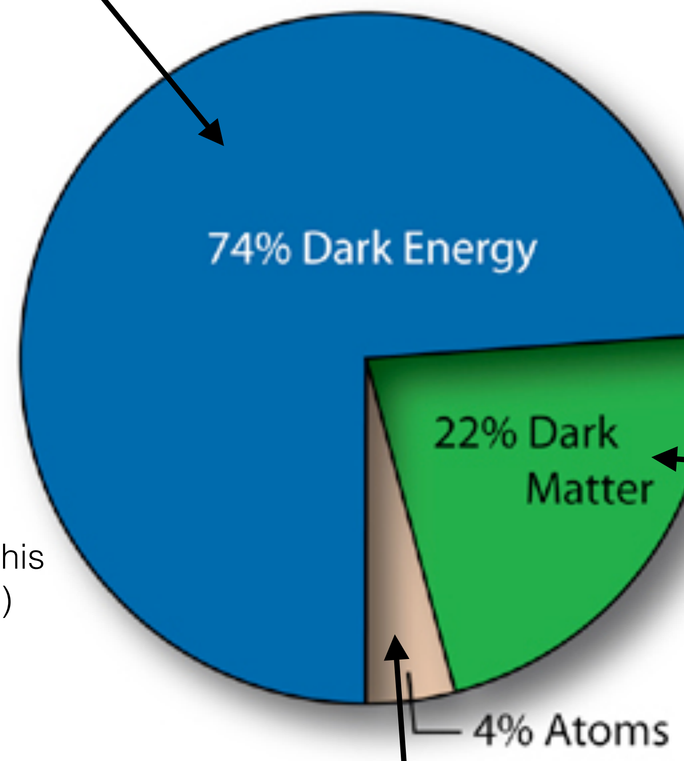
Dark Matter

Francesco Riva
(CERN)

Many slides and material from:
Marco Cirelli, Andrea deSimone, Neil Weiner and many more…

we don’t know anything



(see later how this cake is made)

we know something
(we don’t know (almost) anything)

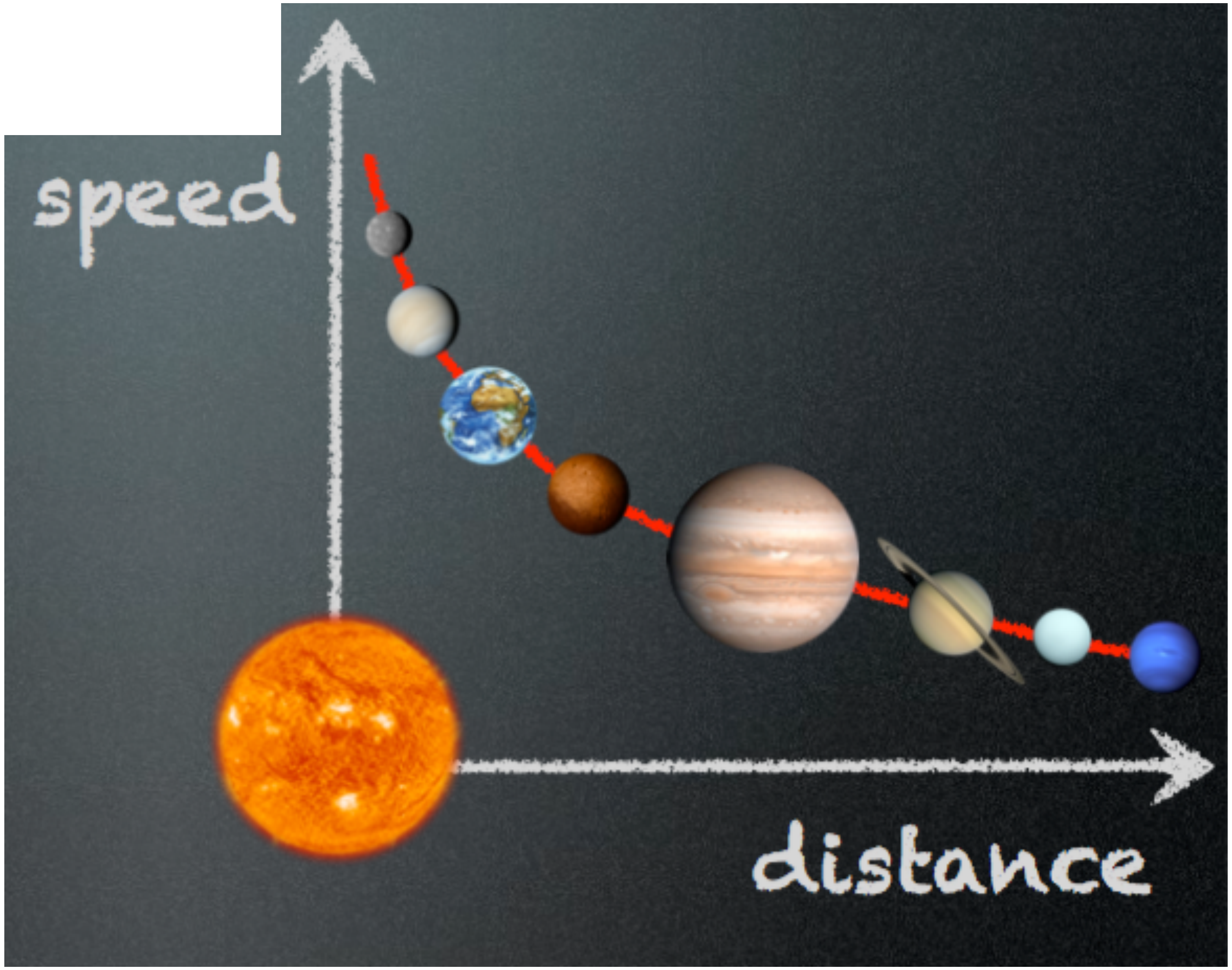
we know (almost) everything

PART 1
Gravitational Evidence for Dark Matter

1. Rotational Curves of Galaxies

In the solar system:

1. Rotational Curves of Galaxies



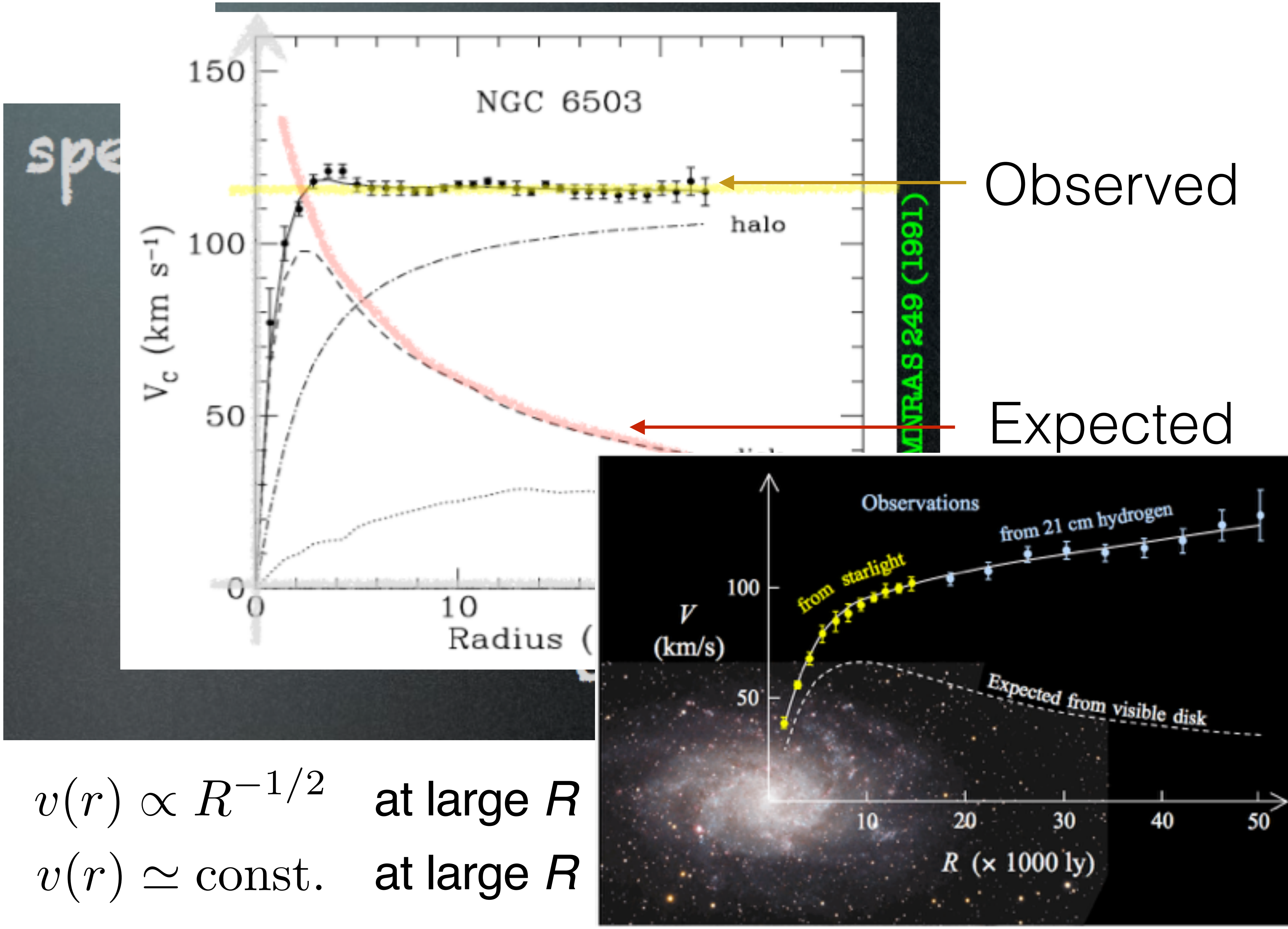
$$m\frac{v_c^2(r)}{r} = \frac{G_N m M(r)}{r^2}$$

‘centrifugal’ ‘centripetal’

$$v_c(r) = \sqrt{\frac{GM}{r}}$$

(Kepler law)

1. Rotational Curves of Galaxies



Observed

Expected

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

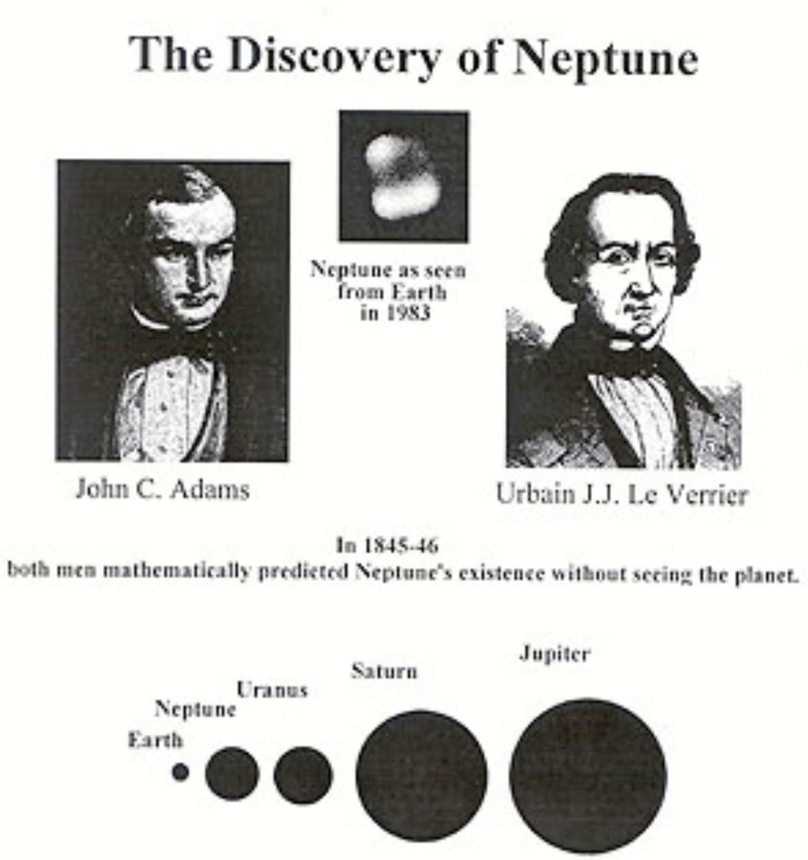
Observations: $v(r) \simeq \text{const.}$ at large *R*

What can the reason be?

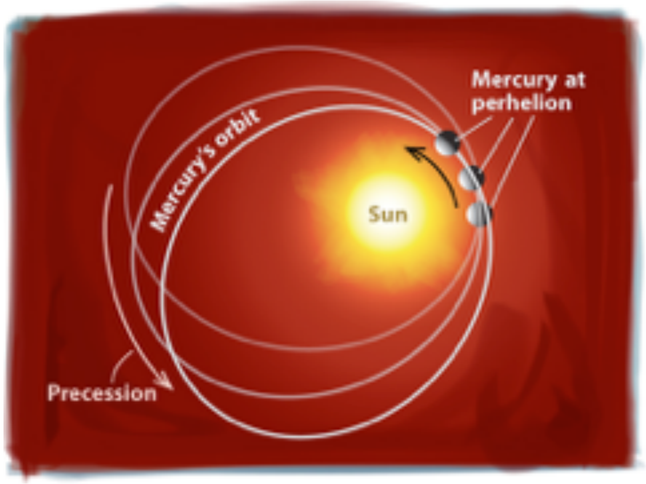
1. Rotational Curves of Galaxies

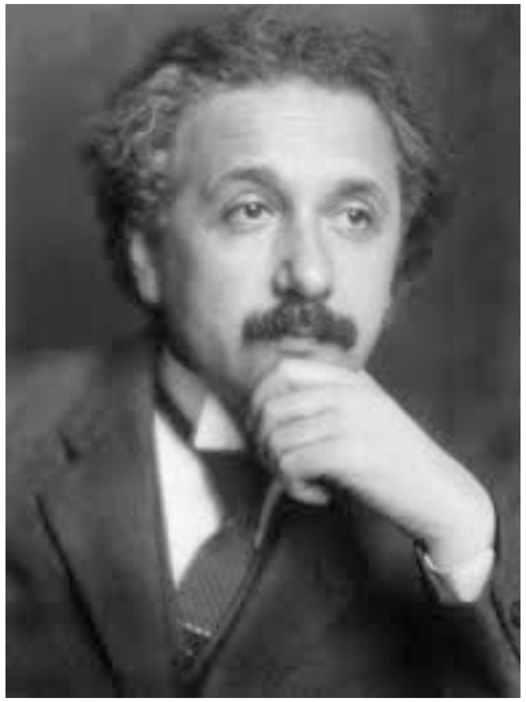
Lessons from the past:

1) Anomaly in Uranus orbit
=
existence of Neptun



2) Anomaly in Mercury orbit
=
failure of Newtonian dynamics
(birth of general relativity)





1. Rotational Curves of Galaxies

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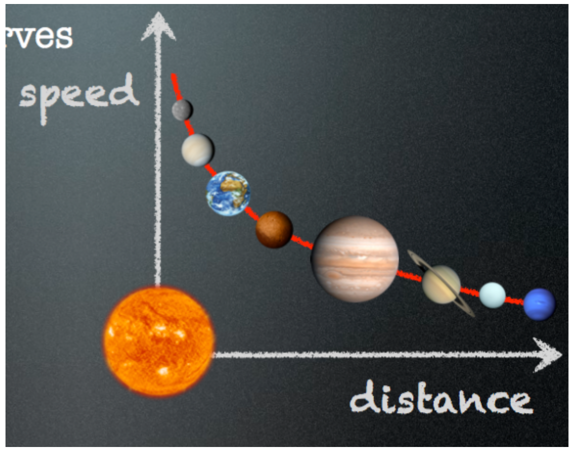


2) Anomaly in Mercury orbit

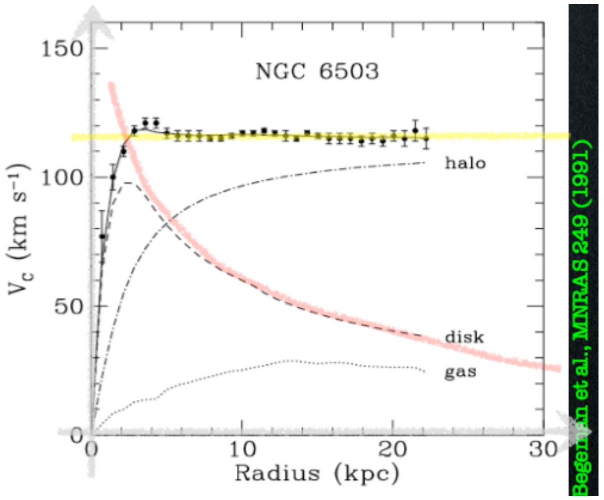
=

failure of Newtonian dynamics
(birth of general relativity - GR)

On galactic scales:

1) New matter

DARK MATTER



2) modification of GR on galactic scale

MOND

(modified newtonian dynamics)

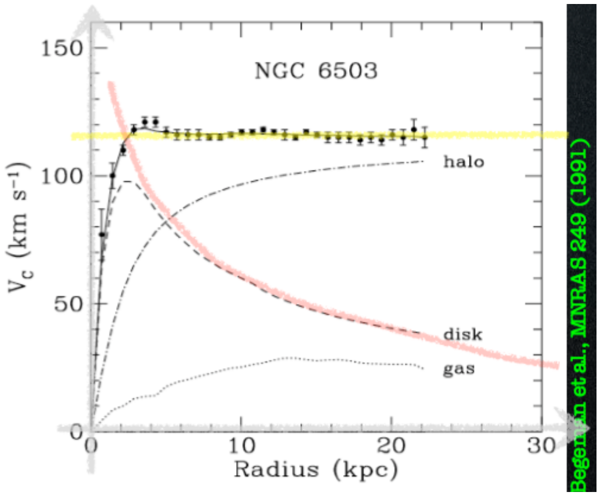
1. Rotational Curves of Galaxies

2) MOND

- Theoretically not as firm as GR
- Experimentally disfavored (see next)

1. Rotational Curves of Galaxies

1) New matter DARK MATTER



at large *R:* $$const \simeq v(R) = \sqrt{\frac{G_N M(R)}{R}}$$

$$M(R) = 4\pi \int_0^R \rho(r) r^2 dr$$

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

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

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

calculated using virial theorem

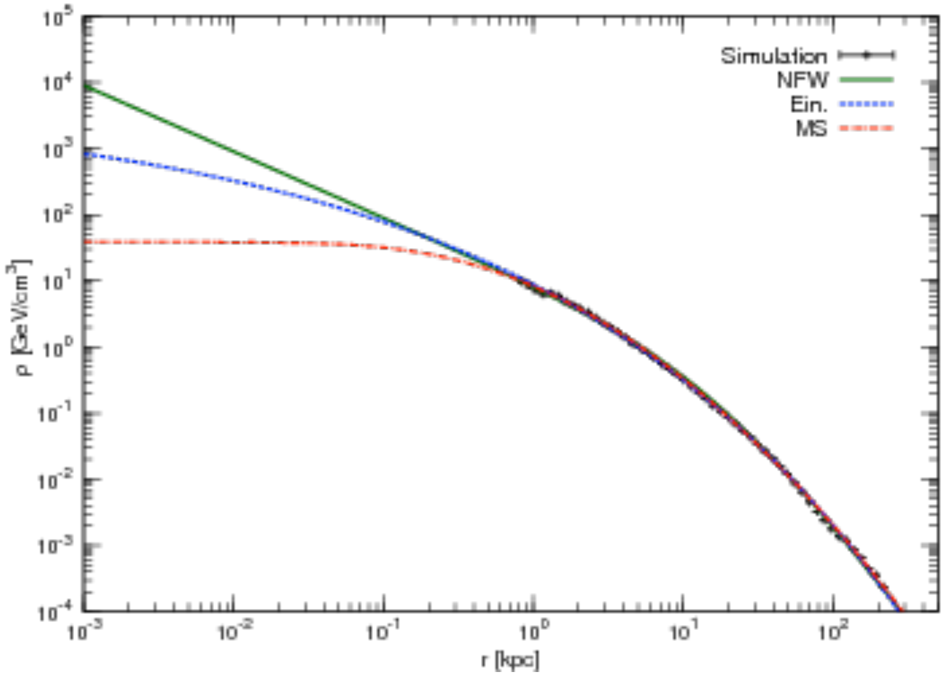
$$\frac{M}{L} \sim 300h \frac{M_\odot}{L_\odot}$$ large)

measured

1. Rotational Curves of Galaxies

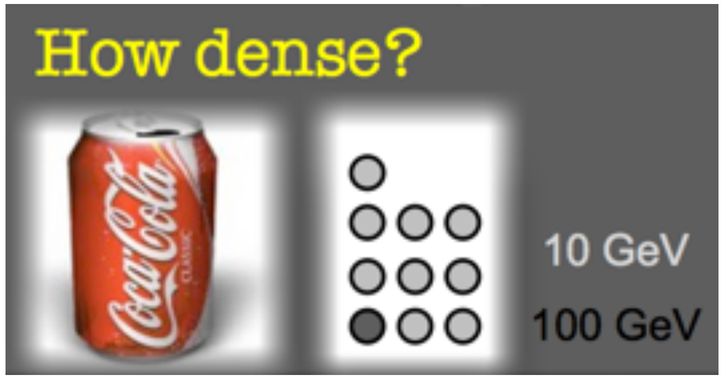
How large/heavy/dense is the (milky way) DM Halo?

From simulations: $M_{\rm halo} \sim 10^{12}\ {\rm M}_\odot$



$\rho_0 \sim 0.3\ {\rm GeV}/{\rm cm}^3$ ⟶

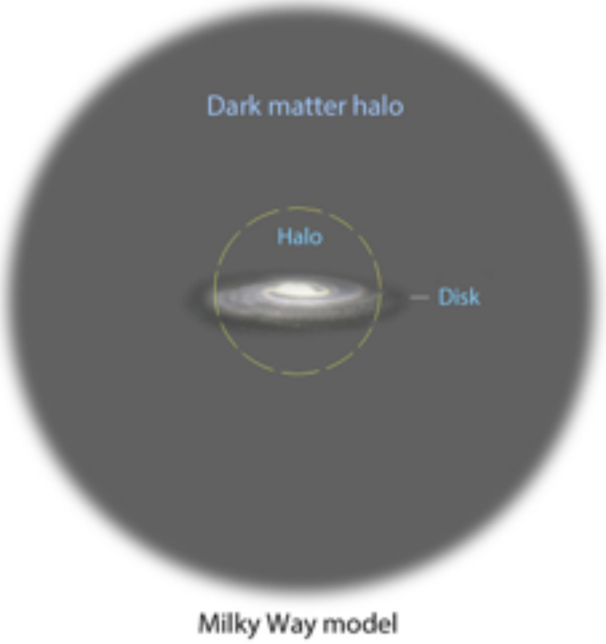
here



$$M_{\rm halo} \sim 4\pi \int_0^{R_{\rm halo}} dr\, r^2 \rho(r) \longrightarrow R_{\rm halo} \sim 100\ \ {\rm kpc}\,,$$

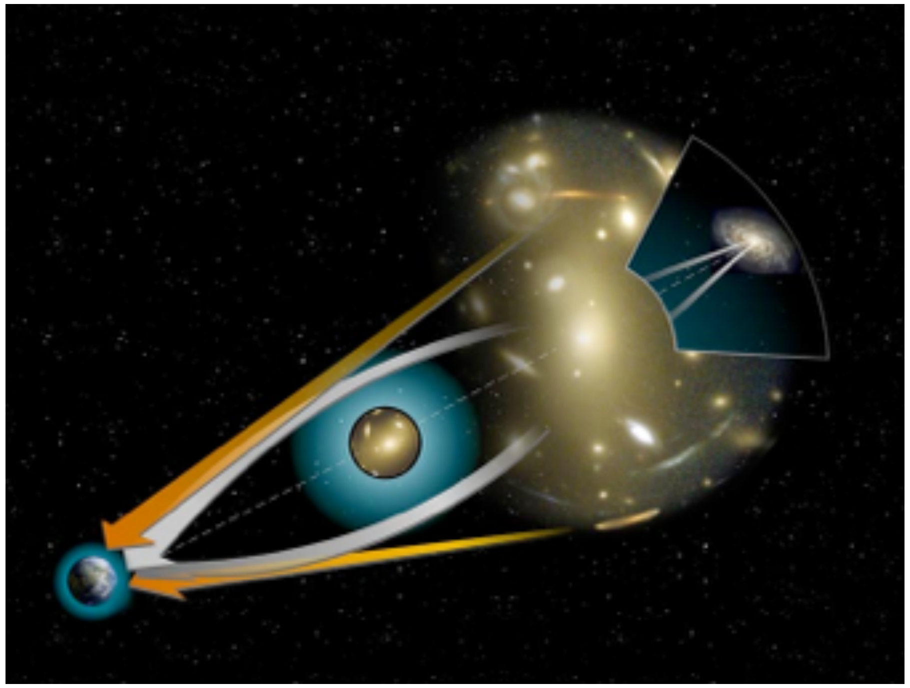
(300’000 ly)

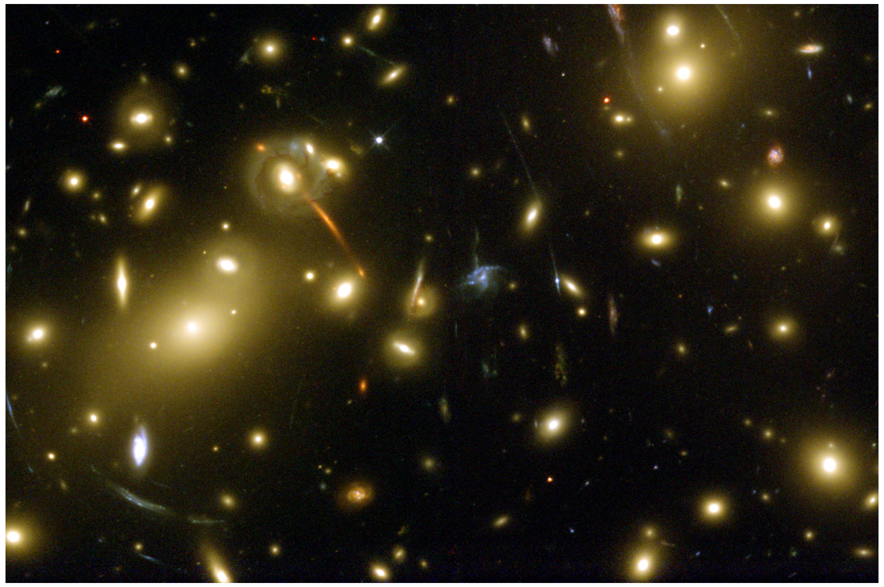
(compared to R$_{\text{milky way}}$= 30-50 kpc)



2. Gravitational lensing

GR: Light bent by (invisible) massive object in foreground





Abell NGC 2218

Reconstruction of DM distribution

3. Bullet Cluster

Two colliding clusters of galaxies

NASA 1E 0657-558
“bullet cluster”
astro-ph/0608247

3. Bullet Cluster

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"bullet cluster"
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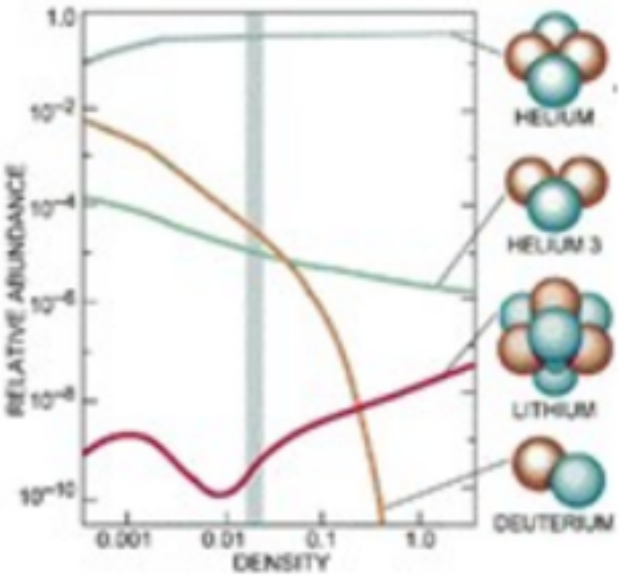
3. Bullet Cluster

This observation disfavors MOND and confirms Dark Matter

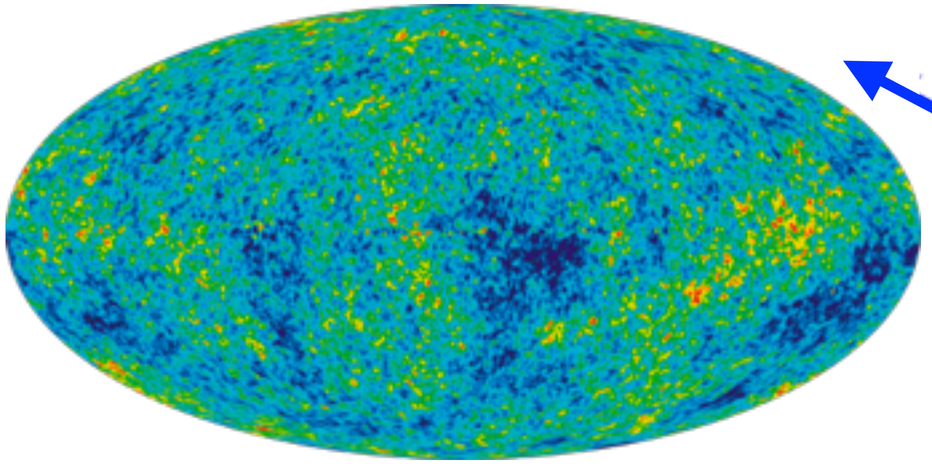
NASA 1E 0657-558
“bullet cluster”
astro-ph/0608247

4. Cosmic Microwave Background (CMB)

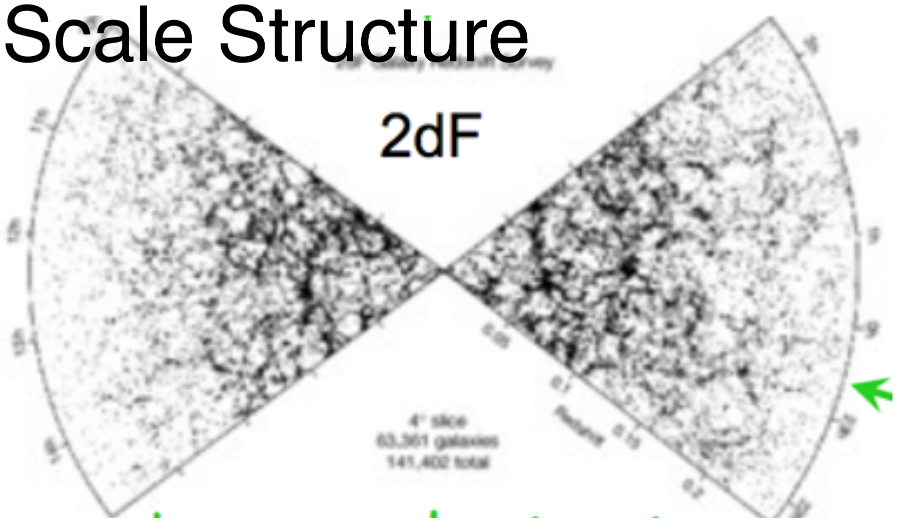
Big Bang Nucleosynthesis(BBN)

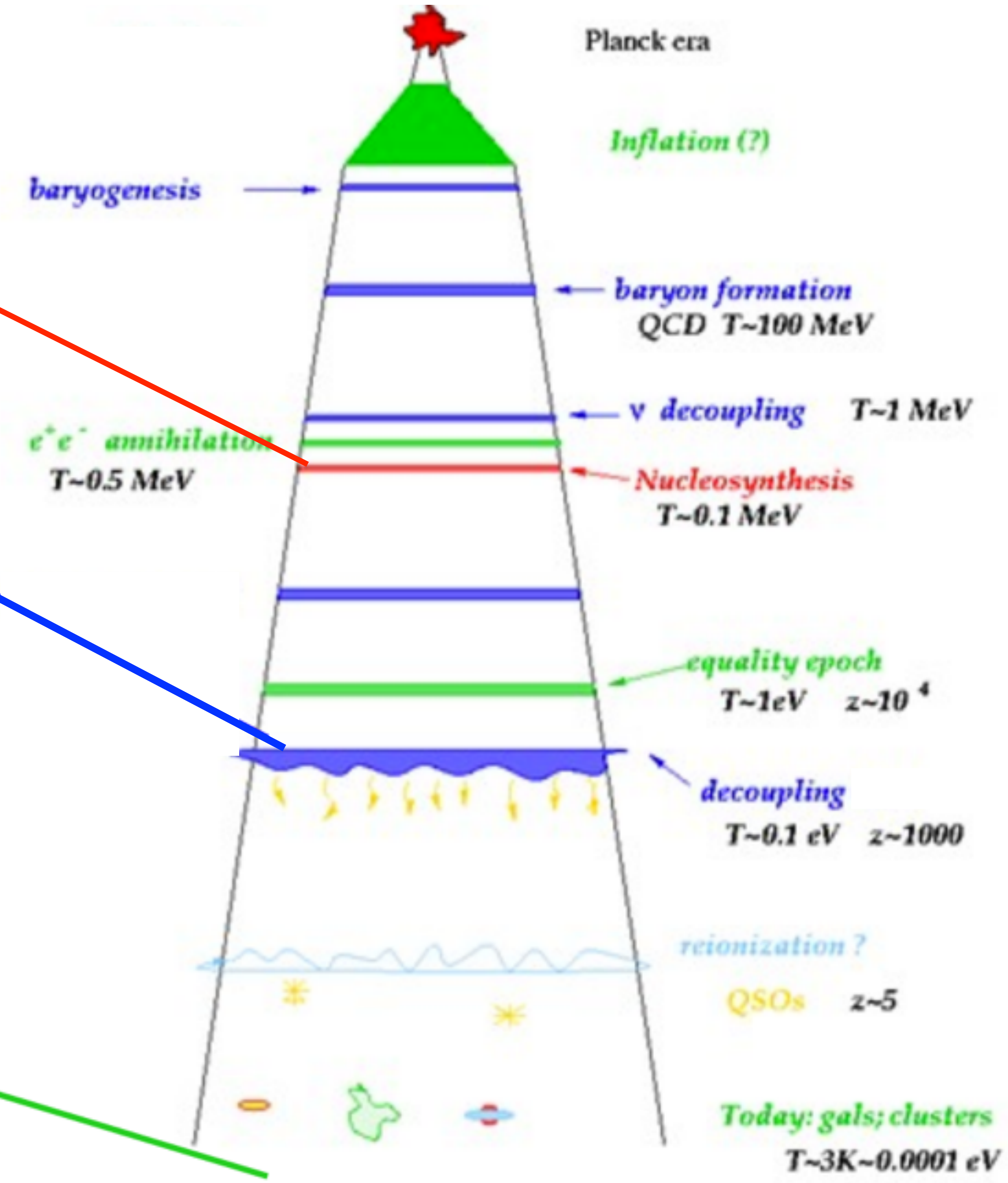


CMB



Large Scale Structure





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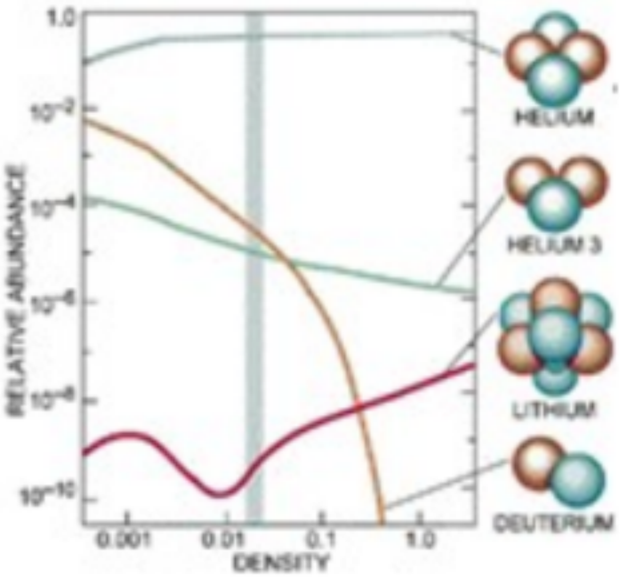
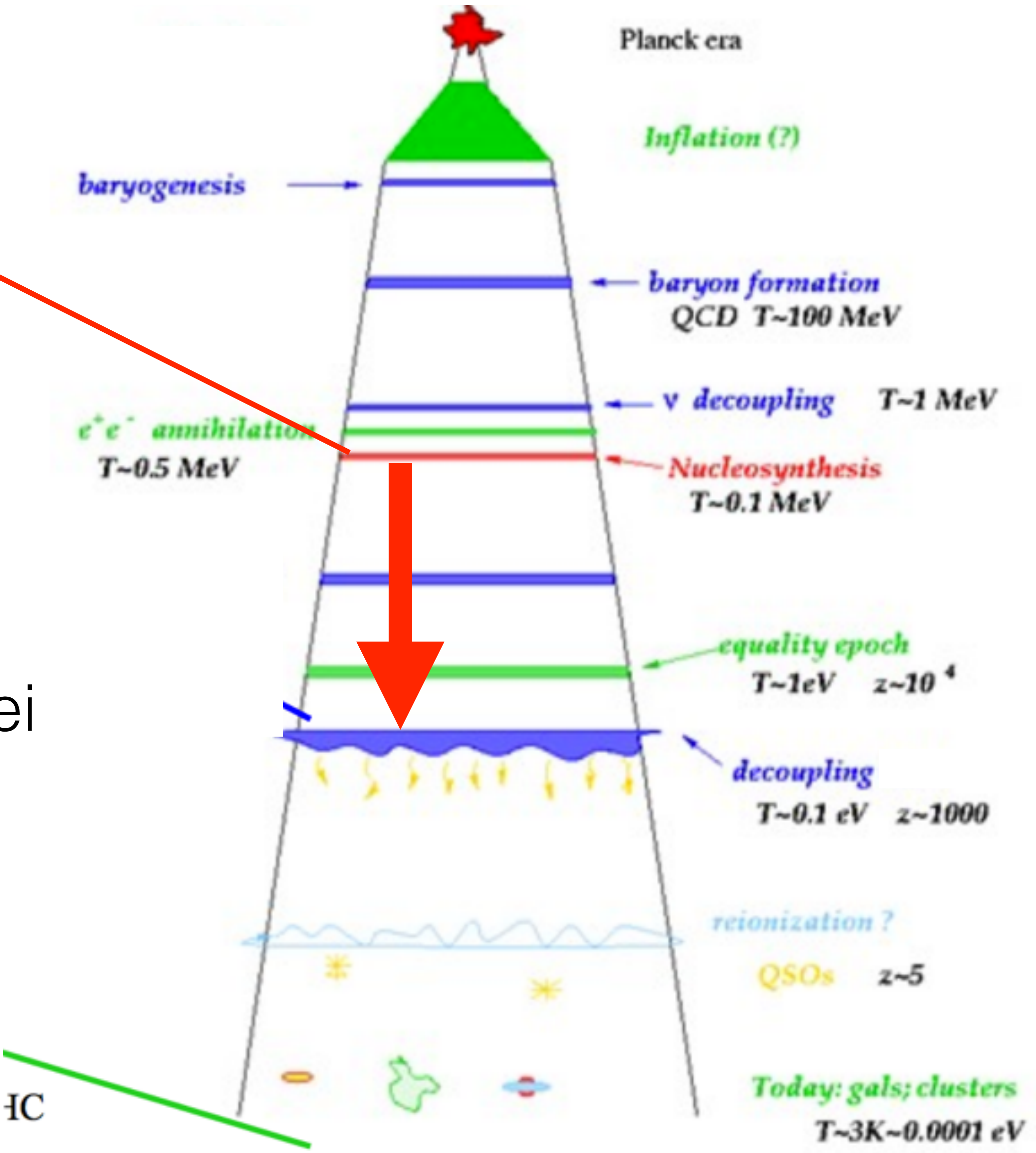
4. Cosmic Microwave Background (CMB)

Big Bang Nucleosynthesis(BBN)



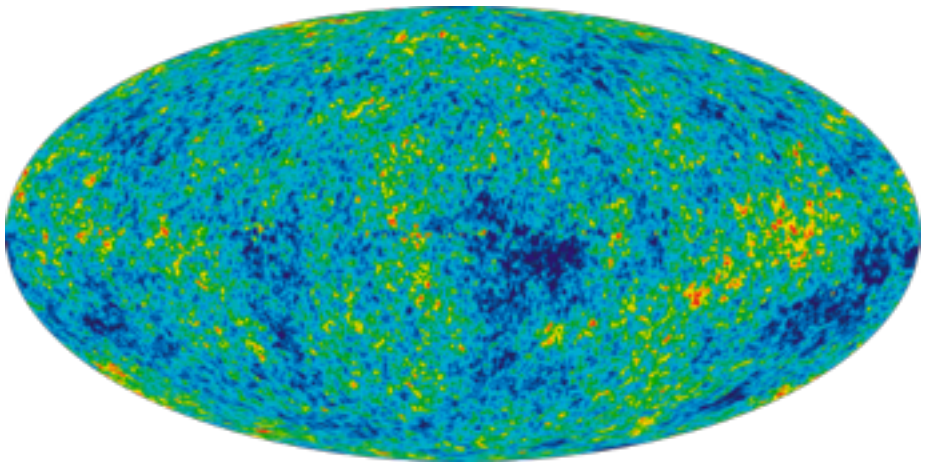
BBN:all neutrons captured in charged nuclei

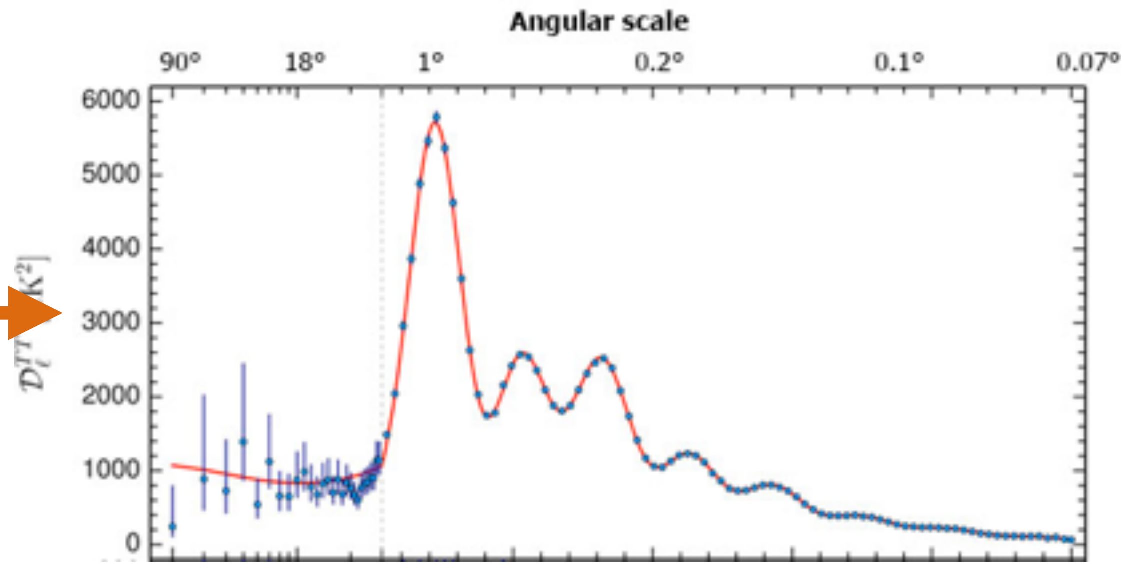
➞Universe opaque



4. Cosmic Microwave Background (CMB)

CMB

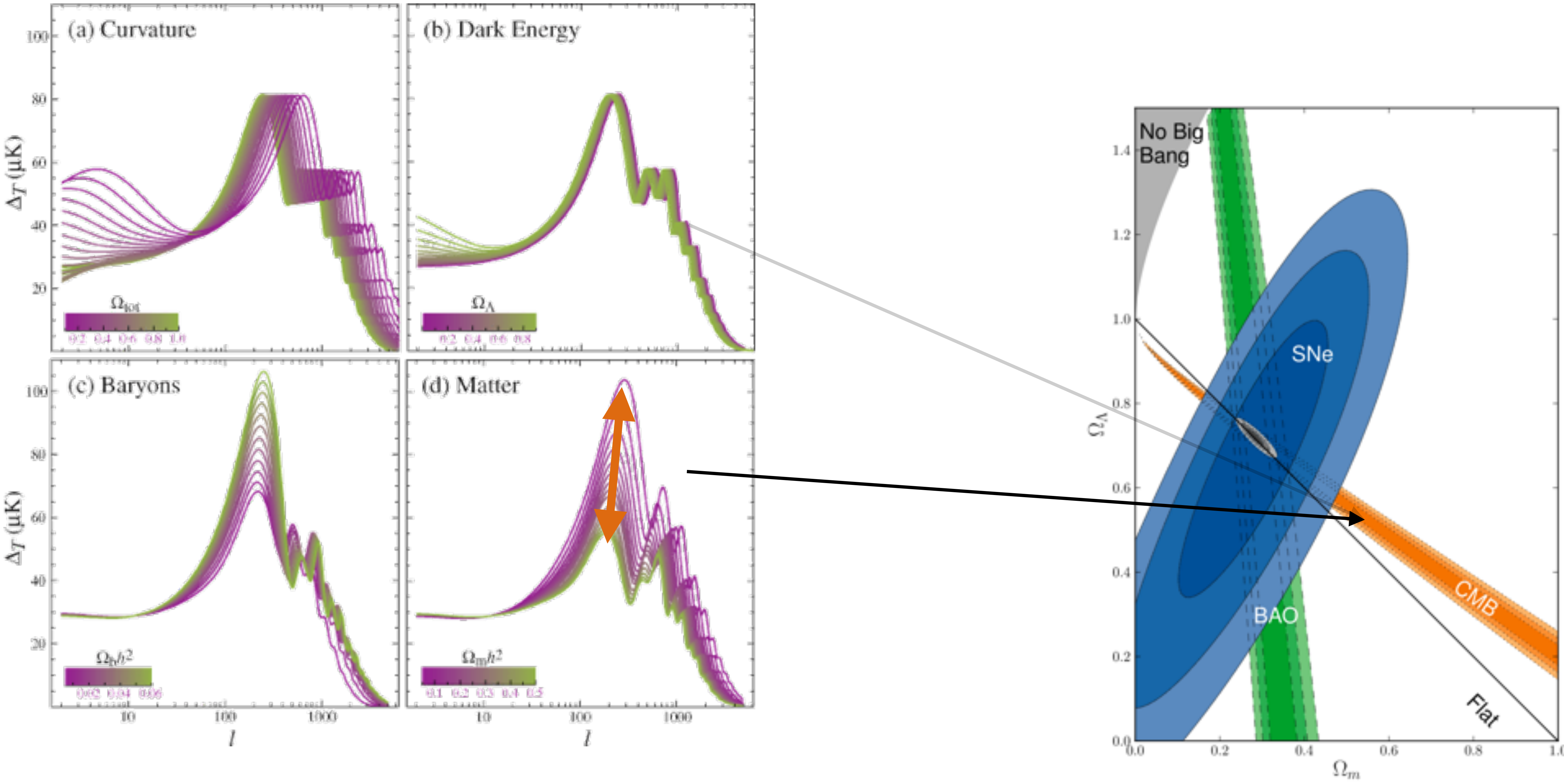




CMB is a last picture of this opaque universe at the moment when N+e combine

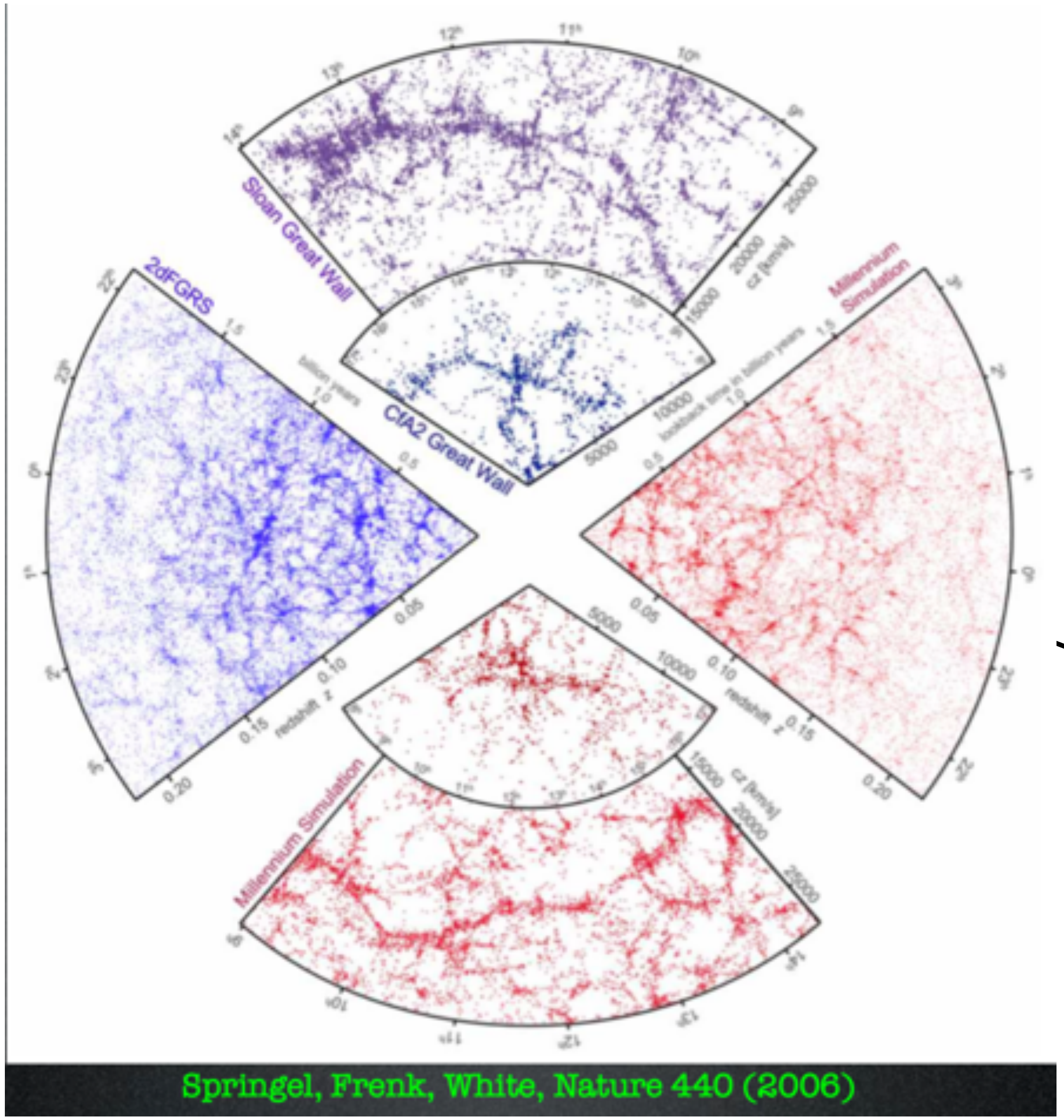
4. Cosmic Microwave Background

Baryons interact with photons, DM doesn't
➙ they leave a different imprint in CMB

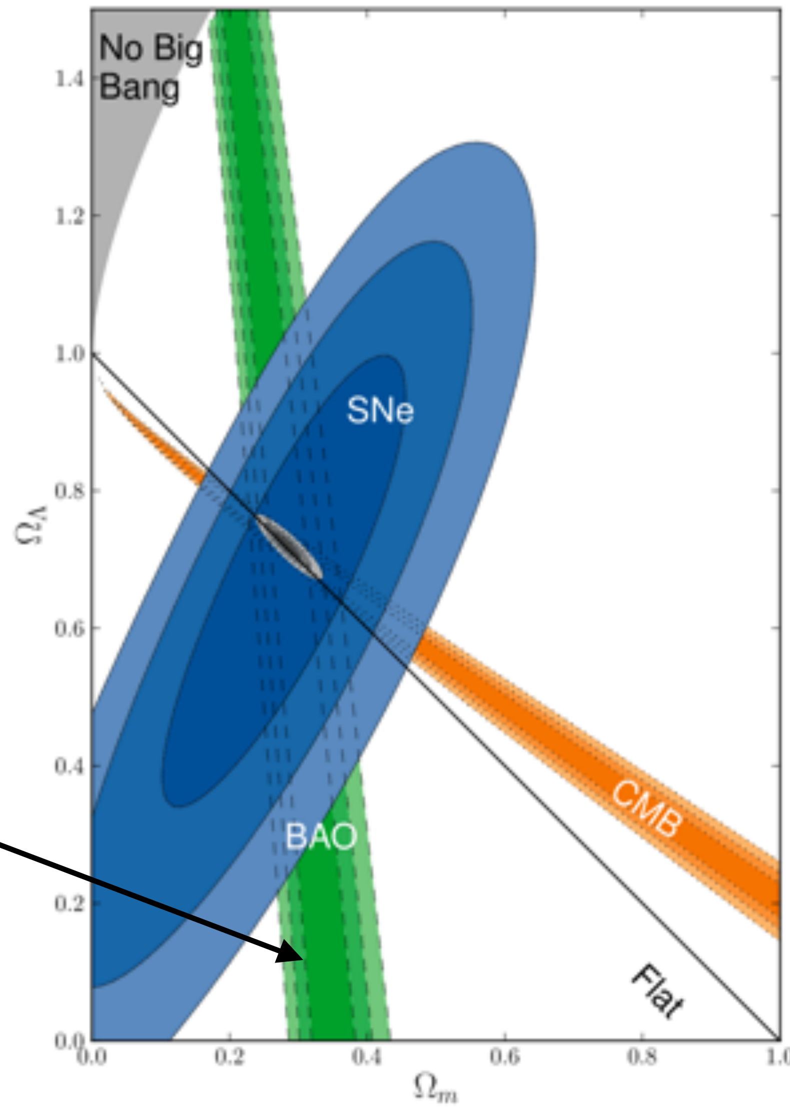


5. Baryon Acoustic Oscillations(BAO)

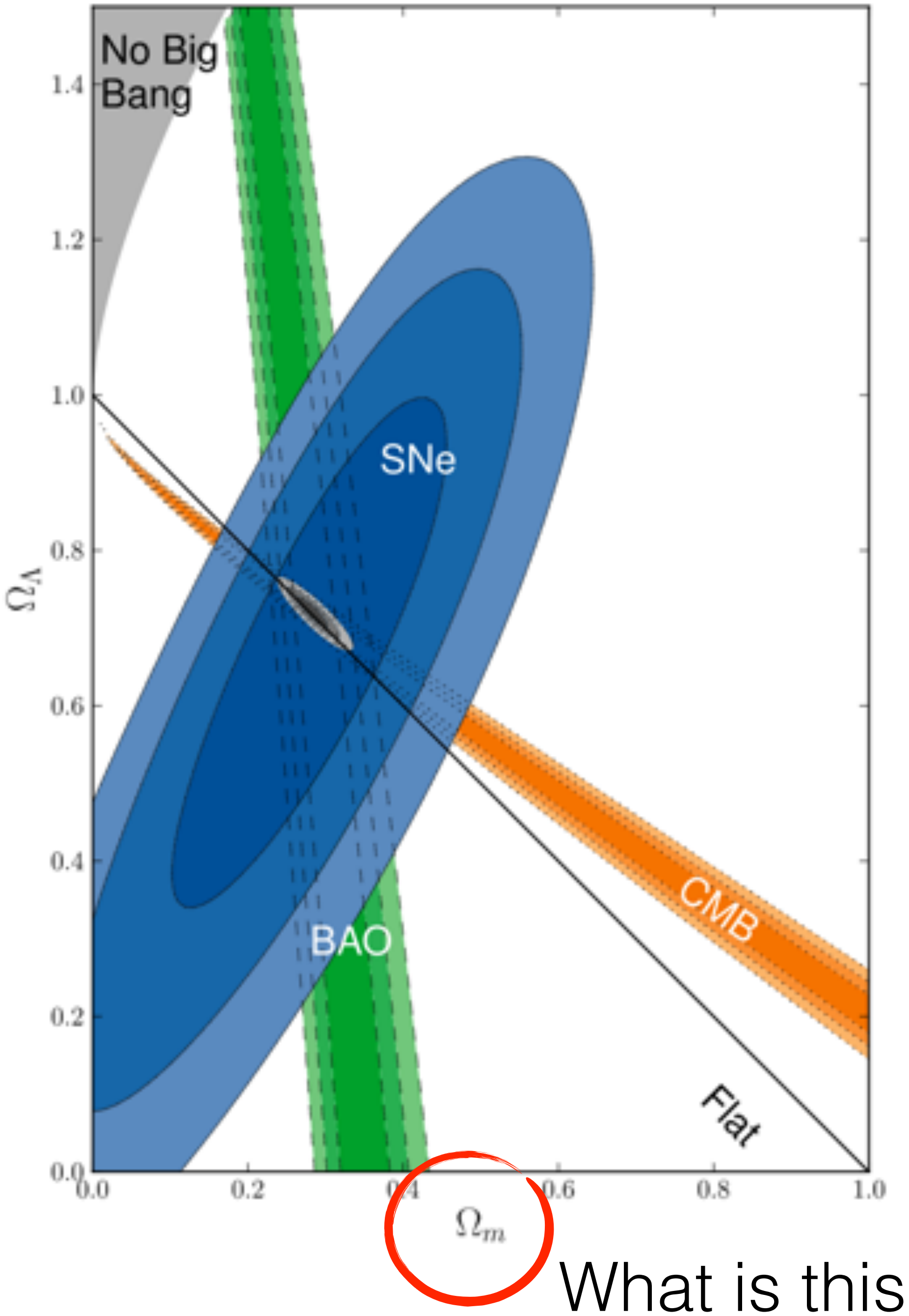
The same “picture” can be taken at later times, by studying distributions of galaxies



Springel, Frenk, White, Nature 440 (2006)



Gravitational DM evidence



What is this?

Einstein equation+isotropy+homogeneity
= Friedman equation

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G_N}{3}\rho_{tot};$$

scale factor of the universe

curvature

total density

$$H(t) = \frac{\dot{a}(t)}{a(t)}$$

Hubble parameter

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

Critical density so that the universe
has no curvature k=0

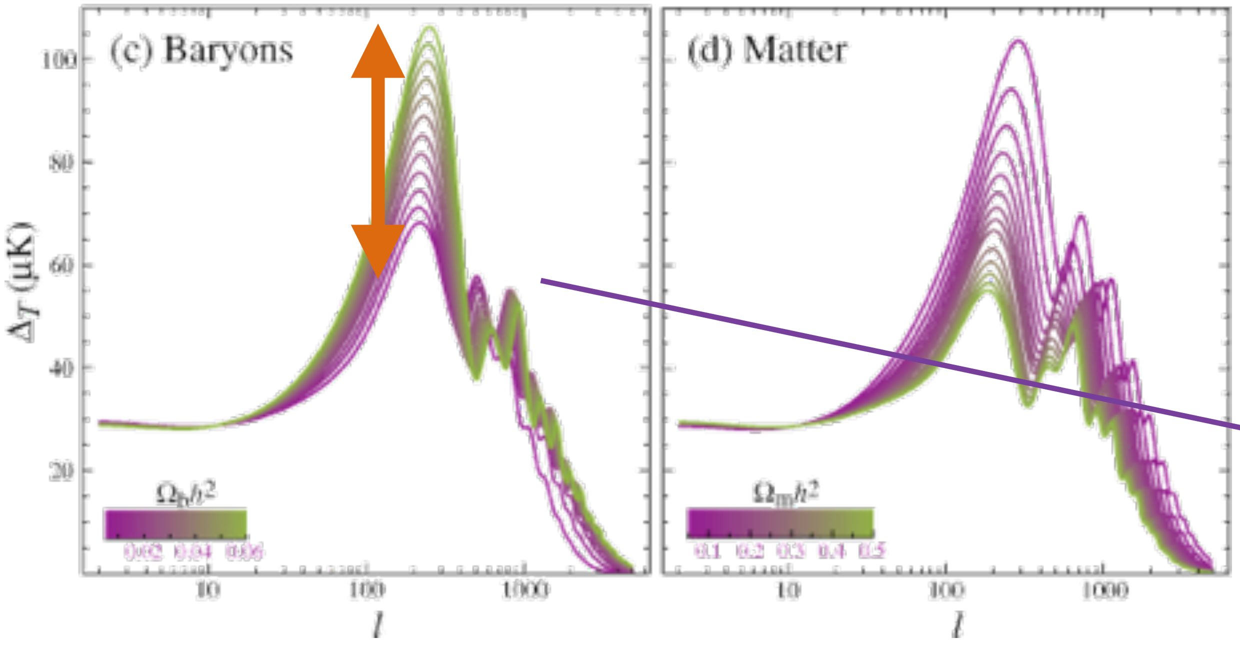
Summary: within the assumption that universe has cold DM and a cosmological constant (ΛCDM model), gravitational evidence for DM is striking

PART 2
What else do we know on Dark Matter?

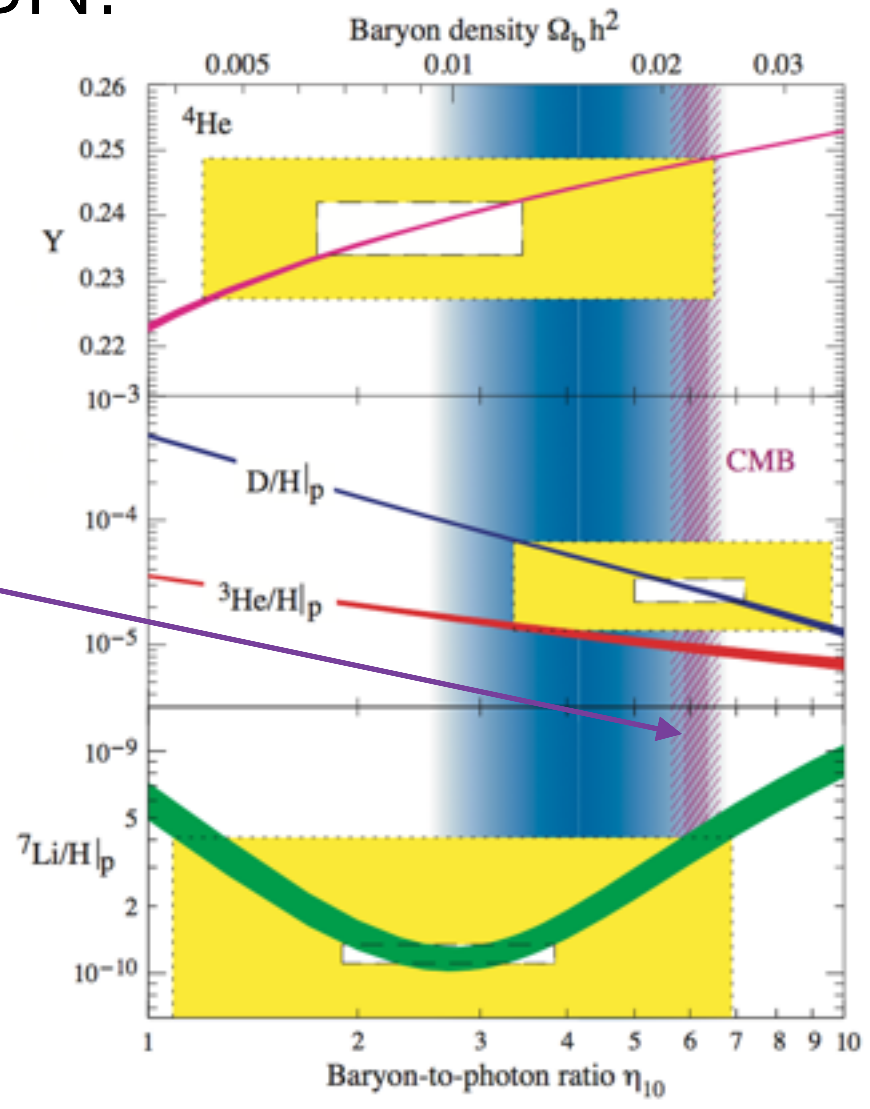
Can DM be a Baryon?

Ratio baryons/photons very well constrained by CMB and BBN

CMB:



BBN:



Baryons cannot collapse as long as photons are coupled - DM can collapse
➙the perturbations we see in CMB imply that some gravitational collapse has taken place

➙DM cannot be a baryon

Can DM be a neutrino?

Lower bound on m_{DM} set by the number of particles that can be confined within a given cell of phase space

depends on spin statistics of the particle

unlimited for bosons (see later)

1 for fermions (Pauli)

phase-space integral (up to maximal velocity v)

velocity set by virial theorem (given the potential it gives the average kinetic energy)

$$M_{\rm halo} = m_{\rm ferm} V \int f(p)\, d^3p \lesssim m_{\rm ferm} V \int^{v} d^3p \sim m_{\rm ferm}\, R_{\rm halo}^3\, (m_{\rm ferm} v)^3$$

$V = \frac{4}{3}\pi R^3$ DM Halo volume

$$\langle v \rangle \sim \sqrt{\frac{G M_{\rm halo}}{R_{\rm halo}}} \sim 200 \;\; {\rm km/s}\,.$$

$$m_{\rm ferm} \gtrsim \left(G^3 M_{\rm halo} R_{\rm halo}^3\right)^{-1/8} \gtrsim {\rm keV}$$

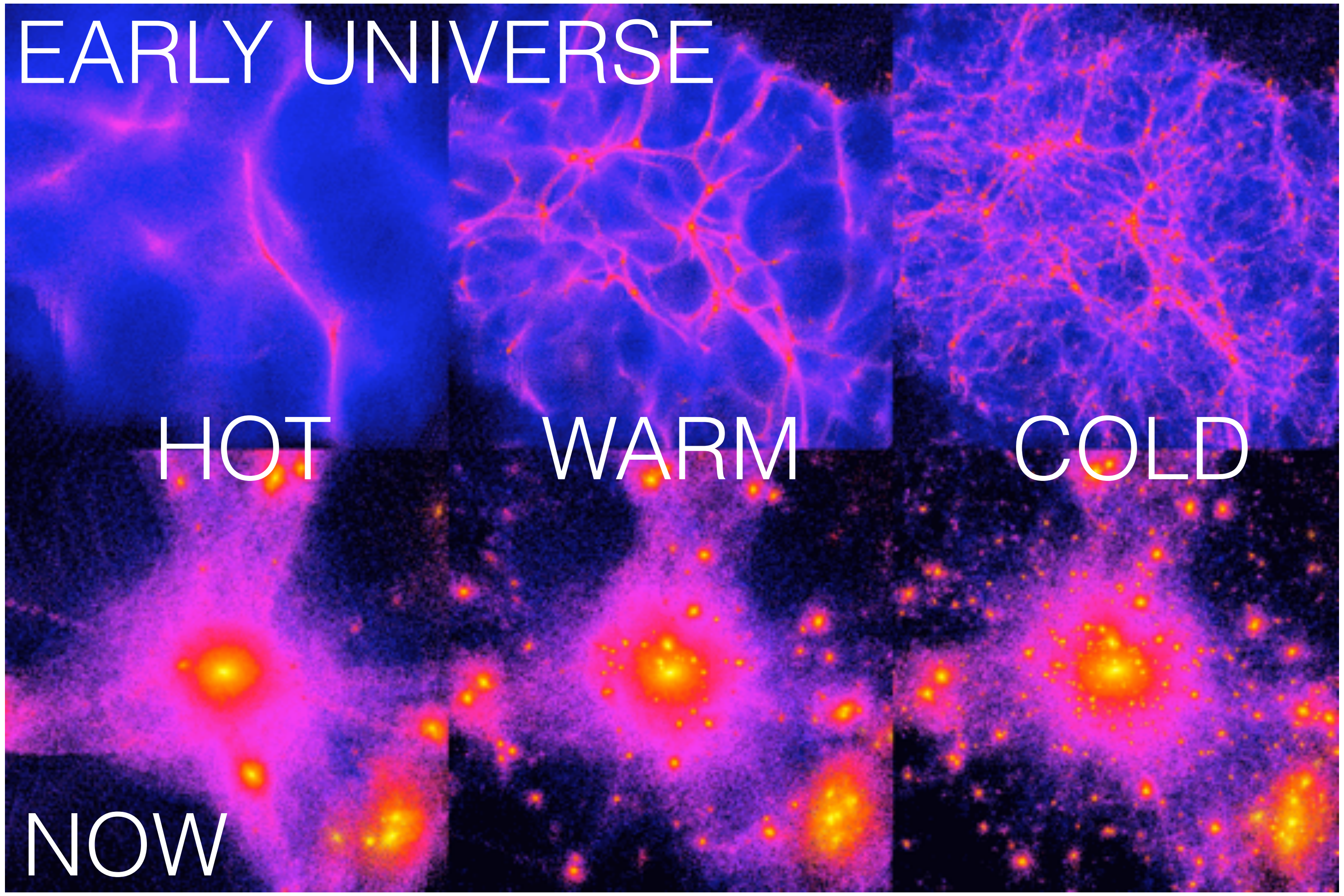
(Gunn-Tremaine bound)

DM cannot be a neutrino, or generally a **fermion** with m<keV

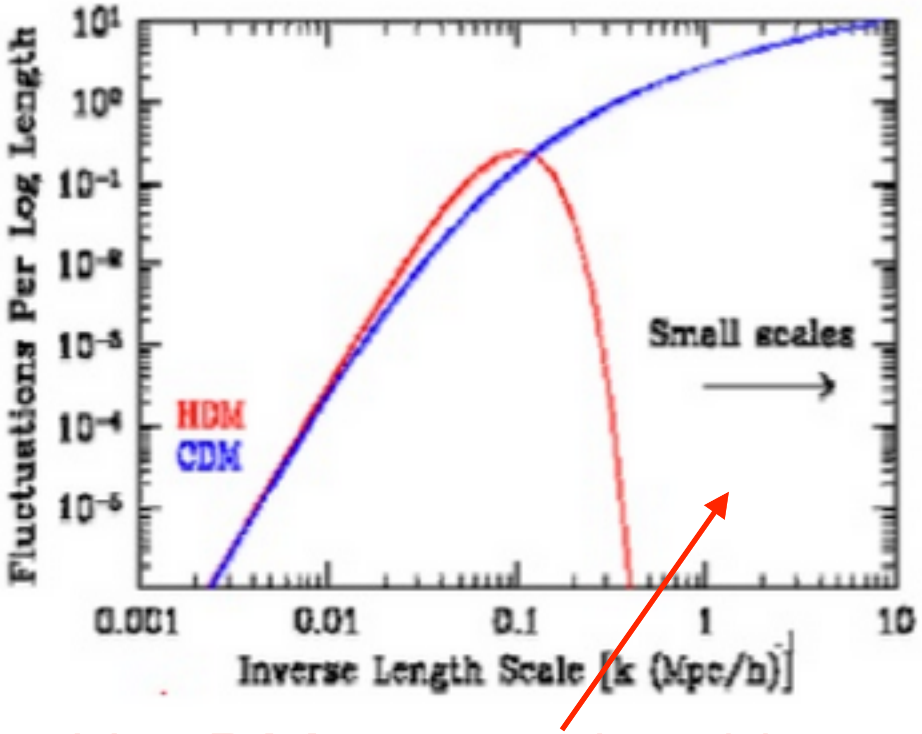
$$\left(\sum m_\nu \lesssim 0.3 {\rm eV}\right)$$

Can DM be a neutrino?

On a more practical level, light DM can be relativistic (HOT) when structure forms, while heavier DM is non-relativistic (COLD)



Cold DM forms hierarchical structures



Hot DM constrained by structure formation at small scales

(there can be very light DM that doesn't thermalize, like axions)

(notice that these constraints depend on thermal history, while previous ones only on Halo formation)

How light/heavy can DM be?

- For a boson (a Lorentz scalar): large occupations number possible (in fact it behave more like a field, see Jaeckel/Barbieri lectures)

  Heisenberg principle still sets bound on m:

$$\Delta x \sim 2R_{\rm halo}$$

$$\Delta x\,\Delta p \sim 1 \qquad\qquad m_{\rm scalar} \gtrsim 10^{-22}\,{\rm eV}\,.$$

$$\Delta p \sim m_\chi v$$

MACHO=MAssiveCompactHaloObjects

- Heavy DM mass constrained from MACHO searches (they would cause lensing when passing in front of bright stars) $10^{57}{\rm GeV} \lesssim m_{\rm DM} \lesssim 10^{67}{\rm GeV}$

Can it interact with us?

(So far we have observed only Gravitational DM interactions)

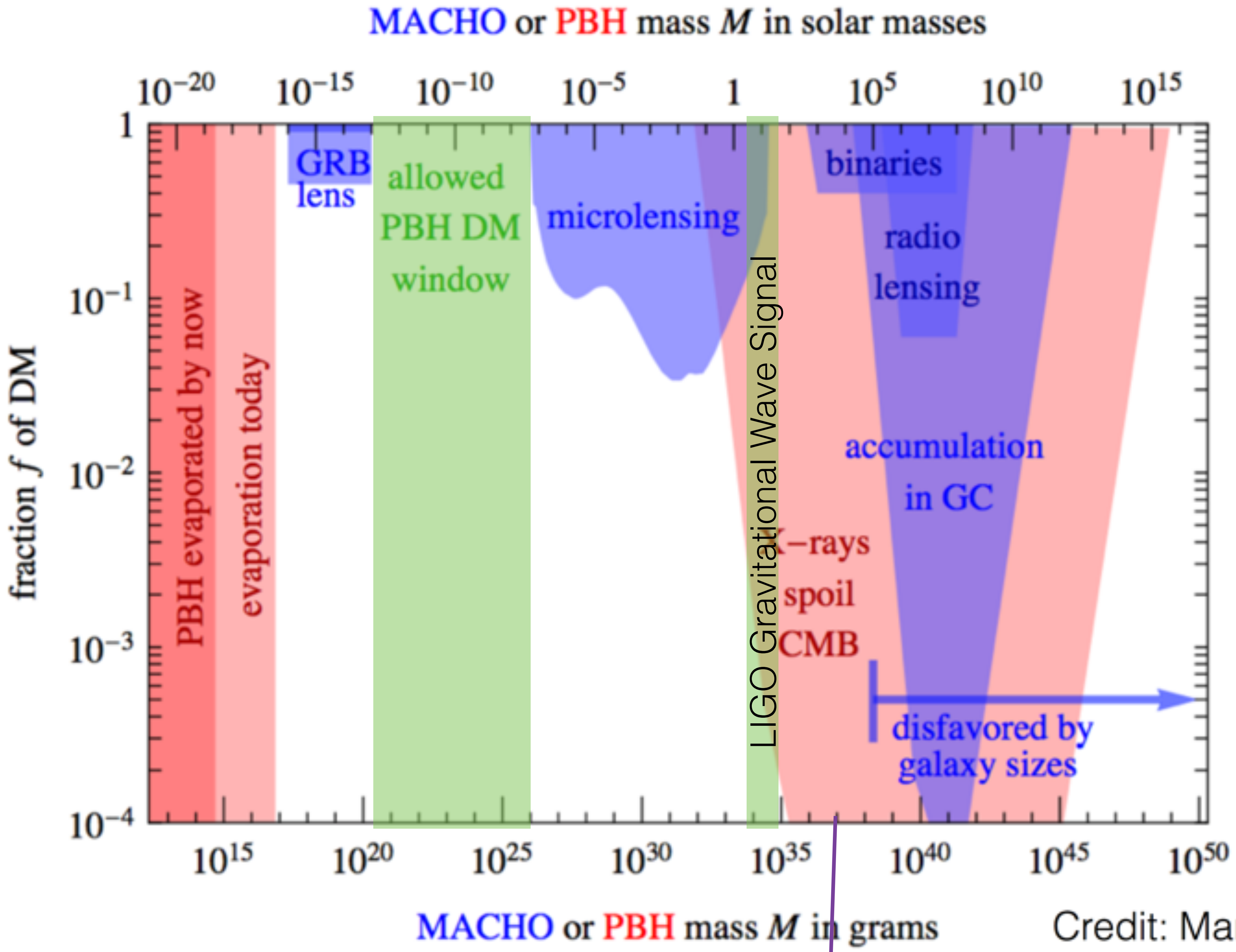
It must be stable on cosmological scales

It cannot be charged electrically or under the strong interaction, otherwise we would have seen it already

More information can be extracted under specific circumstances/assumptions…

→Particle DM
See Barbieri/Jaeckel
→Field DM (very light boson, like the axion)
→Astrophysical object (primordial black holes)

(Primordial Black Holes?)



Credit: Marco Cirelli

How solid is this bound? Can it be that LIGO has detected DM? Even if mass known, it will be difficult to know distributio and confirm DM hypothesis

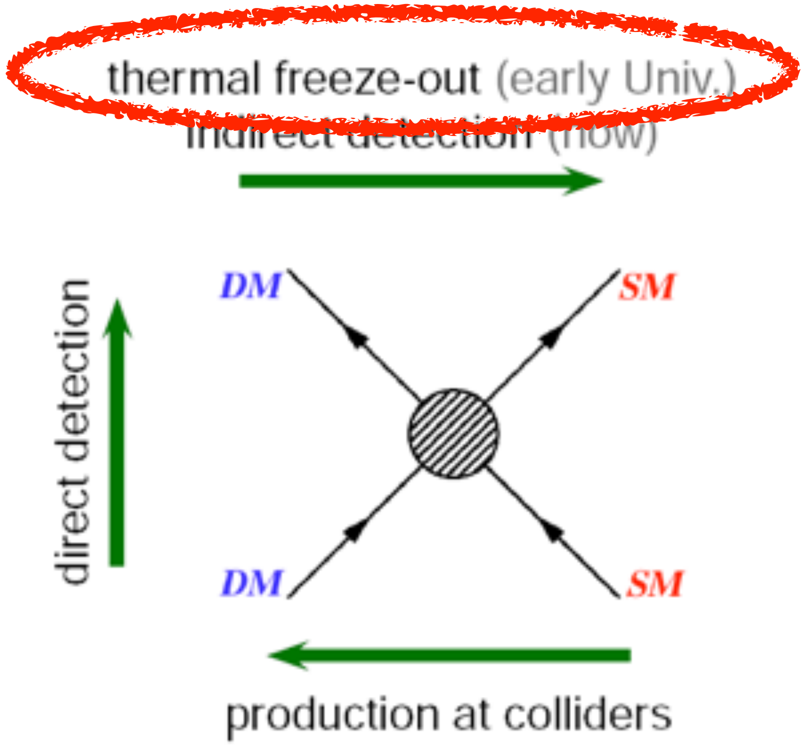
Particle DM

(the most popular scenario)

DM can in principle interact with the SM only gravitationally, and its abundance be fixed by initial conditions after inflation…

(in this case we won’t learn more)

..it might however couple to the SM:



Particle DM - production

If the SM-DM interaction is sizable, DM is in thermal equilibrium in early universe: all information on initial conditions lost!

- initially, in thermal equilibrium

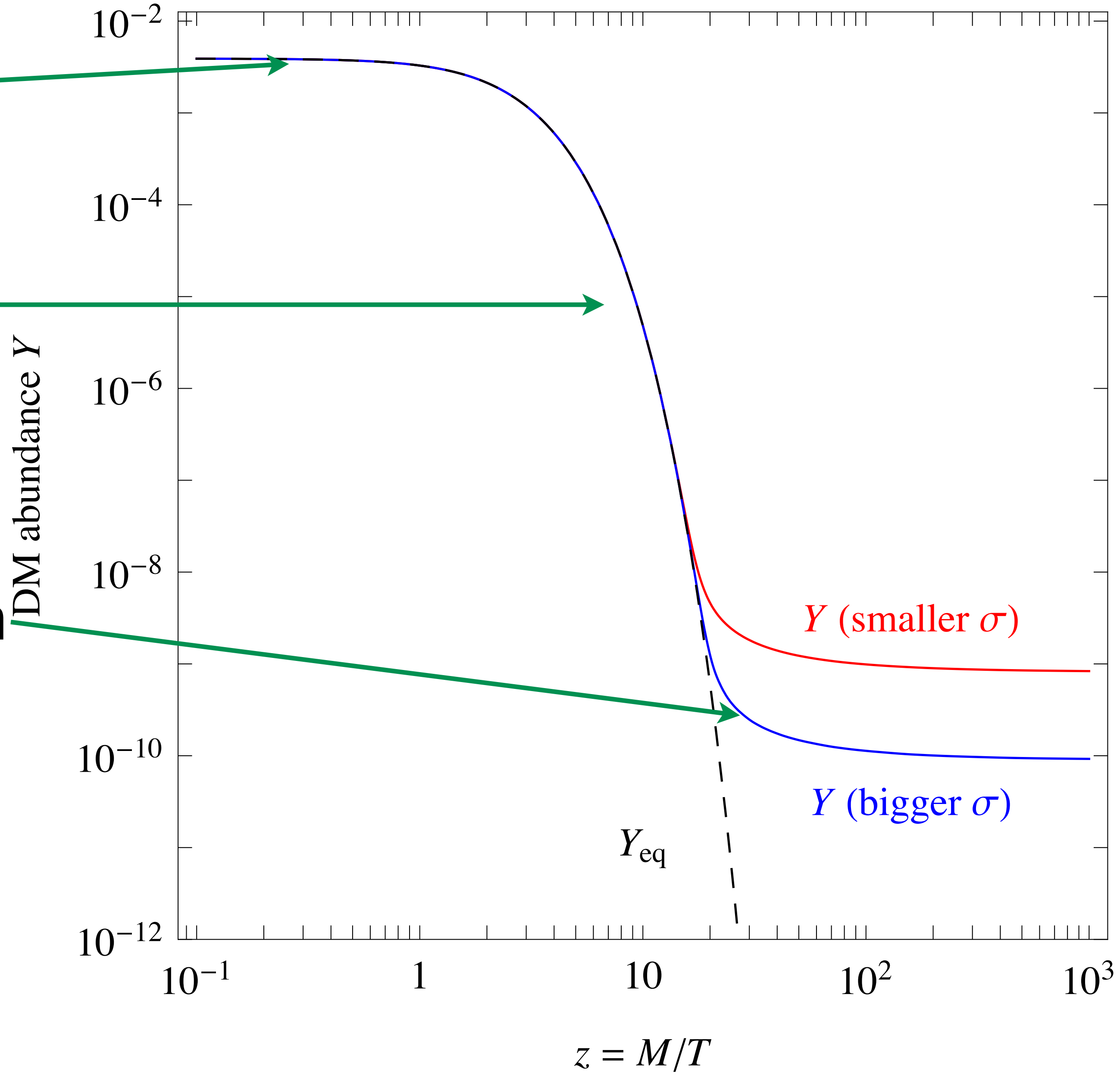
X=DM $\chi\,\chi \leftrightarrow \text{SM SM}$

- 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

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



DM abundance depends only on (measurable) SM-DM interaction!

Particle DM - production

$H = \frac{T^2}{M_{Pl}}$ during radiation domination

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

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

For heavy DM this is determined by Boltzman distribution:

$$n_\chi = n_{\bar\chi} = g_\chi \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi/T}$$

at T_f~m_χ/20 DM particles decouple (too heavy to be produced)

number density of X remains ~ constant

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

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

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

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

→typical weak-scale interactions provide thermal relic with the “right” relic abundance, independently of mass and initial conditions (REMARKABLE COINCIDENCE, a.k.a. “**WIMP MIRACLE**”)

Particle DM - production

here are other possible mechanisms for DM production, beside **freeze-out**
non-thermal production mechanisms)

Asymmetric DM: intriguing coincidence $\Omega_{\rm DM} \simeq 5\,\Omega_{\rm SM}$

explained by possible shared SM-DM conserved charge, so that SM and DM are produced together

Freeze-in: if interactions very small particles never thermalize, but can freeze in (FIMP), also *independently of initial conditions*

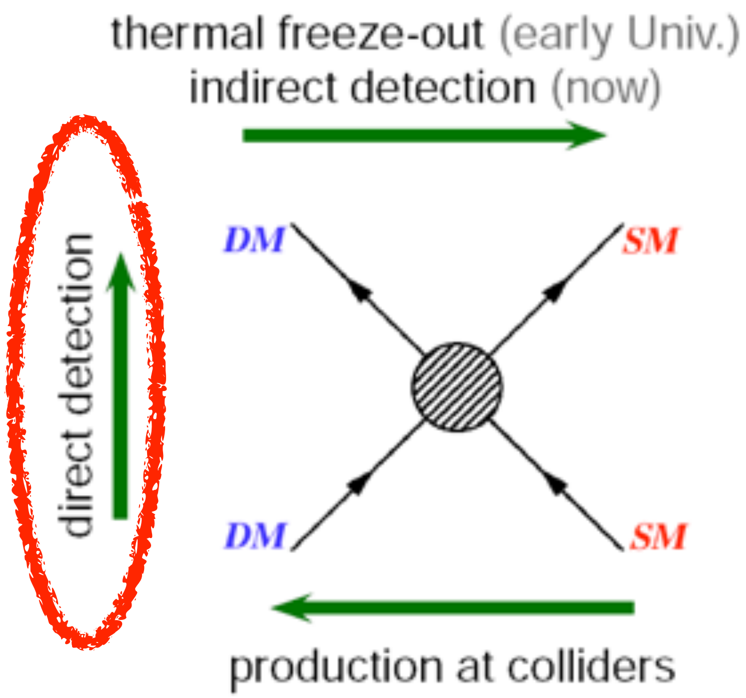
Axions: If DM is a boson (scalar), and is very light, it behaves effectively like a field that oscillates and stores energy (how much depends on initial conditions)

(see Jaekel/Barbieri)

PART 3

How can DM-SM interactions be tested (detected)?

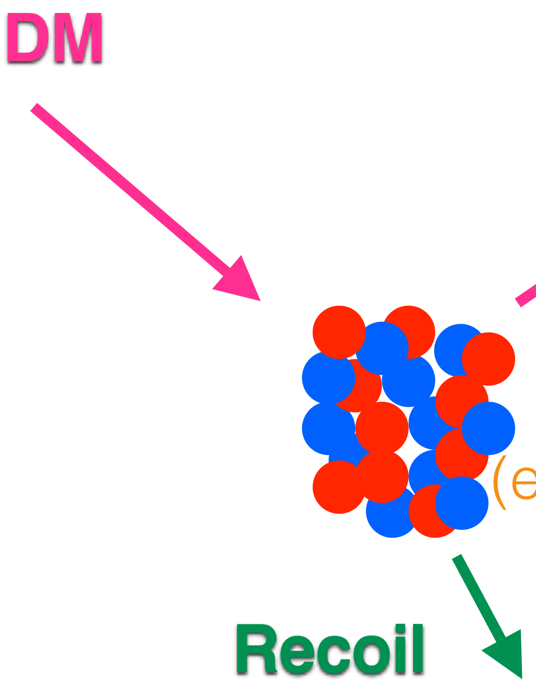
Direct Detection (See Baudis)



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...



$$\mu_{\chi A} = m_\chi M_A/(m_\chi + M_A)$$

$$|\vec{q}|^2 = 2\mu_{\chi A}^2 v^2 (1 - \cos\theta)$$

$$O(10)\mathrm{keV} \sim E_R = \frac{|\vec{q}|^2}{2M_A} \lesssim 2\frac{\mu_{\chi A}^2 v^2}{M_A}$$

(experimental sensitivity)

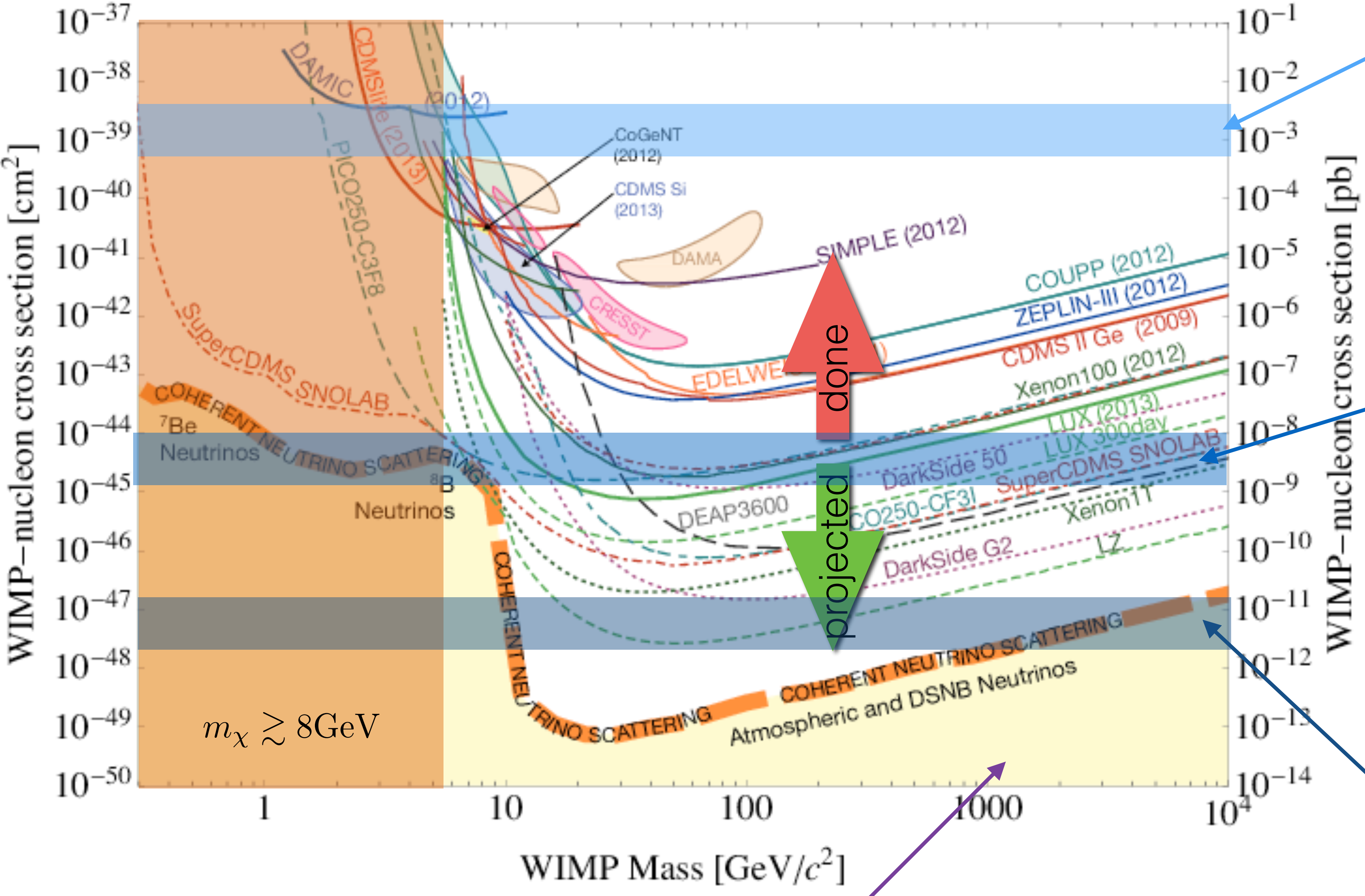
target nuclei mass

Detectable DM:

$$m_\chi \gtrsim 8\mathrm{GeV}$$

Direct Detection

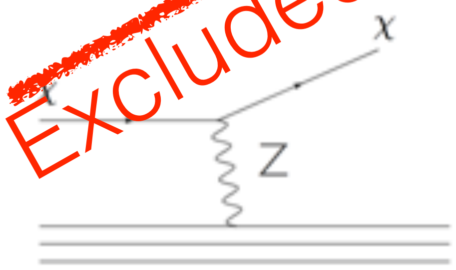
(See Baudis)



~~Z-mediated~~

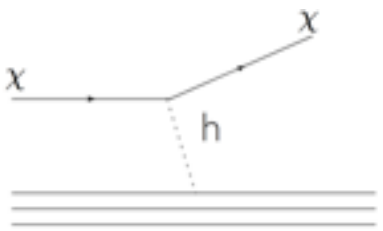
~~$\sigma \sim \alpha_W^2 m_p^2/M_Z^4 \approx 10^{-39}\text{cm}^2$~~

Excluded

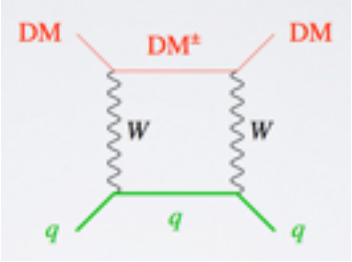


Higgs-mediated

$$g \sim 1 \Rightarrow y_p \sim \frac{1}{\text{few}} \frac{m_p}{v}$$



loop-mediated



Heavier DM is more rare $n_{DM} = \frac{\rho_{DM}}{m_{DM}}$

➙ less events, less constraints

Indirect Detection

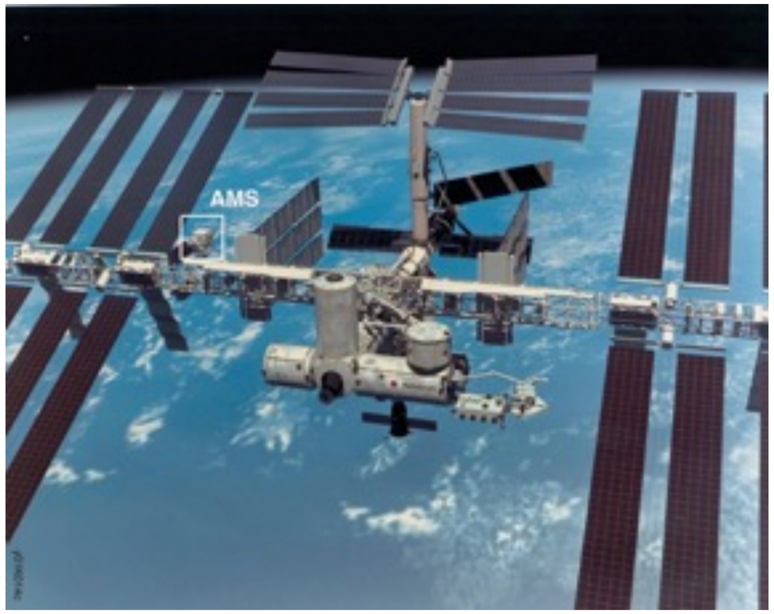
$\mathrm{DM}\ \mathrm{DM} \to e^+e^-, \ldots$

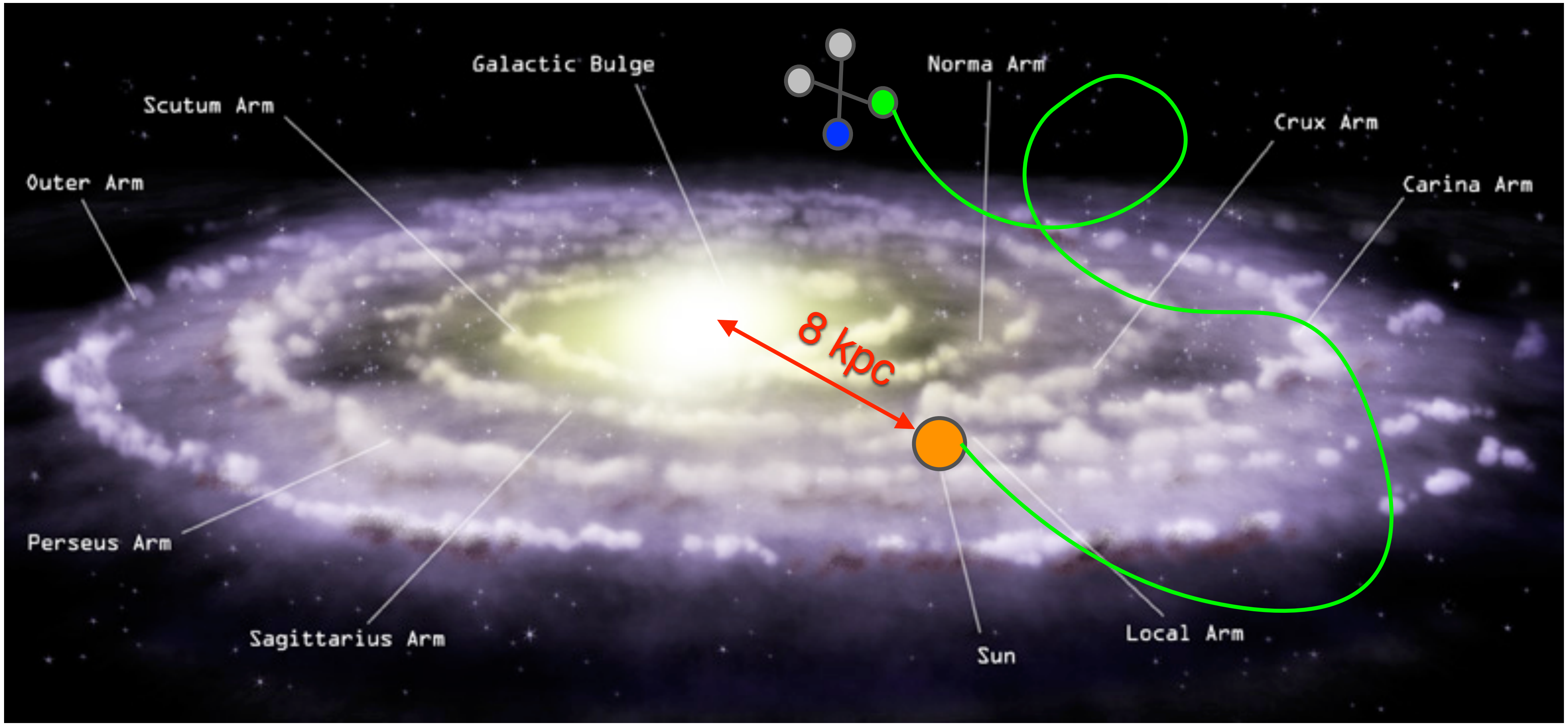
$e^+, \bar{p}$ **AMS-02, Pamela, Fermi, HESS**

γ **ATIC, Fermi**

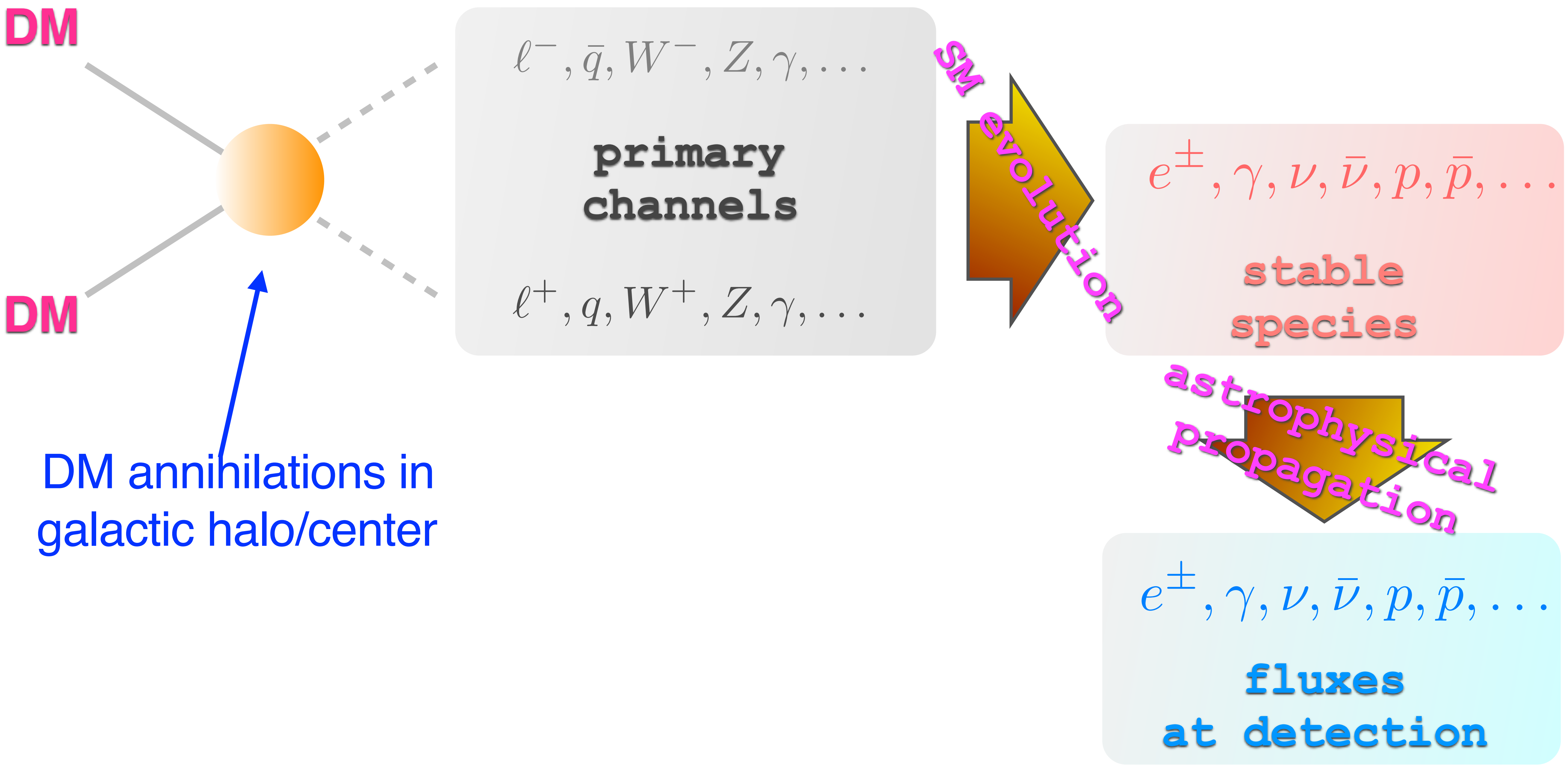
ν **IceCube, Antares, Km3Net**

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





Indirect Detection



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

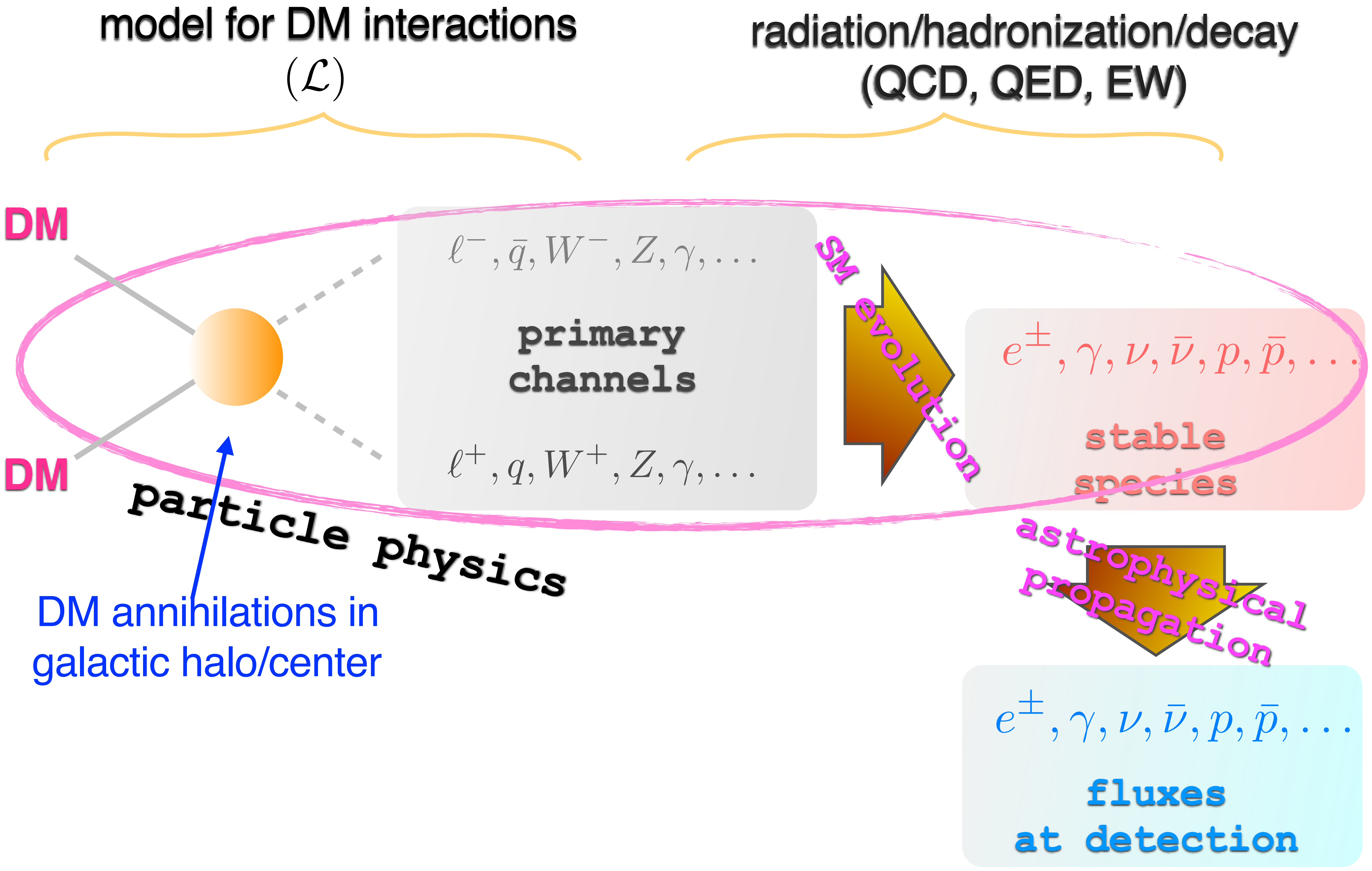
astrophysical propagation

$e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \ldots$

fluxes at detection

DM annihilations in galactic halo/center

Indirect Detection



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

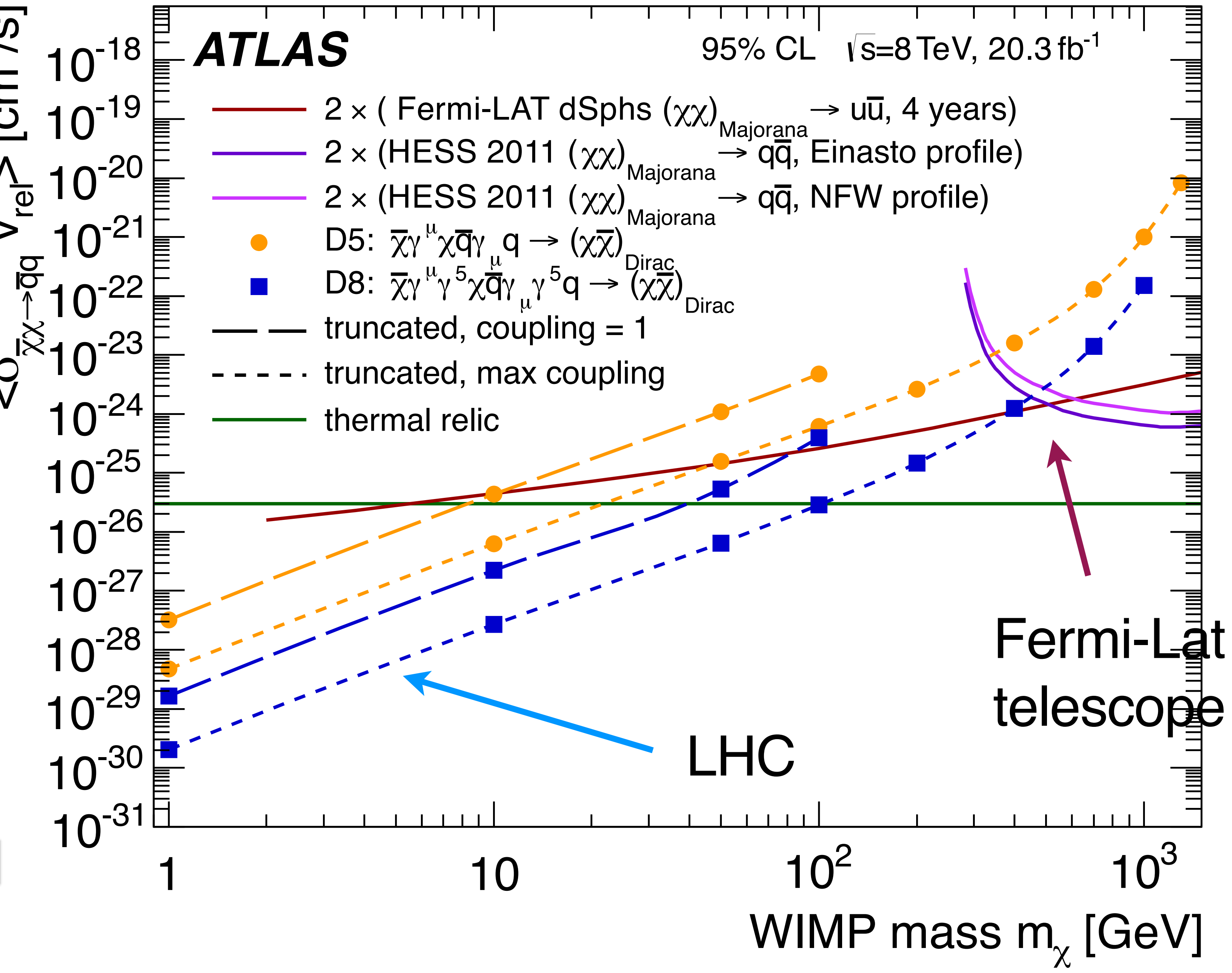
astrophysical propagation

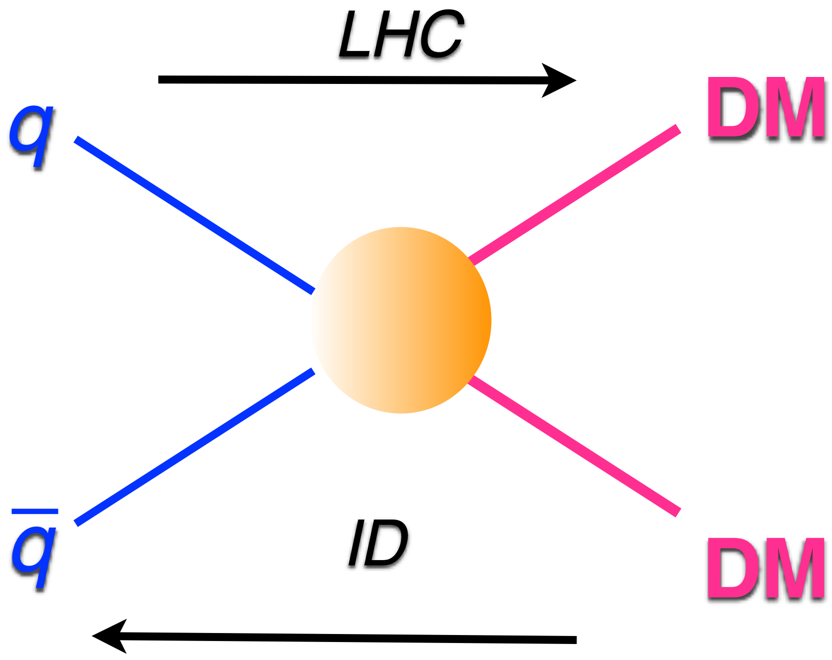
DM annihilations in galactic halo/center

$e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \ldots$

fluxes at detection

Indirect Detection



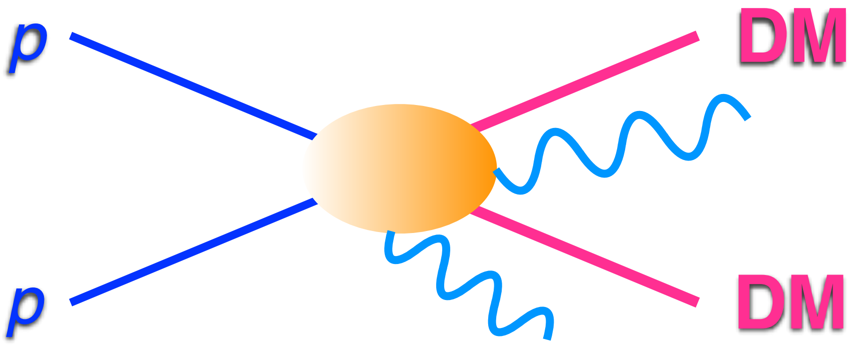


[arXiv:1502.01518]

LHC

- Could be the only test for light DM
- Dark Matter in a collider is like a neutrino (missing $\underbrace{\text{Energy}}_{\text{transverse}}$)

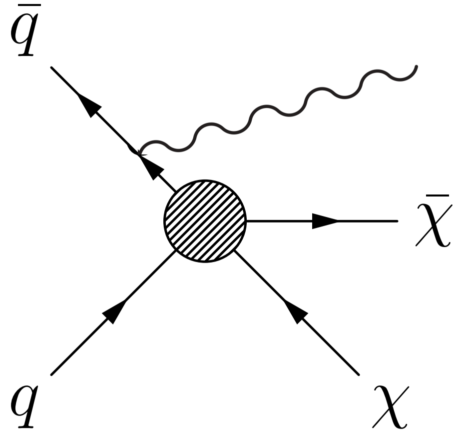
- if stabilized by a Z_2 symmetry → DM produced in pairs



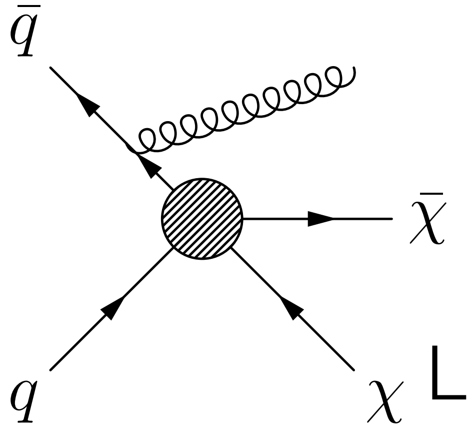
- Difficult search, unless correlating missing E_T with other handles

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

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



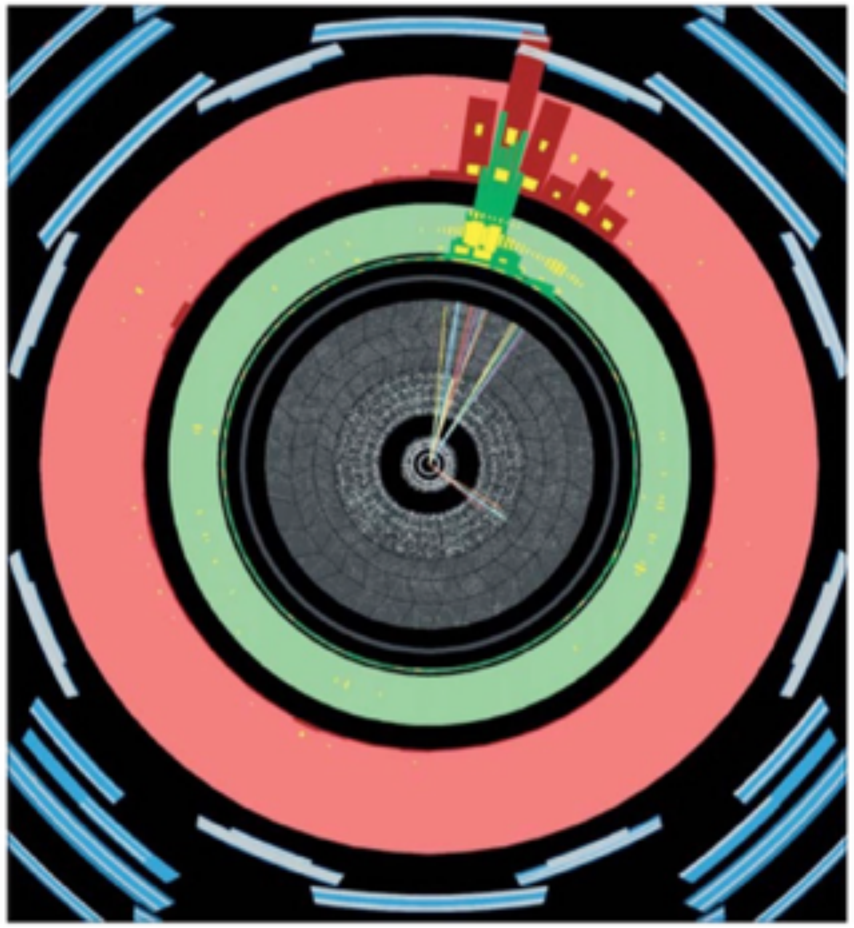
Monophoton + MET



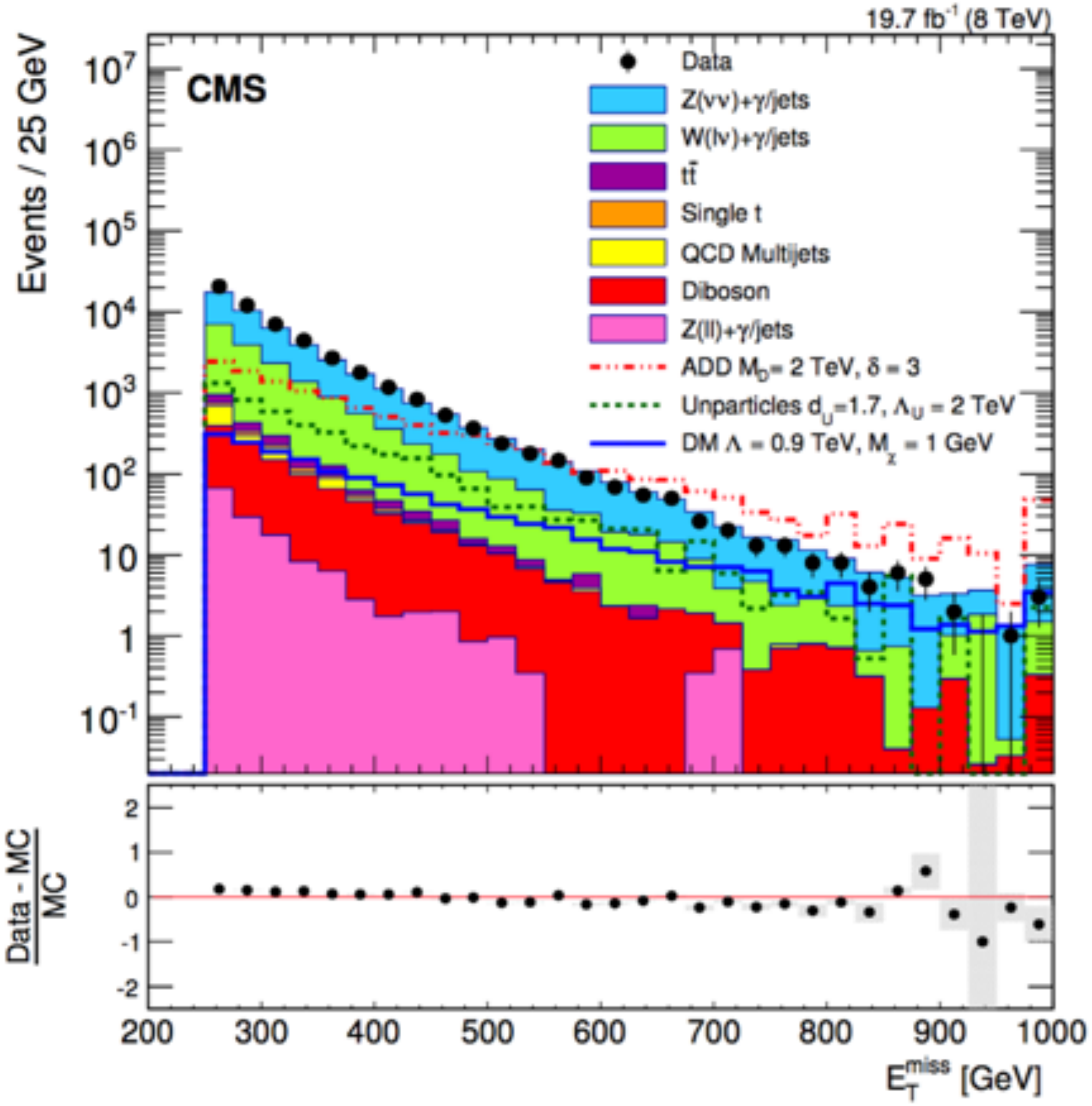
Monojet + MET

Like DD, probes DM couplings
with quarks and gluons

LHC



Mono-jet event from ATLAS (credit: CERN courier)



Main background from $Z \to \bar{\nu}\nu$, so this must be stronger…

(but recall from direct detection that Z-mediated interactions are excluded)

➝need a resonant peak or a different distribution

LHC

So far LHC observed no signal associated with missing E_T

…yet it's important to assess what we have learned from this!

(remember that most of what we know on DM is about negative results)

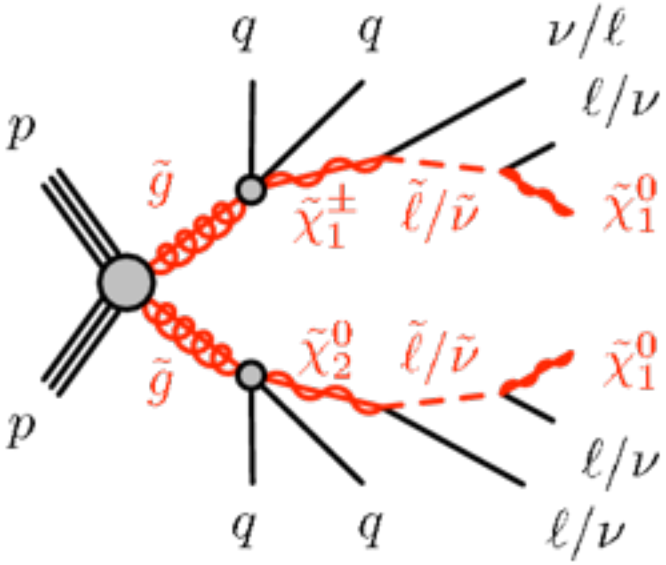
Difficulty: LHC collisions explore a wide unexplored range of energy

few GeV - few TeV

if DM is there, it might not be alone

Exemple: explicit SUSY DM model (neutralino)

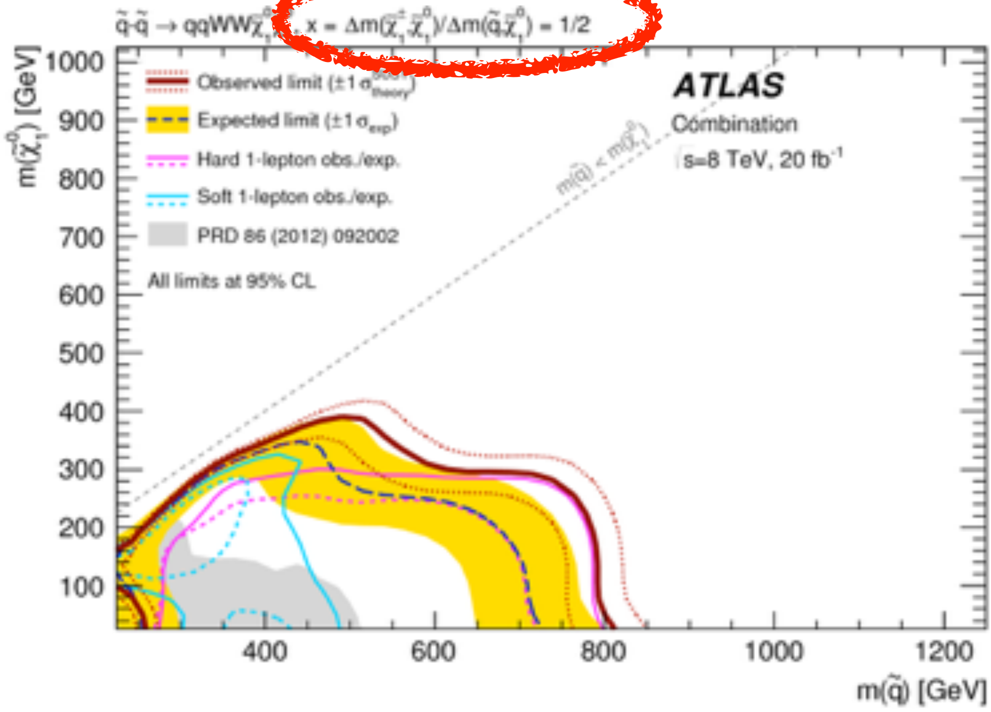
specific assumptions



MET + many jets (+ leptons)

Many new particles involved in process
➝ many parameters!

(and many explicit models)



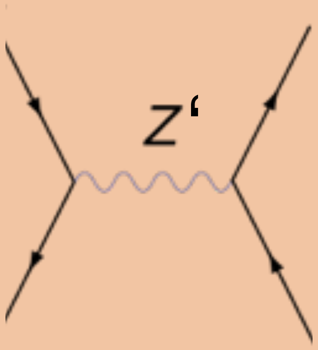
LHC

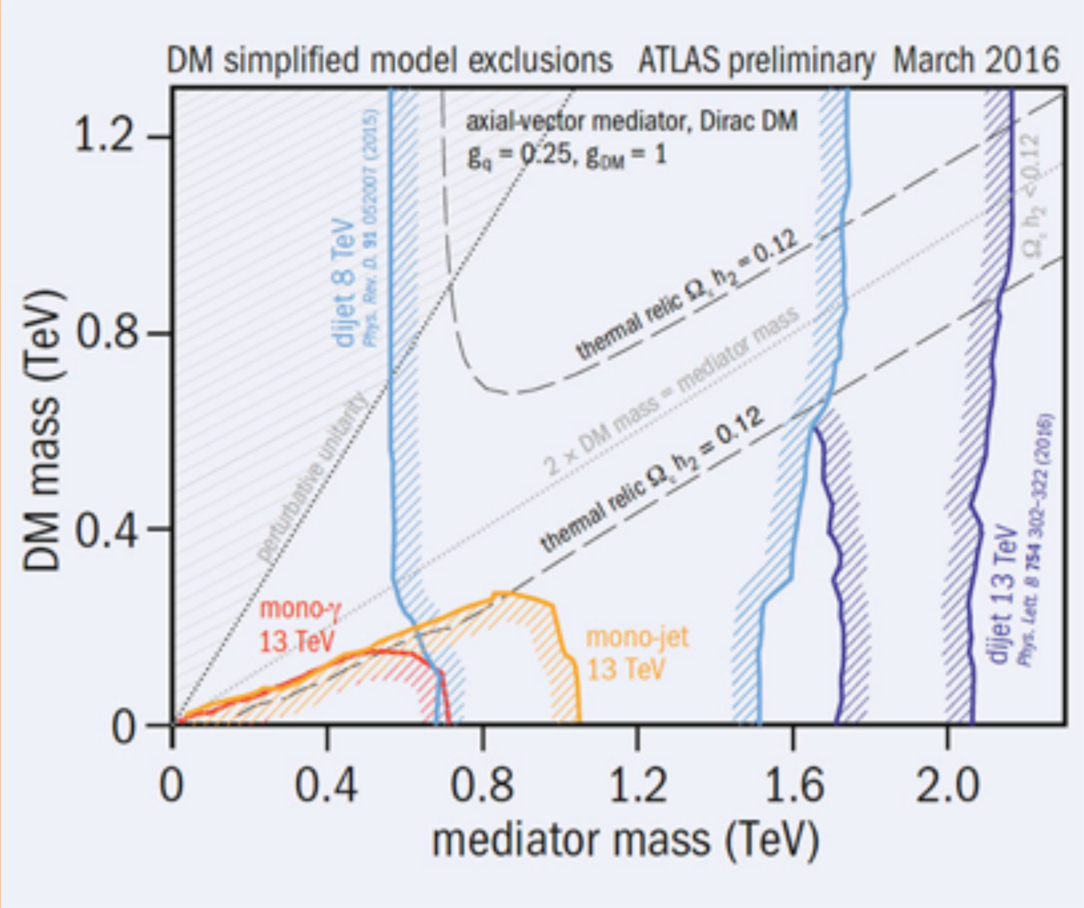
Physical information better captured by *generic* assumptions that encompass broad classes of models

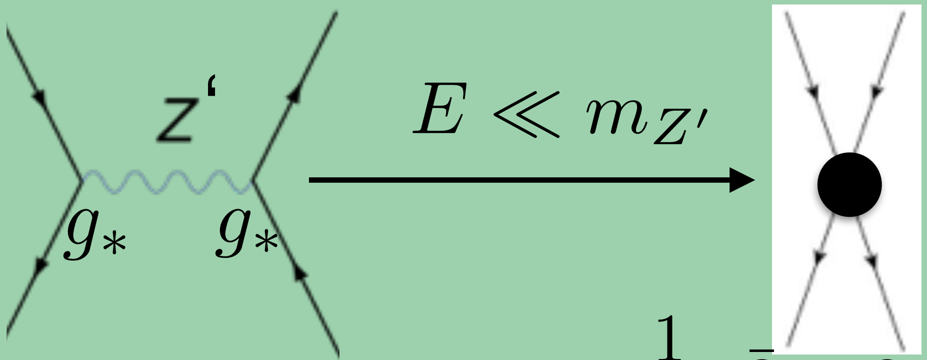
	Simplified Models	**Effective Field Theories (EFTs)**
Assumption:	There is only one mediator	mediator(s) are much heavier than LHC energies
Pro:	Good modeling of missing E	Simple and identifies very few (relevant) parameters
Contra:	Still many parameters/models	With present sensitivity, this hypothesis is not testing weakly coupled models

LHC

Example: DM-SM interaction mediated by new vector Z'

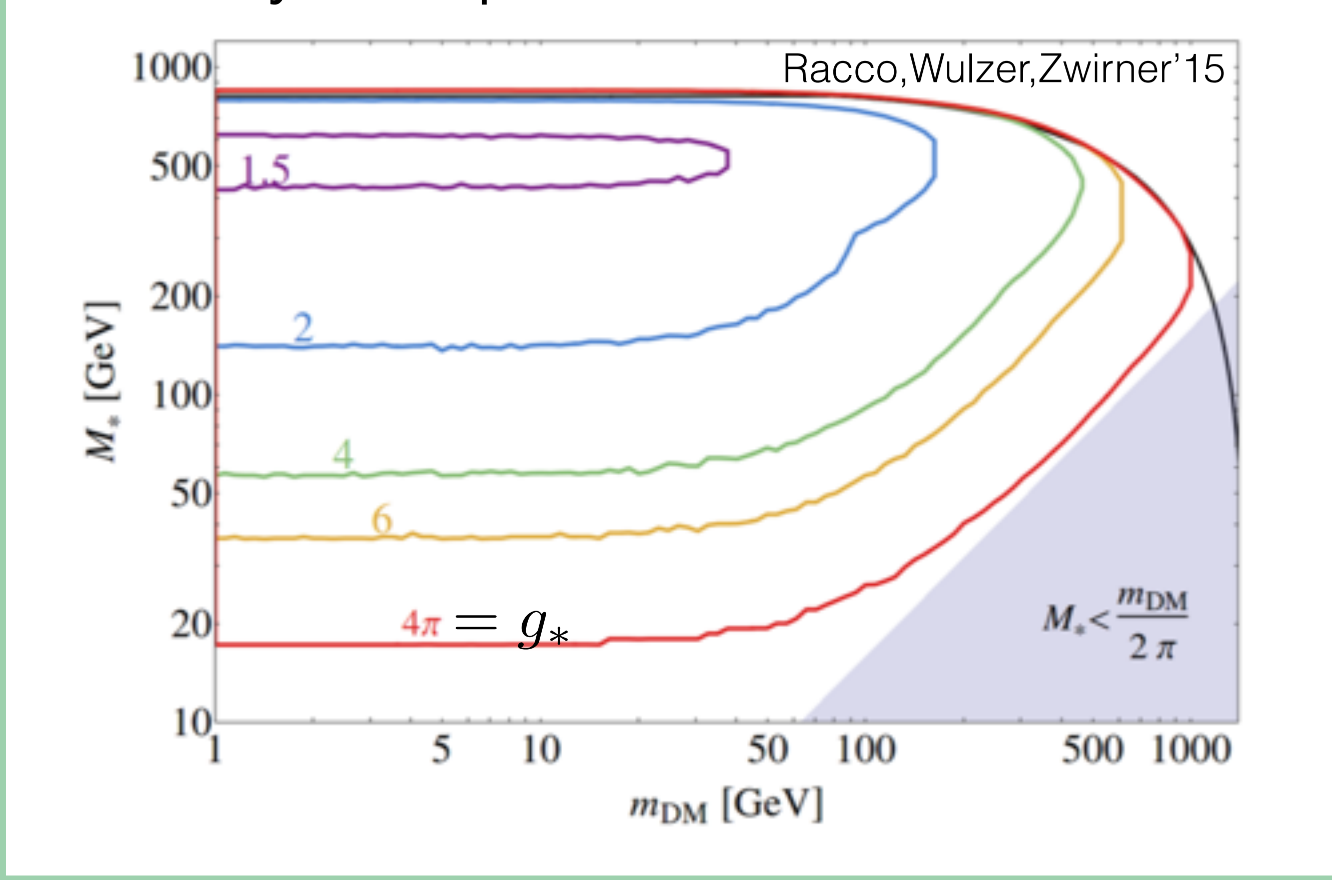






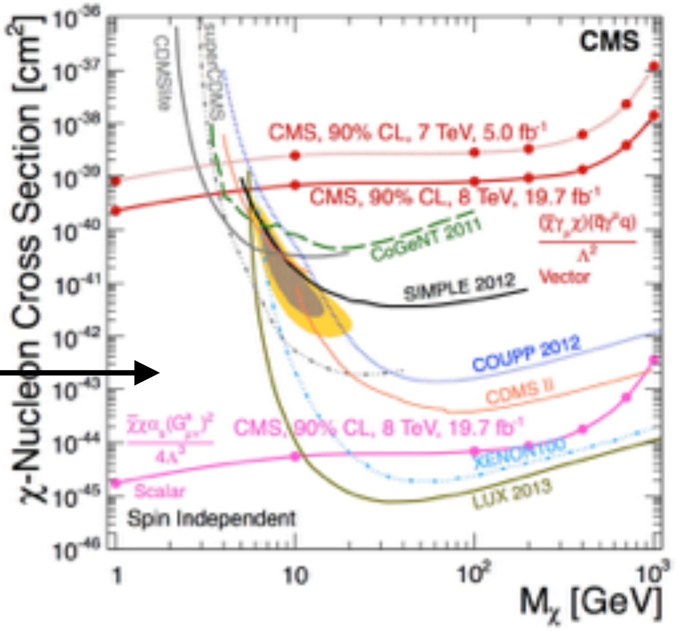
$$\frac{1}{M_*^2}\bar{Q}\gamma_\mu Q\,\bar{\chi}\gamma^\mu\chi$$

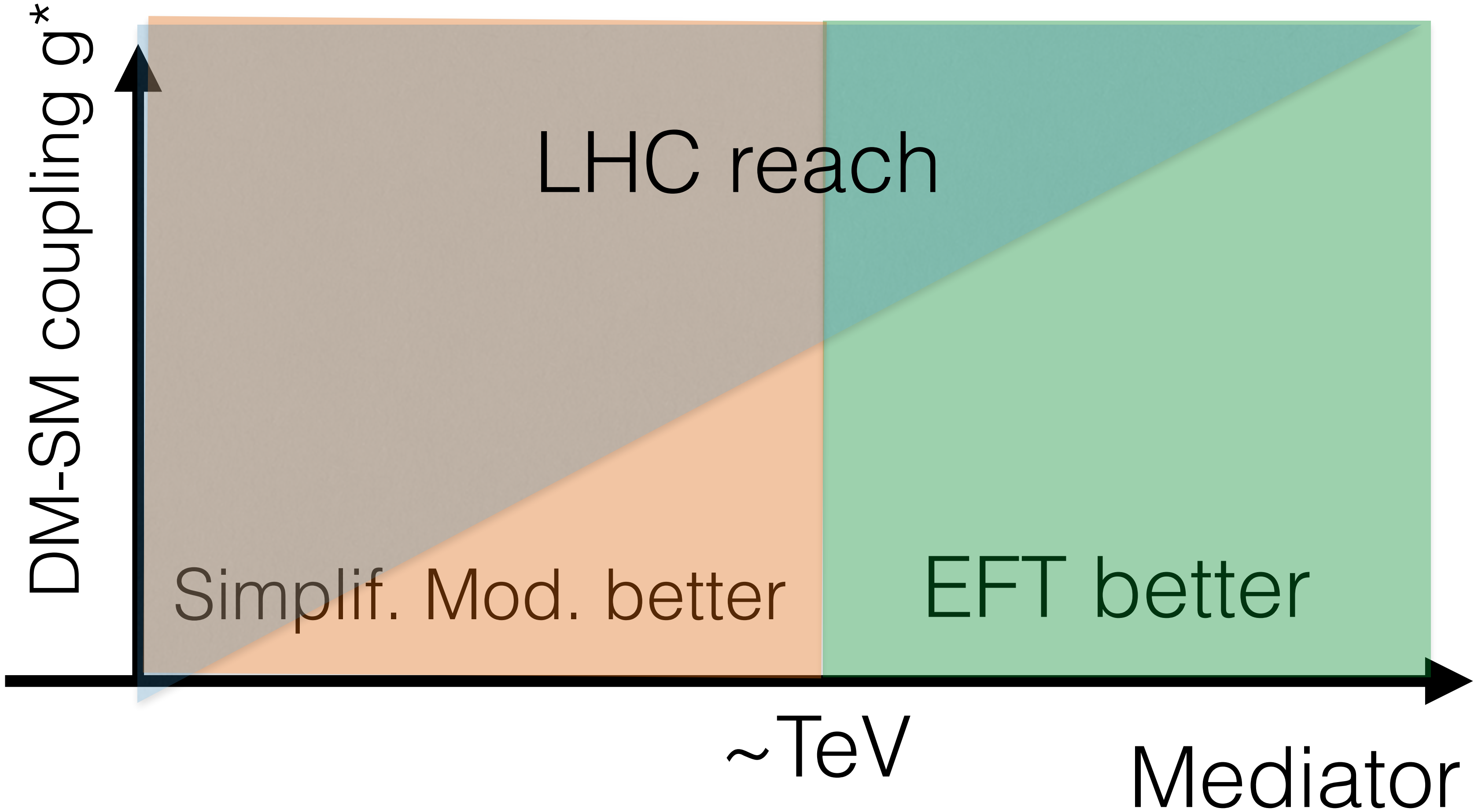
Only one parameter: $M_* = m_{Z'}/g_*$



LHC

LHC best for light DM
(below direct detection threshold)




DM-SM coupling g*

LHC reach

Simplif. Mod. better

EFT better

~TeV

Mediator Mass

- For weakly coupled (light) new physics: EFT
- For strongly coupled (heavy) new physics: EFT

(Moreover pion-like DM doesn’t have a simplified model, only EFT)

Bruggisser,Riva,Urbano’16

➙For maximally strongly coupled DM, mediators up to ~6 TeV are excluded

CONCLUSIONS

- Gravitational evidence for DM striking

  Moreover: not baryon, not neutrino (→BSM), not hot, not SM charged, stable

- If couples also non-gravitationally:
  - freeze-out (or asymmetric DM) provide suggestive production “miracles”
  - Direct(indirect) detection or the LHC might provide further evidence…

  …or they might not

Direct Detection

If (scalar) DM is so light (axion) that it behaves like a field (=large occupation numbers), a sizable signal can still be detected, searching for coherent* effects:

$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

*=Coherence is not guaranteed, even if the initial state is, since the cosmological history of different patches of these field might differ. Nevertheless the coherence time is set by the maximal frequency available to DM, which is determined by the virial velocity and for typical Axion masses $\tau_a \approx \frac{2\pi}{m_a v^2} \approx 10^{-4}\ sec$ is long enough