Precise relic abundance and photon spectra for general Neutralinos

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Collaborators (current):
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References:
[1210.7928, 1303.0200, 1411.6924, 1411.6930, 1601.04718, 1611.00804, 2211.14341]

What is it ? - *"P.R.A.P.S.G.N."*

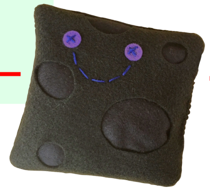
(We are looking for a name…)

- Standalone numerical tool (Mathematica)
- Mixed neutralino DM
- For neutralino DM observables:
  1. Annihilation cross-section (exclusive primary final states)
  2. photon spectrum near endpoint (semi-inclusive γ+X)
  3. Relic abundance

Neutralino DM overview

the MSSM:

Bosons	*squarks*	*sleptons*	gauge bosons (W, B, G)	2 Higgs Bosons
Fermions	quarks	leptons	*gauginos*	*2 Higgsinos*



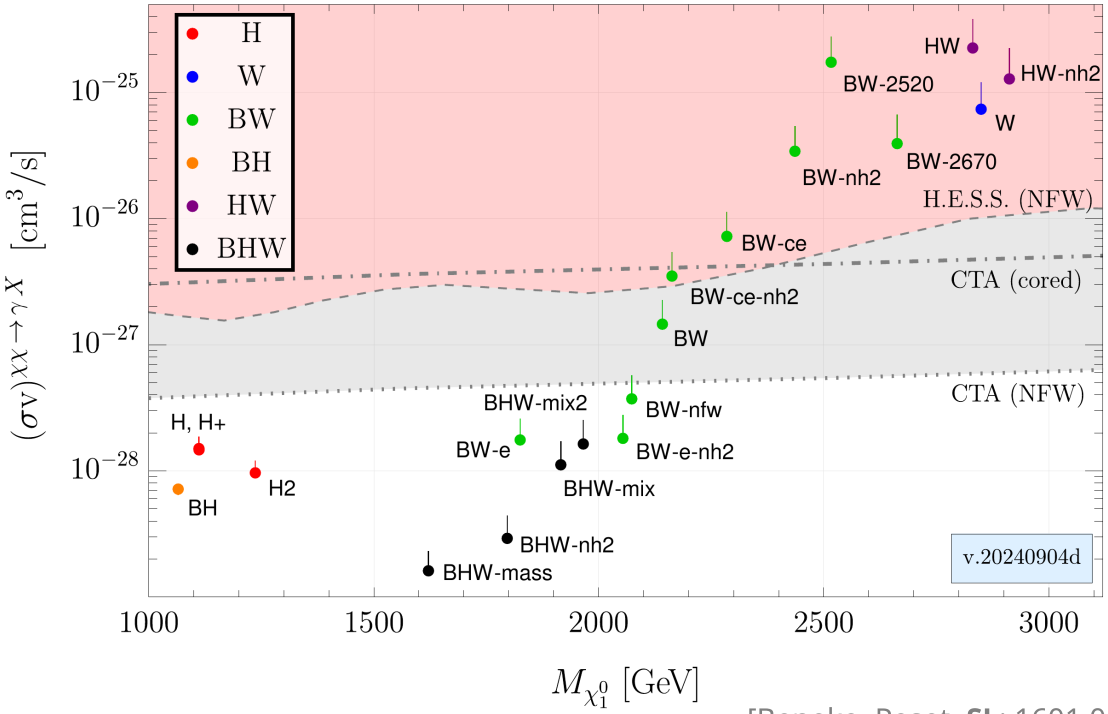
→ LSP = our DM candidate

- neutralino DM = TeV-scale WIMPs
- Many other BSM particles (sfermions, 2 Higgs sector)
  - Include *all* particles in the annihilation
  - $m_{Sf} > 1.25\, m_{\chi}$
  - gluinos irrelevant

Why is it ?

MSSM complexity.

Upcoming γ-ray telescopes probe mixed models.



[Beneke, Peset, **SL**: 1601.04718]

Why is it ? - Non-perturbative effects

MSSM complexity.

Upcoming γ-ray telescopes probe mixed models.

Sommerfeld effect:

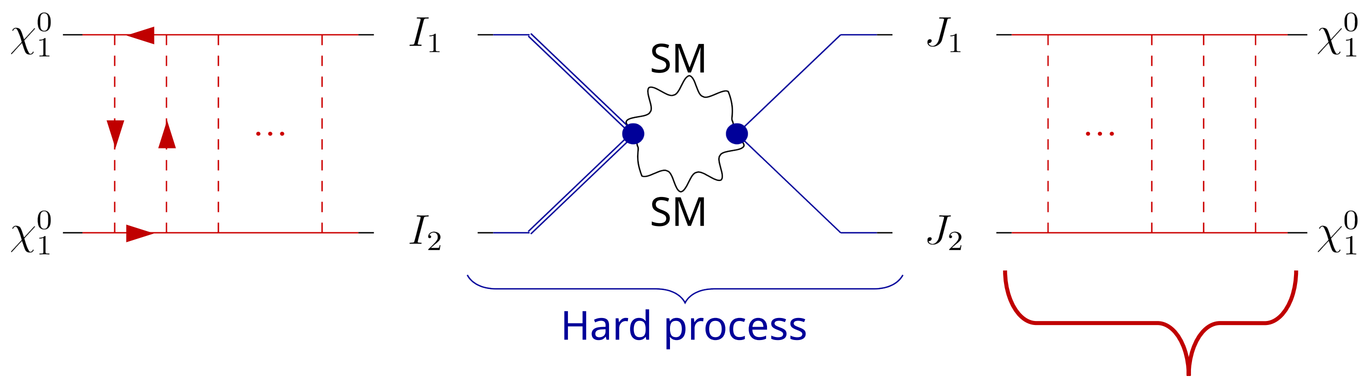
- Initial-state long-range interactions before annihilation
- 2-particle potential for wino+bino+Higgsinos

Sudakov resummation:

- Soft-collinear final-state radiation near the endpoint
- EW-jet emission: $(\gamma\,\gamma) + (\gamma\, Z) \longrightarrow (\gamma_{\mathrm{jet}}\, X_{\mathrm{jet}})$

DM annihilation - overview

absorptive part of forward scattering:



- Long-range potentials of TeV-scale WIPMs: **Sommerfeld effect**
  - Strong enhancements possible
  - Scattering into degenerate states (e.g. $\chi^0\chi^0 \rightarrow \chi^+\chi^-$)

$$(\sigma v)_{i\to f} = S^i_{IJ} \times \Gamma^f_{IJ} \approx S^i \times (a + b\, v^2 + \cdots)$$

- Aim for O(1%) precise Ωh^2

➔ We include hard O(v^2): ***p*-wave & NNLO *s*-wave**

How is it ?

- efficiency: … It’s a Mathematica code. (hugely efficient by use of C-compiled perturbative Γ_{IJ})

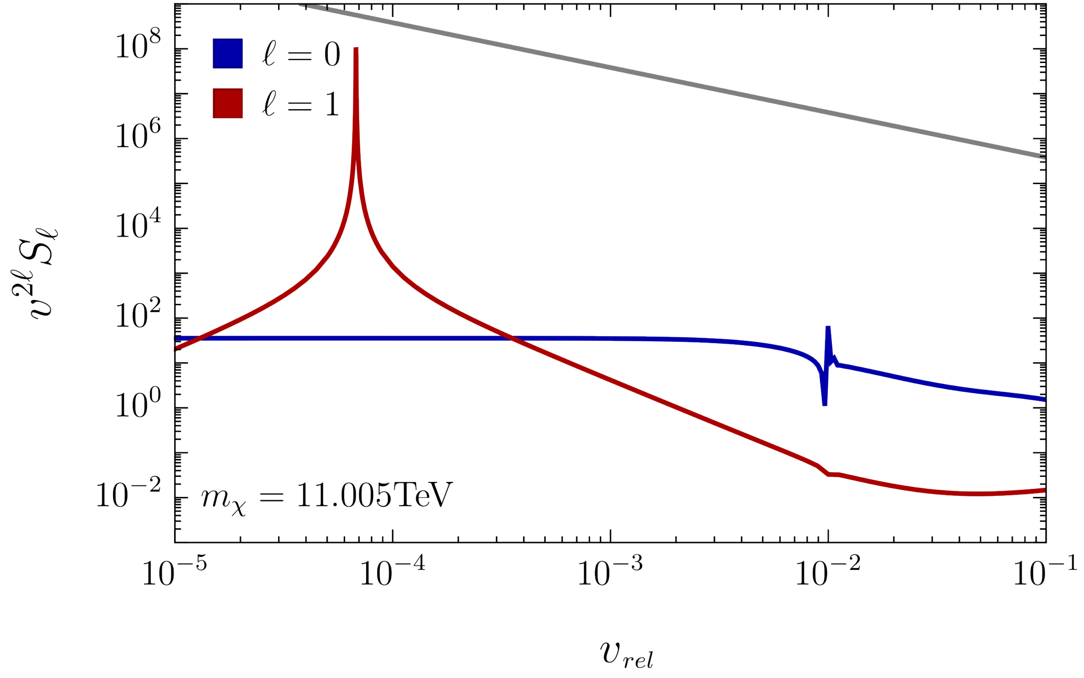
- Reliable.
- Modular.
- Simple.

Example 1: *p*-wave dominance

p-wave can exceed *s*-wave if:

- *s*-wave sees a cancellation
- *p*-wave is enhanced
  ➔ Sommerfeld factors depend on $L=0,1,\ldots$

<u>*pure wino*</u>, using our code. [Beneke, Garny, De Ros: 2403.07108]

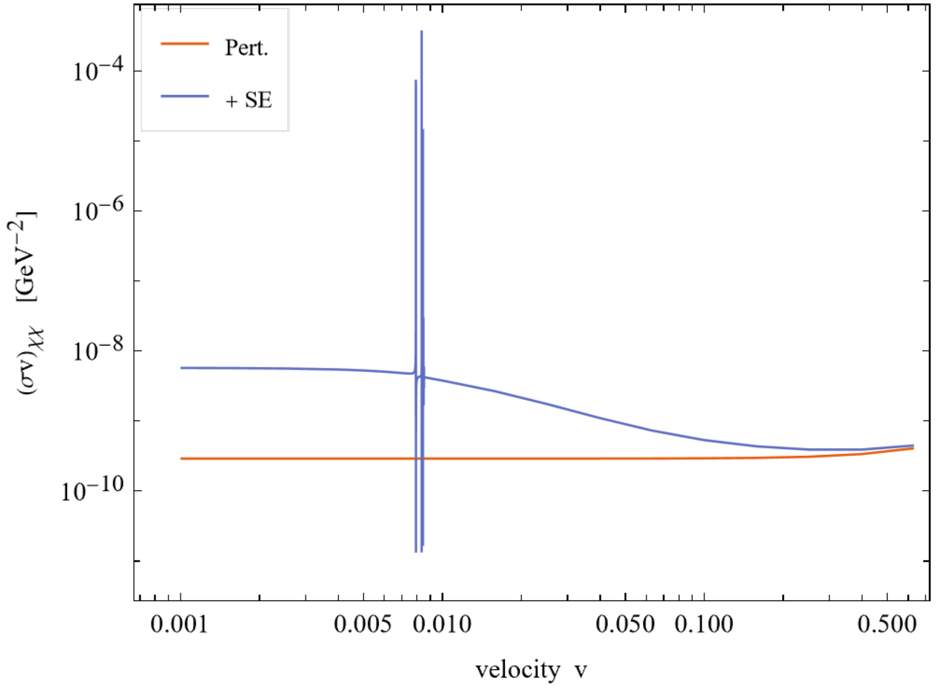


- ➢ Can impact relic density.
- ➢ Strong indirect detection bounds near resonances. (Sommerfeld / QBS / …)

Example 2: Coulomb resonances

simple wino-like model

- $\chi^0\chi^0$ annihilation
- χ^+, χ^- almost degenerate: δm = 167MeV



$M_2 = 4595$ GeV

$M_1 = 2M_2$

$\mu,\ M_{Sf},\ M_{A^0} \gtrsim 15$ TeV

$t_\beta = 15$

Example 2: Coulomb resonances

simple wino-like model … ?

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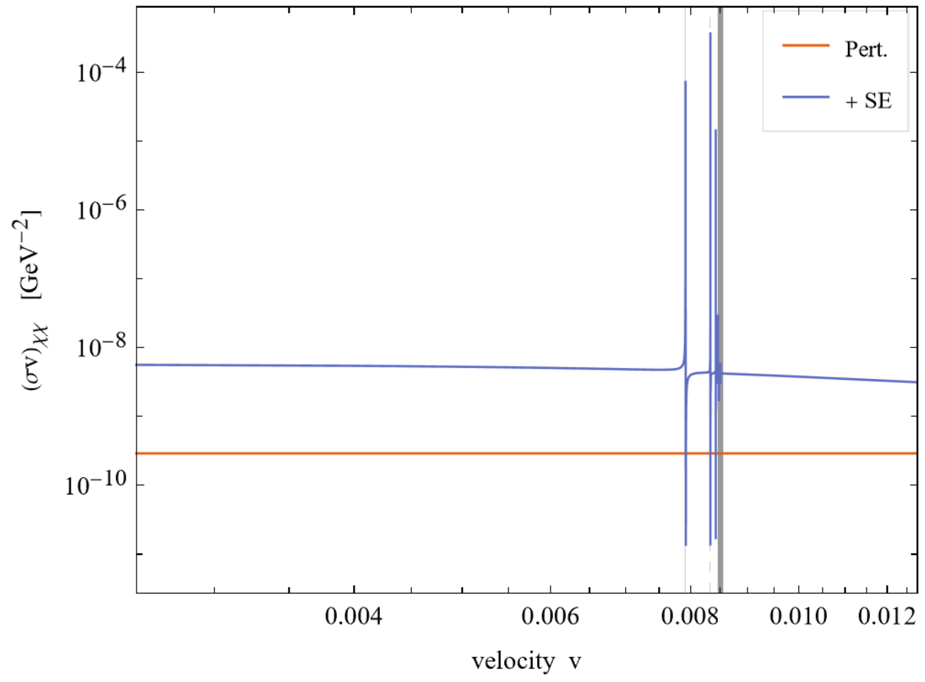

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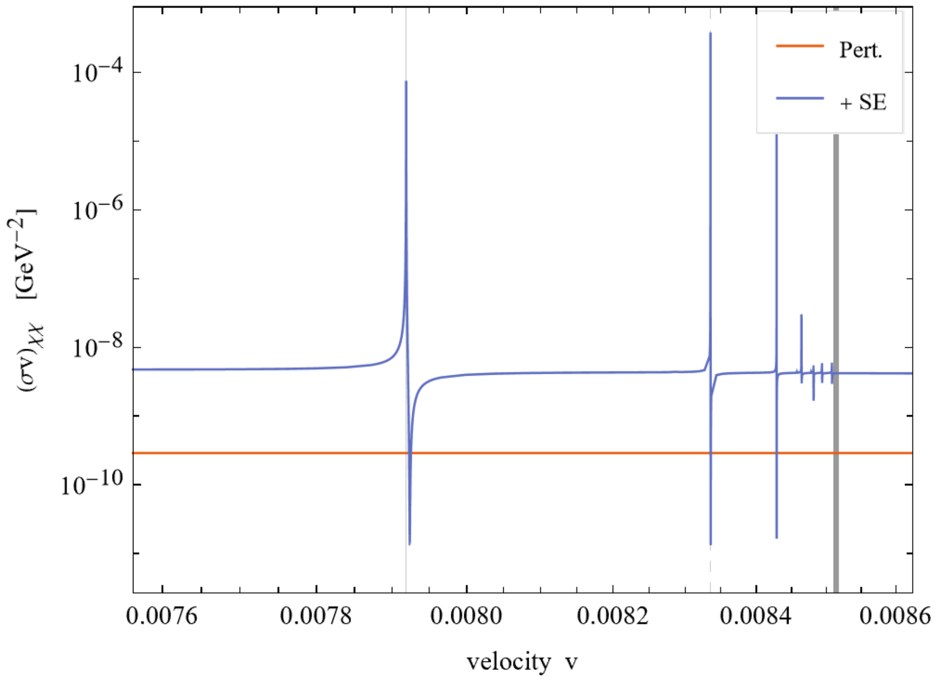

Example 2: Coulomb resonances

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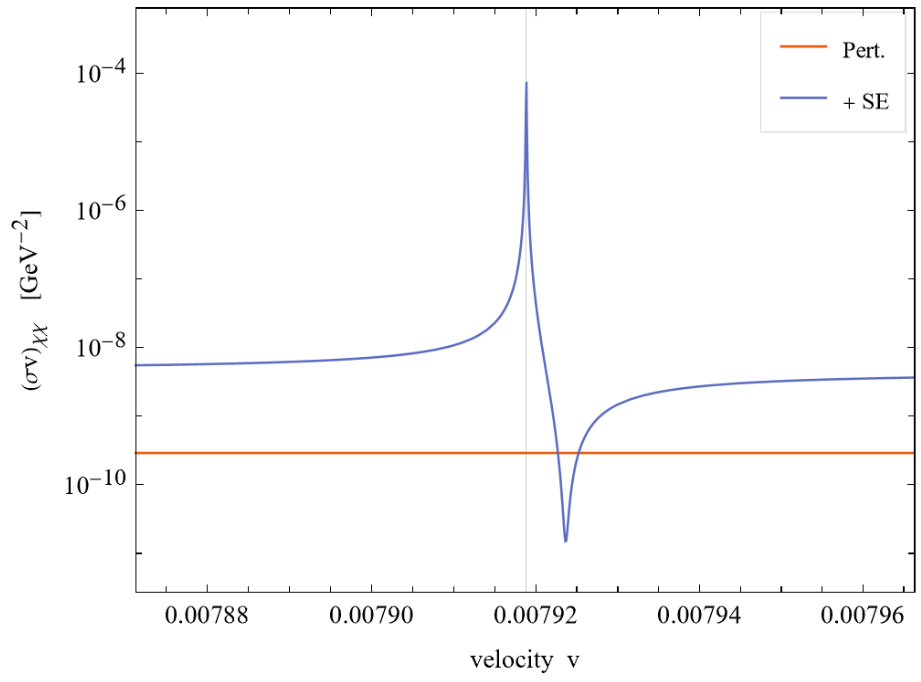
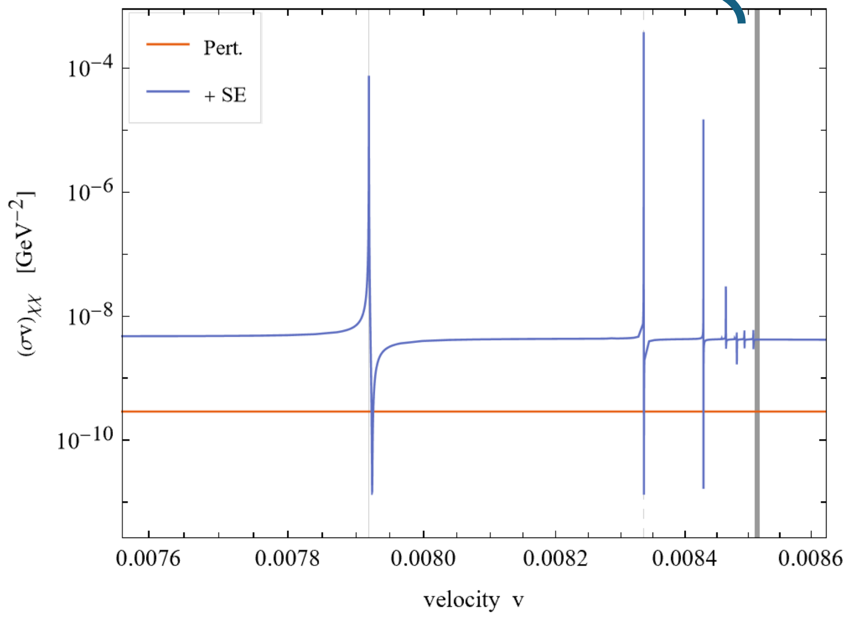
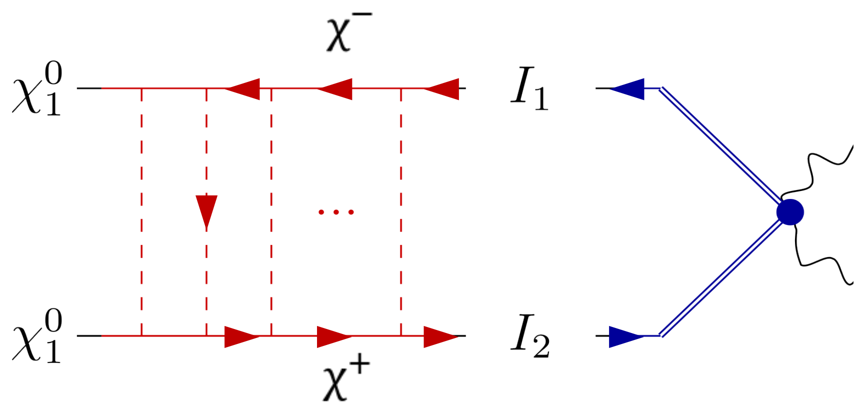


Example 2: Coulomb resonances

$$mv^2 = 2\delta m, \quad \delta m = m_{\chi^+} - m_{\chi^0} > 0$$

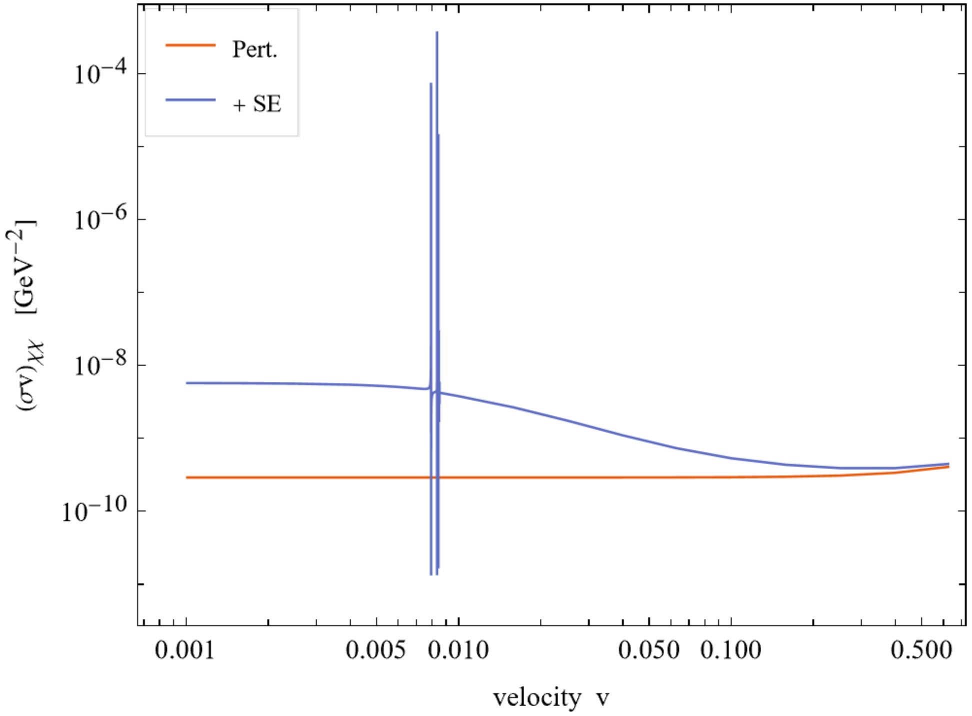
below production threshold





→ *The Sommerfeld effect sees remnants of the ~decoupled bound state spectrum below the $\chi^+\chi^-$ threshold.*

Example 2: Coulomb Resonances



- Extremely narrow resonances just below the chargino threshold.
- Difficult to resolve.
- Dangerous for thermal averaging

preliminary

- Total effect of resonances non-negligible in the thermal average(?)
- impact on indirect detection?

Summary

- Neutralino-DM observables in general MSSM models.
- Many more features / details:
  - One-loop mass corrections
  - Co-annihilation with all 14 states
  - CP violation
  - Sudakov resummation
  - …
- Convenient Mathematica interface
- Currently: finalization & paper writing
  → public release: "soon". (2025)

Talk to me to see an example notebook!