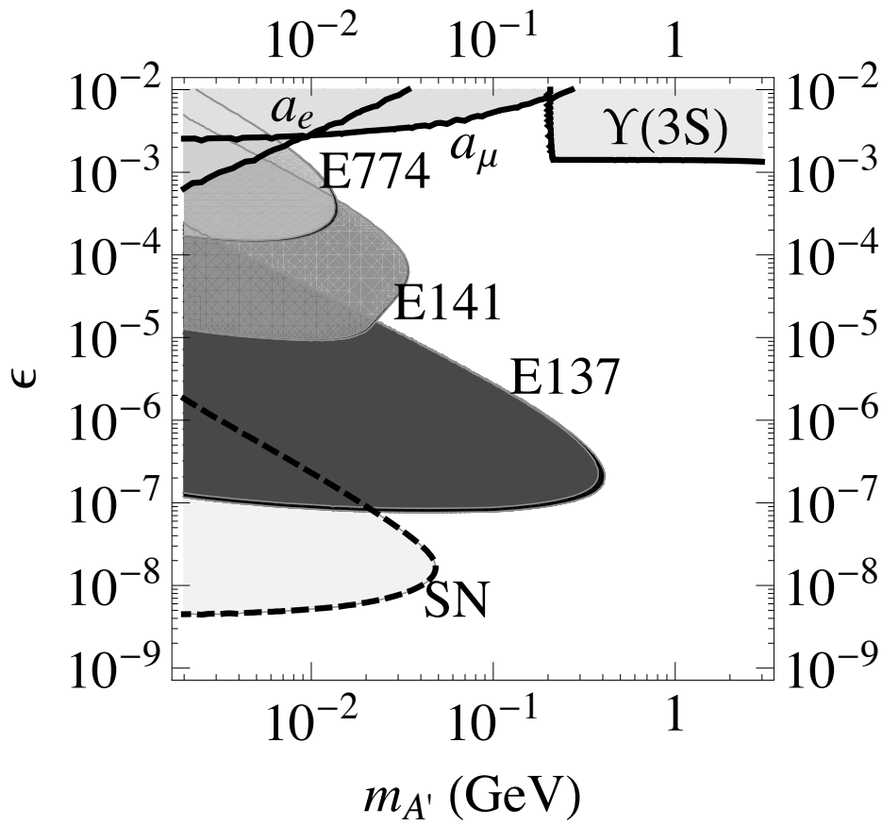
for $M_U \leq 7.8\,\mathrm{GeV}$

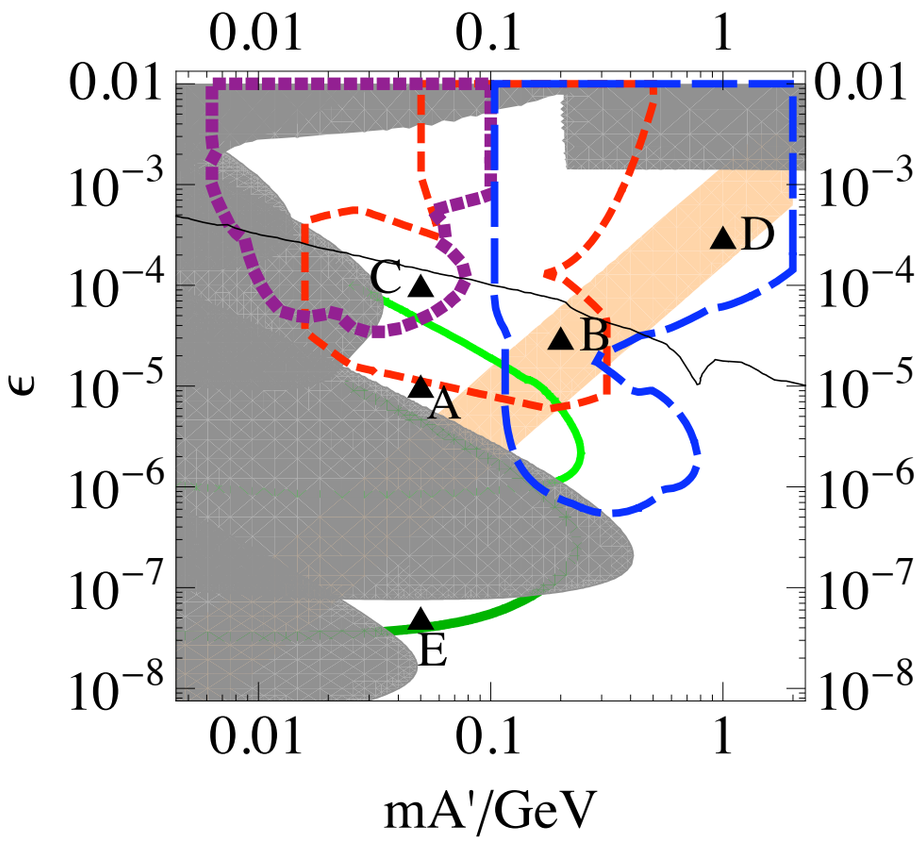
Fixed target experiments [Bjorken, Essig, Schuster and Toro]





- High luminosity
- High energy not required
- Fast, cheap

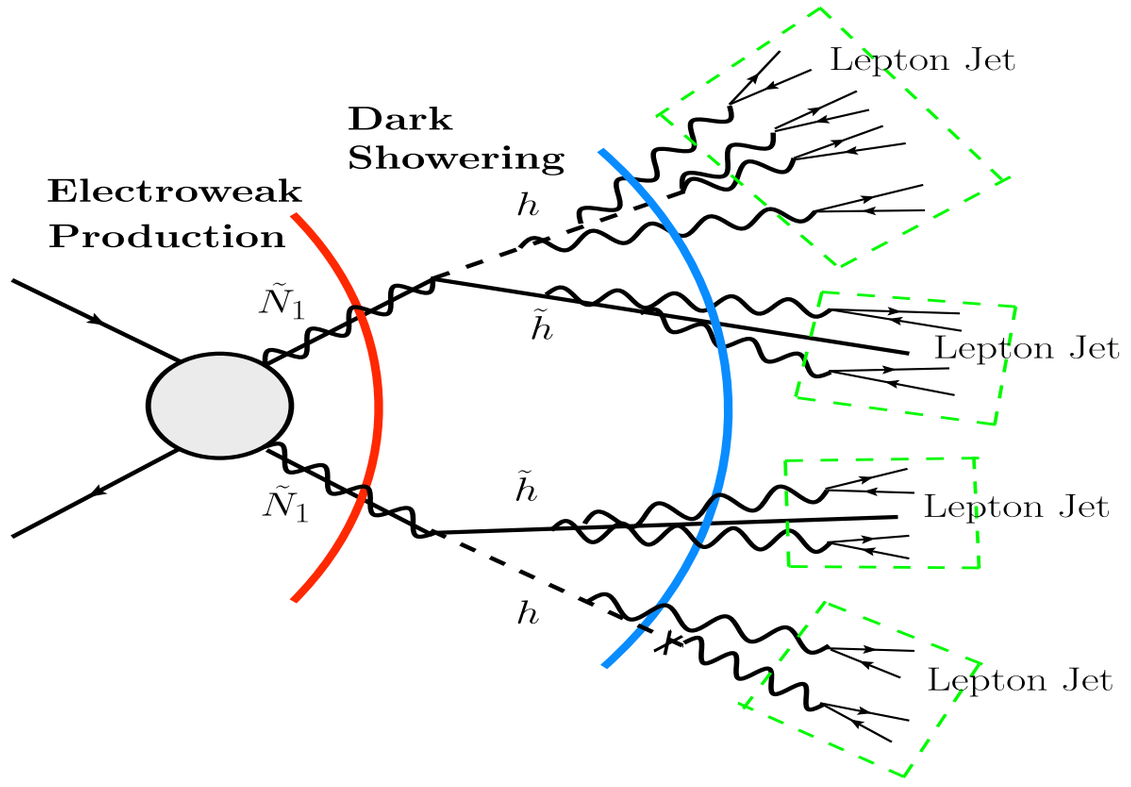




LHC signals

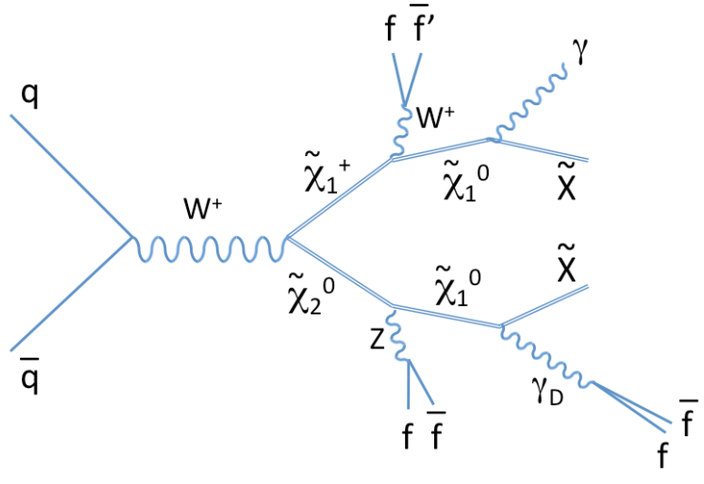
Myriad of possibilities depending on details of Dark Sector

- Missing energy
- High multiplicity
- Lepton jets
- Displaced vertices



[Cheung, Ruderman, Wang, Yavin]

D0 search for dark photons:



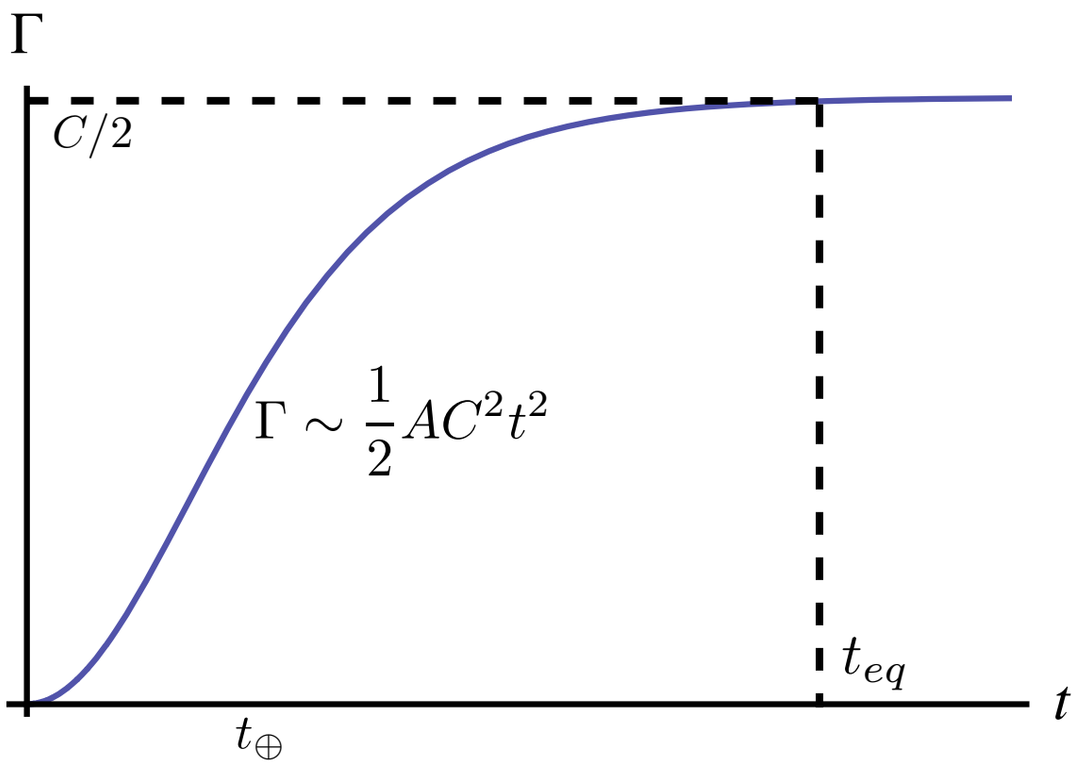
Leptophilic Models

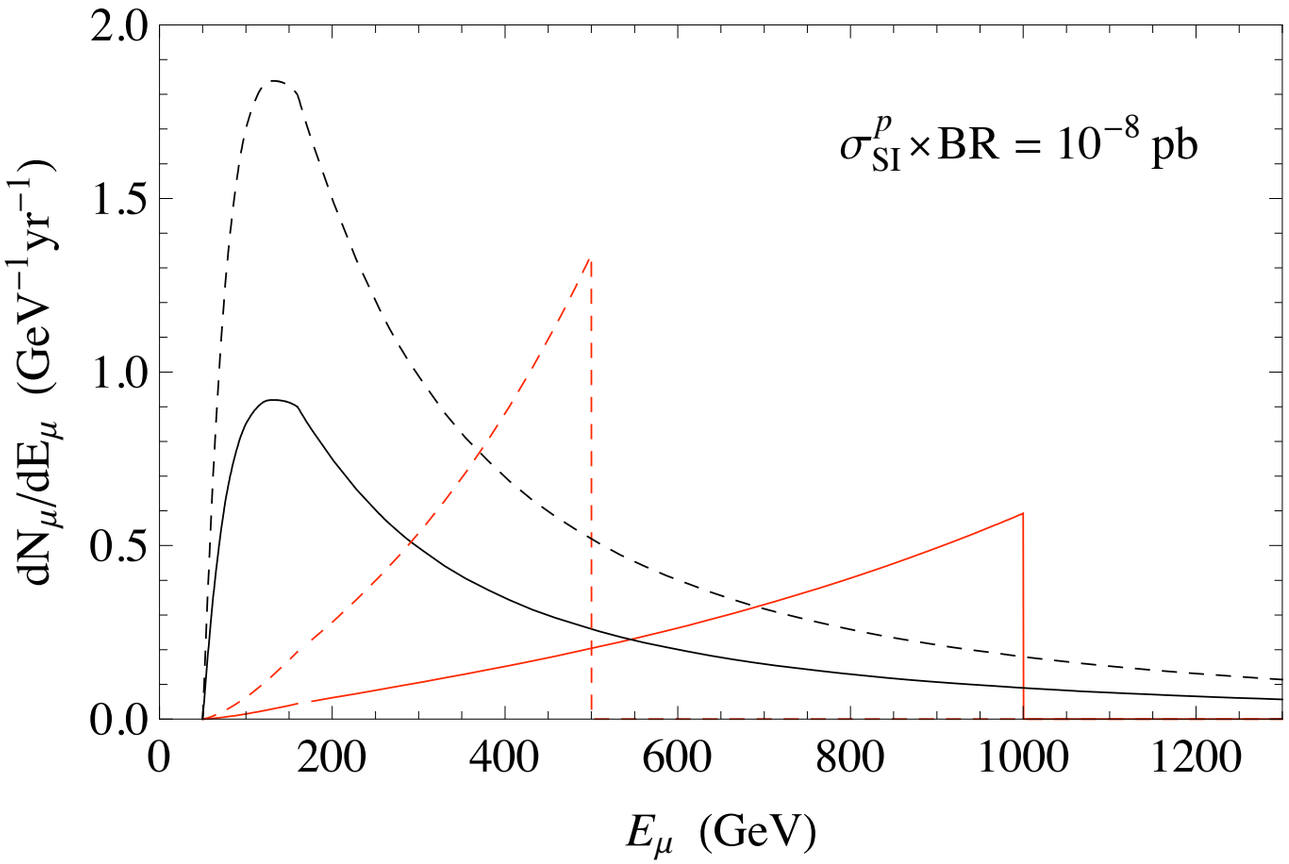
[PJF and Poppitz]

- Leptophilic gauge boson, need not be lighter than proton
- Simple model
- DM annihilates to charged leptons and neutrinos
- Search for upward going earthborn neutrinos at IceCube

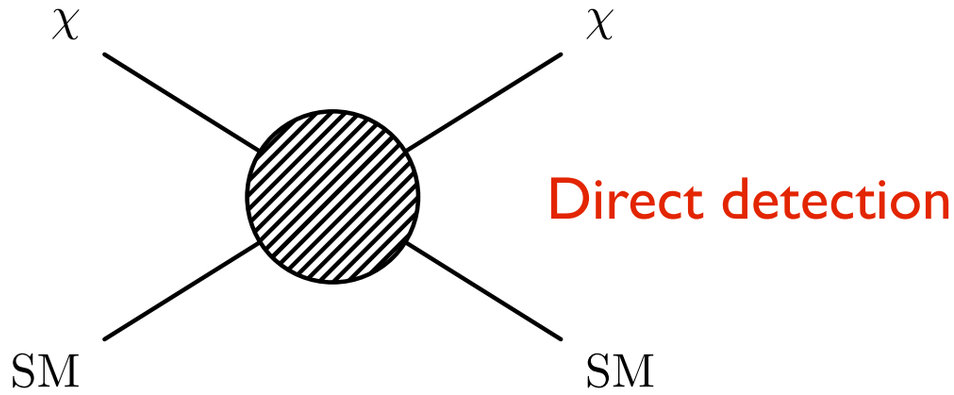
[Delaunay, PJF, Perez]

$$\Gamma = \frac{1}{2} A N^2 = \frac{C}{2} \tanh^2 \left(t_\oplus \sqrt{CA} \right)$$

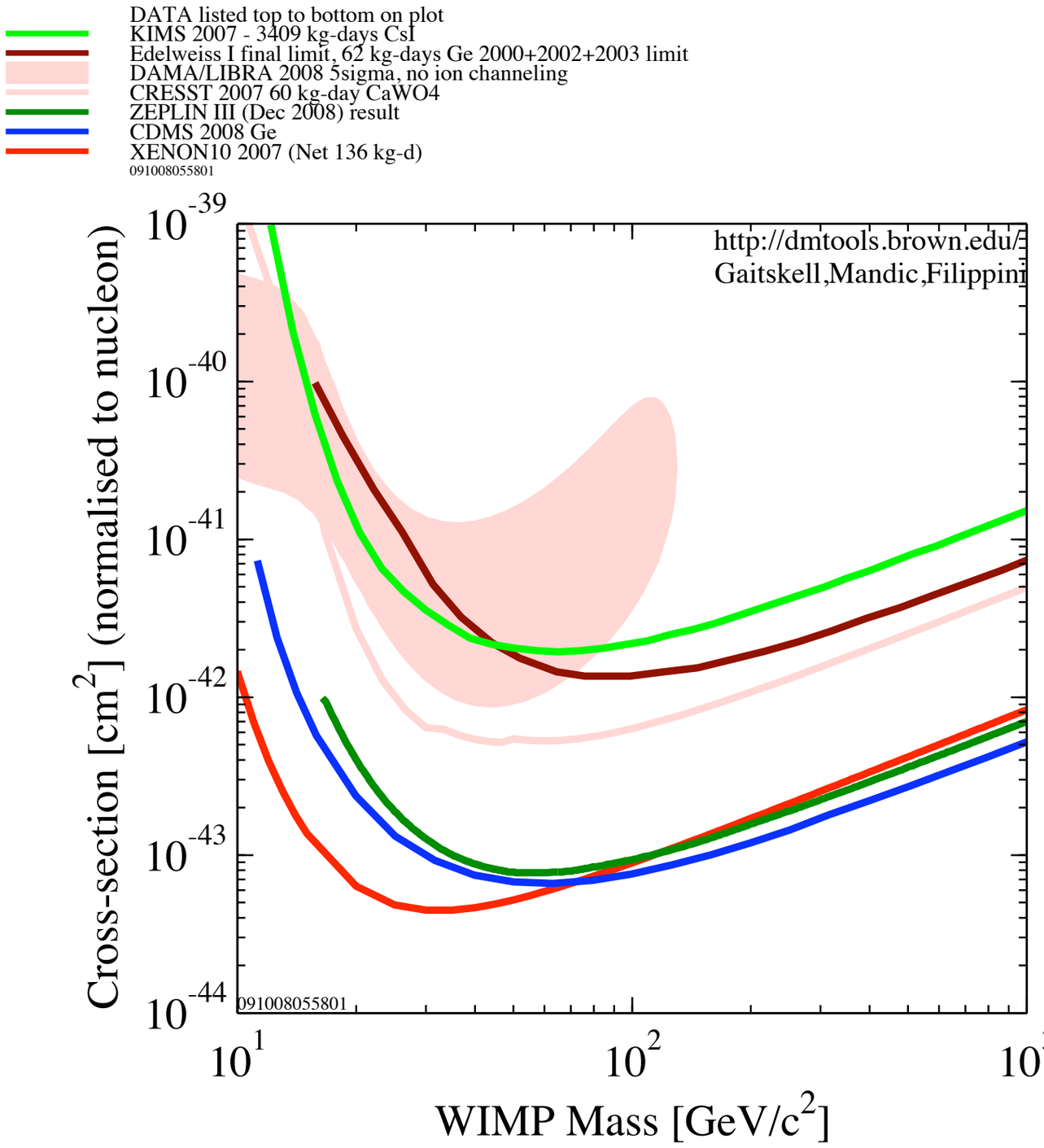




(Another) Motivation for non-standard WIMPs

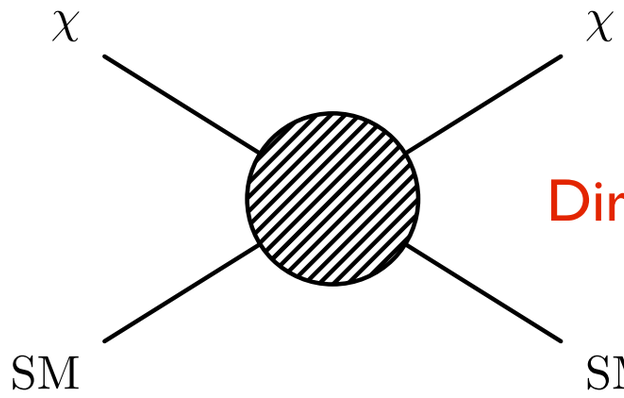


Direct detection



- DAMA and others incompatible
- Rule out normal WIMPs
- Suppressed coupling to Z, Y=0
- Many different experiments

(Another) Motivation for non-standard WIMPs



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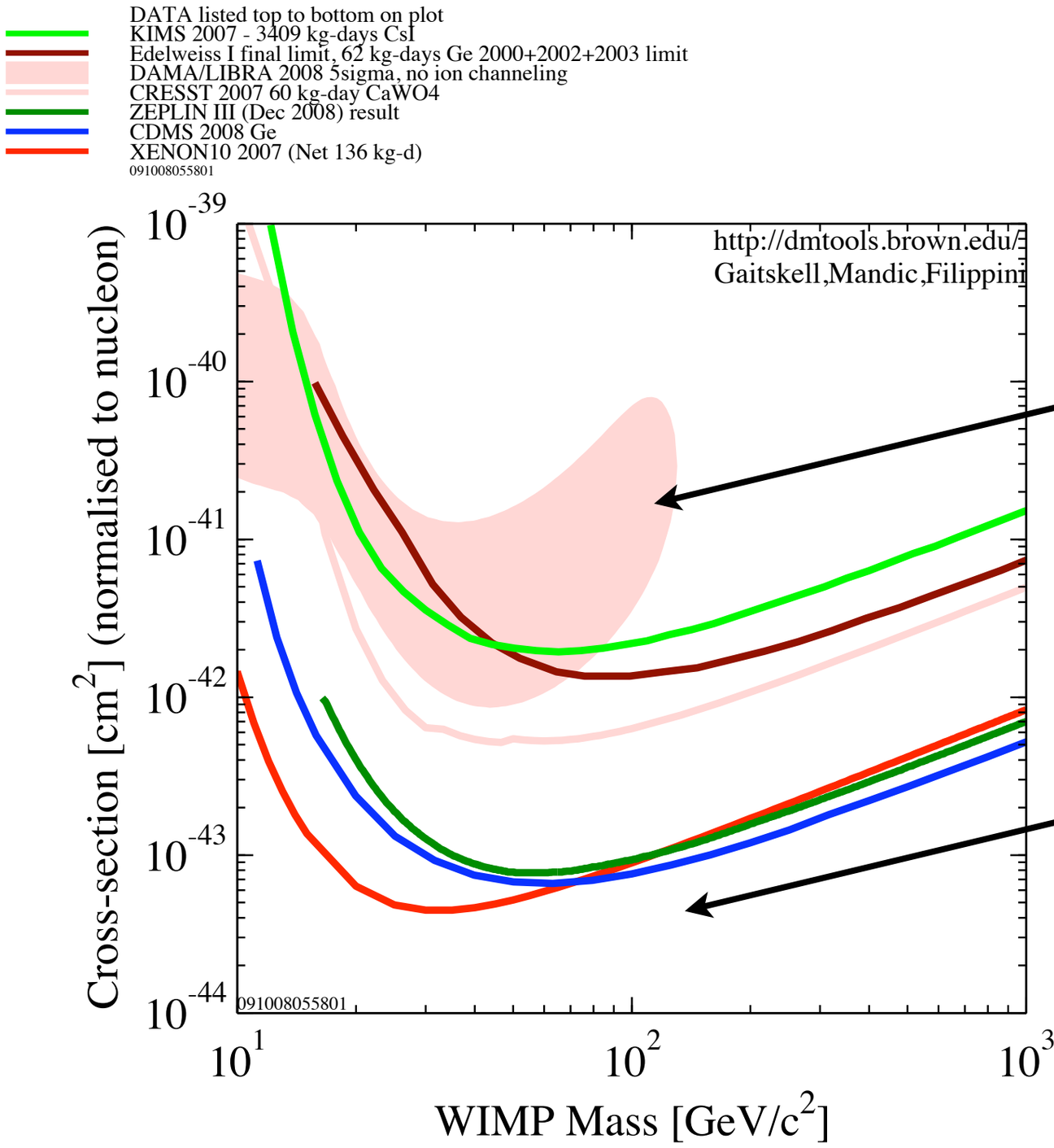

DAMA allowed region

CDMS/XENON etc allowed region

- DAMA and others incompatible
- Rule out normal WIMPs
- Suppressed coupling to Z, Y=0
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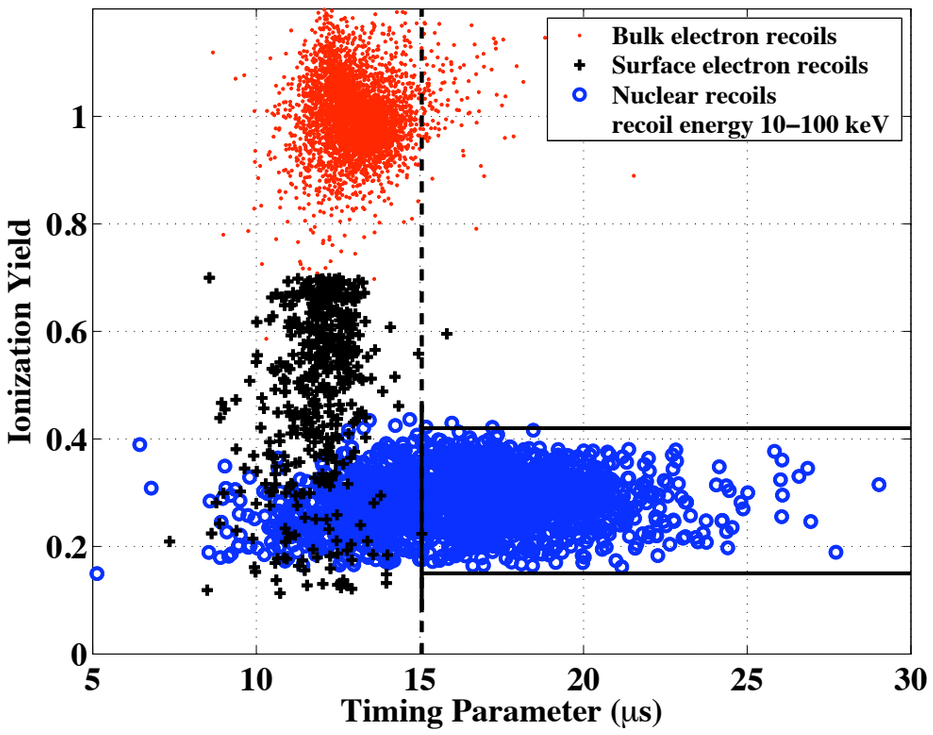
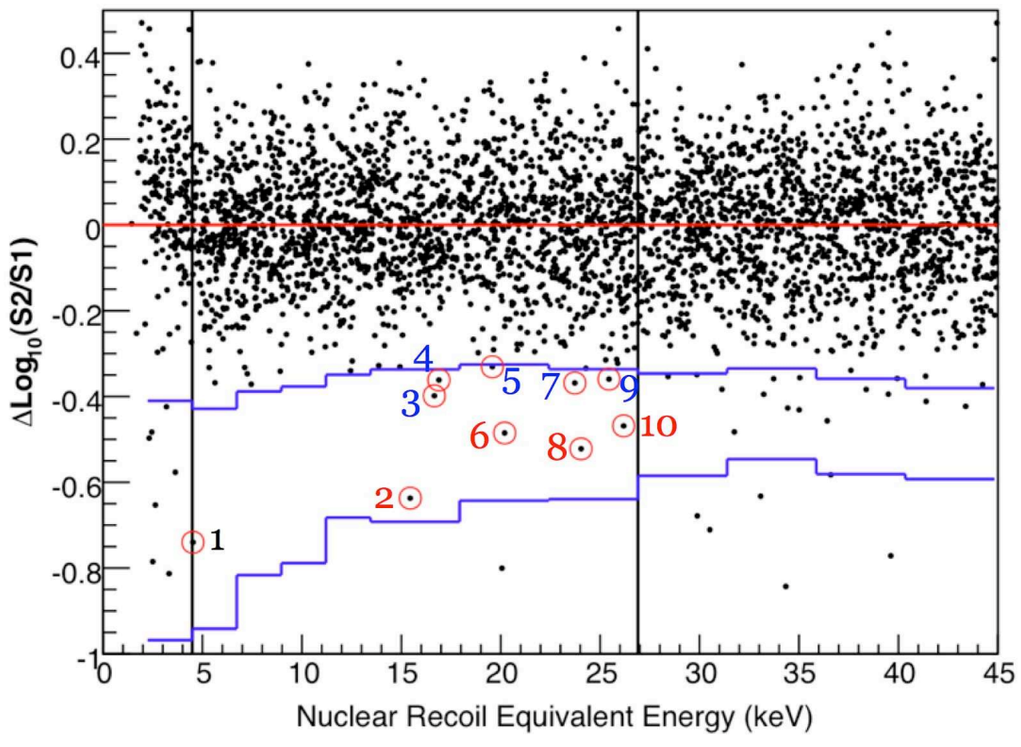
Direct Detection

One Way:

- Remove cosmic backgrounds by going underground
- Shield experiment from radioactive elements
- Cool equipment
- Take multiple measurements to distinguish background from nuclear recoils e.g. ionization, scintillation, phonons



[CDMS collaboration]



[XENON10 collaboration]

Direct Detection

Another way, annual modulation

In galactic frame:

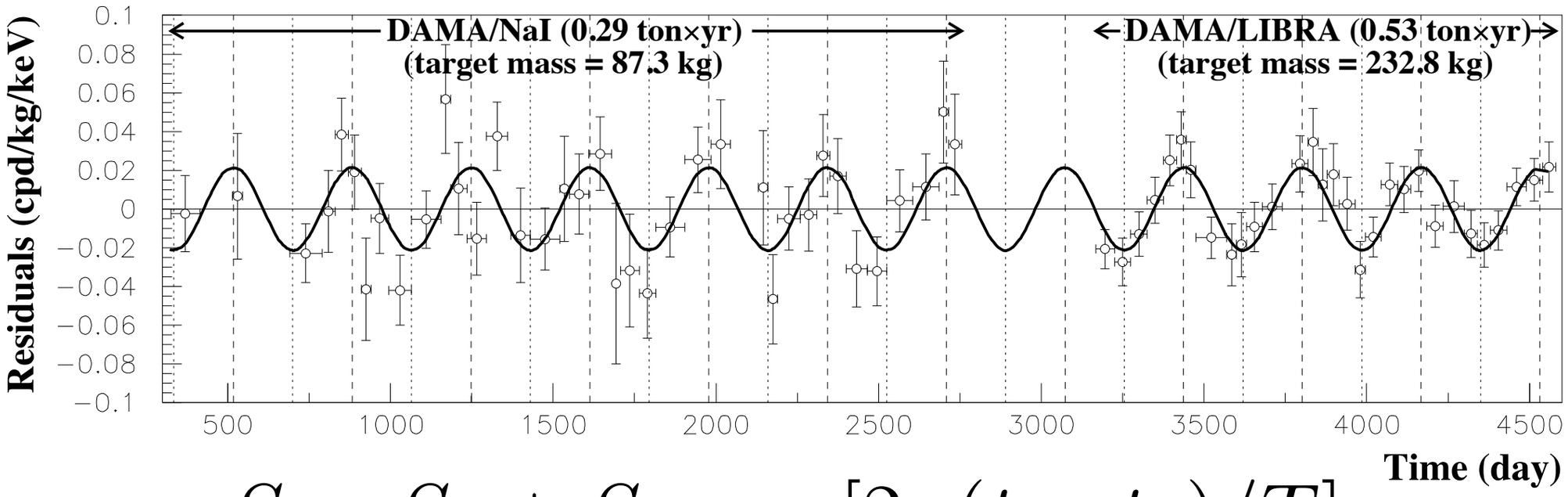
$$f(v) = \frac{1}{(\pi v_0^2)^{3/2}} e^{-v^2/v_0^2}$$

In Earth's frame:

$$f(\vec{v}, \vec{v}_E) = \frac{1}{(\pi\, v_0^2)^{3/2}}\, e^{-(\vec{v}+\vec{v}_E)^2/v_0^2}$$

$$v_E \approx 227 + 14.4 \cos\left[2\pi\left(\frac{t-t_0}{T}\right)\right]$$

8.2σ!



$$S = S_0 + S_m \cos\left[2\pi(t - t_0)/T\right]$$

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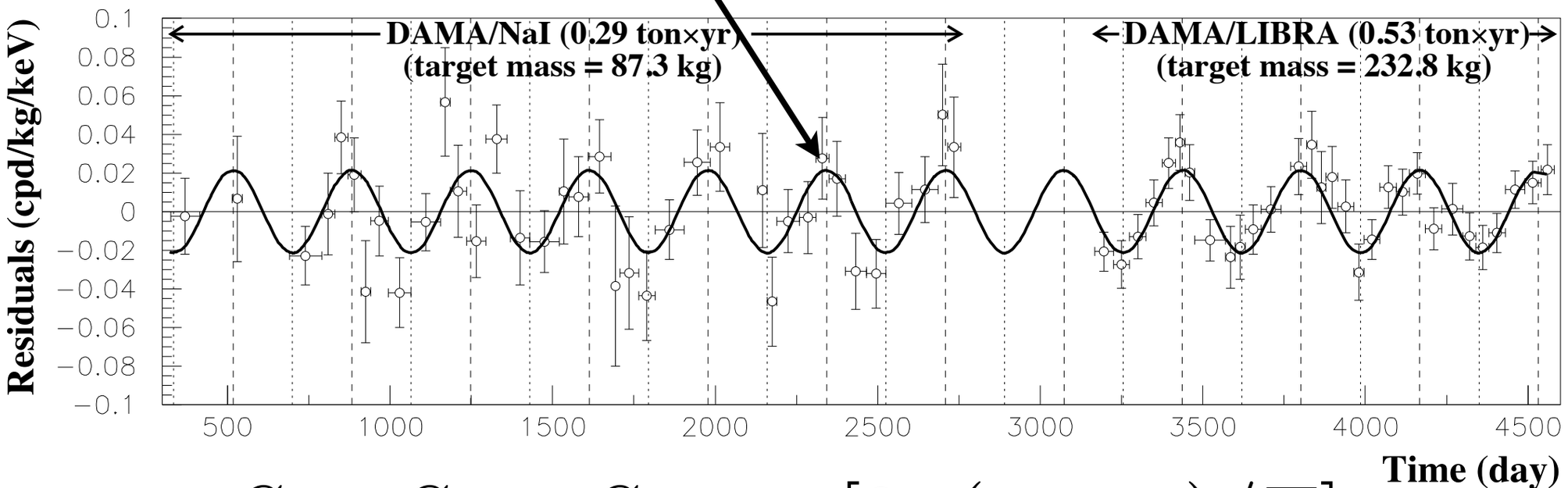
$t_0 = \text{June } 2^{\text{nd}}$

2-4 keV

8.2σ!



$$S = S_0 + S_m \cos\left[2\pi(t - t_0)/T\right]$$

Does annual modulation = discovery of DM?

Many things modulate on a year timescale:

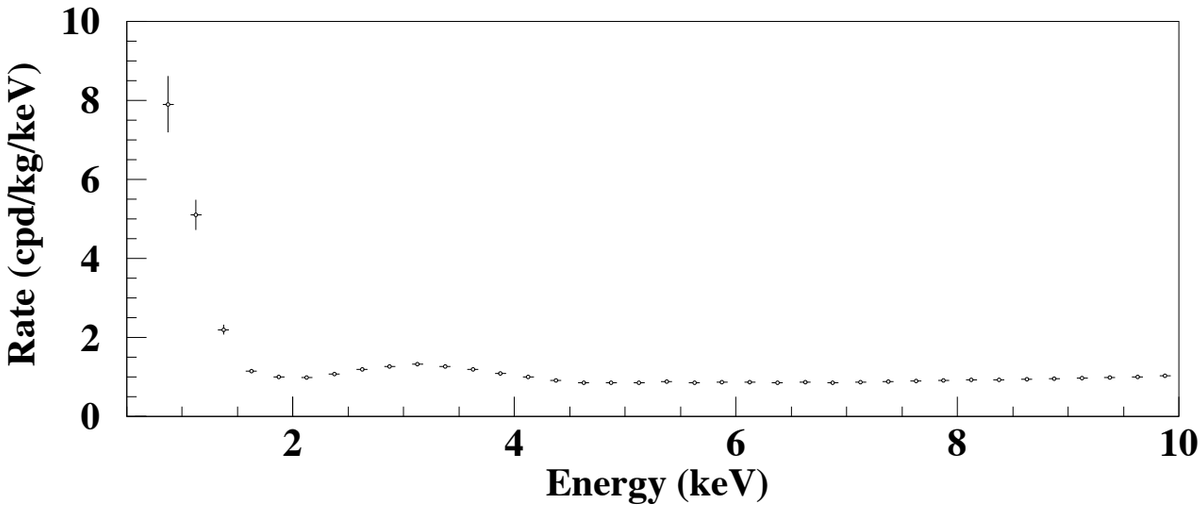
- temperature
- water loading
- radon abundance
- ice-cream sales....

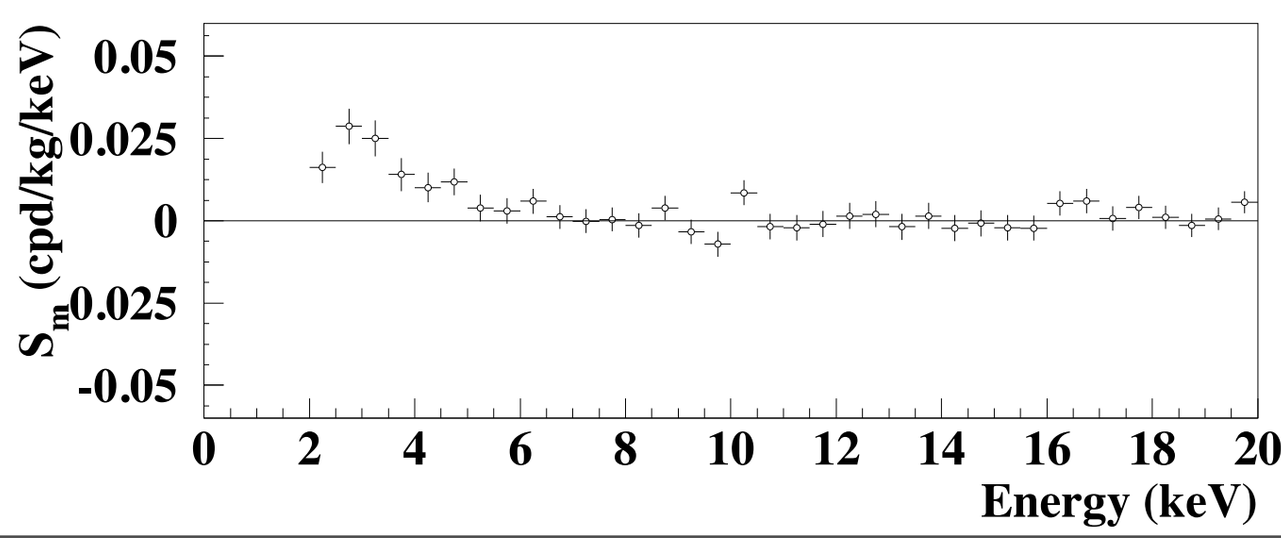
But, very few line up year on year with June 2nd

Possible explanations

- Low mass dark matter with channelling, M~10 GeV
- Leptophilic DM
- Inelastic Dark Matter (iDM)
- Form Factor Dark Matter (FFDM or MDDM)
- Resonant Dark Matter (rDM)

$$S = S_0 + S_m \cos\left[2\pi(t - t_0)/T\right]$$





Possible explanations

- Low mass dark matter with channelling, M~10 GeV
- Leptophilic DM
- Inelastic Dark Matter (iDM)
- Form Factor Dark Matter (FFDM or MDDM)
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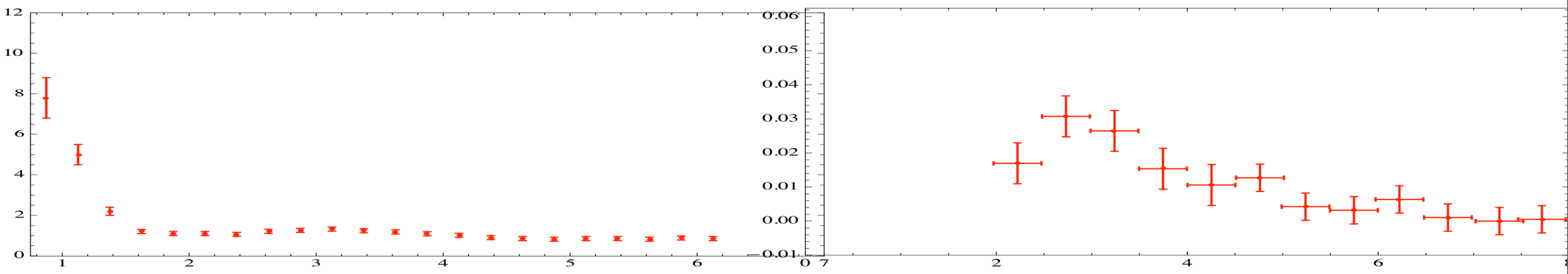

Non-standard WIMP explanations?

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$$\frac{dR}{dE_R} = \frac{N_T\, m_N\, \rho_\chi}{2\,\mu_{N\chi}^2\, m_\chi} \int_{v_{min}}^{v_{max}} d^3\vec{v}\, \frac{f(\vec{v}, \vec{v}_E)}{v}\, \sigma_N\, F^2(E_R)$$

$N_T = N_A/A \quad N_A = 6 \times 10^{26}\,\mathrm{kg}^{-1} \quad m_N = A\, m_p \qquad \mu_{N\chi} = \dfrac{m_N m_\chi}{m_N + m_\chi}$

$\sigma_N =$ nuclear cross section $\qquad F(E_R) =$ form factor

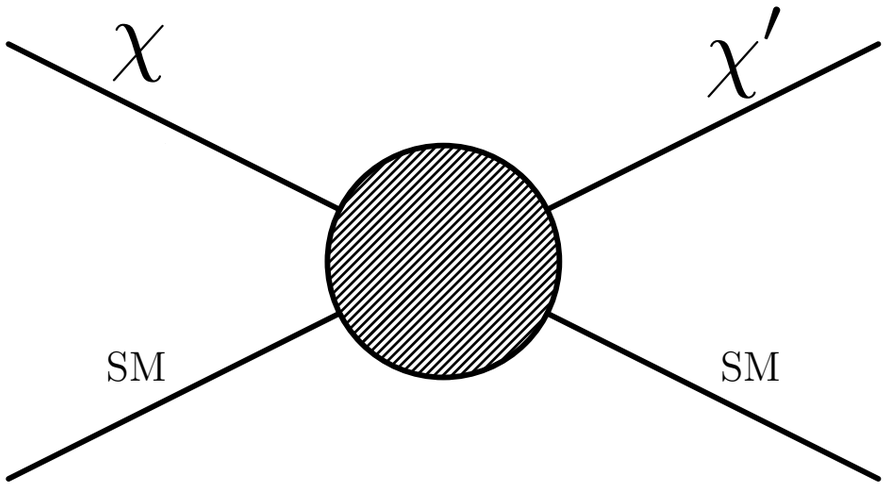
Usual case (WIMP)

$$\sigma_N = \frac{(Z f_p + (A - Z) f_n)^2}{f_p^2} \frac{\mu_{N\chi}^2}{\mu_{n\chi}^2} \sigma_p \qquad v_{min} = \sqrt{\frac{m_N E_R}{2\mu_{N\chi}^2}}$$

$$F(q) = \int d^3r \rho(r)\, e^{i\mathbf{q}.\mathbf{r}} \qquad \rho(r) = \rho_0 \left[1 + e^{\frac{r-c}{a}}\right]^{-1}$$

Inelastic Dark Matter (iDM)

[Weiner and Tucker-Smith]



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$$v_{min} = \sqrt{\frac{1}{2 m_N E_R}} \left(\frac{m_N E_R}{\mu_{N\chi}} + \delta \right)$$

$$m_\chi - m_{\chi'} = \delta \sim 100\,\mathrm{keV}$$

- Requires "large" momentum exchange to upscatter
- Favours high velocity tail of MB distribution
- Increased modulation
- Prefers heavy targets e.g. iodine, xenon, tungsten,..
- Recoil spectrum has a peak, unique feature?

All of the above help to make DAMA consistent with CDMS, predicts events at other heavy element detectors

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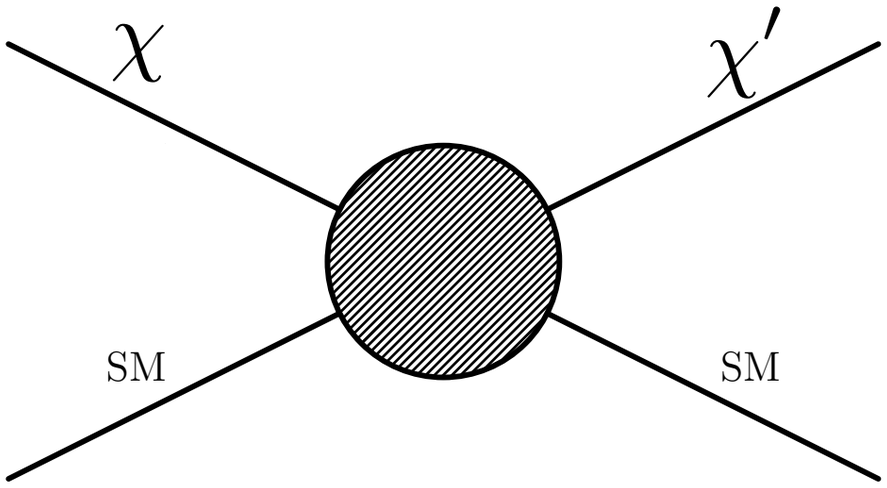

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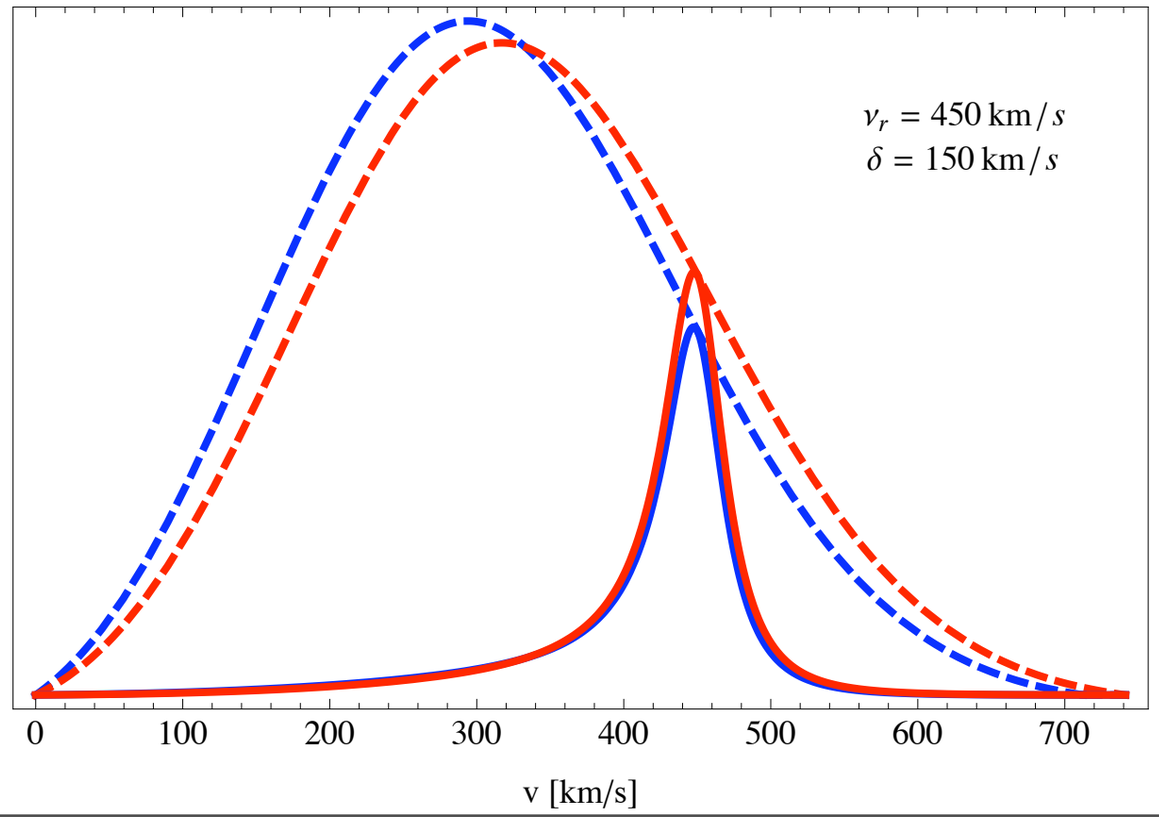
Resonant Dark Matter (rDM) [Bai and PJF]

$$\frac{dR}{dE_R} = \frac{N_T\, m_N\, \rho_\chi}{2\,\mu_{N\chi}^2\, m_\chi} \int_{v_{min}}^{v_{max}} d^3\vec{v}\, \frac{f(\vec{v},\vec{v}_E)}{v}\, \sigma_N\, F^2(E_R)$$

- Cross section is velocity dependent
- In particular the velocity dependence is "resonant"
- Picks out small range of velocities
- Increases modulation
- In our particular model realisation scattering is highly element dependent



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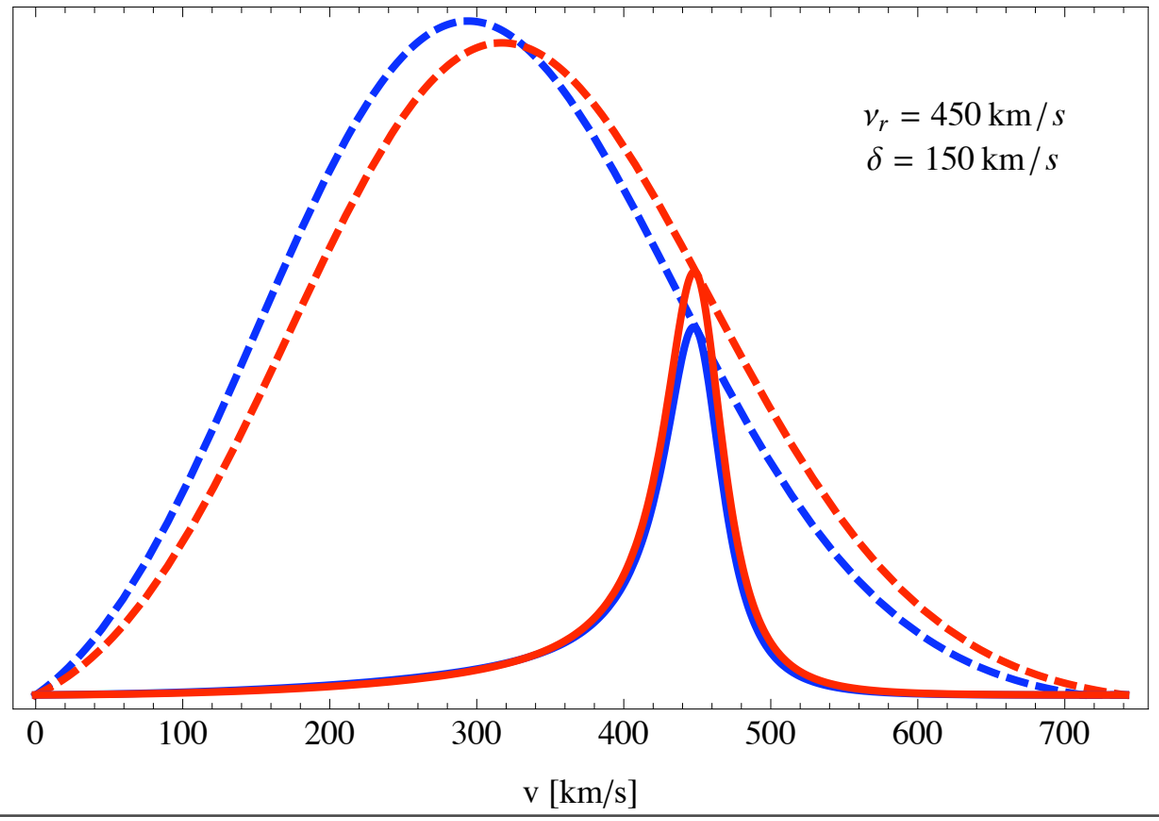
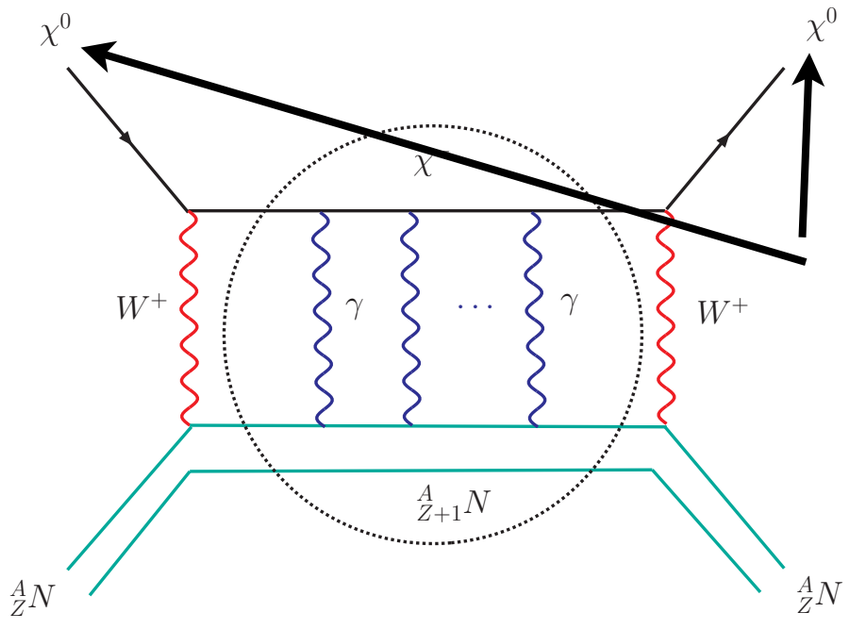
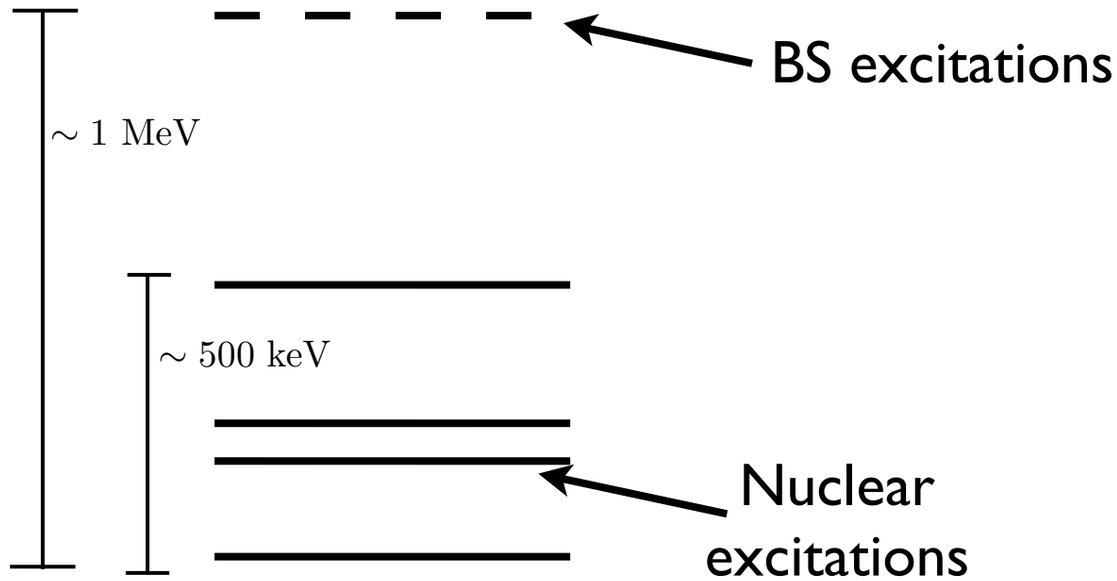


Resonant scattering



Elastic scattering



Excitation energy

$$m_r = m_{\chi^-} + m_{^A_{Z+1}N} + \omega - E_b\,,$$

Speed of DM needed to hit resonance

$$v_r^2 = \frac{2(\Delta + m_{^A_{Z+1}N} - m_{^A_Z N} + \omega - E_b)}{\mu_{\chi N}}$$

Highly element (experiment) dependent

Bound state

If the splitting is small enough there may be an accessible nucleus- χ^- bound state

${}^{A}_{Z}N$	${}^{23}_{11}Na$	${}^{28}_{14}Si$	${}^{74}_{32}Ge$	${}^{127}_{53}I$	${}^{129}_{54}Xe$	${}^{133}_{55}Cs$	${}^{184}_{74}W$
${}^{A}_{Z+1}N$	${}^{23}_{12}Mg$	${}^{28}_{15}P$	${}^{74}_{33}As$	${}^{127}_{54}Xe$	${}^{129}_{55}Cs$	${}^{133}_{56}Ba$	${}^{184}_{75}Re$
Δm (MeV)	3.8	13.8	2.1	0.15	0.7	0.01	1.0
S_n (MeV)	13.1	14.5	8.0	7.3	9.6	7.2	6.5
E_b (MeV)	5.8	7.5	13.5	19.1	19.4	19.6	23.3

CDMS: Si, Ge

DAMA: Na, I

KIMS: Cs,I

Xenon: Xe

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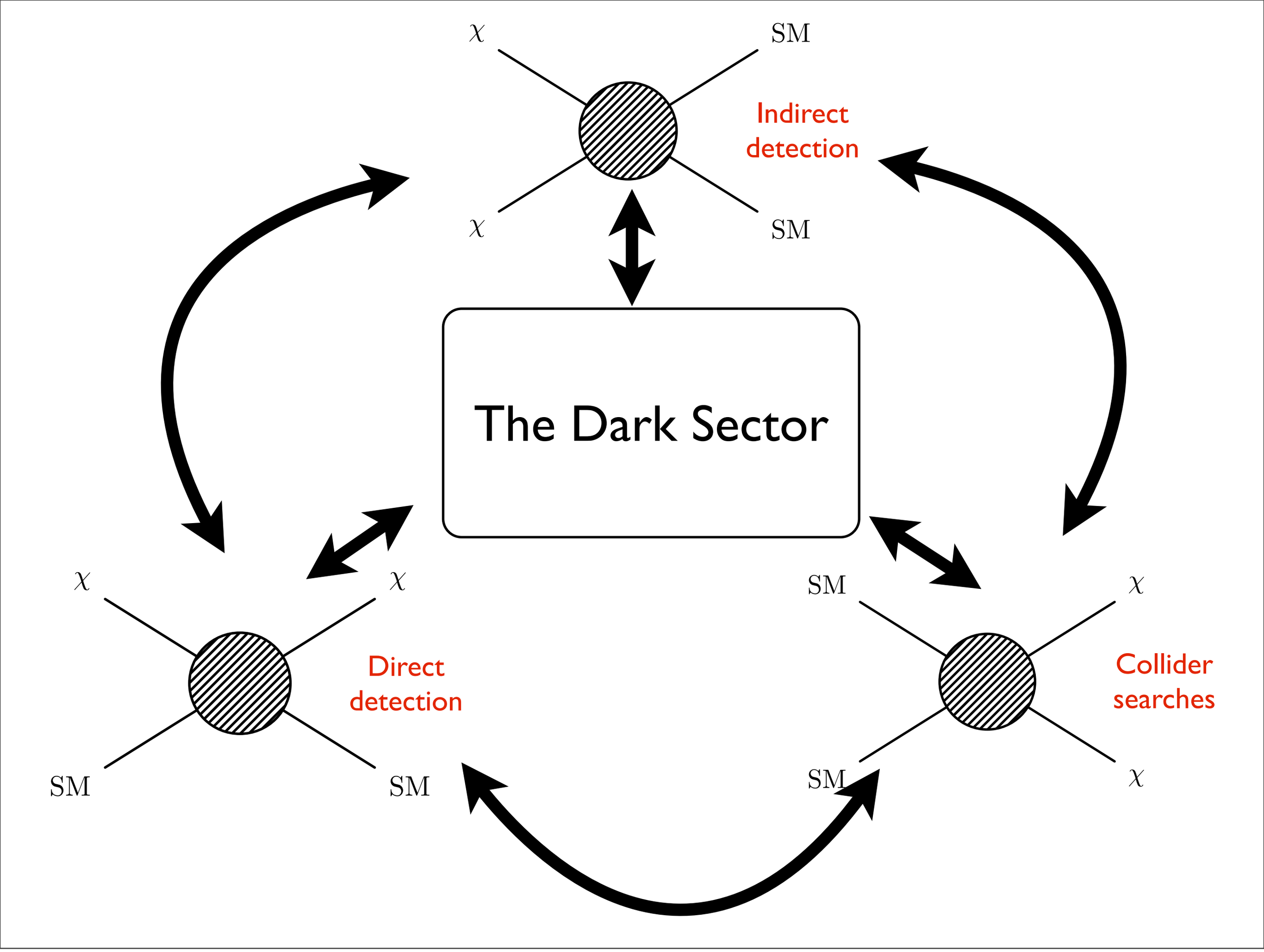
χ
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Indirect
detection
χ
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The Dark Sector
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Direct
detection
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SM
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Collider
searches
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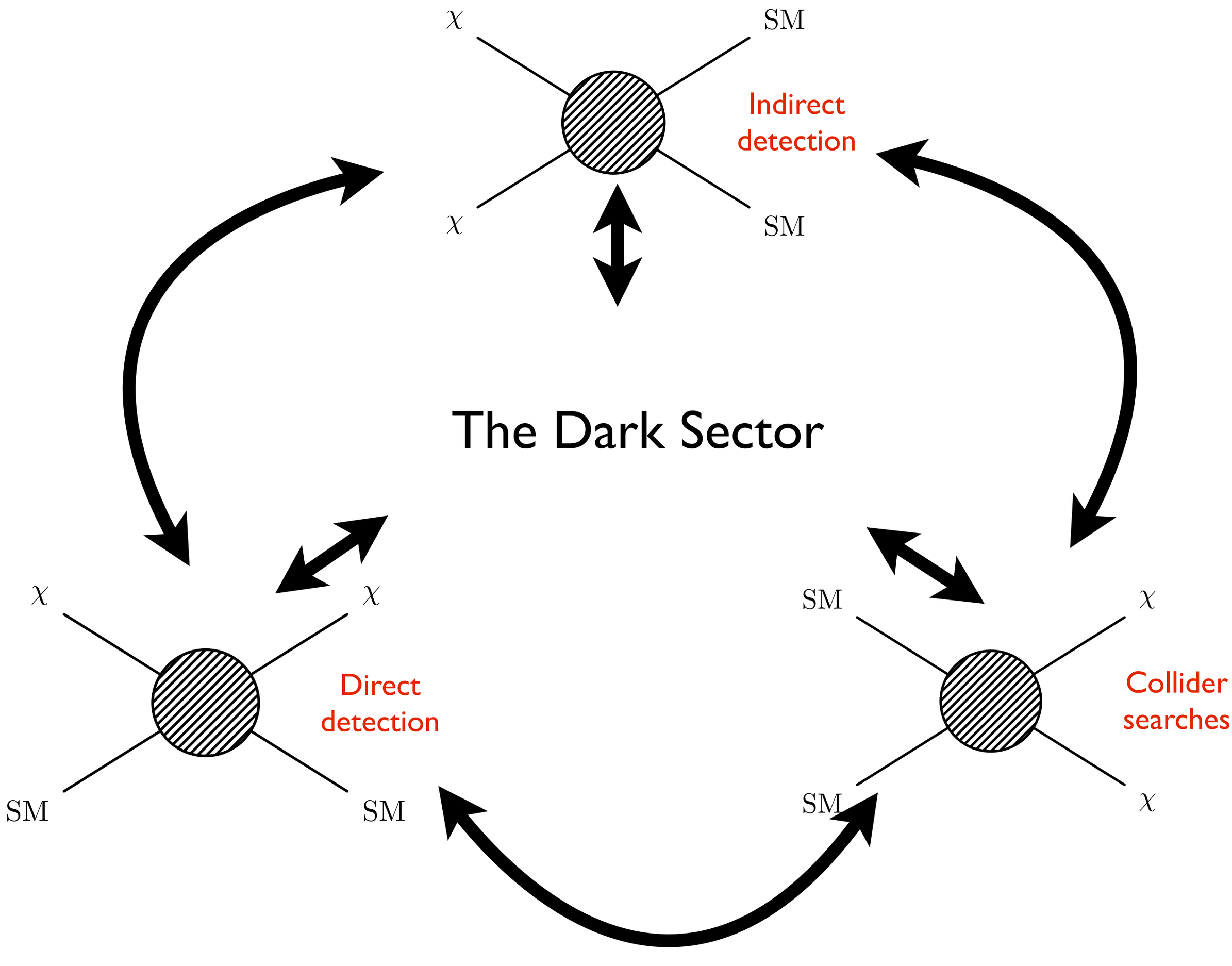
χ
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SM
χ
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Outlook

- Very exciting time
- Dark matter being probed on multiple fronts
- Dark sector may be very non-trivial
- Wealth of new data, more expected
- Explosion in model building
- Many new predictions that can be searched for

Stay tuned.....