ESHEP School, Bansko (Bulgaria) - Sept 2015

Cosmology

Lecture 2

Andrea De Simone

ma per seguir virtute e canoscenza
SISSA

Outline

- **LECTURE 1:**

The Universe around us. Dynamics. Energy Budget.

The Standard Model of Cosmology:
the 3 pillars (Expansion, Nucleosynthesis, CMB).

- **LECTURE 2:**

Dark Energy.
Dark Matter as a thermal relic. Searches for WIMPs.

- **LECTURE 3:**

Shortcomings of Big Bang cosmology. Inflation. Baryogenesis

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2 main sets of evidences for Dark Energy:

1. energy budget:

fit to CMB anisotropy map provides many cosmological parameters:
$\Omega_{tot} \sim 1.0$, $\Omega_{matter} \sim 0.3$, $\Omega_{radiation} \sim 0.0$ $\longrightarrow$ $\boldsymbol{\Omega_\Lambda \sim 0.7}$

2. distant SuperNovae (SN)
(1998-Pelmutter, Schmidt, Riess - Nobel prize 2011)

luminosity distance $d_L = (1+z)r(z)$

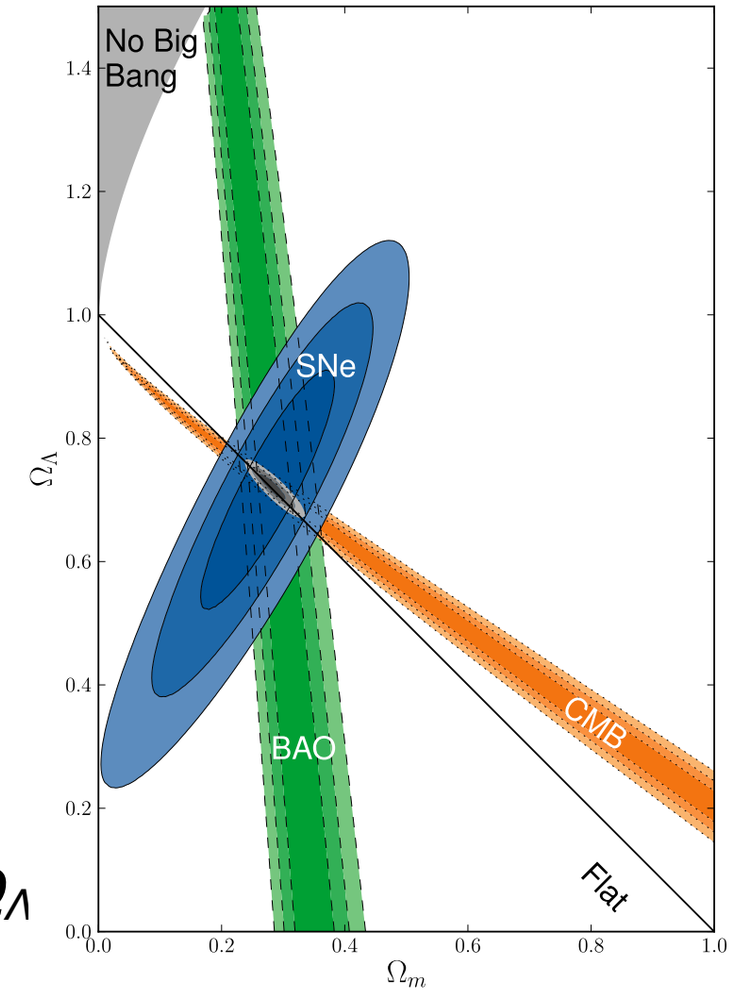
depens on Ω_{matter}, Ω_Λ ,$\Omega_{radiation}$, Ω_k

absolute (*M*) and apparent (*m*) magnitude are related to distance:

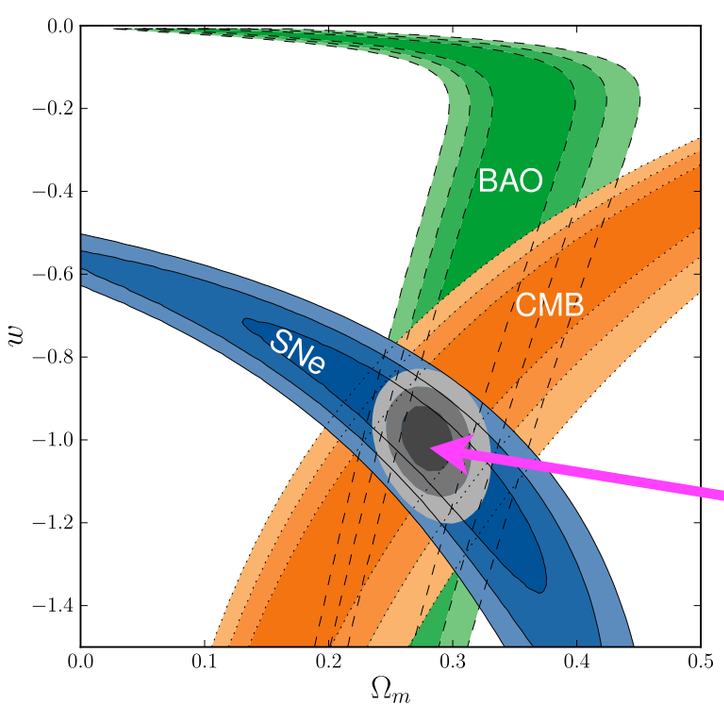
$$m - M = 5\log\left(\frac{d_L}{10\mathrm{pc}}\right) + K$$

SN are 'standard candles' (known absolute magnitude).

Measure *m* → measure d_L → measure Ω_{matter}, Ω_Λ



[arXiv:1105.3470]



new form of energy with negative pressure (**w<0**)

results consistent with **cosmological constant** (vacuum energy with *w=-1*)

so WHAT IS DARK ENERGY?

$$\Omega_\Lambda \simeq 0.7 \Longrightarrow \rho_\Lambda \simeq (\mathrm{meV})^4$$

New physics at the meV scale?

Some form of energy density which stays constant as the Universe expands:

$$\rho_\Lambda \propto a^{-3(1+w)} \sim \text{ const.}$$

at what scales do we expect new physics? M_{weak}~TeV, M_{Planck}~10^{22} GeV

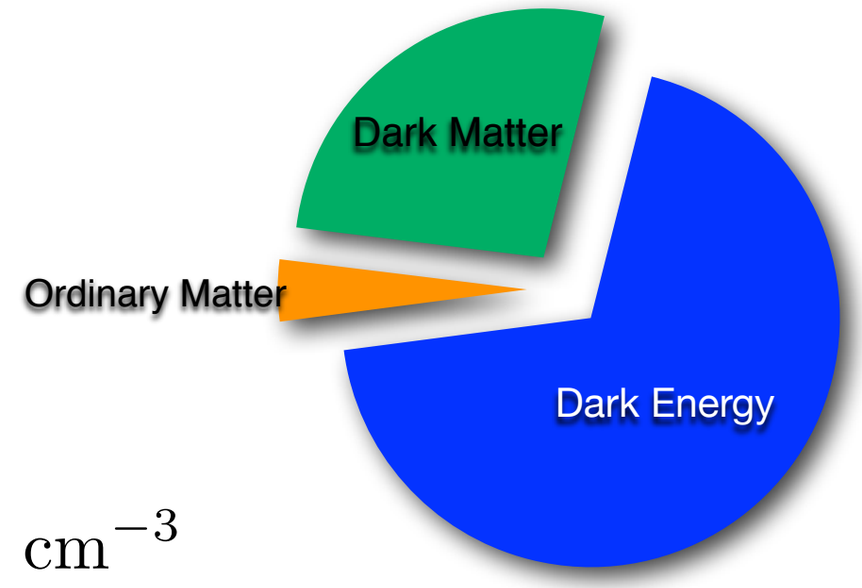
$$\rho_\Lambda \sim 10^{-123} M_{\mathrm{Planck}}^4 \qquad \rho_\Lambda \sim 10^{-60} M_{\mathrm{weak}}^4$$

the "WRONGEST" estimate of particle physics
(and biggest hierarchy problem...)

SO WHAT?

- maybe anthropic principle (we could only live in universes with small Λ)
- maybe quantum gravity...

Energy budget of the Universe



$$\Omega_{\rm DM} \equiv \frac{\rho_{\rm DM}}{\rho_c} \qquad \rho_c \equiv \frac{3H^2}{8\pi G_N} \simeq 1.05 \times 10^{-5} h^2 \ \ {\rm GeV\ cm^{-3}}$$

$$h \equiv \frac{H_0}{100\,{\rm km\ \ s^{-1}\,Mpc^{-1}}} \simeq 0.67 \qquad \Omega_{\rm DM} h^2 = \frac{\rho_{\rm DM}}{\rho_c/h^2} = 0.1196 \pm 0.0031$$

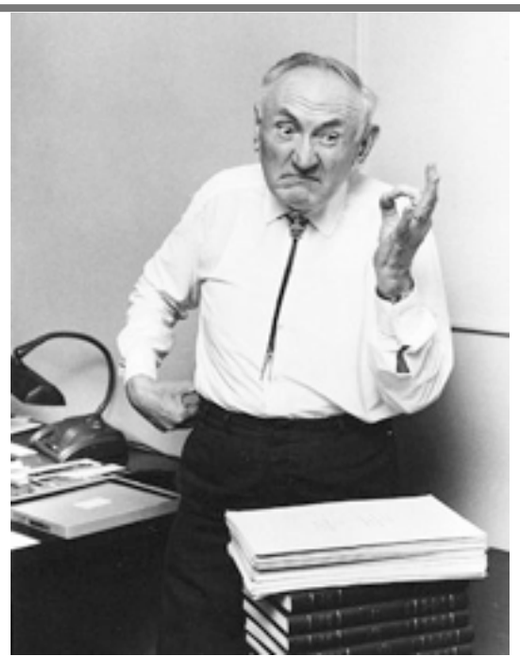
(Planck Coll.)

Observational Evidences for Dark Matter:

- Galaxy clusters
- Galaxies
- Cosmology (CMB and Large Scale Structure formation)

Firmly established, but only **gravitational** interactions are probed

F. Zwicky (1933) measured proper motion of galaxies in Coma cluster (~1000 galaxies within radius ~ 1 Mpc)



Virial Theorem: $\langle V \rangle + 2\langle K \rangle = 0$

$$\langle V \rangle = -\frac{N^2}{2} G_N \frac{\langle m^2 \rangle}{R}$$

average potential en. due to $N^2/2$ pairs of galaxies

$$\langle K \rangle = N \frac{\langle m v^2 \rangle}{2}$$

average kinetic en. due to *N* galaxies

Total mass $$M = N\langle m \rangle \sim \frac{2R\langle v^2 \rangle}{G_N} \Longrightarrow \frac{M}{L} \sim 300h \frac{M_\odot}{L_\odot}$$

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

Rotverschiebung extragalaktischer Nebel. 125

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

"should this be true, this surprising result would show that dark matter is of much greater density than luminous matter"

Most of the matter is NOT LUMINOUS

- X-ray observations

most ordinary mass in clusters is hot gas, emitting X-rays

Pressure is due to electrons: $P(r) = n_e(r) T_e(r)$

Law of hydrostatic equilibrium:

$$dP = -dm \frac{\text{accel}}{\text{Area}} = -\rho_b(R) \frac{dV}{\text{Area}} \frac{G_N M(R)}{R^2} = -\rho_b(R) \frac{G_N M(R)}{R^2} dR$$

where $M(R) = 4\pi \int_0^R \rho(r) r^2 dr$ $\qquad \rho_b(r) = \mu n_e(r) m_b$

$$\frac{dP}{dR} = -\mu n_e(R) m_b \frac{G_N M(R)}{R^2}$$

from temperature maps

from X-ray luminosity and spatial distributions

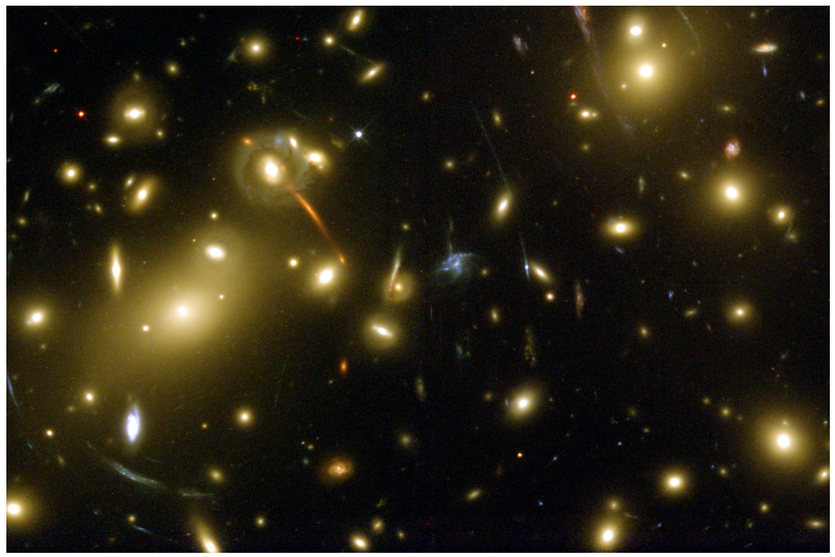
EXTRACT THE MASS

More matter than just baryons!

- Gravitational Lensing

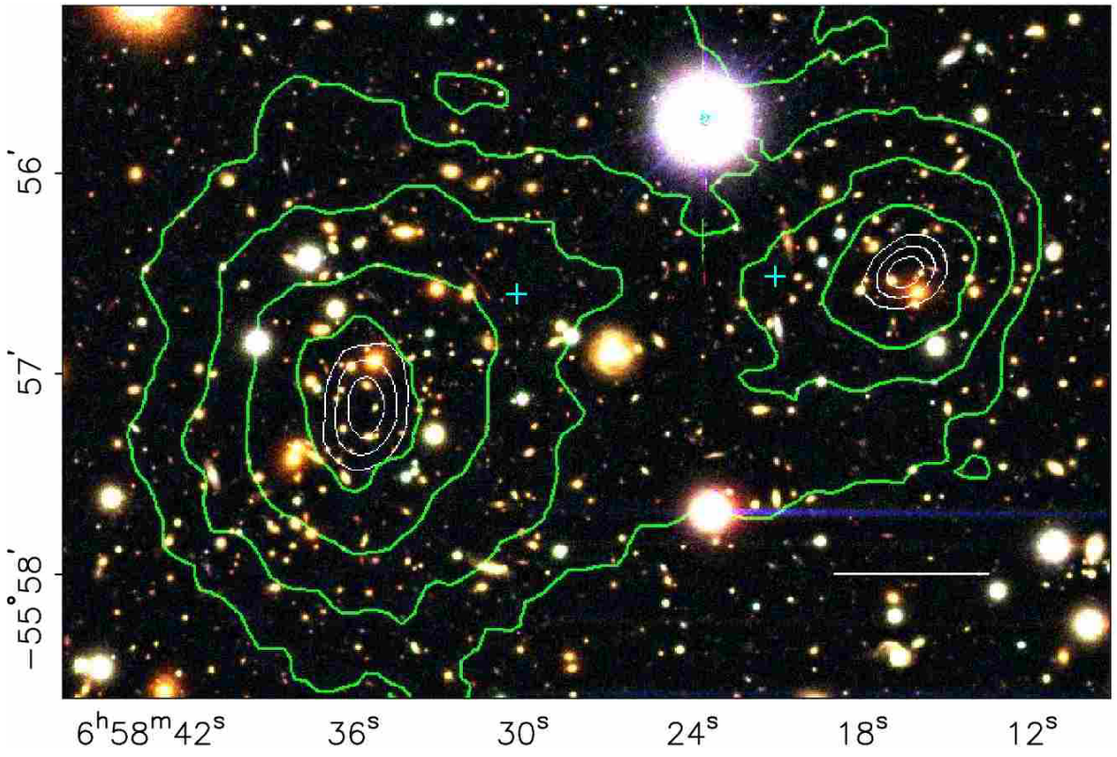
General Relativity at work!

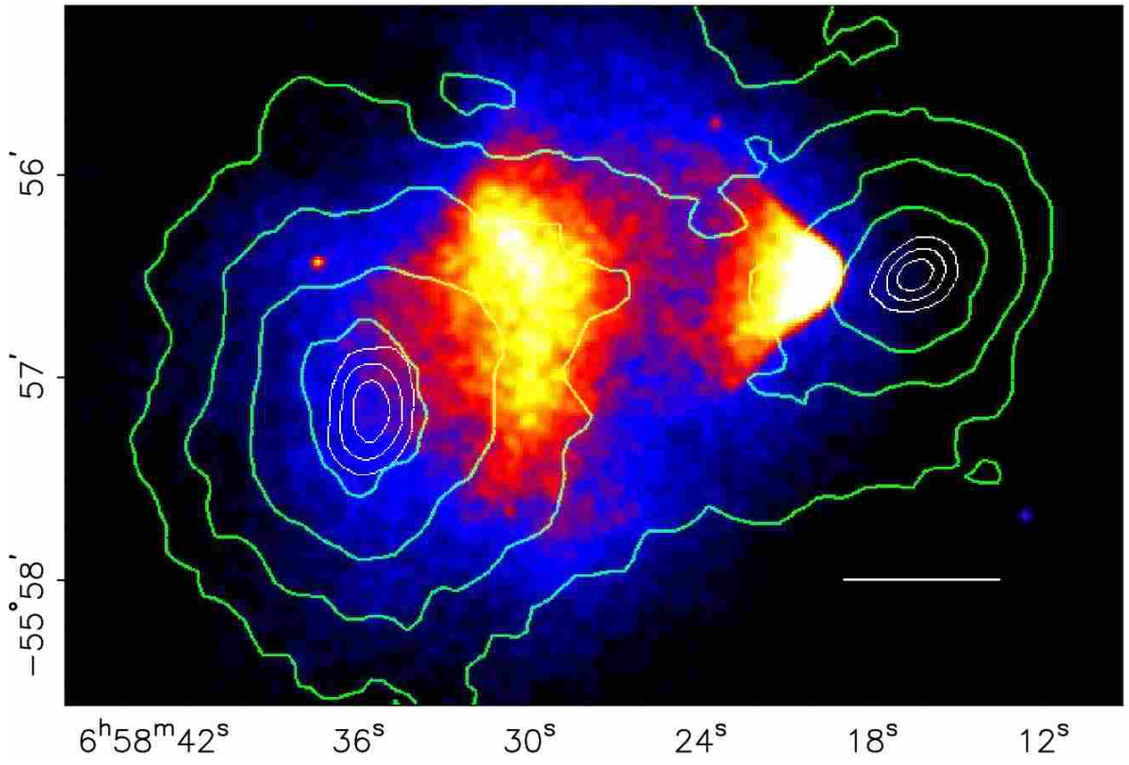
Abell NGC 2218



- "Bullet" Cluster

Two colliding clusters of galaxies



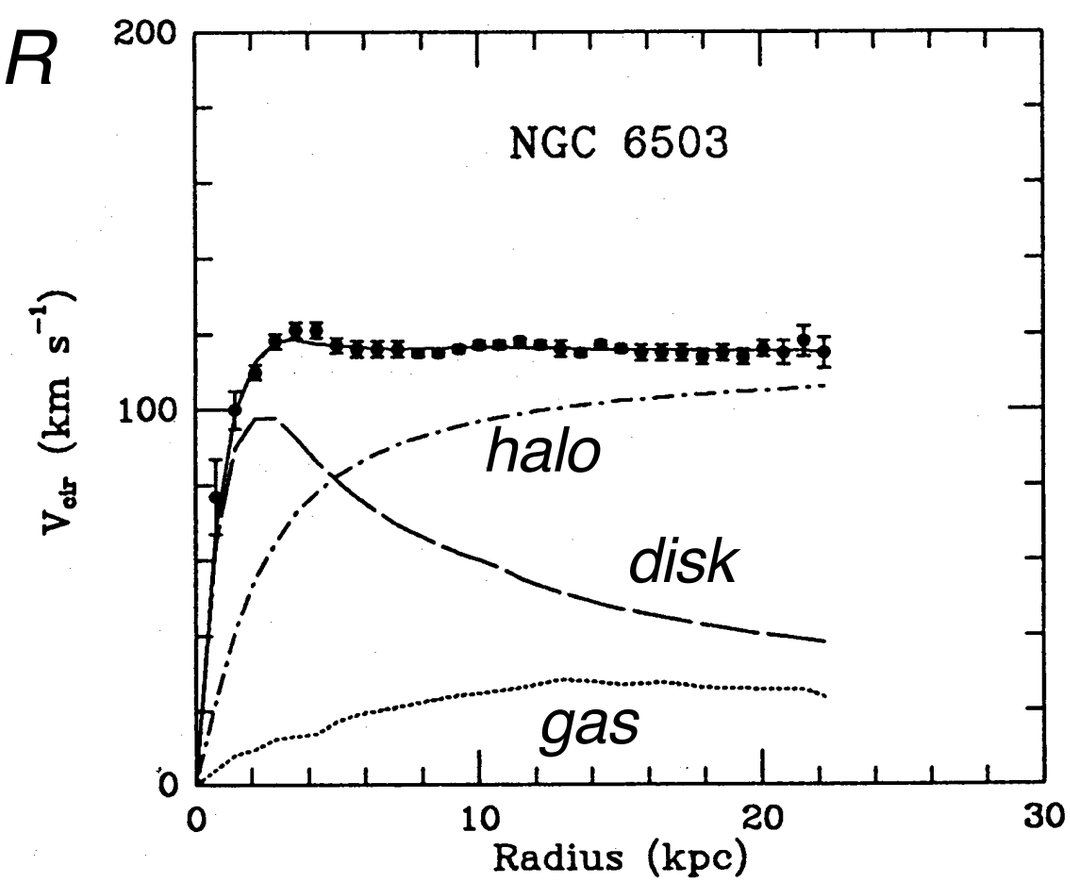


Rotation curves

$$v(R) = \sqrt{\frac{G_N M(R)}{R}}\,, \qquad M(R) = 4\pi \int_0^R \rho(r) r^2 dr$$

Expectation: $v(r) \propto R^{-1/2}$ at large *R*

Observations: $v(r) \simeq \text{const.}$ at large *R*



More matter than visible!
and distributed differently (in the halo)

$M_{\rm DM} \propto R$ requires $\rho_{\rm DM} \propto 1/r^2$

CMB

Recall that CMB temperature maps give accurate information about cosmological parameters (H_0, Ω_{tot}, Ω_B etc...) (see 1st lecture)

Formation of Large-Scale Structures

different DM types give different scenarios:

Hot DM → ``top-down'': large structures fragment into smaller pieces.
Cold DM → ``bottom-up'': smaller objects merge into bigger structures hierarchically.

cosmological observations (CMB and galaxy observations)
+ numerical simulations ***exclude*** HDM.

Problems of Cold DM (?)

"cusp-core problem"

Numerical simulations predict "cuspy" density profiles $\rho \sim r^{-1 \div -1.5}$ (small r)

Observations favor more constant densities

"missing satellite problem"

Numerical simulations predict large number (100-1000) of sub-haloes

Only ~ 10 observed

→ NOT CLEAR SITUATION

Some propose Wark Dark Matter

It may simply be that Numerical Simulations are not accurate enough (baryons not included) and small sub-haloes are invisible.

explanation of flat rotation curves with modification of gravity (rather than DM)?

MOND (MOdified Newtonian Dynamics)

$$\frac{G_N M(R) m}{R^2} = \begin{cases} ma & (a > a_*) \\ ma^2/a_* & (a < a_*) \end{cases}$$

(critical acceleration $a_* \sim 10^{-11} m/s^2$)

$$v(R) = \begin{cases} [G_N M(R)/R]^{1/2} & \text{(Newton)} \\ \boxed{[G_N M(R) a_*]^{1/4}} & \text{(MOND)} \end{cases}$$

(flat)

MOND IS FALSE!

1. evidence for DM is much more than rotation curves
2. bullet cluster contradicts MOND
3. some galaxies do not have a flat rotation curve

Key Properties of Particle DM

- **stable** (or with lifetime at least longer than the age of the Universe)
- **no electric charge**, **no color charge**
- **non-collisional**
- **not hot**
- DM is in a **fluid limit** (not a collection of discrete compact objects)

MAssive Compact Halo Objects (MACHOs) are astrophysical objects with macroscopic mass
(large planets or small dead stars).

MACHOs searches exclude
(using gravitational lensing)

$$10^{-7} M_\odot \lesssim M \lesssim 10 M_\odot$$

A small window for **primordial black holes** still open

$$10^{-13} M_\odot \lesssim M \lesssim 10^{-7} M_\odot$$

Key Properties of Particle DM

- **DM** is **classical (non-relativistic)** today

confined on galactic scales ~ 1 kpc, with densities ~ 1 GeV cm^{-3} and velocities ~ 100 km/s.

For **bosons**: De Broglie wavelength $\lambda = h/p$ must be less than 1 kpc

$$m \gtrsim \frac{h}{1\mathrm{kpc} \cdot v} \simeq \frac{2\pi}{\frac{1}{3}10^{-3}c} \frac{1}{3 \cdot 10^{21}\mathrm{cm}} (2 \cdot 10^{-14}\mathrm{cm} \cdot \mathrm{GeV}) \simeq 10^{-22}\mathrm{eV}$$

(v=100 km/s)

For **fermions**: DM quantum occupation number must be <1 (Pauli)

$$\frac{\rho(r_\odot)}{m}\lambda^3 \lesssim 1 \Longrightarrow \rho(r_\odot) \lesssim \frac{m}{\lambda^3} \Longrightarrow m \gtrsim \left[\frac{h^3 \rho(r_\odot)}{v^3}\right]^{1/4} \simeq 1\mathrm{keV}$$

(Gunn-Tremaine bound)

($\rho(r_\odot) = 0.4 \text{ GeV cm}^{-3} \simeq (0.04\,\mathrm{eV})^4$)

(an incomplete list)

WIMP

neutralino
minimal DM
heavy neutrino
inert Higgs doublet
LKP
LTP
...

non-WIMP

axion
gravitino
sterile neutrino
techni-baryon,
topological defects
primordial black holes
...

WIMP = Weakly Interacting Massive Particle
(or... the “Holy Grail” of DM physics)

Candidates for Dark Matter

(an incomplete list)

WIMP

neutralino
minimal DM
heavy neutrino
inert Higgs doublet
LKP
LTP
...

non-WIMP

axion
gravitino
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WIMP = Weakly Interacting Massive Particle
(or... the “Holy Grail” of DM physics)

Assume:

- X is stable
- X is in thermal eq. at T >> m_X

QUALITATIVE ANALYSIS

- initially, in thermal equilibrium

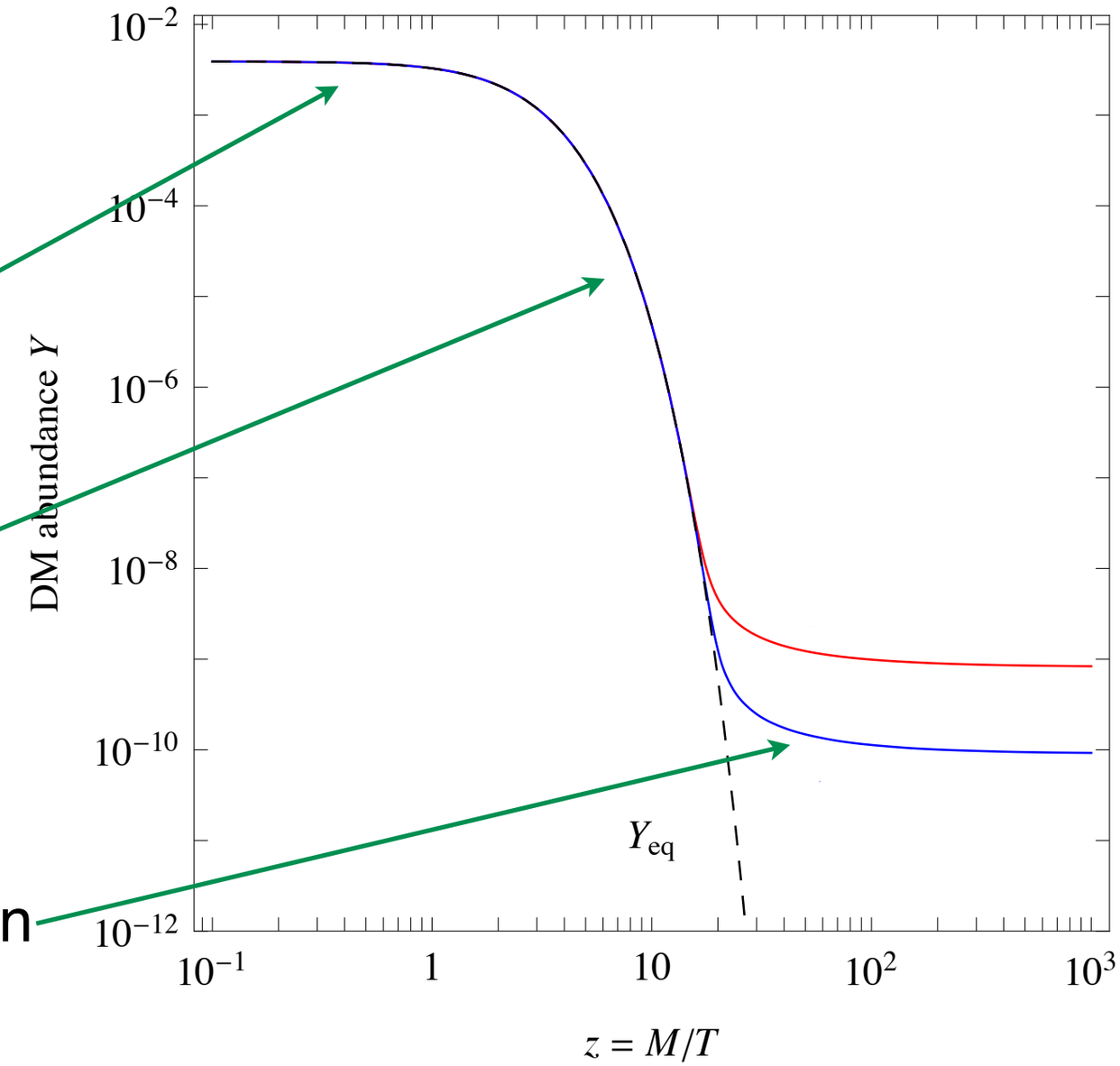
$$\chi\ \chi \leftrightarrow \mathrm{SM}\ \mathrm{SM}$$

- Universe **cools**, less and less X

$$\chi\ \chi \overset{\not\leftarrow}{\rightarrow} \mathrm{SM}\ \mathrm{SM}$$

- Universe **expands**, reaction slows down and X abundance "freezes out" of the expansion

$$\chi\ \chi \overset{\not\leftarrow}{\not\rightarrow} \mathrm{SM}\ \mathrm{SM}$$



Back-of-the-envelope

when annihilation rate becomes smaller than expansion, X decouples from the plasma

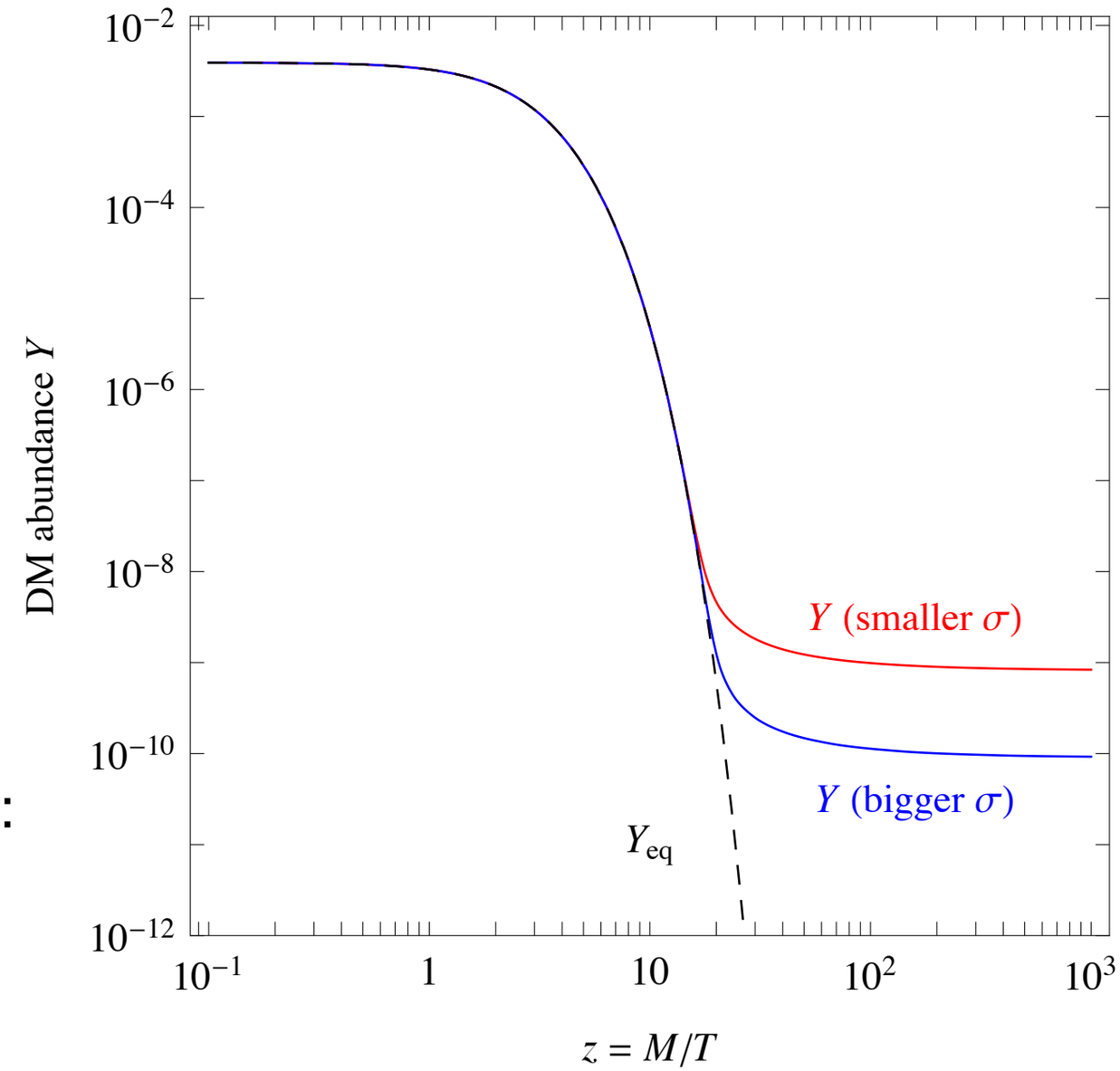
$$\Gamma \lesssim H \quad \Longleftrightarrow \quad \langle n_\chi \sigma \rangle \lesssim T^2/M_P$$

number density of X remains ~ constant

$$\frac{n_\chi}{n_\gamma} \sim \frac{T^2/(M_P\sigma)}{T^3} \sim \frac{1}{M_P\sigma T} \sim \frac{1}{M_P\sigma m_\chi}$$

the energy density of X today (wrt photons) is:

$$\frac{\rho_\chi}{\rho_\gamma} \sim \frac{m_\chi}{T_0}\frac{n_\chi}{n_\gamma} \sim \frac{1}{M_P\sigma T_0}$$



- independent of mass of X
- inversely proportional to cross section (the weakest wins!)

MORE PRECISELY

freeze-out temperature when $n_\chi \sigma v = H$ i.e. $(n_\chi \sigma)_{T_f} = H(T_f)$

where $n_\chi = n_{\bar{\chi}} = g_\chi \left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T}$ $H(T_f) \simeq 1.66\sqrt{g_*}\frac{T_f^2}{M_P} \equiv \frac{T_f^2}{M_P^*}$

$$T_f \simeq \frac{m_\chi}{\ln\left(\frac{g_\chi m_\chi M_P^* \sigma}{(2\pi)^{3/2}}\right)}$$

typically $T_f \sim m_\chi/20$ - $m_\chi/30$

number density after freeze-out $n_\chi(T_f) = \frac{T_f^2}{M_P^* \sigma v}$

is ~ constant until today, up to a redshift dilution $n_\chi(T_0) = \left(\frac{T_0}{T_f}\right)^3 n_\chi(T_f) \propto \frac{1}{T_f} \propto \frac{1}{m_\chi}$

so energy density of X (n_χ* m_χ) today does not depend on m_χ! (actually, T_f contains m_χ)

$$\Omega_\chi h^2 = \frac{(n_\chi(T_0) m_\chi)}{\rho_c/h^2} = \cdots \simeq 0.1 \frac{3 \times 10^{-26} \mathrm{cm}^3/\mathrm{sec}}{\sigma v} \simeq 0.1 \frac{1\ \mathrm{pb}}{\sigma v}$$

typical weak-scale interactions provide thermal relic with the “right” relic abundance
(REMARKABLE COINCIDENCE, a.k.a. “**WIMP MIRACLE**”)

ASIDE (RELIC NEUTRINOS)

neutrinos freeze-out while relativistic (*hot relics*)

number density after freeze-out does not depend on mass

$$n_\nu(T_f) = n_\nu^{\rm eq}(T_f) \sim T_f^3$$

$$\rho_\nu(T_0) = \left(\frac{T_0}{T_f}\right)^3 n_\nu(T_f) m_\nu \propto m_\nu \quad \Rightarrow \quad \Omega_\nu h^2 \propto \sum m_\nu$$

Require neutrinos do not "over-close" the Universe $\Omega_\nu < 1$

$$\sum m_\nu < \mathcal{O}(10) eV$$

Cosmology tells us something non-trivial on particle physics!

WHY WIMPS ARE SO NICE?

- WIMP “miracle”

- SUSY (?), neutralino *in primis*

- link with BSM physics with new particles at weak scale

- multi-sided searches (LHC, direct detection, indirect detection) are possible

3 Pillars of Dark Matter Searches

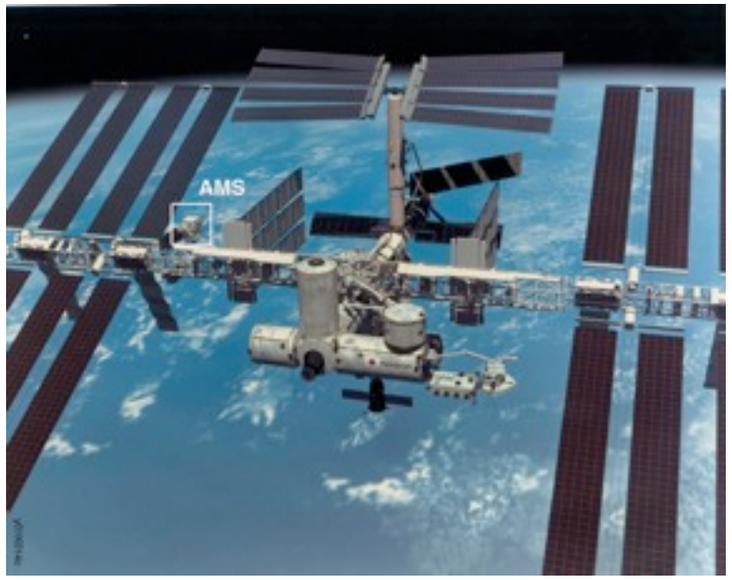
COLLIDER

$p\,p \to \mathrm{DM} + X$

(in LHC we trust...)

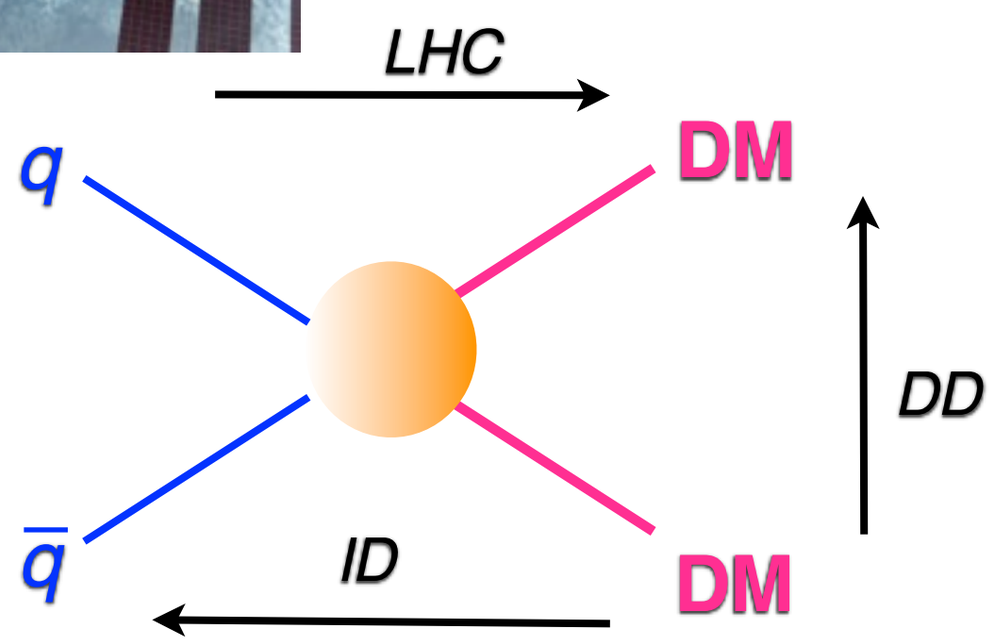
INDIRECT DETECTION

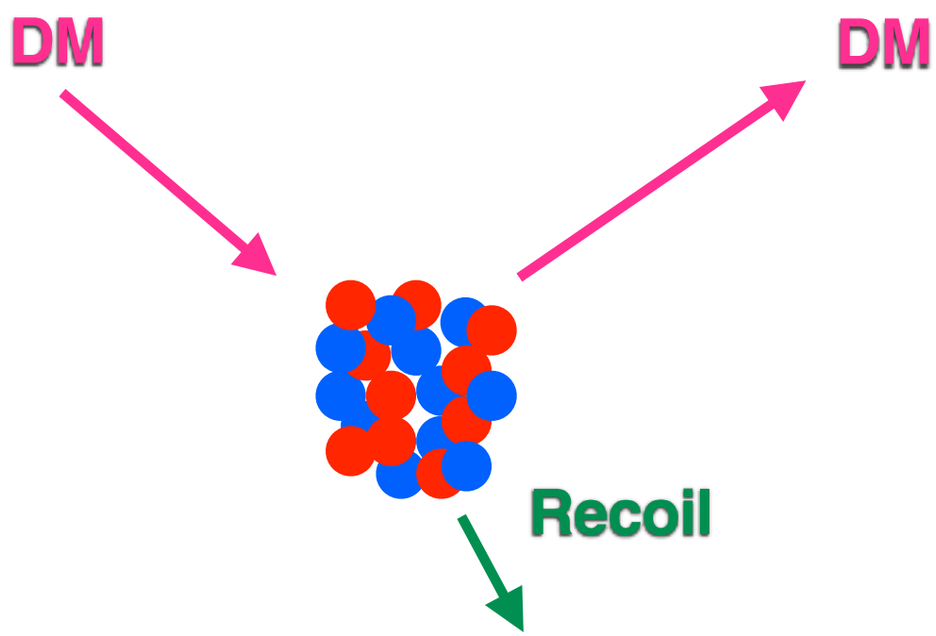
$\mathrm{DM}\ \ \mathrm{DM} \to e^+ e^- \,, \ldots$



DIRECT DETECTION

$\mathrm{DM}\ \ \mathrm{Nucleus} \to \mathrm{DM}\ \ \mathrm{Nucleus}$





DD: looking for the scattering of galactic halo DM on heavy nuclei in underground labs.

$$\mathrm{DM\ \ Nucleus} \to \mathrm{DM\ \ Nucleus}$$

Xenon, CDMS, CRESST, CoGeNT, Edelweiss...

c.o.m. recoil momentum (momentum transfer):

$$|\vec{q}|^2 = 2\mu_{\chi A}^2 v^2 (1-\cos\theta)\,, \qquad \mu_{\chi A} = m_\chi M_A/(m_\chi + M_A)$$

recoil energy imprinted on nucleus: $E_R = \dfrac{|\vec{q}|^2}{2M_A}$

$$E_R^{\max} = 2\frac{\mu_{\chi A}^2 v^2}{M_A}$$

Ex: ^{131}Xe, m_χ=100 GeV

$$E_R^{\max} = 2\left(\frac{v}{200\ \mathrm{km/s}}\right)^2 \left(\frac{2}{3}10^{-3}\right)^2 \frac{100^2\cdot 131}{231^2} 10^6\ \mathrm{keV} \simeq 22\ \mathrm{keV}\left(\frac{v}{200\ \mathrm{km/s}}\right)^2$$

Direct Detection

$$\frac{\#\text{ events}}{\text{time}} = (\#\text{ targets}) \times (\text{WIMP flux on Earth}) \times (\text{cross section})$$

$$= N_T \left(\frac{\rho_\oplus}{M_\chi} v \right) \sigma_{\chi A}$$

total target mass

$$\simeq \frac{1\text{ event}}{\text{yr}} \times \frac{M_T/A}{\text{kg}} \times \frac{\sigma}{10^{-39}\text{cm}^2} \times \frac{\rho_\oplus}{0.3\text{ GeVcm}^{-3}} \times \frac{v}{200\text{ km/s}} \times \frac{100\text{ GeV}}{m_\chi}.$$

spectrum of events per recoil energies

ASTROPHYSICS

PARTICLE PHYSICS

$$\frac{dR}{dE_R} = N_T \frac{\rho_\oplus}{m_\chi} \int_{|\vec{v}|>v_{\rm min}} d^3v |\vec{v}| f(\vec{v},t) \frac{d\sigma_{\chi A}}{dE_R}$$

$$v_{\rm min} = \sqrt{\frac{M_A E_R^{th}}{2\mu_{\chi A}^2}}$$

minimal DM velocity to transfer E^{th} to nucleus

Direct Detection

total event rate

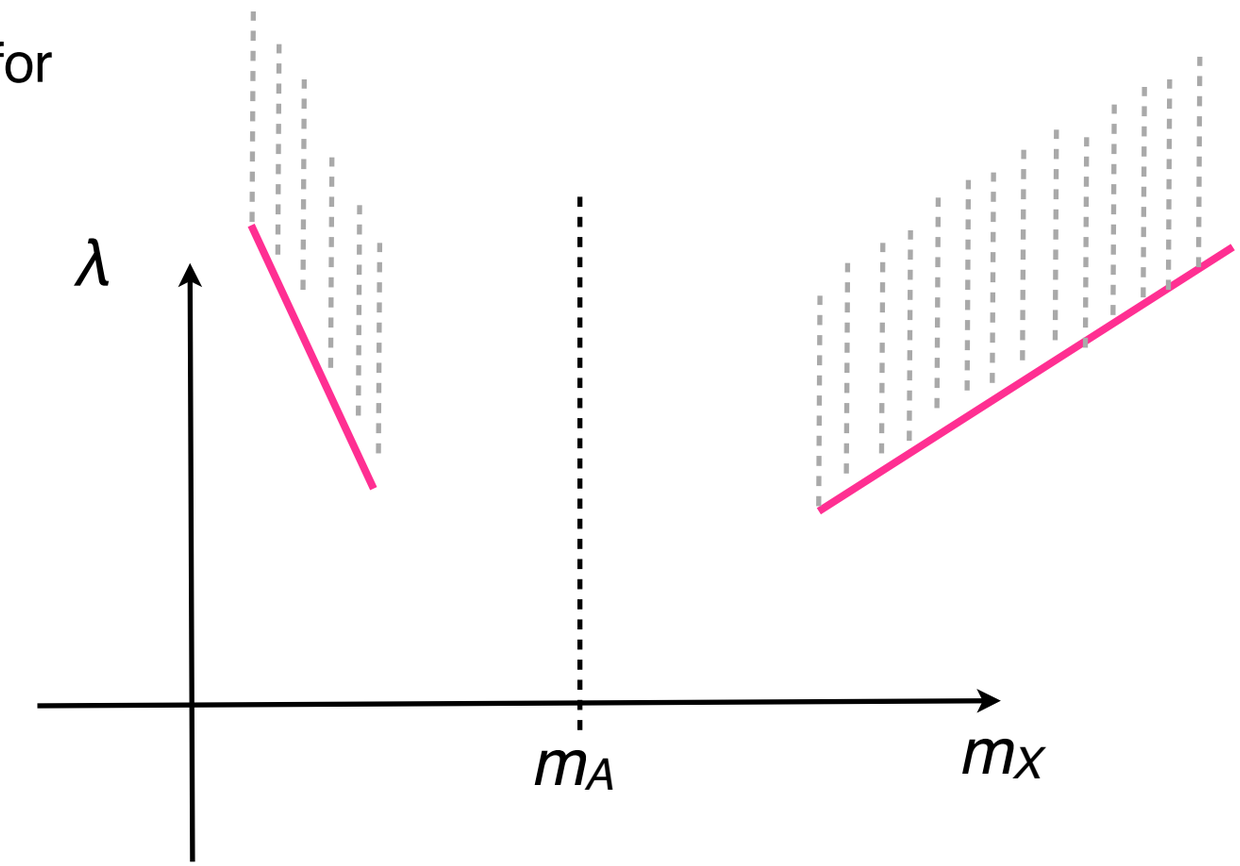
$$R \propto \lambda \mu_{\chi A}^2 / m_\chi < R_{\text{observed}}$$

experimental bound on total number of observed events → limit on coupling

$$\lambda < \lambda_{\text{bound}} \propto \frac{m_\chi}{\mu_{\chi A}^2} \sim \begin{cases} m_\chi^{-1} & (m_\chi \ll m_A) \\ m_\chi & (m_\chi \gg m_A) \end{cases}$$

maximal exclusion power for

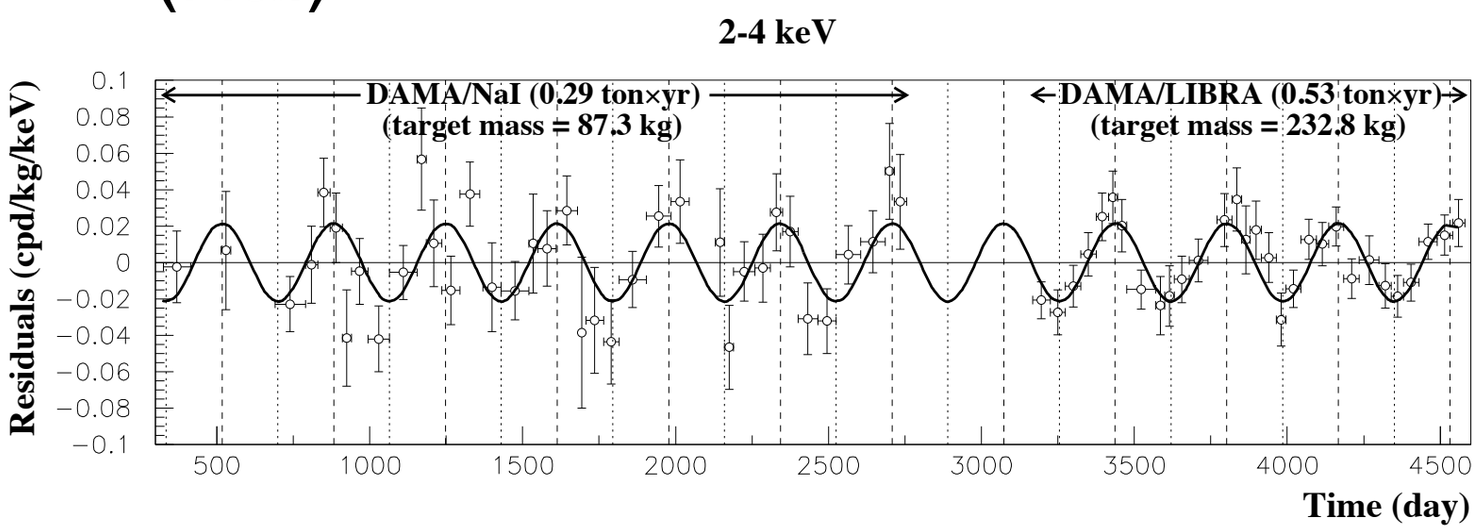
$$m_\chi \simeq m_A$$

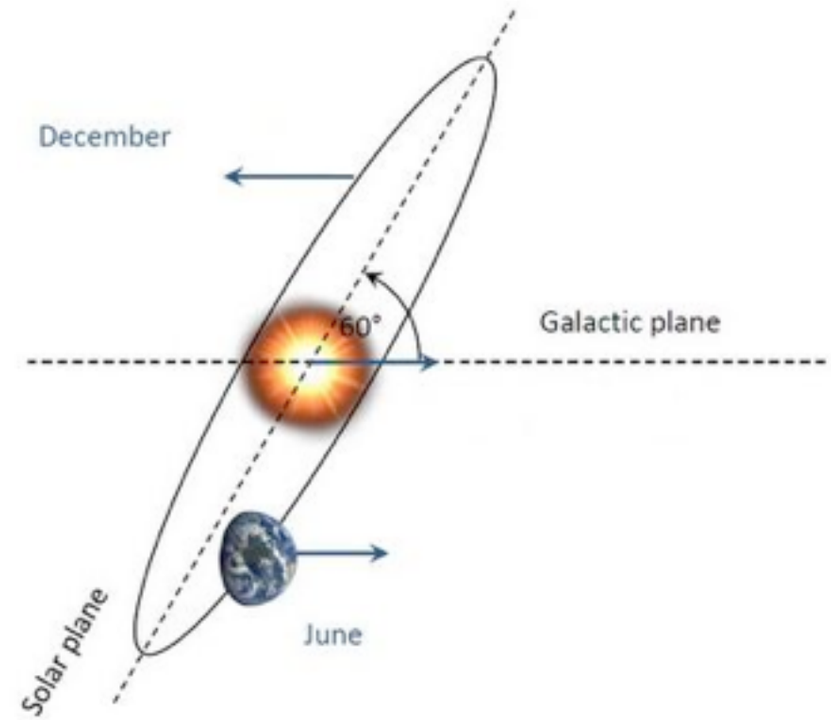


- some experiments (DAMA, CRESST, CoGeNT) see positive hints/signals

DAMA/Libra
(NaI)

8σ observation of annual modulation





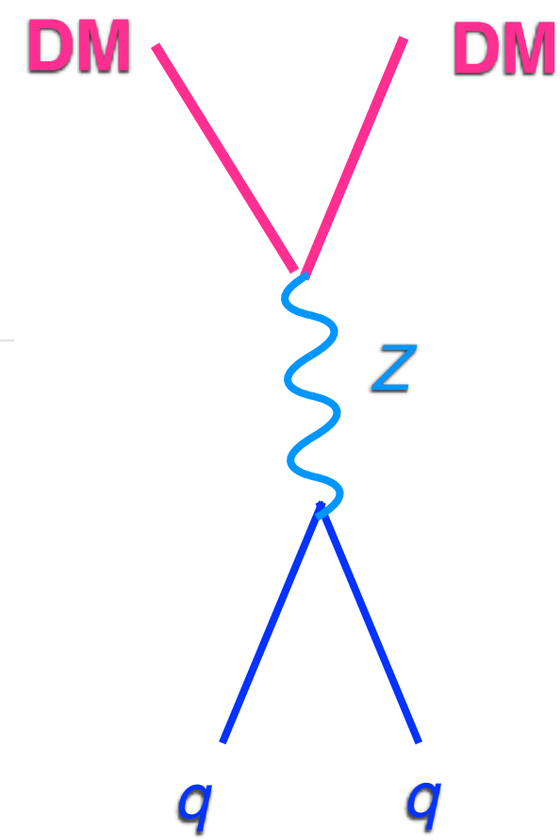
[DAMA Coll - 0804.2741]

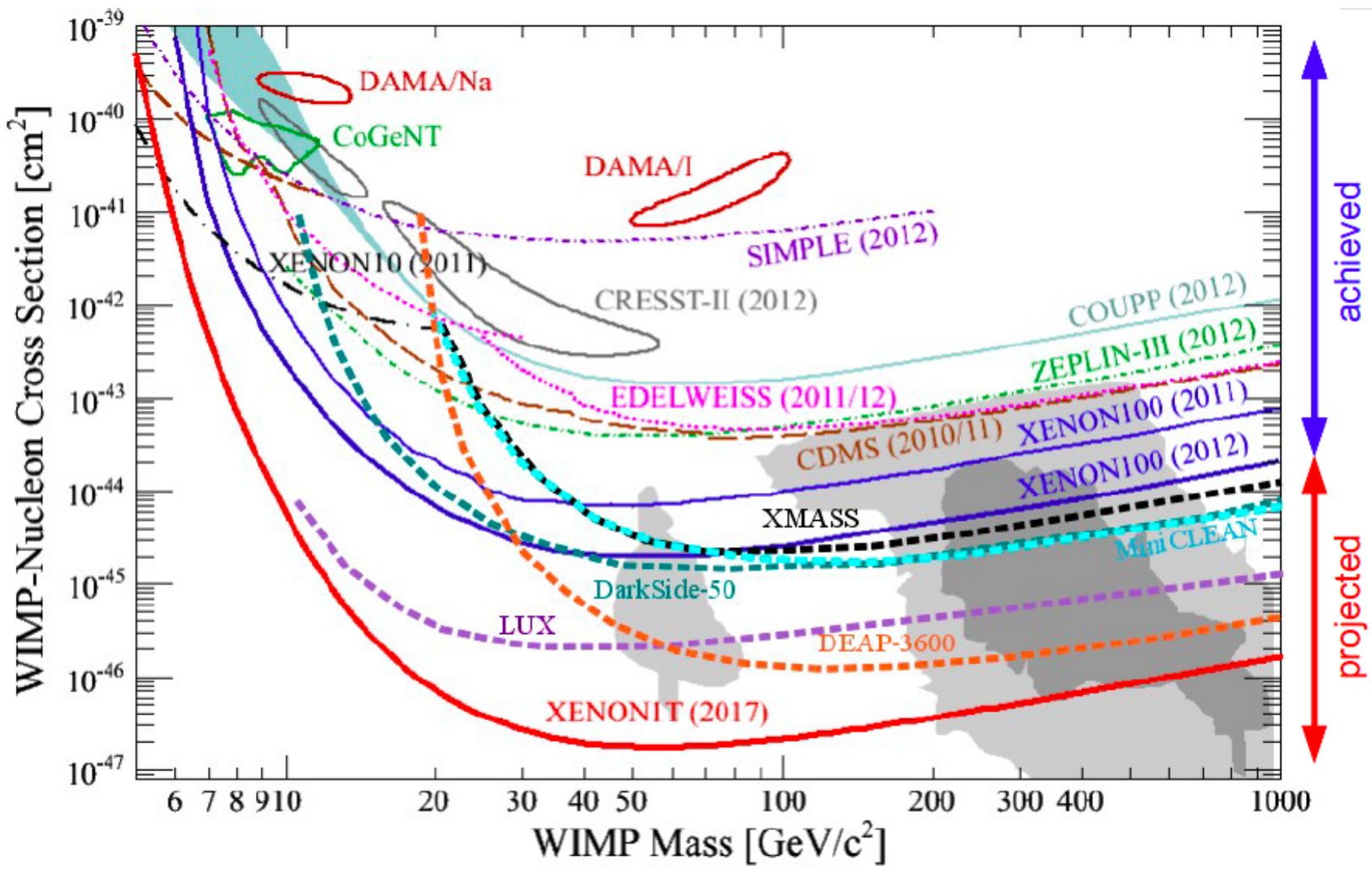
- some other (Xenon, LUX, CDMS-Ge) see no signal → place bounds

puzzling situation: maybe it is telling us something about the WIMP-nuclei interactions or the structure of the DM halo

vector interactions mediated by Z-boson $\sigma \sim \alpha_W^2 m_p^2 / M_Z^4 \approx 10^{-39} \mathrm{cm}^2$

already excluded





ATTENTION: plot not complete!

Indirect Detection

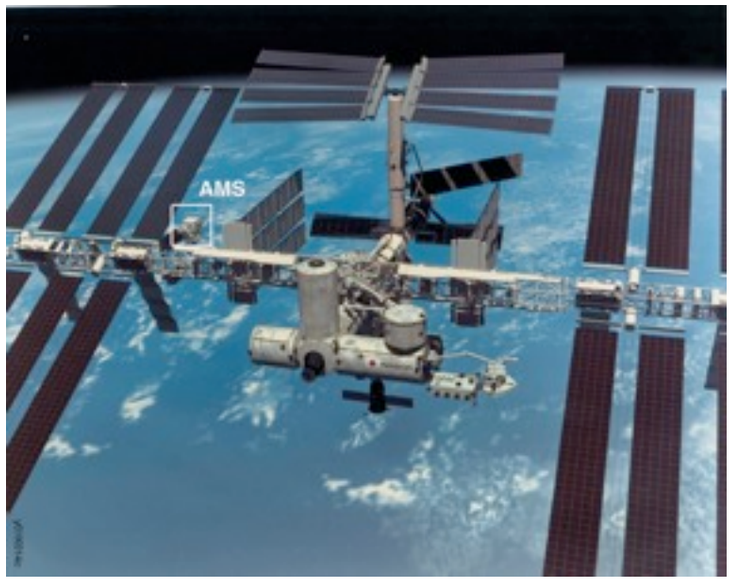
$\mathrm{DM}\ \mathrm{DM} \to e^+e^-, \ldots$

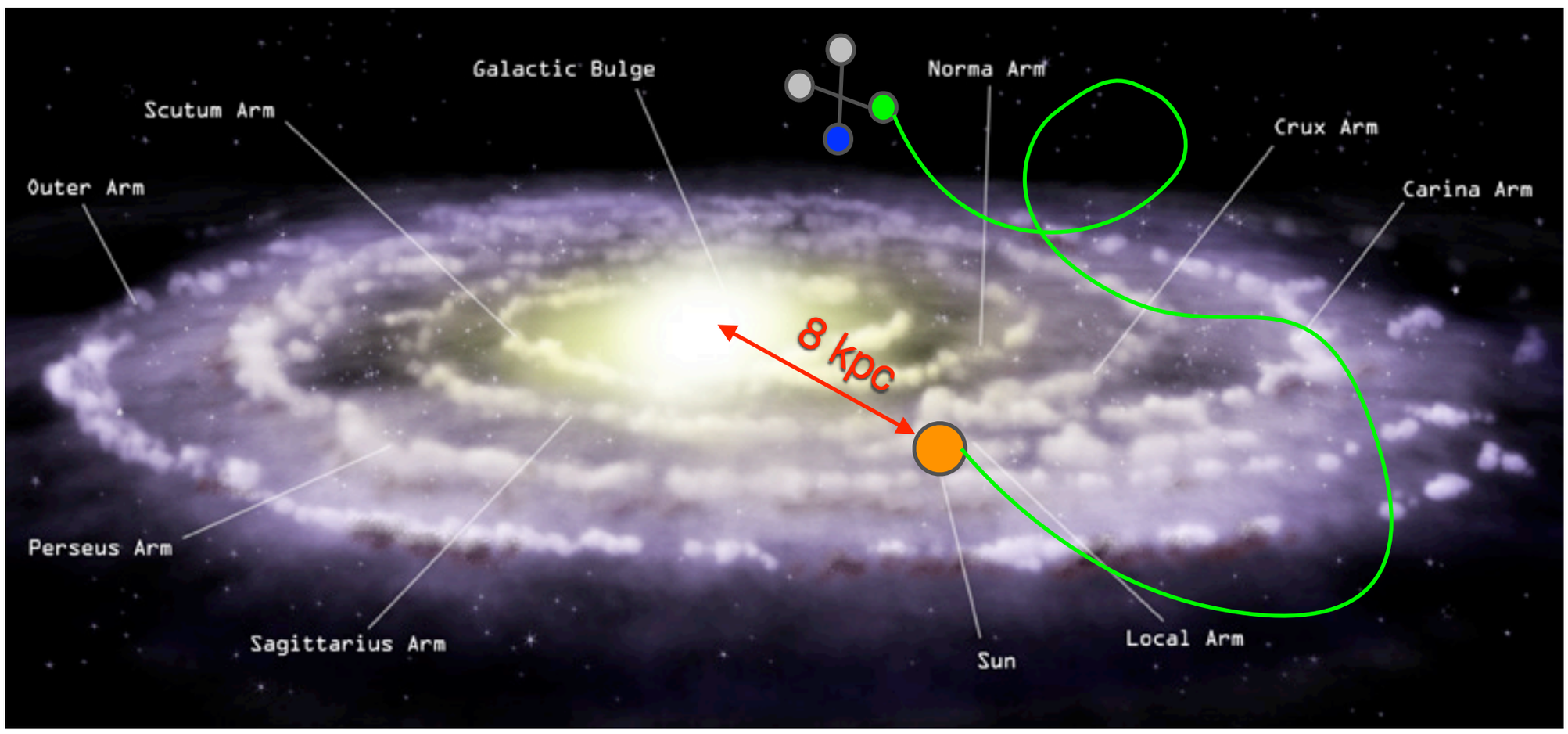
$e^+, \bar{p}$ **AMS-02, Pamela, Fermi, HESS**

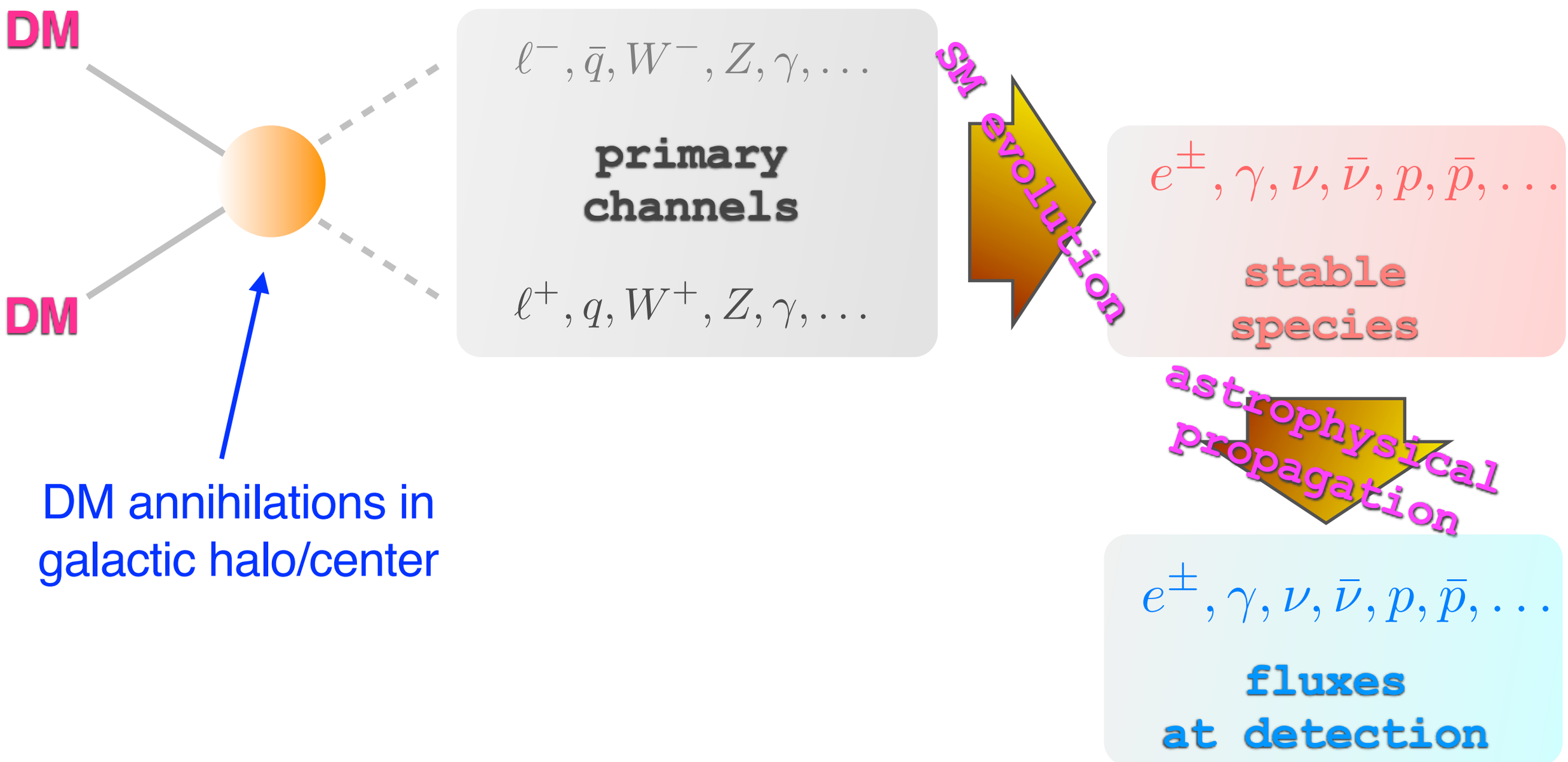
γ **ATIC, Fermi**

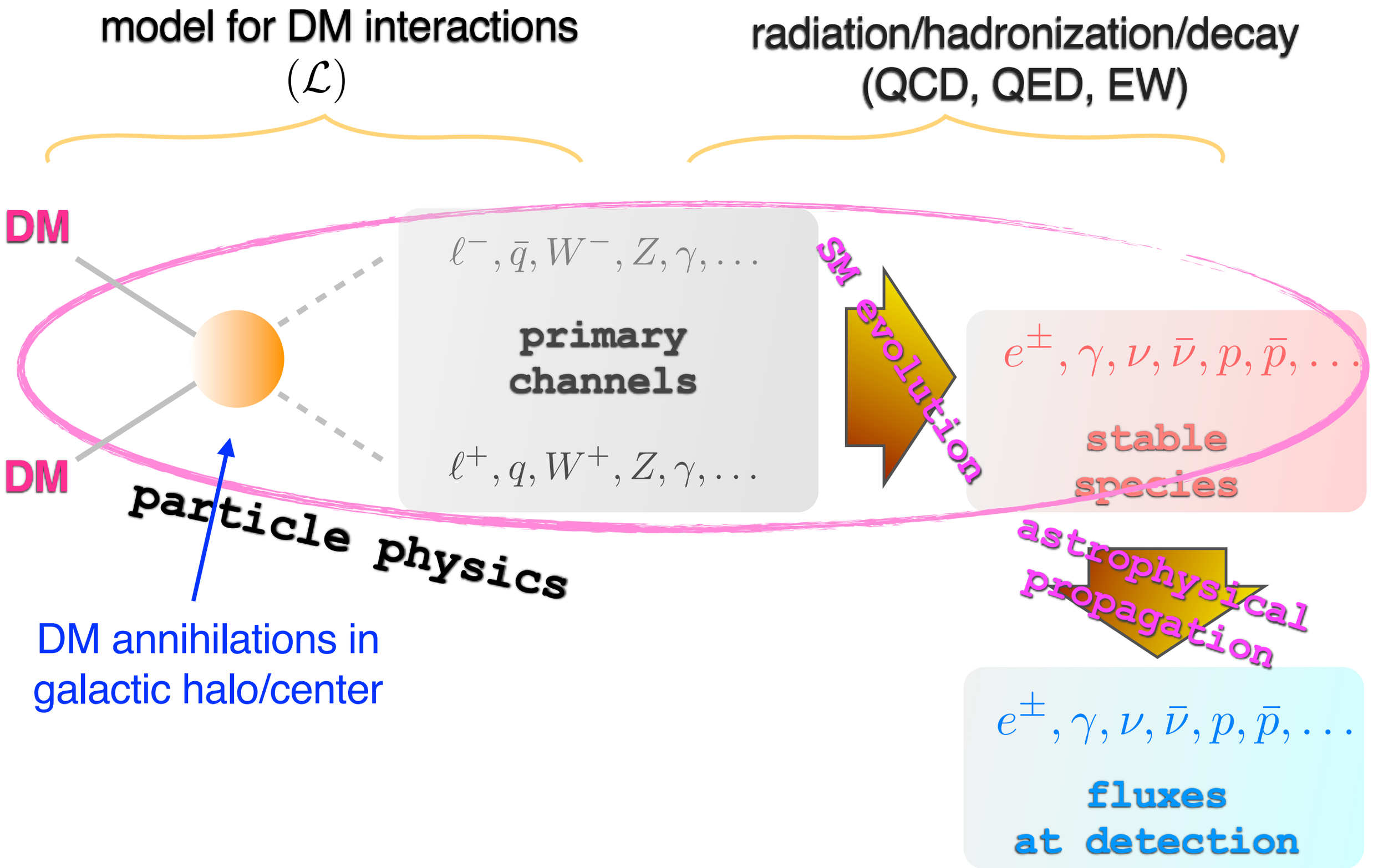
ν **IceCube, Antares, Km3Net**

$\bar{d}$ **GAPS, AMS-02**






DM
DM
$\ell^-, \bar{q}, W^-, Z, \gamma, \ldots$
primary channels
$\ell^+, q, W^+, Z, \gamma, \ldots$
SM evolution
$e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \ldots$
stable species
astrophysical propagation
$e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \ldots$
fluxes at detection
DM annihilations in galactic halo/center


model for DM interactions
$(\mathcal{L})$
radiation/hadronization/decay
(QCD, QED, EW)
DM
DM
$\ell^-, \bar{q}, W^-, Z, \gamma, \ldots$
primary channels
$\ell^+, q, W^+, Z, \gamma, \ldots$
SM evolution
$e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \ldots$
stable species
particle physics
astrophysical propagation
DM annihilations in galactic halo/center
$e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \ldots$
fluxes at detection

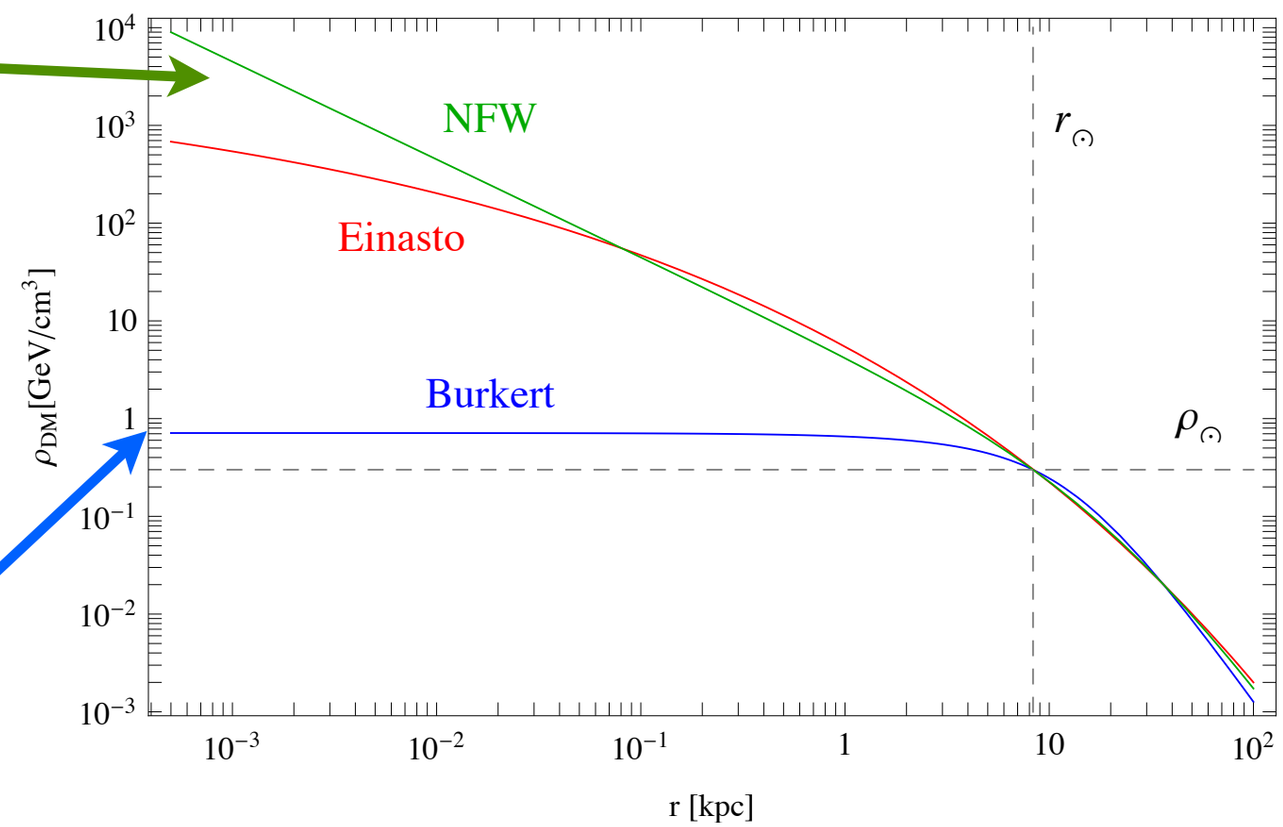
Astrophysics.

Galactic center: bigger signal, bigger bkg

Dwarf Galaxies (DM dominated): smaller signal, smaller bkg

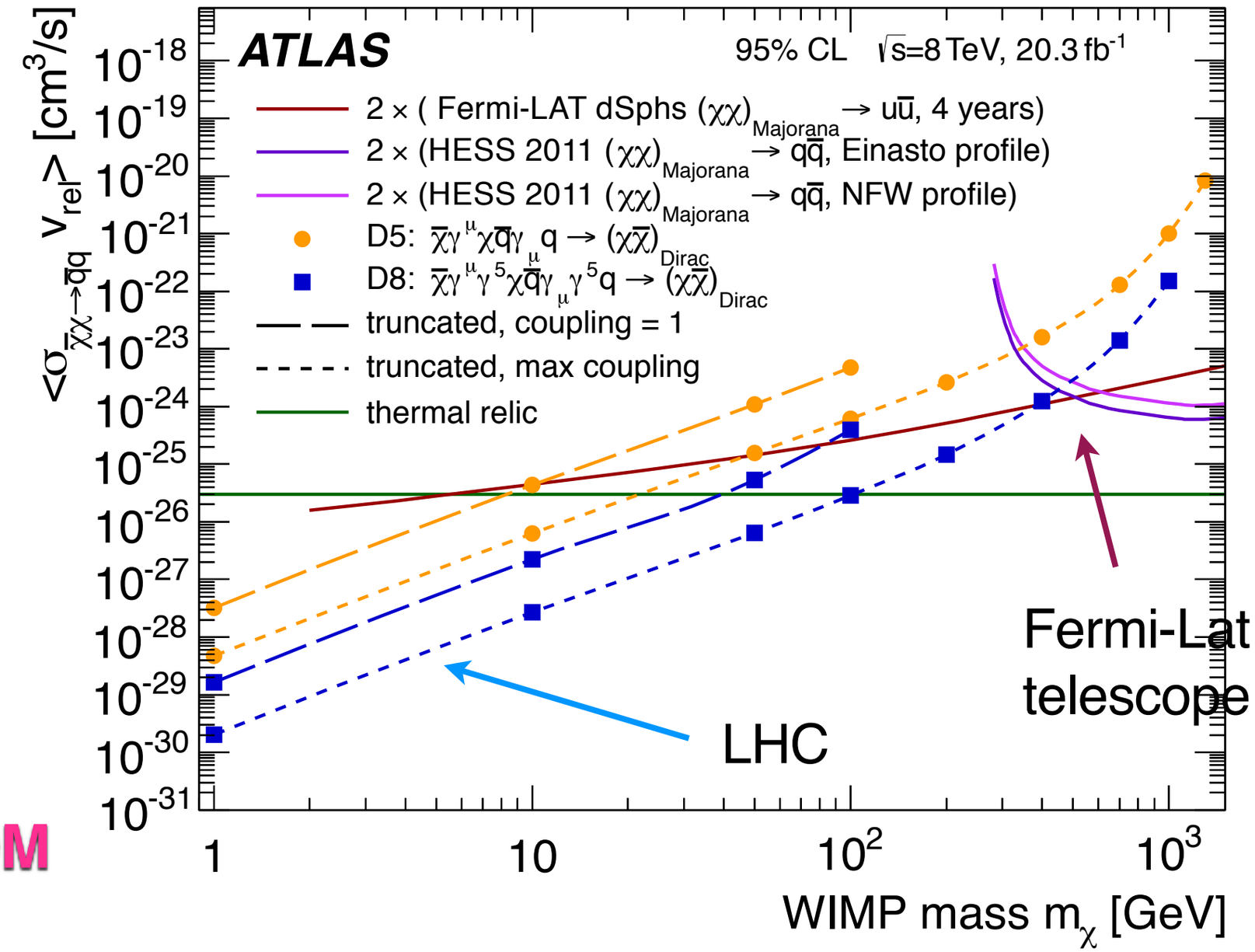
preferred by simulations

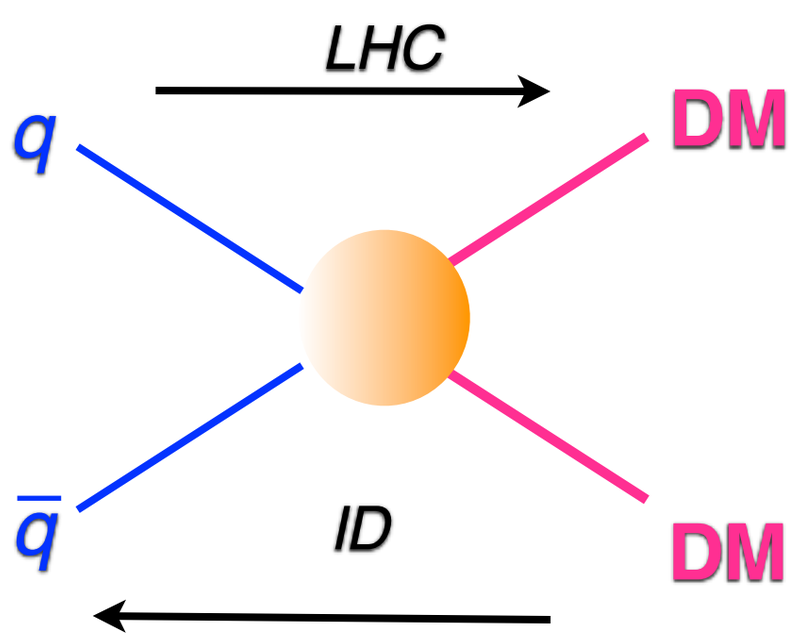
preferred by observations



$$\rho(r) = \begin{cases} \rho_s \left[(1+r/r_s)(1+(r/r_s)^2)\right]^{-1}, & r_s = 12.67 \text{ kpc}, \quad \rho_s = 0.712 \text{ GeV/cm}^3, \quad \text{(Burkert)} \\ \rho_s \exp\left[-\frac{2}{0.17}\left[(r/r_s)^{0.17} - 1\right]\right], & r_s = 28.44 \text{ kpc}, \quad \rho_s = 0.033 \text{ GeV/cm}^3, \quad \text{(Einasto)} \\ \rho_s (r_s/r)\,(1+r/r_s)^{-2}, & r_s = 24.42 \text{ kpc}, \quad \rho_s = 0.184 \text{ GeV/cm}^3, \quad \text{(NFW)} \end{cases}$$

Indirect Detection



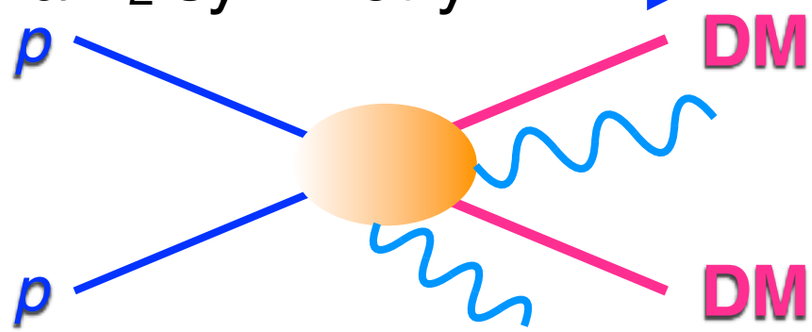


[arXiv:1502.01518]

$$p\,p \to \mathrm{DM} + X$$

Some trivial considerations:

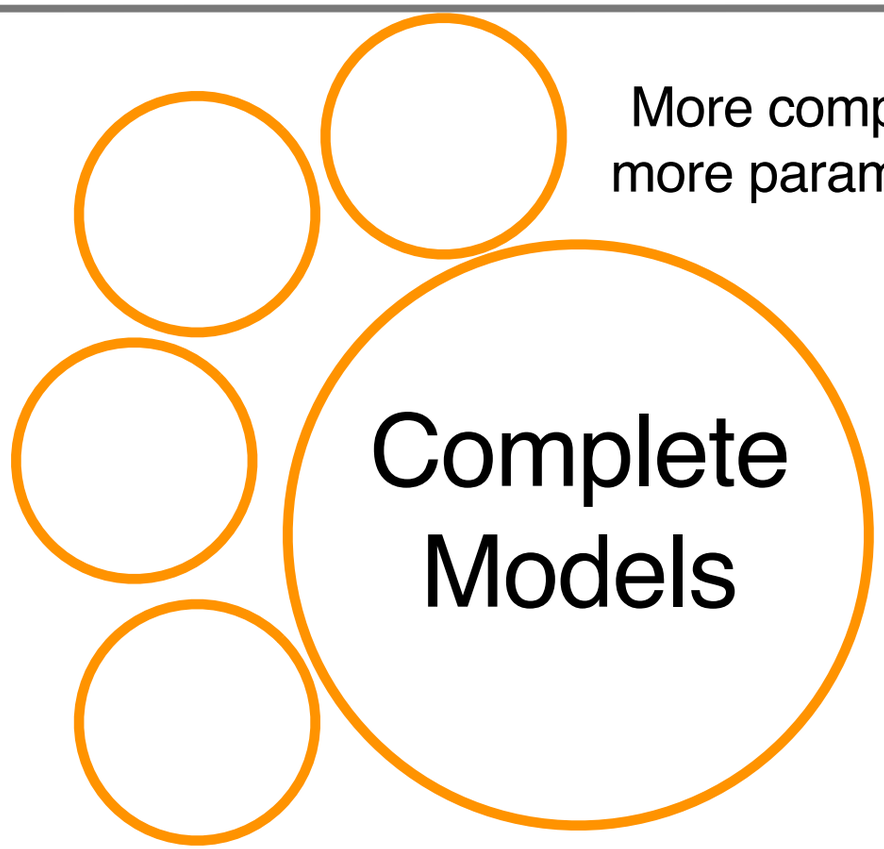
- Dark Matter in a collider is like a neutrino (missing E_T)
- if stabilized by a Z_2 symmetry → DM produced in pairs



- Difficult search, unless correlating missing E_T with other handles

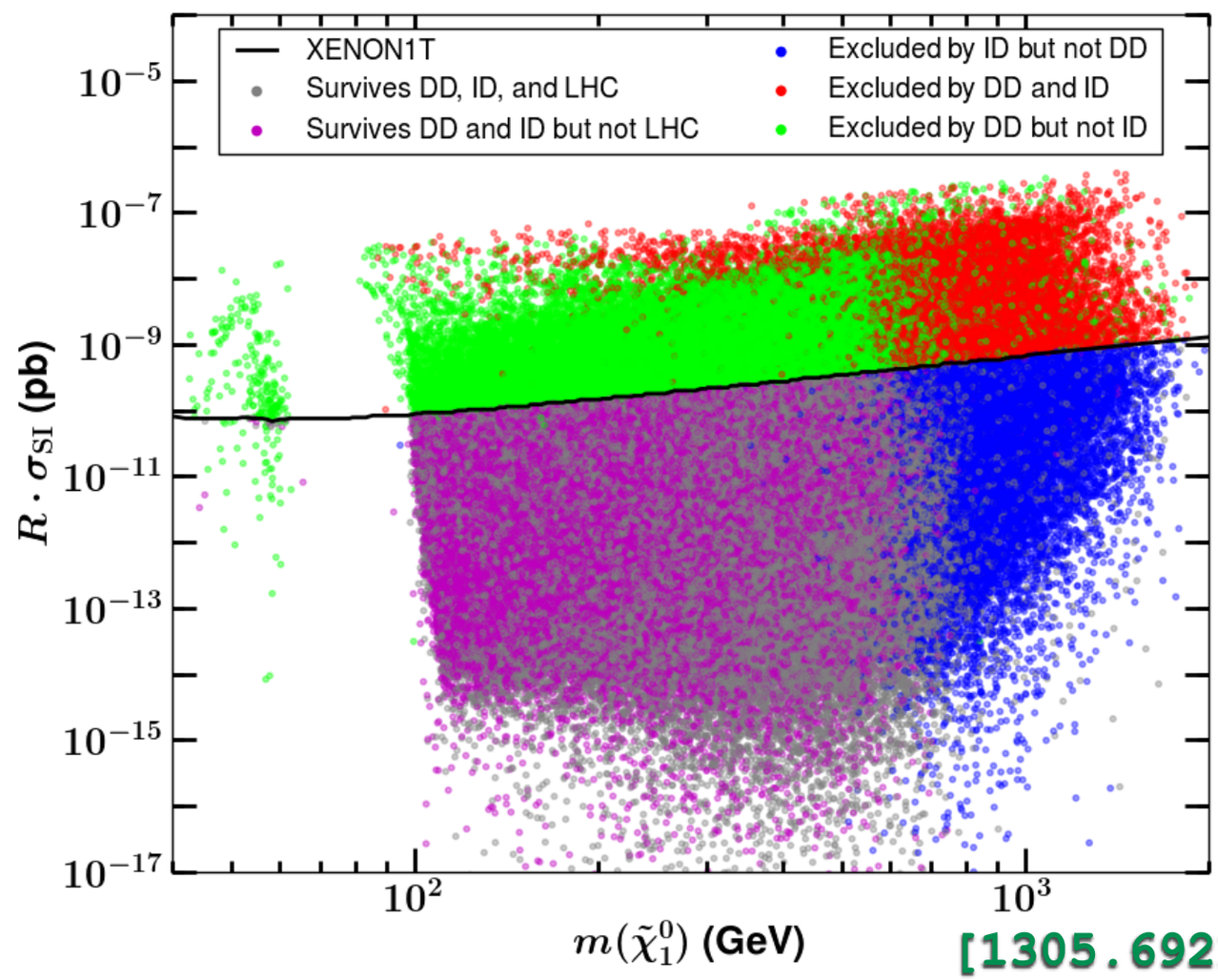
[jets/photons from initial state radiation?
displaced vertices?
accompanying particles?]

- **Need new ideas!**



MSSM, Composite Higgs, Extra-Dim...

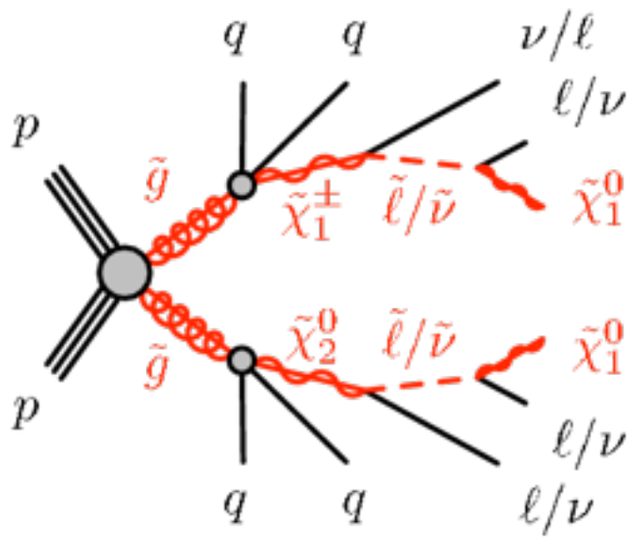
pMSSM scan

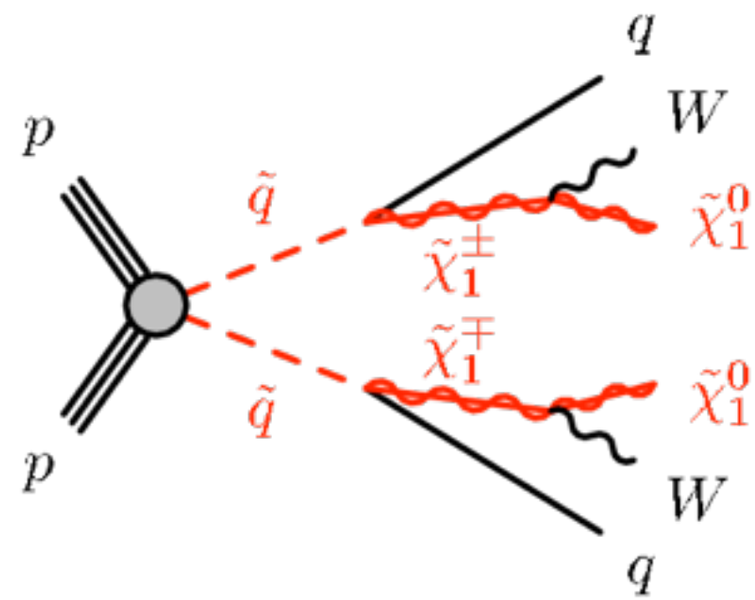


[1305.6921]

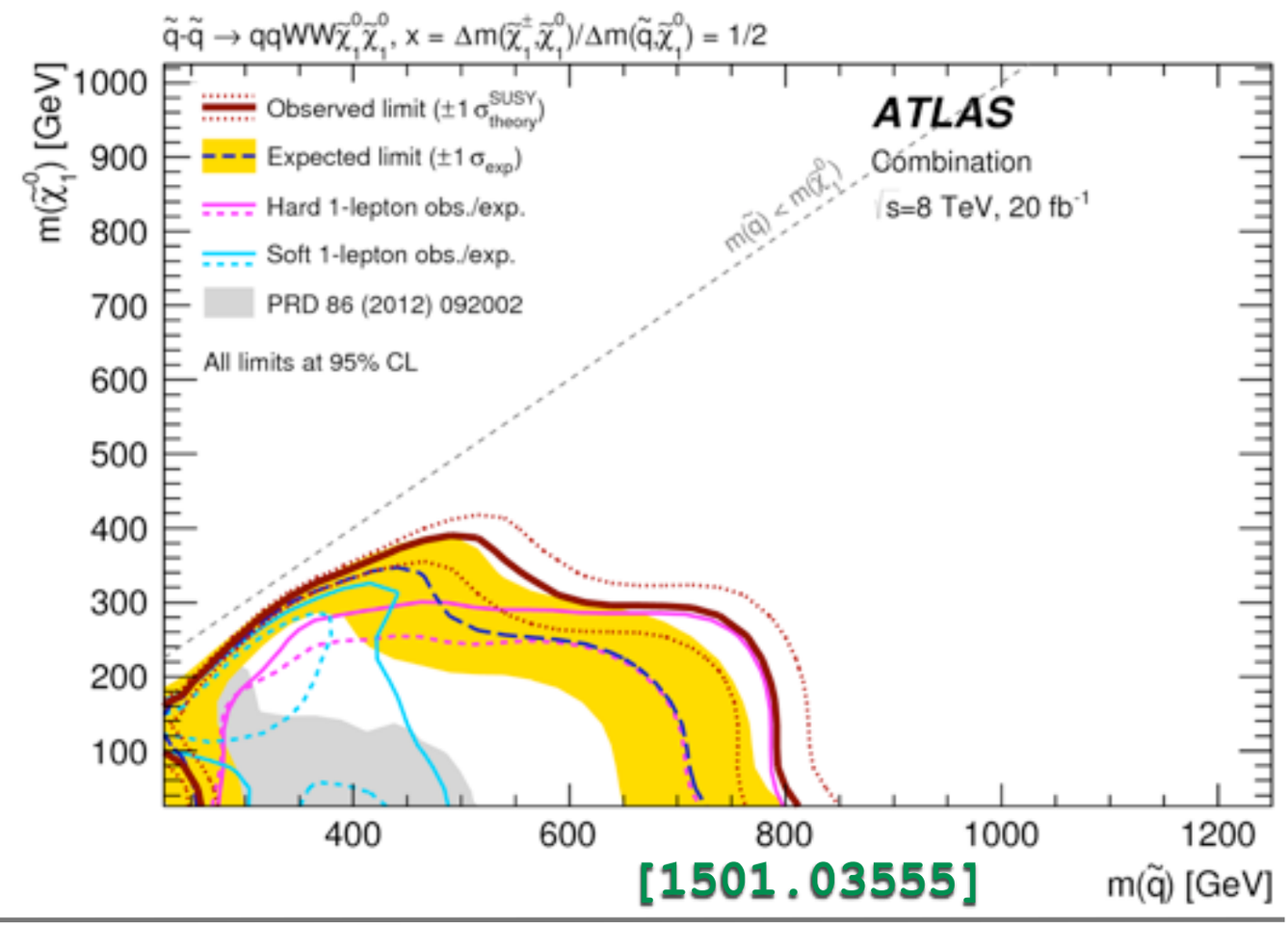
lots of parameters...

Ex:



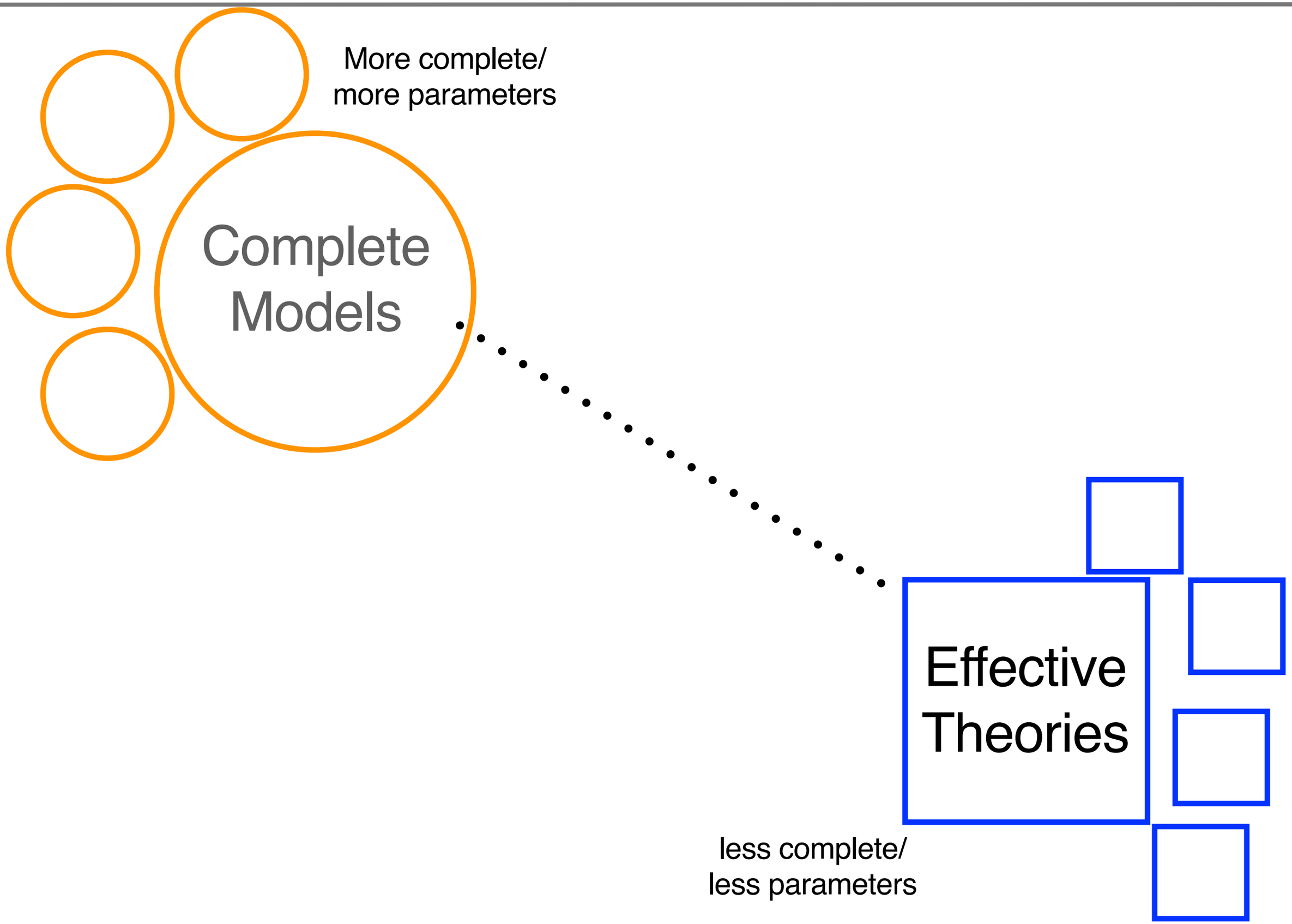


many jets (+ leptons) + MET



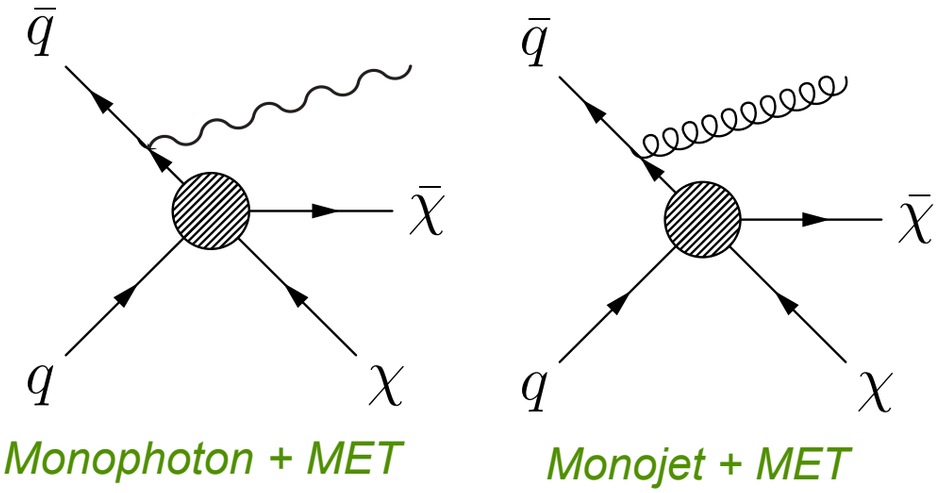
[1501.03555]

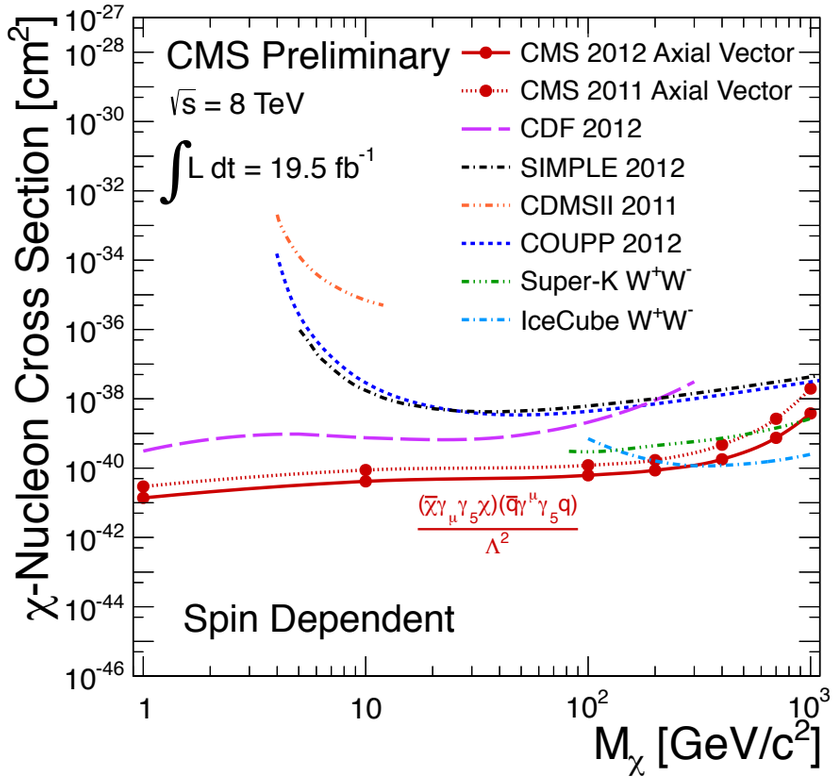
Theory Space



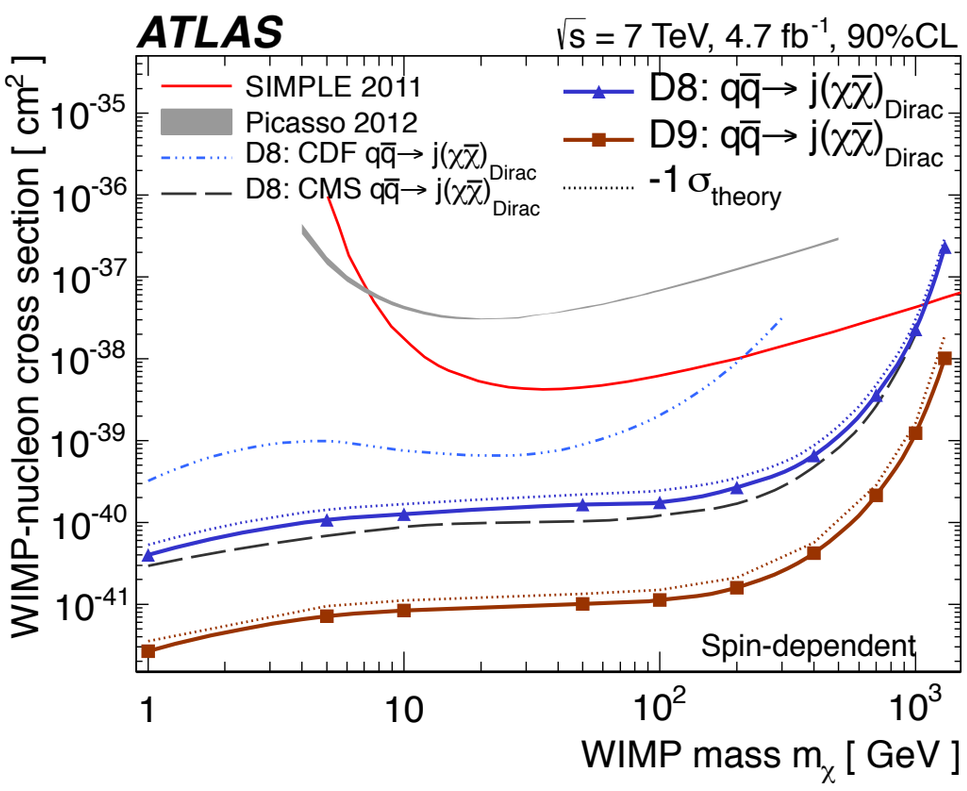
Mono-jet/Mono-Photon

- ✓ constrain DM-quarks interactions and translate into limits on DM-nucleon cross-section
- ✓ complementary/ competitive with direct detection
- ✓ no astrophysical uncertainties





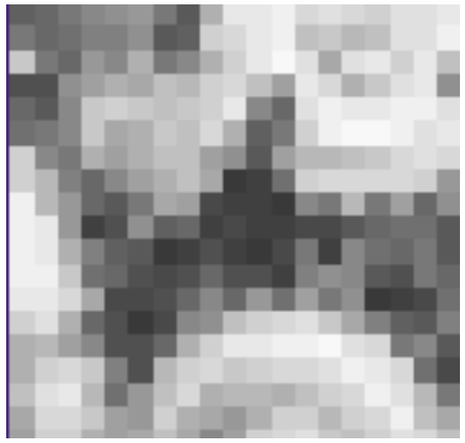
[CMS PAS EXO-12-048]



[ATLAS 1210.4491]

Effective Field Theory Description

effective
low-energy
description



(Λ ~ 1 TeV)

New States

(say, 10 TeV)

M_Z

E

EFT OK

Integrate out the UV physics connecting DM-SM and describe interactions with eff. ops.:

$$\frac{1}{\Lambda^2}(\bar{\chi}\Gamma^A\chi)(\bar{q}\Gamma_A q)$$

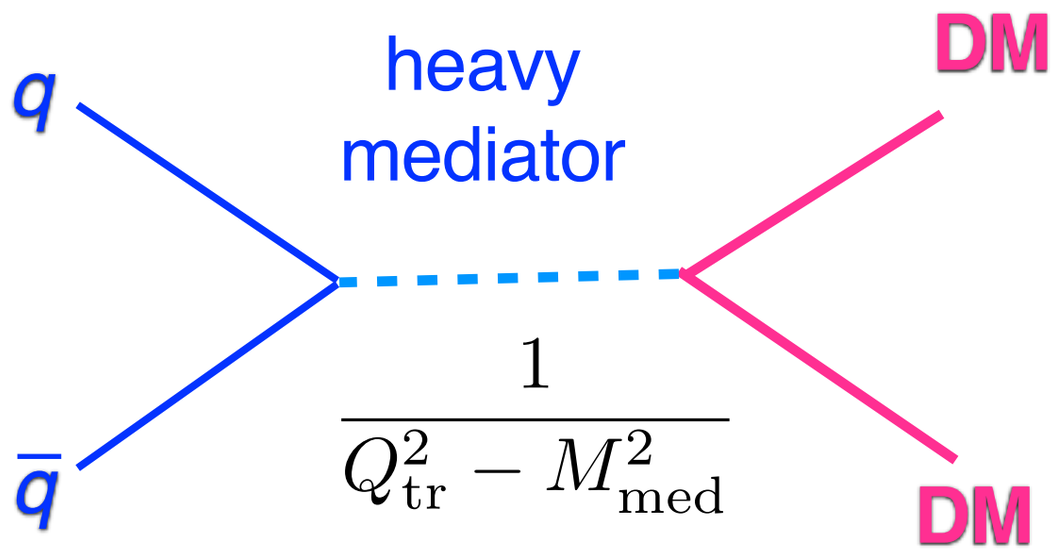
LHC can access regions beyond the validity of the eff. description

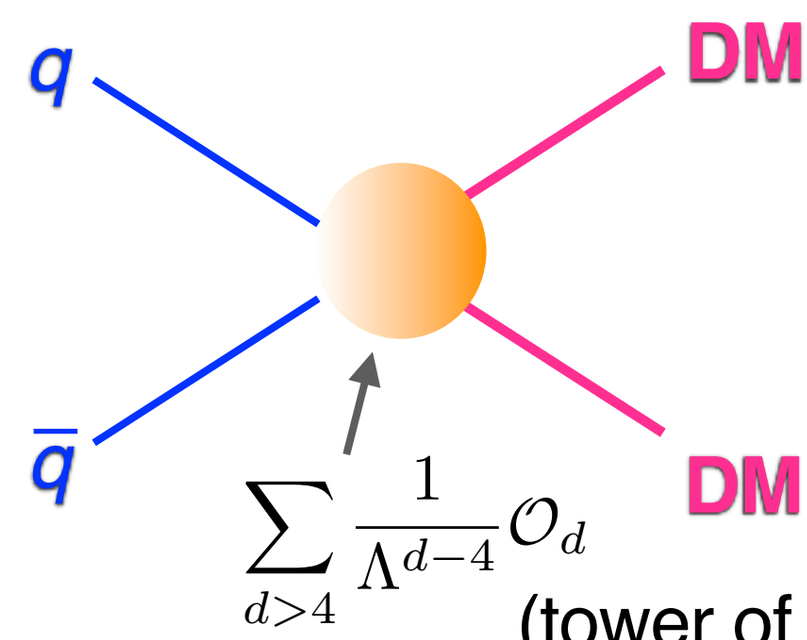
=

→ need to use EFT carefully and consistently

Effective Field Theory Description

- the momentum transfer in the relevant process must be $Q_{\rm tr} \lesssim M_{\rm med}$





(tower of ops.)
$M_{\rm med} = f(g_i, \Lambda)$

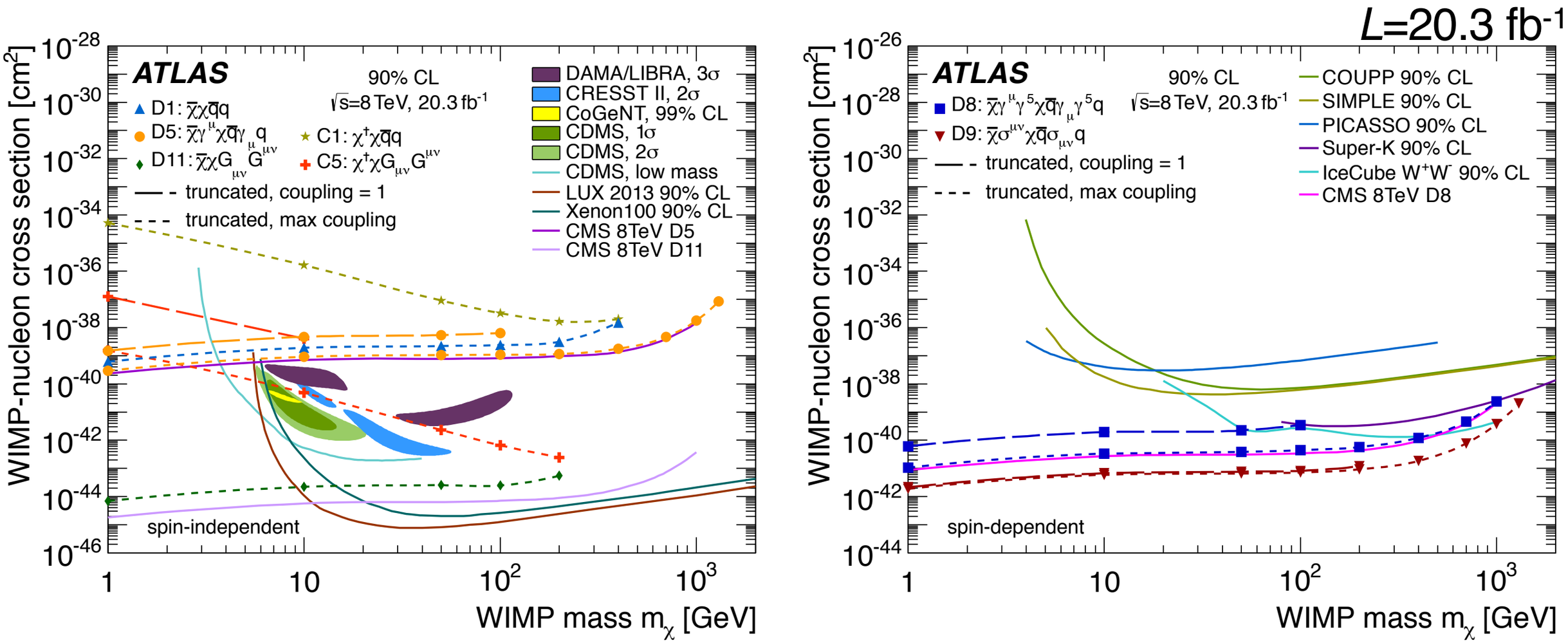
$$\frac{1}{Q_{\rm tr}^2 - M_{\rm med}^2} = -\frac{1}{M_{\rm med}^2}\left[\overbrace{1}^{\text{dim-6}} + \overbrace{\frac{Q_{\rm tr}^2}{M_{\rm med}^2}}^{\text{dim-8}} + \mathcal{O}\left(\frac{Q_{\rm tr}^4}{M_{\rm med}^4}\right)\right]$$

- $Q_{\rm tr}/M_{\rm med}$ measures the badness of the truncation of the tower of effective ops to the lowest dimensional ones

- Usually, lowest order is OK. Not a problem for direct/indirect searches. Situation is different @ LHC.

LHC vs Direct Detection

- use only “selected” events with small enough momentum transfer
- after truncation: theoretically robust limits
- still relevant at low DM masses



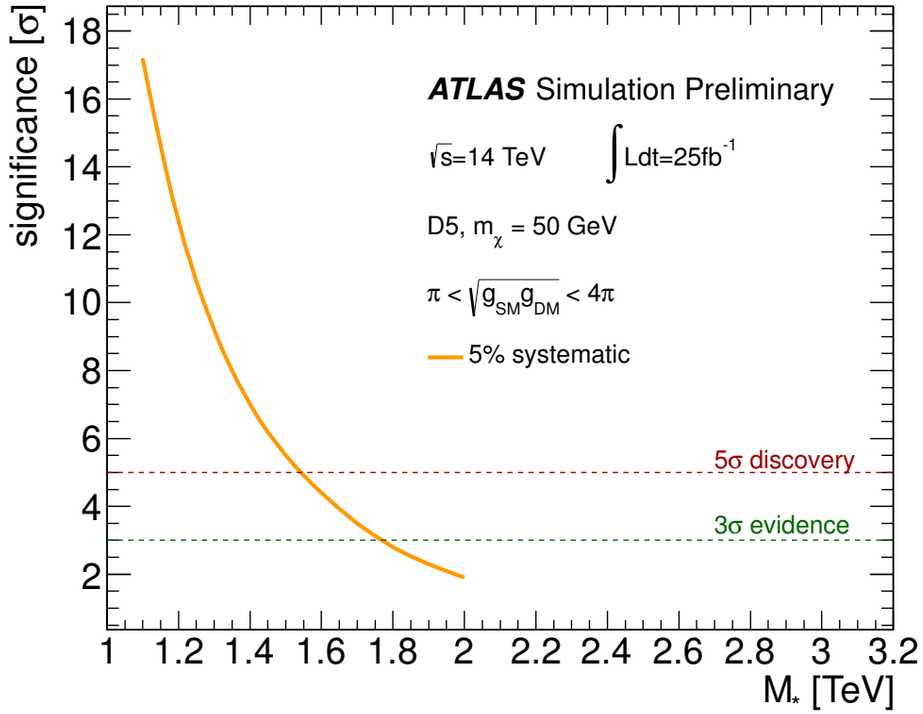
The “money plots”

[ATLAS - 1502.01518]

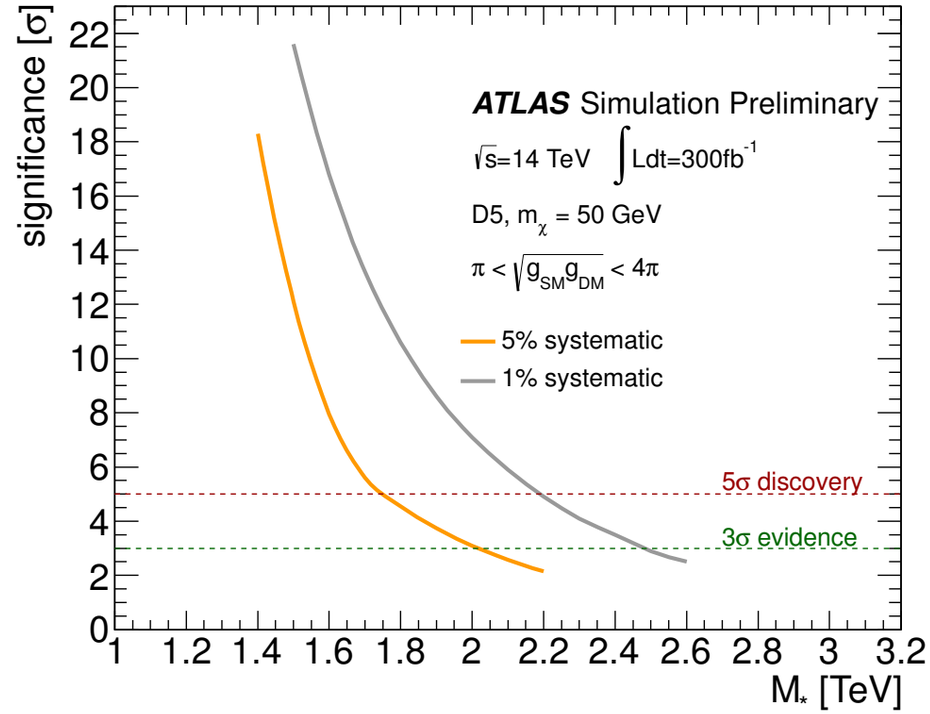
EFT Discovery Potential

$\sqrt{s} = 14\,\mathrm{TeV}$

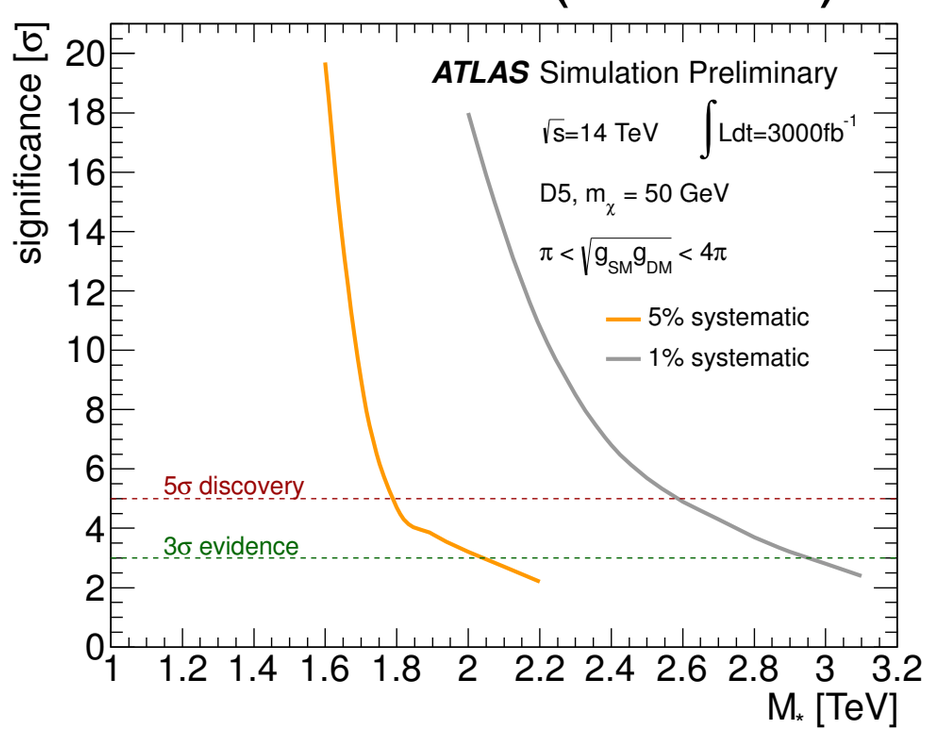
L=25 fb^{-1}



L=300 fb^{-1}



L=3000 fb^{-1} (HL-LHC)



Effective Operator

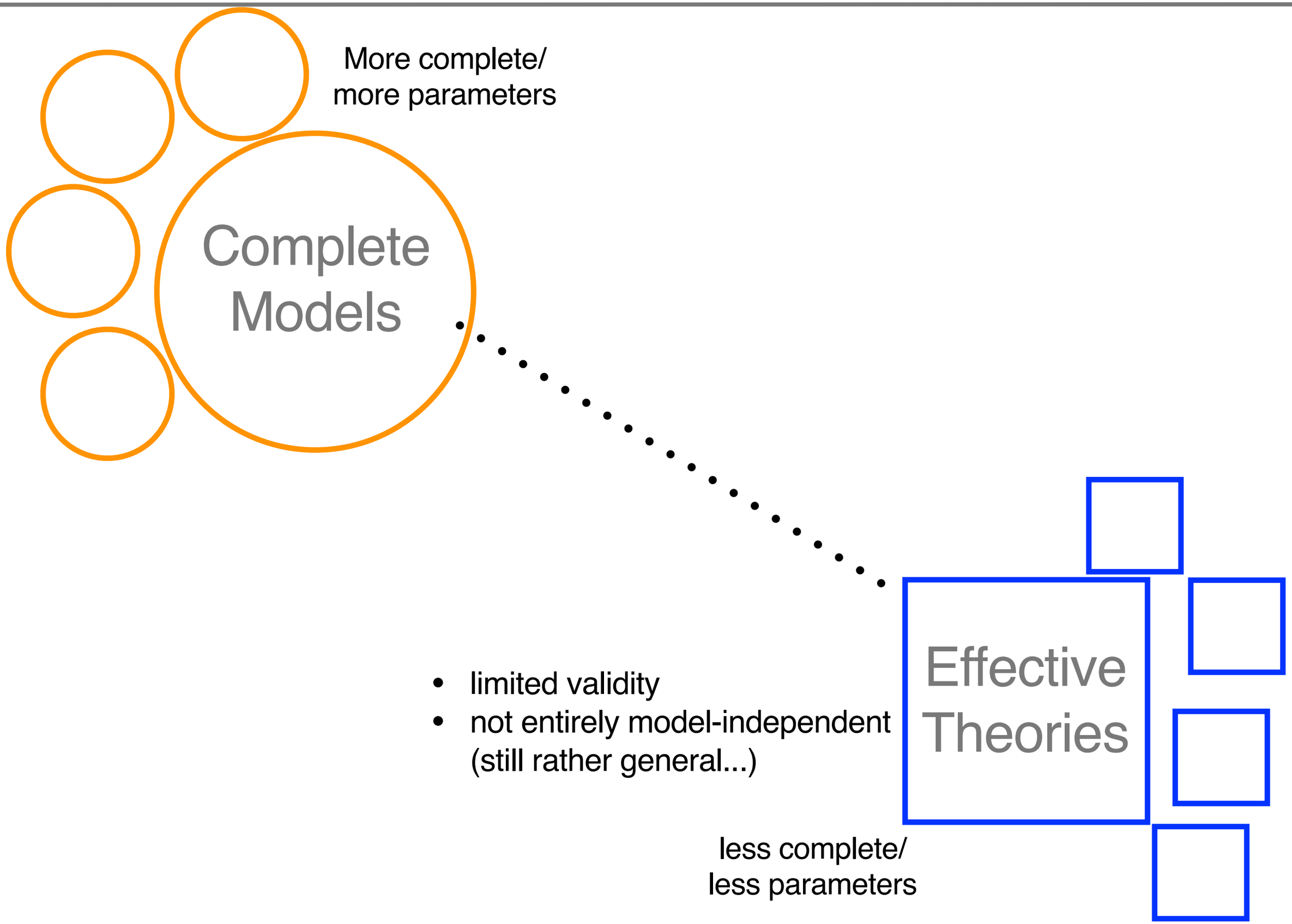
$$(\bar{\chi}\gamma^{\mu}\chi)(\bar{q}\gamma_{\mu}q)$$

$$m_{\mathrm{DM}} = 50\ \mathrm{GeV}$$

EFT validity <u>assumed</u>

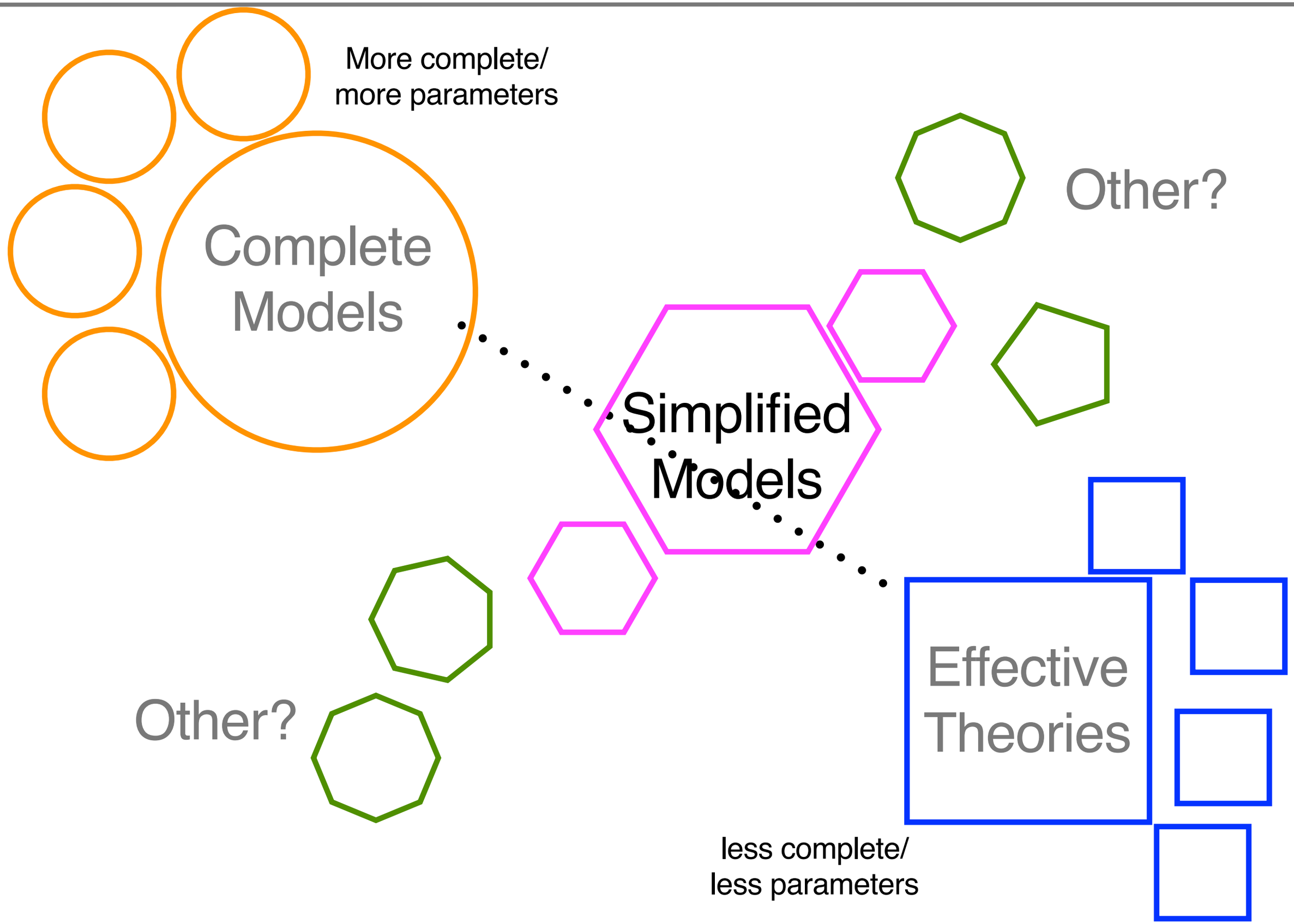
[ATL-PHYS-PUB-2014-0087]

Way Out?



- limited validity
- not entirely model-independent (still rather general...)

Way Out?


More complete/
more parameters
Complete
Models
Other?
Simplified
Models
Other?
Effective
Theories
less complete/
less parameters

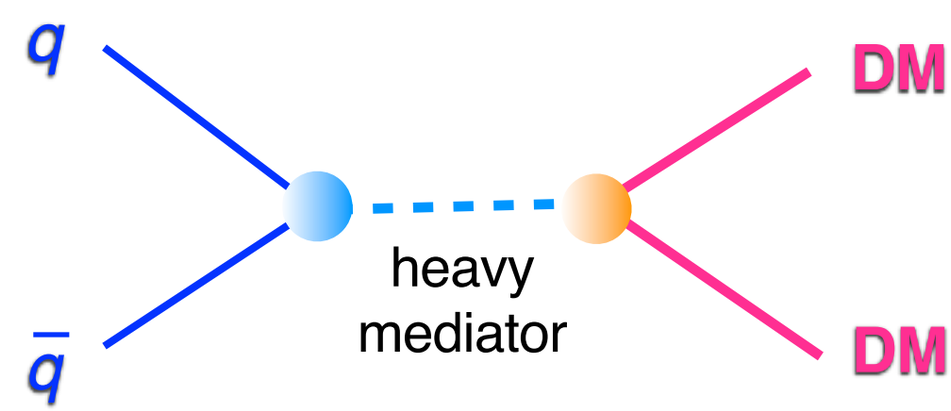
Simplified Models

... just means extending the SM with:

- 1 Dark Matter particle
- 1 Mediator particle connecting DM-SM

>> just another parametrization of unknown high energy physics <<

correspondence
eff ops ⟷ simplified models



✘ 1 or 2 more parameters (*g*'s)

✓ exploit other searches for mediators (e.g. di-jet), complementary to mono-jet

✓ theoretically consistent, no worries about EFT, widths, etc.

Summary of Lecture 2

- Dark Energy is a big question mark (maybe quantum gravity...)
- Dark Matter looks more *bread-and-butter* particle physics
- WIMPs are the Holy Grail of Dark Matter physics
- direct/indirect/collider searches for WIMPs
- ... and if WIMPs are not found in the next ~5 years ???