Heavy WIMPs: status and future prospects

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TMEX-2020, Rencontres du Vietnam, 9th January 2020

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

OUTLINE

1. Introduction
   - DM and the WIMP paradigm
   - Short review of the current status

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

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

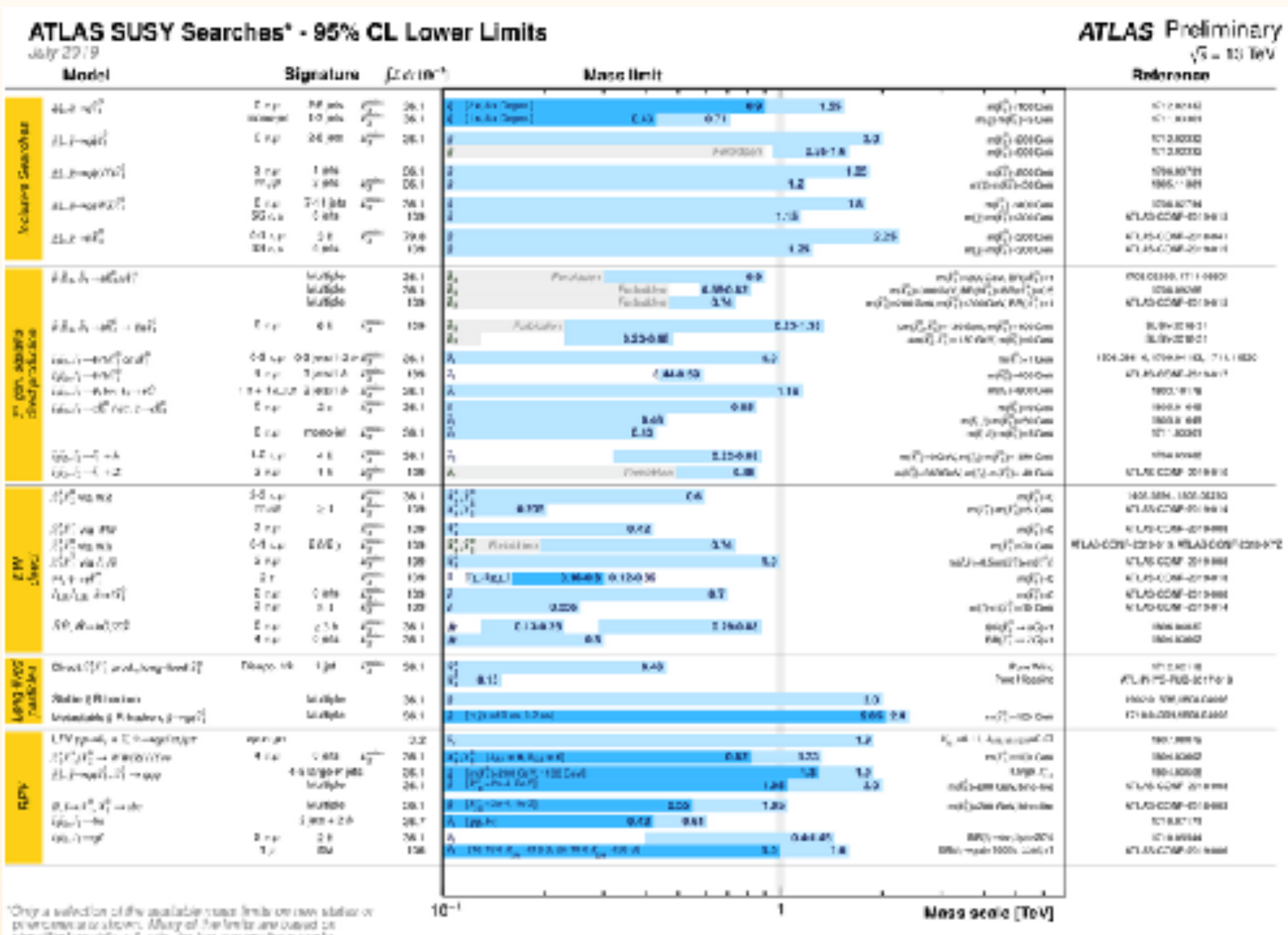
As a bonus: interaction of this strength gives hope for detection in direct, indirect and collider searches!

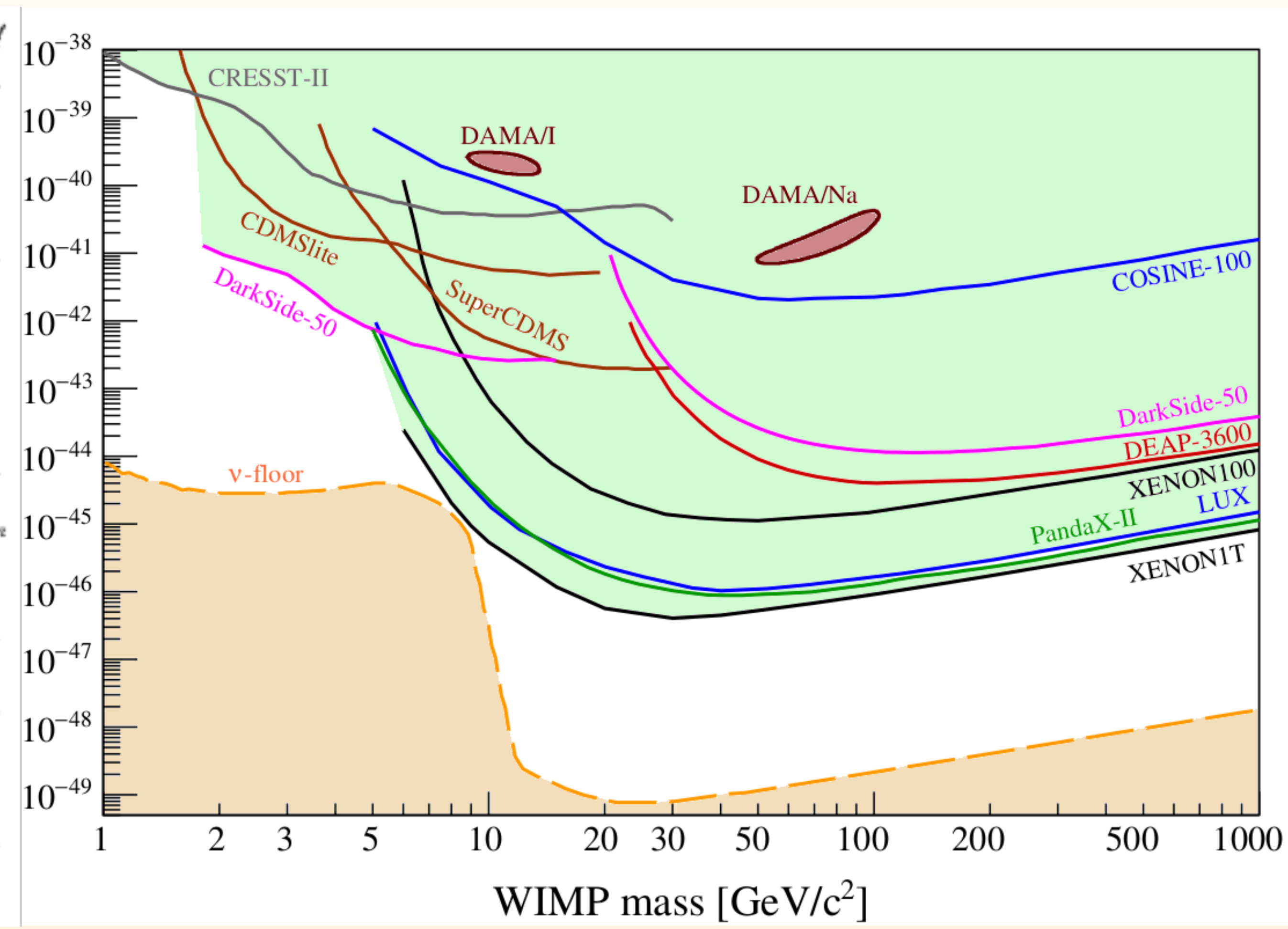
CURRENT LIMITS
AND DECLINE OF THE WIMP PARADIGM

"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





… BUT IN FACT WIMP NOT EVEN SLIGHTLY DEAD

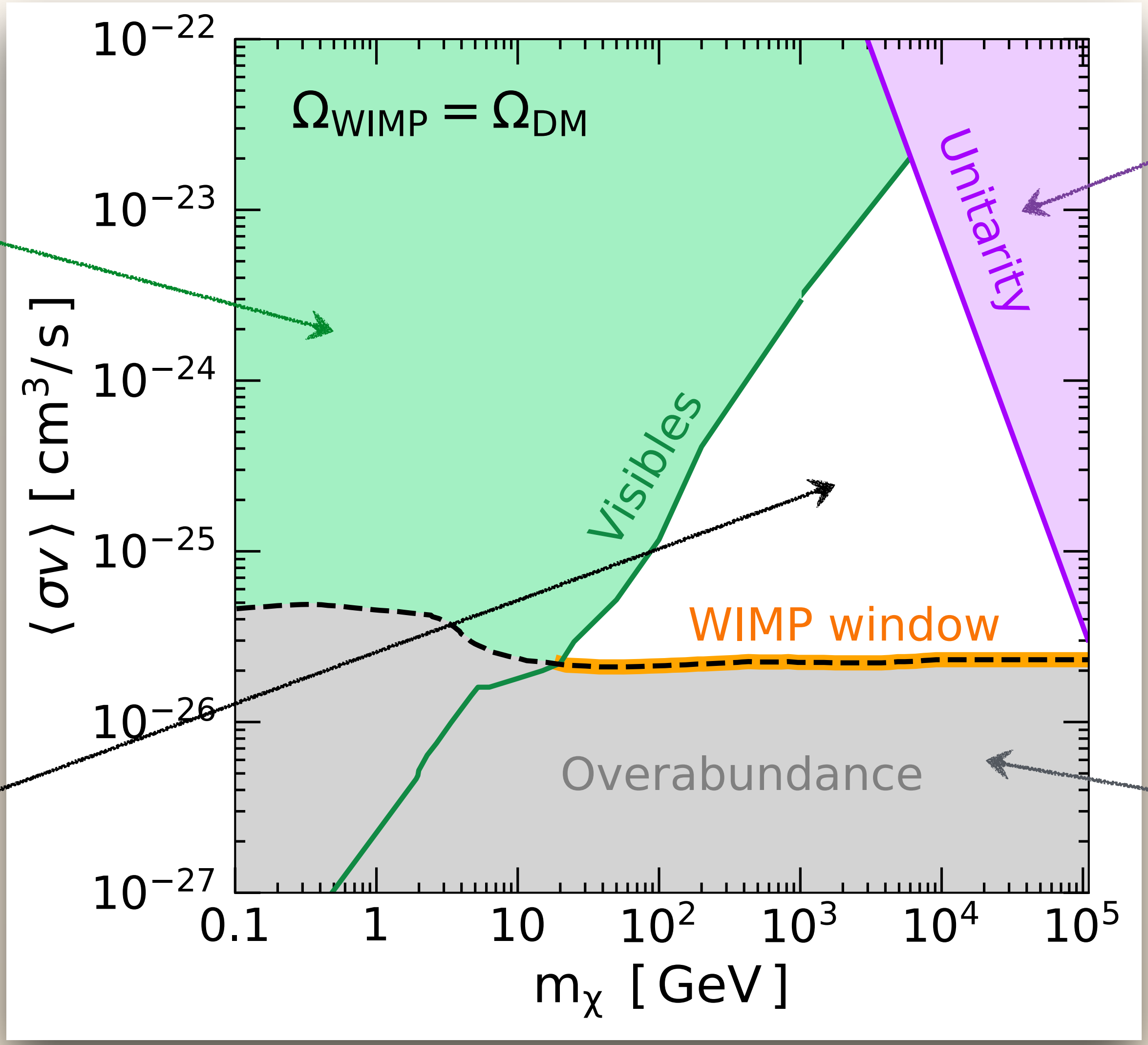
Most of the (strongest) limits are based on assumptions motivated by theoretical prejudice (or convenience) → this can lead to a very broad-brush conclusions

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?

For completely generic DM 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:

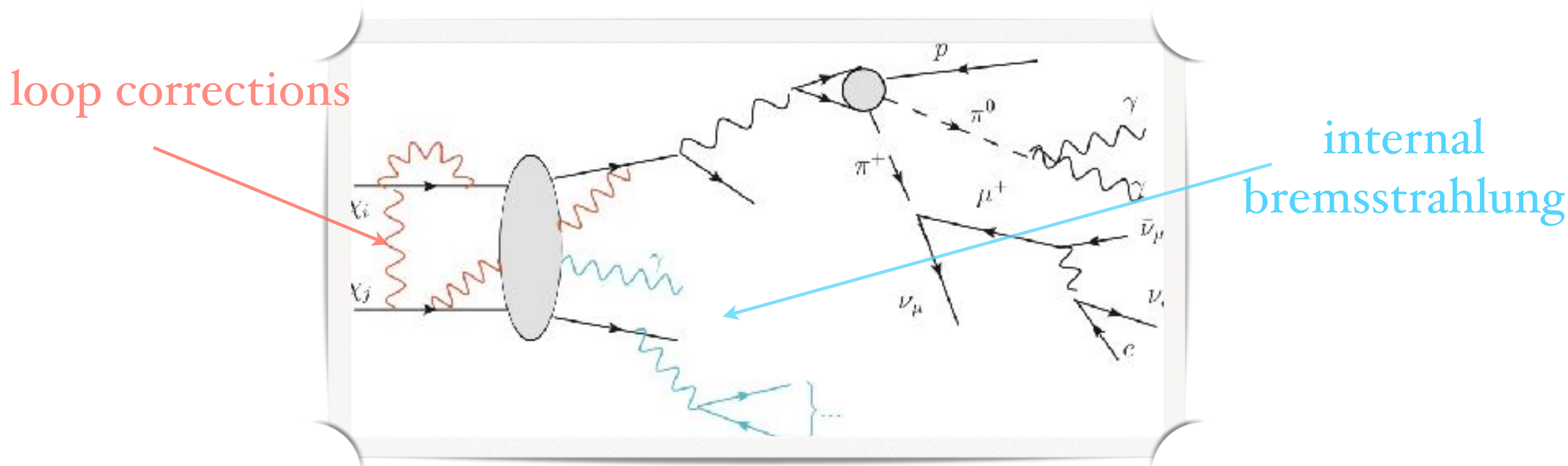
$m_{\rm DM} \gg m_W, m_Z, m_h \quad \Rightarrow$

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

&

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

EW CORRECTIONS



enhancement by large (Sudakov) logarithms:

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

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

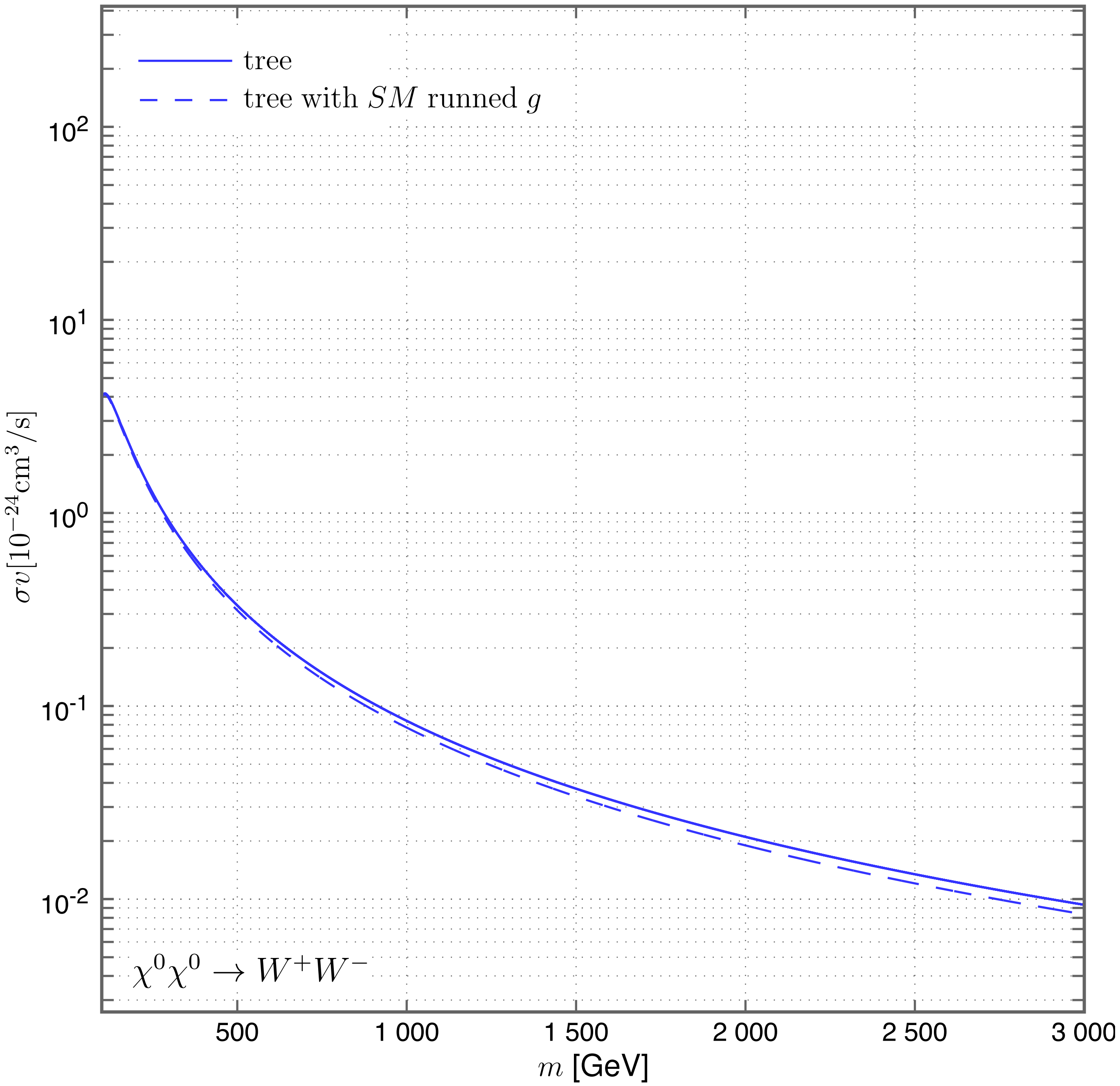
$m \gg m_W$ resambles IR divergence of QED or QCD

⟶ 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

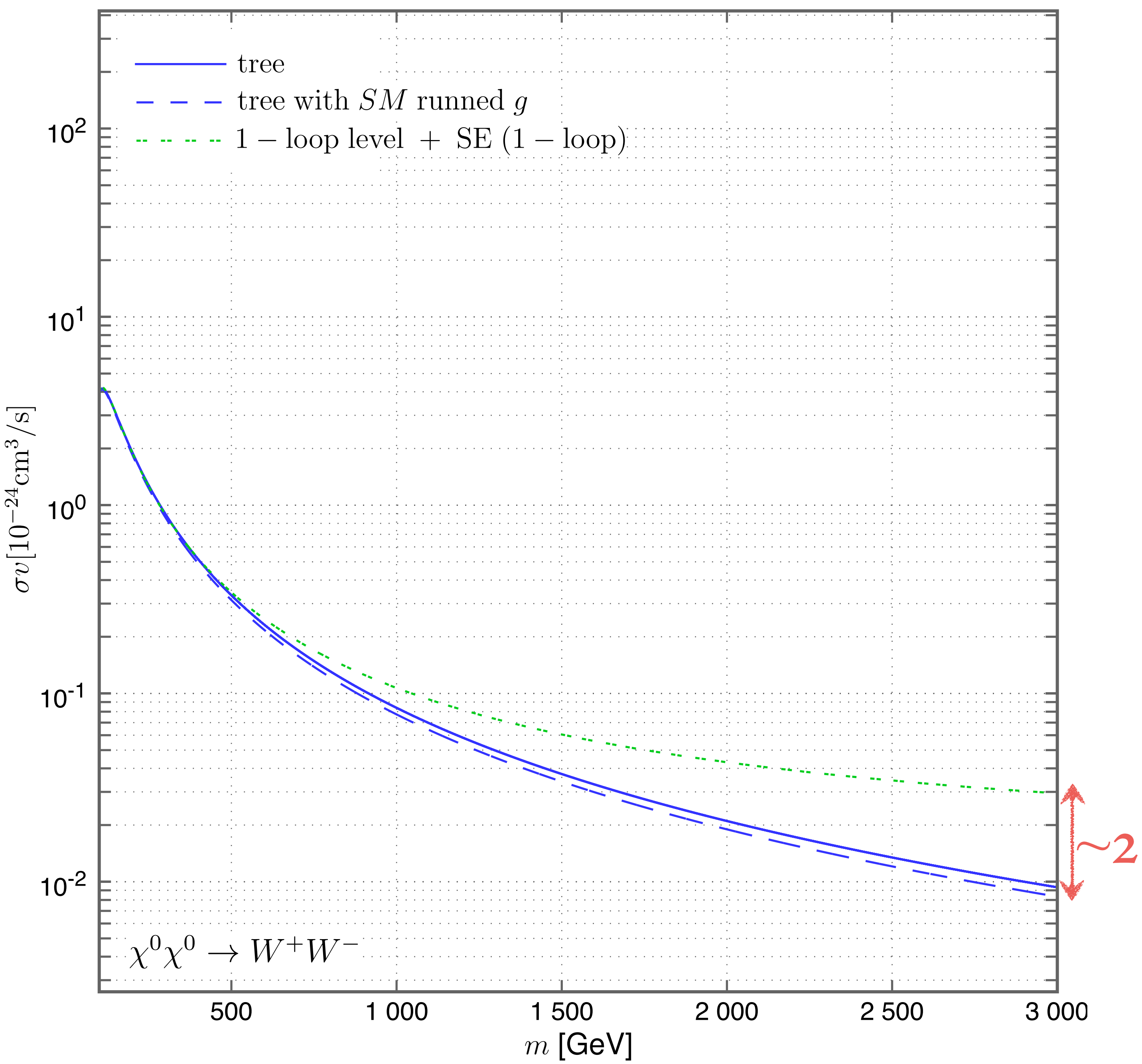


tree level result $\sim 1/m^2$

with g at scale m
with SM running

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

Example:
Wino DM @ 1-loop



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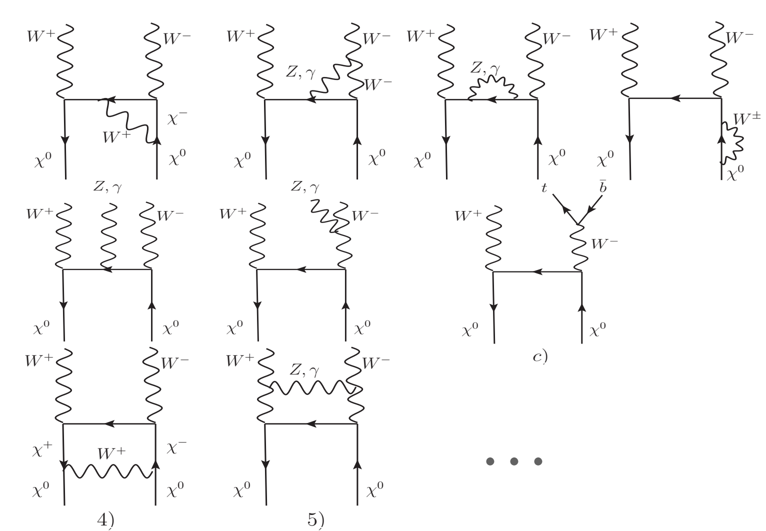


AH, R. Iengo; JHEP 1201 (2012) 163

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

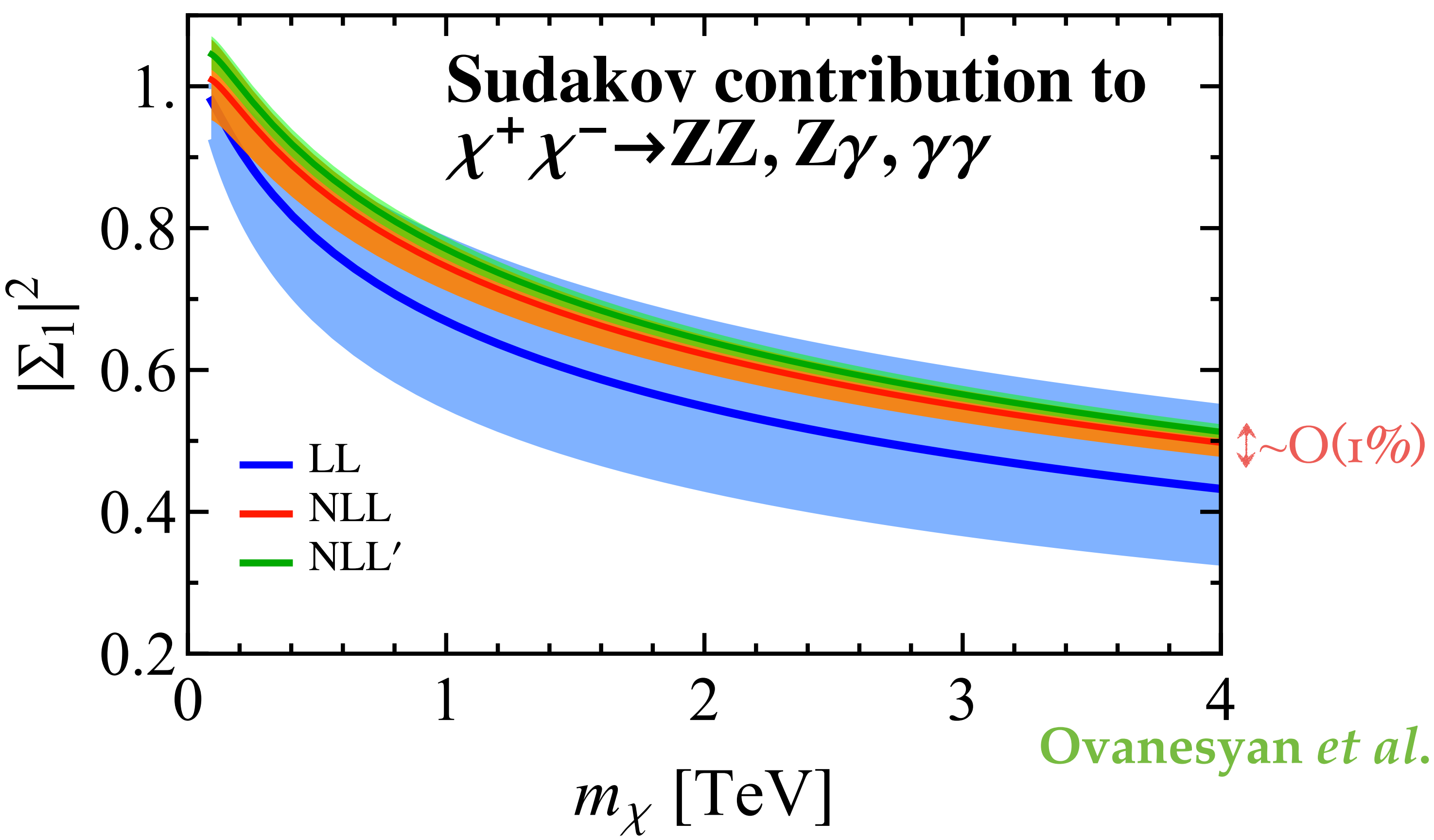
EXCLUSIVE ANNIHILATION

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

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

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

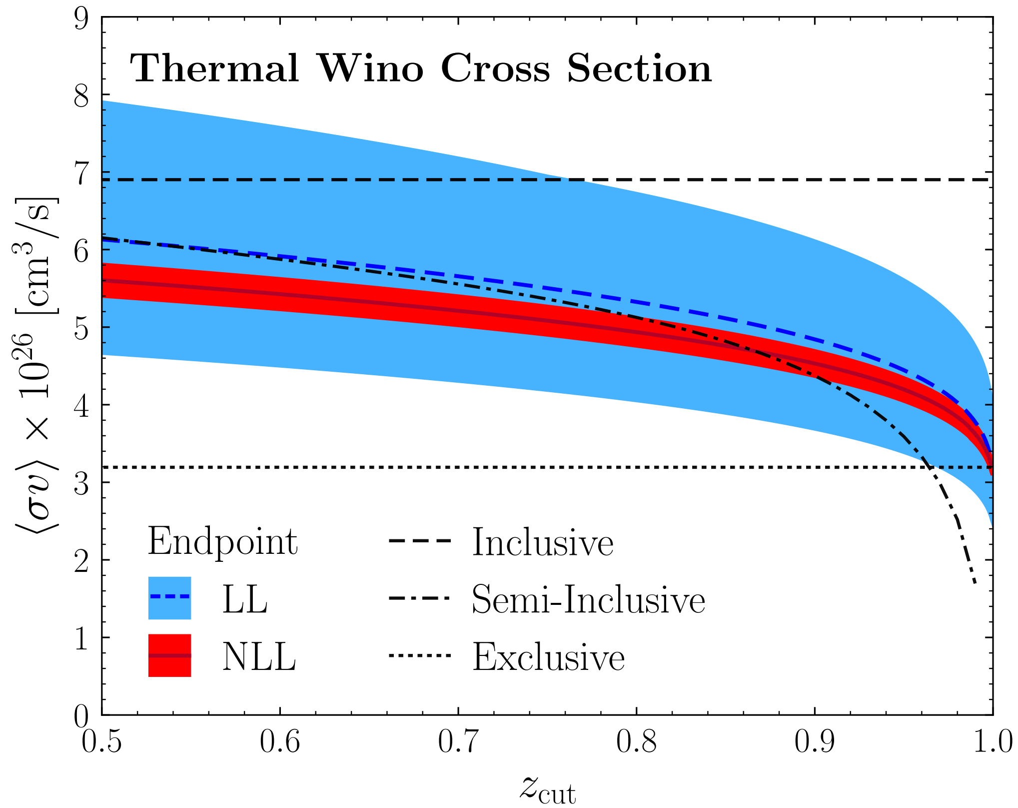
Reminder:

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

EFFECT OF SCET RESSUMMATION

SEMI-INCLUSIVE ANNIHILATION

Baugmart *et al.* '18



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

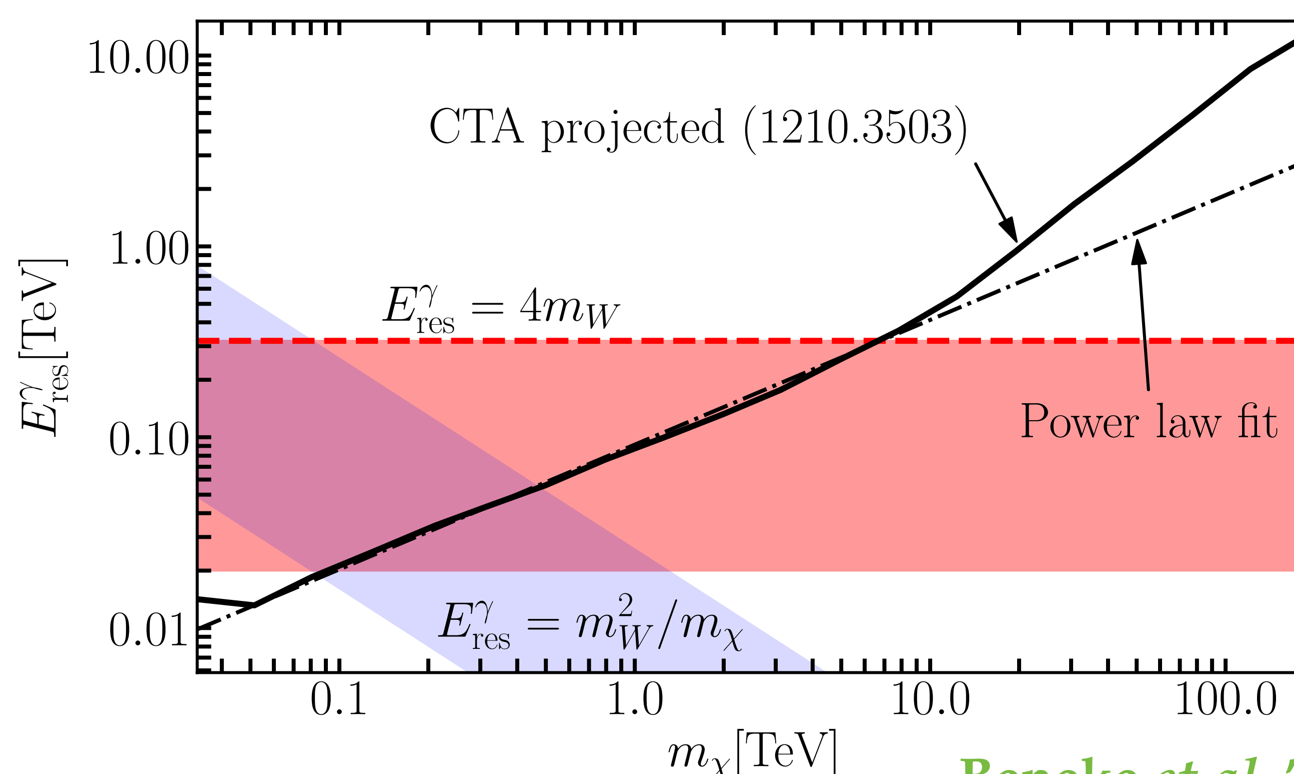
What is observed in e.g. H.E.S.S or CTA is a semi-inclusive single-photon energy spectrum $\gamma + X$

One additional scale 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

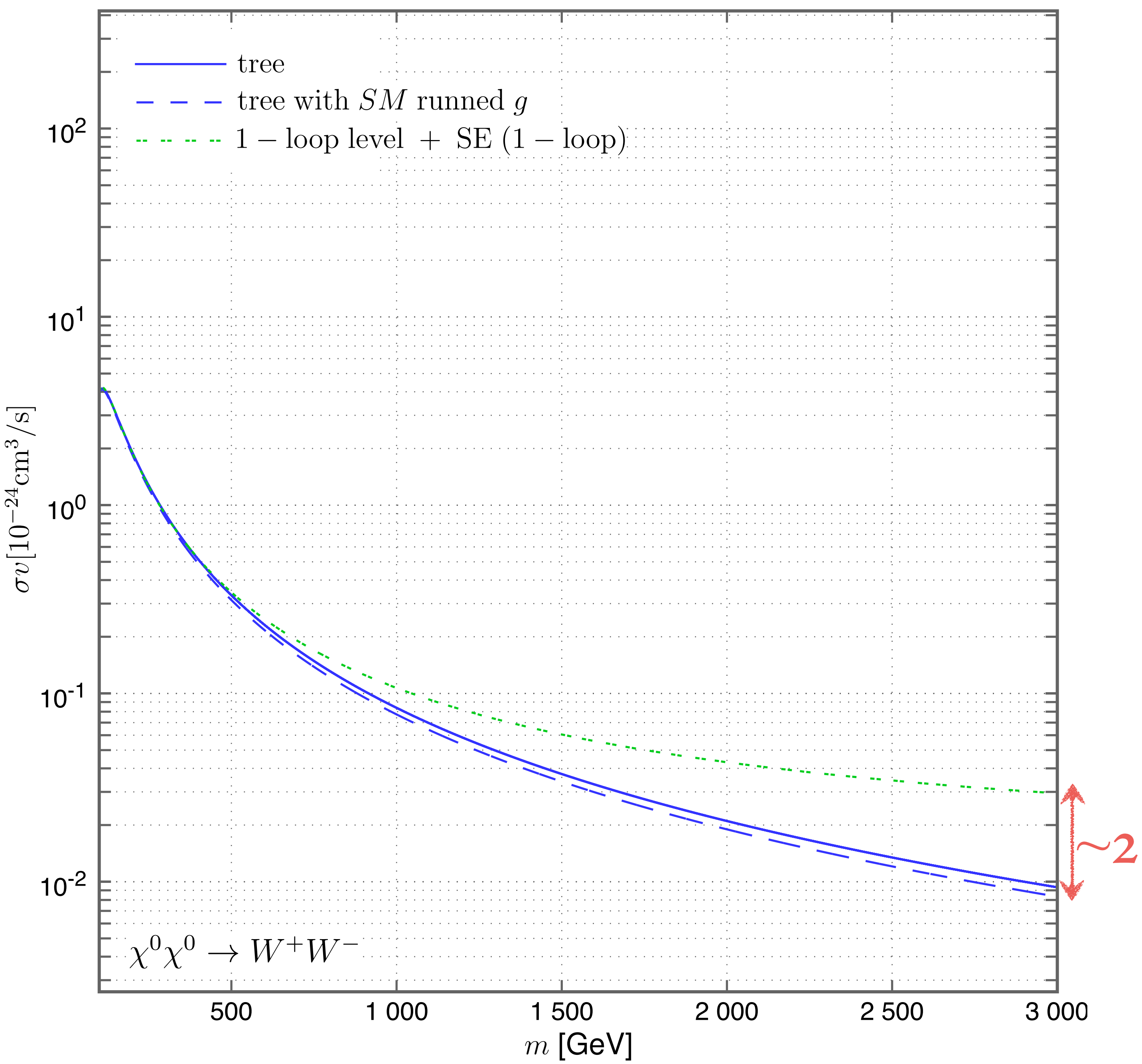
two-step resummation



Beneke *et al.* '19

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

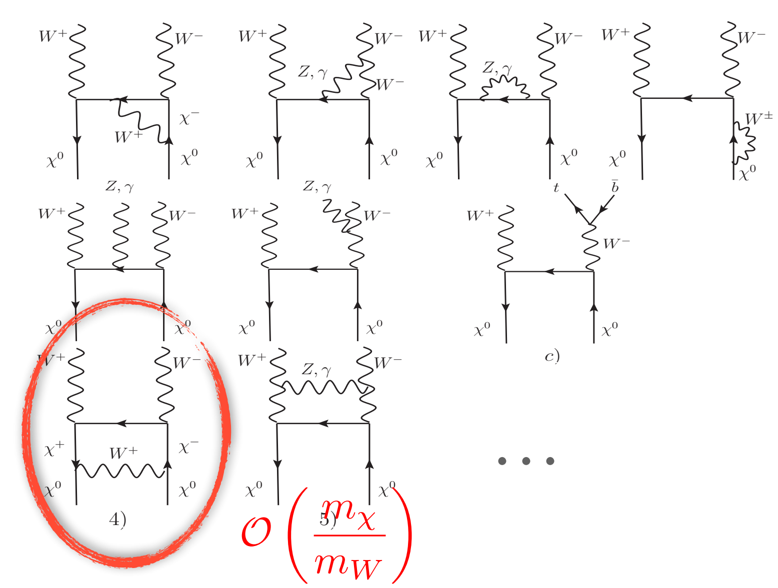
EXAMPLE:
WINO DM @ 1-LOOP



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

with g at scale m
with SM running

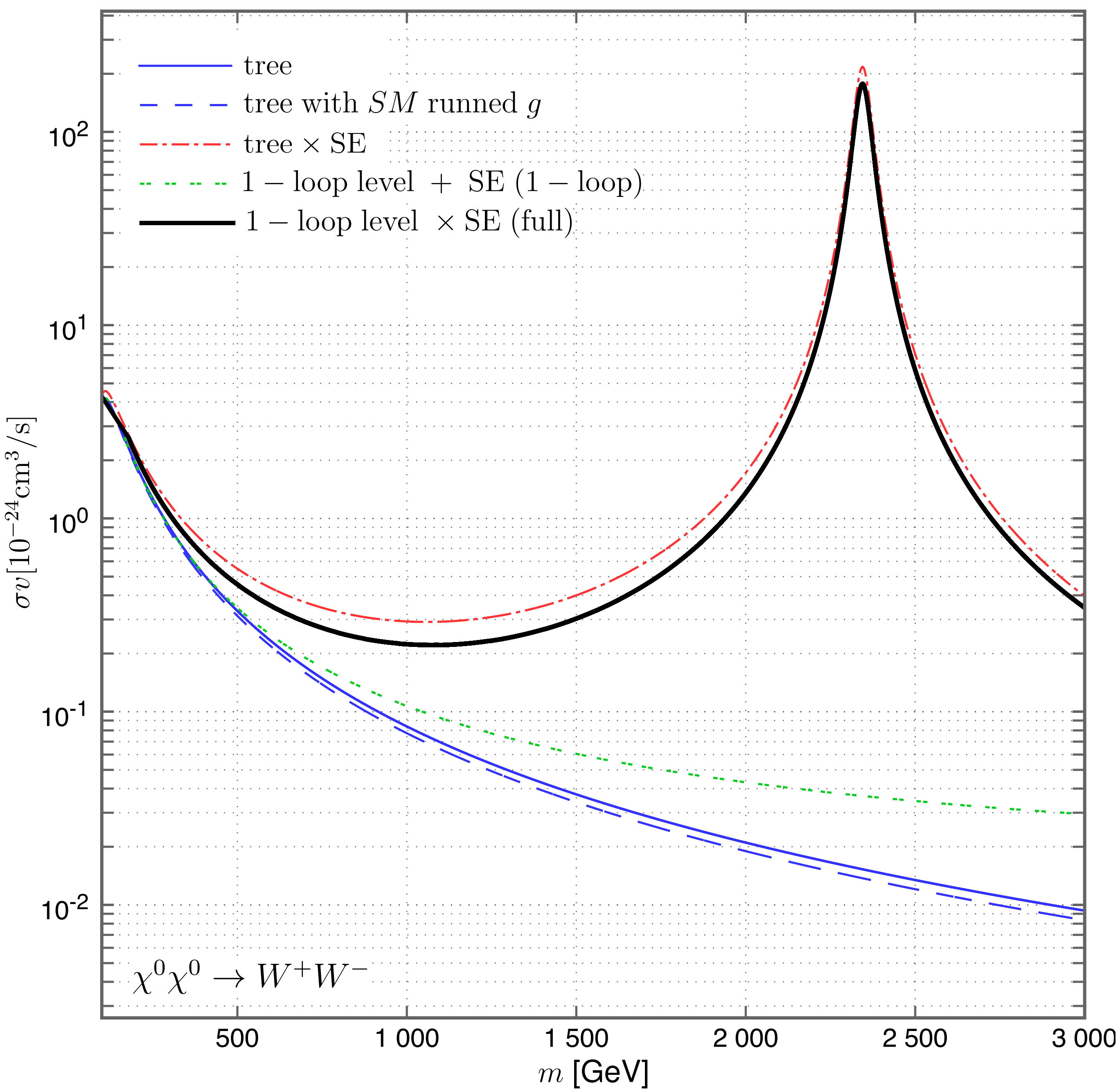
one-loop result



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

EXAMPLE:

WINO DM @ 1-LOOP
& SOMMERFELD EFFECT



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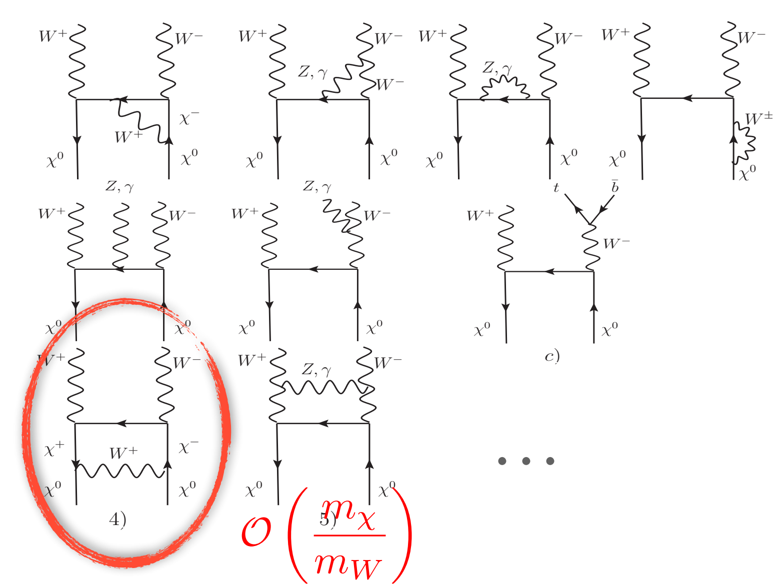
one-loop result



tree level + Sommerfeld

one-loop + Sommerfeld

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

LARGE EW EFFECTS

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&

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

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

resummation to all orders using EFT techniques

SCET
(soft-collinear effective theory)

RG for Wilson coeff.

Sudakov corrections
now @ NLL'

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

NR DM
(non-relativistic DM EFT)

Schroedinger eq. for G's

EW Sommerfeld effect

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

SOMMERFELD EFFECT

re-summation

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

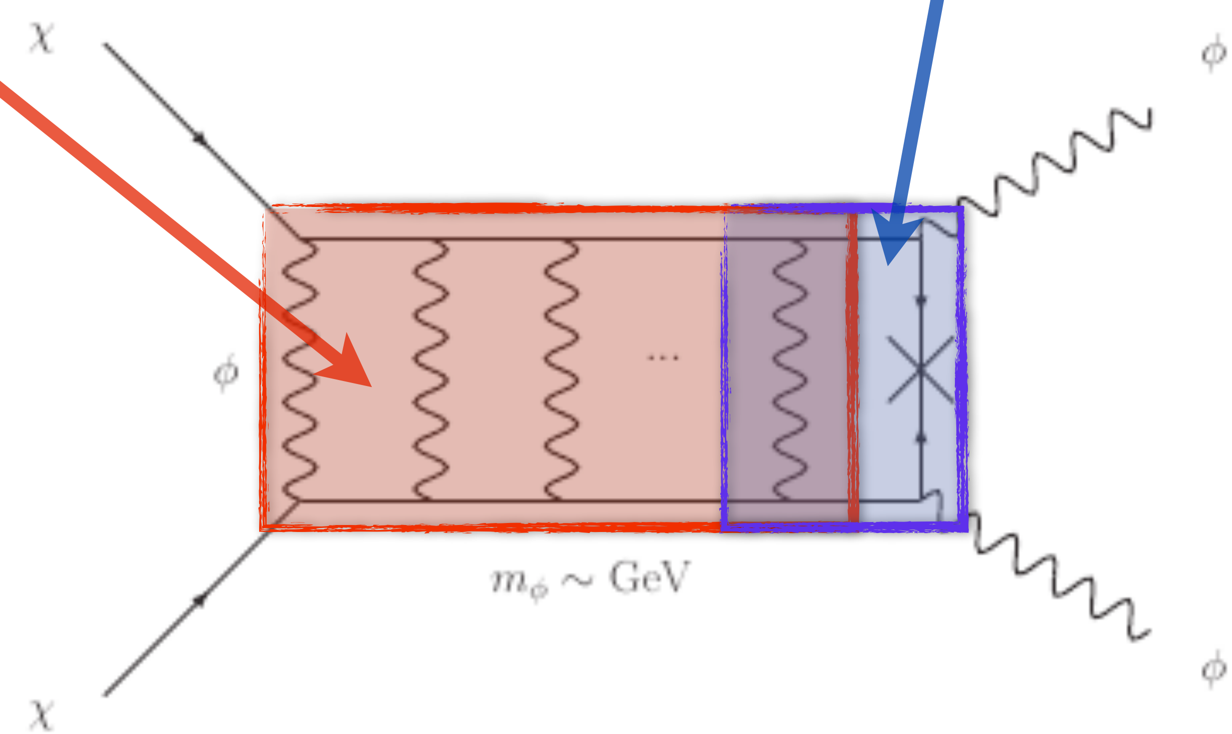
force range — Bohr radius

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

kinetic energy — Bohr energy

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

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



Arkani-Hamed *et al.* '09

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

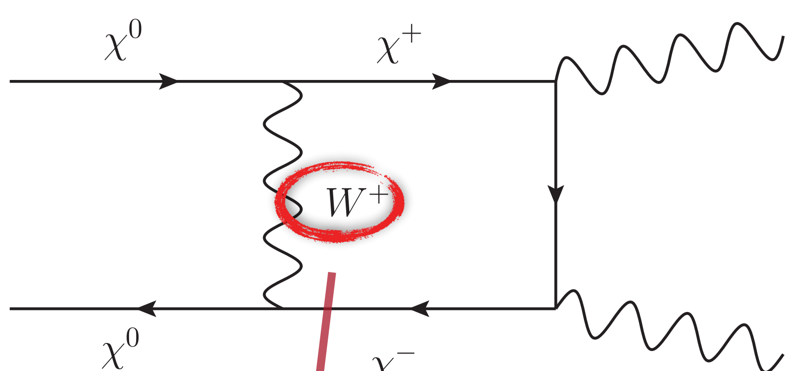
THE SOMMERFELD EFFECT
FROM EW INTERACTIONS

force carriers in the MSSM:

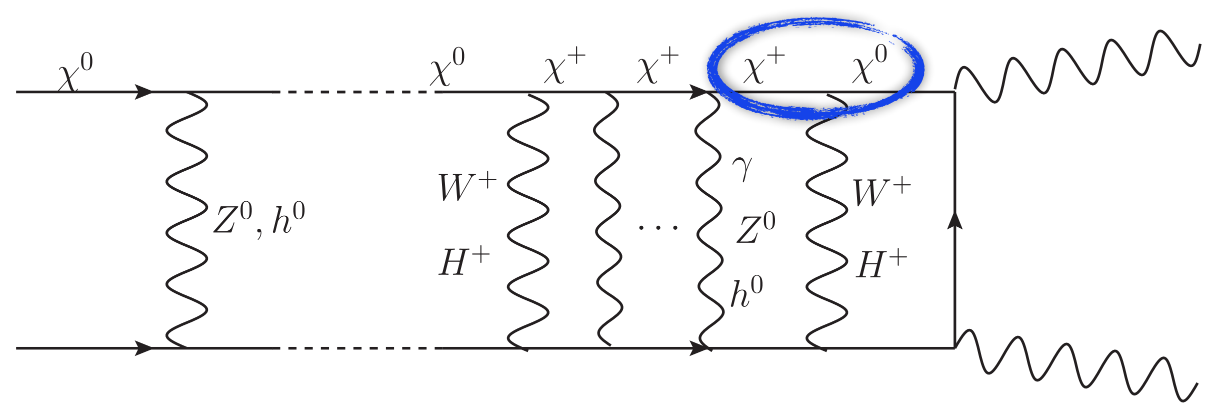
Hisano *et al.* '04,'06

$\delta m \ll m_\chi$

~~γ~~, $W^\pm$, Z^0, h^0_1, h^0_2, $H^\pm$



$m_\chi \gg m_W$



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

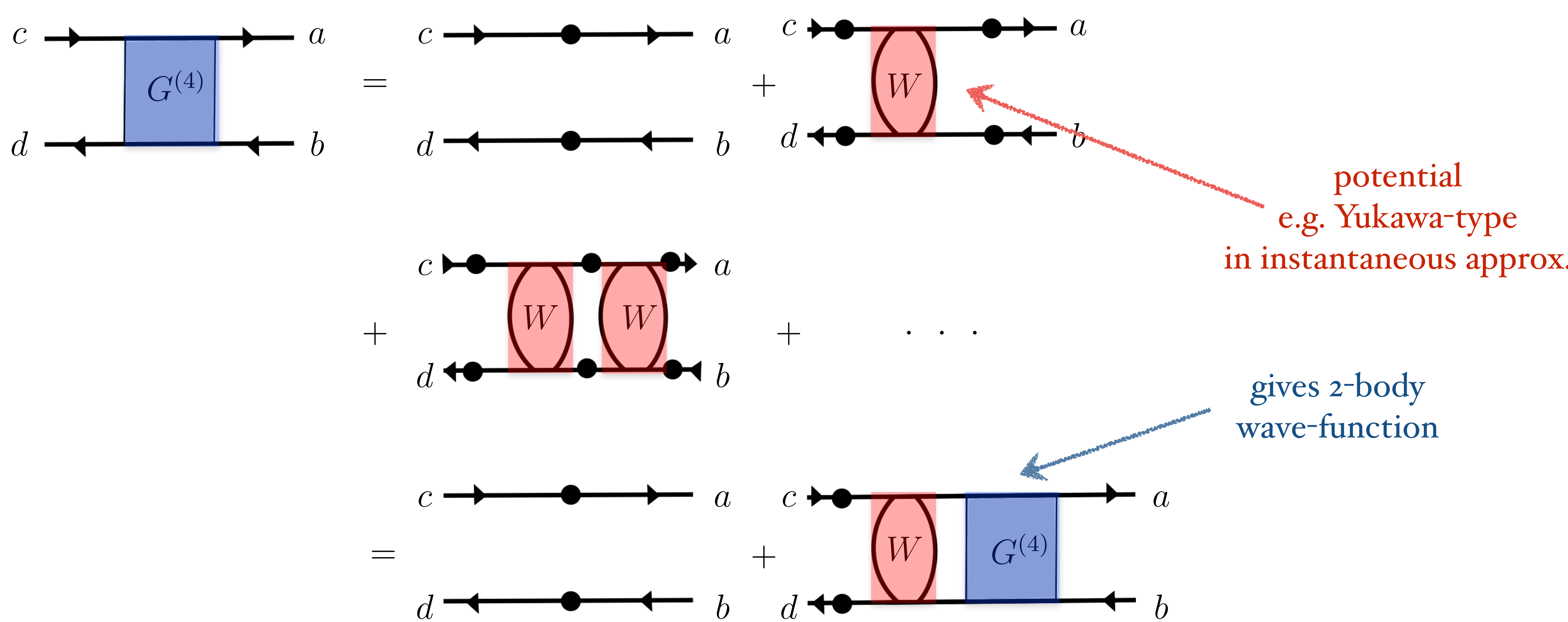
AH, R. Iengo, P. Ullio. '10
AH '11
AH *et al.* '17, M. Beneke *et al.*; '16

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

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

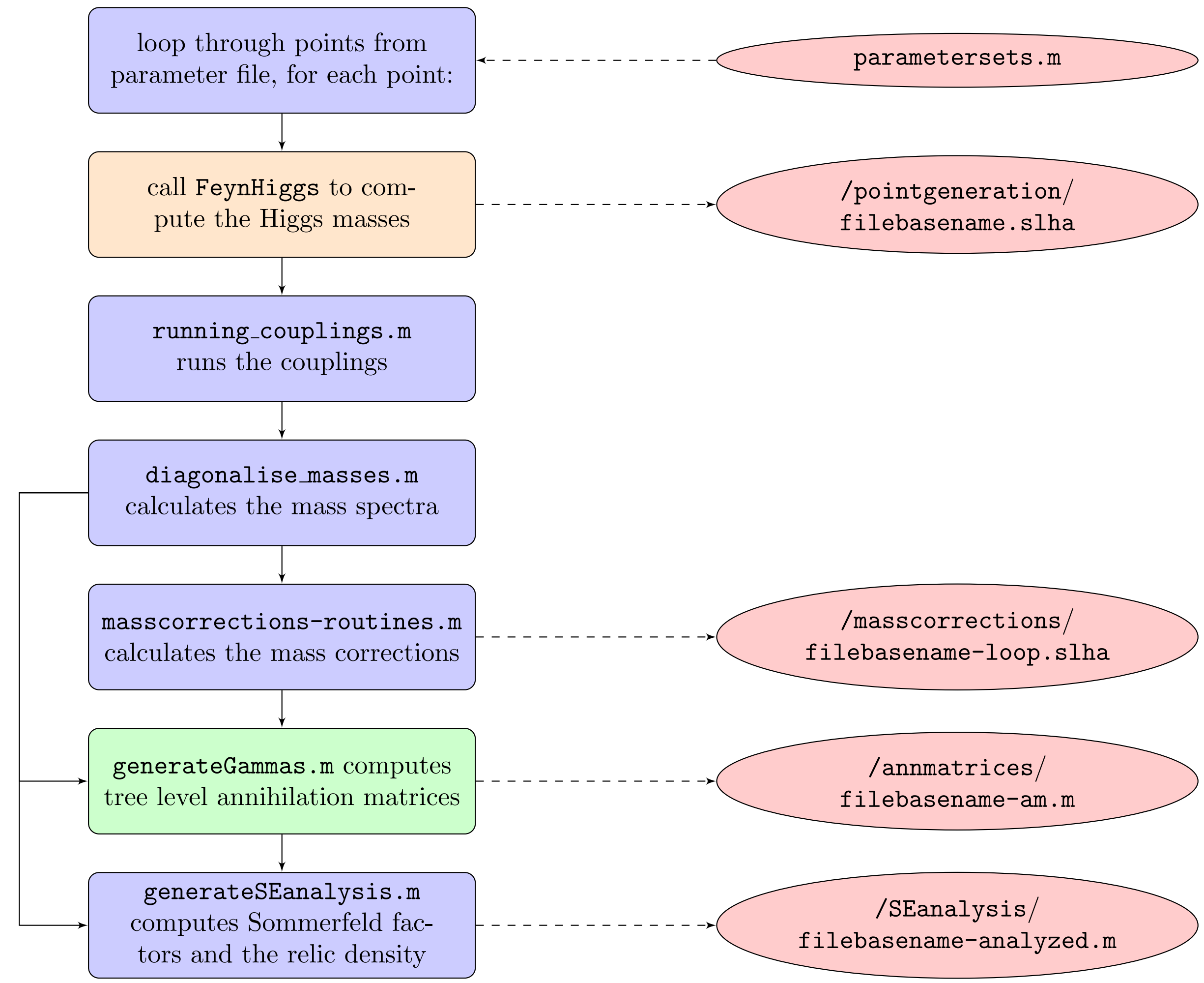
NEW NUMERICAL TOOL

based on EFT, improving accuracy in numerous ways

- suitable for (large scale) scans
- implemented full MSSM
- one-loop on-shell mass splittings and running couplings
- the Sommerfeld effect for P- and $O(v^2)$ S-wave
- off-diagonal annihilation matrices

} not present in DarkSE AH, '11

- present day annihilation in the halo (for ID)
- possibility of including thermal corrections
- ...
- accuracy at O(%), dominated by theoretical uncertainties of EFT

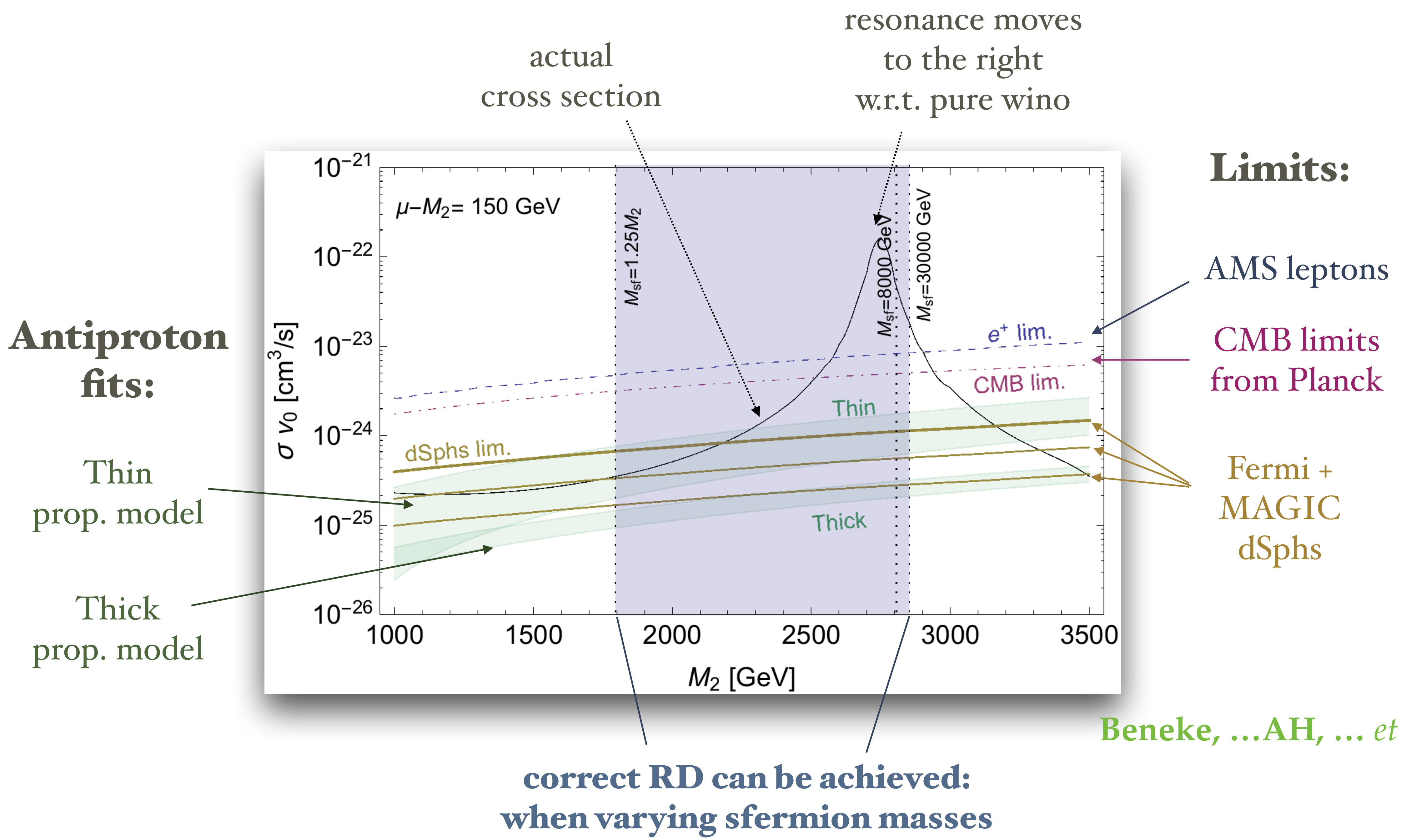


Status: all works as intended, making the code ready for public release

Beneke,..., AH,... *et al.* in preparation

Example result

Wino-Higgsino point



Beneke, …AH, … *et al.*, '16

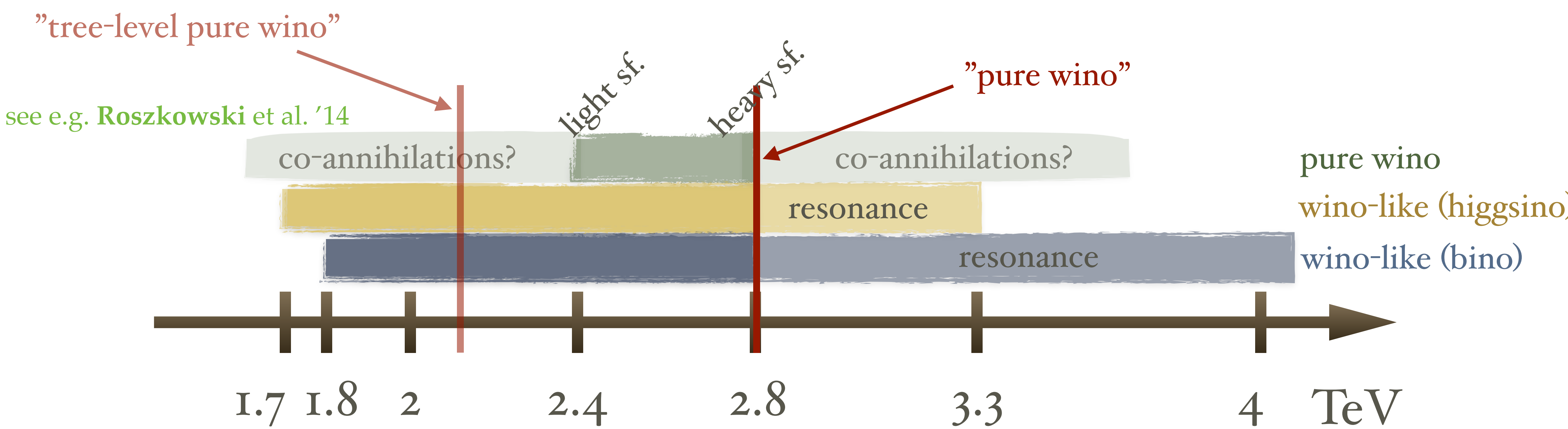
similar study, pure Wino case: Ibe *et al.* '15

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:



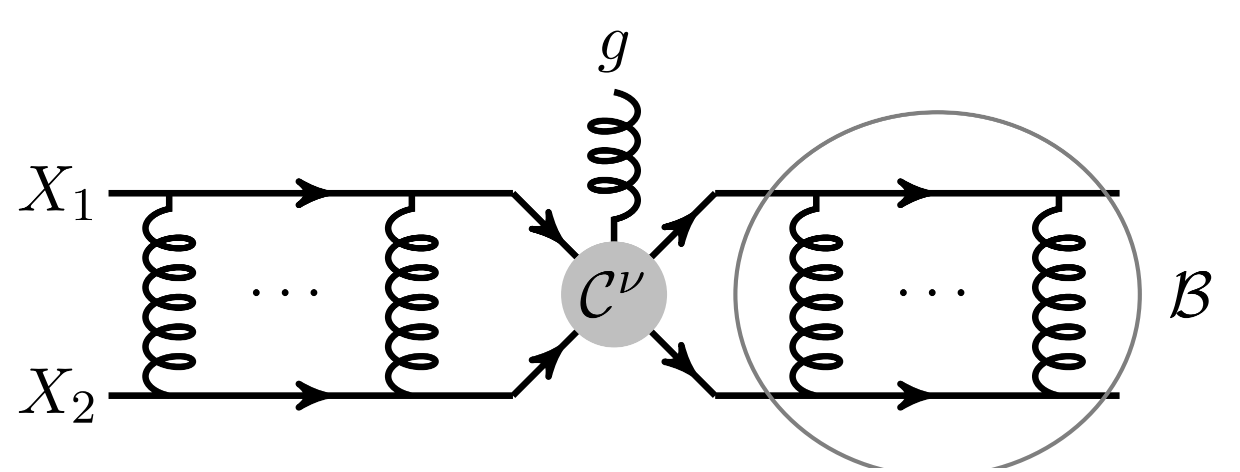
BOUND STATE FORMATION

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.

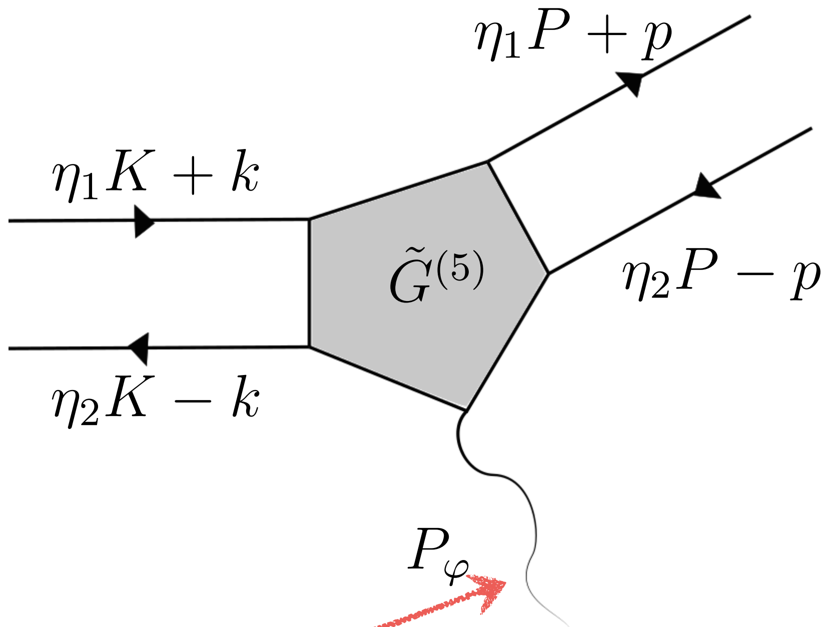
see papers by **K. Petraki** *et al.* '14-19

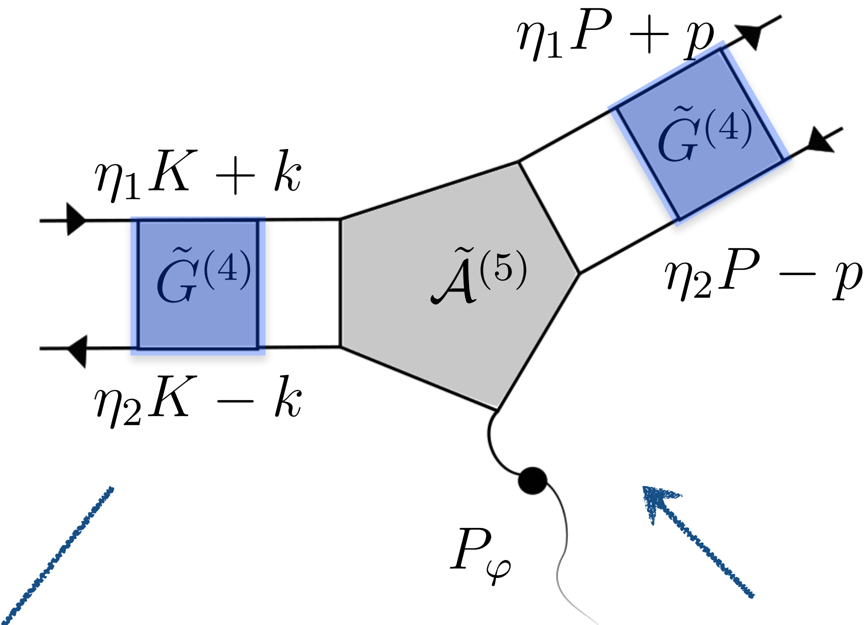
*vide also "WIMPonium"
March-Russel, West '10

How to calculate BSF?

Two options → Non-relativistic EFT → „F" of BSF is not easy, but see e.g. **Asadi** *et al.* '17

Two options → 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…

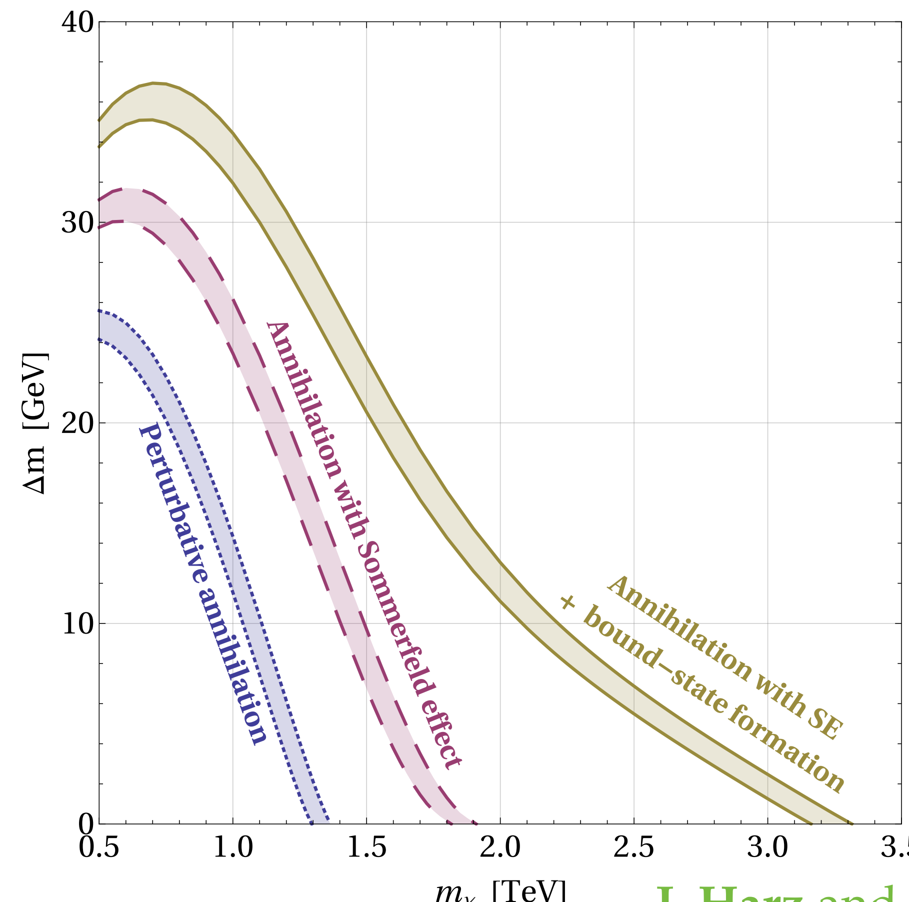
Higgs mediated ⇒ Could lead to DM bound states, but for usual TeV DM models, biggest effect observed is more indirect

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

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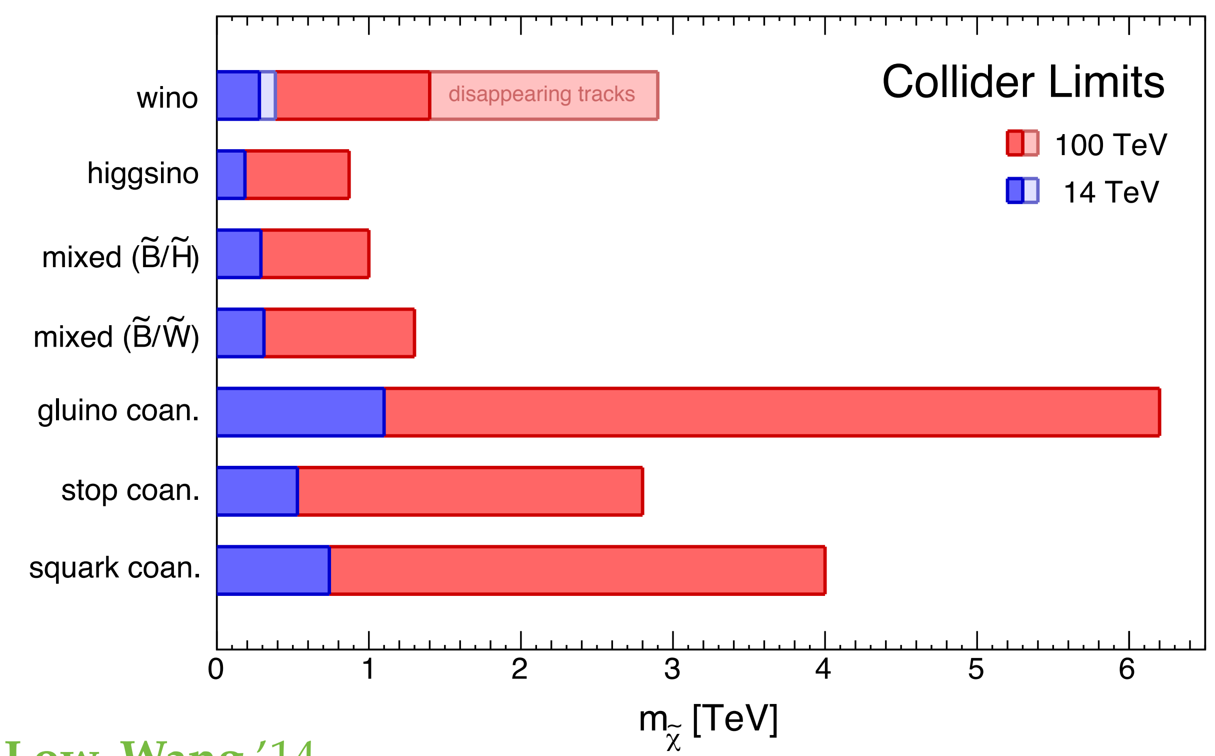
COLLIDER & DIRECT DETECTION

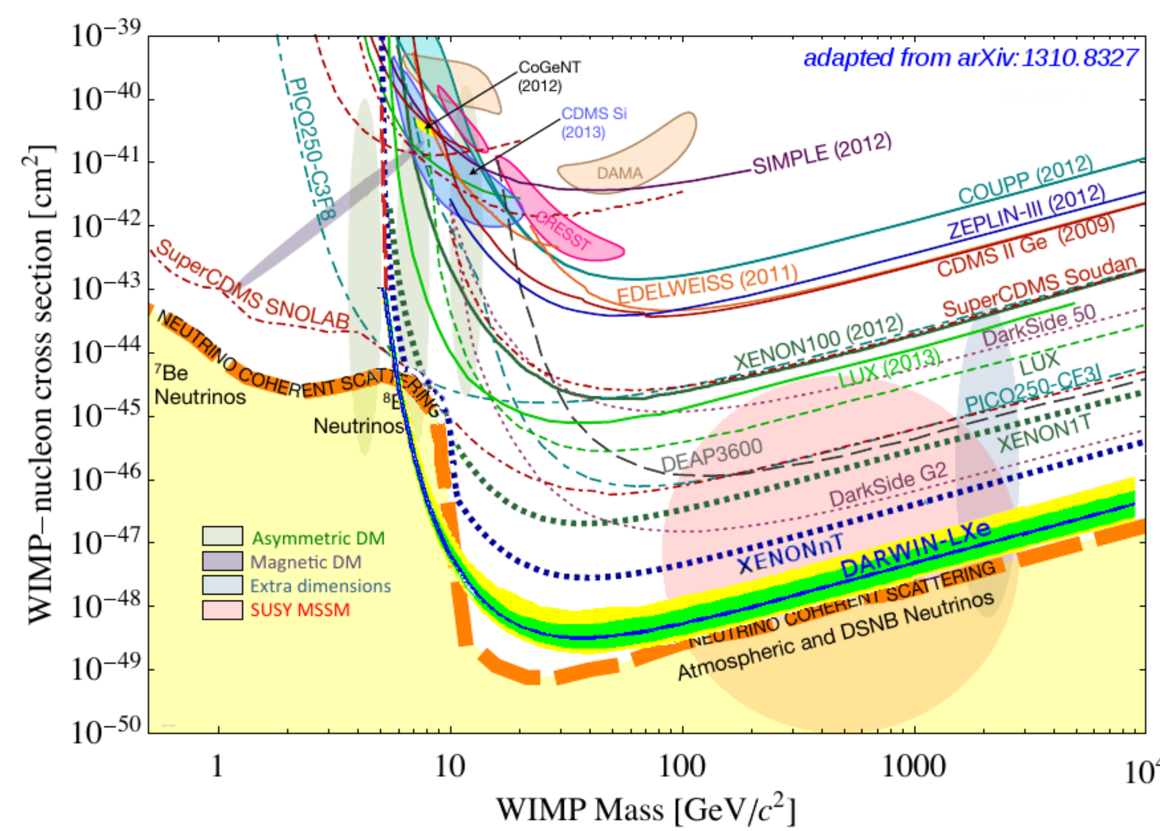


Low, Wang '14

Mixed hopes for TeV regime…
even at 100 TeV collider

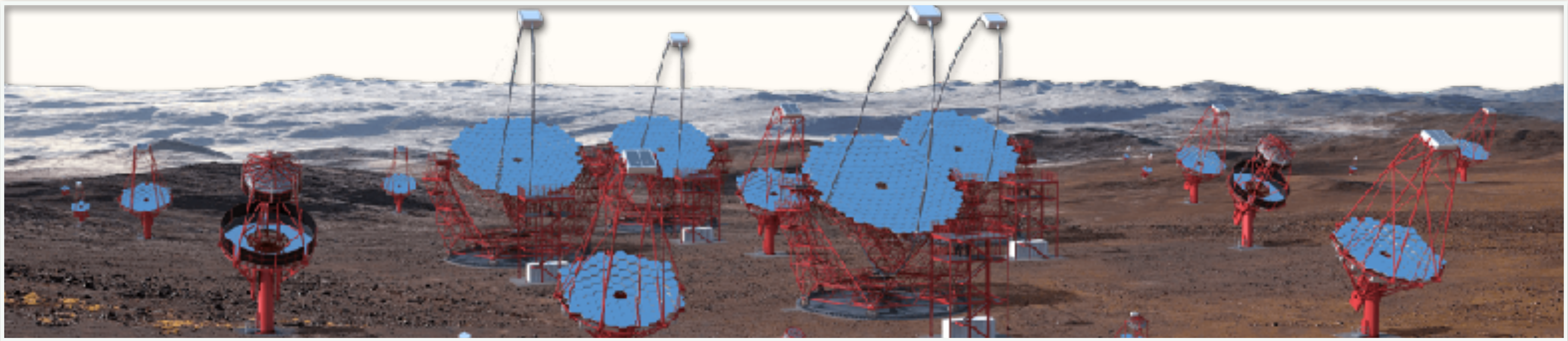
(the plot shows in case of SUSY, but analogous results for generic WIMP)

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)



Considering new data updates and all of the theory improvements above, it is about time for an update of the prospects for heavy neutrinos detection

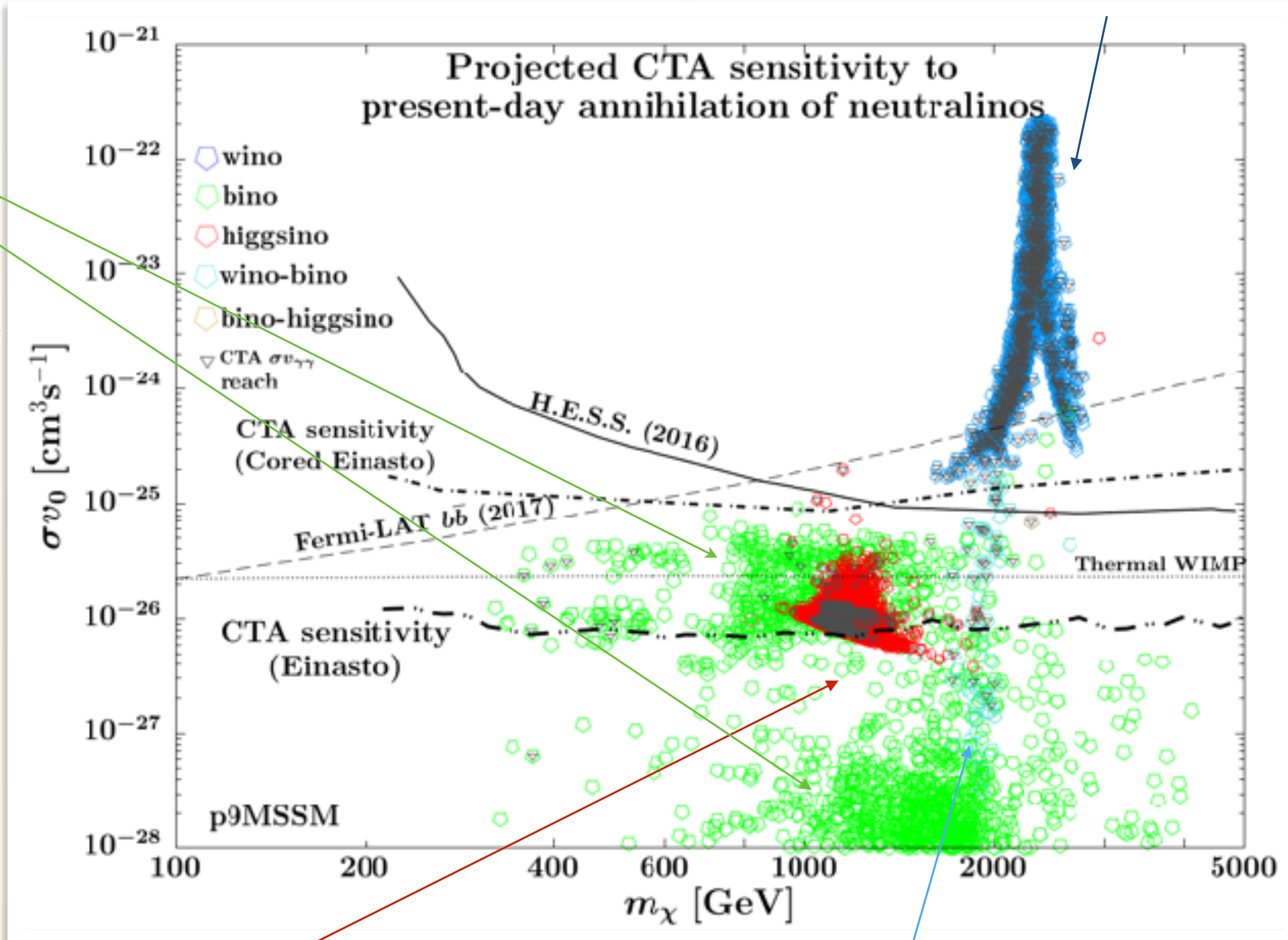
AH, K. Jodłowski, E. Moulin, L. Rinchiuso, L. Roszkowski, E. Sessolo, S. Trojanowski; ’19

- ROI extends up to ±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)

MSSM SCAN RESULTS

Wino - already excluded (?)

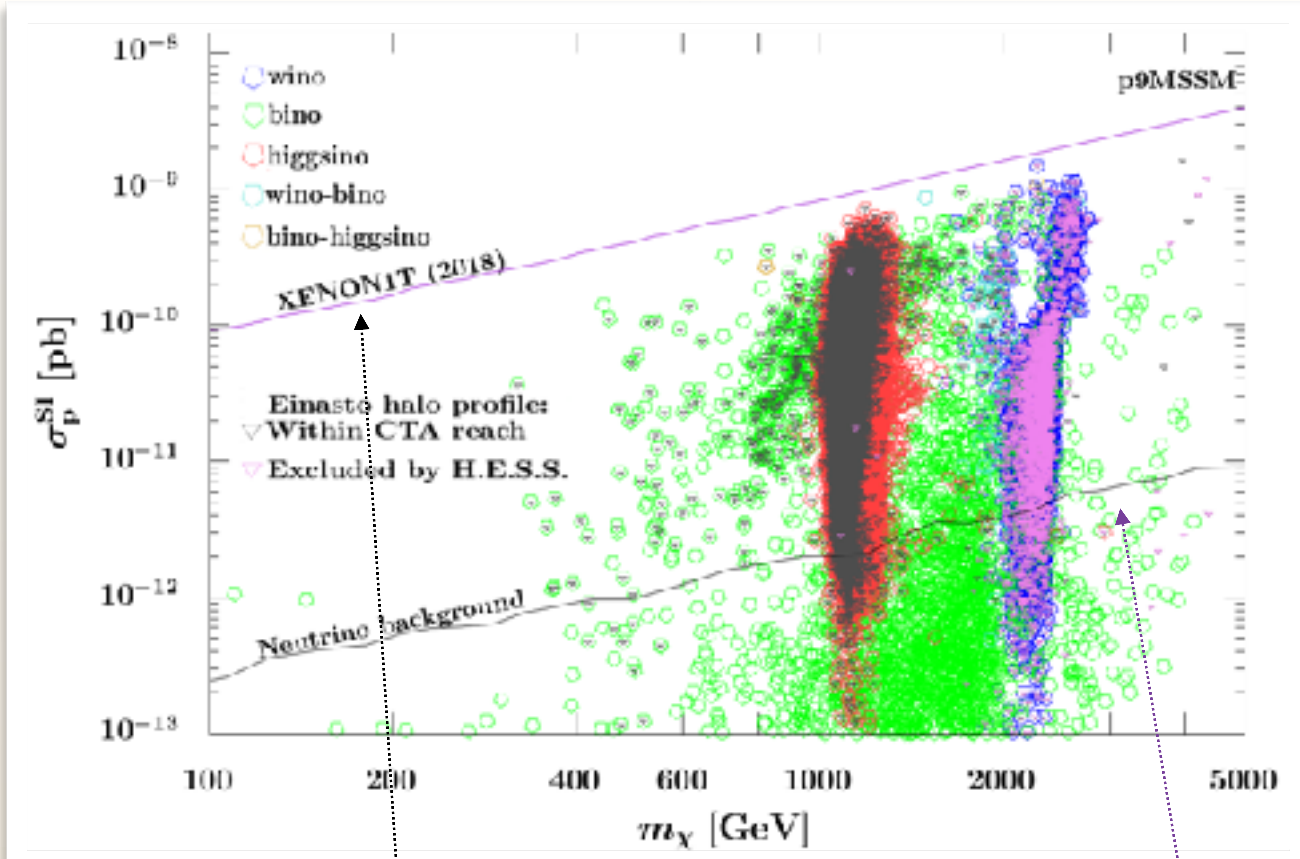
Bino
Require additional mechanism (e.g. co-annihilation)

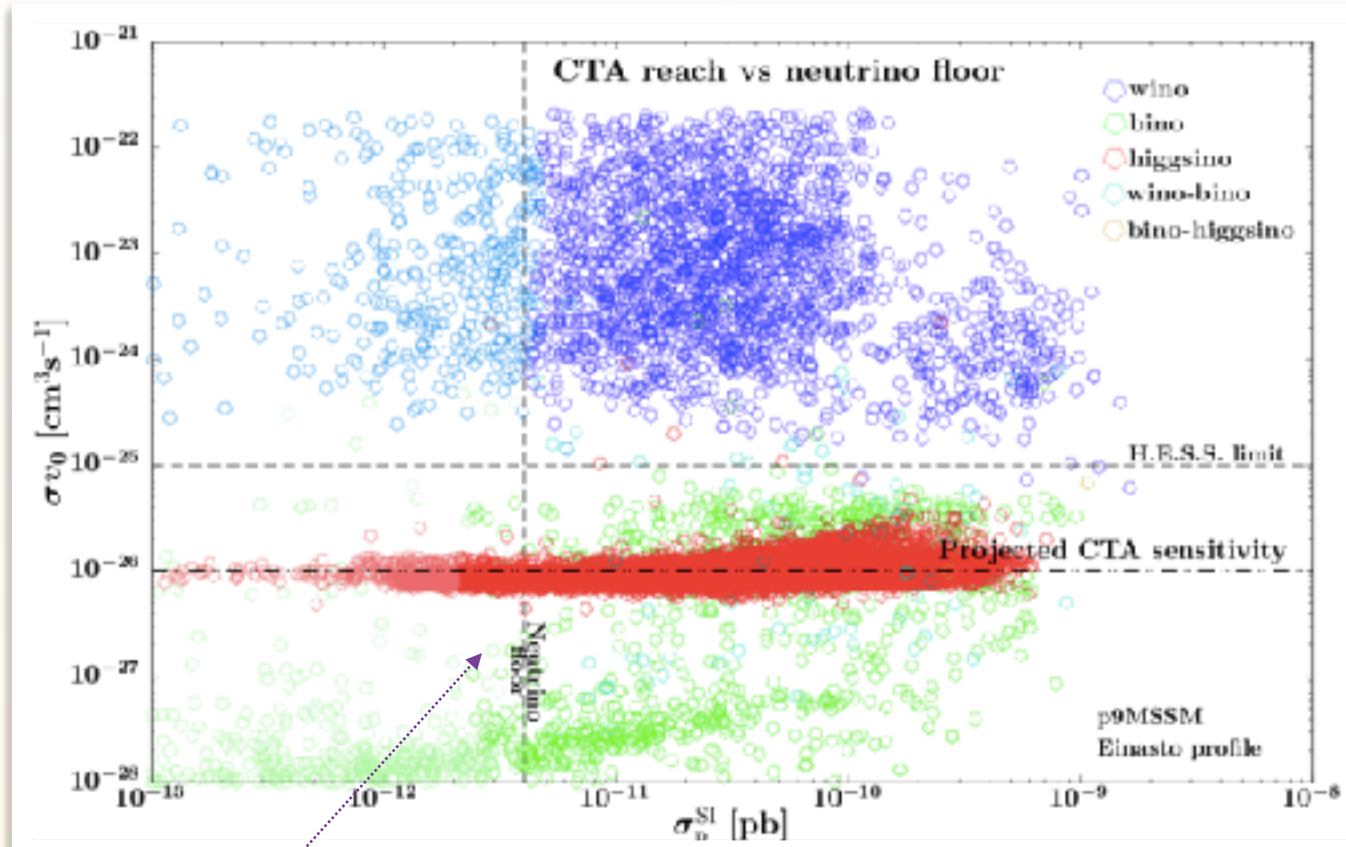


Higgsino
~ 1 TeV region
most promising candidate in MSSM

Bino-wino
In reach of monochromatic line search

COMPLEMENTARITY WITH DD





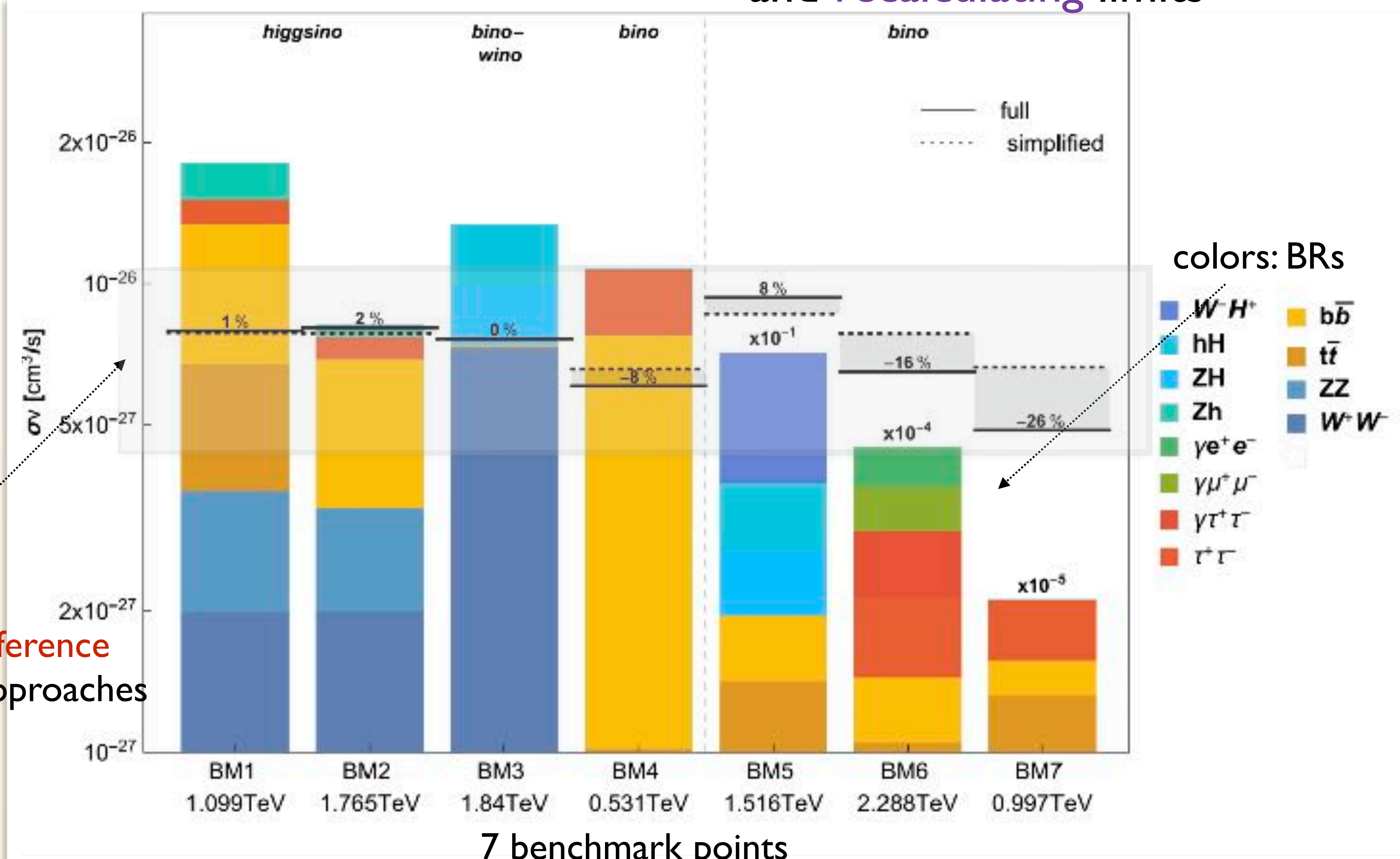
- Wino and Higgsino regions will be probed in the majority of cases, corresponding to:
  - spin-independent scattering cross section below the reach of 1-tonne underground detector searches
  - even well below the irreducible neutrino background
- Higgsinos in the ~1 TeV region are good thermal DM candidates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

ONE DETAIL:

HOW TO GET LIMITS FOR POINT WITH GENERIC BRs?

Typically limits are given for annihilation only to one channel, e.g. $b\bar{b}$

combining limits using BRs vs combining spectra and recalculating limits



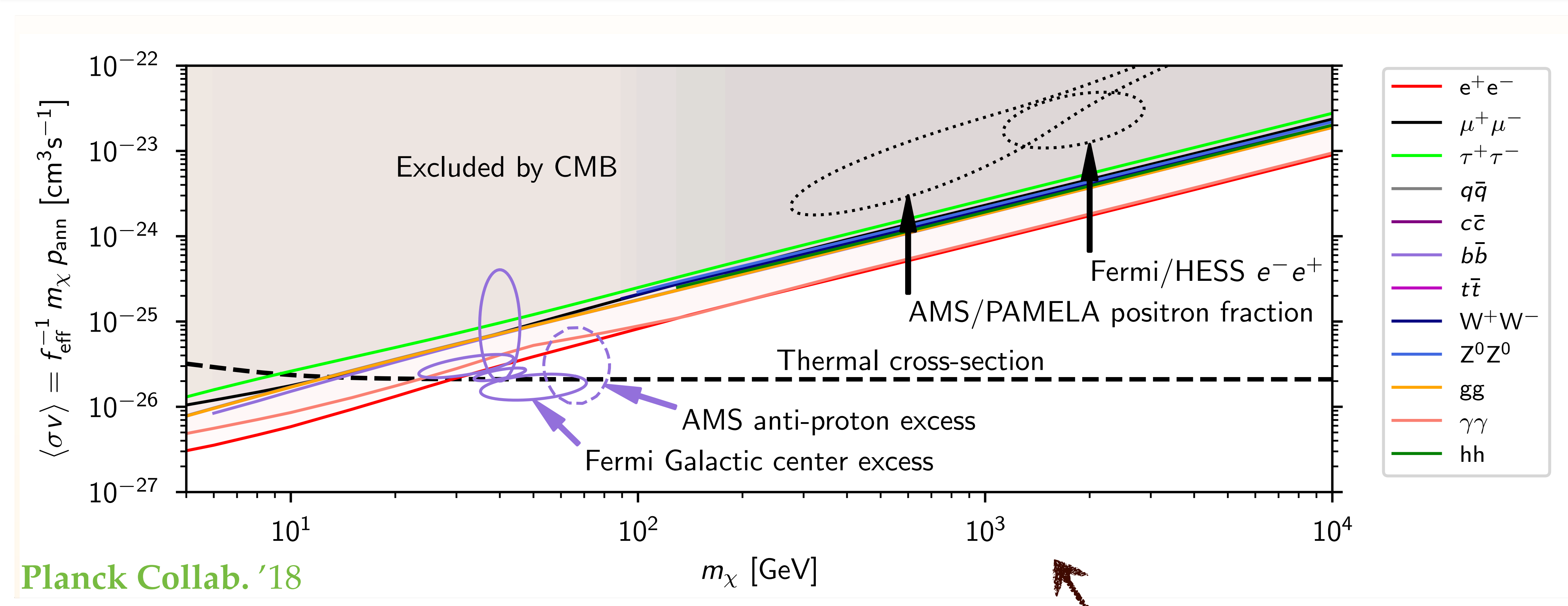
colors: BRs

W^-H^+, hH, ZH, Zh, γe^+e^-, $\gamma\mu^+\mu^-$, $\gamma\tau^+\tau^-$, $\tau^+\tau^-$, $b\bar{b}$, $t\bar{t}$, ZZ, W^+W^-

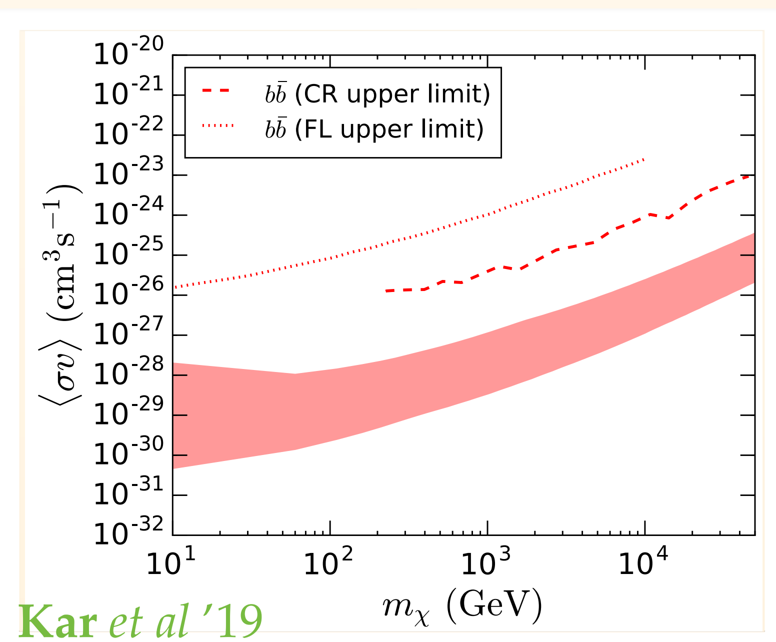
numerical difference between two approaches

…the difference is not large, but worth keeping in mind

CMB & others



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



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)

CONCLUSIONS

1. Most up to date status of heavy neutrinos in the MSSM was presented together with prospects for CTA, including both new data and theoretical developments

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

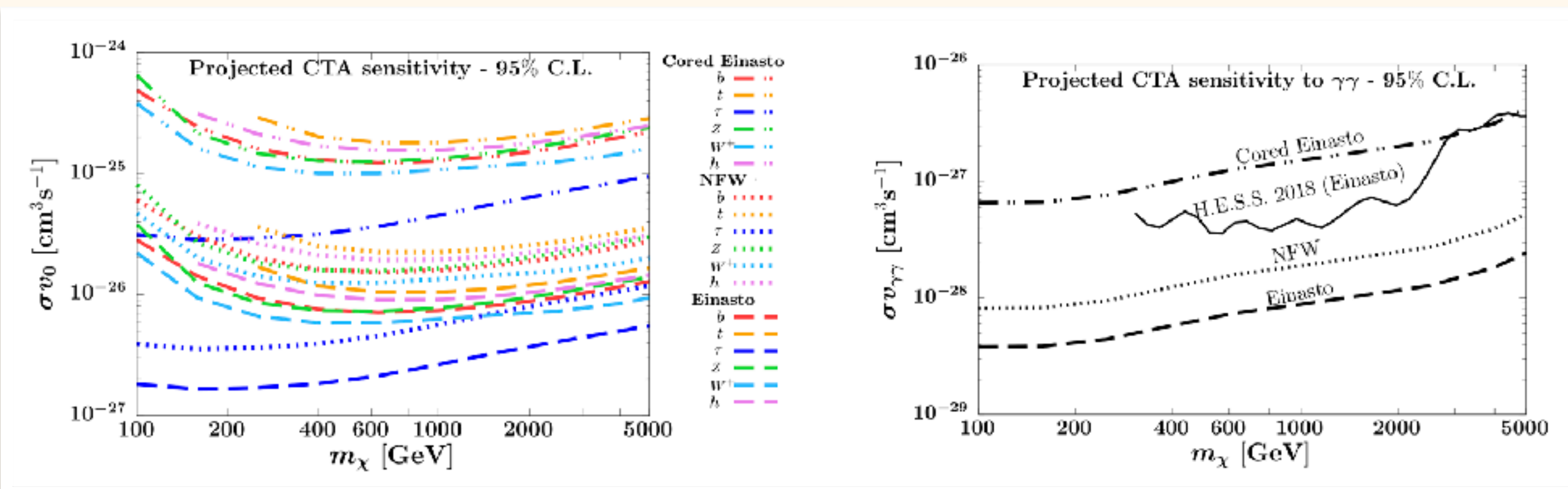
3. Although compared to previous decades, not many causes for optimism on the detection prospects… with CTA starting in few years, consecutive DD detector upgrades and future planned experiments/observations, there is some place for hope for a breakthrough

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

BACKUP

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)



AH *et al.* '19

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

$\Leftarrow$

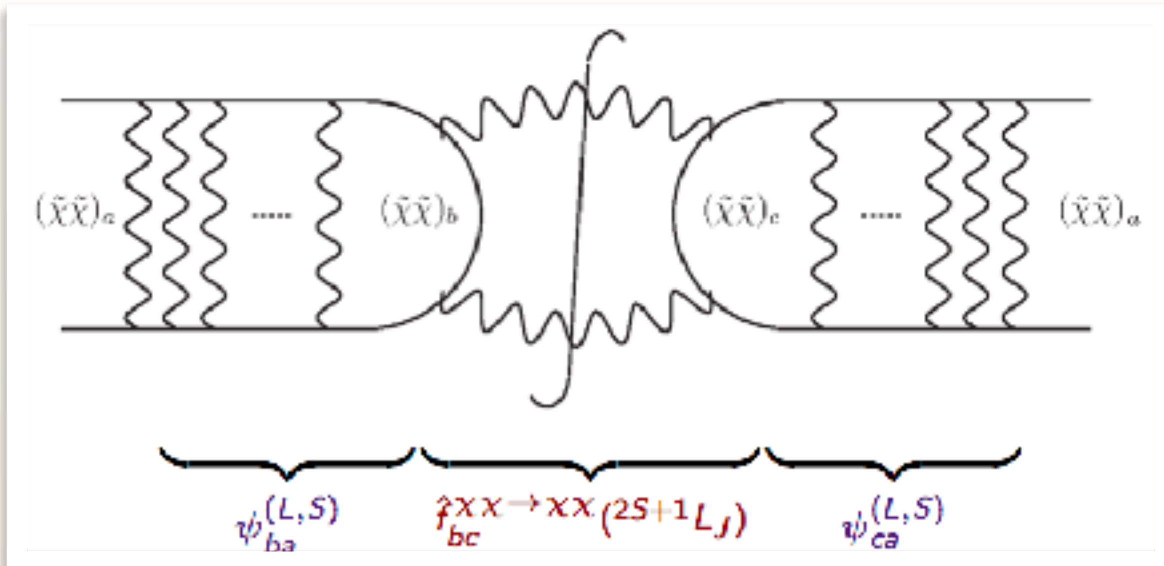
$M_{\rm DM} < 144\,{\rm TeV}$

(for a Majorana fermion)

Smirnov, Beacom '19

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

Details of the Calculation



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

The full cross section:

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

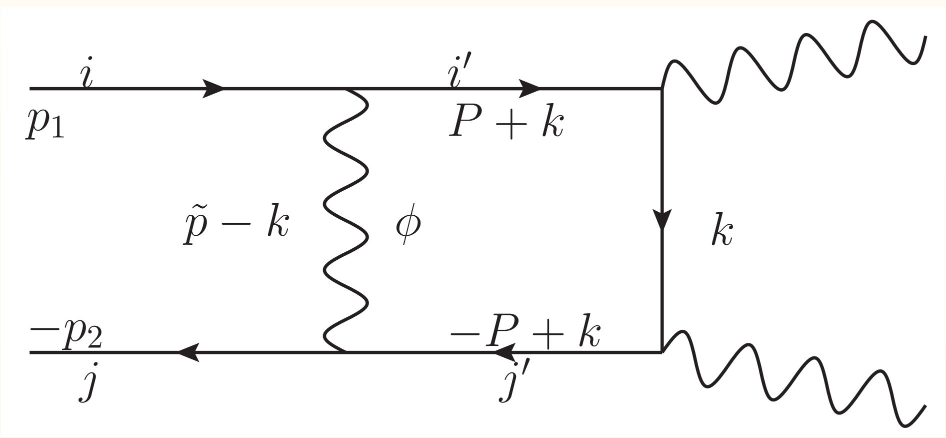
absorptive parts of the Wilson coefficients of local 4-fermion operators

Sommerfeld factors:

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

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:

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

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