Constraints on Dark Matter Annihilation

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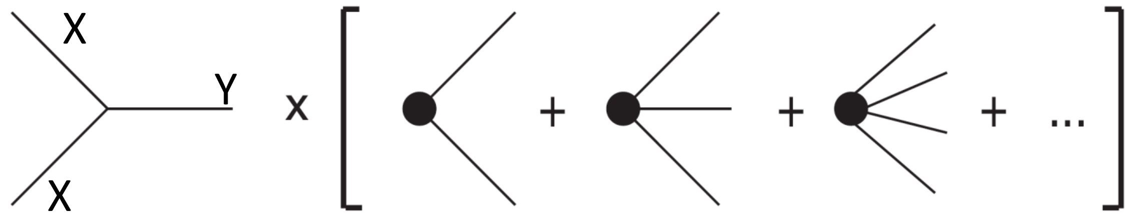
Dark Matter Annihilation –Early Universe

- For ***constant*** velocity averaged cross sections relic abundance predicts: $\langle \sigma v \rangle = 3 \times 10^{-26} cm^3/s$
- ***In general, cross sections are more complicated:***
  - Higher order corrections are dependent on the energy! (think infra-red divergences for example)
  - Breit-Wigners have non-trivial energy dependence.
  - …
- More interesting relic abundance inspired relations possible.
- ***Let's look at s-channel annihilation***

S-channel annihilation cross section



By the Optical Theorem:

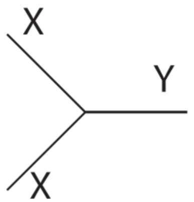
$$\sigma = -\frac{1}{2kE_{CM}} Im\left(\frac{g^2_{XXY} t_{jj'}}{s - m_Y^2 + i m_Y \Gamma_Y}\right)$$

$$= \frac{g^2_{XXY}}{2kE_{CM}} \frac{m_Y \Gamma_Y t_{jj'}}{(s - m_Y^2)^2 + m_Y^2 \Gamma_Y^2}.$$

$$t_{jj'} \approx 4m_X^2 C_{jj'}$$

- Includes propagator corrections to ALL ORDERS in pert. theory
- Includes ALL POSSIBLE number or type of final states
- We consider ALL types of initial states.

Relic calculation non-trivial analytically! Recall: it includes integration over all energies and the entire thermal history of the universe! Also, multiple scale problem!

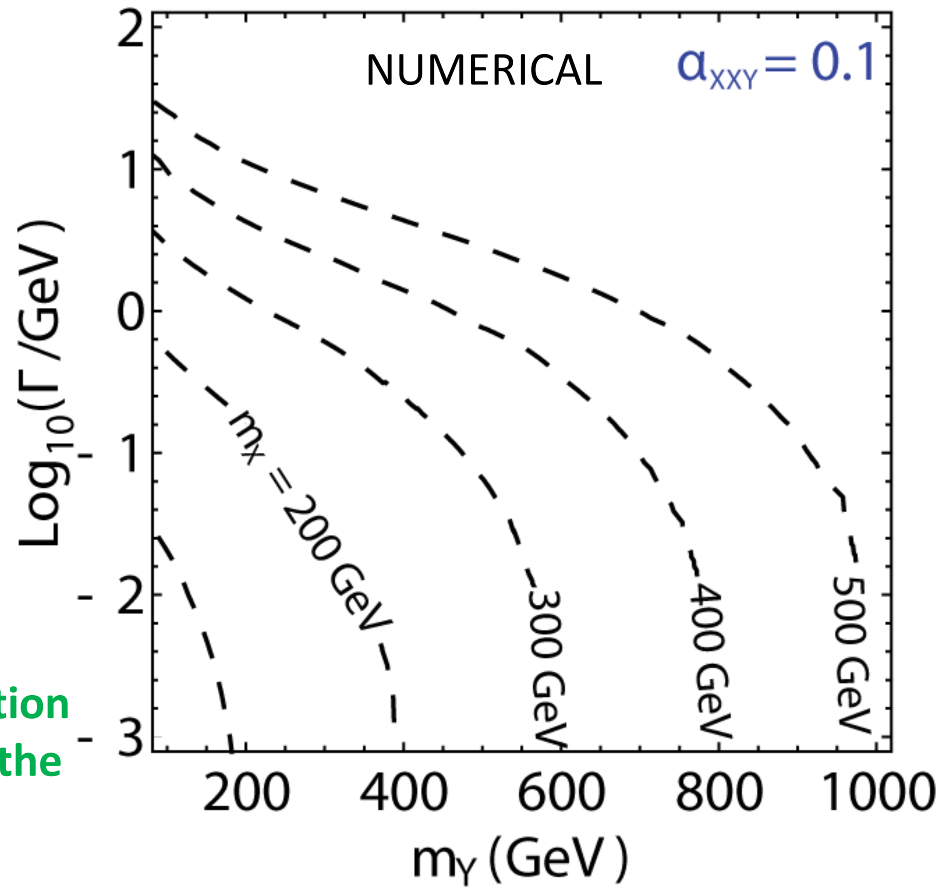


Relic abundance predicts NEW mass-width relations for $m_Y \leq 2m_X$

- We are interested in the relations between parameters ($m_X, m_Y, \Gamma_Y, \alpha, \ldots$)

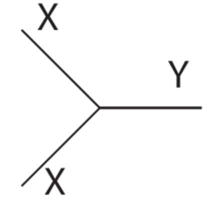
$$\alpha_{XXY} \equiv g_{XXY}^2/4\pi$$

1. For a given m_X and α_{XXY} $\Omega_{\rm DM}h^2 \simeq 0.1$ produces a unique curve in the (m_Y, Γ_Y) space. (Black dashed line - numerical)



Constant relic abundance does not give you a number for the cross section It gives you a relationship between the parameters . More challenging!

A formula is worth a 1000 numerical calculations



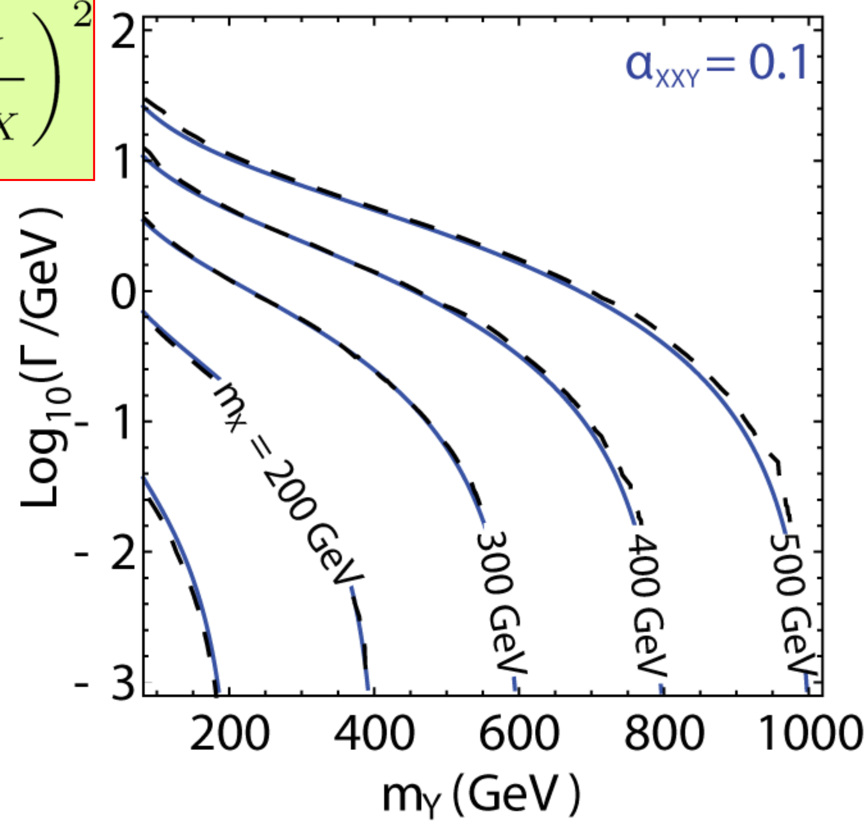
- Analytic s-channel relic calculation complicated!
- Good approximation possible!

$$\Gamma_Y(m_Y) \ = \ \frac{\sqrt{6}}{C_{jj'}\alpha_{XXY}}(2.61 \times 10^{-9} GeV^{-2}) \times m_X^3 \left(1 + \frac{m_X}{2m_Y}\right)\left(1 - \frac{m_Y}{2m_X}\right)^2$$

Replaces $\langle \sigma v \rangle = 3 \times 10^{-26} cm^3/s$

Black/Dashed – Numerical

Blue/Solid - Approximation

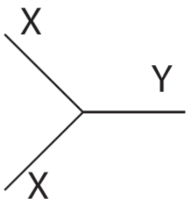


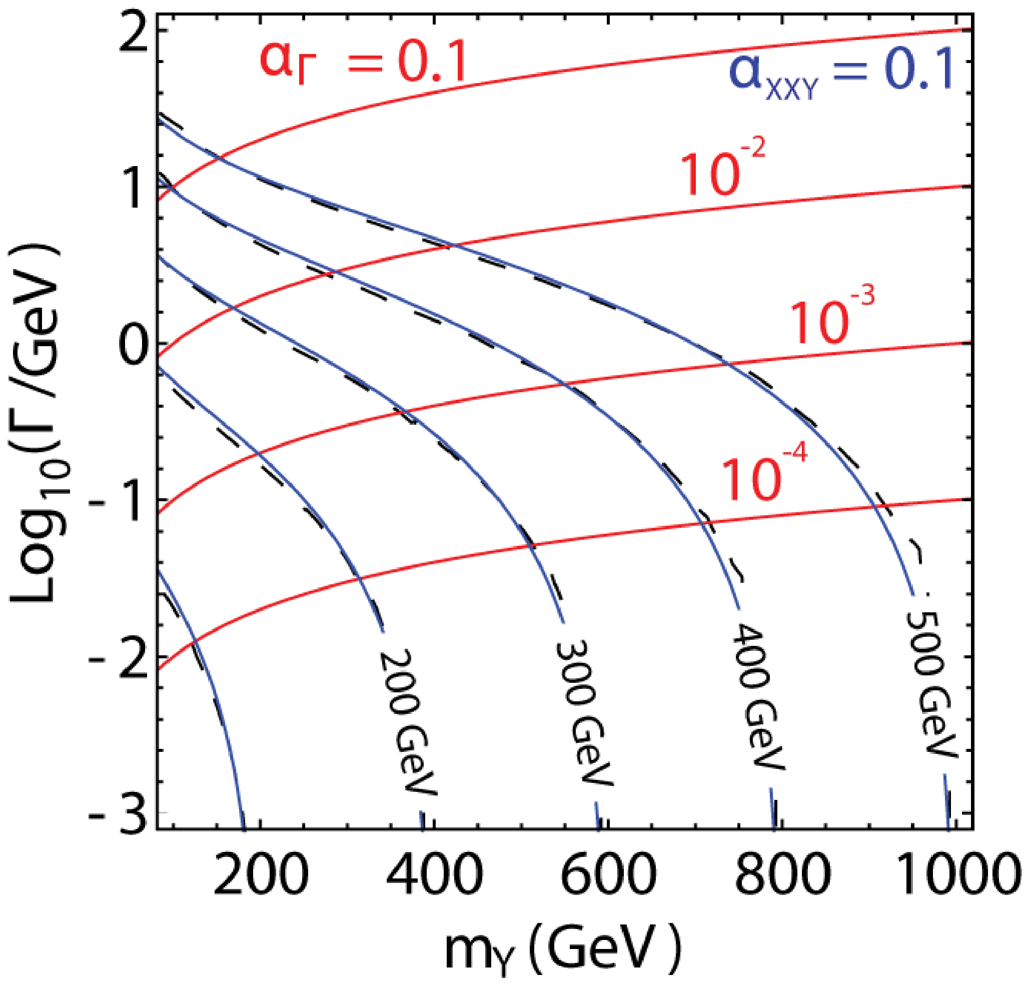
The approximation relates all 5 parameters of the problem!

No need for further numerical calculations!

Calculable widths and immediate results

Widths as calculable features





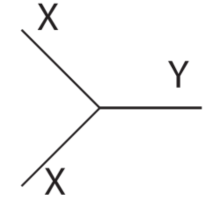
Let: $$\Gamma_Y = m_Y \alpha_\Gamma$$

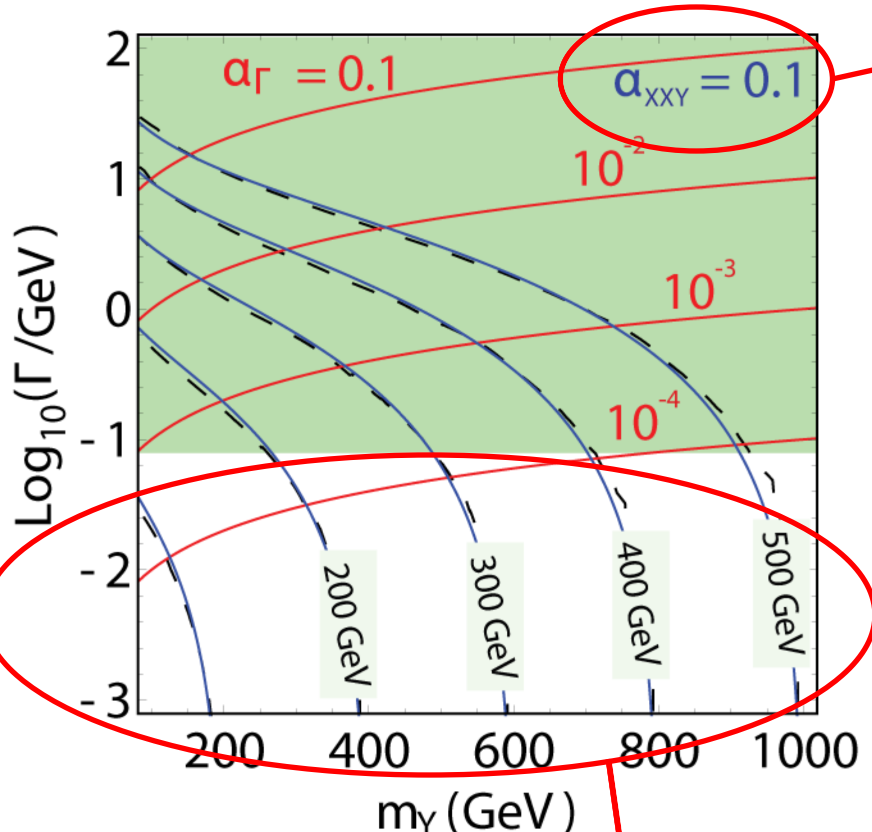
Allows to consider many models at once

Couplings, kinematics, etc.

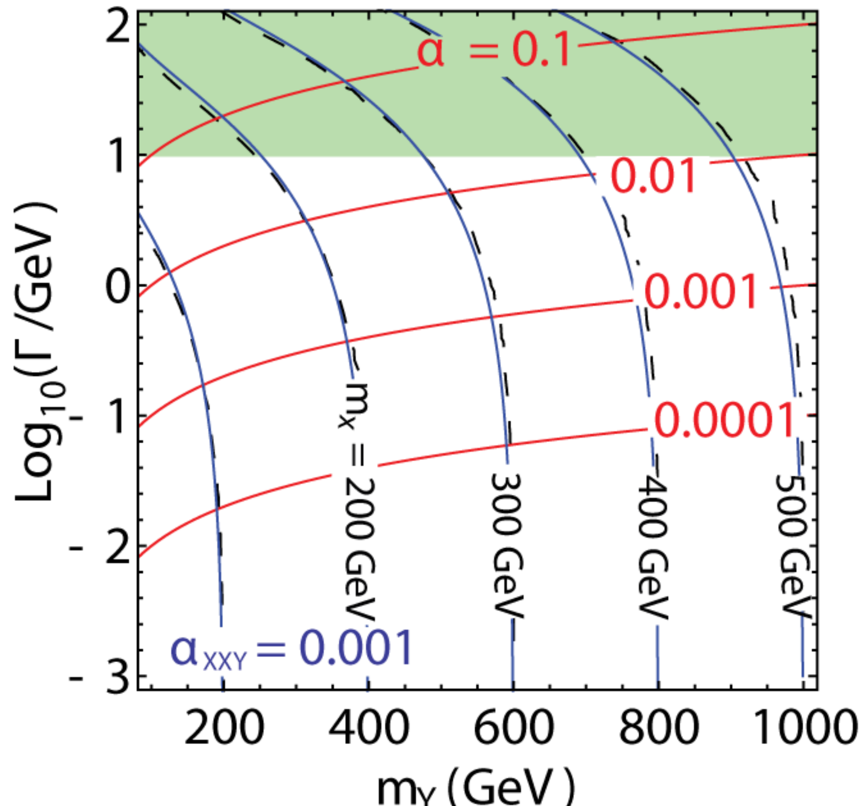
Consistency occurs at the intersection of red lines with lines representing constant relic abundance.

Small Width Limit:
Poles near Threshold and Fine Tuning





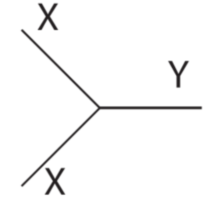
This is a pretty strong coupling. Weaker couplings pushes the Blue/Black lines up.



Small widths force the pole into a finely tuned region near threshold

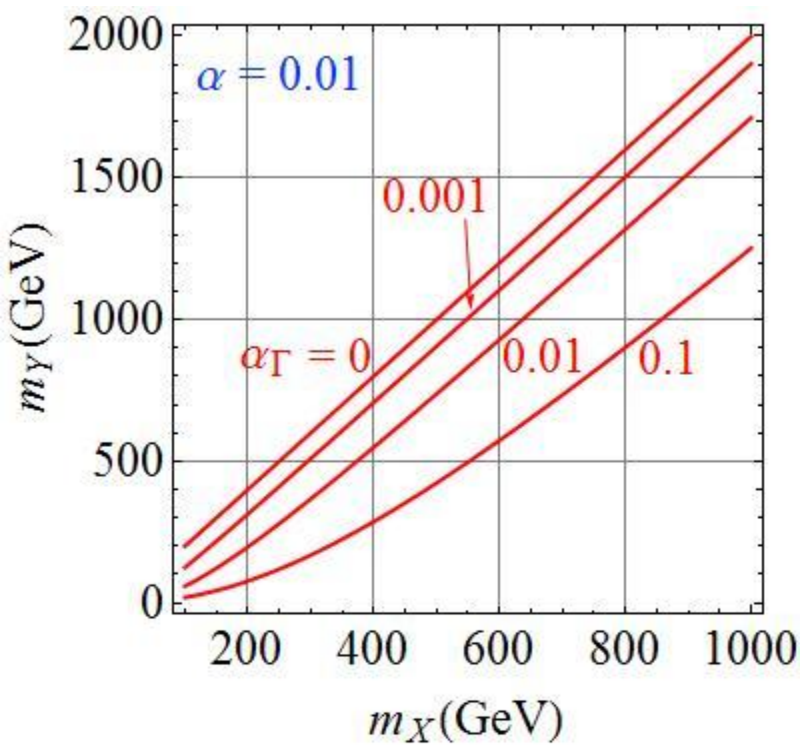
Green regions are NOT finely tuned

Heavy Dark Matter Limit
Another New Fine Tuning Problem

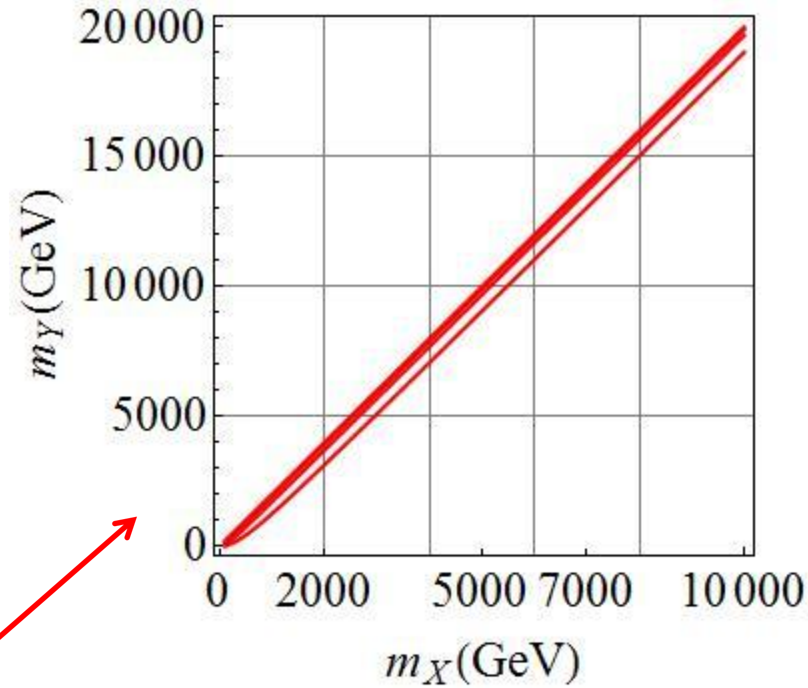


$$\Gamma_Y \sim \alpha_\Gamma m_Y$$

Allows for a relation between the mass of Y and mass of X

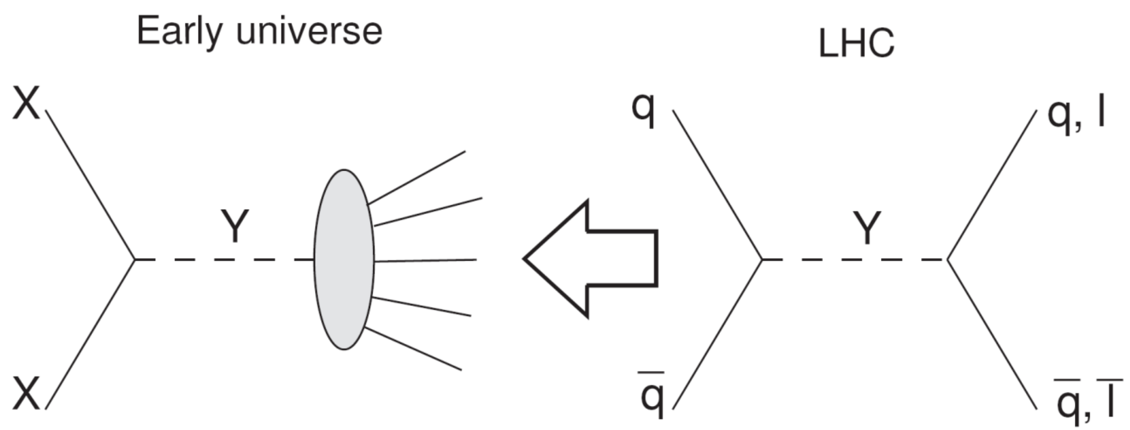


Large m_x



$$m_Y \approx 2m_X - 4\sqrt{\frac{2}{5}}\left(\frac{\alpha\alpha_\Gamma C_{jj'}}{2.61\sqrt{6}\times 10^{-9}GeV^{-2}}\right)^{1/2}$$

Example: Z' search at the LHC



Could Y (LHC) be the Y(DM)? Consistent param. regions?

$$\Gamma_Y(m_Y) = \frac{\sqrt{6}}{C_{jj'}\alpha_{XXY}}(2.61\times 10^{-9} GeV^{-2}) \times m_X^3 \left(1+\frac{m_X}{2m_Y}\right)\left(1-\frac{m_Y}{2m_X}\right)^2$$

… if dark matter dominantly annihilated into Y

No Numerical Calculation Necessary!

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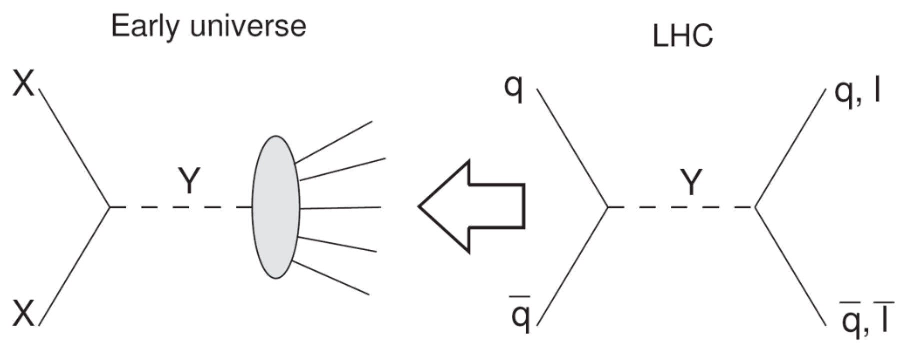
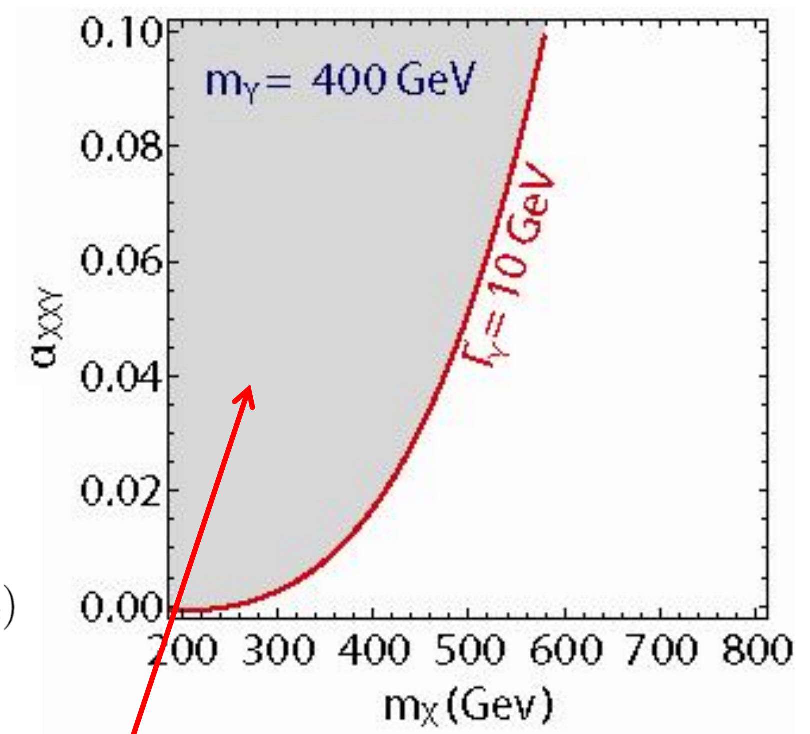
Example: Z' search at the LHC

- **What if more DM annihilation channels contribute?**
- **Assume no large destructive interference terms.**



$$\Gamma_Y(m_Y) \leq \frac{\sqrt{6}}{C_{jj'}\alpha_{XXY}}(2.61 \times 10^{-9} GeV^{-2}) \times m_X^3 \left(1 + \frac{m_X}{2m_Y}\right)\left(1 - \frac{m_Y}{2m_X}\right)^2 \quad (14)$$

$$when \quad \langle\sigma v\rangle_{tot} \geq \langle\sigma v\rangle_s,$$



Shaded region to the left of the curve is not allowed

Half of parameter space cut off with no need for parameter space search.

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Indirect Detection (Backup slides)

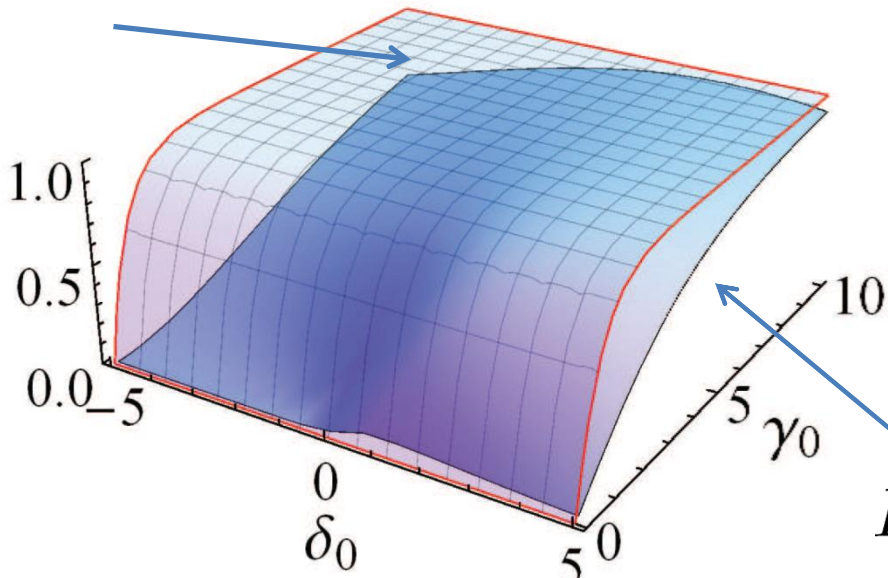
Upper limits on s-channel annihilation in the halo

- Useful parameterization (wrt. the energy scale of the halo):

$$\gamma_0 = \frac{\Gamma}{2E_0}; \quad \delta_0 = \frac{E_{res}}{E_0}.$$

$$\langle \sigma v \rangle \equiv \int dv\, v\, \Phi(v)\, \sigma(\delta_0, \gamma_0) \sim I(\delta_0, \gamma_0)/m_X^2$$

$1 - e^{-\frac{\pi}{4}\gamma_0}$



$I(\gamma_0,\ \delta_0)$

$$I(\delta_0, \gamma_0) \leq 1 - e^{-\frac{\pi}{4}\gamma_0}$$

Backovic, Ralston **arXiv: 0910.1113**

Annihilation through a bound state

Condition for a bound state:

$$\alpha_X \gtrsim \kappa \frac{\mu}{m_X}$$

Hydrogen-like bound states will roughly be described by:

$$E_{res} \sim m_X \alpha_X^2$$

$$\Gamma \sim \alpha_X^{4+A} m_X$$

A>0

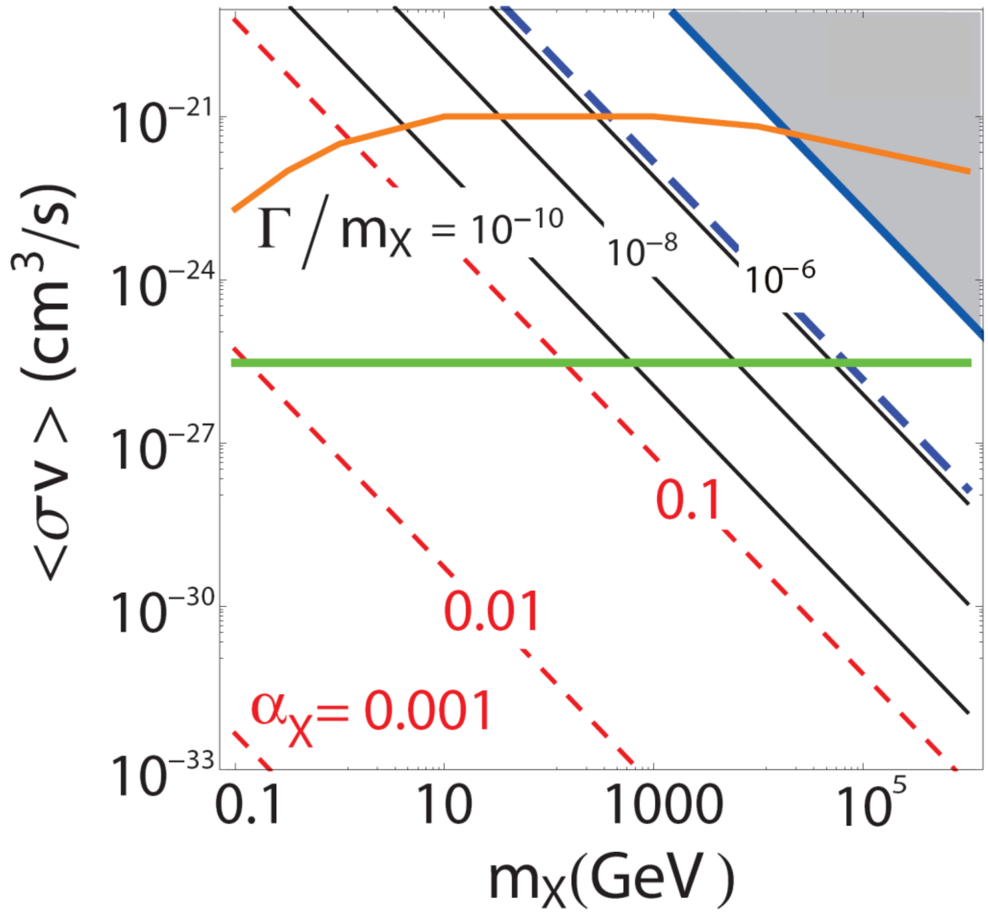
Backovic, Ralston **arXiv: 0910.1113**

Upper limits on s-channel annihilation in the halo

- Any simple pole

$$I(\delta_0, \gamma_0) \leq 1 - e^{-\frac{\pi}{4}\gamma_0}$$

- Bound state
- Neutrino limit
  (Beacom, Bell, Mack arXiv:astro-ph/0608090v2)
- Unitarity bound
- Lower bound from cosmology



Large enhancements possible, but fine tuning required to saturate upper limits!

Backovic, Ralston **arXiv: 0910.1113**

Thank you!