

BEYOND THE STANDARD MODEL

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i\bar{\psi} \not{D} \psi + \text{h.c.} \\ & + \chi_i Y_{ij} \chi_j \phi + \text{h.c.} \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

Particle Physics Day
Jyväskylä 16.11.2021



CURRENT LIMITS ON NEW PHYSICS:

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: July 2021

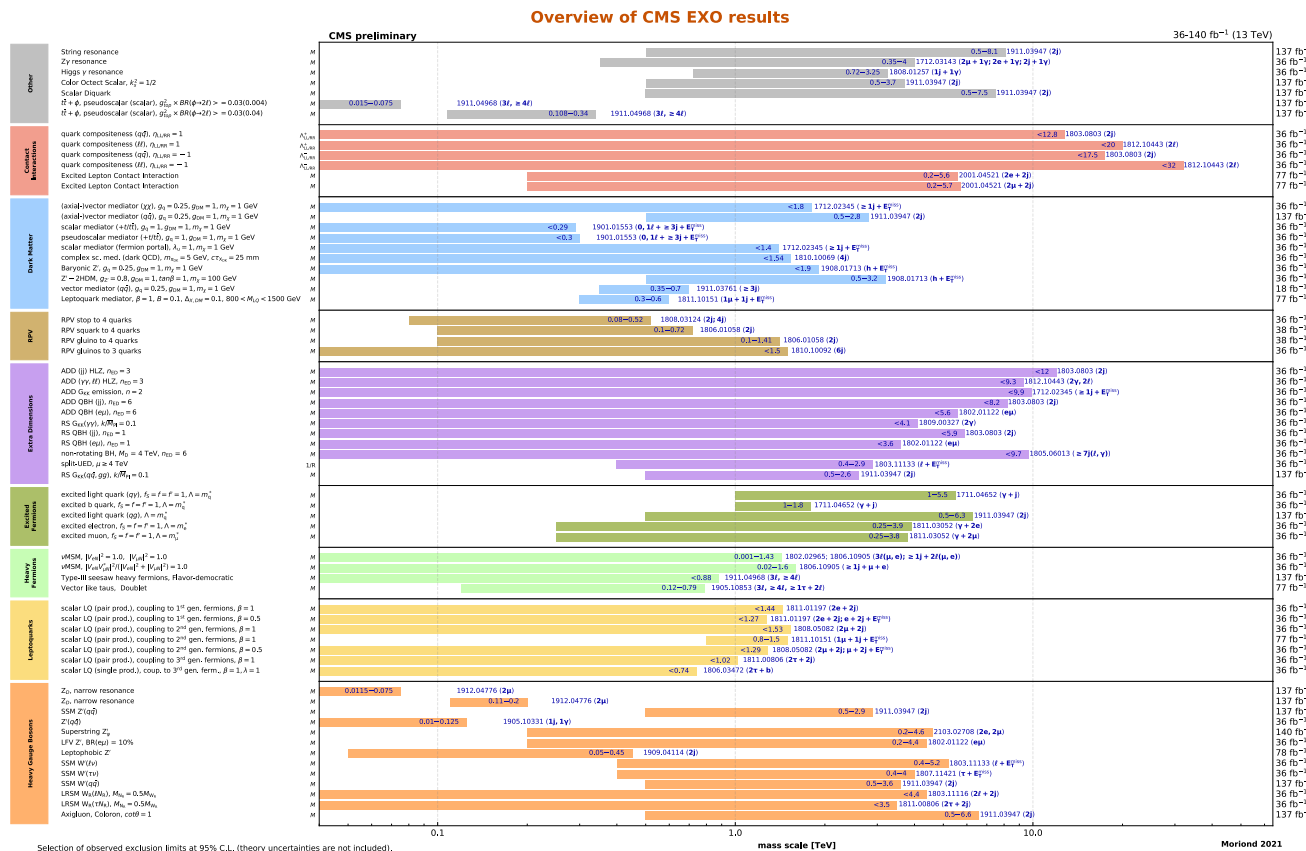
ATLAS Preliminary

$$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1} \quad \sqrt{s} = 8, 13 \text{ TeV}$$

Model	ℓ, γ	Jets†	E_{miss}^\dagger	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
Extra dimensions	ADD $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	M_D 11.2 TeV M_2 8.6 TeV M_{KK} 8.9 TeV M_{KK} 9.55 TeV	2102.10874 1707.04147 1703.09127 1512.02586 2102.13045 1808.02380 2004.14636 1804.10823 1803.09678
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	Z' mass 2.42 TeV Z' mass 2.1 TeV	1903.06248 1708.07242 1805.00299 2005.05138 1906.05609
CI	CI $qqqq$	$2 e, \mu$	$2 j$	-	37.0	A 21.8 TeV η_{LL}	1703.09127
DM	Axial-vector med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	m_{DM} 376 GeV	2102.10874
LO	Scalar LO 1 st gen	$2 e$	$\geq 2 j$	Yes	139	LO mass 1.8 TeV	2006.05872
Heavy quarks	VLO $T\bar{T} \rightarrow Z\ell + X$	$2e/2\mu/3e/\mu$	$\geq 1b, \geq 1j$	-	139	T mass 1.4 TeV	ATLAS-CONF-2021-024
Excited fermions	Excited quark $q^* \rightarrow qg$	1γ	$1 j$	-	139	q^* mass 3.7 TeV	1708.10440
Other	Type III Seesaw	$2,3,4 e, \mu$	$\geq 2 j$	Yes	139	N^0 mass 910 GeV	ATLAS-CONF-2021-023

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).



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 “naturalness problem”:

$$m_H \sim m_0 + \Lambda^2$$

Resolved by adding a spectrum of bosons and fermions

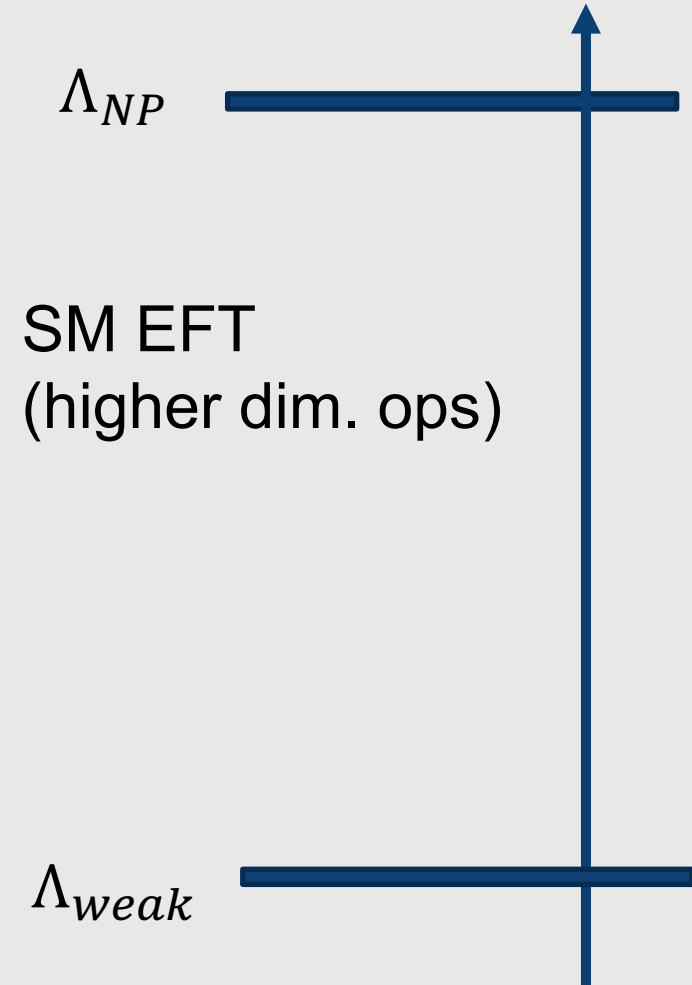
or

making the scale dynamical, leading to composite spectrum.

IS THERE A NEW LIGHT RESONANCE?

NO.

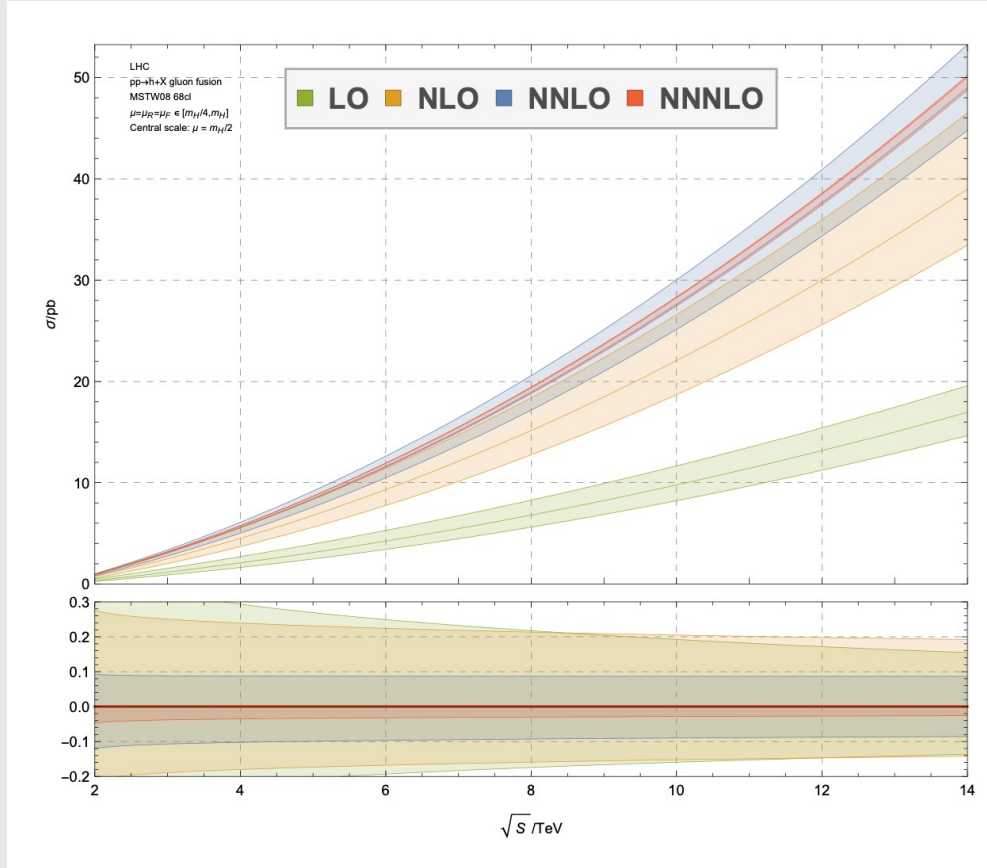
(N)NMSSM,
(Pseudo)Goldstone Higgs,
Walking Technicolor



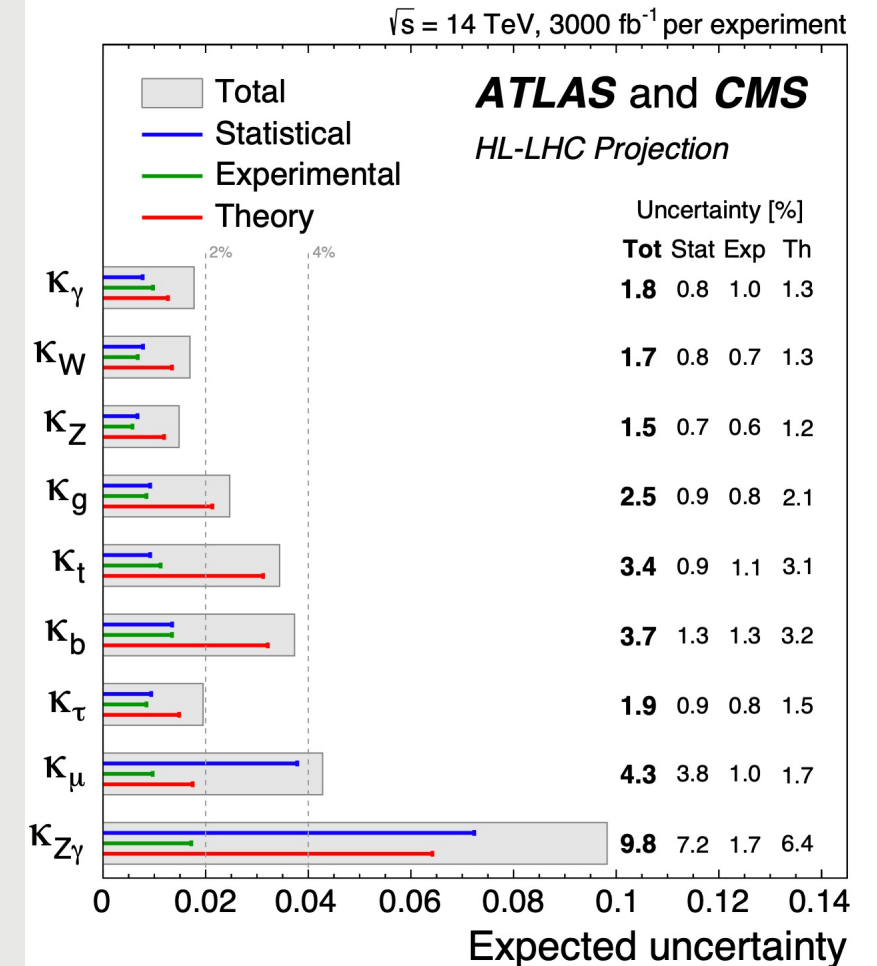
PRECISION MEASUREMENTS

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

Higgs production at NNNLO 1503.06056

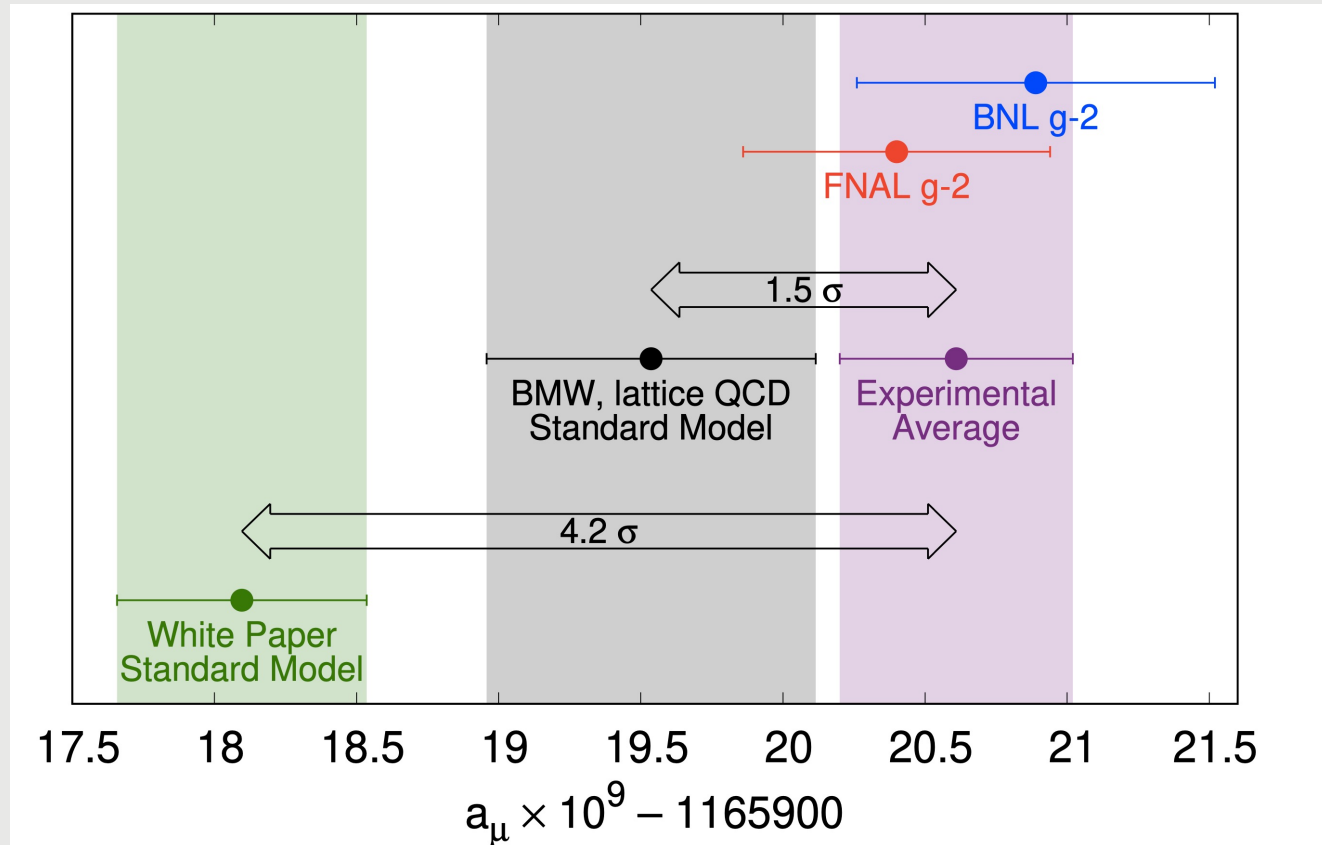
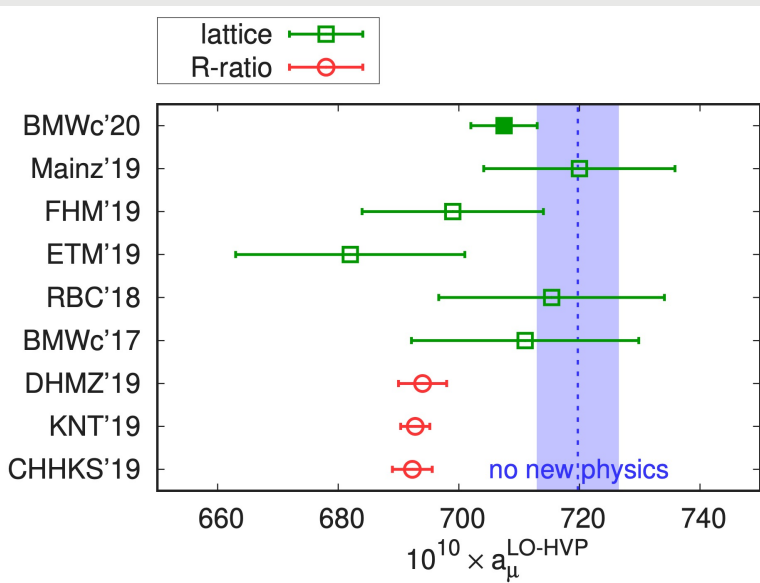
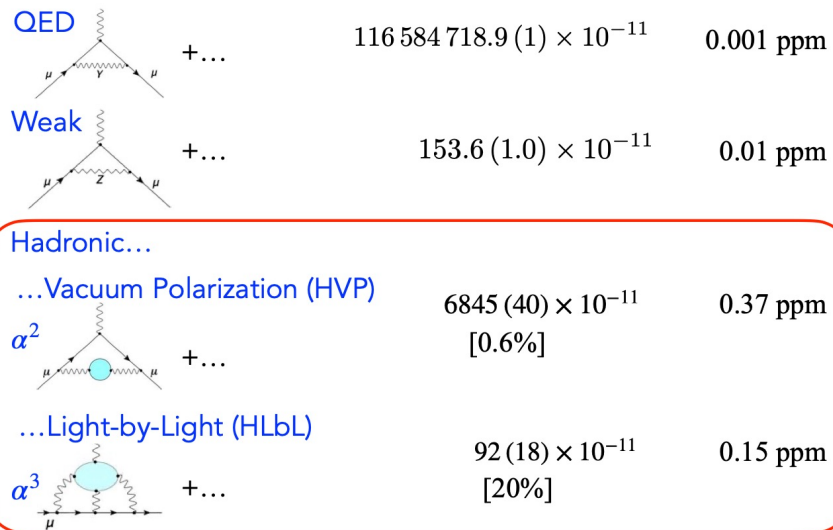


Much theory work required:



MAGNETIC MOMENTS

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



2002.12347

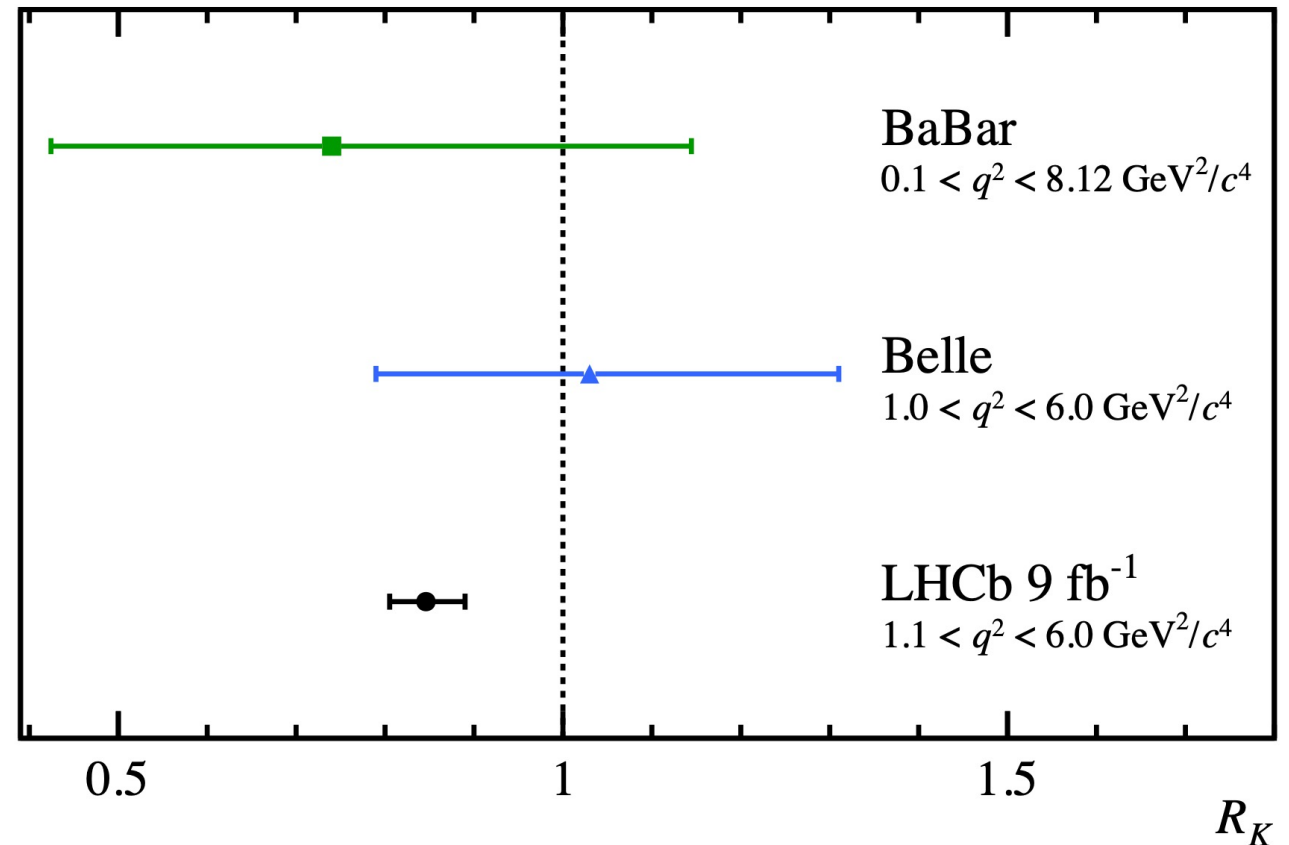
RARE PROCESSES

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

In SM $R_K = 1 + (\text{rad. corrections})$

LHCb (2103.11769):

Lepton flavor violation at 3.1σ



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

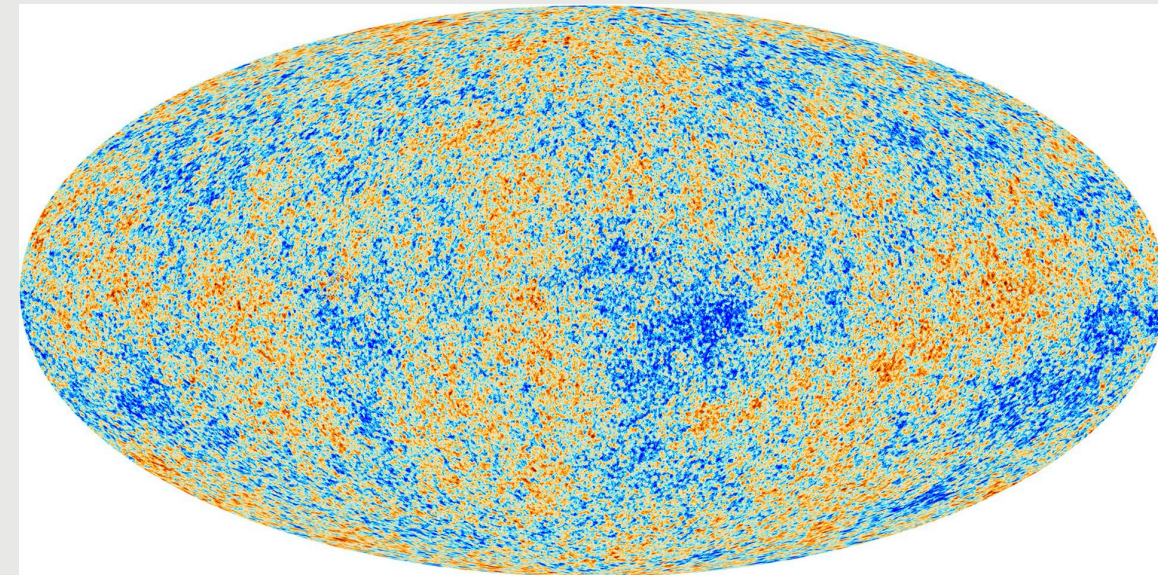
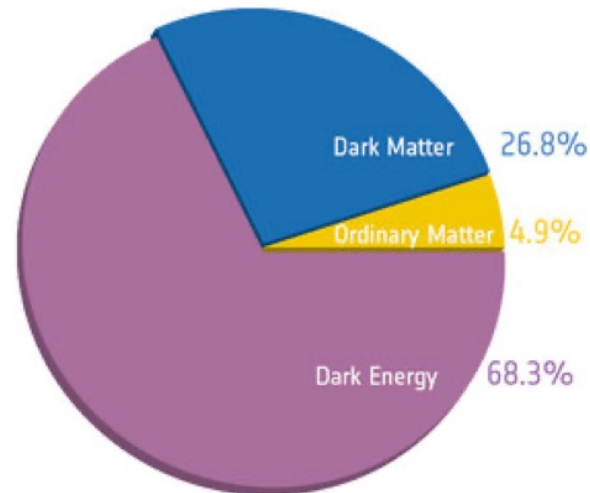
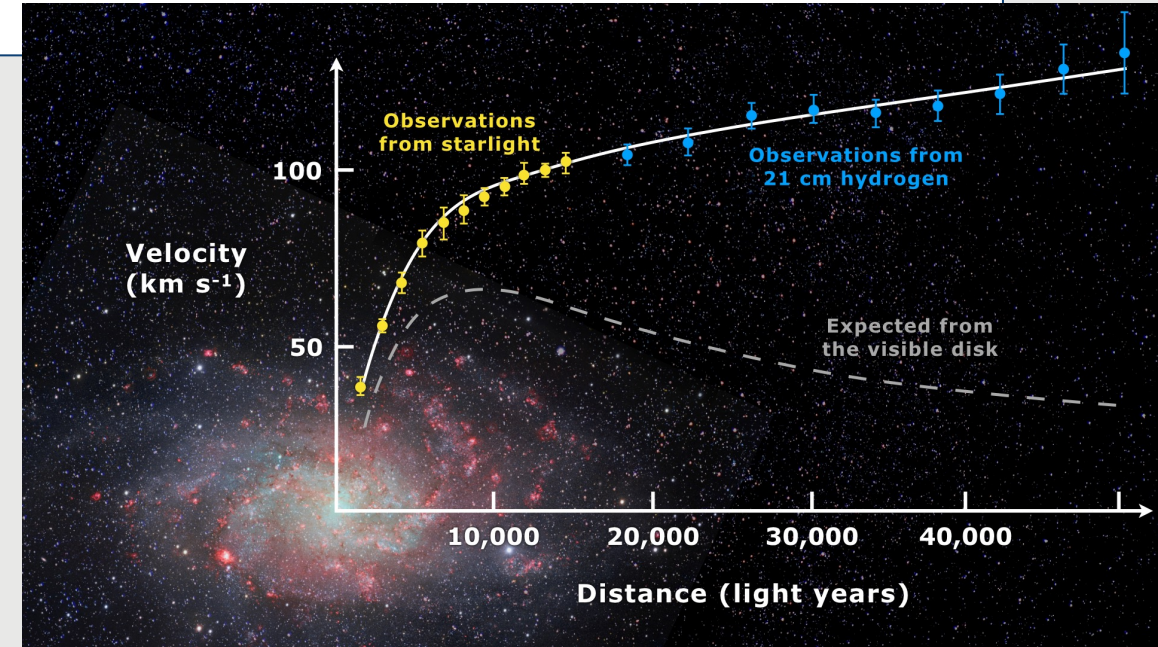
A stable, neutral massive particle:

Galaxies: rotational velocities of stars

Clusters: velocity distribution of galaxies

Observable universe: CMB data

$$\Omega_{DM} \approx 0.268$$



DARK MATTER: MAIN QUESTIONS

MSSM

Nature of DM?

Well motivated: a superpartner

Mass scale of DM?

Hierarchy/ naturalness: around EW scale

Stability of DM?

Put in by hand: R-parity.

DARK MATTER: MAIN QUESTIONS

TECHNICOLOR

Nature of DM?

Well motivated: a technibaryon

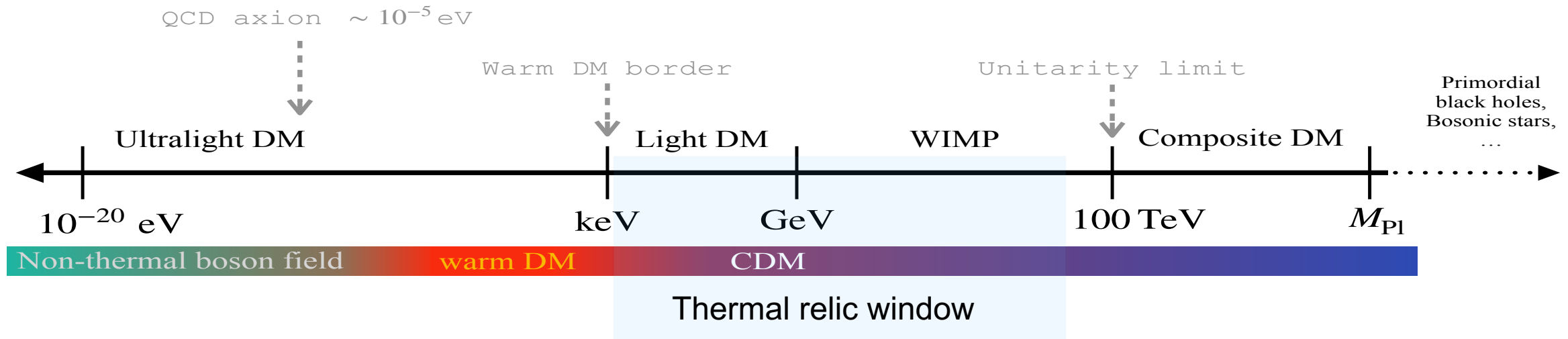
Mass scale of DM?

Above TeV

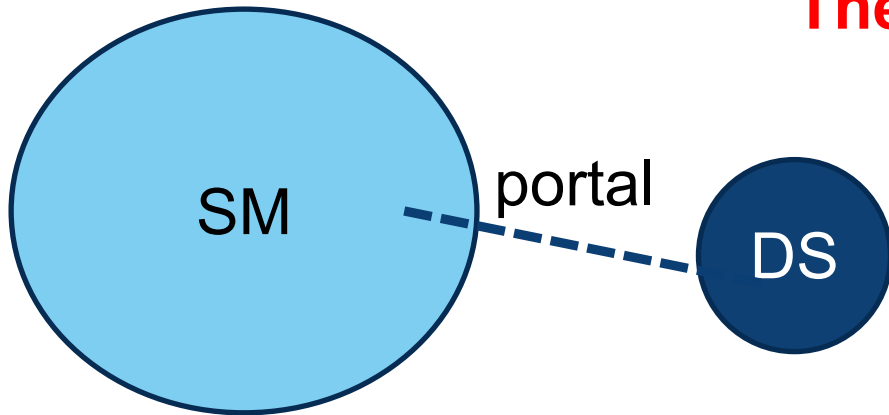
Stability of DM?

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:

$$\dot{f} = \Gamma(k)(f - f_{eq})$$

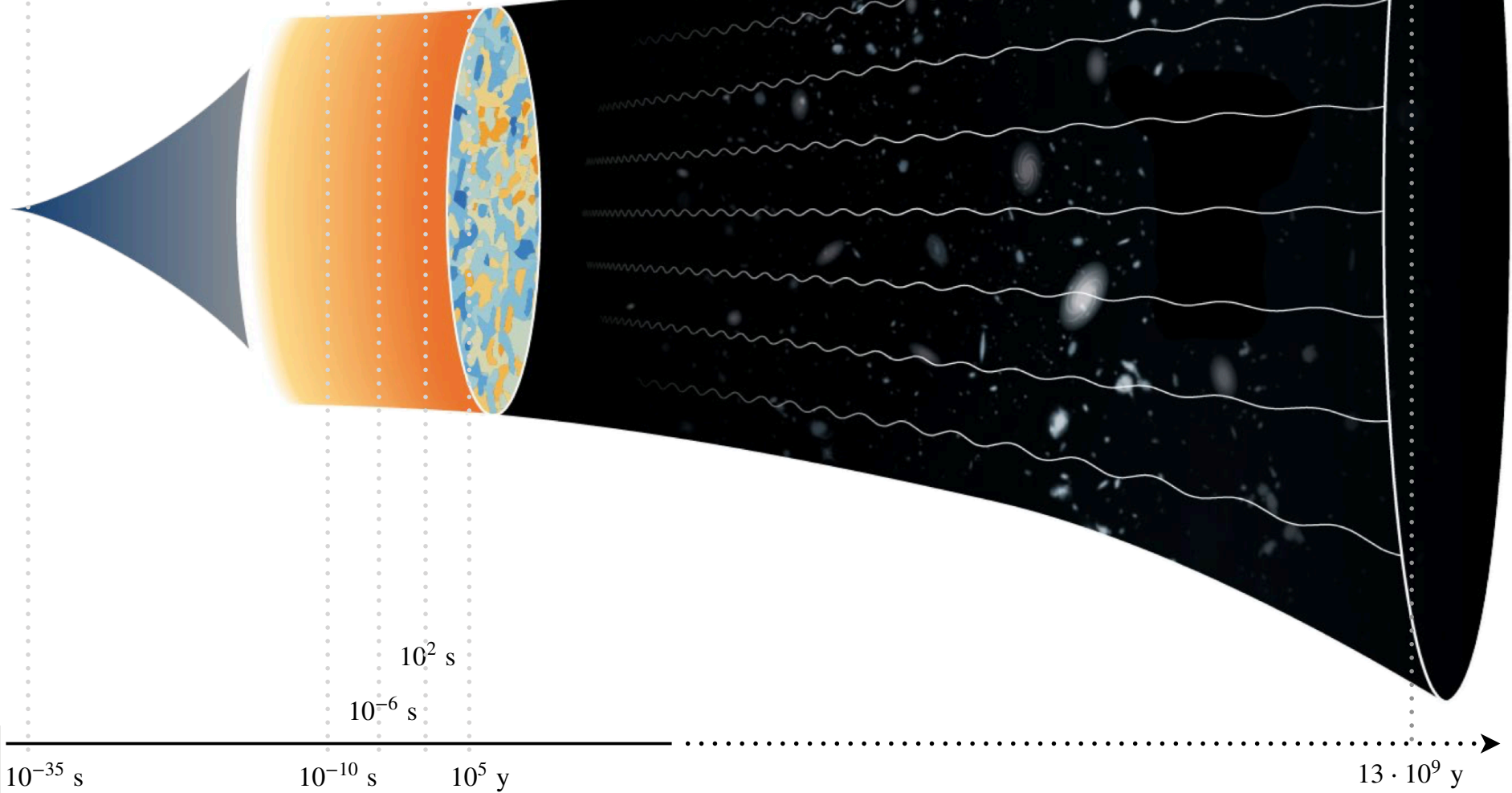
Inflation ?

EW
PT

QCD
PT

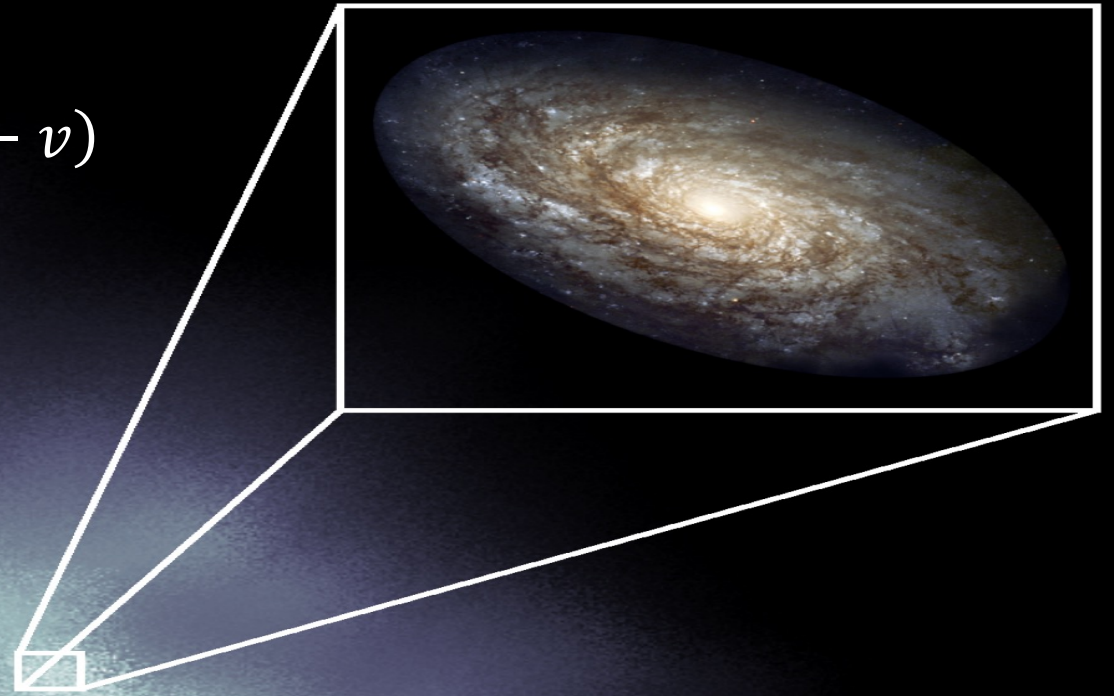
BBN

CMB



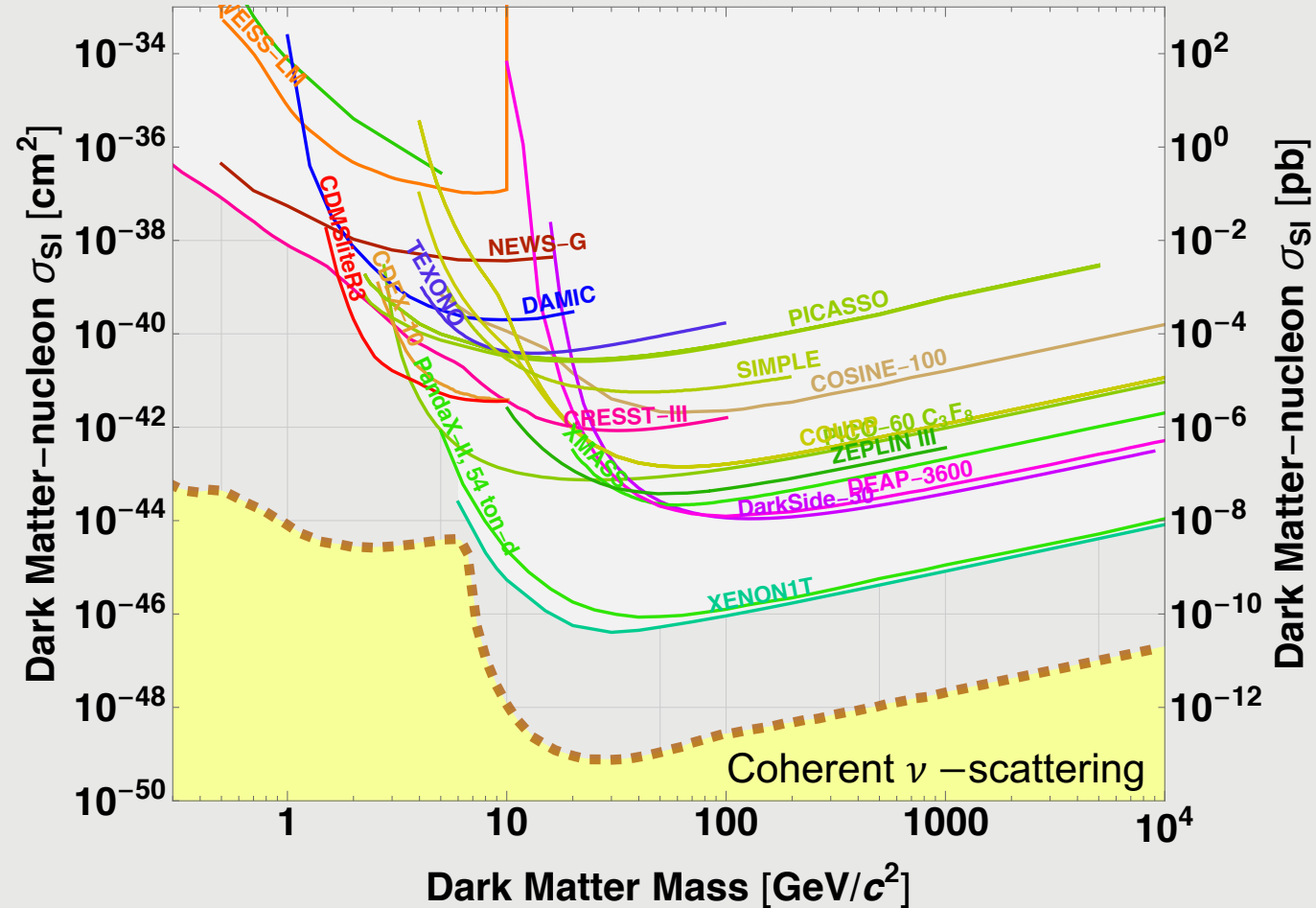
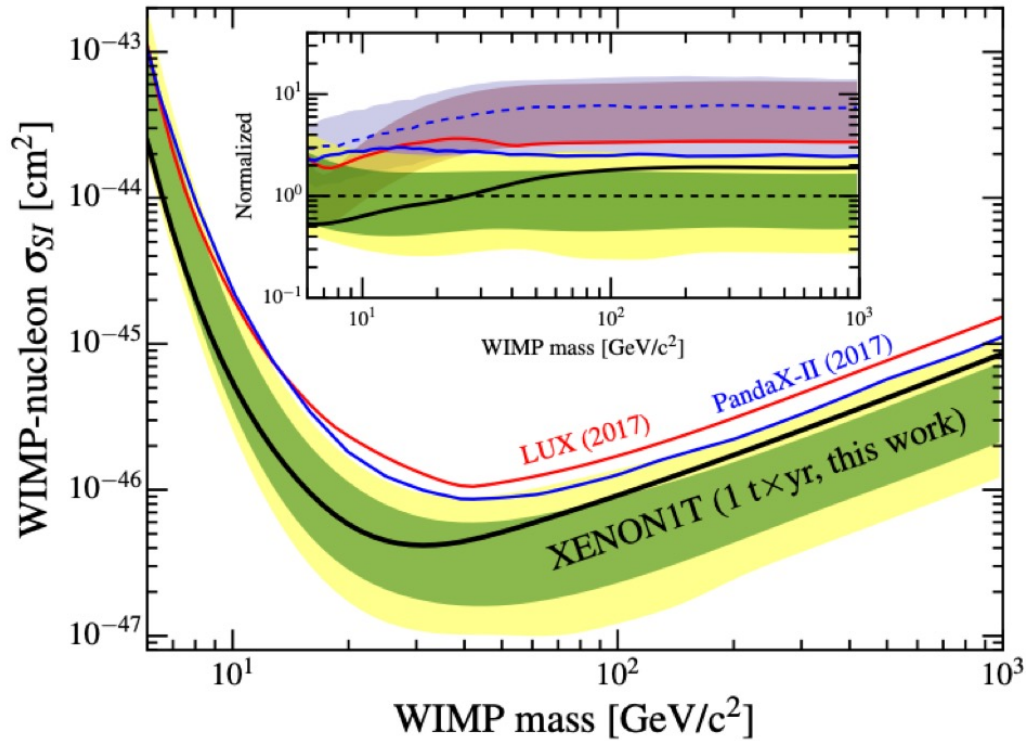
$$\rho_{DM} \simeq 0.3 \text{ GeV}/\text{cm}^3$$

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

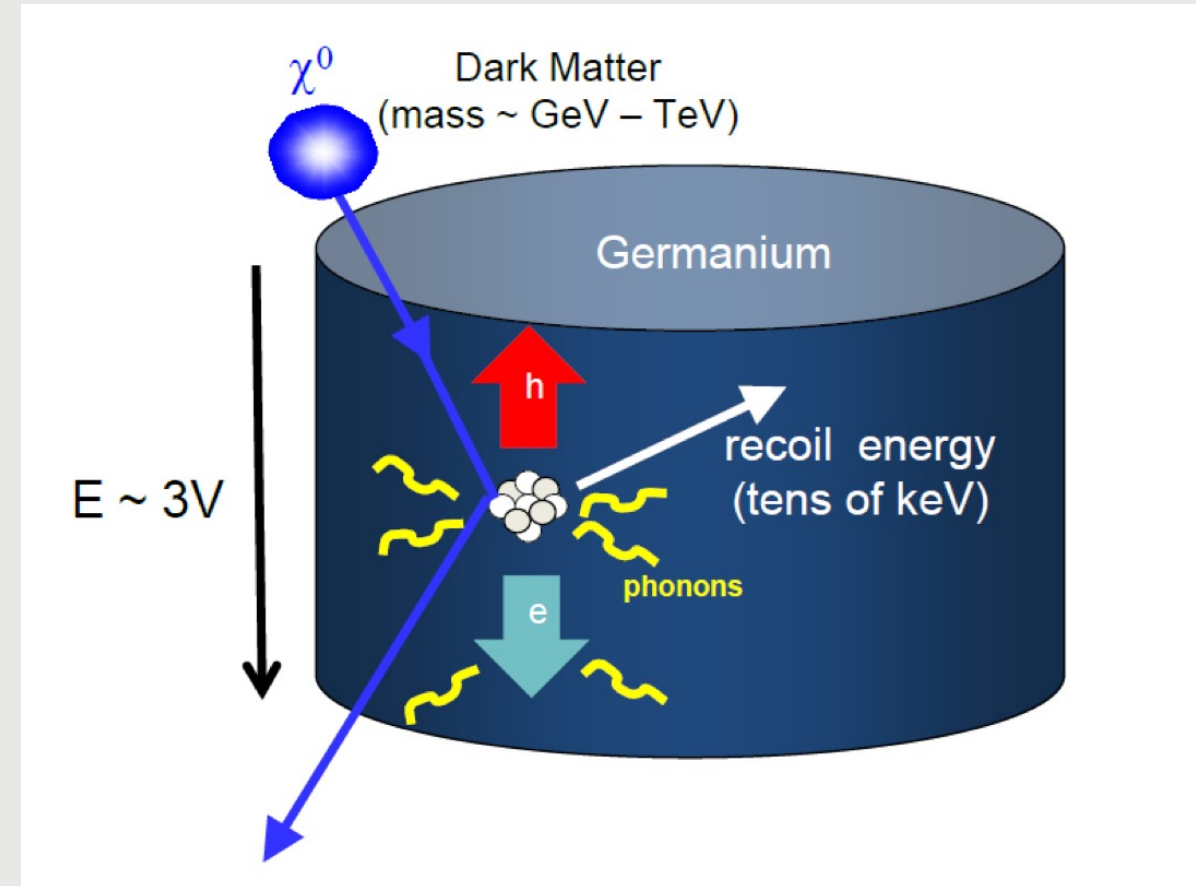
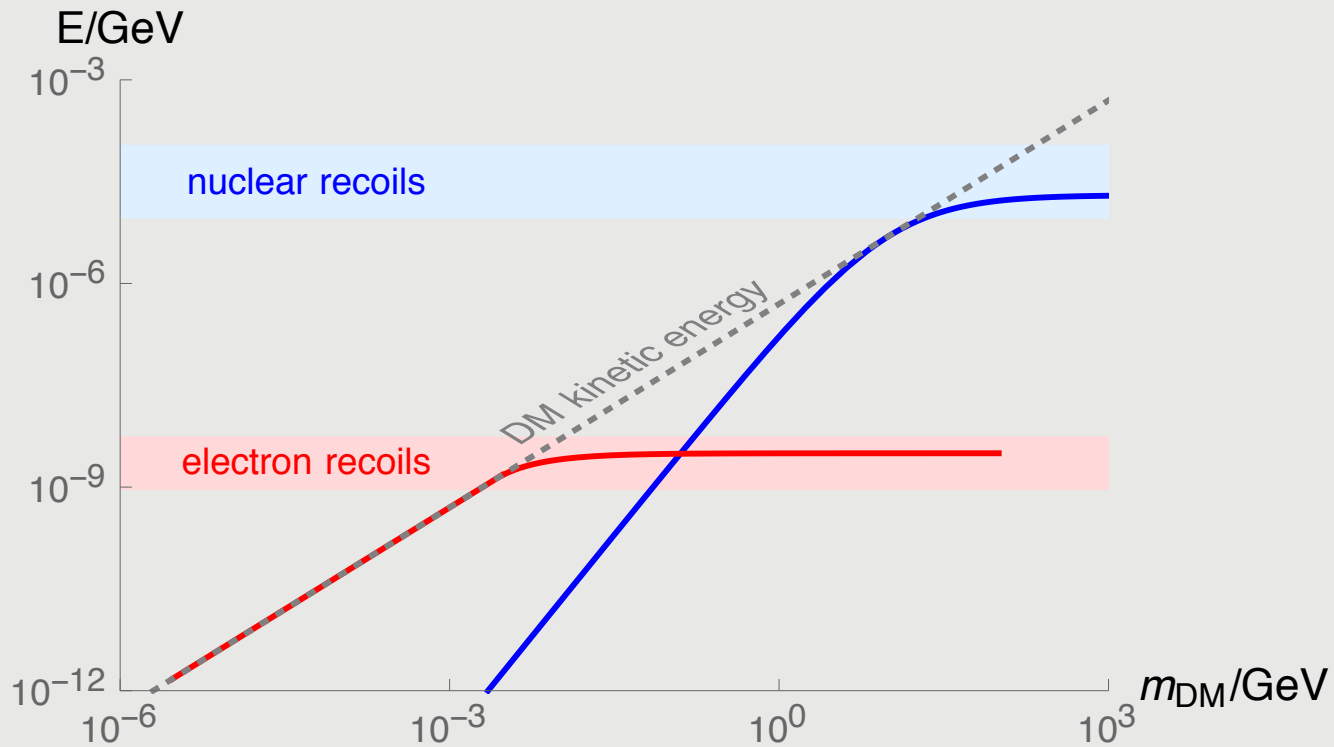


DM SCATTERING ON NUCLEI

Xenon1T 1805.12562



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

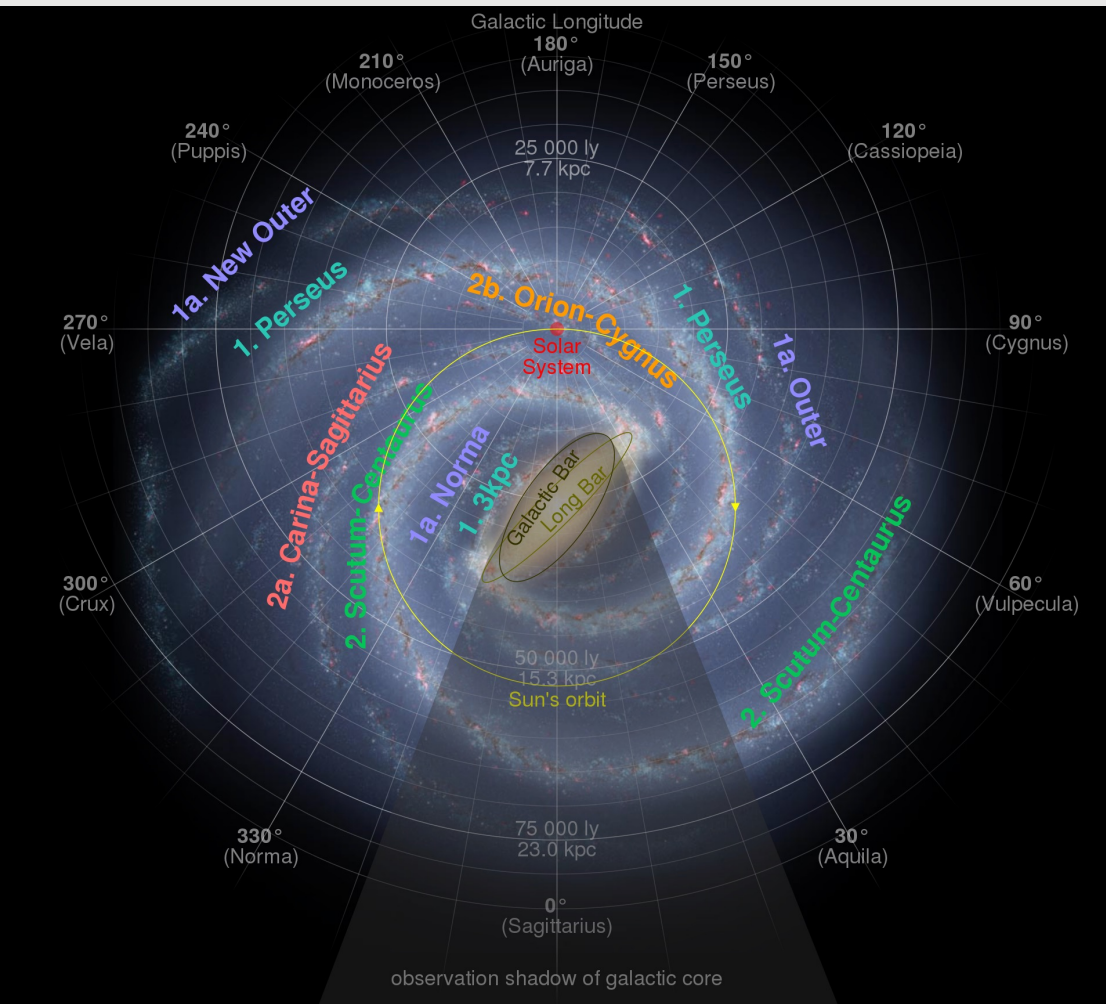


Smaller DM masses, smaller recoil energies.

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

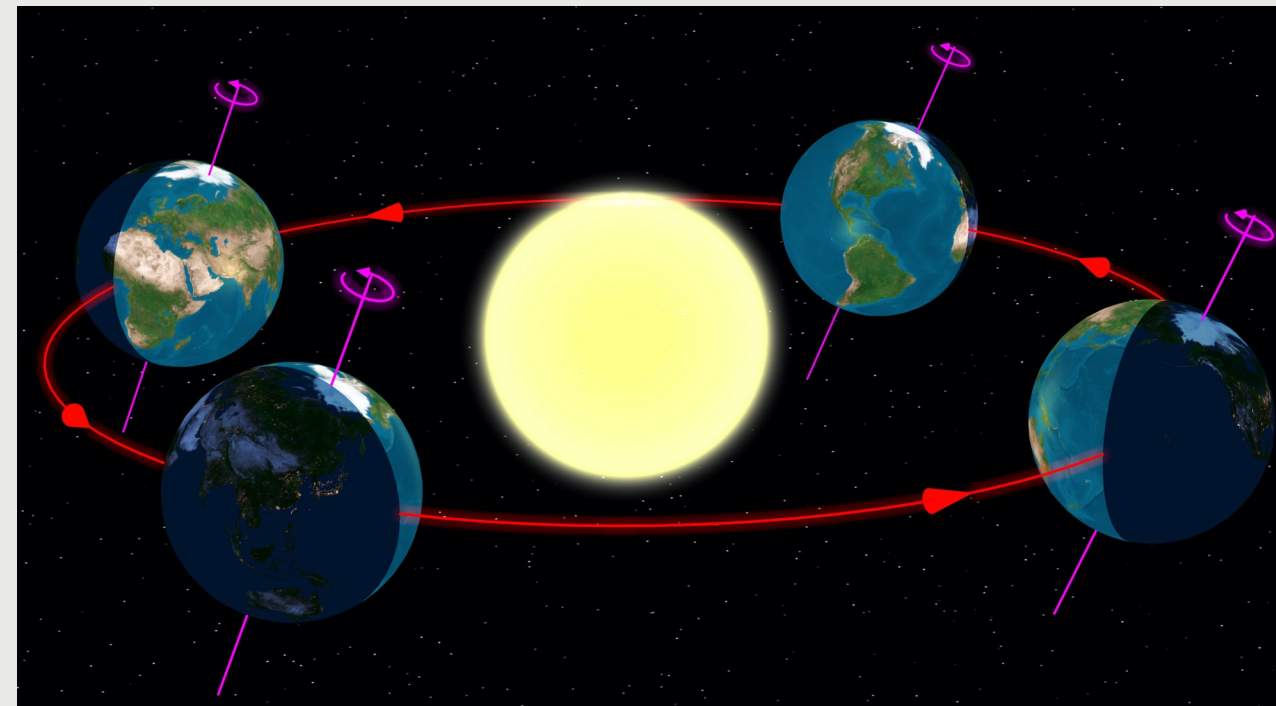
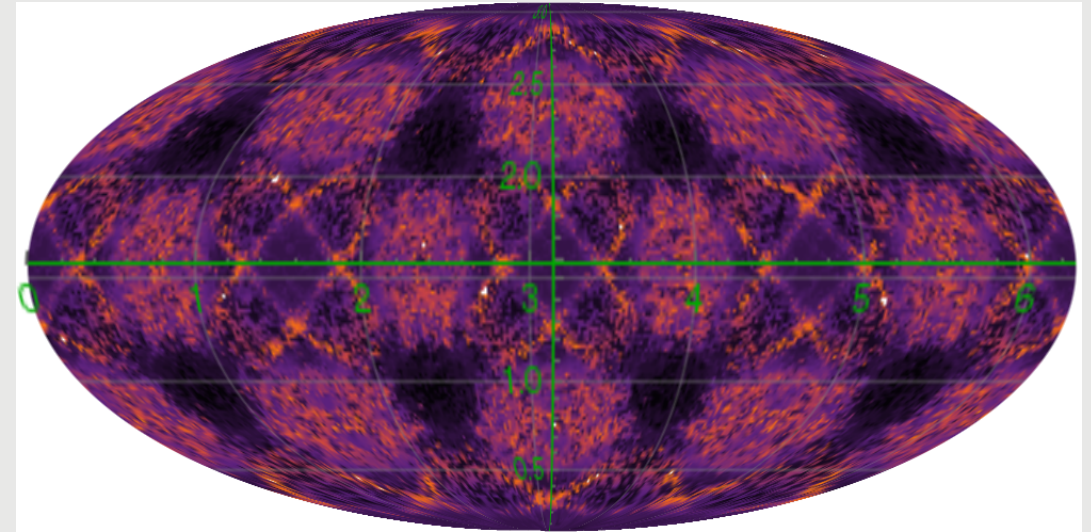
Effects dependent on material properties.

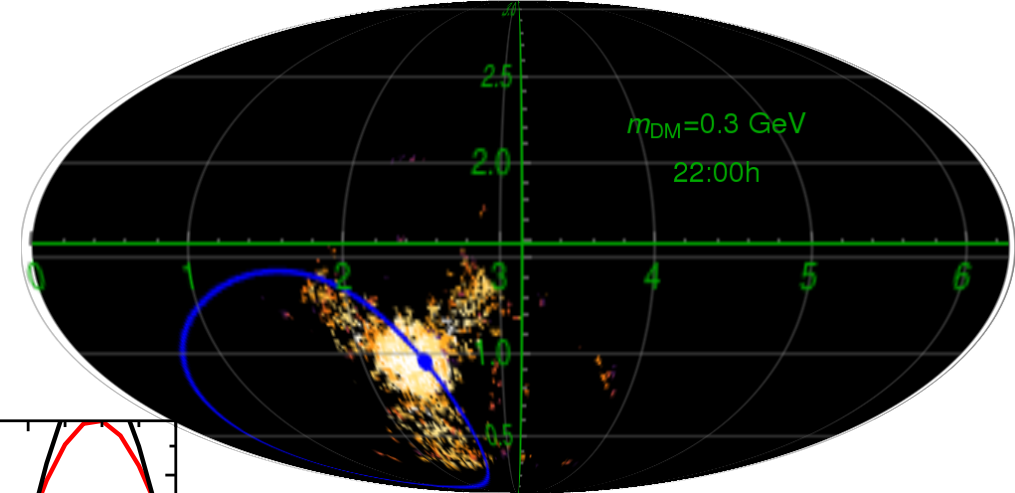
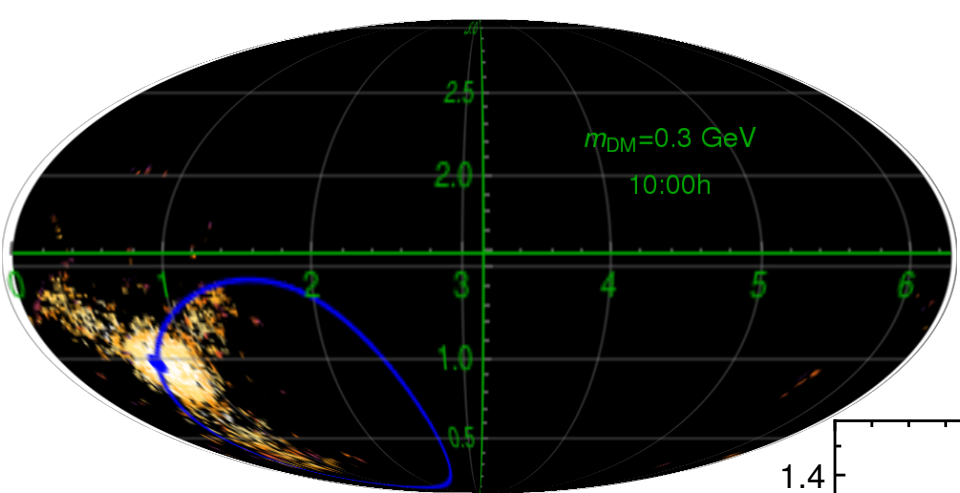
Constant level of recoils
as the Sun moves in the Galaxy.



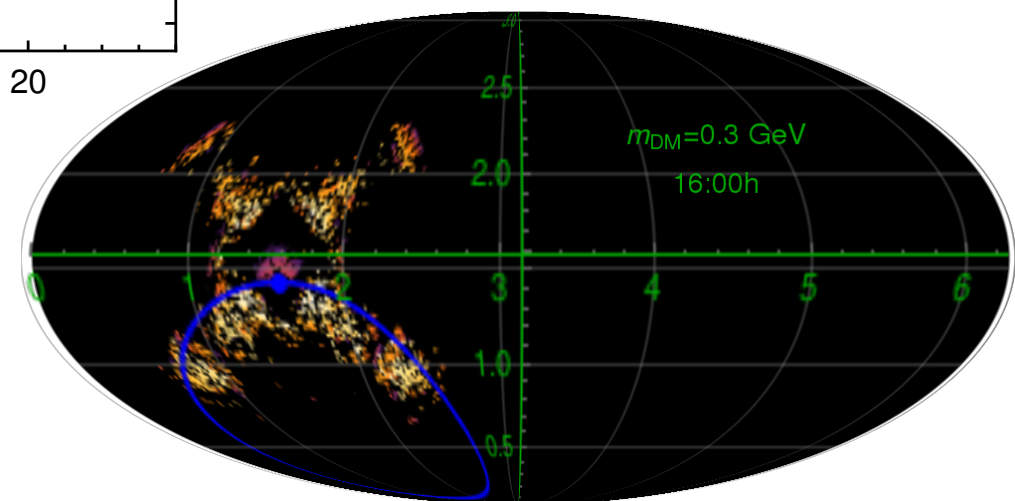
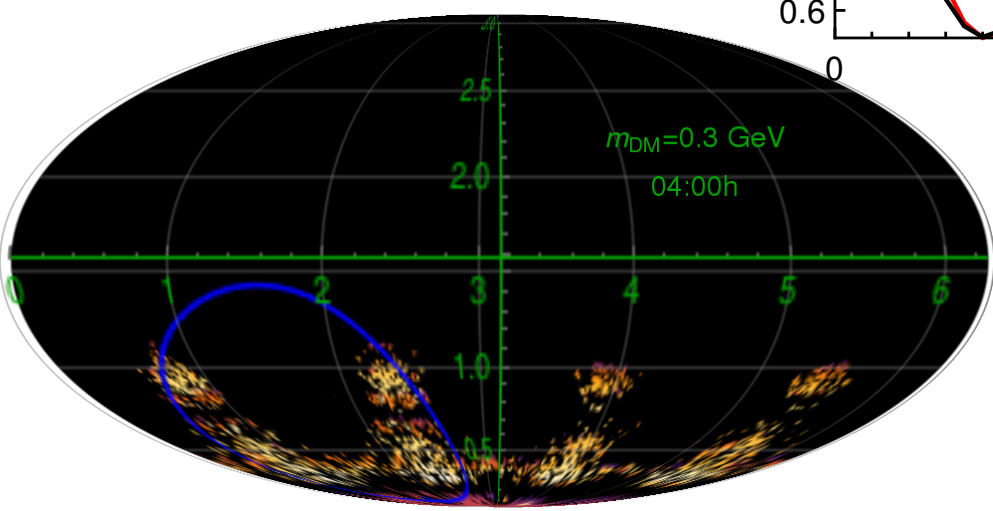
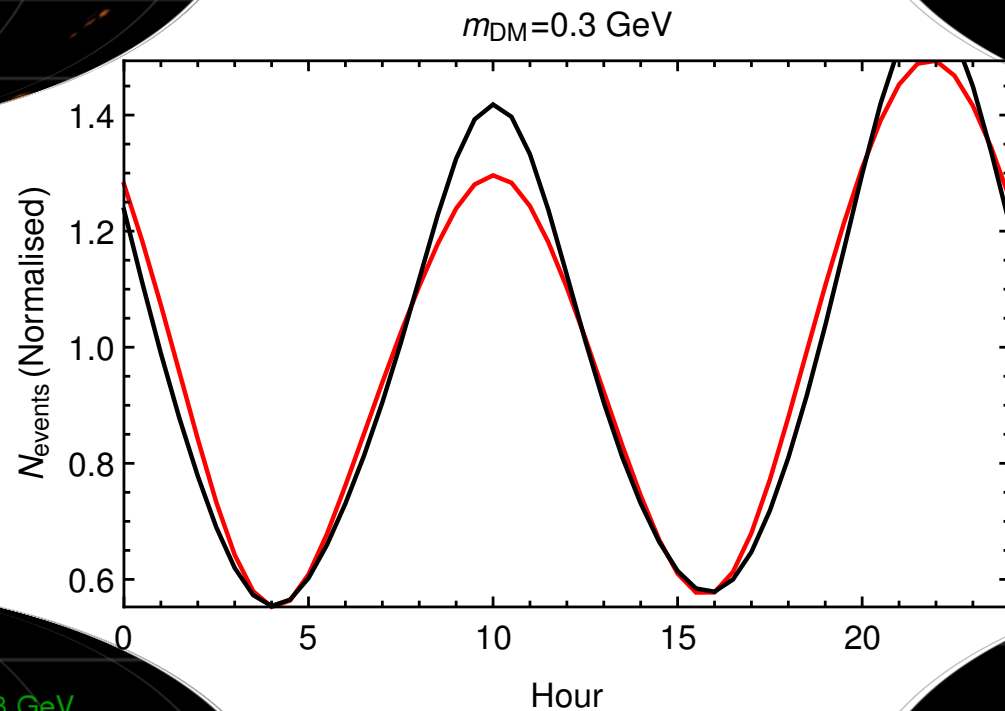
Additional effects from
movement of the Earth

Threshold energies in Ge





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