HEAVY WIMPS:
STATUS AND FUTURE PROSPECTS

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Weakly - in the sense of the EW scale

(as opposed to generic meaning of „weak”…)

Interacting - with the SM

(as opposed to secluded models…)

Massive - GeV or more

(as opposed to simply having non-zero mass…)

Particle

Heavy = ~TeV scale mass

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"

Every massive particle with not-too-weak interactions (with the SM or within dark sector) will thermalize in the early Universe, leading to a very high initial number density

→ there has to exist a mechanism to suppress such high DM population not to overclose the Universe (e.g., freeze-out, asymmetric, freeze-in, …)

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

(Bonus: interaction of this strength gives hope for detection in direct, indirect and collider searches)

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(Bonus: interaction of this strength gives hope for detection in direct, indirect and collider searches)

even if the Hierarchy Problem (naturalness) turns out to be misguided → WIMPs are related to realistic BSM physics!

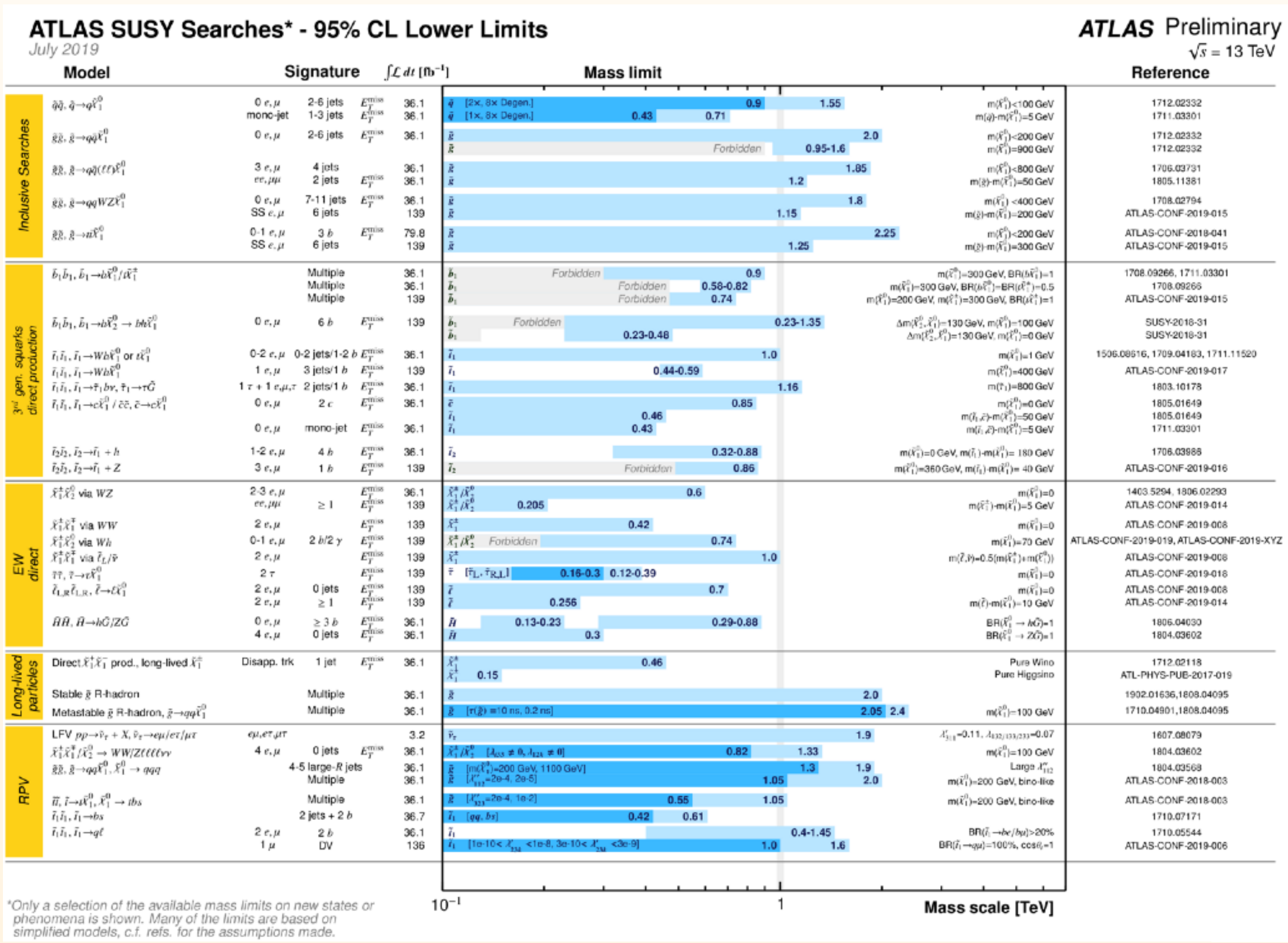
CURRENT LIMITS
AND APPARENT DECLINE OF THE WIMP PARADIGM

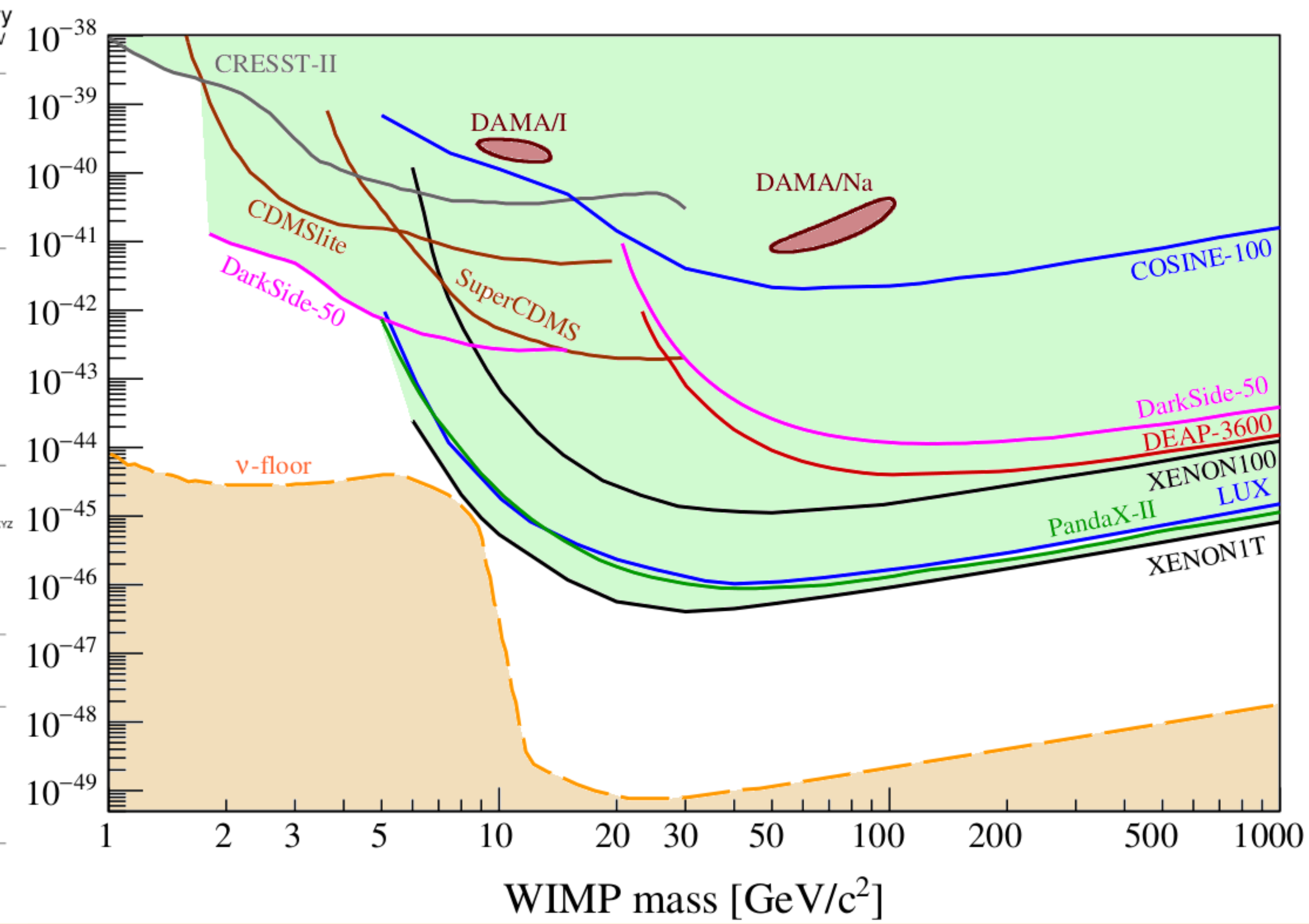
"The great tragedy of science - the slaying of a beautiful hypothesis by an ugly fact"

Aldous Huxley

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

*convincing



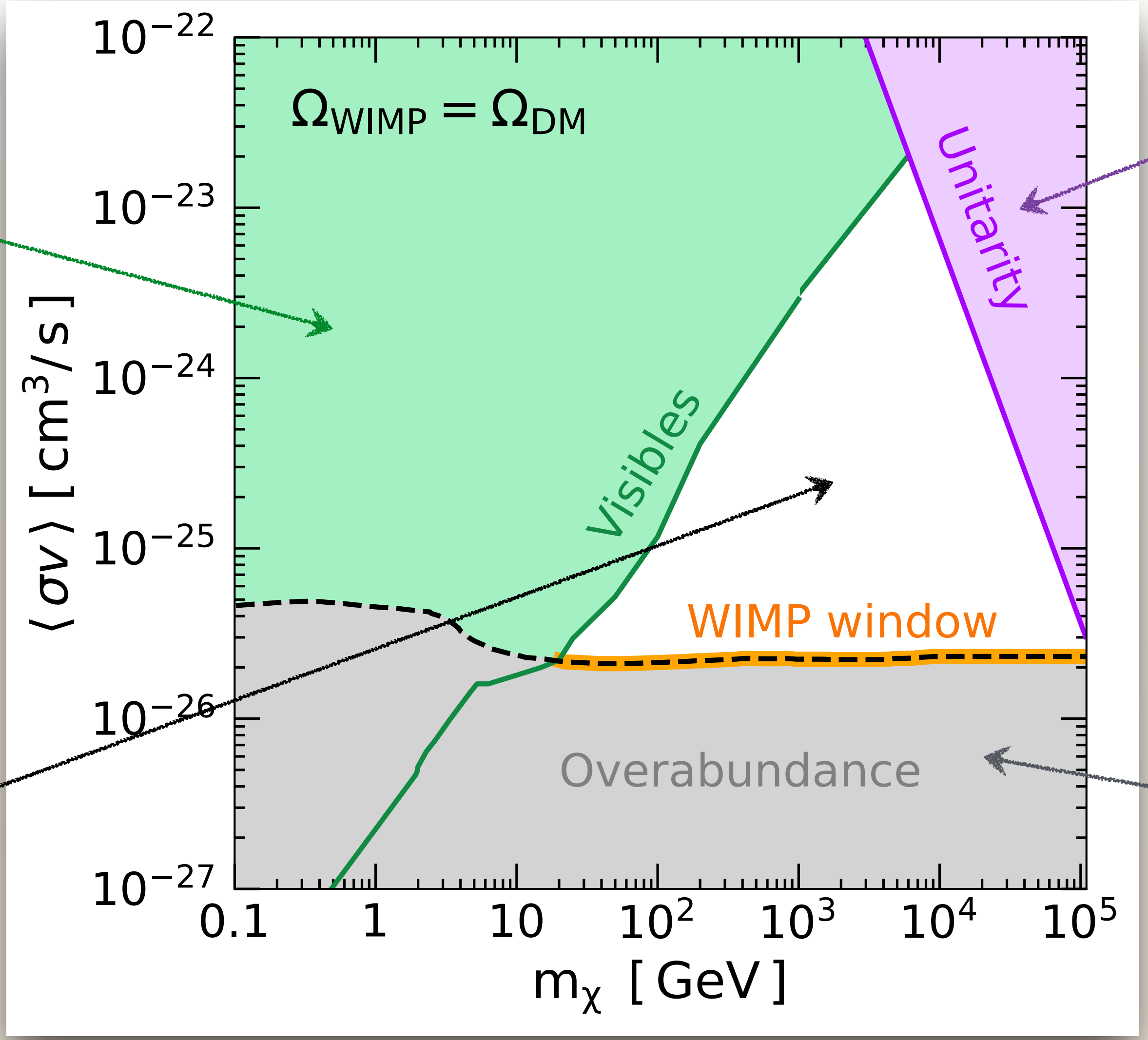


… BUT IN FACT WIMP
"NOT EVEN SLIGHTLY DEAD"

R. Leane *et al*; 1805.10303

excluded by observations

predicted probabilities can be >1



all fine!

too much dark matter

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

this can lead to a very broad-brush conclusions

Why **not** to go to TeV…

…and Why it is worth it

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

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

Why TeV scale is different?

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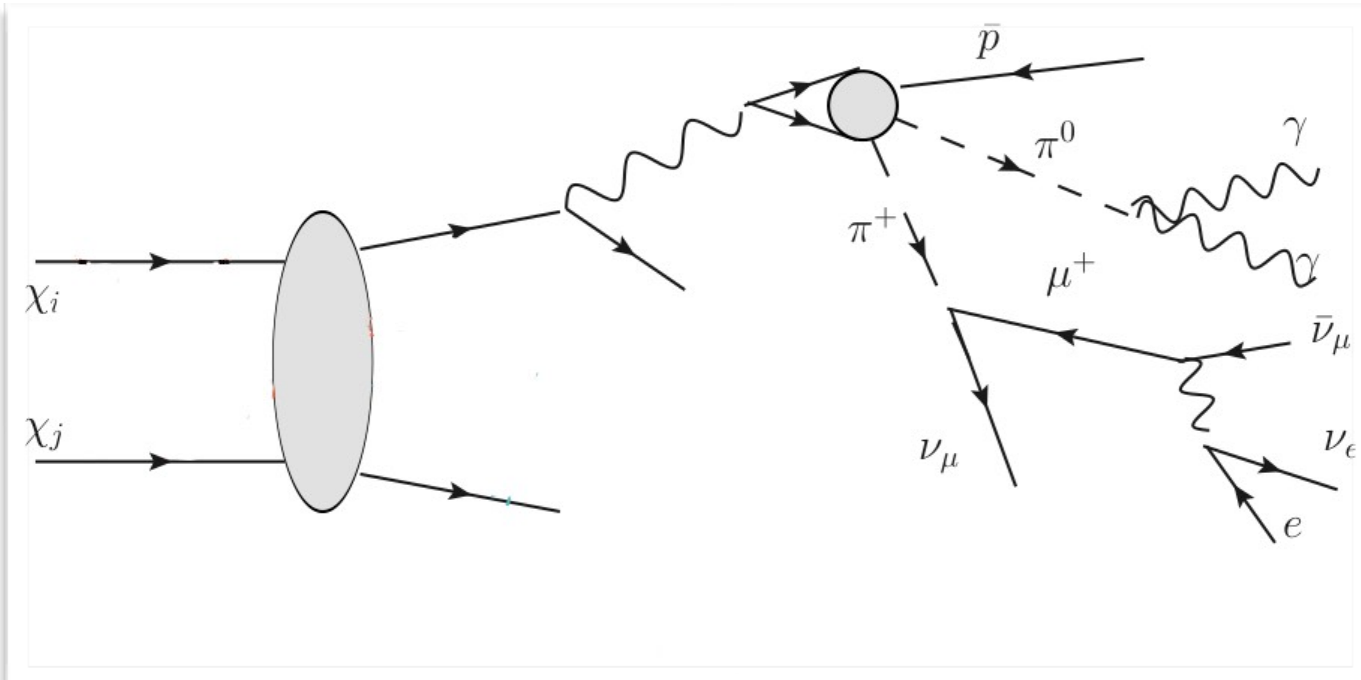
For a WIMP, however, one major difference:

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

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 RESUMMATION

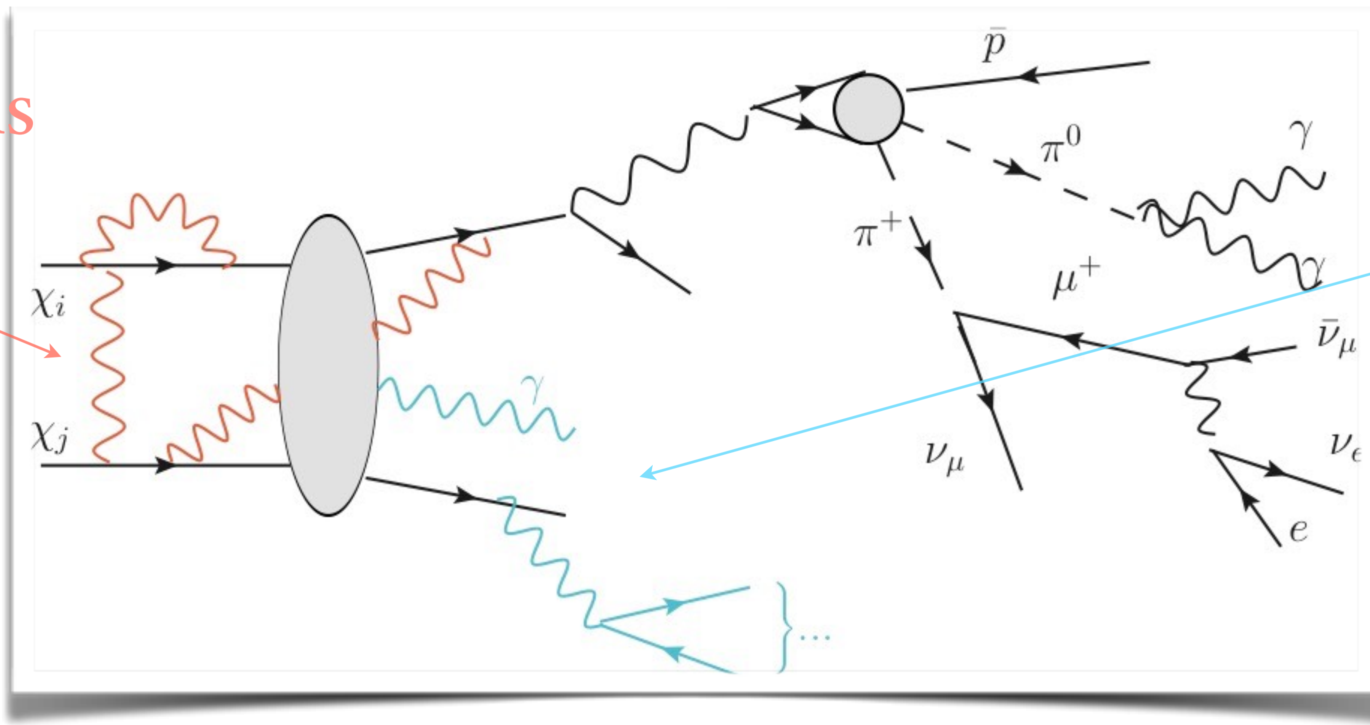
EW CORRECTIONS



EW CORRECTIONS

loop corrections

internal bremsstrahlung



enhancement by large (Sudakov) logarithms:

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

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

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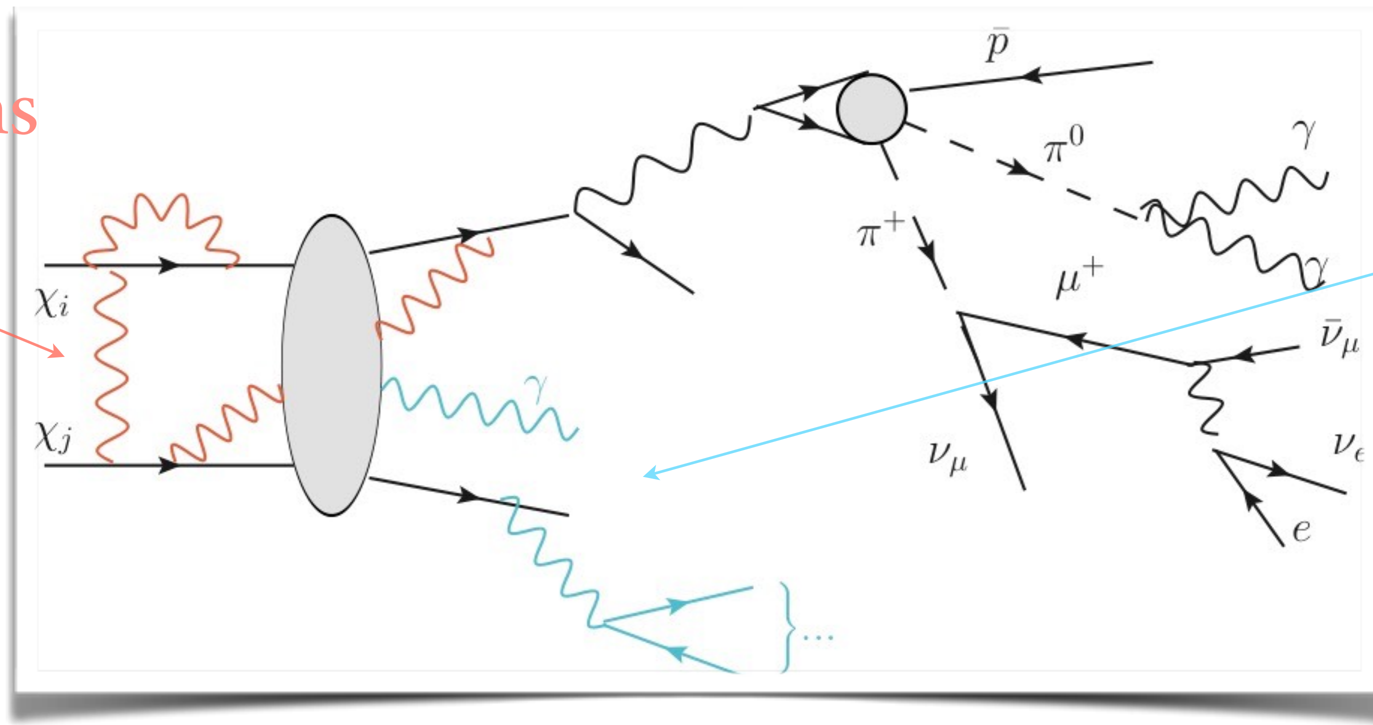

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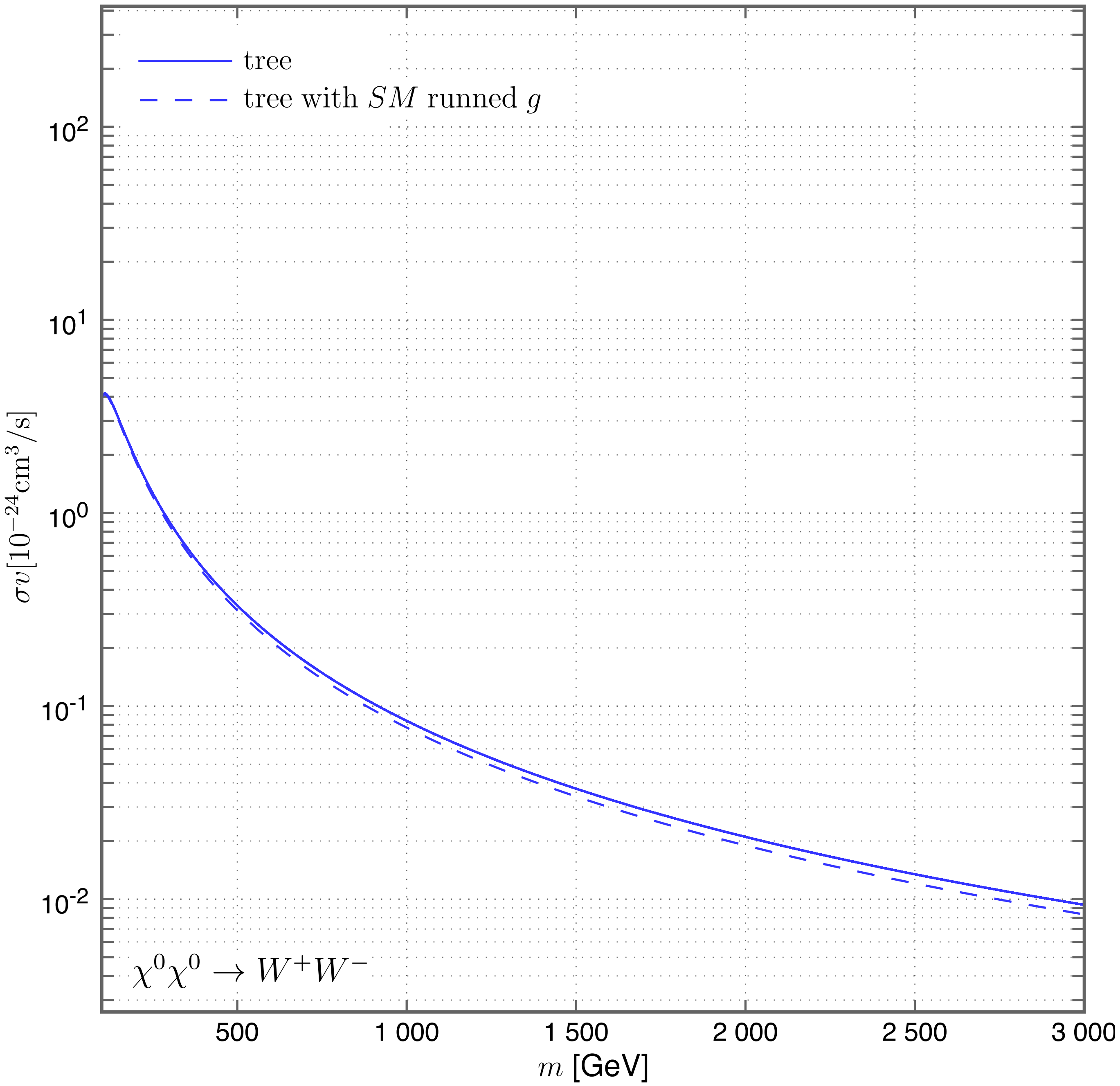
$m \gg m_W$ regime resembles IR divergence of QED or QCD

Ciafaloni *et al.* '00

The foundation of the importance of EW corrections for the ID as included e.g. in 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

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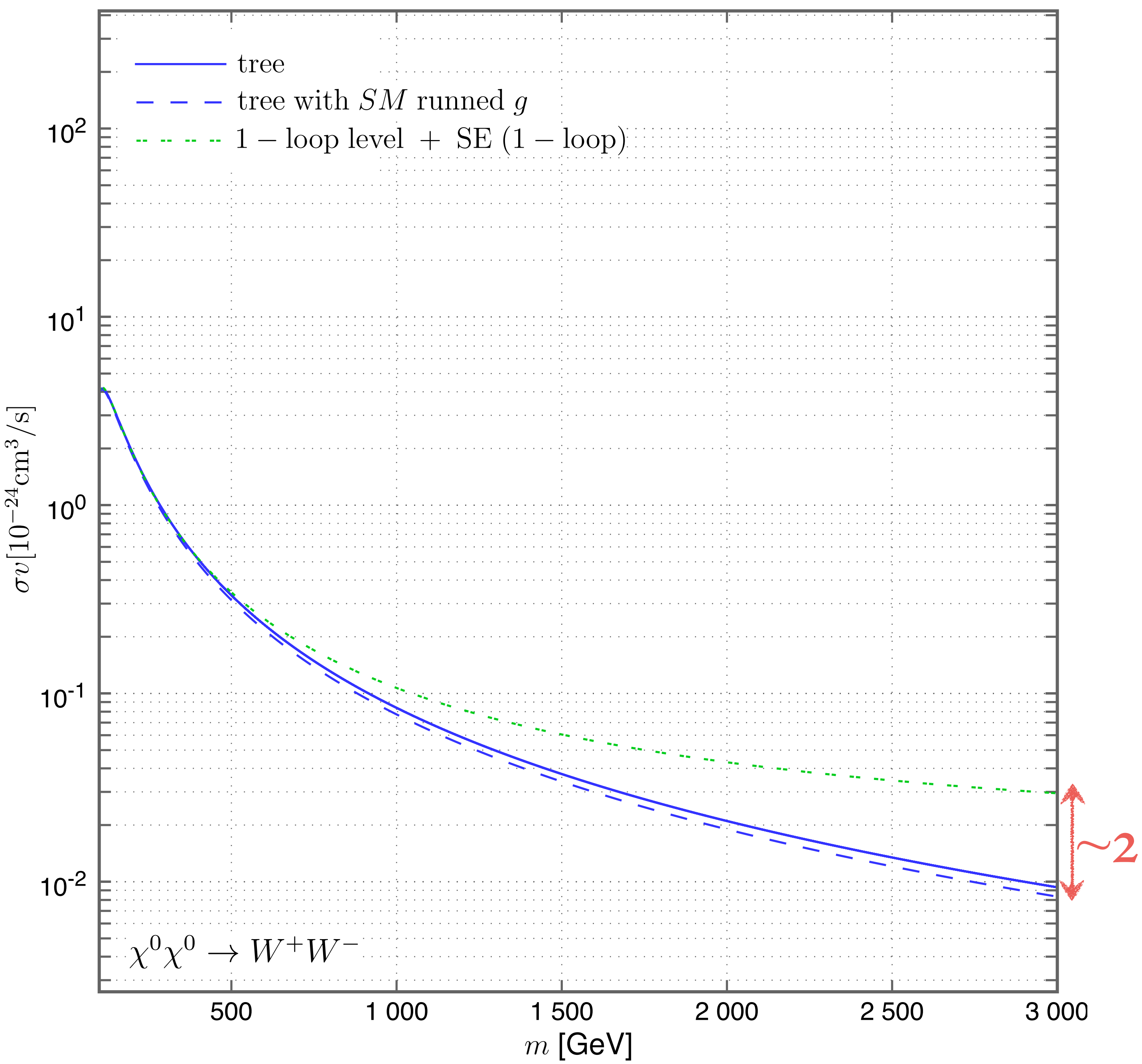

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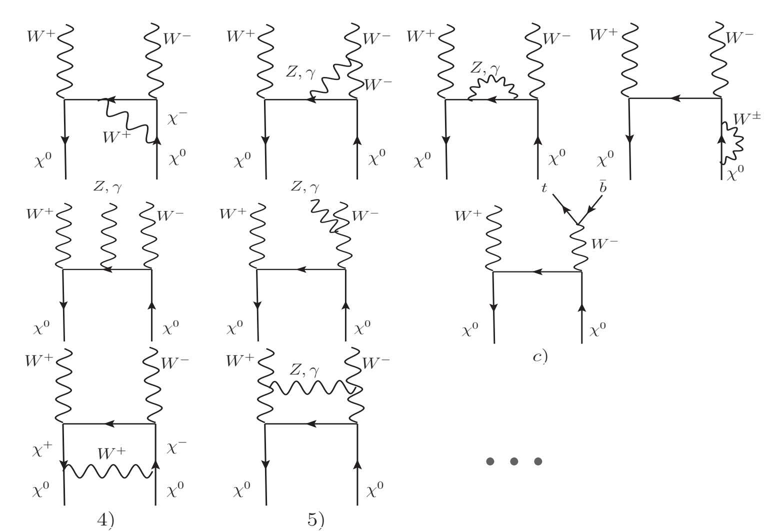

AH, R. Iengo; JHEP 1201 (2012) 163

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

LARGE EW EFFECTS

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SCET
(soft-collinear effective theory)

SCET:
an EFT based not 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

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SCET
(soft-collinear effective theory)

RG for Wilson coeff.

Sudakov corrections
@ NLL

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

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Effect of SCET resummation

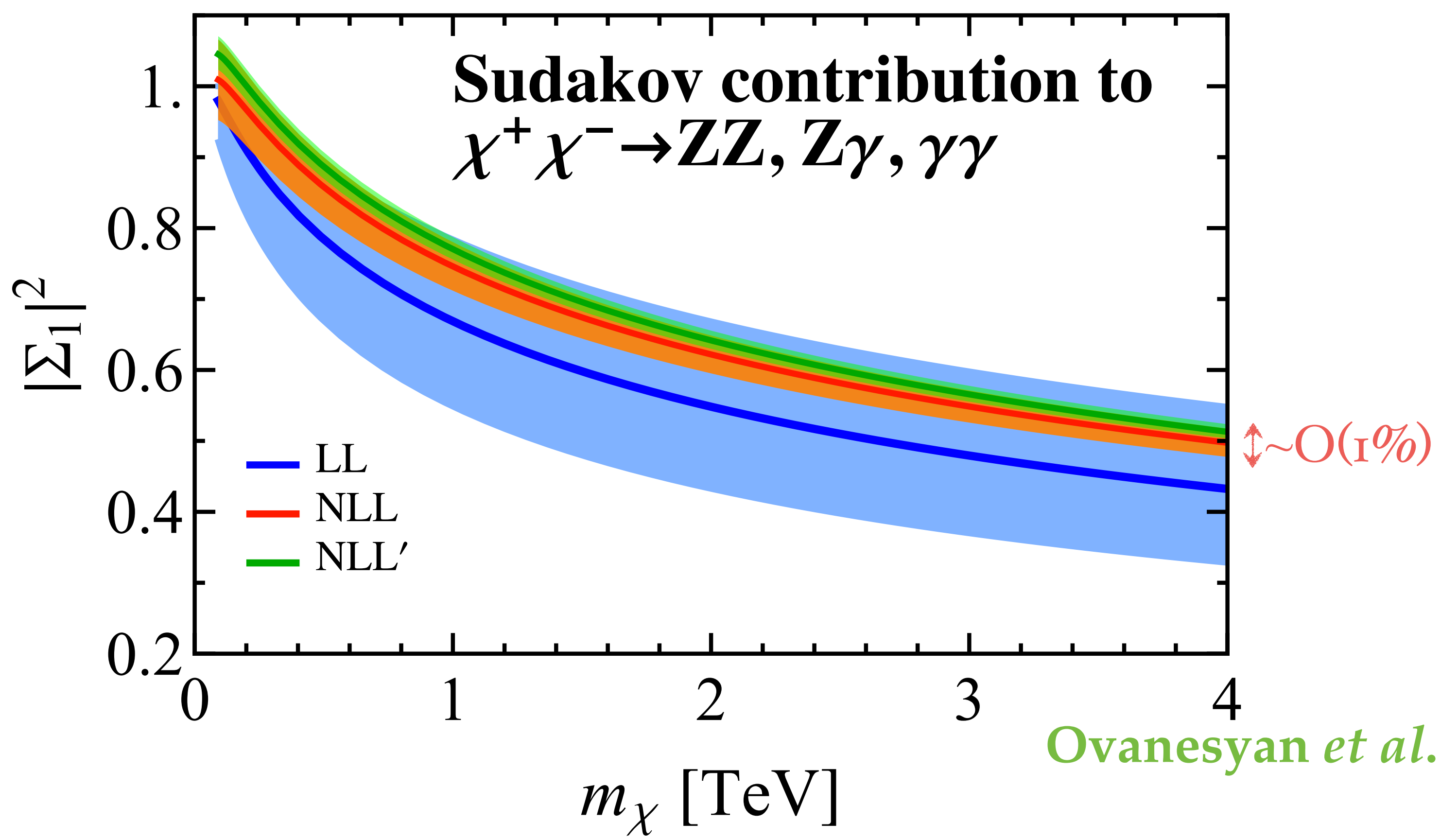
Exclusive annihilation

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

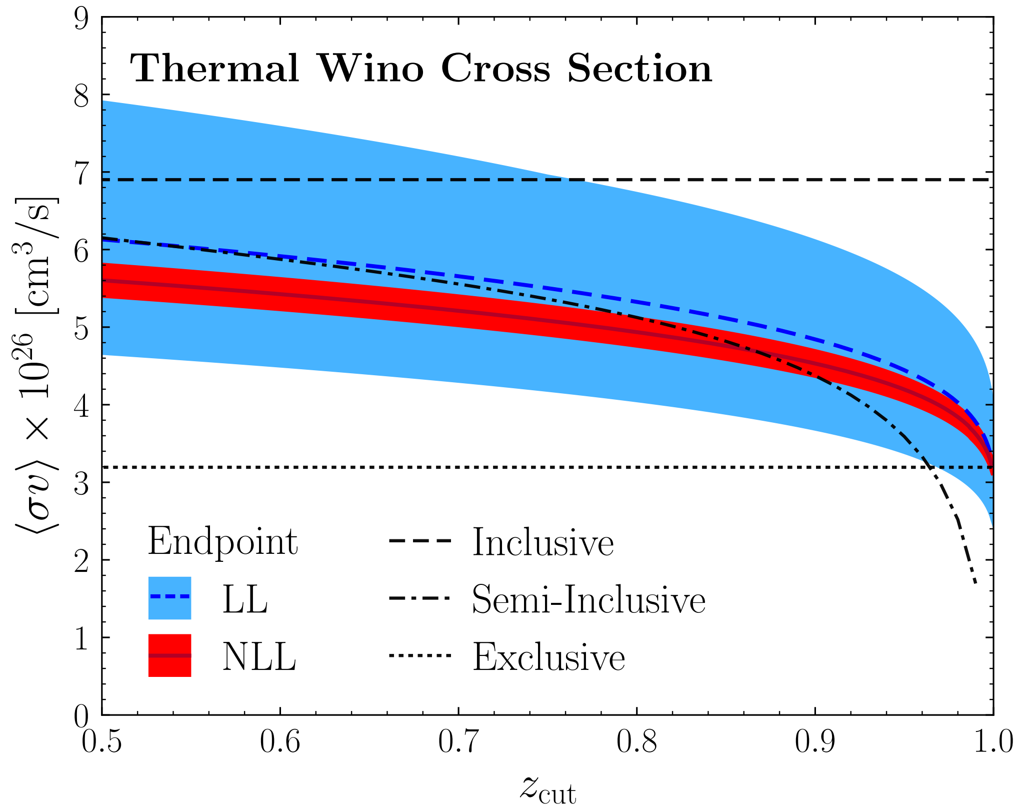
Reminder:

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

EFFECT OF SCET RESUMMATION

SEMI-INCLUSIVE ANNIHILATION

Baugmart *et al.* '18



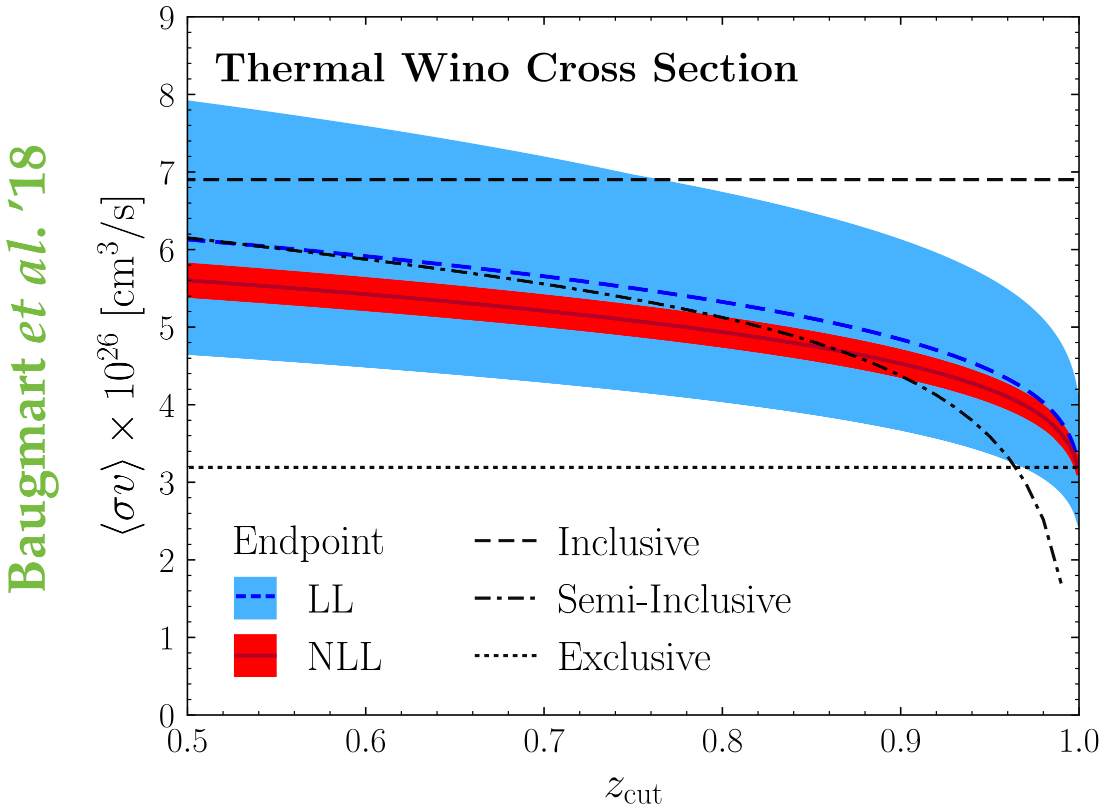
$z = E^{\gamma}_{\rm res}/m_{\chi}$

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: $E^{\gamma}_{\rm res}$

Effect of SCET resummation

Semi-inclusive annihilation



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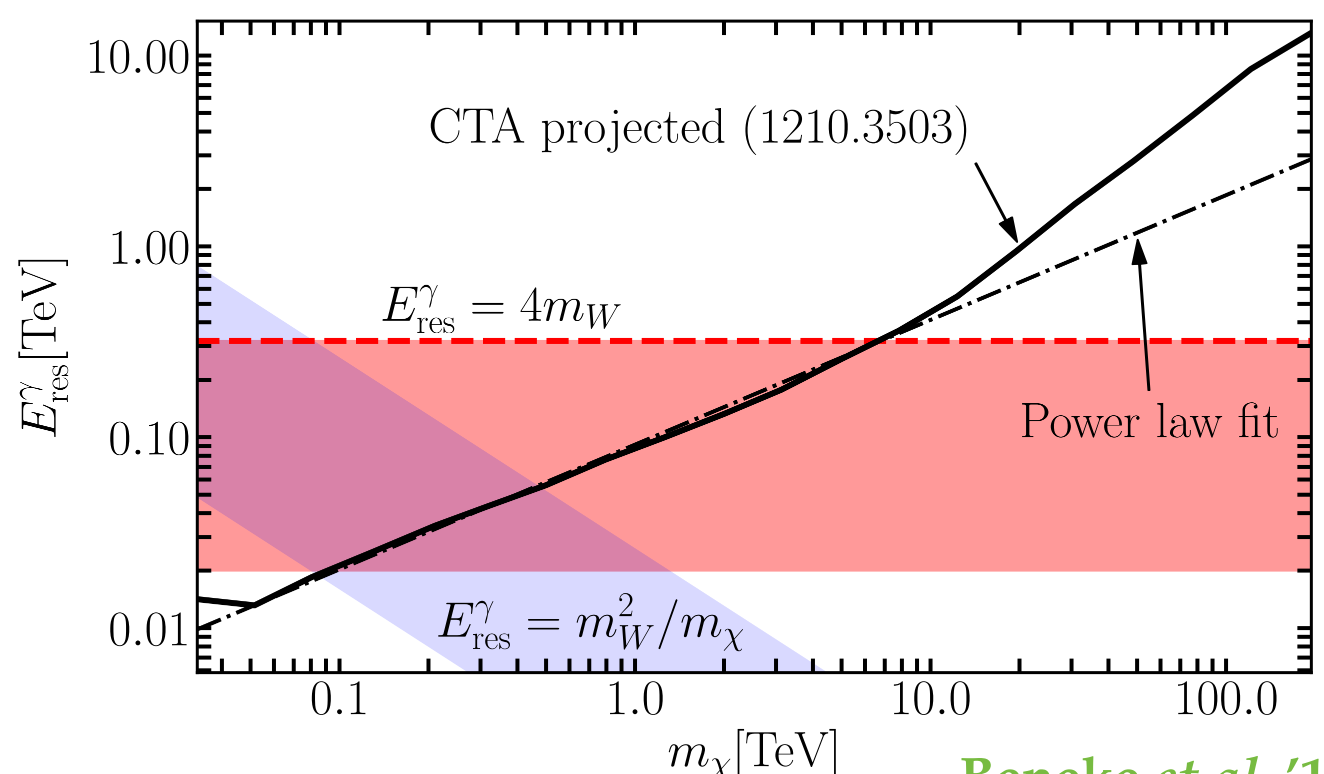
Energy resolution regimes:

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

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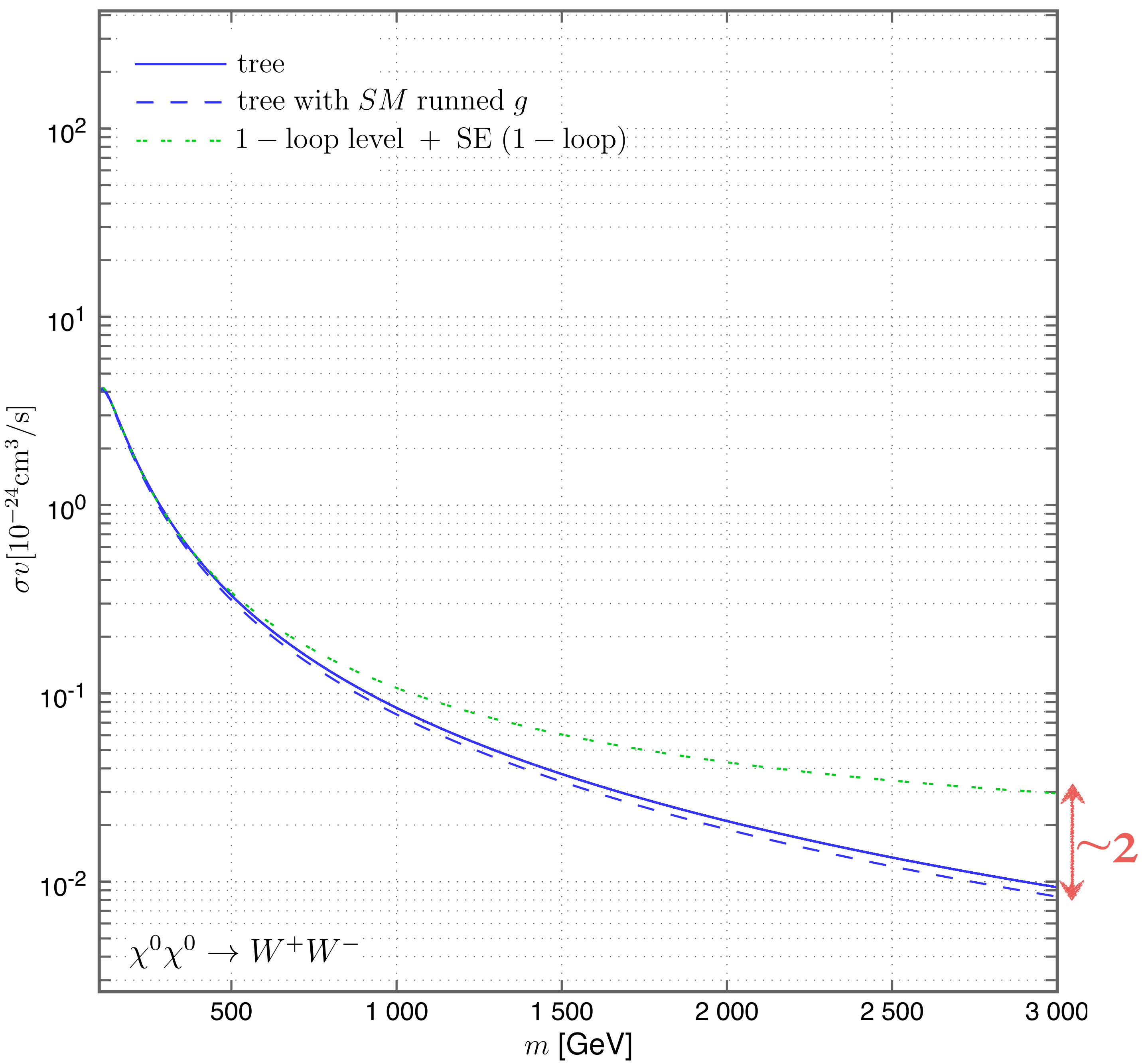
WINO DM @ 1-LOOP



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

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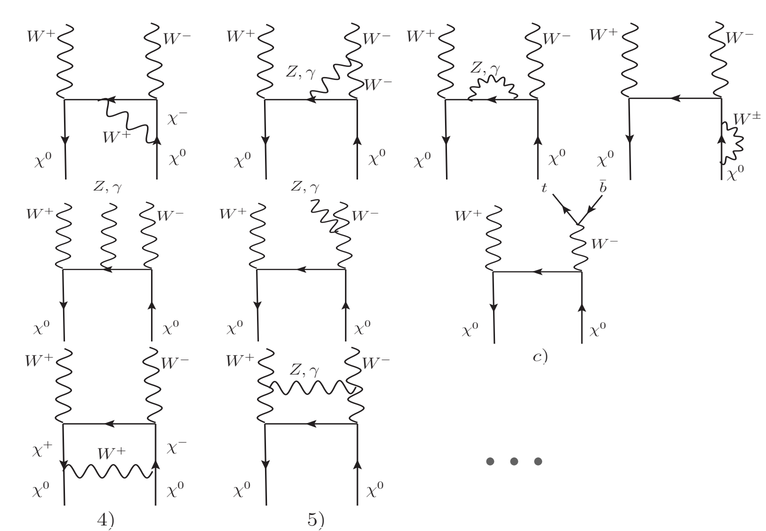

AH, R. Iengo; JHEP 1201 (2012) 163

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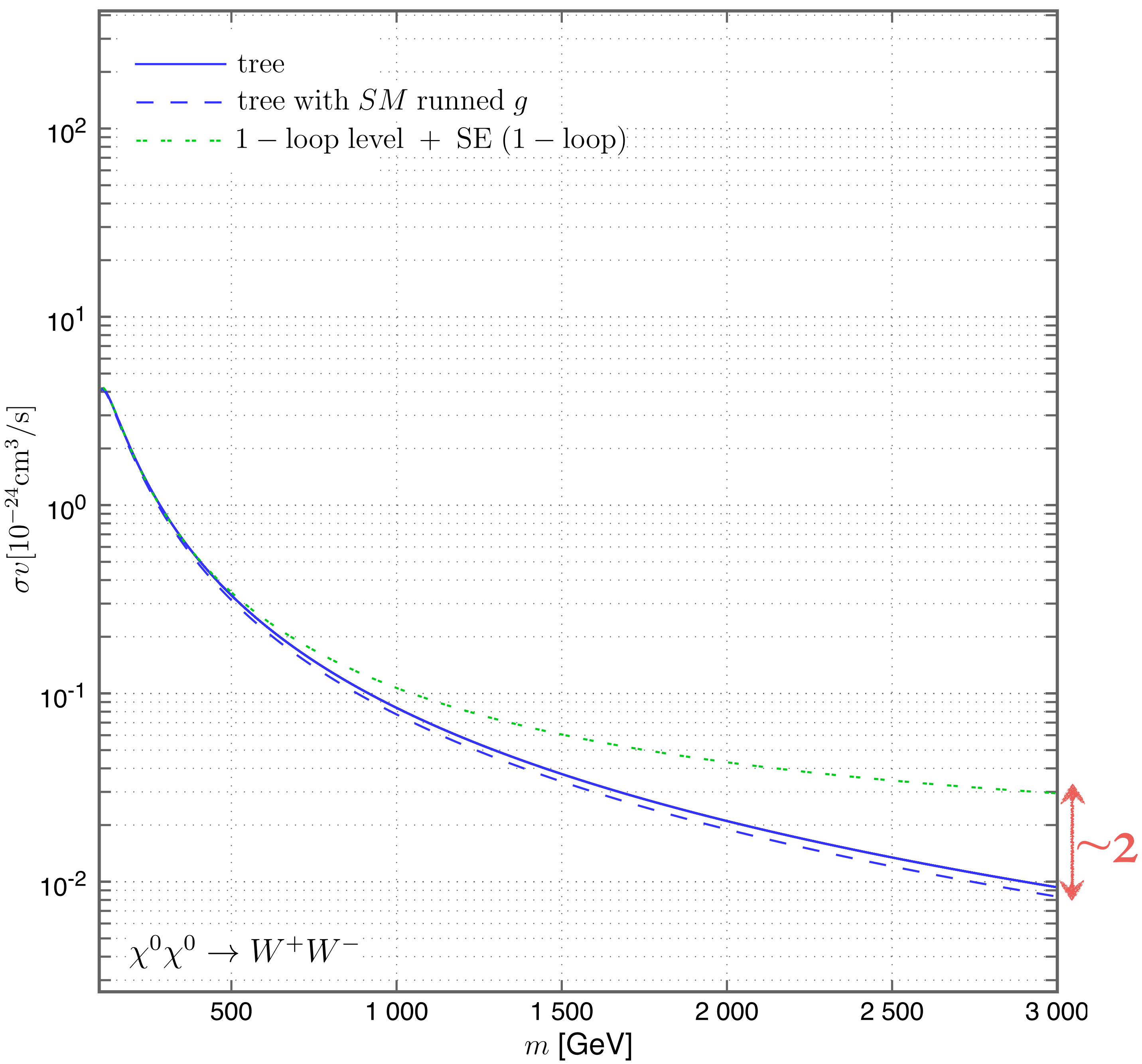

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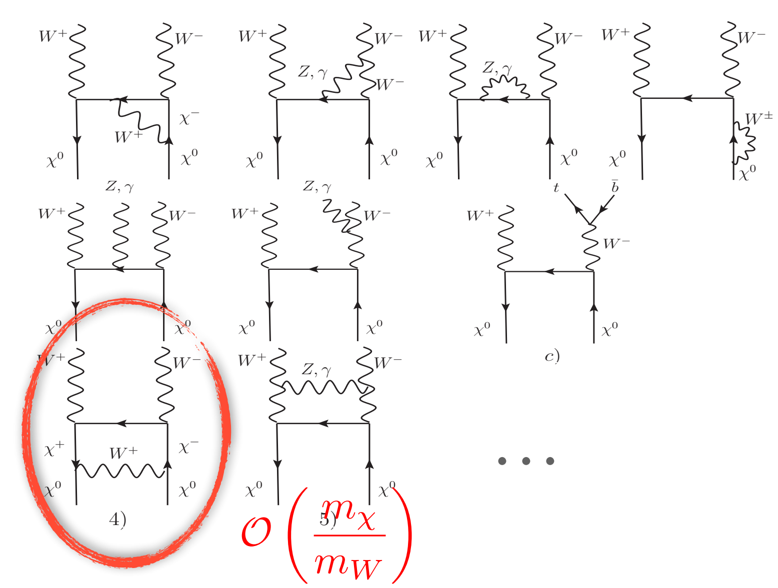
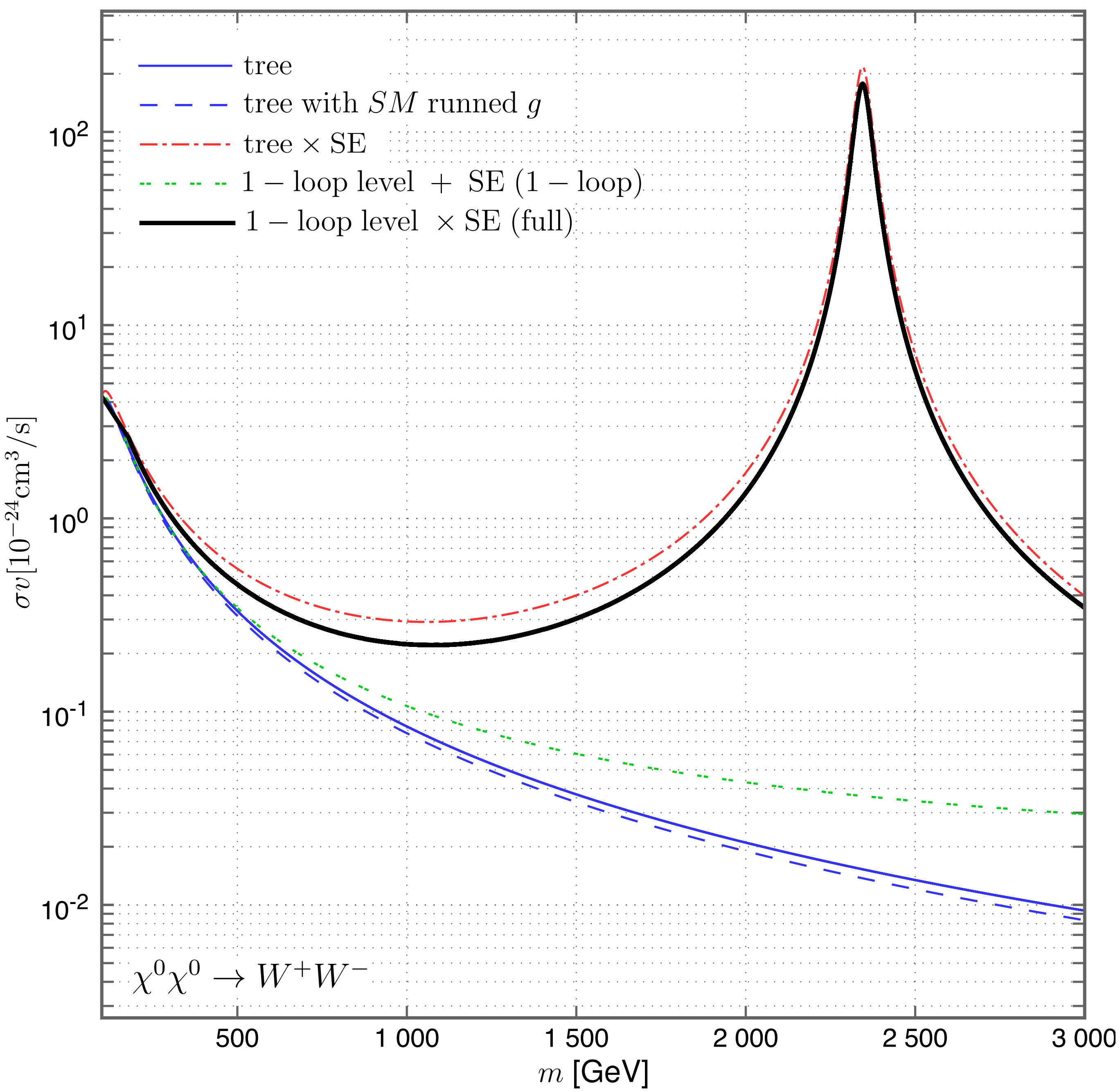


AH, R. Iengo; JHEP 1201 (2012) 163

Example:
Wino DM @ 1-loop
& Sommerfeld effect



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

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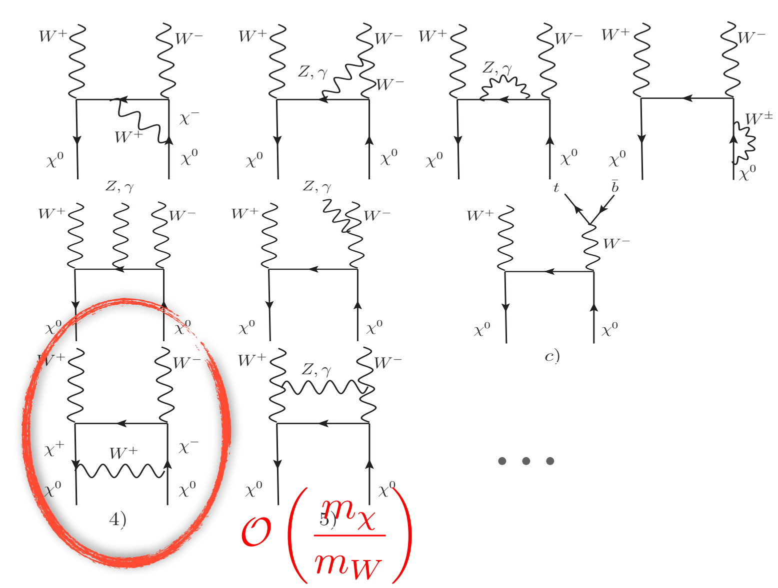
one-loop result



tree level + Sommerfeld

one-loop + Sommerfeld

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

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

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, ...

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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; …

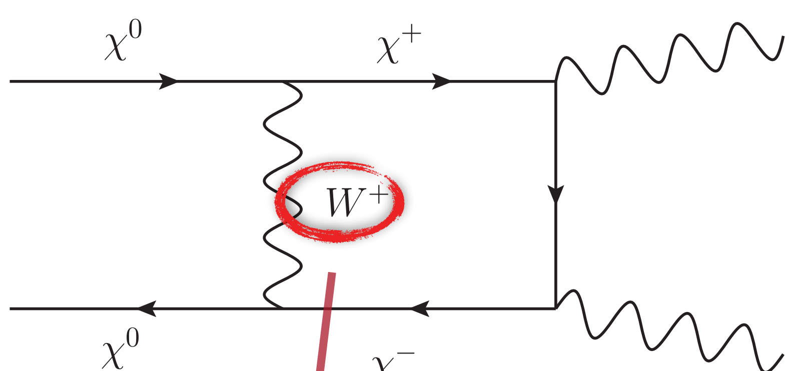
THE SOMMERFELD EFFECT
FROM EW INTERACTIONS

Hisano *et al.* '04,'06

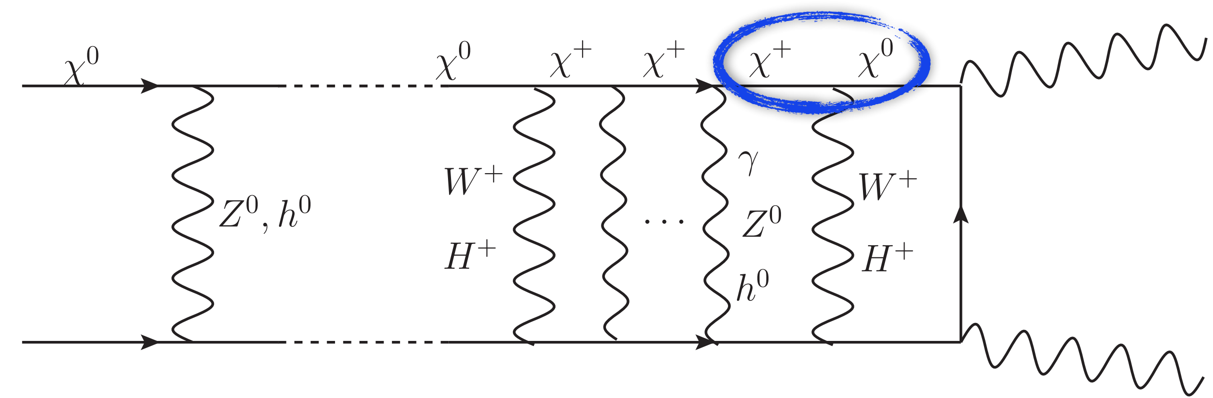
force carriers in the MSSM:

$\cancel{\gamma}$, $W^{\pm}$, 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

$\rightarrow$ effect of $\mathcal{O}(\text{few})$

for the relic density

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

AH '11

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

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

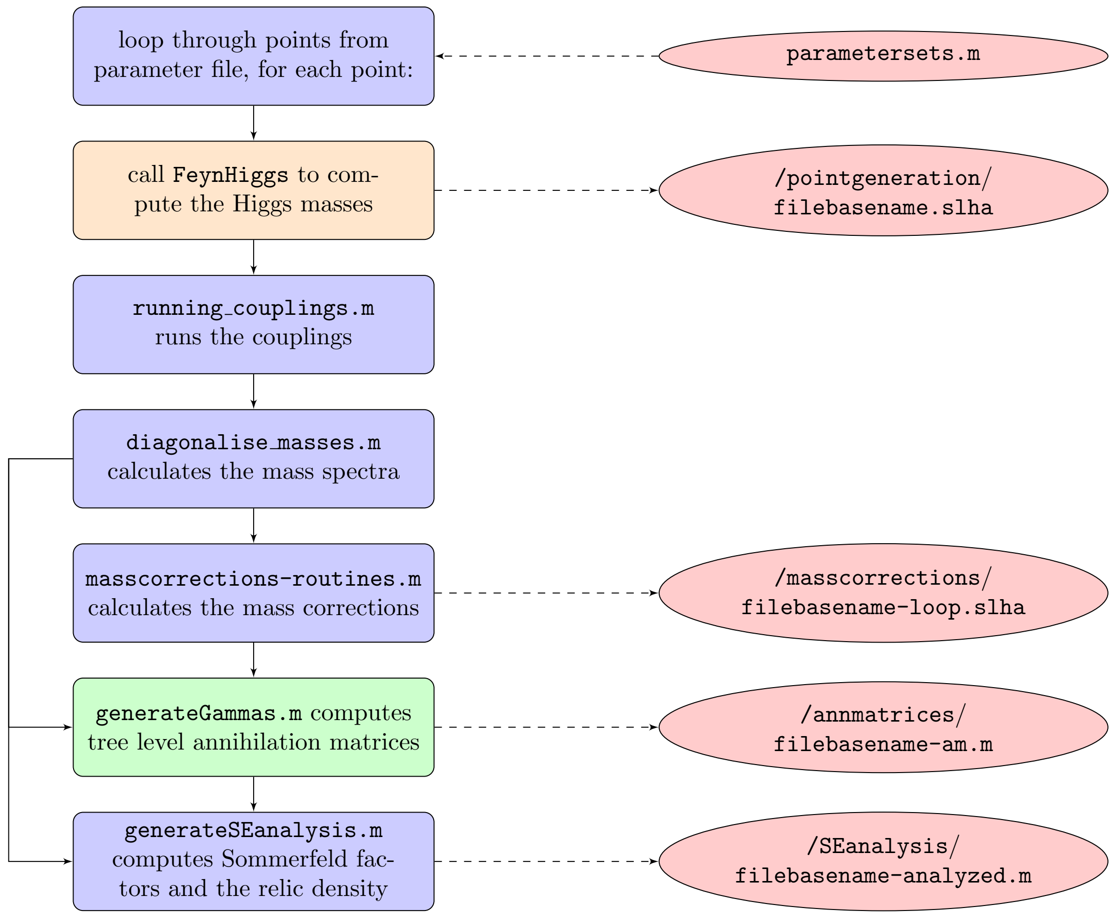
NEW NUMERICAL TOOL

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

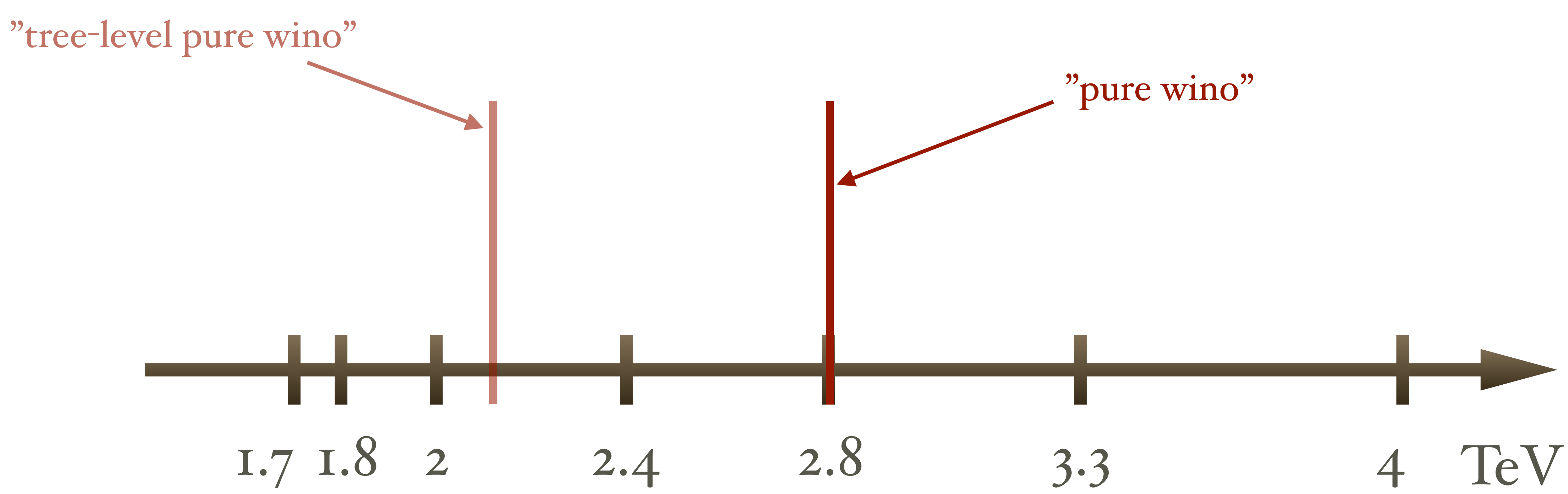
Beneke,..., AH,... *et al.* in preparation

EXAMPLE:
WINO-LIKE 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:



Beneke, …AH, … *et al.*, '16

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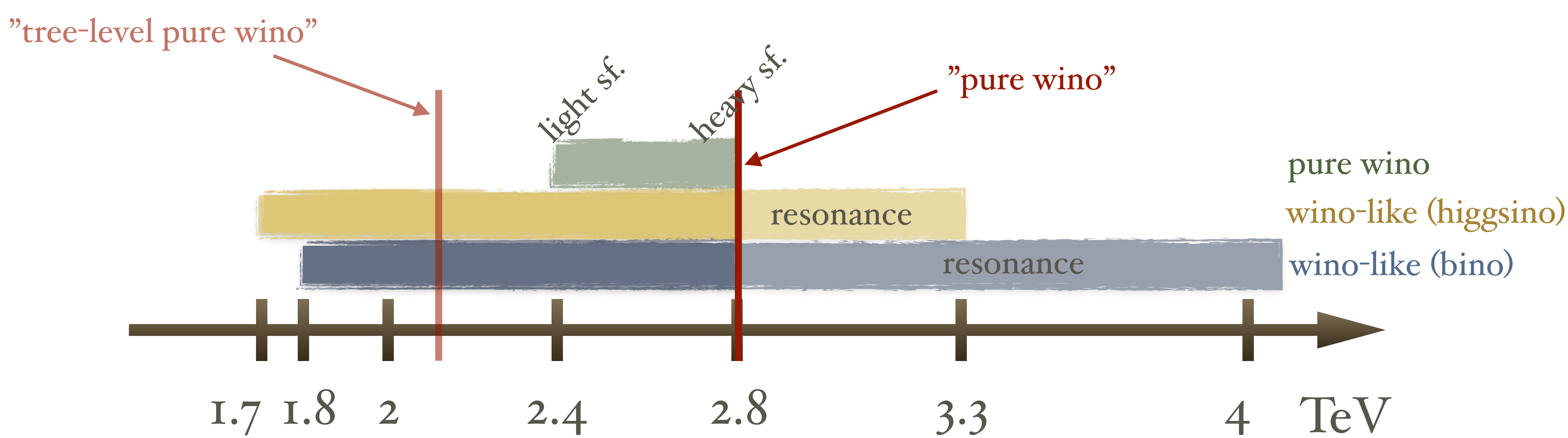


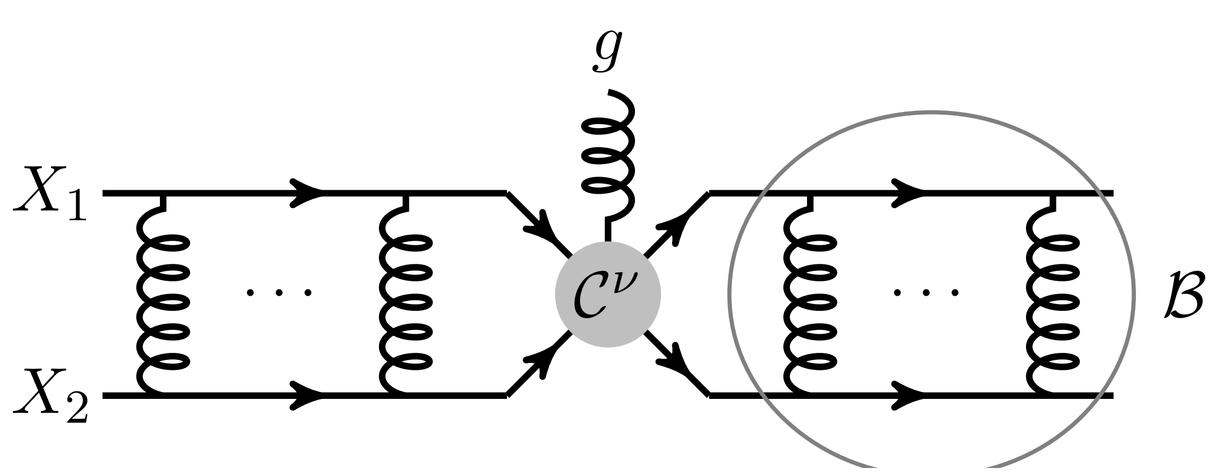
Bound State Formation

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

EXAMPLE:
IMPACT ON THE UNITARITY BOUND

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

$\Longrightarrow$ 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:

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

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.

$\Swarrow$

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, …)

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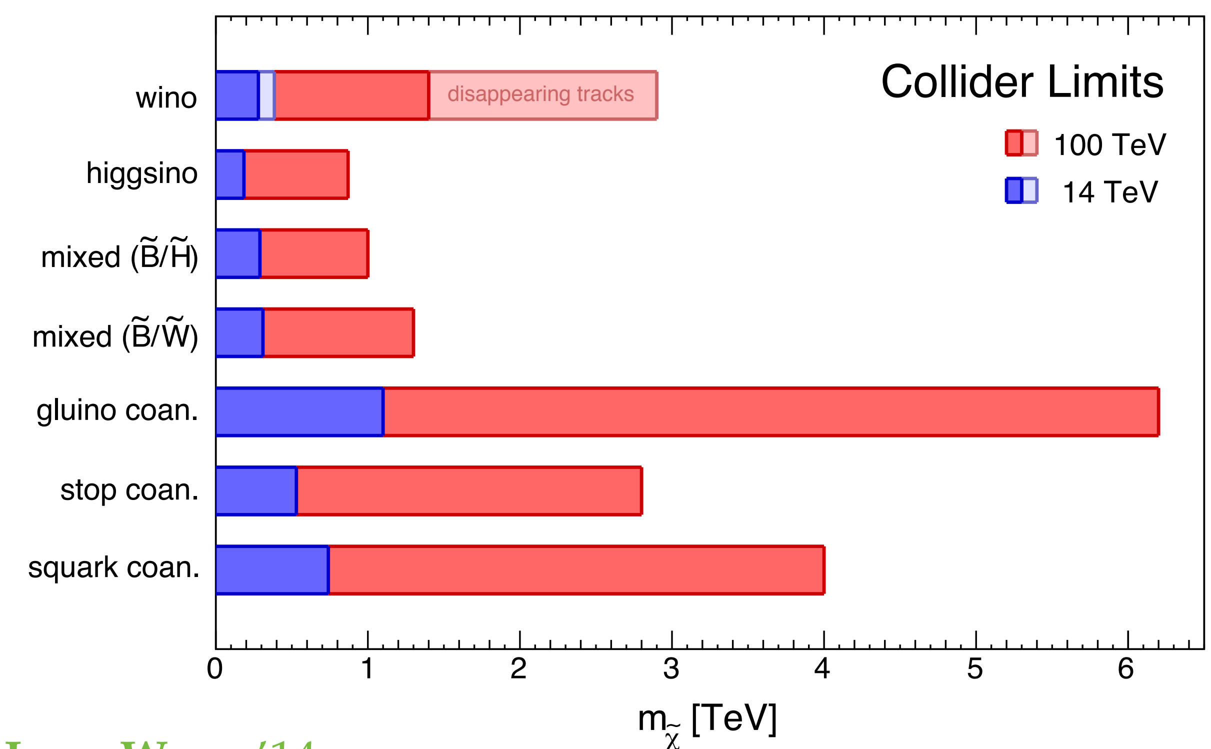
COLLIDER & DIRECT DETECTION

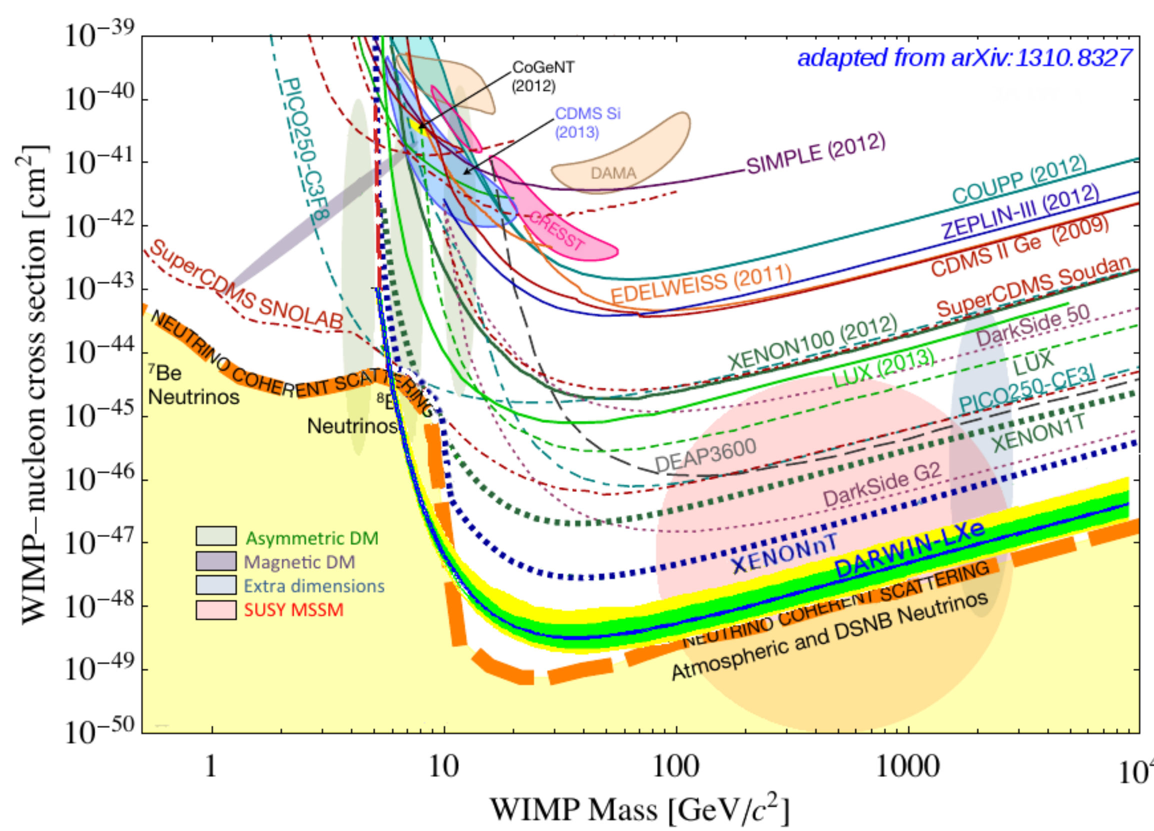


Low, Wang '14

Mixed hopes for TeV regime…
even at 100 TeV collider

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

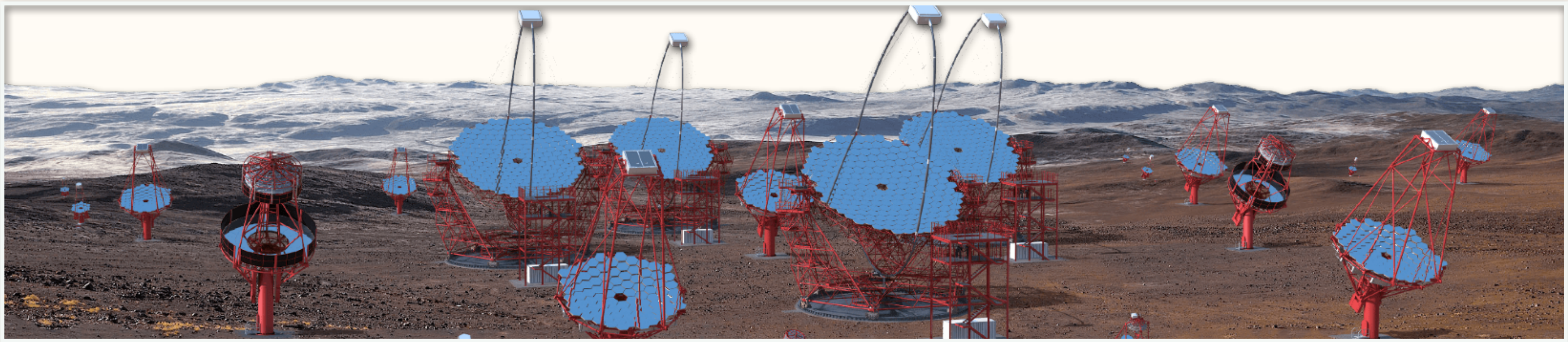
In Direct Detection expected event rate drops for TeV masses (lower number density) and many models give predictions below neutrino floor



Gamma Rays

Considering new data and the theory improvements above,
it was about time for an update of the prospects for heavy neutralinos detection

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



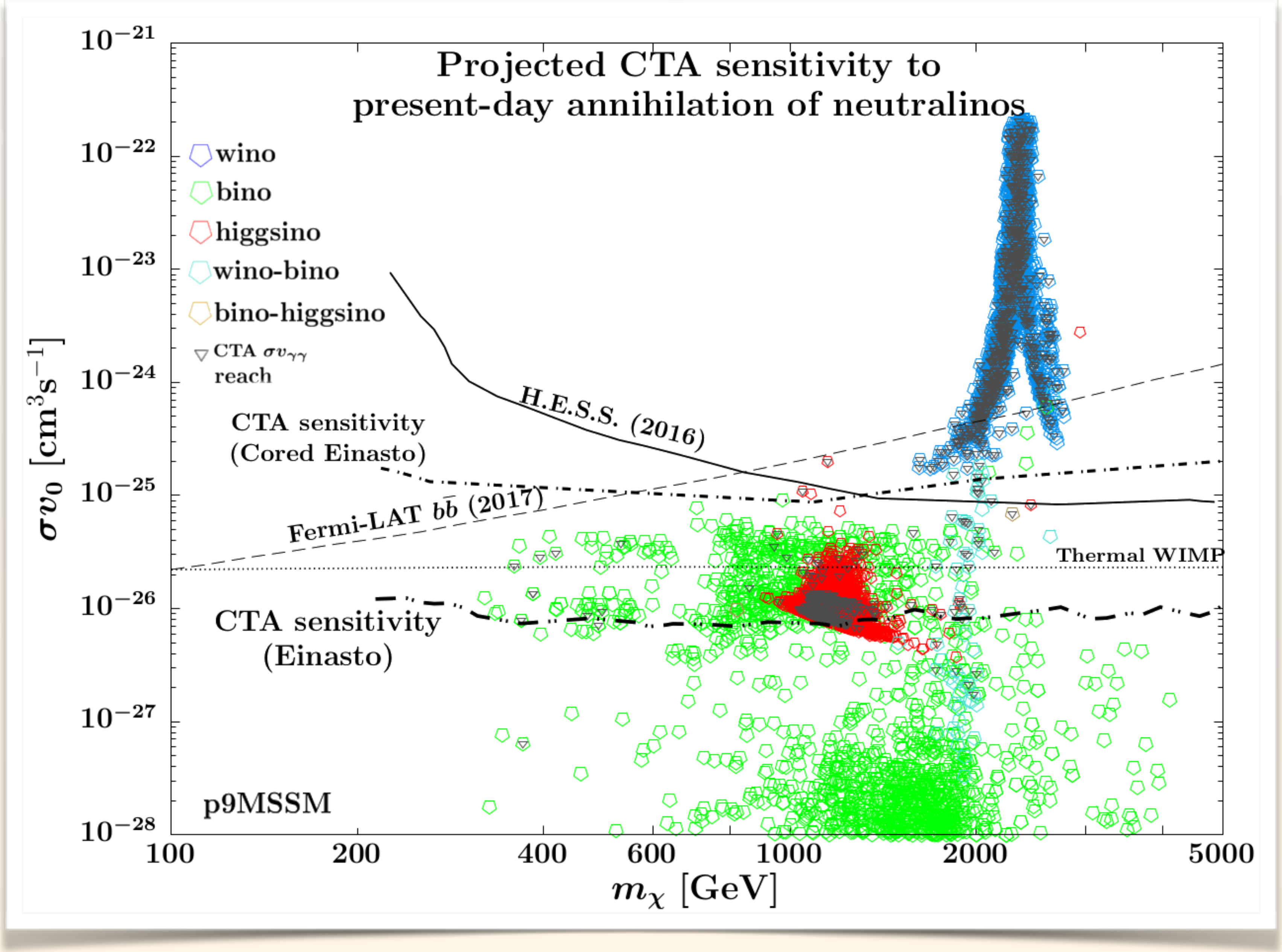
Analysis facts:

- general 9-param. phenomenological (p9MSSM) scan
- new data from DD, collider, Higgs and flavor physics
- CTA Southern array sensitivity using:
  - latest instrument response functions
  - dedicated 3D log likelihood ratio test statistics
- ROI extends up to $\pm 5^\circ$ from the GC both in longitude and latitude, 500h exposure, E_{th}=30 GeV
- DM profiles: *Einasto, NFW* and *Cored Einasto* (r_{core} = 3 kpc)

p9MSSM scan parameters:

Parameter	Range
bino mass	$-10 < M_1 < 10$
wino mass	$0.1 < M_2 < 10$
gluino mass	$M_3 = 20$
trilinear couplings	$-30 < A_t = A_b = A_\tau < 30$
pseudoscalar mass	$0.1 < m_A < 10$
μ parameter	$-10 < \mu < 10$
3rd gen. left soft squark mass	$0.1 < m_{\tilde{Q}_3} < 30$
3rd gen. right up soft squark mass	$0.1 < m_{\tilde{t}_R} < 30$
3rd gen. right down soft squark mass	$m_{\tilde{b}_R} = 20$
1st/2nd gen. soft squark masses	$m_{\tilde{Q}_{1,2}} = m_{\tilde{d}_R,\tilde{s}_R} = 20$
soft slepton masses	$0.1 < m_{\tilde{\tau}_R} = m_{\tilde{L}_3} < 10$
soft slepton masses	$m_{\tilde{e}_R,\tilde{\mu}_R} = m_{\tilde{L}_{1,2}} = 20$
ratio of Higgs doublet VEVs	$1 < \tan\beta < 62$
Nuisance parameter	Central value, error
Top pole mass m_t (GeV)	(173.34, 0.76) [49]

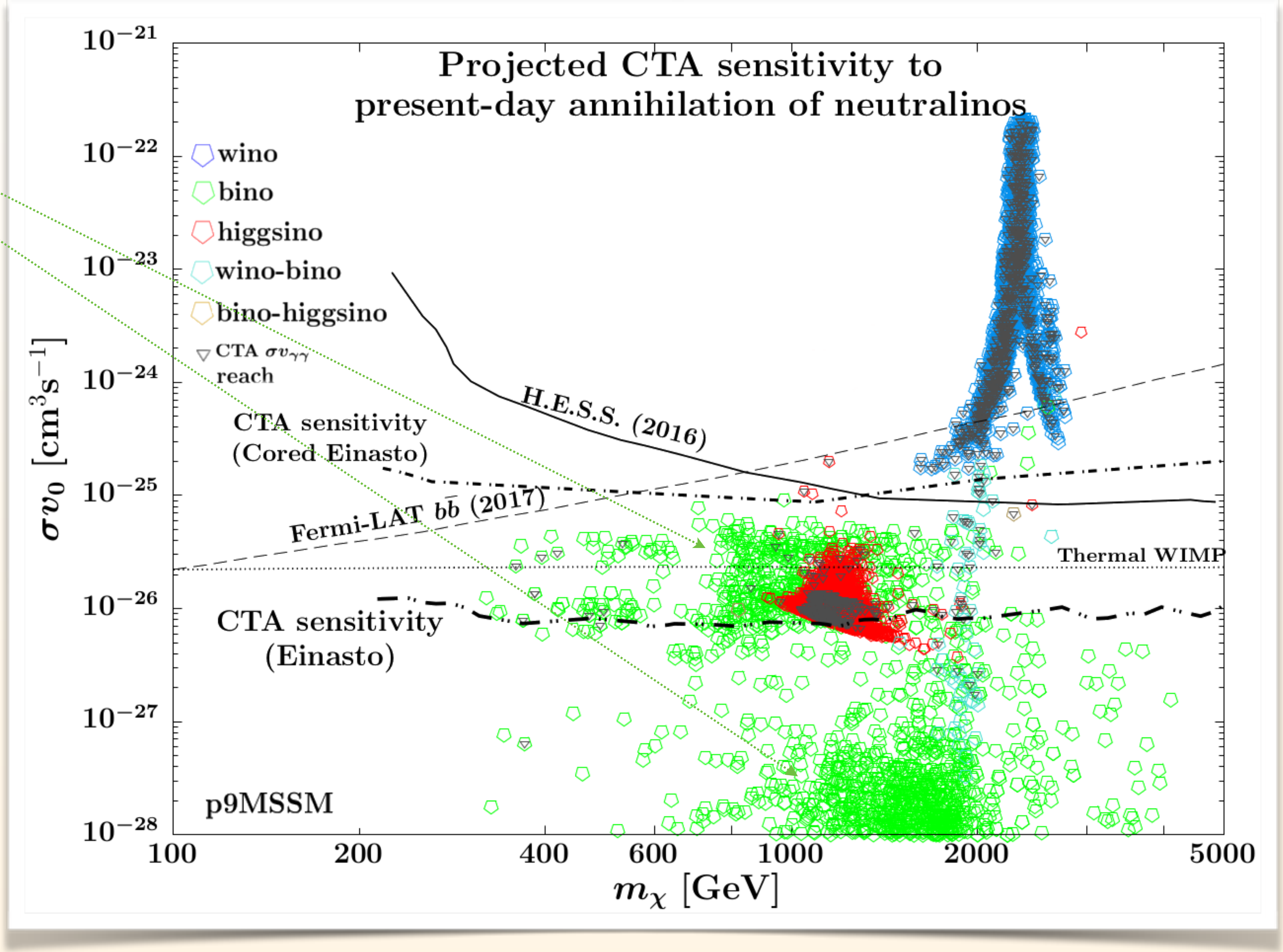
SCAN RESULTS



SCAN RESULTS

Bino

Require additional mechanism (e.g. funnel or co-annihilation)

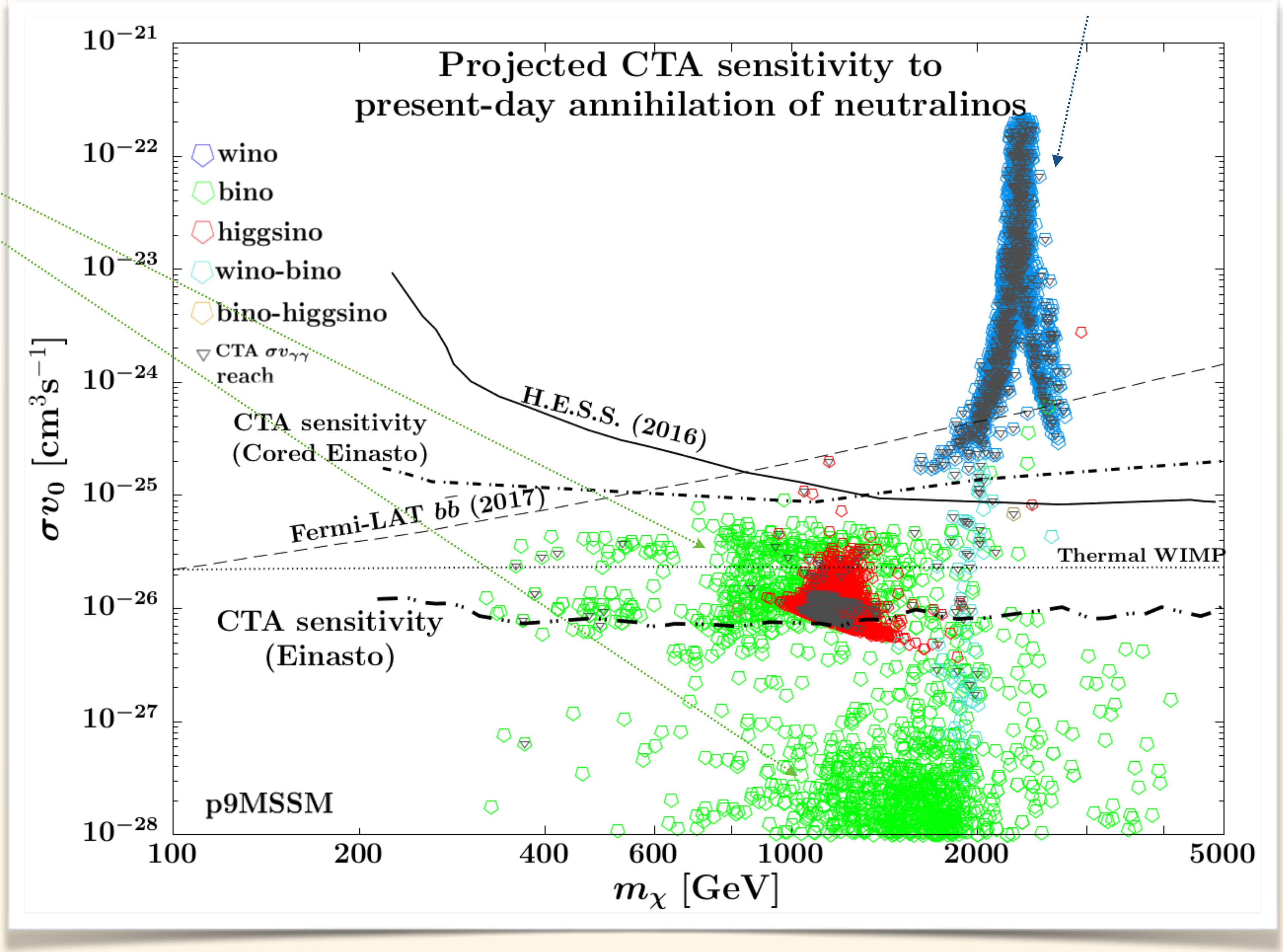


SCAN RESULTS

Wino - excluded*

*unless very cored DM profile

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



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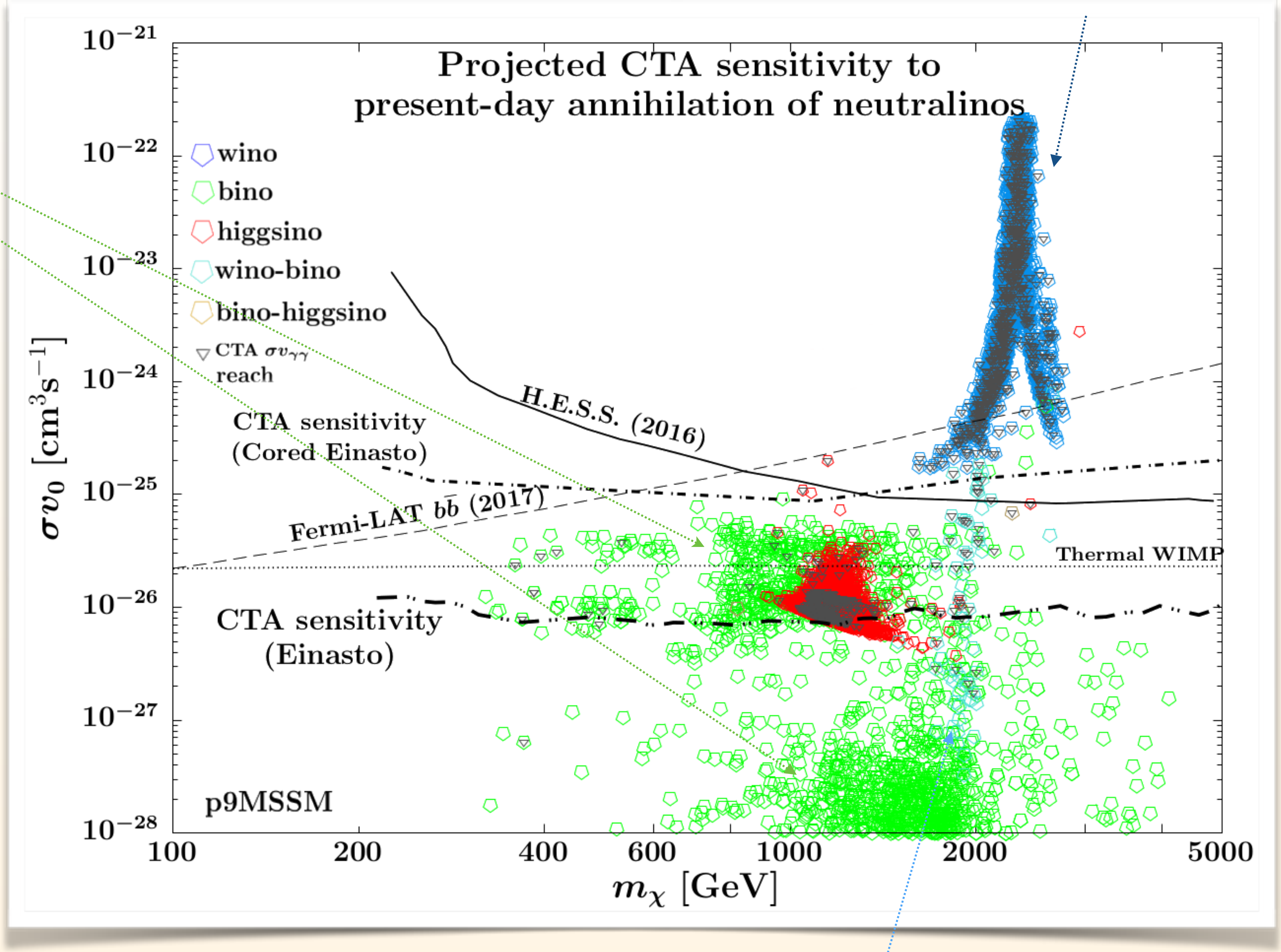


Bino-wino

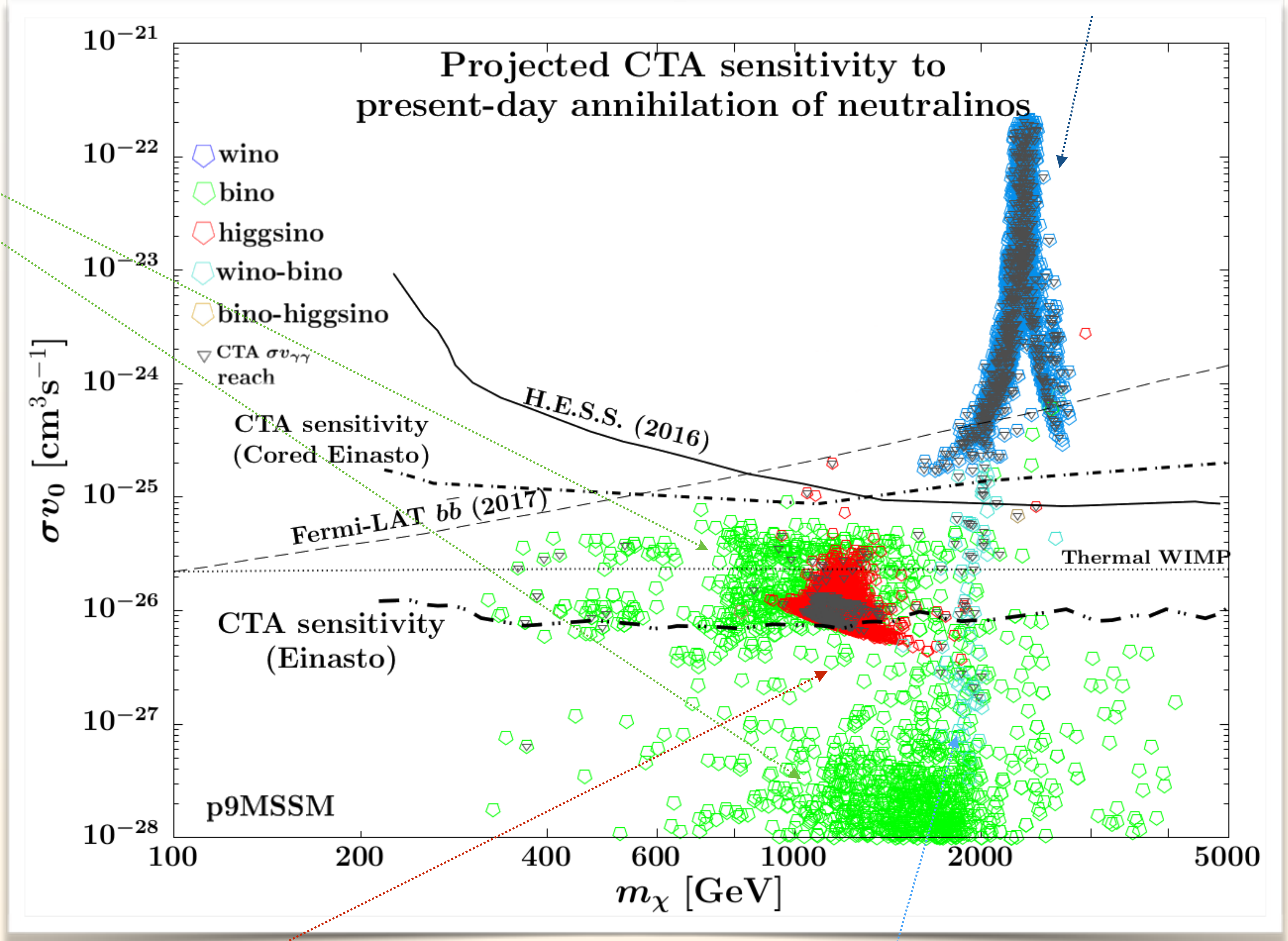
In reach of monochromatic line search

SCAN RESULTS

Wino - excluded*

*unless very cored DM profile

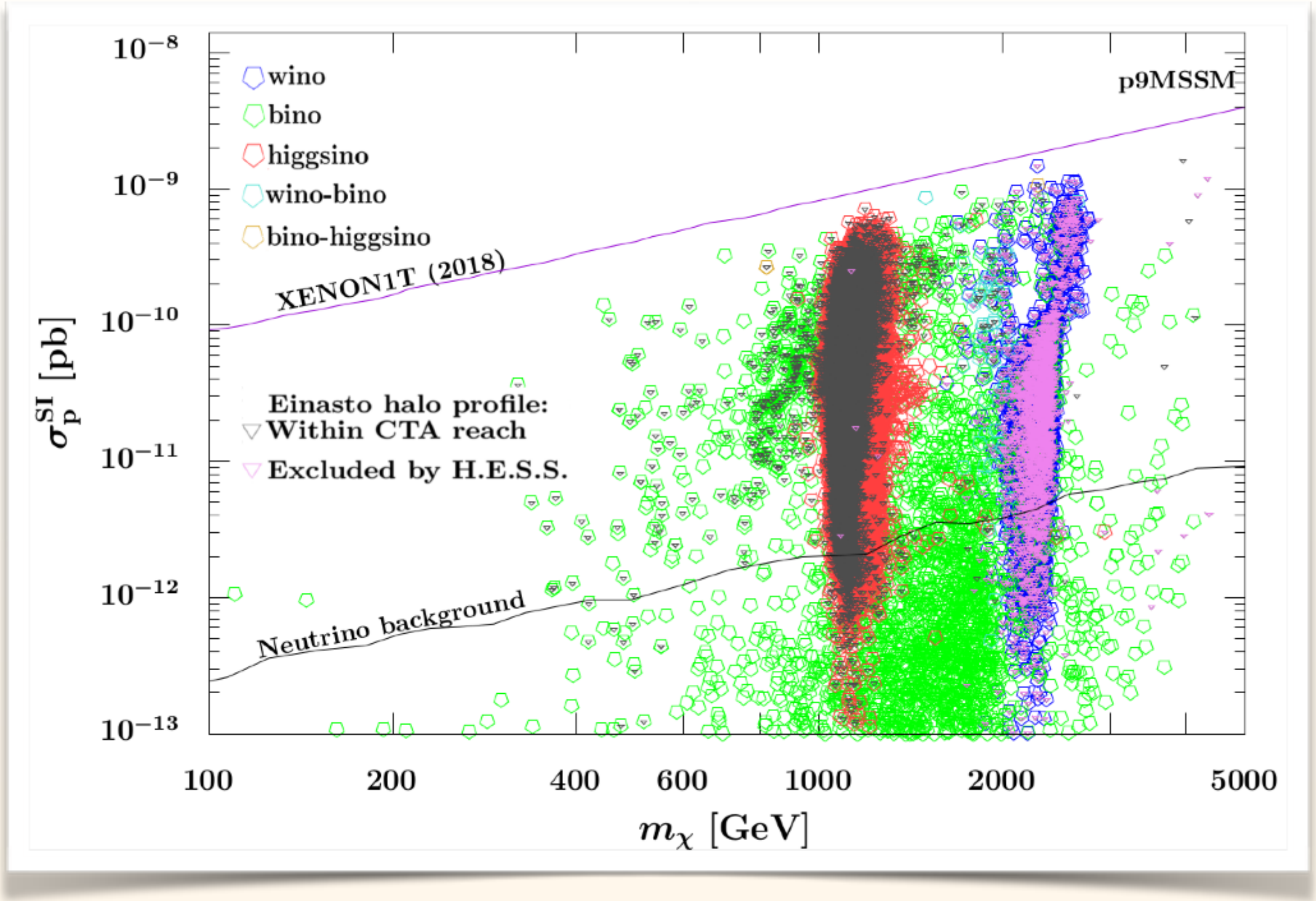
Bino
Require additional mechanism (e.g. funnel or co-annihilation)



Higgsino
~ 1 TeV region
most promising candidate in MSSM

Bino-wino
In reach of monochromatic line search

Complementarity with DD

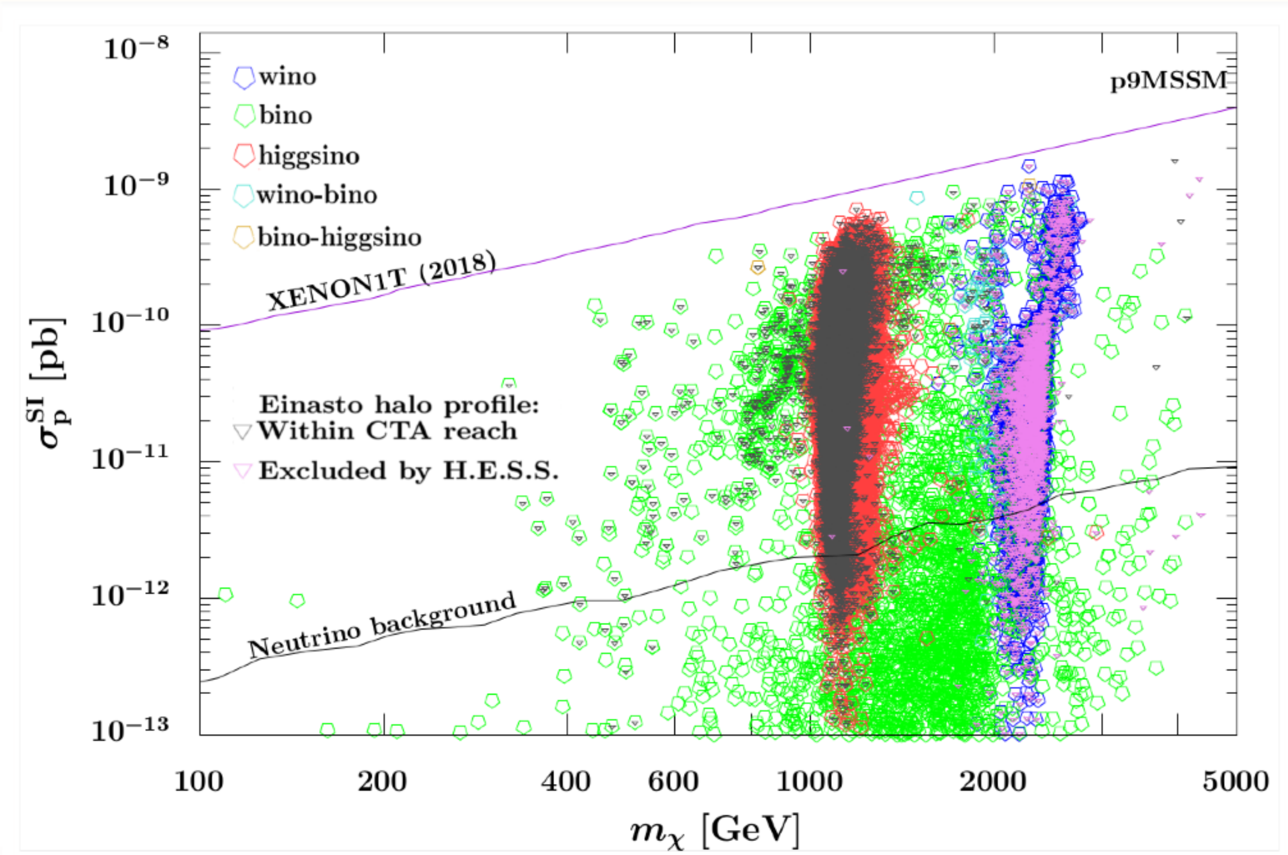


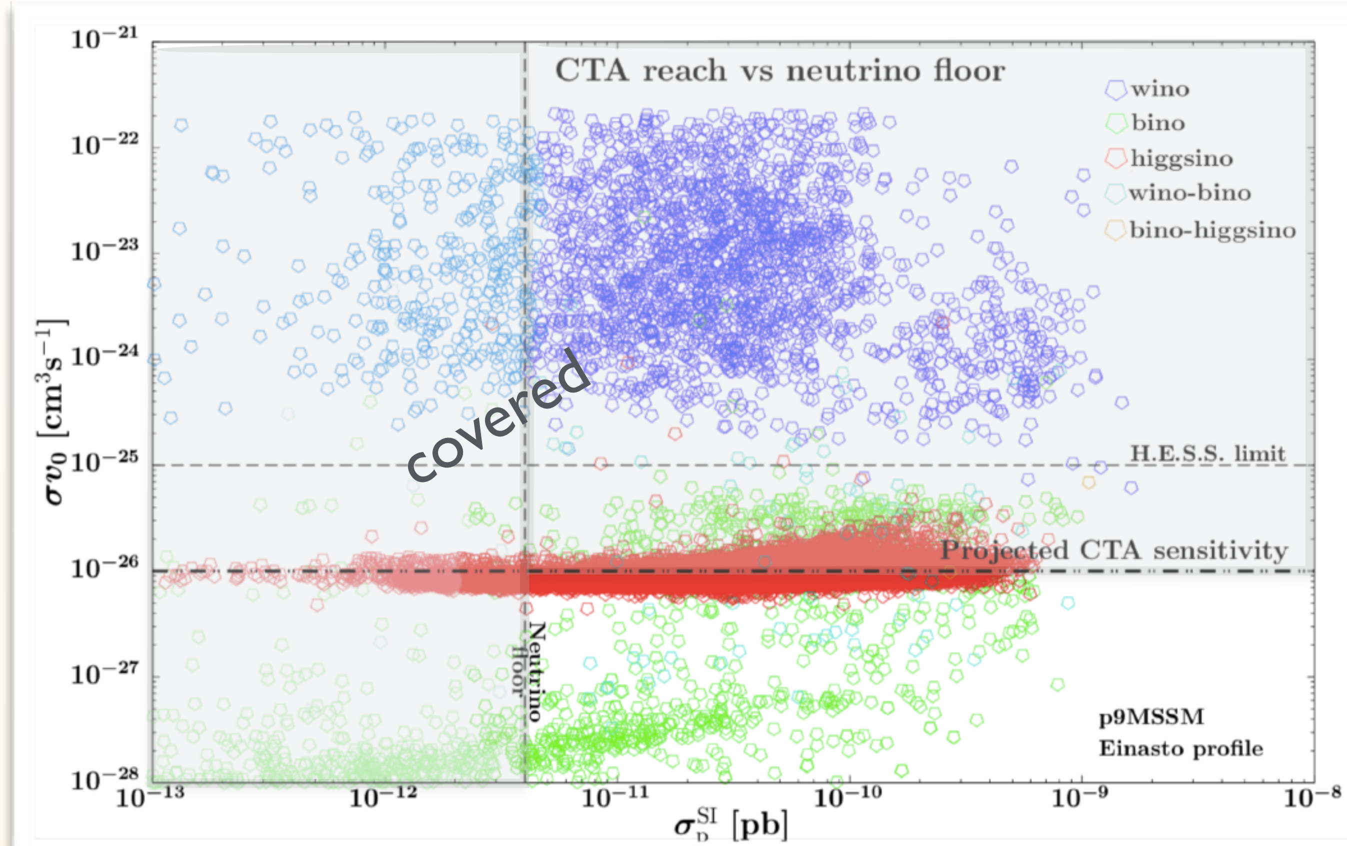
H.E.S.S. already excludes Wino-like points (subject to profile uncertainty)

↓

CTA can cover points that go significantly below DD sensitivities, even below the neutrino floor!

COMPLEMENTARITY WITH DD





H.E.S.S. already excludes Wino-like points (subject to profile uncertainty)

↓

CTA can cover points that go significantly below DD sensitivities, even below the neutrino floor!

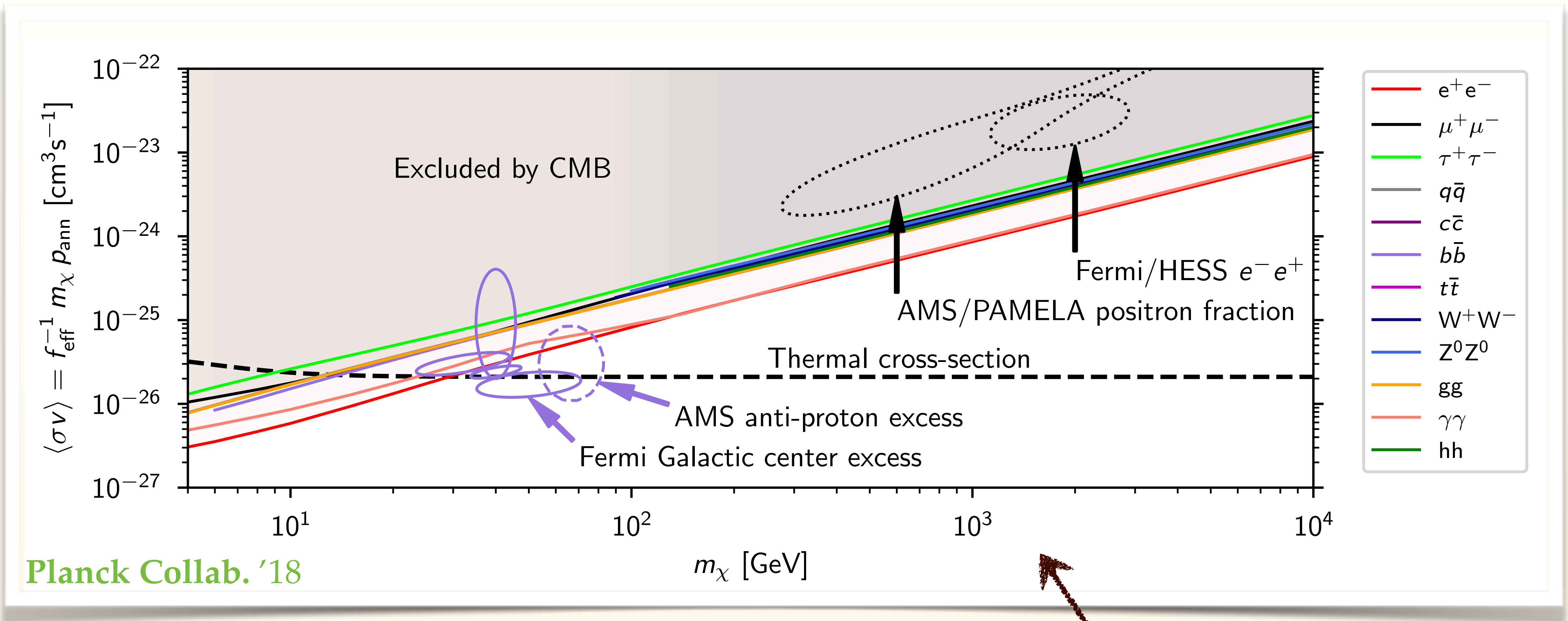
Combining CTA and DD upgrades will cover whole Wino-like region and large part of pure Higgsino

↓

the ~1 TeV Higgsino region is a perfect thermal DM candidate, still not constrained by the data!

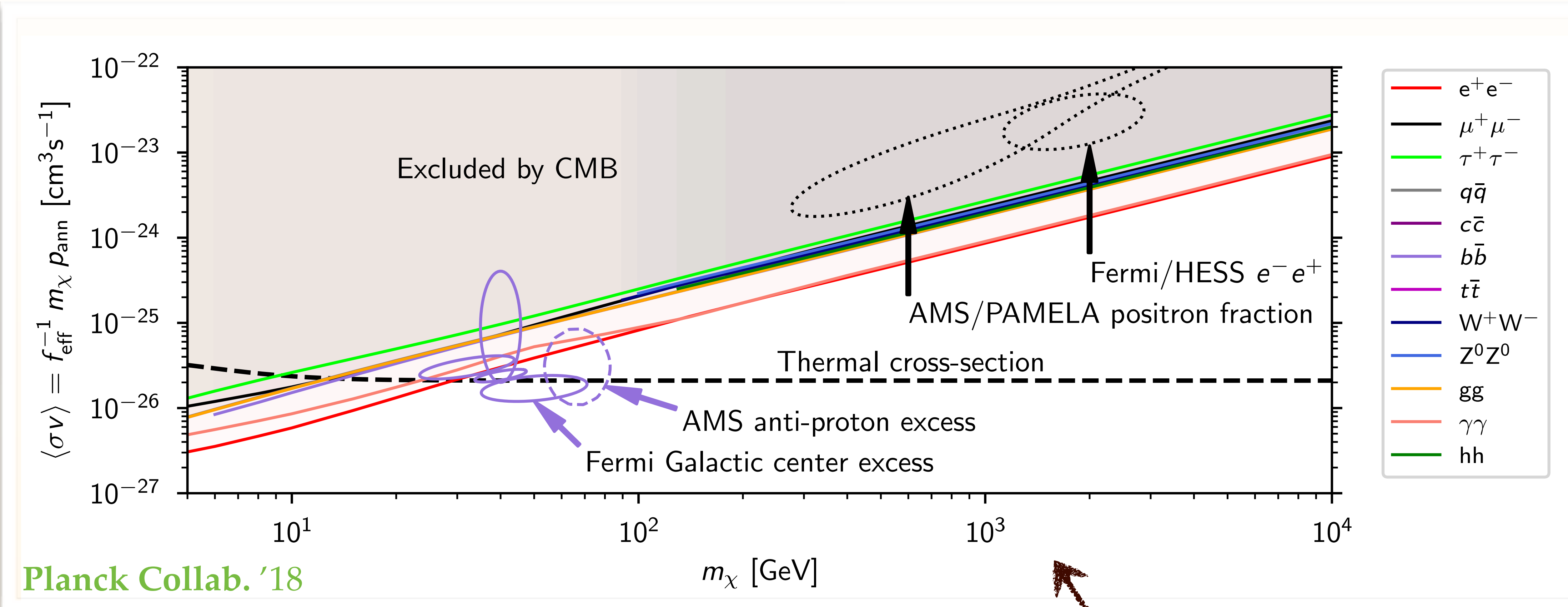
L. Roszkowski, E. Sessolo, A. Williams; '15

CMB & OTHERS

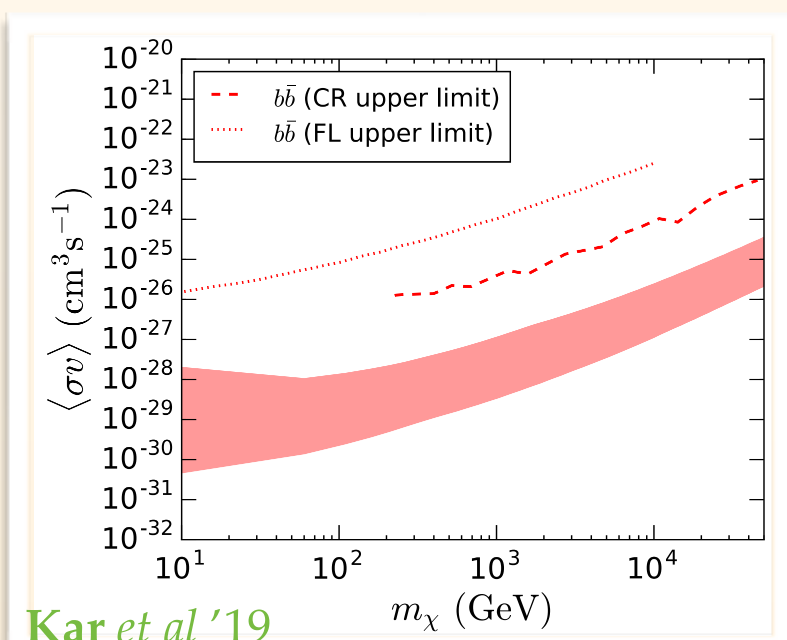


There are other ID channels, e.g. in CRs, that can constrain (or give a signal) of TeV scale DM. But keep in mind that CMB limits are comparable and need to be reckoned with

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. 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

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

CTA will bring an order of magnitude improvement over H.E.S.S. + can cover large part of the Higgsino DM region