DARK MATTER AT THE TEV FRONTIER

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University of Warsaw, 24th October 2019

OUTLINE

1. Introduction
   - DM and the WIMP paradigm
   - Current status and *'crisis'* in the DM community
2. DM theory at the TeV scale
   - General overview
   - Large Logs and resummation
   - Sommerfeld effect + Bound states
3. Observational prospects
   - Direct detection, LHC, ...
   - Indirect: gamma-rays, CMB, CRs, radio, ...
4. Summary

DARK MATTER

STATUS IN A NUTSHELL

1. We know nearly nothing at all about dark matter
   - origin
   - nature
   - interactions
   - structure
   - …

2. We know quite a lot about dark matter
   - it is there!
   - particle(s) vs. sth else
   - large scale structure
   - limits on interactions
   - mechanisms of origin
   - …

WIMP

Weakly Interacting and Massive

In a weak sense:

DM cannot interact too strongly with the SM (or it would be seen) and has to have a mass to contribute to observed gravitational potential (now and during the structure formation)

In a strong sense:

interacting through SM weak interactions

and (therefore) also massive

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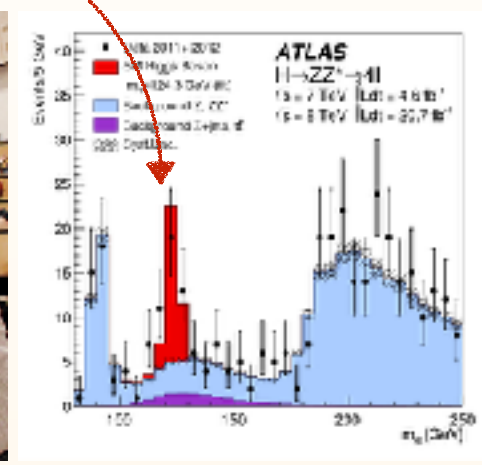
NEW PHYSICS

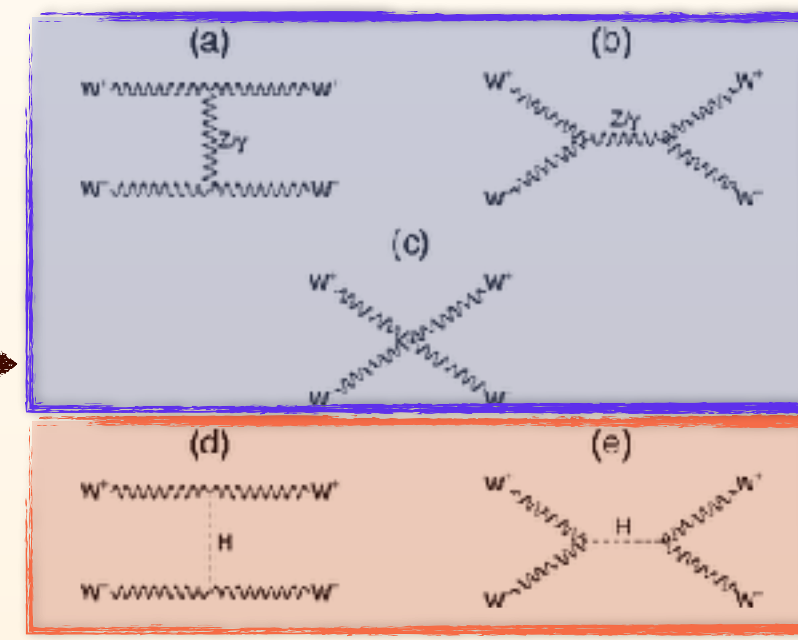
(IS ALWAYS) AROUND THE CORNER

July 2012 - the Higgs boson



since then:

but then we <u>knew</u> sth is there: *vide* so-called unitarization of the WW scattering cross section



EW part

Higgs

Now, after the Higgs was found - **The Hierarchy Problem**

$$\Delta m_h^2 = \frac{3\Lambda^2}{8\pi^2 v^2}\left[4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2\right] + \mathcal{O}\left(\log\frac{\Lambda}{v}\right)$$

or in other words: why is the Higgs boson so light?

THE ORIGIN OF DARK MATTER
AND THE „WIMP MIRACLE"

Dark matter could be created in many different ways…

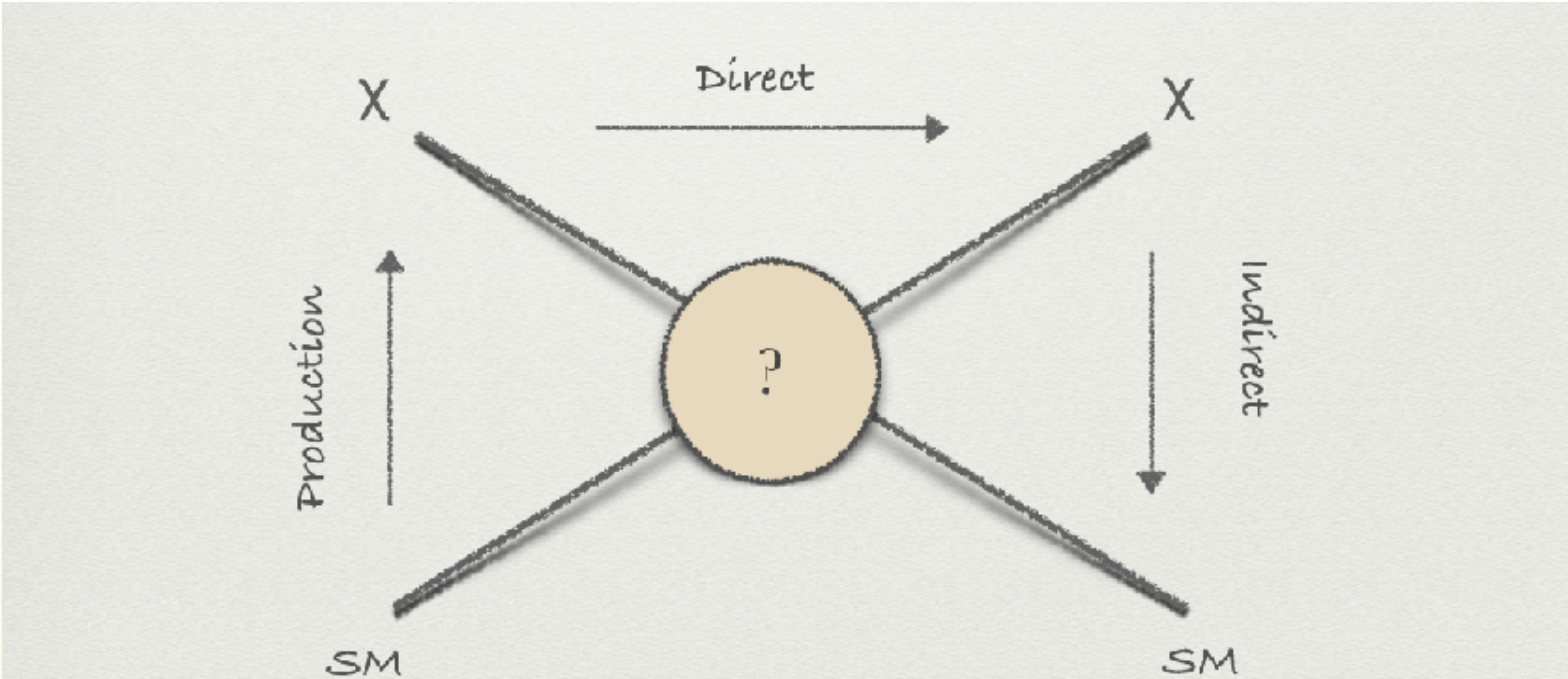
…but <u>every</u> massive particle with not-too-weak interactions with the SM will be produced thermally, with relic abundance:

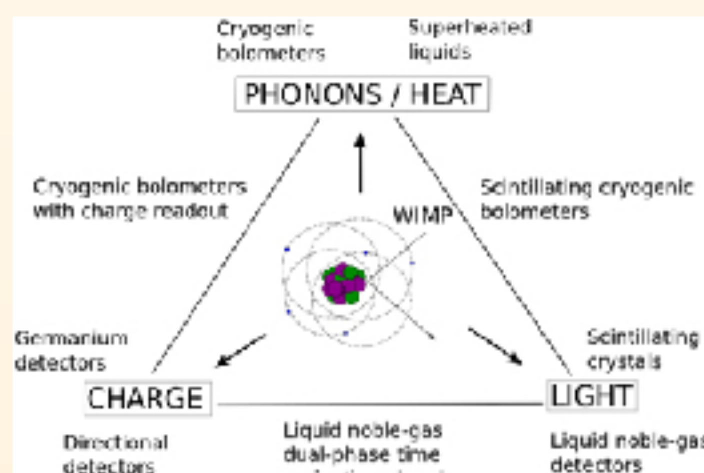
Lee, Weinberg '77; + others

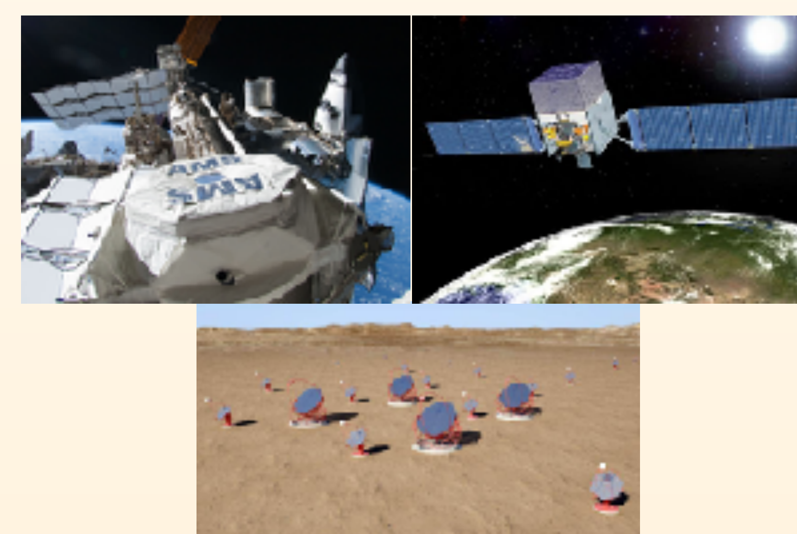
$$\Omega_\chi h^2 \approx 0.1 \, \frac{3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

This is dubbed the *WIMP miracle* because it coincidentally seem to point to the same energy scale as suggested by the Hierarchy Problem

WIMP DETECTION





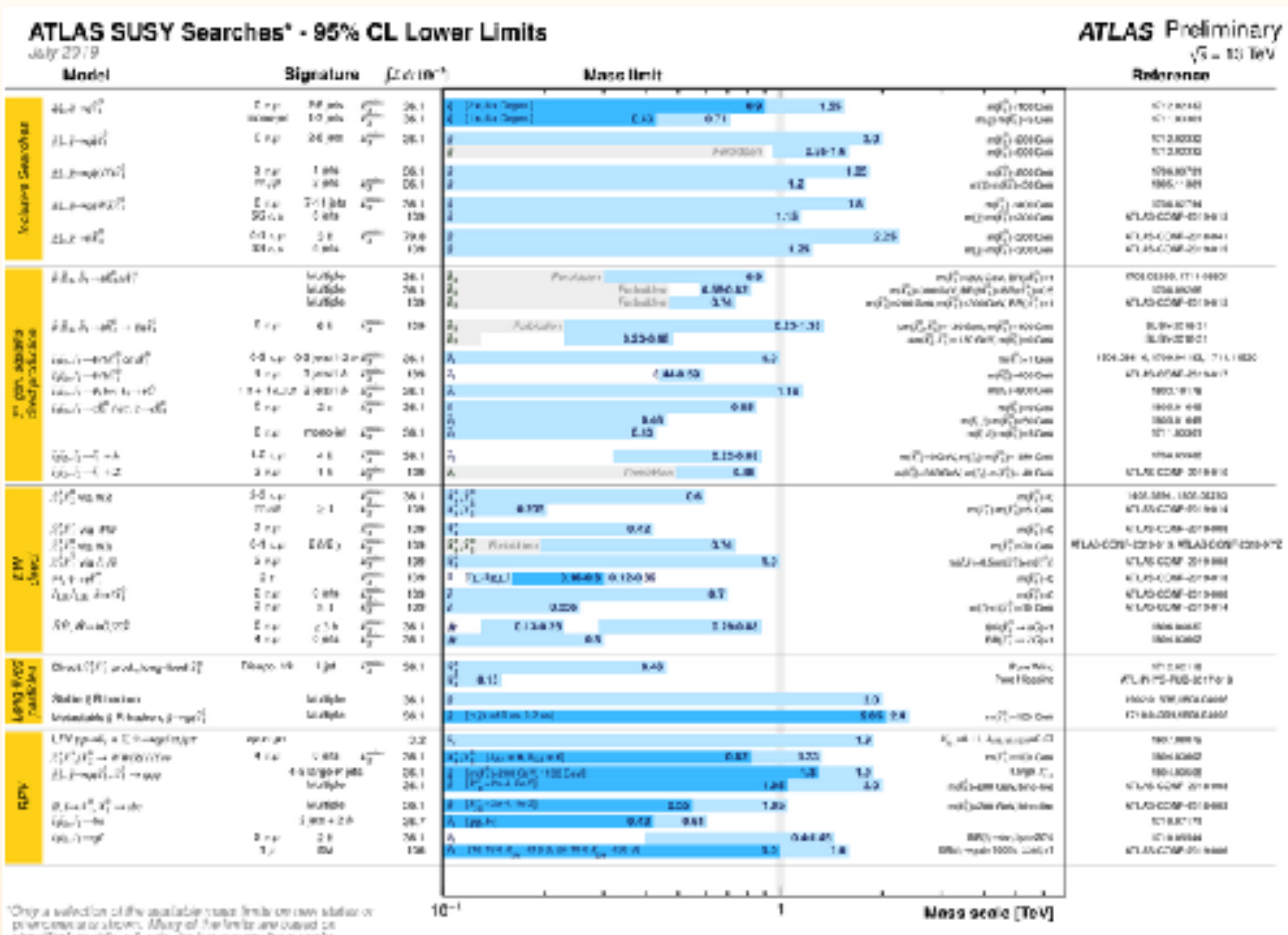


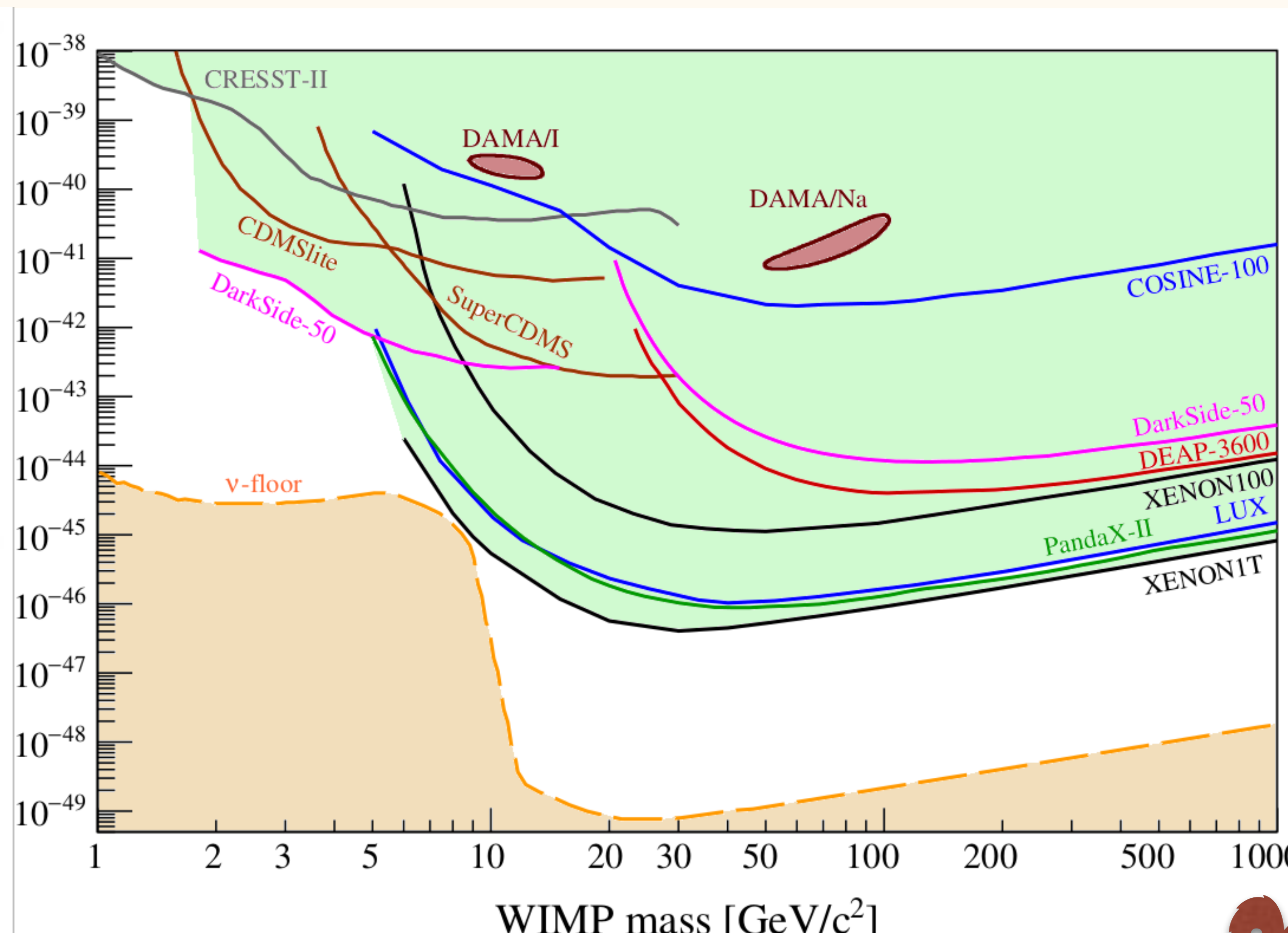
CURRENT LIMITS
AND DECLINE OF THE WIMP PARADIGM

"The great tragedy of science - the slaying of a beautiful hypothesis by an ugly fact"
Aldous Huxley

On both Direct Detection and LHC front no* signal of DM particle!

*convincing





Time for a New Paradigm?

A New Era in the Quest for Dark Matter

Gianfranco Bertone[1] and Tim M.P. Tait[1,2]

ABSTRACT

There is a growing sense of 'crisis' in the dark matter community, due to the absence of evidence for the most popular candidates such as weakly interacting massive particles, axions, and sterile neutrinos, despite the enormous effort that has gone into searching for these particles. Here, we discuss what we have learned about the nature of dark matter from past experiments, and the implications for planned dark matter searches in the next decade. We argue that diversifying the experimental effort, incorporating astronomical surveys and gravitational wave observations, is our best hope to make progress on the dark matter problem.

Nature, volume 562, pages 51–56 (2018)

From HEP perspective it all may feel quite depressing…

(…) the new guiding principle should be "no stone left unturned".

→ i.e. test all ideas in all possible ways…

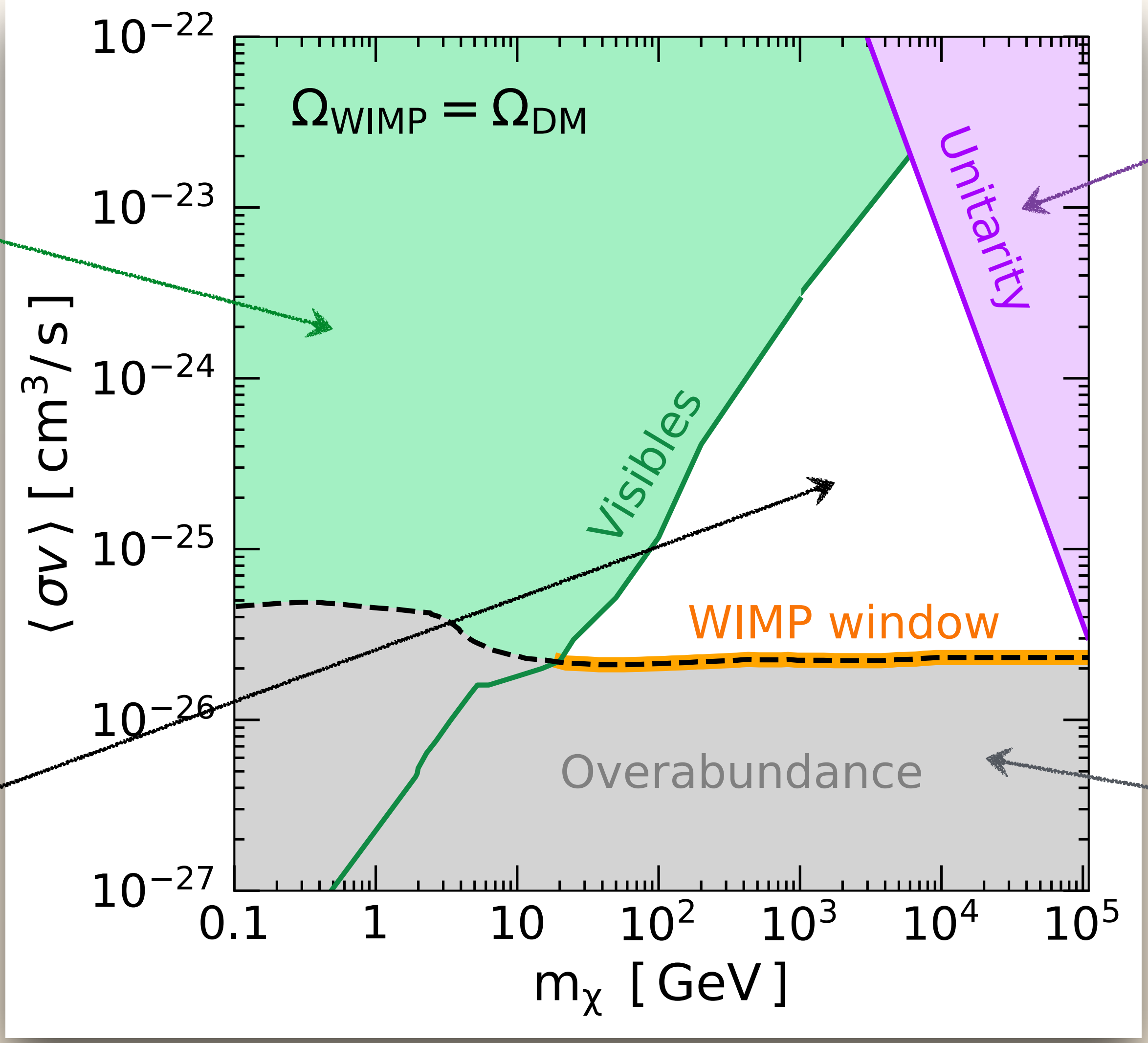
… BUT IN FACT WIMP NOT EVEN SLIGHTLY DEAD

Most of the (strongest) limits are based on assumptions motivated by theoretical prejudice (or convenience)

→ this can lead to a very broad-brush conclusions

excluded by observations

predicted probabilities can be >1



all fine!

too much dark matter

R. Leane *et al*; 1805.10305

Why not to go to TeV…

- Little Hierarchy Problem: further away from the lamppost (LHC), fine tuning gots worse for simplest models (e.g. CMSSM)
- Thermal abundance requires large couplings (unitarity bound) or specific mechanism

---

…and Why it is worth it

- There is no reason in principle not to consider full thermal range up to unitarity limit (apart from naturalness mentioned above)
- Even SUSY has regions in that regime and there are many more models on the market
- Theory: new phenomena and new challenges appear

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WHY TEV SCALE IS DIFFERENT?

If  then it is actually not <u>that</u> different…

what changes:

- more difficult to test (LHC - energy, DD&ID - number density)
- unitarity limit (if thermally produced)
- DM dynamics during EW phase transition

For a WIMP, however, one major difference:

$$m_{\rm DM} \gg m_W, m_Z, m_h \quad \Rightarrow$$

I. SU(2) non-Abelian - leads to Sudakov corrections

&

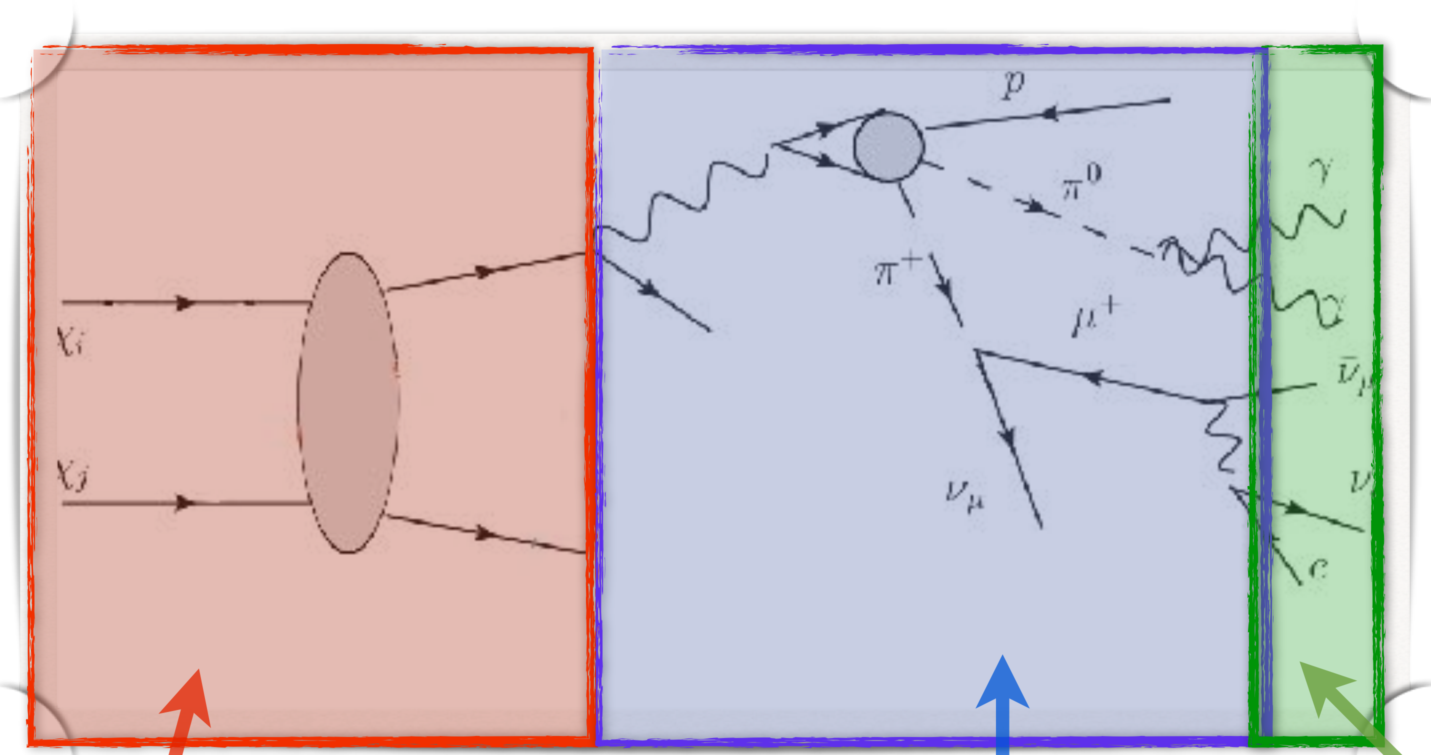
II. electroweak (and Higgs mediated) interactions become <u>long-ranged</u>

I.

SUDAKOV-TYPE LARGE LOGS

AND THEIR RESSUMATION

DM INDIRECT SEARCHES



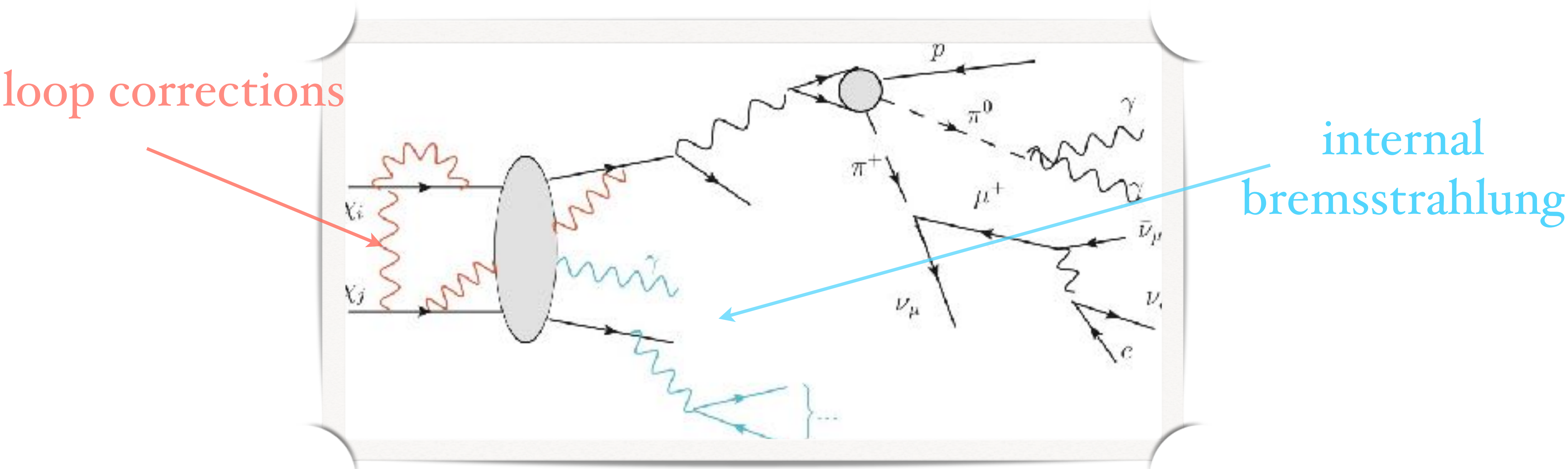
primary annihilation process

shower development: splitting, hadronization, fragmentation/decay (e.g. PYTHIA)

indirect detection

*This Feynman diagram is an approximation of lowest order in perturbation theory!
Actual process can contain many more interactions

EW CORRECTIONS



enhancement by large (Sudakov) logarithms:

$$\alpha_2 \log \frac{m^2}{m_W^2} \qquad\qquad \alpha_2 \left(\log \frac{m^2}{m_W^2} \right)^2$$

$$m = 1 \text{ TeV},\ \alpha_2 \approx \frac{1}{30} \quad \Rightarrow \quad \approx 0.17 \qquad\qquad \approx 0.86$$

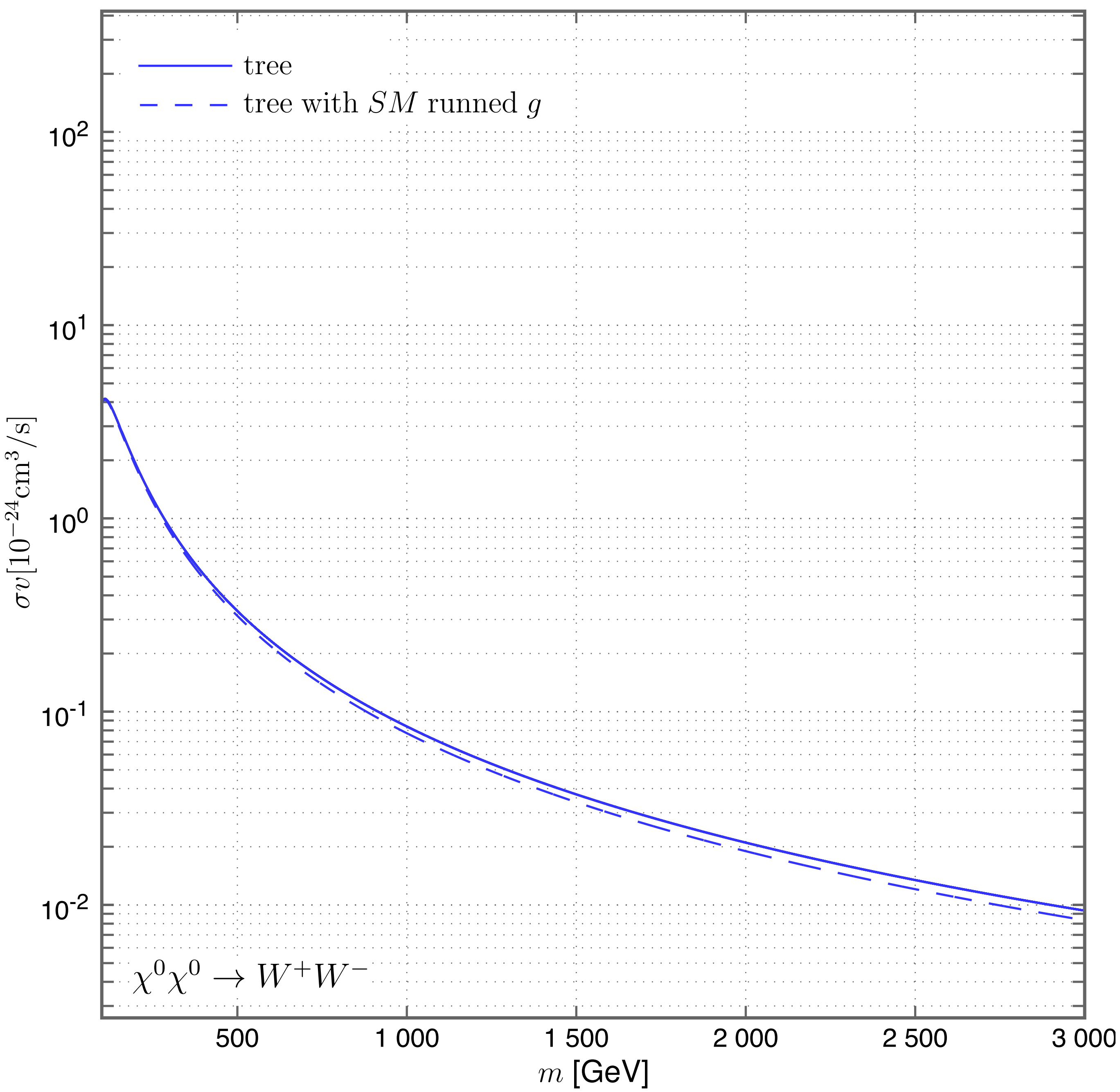
$m \gg m_W$ resambles IR divergence of QED or QCD

→ Bloch-Nordsieck violation Ciafaloni *et al.* '00

Bloch-Nordsieck: QED in the **inclusive** cross-section IR logs cancel
Kinoshita-Lee-Nauenberg: generalized to SM, but only when summed over initial non-abelian charge

PPPC 4DM ID: Cirelli *et al.*, '11

EXAMPLE:
WINO DM @ 1-LOOP



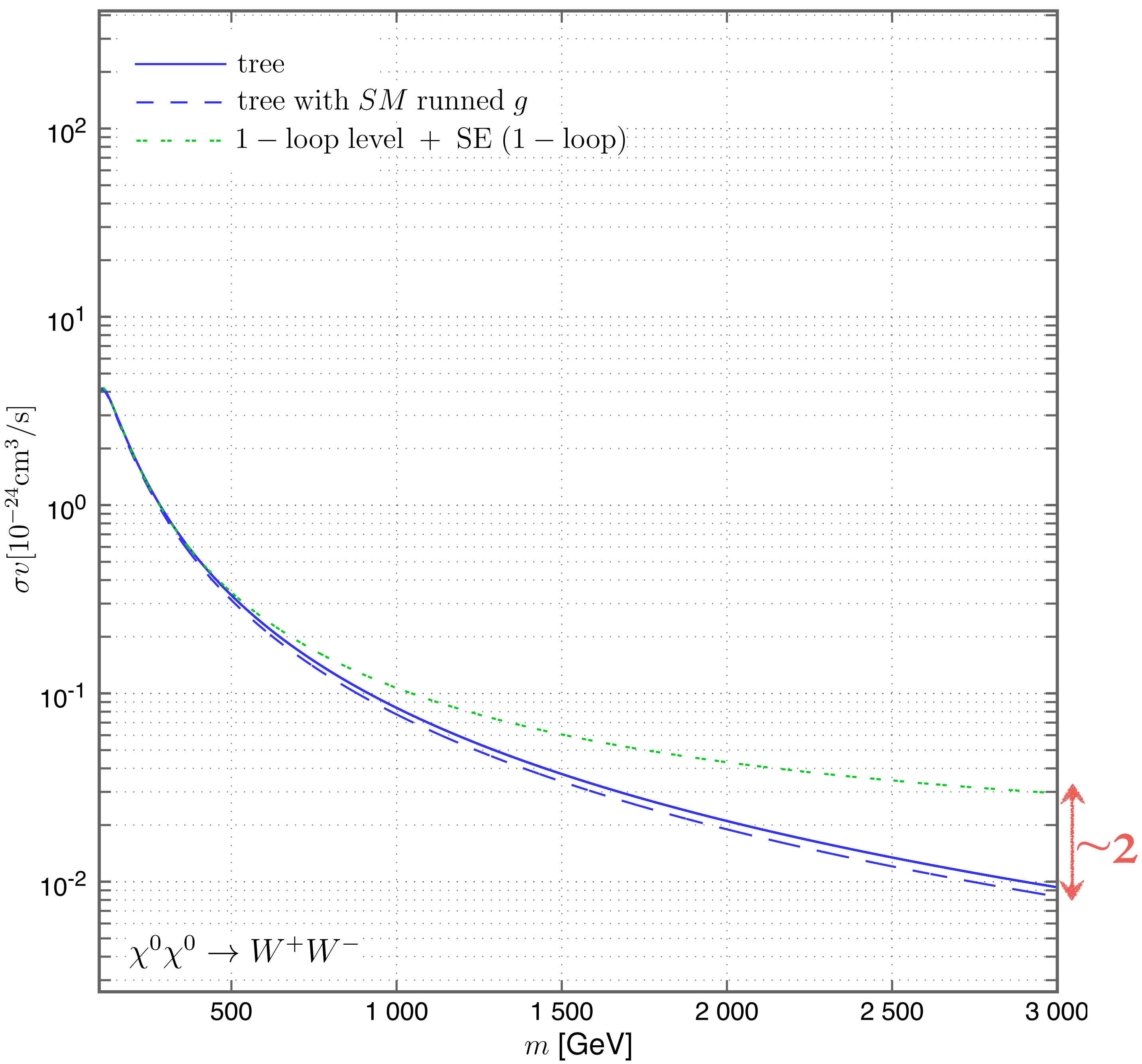
tree level result $\sim 1/m^2$

with g at scale m

with SM running

AH, R. Iengo; JHEP 1201 (2012) 163

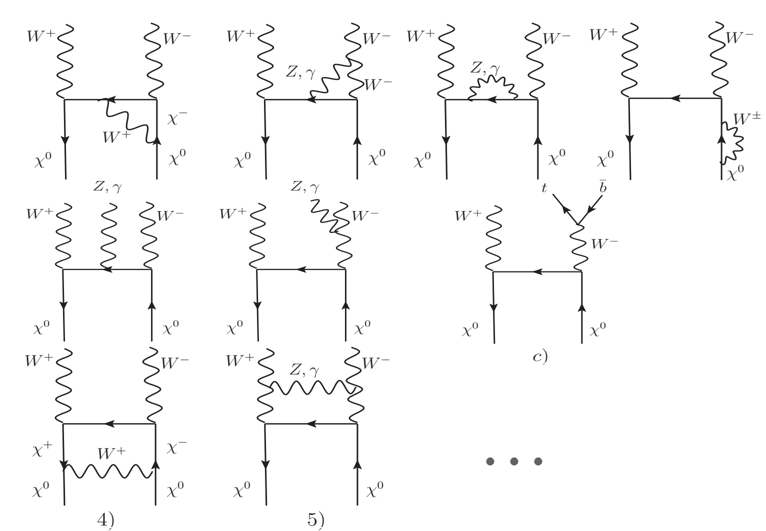
EXAMPLE:
WINO DM @ 1-LOOP



tree level result $\sim 1/m^2$

with g at scale m
with SM running

full one-loop result



AH, R. Iengo; JHEP 1201 (2012) 163

LARGE EW EFFECTS

$\alpha_2\left(\log\frac{m_\chi^2}{m_W^2}\right)^2$

&

$\alpha_2 \log\frac{m_\chi^2}{m_W^2}$

resummation to all orders
using EFT techniques

SCET
(soft-collinear effective theory)

RG for Wilson coeff.

Sudakov corrections
now @ NLL'

Baugmart *et al.* '14; Bauer *et al.* '14; Ovanesyan *et al.* '14, '16, …

SCET:
an EFT not based on dim. of operators but different momenta regimes and allows to treat light energetic states. It includes different low-energy fields (soft and collinear) and helps in factorization of their impact from the hard process.

for intro see e.g. in **Becher, Broggio, Ferroglia** '14

EFFECT OF SCET RESSUMATION

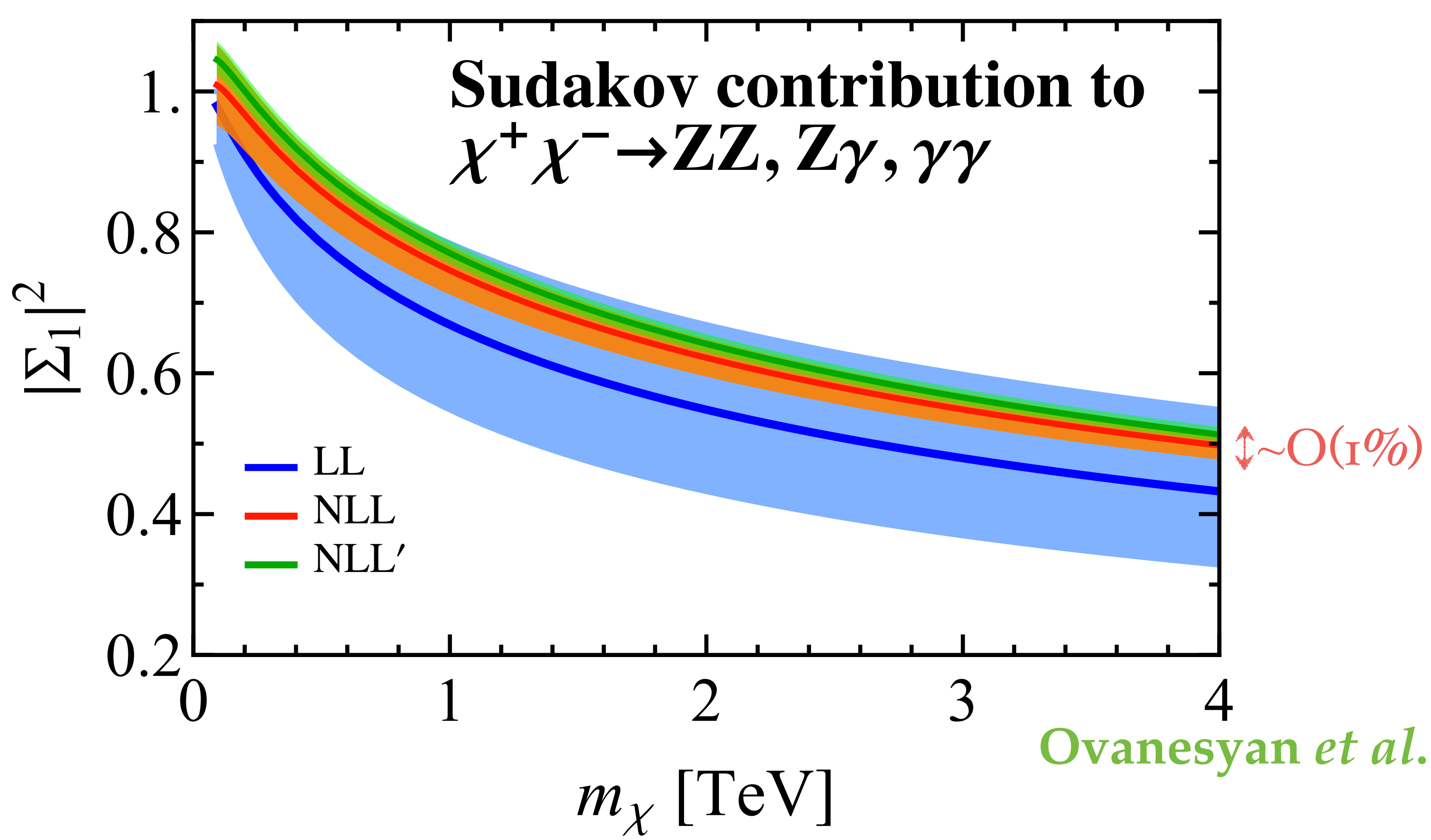
EXCLUSIVE ANNIHILATION

Using SCET the contribution for large logarithms and (large logarithms)^2 can be summed to all orders:

$$\ln \frac{C}{C^{\rm tree}} \sim \sum_{k=1}^{\infty} \Big[\underbrace{\alpha_2^k \ln^{k+1}}_{\rm LL} + \underbrace{\alpha_2^k \ln^{k}}_{\rm NLL} + \underbrace{\alpha_2^k \ln^{k-1}}_{\rm NNLL} + \dots \Big]$$

Example: how value and uncertainty of the calculation changes with accuracy order for Wino DM exclusive annihilation

NLL' = NLL + $\mathcal{O}(\alpha_2)$



Ovanesyan *et al.* '16

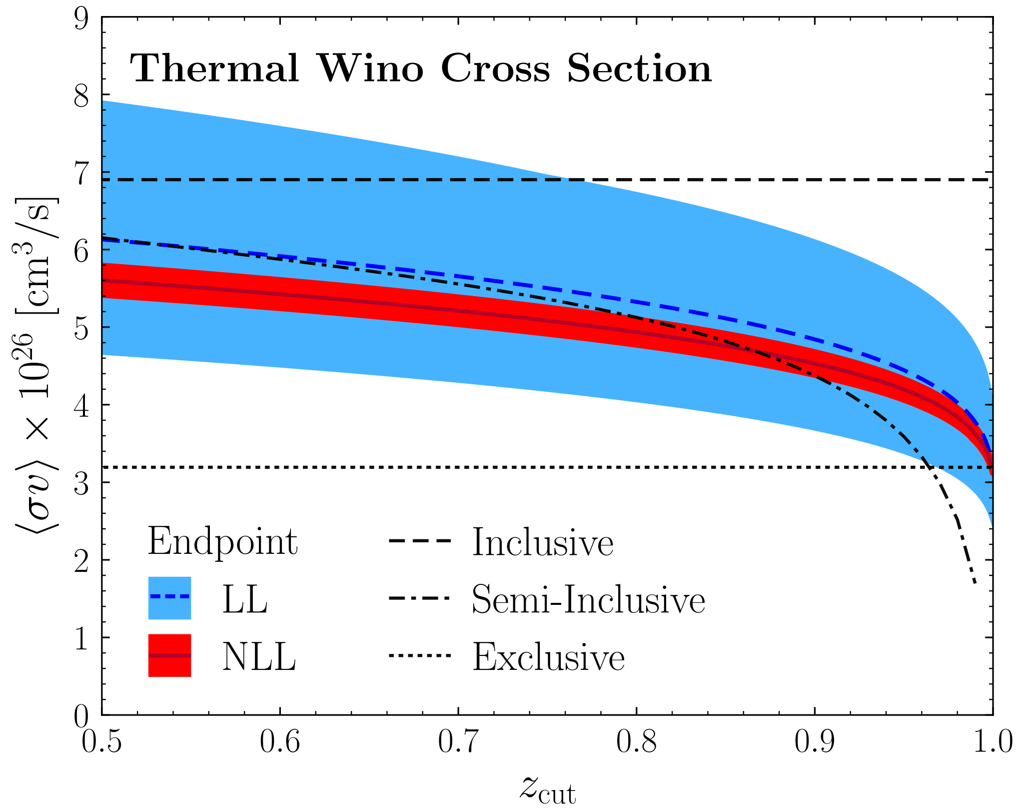
Reminder:

This (relatively complicated computation) does **not** have to be done if DM is lighter!

EFFECT OF SCET RESSUMATION

SEMI-INCLUSIVE ANNIHILATION

Baugmart *et al.* '18



$z = E^{\gamma}_{\rm res}/m_{\chi}$

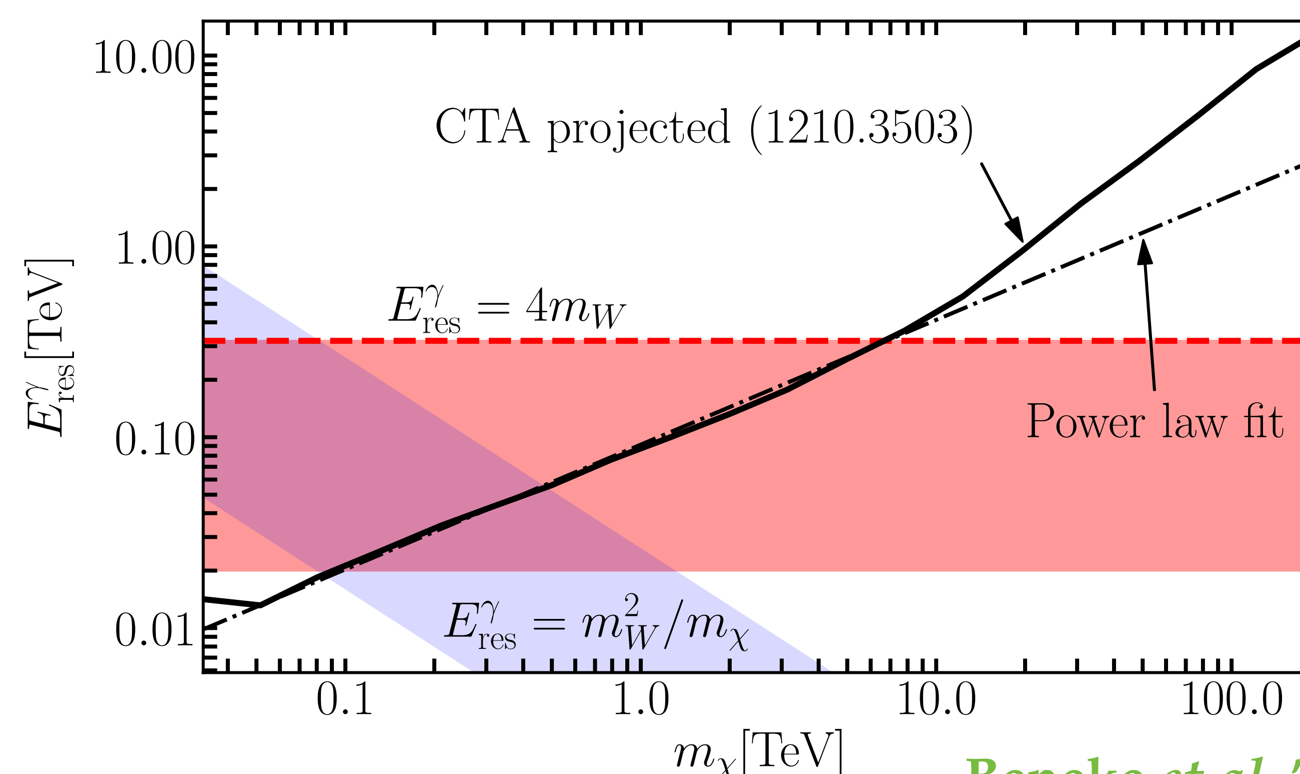
What is observed in e.g. H.E.S.S or CTA is a semi-inclusive single-photon energy spectrum $\gamma + X$

One <u>additional scale</u> in EFT: $E^{\gamma}_{\rm res}$

Energy resolution regimes:

narrow : $E^{\gamma}_{\rm res} \sim m_W^2/m_{\chi}$	NLL'
intermediate : $E^{\gamma}_{\rm res} \sim m_W$	NLL'
wide : $E^{\gamma}_{\rm res} \gg m_W$	NLL

two-step resummation

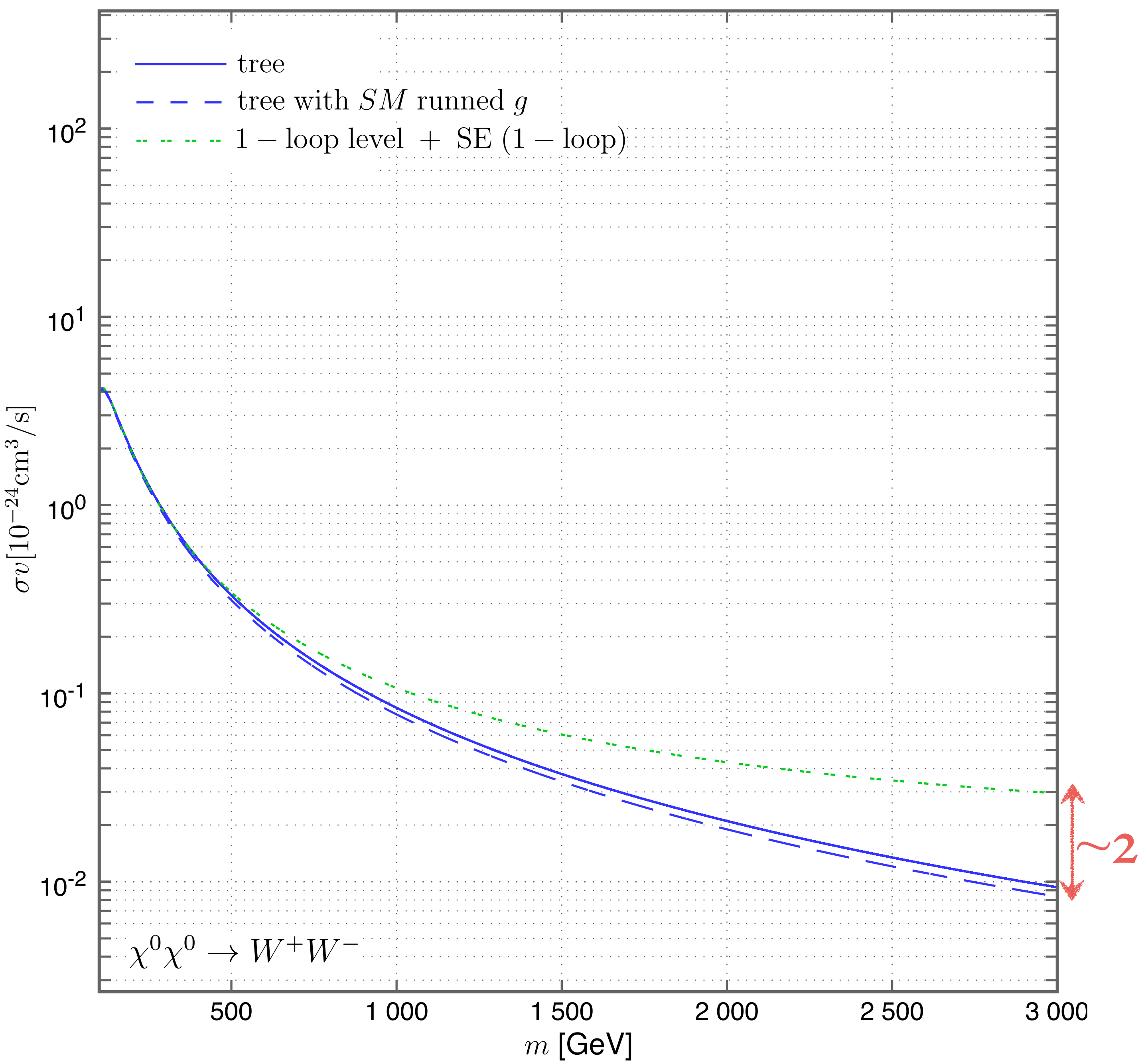


Beneke *et al.* '19

Bottom line: all regimes are well studied - but for now only for simple models

II.
Long range EW interactions
Sommerfeld Effect & DM bound states

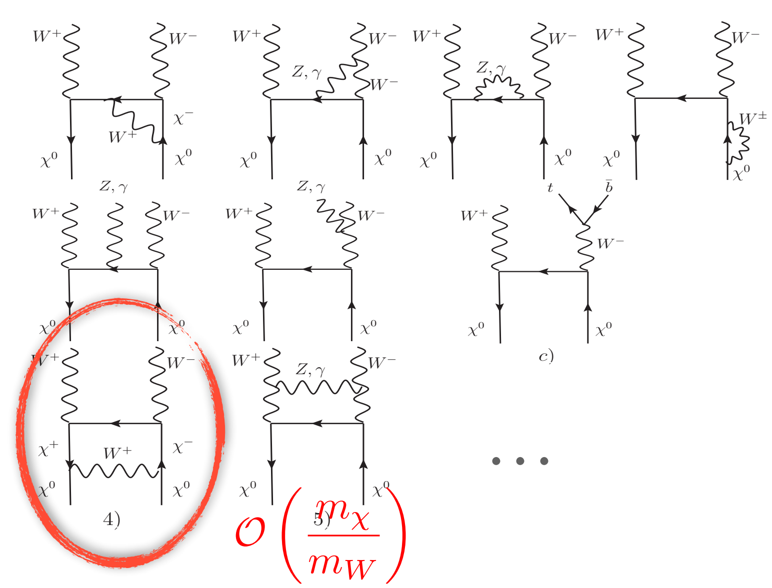
EXAMPLE:
WINO DM @ 1-LOOP



tree level result $\sim 1/m^2$

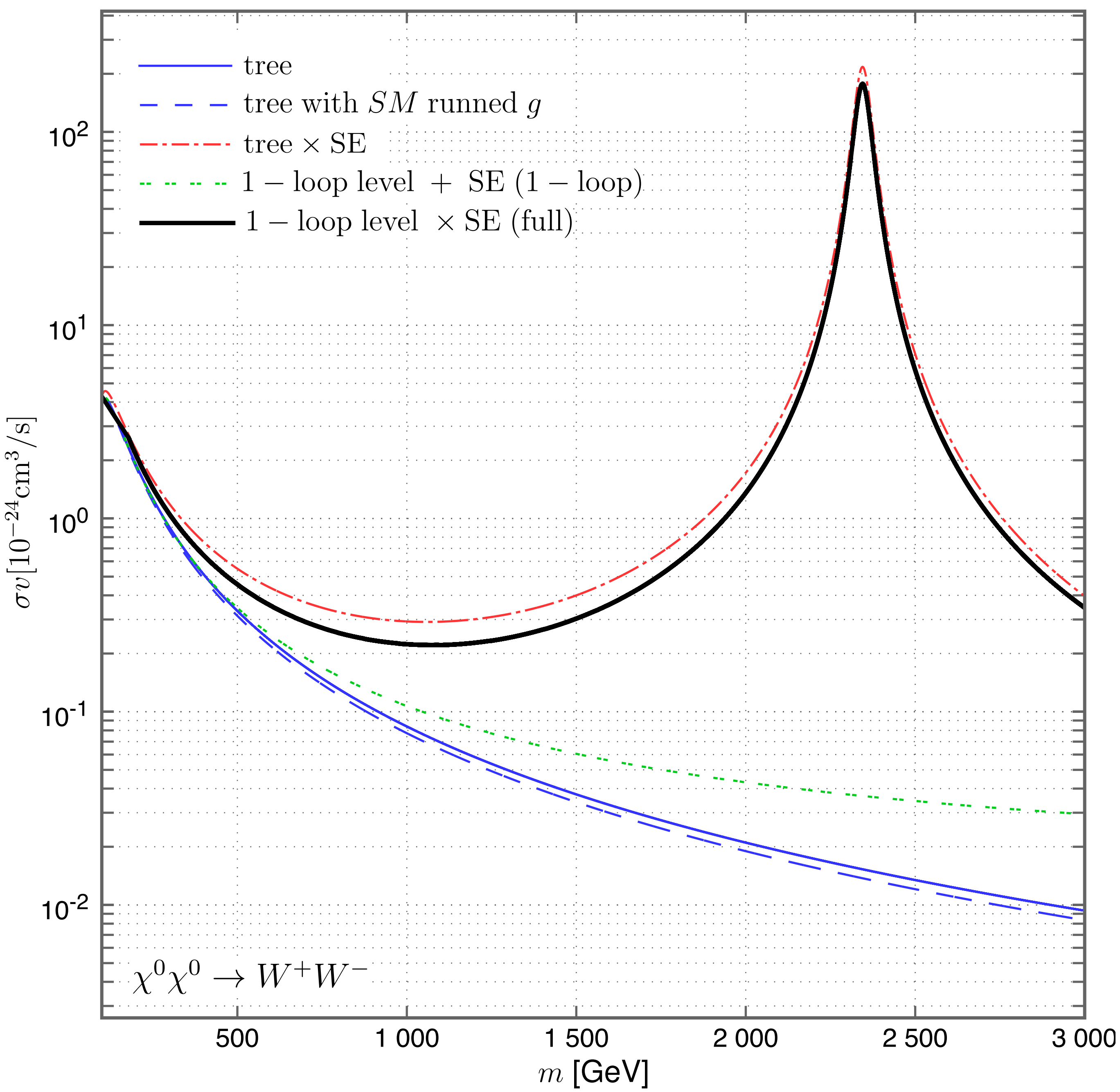
with g at scale m
with SM running

full one-loop result



AH, R. Iengo; JHEP 1201 (2012) 163

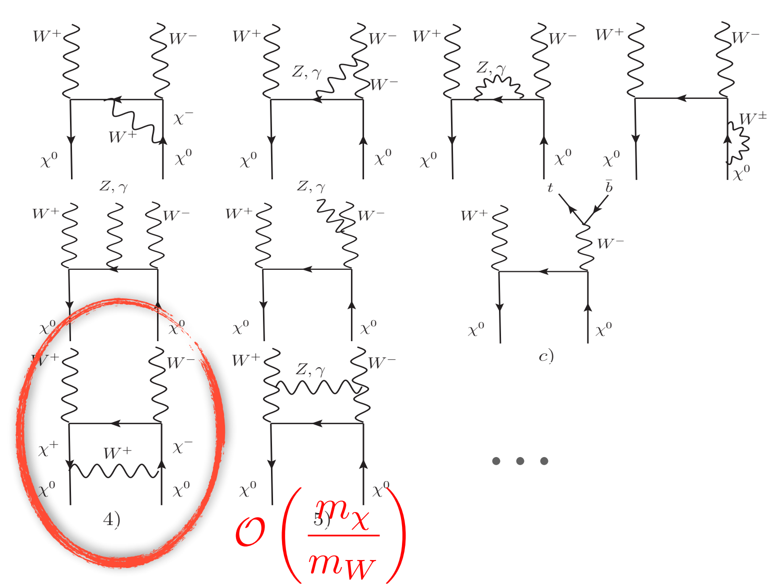
Example:
Wino DM @ 1-loop
& Sommerfeld effect



tree level result $\sim 1/m^2$

with g at scale m
with SM running

full one-loop result



tree level + Sommerfeld

one-loop + Sommerfeld

AH, R. Iengo; JHEP 1201 (2012) 163

LARGE EW EFFECTS

$\alpha_2 \left(\log \frac{m_\chi^2}{m_W^2} \right)^2$

&

$\alpha_2 \log \frac{m_\chi^2}{m_W^2}$

$\alpha_2 \frac{m_\chi}{m_W}$

resummation to all orders using EFT techniques

SCET
(soft-collinear effective theory)

NR DM
(non-relativistic DM EFT)

RG for Wilson coeff.

Schroedinger eq. for G's

Sudakov corrections
now @ NLL'

EW Sommerfeld effect

Baugmart *et al.* '14; Bauer *et al.* '14;
Ovanesyan *et al.* '14, '16, …

Hisano *et al.* '04, '05, '06, '07,; … ;
Beneke *et al.* '12, '13, '15; …

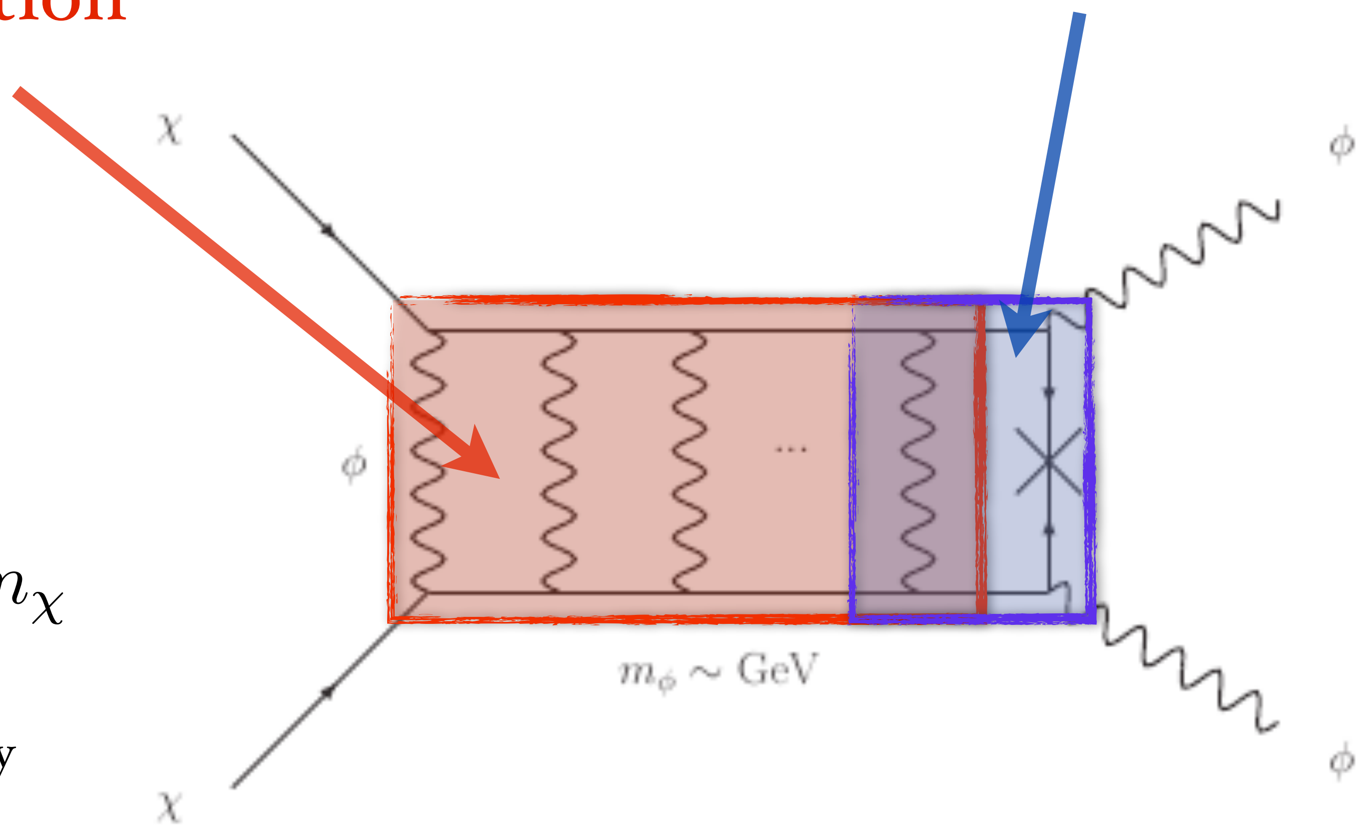
SOMMERFELD EFFECT

one-loop $\propto \alpha \dfrac{m_\chi}{m_\phi}$

re-summation

$$\frac{1}{m_\phi} \gtrsim \frac{1}{\alpha m_\chi}$$

force range — Bohr radius



$$m_\chi v^2 \lesssim \alpha^2 m_\chi$$

kinetic energy — Bohr energy

$$\sigma_{\rm SE} = S(v)\,\sigma_0$$

Arkani-Hamed *et al.* '09

⟶ in a special case of Coulomb force: $S(v) = \dfrac{\pi\alpha/v}{1-e^{-\pi\alpha/v}} \approx \pi\dfrac{\alpha}{v}$

THE SOMMERFELD EFFECT

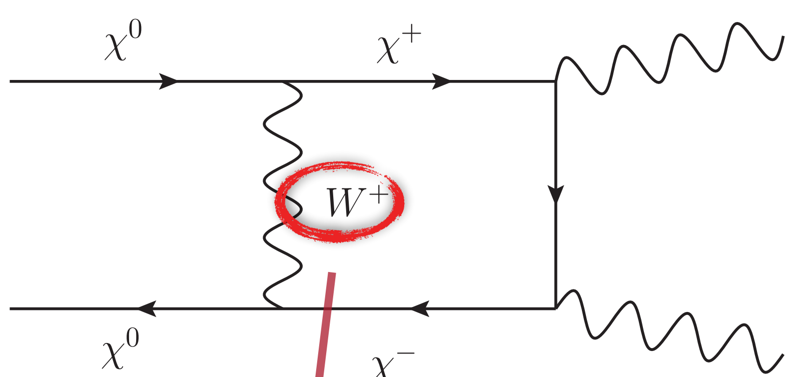
FROM EW INTERACTIONS

Hisano *et al.* '04,'06

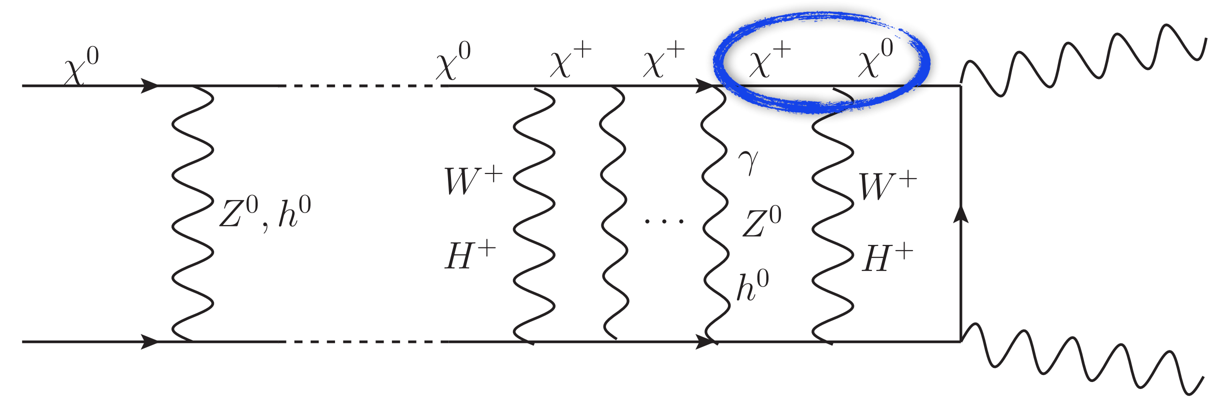
force carriers in the MSSM:

~~γ~~, $W^{\pm},\ Z^0,\ h_1^0,\ h_2^0,\ H^{\pm}$

$\delta m \ll m_\chi$



$m_\chi \gg m_W$



at TeV scale $\Rightarrow$ generically effect of $\mathcal{O}(1-100\%)$

on top of that resonance structure

→ effect of $\mathcal{O}(\text{few})$

for the relic density

AH, R. Iengo, P. Ullio. '10

AH '11

AH *et al.* '17, M. Beneke *et al.*; '16

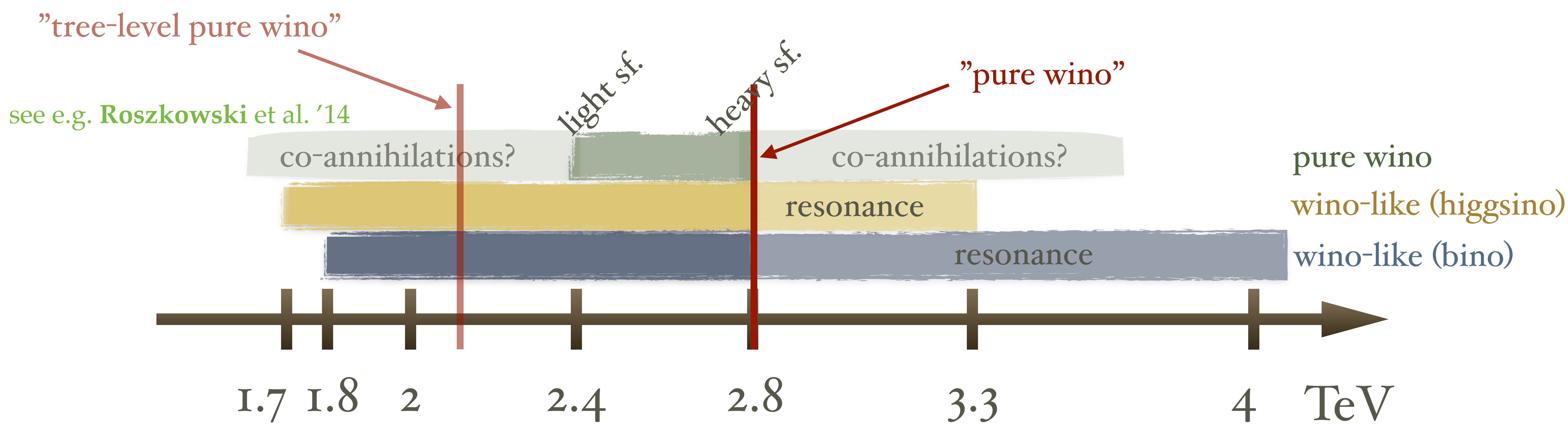
can be understood as being close to
a threshold of lowest bound state

EXAMPLE:
WINO DM

(this is the most studied case: simple & large effect)

Q: what is the mass of Wino-like neutralino in the MSSM that gives the correct thermal relic density?

A:



Currently only available tool for the MSSM:

DarkSE package extending the relic density by SE in DarkSUSY

AH, '11

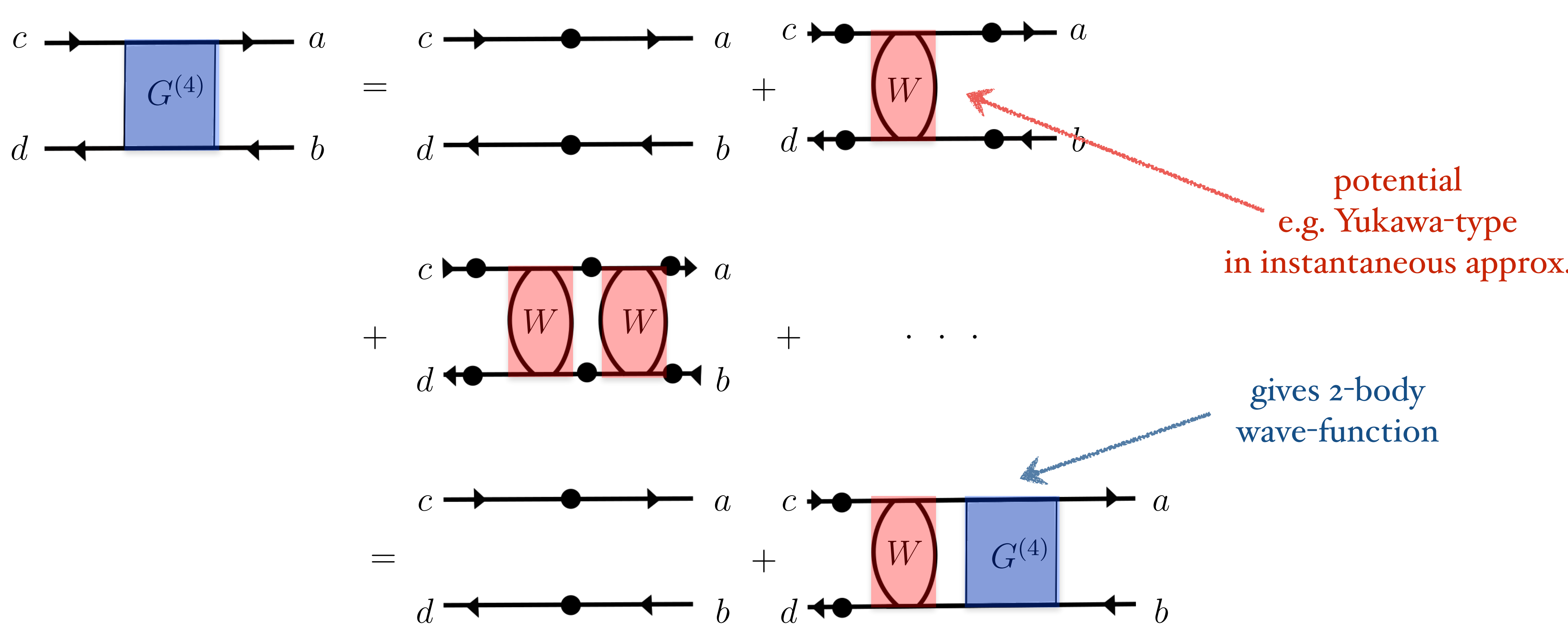
... but new code in production based on EFT, improving accuracy in numerous ways

Beneke,..., AH,... *et al.*

How to calculate SE?

Two options → Non-relativistic EFT → potential region → Schroedinger eq. for 2-body wave-function

Two options → Dyson-Schwinger eq. → Bethe-Salpeter eq. → Schroedinger eq. for 2-body wave-function



$$G^{(4)}(p,p') = (2\pi)^4\delta^{(4)}(p-p')S(p) + S(p)\int \frac{d^4q}{(2\pi)^4} W(p,q)G^{(4)}(q,p')$$

Outcome: modified 2-body wave-functions that are then used to compute the cross sections with SE

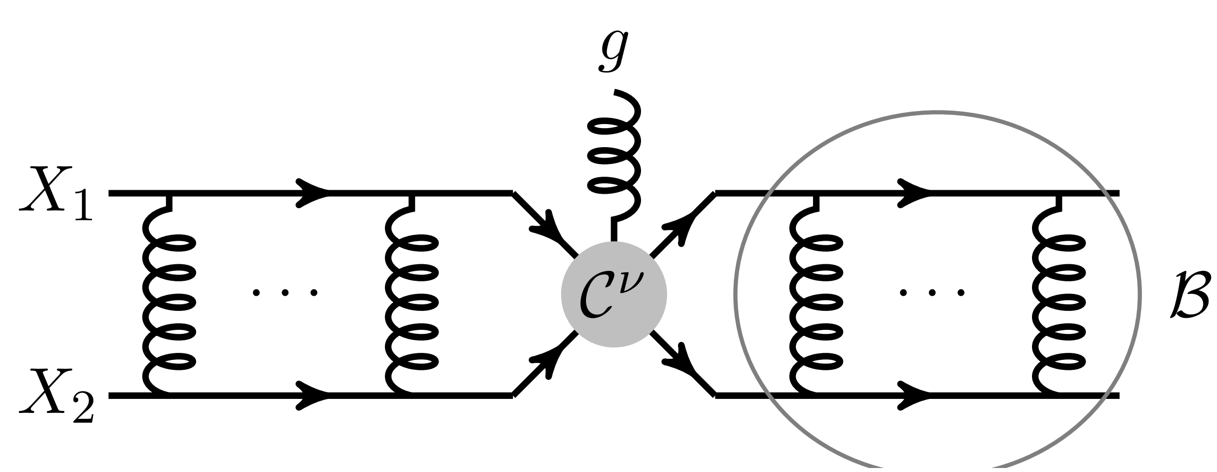
Bound State Formation

As noticed before Sommerfeld effect has resonances when Bohr radius ~ potential range, i.e. when close to a bound state threshold → Can DM form actual bound states from such long range interactions?

↓

Yes, it can!

Q: How to describe such bound states and their formation?



free DM states DM bound state

*the effect was first studied in simplified models with light mediators, then gradually extended to non-Abelian interactions, double emissions, co-annihilations, etc.

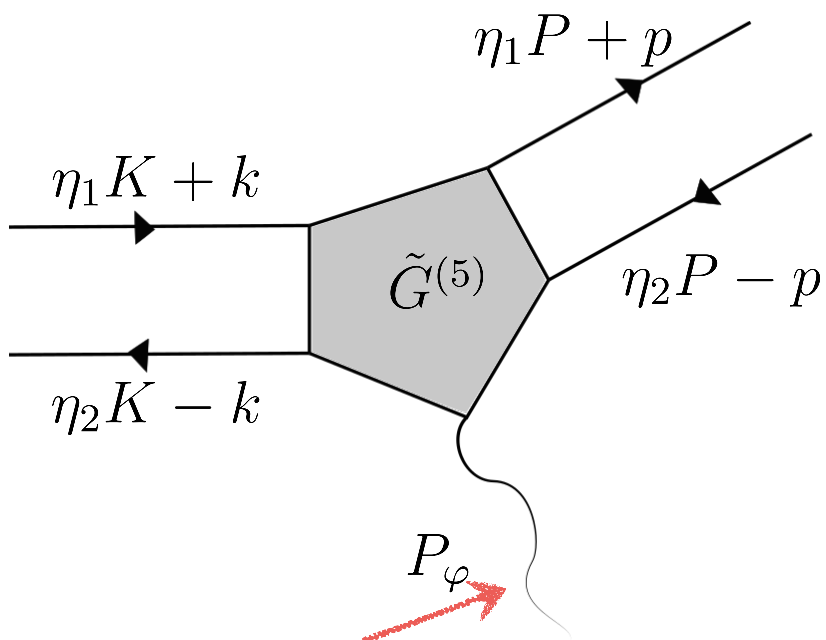
see papers by **K. Petraki** *et al.* '14-19

**vide also "WIMPonium"
March-Russel, West '10

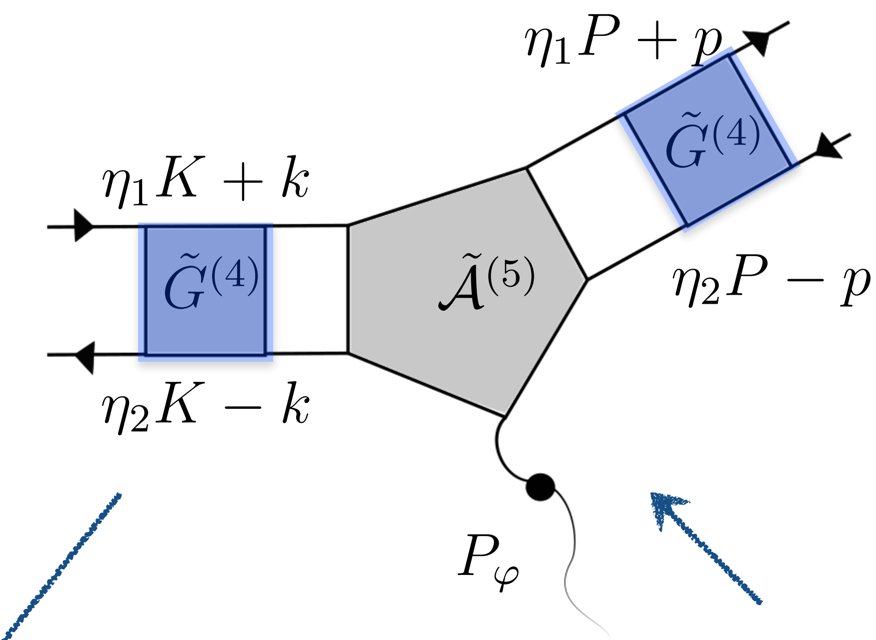
How to calculate BSF?

Two options

- Non-relativistic EFT ⟶ „F" of BSF is not easy, but see e.g. **Asadi** *et al.* '17
- Dyson-Schwinger eq. ⟶ Bethe-Salpeter eq. ⟶ Schroedinger eq.



5-point function with one particle emission



Factorization of hard and potential parts

$$\mathbf{1} = \sum_n \int \frac{d^3Q}{(2\pi)^3\, 2\omega_{\mathbf{Q},n}} |\mathcal{B}_{\mathbf{Q},n}\rangle\langle\mathcal{B}_{\mathbf{Q},n}| + \int \frac{d^3q}{(2\pi)^3} \frac{d^3Q}{(2\pi)^3} \frac{1}{2\omega_{\mathbf{Q},\mathbf{q}}\, 2\varepsilon_{\mathbf{Q},\mathbf{q}}} |\mathcal{U}_{\mathbf{Q},\mathbf{q}}\rangle\langle\mathcal{U}_{\mathbf{Q},\mathbf{q}}|$$

Decomposition on complete set of states contains both bound and free states

Outcome: modified 2-body bound and free wave-functions

BSF
For TeV scale WIMP

Electroweak interactions are stronger and longer ranged than Higgs mediated…
but also more complicated (non-Abelian + massive mediators)

here as far as I know work is still in progress…

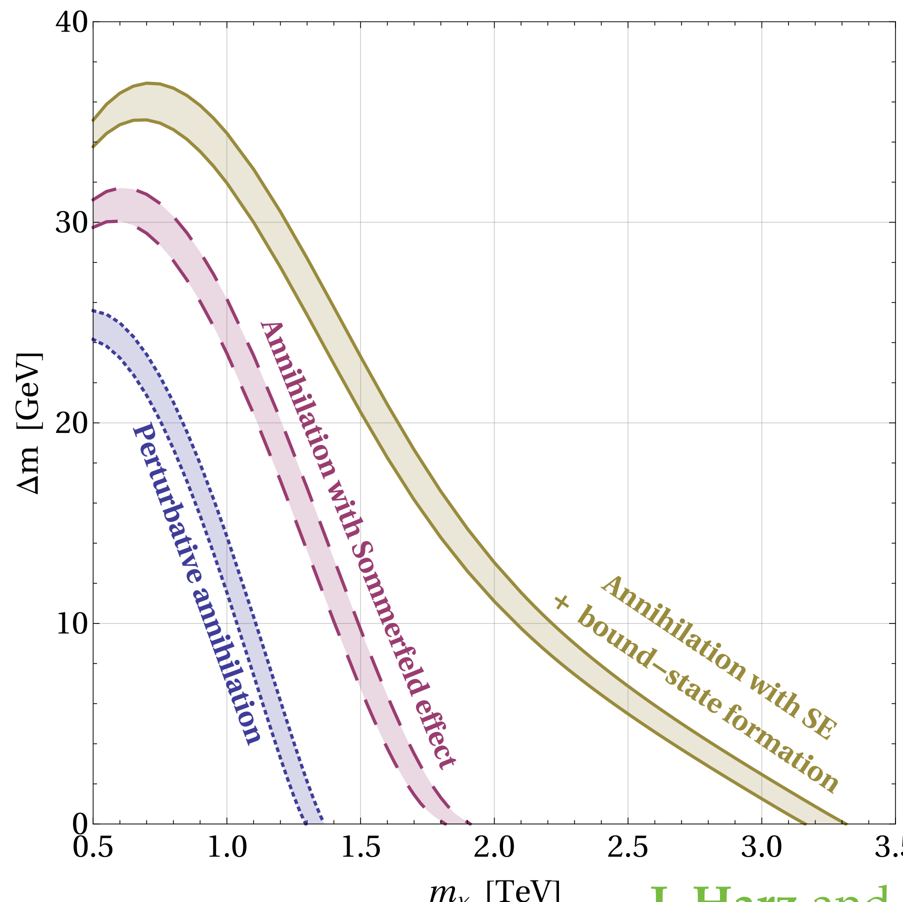
Higgs mediated ⇒ Could lead to DM bound states, but for usual TeV DM models, biggest effect observed is more indirect

e.g. produces tighter bound states of squarks - less inefficient dissociation - more efficient DM depopulation

J. Harz and K. Petraki '19

but e.g.: co-annihilation with squarks and QCD squark bound states

significant modification of the annihilation rate - large effects on the DM models, especially in the TeV scale



J. Harz and K. Petraki '18

EXAMPLE:
IMPACT ON THE UNITARITY BOUND

Conservation of probability (for any partial wave) $\Longrightarrow$ $(\sigma v_{\rm rel})^J_{\rm total} < (\sigma v)^J_{\rm max} = \dfrac{4\pi(2J+1)}{M_{\rm DM}^2 v_{\rm rel}}$

$\Longrightarrow$ upper limit on DM mass if thermally produced: "$M_{\rm DM} < 340\,{\rm TeV}$" (for a Majorana fermion and $\Omega h^2 = 1$)

$M_{\rm DM} < 200\,{\rm TeV}$ (updated)

Griest and **Kamionkowski** '89

With the bound state annihilation taken into account:

$$(\sigma v_{\rm rel})_{\rm total} = (\sigma v_{\rm rel})_{\rm ann} + \sum_I (\sigma_I v_{\rm rel})_{\rm BSF}$$

but some of the bound states dissociate before they are able to annihilate!

$\Downarrow$

$(\sigma v_{\rm rel})_{\rm total}$ overestimates the cross section in the Boltzmann eq.

$\Leftarrow$

maximal attainable mass for thermal DM is lower

$M_{\rm DM} < 144\,{\rm TeV}$ $\Leftarrow$

(for a Majorana fermion)

Smirnov, Beacom '19

(see also **von Harling, Petraki** '14, **Cirelli** *et al.* '16, …)

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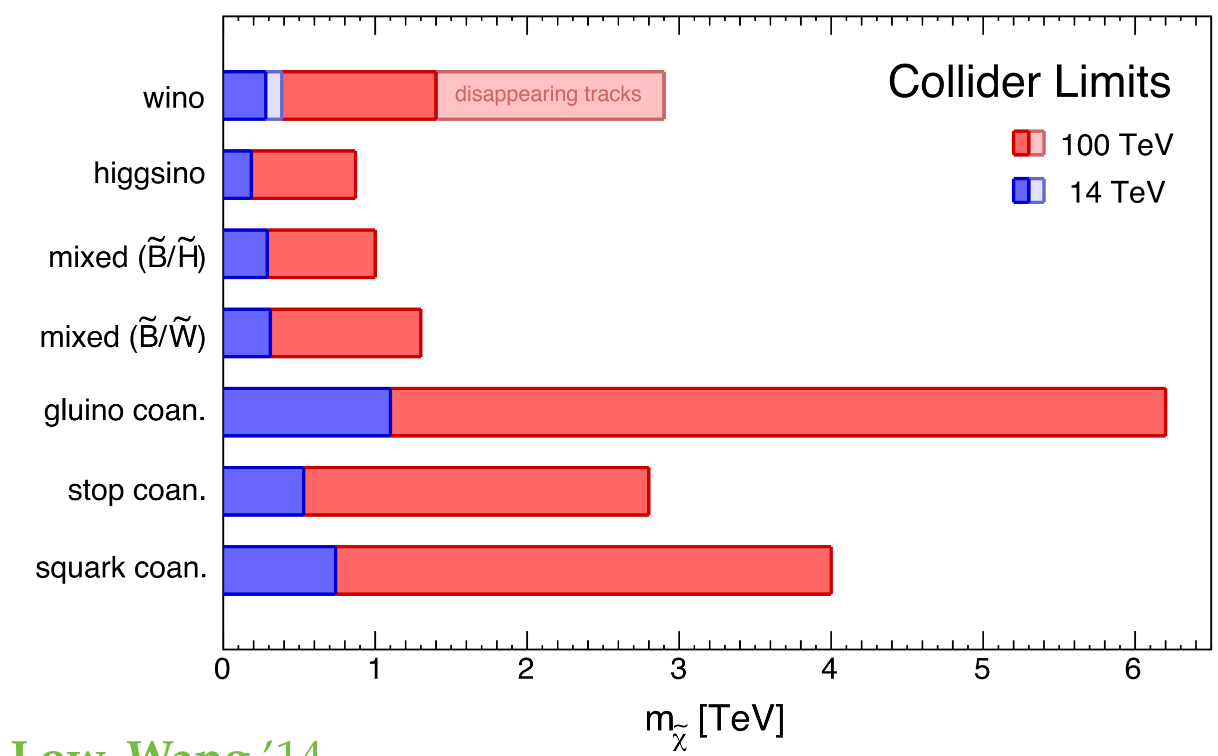
Collider & Direct Detection

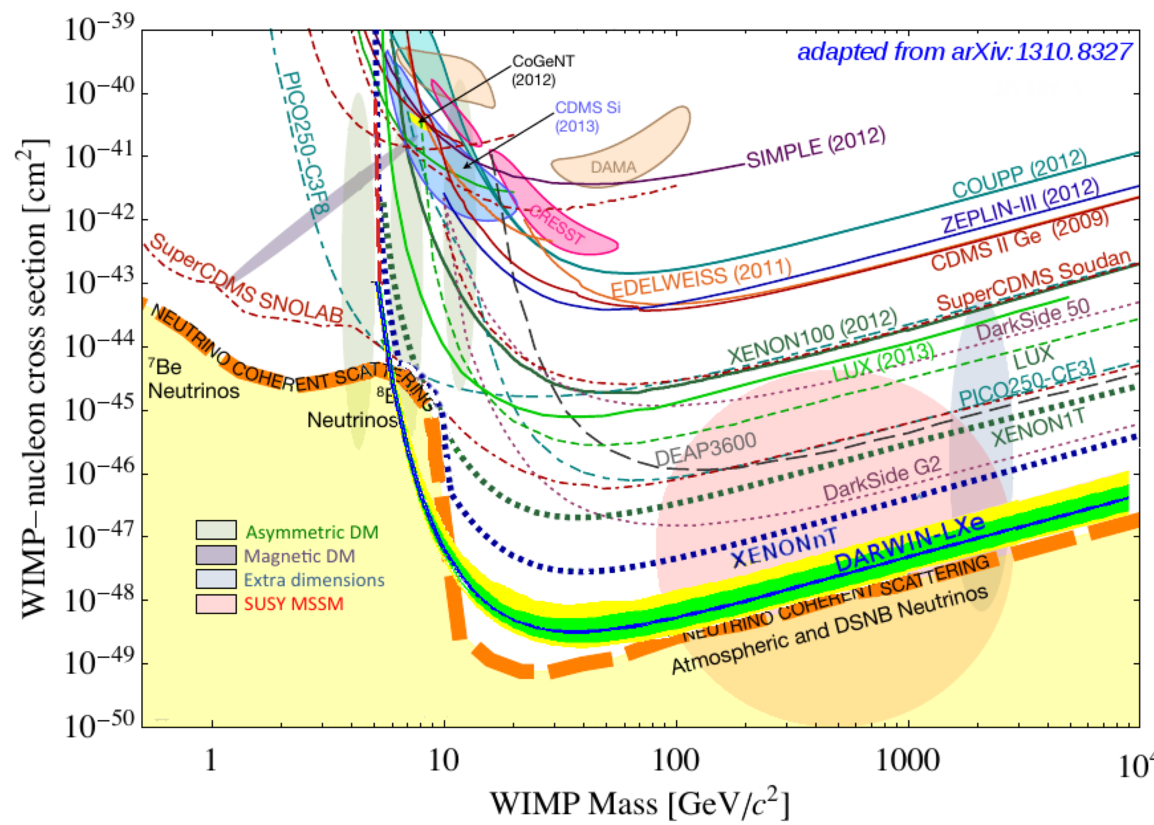


Low, Wang '14

Mixed hopes for TeV regime…
even at 100 TeV collider

(the plot shows in case of SUSY, but analogous results for generic WIMP)

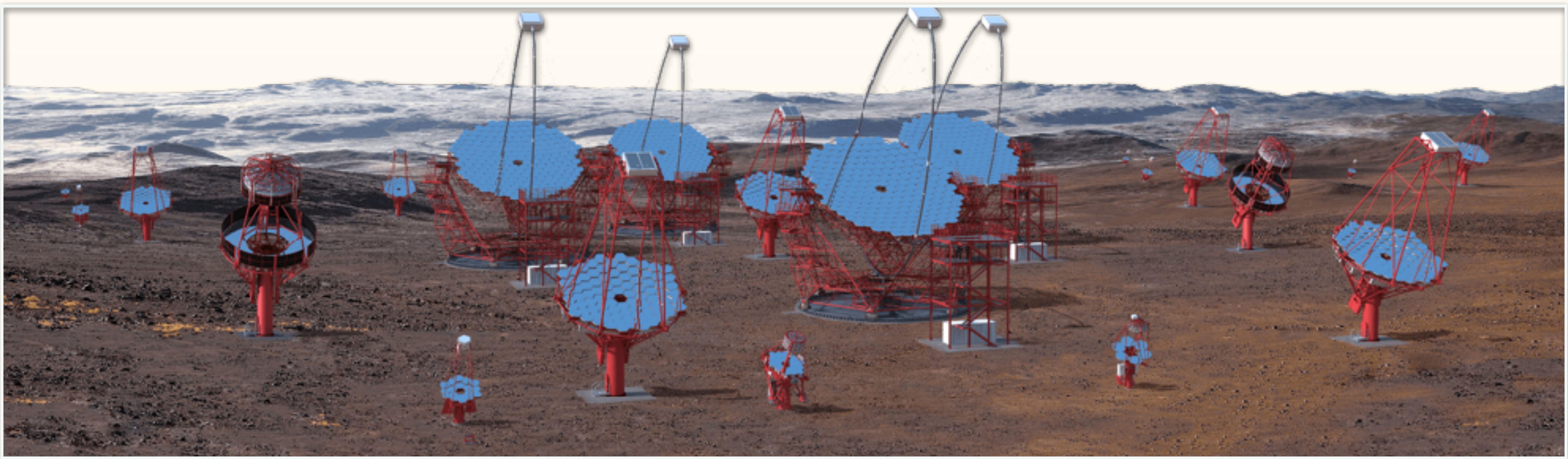
In Direct Detection expected event rate drops for TeV masses (lower number density) and many models give predictions below neutrino floor



GAMMA RAYS

Rich science program in multi-TeV gamma rays, mostly based on Cherenkov light detection (H.E.S.S., MAGIC, VERITAS, HAWC and soon CTA)

→ new hope for TeV DM searches



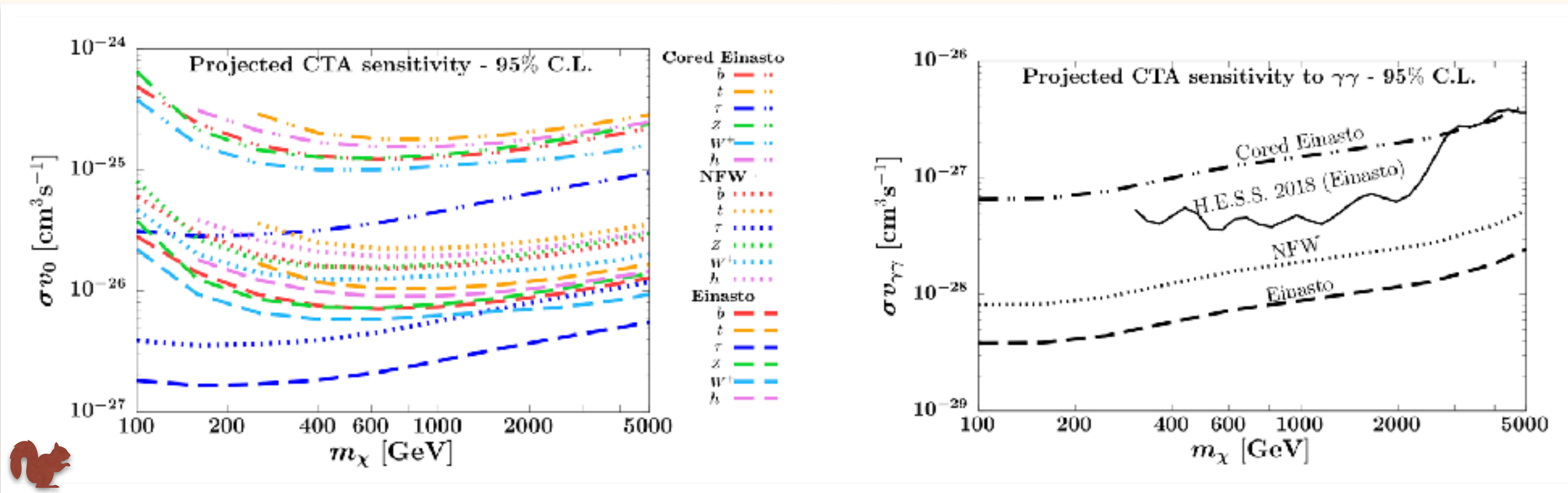
CTA - Cherenkov Telescope Array

- In advanced stage of pre-construction - with production beginning in 2021
- Dedicated DM programme with 500 h of observations already planned
- Principal target is the Galactic halo within several degrees of the GC

Cherenkov Telescope Array Consortium, 1709.07997

PROJECTED CTA LIMITS

- ROI extends up to $\pm 5°$ from the GC both in longitude and latitude
- We derived CTA Southern array sensitivity using:
  - latest instrument response functions
  - 3-dim. log likelihood ratio test statistics
- Three different choices of the DM Galactic halo profile: **Einasto**, **NFW** and **Cored Einasto** (r_{core} = 3 kpc)



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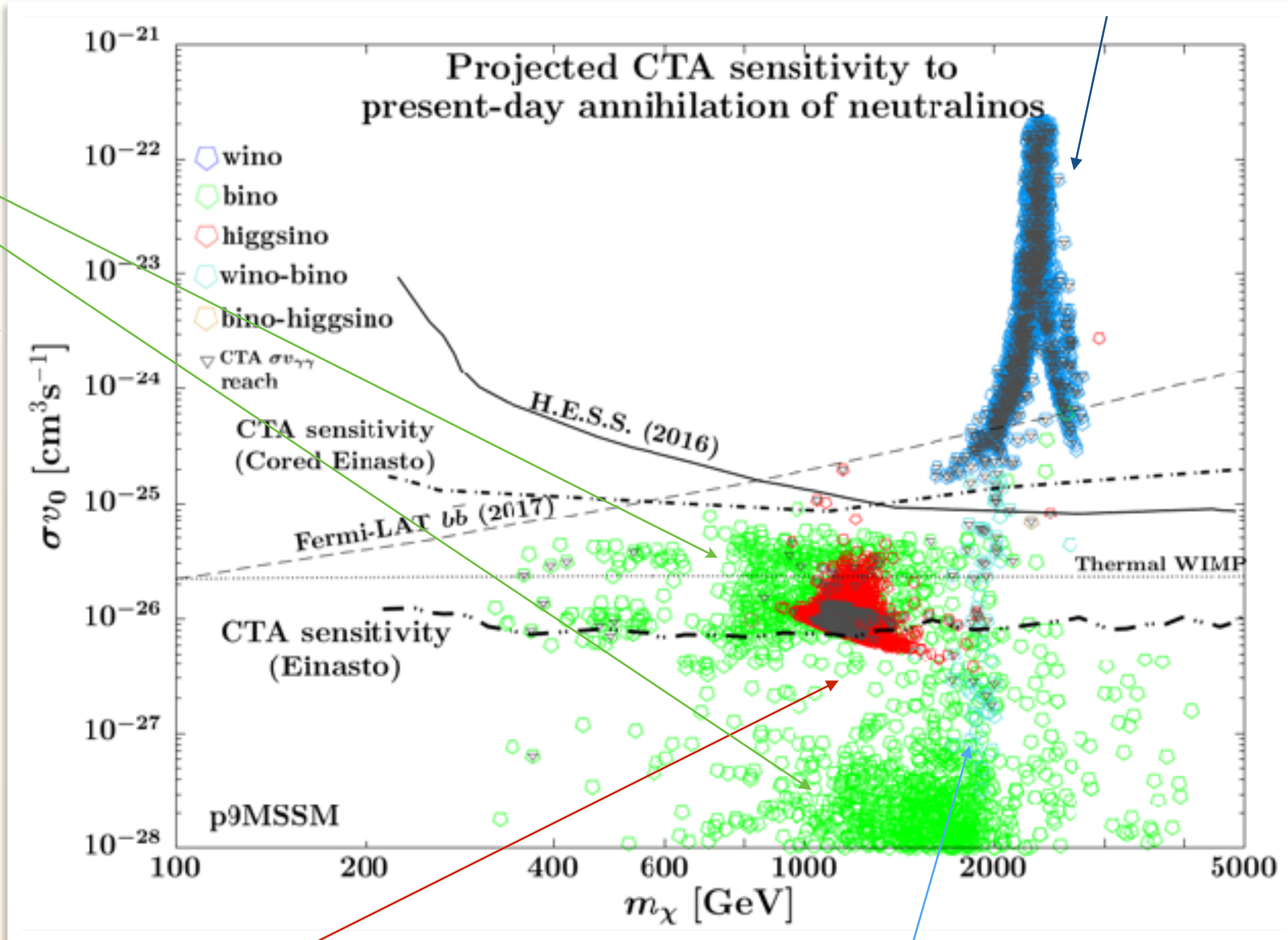
MSSM SCAN RESULTS

Wino - already excluded (?)

Bino
Require additional mechanism (e.g. co-annihilation)



Higgsino
~ 1 TeV region
most promising candidate in MSSM

Bino-wino
In reach of monochromatic line search

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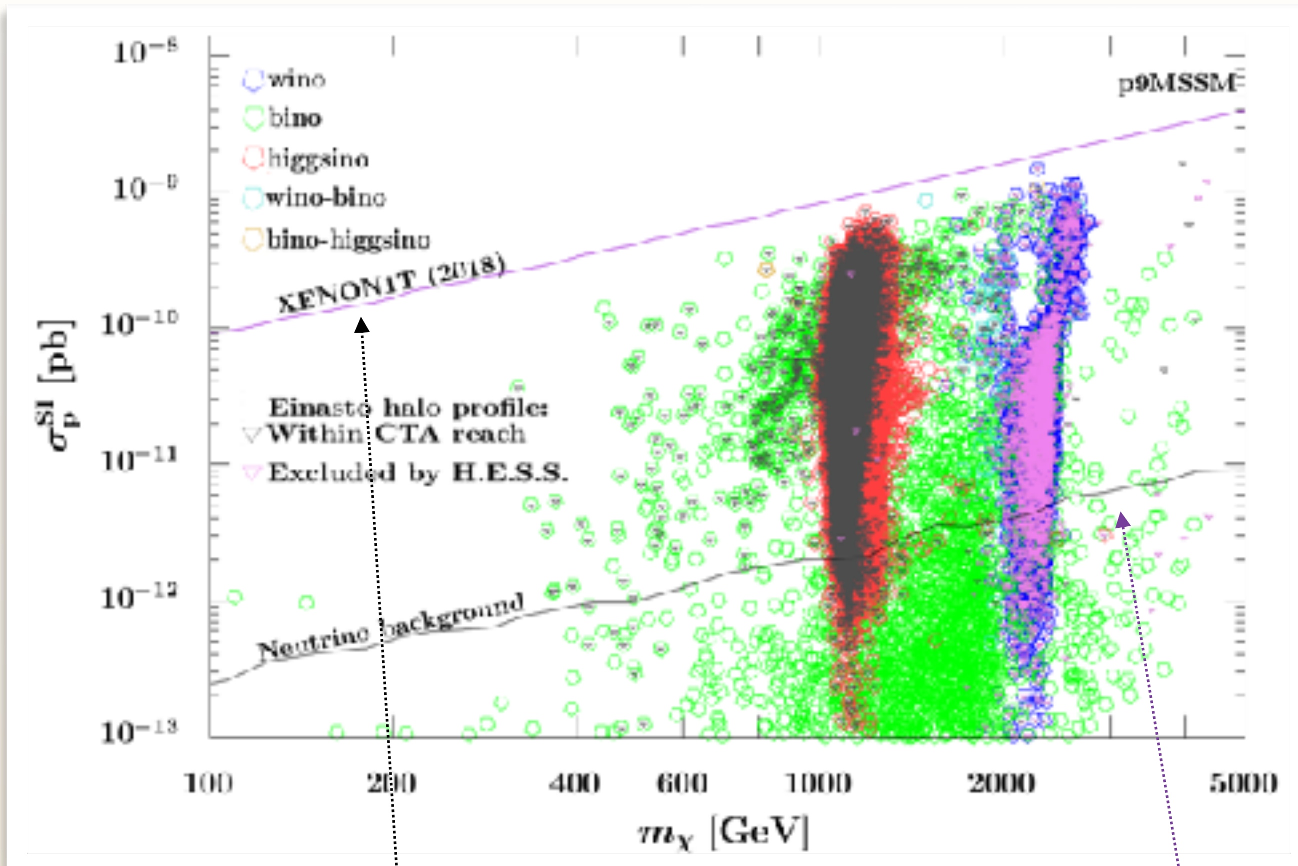
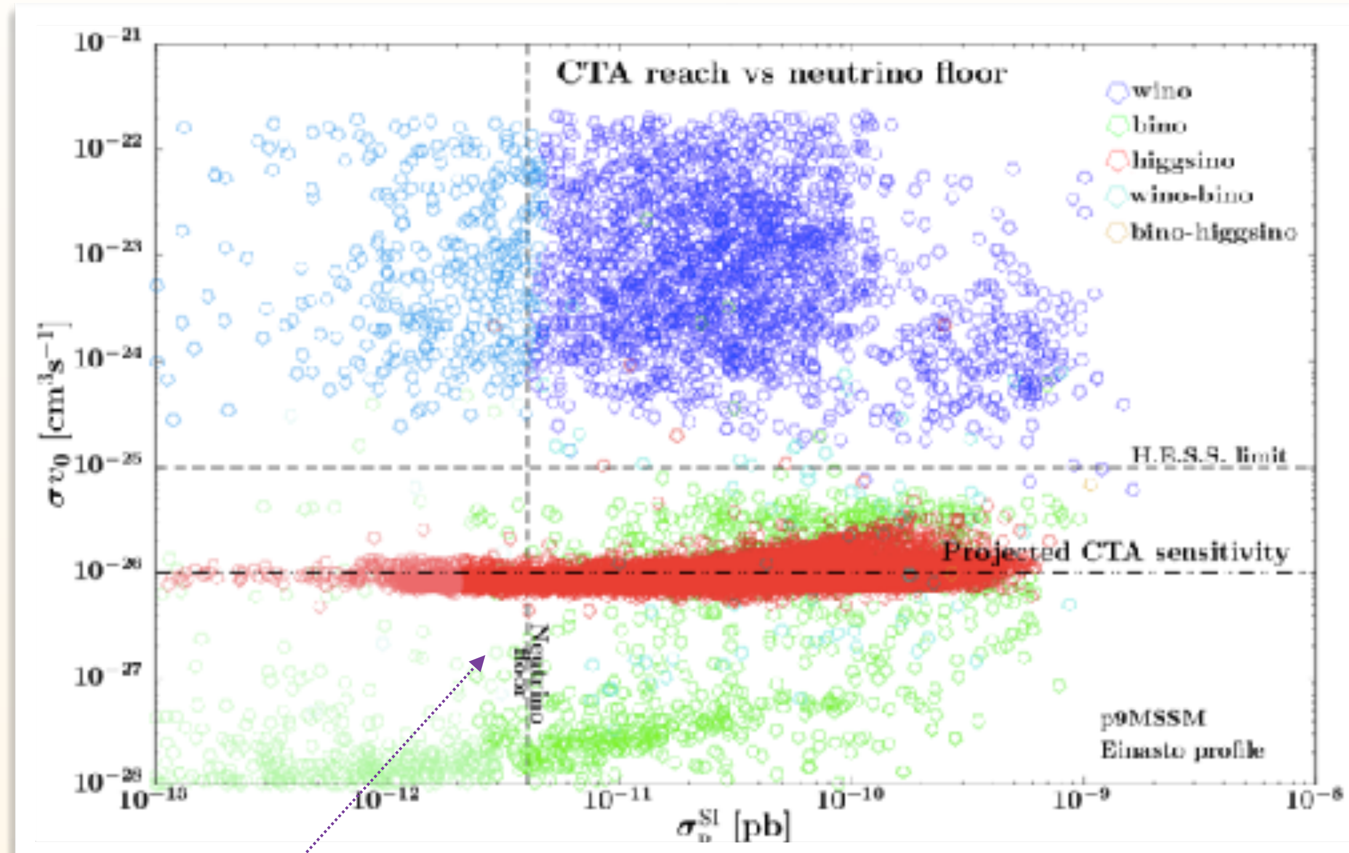
COMPLEMENTARITY WITH DD





- Wino and Higgsino regions will be probed in the majority of cases, corresponding to:
  - spin-independent scattering cross section below the reach of 1-tonne underground detector searches
  - even well below the irreducible neutrino background
- Higgsinos in the ~1 TeV region are good thermal DM candidates
  - Not directly constrained by collider and DD searches $\Longrightarrow$ complementarity

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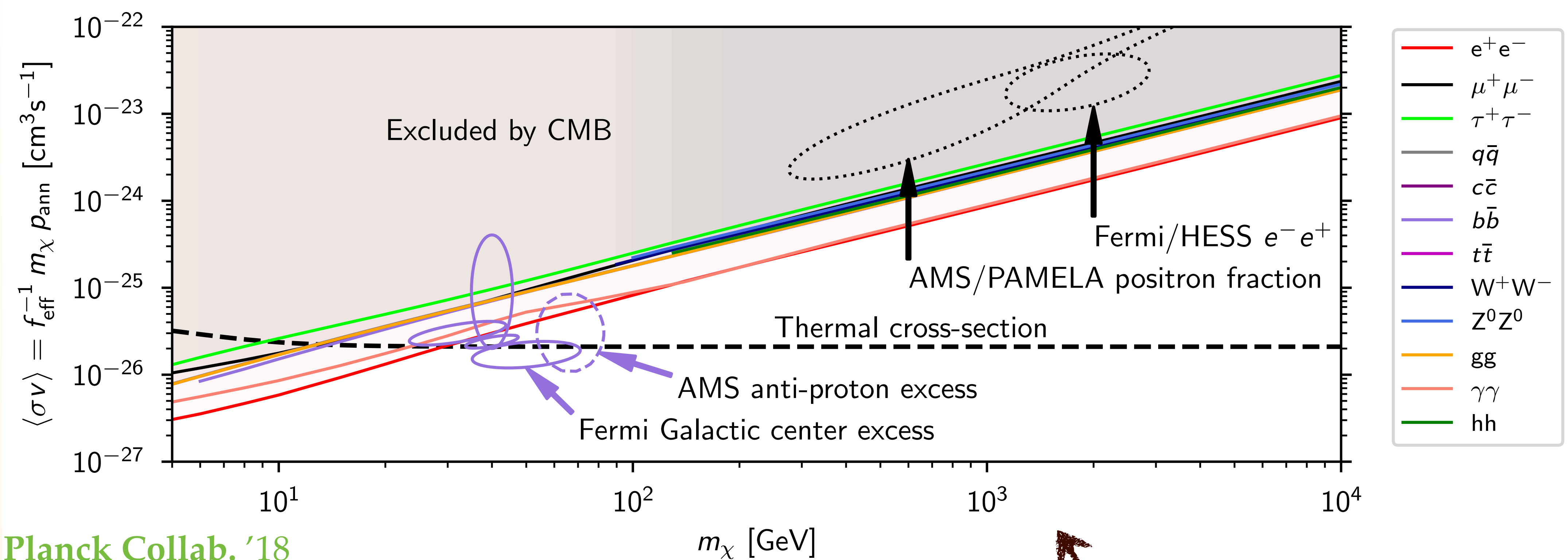
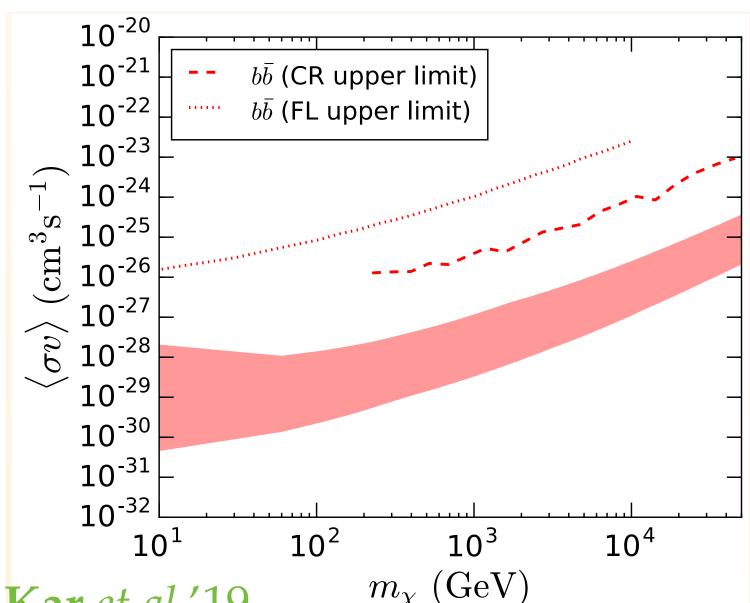
CMB & OTHERS



Planck Collab. '18

There are other ID channels, e.g. in CRs, that can constrain (or give a signal) of TeV scale DM. But keep in mind that CMB limits are comparable and need to be reckoned with



Kar *et al* '19

keep an eye on SKA

(I would take these prospects with grain of salt, but if SKA is indeed built, it has potential of significantly pushing the limits, also in the TeV regime)

Outline

1. Introduction
    - DM and the WIMP paradigm
    - Current status and *'crisis'* in the DM community
2. DM theory at the TeV scale
    - General overview
    - Large Logs and resummation
    - Sommerfeld effect + Bound states
3. Observational prospects
    - Direct detection, LHC, …
    - Indirect: gamma-rays, CMB, CRs, radio, …
4. Summary

IS IT ALL BAD?

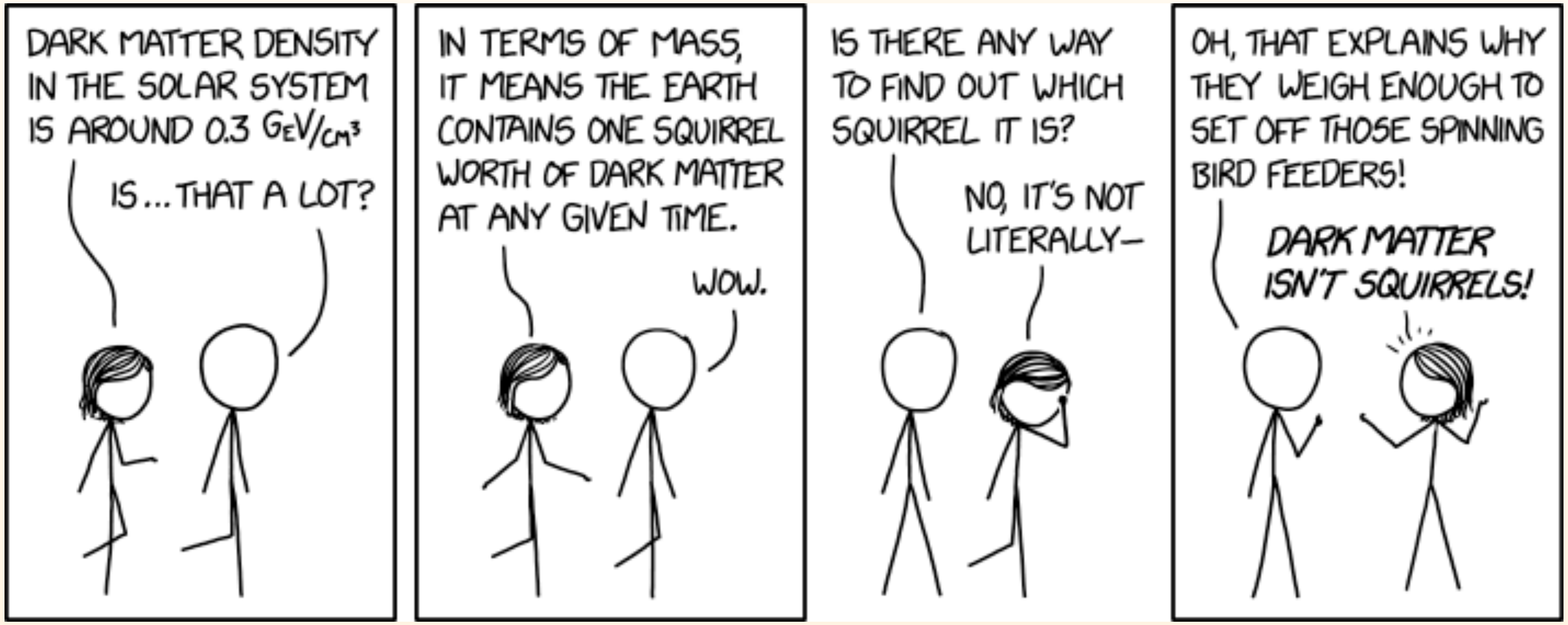
(INSTEAD OF CONCLUSIONS)

1. Compared to previous decades, not many causes for optimism on the detection prospects… *but* with CTA starting in few years, consecutive DD detector upgrades and future planned experiments/observations, there is some place for hope for new data

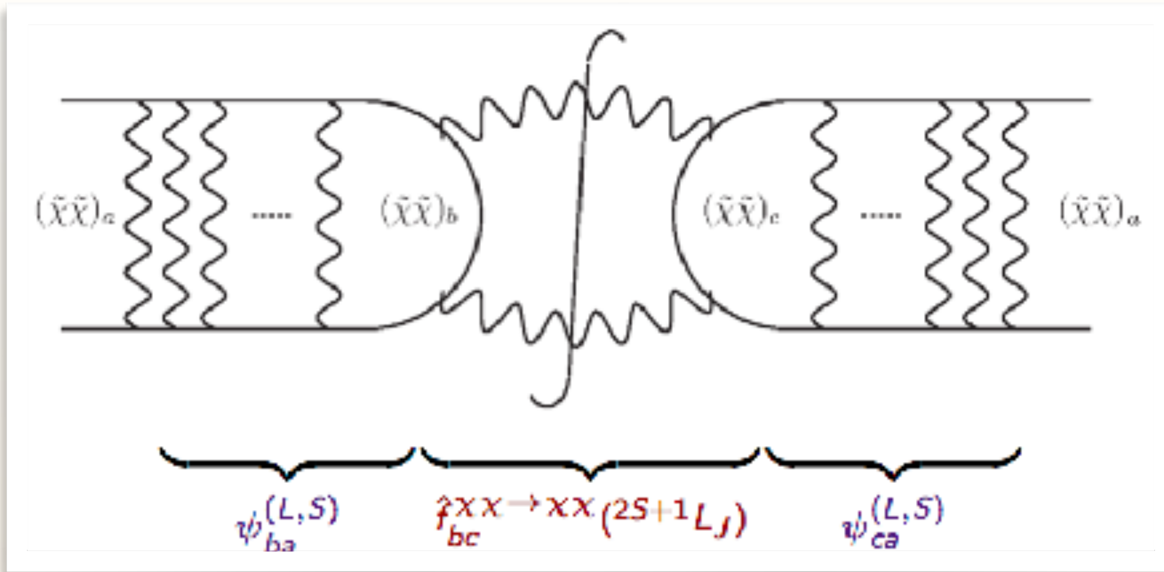
(if looking only on the TeV DM; if instead widening range to other regimes much more activity ahead)

2. The relatively minor change of the energy scale (from 10-100 GeV to 1-100 TeV) shows how careful we need to be on the theory side when determining predictions for DM properties - broad-brush conclusions can be quite misleading

BACKUP


DARK MATTER DENSITY IN THE SOLAR SYSTEM IS AROUND 0.3 GeV/cm³
IS... THAT A LOT?
IN TERMS OF MASS, IT MEANS THE EARTH CONTAINS ONE SQUIRREL WORTH OF DARK MATTER AT ANY GIVEN TIME.
WOW.
IS THERE ANY WAY TO FIND OUT WHICH SQUIRREL IT IS?
NO, IT'S NOT LITERALLY—
OH, THAT EXPLAINS WHY THEY WEIGH ENOUGH TO SET OFF THOSE SPINNING BIRD FEEDERS!
DARK MATTER ISN'T SQUIRRELS!

Details of the Calculation



Sommerfeld factors computed by solving Schroedinger eq. for $\psi_{ba}^{(L,S)}$

The full cross section:

$$\sigma^{(\chi\chi)_a\to\,\text{light}}\, v_{\text{rel}} = S_a[\hat{f}_h(^1S_0)]\; \hat{f}_{aa}(^1S_0) + S_a[\hat{f}_h(^3S_1)]\; 3\,\hat{f}_{aa}(^3S_1) + \frac{\vec{p}_a^{\,2}}{M_a^2}\Big(S_a[\hat{g}_\kappa(^1S_0)]\; \hat{g}_{aa}(^1S_0) + S_a[\hat{g}_\kappa(^3S_1)]\; 3\,\hat{g}_{aa}(^3S_1) + S_a\left[\frac{\hat{f}(^1P_1)}{M^2}\right] \hat{f}_{aa}(^1P_1) + S_a\left[\frac{\hat{f}(^3P_{\mathcal{J}})}{M^2}\right] \hat{f}_{aa}(^3P_{\mathcal{J}})\Big)\,,$$

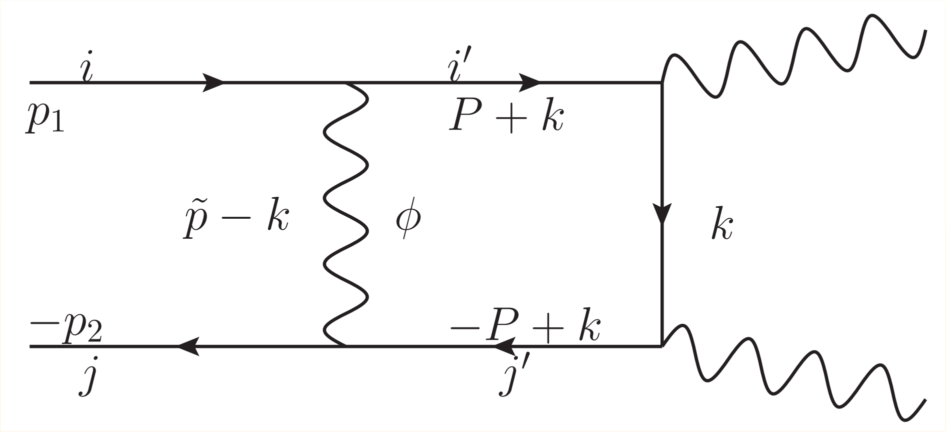
absorptive parts of the Wilson coefficients of local 4-fermion operators

Sommerfeld factors:

$$S_a[\hat{f}(^{2S+1}L_J)] = \frac{\left[\psi_{ca}^{(L,S)}\right]^* \hat{f}_{bc}^{\chi\chi\to\chi\chi}(^{2S+1}L_J)\,\psi_{ba}^{(L,S)}}{\hat{f}_{aa}^{\chi\chi\to\chi\chi}(^{2S+1}L_J)}$$

SOMMERFELD FACTORS
THE METHOD

Idea: treat every possible interaction separately



compute potentials and obtain set of Schrodinger eqns.:

R. Iengo, JHEP 0905 (2009) 024

$$\frac{d^2\varphi_{ij}(x)}{dx^2} + \frac{m^r_{ij}}{m^r_{ab}}\left[\left(1-\frac{2\delta m_{ij}}{\mathcal{E}}\right)\varphi_{ij}(x) + \frac{1}{\mathcal{E}}\sum_{i'j'} V^{\phi}_{ij,i'j'}(x)\varphi_{i'j'}(x)\right] = 0$$

with:

$$V^{\phi}_{ij,i'j'}(x) = p\frac{c_{ij,i'j'}(\phi)}{4\pi}\frac{e^{-\frac{m_\phi}{p}x}}{x}$$

and solving for:

$$S_{ij} = |\partial_x \varphi_{ij}(x)|^2_{x=0}$$

notation:

$\mathcal{E} = \vec{p}^{\,2}/2m^{ab}_r \qquad x = p\,r$

$\delta m_{ij} = m_{i'} + m_{j'} - (m_i + m_j)$