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WEAKLY-INTERACTING MASSIVE PARTICLES AND WHERE TO FIND THEM

a minimal journey through the forest of dark matter searches

Istituto Nazionale di Fisica Nucleare

From the conclusions of a keynote talk
at a US conference in 2015:

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"Nothing is as hard as looking for a black cat
in a dark room, especially if there is no cat."

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From the conclusions of a keynote talk
at a US conference in 2015:

~~"Nothing is as hard as looking for a black cat in a dark room, especially if there is no cat."~~

we'll try to cover:

- what is Dark Matter
- which ideas make sense to look for it
- how far we are from answering

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Why we look for WIMPs

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MASS THROUGH LIGHT

naive astronomy: measure **mass** by observing **light**

$$\frac{M_\odot}{L_\odot} = 5.1 \cdot 10^3\,\mathrm{kg/W}$$

1930s: this "luminous mass" does not equal gravitational mass

look at motion of stars in galactic plane, or galaxies in Coma cluster

$$F(r) = G\frac{mM(r)}{r^2} = m\frac{v^2}{r} \Longrightarrow v(r) = \sqrt{\frac{GM(r)}{r}} \propto 1/\sqrt{r}$$

from emitted light (and assumed M/L ratio)

from redshift measurements

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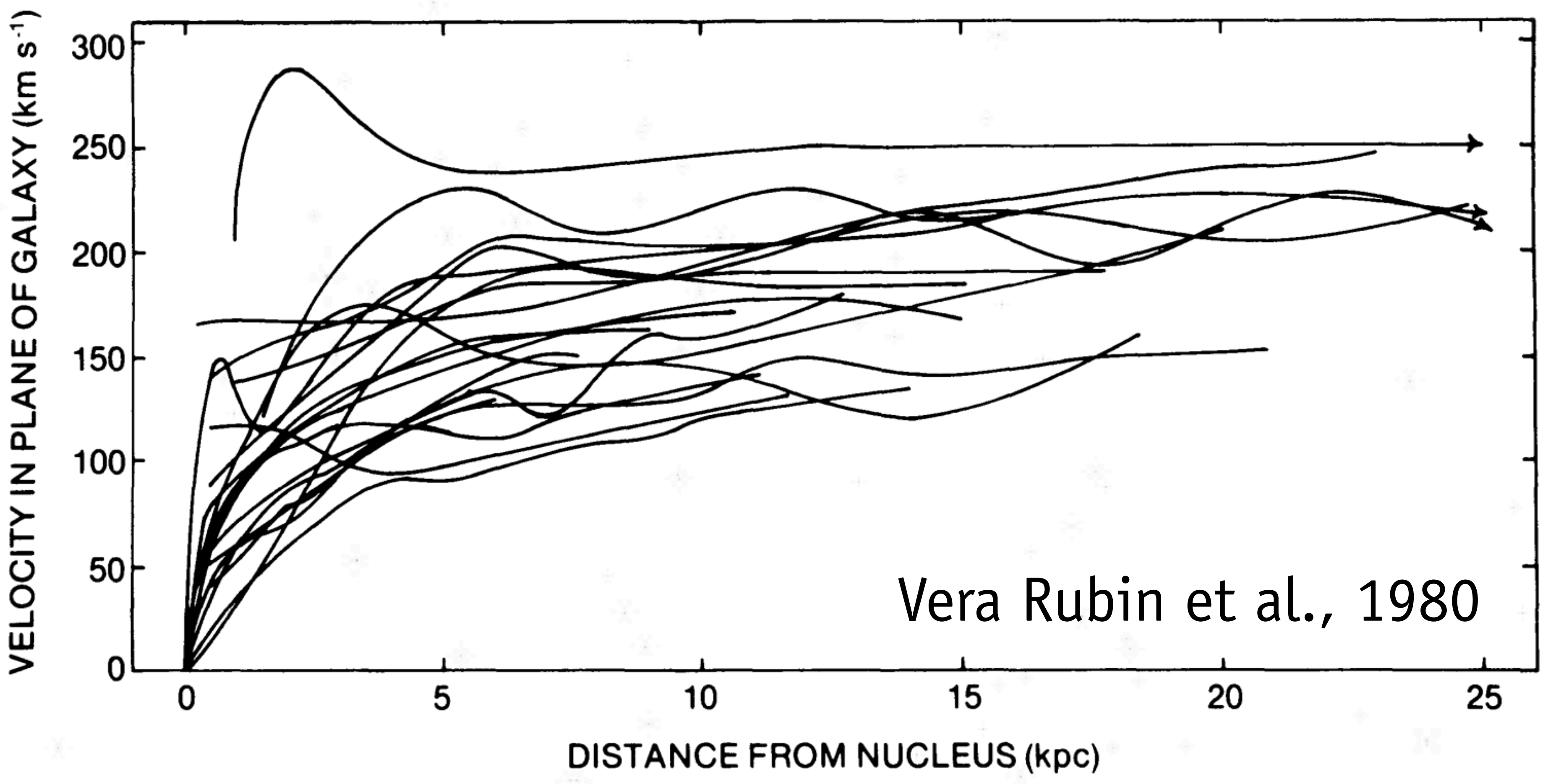
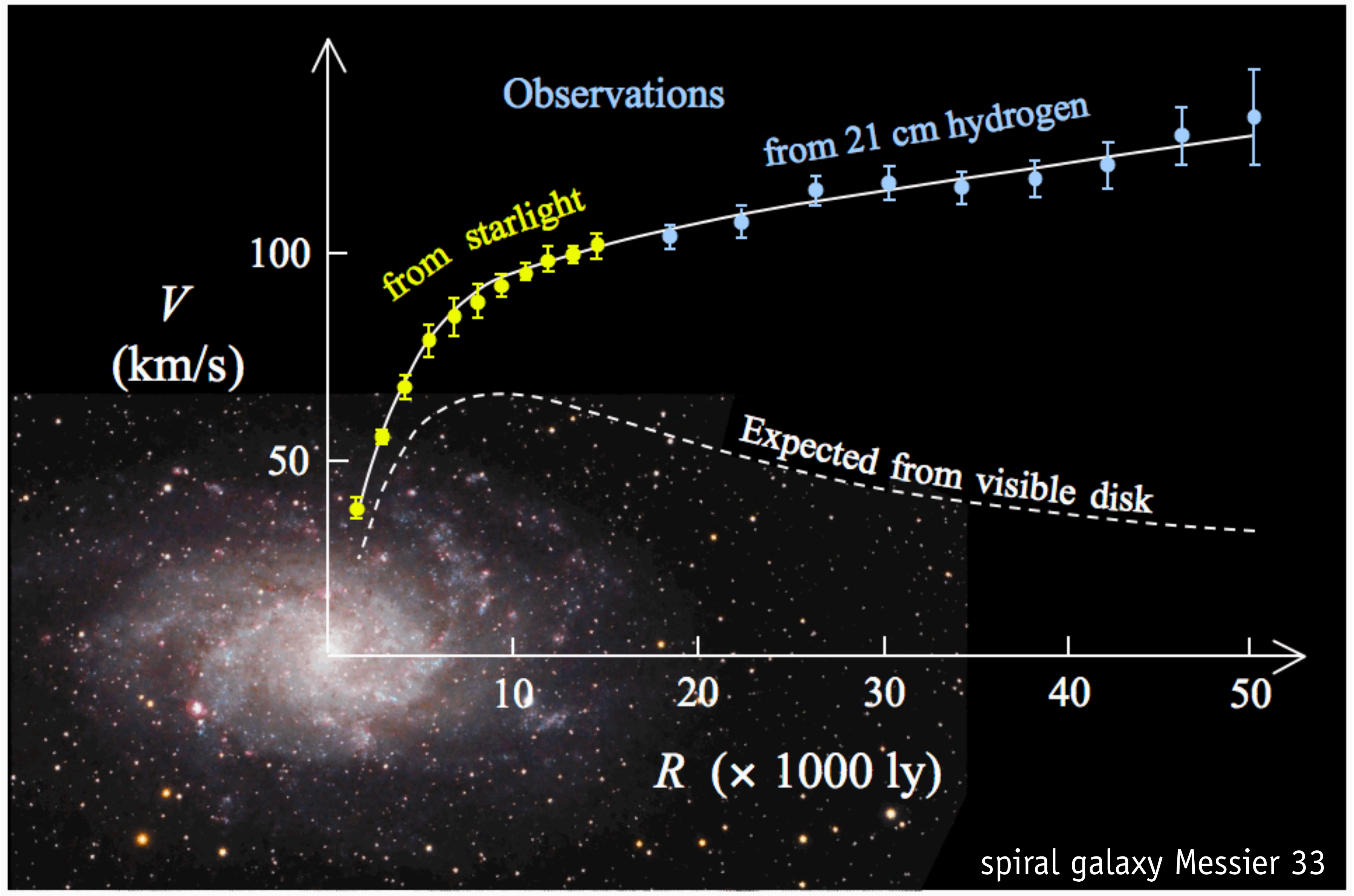
1970s: systematic studies on galaxies' massive, invisible halo



$$\rho_{DM}(r) \propto 1/r^2$$



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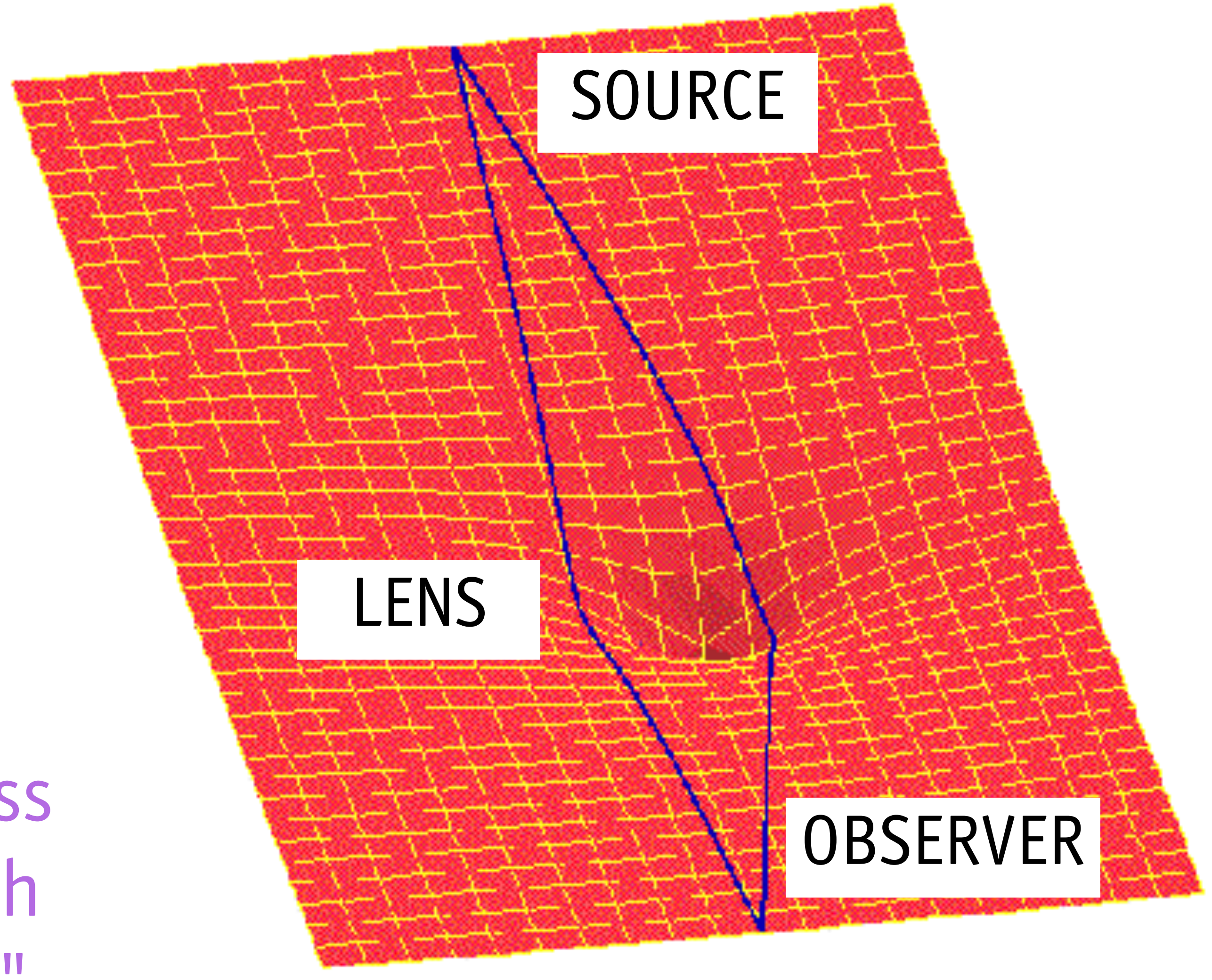
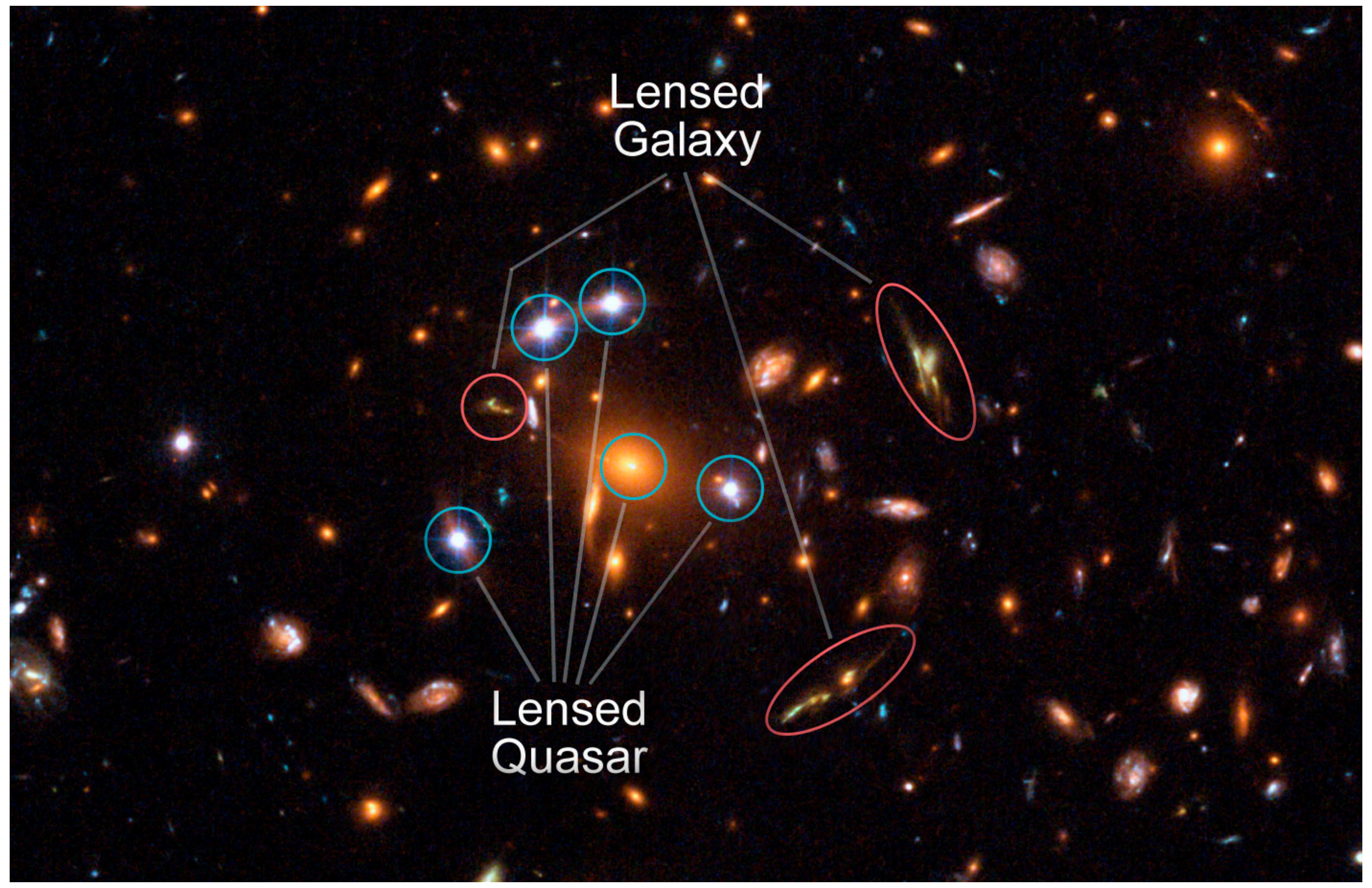
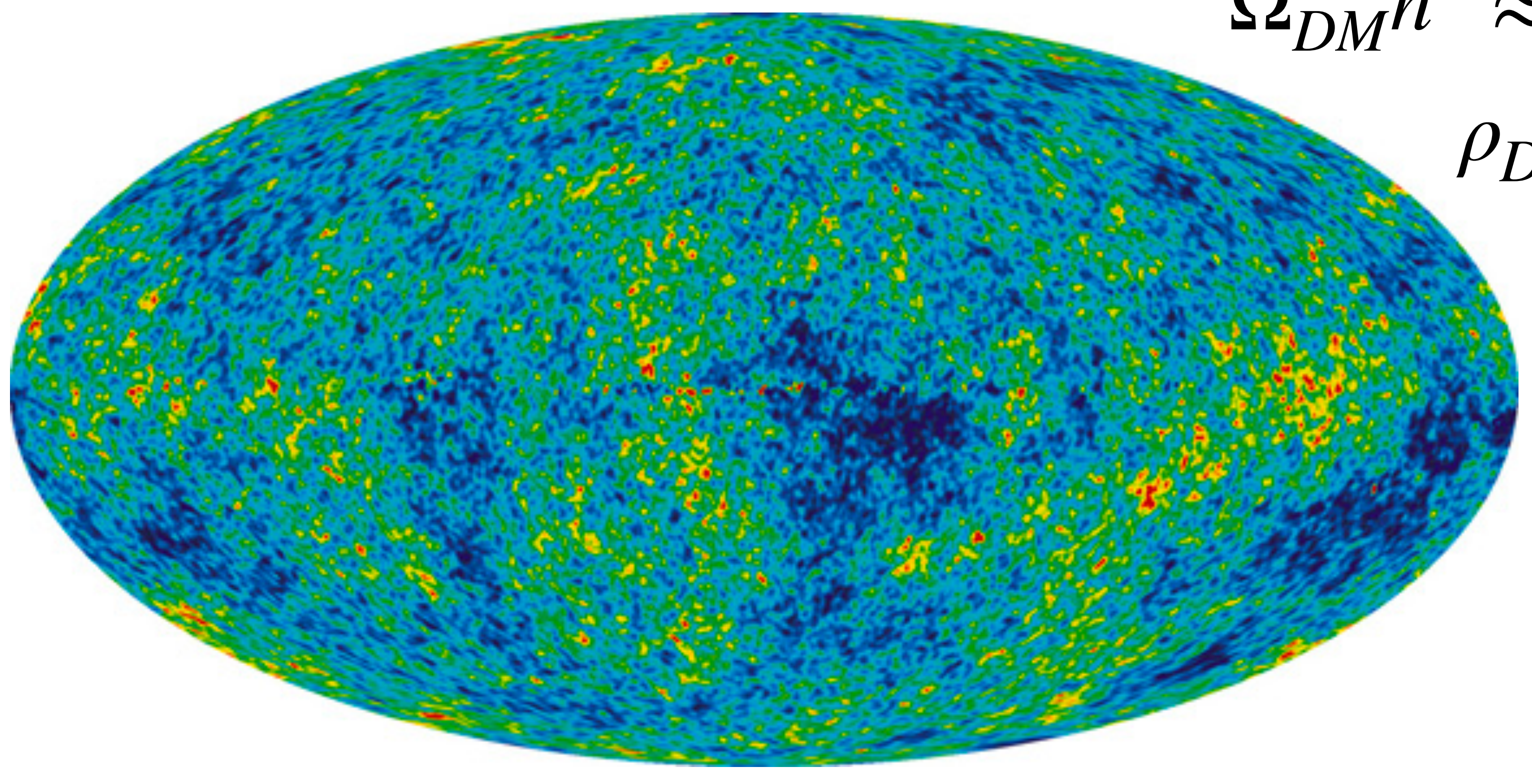
1980+: further evidence from gravitational lensing & CMB

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{d_{LS}}{d_L d_S}}$$

inferred lens mass inconsistent with "luminous mass"

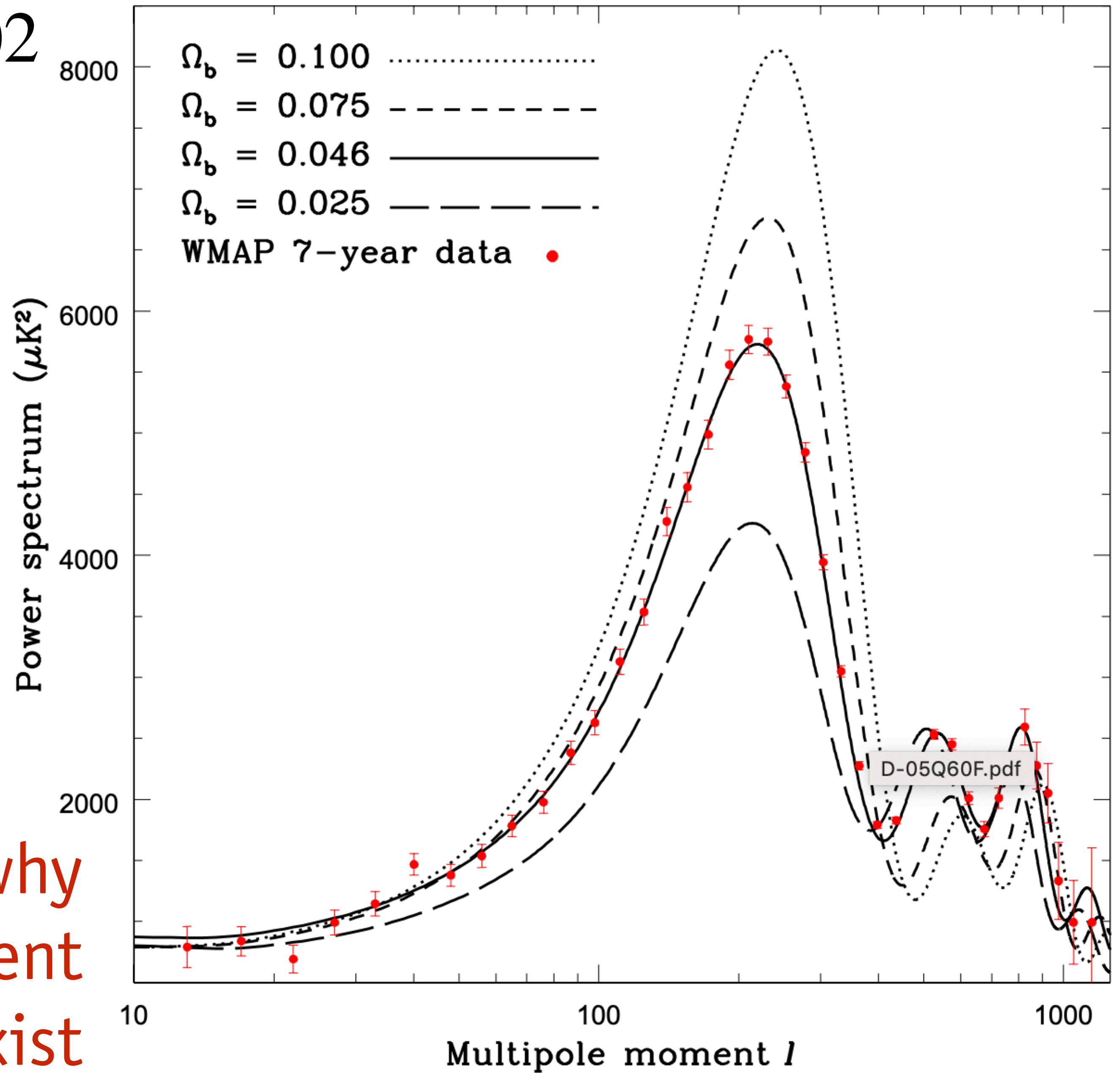






$$\Omega_{DM}h^2 \approx 0.12 > \Omega_m h^2 \approx 0.02$$

$$\rho_{DM} \approx 0.3\,\mathrm{GeV/cm^3}$$



dark matter required to explain why CMB fluctuations are 1:10^{-5} yet current structures exist

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WHERE DOES DARK MATTER COME FROM?

early universe: thermal equilibrium (same rate of interaction and annihilation)

$$\chi\bar{\chi} \leftrightarrow X\bar{X}$$

as universe expanded:

1) particles lost kinetic energy to produce heavier particles
2) particles got diluted, hence interaction rate diminished

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WHERE DOES DARK MATTER COME FROM?

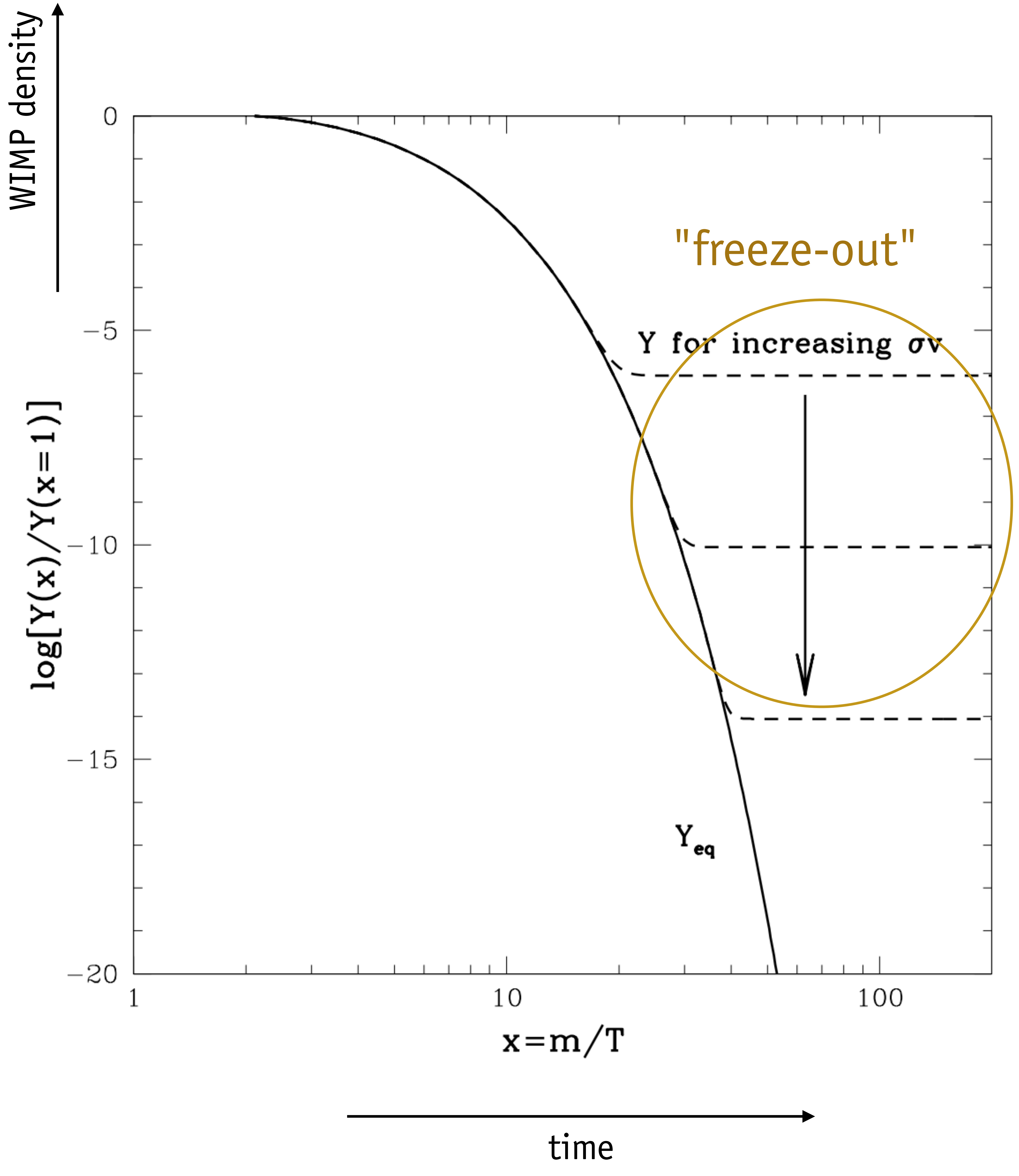
towards equilibrium: the Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\rm ann} v \rangle (n^2 - n_{\rm eq}^2)$$

particle number density

universe expands

thermal average of total annihilation cross-section



strong evidence of dark matter across many scales: how should a **particle candidate** look like?

$$\Omega_{DM} h^2 = \frac{m_{DM} n}{\rho_c} \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle} \sim 0.12$$

↓ 0.3 GeV/cm³

$$\langle \sigma_{\mathrm{ann}} v \rangle \approx \alpha_{\mathrm{EM}} / m_{DM}^2$$

if DM candidate interacts with a "weak" interaction, one gets correct order of magnitude of relic density: **WIMP miracle**?

-> need a new, neutral particle beyond the Standard Model

neutrinos are too fast to explain structure formation, and fail at giving the correct relic density

$$\Omega_\nu h^2 = \sum_{i=1}^{3} \frac{g_i m_i}{90\,\mathrm{eV}} < 0.0076 \ll \Omega_{dm}$$

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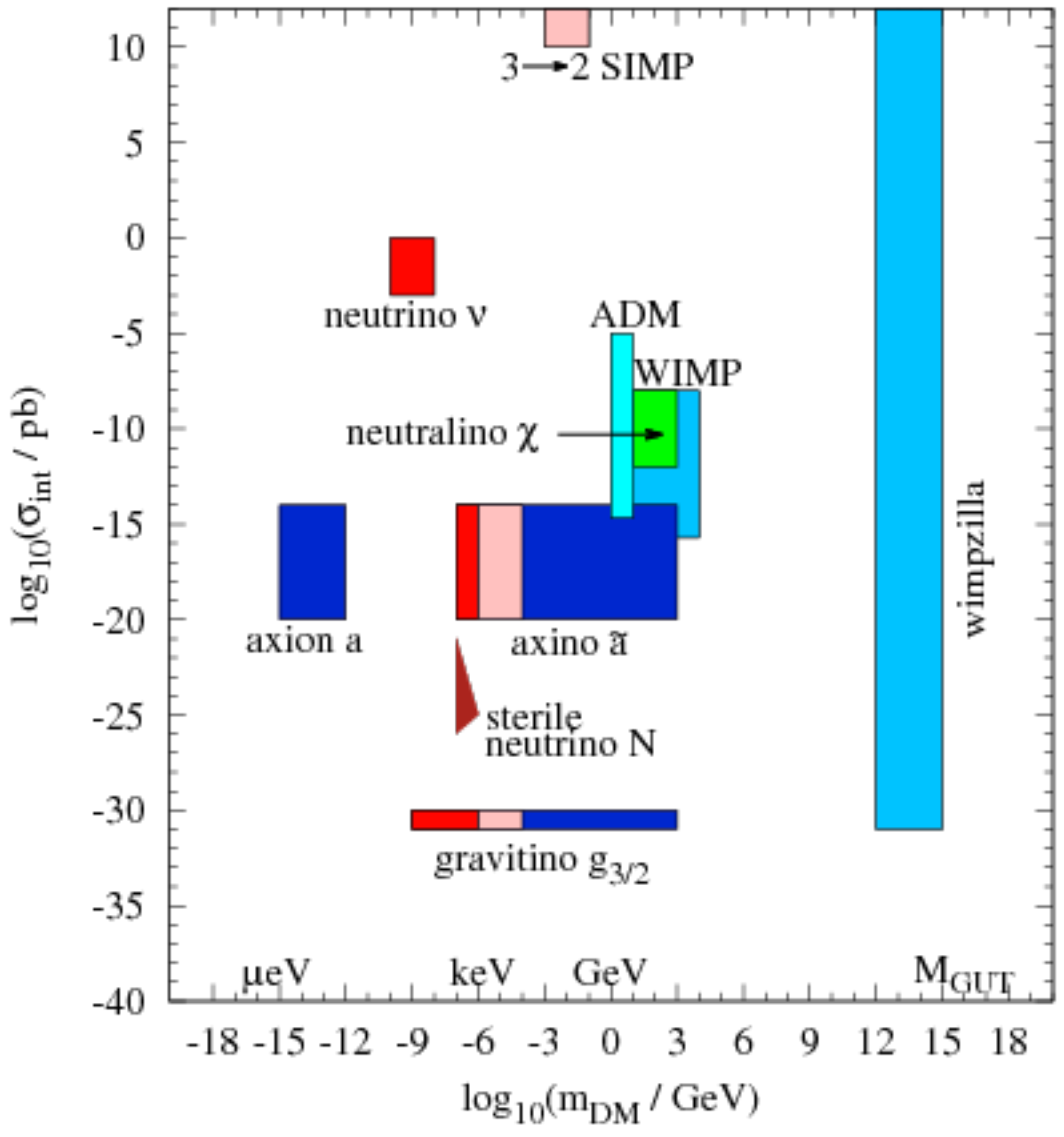
massive
to explain gravitational observations

weakly interacting
if interacting at all...

explain relic abundance
correct annihilation rate and couplings

stable
lifetime > 10^{17} s

typical interaction cross-section



DM mass

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How we may detect them

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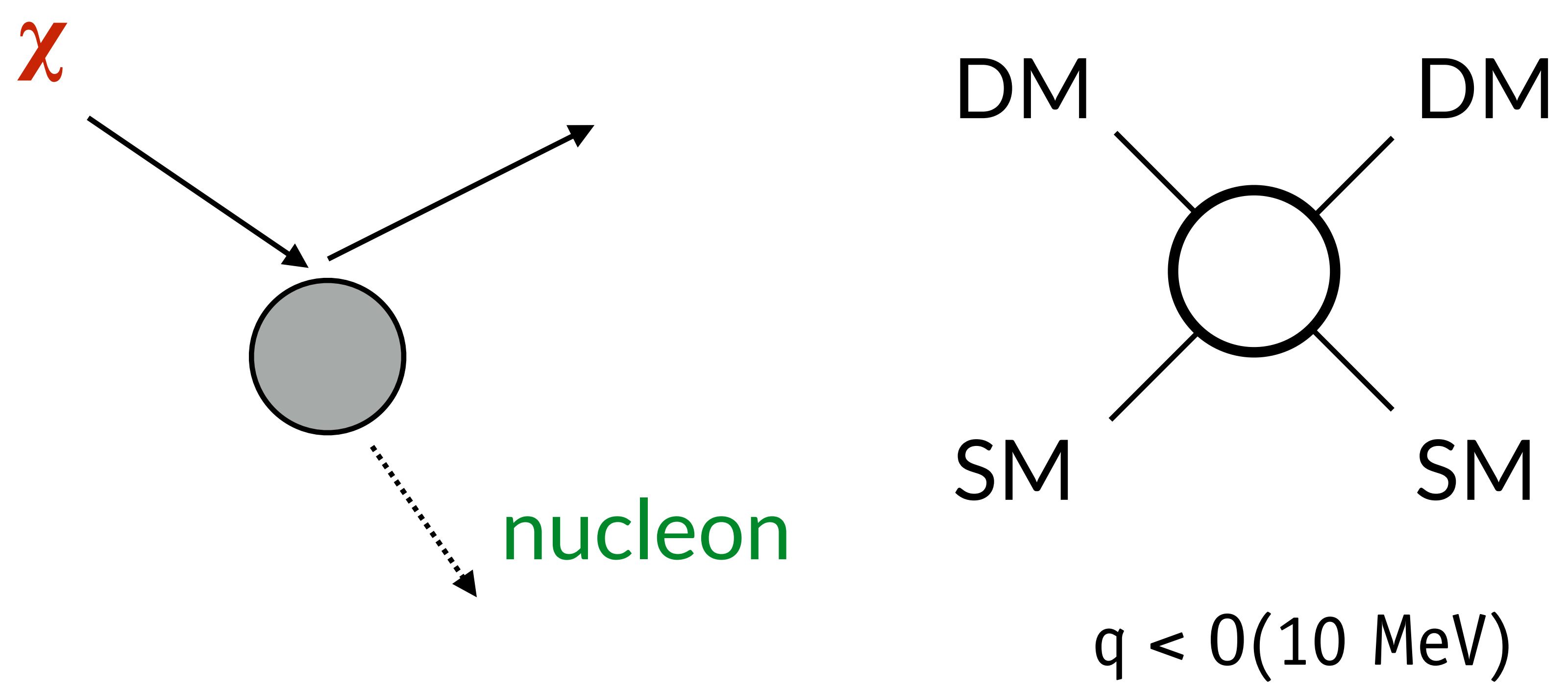
Method #1: Use the available Dark Matter

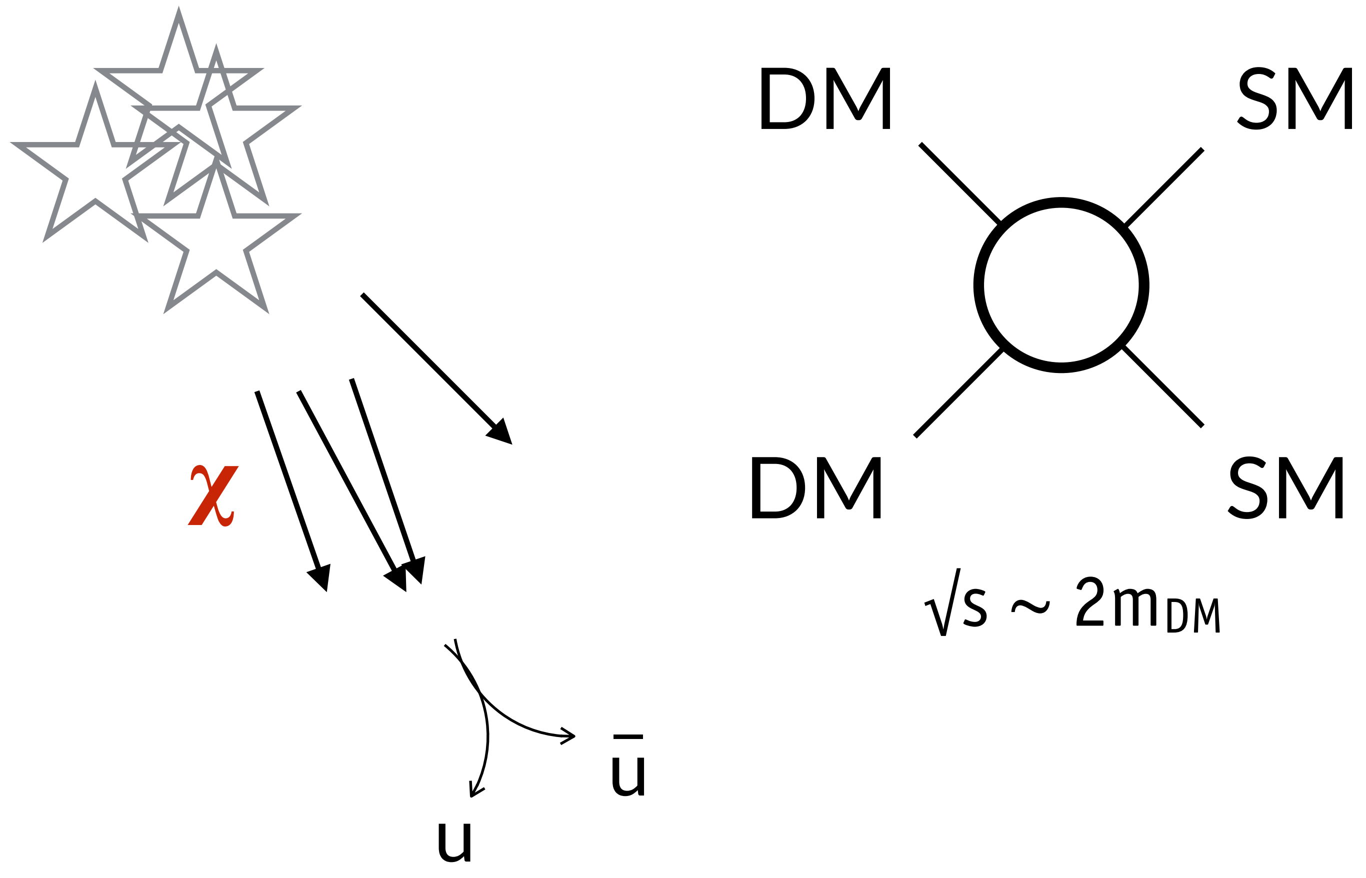
direct detection



must know: nucleon form factors, DM local density, background levels…

- build detectors which may detect the existing Dark Matter (DM)
- hope they do
  - experimental challenge set by DM mass and nature of DM-SM interaction

indirect detection



[spoiler alert:
there is a method #2]

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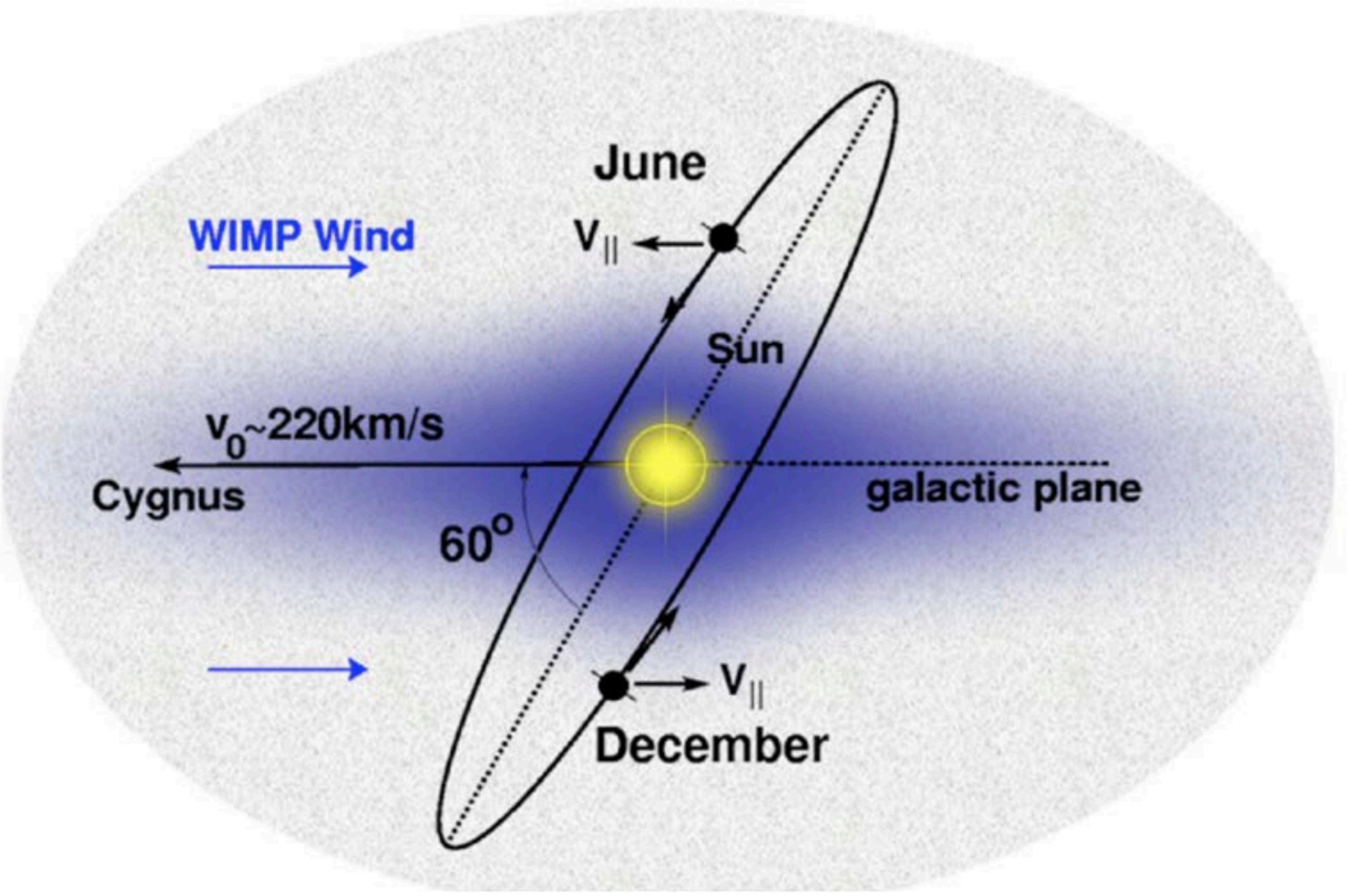
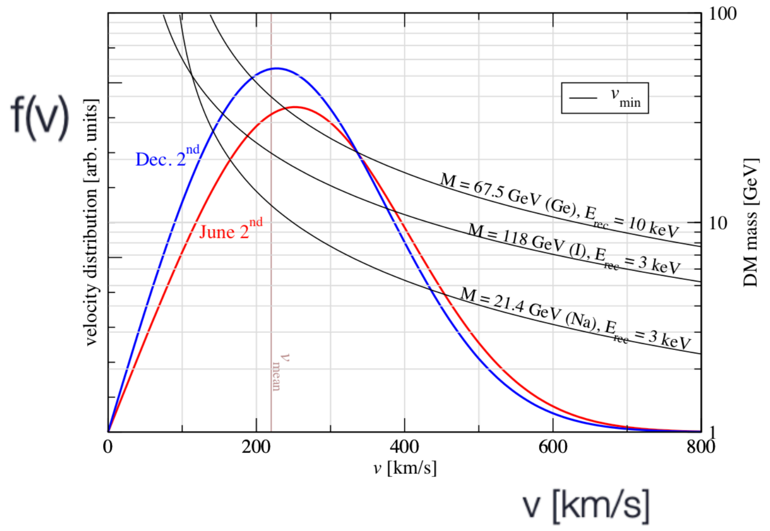
WIMPS in our
galaxy (Milky Way)
p
$E_R \sim$ keV
some kind of target
Credits: Google

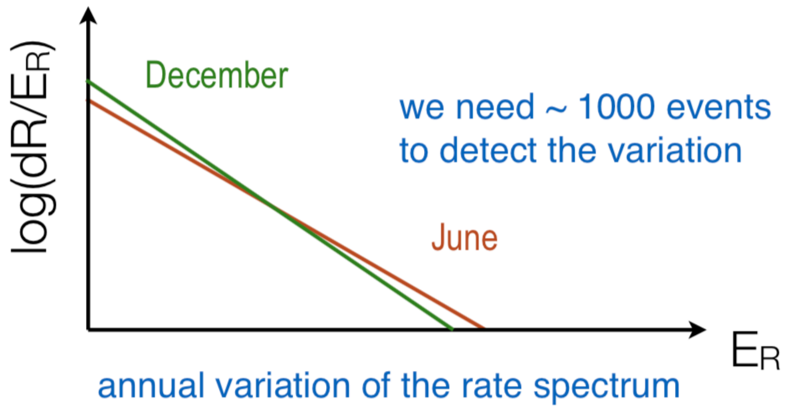
HOW WOULD A SIGNAL LOOK LIKE?

the Milky Way is immersed in a halo of DM particles - Earth rotates around the Sun, so we see an "apparent wind" with **v ~ 220 km/s**





v follows a Maxwellian velocity distribution (from 0 to the escape velocity from the MW)



June 2nd

$$N(E,t) = N_0(E) + N_m(E)\,\cos\left(\frac{2\pi}{T}(t - t_0)\right)$$

1 year

a signal would show
~7% yearly modulation

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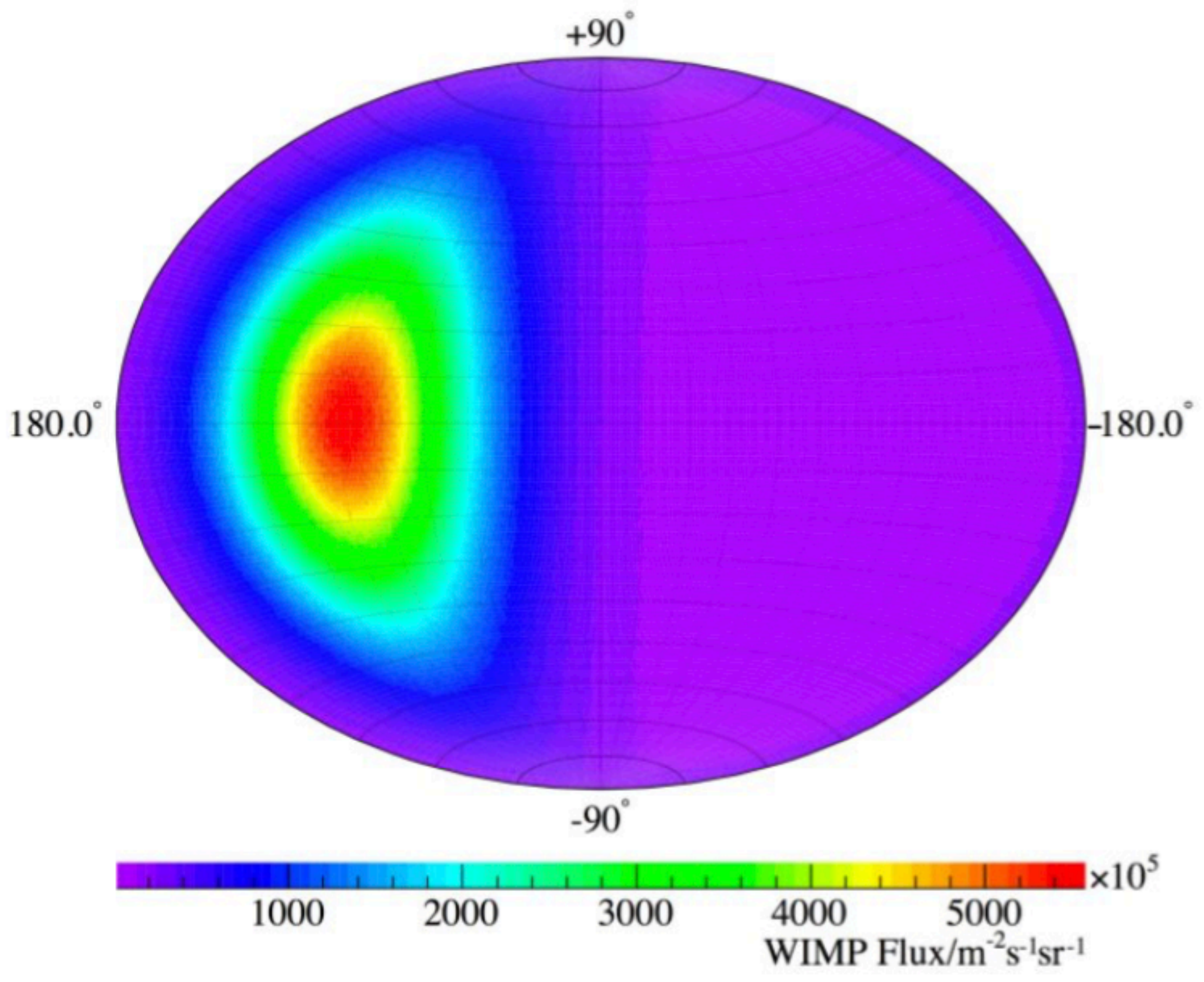
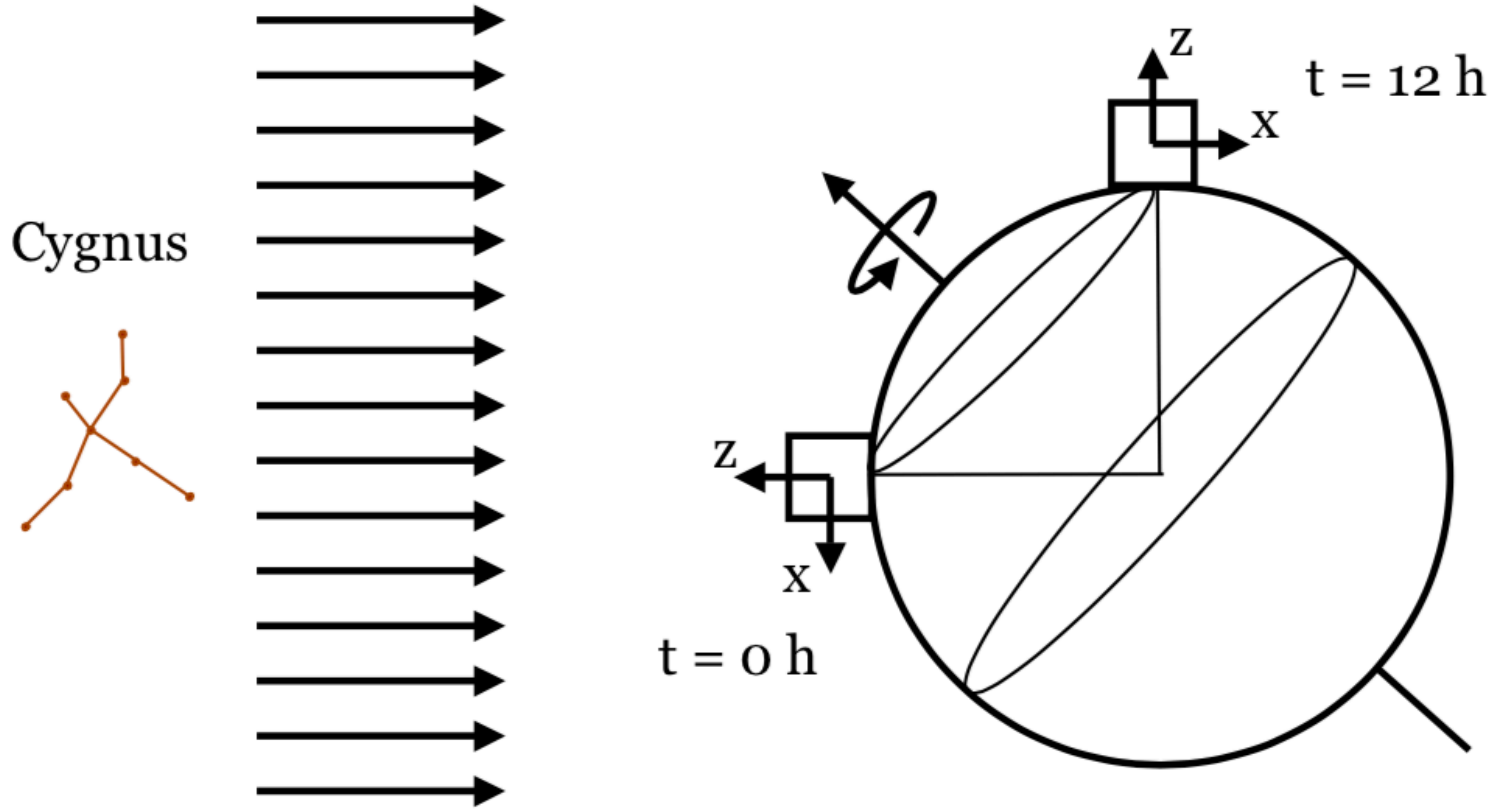
Earth also rotates around its own axis, so signal direction should change by 90 degrees every 12 hours



Projection of the WIMP flux in Galactic coordinates



smoking guns, but:
- need time **stability** of detector calibration/response/backgrounds
- need ~1000 (10) events for testing annual (daily) modulation

a signal would show ~30% daily modulation

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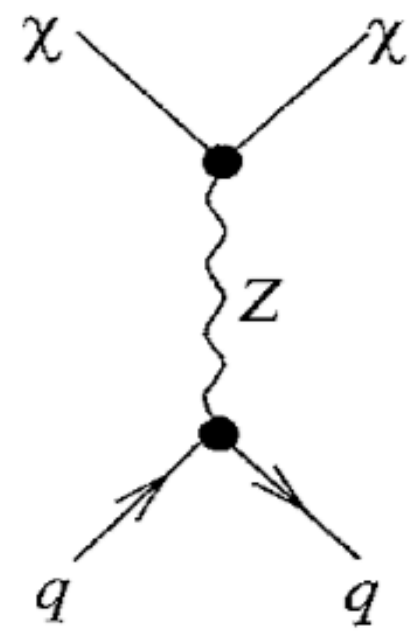

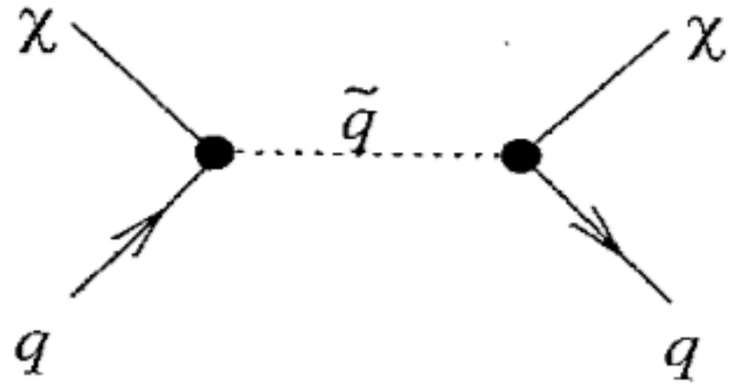

source	events/cm²/min
solar neutrinos	~4×10^{12}
cosmic ray muons	1
100 GeV WIMP	4×10^{5}
1 TeV WIMP	4×10^{4}

how many events? for a 100 GeV WIMP:

$$\phi_\chi = \frac{\rho_\chi}{m_\chi} \times \langle v \rangle = 6.6 \times 10^4\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

we deal with **rare events**: one usually reasons in terms of event rates per target (fiducial) mass and data taking time

$$R = \frac{N_A}{A} \times \phi_\chi \times \sigma \sim 0.13\,\mathrm{events\,kg}^{-1}\mathrm{yr}^{-1}$$

typical: < O(10 tons), 5-10 years

experimental needs:

- **ton-scale detectors** to collect enough events for discovery
- must **suppress backgrounds** (radioactivity, cosmics, neutrinos...)

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EVENT RATE, IN A NUTSHELL

1. kinematics & velocity distribution

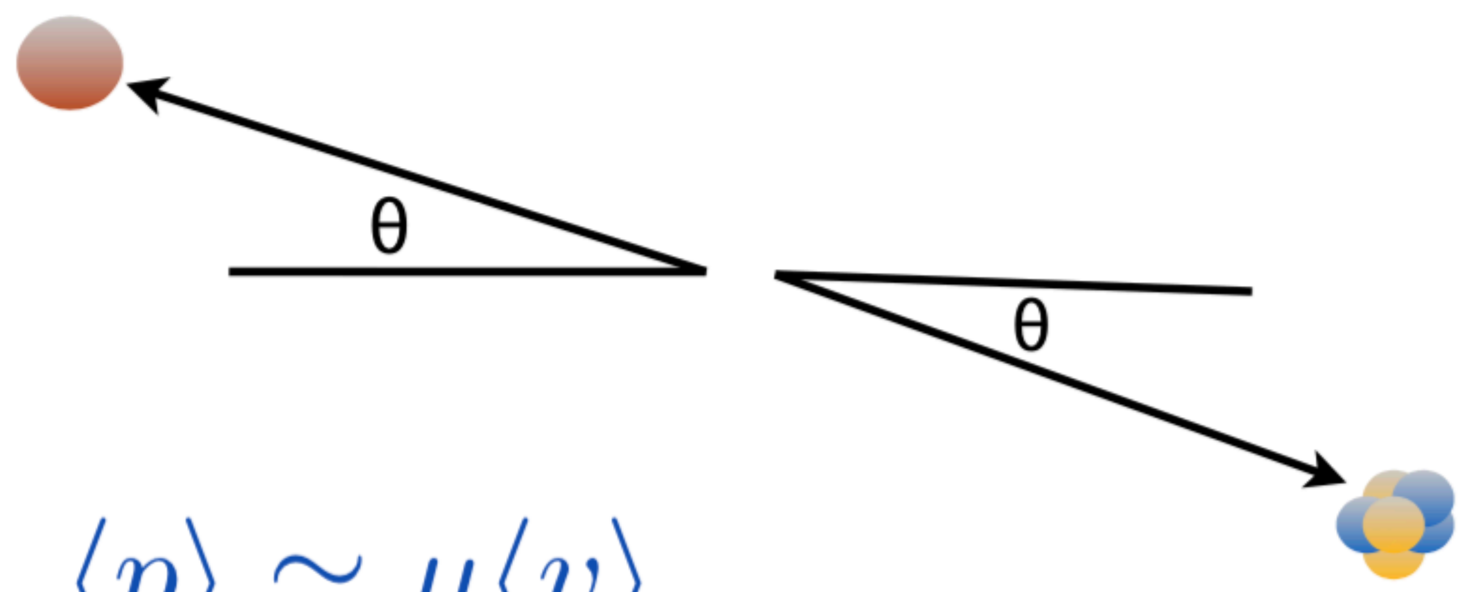
what we measure

dependence on incident energy

$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta)$$

~30 keV for $m_N = m_{DM} = 100$ GeV

reduced mass of the nucleon-WIMP system



$$\langle p \rangle \simeq \mu \langle v \rangle$$

2. WIMP-parton interaction

spin independent ~ A^2

$$\mathscr{L}_{\rm eff} = \frac{1}{\Lambda^2}(\bar{\chi}\Gamma_{\rm dark}\chi)(\bar{\psi}\Gamma_{\rm vis}\psi)$$

$$\Gamma \in \{1, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}, \sigma_{\mu\nu}\gamma_5 \ldots\}$$

3. nuclear form-factor

$$\lambda = \frac{h}{p} \simeq 20\ \mathrm{fm} > r_0 A^{1/3}\ \mathrm{fm}$$

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$$\frac{dR}{dE_R} = R_0 S(E_R) F^2(E_R) I$$

form factor correction

interaction type [spin (in)dependent]

spectral function (masses and kinematics)

$$R_0 \equiv \frac{2}{\sqrt{\pi}} \frac{N_A}{A} \frac{\rho_{DM}}{m_{DM}} \sigma_0 v_0$$

for spin-independent interactions:

$$M(\vec{q}) = f_n\, A \underbrace{\int d^3x\, \rho(\vec{x})\, e^{i\,\vec{q}\cdot\vec{x}}}_{F(\vec{q})} \quad \Rightarrow \quad \sigma \propto |M|^2 \propto A^2$$

mass number

fundamental couplings to nucleons

Fourier-transform of the density of scattering centers

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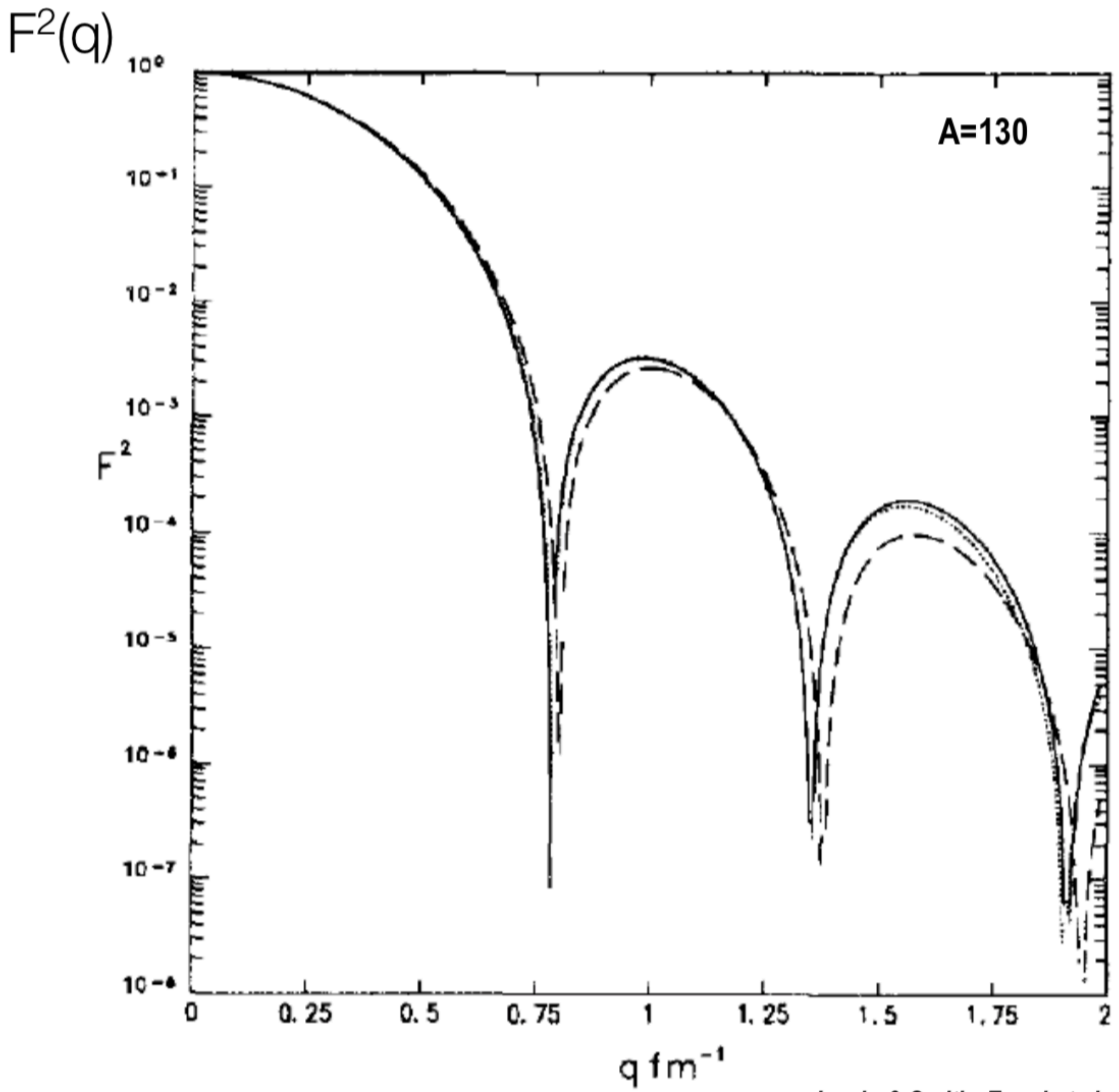
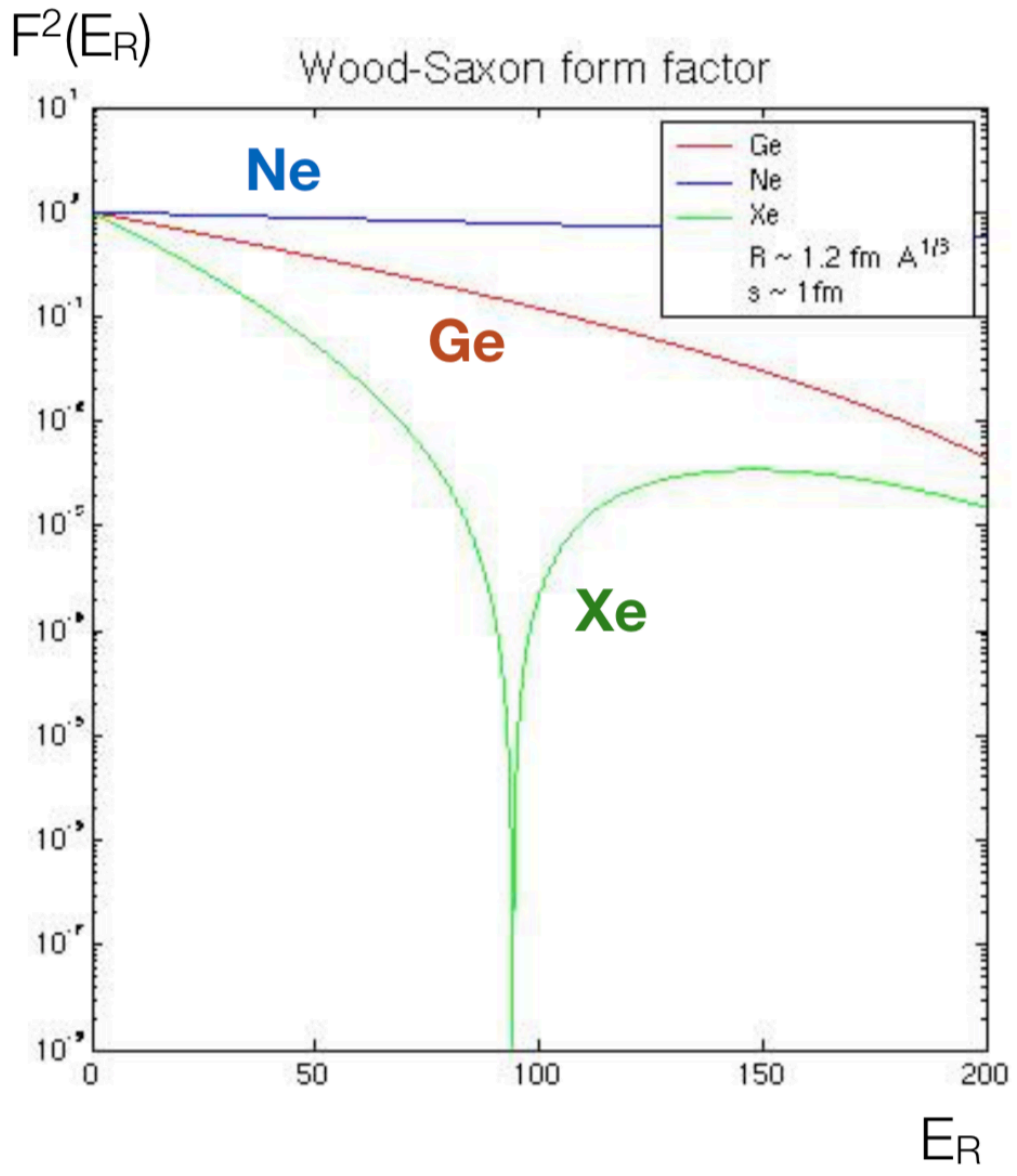
FORM FACTOR, THE UNDERGROUND STONE GUEST



Lewin & Smith; Engel et al



depending on the recoil energy, the nuclear structure of each target is seen differently by the incoming DM particle

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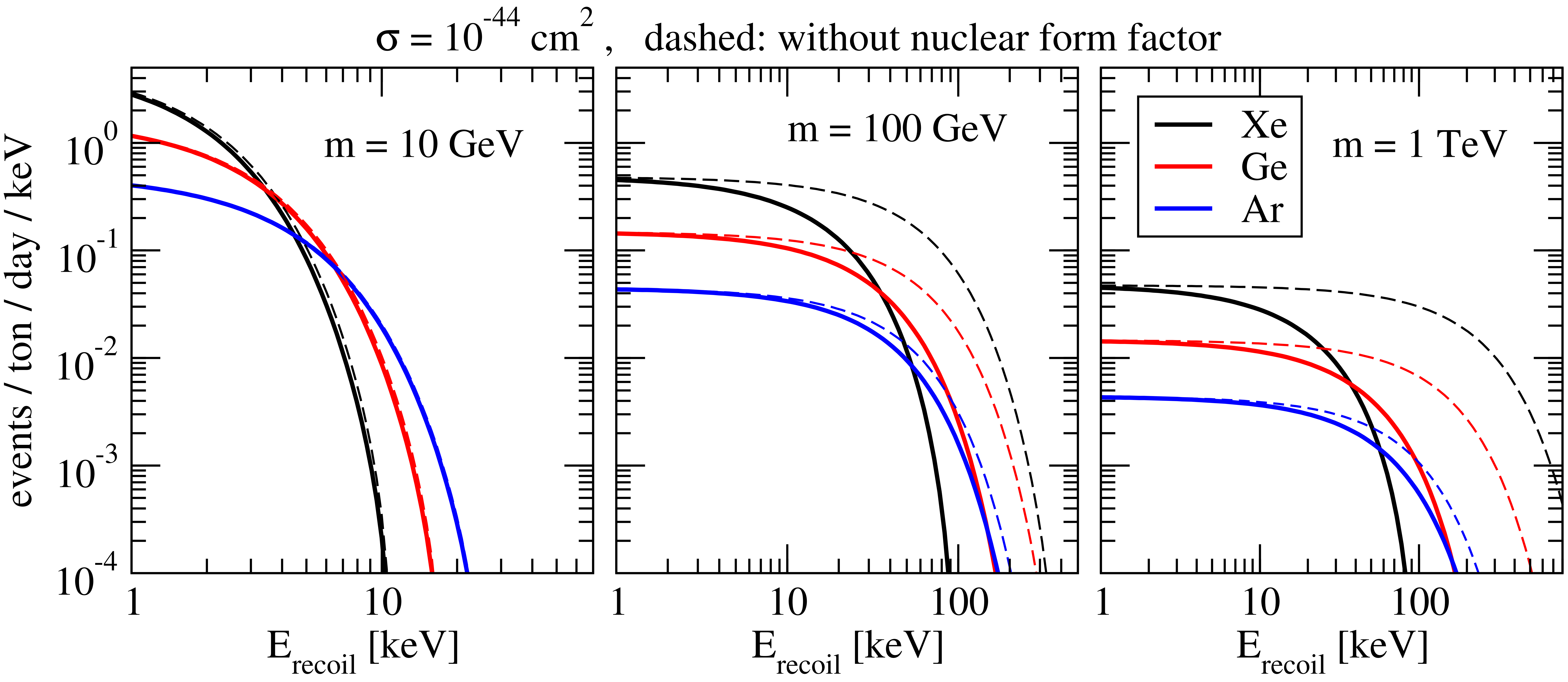
FORM FACTOR, THE UNDERGROUND STONE GUEST



the form factor effect is dominant for higher WIMP masses and influences our choice of the target material

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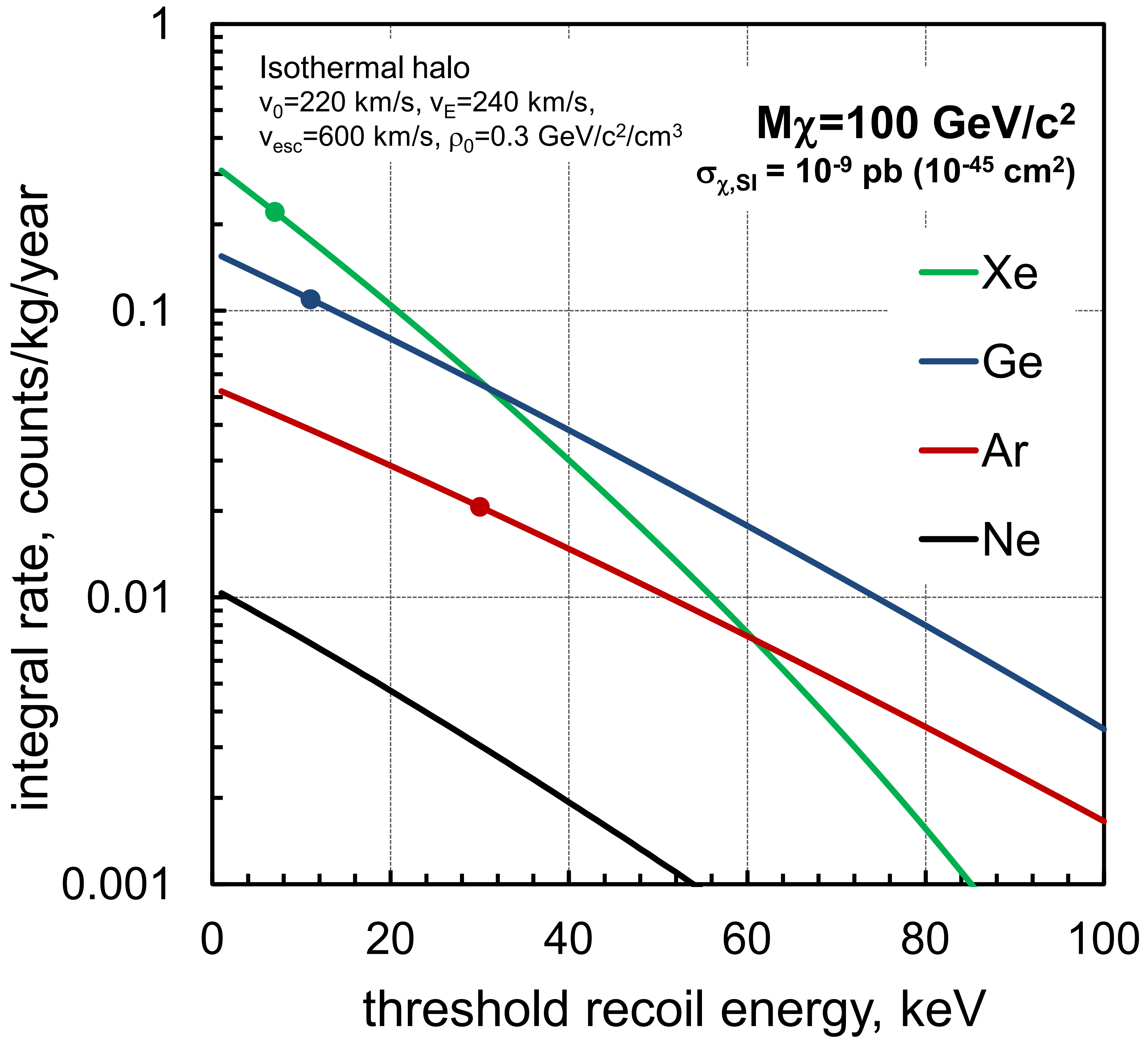
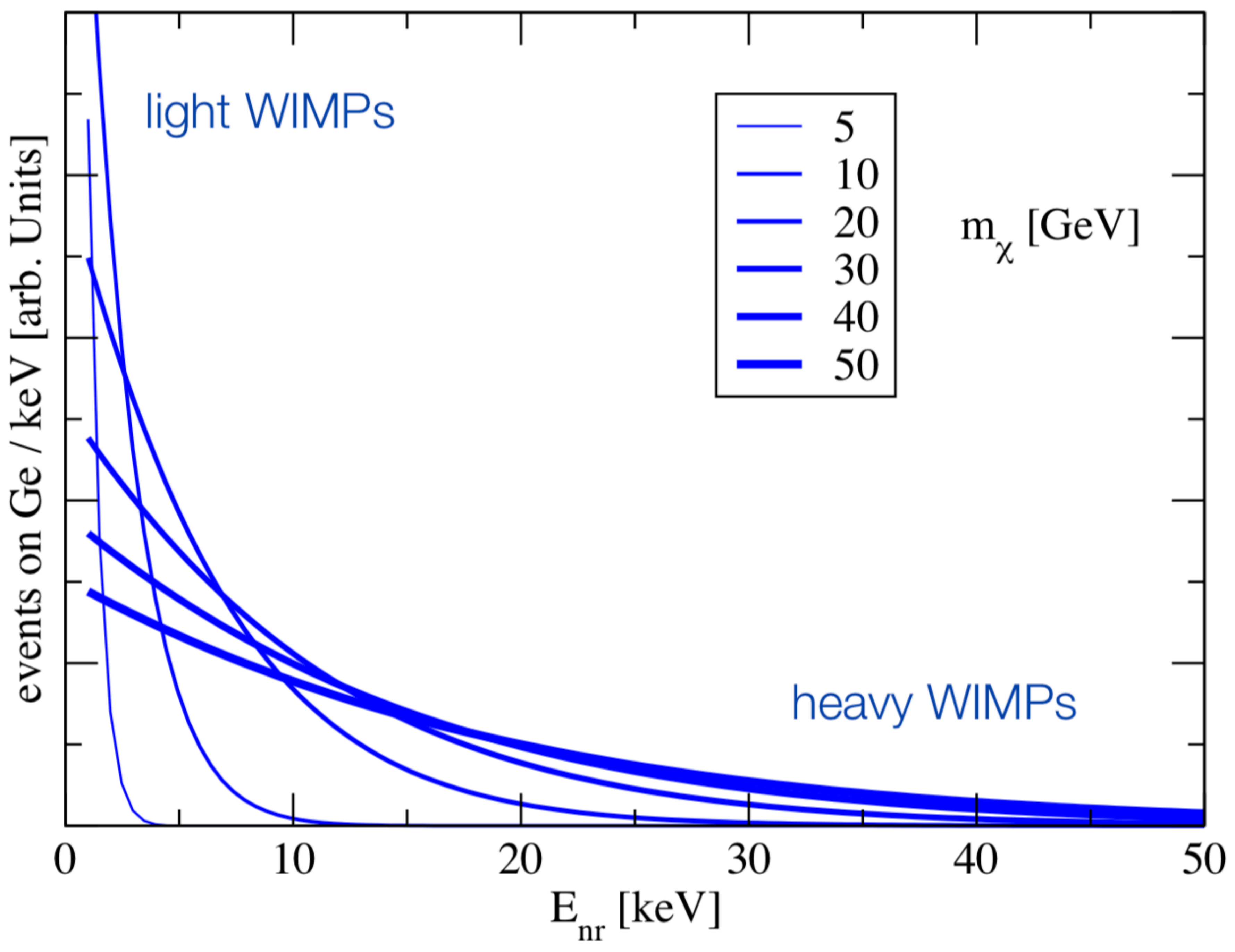
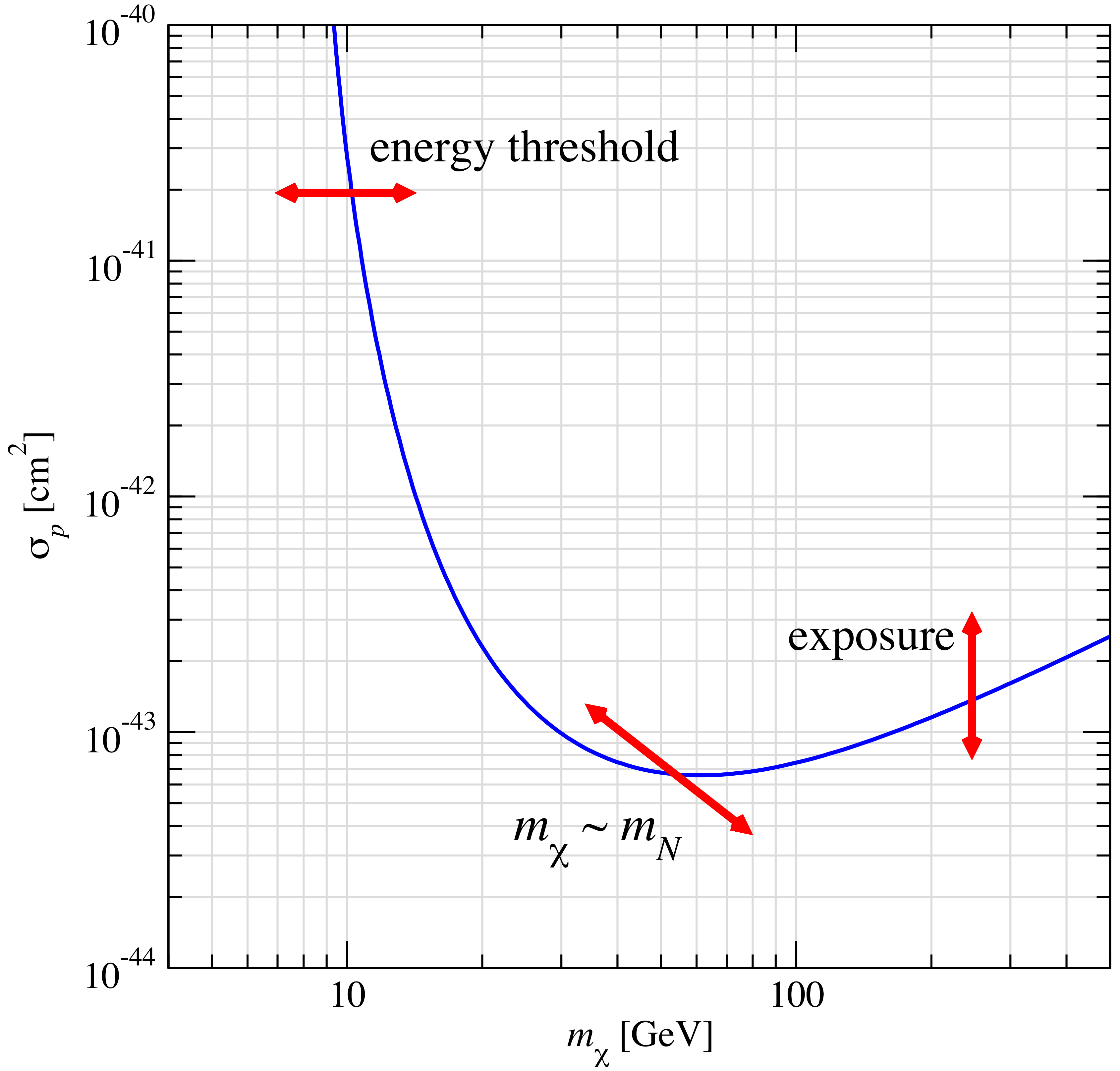
CHOOSING THE TARGET



- energy **threshold** of each experiment is a **trade-off** between sensitivity and noise+backgrounds+resolution
- choice of **target** affected also by **backgrounds**/detection/cost

THE TYPICAL DIRECT DETECTION RESULT





- need **detectors** sensitive to **keV** energies to probe WIMPs (compare to LHC calorimeters...)
- usually **massive** (ton-scale), years of data taking (ultimately necessary to check if signal modulates as expected)

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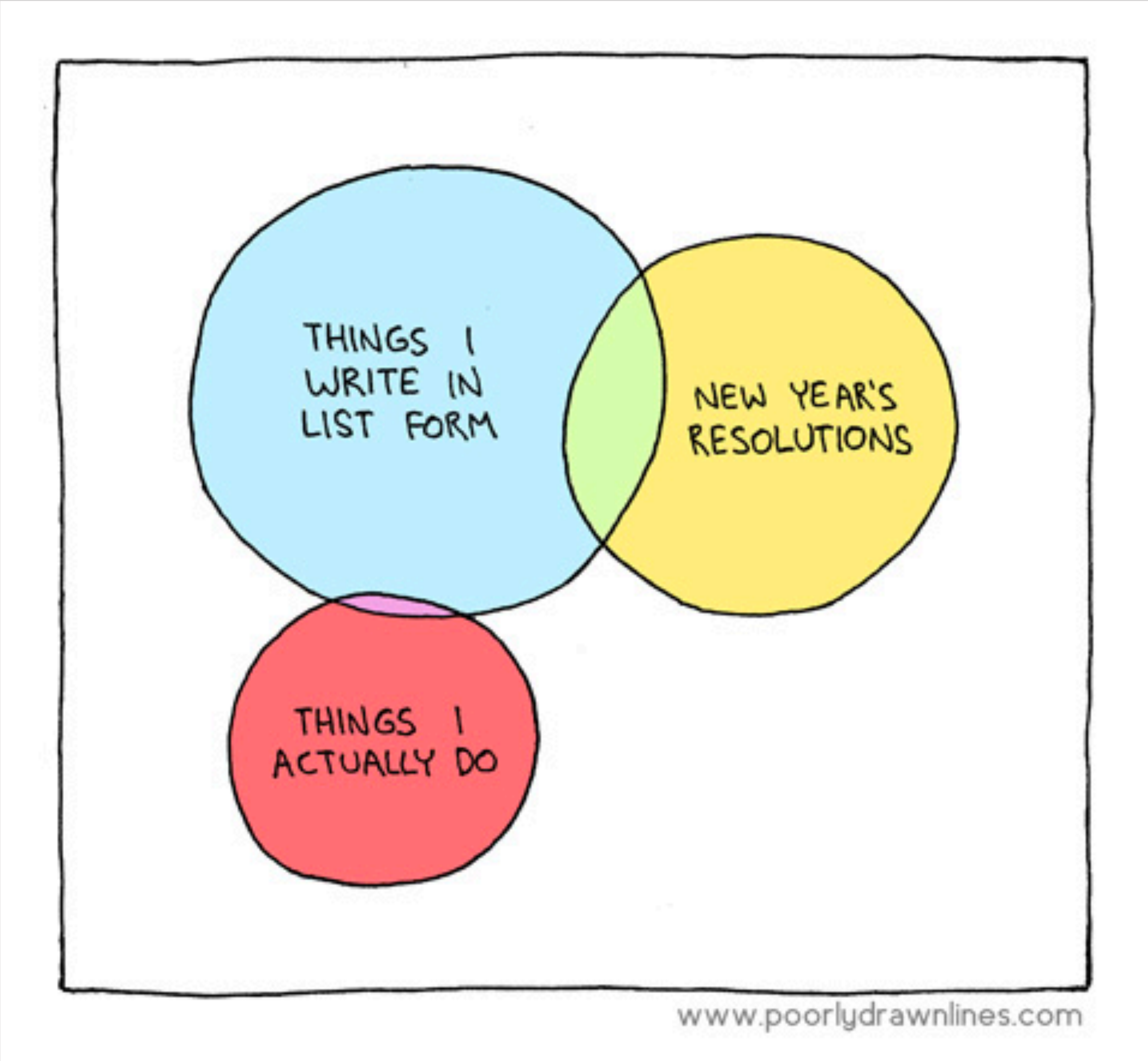
How it's done underground



choose physics signal
charge, light, phonons...

measure detector response
calibration, monitoring

suppress backgrounds
with shielding and analysis-level

make sure it's dark matter
measure modulation and direction

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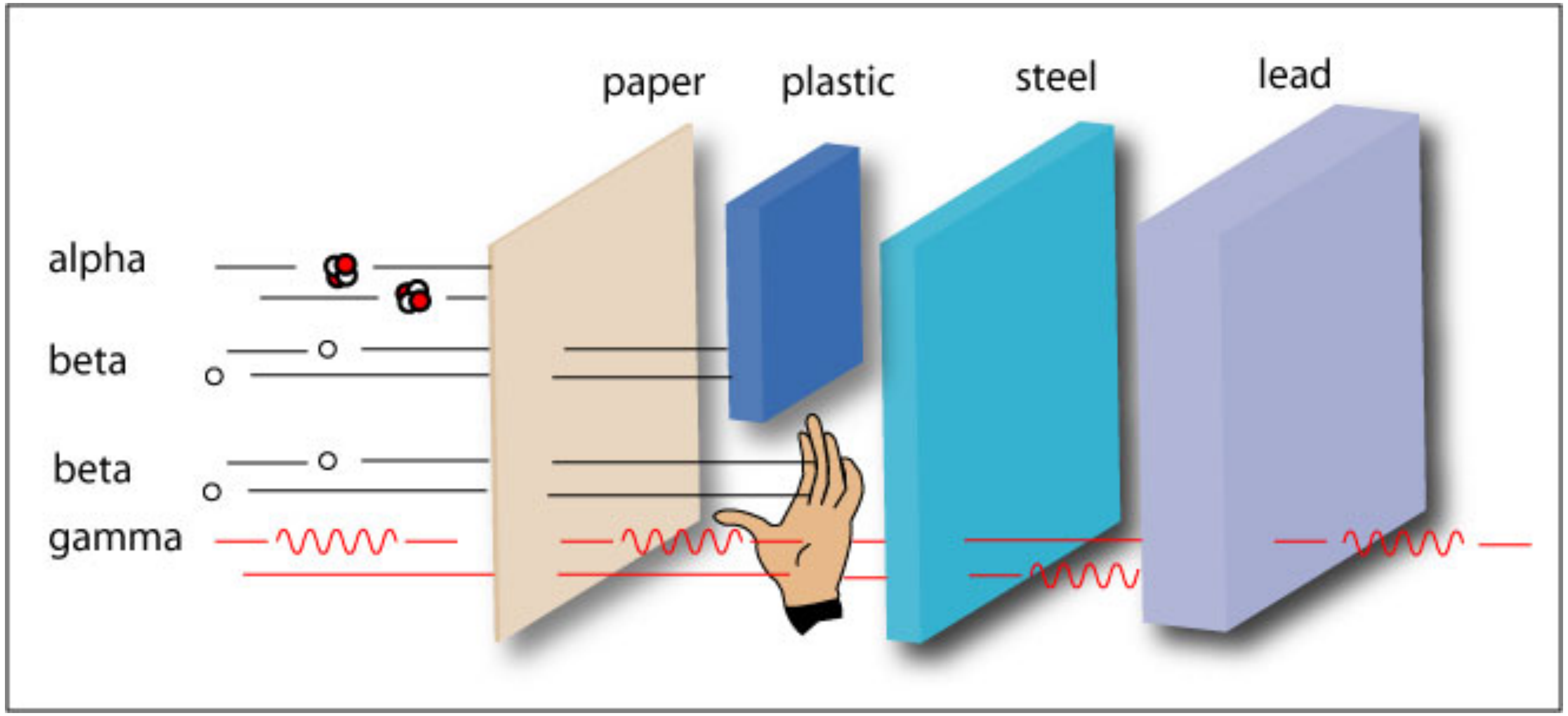
RADIOACTIVITY



key issue: WIMP event rate is low

radioactivity is the main background (e.g. 2 MeV photons → 14 cm in LAr)

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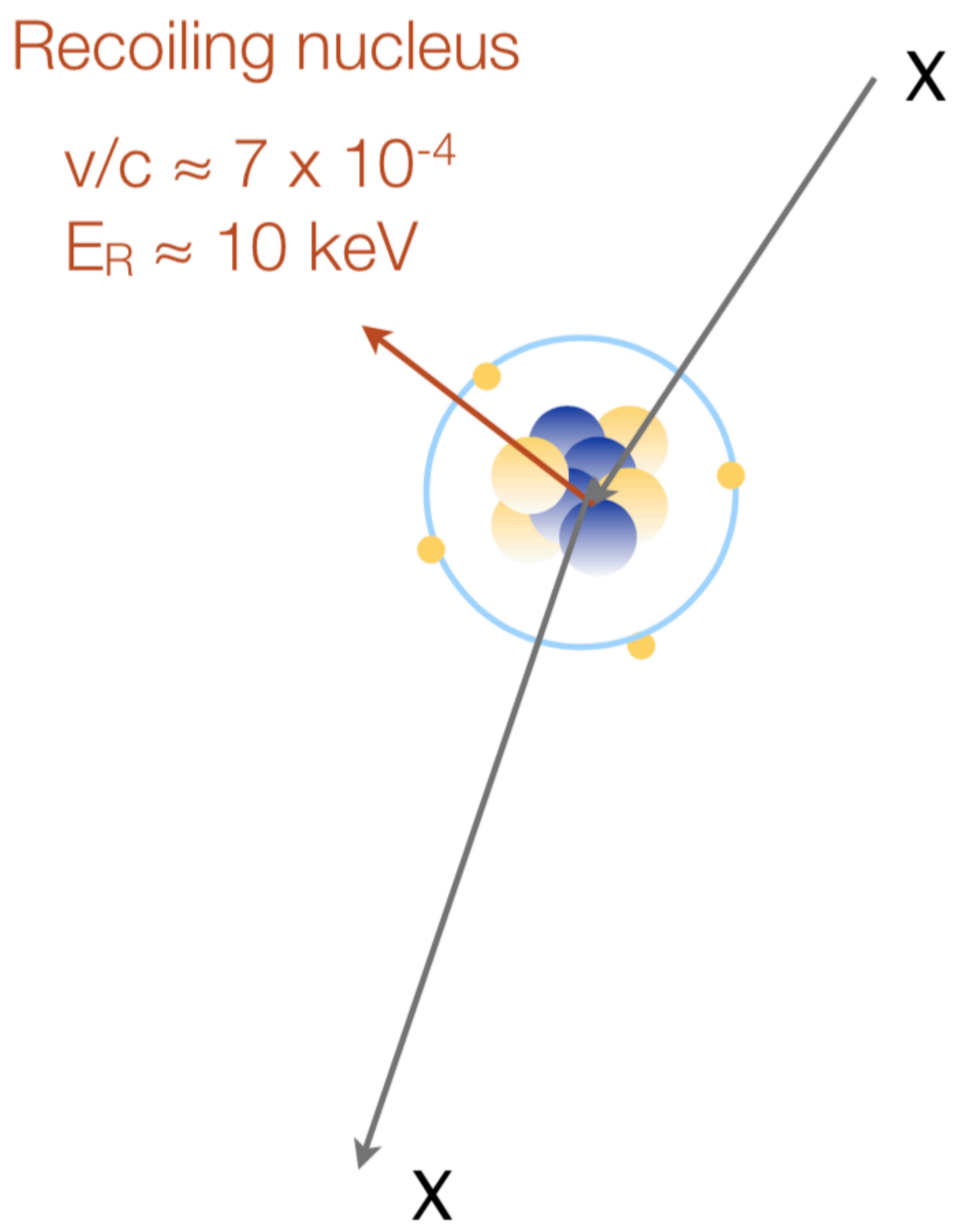
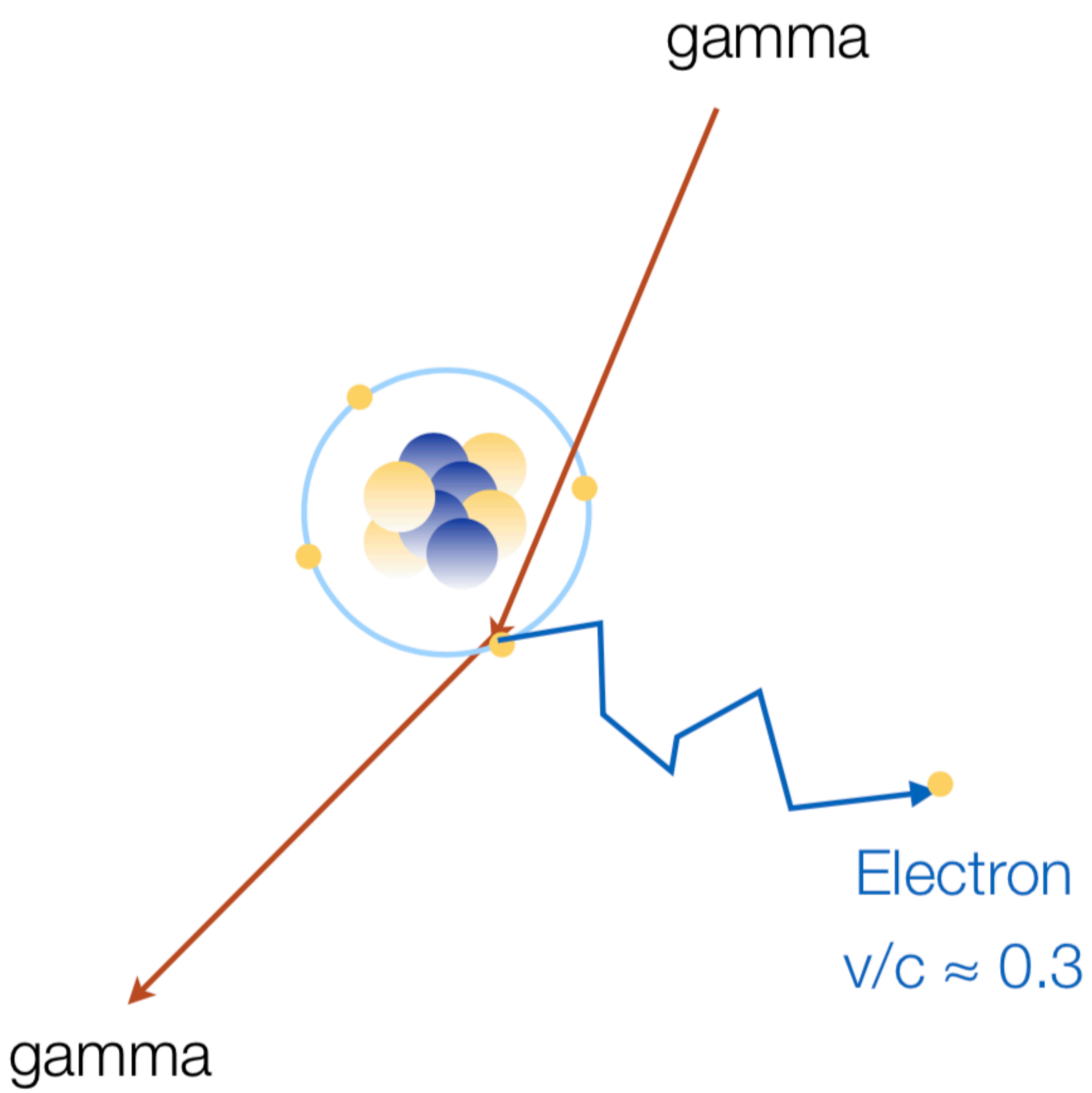
signal
(nuclear recoil, NR)



γ/β radiation
(electron recoil, ER)



we want to reconstruct and discriminate these kinds of signals

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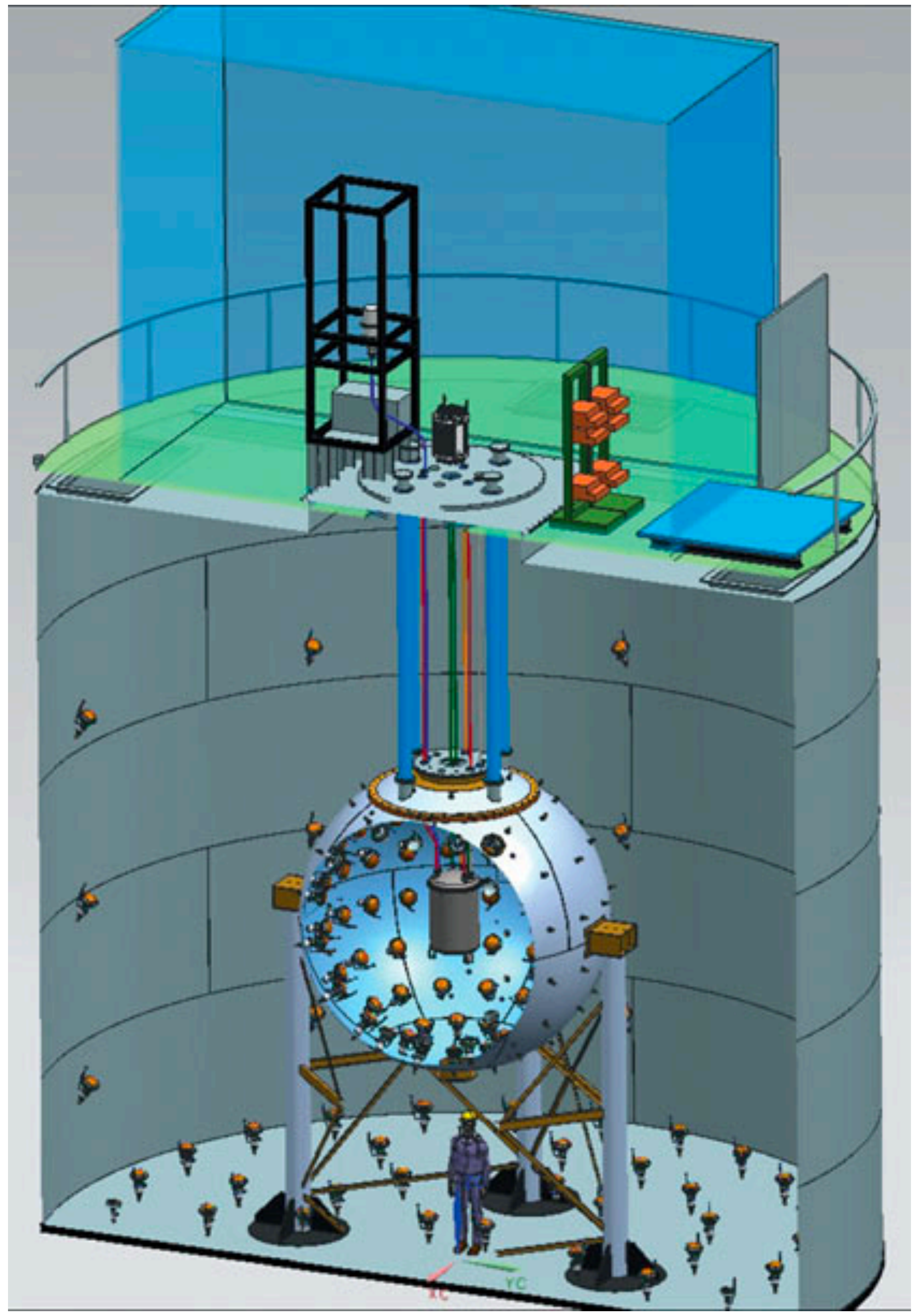
BACKGROUNDS

- **external radiation**: shields and vetoes
  - example of shields: Pb (gammas), water (neutrons)
  - example of active vetoes: Cherenkov (muons), scintillators (gamma, neutrons)
  - use underground labs (LNGS, SNOLAB) to suppress cosmic rays (mostly muons)
- **internal radiation** from detector components: suppress & use MC
  - analysis techniques (e.g. ML) to define fiducial volume



- **neutrinos** constitute the ultimate background for the current generation of detectors
  - they may come from the Sun, supernovae, atmosphere...
  - they really look like DM
  - ~~Obi-Wan-Kenobi~~ directionality would be our only hope

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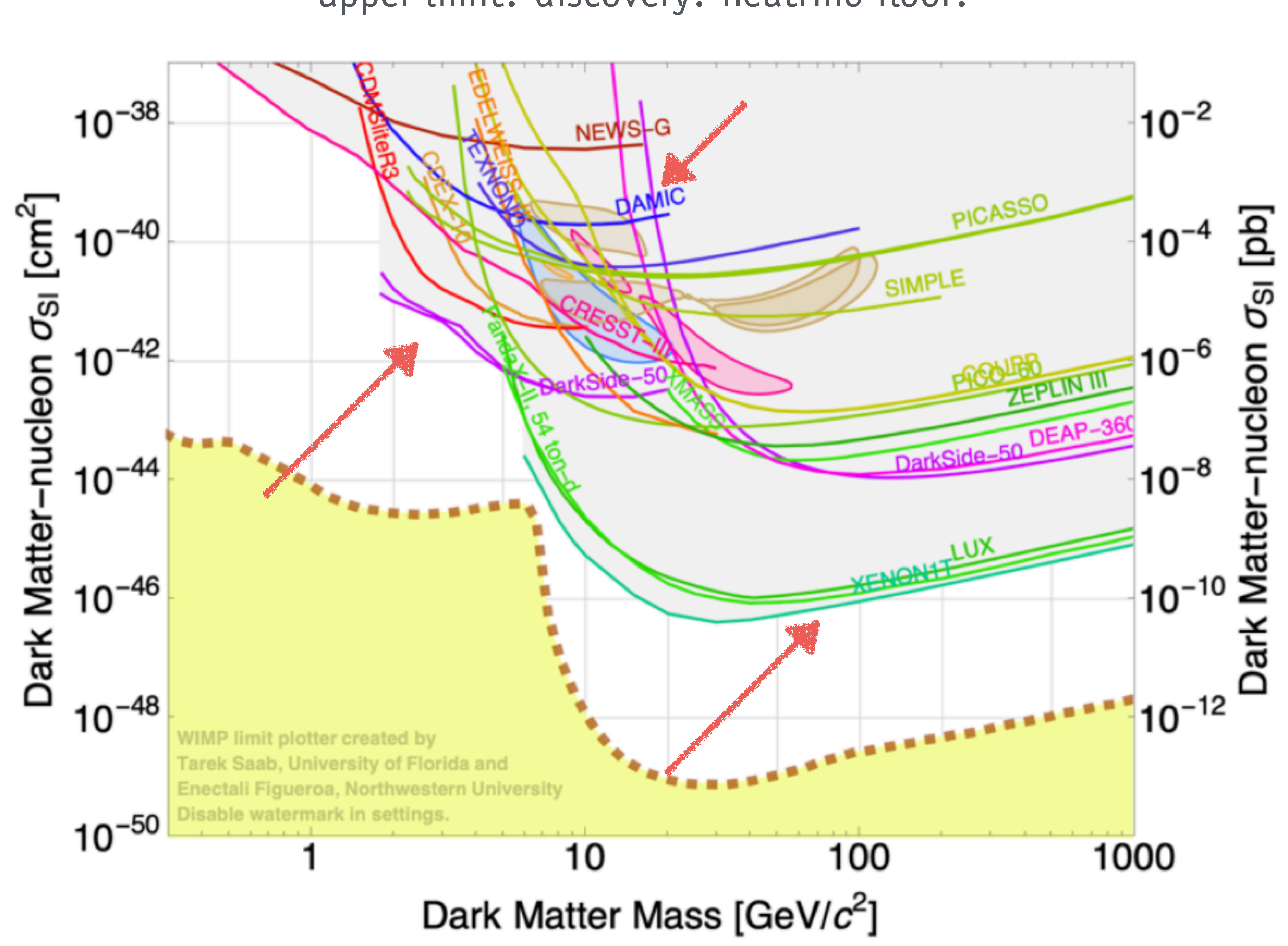
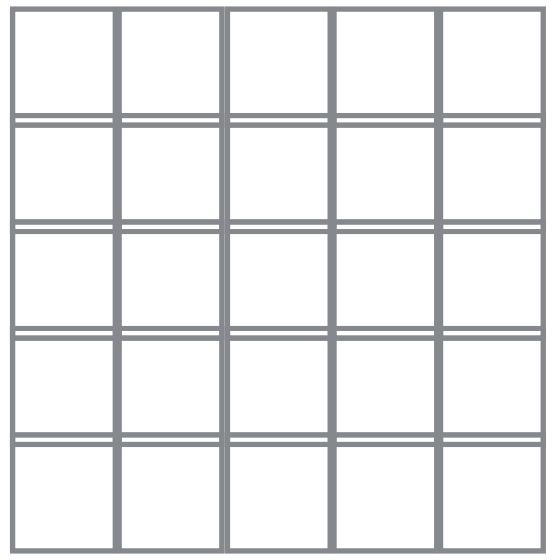
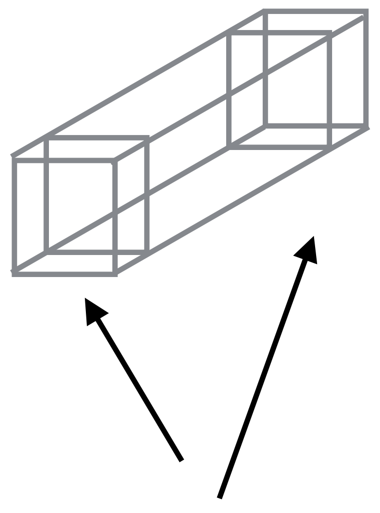
upper limit? discovery? neutrino floor?



THE MYSTERY OF DAMA

5x5 matrix





PMTs in coincidence (reduce noise)

look for single-hit **scintillation** light in 25 NaI(Tl) crystals, 9.7 kg each

3-5 g/cm3 at room temperature, read out by 2 radiopure PMTs each

1 keV_{ee} threshold, 2.4 ton year

but: ^{40}K contamination gives **3.2 keV** e^-

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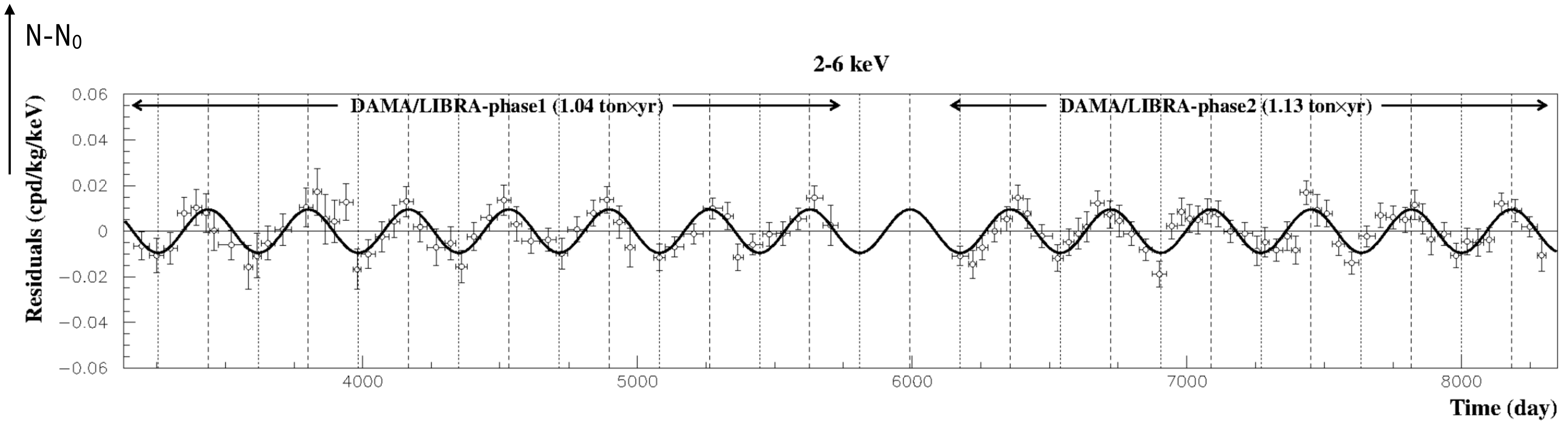
DAMA claims a ~12σ observation of an annual-modulation signal

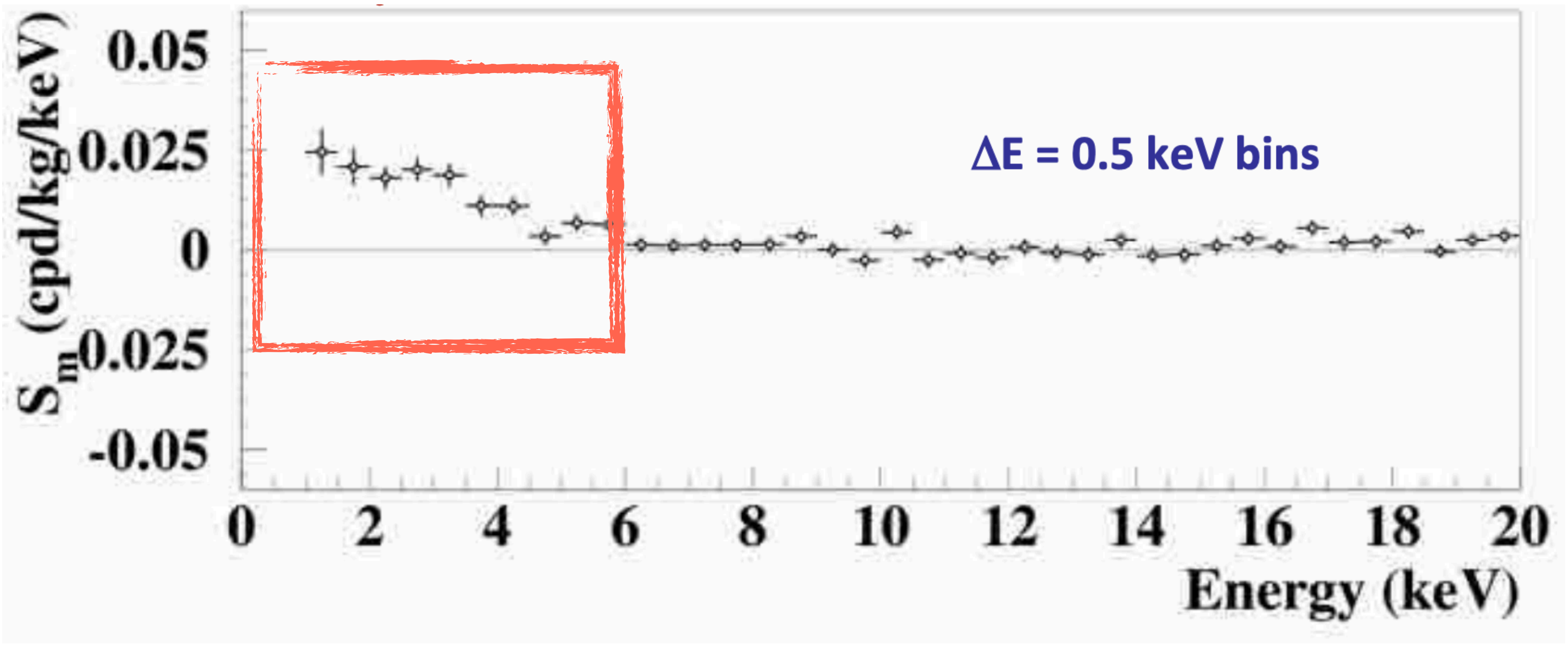
but no independent experiment managed to reproduce these results so far



time (days)

$$N(E,t) = N_0(E) + N_m(E)\cos\left(\frac{2\pi}{T}(t-t_0)\right)$$

Nm (events/kg/day per keV) in different energy bins



results not reproduced by any other experiment yet

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Worldwide WIMP Searches

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1. WIMP interacts with nucleus
2. nucleus travels in liquid losing energy
   a) excites atom?
   b) ionises atom?
   c) "heats" medium?

experimental strategy: detect a) and b) by detecting light emitted in these processes

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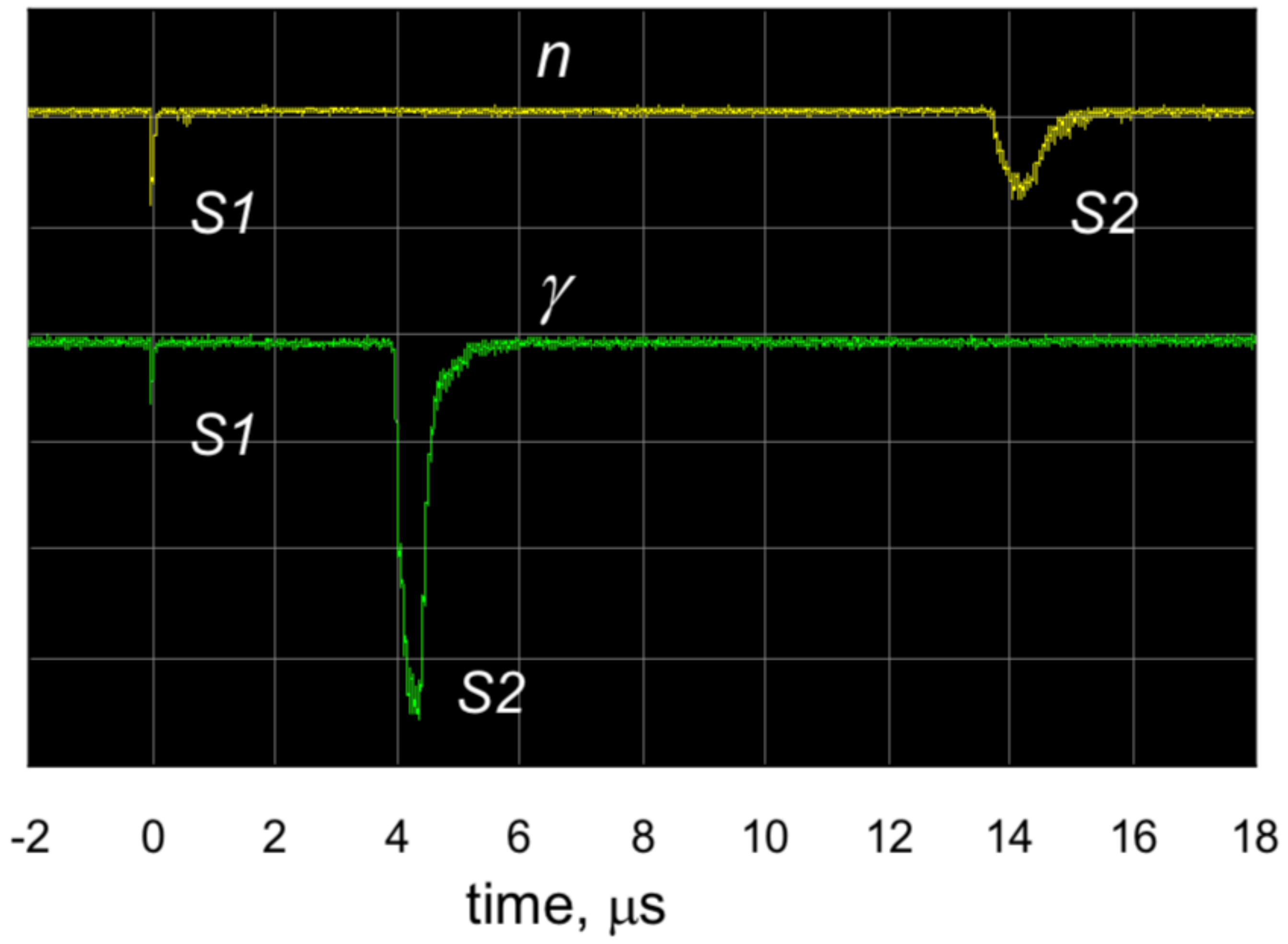
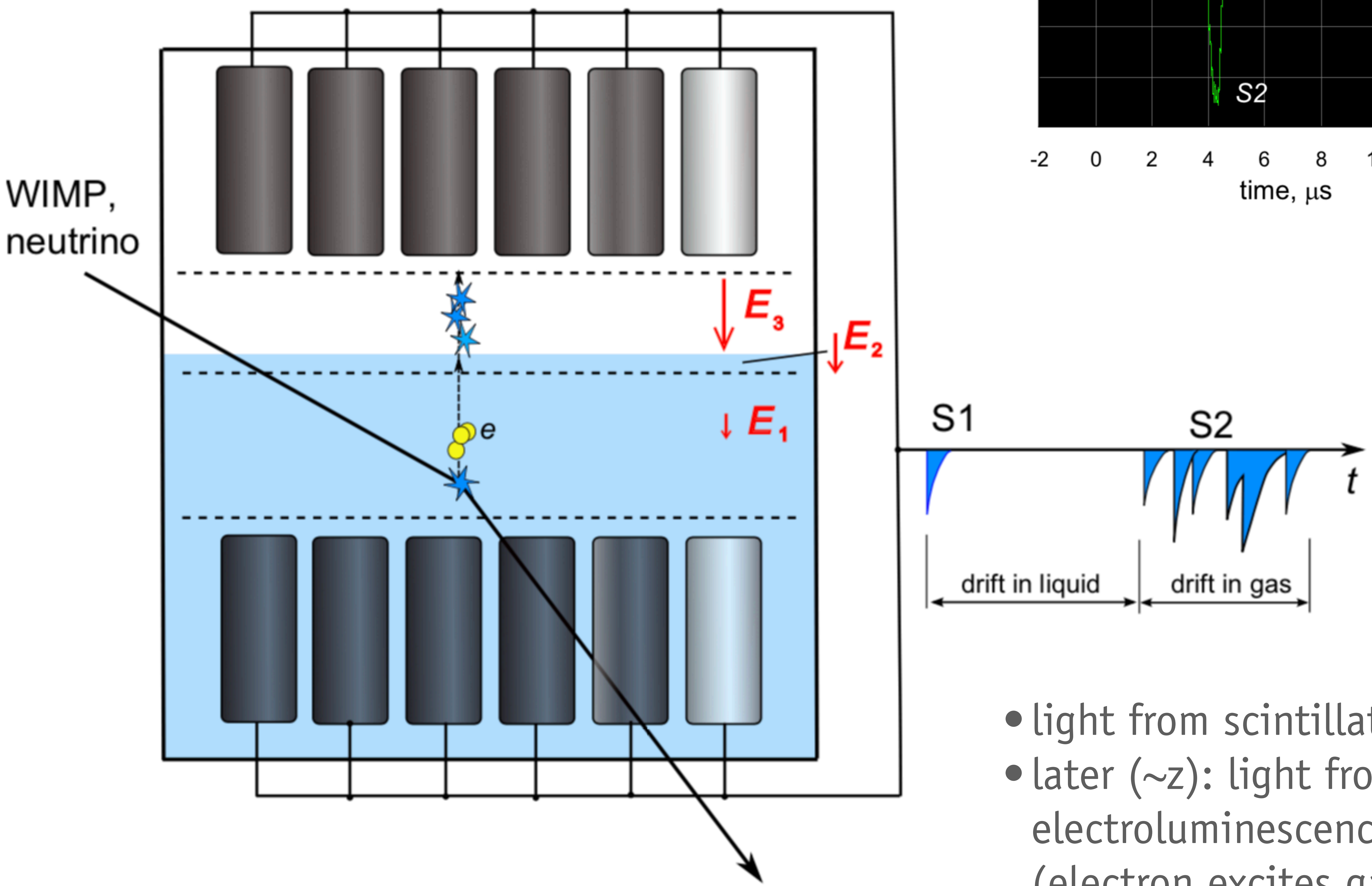
THE DUAL-PHASE TPC CONCEPT

$E_{liquid} \sim 200$ V/cm ($v_{drift} \sim 1$ mm/μs)
$E_{gas} \sim 3$ kV/cm





- light from scintillation in liquid
- later (~z): light from electroluminescence in gas (electron excites gas)

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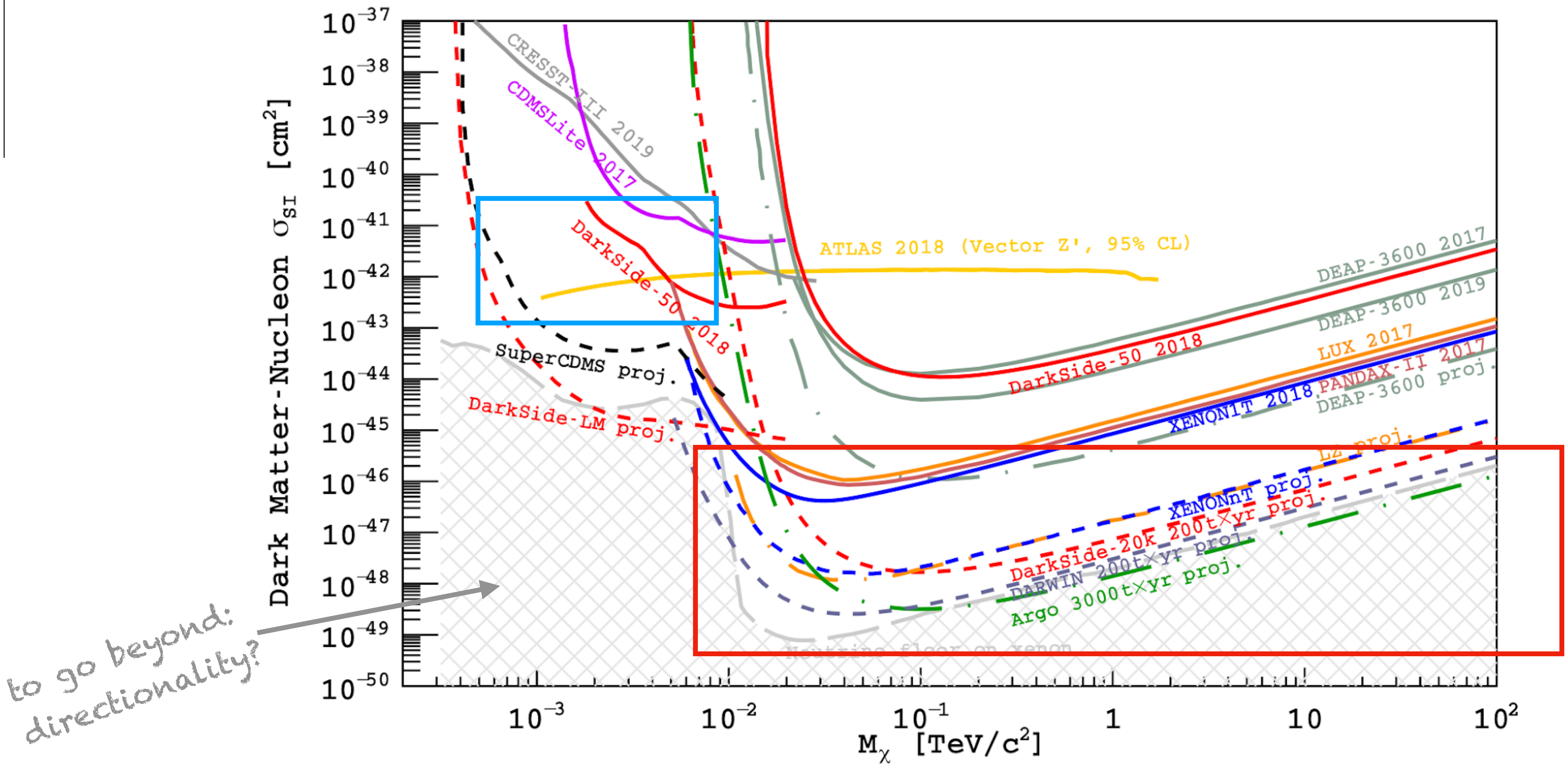
PUTTING DIRECT DETECTION ALTOGETHER



complementary strategies to reach neutrino floor

sensitivity driven by noble liquids (scintillation+ionisation vs ionisation-only)

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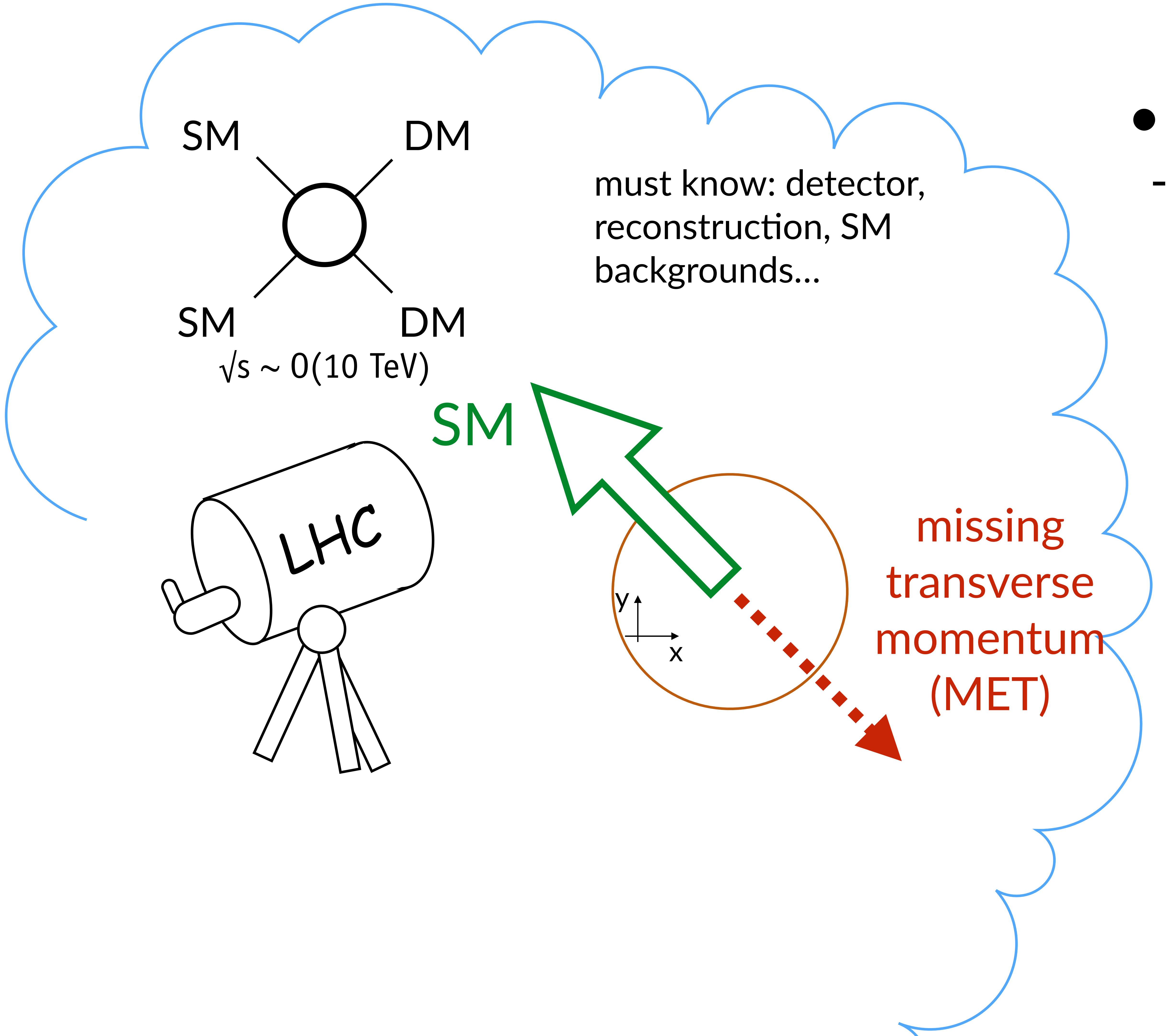
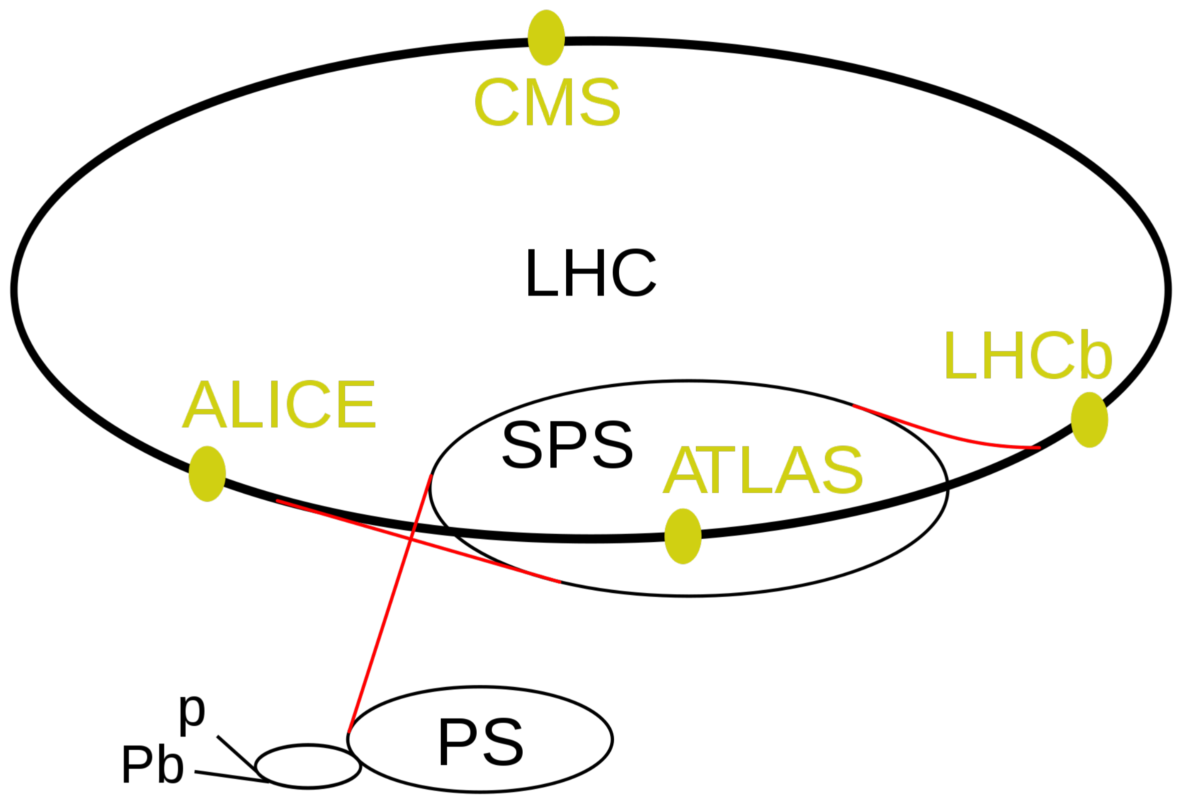
Why collider searches

What about producing WIMPs?



- build a collider which might produce DM
- build detectors which can detect everything else
- hope they do
  - experimental challenge set by needed precision and nature of DM-SM interaction



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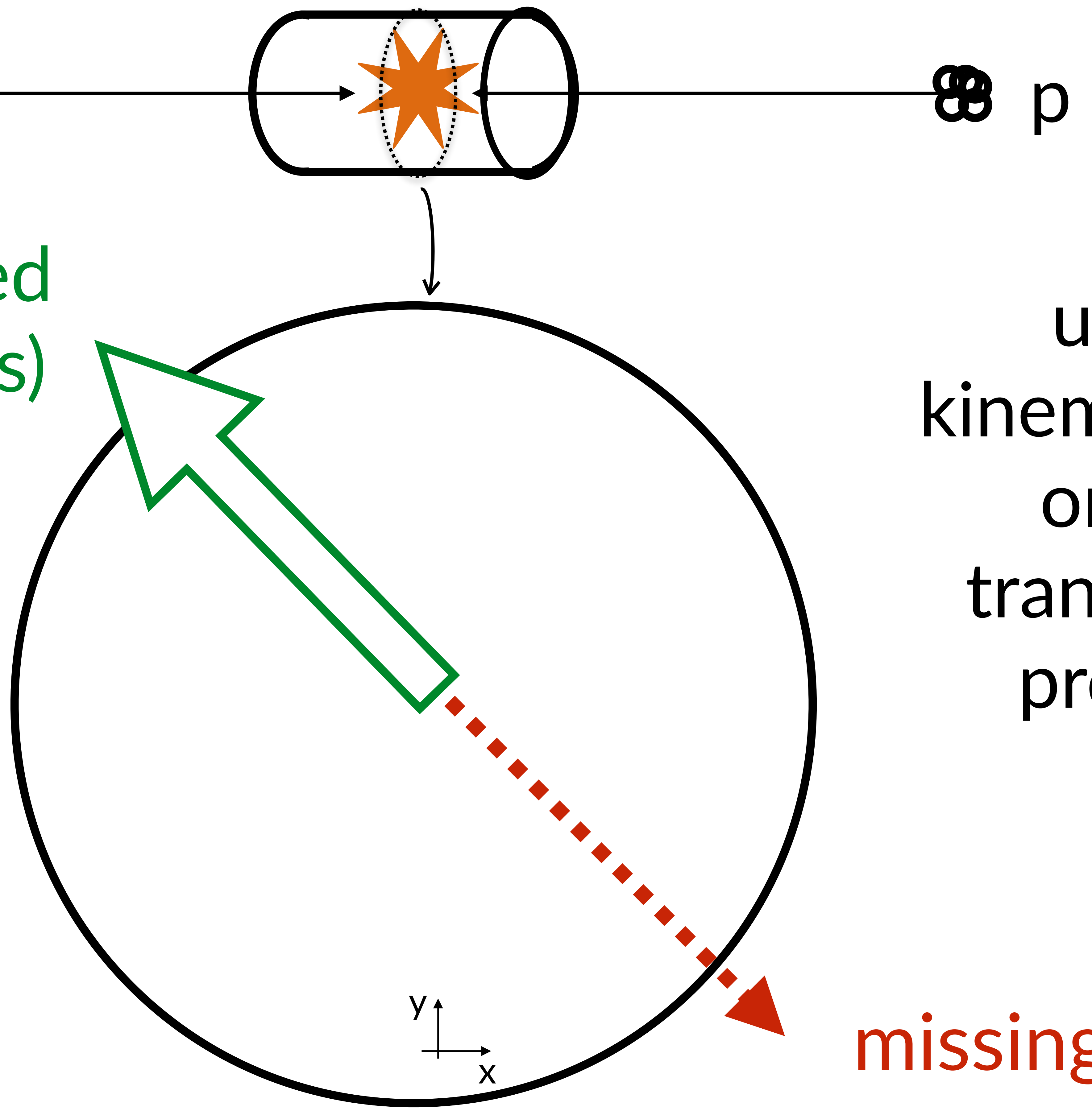
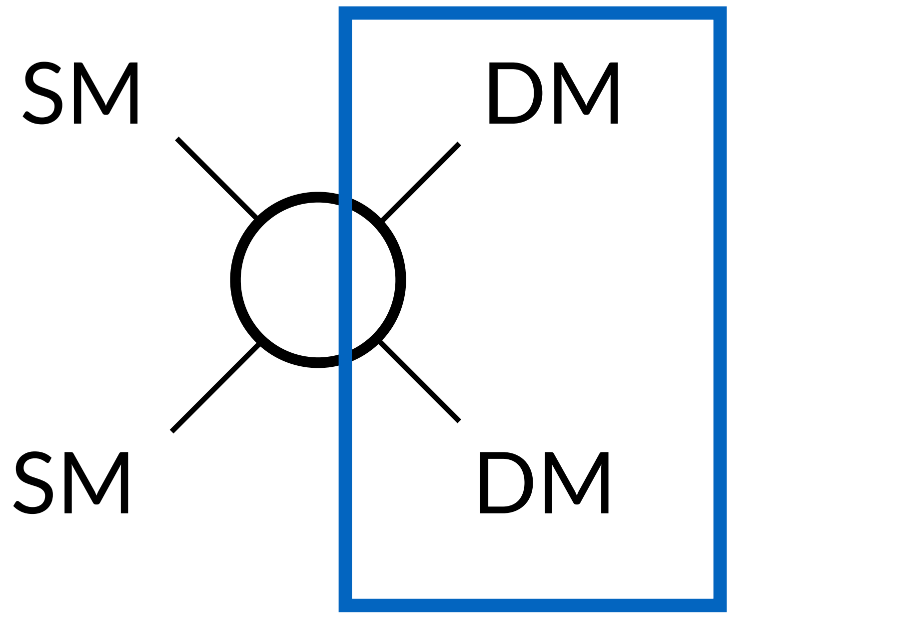
The invisible, through the visible

pp collisions @ 13 TeV



use the fact kinematics is closed on the plane transverse to the proton beams



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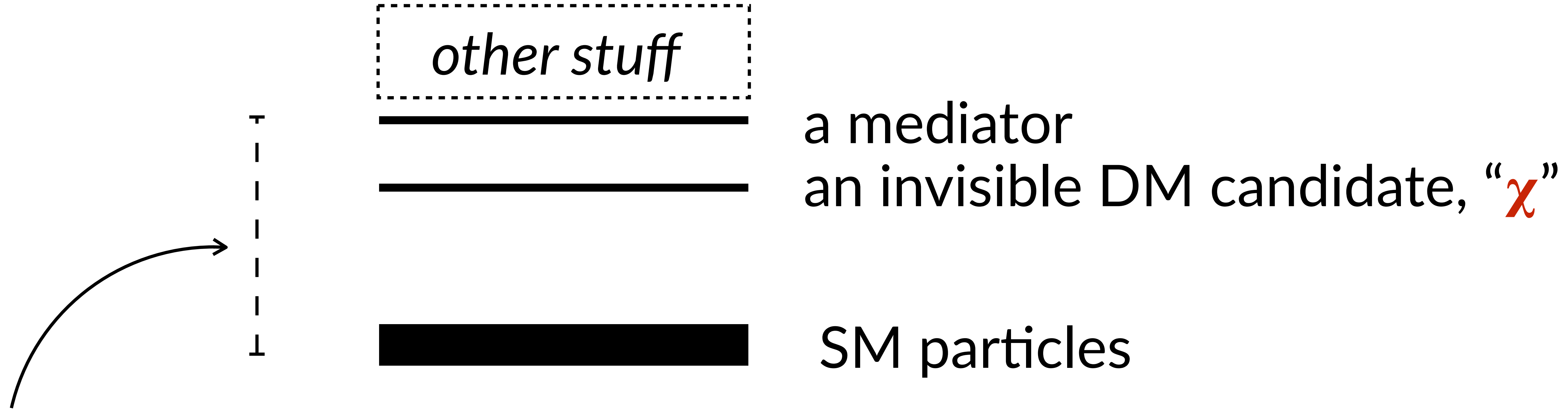
Extending the Standard Model

or: what are we all looking for?



*$\Delta m >> q^2$: **effective field theory** (as in the case of direct detection: Fermi-like interaction!)*
*$\Delta m <\sim q^2$: use **simplified models***

(simplified Lagrangian w.r.t. UV-complete models like SUSY)

	mediator	**DM**	**coupling strength**
direct detection	choice of the target	choice of the technology	reach neutrino bkg
LHC	choice of the final state	almost irrelevant if < O(100 GeV)	background estimation, luminosity

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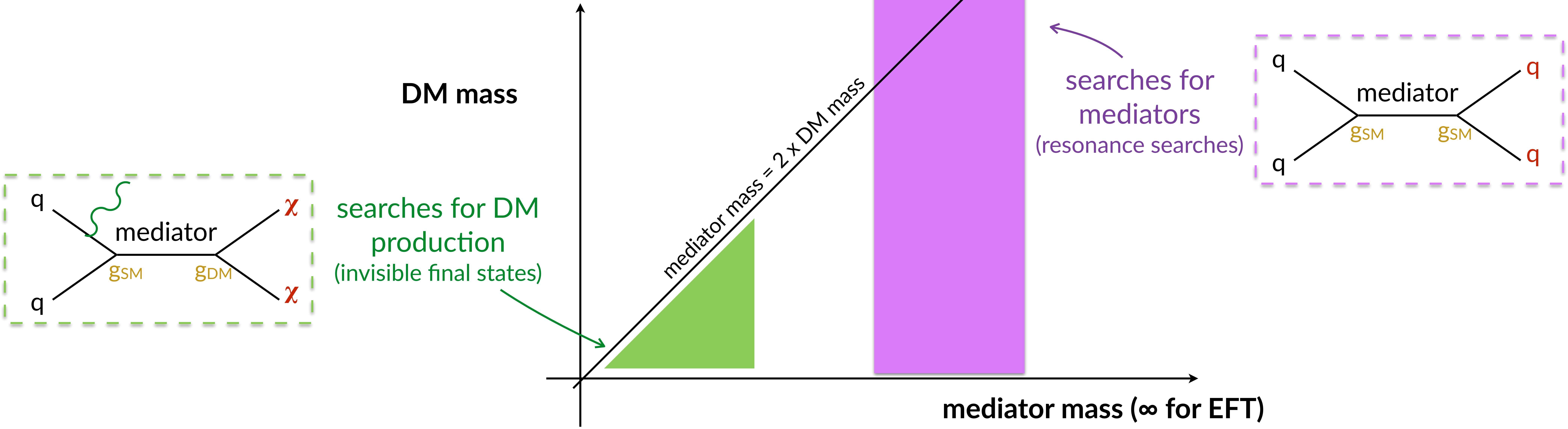
THE TYPICAL SIMPLIFIED MODEL

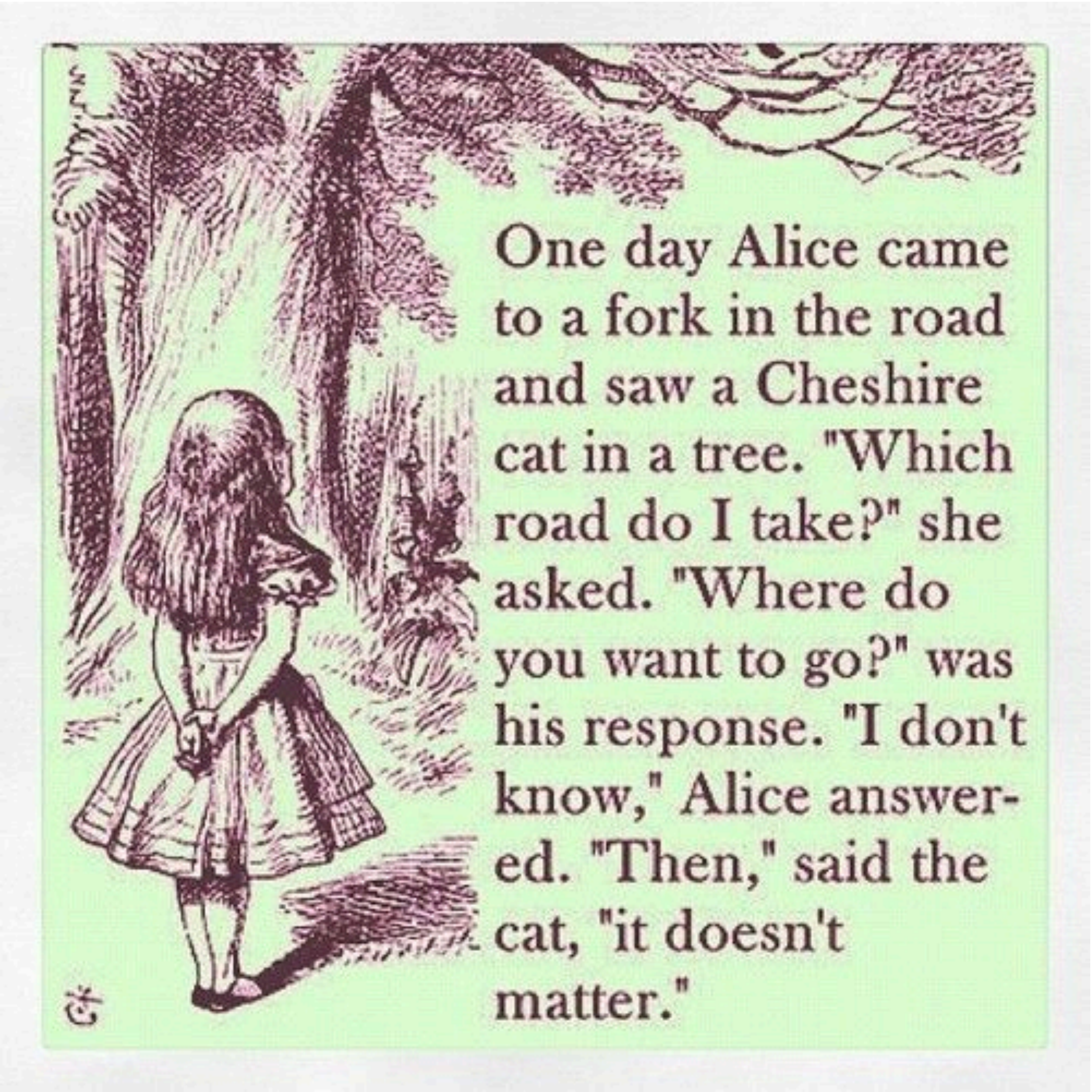
$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q$$

$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\gamma_5\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu\gamma_5 q$$



- once interaction is fixed (e.g. vector), parameter space is (at least) 4-dimensional
  - mediator mass, DM mass, mediator-SM coupling strength, mediator-DM coupling strength
- results often expressed in terms of 2D slices at **fixed couplings**

WHICH ROAD DO I TAKE?



- LHC may produce DM, and hence characterise a possible discovery
  - strength: synergy of (often non-trivial) final states
  - limitation: "invisible" requires trigger and MET
- experimental strategy: cover all possible channels and explore the theory "idea space"

		LHC	direct detection	indirect detection
can use bb/tt + MET and multiple signatures (mediator couples à la Yukawa with quark masses)	**scalar**	low xsec, soft MET	:|	
	pseudo-scalar	low xsec, soft MET	:'((velocity suppressed)	:)
can use jets + MET and confirm with mediator searches & ancillary channels (MET+gamma, MET+W/Z...)	**vector**	large xsec	:) (spin independent)	
	axial-vector	large xsec	:((spin-dependent: experimental issue)	

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different people see different things...

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Invisible channels

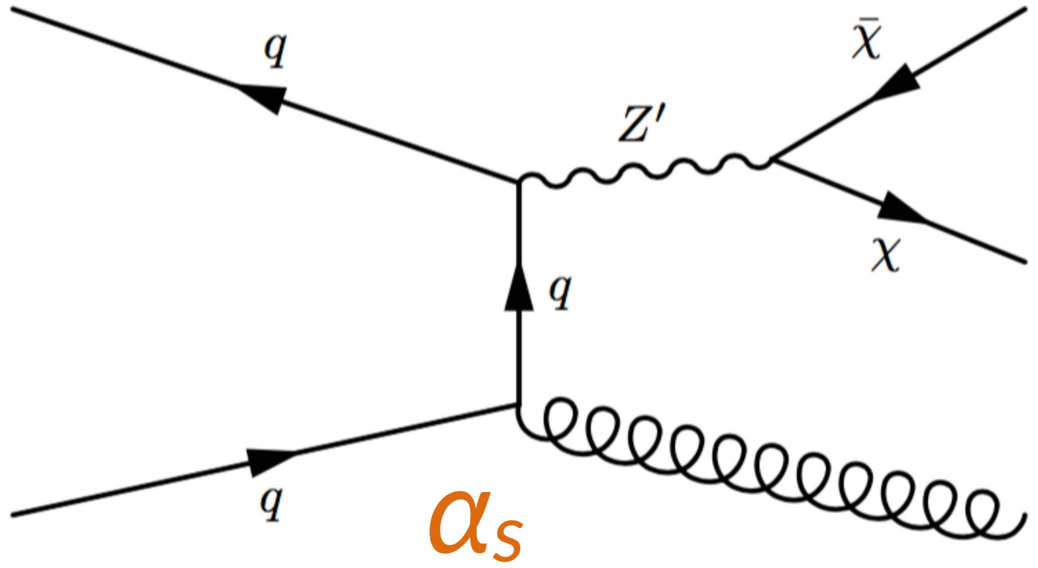
mono-jet, mono-W/Z, mono-photon...

[* plots by ATLAS, but CMS has similar approach]

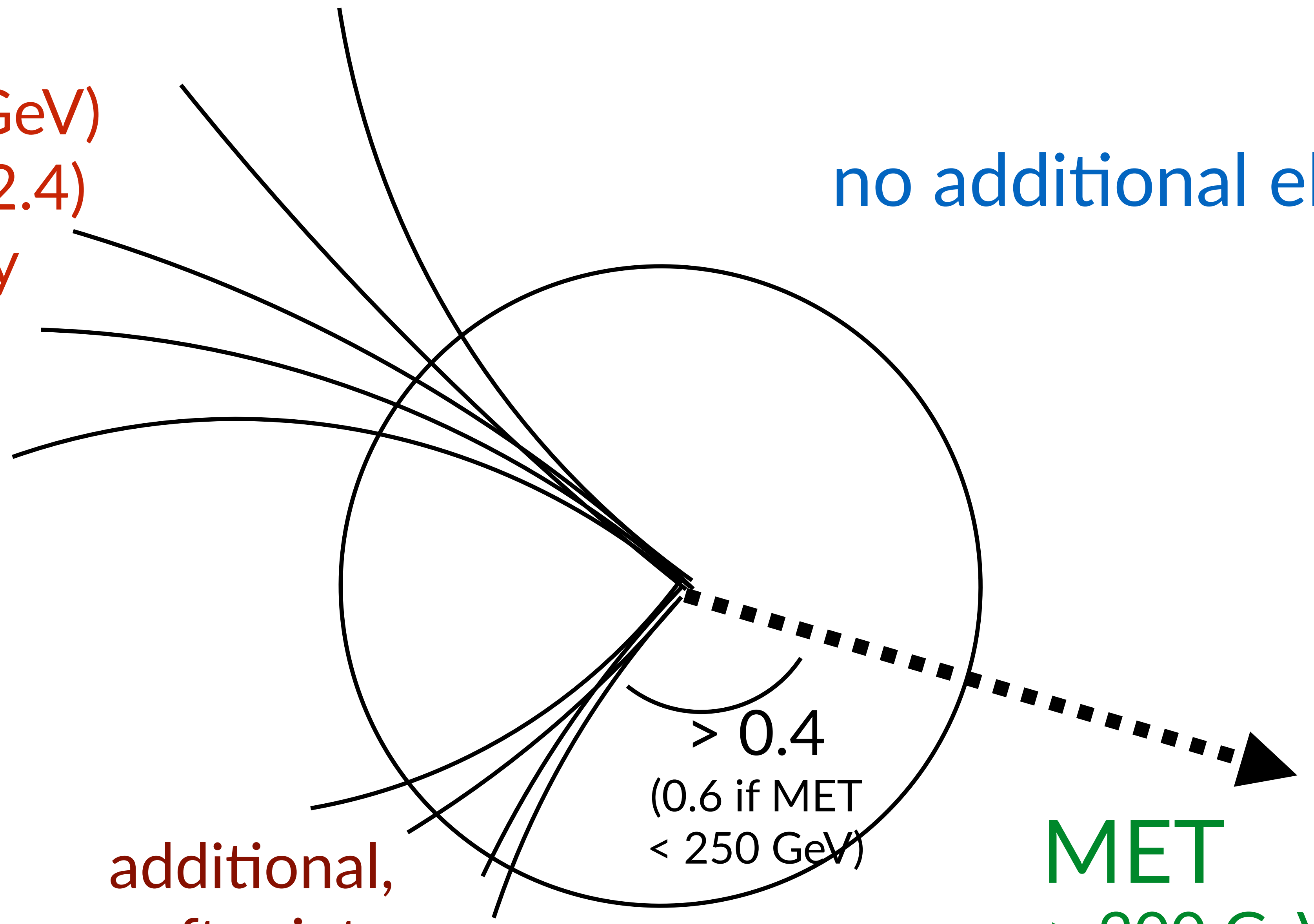
"MONO-JET"

arXiv:2102.10874

best channel if tagging object comes from ISR! (pay only α_s)



jet
high-pT (150 GeV)
central (|η|<~2.4)
tight quality

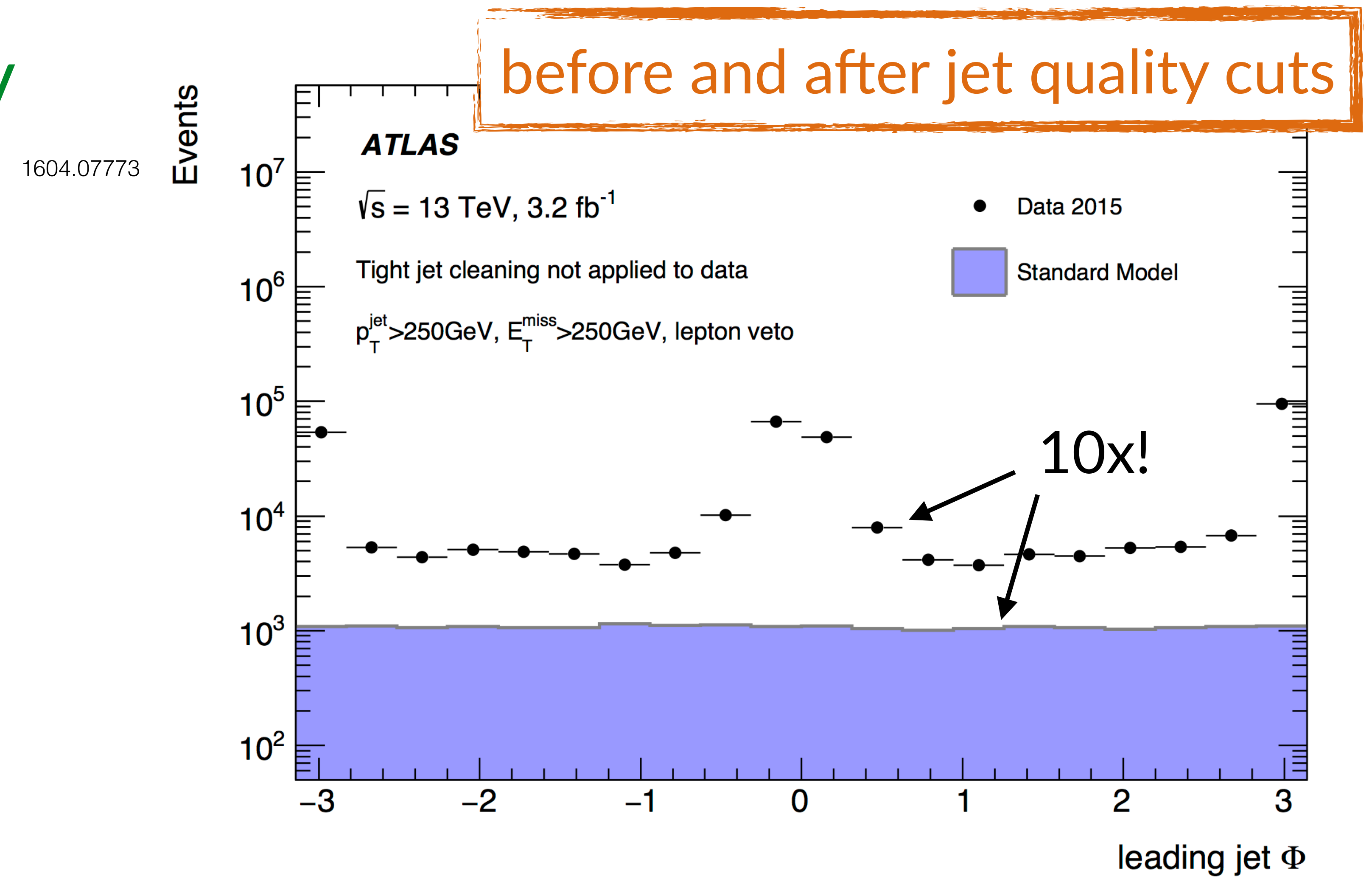


additional,
softer jets
(up to 3)

no additional electron or muon or photon

+ trigger
MET > 70 GeV
(fully efficient above 200 GeV)

MET
> 200 GeV



same signature as

- Z(νν) + jets, W(τ[qq']ν) + jets…
  - normalisation from simultaneous fit to p_T(W/Z) distributions in lepton control regions
- use calorimeter segmentation to reject beam & instrumental background

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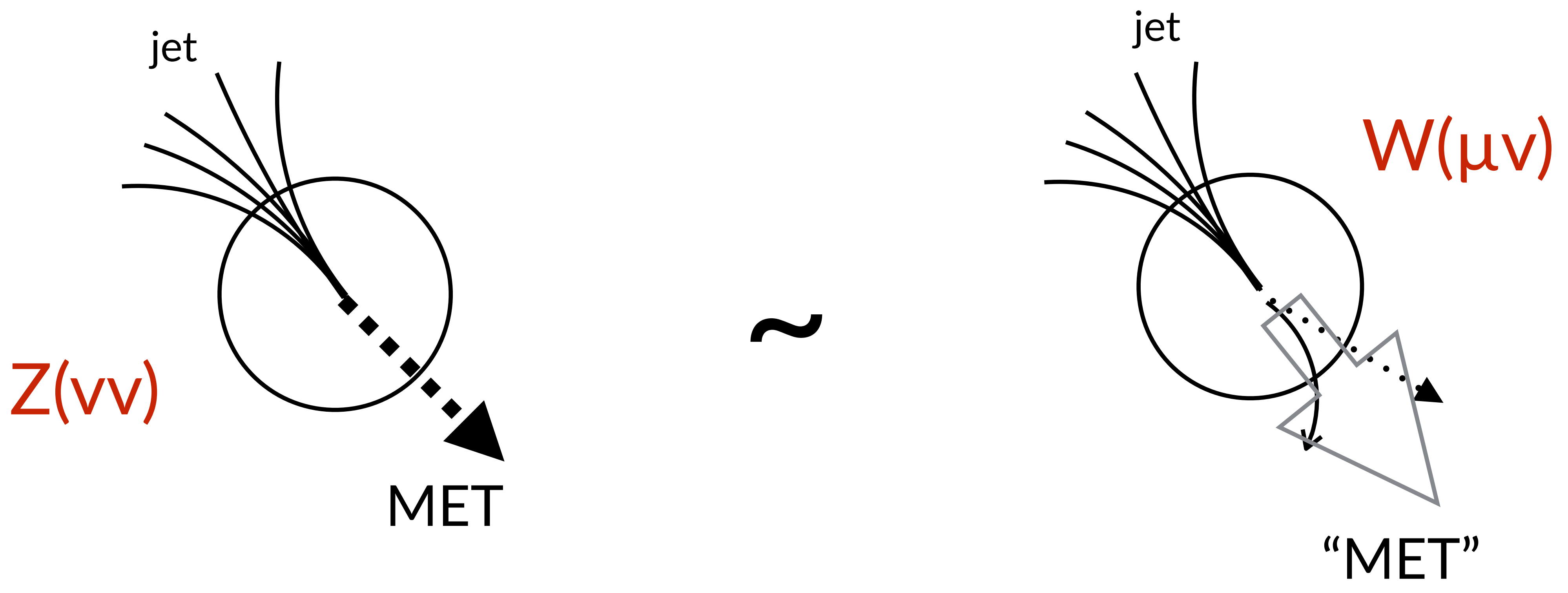
Reducing the irreducible: estimating V+jets (V=W or Z)

if we pretend leptons are invisible:



- fully link the Z(νν)+jets cross-section to the W(μν)+jets one

$$N_{meas}(Z\nu\nu) = k * N_{meas}(W\mu\nu/e\nu) = k * N_{meas}(Z\mu\mu)$$

from a fit to data enriched in W/Z+jets

- background uncertainty from residual differences between Z(νν) and the rest (e.g. muon uncertainties)

- do this differentially, as a function of $p_T(V)$ -> why?

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two ways to do that

option A: "transfer factor" technique

$$N(Z \to \nu\nu, \text{data}) \approx N(Z \to \nu\nu, \text{MC}) \cdot \frac{N(W \to \mu\nu, \text{data})}{N(W \to \mu\nu, \text{MC})}$$

transfer factor

- as in SM measurements
- becomes complex when adding more regions (subtract & correlate backgrounds)

option B: "simultaneous fit"

$$\mathcal{P}(n_{cb}, a_p \,|\, \phi_p, \alpha_p, \gamma_b) = \prod_{c \in \text{channels}} \prod_{b \in \text{bins}} \text{Pois}(n_{cb}|\nu_{cb}) \cdot G(L_0|\lambda, \Delta_L) \cdot \prod_{p \in \mathbb{S}+\mathbf{\Gamma}} f_p(a_p|\alpha_p)$$

normalisation factors (free)
nuisance parameters (systematics)
nuisance parameters (low MC stats)

- as in Higgs discovery
- each background (and systematic variation) corresponds to a histogram
- systematic nuisance parameters describe how uncertainties impact bin contents across regions

option **B** is nowadays the state-of-the-art

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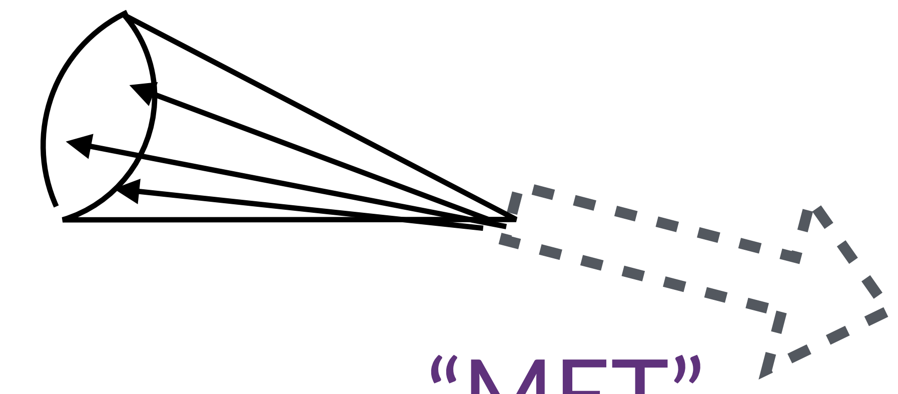
p_T(W/Z) IN "MONO-JET" CONTROL REGIONS

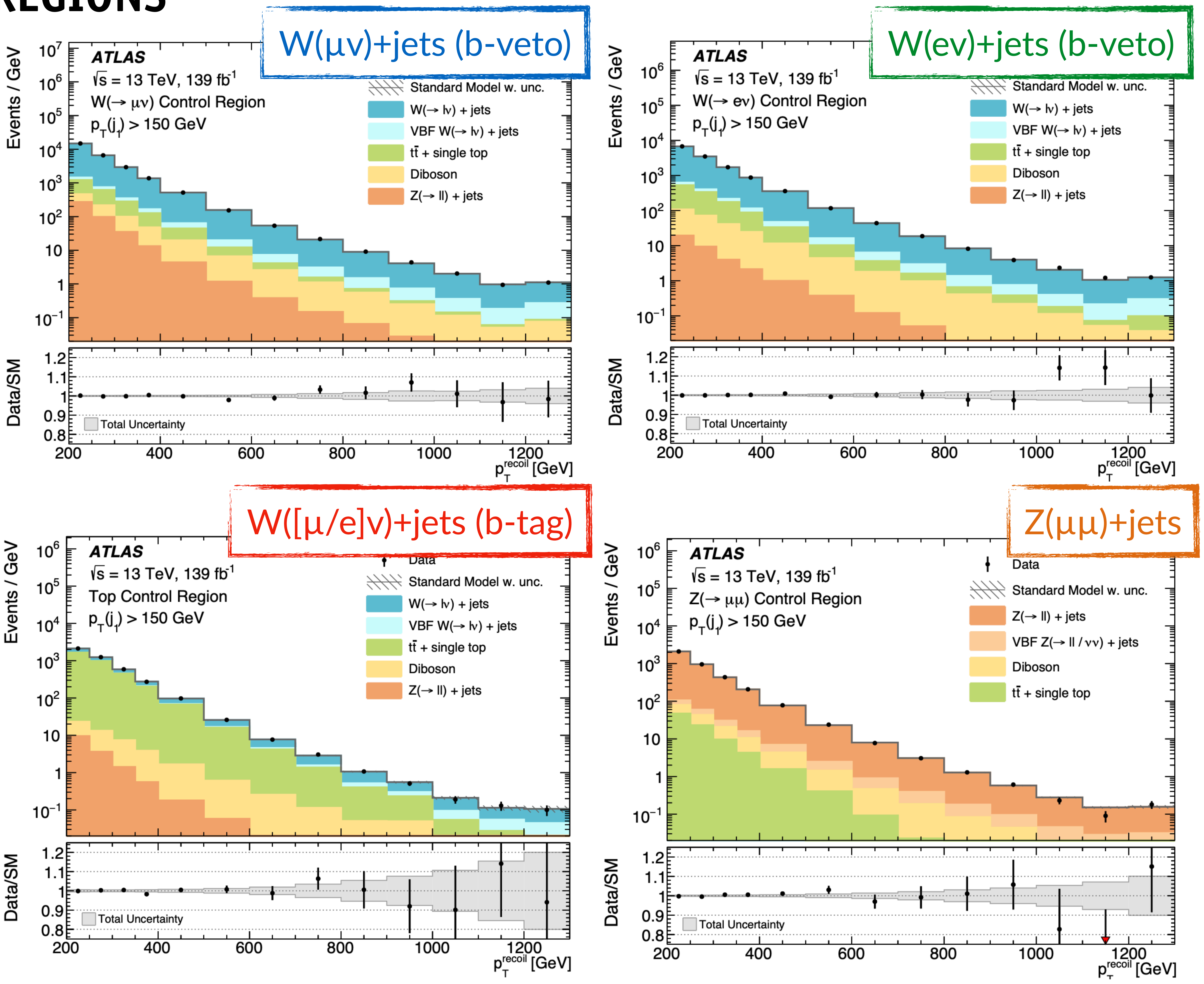
fit parameters:

- W/Z normalisation (free, common also to Z(νν)+jets)
- ttbar/single-t normalisation
- shape/ normalisation uncertainties (constrained)

jet



“MET”
(|$\mathbf{p}_T^{(lep's)}$+MET|)



[results of CR-only fit]

also: Z(ee)+jets CR

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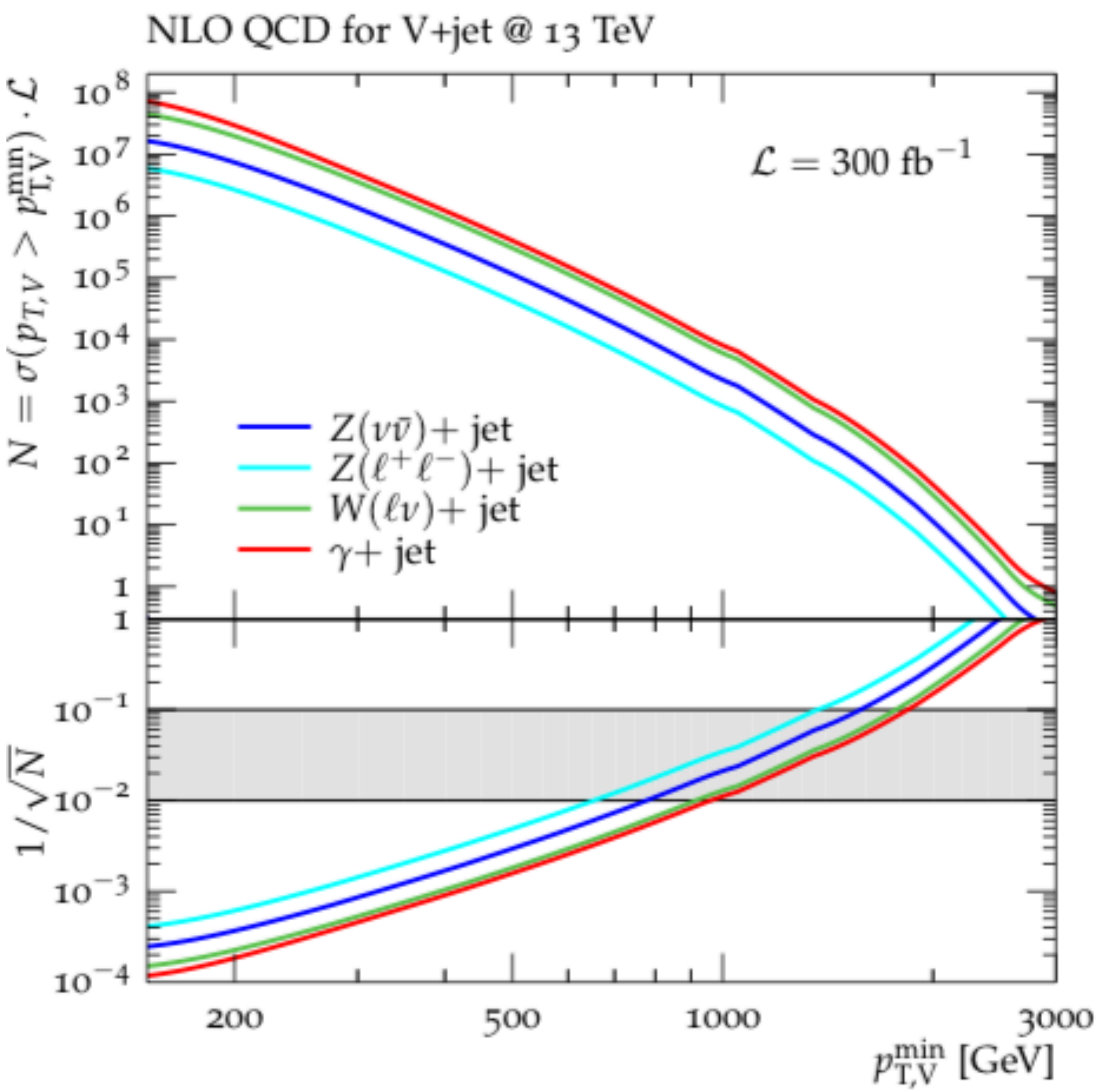
WEAPONS OF Z(νν) DESTRUCTION

arXiv:1705.04664v1

v2 goes to NNLO in QCD, implemented recently @ ATLAS

V+jets xsec x BR, as a function of p_T



produce more W+jets than Z(ll)+jets: use both to reduce statistical uncertainties

$$\mathcal{L}(K) = \prod_{\text{region } i} \mathrm{Pois}\left(N_{OBS}^{(i)} \,\middle|\, K \times N_{MC}^{(i)}\right)$$

- fit from data a common, global scale factor to W and Z normalisation
- assume the W/Z cross-section ratio is known to a given precision

(ATLAS MC accuracy: Sherpa NLO up to 2 partons, LO up to 4 partons)

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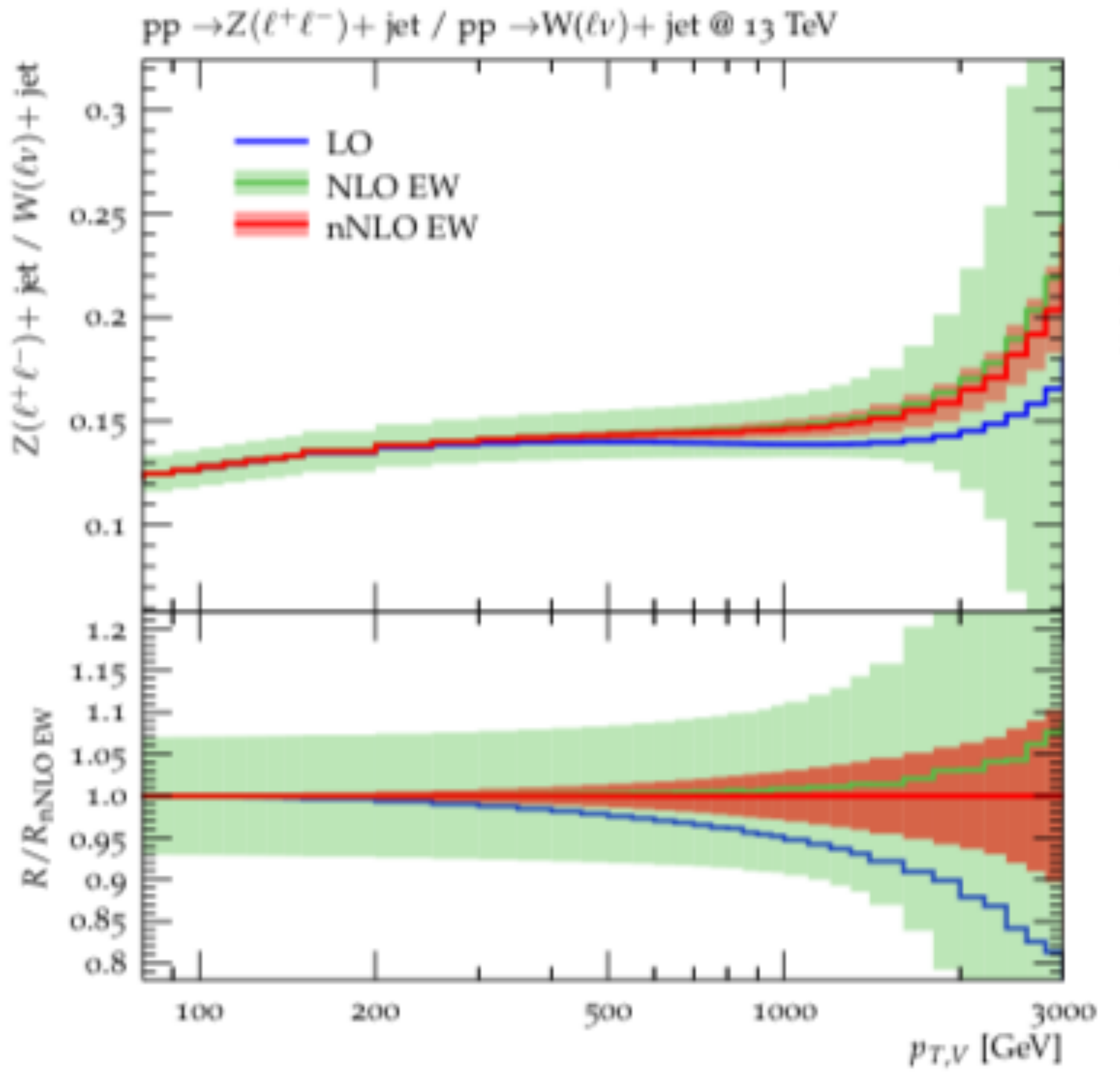
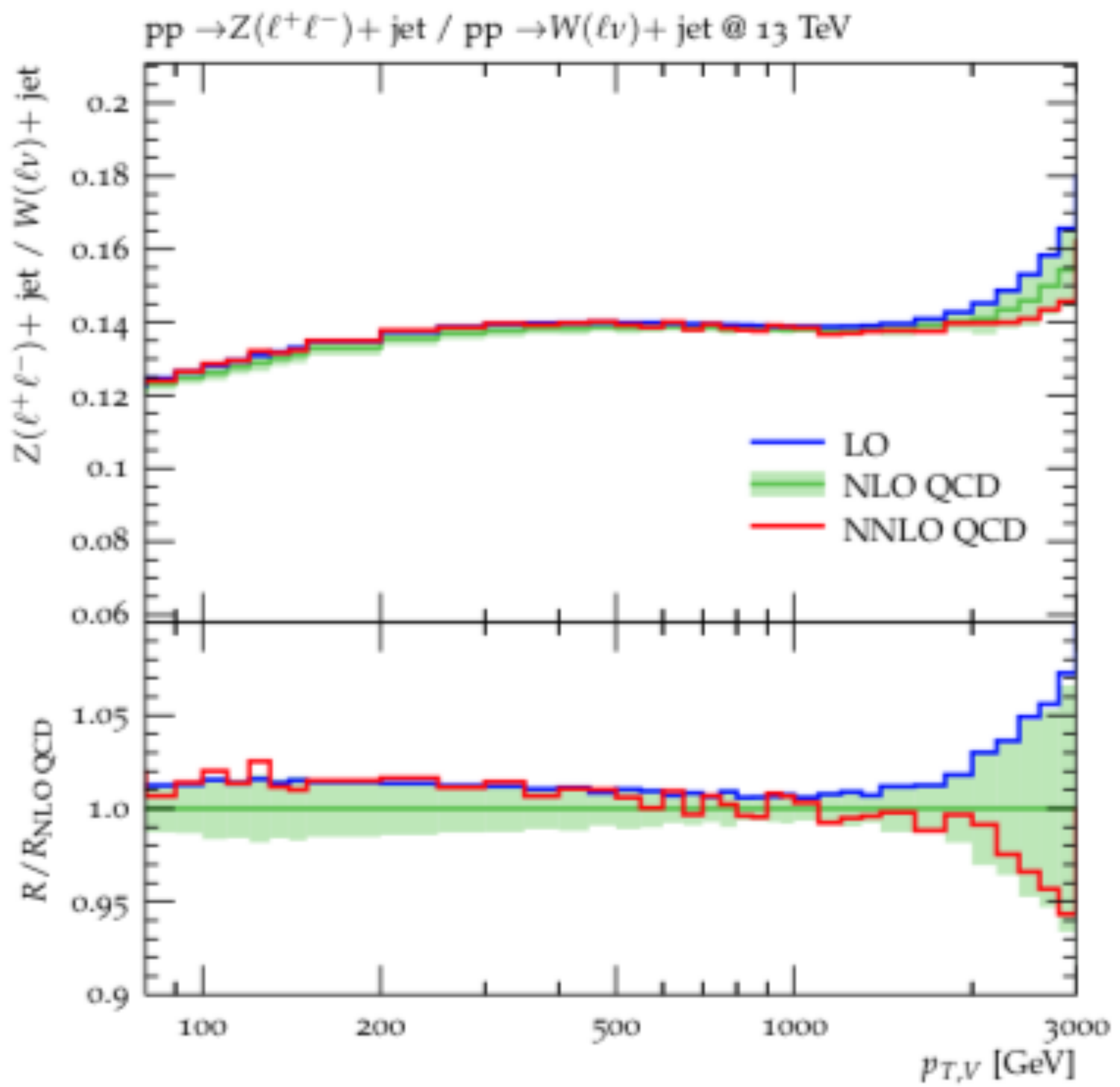
CROSS-SECTION RATIOS AT HIGHER ORDERS

EW uncertainties >> QCD uncertainties





key points:

- shape and normalisation uncertainties on the W/Z cross-section ratio
  - correlation scheme from state-of-the-art theory calculations
- fit an overall correction factor common to W and Z

HOW THIS AFFECTS A SEARCH

Source of uncertainty and effect on the total SR background estimate [%]			
Flavor tagging	0.1 – 0.9	τ-lepton identification efficiency	0.1 – 0.07
Jet energy scale	0.17 – 1.0	Luminosity	0.01 – 0.05
Jet energy resolution	0.15 – 1.3	Noncollision background	0.2 – 0.0
Jet JVT efficiency	0.01 – 0.03	Multijet background	1.0 – 0.0
Pileup reweighting	0.4 – 0.24	Diboson theory	0.01 – 0.22
E_T^{miss} resolution	0.34 – 0.04	Single-top theory	0.13 – 0.28
E_T^{miss} scale	0.5 – 0.25	$t\bar{t}$ theory	0.06 – 0.7
Electron and photon energy resolution	0.01 – 0.08	V+jets τ-lepton definition	0.04 – 0.16
Electron and photon energy scale	0.3 – 0.7	V+jets pure QCD corrections	0.24 – 1.1
Electron identification efficiency	0.5 – 1.0	V+jets pure EW corrections	0.17 – 2.2
Electron reconstruction efficiency	0.15 – 0.2	V+jets mixed QCD–EW corrections	0.02 – 0.7
Electron isolation efficiency	0.04 – 0.19	V+jets PDF	0.01 – 0.7
Muon identification efficiency	0.03 – 0.9	VBF EW V+jets backgrounds	0.02 – 1.1
Muon reconstruction efficiency	0.4 – 1.5	Limited MC statistics	0.05 – 1.9
Muon momentum scale	0.1 – 0.7		
Total background uncertainty in the Signal Region: 1.5%–4.2%			

THE BIGGER PICTURE

Source of uncertainty and effect on the total SR background estimate [%]			
Flavor tagging	0.1 – 0.9	τ-lepton identification efficiency	0.1 – 0.07
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Muon momentum scale	0.1 – 0.7		
Total background uncertainty in the Signal Region: 1.5%–4.2%			

"a precision search"?

[you may attempt at unfolding the Zνν/Wlν cross-section ratio and do better - can you?]

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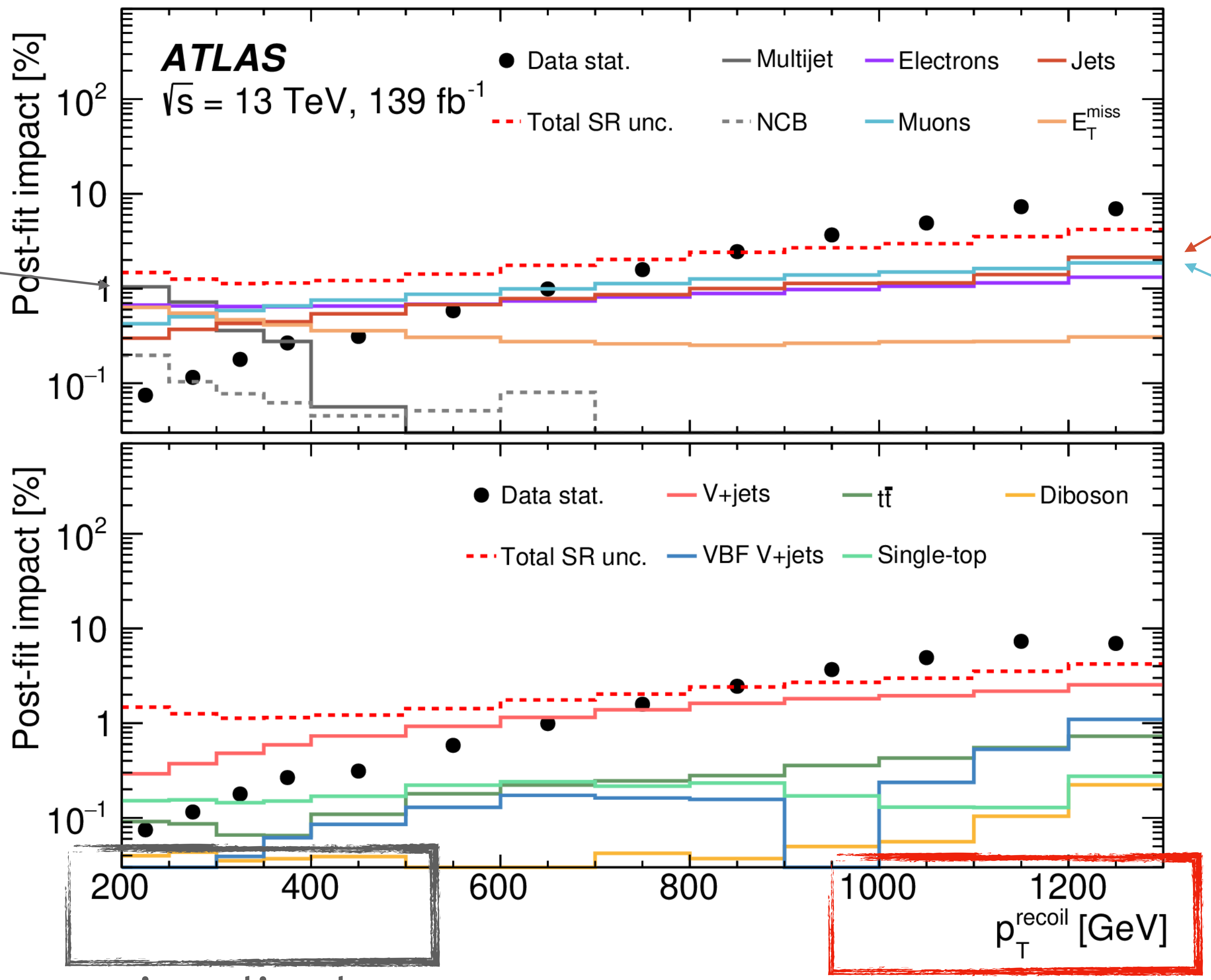
OR A SEARCH FOR PRECISION?

MET comes from mismeasured jets



very hard to calibrate high-energy jets (multi-jet balance, punch-through…)

no standard candle beyond the Z boson

spin-0 interactions live here

spin-1 interactions live here

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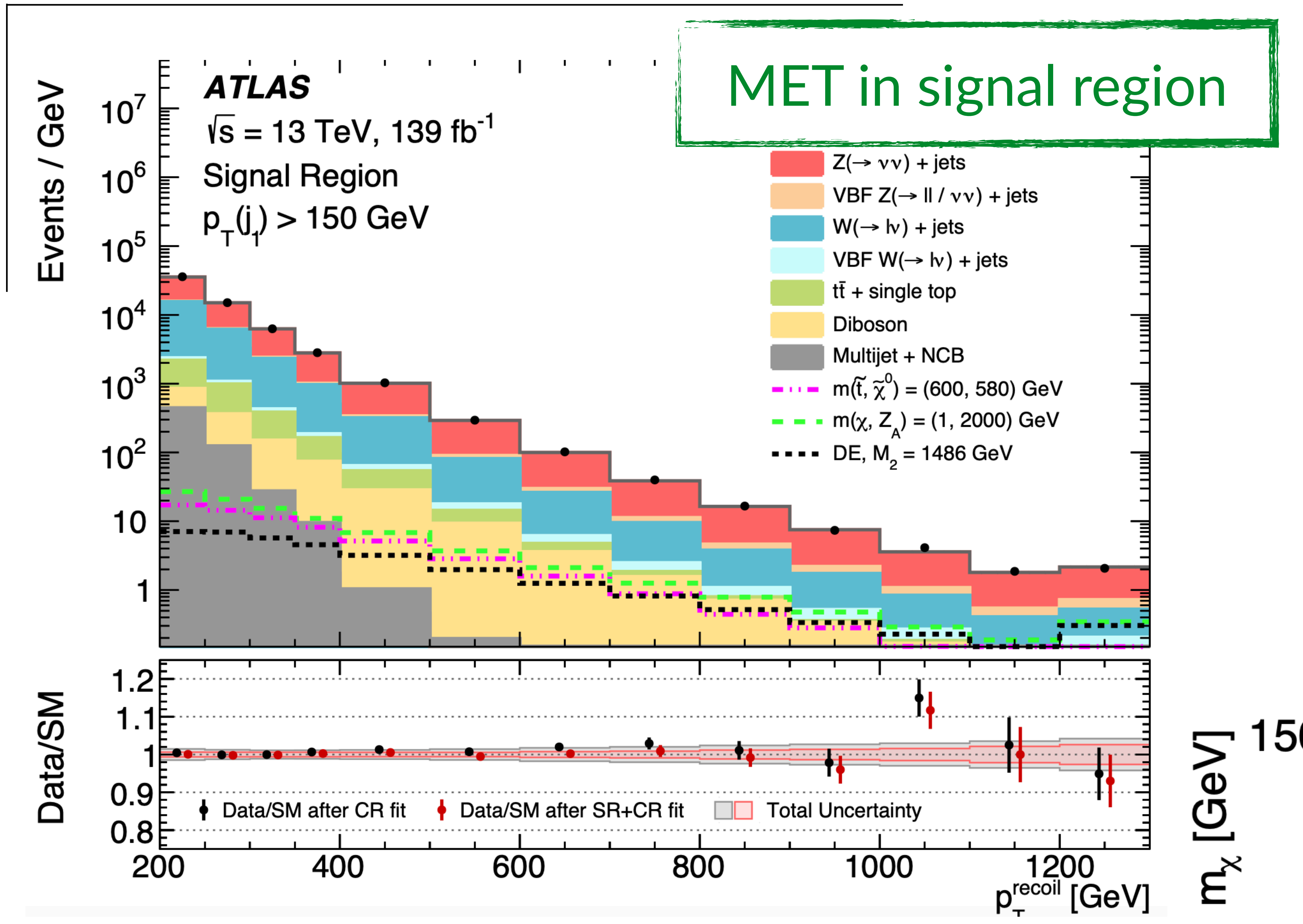
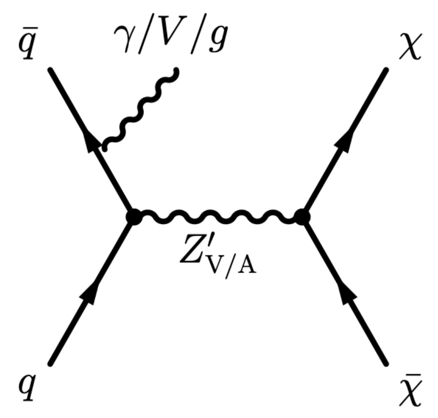
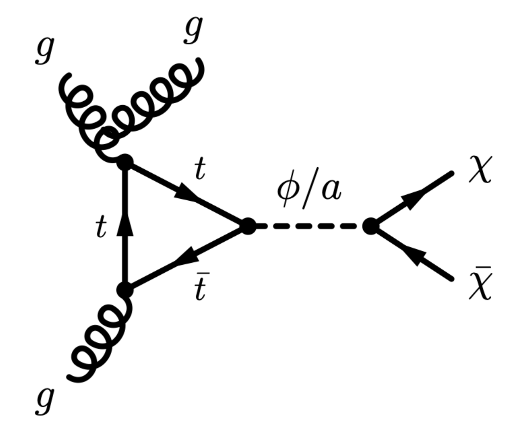
"MONO-JET" RESULTS

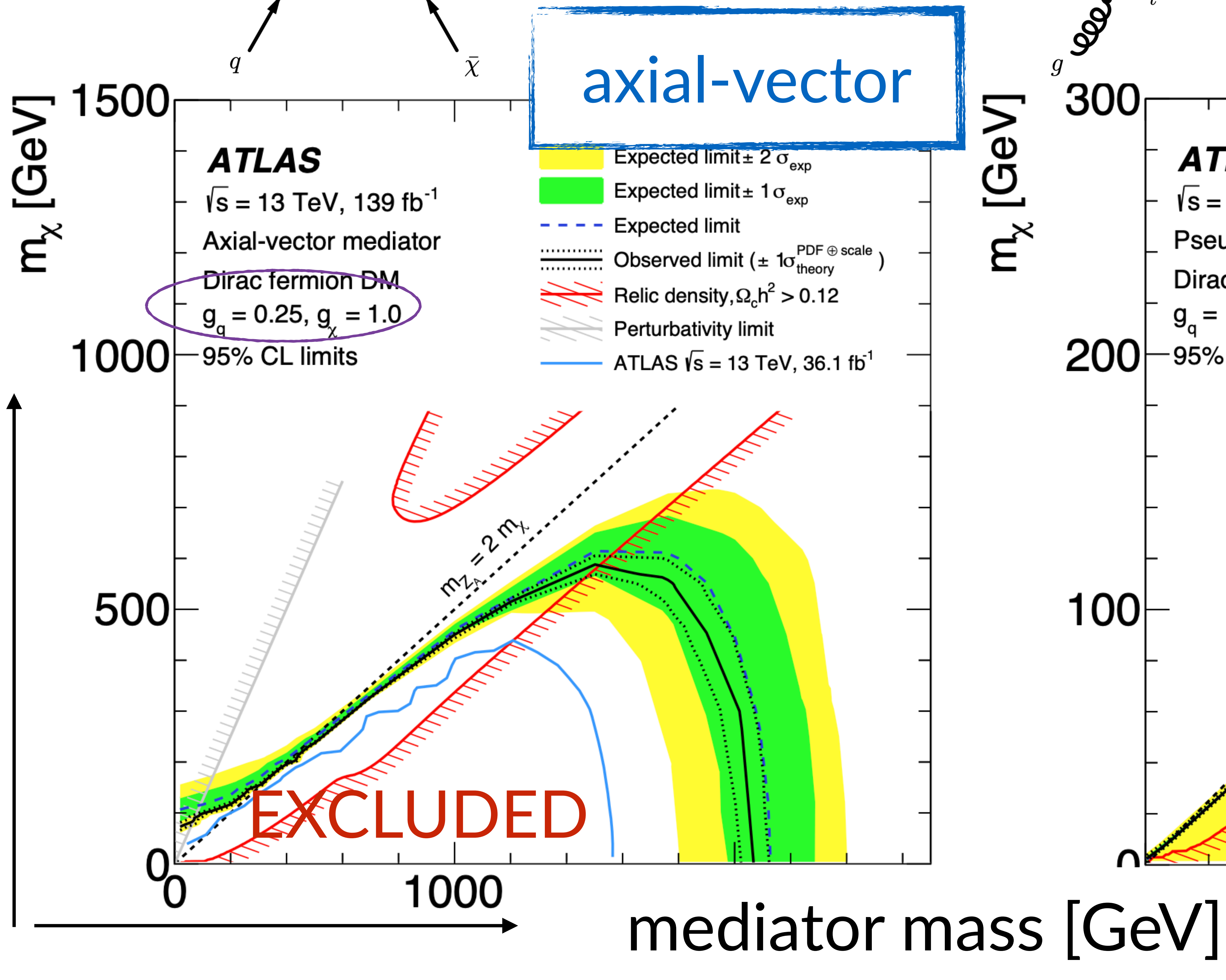
[results of CR+SR fit]

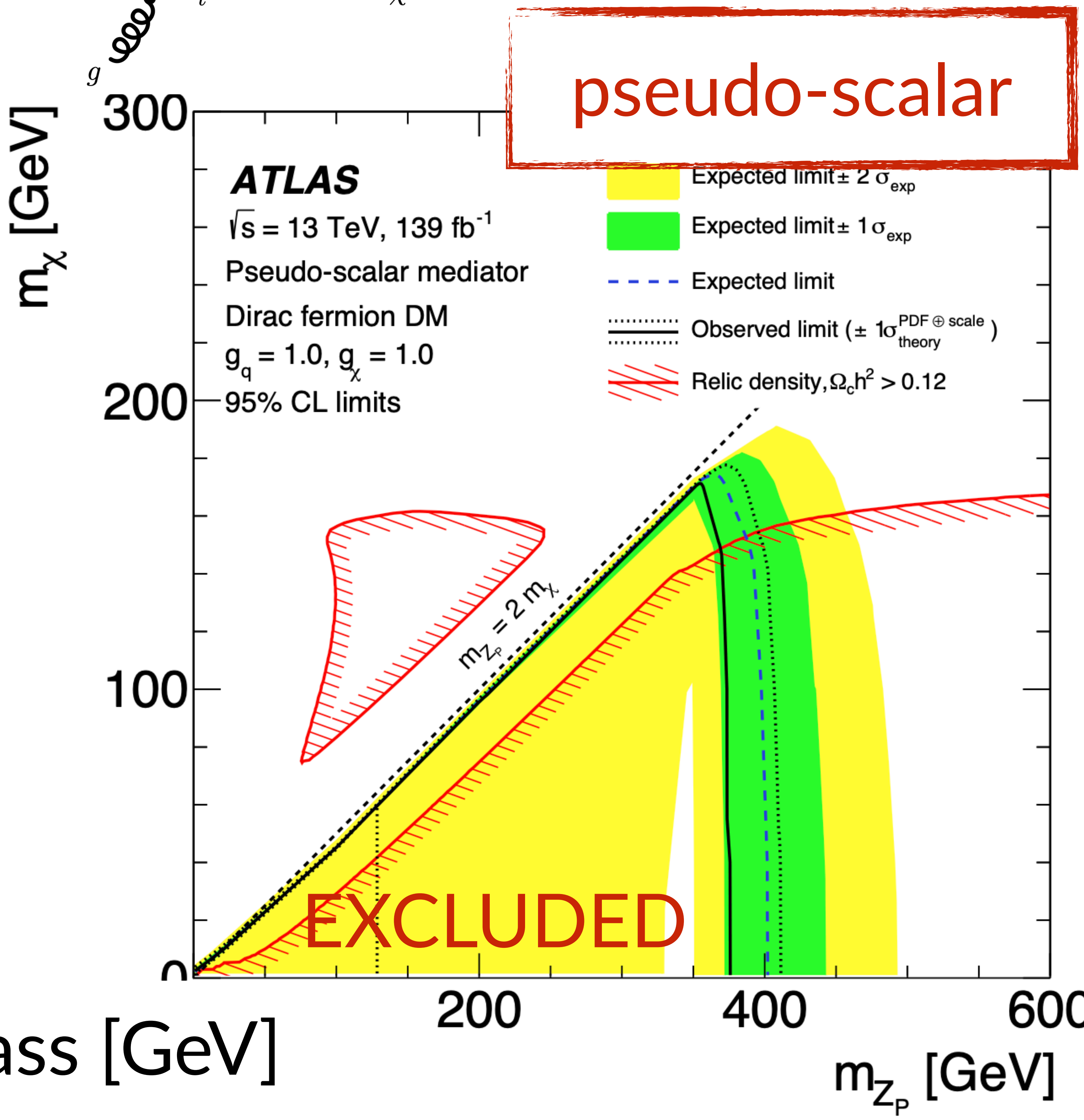


- 1.5-4.2% uncertainty on signal region background
  - theo: 0.3-1% for the W(lv)/Z(ll)->Z(vv) extrapolation
  - exp: electron/muon efficiency, jet energy scale/reso
- probing s-channel ($J^P=0^-$, 1^+, 1^-) and t-channel [36 fb^{-1} only] DM-SM interactions







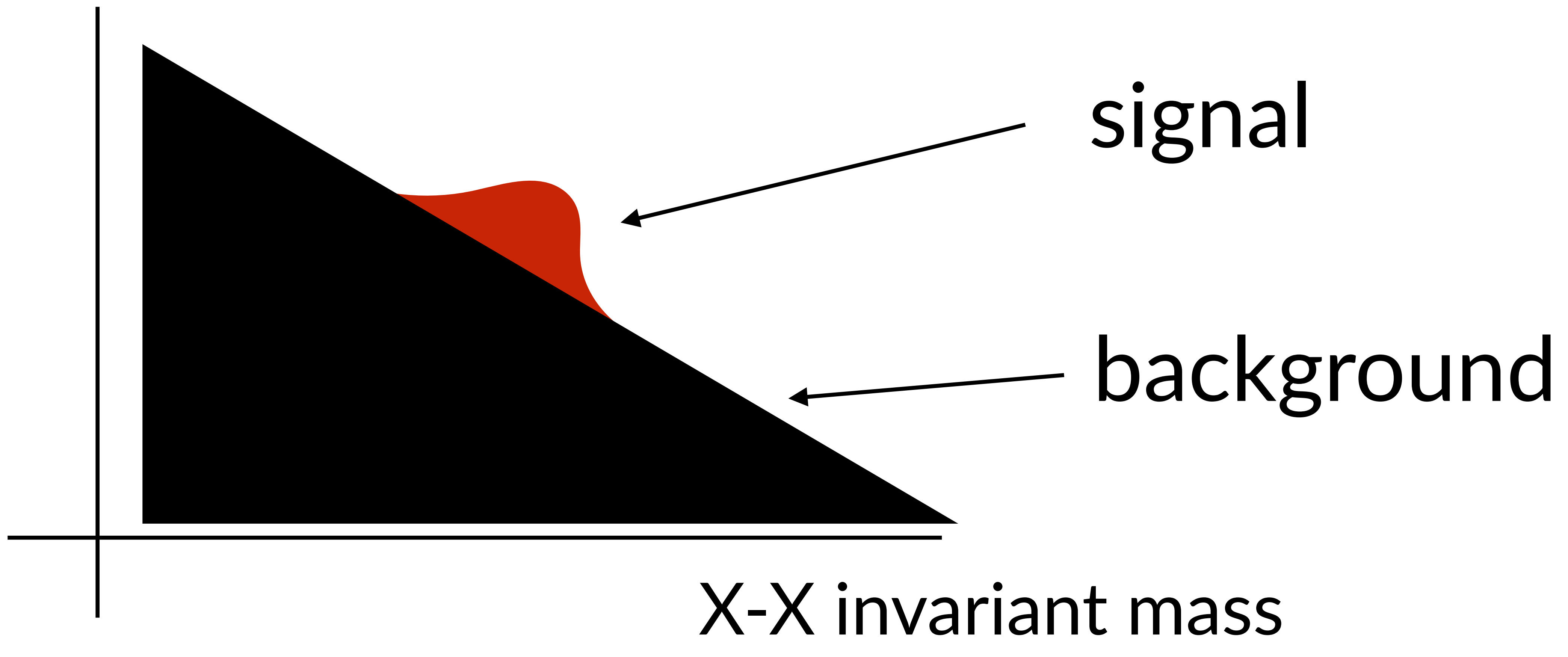


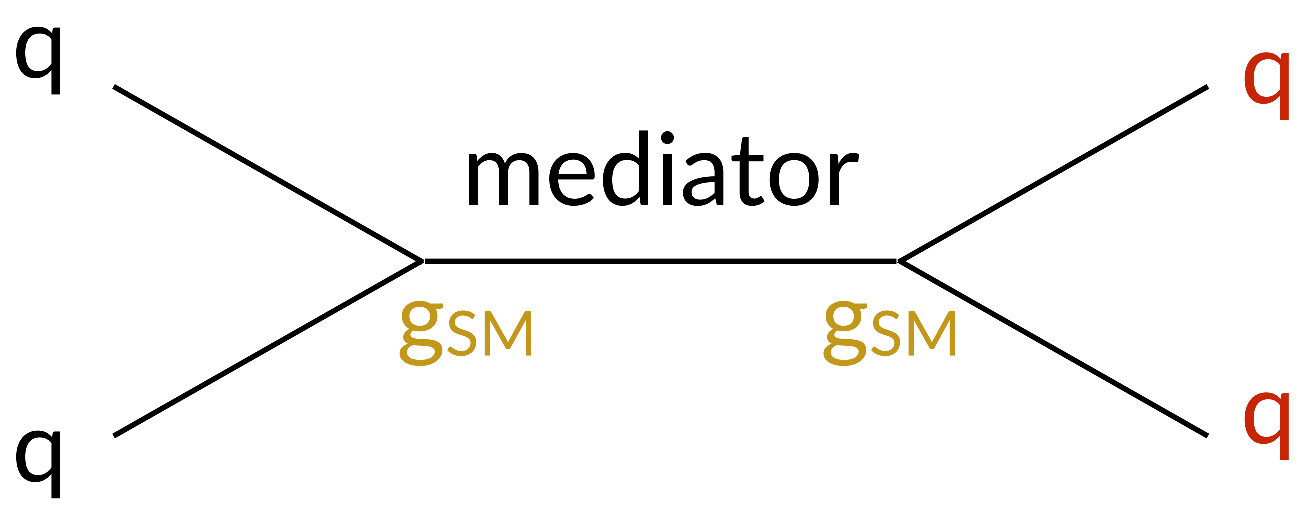
discovery potential for these WIMP models depends on assumed interaction and couplings

The visible

di-jet, di-lepton, di-top…

IF WE LOOK FOR THE MEDIATOR





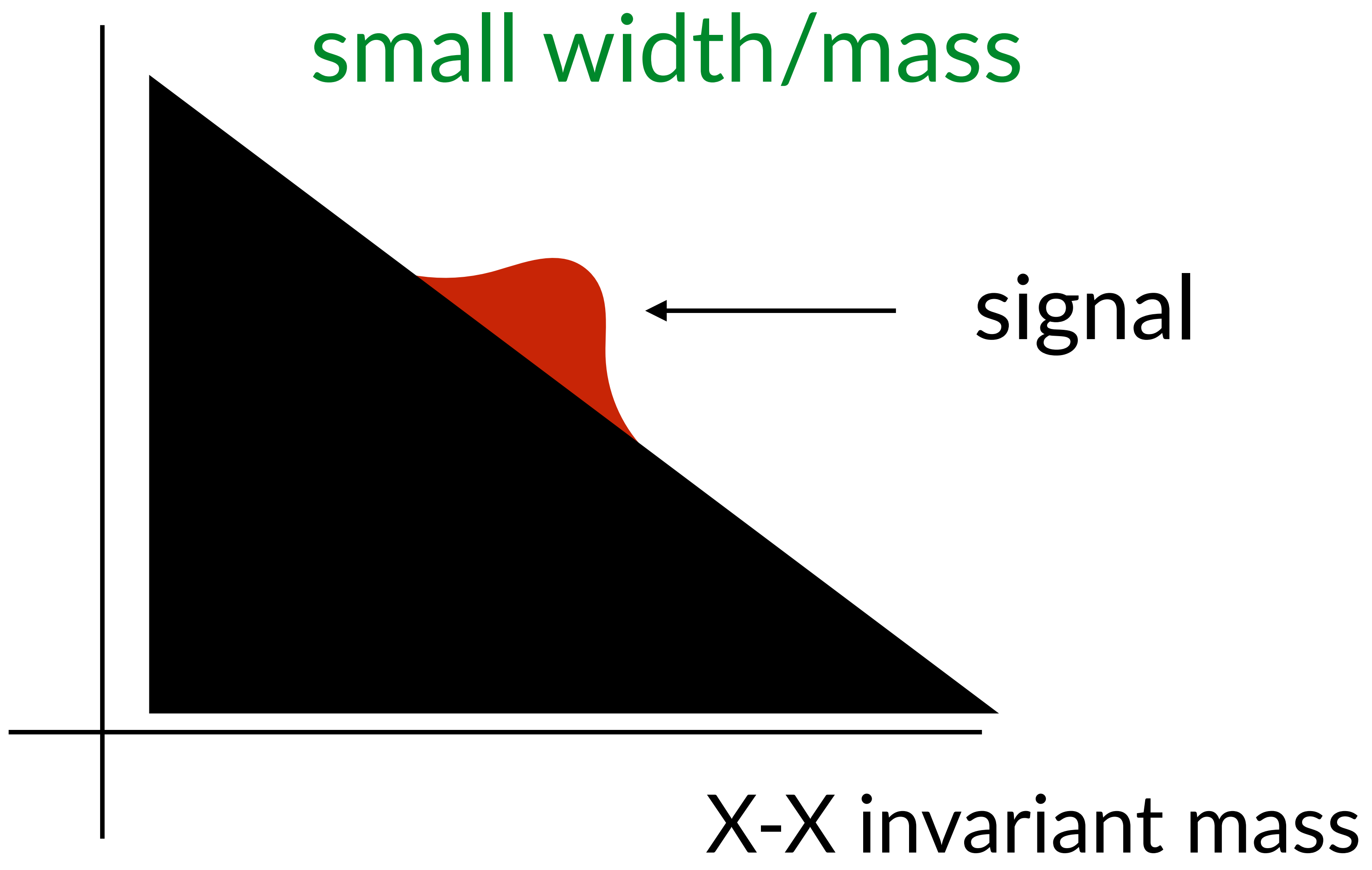
(di-jet case)

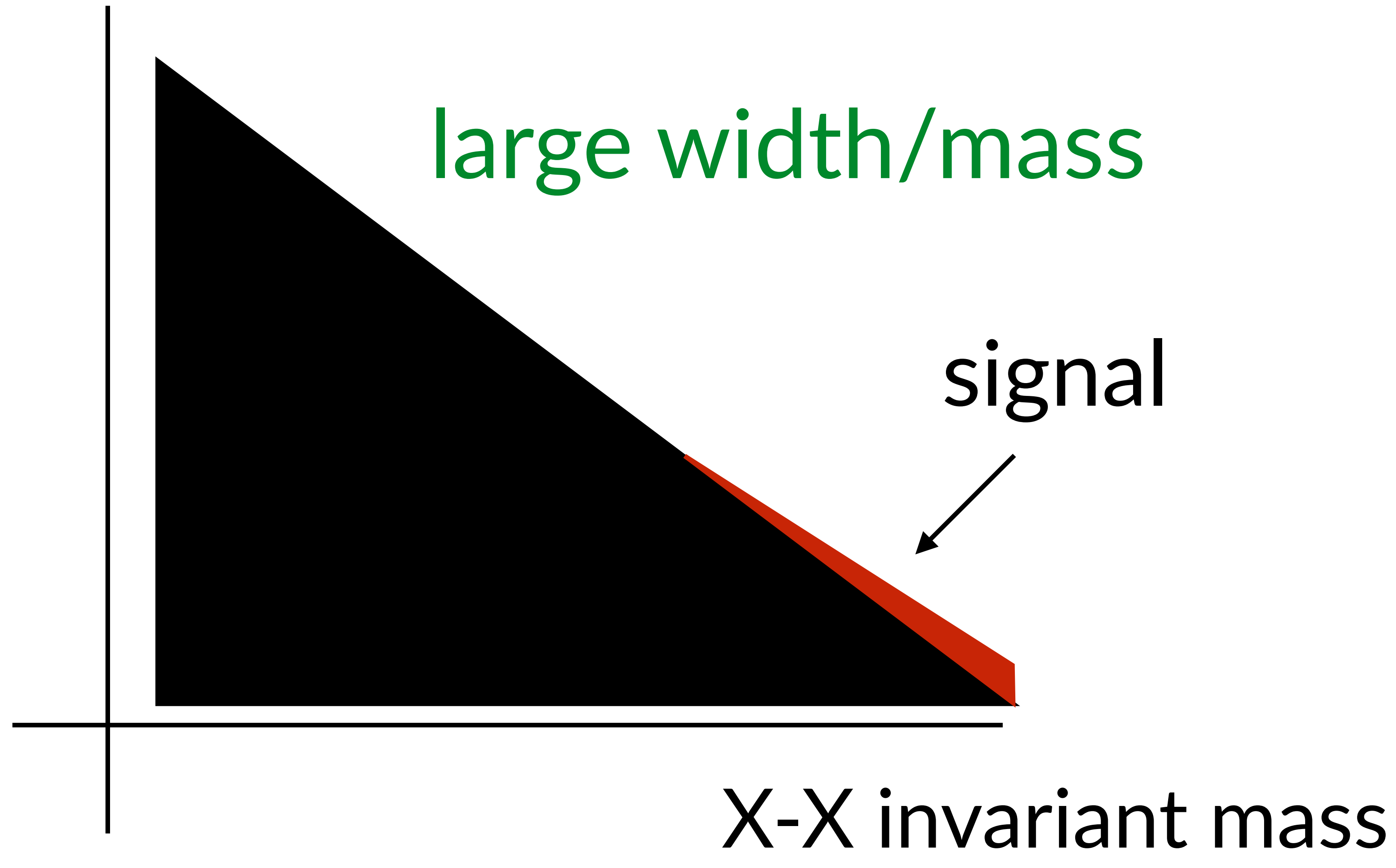
Ye Olde Resonance Discovery Algorithm

1. collect the events
2. discriminate signal from background

let's take di-jet as an example

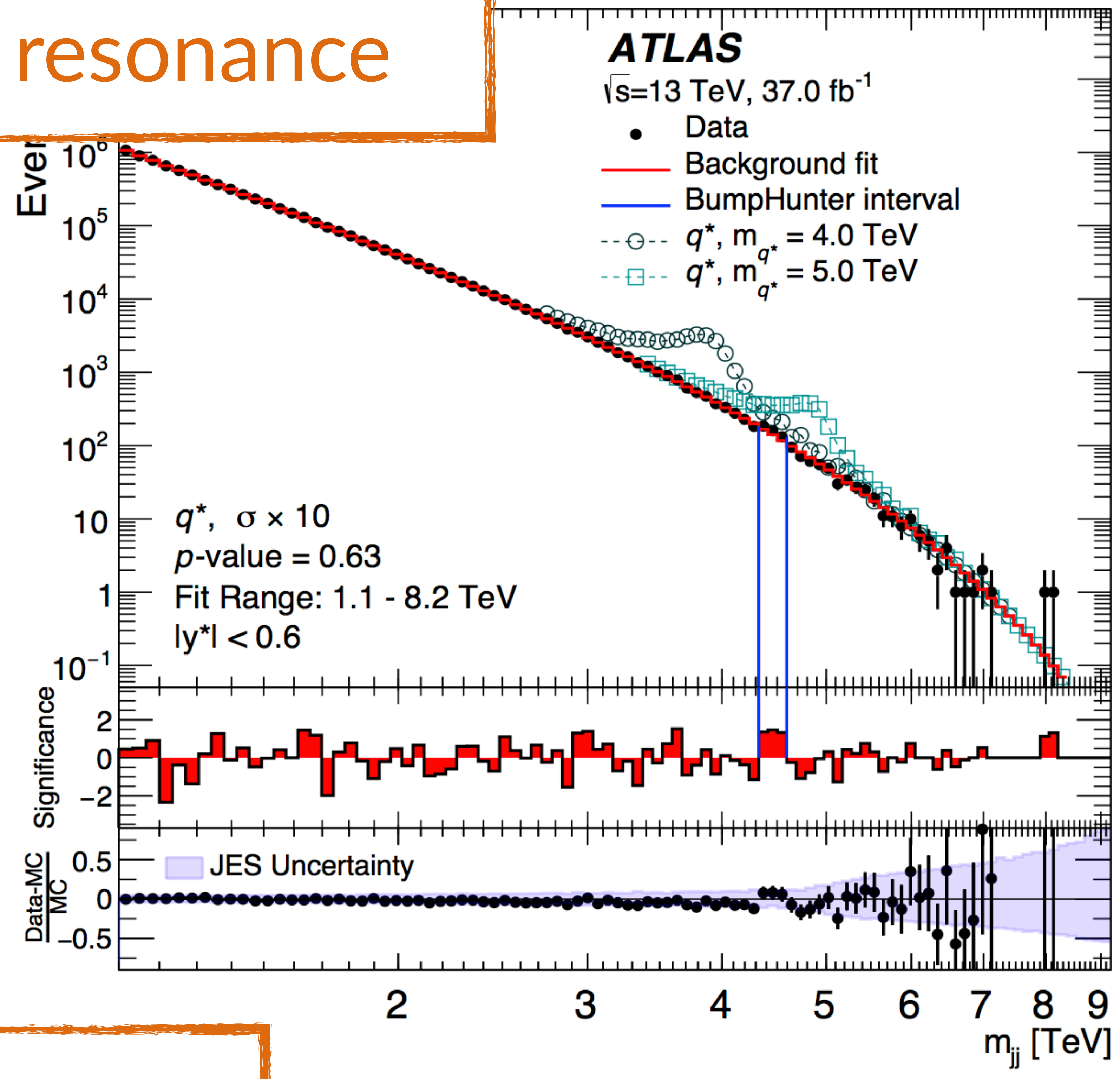
TWO WAYS OF DOING SO



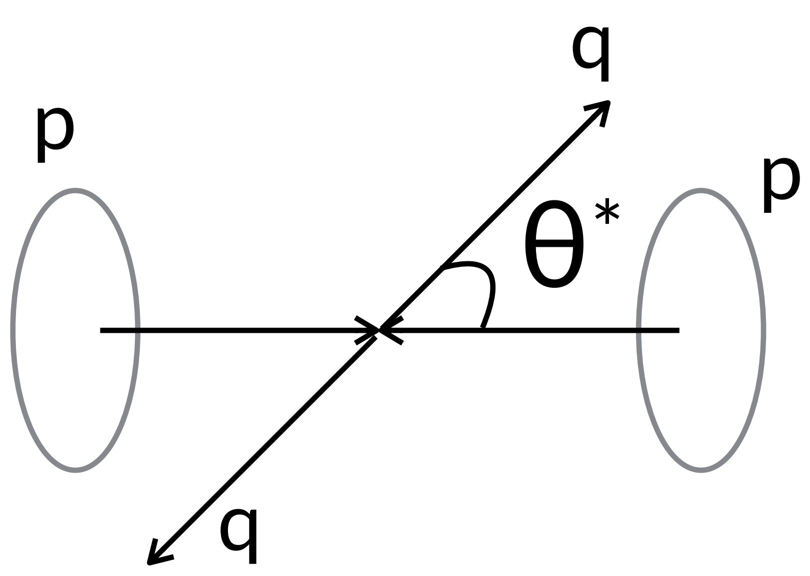


mediator-SM/DM coupling sets event rate and peak width

di-jet resonance



di-jet angular



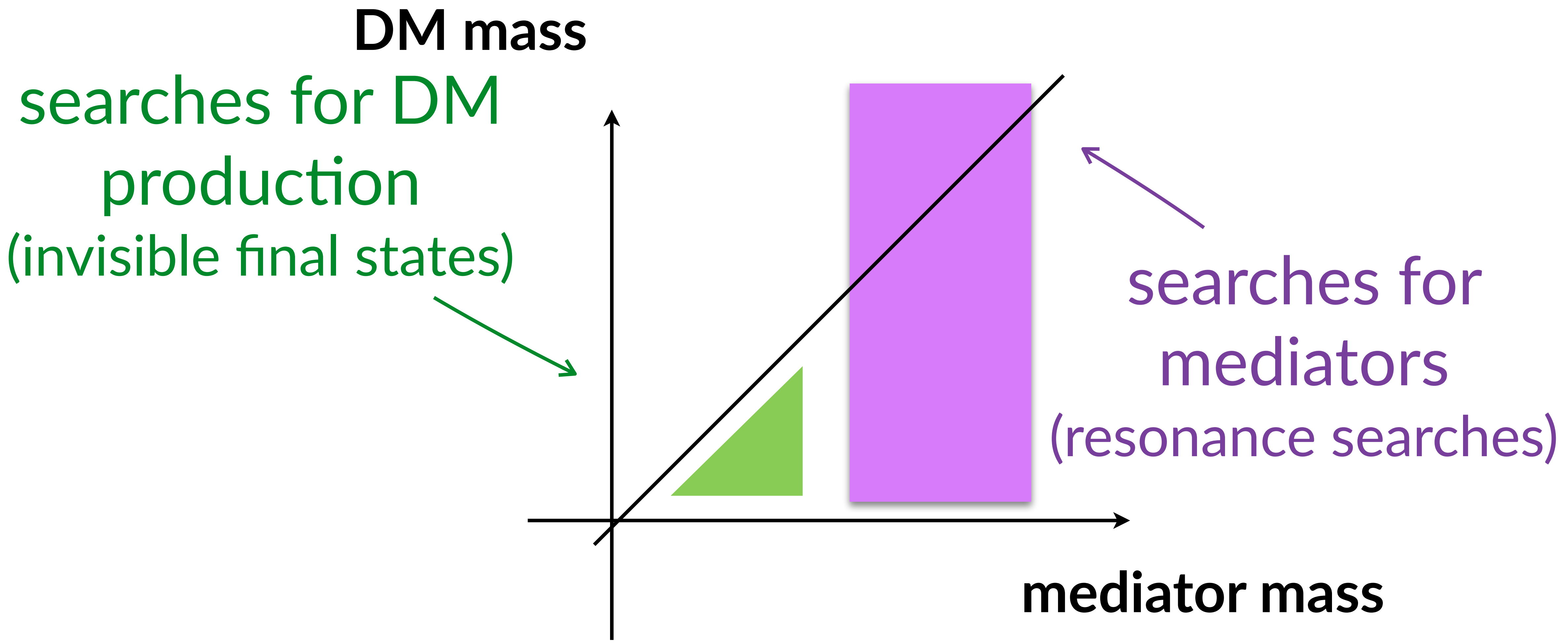
use instead:

$$\chi_{\mathrm{dijet}} = e^{|y_1-y_2|} \sim \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$

extends searches at higher masses (~4 TeV) and couplings

Implications for direct detection

1. take LHC results (high Q²) at fixed values of the couplings



focus on spin-1 due to available luminosity

2. extrapolate to low Q² of direct detection (EFT)

caveat: 1605.04917

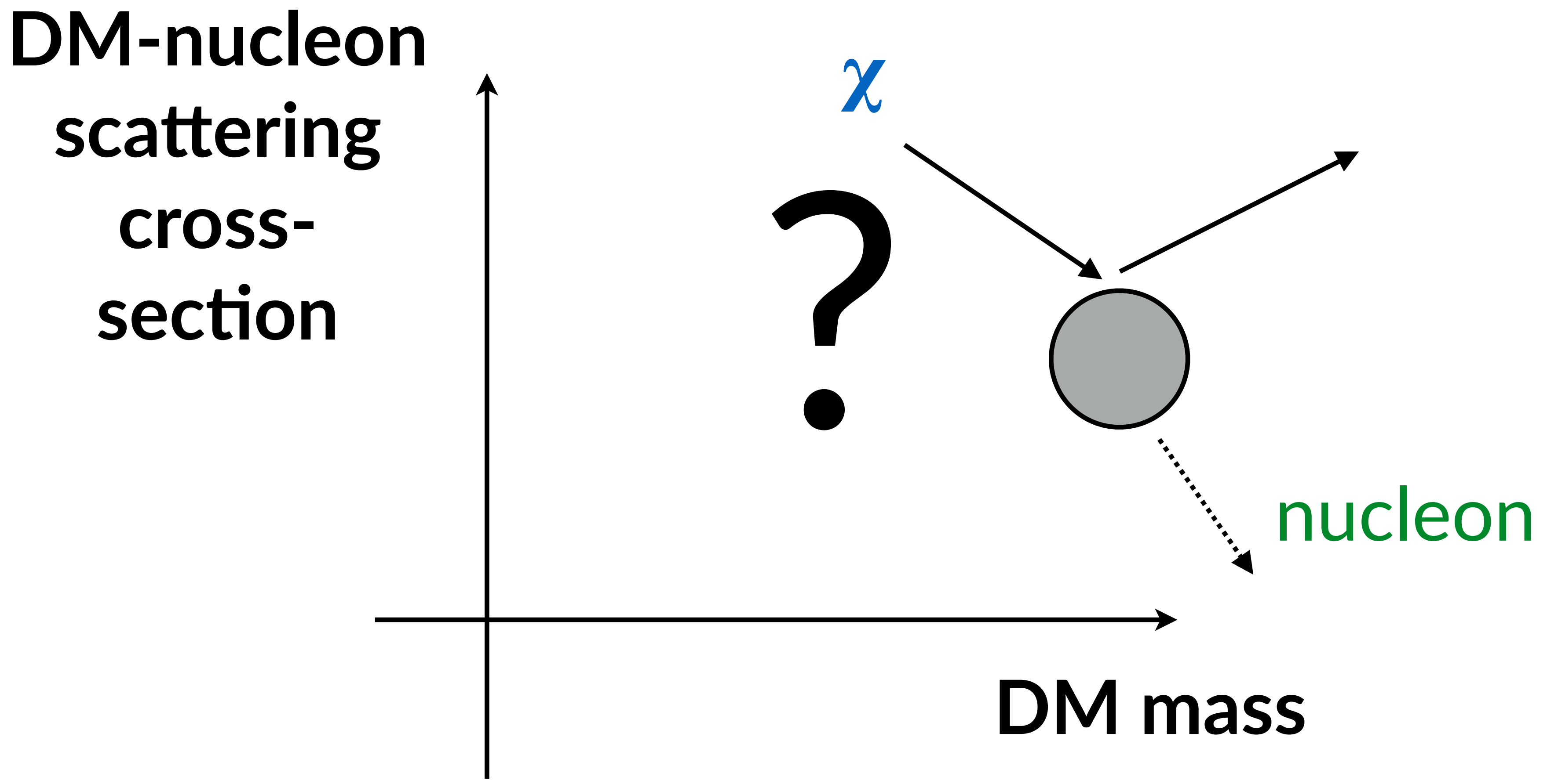
0^+ $\sigma_{\rm SI} \approx 1.1 \times 10^{-39}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$

0^- $\sigma_{\rm SI} \approx 0$ (suppressed by velocity dependent terms)

1^+ $\sigma_{\rm SI} \approx 6.9 \times 10^{-43}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{125\ {\rm GeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$

1^- $\sigma^{\rm SD} \approx 3.8 \times 10^{-41}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$

3. compare



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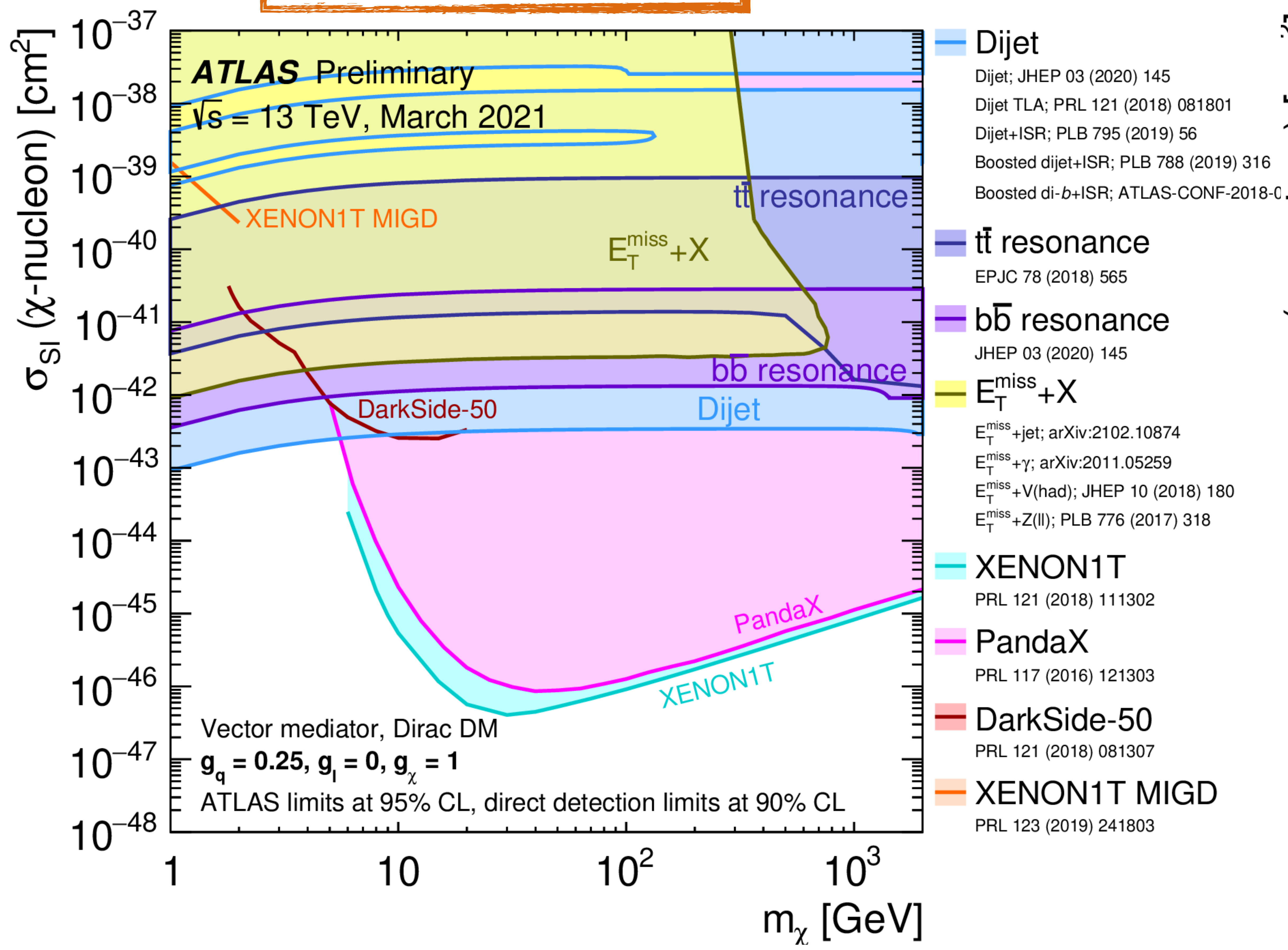
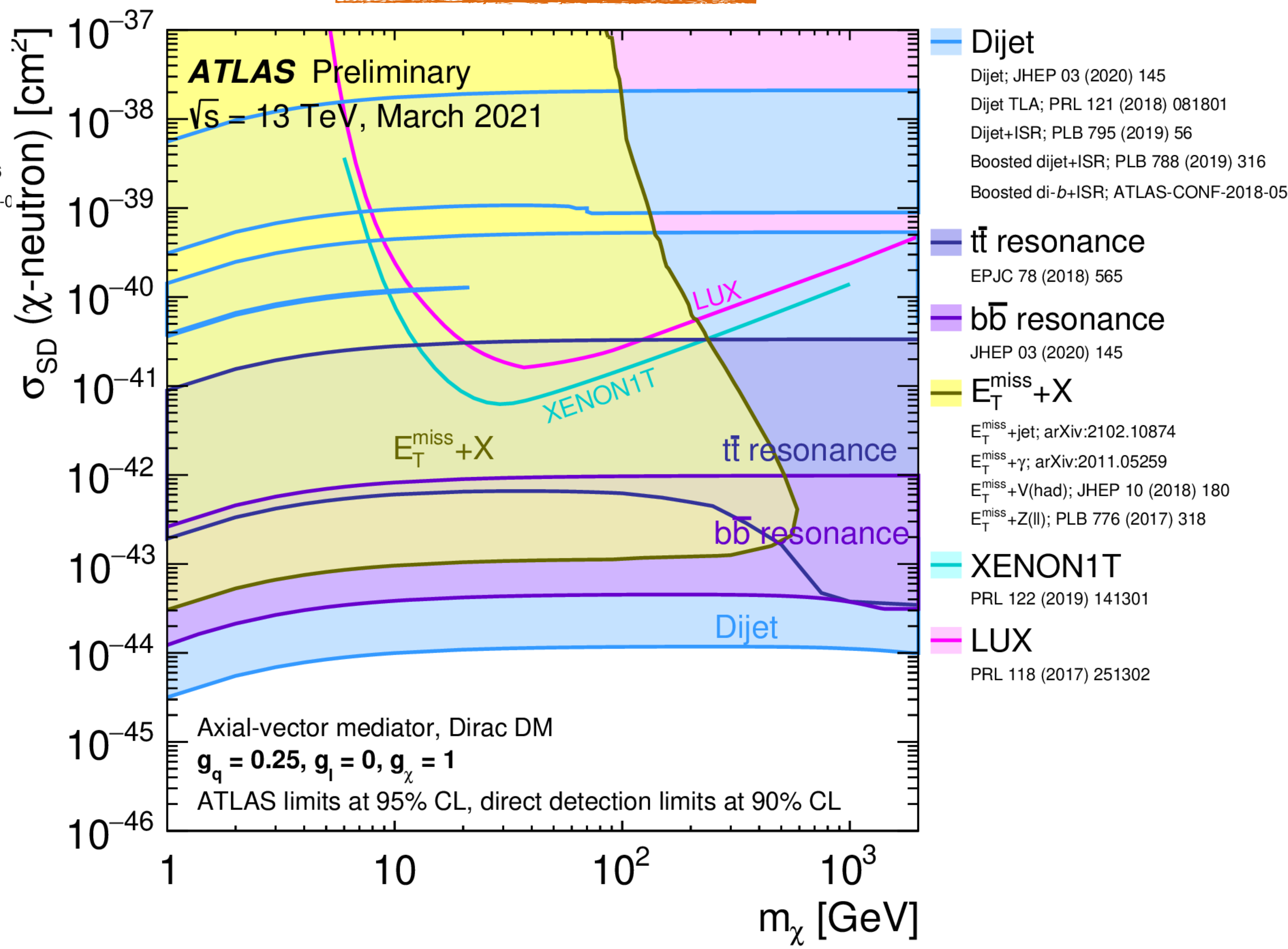
SPIN-1 NEUTRAL MEDIATOR: ATLAS VS UNDERGROUND

spin-independent scattering

leptophobic

spin-dependent scattering



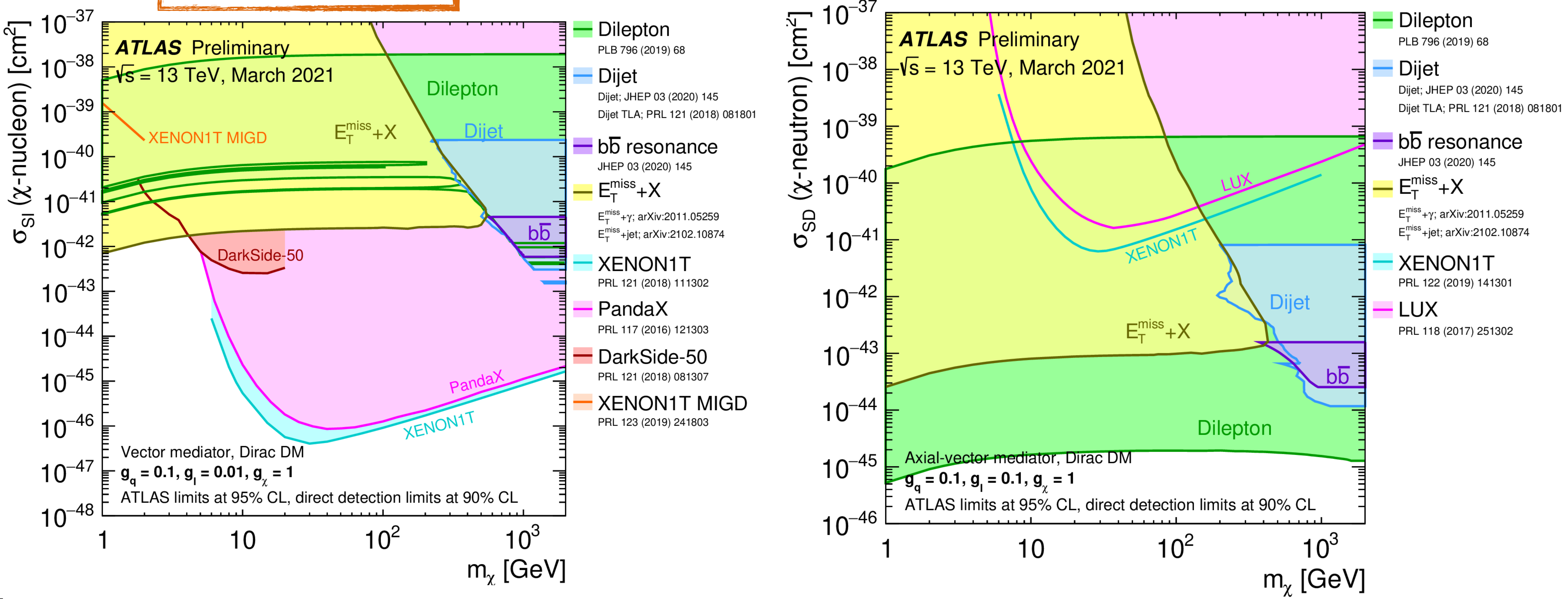


SPIN-1 NEUTRAL MEDIATOR: ATLAS VS UNDERGROUND

spin-independent scattering

leptophilic

spin-dependent scattering



key message: results are **complementary** but depend on the **model hypotheses** (how the WIMP couples to SM particles)

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When we'll know more

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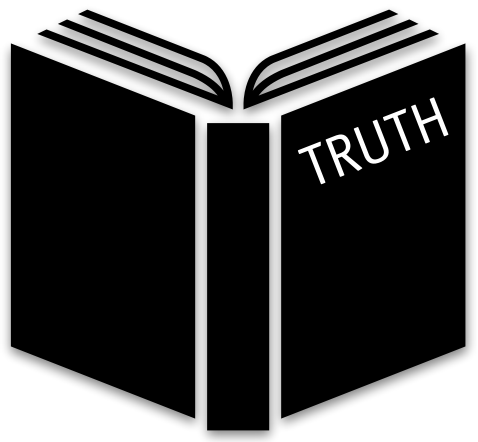
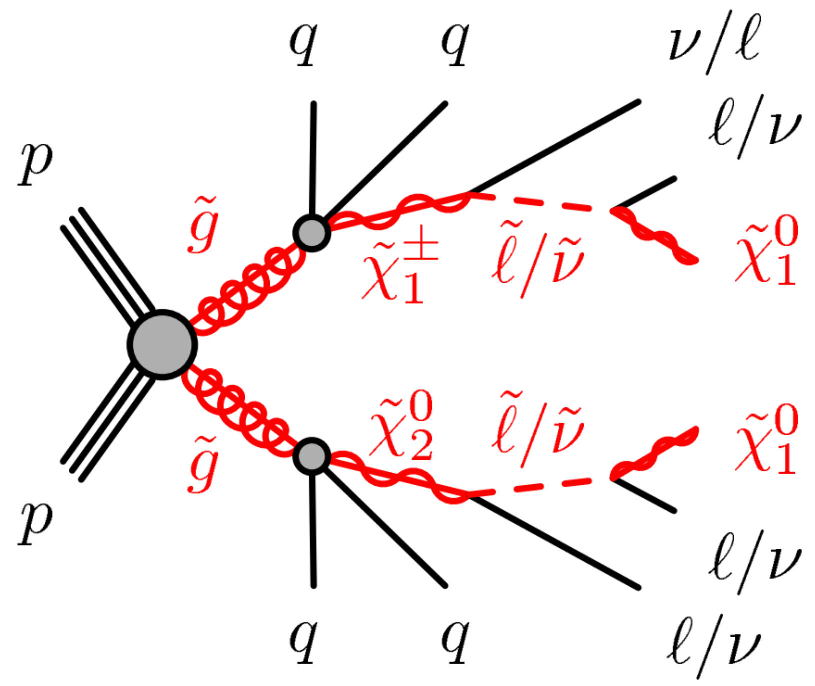
Higgs boson may → decay to WIMPs
→ be produced with WIMPs
→ decay to metastable states

metastable states may → produce WIMPs



UV-complete theory

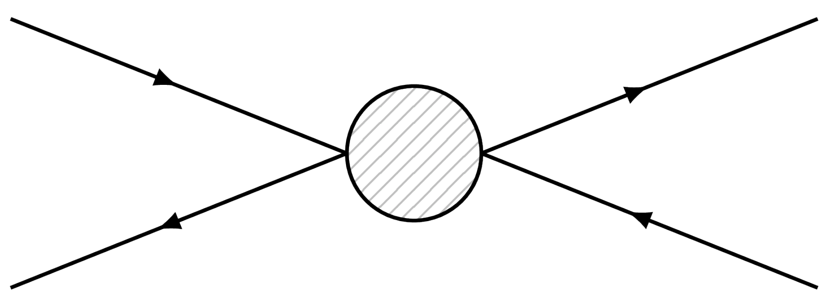
simplified model



almost all LHC searches have implications for DM

the question is how to convert this into a quantitative statement

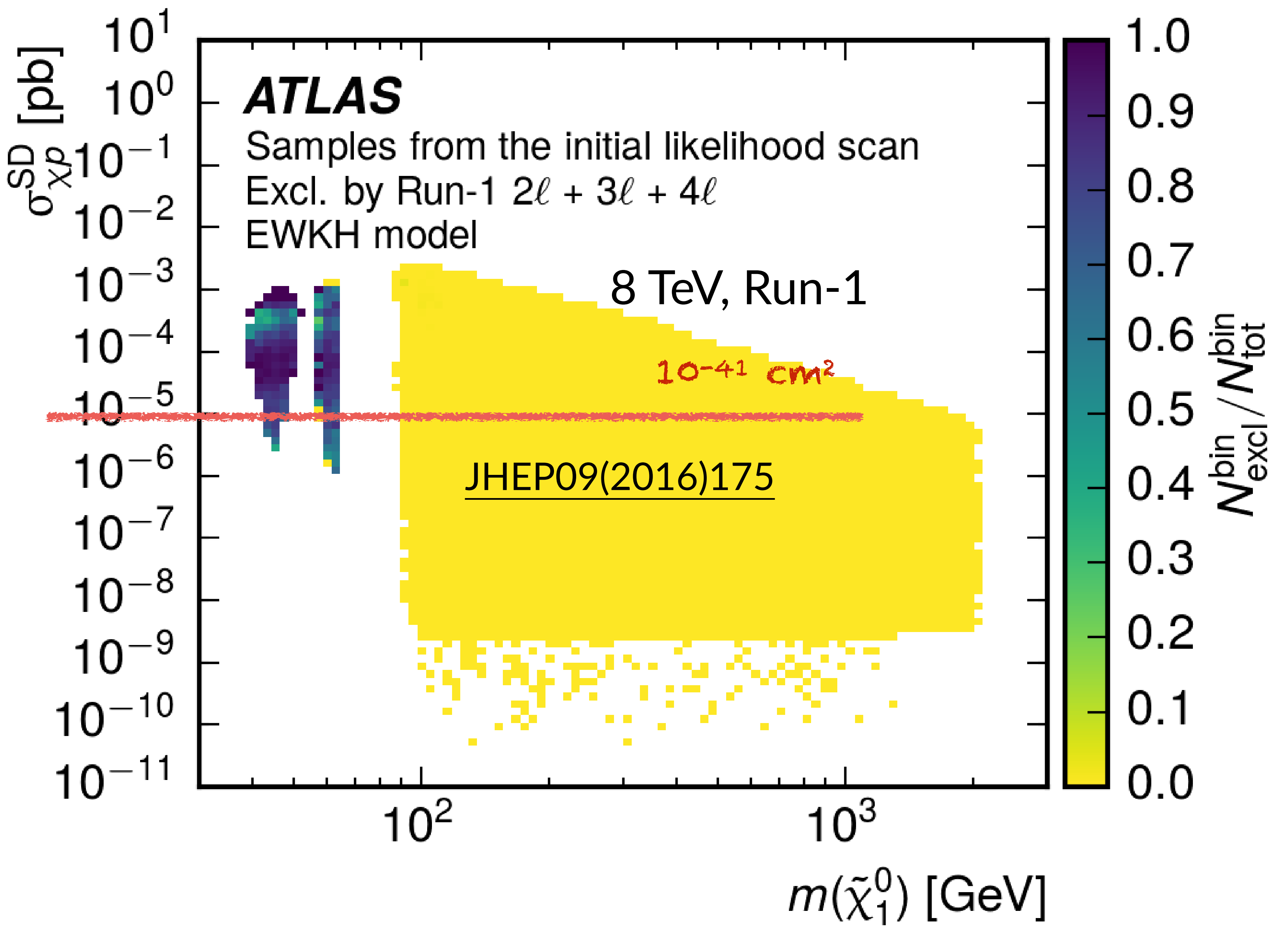
effective field theory

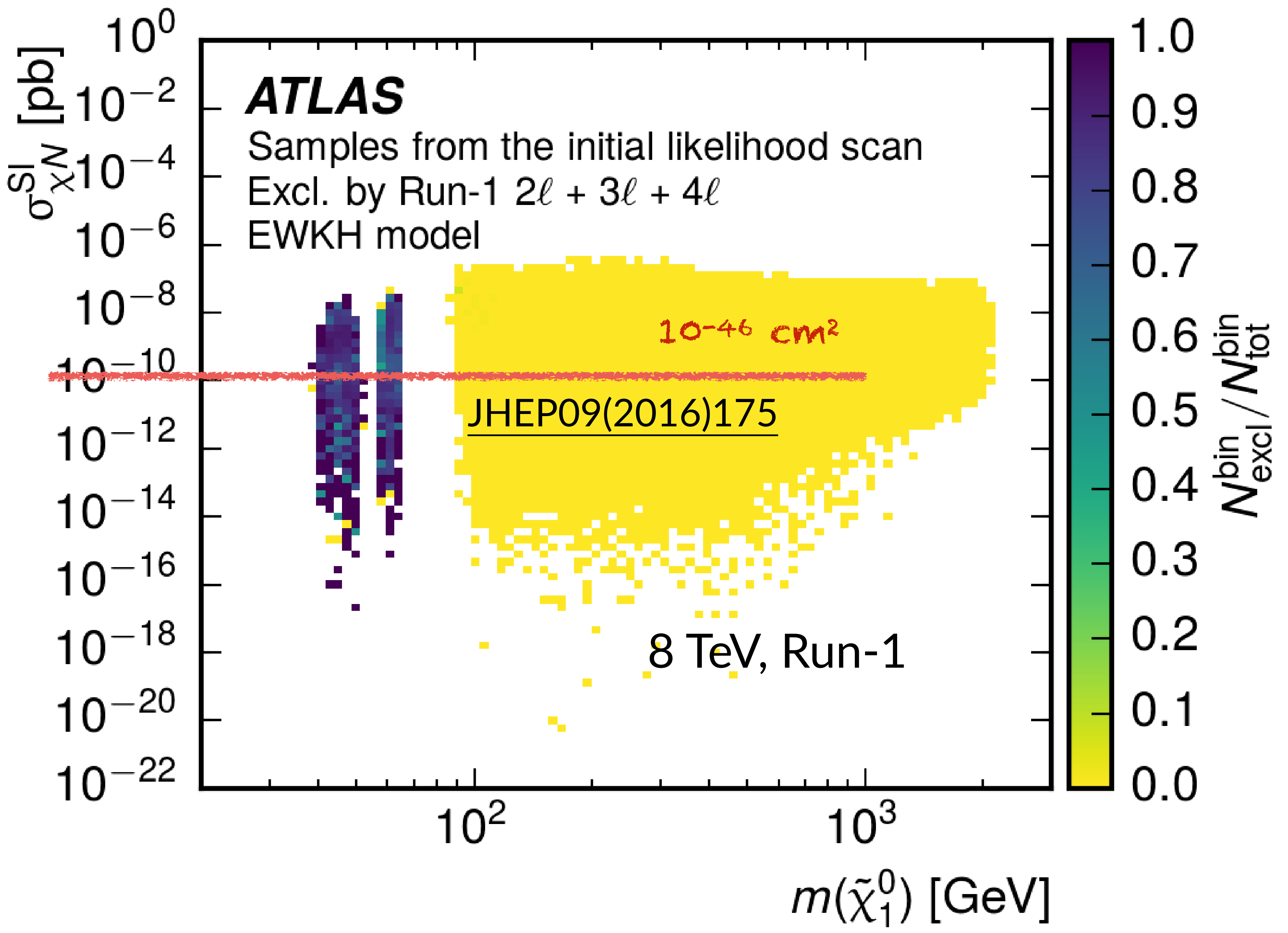


63

CORNERING SUPERSYMMETRY

- take Run-1 SUSY search results
- take a simplified version of pMSSM
- scan parameter space in regions which explain relic DM abundance (relic density and flavour constraints, + relaxed DD constraints)
- check how many points are excluded





yellow means **<10% of the explored parameter space** was excluded

must analyse 13 TeV data exploiting all signatures

could really use some higher energy collider

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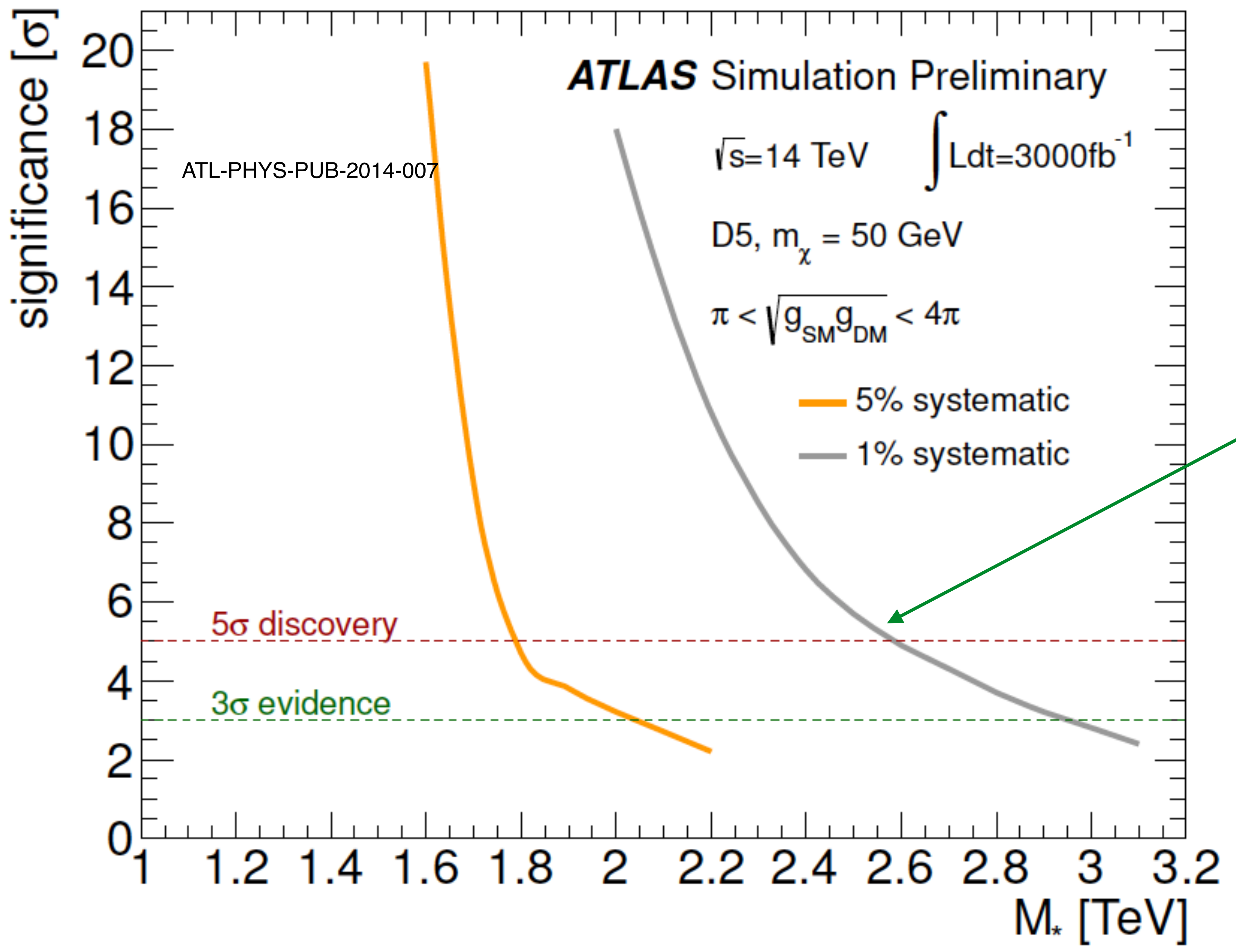
The % challenge

see also https://indico.cern.ch/event/539266

jet+MET: reach in scale of new physics (EFT) for 3 ab^{-1}



you need this level of precision…

- higher pileup, less room for MET triggers
  - spin-0 becomes more and more challenging
  - must exploit trigger tracking info also at L1
    - ➡ data scouting?
- “precision search”: need %-level systematics
  - lepton and jet uncertainties
  - theory work needed!
    - ➡ use SM V+jets measurements?

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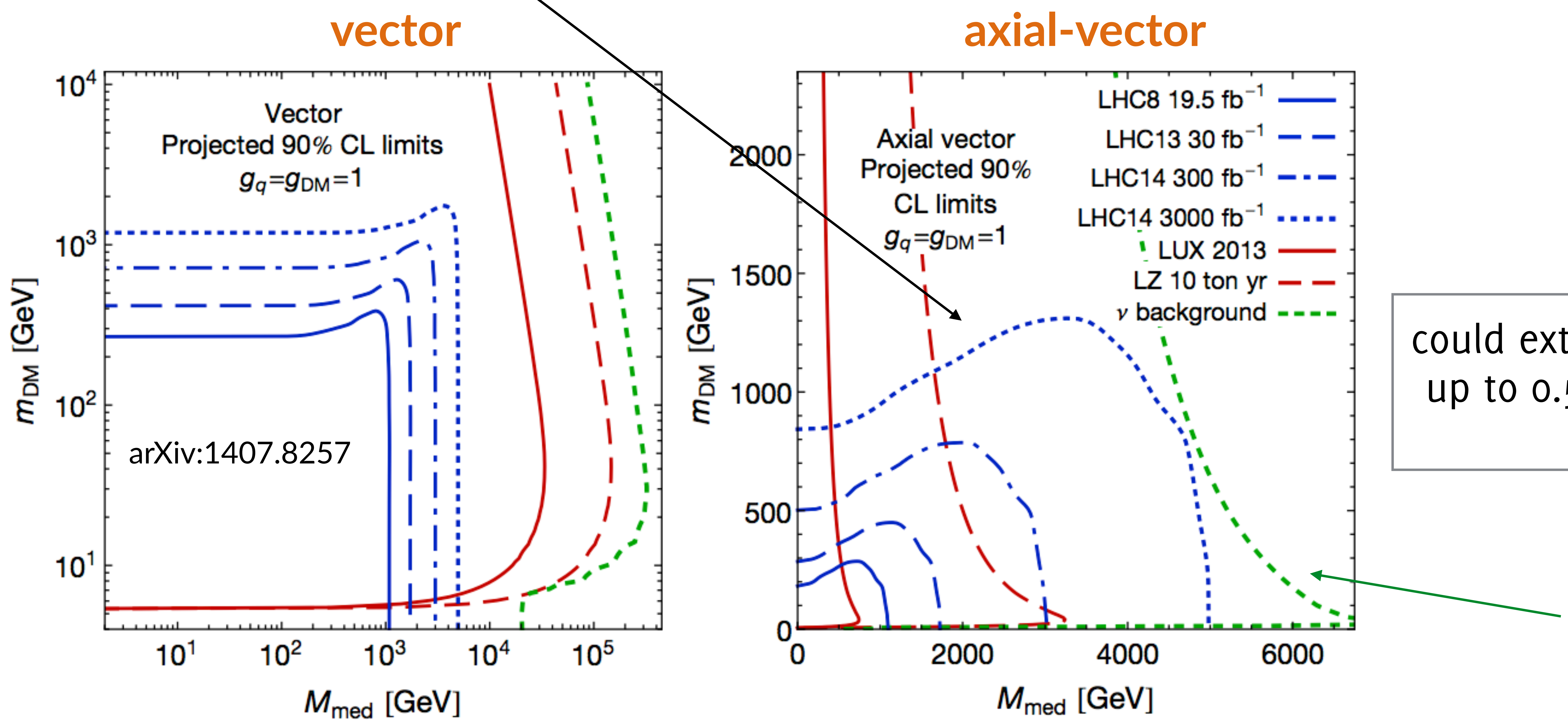
The complementarity challenge

- high-lumi LHC can beat direct detection up to neutrino background
- explore lower-cross-section extensions of the SM (SUSY, long-lived particles (e.g. 1707.05326)…)

region to the left of each curve is expected exclusion; LHC := “mono-jet”



could extend the m_{DM} sensitivity up to 0.5 TeV in ~5 years (mind the couplings!)

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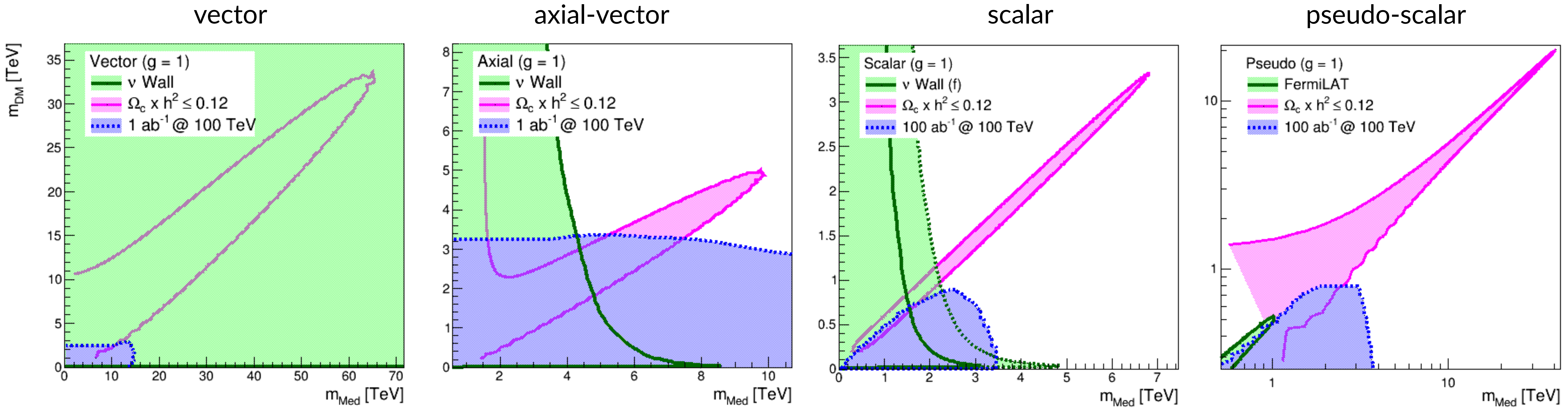
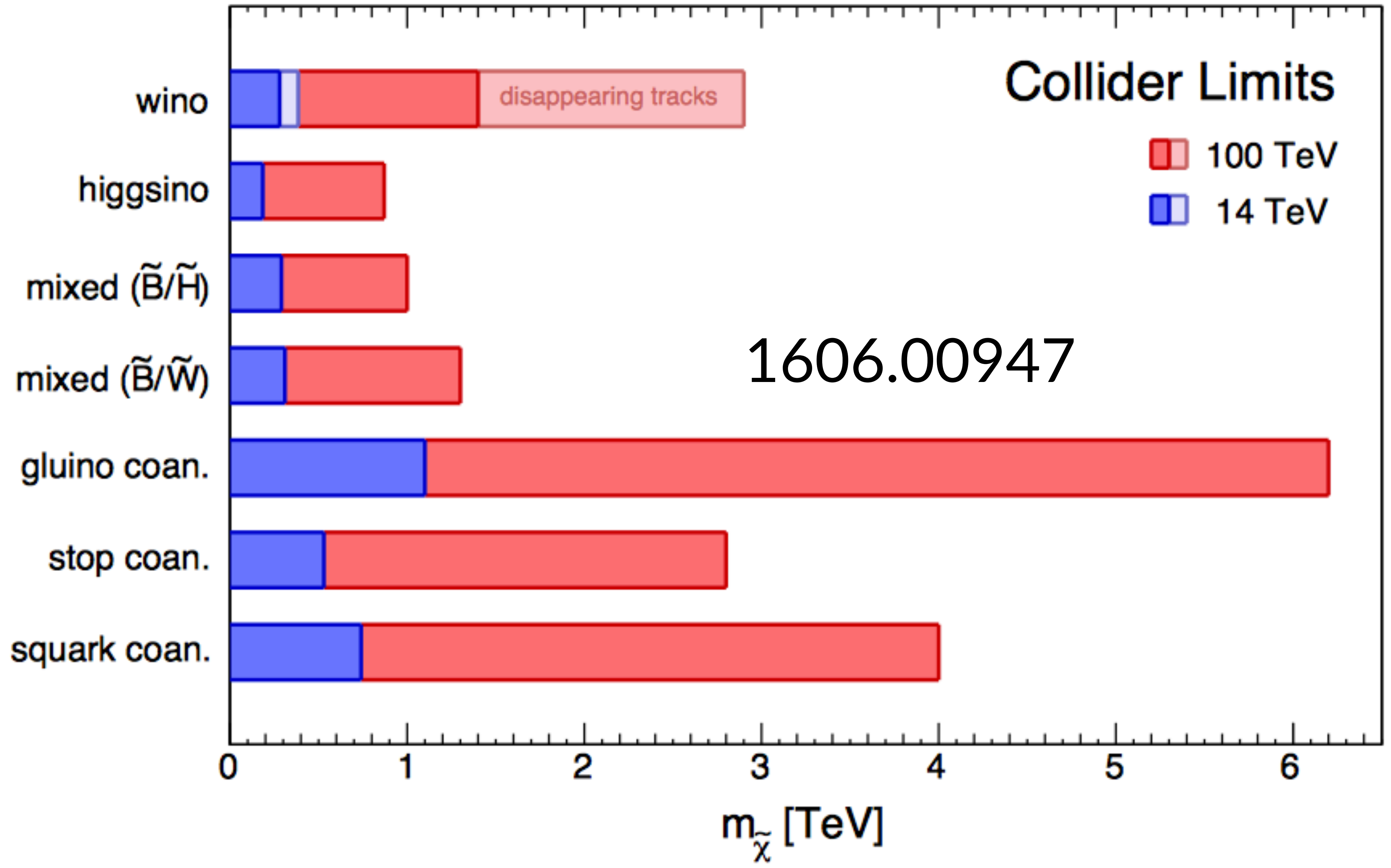
What about higher energy?



green: xsec <= neutrino bkg
blue: 1000 fb^{-1} @ 100 TeV
purple: compatible with measured relic density

(for some choice of the couplings)



a higher-energy circular collider may push sensitivity to the TeV scale

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dark matter exists
and we hope to see its interactions

need multiple strategies
instrumental and low- vs high-Q^2

rare events, complex processes
hard-to-model vs high-energy

complementary answers
time will unveil the right questions