Prejudices and Requirements from Theory for Dark Matter searches

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HEPHY & TU Vienna Workshop
on future DM experiments
Oct 15, 2013

educated guesses

~~Prejudices~~ and Requirements

from Theory

for Dark Matter searches

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Outline

1. The case for particle Dark Matter
2. A classification-scheme for Dark Matter models
3. The WIMPs paradigm
   - laboratory detection (direct detection, LHC)
   - implications of the recent Higgs discovery
4. The light DM frontier
   - motivation and caveats
5. New opportunities for rare underground event searches
6. Some comments on DAMA

Missing mass on all scales relevant to astrophysics

stellar kinematics above the galactic disc < 4 kpc

$$\rho_{\mathrm{DM,local}} = 0.3 \pm 0.1\,\mathrm{GeV/cm^3}$$

Bovy & Tremaine 2012

satellites of Milky Way as "test particles"

$$M_{\mathrm{halo}} \simeq 2 \times 10^{12} M_{\odot}$$

e.g. Wilkinson, Evans 1999

Xray emission of hot intracluster gas, gravitational lensing, filaments of DM in superclusters

e.g. Allen et al 2011
Dietrich et al 2012

CMB, BAO, SN1a, ...

$$\Omega_{\mathrm{CDM}} h^2 = 0.1187 \pm 0.0017$$
$$\Omega_{\mathrm{CDM}} \simeq 5\Omega_{\mathrm{B}} \simeq 26\%$$

Planck collab. (2013)

Candidate solutions

Unaccounted astrophysical objects?

Ruled out as principal halo component e.g. Tisserand et al (2007)

Modified Newtonian Dynamics/gravity?

Jury is out, but not clear how to explain wealth of observations or even formulate a theory e.g. Slosar et al (2005)

Particle Dark Matter (by Occam's razor)

=> electrically neutral species covers the entire gravitational side
=> microscopic DM properties are largely unknown

a model many theorists like for its **inner** beauty

$$
\begin{aligned}
\frac{1}{e}\mathscr{L}_{\rm sugra} = & -\frac{M_P^2}{2}R + g_{ij^*}\tilde{\mathscr{D}}_\mu\phi^i\tilde{\mathscr{D}}^\mu\phi^{*j} - \frac{1}{2}g^2\left[({\rm Re}f)^{-1}\right]^{ab}D_{(a)}D_{(b)} \\
& + ig_{ij^*}\overline{\chi}_L^j\gamma^\mu\tilde{\mathscr{D}}_\mu\chi_L^i + \varepsilon^{\mu\nu\rho\sigma}\overline{\psi}_{L\mu}\gamma_\nu\tilde{\mathscr{D}}_\rho\psi_{L\sigma} \\
& - \frac{1}{4}{\rm Re}f_{ab}F_{\mu\nu}^{(a)}F^{\mu\nu(b)} + \frac{1}{8}\varepsilon^{\mu\nu\rho\sigma}{\rm Im}f_{ab}F_{\mu\nu}^{(a)}F_{\rho\sigma}^{(b)} \\
& + \frac{i}{2}{\rm Re}f_{ab}\overline{\lambda}^a\gamma^\mu\tilde{\mathscr{D}}_\mu\lambda^b - e^{-1}\frac{1}{2}{\rm Im}f_{ab}\tilde{\mathscr{D}}_\mu\left[e\overline{\lambda}_R^a\gamma^\mu\lambda_R^b\right] \\
& + \Bigg[-\sqrt{2}g\partial_i D_{(a)}\overline{\lambda}^a\chi_L^i + \frac{1}{4}\sqrt{2}g\left[({\rm Re}f)^{-1}\right]^{ab}\partial_i f_{bc}D_{(a)}\overline{\lambda}^c\chi_L^i \\
& + \frac{i}{16}\sqrt{2}\partial_i f_{ab}\overline{\lambda}^a[\gamma^\mu,\gamma^\nu]\chi_L^i F_{\mu\nu}^{(b)} - \frac{1}{2M_P}gD_{(a)}\overline{\lambda}_R^a\gamma^\mu\psi_\mu \\
& - \frac{i}{2M_P}\sqrt{2}g_{ij^*}\tilde{\mathscr{D}}_\mu\phi^{*j}\overline{\psi}_\nu\gamma^\mu\gamma^\nu\chi_L^i + {\rm h.c.}\Bigg] \\
& - \frac{i}{8M_P}{\rm Re}f_{ab}\overline{\psi}_\mu[\gamma^m,\gamma^n]\gamma^\mu\lambda^a F_{mn}^{(b)} \\
& - e^{K/2M_P^2}\Bigg[\frac{1}{4M_P^2}W^*\overline{\psi}_{R\mu}[\gamma^\mu,\gamma^\nu]\psi_{L\nu} - \frac{1}{2M_P}\sqrt{2}D_iW\overline{\psi}_\mu\gamma^\mu\chi_L^i \\
& + \frac{1}{2}\mathscr{D}_iD_jW\overline{\chi_L^c}^i\chi_L^j + \frac{1}{4}g^{ij^*}D_{j^*}W^*\partial_i f_{ab}\overline{\lambda}_R^a\lambda_L^b + {\rm h.c.}\Bigg] \\
& - e^{K/M_P^2}\left[g^{ij^*}(D_iW)(D_{j^*}W^*) - 3\frac{|W|^2}{M_P^2}\right] + \mathcal{O}(M_P^{-2}),
\end{aligned}
$$

local supersymmetry (supergravity)

see recent work by Eberl, Spanos (2013)

a model many theorists like for its **outer** beauty

$$\mathcal{L} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \lambda S^2 (H^\dagger H)$$

"minimal DM"

2.
Classification-scheme for particle DM

Classification of Dark Matter

What is the abundance of χ for $T \gg m_\chi$?

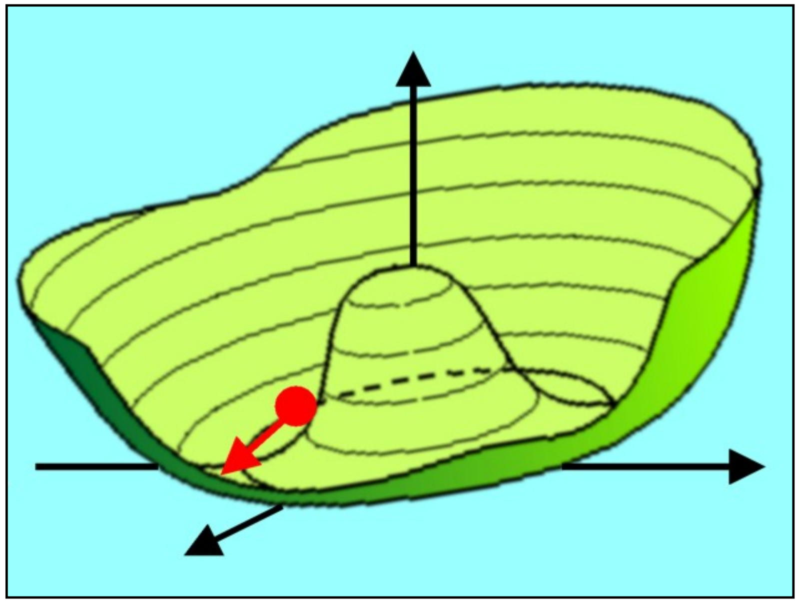
- HUGE $N_\chi / N_\gamma \gg 1$

Axions, PNGBs

classical field oscillations
populate zero mode

$m_a(T) \simeq H(T)$

fundamentally massless field, potential at low-energies/T provides mass; very-light (< eV) and feebly interacting



Constrained from astrophysics and searched for via coupling to photon

Classification of Dark Matter

What is the abundance of χ for $T \gg m_\chi$?

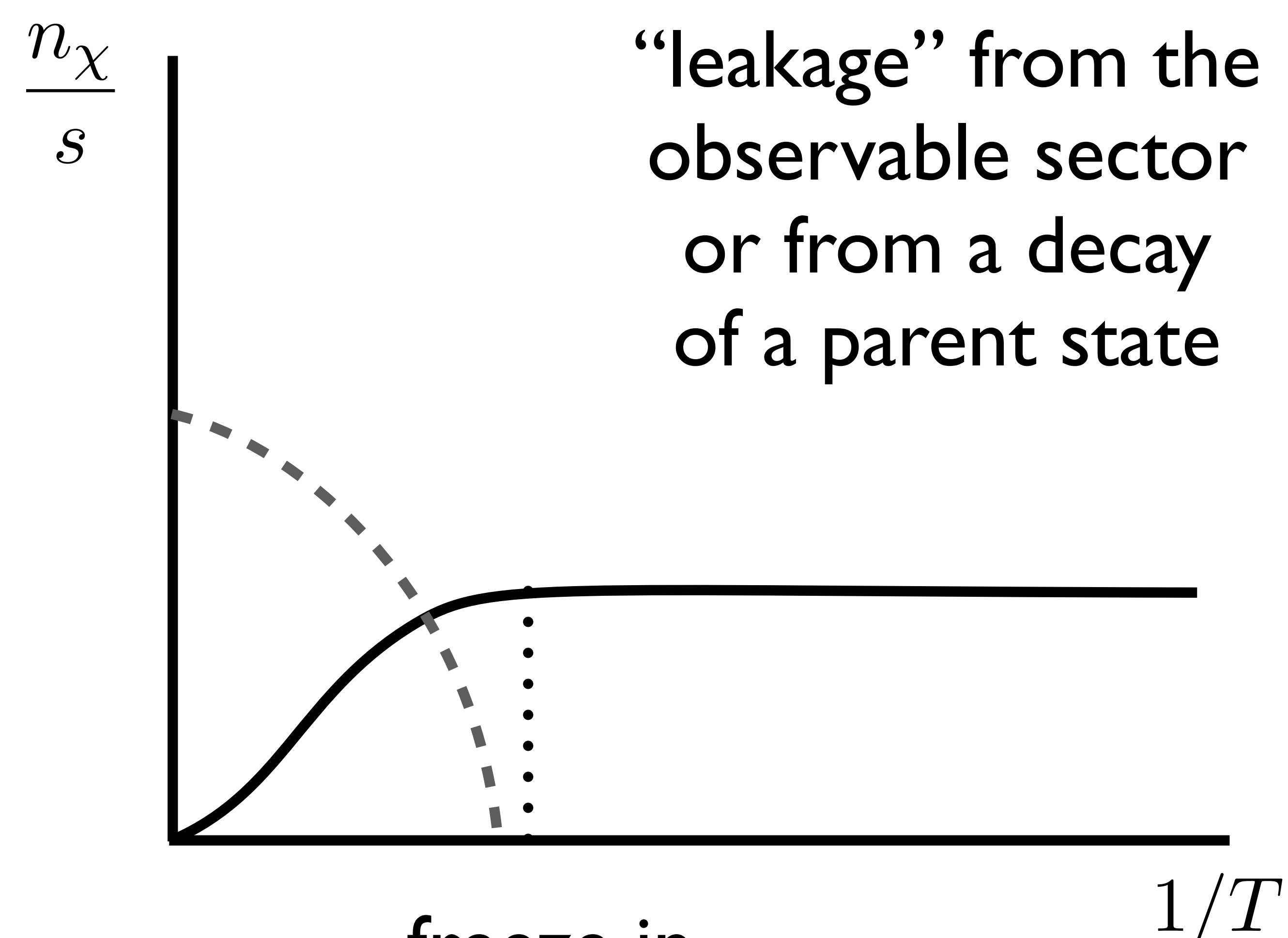
- TINY $N_\chi/N_\gamma \ll 1$

  $\Gamma_\chi \ll H(T)$

  "super-WIMPs"

  gravitinos, sterile neutrinos, and other feebly interacting species

  weak link to SM makes them hard to detect



"leakage" from the observable sector or from a decay of a parent state

freeze in
$m_\chi/T \simeq 1$

Classification of Dark Matter

What is the abundance of χ for $T \gg m_\chi$?

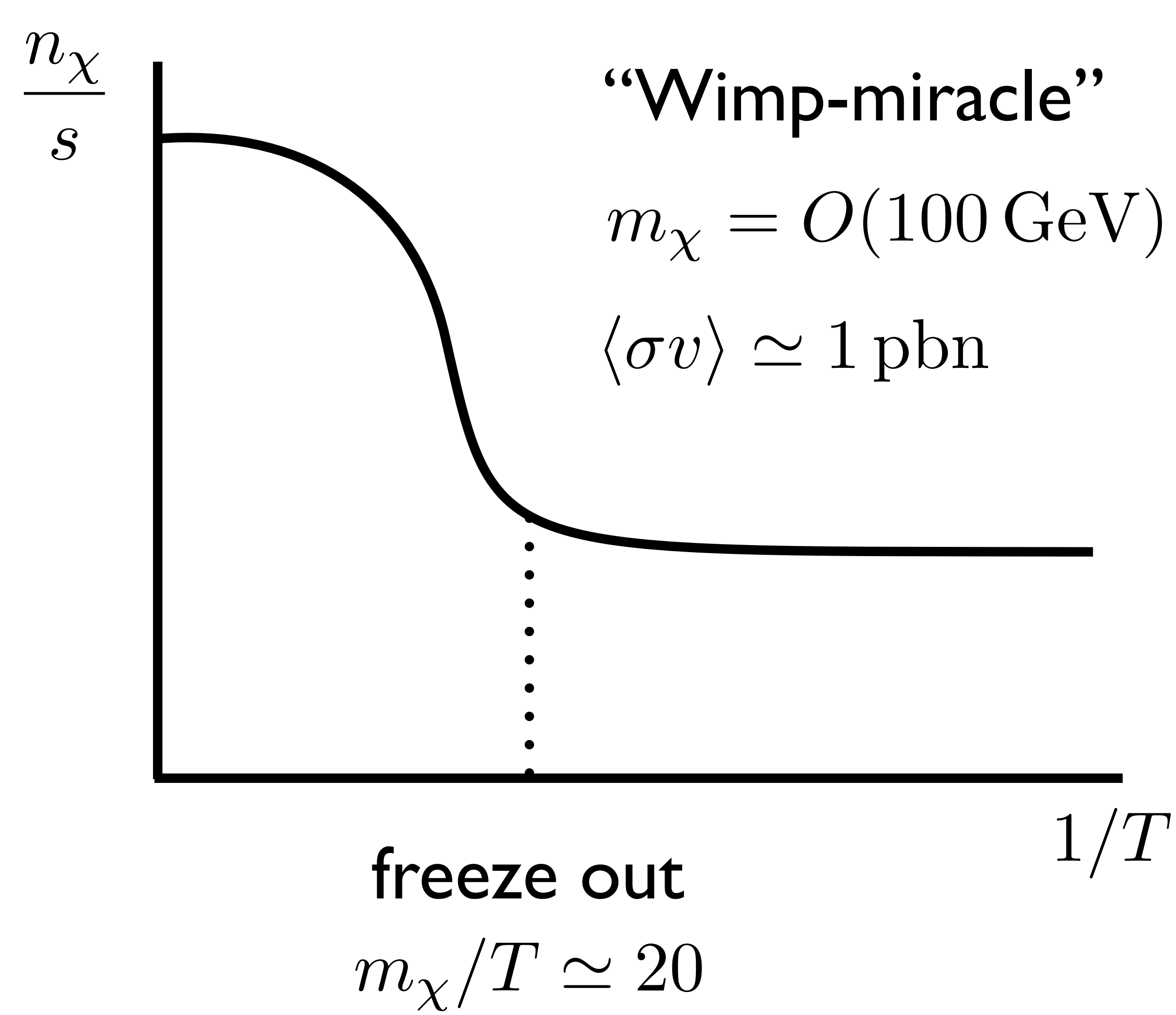
- NORMAL $N_\chi / N_\gamma \sim 1$

$\Gamma_\chi \gg H(T)$

$\Gamma_\chi = n_\chi \langle \sigma v \rangle$

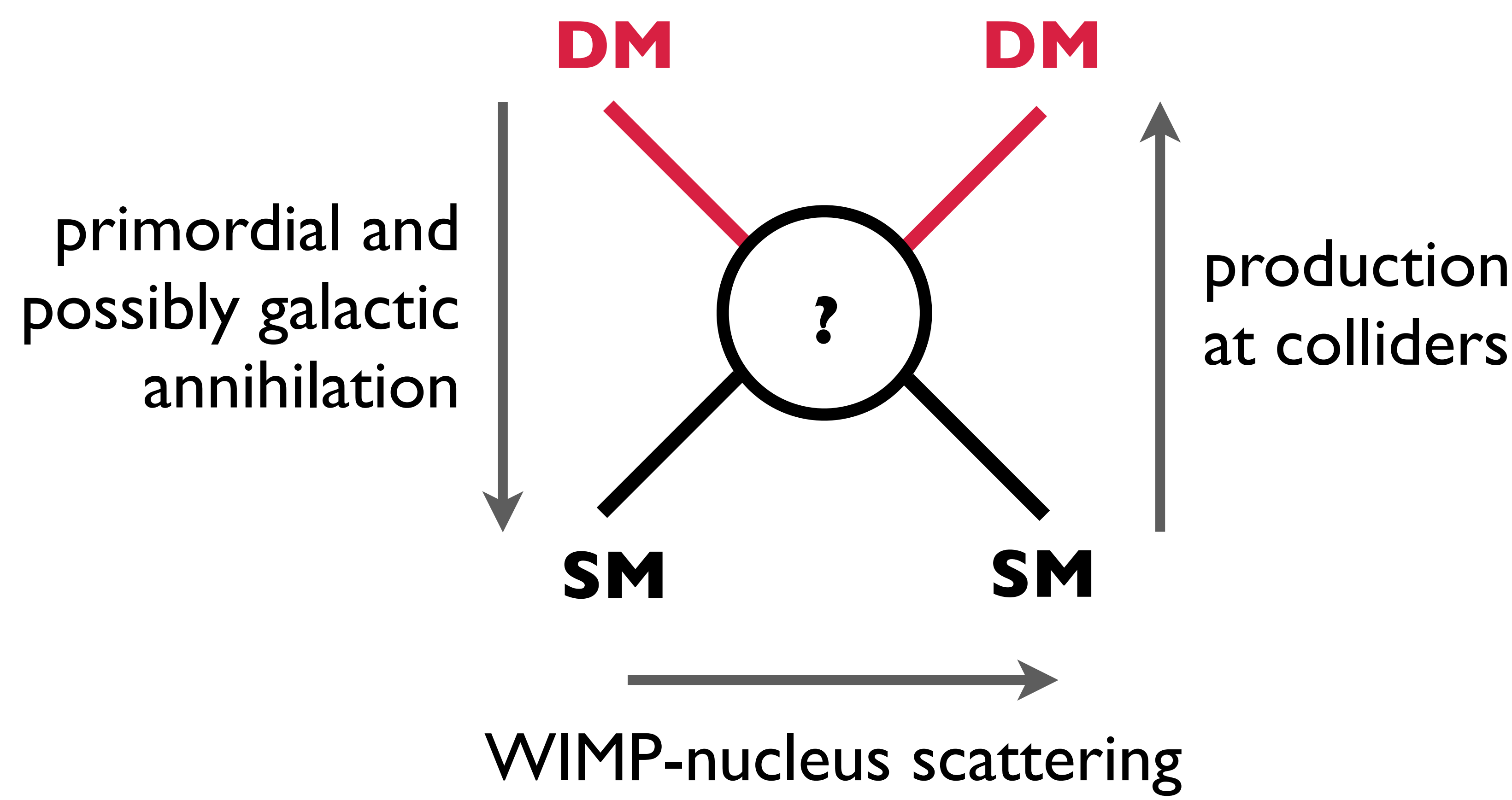
"WIMPs"
(weakly massive interacting particles)

e.g. SUSY neutralinos and many models



3.
WIMPs

WIMP paradigm



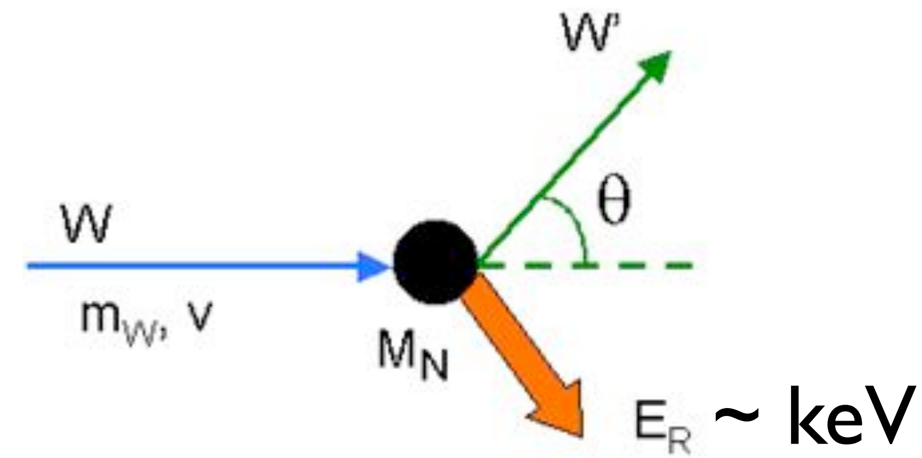
$$\Omega_\chi h^2 \approx 0.12 \times \frac{1\,\mathrm{pb}\,c}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

=> electroweak scale physics with weak strength interactions $\sigma_{\mathrm{ann}} v \approx \alpha_\chi^2 / m_\chi^2$

=> fuels hopes for a laboratory test of the DM paradigm

We want to know what are the legs, what is inside the circle and how well the expectation from σ_{ann} carries over?

Direct detection



Rate = particle flux x cross section

$$\frac{dR(t)}{dE_R} = N_T \frac{\rho_0}{m_{\rm DM}} \int_{v \geqslant v_{\rm min}} d^3\mathbf{v}\, v\, f_{\rm LAB}(\mathbf{v}) \frac{d\sigma}{dE_R} \qquad [\mathrm{cpd/kg/keV}]$$

Astrophysics | local DM density | DM velocity distribution in the LAB frame | recoil cross section | *Particle Physics*

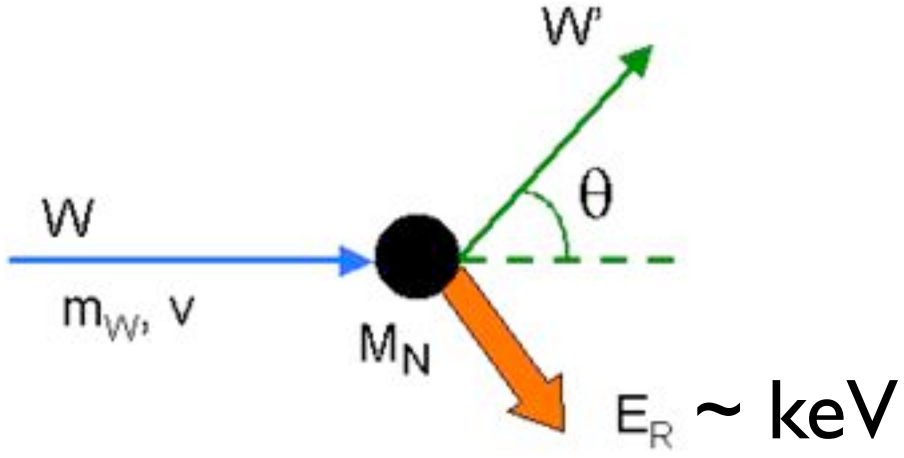
Contributions to f(v)

- isotropic smooth (Maxwellian)
- substructure $(p < 10^{-4})$
- debris flow, streams

Very little is known

- largely dissipationless
- stable on cosmological timescales

Direct detection
Astrophysics



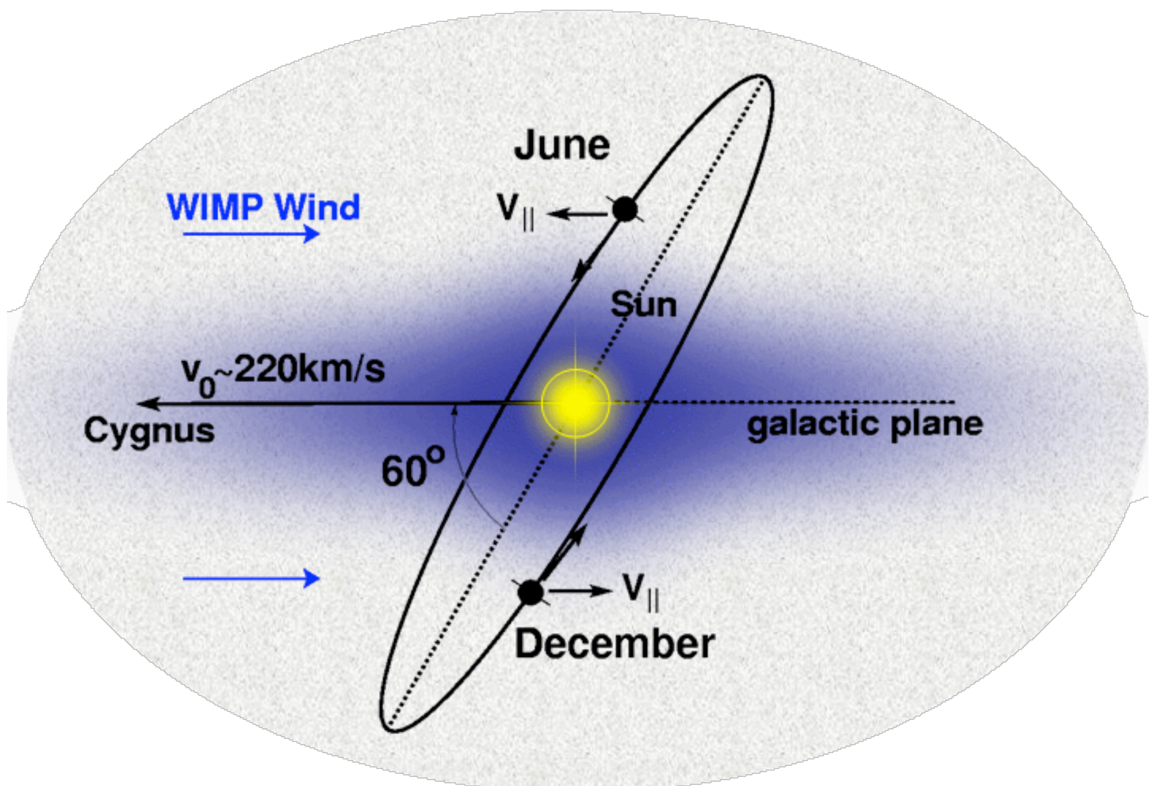
$$\frac{dR(t)}{dE_R} = N_T \frac{\rho_0}{m_{\rm DM}} \int_{v \geqslant v_{\rm min}} d^3\mathbf{v}\, v\, f_{\rm LAB}(\mathbf{v}) \frac{d\sigma}{dE_R} \qquad [\text{cpd/kg/keV}]$$

$$f_{\rm LAB}(\mathbf{v}) \;\downarrow\; f_{\rm GAL}(\mathbf{v}_{\rm obs} + \mathbf{u})$$

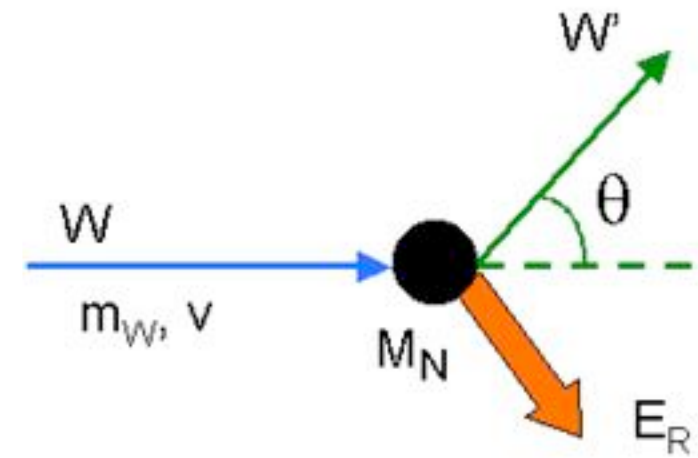
$$|\mathbf{v}_{\rm obs}| = |\mathbf{v}_\odot| + \frac{1}{2} V_\oplus \cos\omega(t - t_0)$$

$$t_0 \simeq 152\,\text{days} \quad (\text{June 2nd})$$

geometric prediction
for a principal isotropic
velocity distribution



Direct detection
Astrophysics

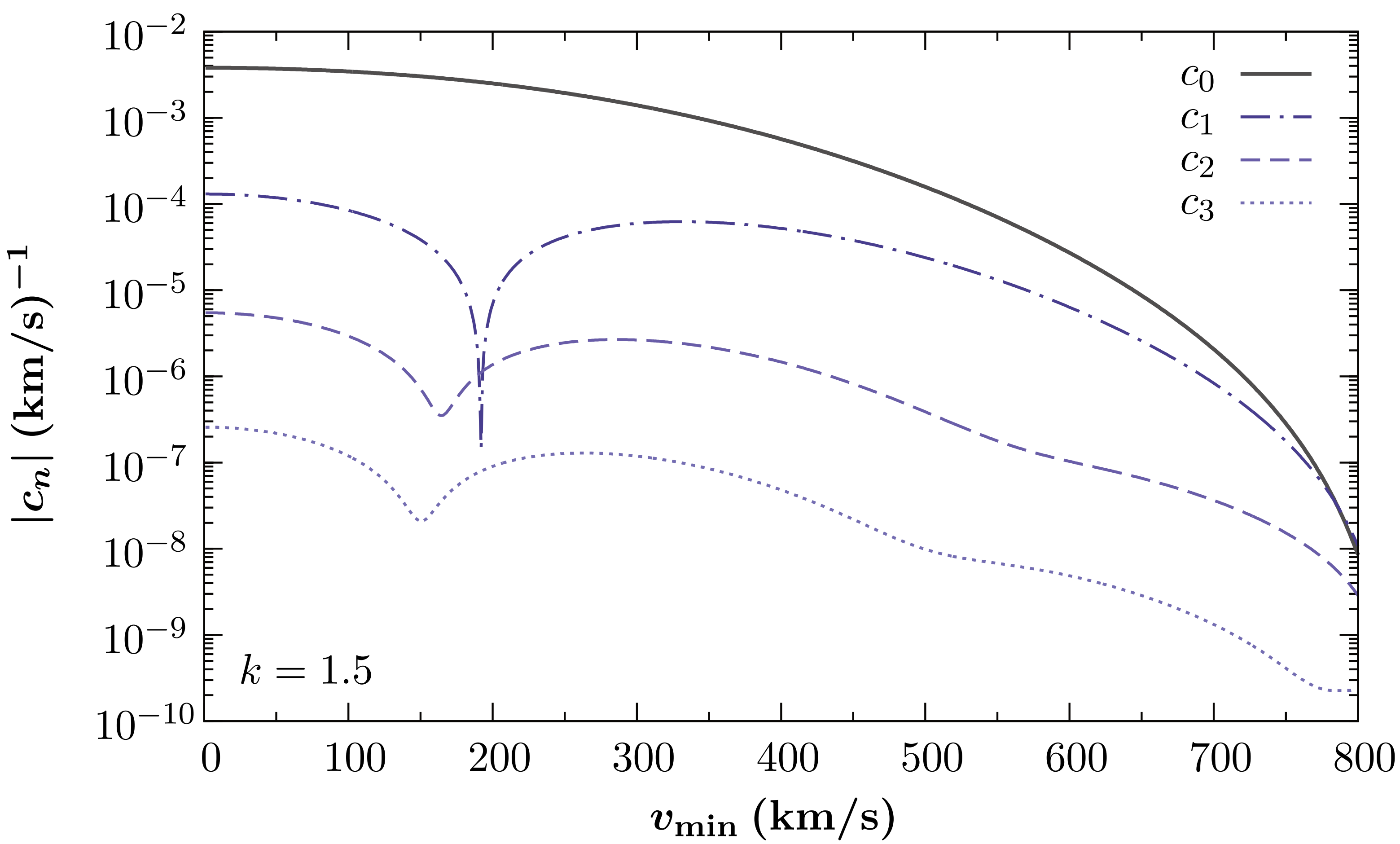


~ keV

$$\frac{dR(t)}{dE_R} \sim c_0(v_{\min}) + c_1(v_{\min})\cos\left[\omega(t-t_0)\right] + \text{higher harmonics}$$

Chang, JP, Yavin (2012)

↑ annual modulation



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

Direct detection
Astrophysics

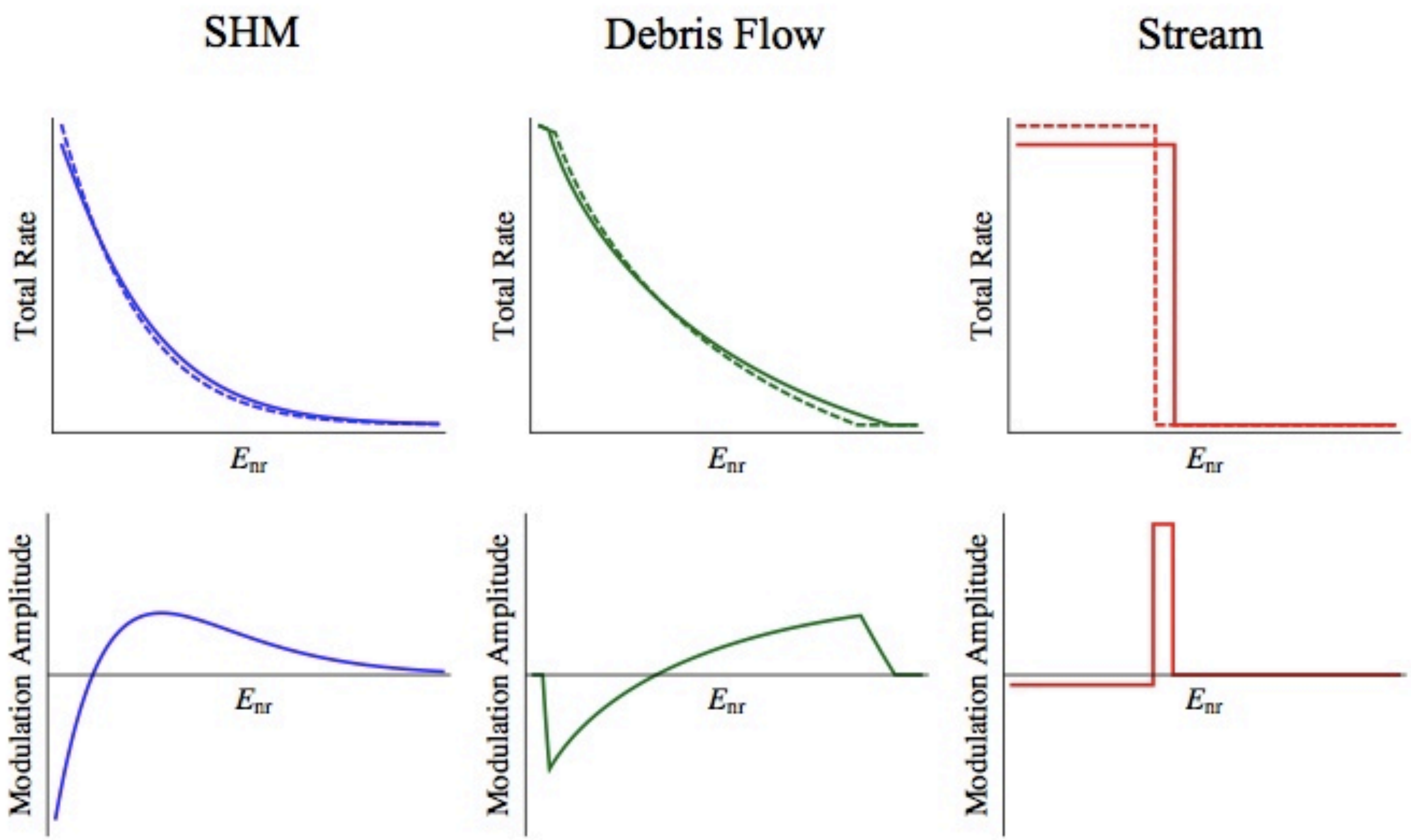


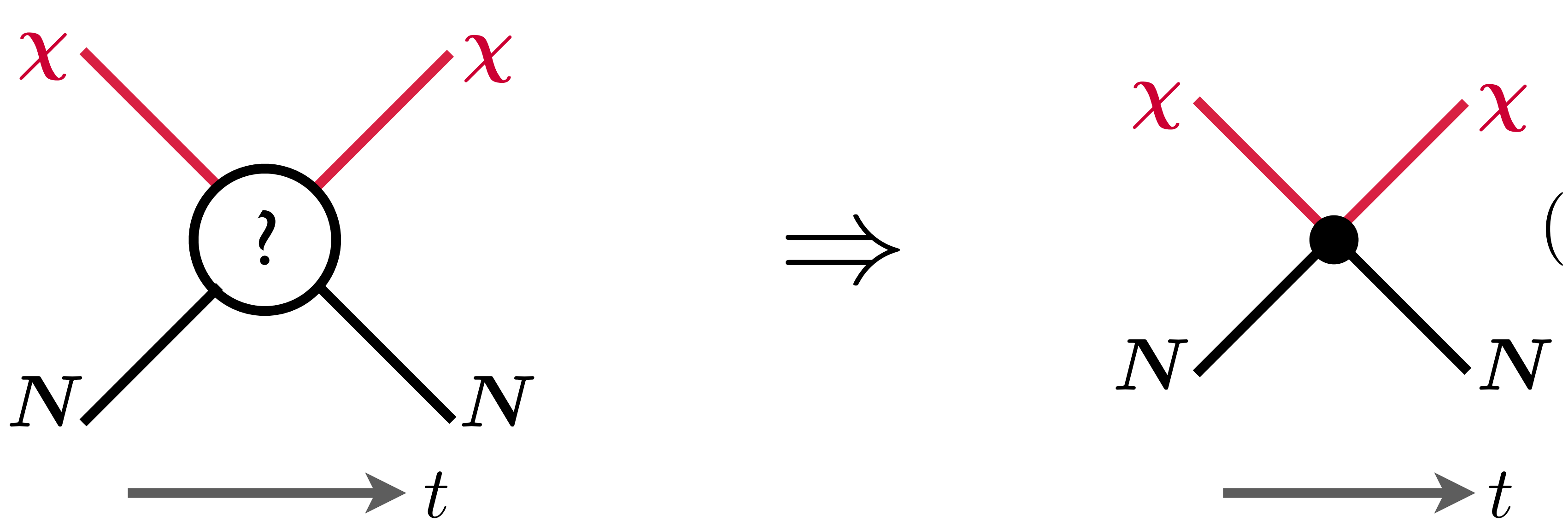
Fig. from Freese, Lisanti, Savage (2012)

Affect phase of annual modulation
as well as higher harmonics

Direct detection
Particle physics

- DM models can be recast in form of *effective operators* between DM χ and nucleons N, because $|q_{\rm max}| \sim O(100\,{\rm MeV})$

$$E_R = \frac{|\mathbf{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1-\cos\theta_*) \qquad v_{\rm max} \sim 2\times 10^{-3}$$



$$(\chi \mathcal{O}_\chi \chi)(N \mathcal{O}_N N)$$

- operators $O_{\chi,N}$ and their coefficients determined by the concrete model

Direct detection
Particle physics

- in the non-relativistic limit with small q => a simple picture emerges

$$\mathcal{L}_{\rm int} = \sum_{N=n,p} \sum_i c_i^{(N)} \mathcal{O}_i \, \chi^- \chi^+ N^- N^+$$

see, in particular,
Fan, Reece, Wang (2010)
Fitzpatrick et al. (2013)

$$\mathcal{O}_i = \mathbf{1},\ \vec{S}_\chi \cdot \vec{S}_N,\ v^2, (\vec{S}_\chi \times \vec{q}) \cdot \vec{v}, \ldots$$

counts nucleons
coherent in A, Z

spin-spin coupling
$\langle S_n \rangle,\ \langle S_p \rangle$

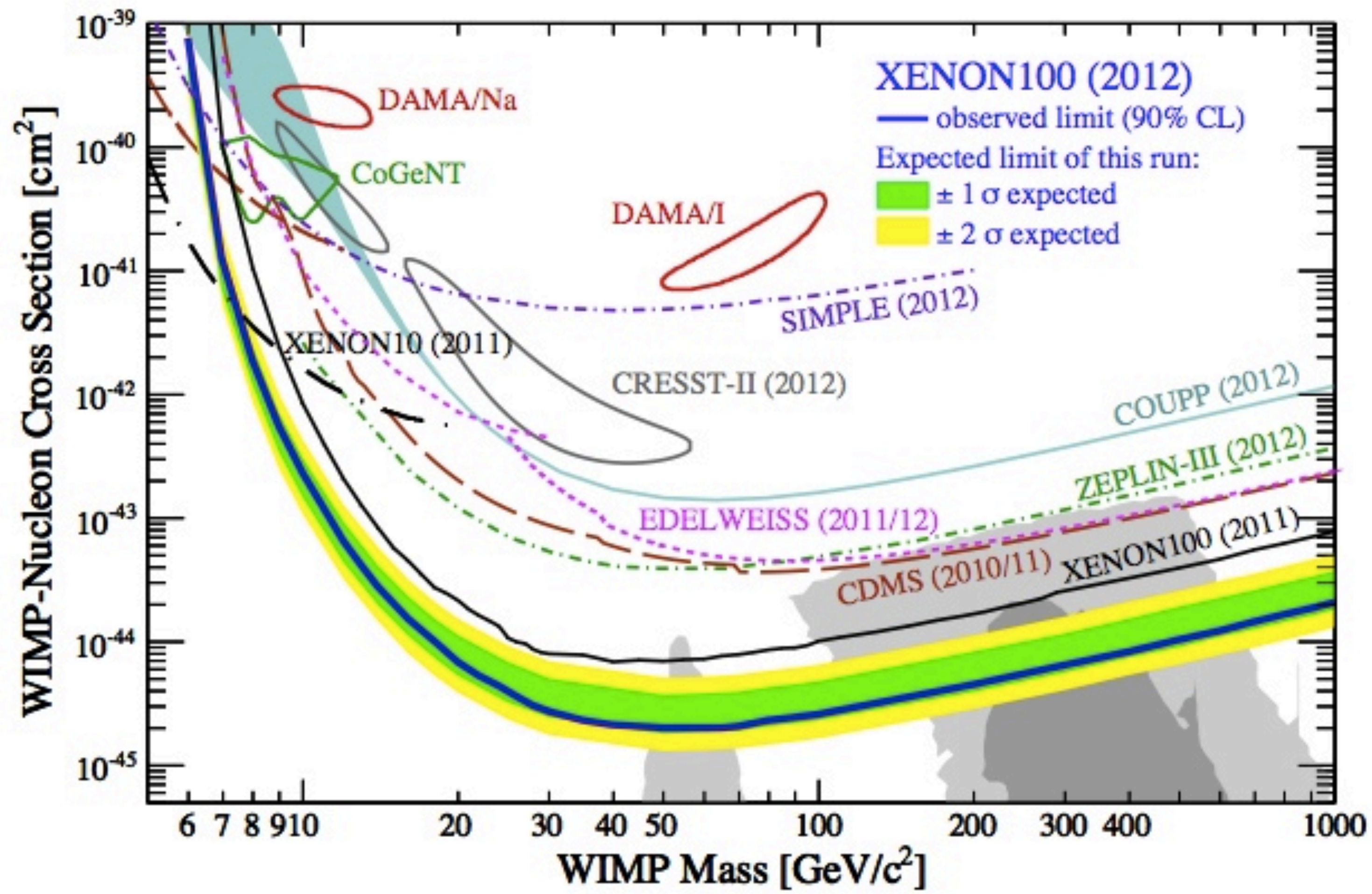
velocity suppressed
and/or momentum-dep.

=> direct detection is usually discussed in terms of
spin dependent (SD) and spin-independent (SI) scattering

SD: $(\bar{\chi}\gamma_\mu\gamma^5\chi)(\bar{q}\gamma^\mu\gamma^5 q)$ SI: $(\bar{\chi}\chi)(\bar{q}q)$

Direct detection
Current status

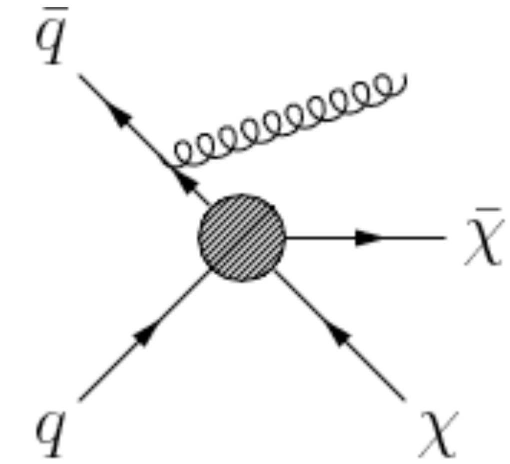
- XENON100 dominates limits on heavy WIMPs
- DAMA's long-standing claim seemingly excluded by other null results
- Much commotion in the $m_{\rm DM} \sim 10\,{\rm GeV}$ ballpark: CDMS-Si, CRESST, CoGeNT



Very interesting period:

- too many anomalies in the light WIMP regime?
- coming LUX results, new approaches (COUPP, DAMIC), clarification of anomalies (CRESST, DAMA), next-generation in construction => J. Jochum's talk

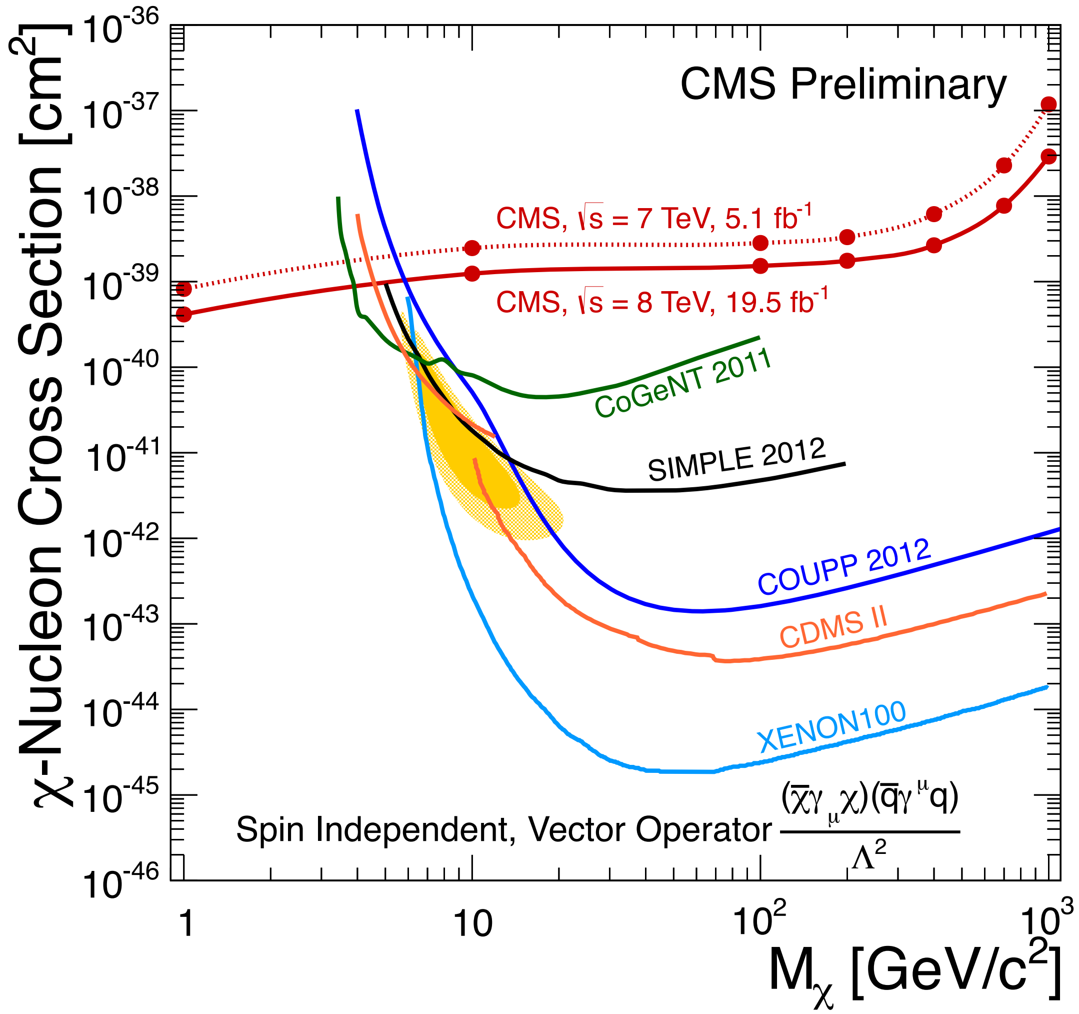
DM at the LHC

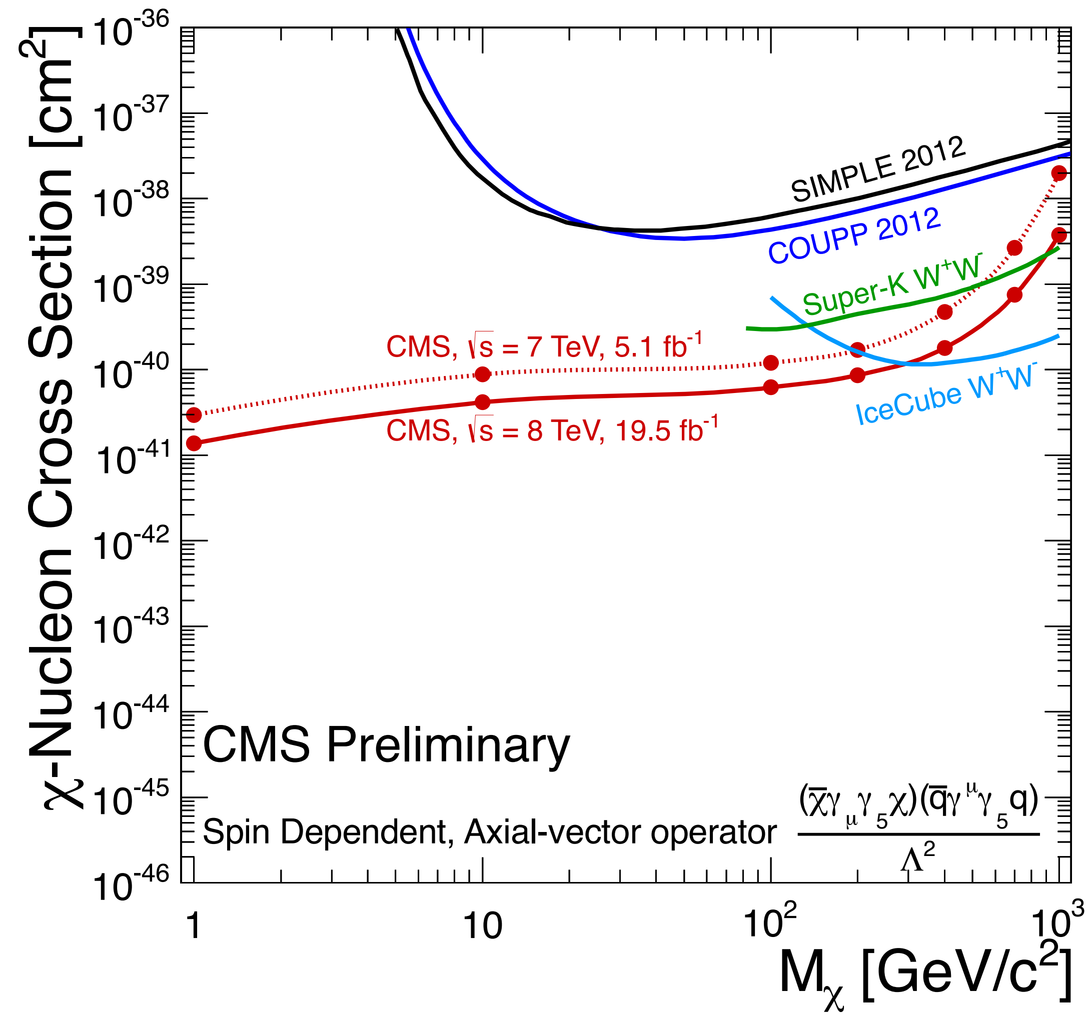


- Effective theory in which only the DM and SM fields appear (=contact) provide the simplest parameterization of new physics

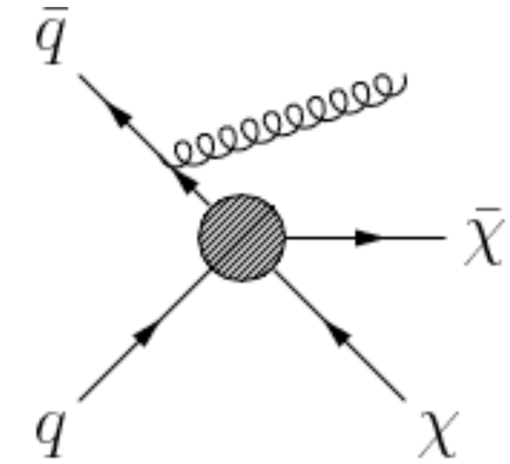
  => mono-jet/photon/W/Z + missing momentum

CMS (2013)





DM at the LHC



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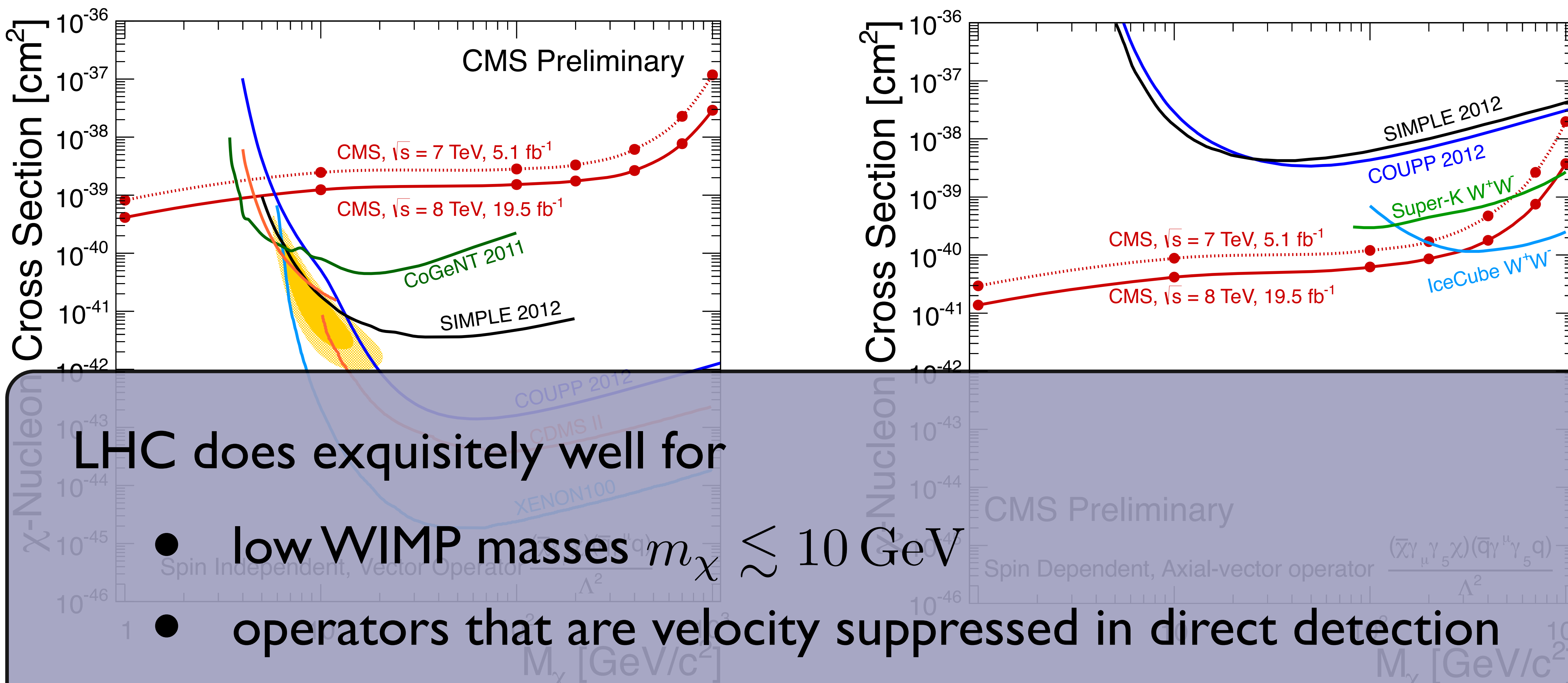


LHC does exquisitely well for

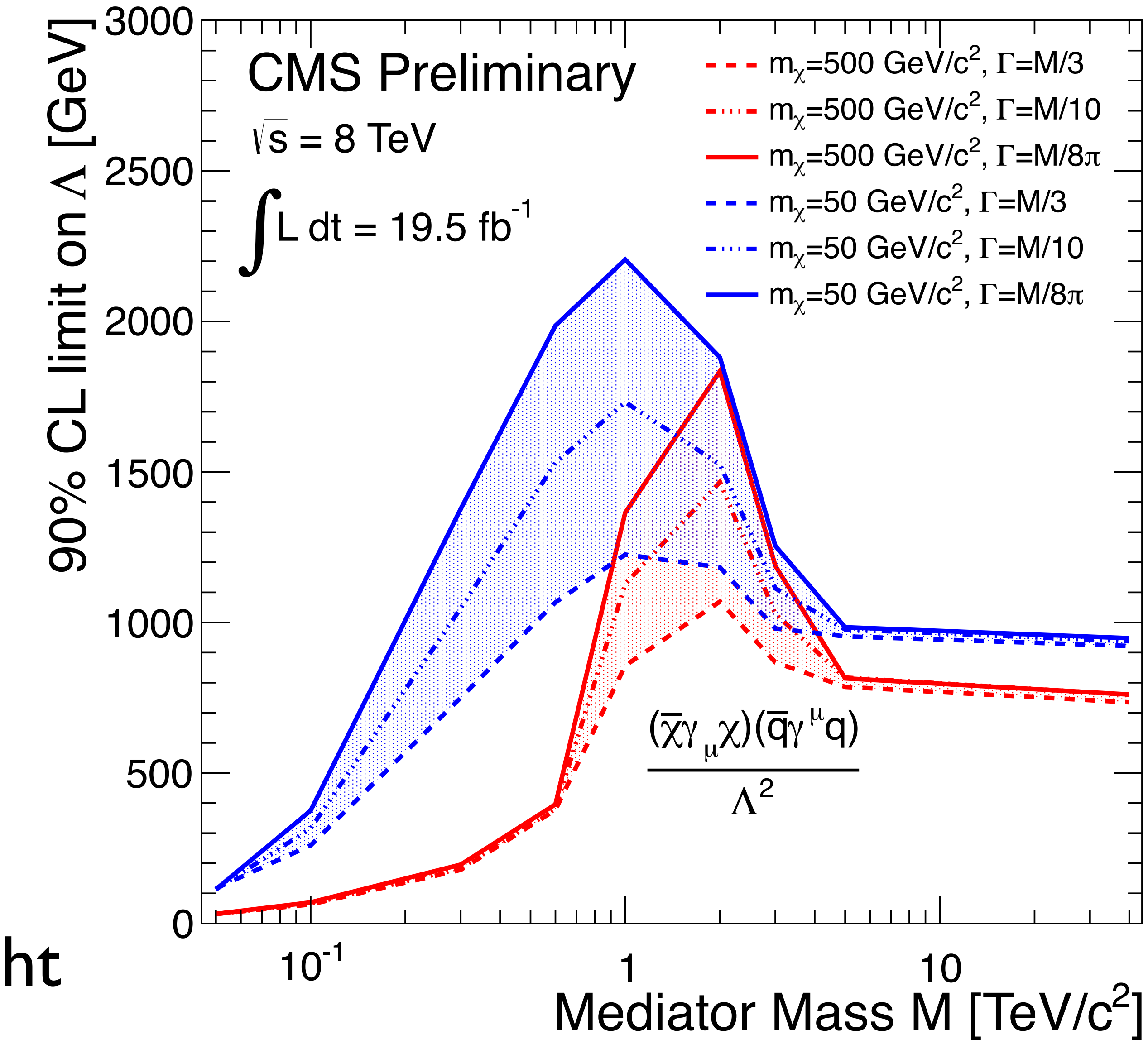
- low WIMP masses $m_\chi \lesssim 10\,\mathrm{GeV}$
- operators that are velocity suppressed in direct detection

DM at the LHC - II

Effective field theory approach breaks down, once $q^2 \simeq m^2_{\rm mediator}$

=> results can be cast as a limit on the contact interaction scale Λ

CMS (2013)



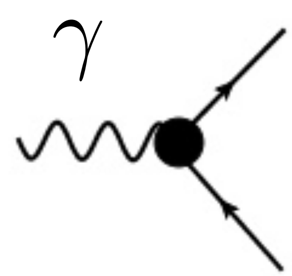
LHC limits are stringent for contact operators, but can go away completely for light mediators!

=> accessible UV content can be caught in "simplified models" with content SM+DM+mediator

Force carriers

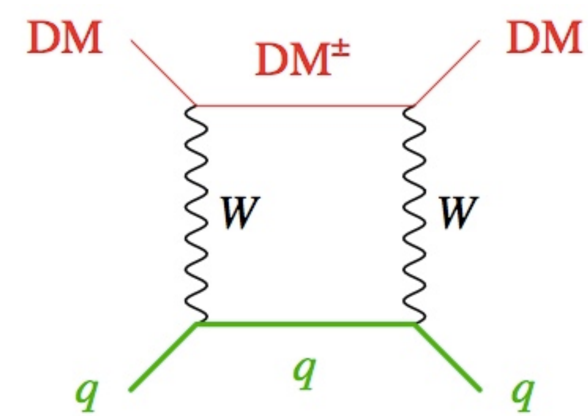
Photon:
milli-charged DM; neutral DM interacting via EM form factors

Examples of recent works:
Kouvaris (2013);
Ho, Scherrer (2013);
Weiner, Yavin (2013);
Yavin, Tamarit (2013);
Dissauer et al (2013);



EW-bosons:
DM in electroweak multiplets
Cirelli, Fornengo, Strumia (2007)

SUSY gauginos; (Z excluded)



Higgs boson:
Inert Higgs, Higgs portal models, SUSY
Deshpande, Ma (1978);
Silveira, Zee (1985);
McDonald (1993);
Burgess, Pospelov, ter Veldhuis (2000)

- **New physics mediators**
  squarks, Z', ...
  (whatever you can think of)

Impact of the Higgs results

- "Higgs Portal"

  $$\mathcal{L}_{\rm int} = -\lambda S^2 (H^\dagger H)$$

  Silveira, Zee (1985); McDonald (1993); Burgess, Pospelov, ter Veldhuis (2000)

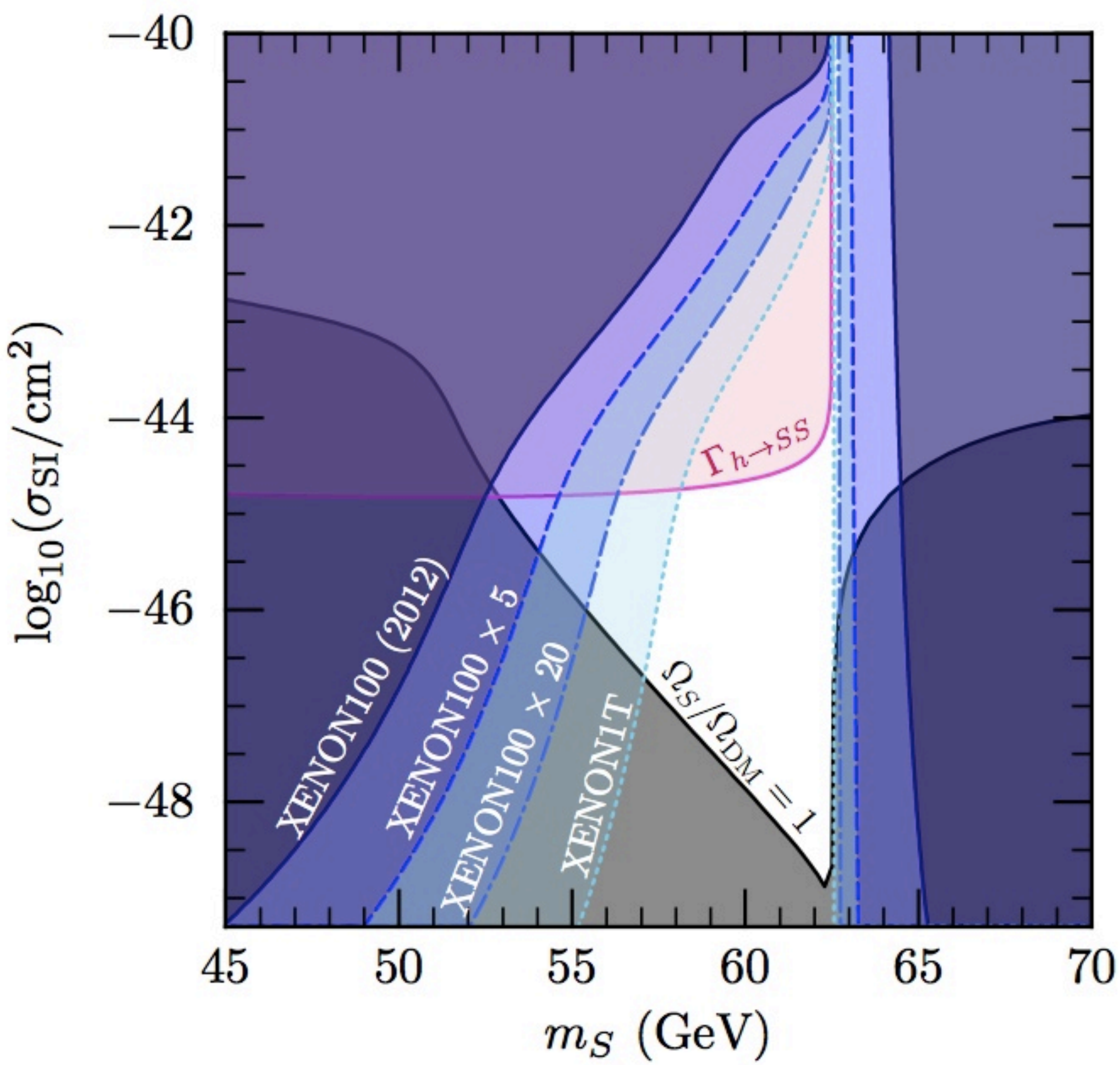
  => relic abundance via annihilation through H

  => direct detection via H-nucleon coupling $\langle n | m_q \bar{q} q | n \rangle$

- LHC results slain DM models with $m_{\rm DM} \lesssim 60\,{\rm GeV}$

  Higgs decays invisibly into DM

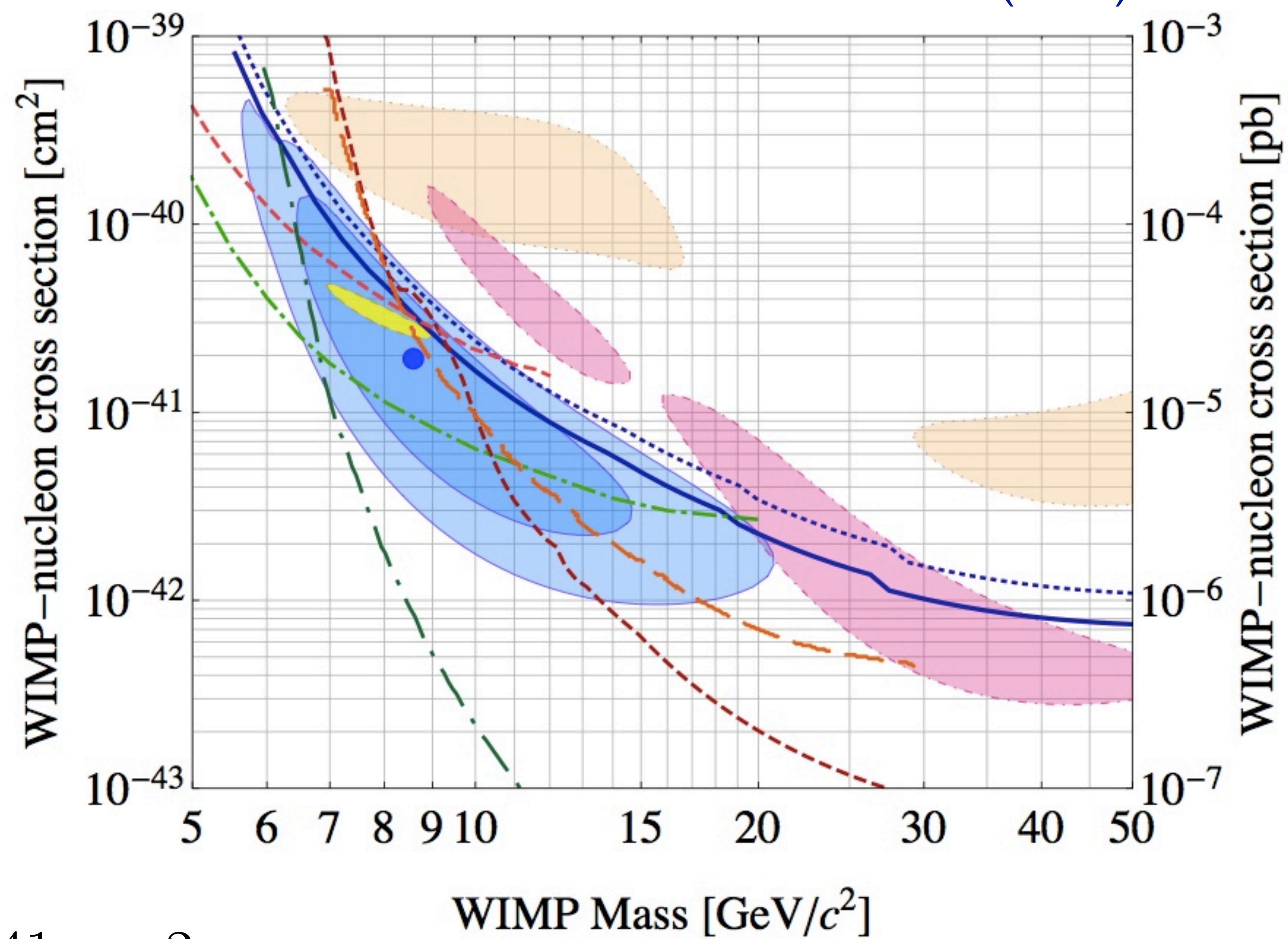
  => light-DM models run out of SM mediators



e.g. Cline et al. (2013)

4.
Light DM frontier

Four signals - one species?



- $7\,\mathrm{GeV}$ WIMP with $\sigma_n \sim 10^{-41}\,\mathrm{cm}^2$?
- XENON100 provides most stringent constraint, but 2 events in the acceptance window have low ionization/scintillation ratio:

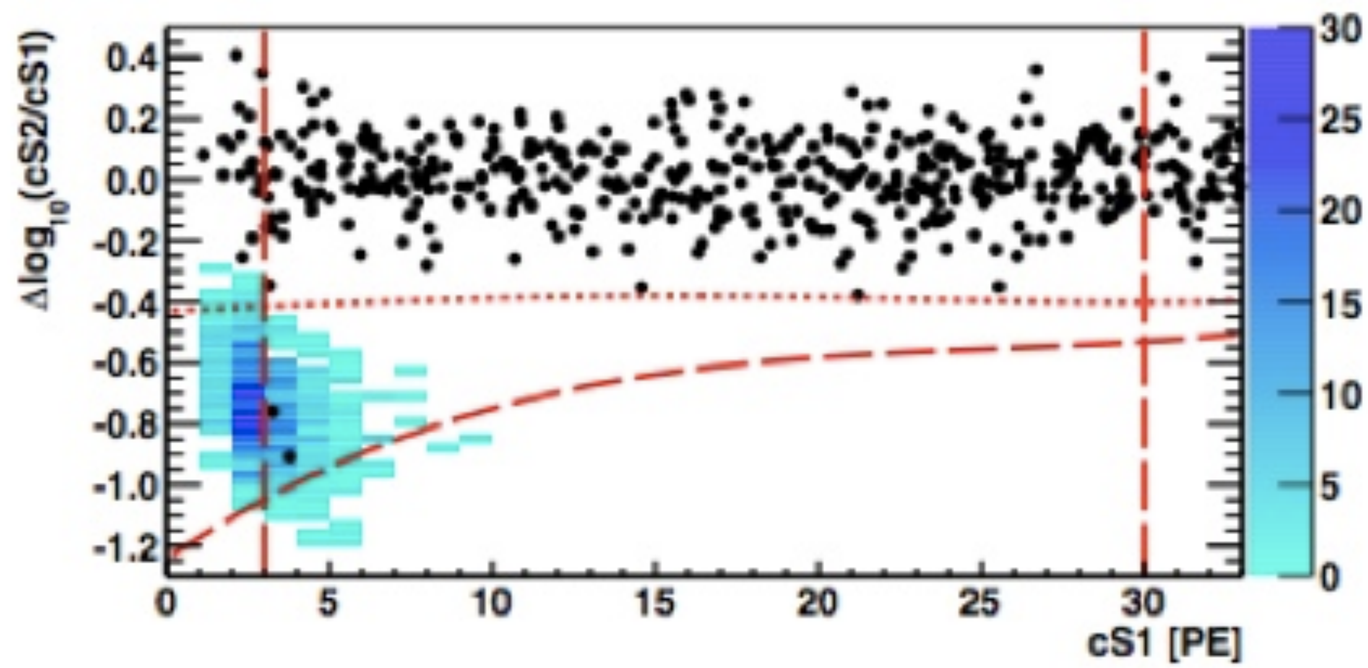
  => issues with nuclear recoil calibration $S1 \to E_R$
  => LUX has higher light-yield than XENON100, an can pick up signal
- (controversial) claims about indirect signals from GC

e.g. overview paper Hooper (2012)

Sorensen (2012)
XENON100 (2012, 2013)

Four signals - one species?

2 events do look like a 8 GeV WIMP



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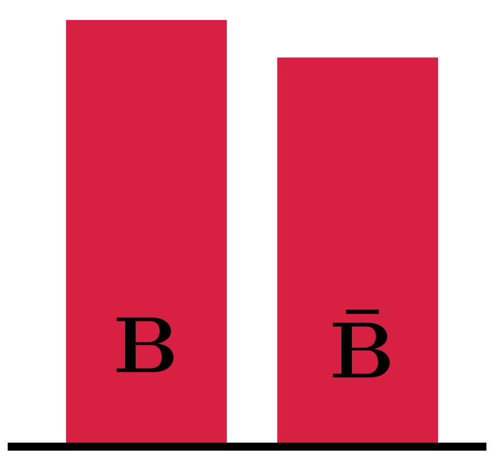
GeV-scale DM:
An alternative to the WIMP miracle

- Why are the energy densities of DM and matter so similar?

$$\rho_{\rm DM}/\rho_B \simeq 5$$

- "normal WIMP": DM abundance is set by the microscopic properties of the hidden sector and its link to SM, $\Omega_\chi \propto 1/\langle \sigma v \rangle$
- In contrast, baryon density is set by chemical potential $\eta_B = \mathcal{O}(10^{-10})$



SM: asymmetry prevents annihilation catastrophe

$\Rightarrow$

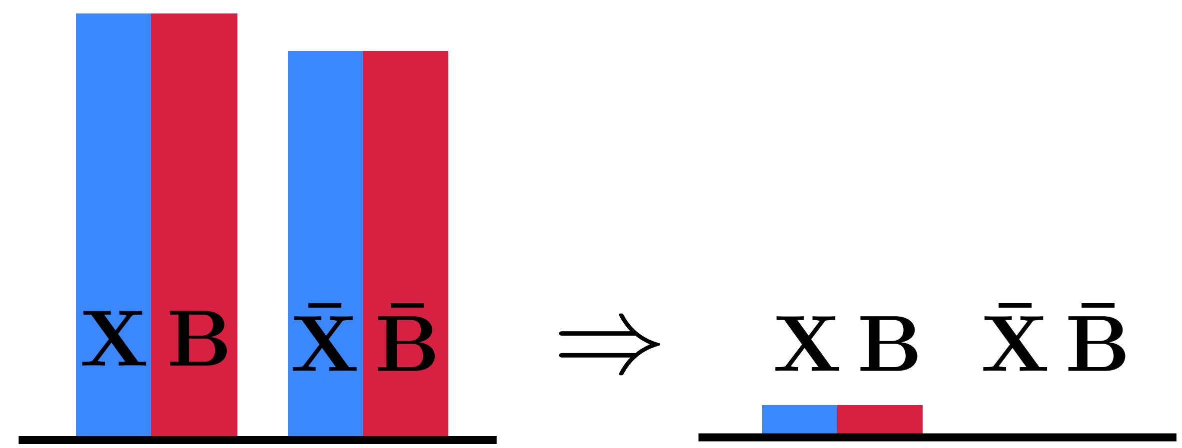
GeV-scale DM: An alternative to the WIMP miracle

“Asymmetric DM”

- Idea: DM carries asymmetry related to SM one

$$n_\chi - n_{\bar{\chi}} \sim n_B - n_{\bar{B}}$$

$$m_\chi \sim 5 m_B \simeq 5\,\mathrm{GeV}$$



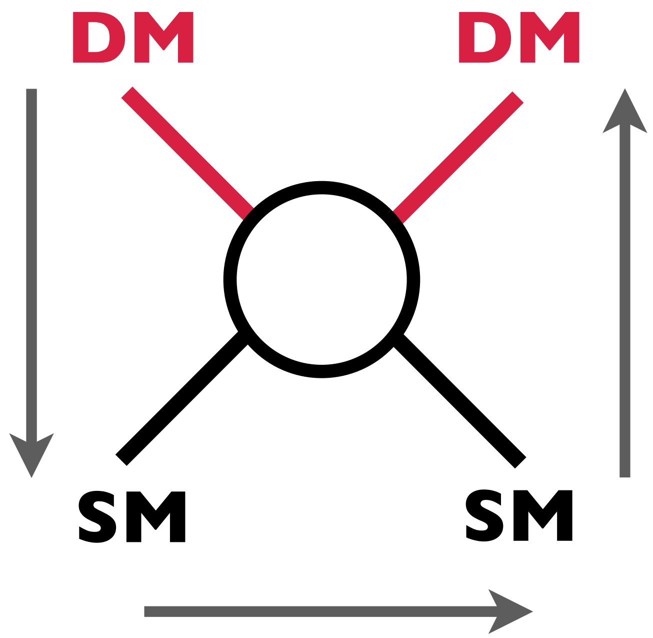
- Primordial symmetric component must annihilate away efficiently through light mediator ϕ => direct detection prospects:

$$\sigma_n \gtrsim 10^{-48}\,\mathrm{cm}^2 \left(\frac{m_\chi}{\mathrm{GeV}}\right)^2 \left(\frac{\mathrm{GeV}}{m_\phi}\right)^6 \left(\frac{\mu_n}{0.5\,\mathrm{GeV}}\right)^2$$

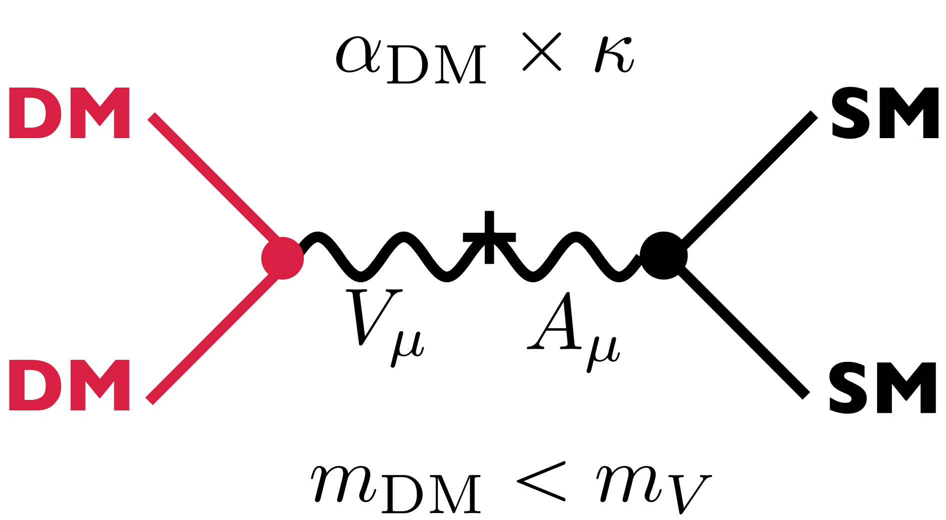
Lin, Yu, Zurek (2012)

- Indirect signals diminished, unless symmetric component is re-populated by oscillations

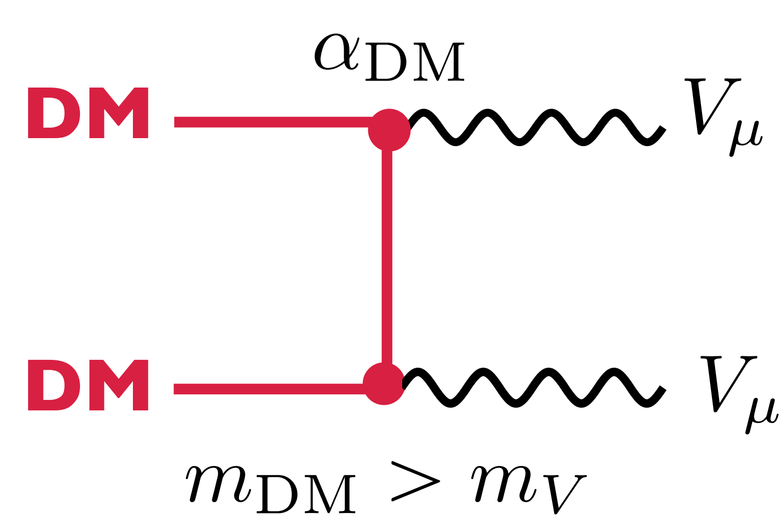
A caveat to our favorite diagram



- Light, new force carriers
  can invalidate our picture of “rotating” the diagram, e.g.



vs.



“normal WIMP”

“secluded WIMP”

Pospelov, Ritz, Voloshin (2007);

- both are WIMPs with 1pb annihilation c.s., but the left can completely elude direct detection
- light V_μ can be searched for at the “intensity frontier”

5.
New opportunities for rare underground event searches

DD of super-WIMP DM

e.g. keV-scale axions

- Defining feature of a "super-WIMP" is feeble interaction with SM

=> compensate tiny cross-section by large abundance in the rate

$$\text{Rate} \propto \sigma v_{\text{DM}} \times \rho_{\text{DM}}/m_{\text{DM}}$$

$$\downarrow$$

$$100\,\text{GeV}/10\,\text{keV} = 10^7$$

=> Absorption needed to produce a measurable signal => bosonic DM
=> hidden in the electron band.

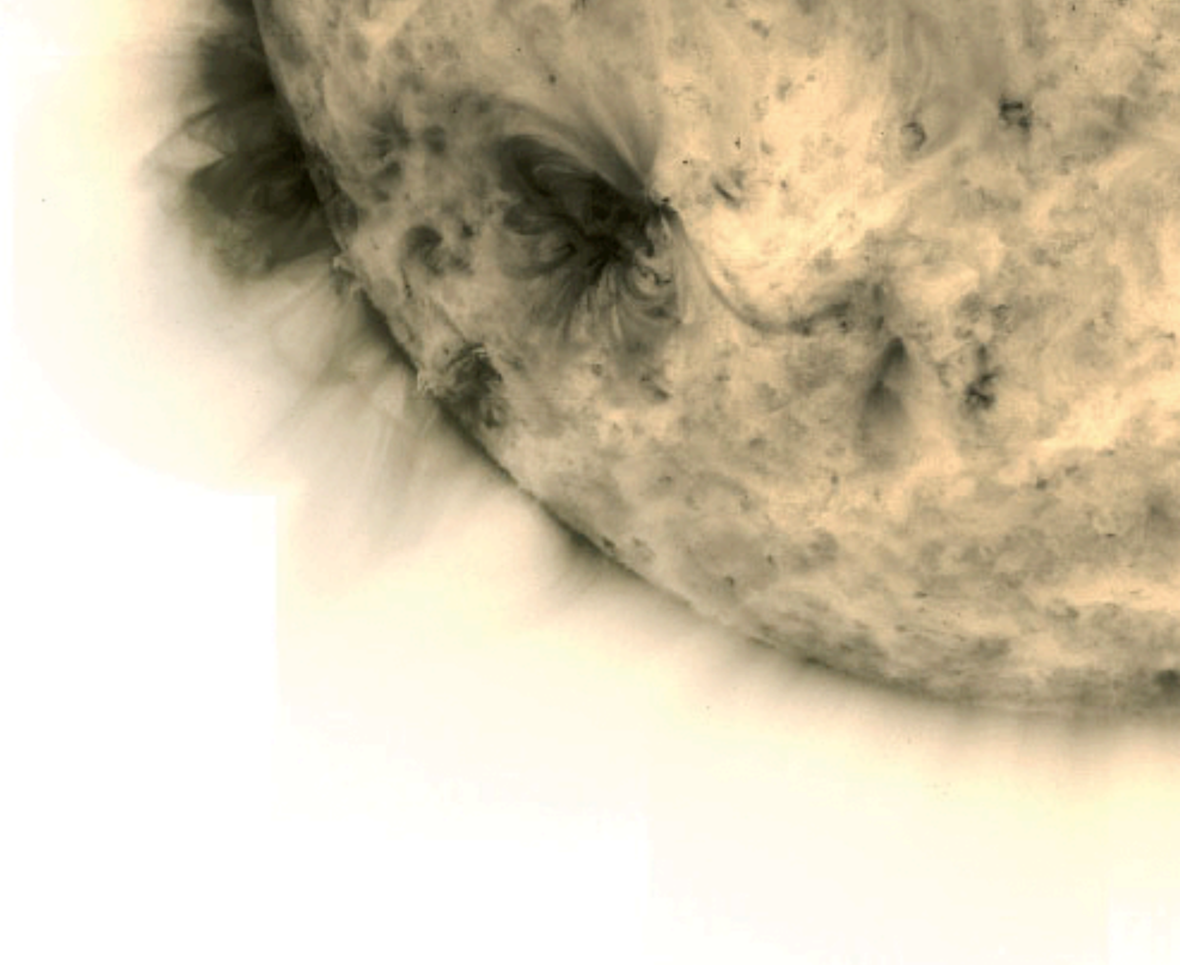
recently, Edelweiss collab. (2013)

- Can we use Modulation for its detection?

NO, because absorption process: $\sigma_{\text{abs}} v \approx \text{const}$ "Bethe's law"

Modulation fraction $\sim 10^{-6}$

DD experiments as helioscopes



Modulation from anything that comes out of the sun. It must not be DM!

$$\mathrm{Rate}(\mathrm{t}-\mathrm{t}_0) = \mathrm{Rate}_0 \times \left(\frac{L_0}{L(t-t_0)} \right)^2$$

Rate largest in January, ~ 3% amplitude

$$L_0 = 1\,\mathrm{AU} \qquad \epsilon = 0.0167\ \ (\mathrm{eccentricity}) \qquad t_0 \simeq 3\ \mathrm{Jan}\ \ (\mathrm{perihelion})$$

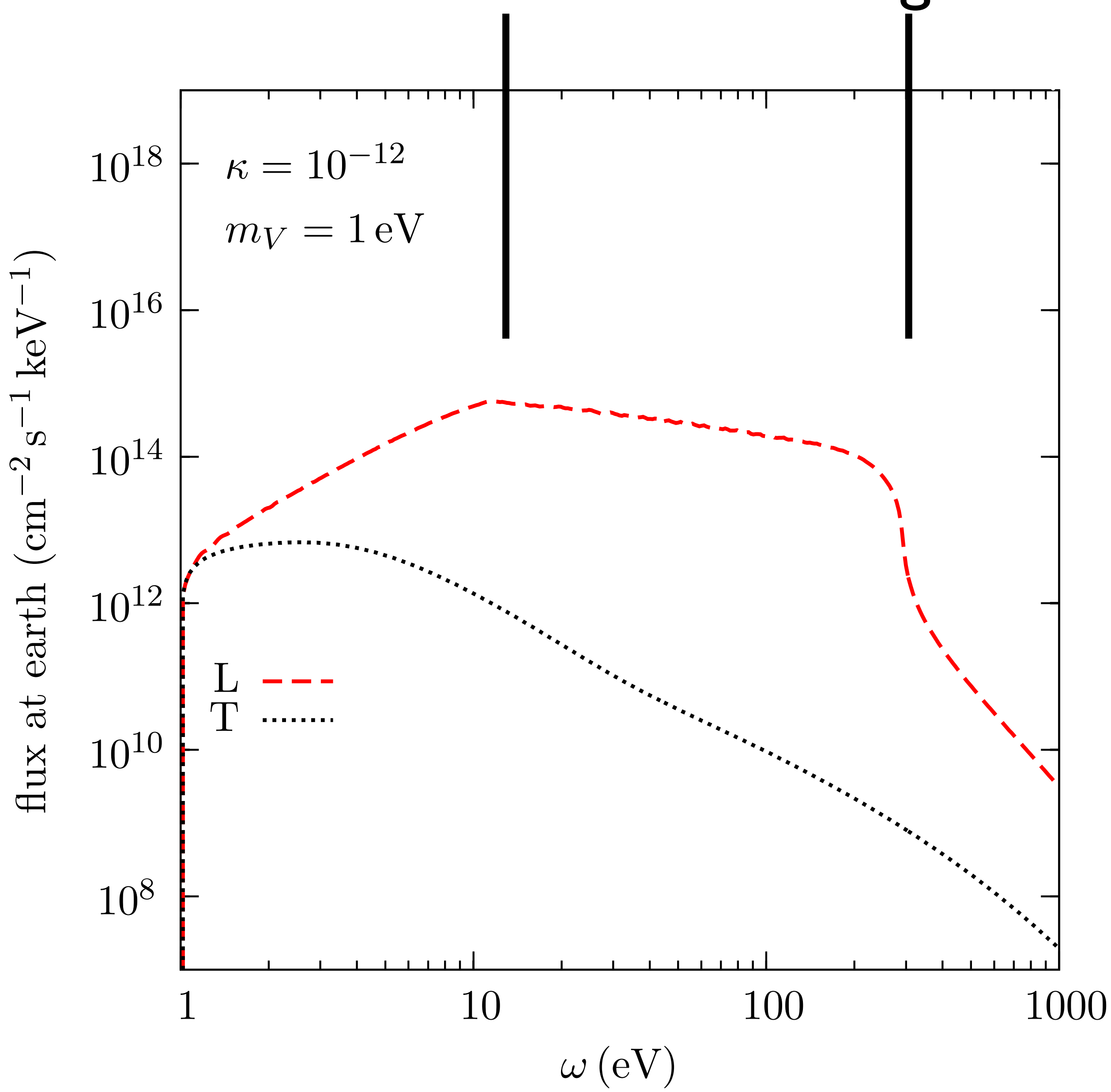
Axions, ALPs,
new states with masses below $m_\phi \lesssim \mathcal{O}(1\,\mathrm{keV}) \simeq T_{\mathrm{sun,core}}$

Theorist's task to explore models that can do that.

DD experiments as helioscopes

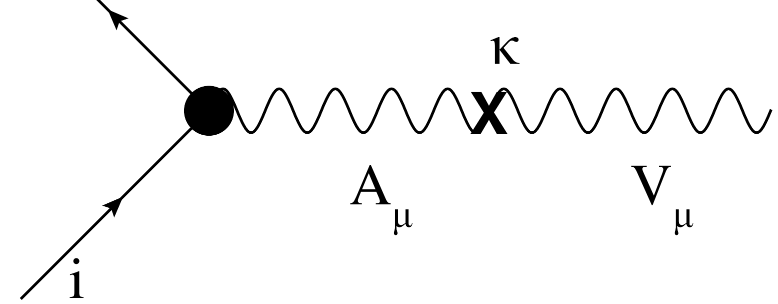
atomic ionization threshold

end of resonance region



our recent attempt:
"Dark Photons"

$$-\frac{\kappa}{2} V^{\mu\nu} F^{Y}_{\mu\nu}$$

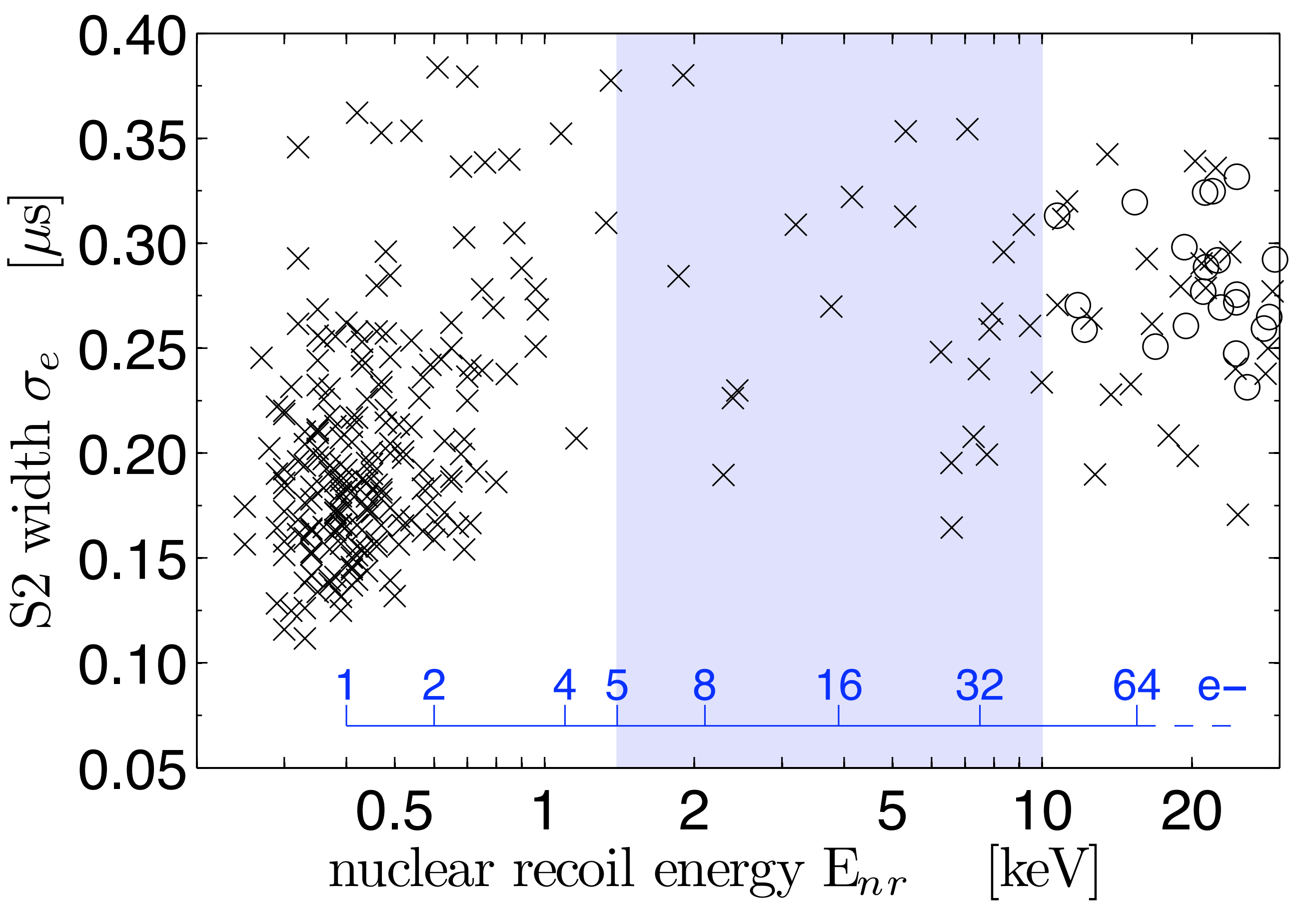


flux of longitudinal Dark Photons dominates with energies in the sub-keV region

An, Pospelov, JP (2013)

DD experiments as helioscopes

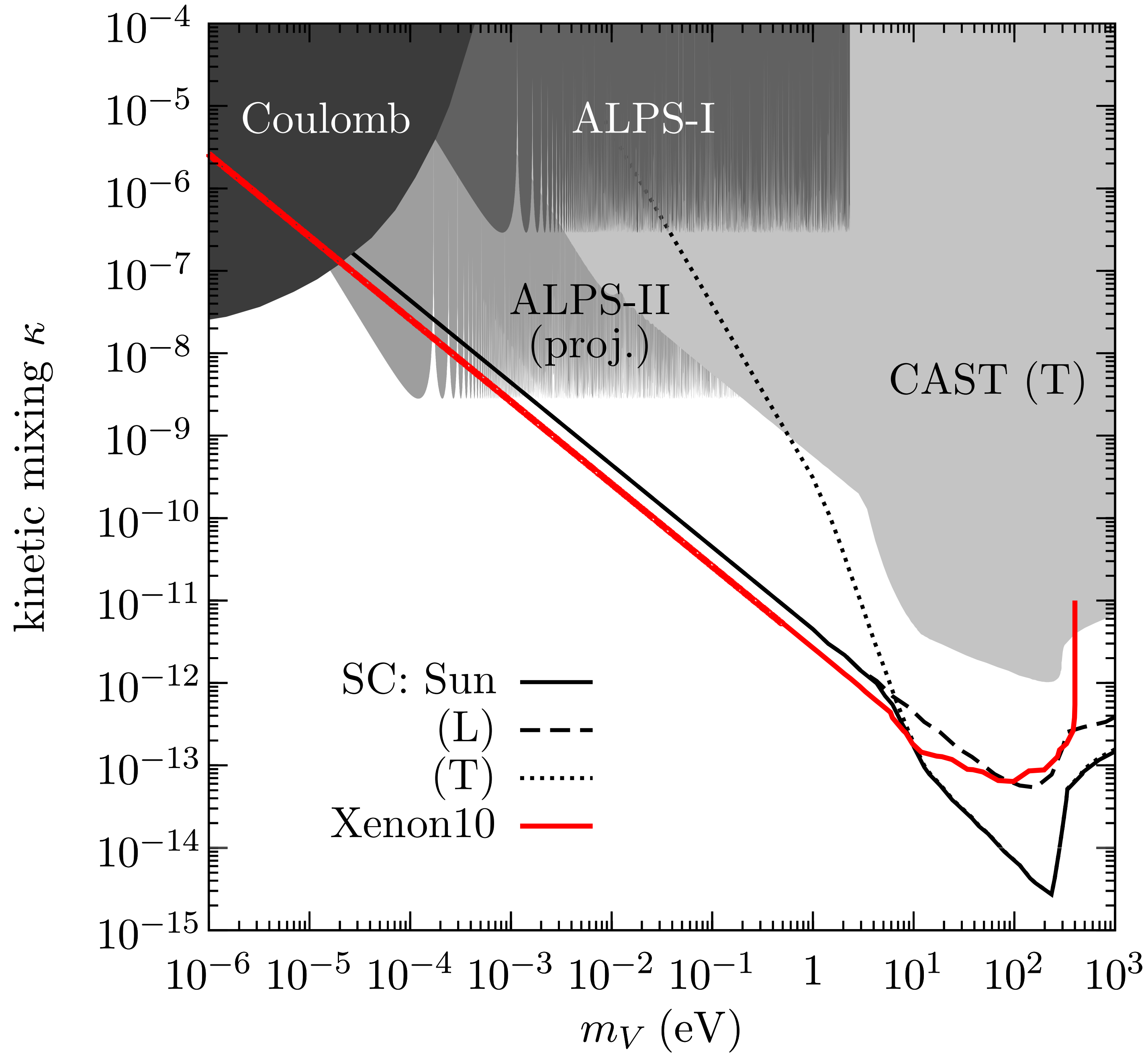
- Xenon10 low threshold study: ionization only



Angle et al. (2011)

DD experiments as helioscopes

- Xenon10 low threshold study: ionization only
- CoGeNT does not yield a limit: required flux is not sustained by the sun (and likewise for CRESST)
- Moral: for sub-keV states astrophysical limits are very hard to compete with (but we keep looking)



An, Pospelov, JP (2013)

Neutrino Physics with DD experiments

Pospelov (2011)
Harnik, Kopp, Machado (2012)
Pospelov, JP (2012)
JP et al, in preparation (2013)

new neutrino

new force

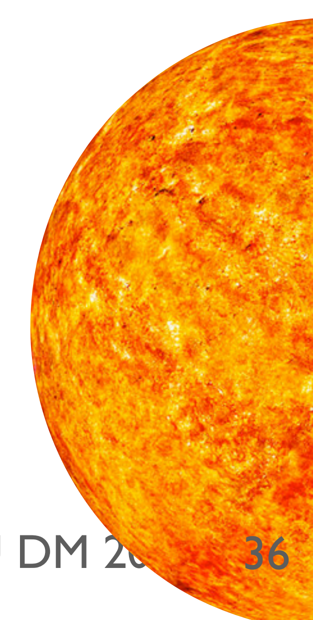
$$\mathcal{L}_{\rm eff} = -G_B (\bar{\nu}_b \gamma^\mu \nu_b) J_{B,\mu}$$

baryon current

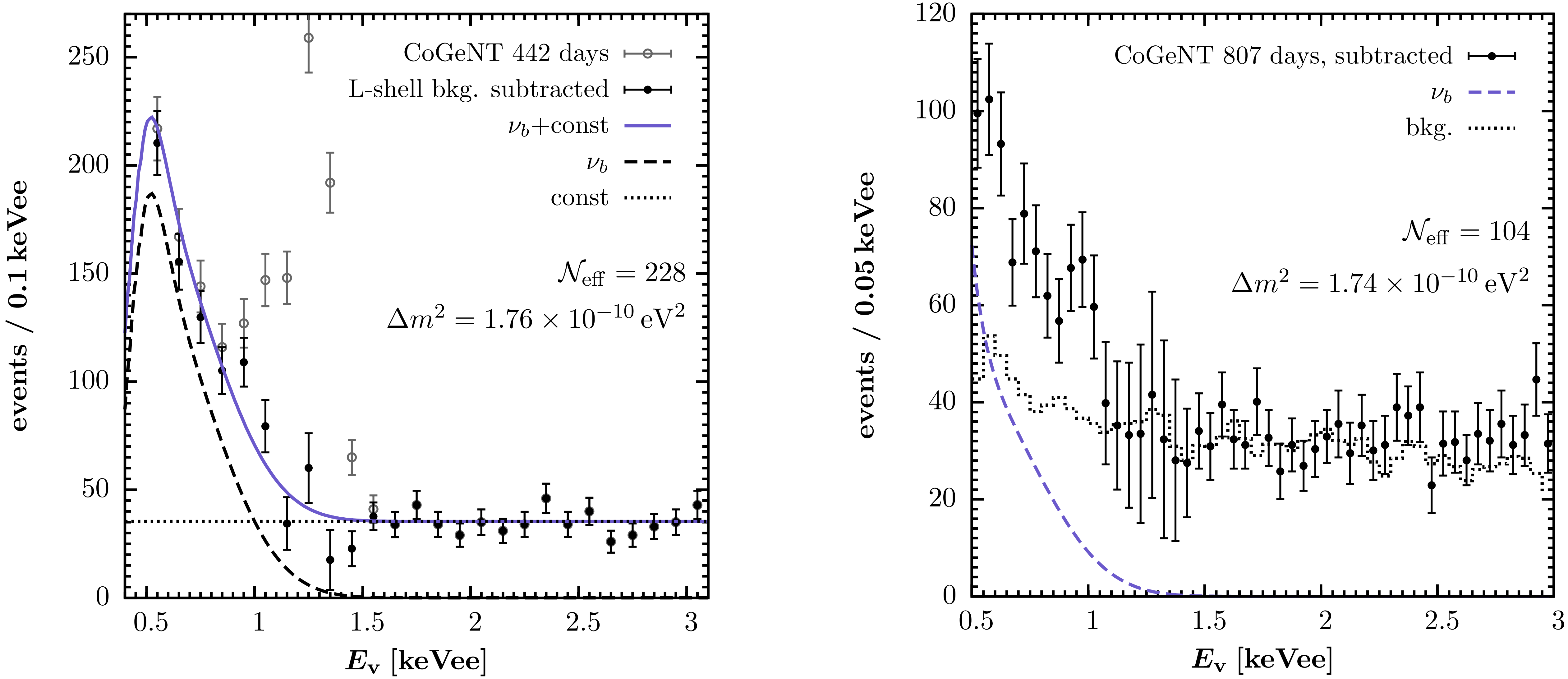
=> for MeV-scale ν_b NC-like coherent scattering on nuclei

$$E_R^{\rm max} = \frac{(2E_\nu)^2}{2m_N} = \mathcal{O}(\rm keV)$$

$$L_{\rm osc} = \frac{4\pi E_\nu}{\Delta m^2} \approx 1\,{\rm kpc} \left(\frac{10^{-10}\,{\rm eV}^2}{\Delta m^2}\right)\left(\frac{E_\nu}{1\,{\rm PeV}}\right)$$



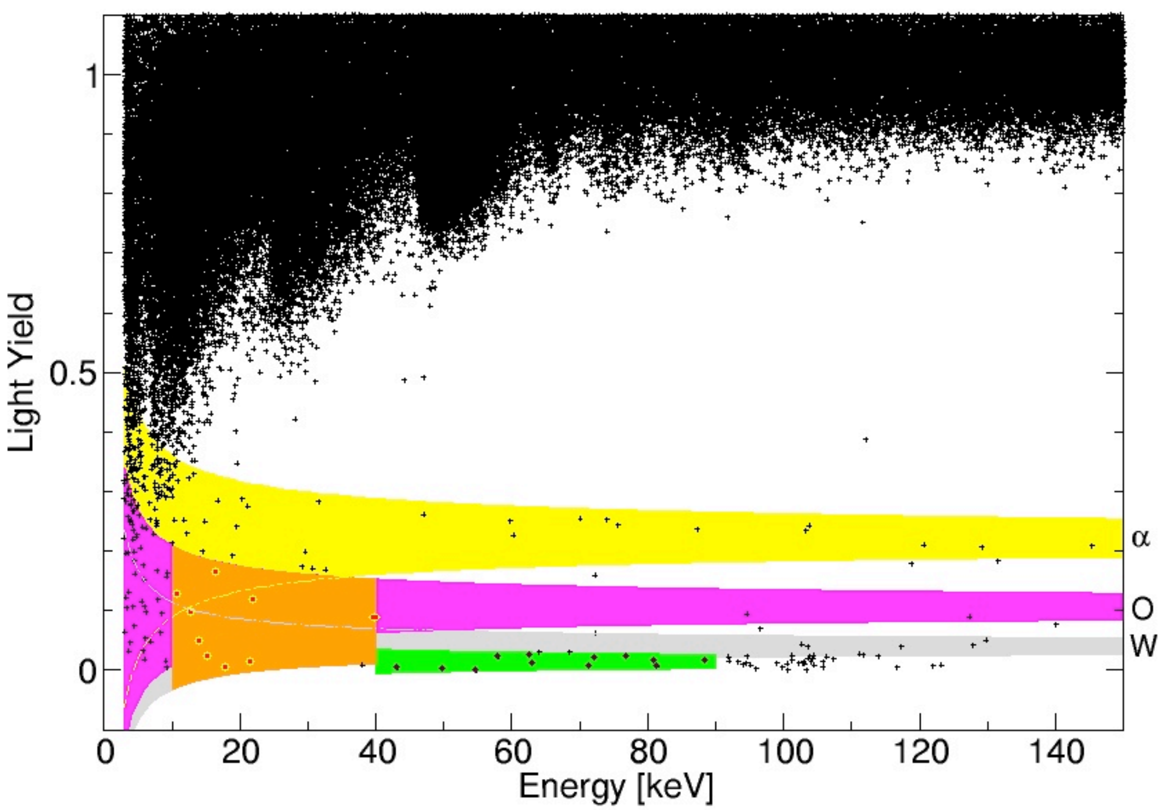
Neutrino Physics with DD experiments



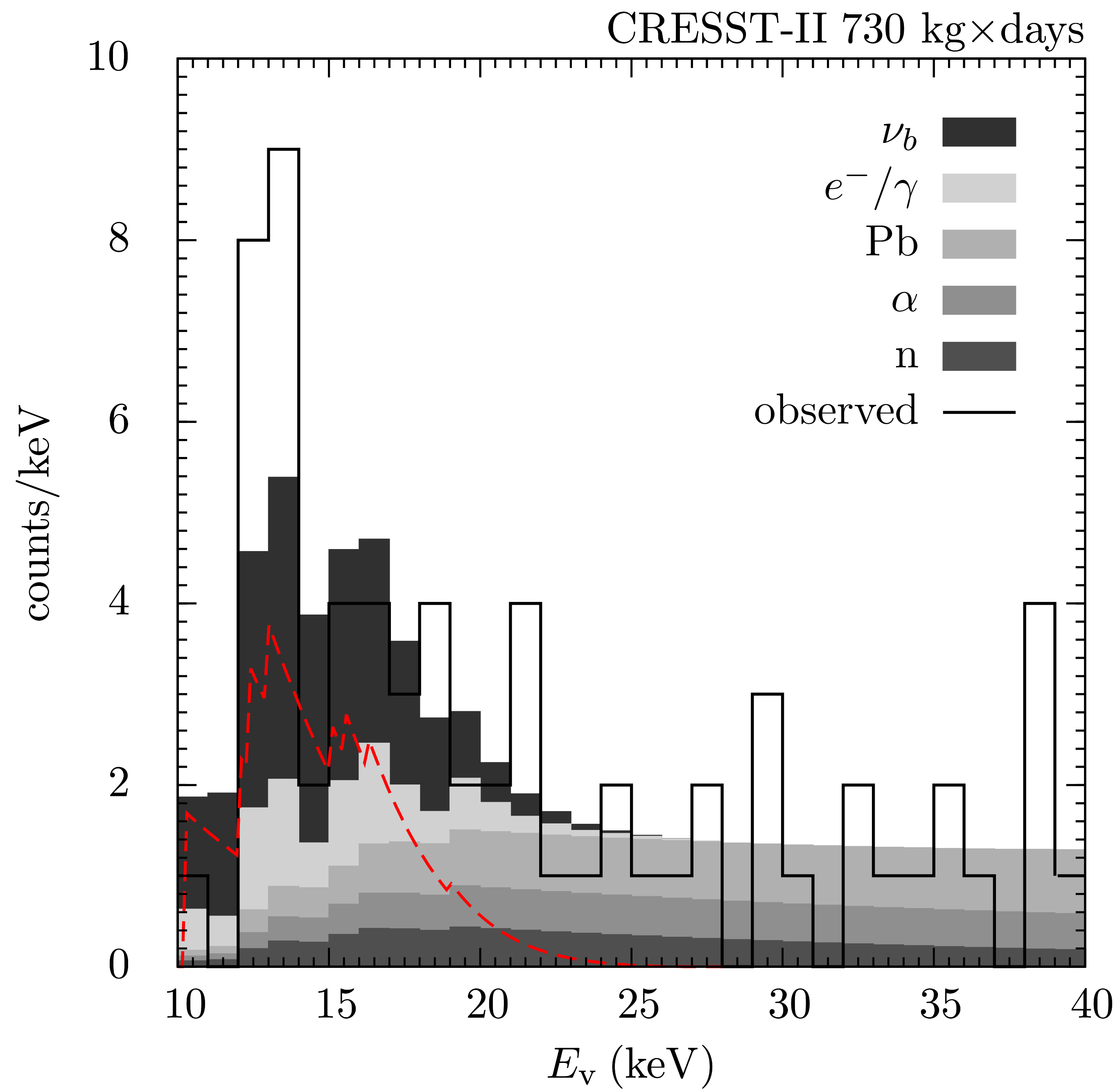
2012 $\Longrightarrow$ 2013

Neutrino Physics with DD experiments

CRESST-II



Angloher et al EPJC 2012



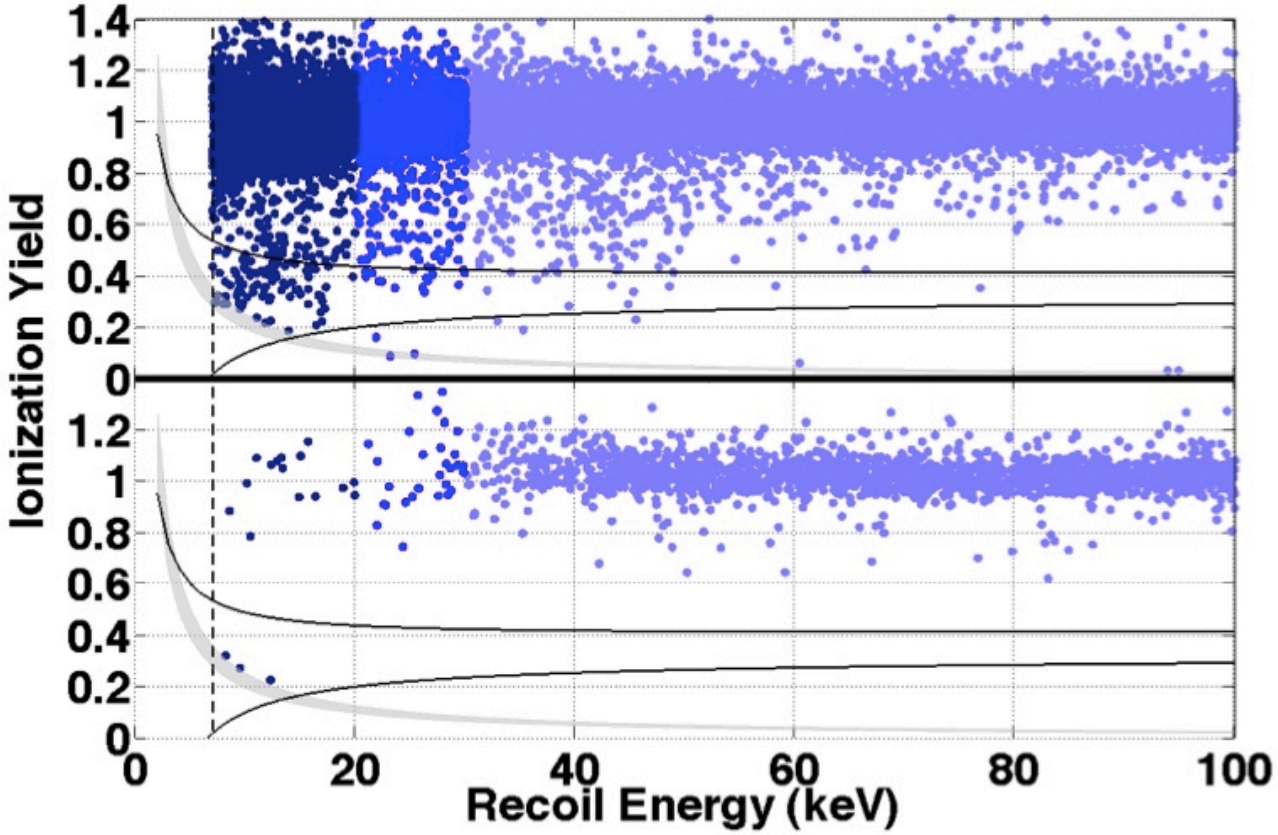
$$\chi^2_P/\text{d.o.f.} = 27.8/28$$

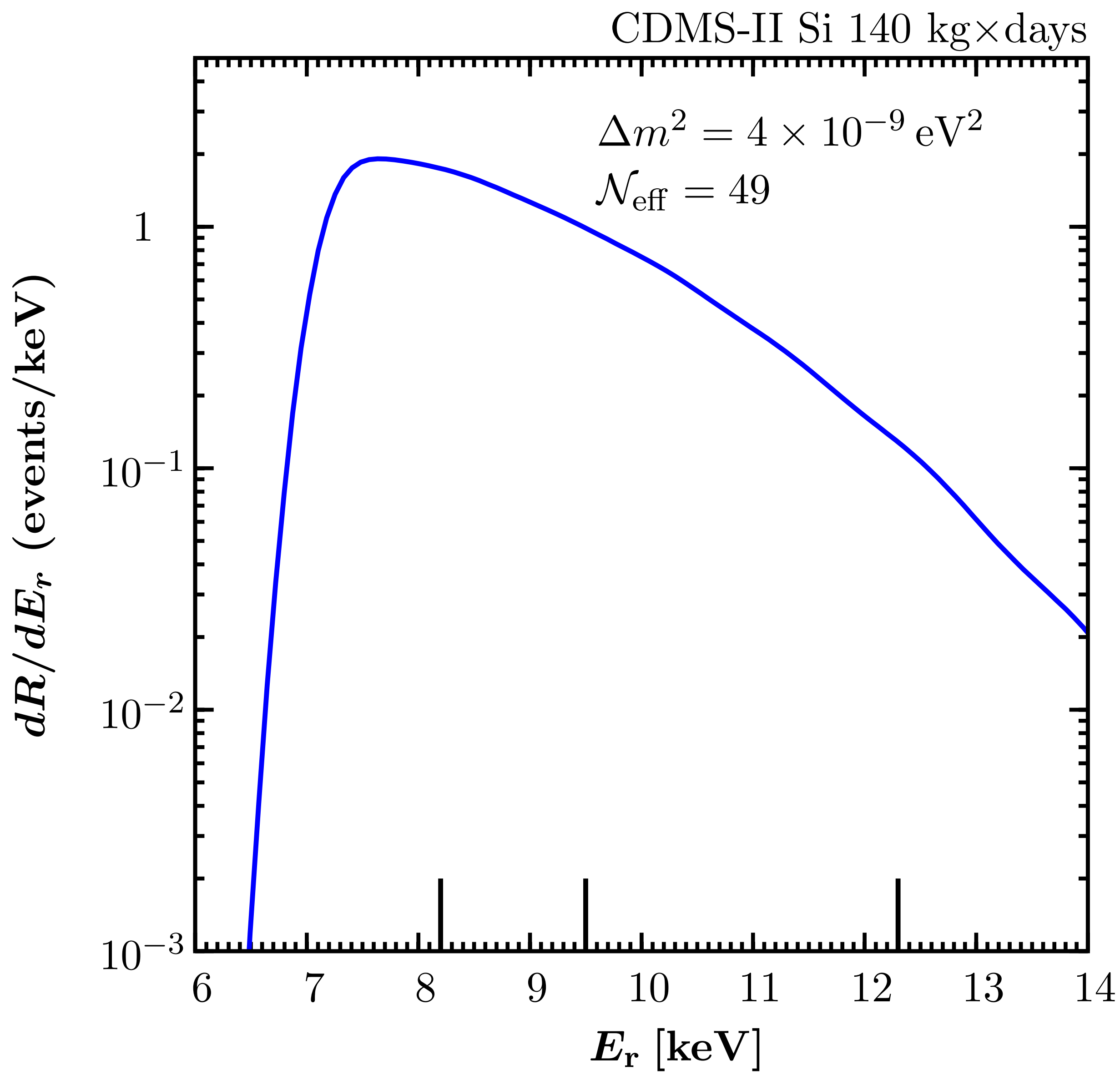
- 8 $CaWO_4$ crystals, 730kg days
- 67 events, only half understood as background

Neutrino Physics with DD experiments

CDMS-Si 2013

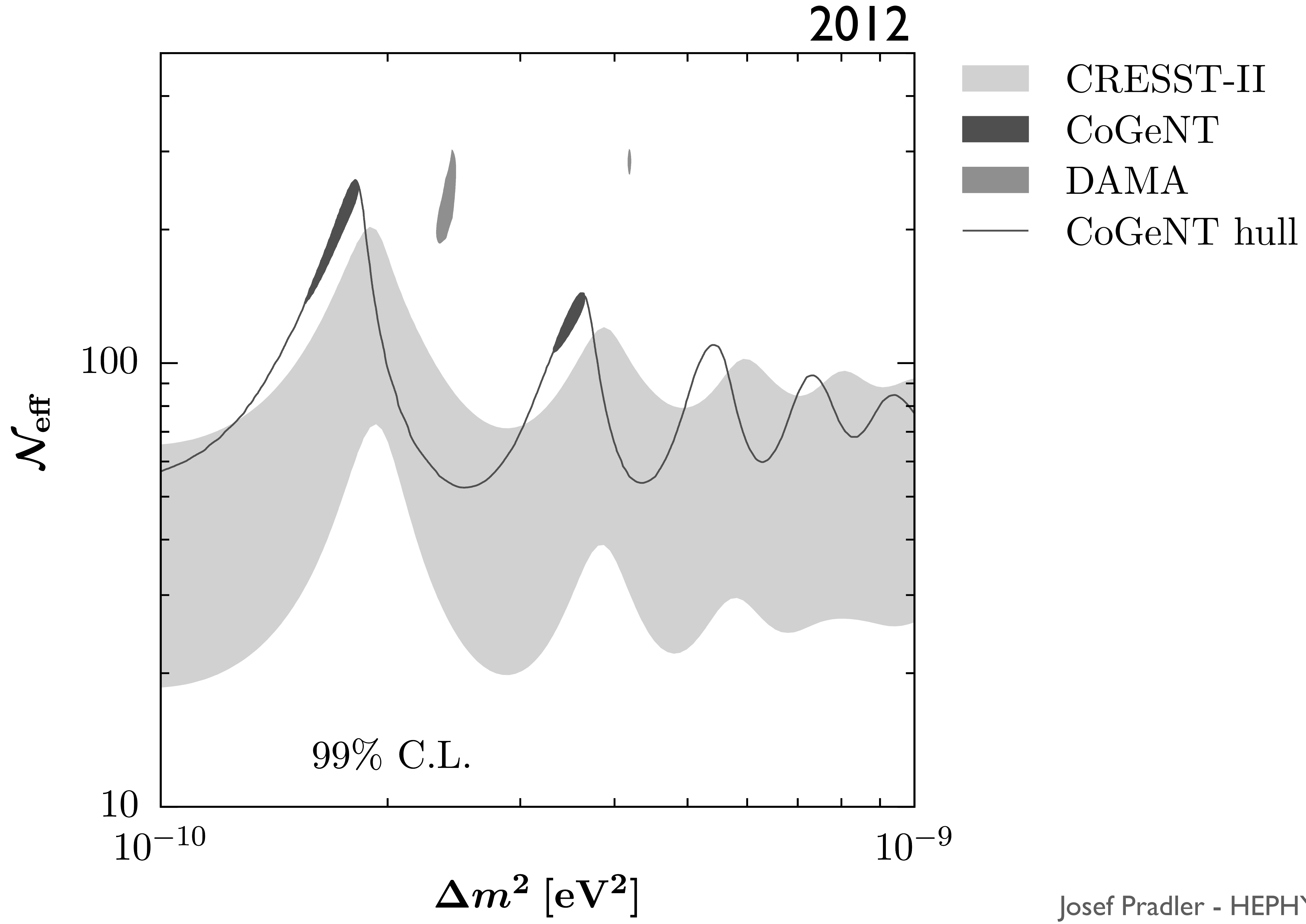
3 events, 0.2% probability of *known background-only* hypothesis





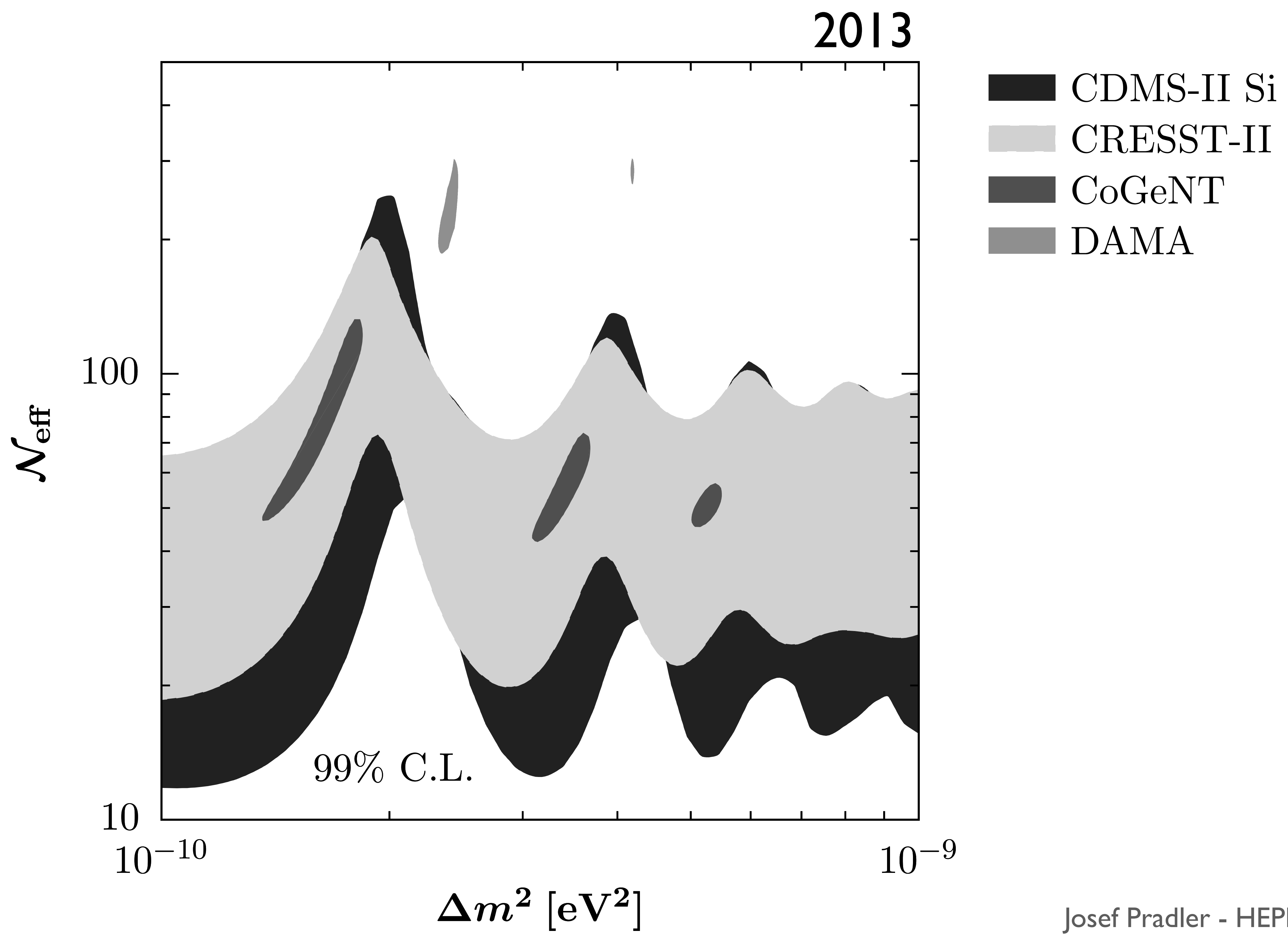
Neutrino Physics with DD experiments

(in preparation)



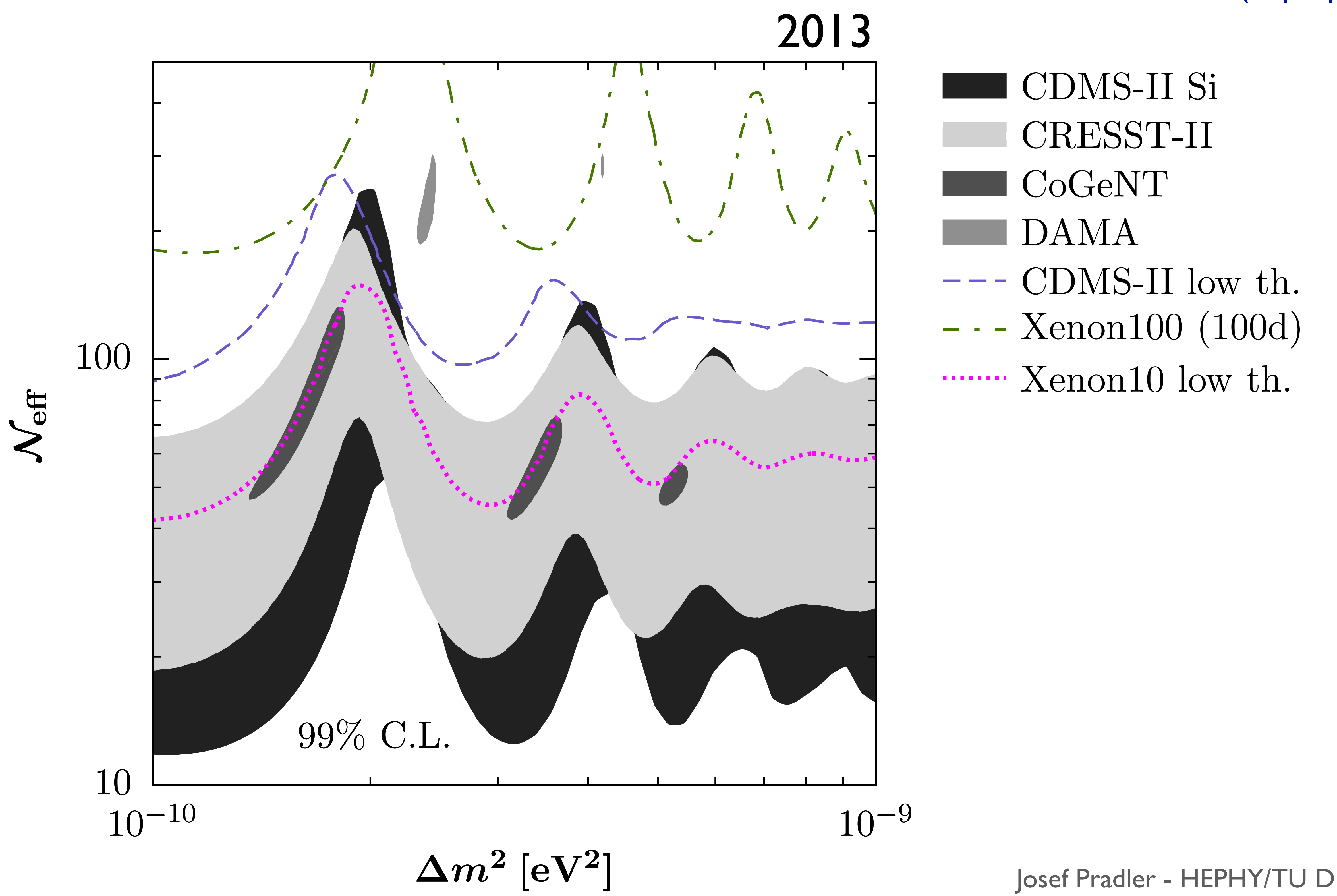
Neutrino Physics with DD experiments

(in preparation)



Neutrino Physics with DD experiments

(in preparation)

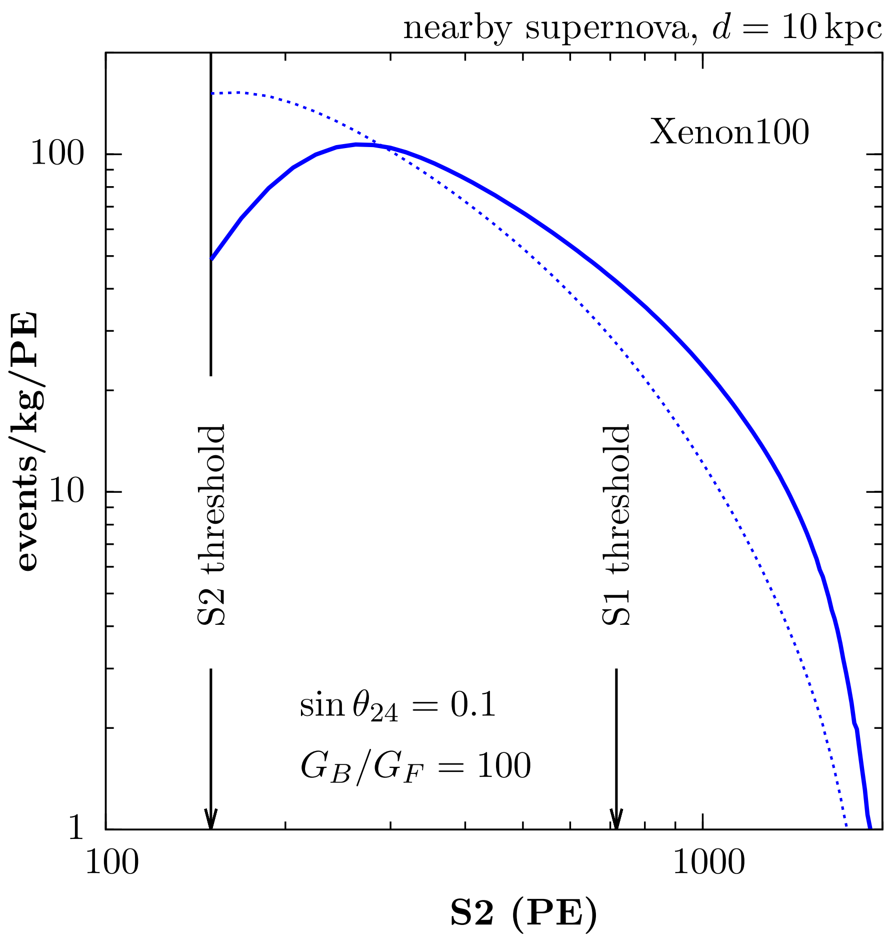


Neutrino Physics with rare event searches

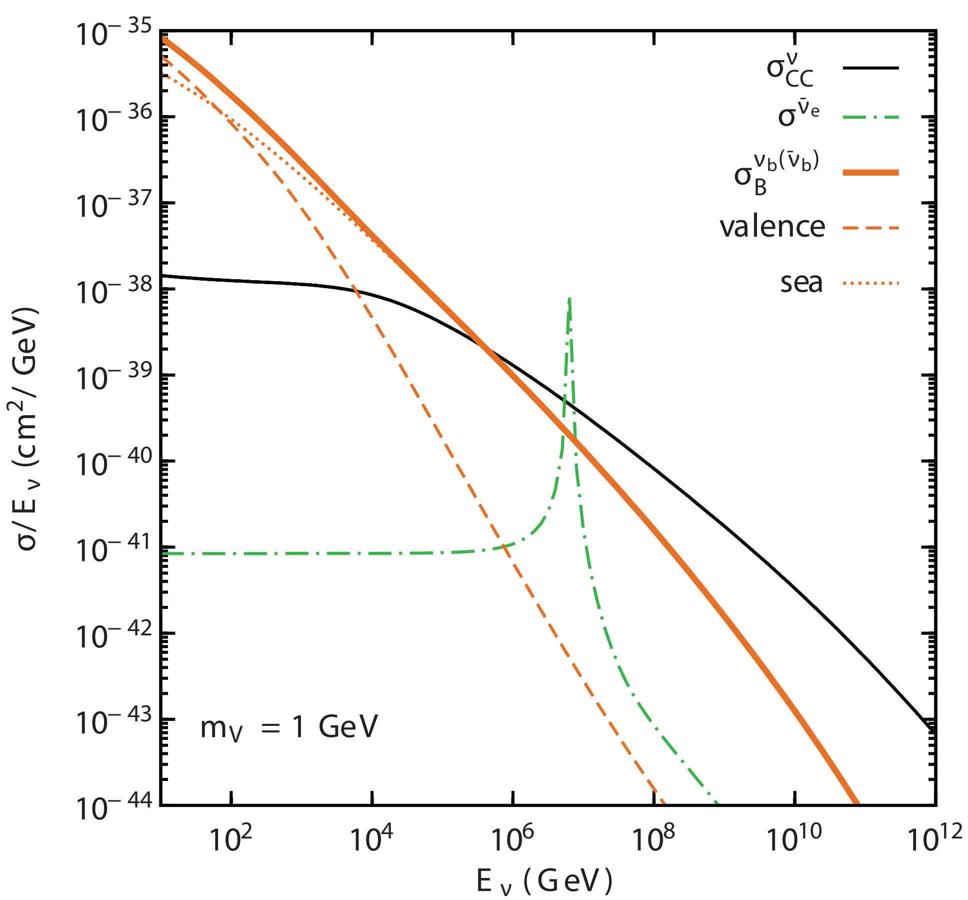
Signal morphology is very similar to light DM:
Boron-8 flux looks like a light WIMP!

Here are complementary probes: (in preparation)

nearby supernovae



IceCube: TeV-PeV

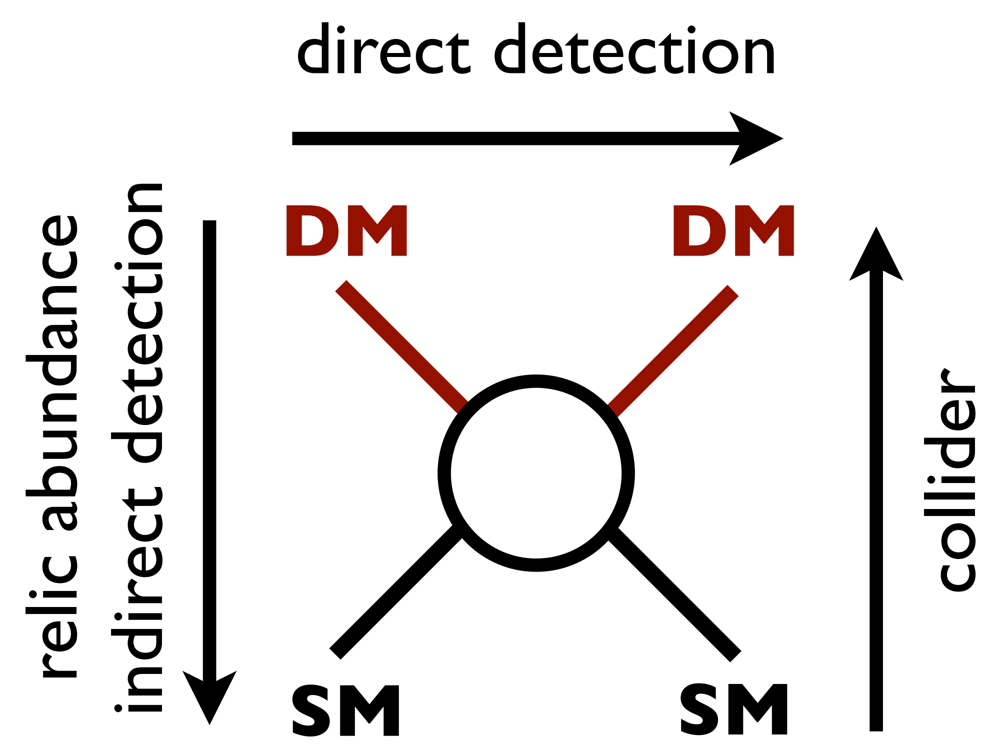


cheat-sheet for a WIMP miracle

- What if direct link to SM is too feeble?

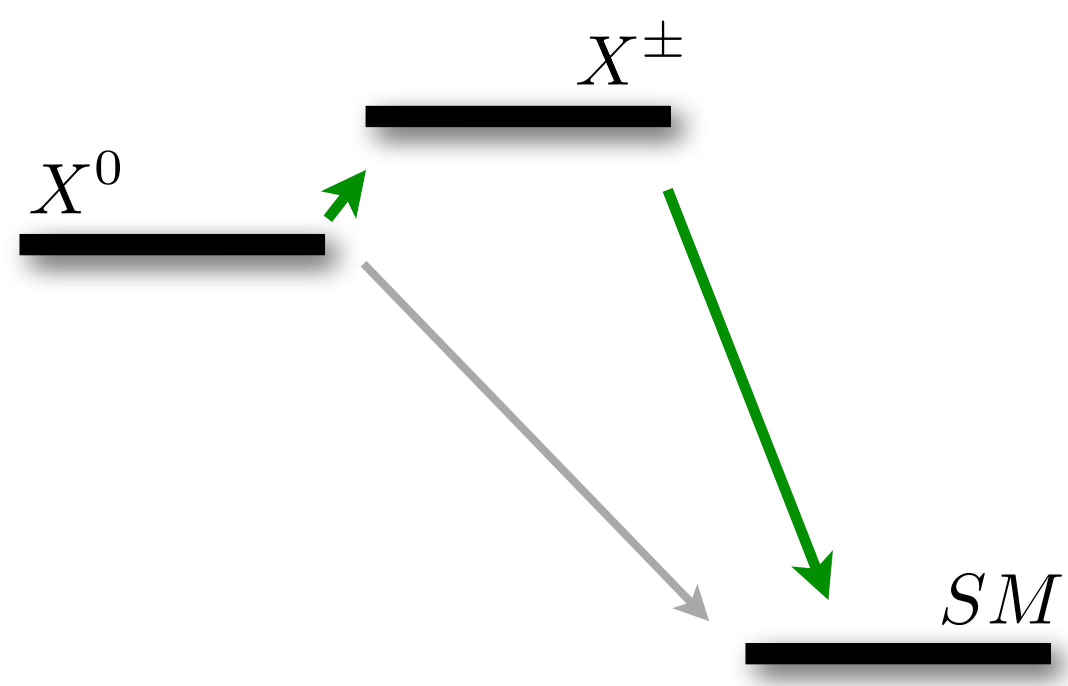
  => no correct thermal abundance

  => little direct detection prospects



- Co-annihilation can guarantee abundance Griest, Seckel PRD 1991

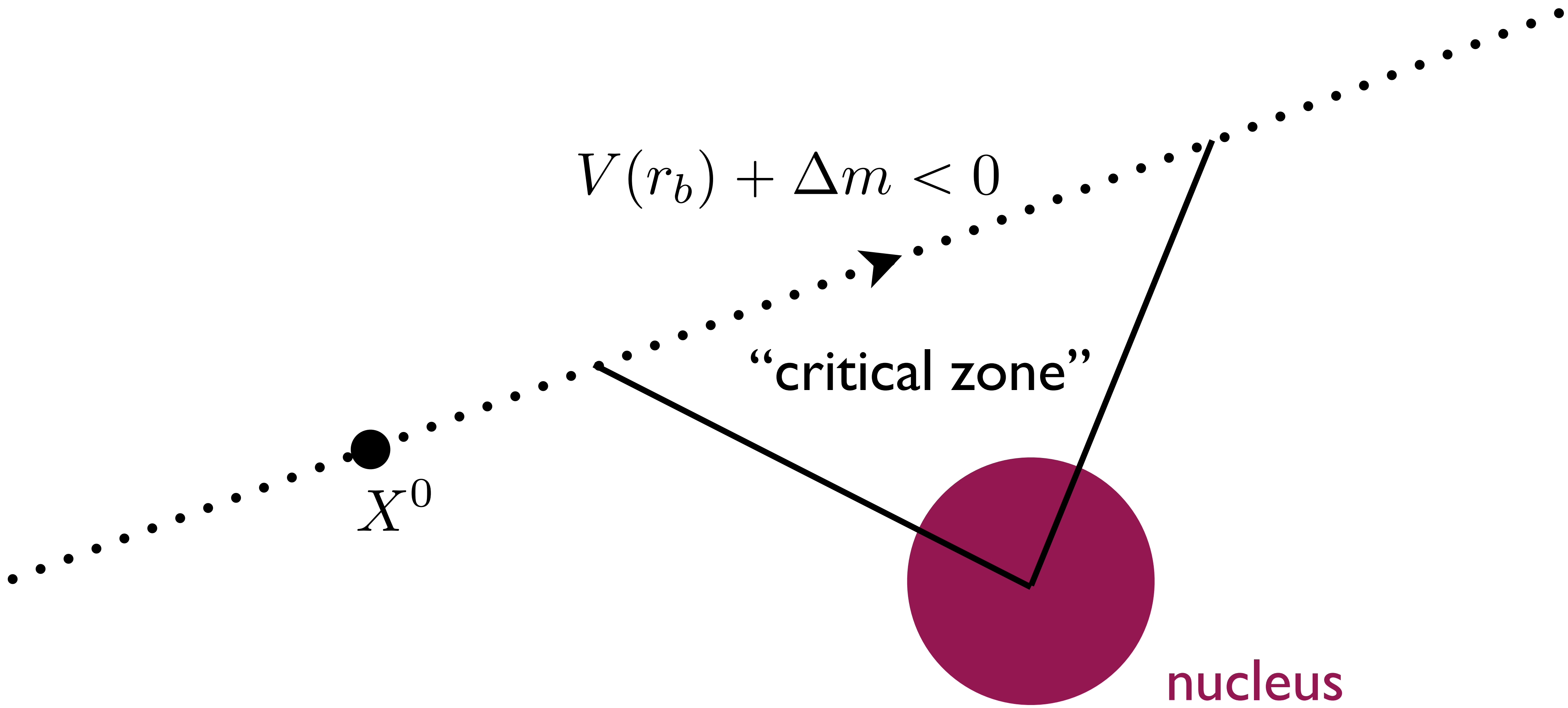
$$X^0 X^\pm \to SM$$
$$X^0 X^0 \to X^+ X^- \to SM$$
$$T_{\rm freeze} \simeq \frac{m_{X^0}}{20} \Rightarrow \Delta m \lesssim 0.05 m_{X^0}$$



Excited states of DM in the coannihilation strip

- in the potential of the nucleus, excited state is accessible

  => capture $E_b = \mathcal{O}(\mathrm{MeV})$



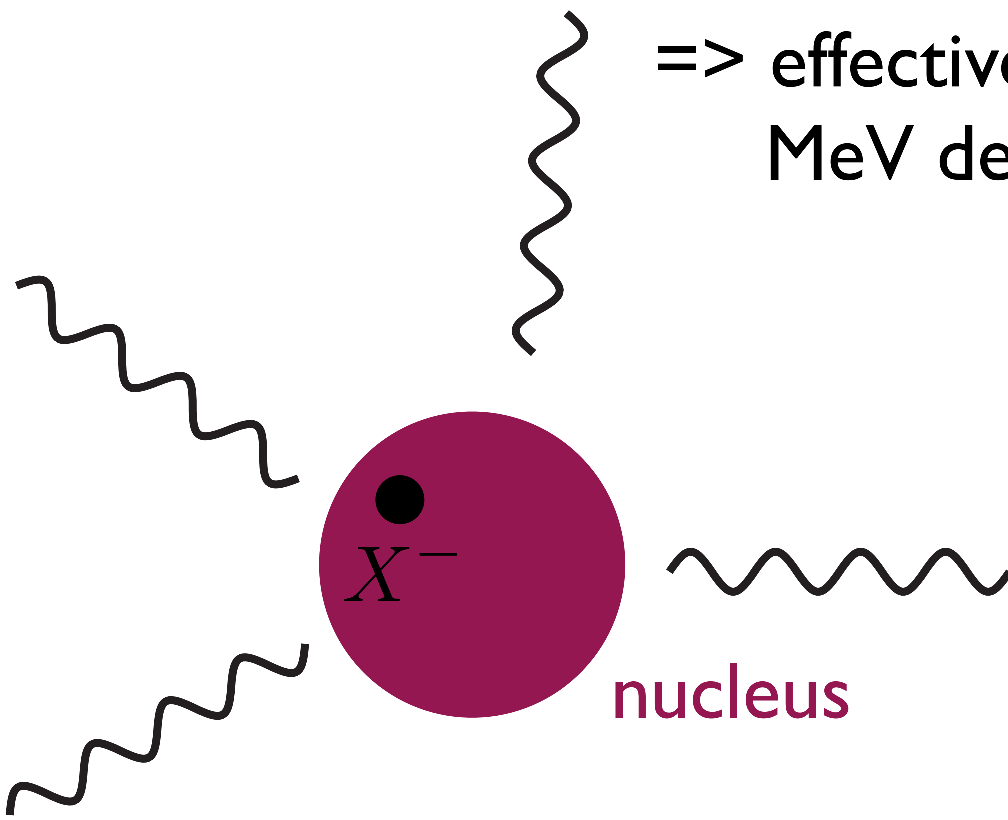
Excited states of DM in the coannihilation strip

- in the potential of the nucleus, excited state is accessible

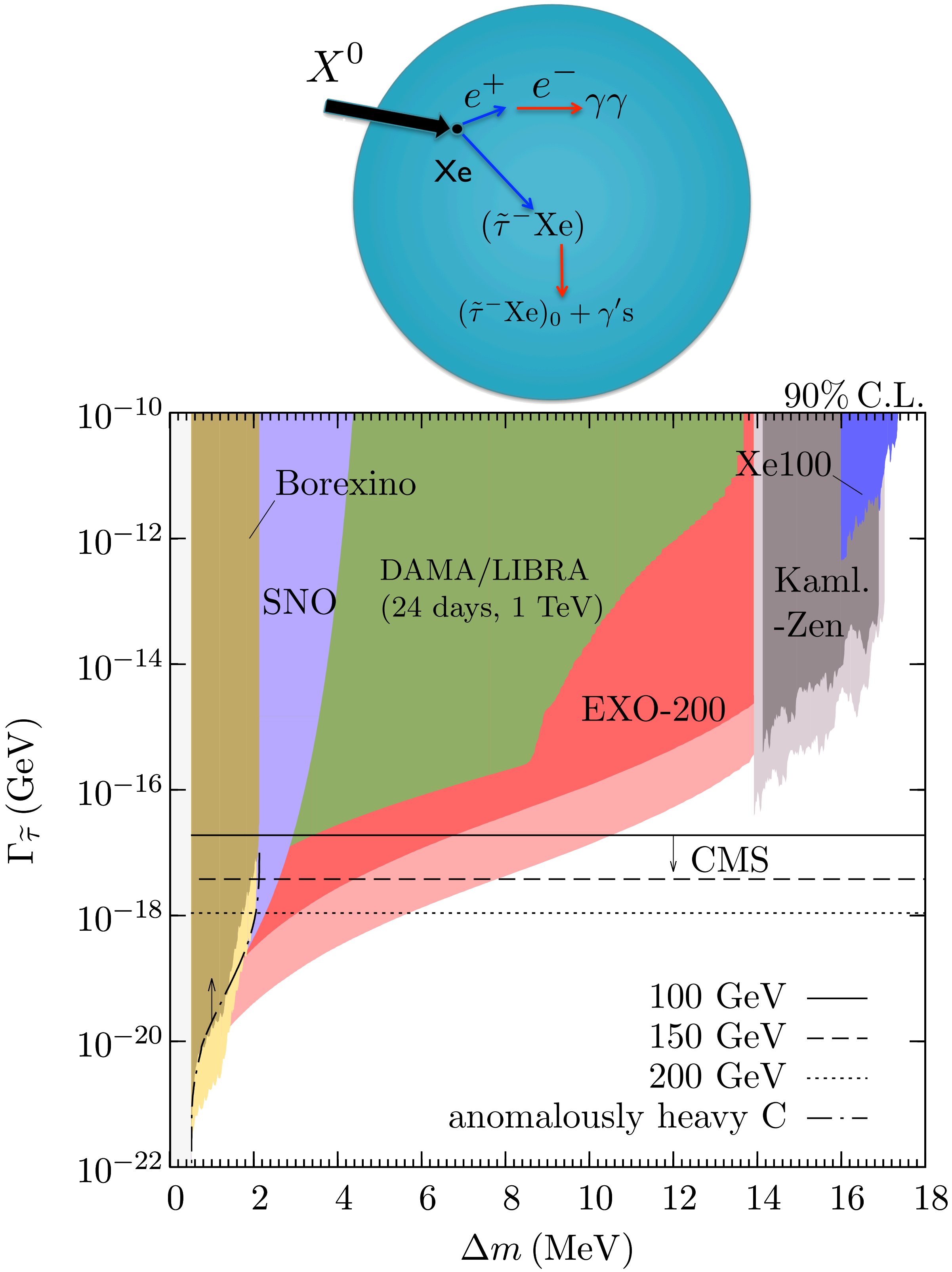
  => capture $E_b = \mathcal{O}(\text{MeV})$

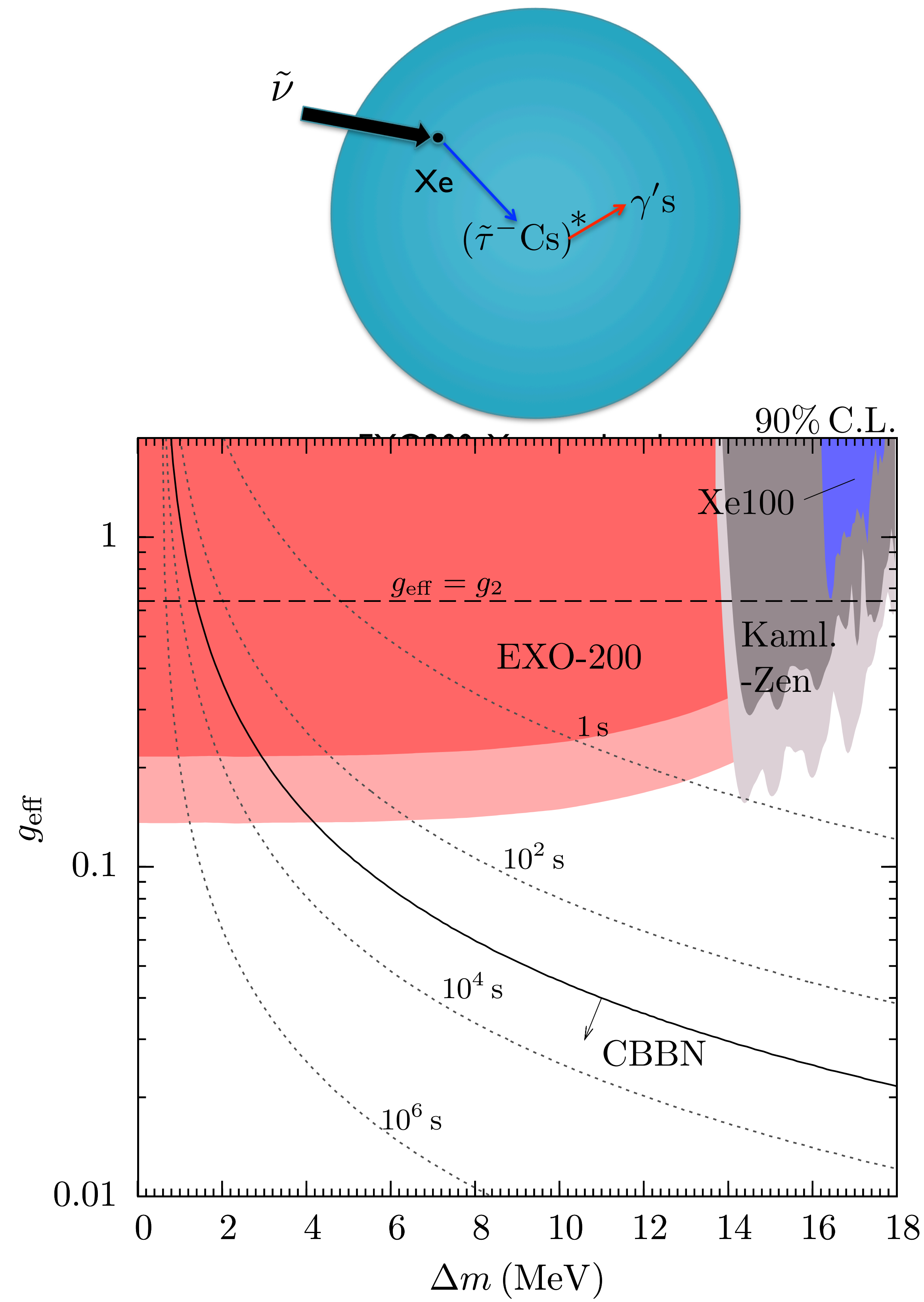
- offers a new kind of signature

=> effective monochromatic
MeV depositions in the detector!



Constraints from WIMP-captures





An, Pospelov, JP (2012)

Conclusions/Summary

- Invisible width of the Higgs $\Gamma_{\rm inv} \lesssim 20\% \,(2\sigma)$ sets a stringent constraint on (or kills) models with Higgs mediation and light WIMP mass $m_{\rm DM} \lesssim 60\,{\rm GeV}$

- LHC (mono-jet) searches complementary to direct detection experiments, probing light wimps and DD-velocity suppressed operators

- Light DM models with $m_{\rm DM} \lesssim 10\,{\rm GeV}$ are theoretically well motivated and light mediators are usually required to guarantee primordial annihilation

  => WIMPs can be "secluded" from SM, which breaks the degeneracy between annihilation and direct detection cross sections.

  => the same light mediators were also put forward as explanation of the CR positron excesses: boost of galactic annihilation, leptonic final states (new science cases at the intensity frontier)

Conclusions/Summary - II

Discussed some concrete, “out-of-the-box” examples for direct detection:

- (modulating) solar fluxes of ALP-like particles yield electron recoils
  => hard to gain enough sensitivity in view of astrophysical limits
- a stronger than G_F interacting neutrino looks like light-DM
  => differential recoil from multiple-targets and directionality can be important discriminators
  => other astrophysical probes (nearby and diffuse SN, IceCube)
- MeV-scale energy depositions from WIMP-captures are possible
  => entire (non-)recoil spectrum can be of interest

DAMA’s decade long claim:

- CR muons are unlikely to induce modulation
- appears to us that stronger modulating signals are needed to beat apparent backgrounds