ESHEP 2018, Maratea (Italy)

Cosmology and Dark Matter

Lecture 2

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> 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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> Dark Energy

2 main sets of evidences for Dark Energy:

1. energy budget:

fit to CMB anisotropy map provides
many cosmological parameters:

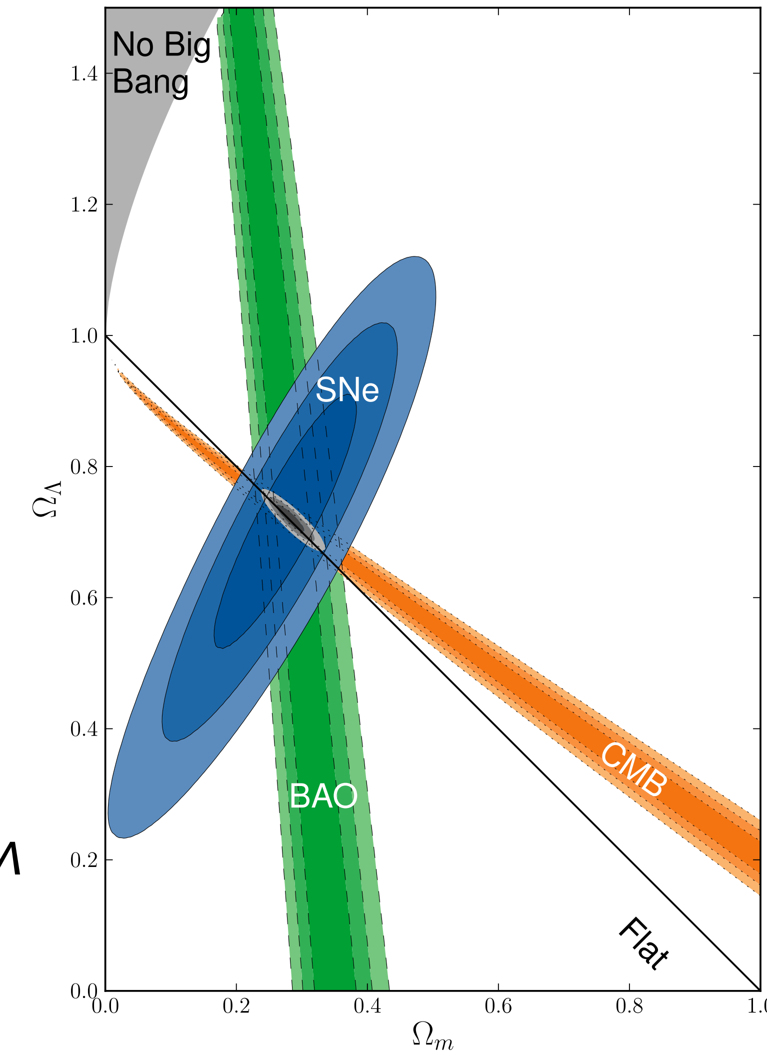
$\Omega_{tot} \sim 1.0, \; \Omega_{matter} \sim 0.3, \; \Omega_{radiation} \sim 0.0 \longrightarrow \mathbf{\Omega_{\Lambda} \sim 0.7}$

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

> Dark Energy

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

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



[arXiv:1105.3470]

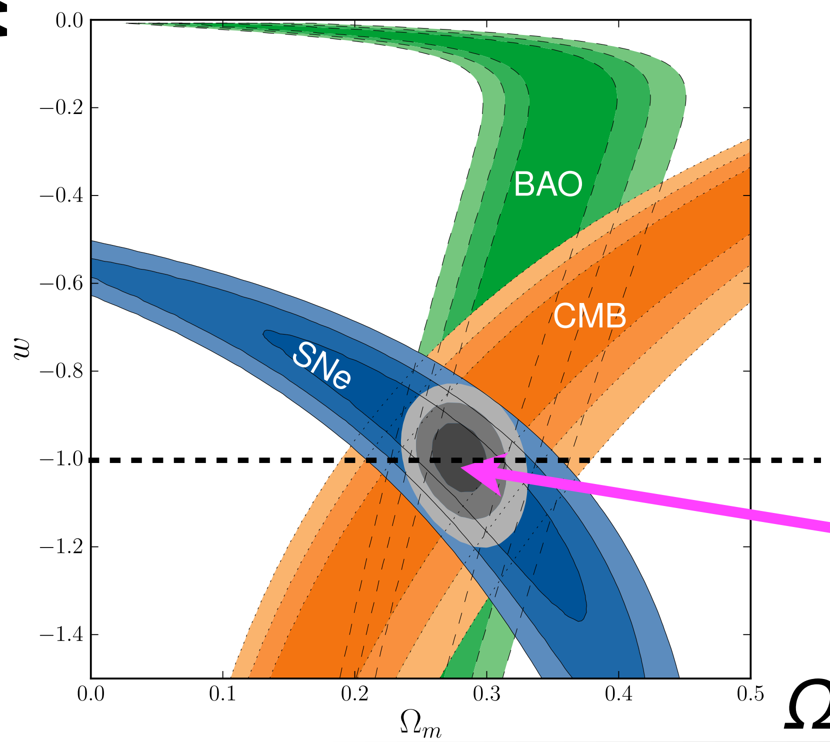
absolute (M) and apparent (m) magnitudes are related to distance:

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

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

Measure m ⟶ measure d_L ⟶ measure Ω_{matter}, Ω_Λ

w



Ω_{matter}

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

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

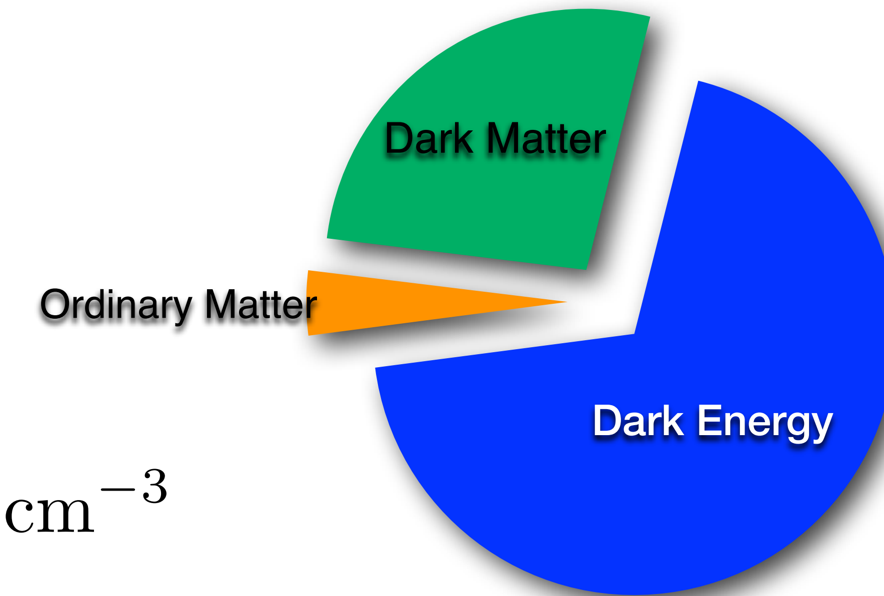
the "WRONGEST" estimate of particle physics
(and biggest hierarchy problem...)

SO WHAT?

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

> Evidences for Dark Matter

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

> Dark Matter in Galaxy Clusters

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

> Dark Matter in Galaxy Clusters

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

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

from temperature maps

from X-ray luminosity and spatial distributions

EXTRACT THE MASS

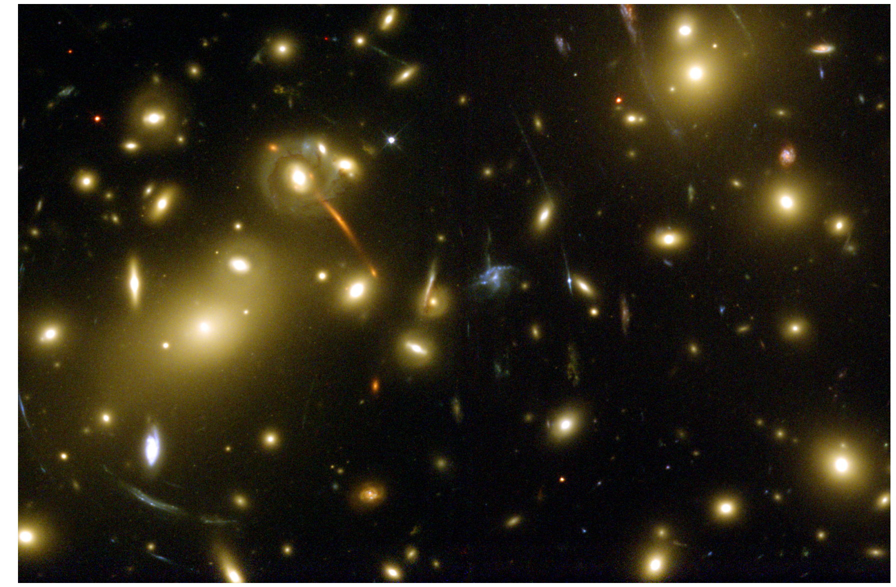
More matter than just baryons!

> Dark Matter in Galaxy Clusters

- Gravitational Lensing

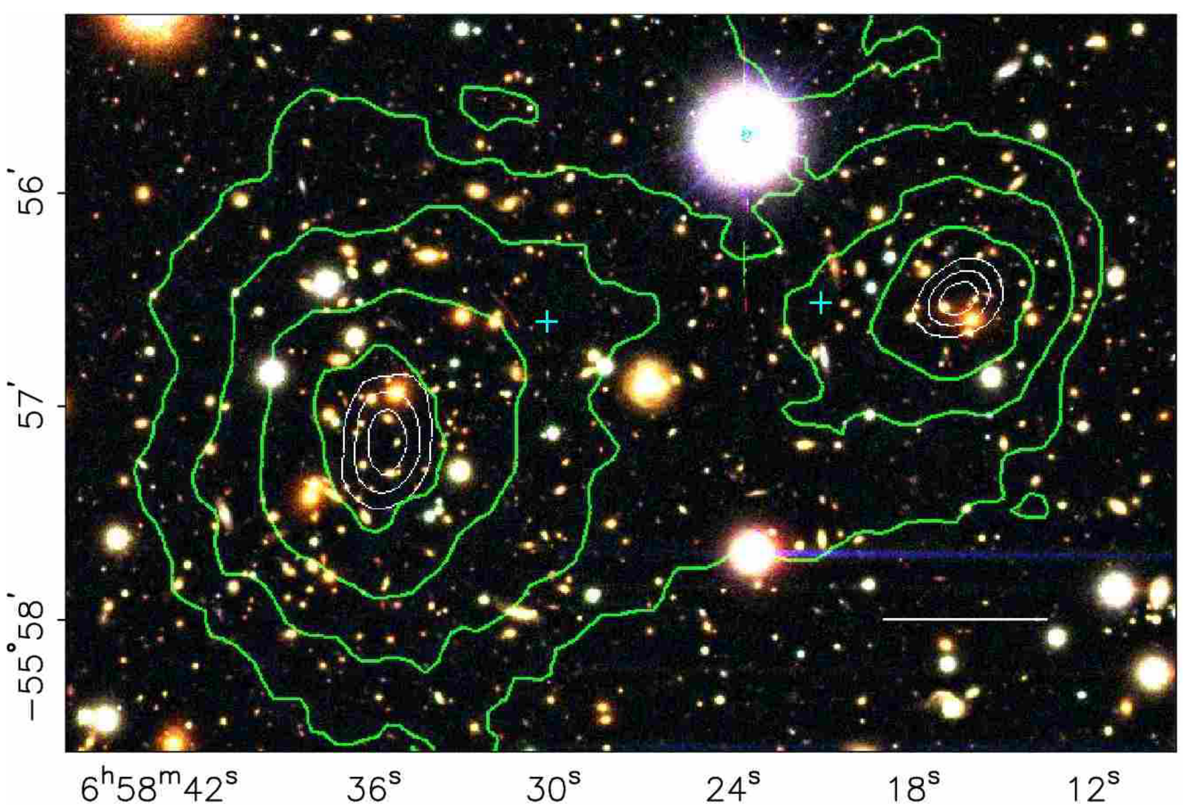
General Relativity at work!

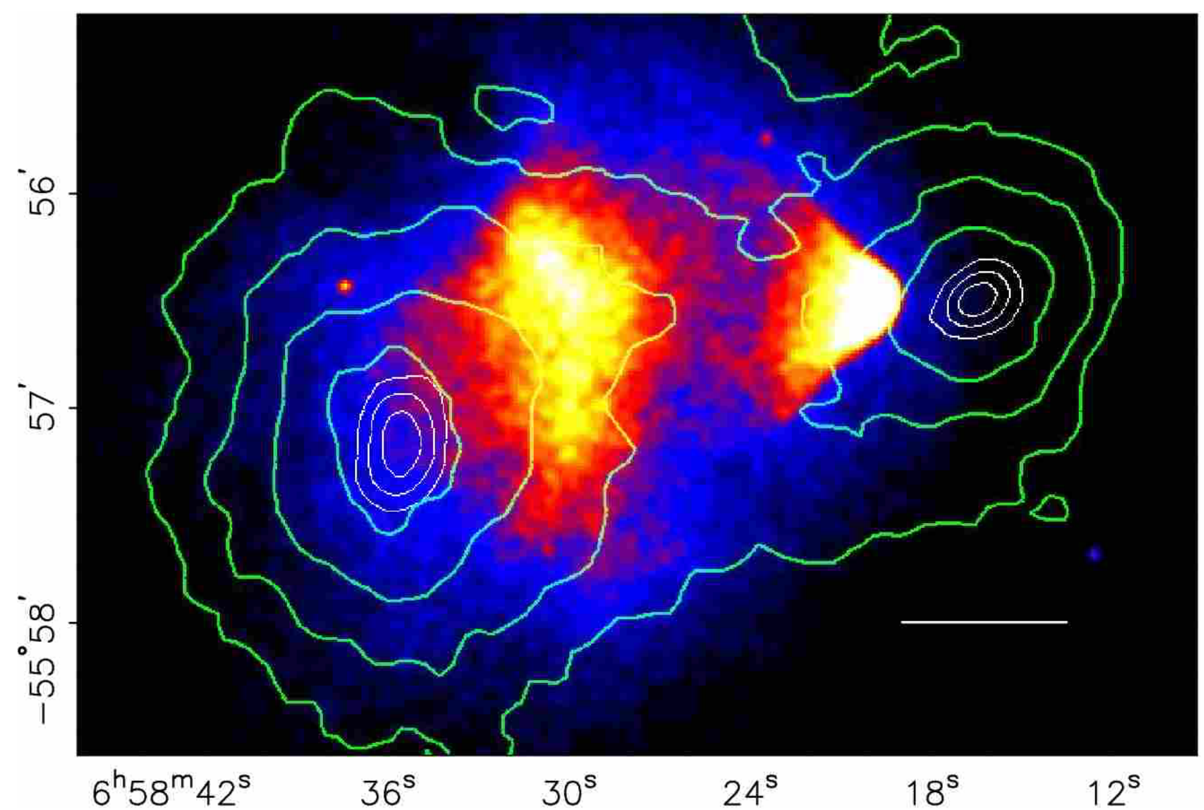
Abell NGC 2218



- "Bullet" Cluster

Two colliding clusters of galaxies





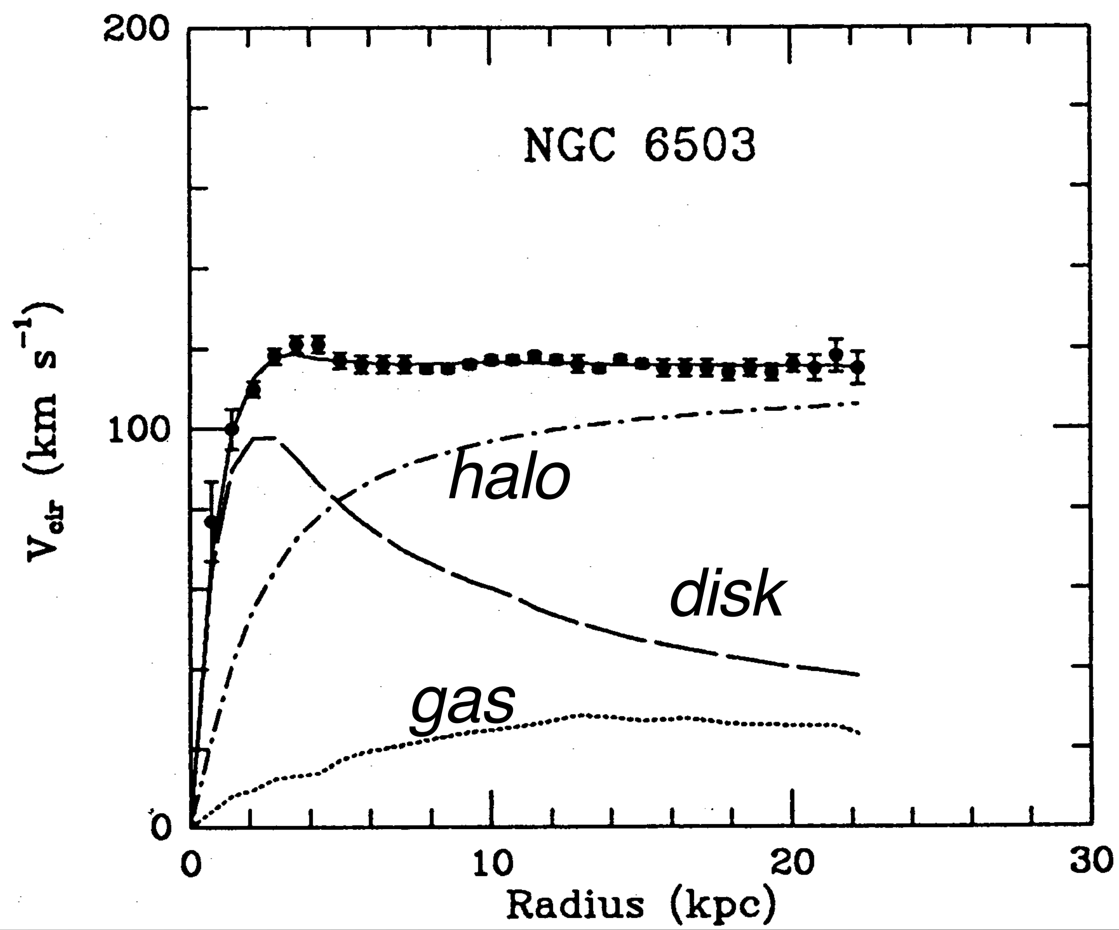
> Dark Matter in Galaxies

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: $v(R) \simeq \mathrm{const.}$ at large *R*



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

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

> Dark Matter in Cosmology

- 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 ("cored") densities

- "missing satellite problem"

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

Only ~ 10 observed

→ UNCLEAR SITUATION

Some propose **Wark Dark Matter**

It may simply be that:
. numerical sims. are not accurate enough (baryons not included)
. small sub-haloes are invisible.

> Alternatives to Dark Matter (?)

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

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

(flat)

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

MOND IS FALSE!

> 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

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

(v=100 km/s)

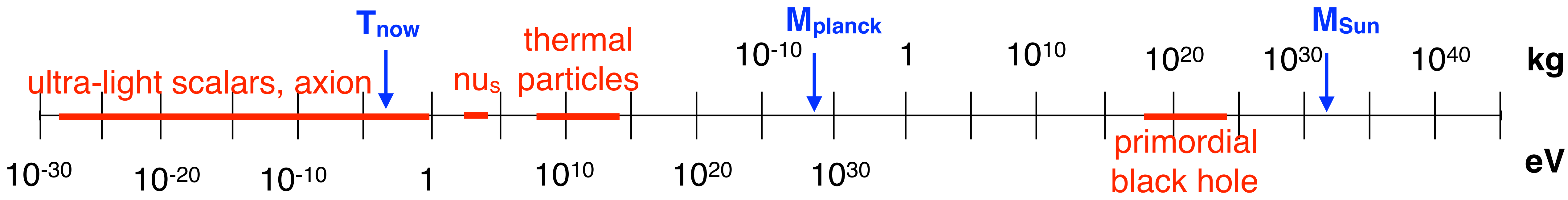
For **fermions**: DM quantum occupation number must be <1 (Pauli excl.)

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

(Gunn-Tremaine bound)

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

> Landscape of DM theories



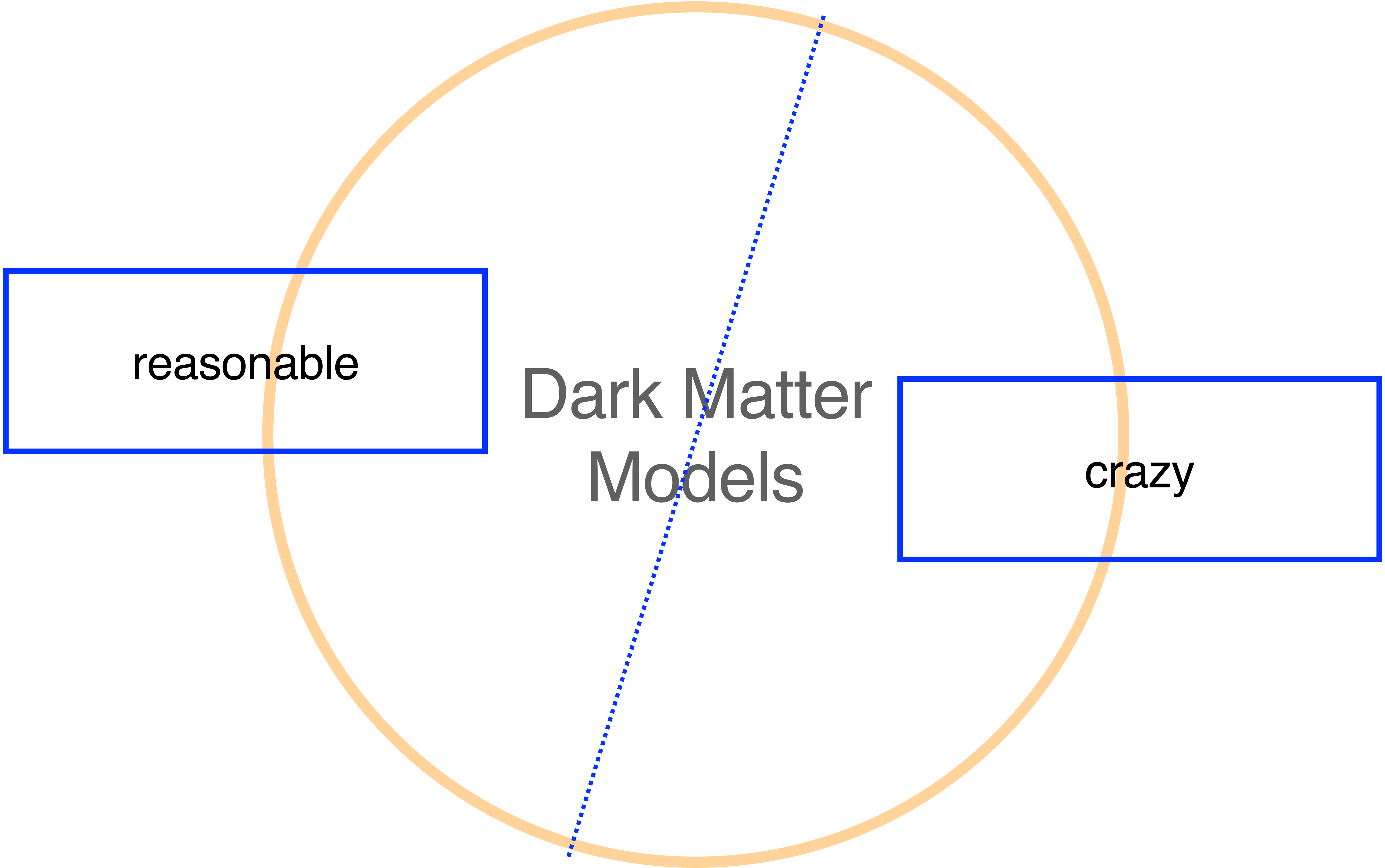
Wide landscape of DM models

DM masses spanning several orders of magnitude

No preferred mass scale

we are not sure where to look for DM (unlike e.g. the Higgs)

> Landscape of DM theories



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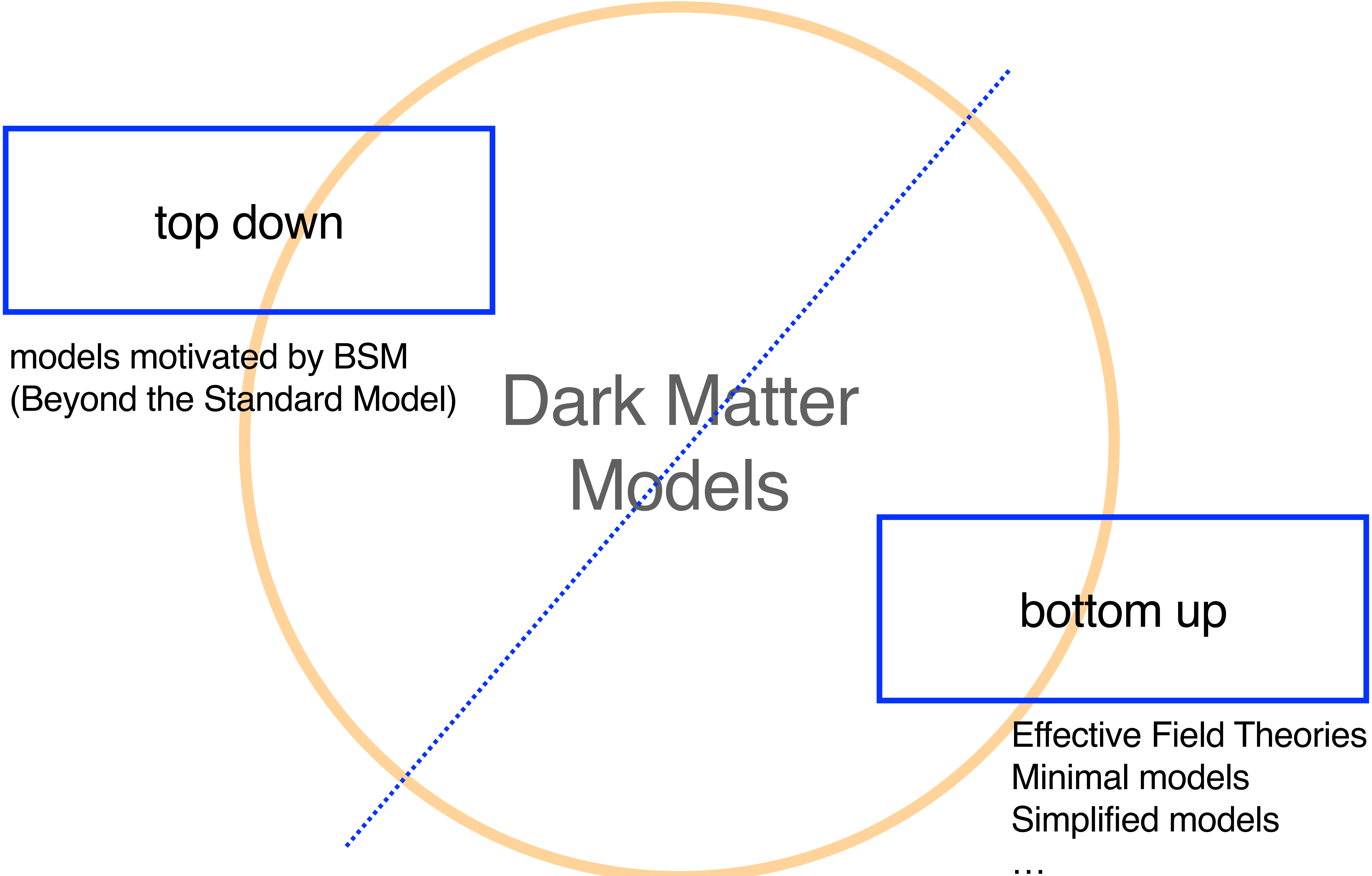

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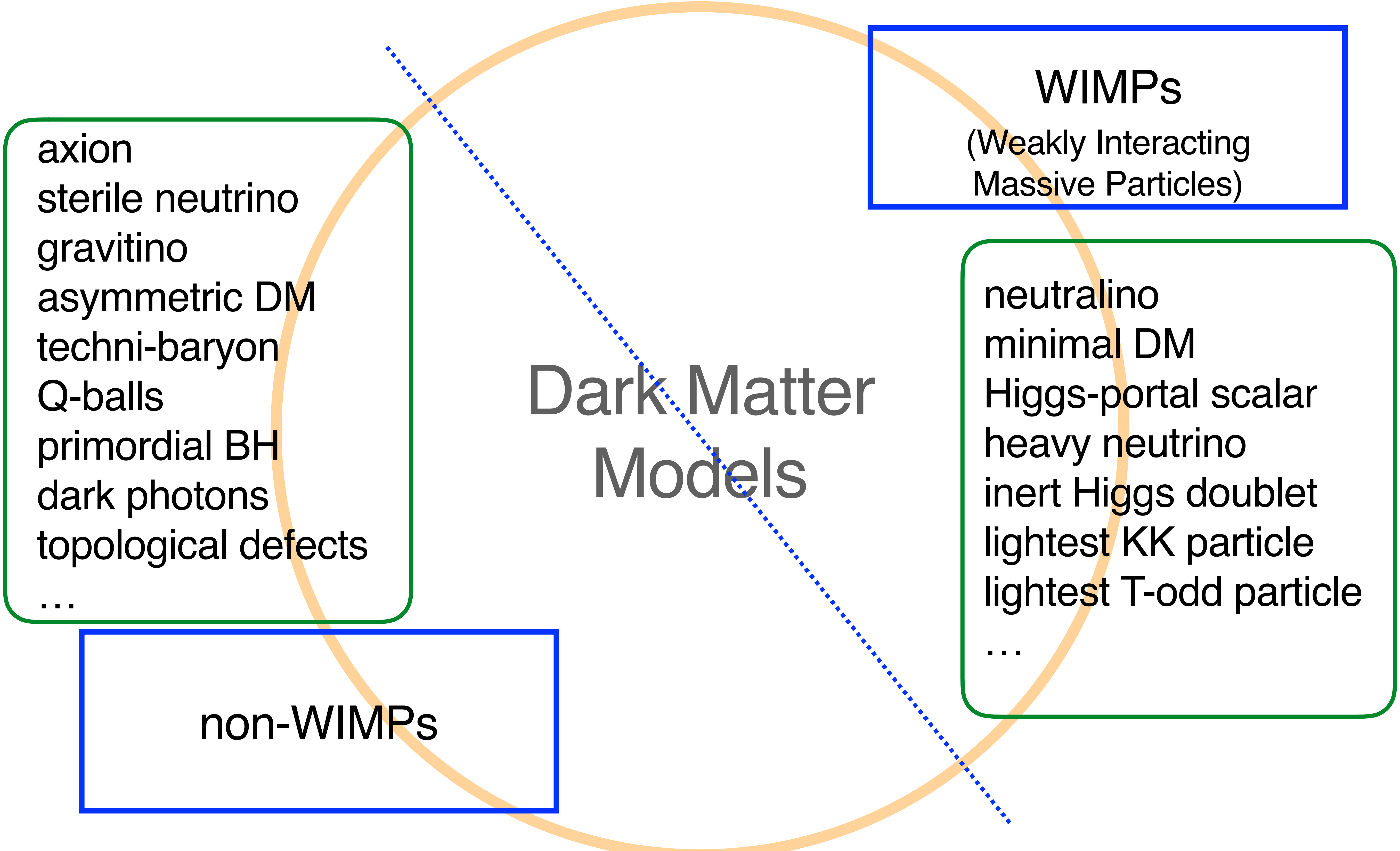


> WIMPs

Weakly Interacting Massive Particles
(or… the “Holy Grail” of DM physics)

Ingredients for a WIMP recipe:

- **massive** particle in 1 GeV — 100 TeV range
- **weak** interactions with the SM
- thermal **freeze-out** in the early universe

From now on: DM = WIMP

> Thermal Production

Assume:

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

<u>**QUALITATIVE ANALYSIS**</u>

- initially, in thermal equilibrium

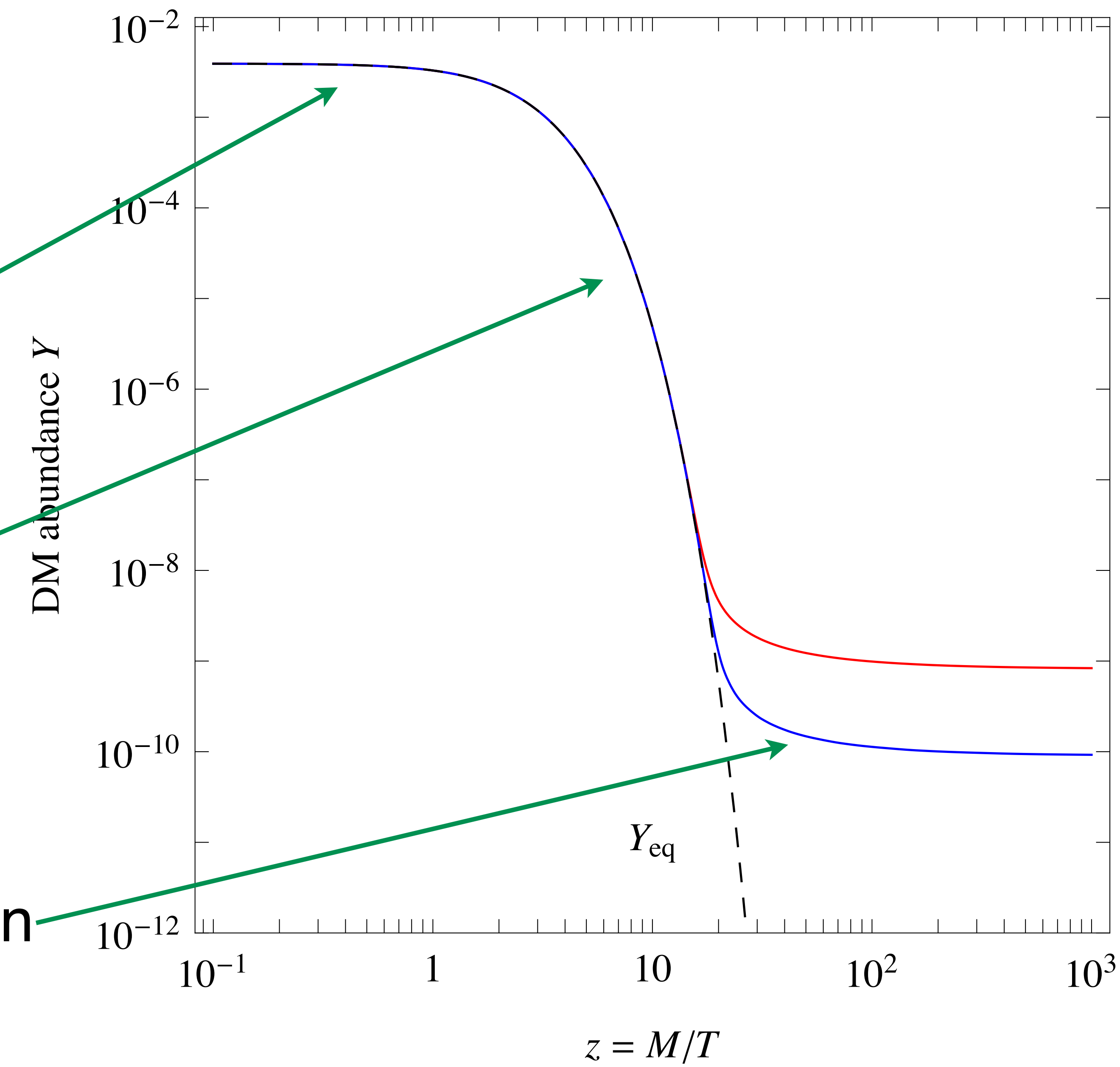
$$\chi\,\chi \leftrightarrow \text{SM SM}$$

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

$$\chi\,\chi \overset{\not\leftarrow}{\rightarrow} \text{SM SM}$$

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

$$\chi\,\chi \overset{\not\leftarrow}{\not\rightarrow} \text{SM SM}$$



Back-of-the-envelope

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

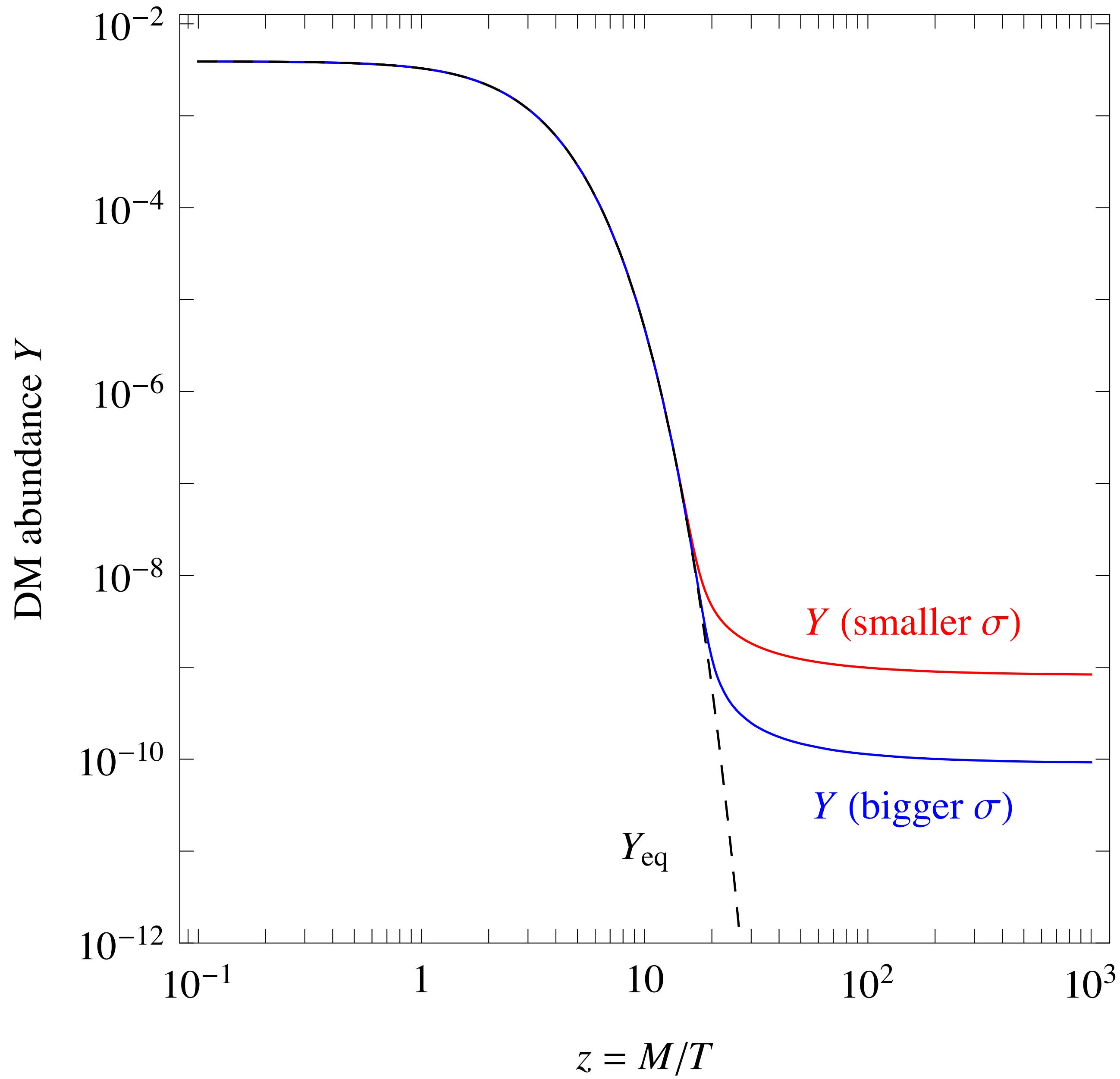
$$\Gamma \lesssim H \quad \Longleftrightarrow \quad \langle n_\chi \sigma \rangle \lesssim T^2/M_P$$

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!)

> Thermal Production

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)

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

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 $\Omega_\nu < 1$

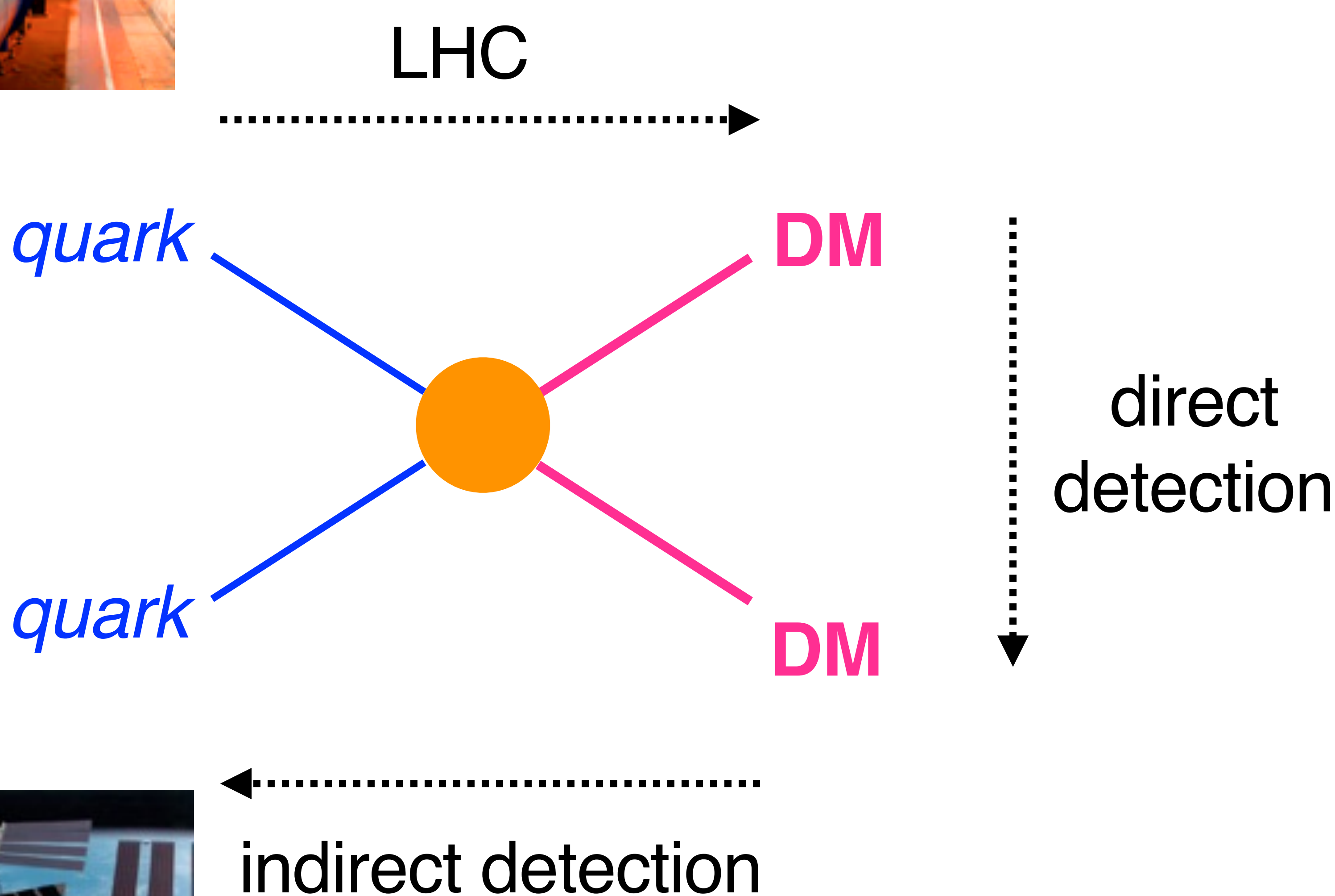
$$\sum m_\nu < \mathcal{O}(10) eV$$

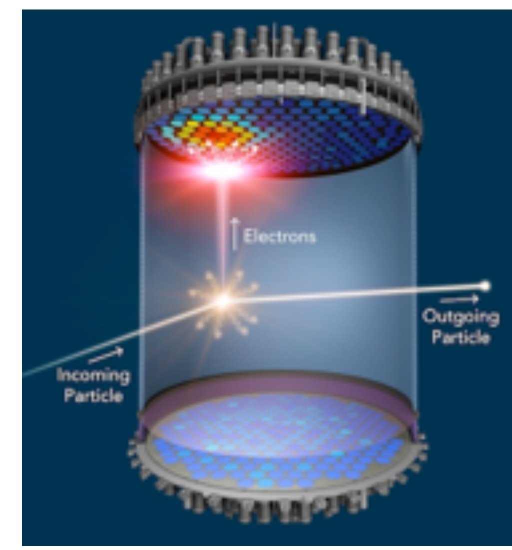
Cosmology tells us something non-trivial on particle physics!

Why are WIMPs so nice?

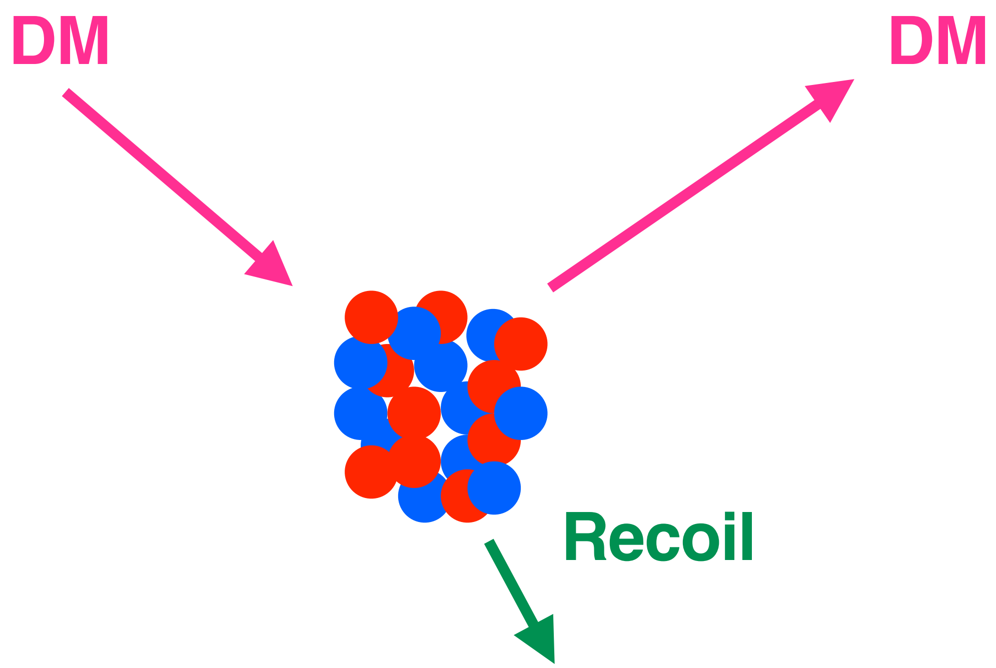
- WIMP “miracle”
- Common production mechanism (freeze-out)
- Motivated by Hierarchy Problem (SUSY neutralino *in primis*)
- Link with BSM physics with new particles at weak scale
- Multi-sided searches are possible
  (LHC, direct detection, indirect detection)

> 3 Pillars of Dark Matter Searches





> Direct Detection



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

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

Xenon, LUX, 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

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

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

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

total target mass (M_T)

rate of events per recoil energies

ASTROPHYSICS

PARTICLE PHYSICS

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

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

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

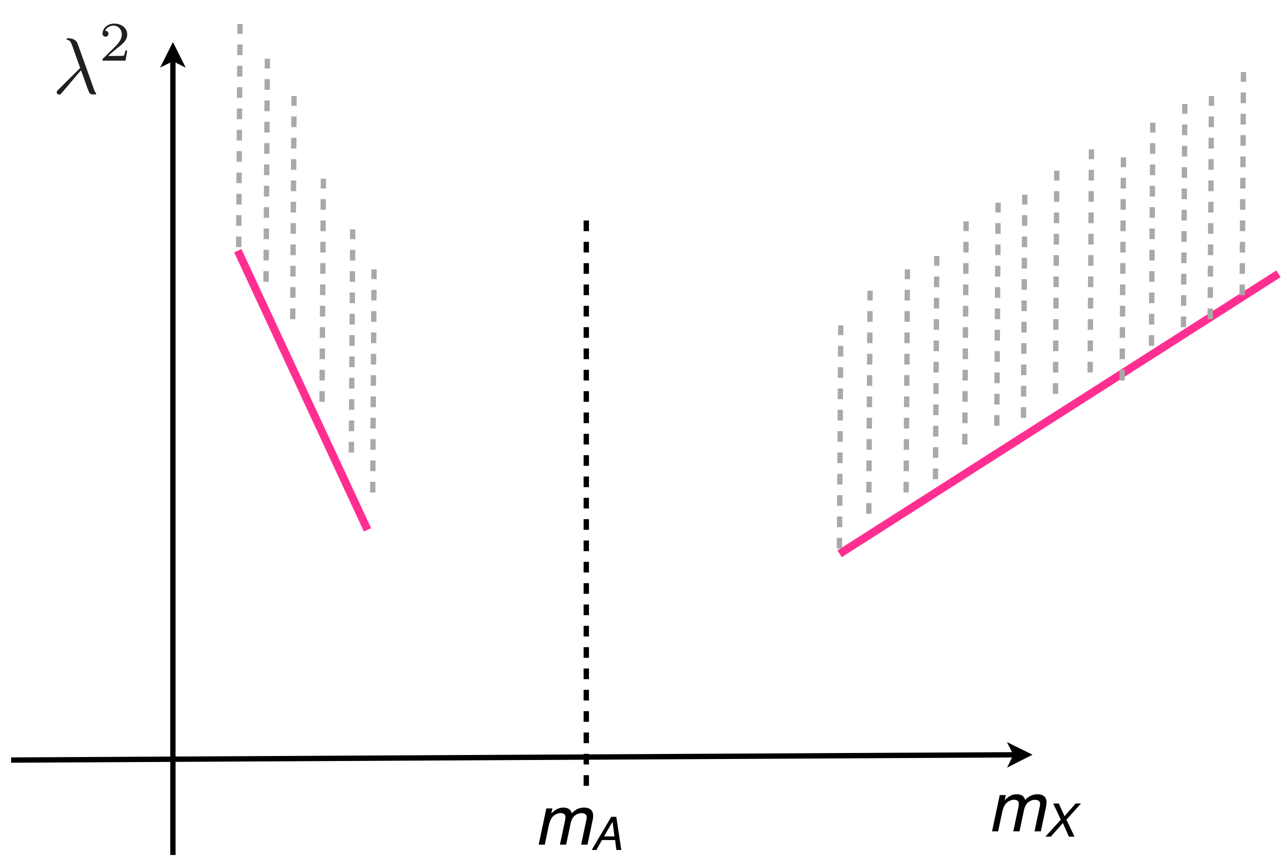
> Direct Detection

total event rate $R \propto \sigma/m_\chi \sim \lambda^2 \mu_{\chi A}^2/m_\chi < R_{\rm observed}$

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

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

maximal exclusion power for $m_\chi \simeq m_A$

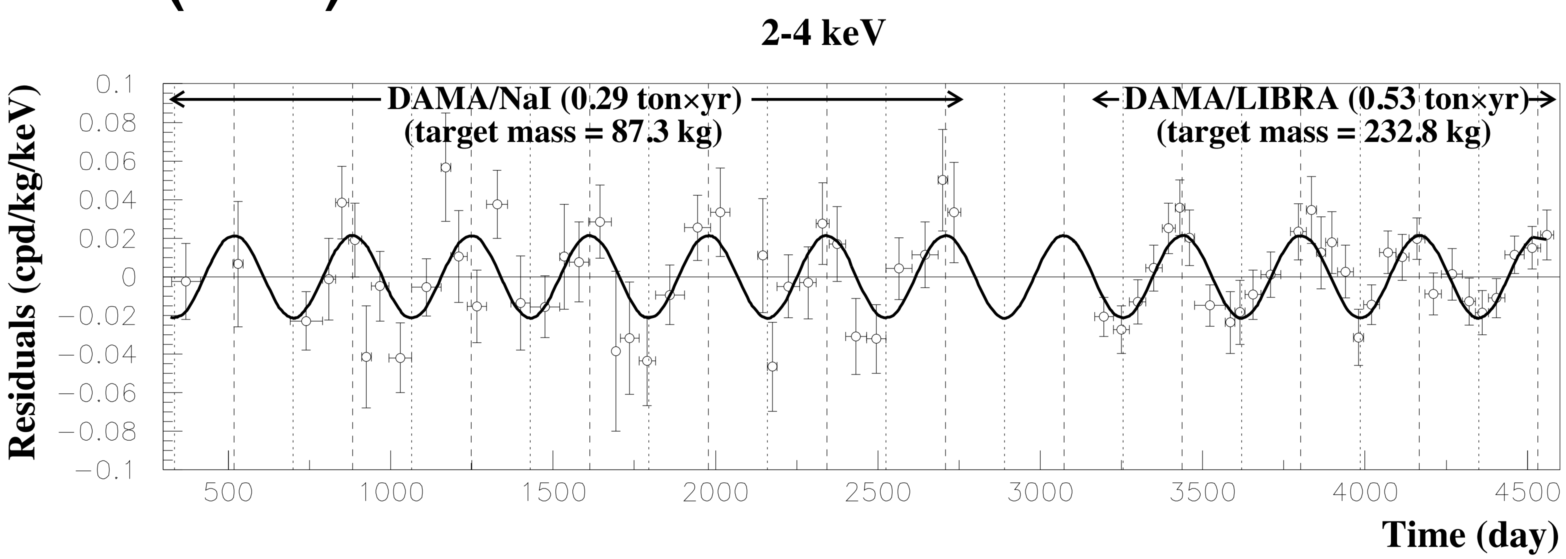


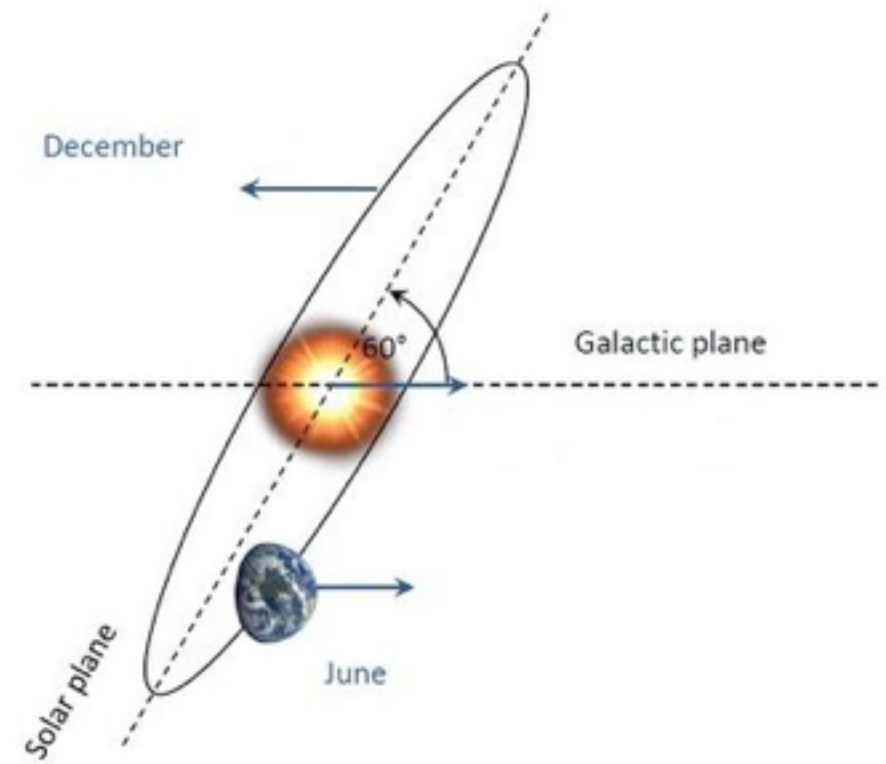
> Direct Detection

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

DAMA/Libra
(NaI)

8σ observation of annual modulation

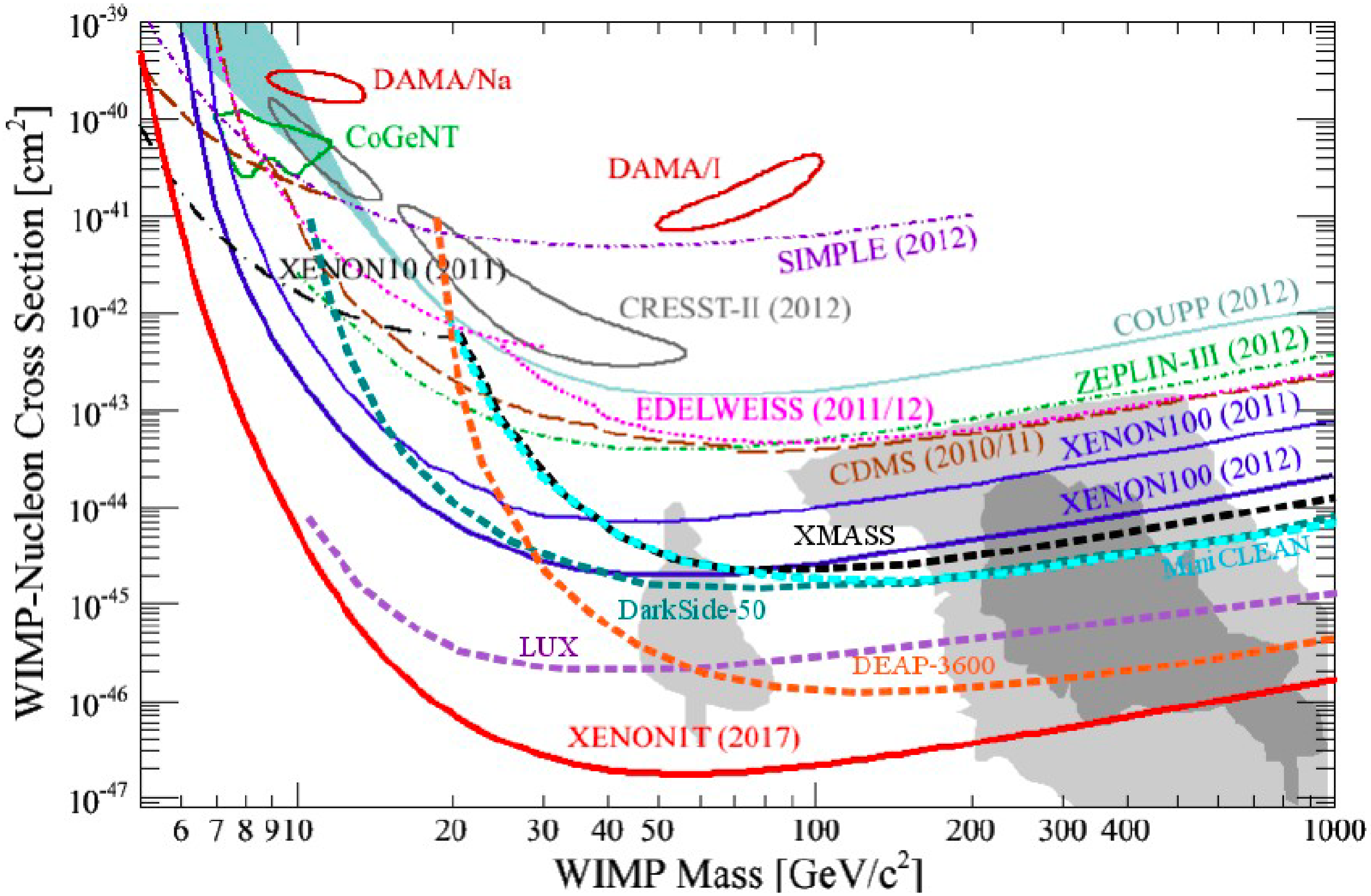


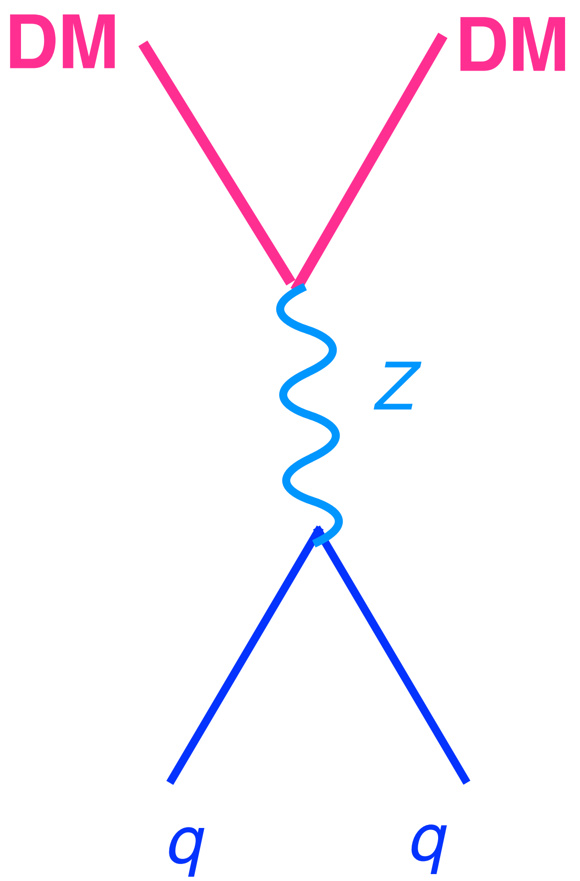


[DAMA Coll - 0804.2741]

- some others (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 already excluded

$$\sigma \sim \alpha_W^2 m_p^2 / M_Z^4 \approx 10^{-39} \mathrm{cm}^2$$

> Indirect Detection

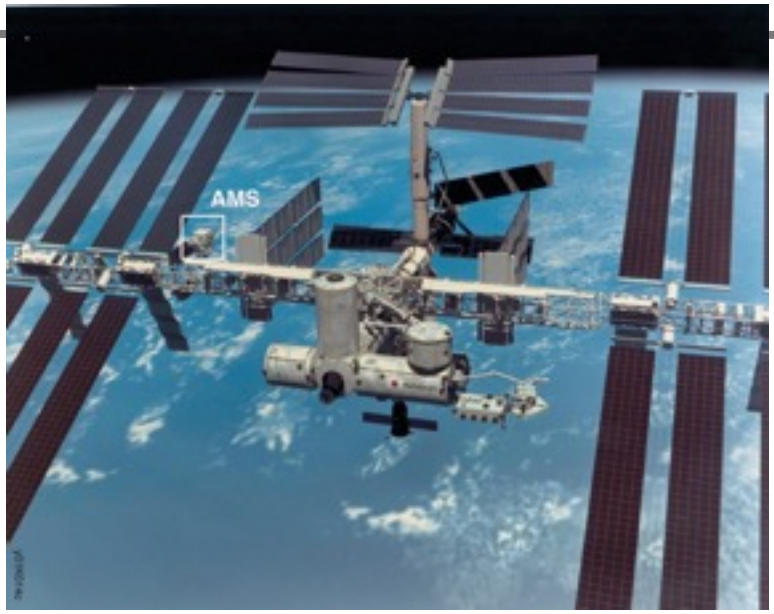
$$\text{DM DM} \to e^+e^-, \ldots$$

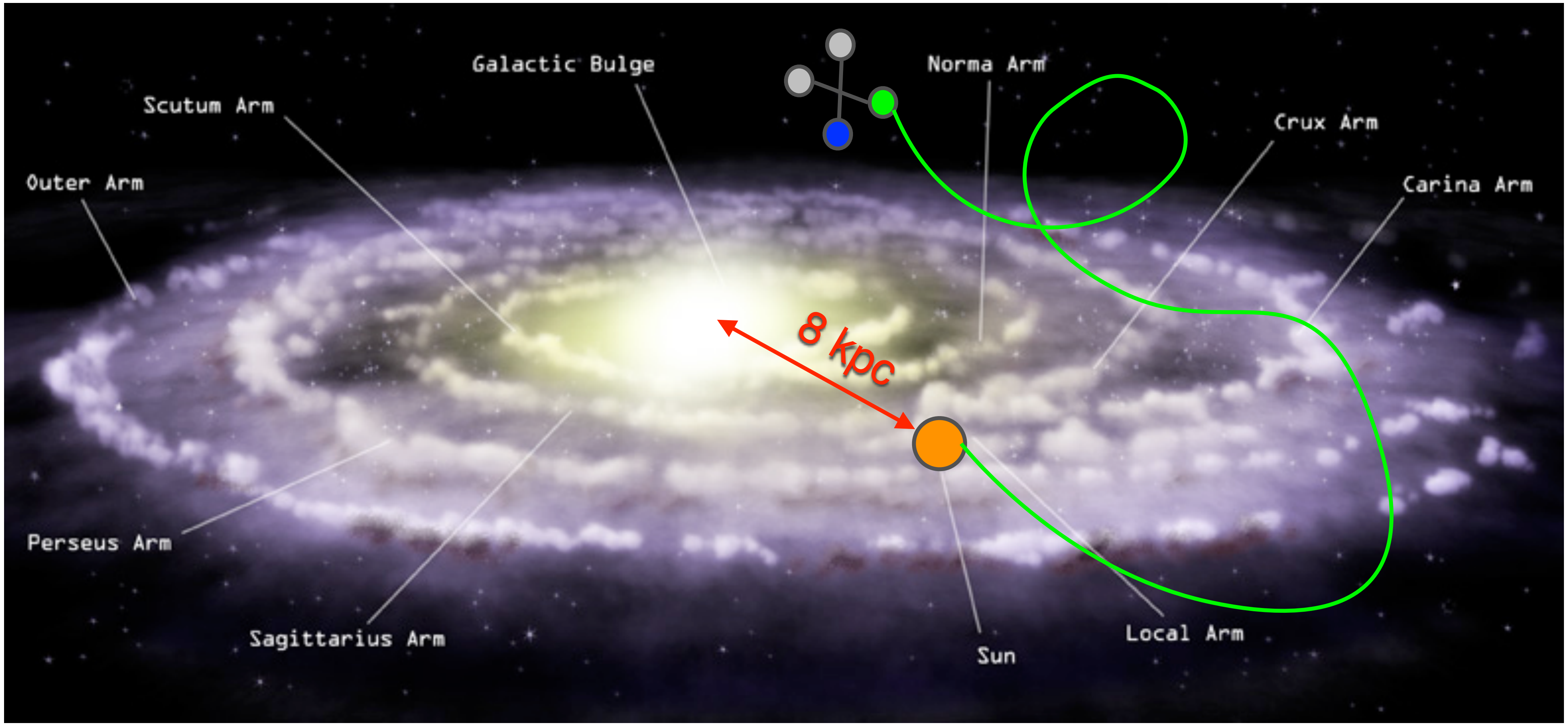
$e^+, \bar{p}$ **AMS-02, Pamela, Fermi, HESS**

γ **ATIC, Fermi**

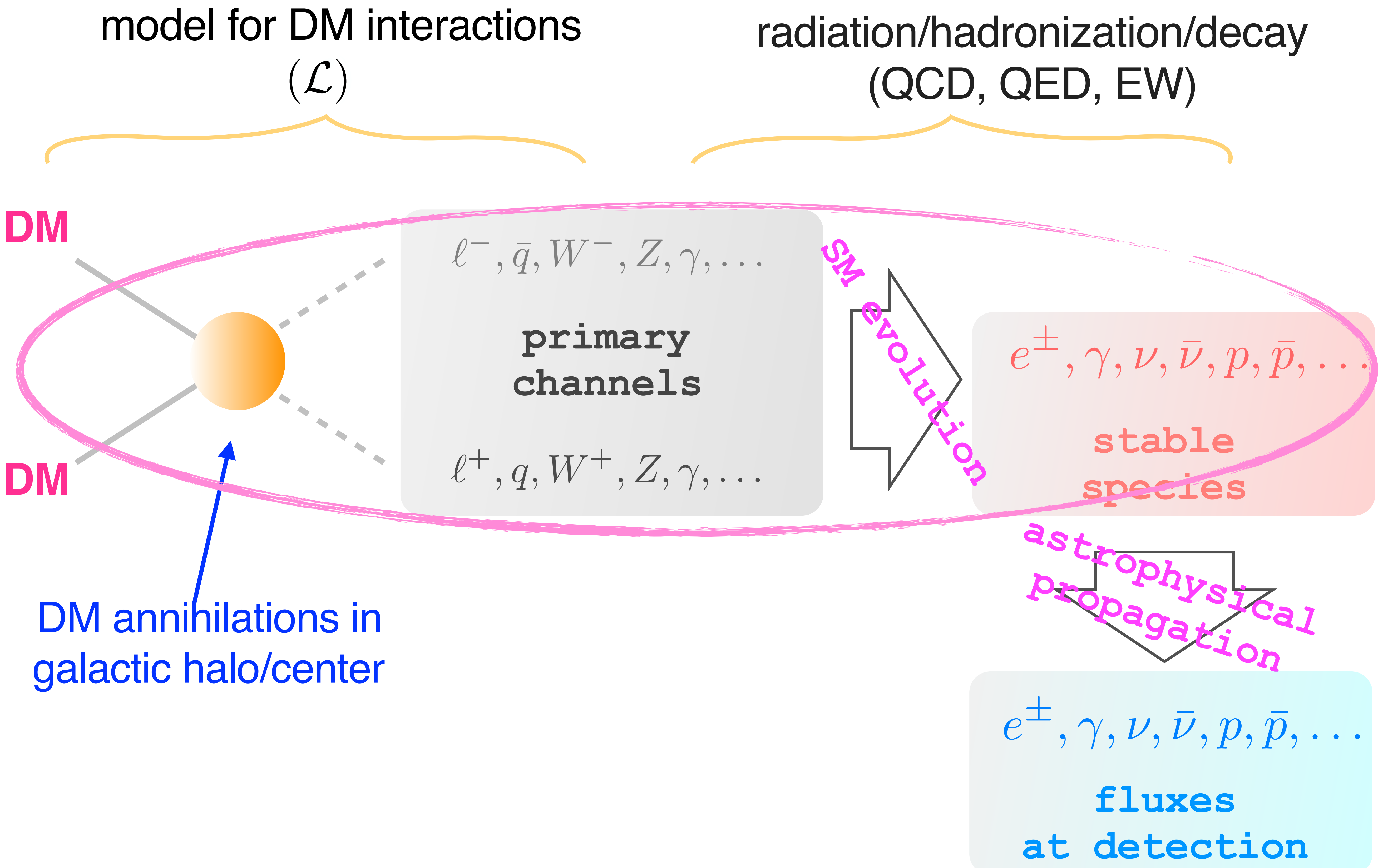
ν **IceCube, Antares, Km3Net**

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





> Indirect Detection



> Indirect Detection

Astrophysics

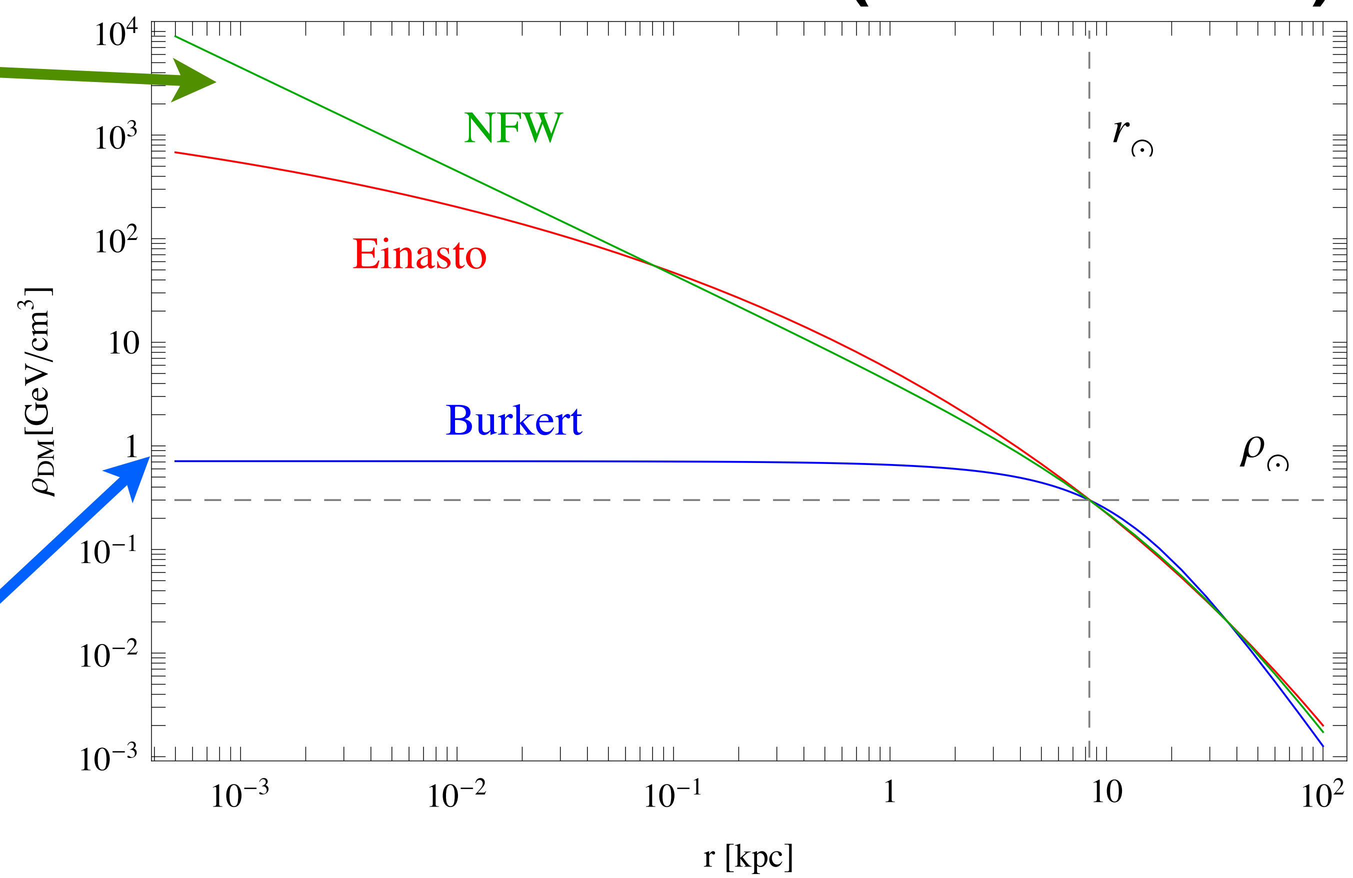
Galactic center: bigger signal, bigger bkg

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

(Halo Profiles)

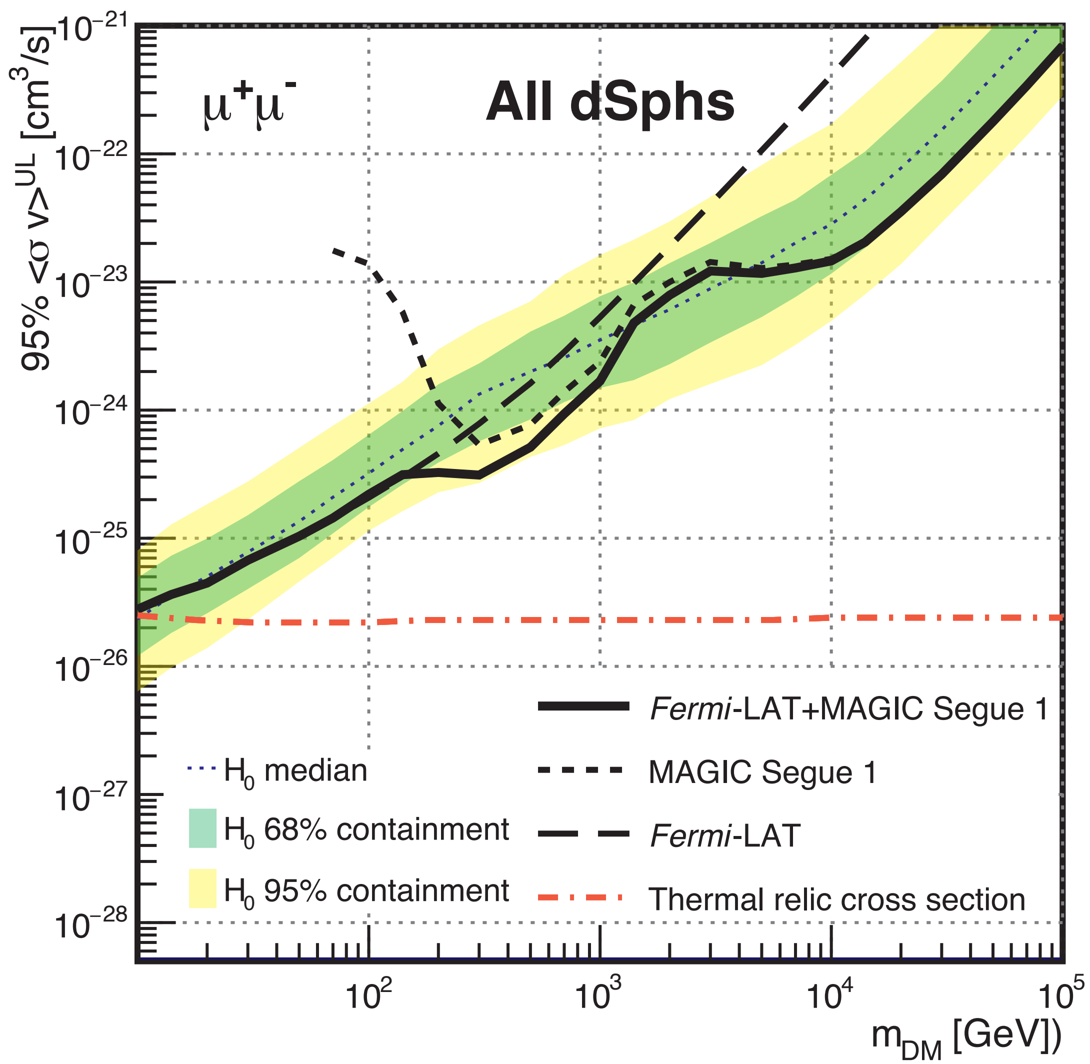
preferred by simulations

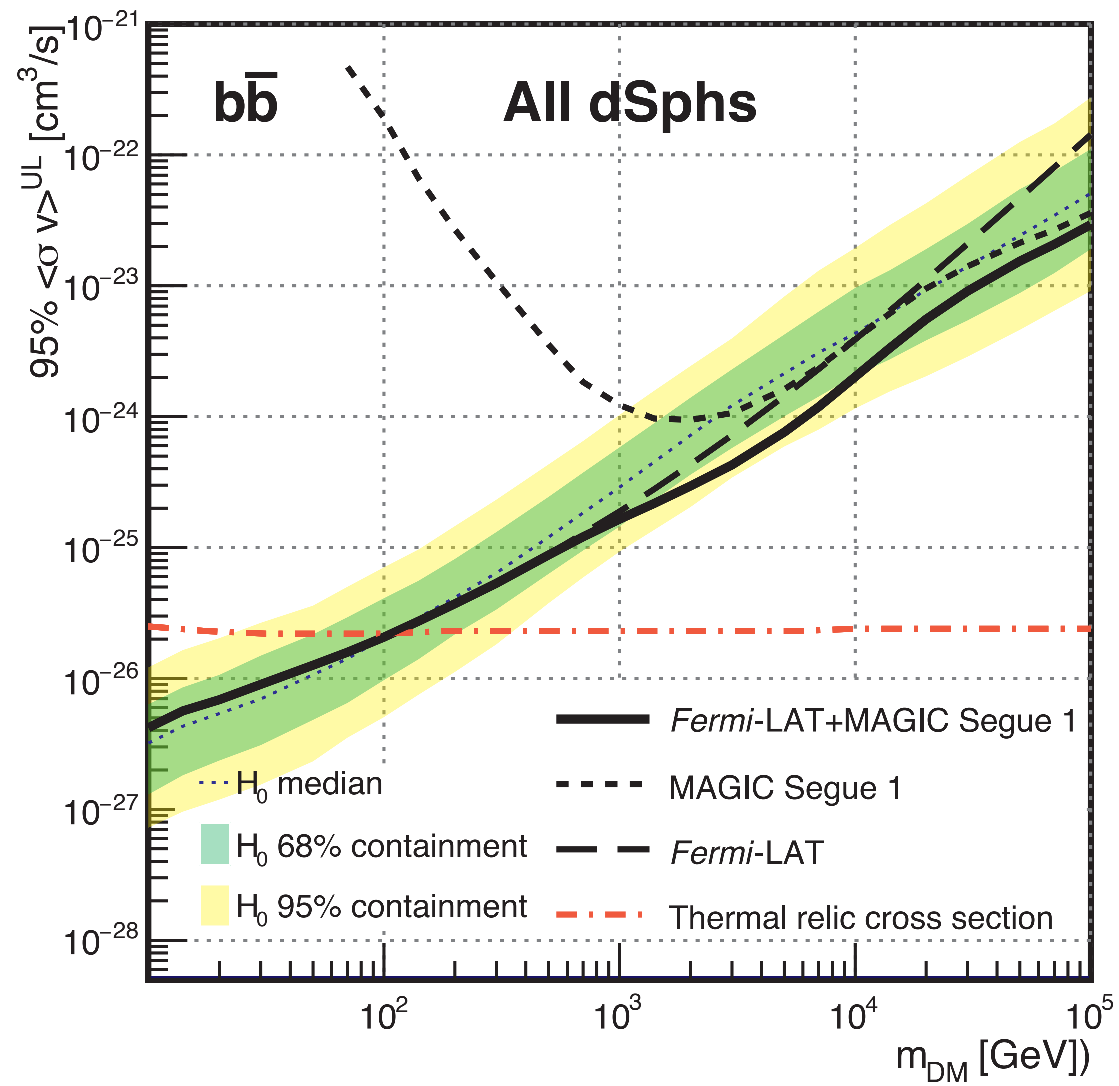
preferred by observations



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

> Indirect Detection



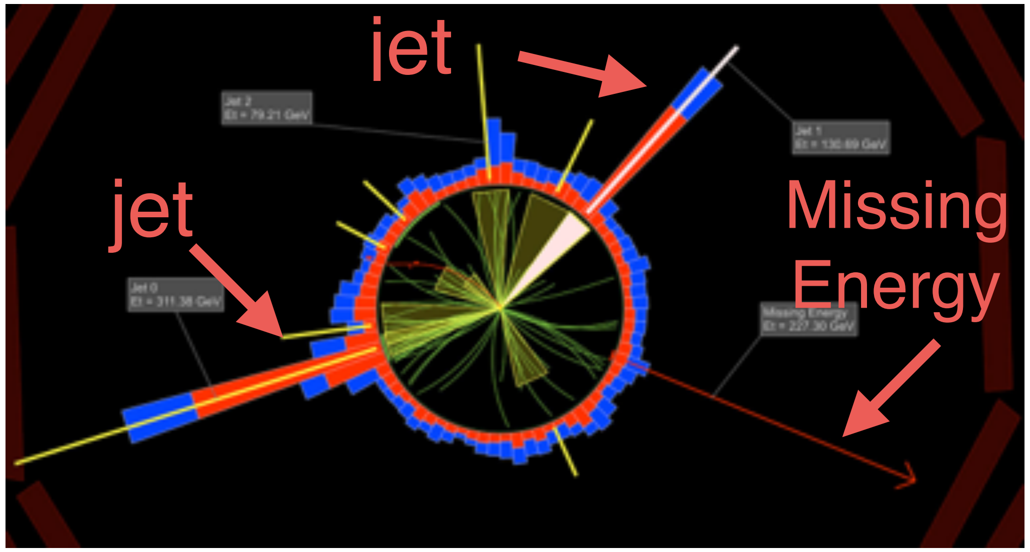


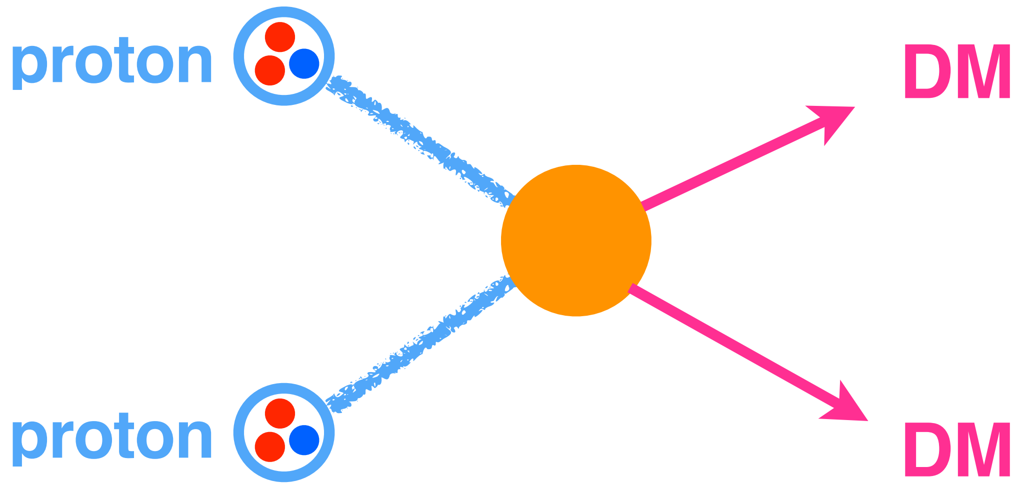
[Fermi-LAT+MAGIC, arXiv:1601.06590]

How does DM show up at LHC?

no interactions… no tracks

looks like a neutrino (missing energy)





DM produced in pairs

if stabilized by a Z_2 symmetry

Need to correlate MET with other handles

jet from Initial State Radiation, accompanying particles, …

Caveat Emptor: **LHC cannot discover the DM**

no way to test stability of the escaping particle on cosmological scales

> … but no signal so far!

MAYBE:

1. DM does not interact with ordinary matter

we are only sure that DM has **gravitational** interactions

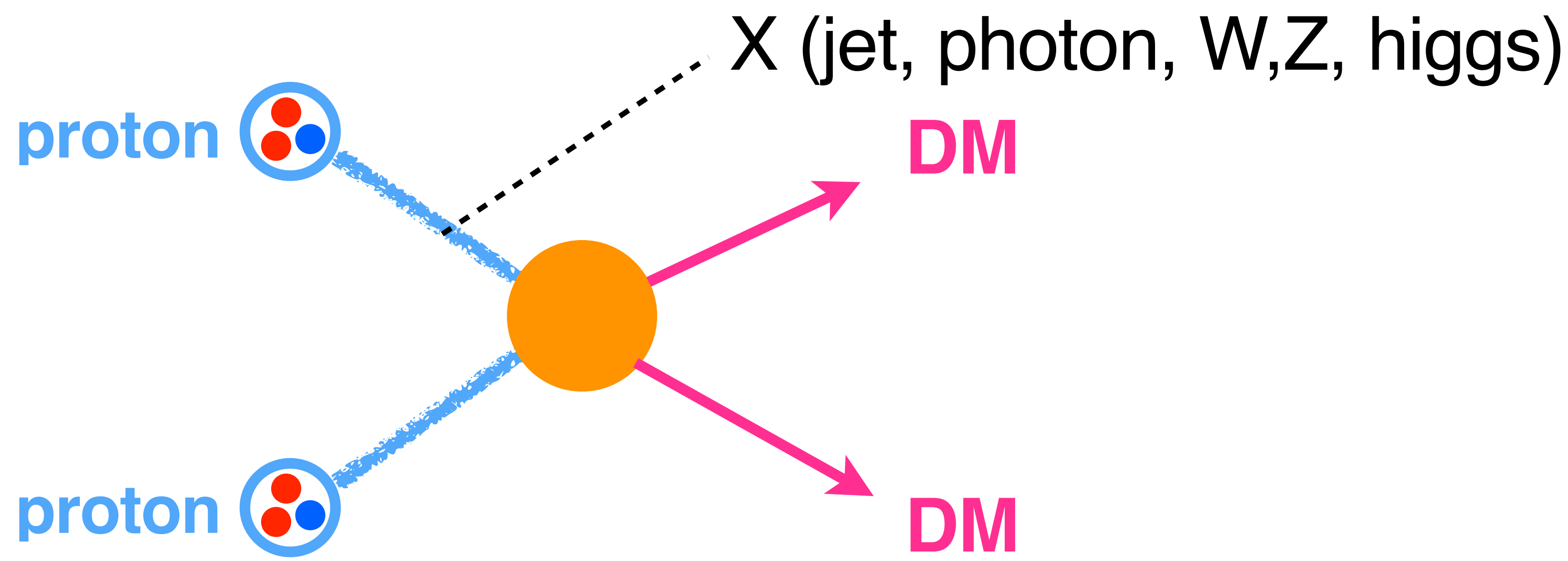
2. DM physics is not accessible by LHC

DM is too light/heavy or interacting too weakly

3. We have not explored all the possibilities

DM may be buried under large bkg
or hiding behind unusual signatures

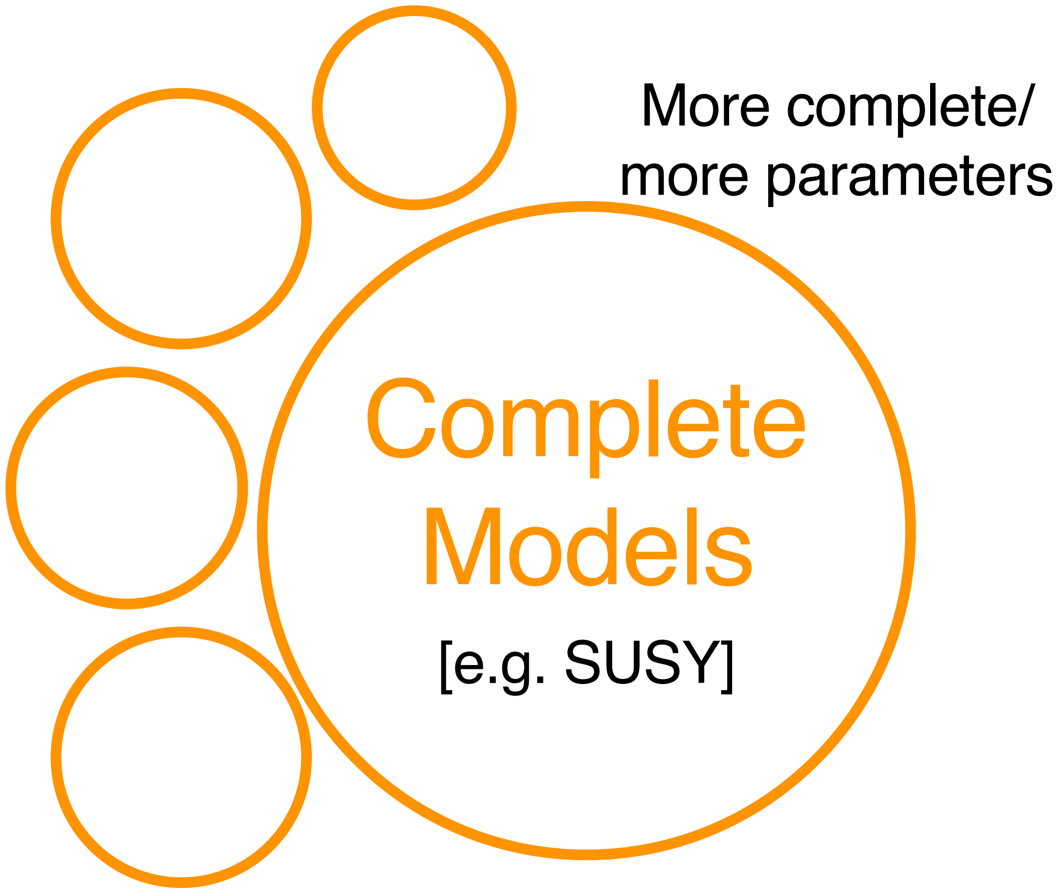
> Mono-X + MET



- ✓ general
- ✓ well-known bkg (Z,W->nu)
- ✓ complementary/competitive with direct detection

- ✗ irreducible bkg
- ✗ small signal/bkg
- ✗ limited by systematics

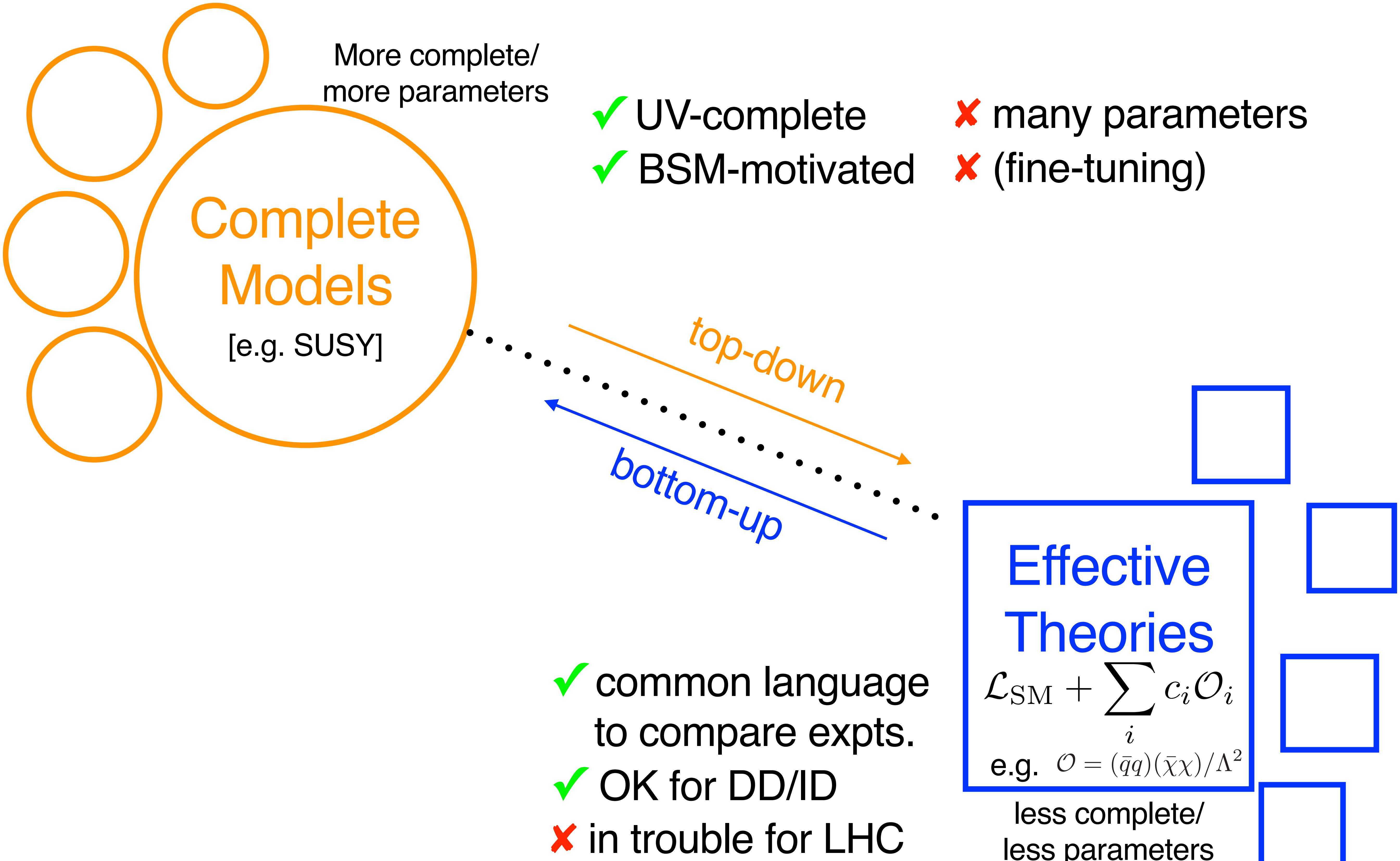
> Which DM models to test?



✓ UV-complete
✓ BSM-motivated

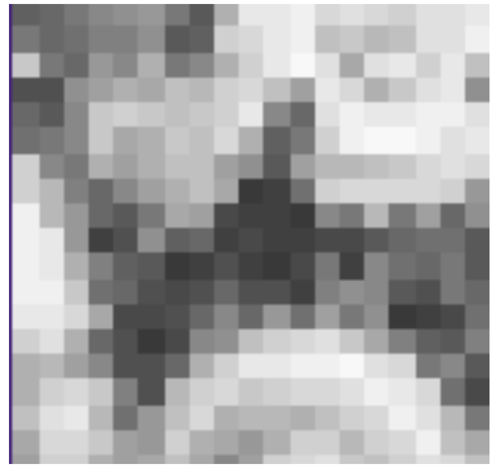
✘ many parameters
✘ (fine-tuning)

> Which DM models to test?



> EFT 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

> Which DM models to test?

Complete Models

[e.g. SUSY]

More complete/
more parameters

top-down

bottom-up

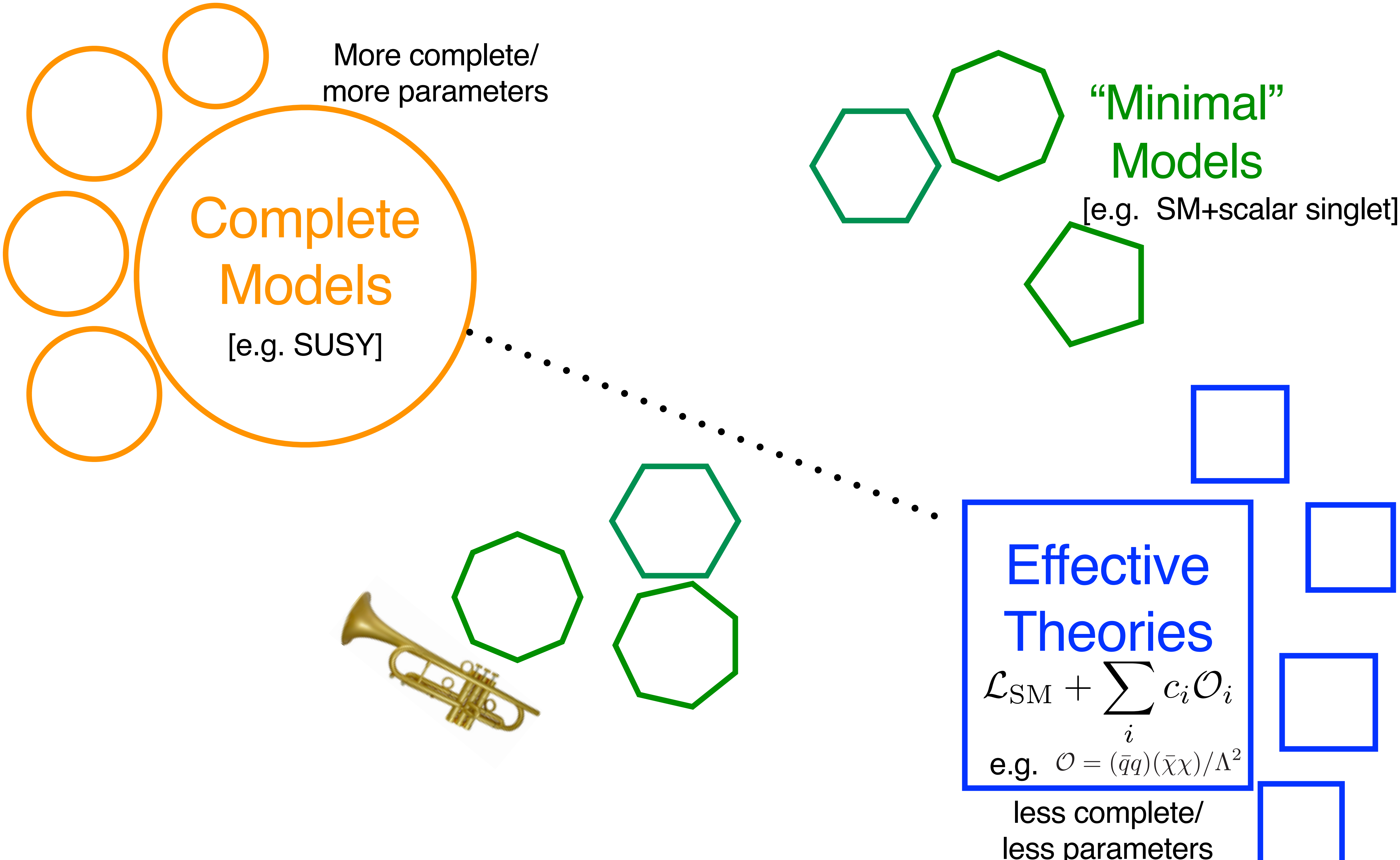
Effective Theories

$$\mathcal{L}_{\rm SM} + \sum_i c_i \mathcal{O}_i$$

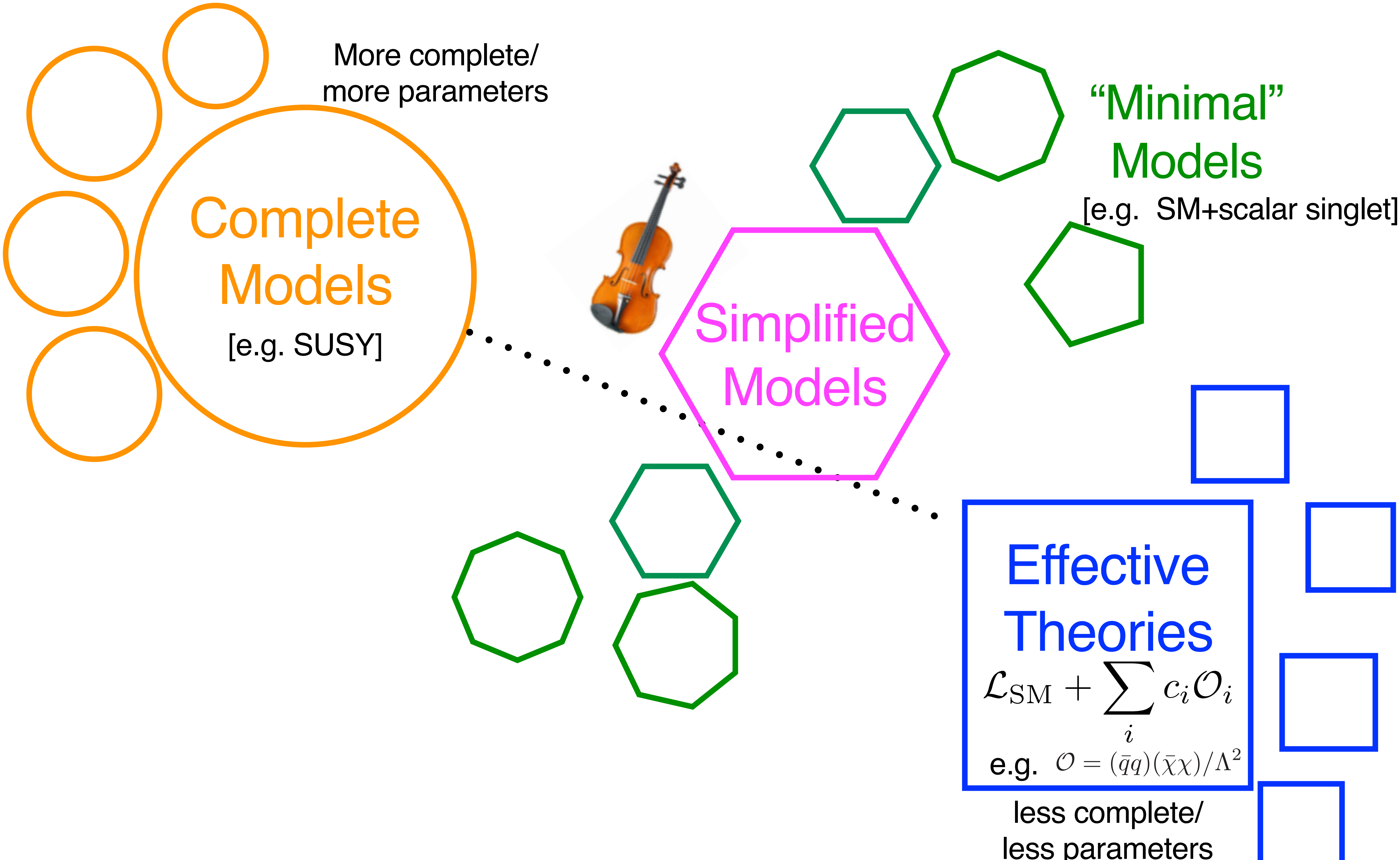
e.g. $\mathcal{O} = (\bar{q}q)(\bar{\chi}\chi)/\Lambda^2$

less complete/
less parameters

> Which DM models to test?



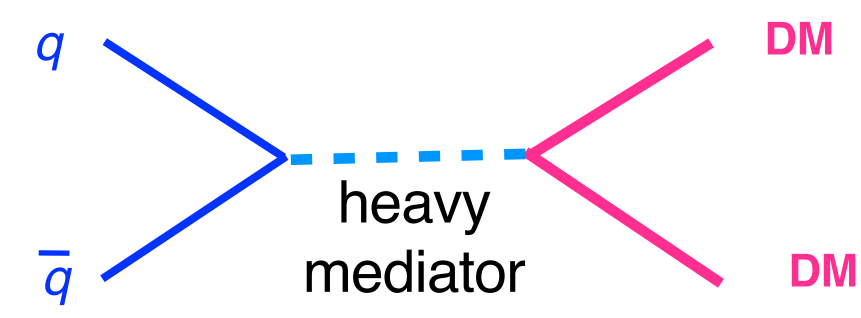
> Which DM models to test?



> Simplified Models

Simplified Model **recipe**:

- take the Standard Model
- add 1 Dark Matter particle
- add 1 Mediator particle connecting DM-SM
- [add some other particle as required]



just another parametrization of unknown high-energy physics

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

✓ less params than complete models

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

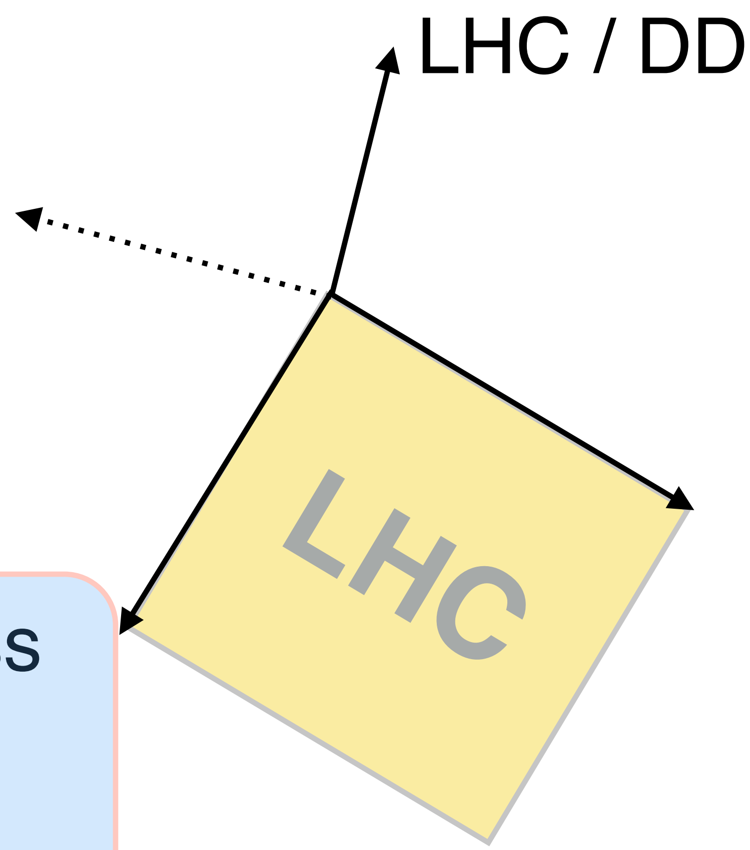
✘ more parameters than EFT

✘ hard to catch all possibilities of complete models

from DM search to MEDIATOR search

> Simplified Models

multi-dimensional exploration



combine different process involving DM (mono-jet + mono-W/Z + mono-H…)

combine DM + mediator searches (di-jet…)

> Simplified Models

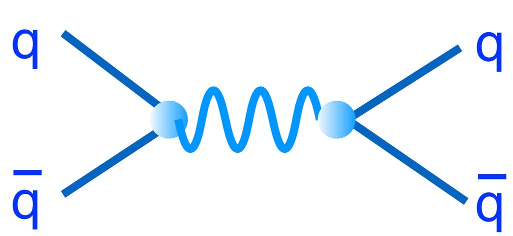
4-dimensional parameter space

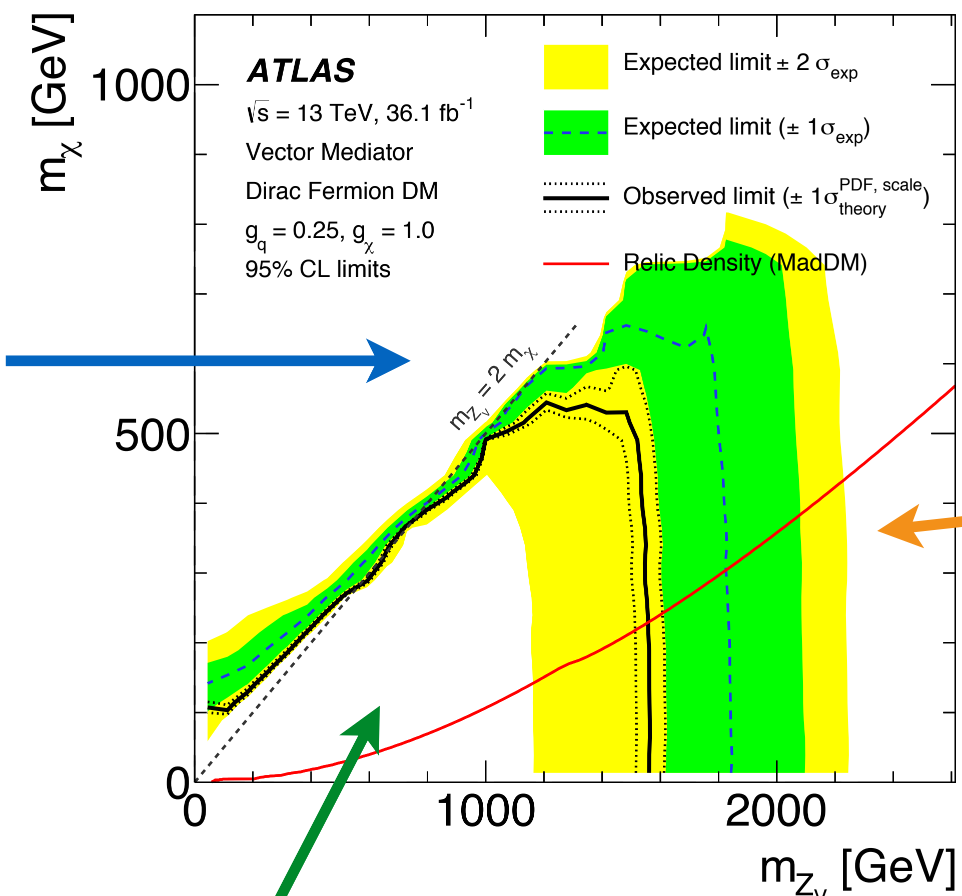
$$\{m_{\rm DM}, M_{\rm med}, g_{\rm DM}, g_q\}$$

Mass-mass plane

slice of parameter space with fixed couplings

off-shell ($M_{\rm med} < 2m_{\rm DM}$)
(use e.g. di-jet)





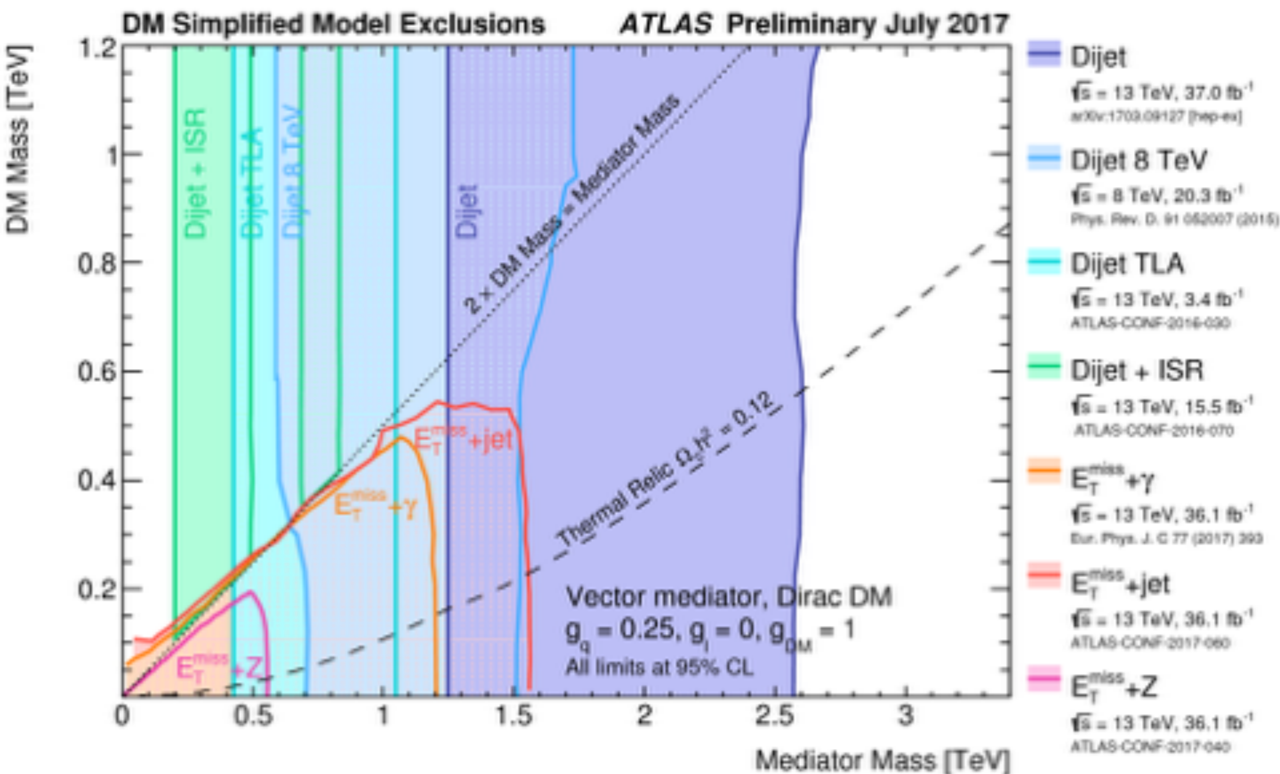
vector mediator

EFT
(large $M_{\rm med}$)

on-shell ($M_{\rm med} > 2m_{\rm DM}$)

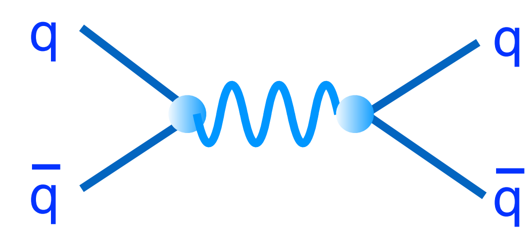
[ATLAS - 1711.03301]

> Simplified Models



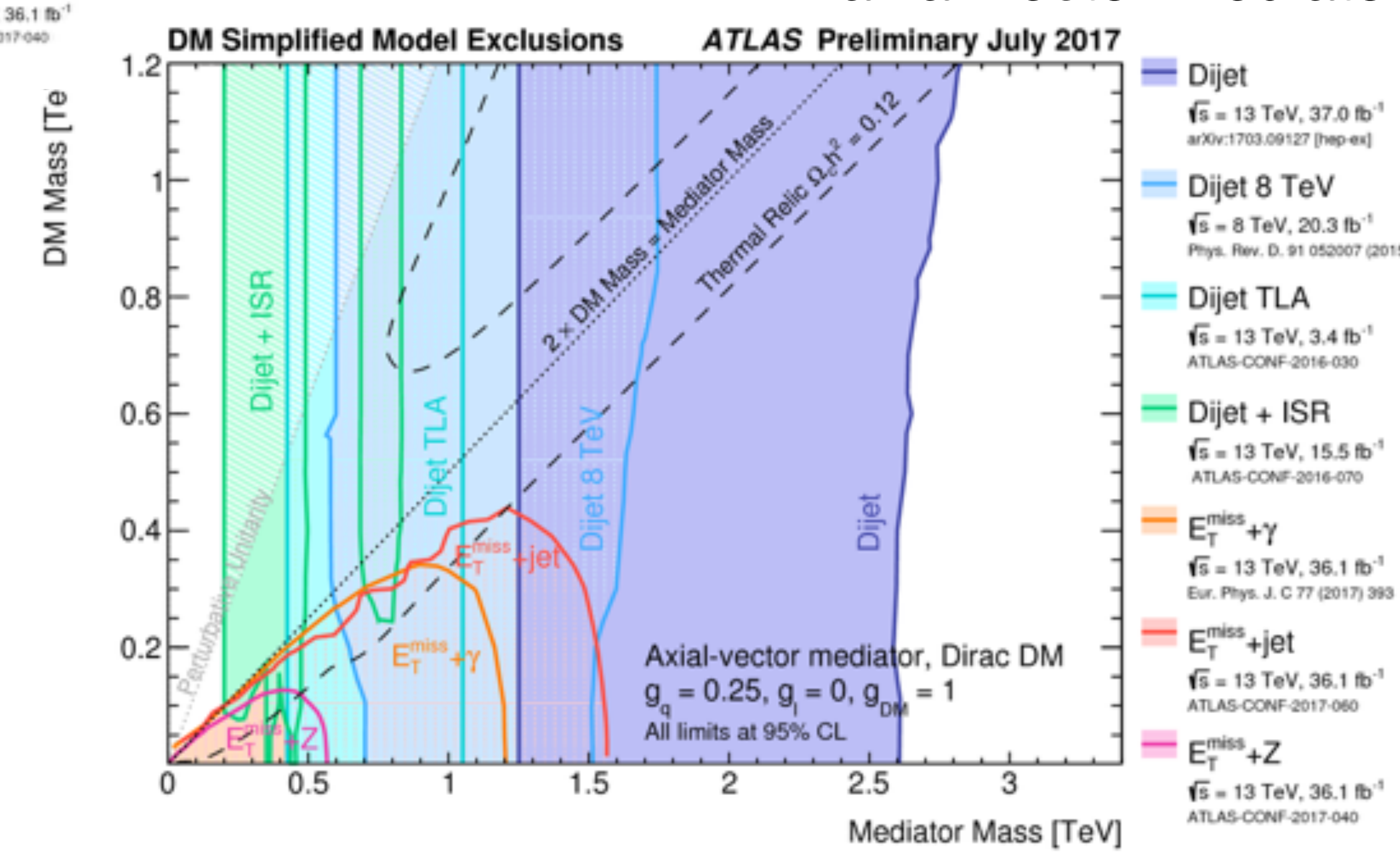
vector mediator

Combine with mediator searches



di-jet

axial-vector mediator



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/

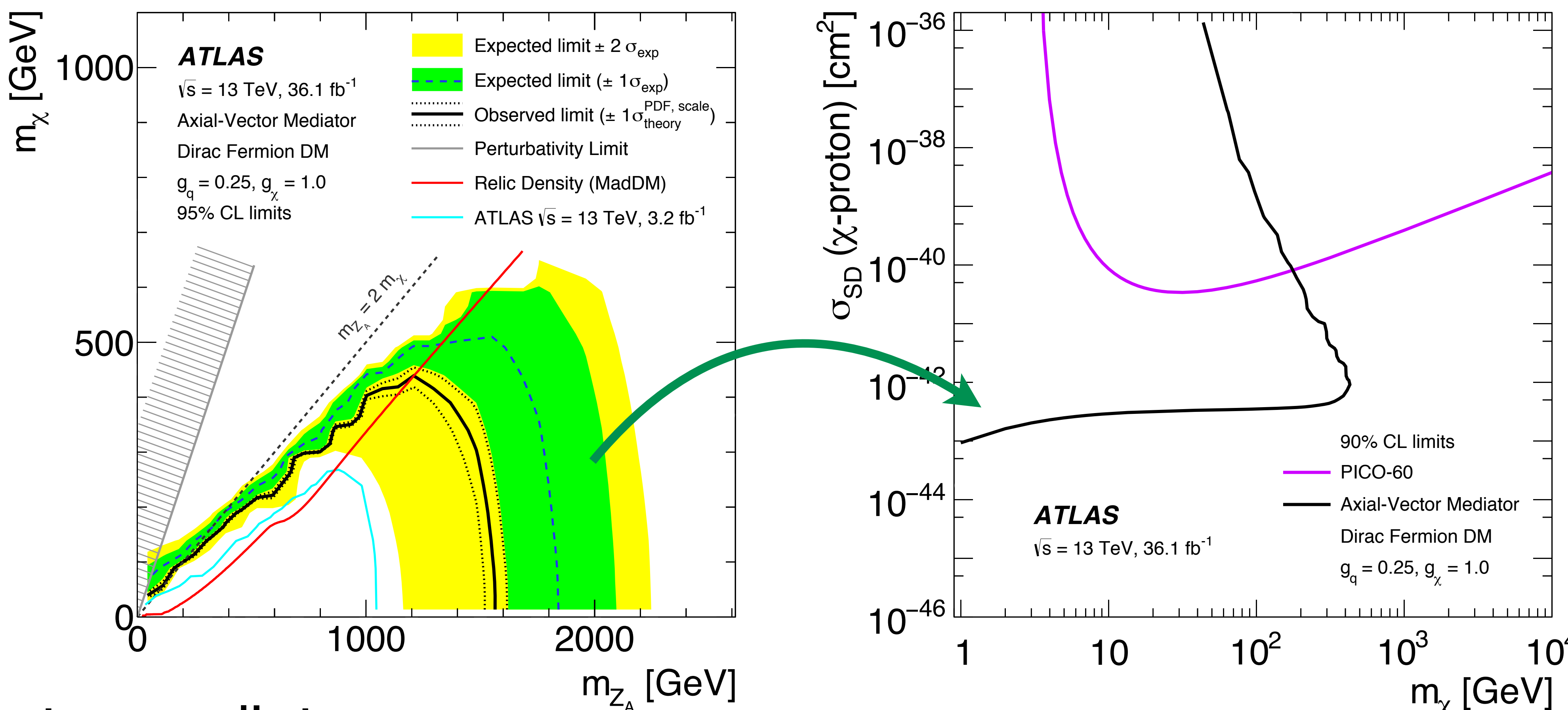
> Simplified Models: LHC vs DD

Link to direct detection

$$\sigma_{\rm SI,SD} \propto \frac{(g_q g_{\rm DM})^2}{M_{\rm med}^4}$$

[no astrophysical uncertainties ✓]

plug in $M_{\rm med}$ from the mass-mass plane



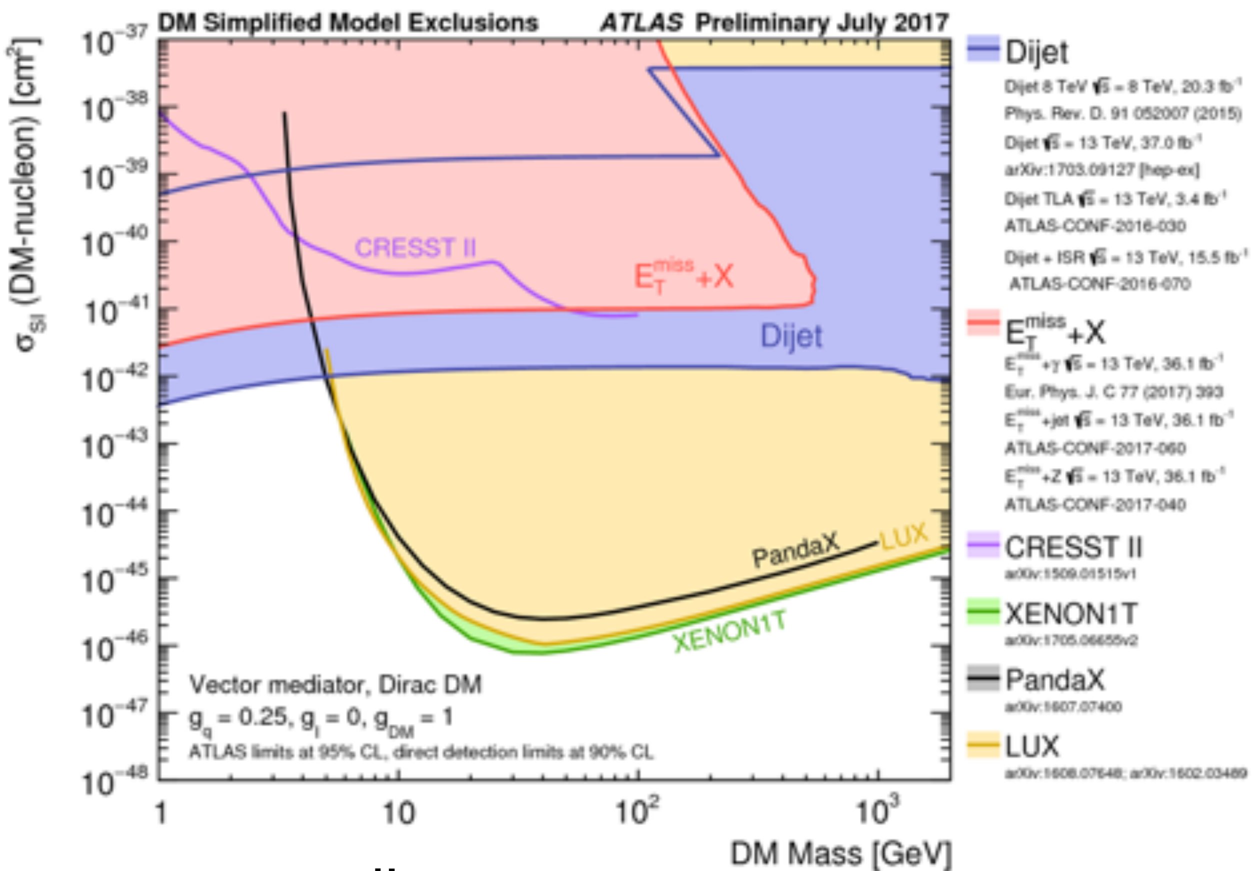
axial-vector mediator

recommend to plot 90% CL (instead of 95% CL) to comply with DD standards

[ATLAS - 1711.03301]

[CMS - 1712.02345]

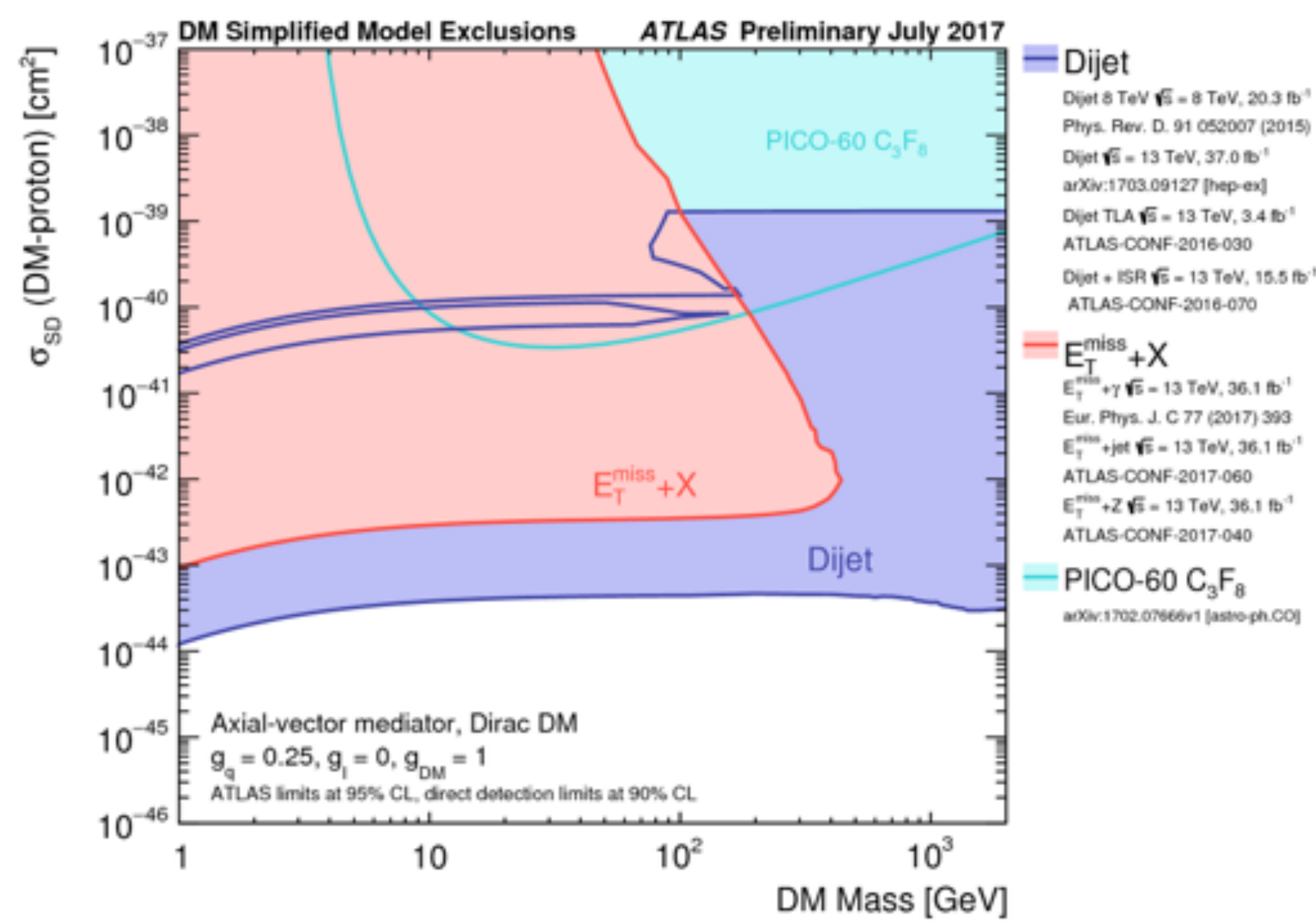
> Simplified Models: LHC vs DD



vector mediator

The "money plots"

axial-vector mediator



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/

Is this the whole story?

" if all you have is a hammer, everything looks like a nail… "

Need to look for other tools*

* less conventional / unexplored phenomenology
* data-driven approaches, new/deeper views into data
* …?

> 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
  (but non-WIMPs are very interesting too!)

- multi-sided searches for WIMPs (direct/indirect/LHC)

- ... and if WIMPs are not found in the next ~5 years ???