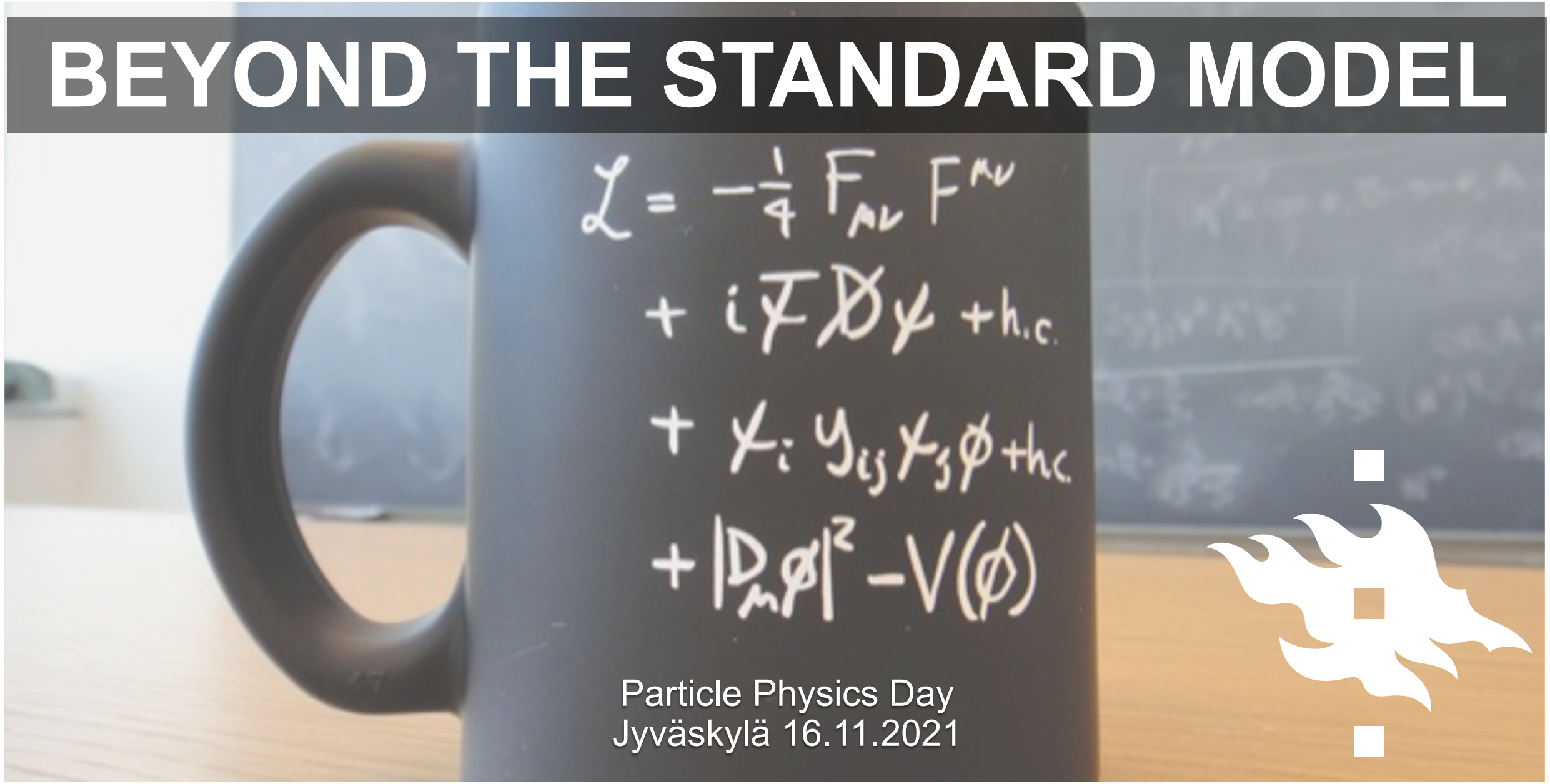
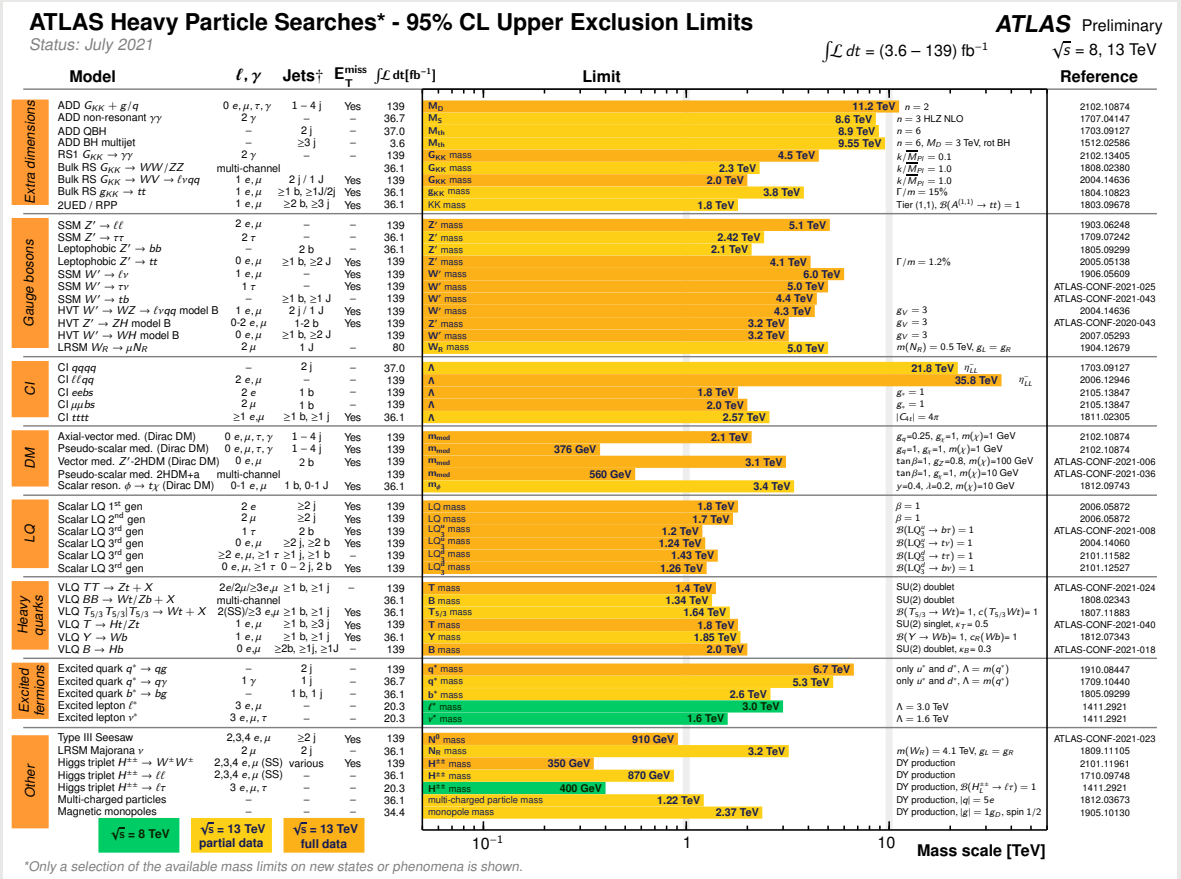
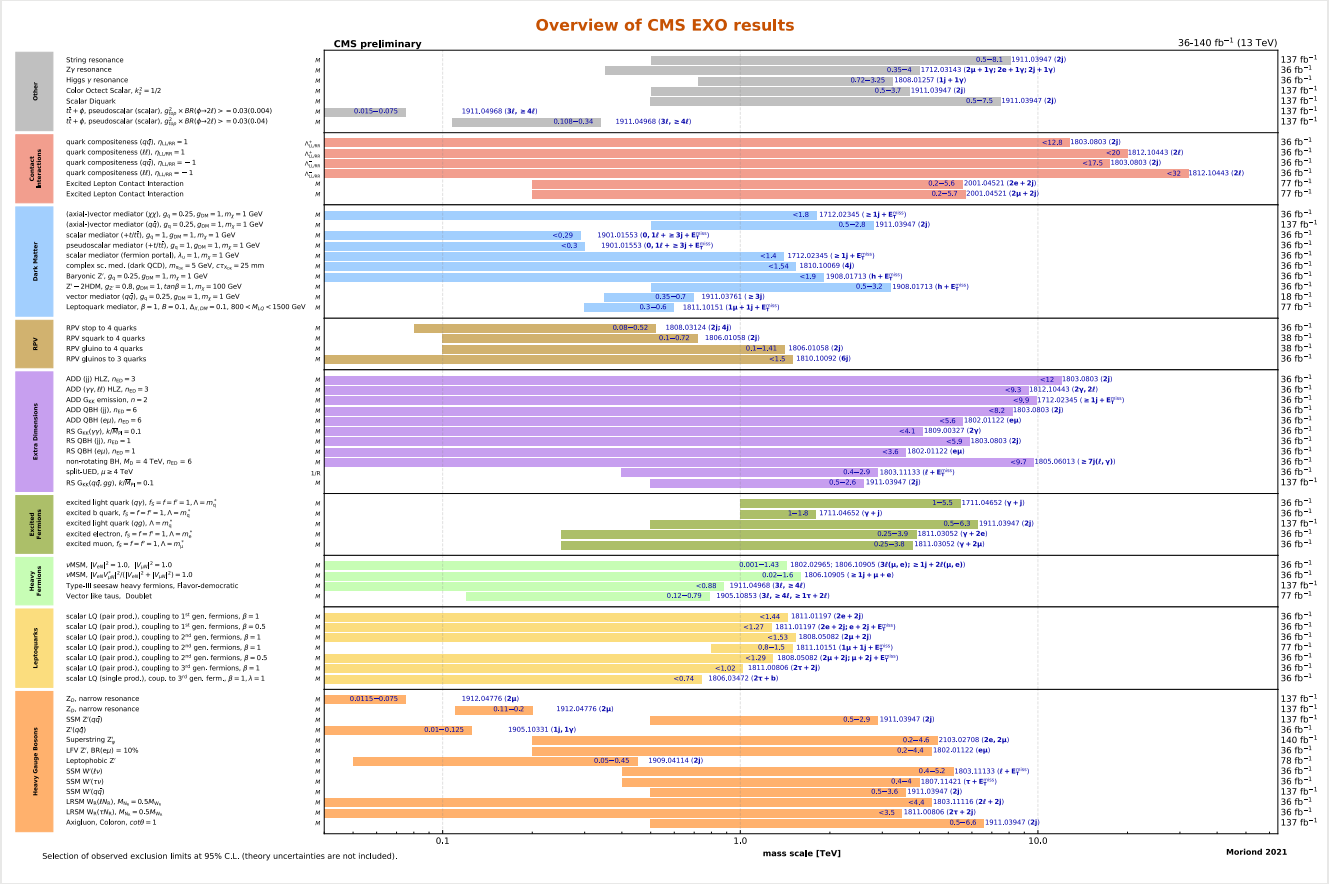
BEYOND THE STANDARD MODEL



Particle Physics Day
Jyväskylä 16.11.2021

CURRENT LIMITS ON NEW PHYSICS:





There is no target scale !

COMPARE TO EARLIER DISCOVERIES:

- Beyond the Fermi theory: W and Z bosons
- Beyond the bottom quark: top quark
- Beyond the electroweak theory: the Higgs boson

New physics scale known

Now: no.

MODEL LANDSCAPE BEFORE THE HIGGS DISCOVERY

Driven by “naturality problem”:

$m_H \sim m_0 + \Lambda^2$

Resolved by adding a spectrum of bosons and fermions

or

making the scale dynamical, leading to composite spectrum.

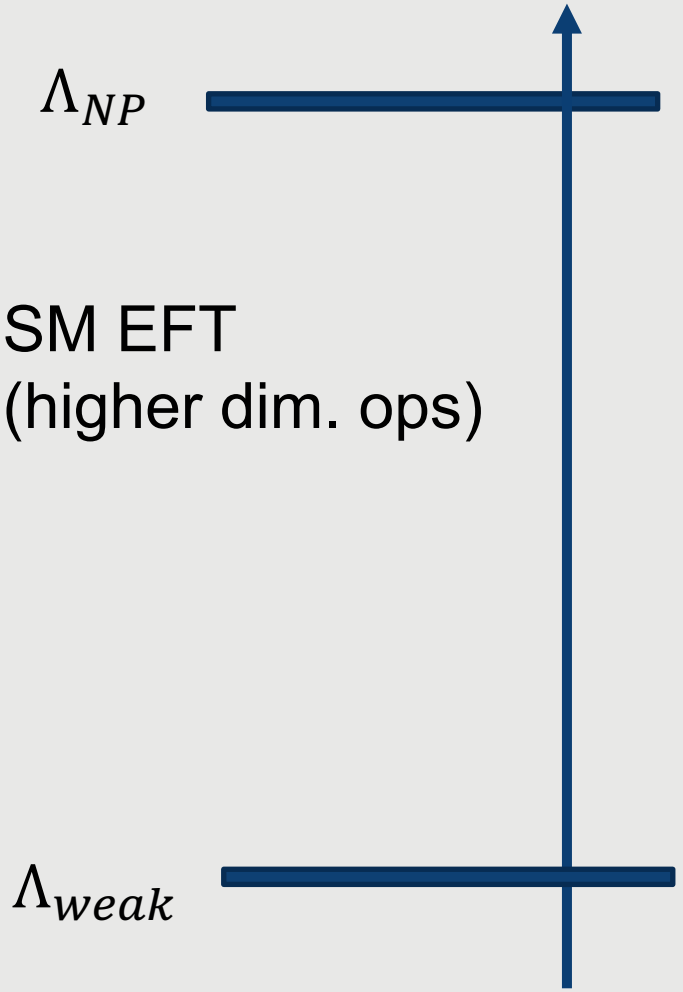
IS THERE A NEW LIGHT RESONANCE?

NO.

(N)NMSSM,

(Pseudo)Goldstone Higgs,

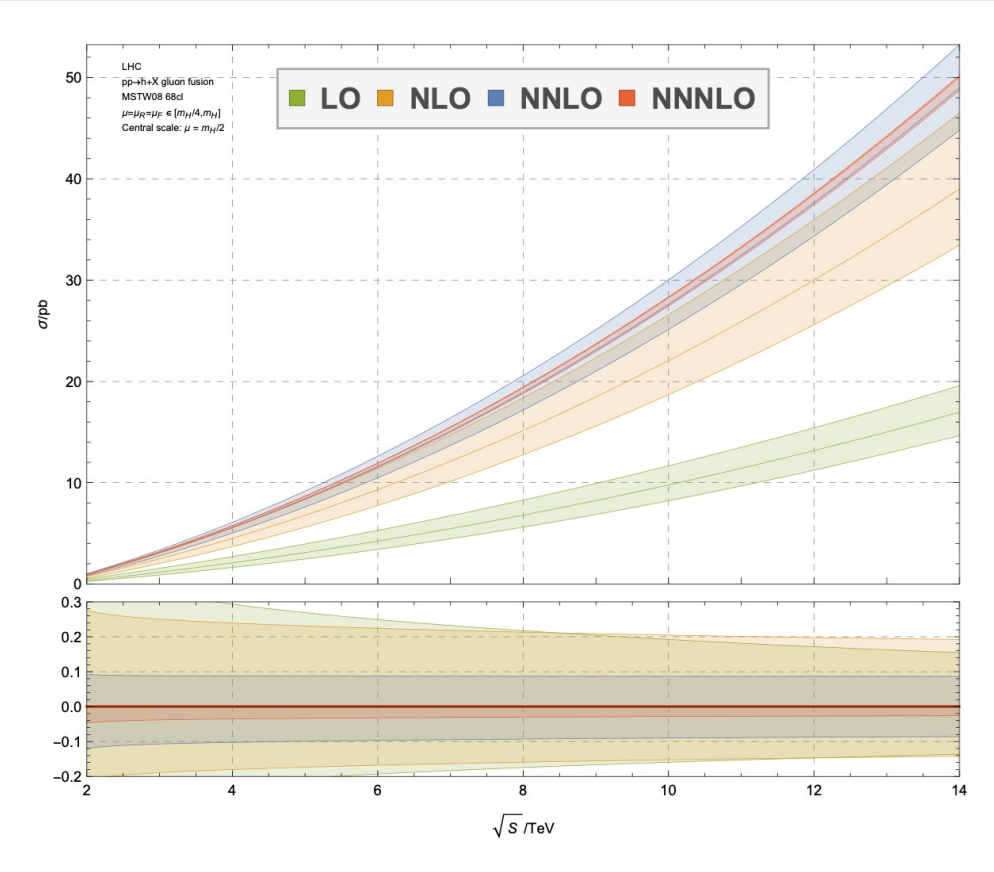
Walking Technicolor



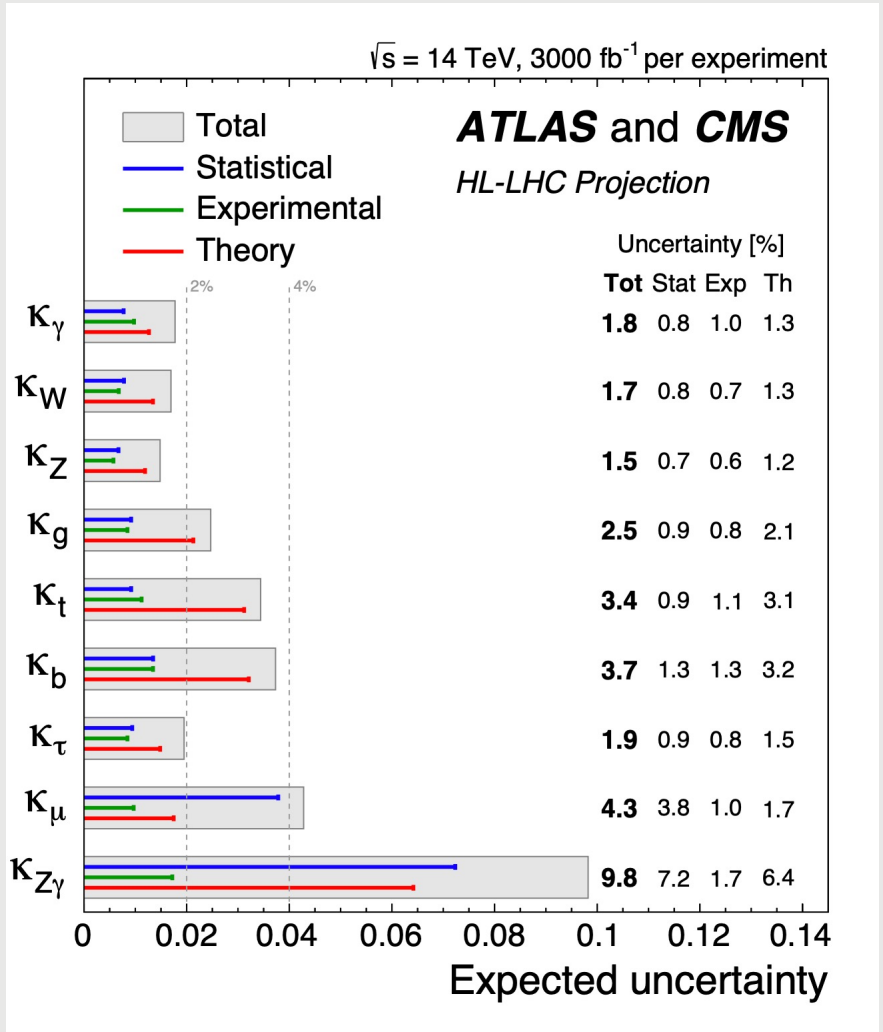
PRECISION MEASUREMENTS

e.g. $\kappa_i = (\text{Higgs coupling } i)/(\text{SM Higgs coupling } i)$

Higgs production at NNNLO 1503.06056



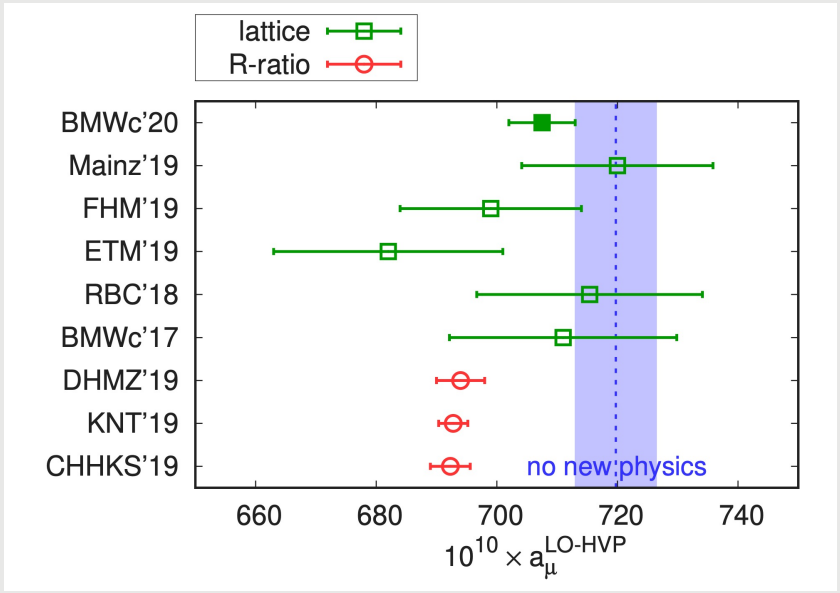
Much theory work required:

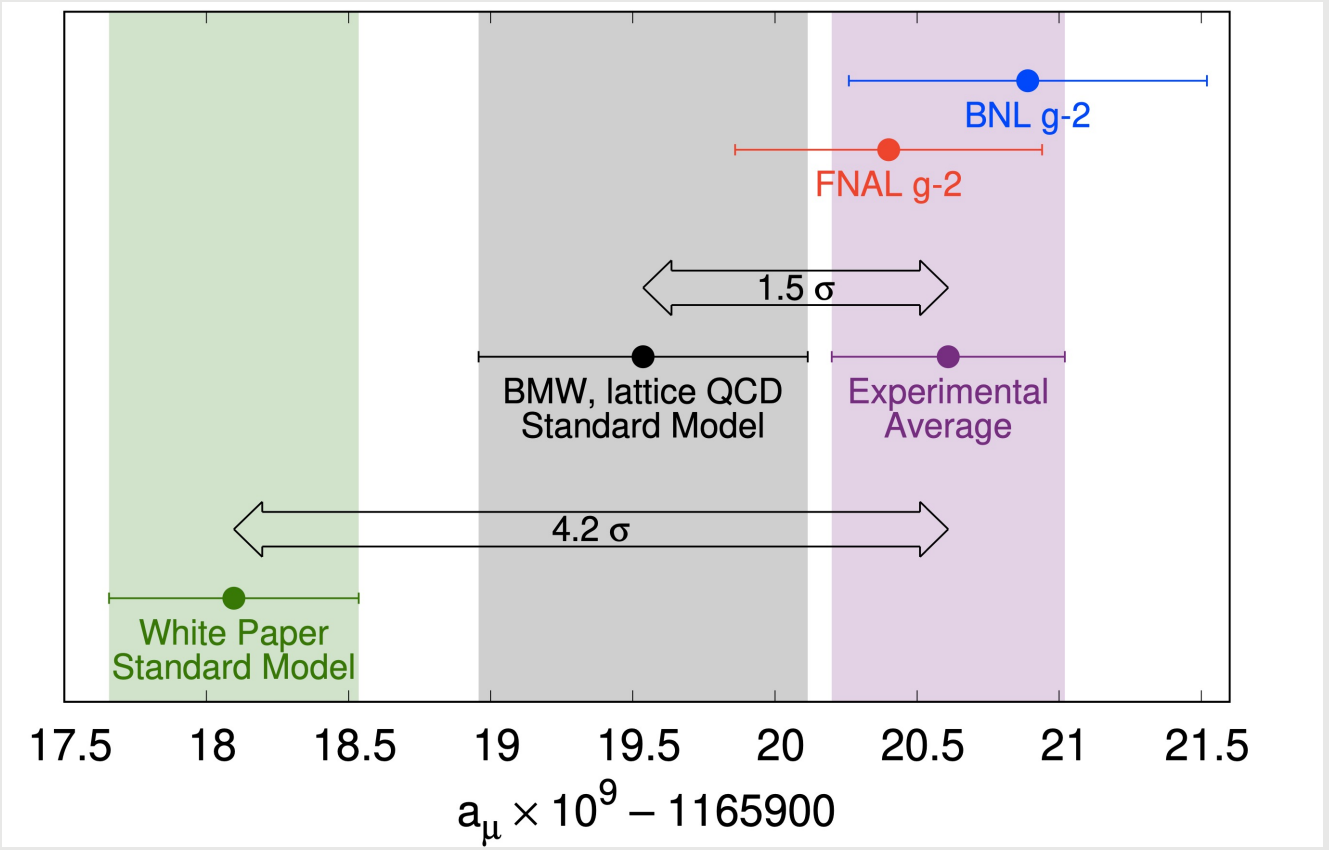


MAGNETIC MOMENTS

$$a_\mu(\text{SM}) = a_\mu(\text{QED}) + a_\mu(\text{Weak}) + a_\mu(\text{Hadronic})$$

QED +…	$116\,584\,718.9\,(1) \times 10^{-11}$	0.001 ppm
Weak +…	$153.6\,(1.0) \times 10^{-11}$	0.01 ppm
Hadronic…		
…Vacuum Polarization (HVP) α^2 +…	$6845\,(40) \times 10^{-11}$ [0.6%]	0.37 ppm
…Light-by-Light (HLbL) α^3 +…	$92\,(18) \times 10^{-11}$ [20%]	0.15 ppm





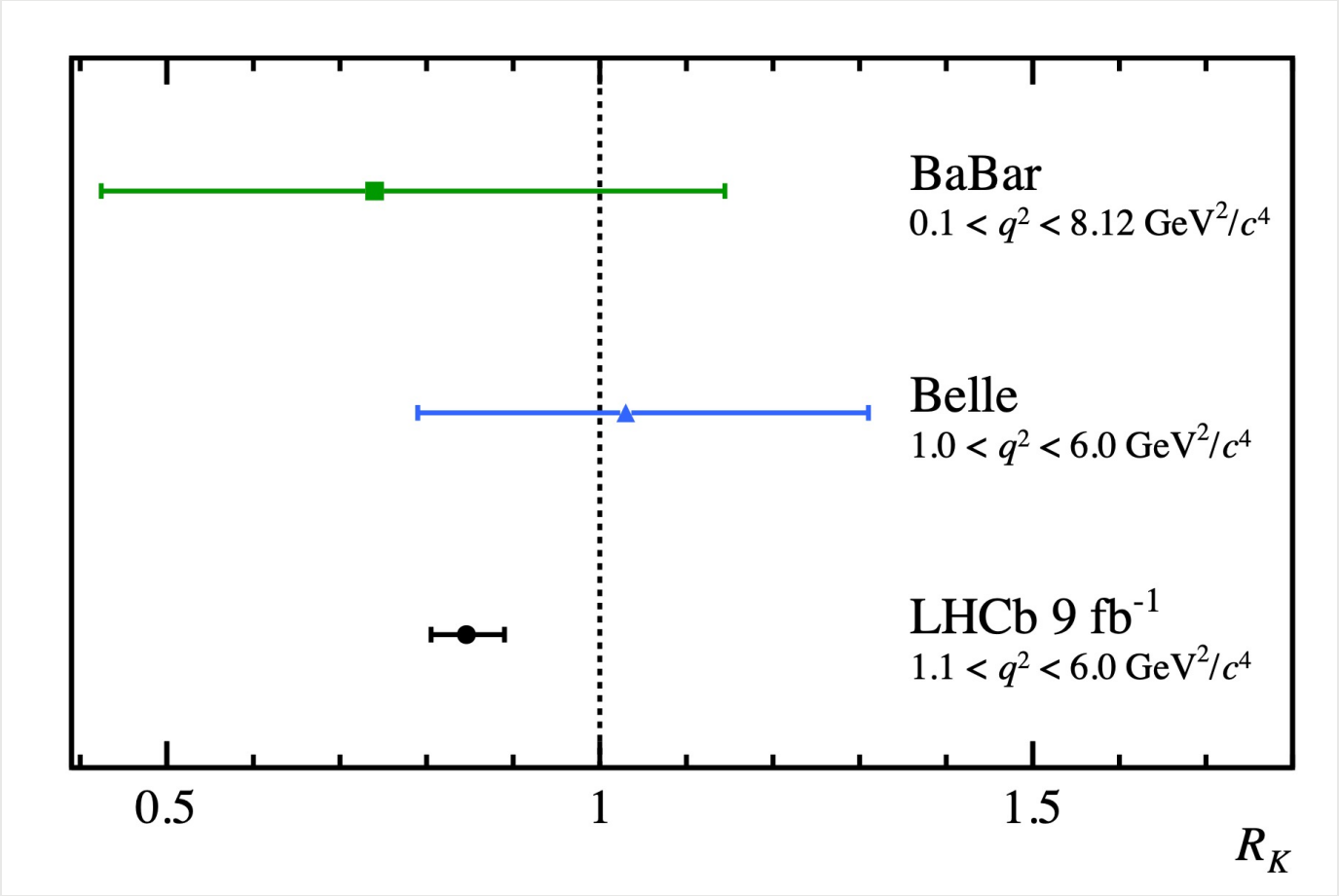
2002.12347

RARE PROCESSES

$$R_K = \frac{\int_{Q_1^2}^{Q_2^2} \frac{dB(B^+ \to K^+ \mu^+ \mu^-)}{dq^2} dq^2}{\int_{Q_1^2}^{Q_2^2} \frac{dB(B^+ \to K^+ e^+ e^-)}{dq^2} dq^2}$$

In SM $R_K = 1$ +(rad. corrections)

LHCb (2103.11769):
Lepton flavor violation at 3.1 σ



SM: FANTASTICALLY SUCCESSFUL YET GLARINGLY INCOMPLETE

Precision computations needed.

Many unanswered questions:

- Dark matter?
- Patterns of fermion masses?
- Baryogenesis?
- Strong CP violation?
- Origin of EW scale?
- Why three generations?
- Why one Higgs doublet?

DARK MATTER: EVIDENCES

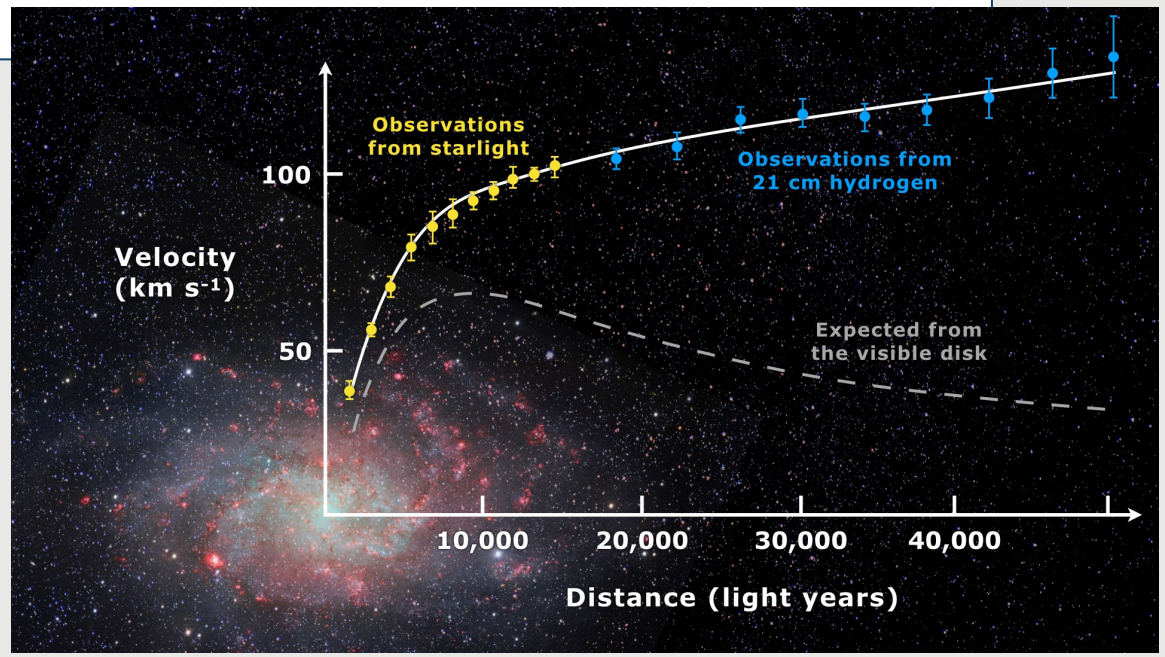
A stable, neutral massive particle:

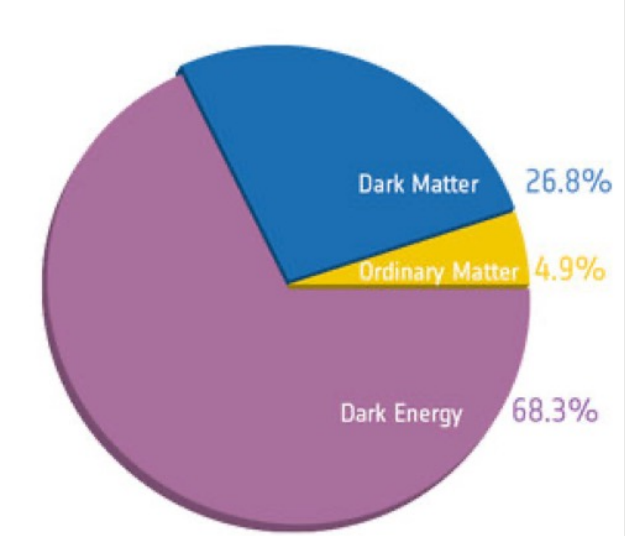
Galaxies: rotational velocities of stars

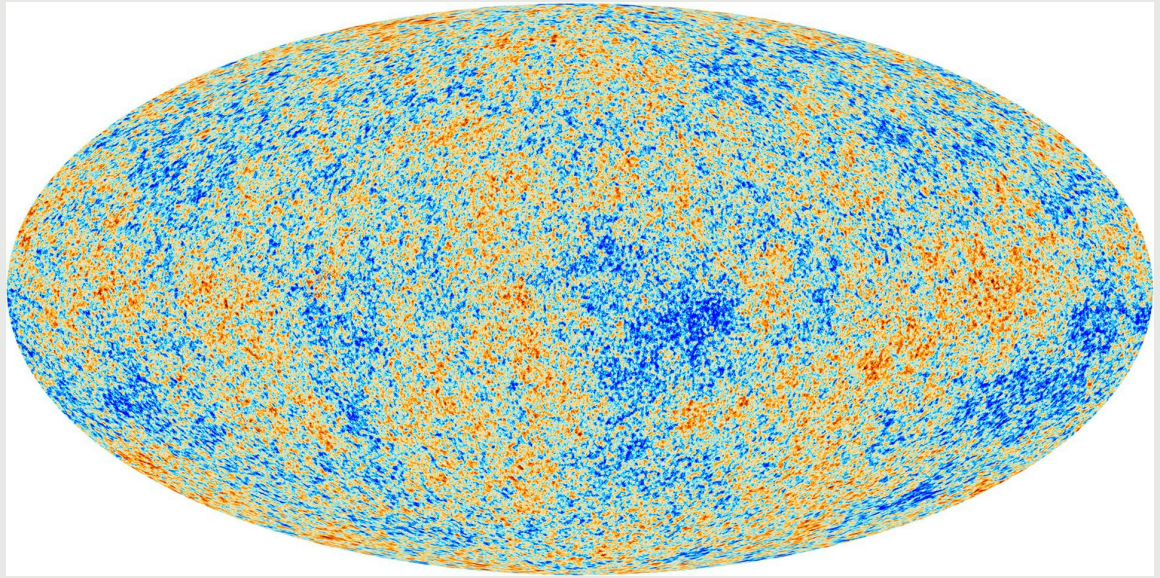
Clusters: velocity distribution of galaxies

Obsevable universe: CMB data

$\Omega_{DM} \simeq 0.268$







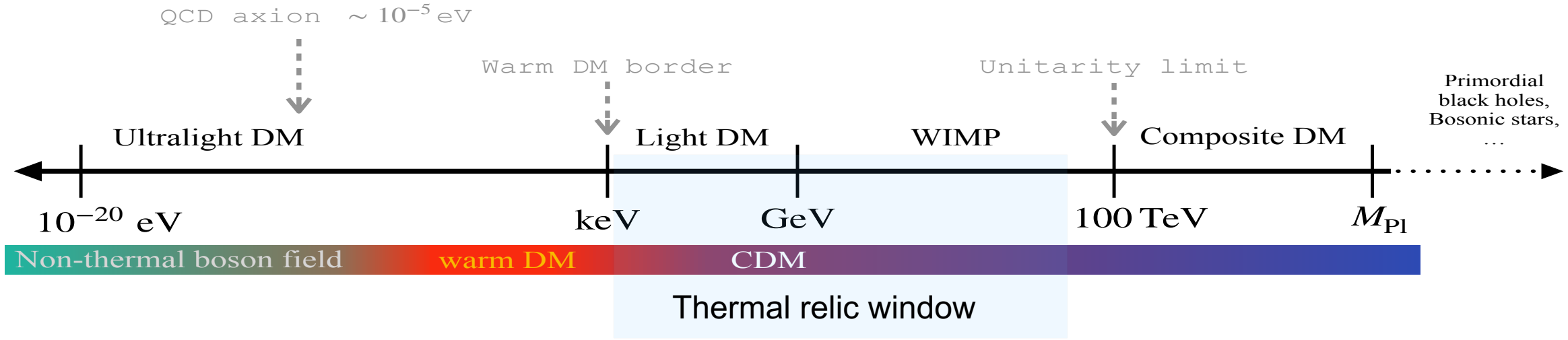
DARK MATTER: MAIN QUESTIONS

	MSSM
Nature of DM?	Well motivated: a superpartner
Mass scale of DM?	Hierarchy/ naturality: around EW scale
Stability of DM?	Put in by hand: R-parity.

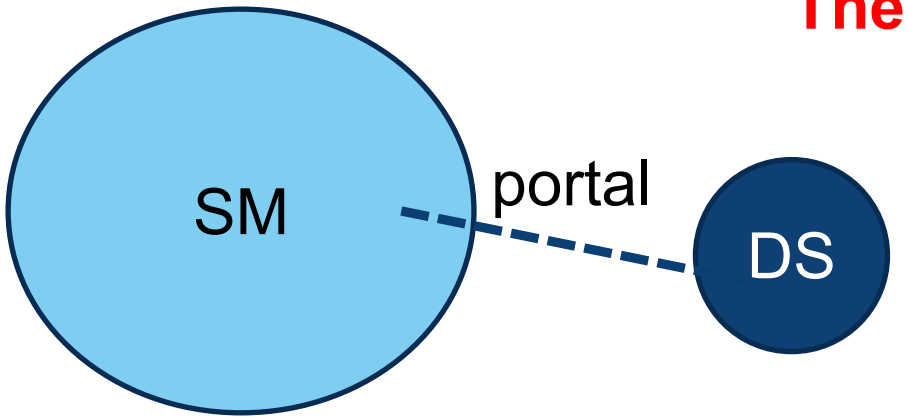
DARK MATTER: MAIN QUESTIONS

	TECHNICOLOR
Nature of DM?	Well motivated: a technibaryon
Mass scale of DM?	Above TeV
Stability of DM?	Technibaryon number

DARK MATTER: MAIN QUESTIONS

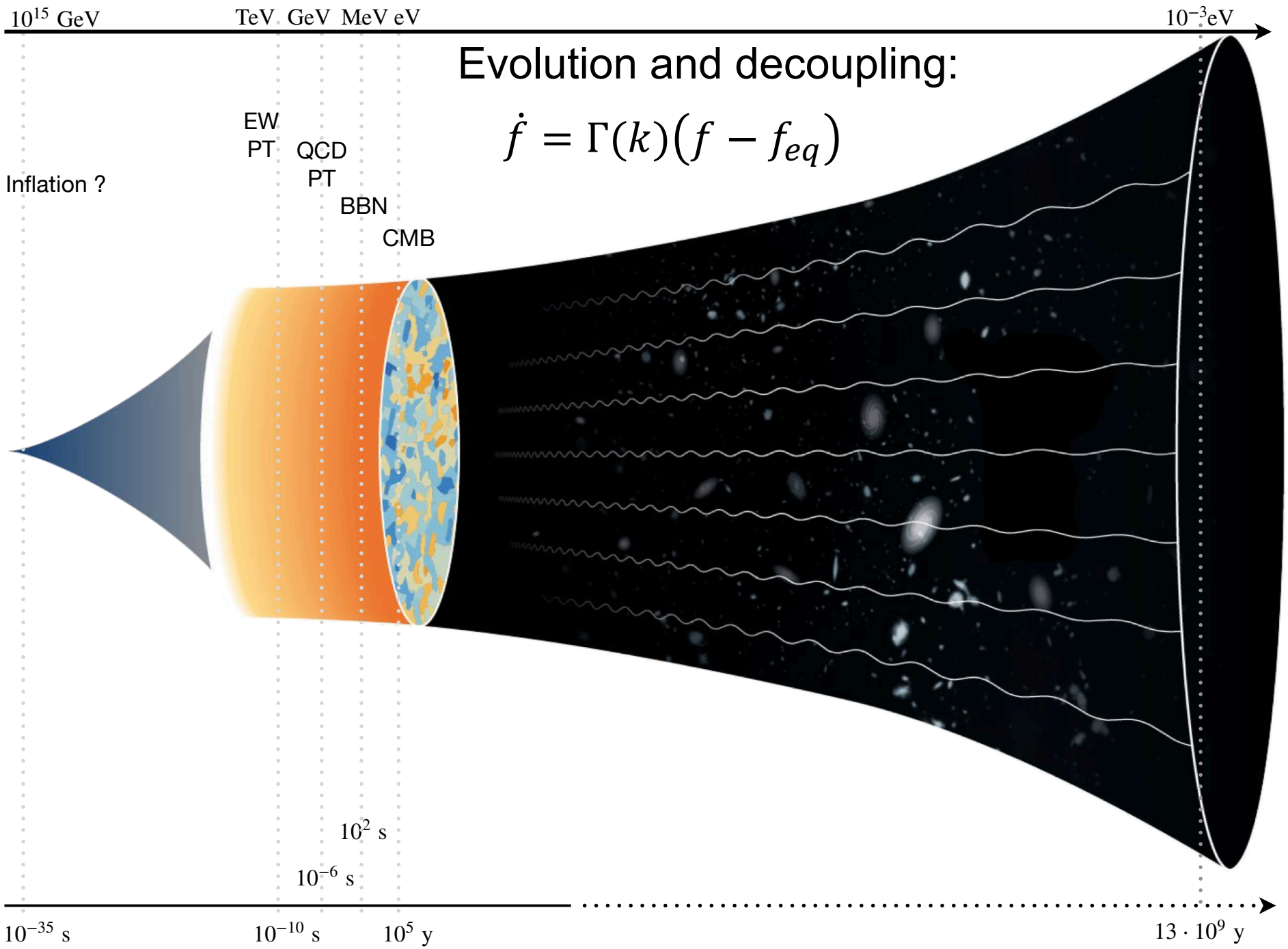


There is no target scale !



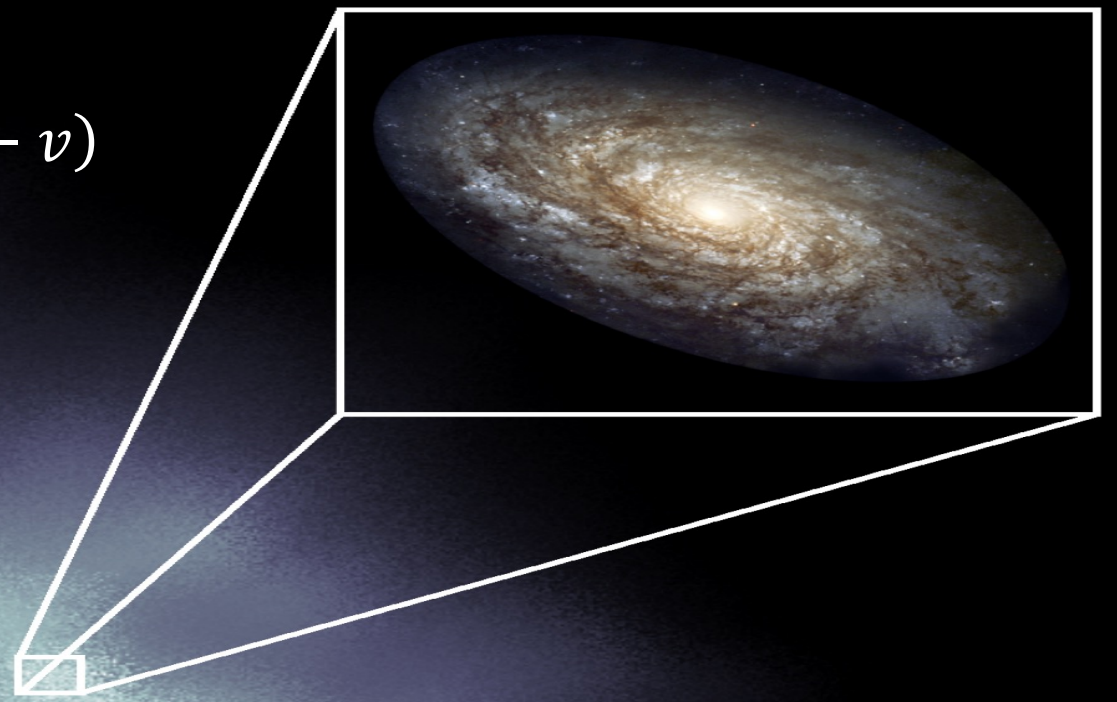
SM as observed + hidden sector

Simple benchmark models for DM


10^{15} GeV
TeV
GeV
MeV
eV
10^{-3}eV
Evolution and decoupling:
$\dot{f} = \Gamma(k)(f - f_{eq})$
EW PT
QCD PT
Inflation ?
BBN
CMB
10^{2} s
10^{-6} s
10^{-35} s
10^{-10} s
10^{5} y
$13 \cdot 10^{9}$ y

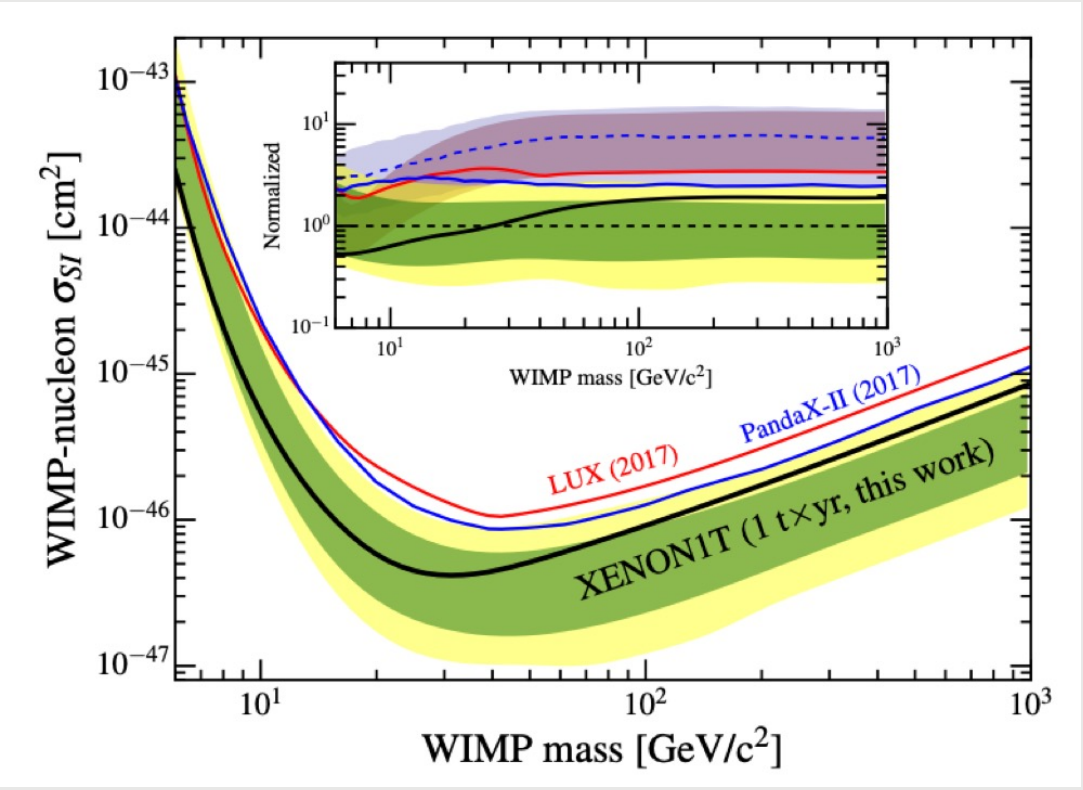
$\rho_{DM} \simeq 0.3$ GeV/cm^3

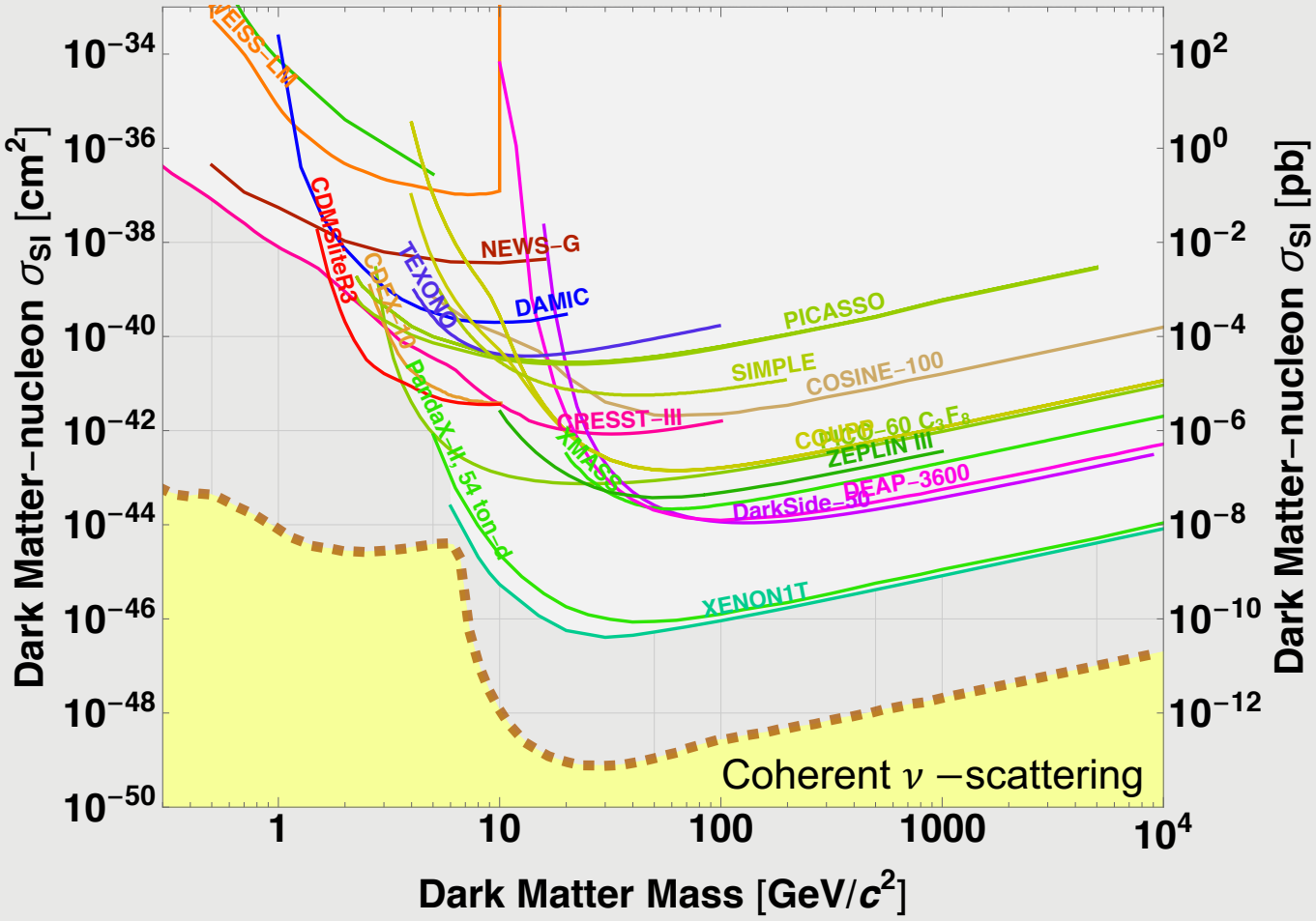
Velocity distribution: $f(v) \sim \exp\left(-\frac{v^2}{v_0^2}\right)\theta(v_{esc} - v)$



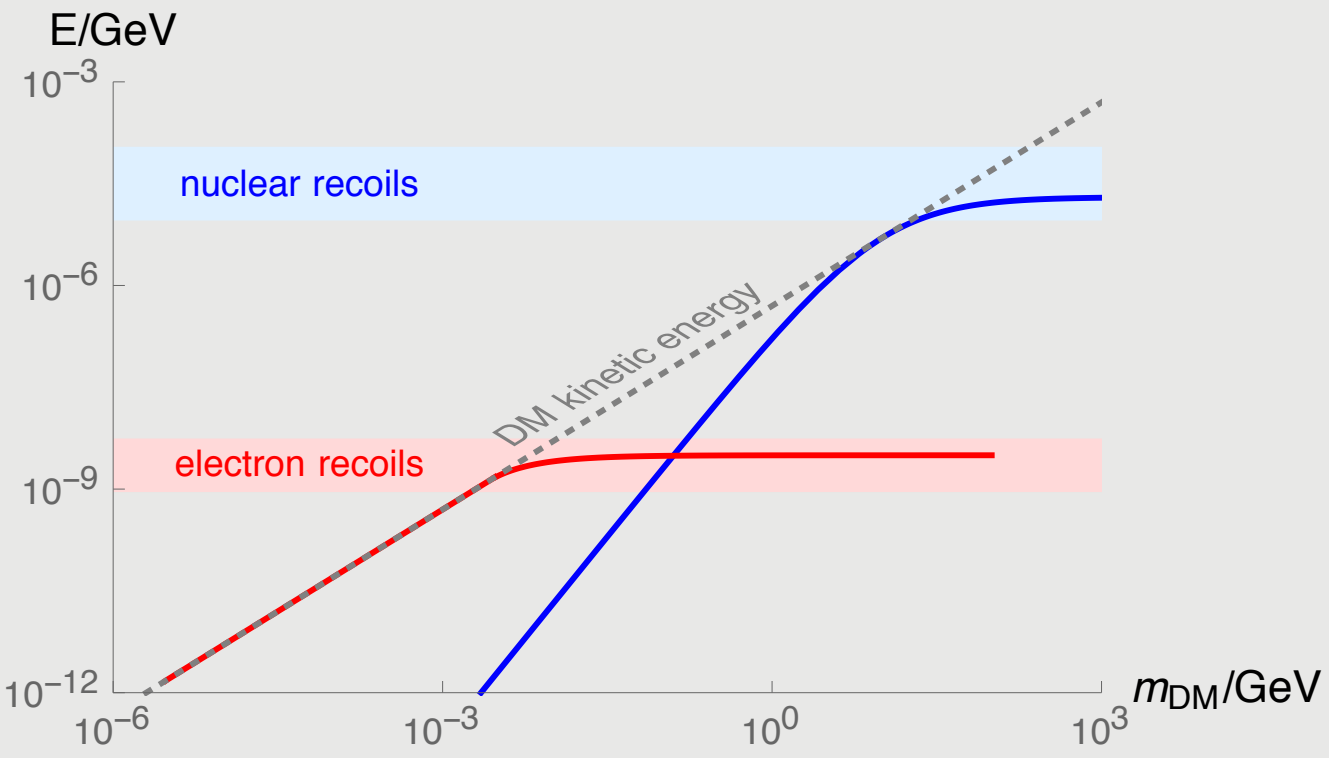
DM SCATTERING ON NUCLEI

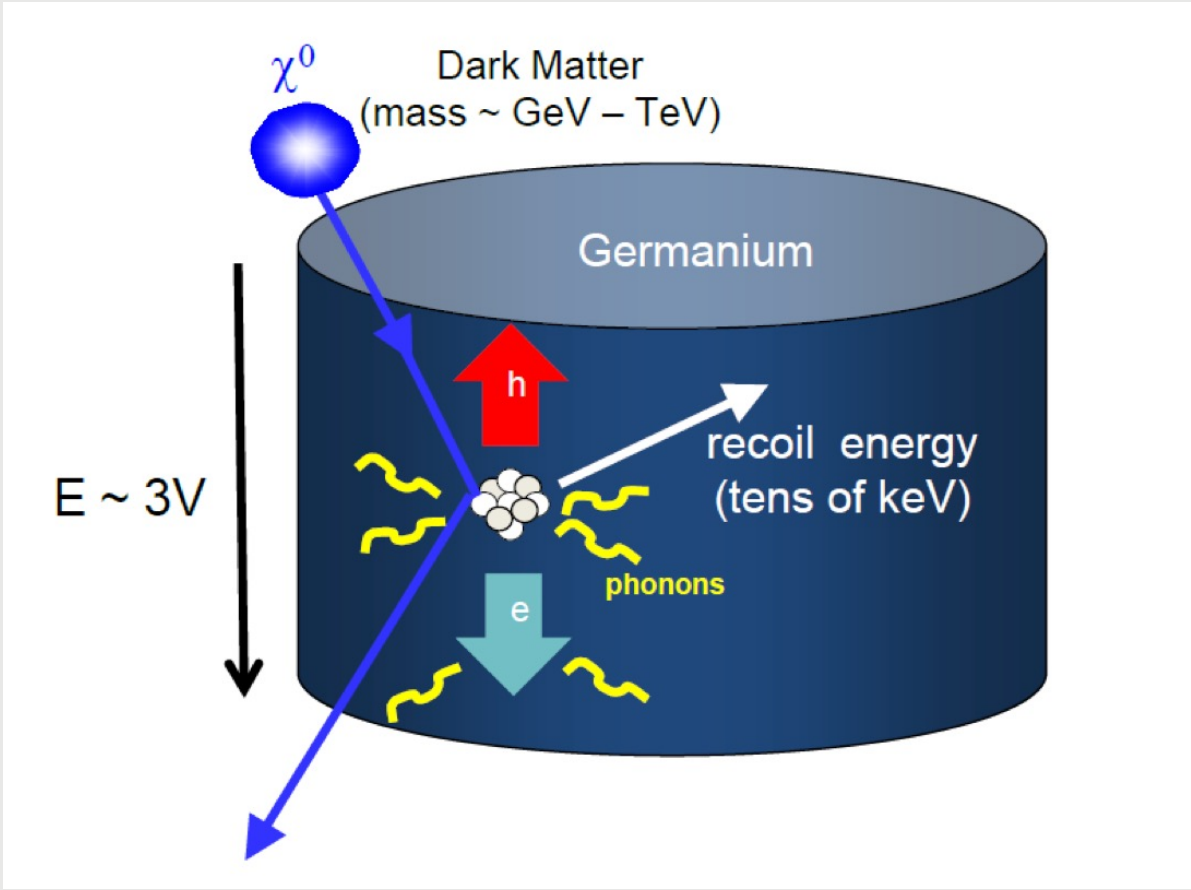
Xenon1T 1805.12562





$$\frac{dR}{dE_R} = N_T n_{DM} \int \frac{d\sigma}{dE_R} v f(v) d^3v$$



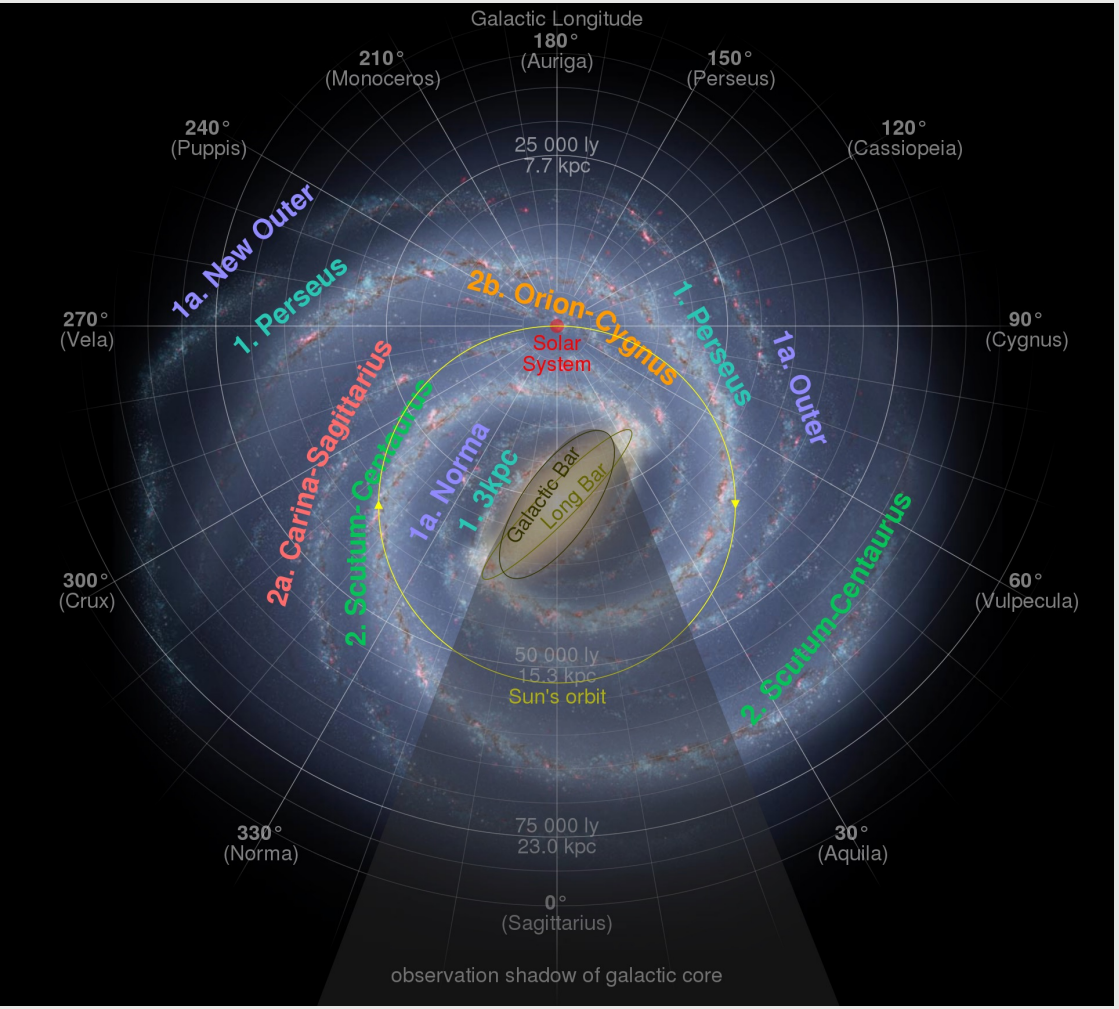


Smaller DM masses, smaller recoil energies.

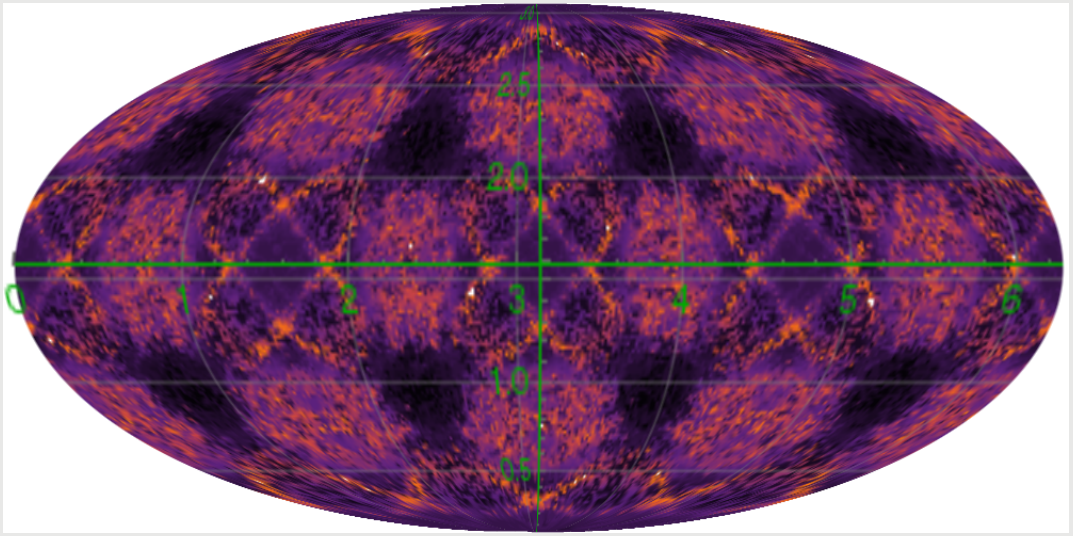
$E \sim O(10 - 100\ \mathrm{eV}) \sim$ atomic displacement energy.

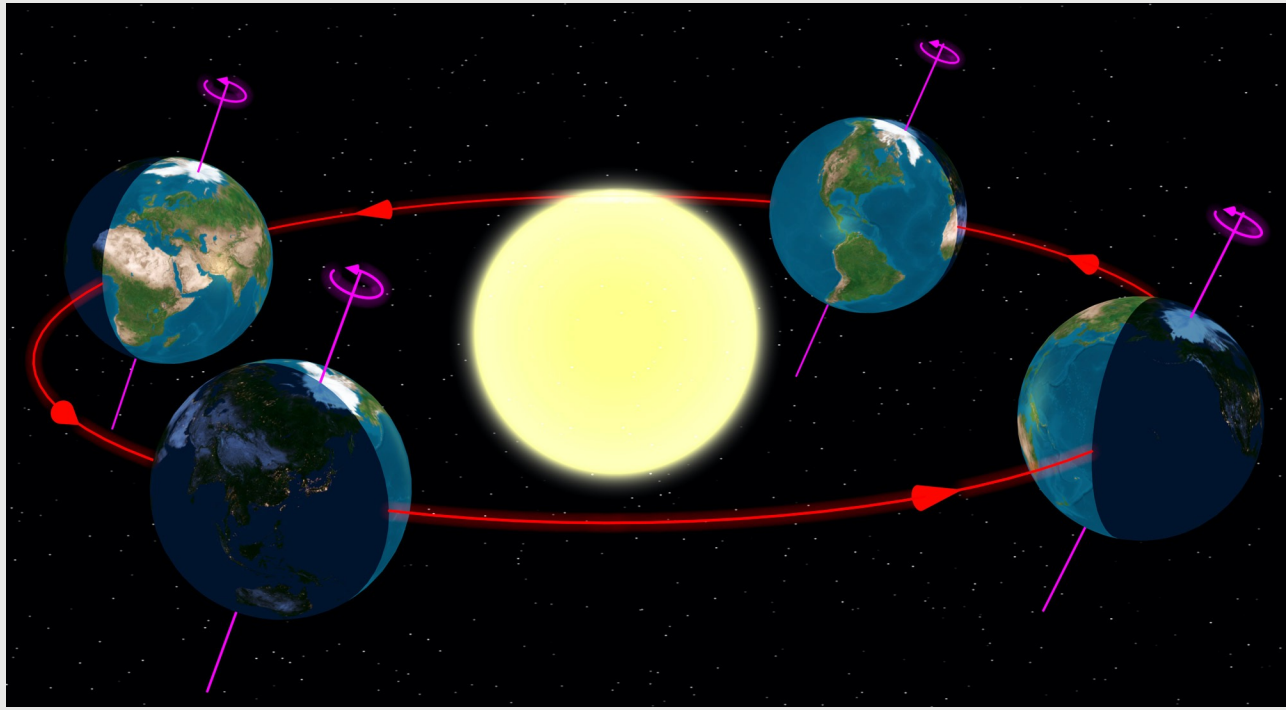
Effects dependent on material properties.

Constant level of recoils
as the Sun moves in the Galaxy.

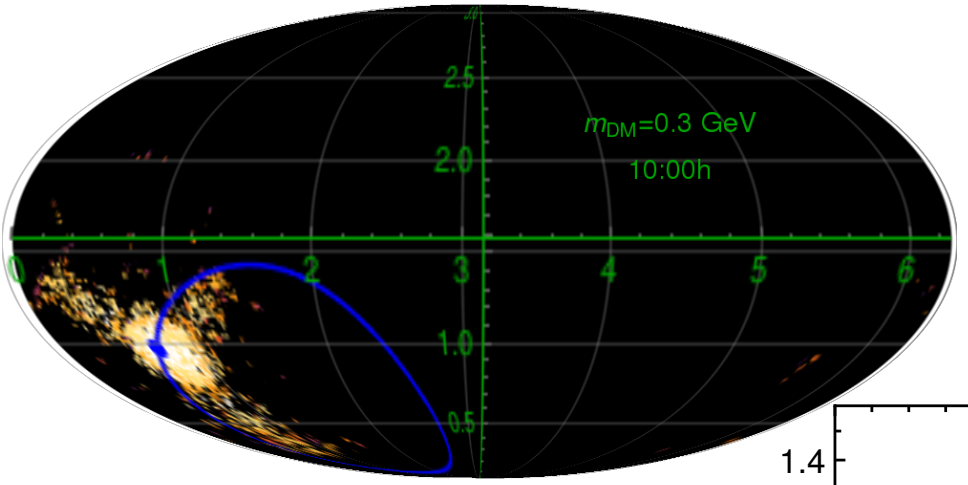


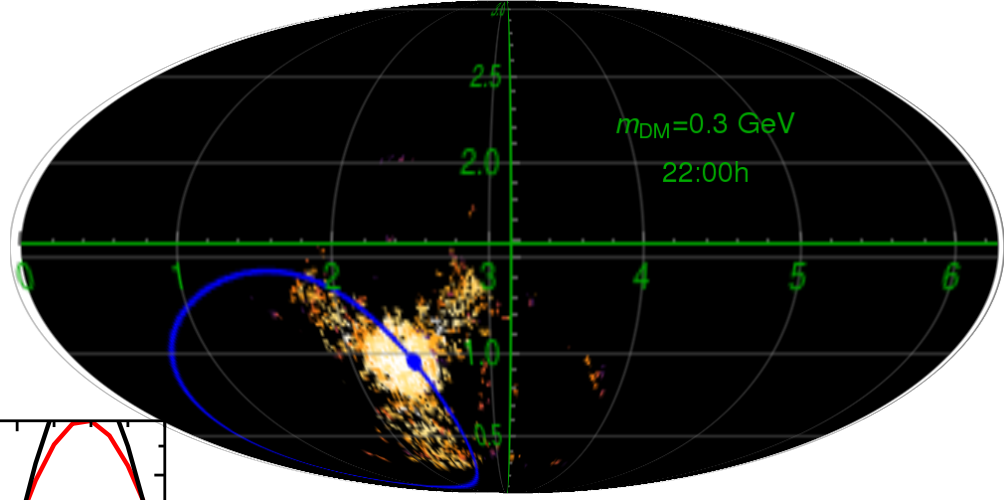
Threshod energies in Ge



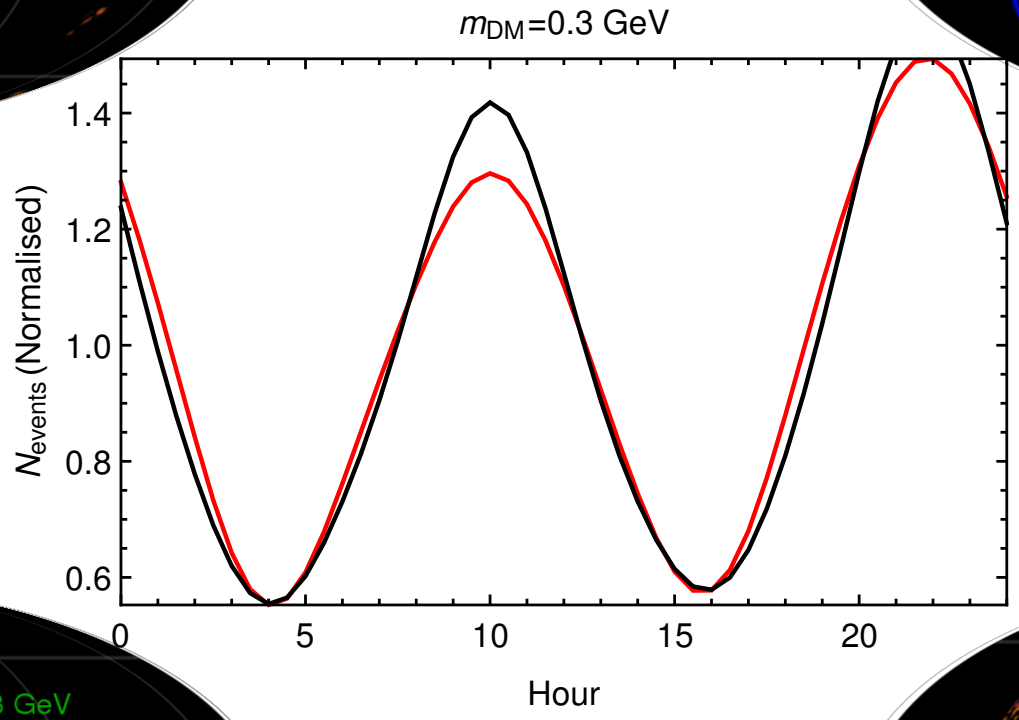


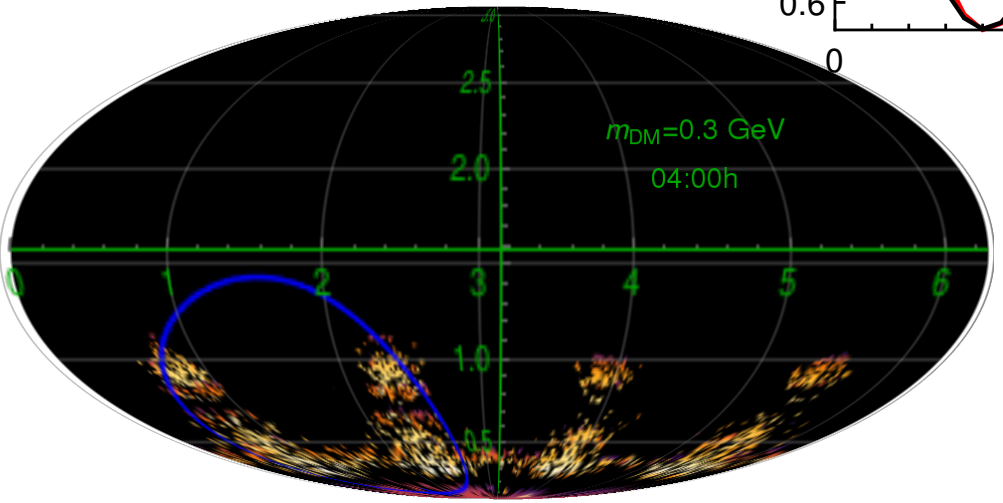
Additional effects from
movement of the Earth

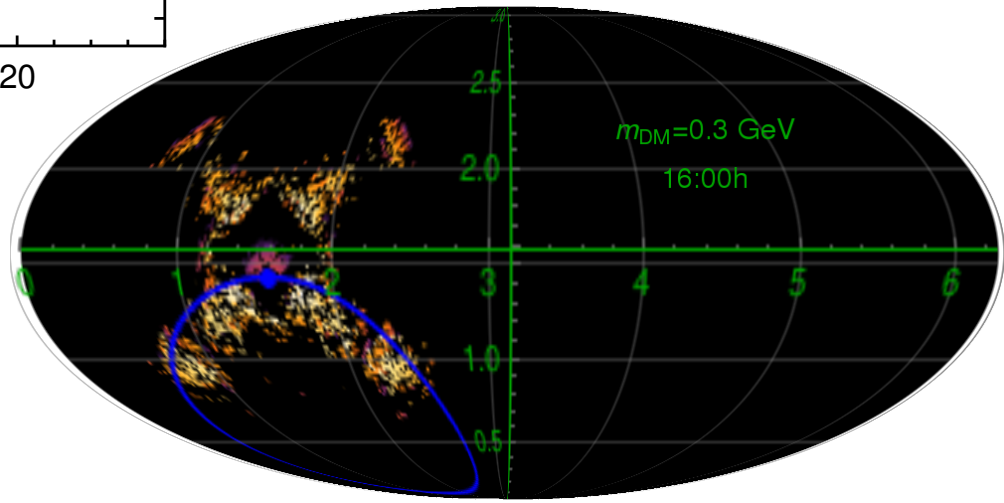




Total rate:







1903.08654
2103.08511

CONCLUSIONS

There are things we know
- SM

There are things we know we do not know,
- SM observables at high precision
- Nature of DM

Lots of interesting work to be done
- Precision QFT, lattice,…
- New concepts for DM detection
- Connections to materials science