PARTICLE DARK MATTER

AT A CROSSROADS

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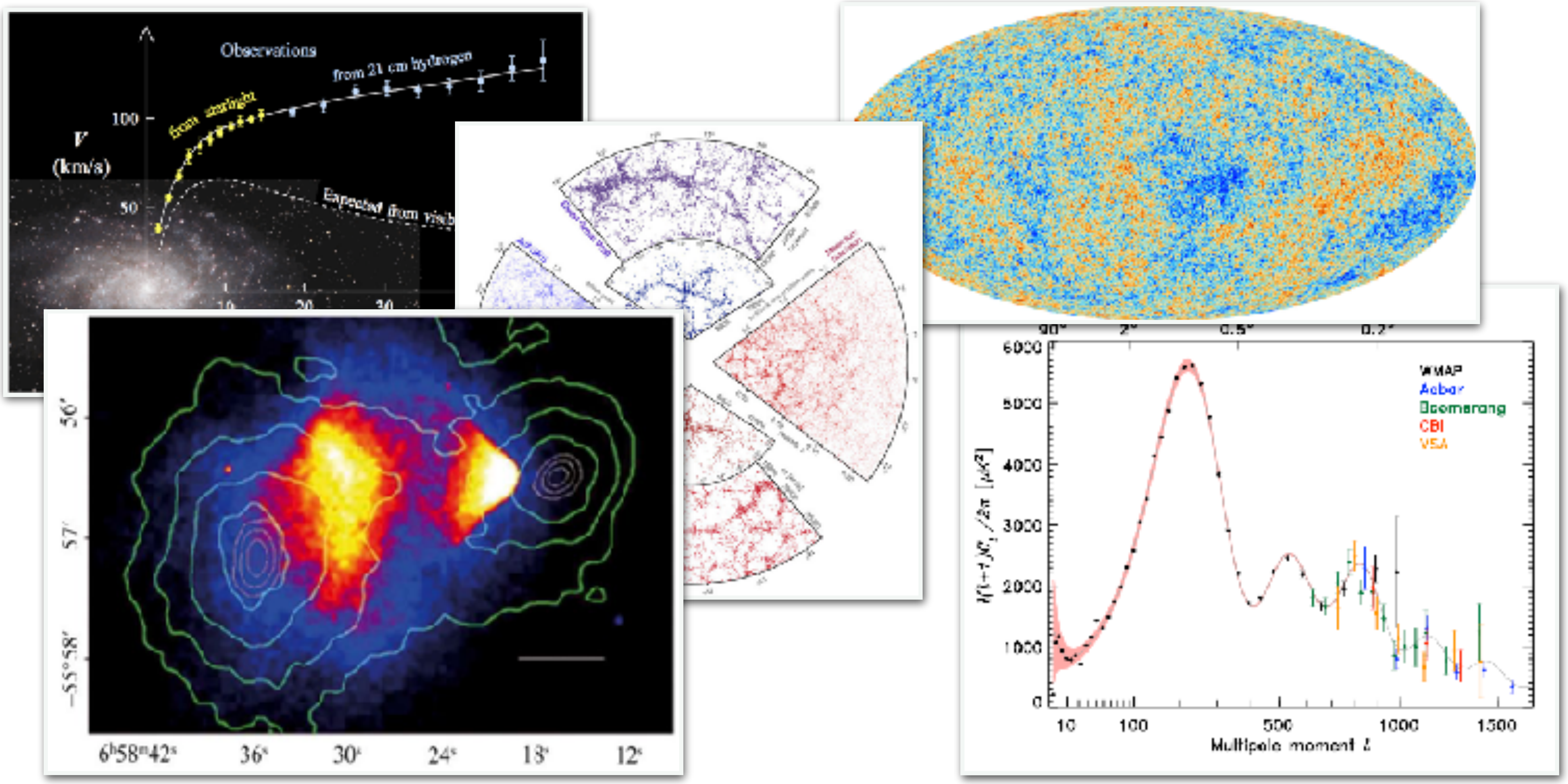
ITA Colloqium, 9th November 2018

DARK MATTER

I don’t think there is any need for convincing you that DM exists…



$\Longrightarrow$ Evidence on all scales!

… but perhaps I should argue why particle DM

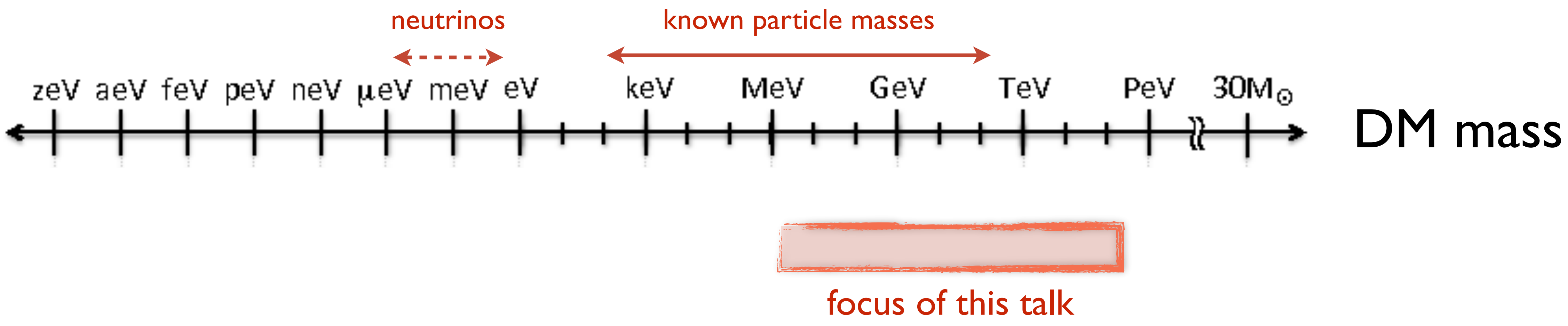
PARTICLE PHYSICIST'S PERSPECTIVE:

We know that the Standard Model (of particle physics) in not complete

its extension could *in principle* be extremely minimal… but it is far more likely that there are (many?) new particles we do not know yet

it is quite possible that some of them are stable and then they are **a** dark matter

if so it is very natural to expect that they are also **the** dark matter



OUTLINE

1. Vanilla WIMP and why is (was?) it so attractive?
    - hope for new physics around the weak scale
    - clear path for detection techniques
    - thermal production mechanism
2. Going heavier - is it all bad?
    - possible avenues
    - new challenges at the TeV scale
3. Going lighter - is it all contrived?
    - confronting experiments
    - new input from astrophysics & cosmology
4. A new hope?

CHAPTER #1

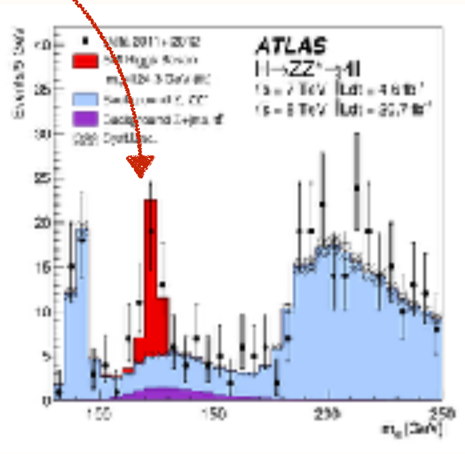
VANILLA WIMP

NEW PHYSICS

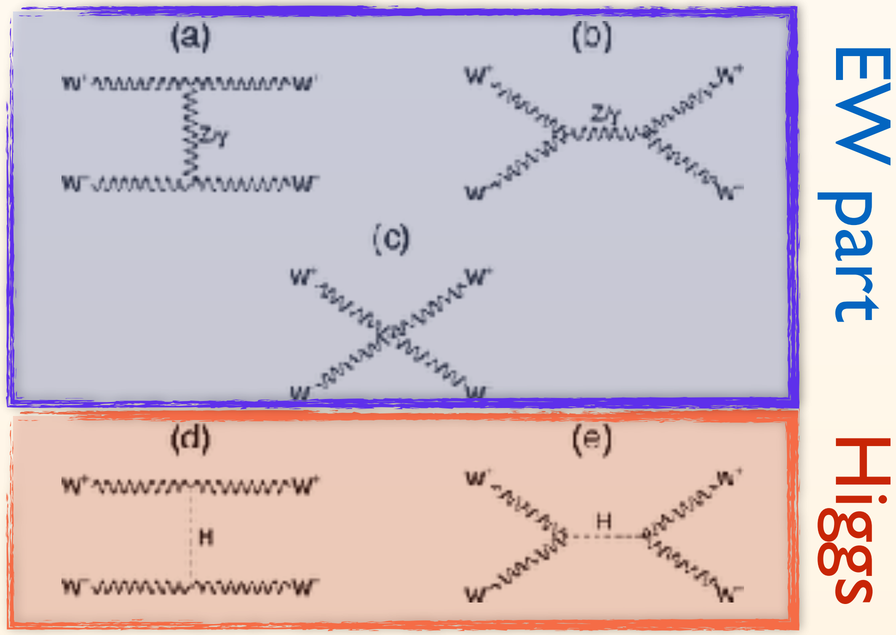
(IS ALWAYS) AROUND THE CORNER

July 2012 - the Higgs boson

since then:



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



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

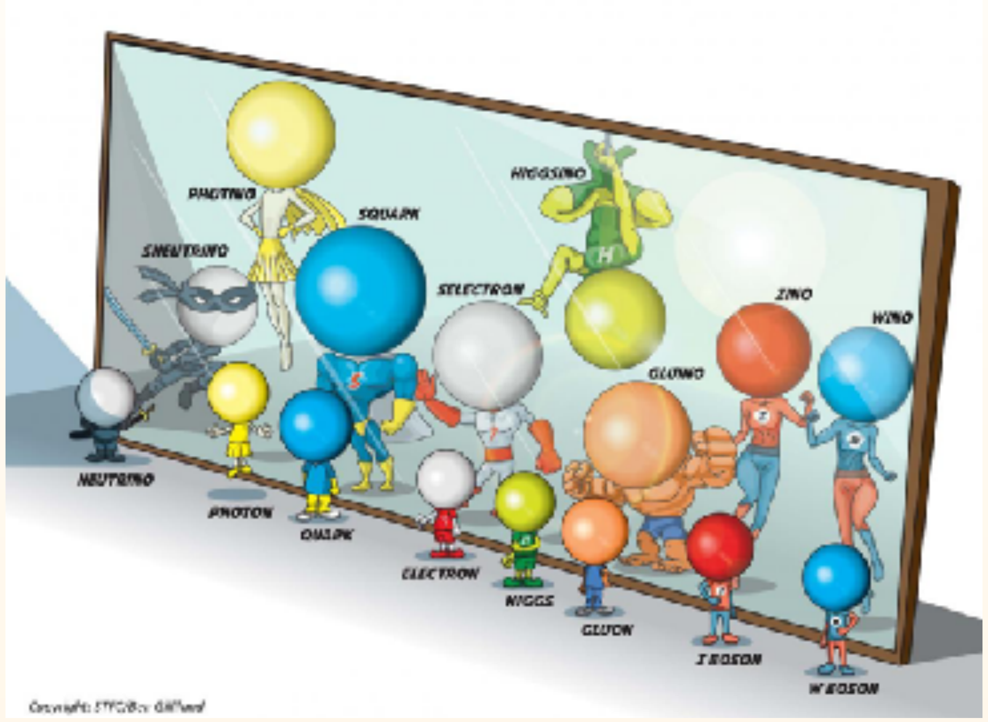
$$\Delta m_h^2 = \frac{3\Lambda^2}{8\pi^2 v^2}\left[4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2\right] + \mathcal{O}\left(\log\frac{\Lambda}{v}\right)$$

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

SUPERSYMMETRY

(STILL) BEST MOTIVATED FRAMEWORK BEYOND SM

What people think about SUSY :



Copyright: STFC/Ben Gilliland

What SUSY *really* is:

$$
\begin{aligned}
\{Q_\alpha, Q_\beta\} &= \{\bar{Q}_{\dot\alpha}, \bar{Q}_{\dot\beta}\} = 0 \ , \\
\{Q_\alpha, \bar{Q}_{\dot\beta}\} &= 2(\sigma^\mu)_{\alpha\dot\beta} P_\mu \ , \\
[Q_\alpha, P_\mu] &= [\bar{Q}_{\dot\alpha}, P_\mu] = 0 \ , \\
[Q_\alpha, M_{\mu\nu}] &= -\frac{1}{2}(\sigma_{\mu\nu})_\alpha{}^\beta Q_\beta \ , \\
[\bar{Q}_{\dot\alpha}, M_{\mu\nu}] &= -\frac{1}{2}(\bar\sigma_{\mu\nu})_{\dot\alpha}{}^{\dot\beta} \bar{Q}_{\dot\beta} \ .
\end{aligned}
$$

$$
\mathcal{L}_{SUSY} = \int \mathrm{d}^2\theta W(\{\Phi_i\}) + \frac{1}{16g^2}\int \mathrm{d}^2\theta \mathrm{Tr}(W_\alpha W^\alpha) + \int \mathrm{d}^2\theta \mathrm{d}^2\bar\theta \bar\Phi \, e^{2gV}\Phi + \mathrm{h.c}
$$

SUSY features:

- great simplification of the theory
- Coleman-Mandula theorem
- elegant solution to Hierarchy Problem
- needed by String Theory
- coupling unification
- DM candidate for free

SUSY bugs:

- hasn't been found yet…

(however this bug might turn out to be a feature…)

SUPERSYMMETRY
AND THE DARK MATTER

Of course, our everyday world is **not** supersymmetric - SUSY has to be broken - if it happens roughly at energy scales in reach of the LHC

we call it "low scale" SUSY

Lepton & Baryon conservation can be ensured if one impose *R-parity*:

$$\boxed{P_R = (-1)^{3(B-L)+2s}}$$

i.e. $\boxed{\text{superparticles}: \quad P_R = -1, \text{ particles } P_R = +1.}$

A corollary: lightest superparticle (LSP) is automatically stable!

Moreover it can have properties required of dark matter particle and even better - one that interacts with the SM strongly enough to potentially give signals

if "low scale" SUSY

WIMP

WEAKLY INTERACTING AND MASSIVE

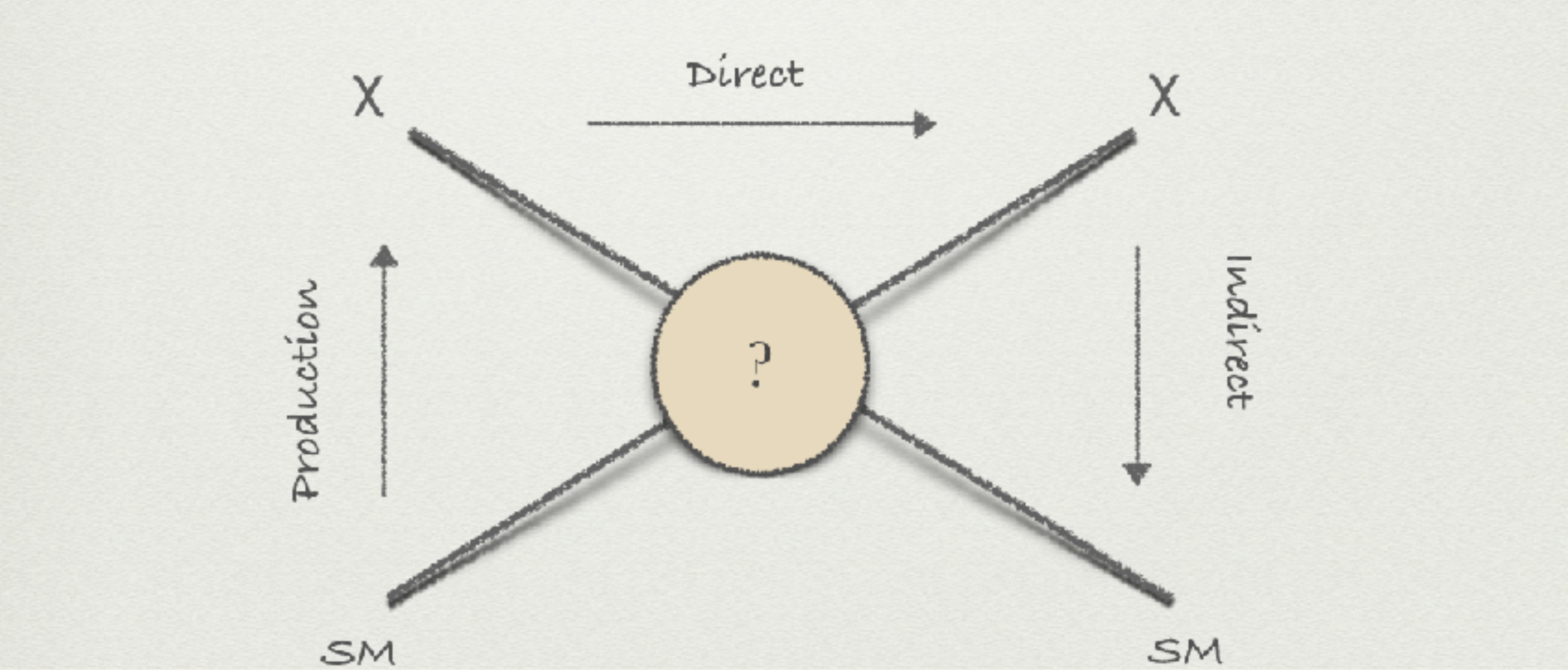
In a weak sense:

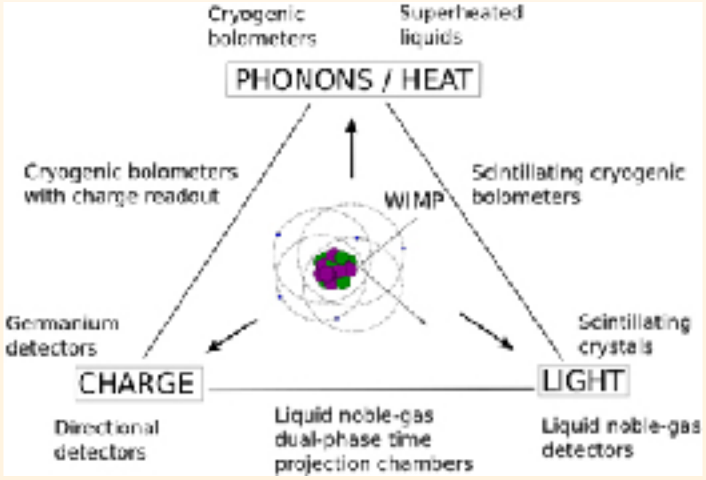
DM cannot interact too strongly, as we would see it
and has to have a mass to contribute to observed gravitational potential (now and during the structure formation)

In a strong sense:

interacting through SM weak interactions and (therefore)
not too light

WIMP DETECTION





THERMAL RELIC DENSITY

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

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

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

$\Gamma_{\mathrm{ann}} > H$ DM in equilibrium

$T \uparrow$ $\Gamma_{\mathrm{ann}} \sim H$ $\boxed{\text{chemical decoupling}}$ $\downarrow$ time

$\Gamma_{\mathrm{ann}} < H$ freeze-out

MOTIVATION

THERMAL RELIC DENSITY

Theory:

I. Natural

Comes out automatically from the expansion of the Universe

Naturally leads to cold DM

II. Predictive

No dependence on initial conditions

Fixes coupling(s) $\Rightarrow$ signal in DD, ID & LHC

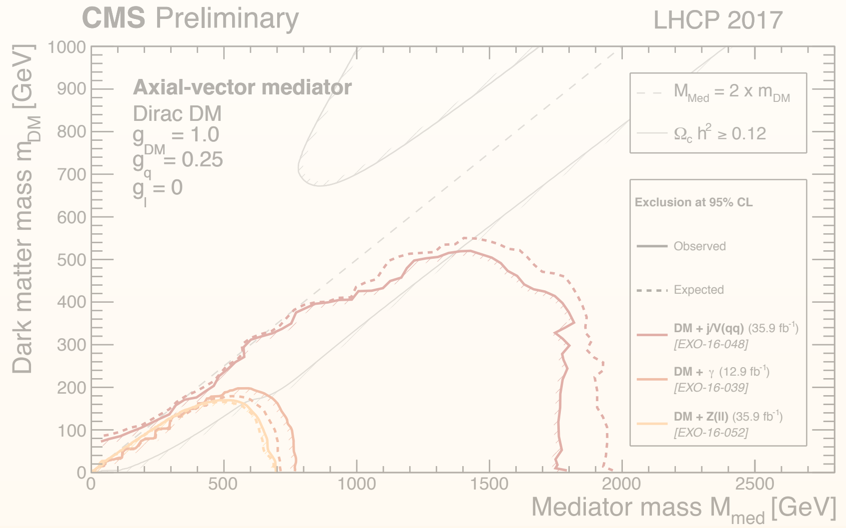
III. It is not optional

Overabundance constraint

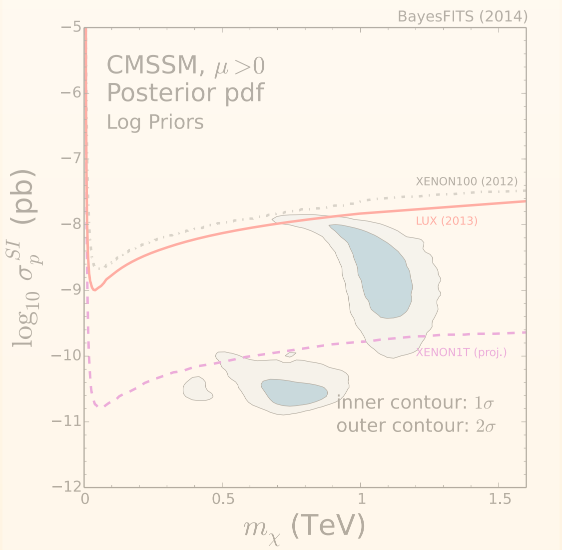
To avoid it one needs quite significant deviations from standard cosmology

Experiment:

…as a constraint:



…as a target:



"(…) besides the Higgs boson mass measurement and LHC direct bounds, the constraint showing **by far the strongest impact** on the parameter space of the MSSM is the **relic density**"

Roszkowski et al. '14

…as a pin:

When a dark matter signal is (finally) found: relic abundance can pin-point the particle physics interpretation

THERMAL RELIC DENSITY

STANDARD APPROACH

Boltzmann equation for $f_\chi(p)$:

$$E\left(\partial_t - H\vec{p}\cdot\nabla_{\vec{p}}\right) f_\chi = \mathcal{C}[f_\chi]$$

*assumptions for using Boltzmann eq:
classical limit, molecular chaos,...

...for derivation from thermal QFT
see e.g., 1409.3049

$\Downarrow$ integrate over p
(i.e. take 0th moment)

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_{\chi\bar\chi\to ij}\sigma_{\rm rel}\rangle^{\rm eq}\left(n_\chi n_{\bar\chi} - n_\chi^{\rm eq} n_{\bar\chi}^{\rm eq}\right)$$

where the thermally averaged cross section:

$$\langle\sigma_{\chi\bar\chi\to ij}v_{\rm rel}\rangle^{\rm eq} = -\frac{h_\chi^2}{n_\chi^{\rm eq} n_{\bar\chi}^{\rm eq}}\int\frac{d^3\vec{p}_\chi}{(2\pi)^3}\frac{d^3\vec{p}_{\bar\chi}}{(2\pi)^3}\,\sigma_{\chi\bar\chi\to ij}v_{\rm rel}\; f_\chi^{\rm eq} f_{\bar\chi}^{\rm eq}$$

$\Downarrow$

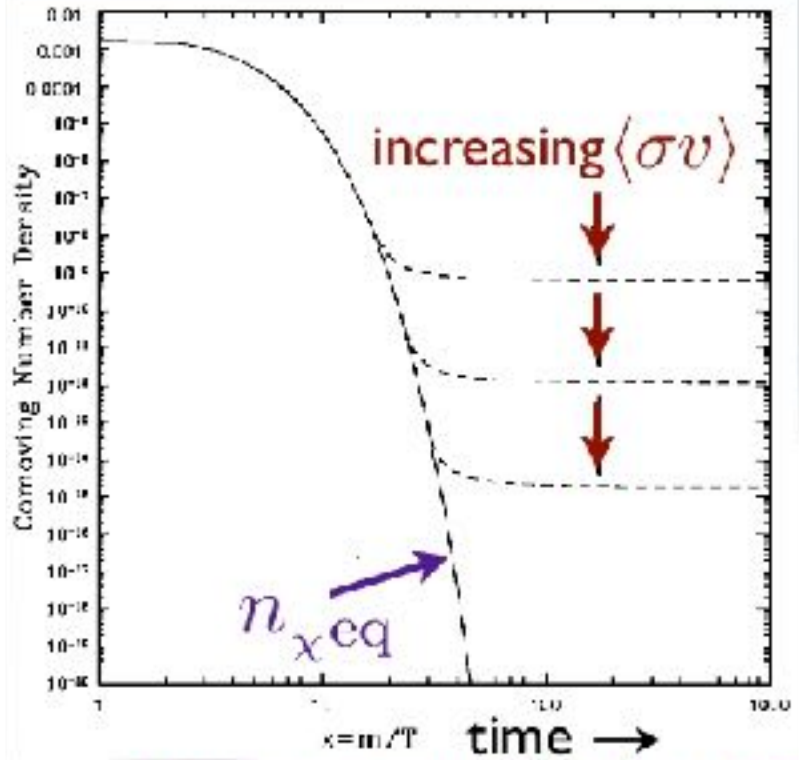


Fig.: Jungman, Kamionkowski & Griest, PR'96

Critical assumption:
kinetic equilibrium at chemical decoupling

$$f_\chi \sim a(\mu) f_\chi^{\rm eq}$$

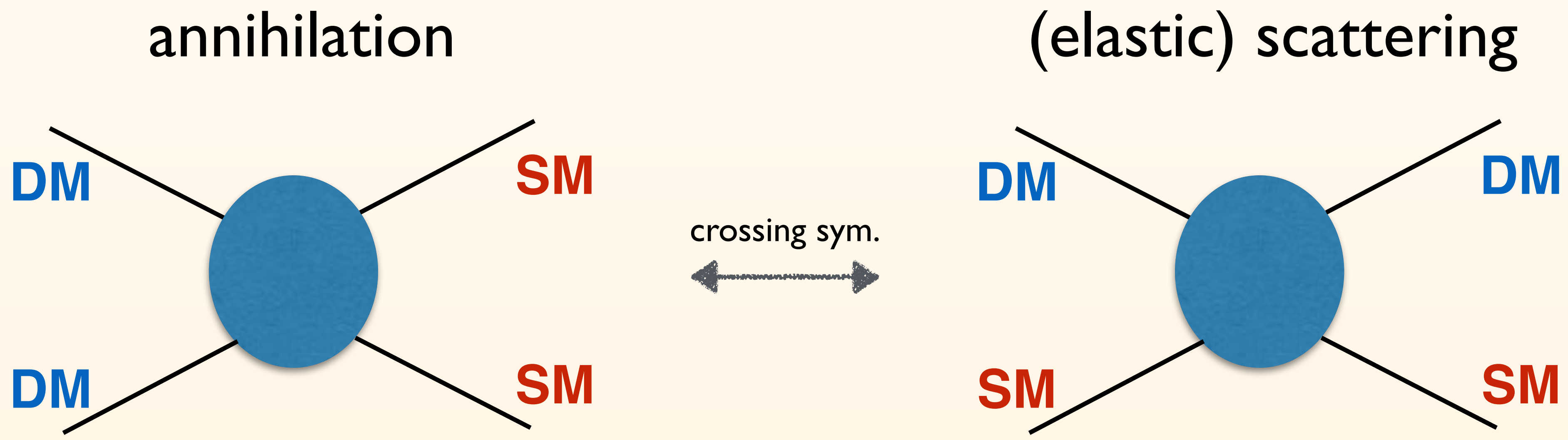
INTERLUDE: WHAT IF KD VERY EARLY?

Recall: in *standard* thermal relic density calculation:

Critical assumption:

kinetic equilibrium at chemical decoupling

$$f_\chi \sim a(\mu) f_\chi^{\mathrm{eq}}$$



$$\sum_{\mathrm{spins}} \left|\mathcal{M}^{\mathrm{pair}}\right|^2 = F(p_1, p_2, p_1', p_2') \quad >> \quad \sum_{\mathrm{spins}} \left|\mathcal{M}^{\mathrm{scatt}}\right|^2 = F(k, -k', p', -p)$$

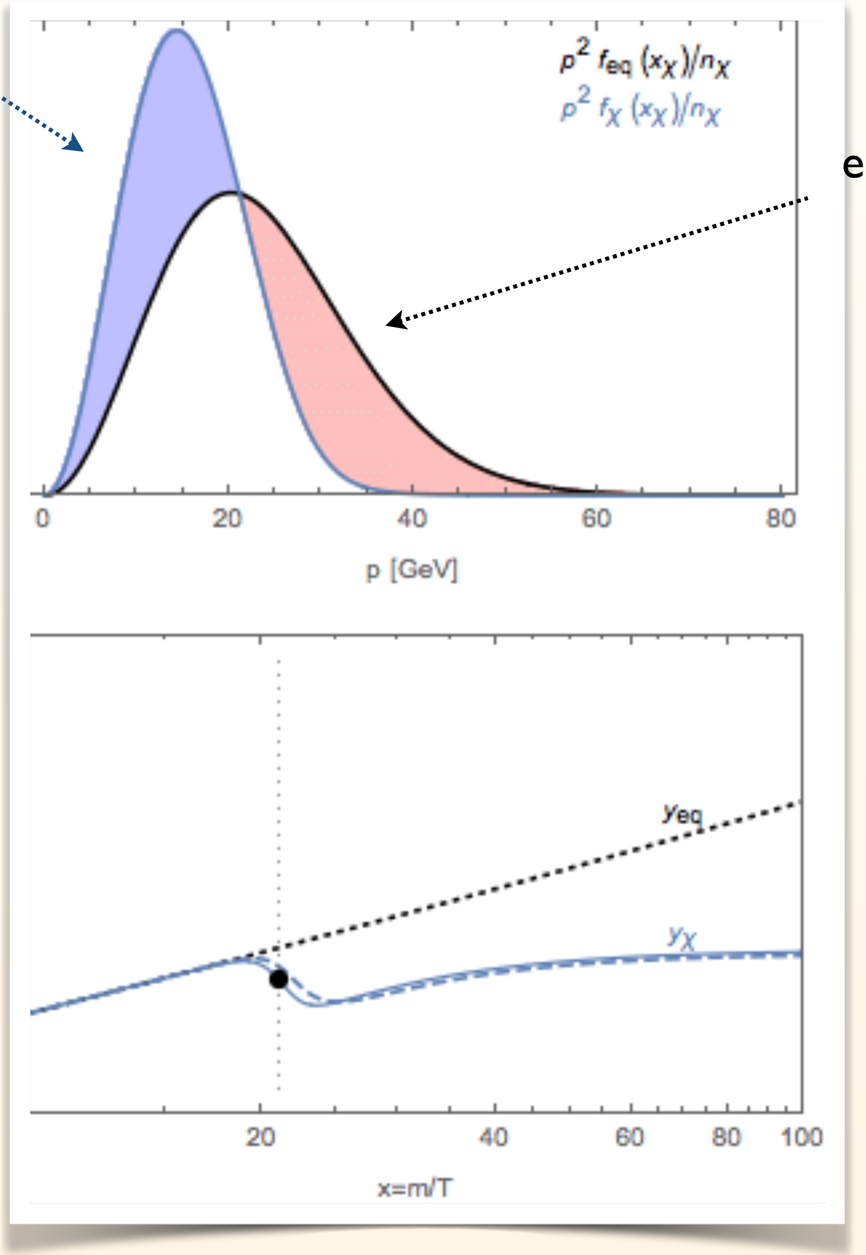
... then *standard* thermal relic density calculation fails!

T. Binder, T. Bringmann, M. Gustafsson and AH, Phys.Rev. D96 (2017)

FULL PHASE-SPACE EVOLUTION

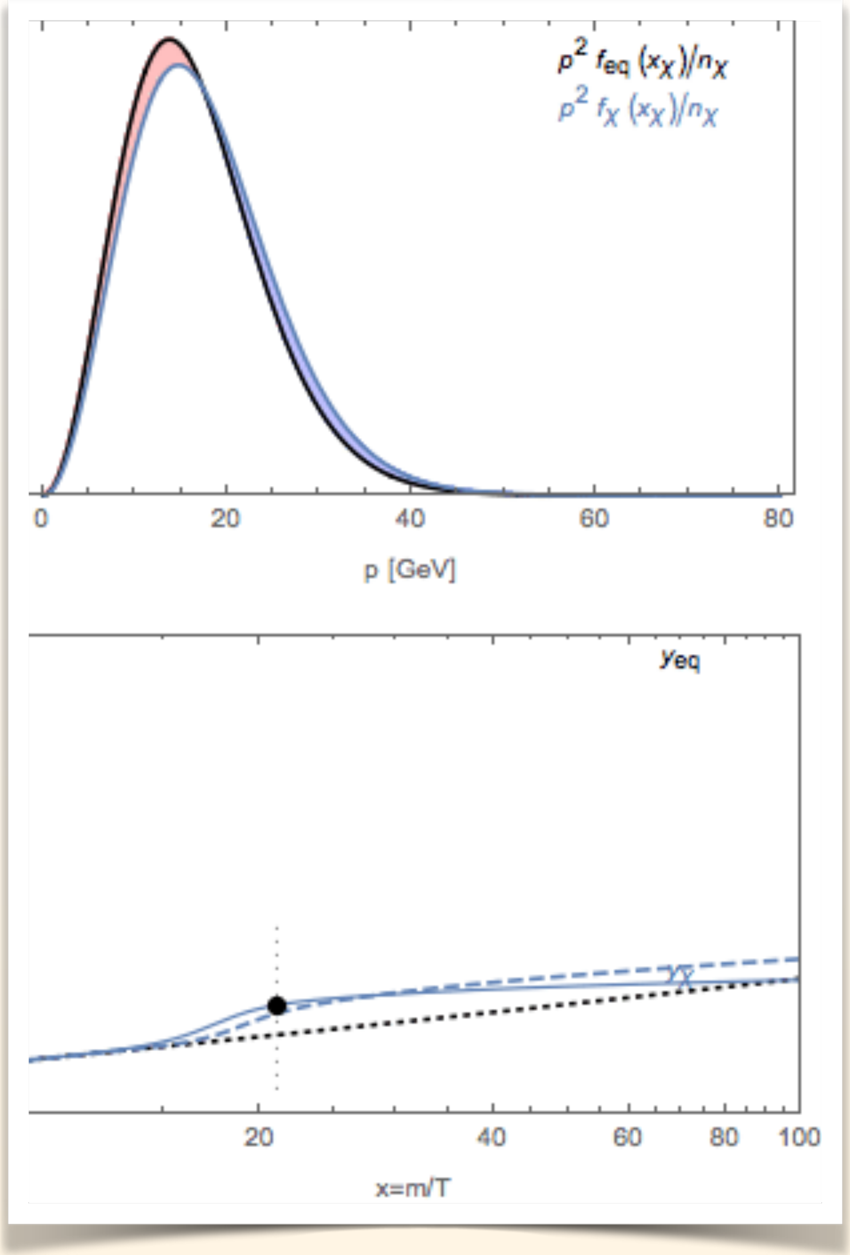
m_{DM} = 58 GeV

blue - full solution for f_{DM} at T_{DM}



black - equilibrium at T_{DM}

m_{DM} = 62.5 GeV



significant deviation from equilibrium shape already around freeze-out

→ effect on relic density largest, both from different T and f_{DM}

large deviations at later times, around freeze-out not far from eq. shape

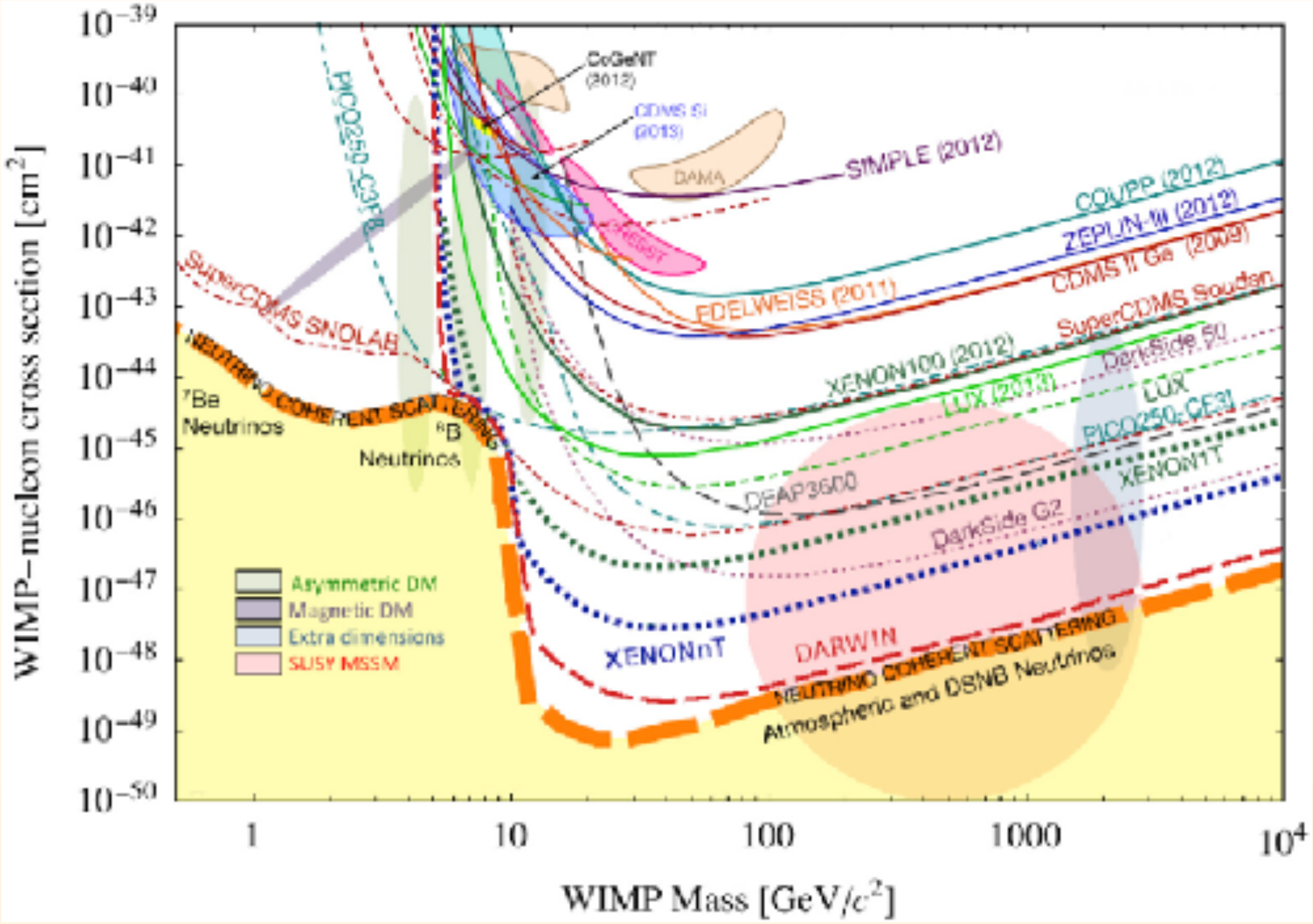
→ effect on relic density ~only from different T

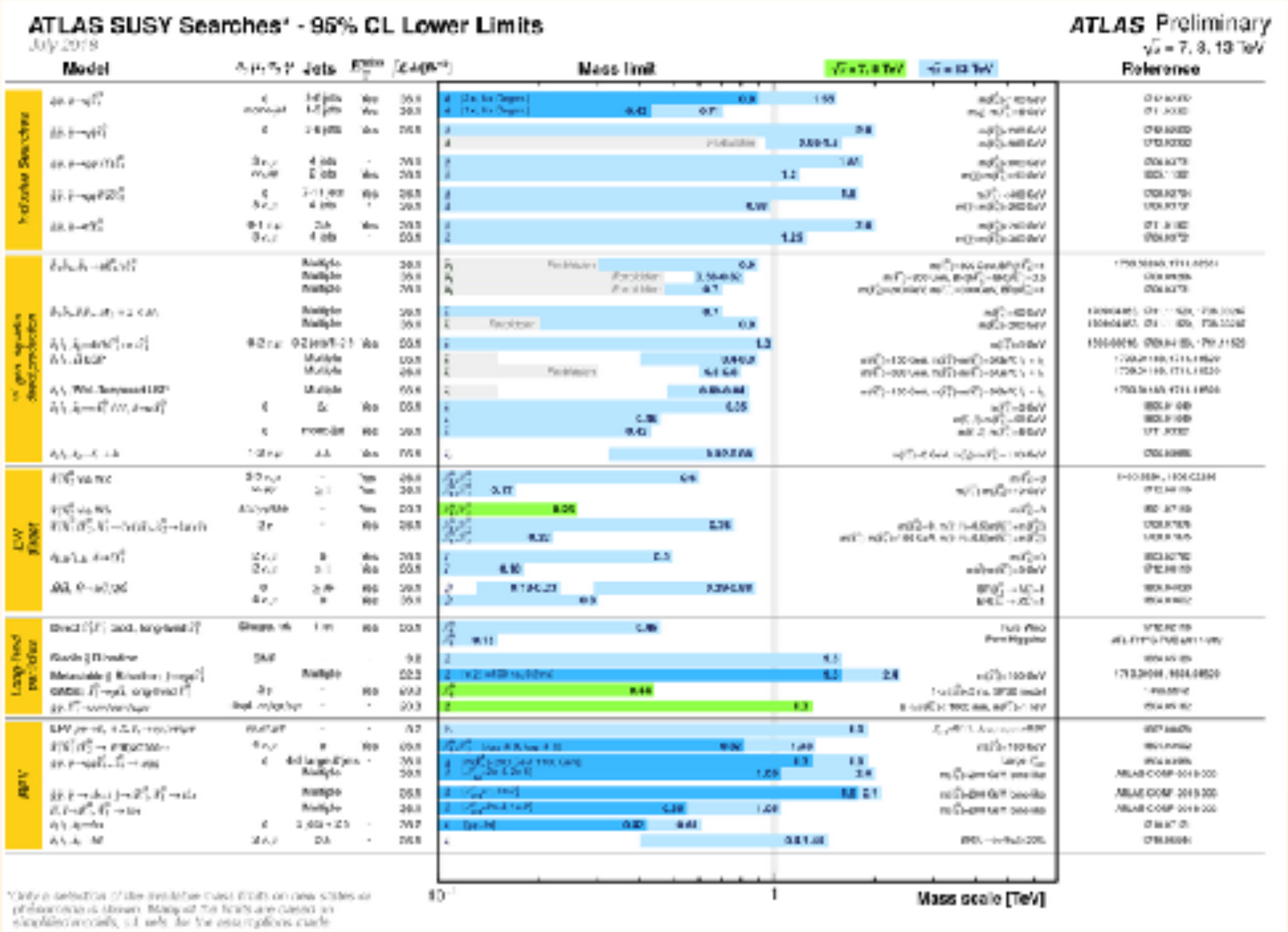
CURRENT LIMITS

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!





ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

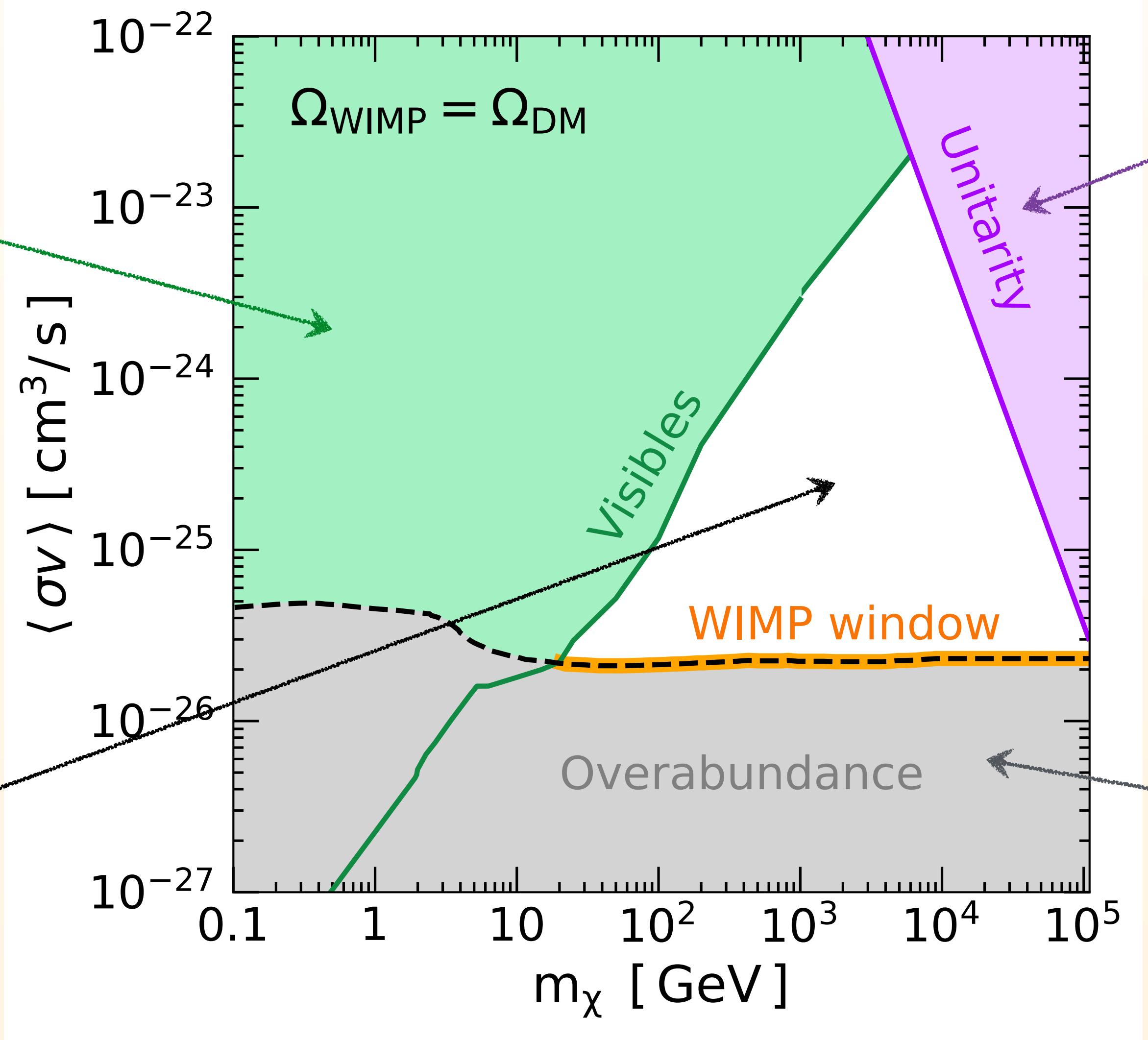
Common feeling: low scale SUSY in "dire restraints"

*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!

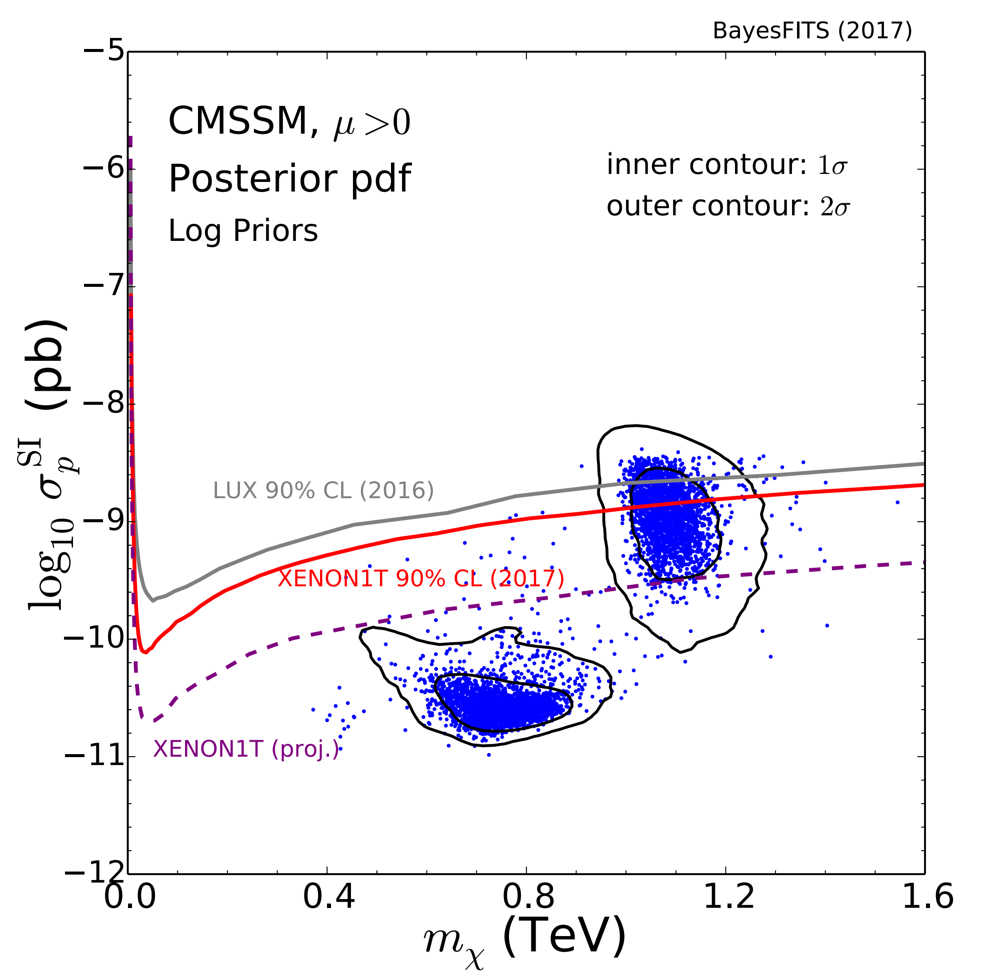
too much dark matter

R. Leane *et al*; 1805.10305

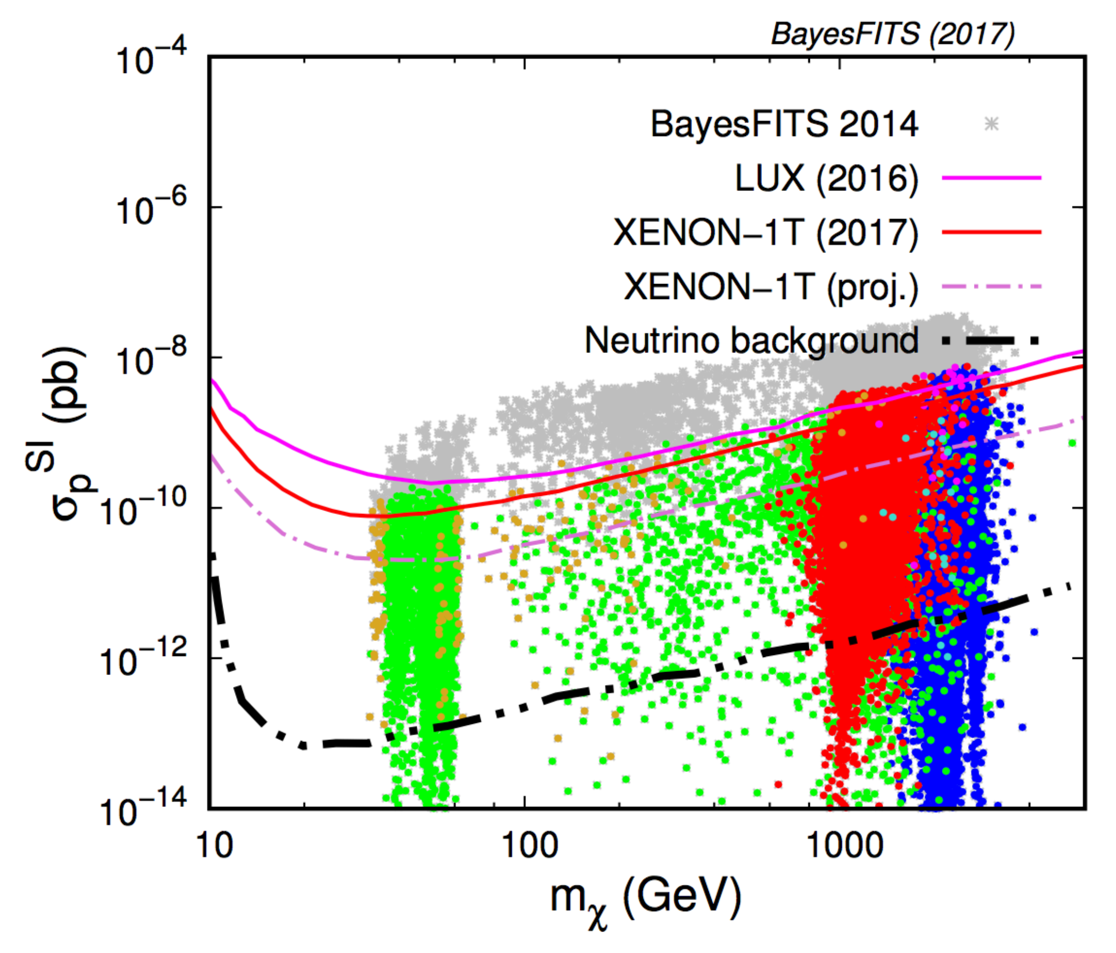
SUSY WIMP

ALSO ACTUALLY QUITE OK

CMSSM points satisfying all the constraints and giving good DM candidate:



generalization to the full pMSSM:



CMSSM- constrained Minimal Supersymmetric Standard Model
pMSSM- phenomenological Minimal Supersymmetric Standard Model

CHAPTER #2

DM AT THE TEV SCALE

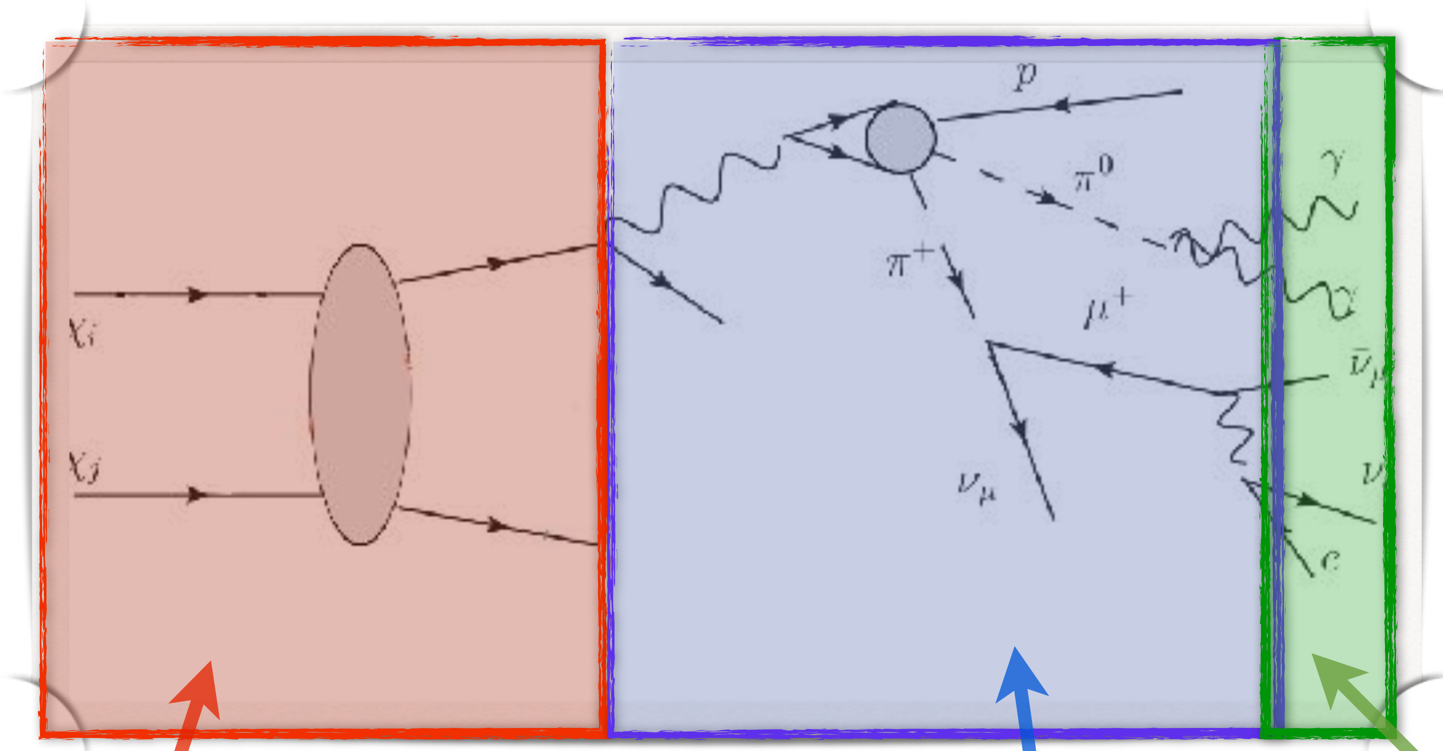
WHY NOT TO GO TO TEV…

- 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)
- We have already seen that **even SUSY** has regions in that regime and there are many more models on the market
- Fun: new phenomena and new challenges appear

INDIRECT DM DETECTION



primary annihilation process

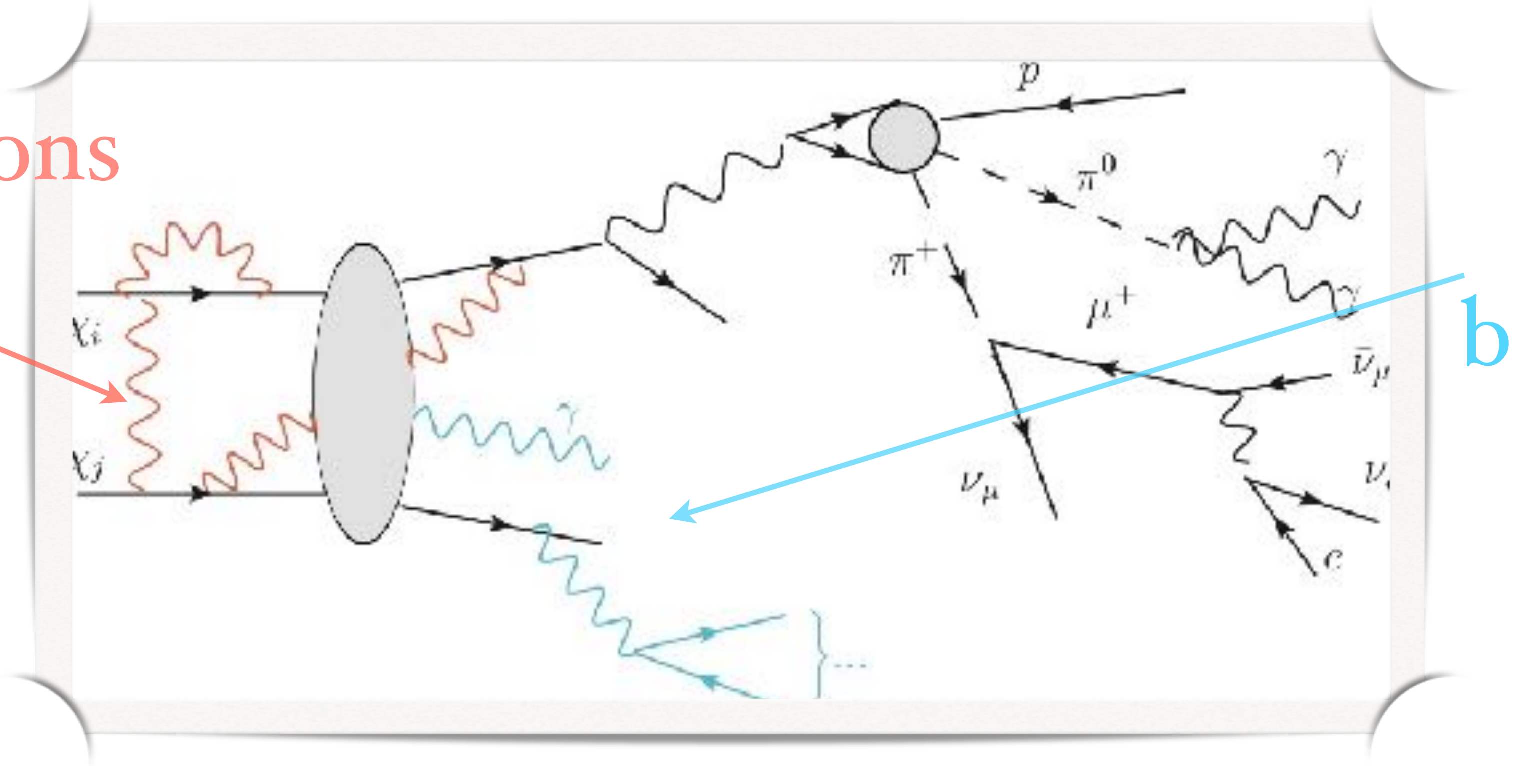
shower development: splitting, hadronization, fragmentation/decay (e.g. PYTHIA)

indirect detection

This Feynman diagram is an approximation of lowest order in perturbation theory!

Actual process can contain many more interactions

EW CORRECTIONS



loop corrections

internal bremsstrahlung

enhancement by large (Sudakov) logarithms:

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

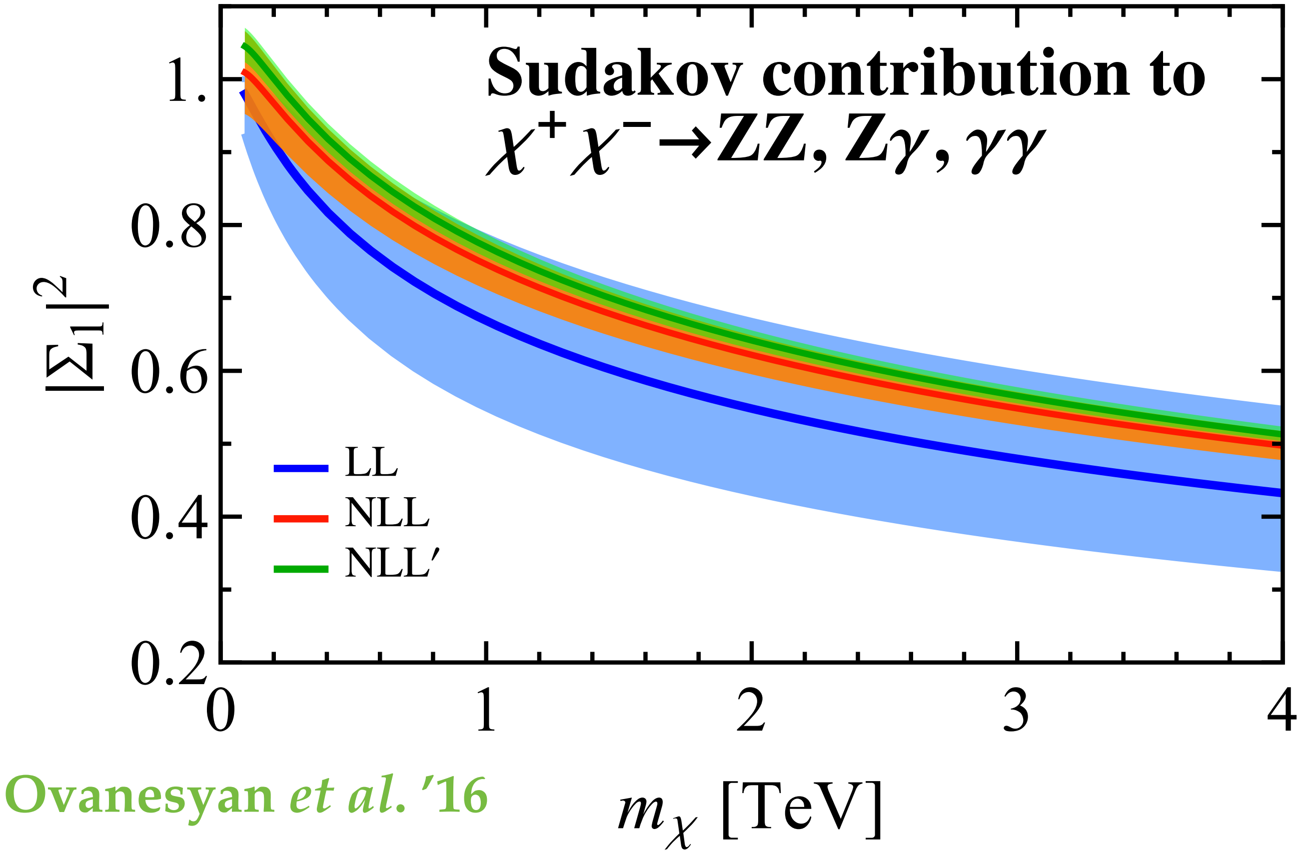
$$m = 1\ \text{TeV},\ \alpha_2 \approx \frac{1}{30} \quad \Rightarrow \quad \approx 0.17 \qquad \approx 0.86$$

Ciafaloni *et al.*, Nucl. Phys. B589 (2000) 359

LL RESSUMATION

Using EFT techniques the contribution for large logarithms can be summed to all orders:

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



Ovanesyan *et al.* '16

This is a relatively complicated computation, which does **not** have to be done if DM is lighter!

SOMMERFELD EFFECT

re-summation

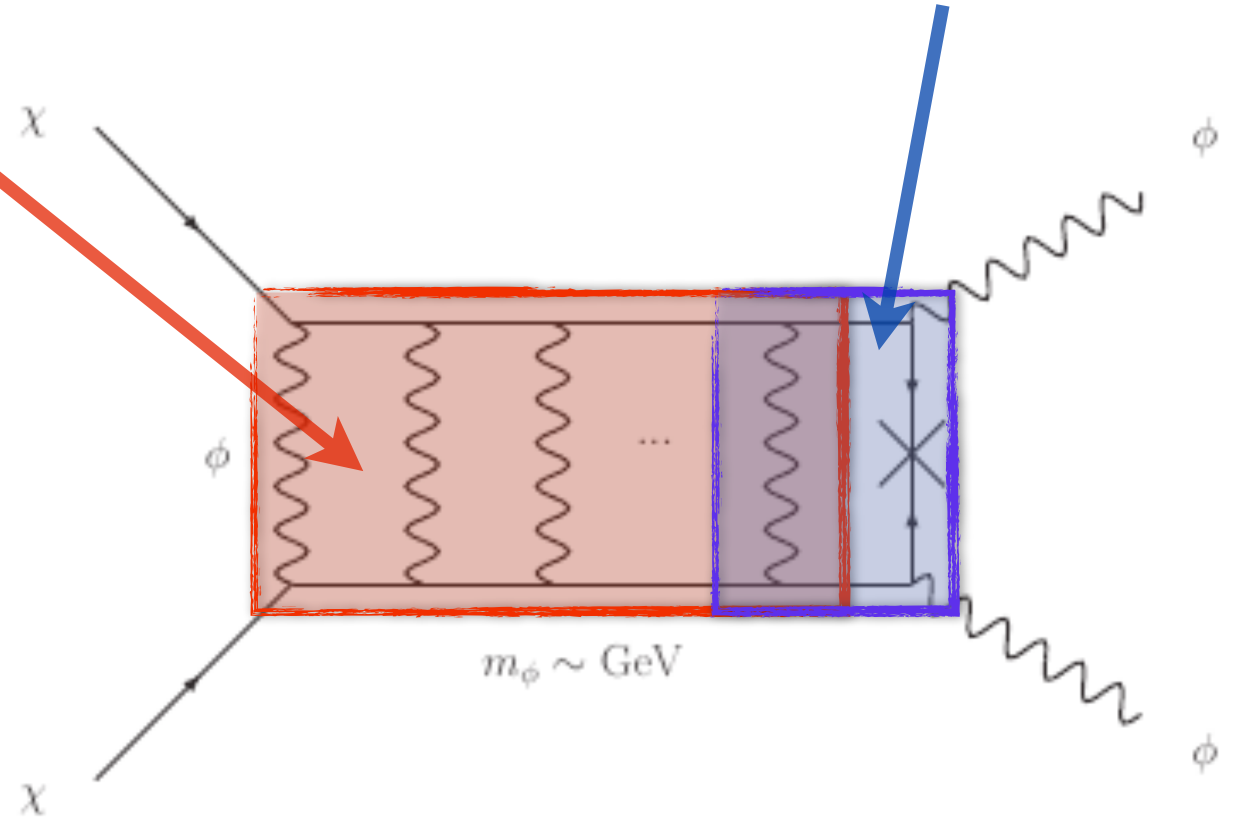
one-loop $\propto \alpha \frac{m_\chi}{m_\phi}$

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

force range | Bohr radius

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

kinetic energy | Bohr energy



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

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

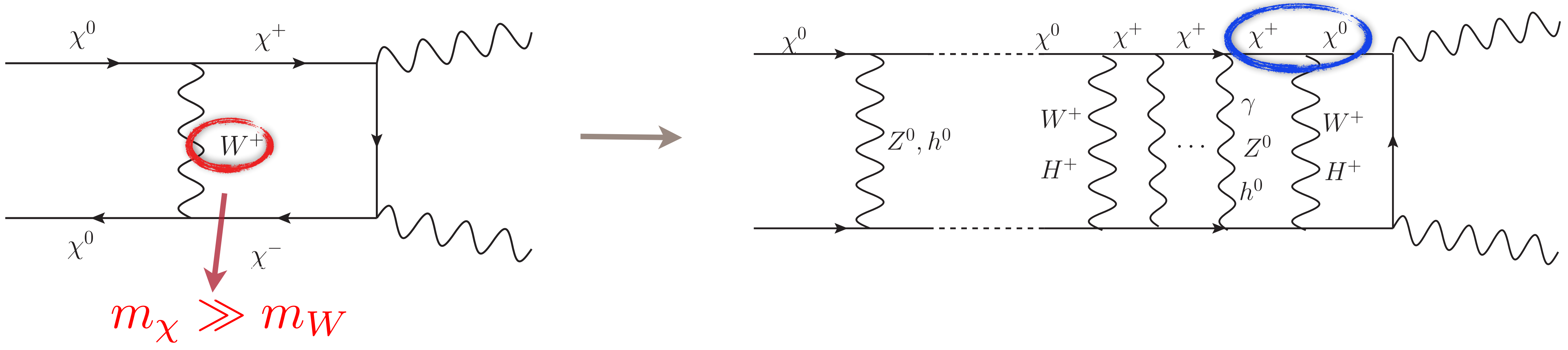
FROM EW INTERACTIONS

Hisano *et al.* '04,'06

force carriers in the MSSM:

$\cancel{\gamma}, W^{\pm}, Z^0, h_1^0, h_2^0, H^{\pm}$

$\delta m \ll m_\chi$



$m_\chi \gg m_W$

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

on top of that resonance structure

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

for the relic density

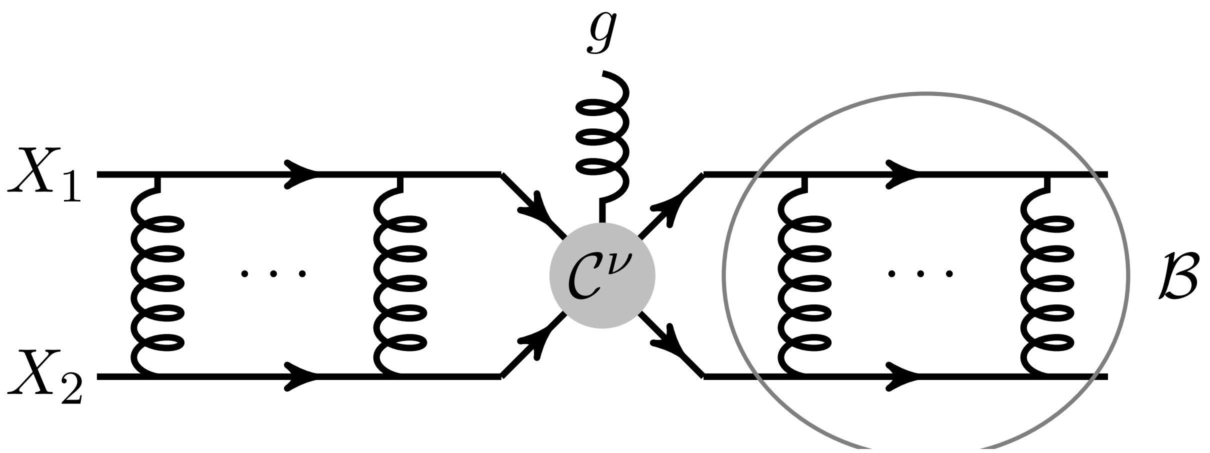
AH, R. Iengo, P. Ullio. '10

AH '11

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

BOUND STATE FORMATION

see papers by **K. Petraki** et al. '14-18

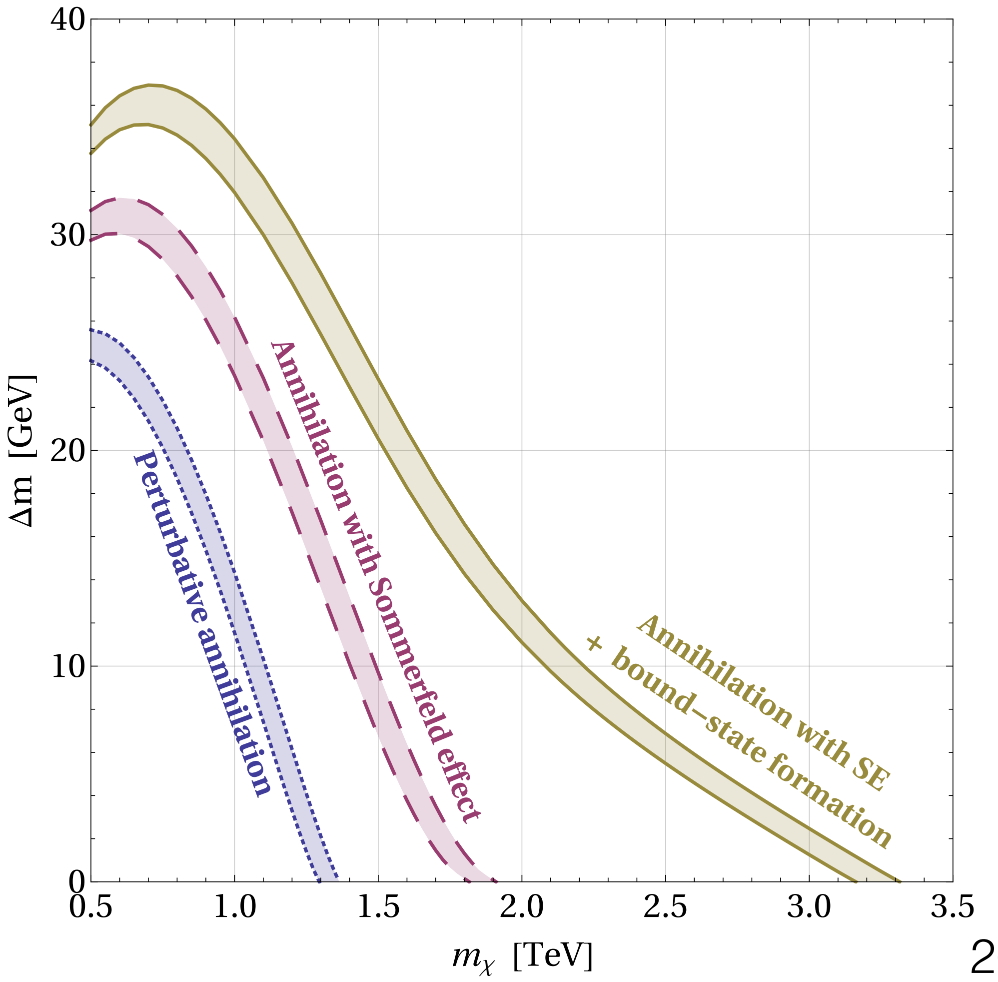


can happen when long range force between DM states is present

free DM states

DM bound state

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

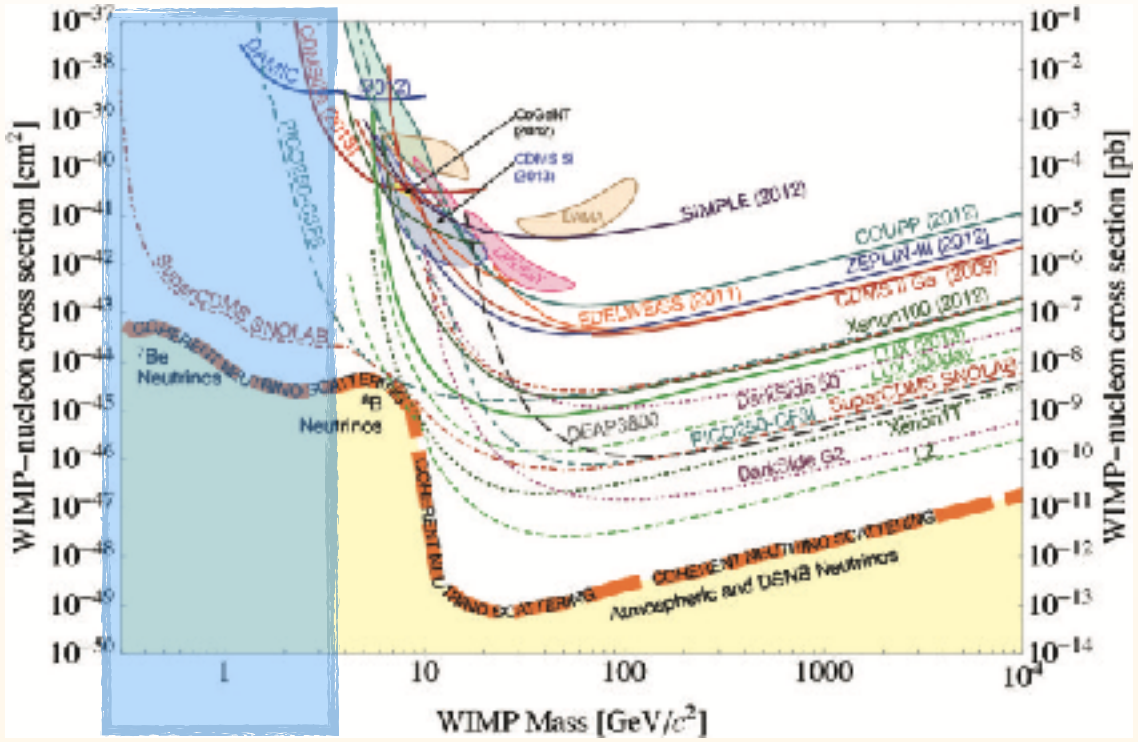


CHAPTER #3

LIGHT DM

MeV-GeV scale DM

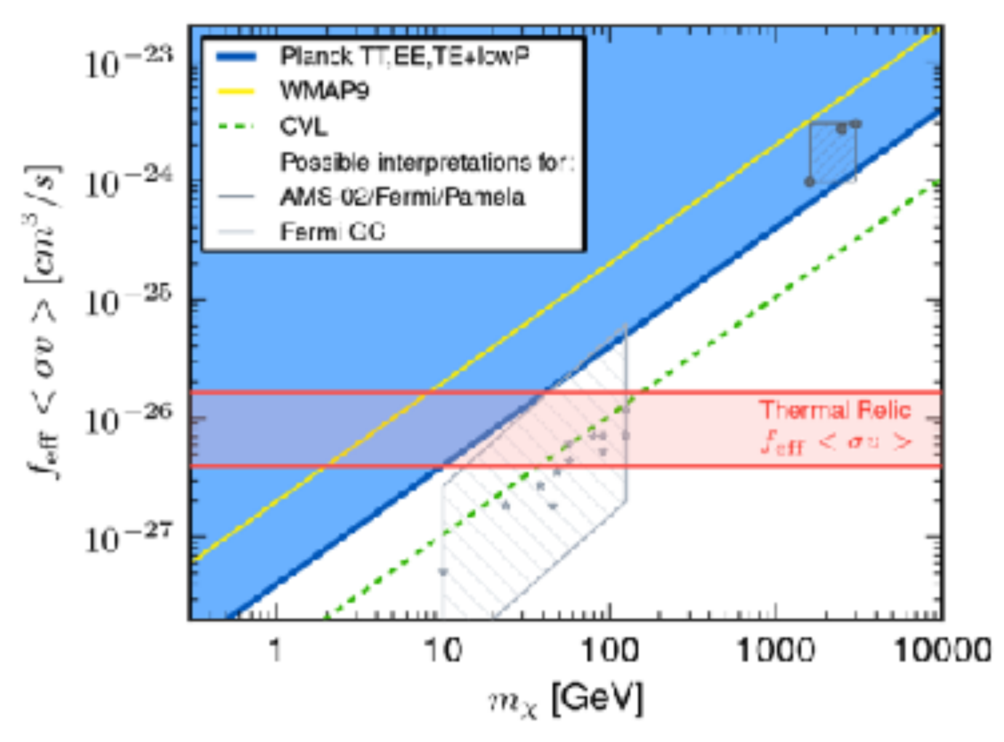
Below the sensitivity threshold for most Direct Detection experiments



But needs **very weak** coupling to visible sector:

i. light = easier to produce at colliders

ii. limits from cosmology are quite strong



iii. thermal relic density ~(mass/coupling)^2

Are there any upsides?

LIGHT DM MOTIVATION

Few arguments in favor of MeV-GeV dark sector:

Mass scale of known visible matter

→ just an observation…

Natural region for hidden dark sectors coupled to SM at loop level

→ coupling to SM suppressed radiatively instead of due to heavy mass scale

For fixed mass density - lighter DM means higher number density

→ stronger/different indirect detection signals

DM self-interactions: $0.1\,\mathrm{cm}^2\,\mathrm{g}^{-1} < \langle \sigma_T \rangle_{30}/m_\chi < 10\,\mathrm{cm}^2\,\mathrm{g}^{-1}$

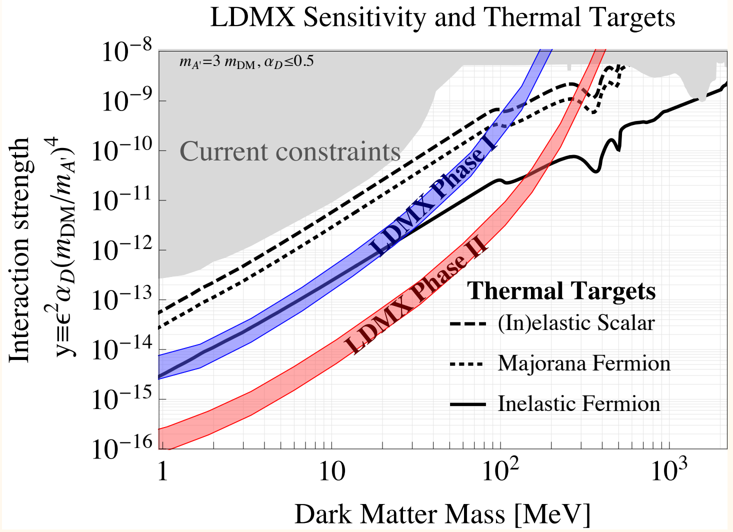
→ the lighter, the stronger

DETECTION OF LIGHT DM

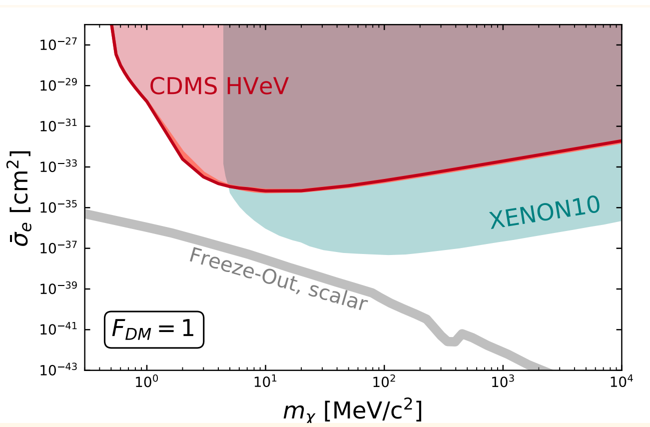
List of strategies:

1. standard Indirect Detection - looking at data in lower energies

2. Fixed target accelerator experiments, e.g. LDMX →



3. Direct Detection - scattering on electrons

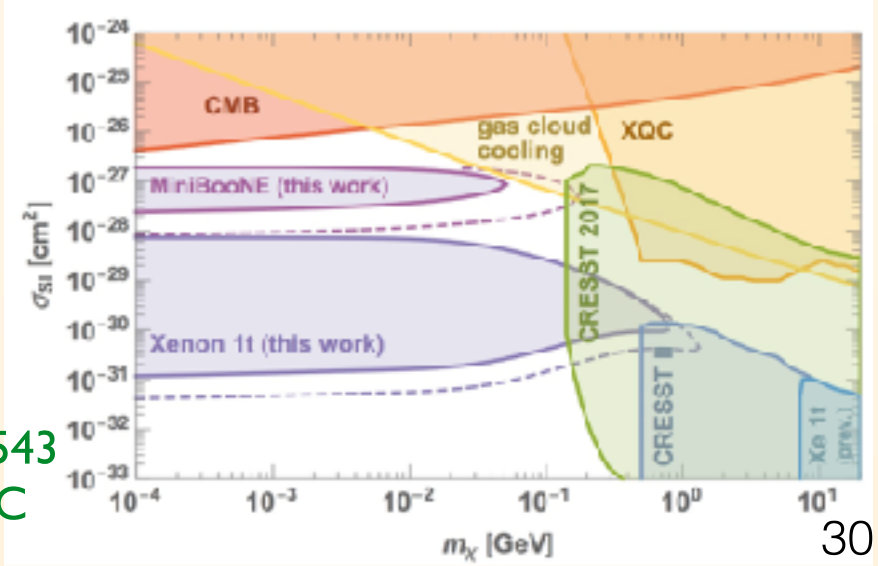


4. Scattering (elastic or inelastic) on CRs in present and Early Universe

see e.g. Capiello et al. 1810.07705

5. …

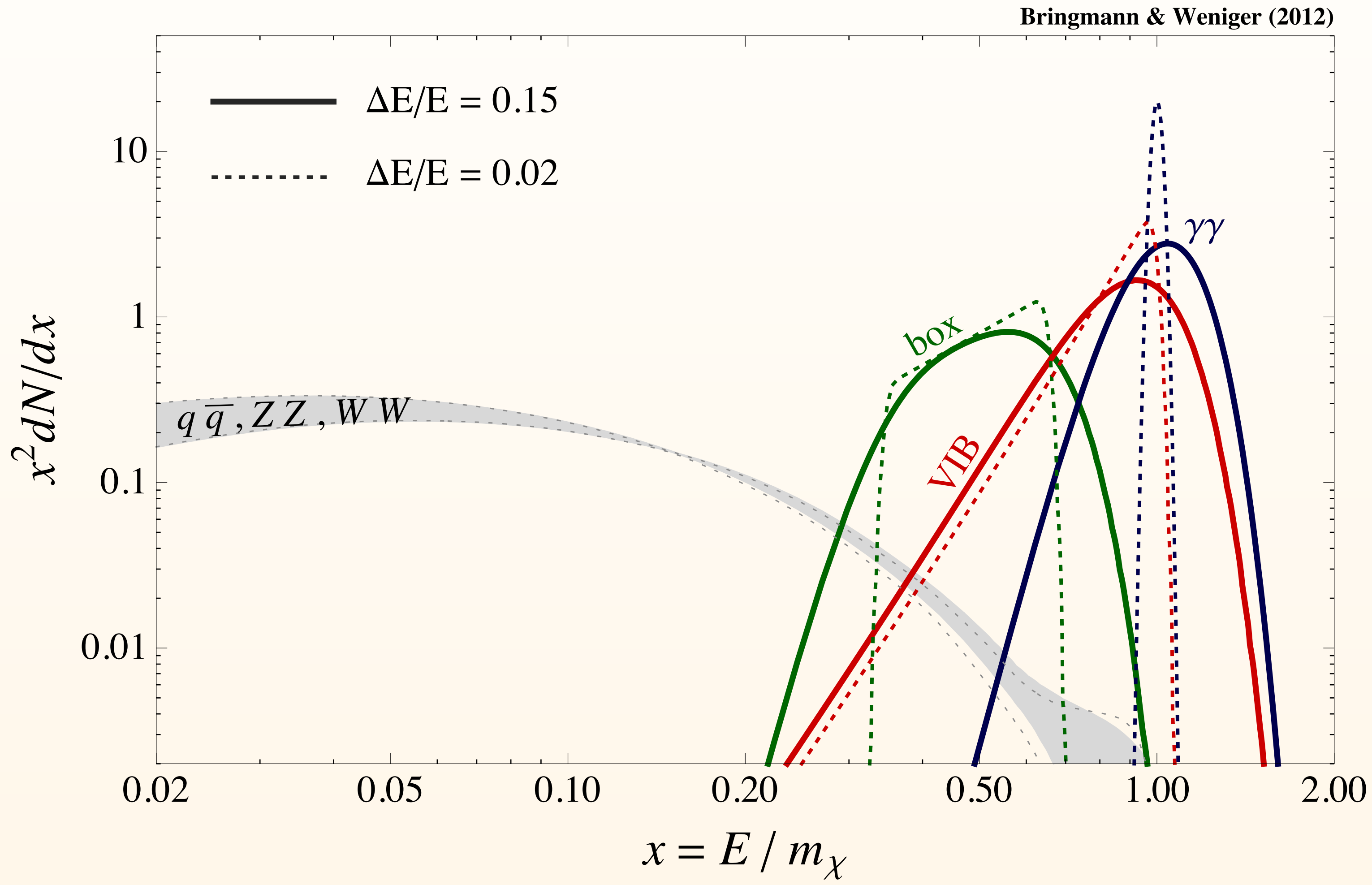
Some of the limits:



T. Bringmann, M. Pospelov; 1810.10543
- to see more join our Bi-weekly JC
today at 2.15pm!

SPECTRAL FEATURES

WHAT CAN WE LOOK FOR?



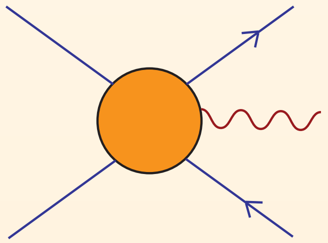
Gamma-ray lines

$\chi\chi \to \gamma\gamma$

generically loop-suppressed

Internal Bremsstrahlung

$\chi\chi \to \bar{f} f \gamma$



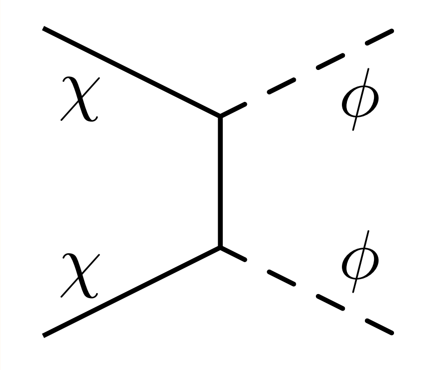
Box-shaped

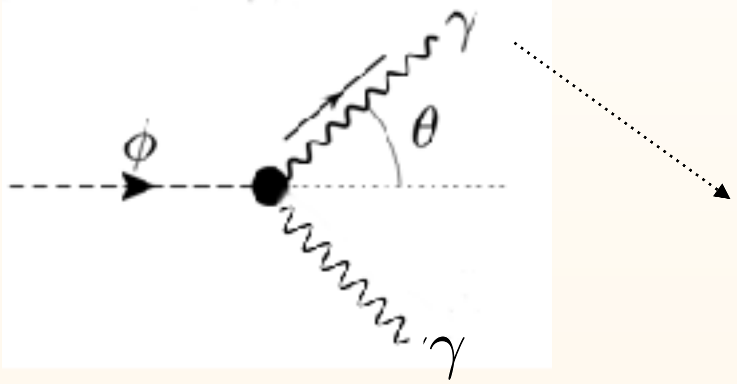
$\chi\chi \to \phi\phi \implies \phi \to \gamma X$

tree-level;
cascade decay

GAMMA-RAY BOXES

Consider a process: $\chi\chi \to \phi\phi \Rightarrow \phi \to \gamma\gamma$





In the LAB frame:

$$E_\gamma = \frac{m_\phi^2}{2\,m_{DM}}\left(1-\cos\theta\sqrt{1-\frac{m_\phi^2}{m_{DM}^2}}\right)^{-1}$$

If ϕ produced at rest $\longrightarrow$ monochromatic line...

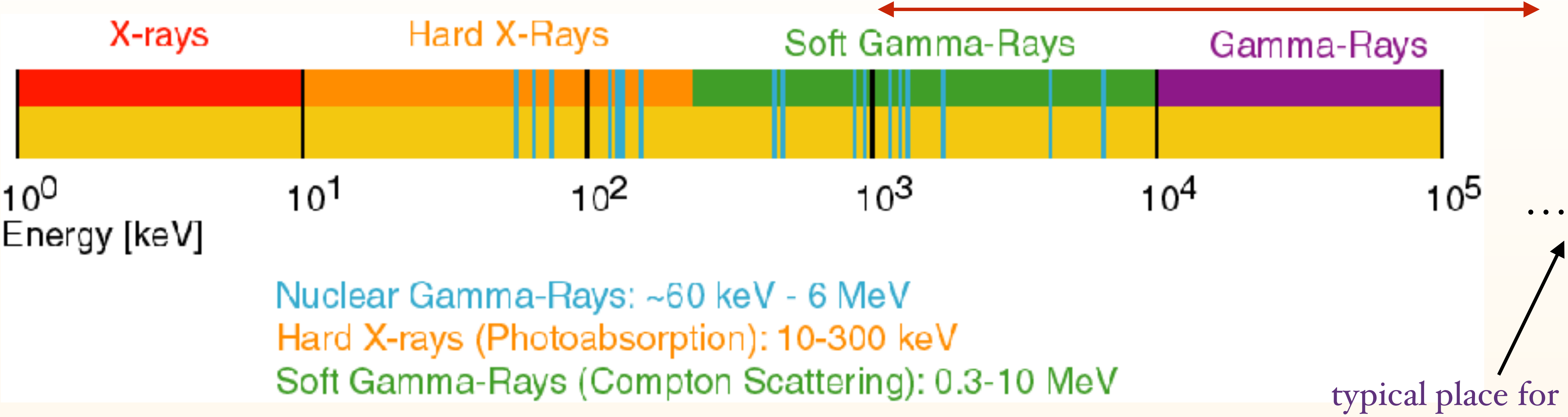
...if not, boosted to give a box shaped spectrum:

$$\frac{dN_\gamma}{dE} = \frac{2}{\Delta E}\left[\Theta(E-E_-) - \Theta(E-E_+)\right]$$

(For narrow boxes I may use the box and line terms interchangeably...)

KNOWN GAMMA-RAY LINES

„MeV-gap”

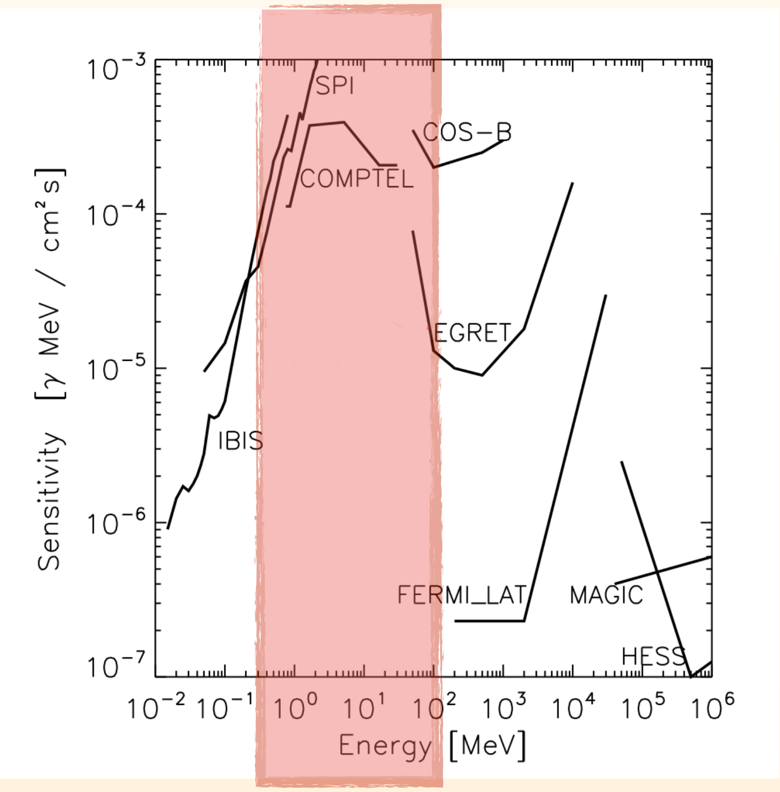


....

typical place for
gamma-line
searches;

figure borrowed from Steve Boggs ’07

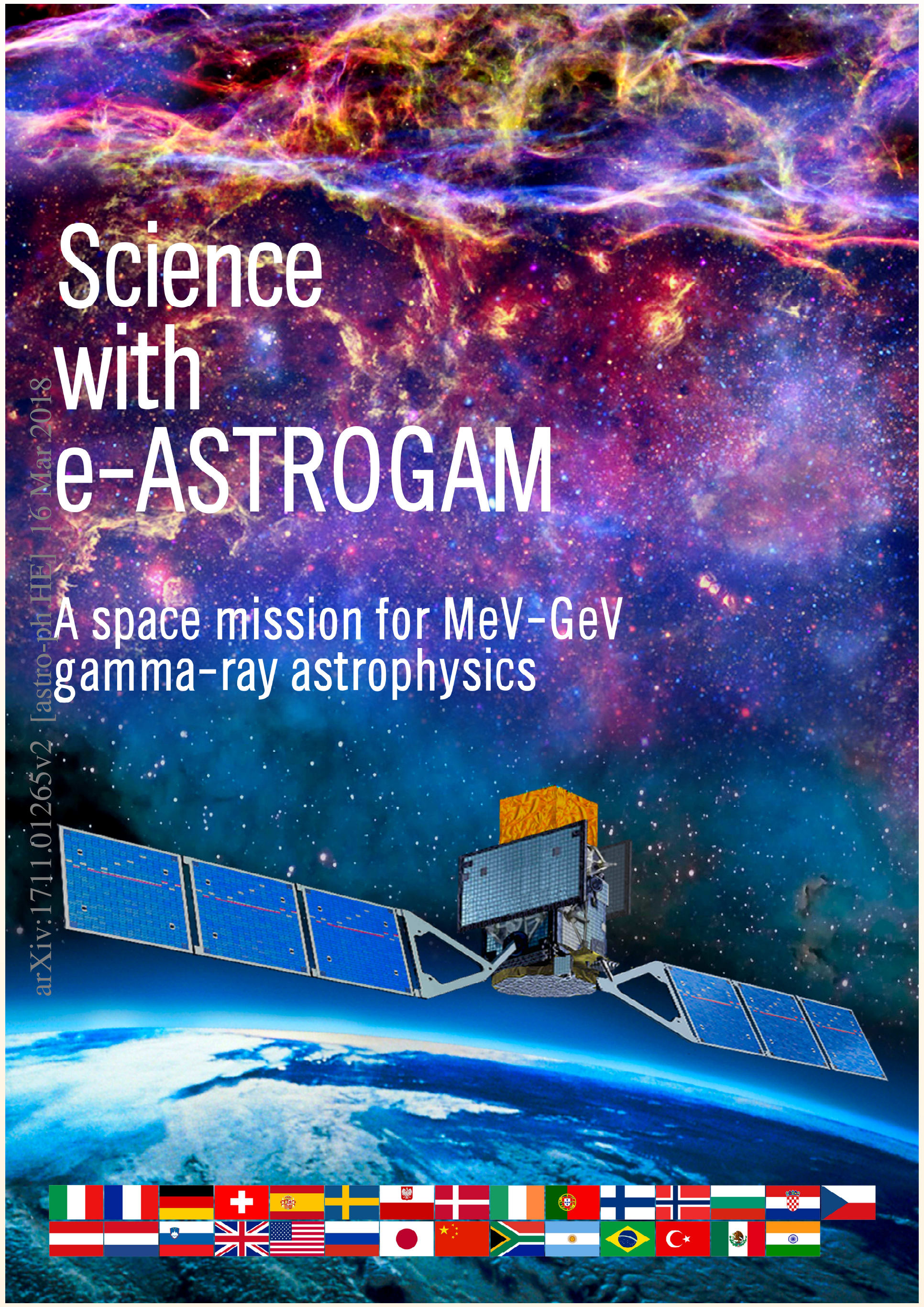
The MeV-gap contains a timely sweet
spot for spectral features searches:
no background lines + scarce complementary data

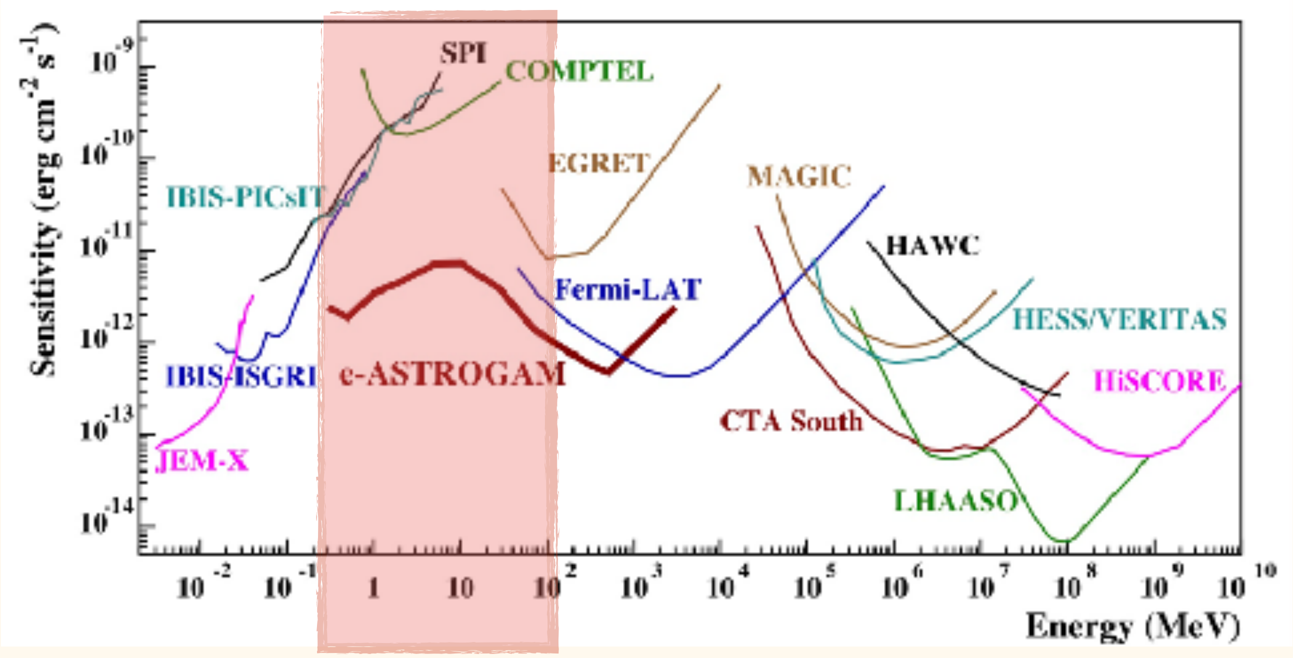


„MeV-gap”

e-ASTROGAM http://eastrogam.iaps.inaf.it

submitted (w/o success) to M5 ESA Call





Main features:

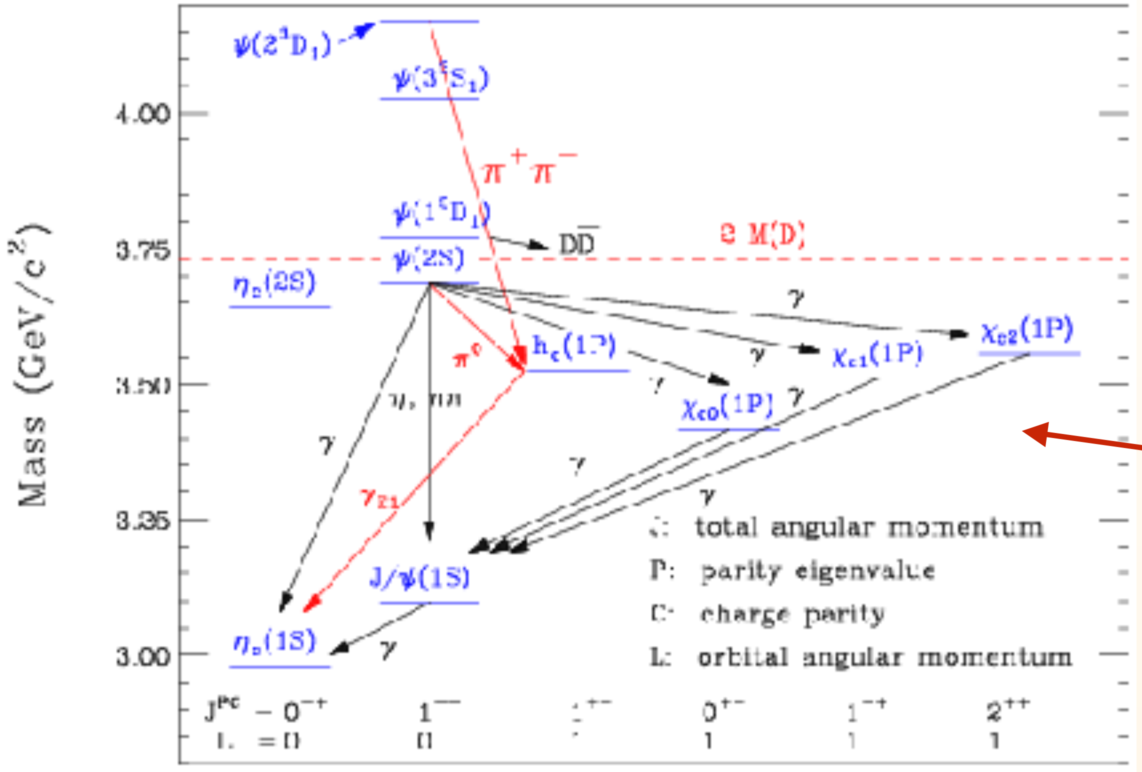
- Broad energy coverage (0.3 MeV to 3 GeV);
- Large FoV (>2.5 sr), ideal to detect transient sources and hundreds of GRBs;
- Pioneering polarimetric capability for both steady and transient sources;
- Optimized source identification capability obtained by the best angular resolution (about 0.15 degrees at 1 GeV);
- <ms trigger and alert capability for GRBs and other transients;
- Combination of Compton and pair-production detection techniques

A. De Angelis (ed) et al., JHEAp 19 (2018) 1-106
@UiO: T. Bringmann, AH, A. Raklev, J. Van den Abeele

MESON SPECTROSCOPY

Transitions between meson states lead to monochromatic pions or photons:

E.g.:



energy scale of the lines: O(100 MeV)

B and D mesons are composed from one light and one heavy quark

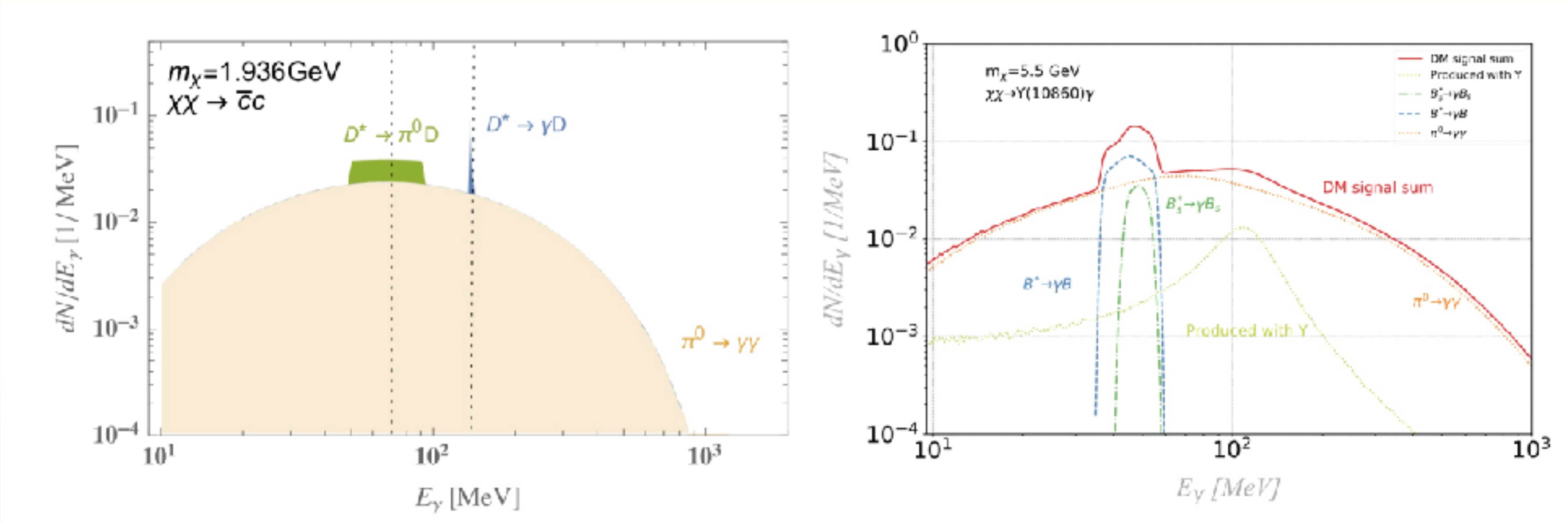
can be produced in annihilation to $b\bar{b}$ and $c\bar{c}$

do not show up in astrophysical background

MeV SPECTRAL FEATURES

T. Bringmann, A. Galea, AH and Ch. Weniger; Phys.Rev. D95 (2017)

Spectral boxes coming from **excited meson** decays:

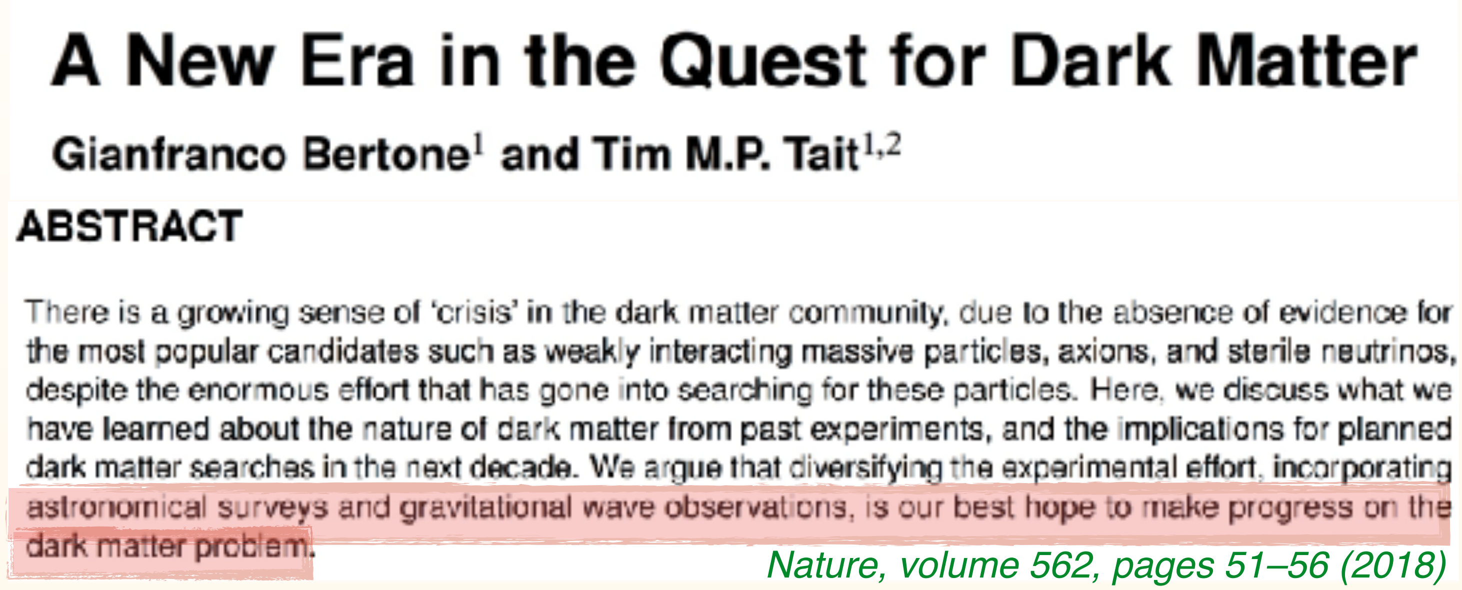


…and from formation of **bound states** with accompanying photon emission

A. Raklev, I. Strümke, J. van den Abeele

A NEW HOPE?

(INSTEAD OF CONCLUSIONS)



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".*

… but precision cosmology & astrophysics has a potential to provide the so-much needed observational input and show which way to follow

In any case a lot of physics still awaits to be understood in how the Dark Matter came to life and how it can reveal itself to us

P.S.

… SO, WHAT WILL IT BE THEN?

On one hand a decent, robust and well motivated theory (WIMP) on which you can still safely bet… though perhaps bit rusty now

On the other new challenging ideas and mechanisms, that might bring some new fresh air… but first have to prove their worth

vs.

(Though we'll probably wait bit longer than a month to see what DM theory will prevail)