

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

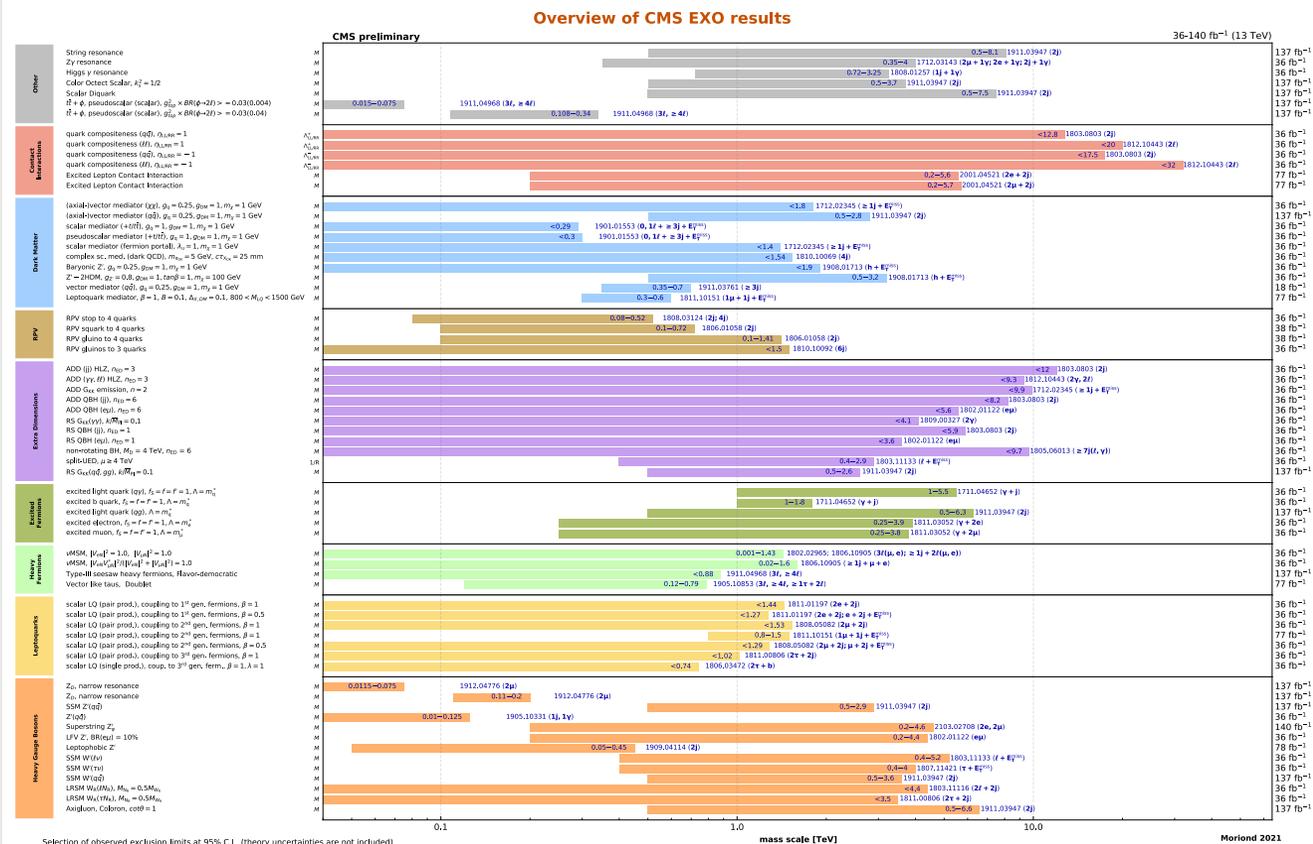
ATLAS Preliminary

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

Model	ℓ, γ	Jets†	E_{miss}^T	$ \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions						
ADD $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	$1-4j$	Yes	139	M_D 11.2 TeV	2102.10874
ADD non-resonant $\gamma\gamma$	2γ			36.7	M_2 8.6 TeV	1707.04147
ADD OBH		$\geq 2j$		37.0	M_{BH} 8.9 TeV	1703.09127
ADD BH multijet		$\geq 3j$		3.6	M_{BH} 9.55 TeV	1512.02586
RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ			139	G_{KK} mass 2.3 TeV	2102.130405
Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel			36.1	G_{KK} mass 4.5 TeV	1808.02380
Bulk RS $G_{KK} \rightarrow W\gamma$	$1 e, \mu$	$2j/1j$	Yes	139	G_{KK} mass 2.0 TeV	2004.14636
Bulk RS $G_{KK} \rightarrow t\bar{t}$	$1 e, \mu$	$\geq 1b, \geq 1J/2j$	Yes	36.1	KK mass 3.8 TeV	1804.10823
2UED / RPP	$1 e, \mu$	$\geq 2b, \geq 3j$	Yes	36.1	KK mass 1.8 TeV	1803.09678
						Tier (1,1), $2(A^{(1,1)} \rightarrow t\bar{t}) = 1$
Gauge bosons						
SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$			139	Z' mass 2.42 TeV	1903.06248
SSM $Z' \rightarrow \tau\tau$	2τ	$\geq 2b$		36.1	Z' mass 2.1 TeV	1708.07242
Leptophobic $Z' \rightarrow b\bar{b}$	$0 e, \mu$	$\geq 1b, \geq 2J$	Yes	139	Z' mass 4.1 TeV	1805.00299
SSM $W' \rightarrow \ell\nu$	$1 e, \mu$		Yes	139	W' mass 6.0 TeV	2005.05138
SSM $W' \rightarrow \tau\nu$	1τ		Yes	139	W' mass 5.0 TeV	1906.05609
SSM $W' \rightarrow d\bar{s}$		$\geq 1b, \geq 1J$	Yes	139	W' mass 4.4 TeV	ATLAS-CONF-2021-025
HVT $W' \rightarrow WZ \rightarrow \ell\nu\gamma q$ model B	$1 e, \mu$	$2j/1j$	Yes	139	W' mass 4.3 TeV	2004.14636
HVT $Z' \rightarrow ZH$ model B	$0, 2 e, \mu$	$1, 2 b$	Yes	139	Z' mass 3.2 TeV	ATLAS-CONF-2021-043
HVT $W' \rightarrow WH$ model B	$0 e, \mu$	$\geq 1b, \geq 2J$	Yes	139	W' mass 3.2 TeV	2007.05293
LRSM $W_R \rightarrow \mu N_R$	2μ	$1, 1 b$	Yes	80	W_R mass 5.0 TeV	1904.12679
						$m(N_R) = 0.5 \text{ TeV}, g_L = g_R$
CI						
CI $q\bar{q}q\bar{q}$		$2j$		37.0	A 21.8 TeV	1703.09127
CI $\ell\bar{\ell}q\bar{q}$	$2 e, \mu$	$1b$		139	A 35.8 TeV	2006.12946
CI $e\bar{e}b\bar{b}$	$2 e$	$1b$		139	A 1.8 TeV	2105.13847
CI $\mu\bar{\mu}b\bar{b}$	2μ	$1b$		139	A 2.0 TeV	2105.13847
CI $t\bar{t}t\bar{t}$	$\geq 1 e, \mu$	$\geq 1b, \geq 1j$	Yes	36.1	A 2.57 TeV	1811.02305
DM						
Axial-vector med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	$1-4j$	Yes	139	m_{DM} 376 GeV	2102.10874
Pseudo-scalar med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	$1-4j$	Yes	139	m_{DM} 2.1 TeV	2102.10874
Vector med. Z' -2HDM (Dirac DM)	$0 e, \mu$	$2b$	Yes	139	m_{DM} 3.1 TeV	ATLAS-CONF-2021-006
Pseudo-scalar med. 2HDM+a	multi-channel		Yes	139	m_{DM} 560 GeV	ATLAS-CONF-2021-036
Scalar reson. $\phi \rightarrow t\bar{t}$ (Dirac DM)	$0-1 e, \mu$	$1b, 0-1j$	Yes	36.1	m_{DM} 3.4 TeV	1812.09743
LO						
Scalar LO 1 st gen	$2 e$	$\geq 2j$	Yes	139	LO mass 1.8 TeV	$\beta = 1$
Scalar LO 2 nd gen	2μ	$\geq 2j$	Yes	139	LO mass 1.7 TeV	$\beta = 1$
Scalar LO 3 rd gen	1τ	$2b$	Yes	139	LO mass 1.2 TeV	$\beta(LQ_1^* \rightarrow b\bar{r}) = 1$
Scalar LO 3 rd gen	$0 e, \mu$	$\geq 2j, \geq 2b$	Yes	139	LO mass 1.24 TeV	$\beta(LQ_2^* \rightarrow \tau\bar{r}) = 1$
Scalar LO 3 rd gen	$\geq 2 e, \mu, \geq 1\tau$	$\geq 1j, \geq 1b$	Yes	139	LO mass 1.43 TeV	$\beta(LQ_3^* \rightarrow \tau\bar{r}) = 1$
Scalar LO 3 rd gen	$0 e, \mu$	$\geq 1\tau, \geq 2j, 2b$	Yes	139	LO mass 1.26 TeV	$\beta(LQ_4^* \rightarrow b\bar{r}) = 1$
Heavy quarks						
VLO $T\bar{T} \rightarrow Zt + X$	$2e/2\mu/3e, \mu$	$\geq 1b, \geq 1j$		139	T mass 1.4 TeV	ATLAS-CONF-2021-024
VLO $BB \rightarrow Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	1808.02343
VLO $T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS)/\geq 3 e, \mu$	$\geq 1b, \geq 1j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	1807.11883
VLO $T \rightarrow Ht/Zt$	$1 e, \mu$	$\geq 1b, \geq 1j$	Yes	139	T mass 1.8 TeV	ATLAS-CONF-2021-040
VLO $Y \rightarrow Hb$	$1 e, \mu$	$\geq 1b, \geq 1j$	Yes	36.1	Y mass 1.85 TeV	1812.07343
VLO $Q \rightarrow Hb$	$0 e, \mu$	$\geq 2b, \geq 1j, \geq 1J$	Yes	139	B mass 2.0 TeV	ATLAS-CONF-2021-018
Excited fermions						
Excited quark $q^* \rightarrow qg$		$2j$		139	q^* mass 6.7 TeV	1910.08447
Excited quark $q^* \rightarrow q\gamma$	1γ	$1j$		36.7	q^* mass 3.7 TeV	1708.10440
Excited quark $b^* \rightarrow bg$		$1b, 1j$		36.1	b^* mass 2.6 TeV	1805.02999
Excited lepton ℓ^*	$3 e, \mu$			20.3	ℓ^* mass 3.0 TeV	1411.2921
Excited lepton ν^*	$3 e, \mu, \tau$			20.3	ν^* mass 1.6 TeV	1411.2921
Other						
Type III Seesaw	$2, 3, 4 e, \mu$	$\geq 2j$	Yes	139	N^0 mass 910 GeV	ATLAS-CONF-2021-023
LRSM Majorana ν	2μ	$2j$	Yes	36.1	N mass 3.4 TeV	1809.11105
Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$	$2, 3, 4 e, \mu$ (SS)	various	Yes	36.1	$H^{\pm\pm}$ mass 350 GeV	2101.11061
Higgs triplet $H^{\pm\pm} \rightarrow \tau\tau$	$2, 3, 4 e, \mu$ (SS)		Yes	36.1	$H^{\pm\pm}$ mass 870 GeV	1710.09748
Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$		Yes	20.3	$H^{\pm\pm}$ mass 400 GeV	1411.2921
Multi-charged particles				36.1	multi-charged particle mass 1.22 TeV	1812.03673
Magnetic monopoles				34.4	monopole mass 2.37 TeV	1905.10130

*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.

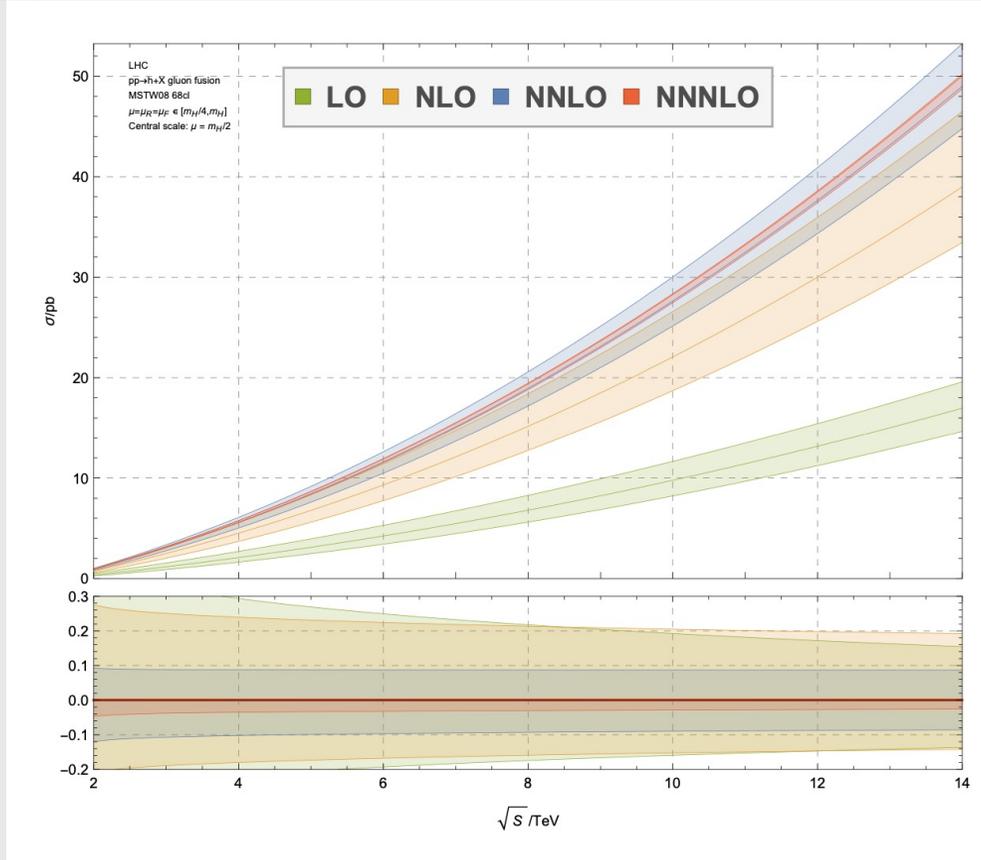
(N)NMSSM,
(Pseudo)Goldstone Higgs,
Walking Technicolor



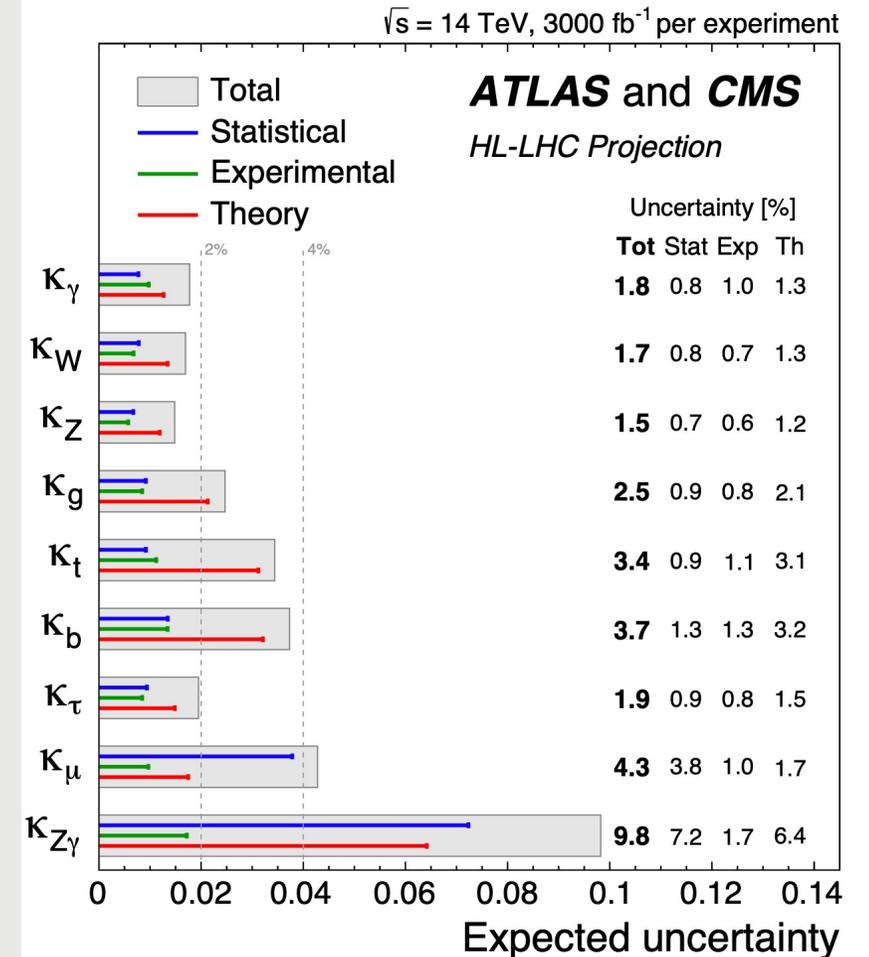
PRECISION MEASUREMENTS

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

Higgs production at NNNLO 1503.06056

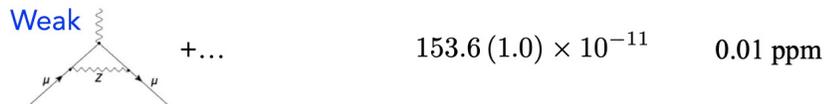
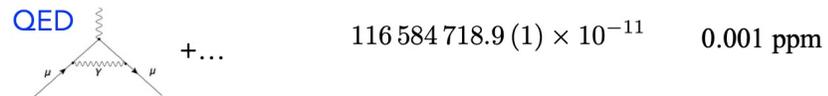


Much theory work required:

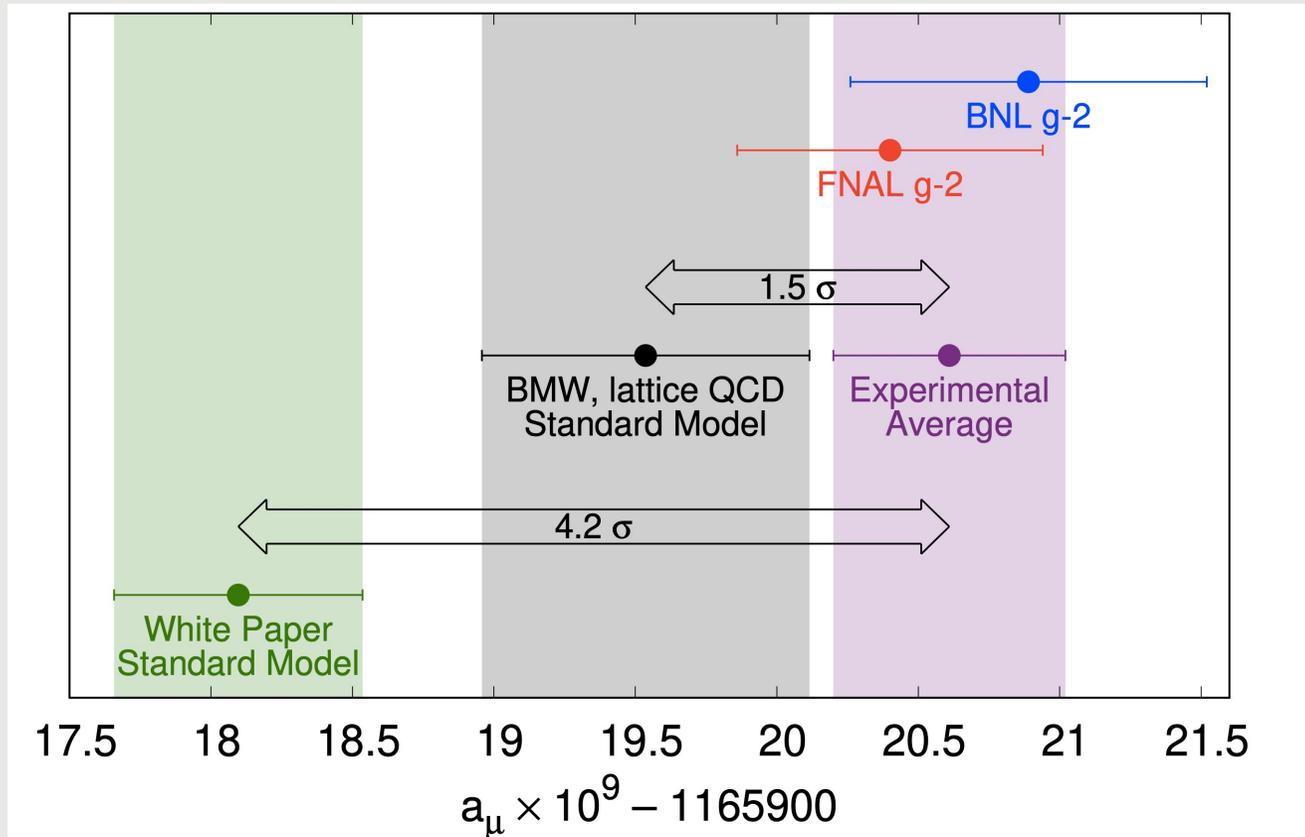
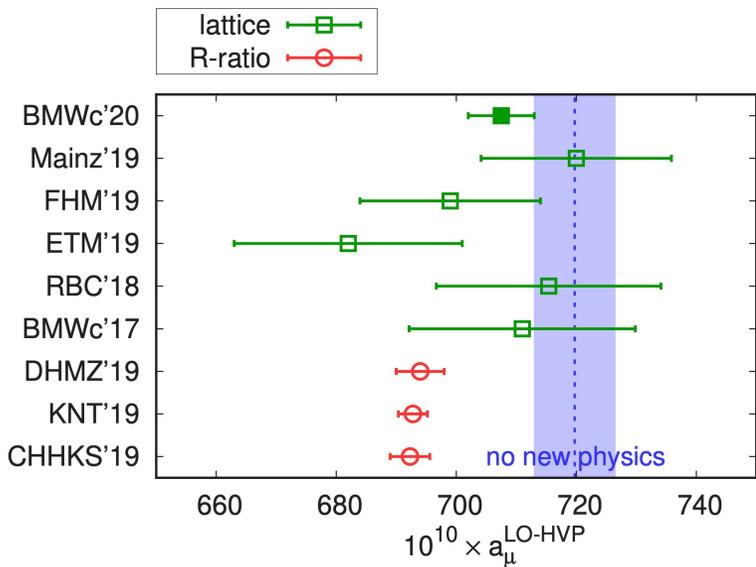
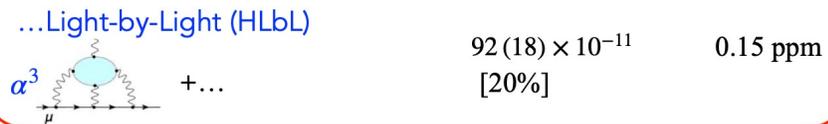


MAGNETIC MOMENTS

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



Hadronic...



2002.12347

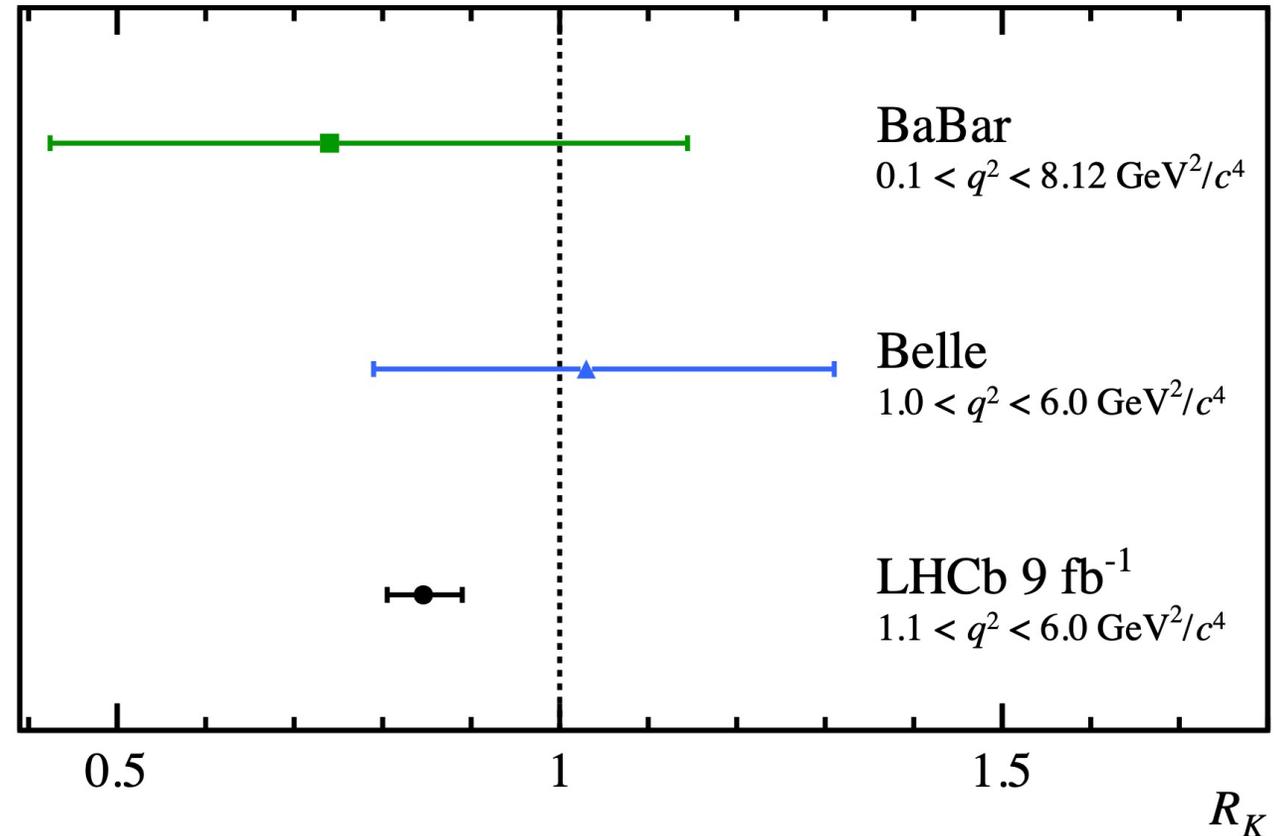
RARE PROCESSES

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

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

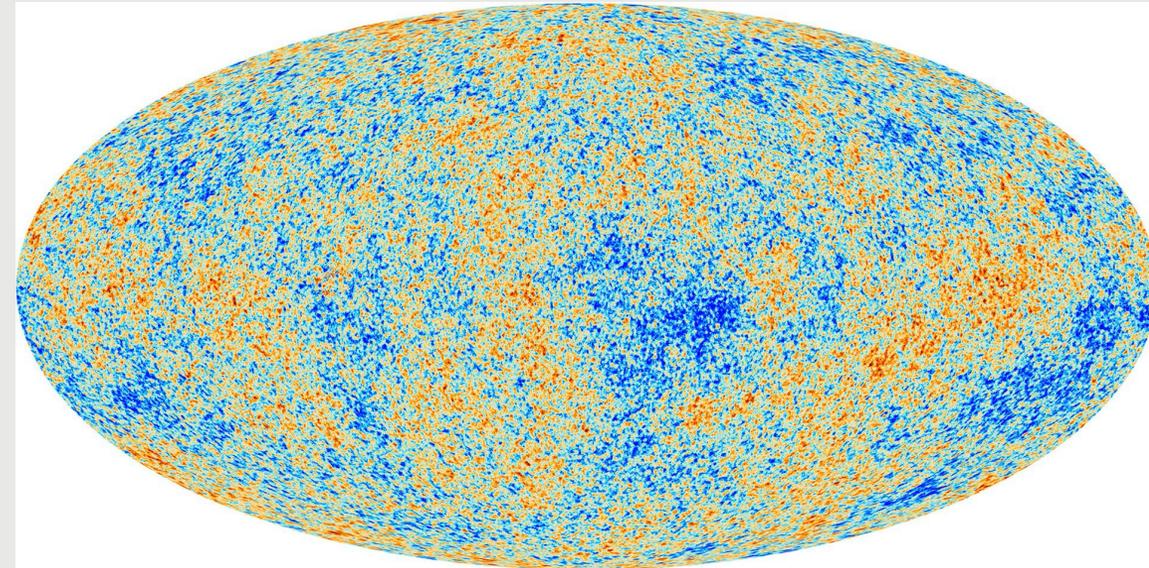
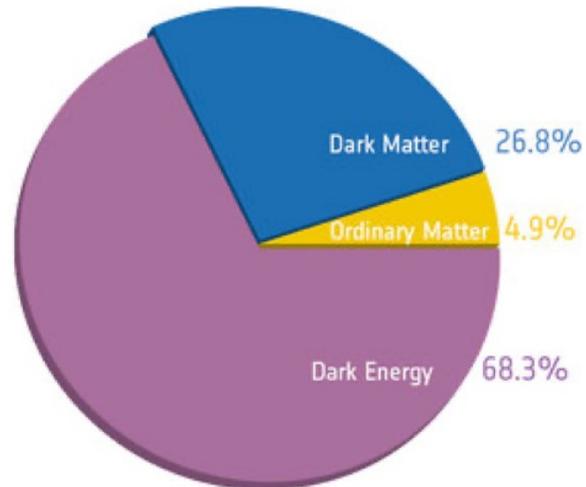
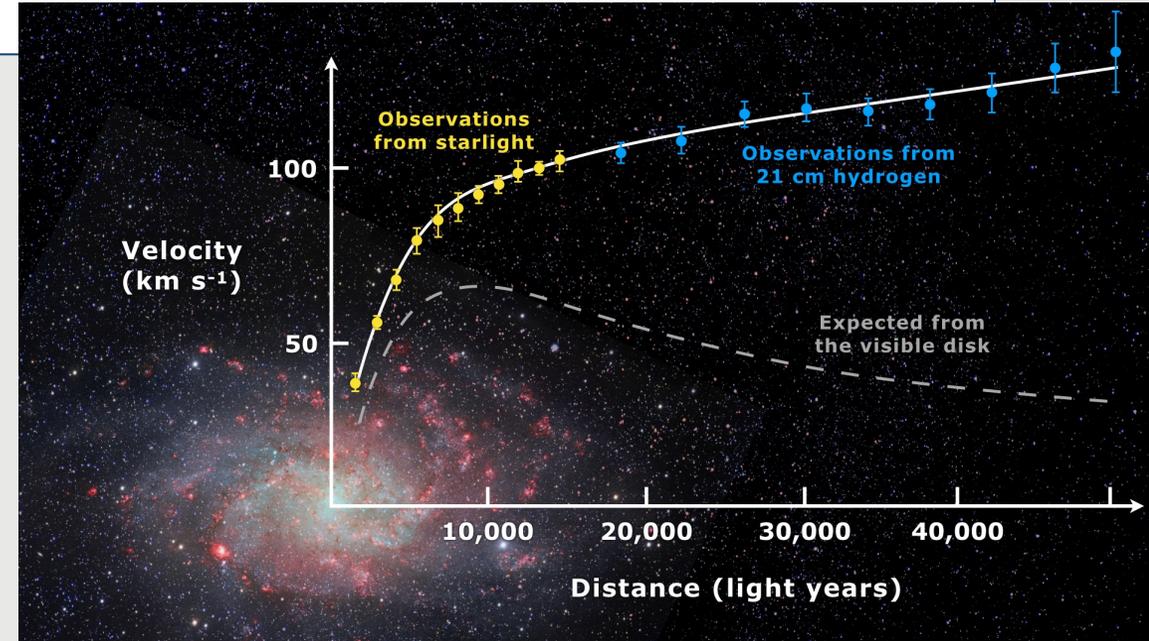
A stable, neutral massive particle:

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

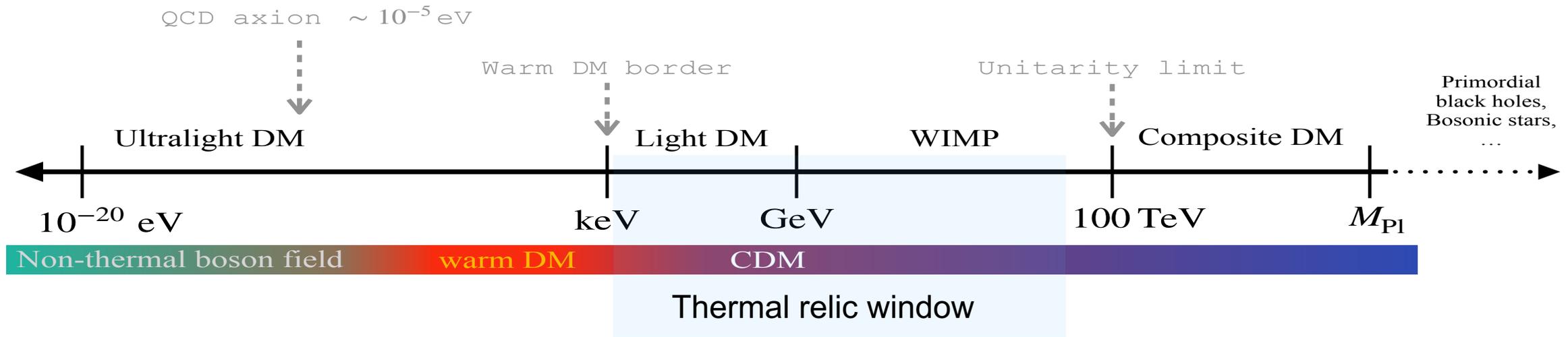
Mass scale of DM?

Above TeV

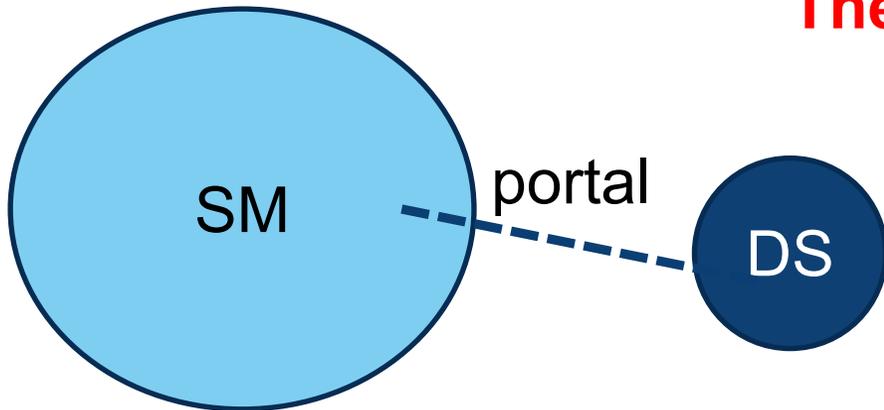
Stability of DM?

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:

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

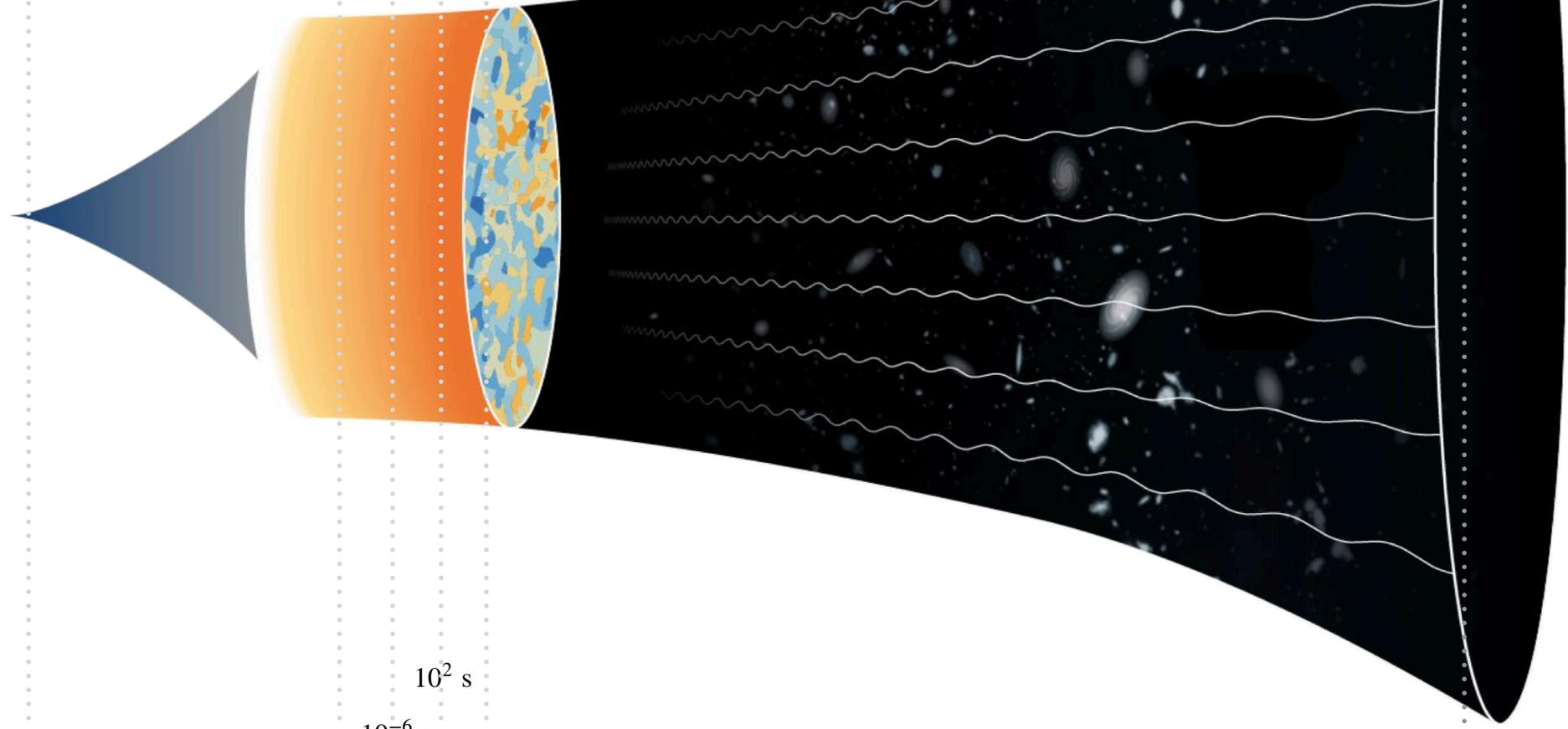
Inflation ?

EW
PT

QCD
PT

BBN

CMB



10^{-35} s

10^{-10} s

10^2 s

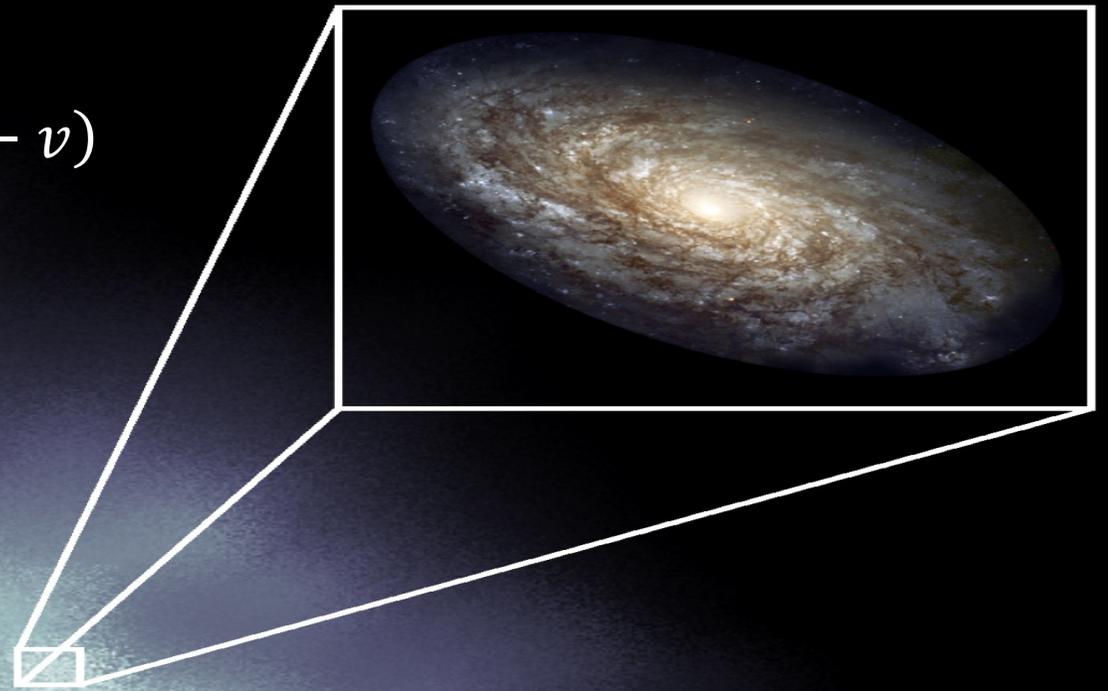
10^{-6} s

10^5 y

$13 \cdot 10^9$ y

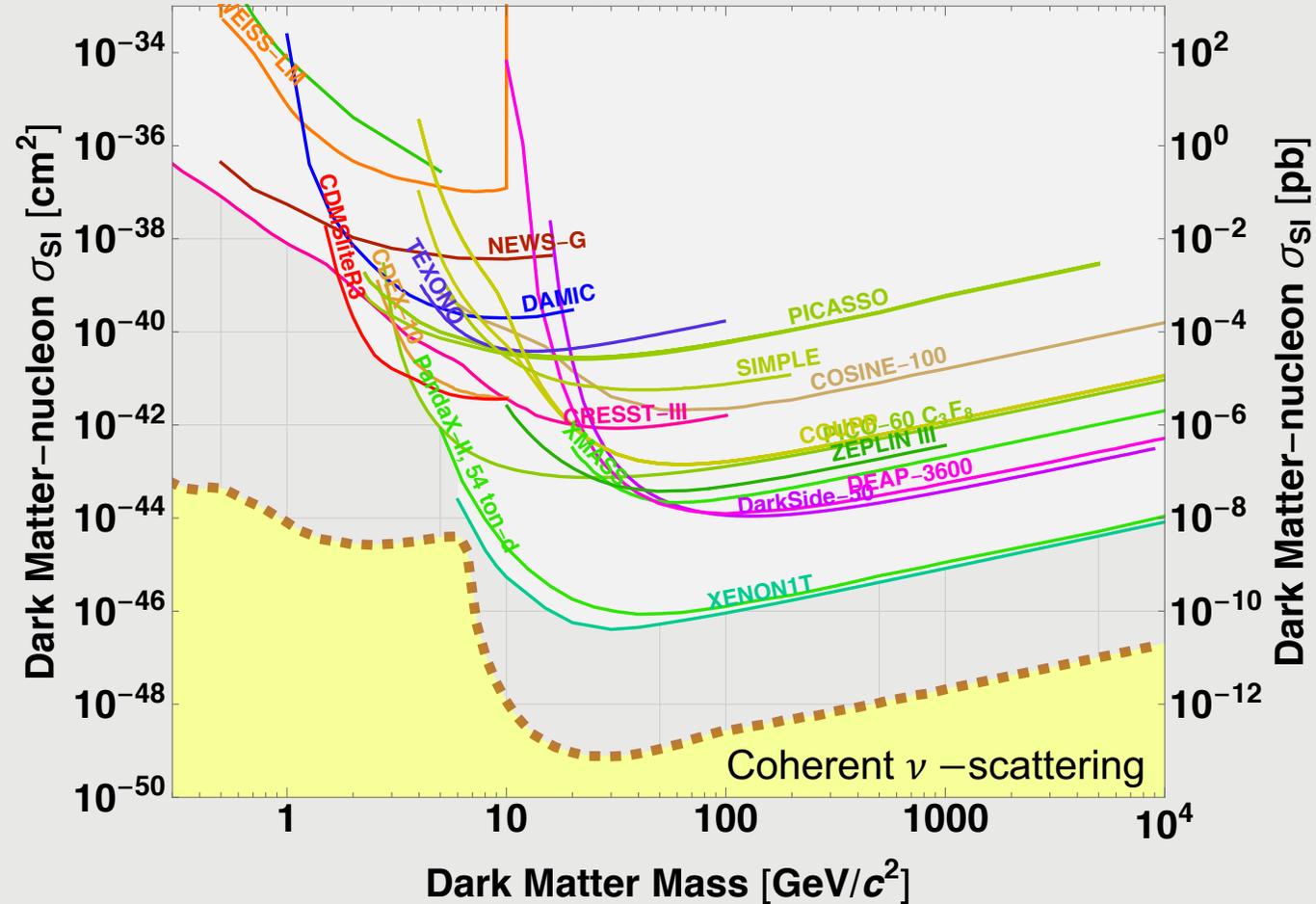
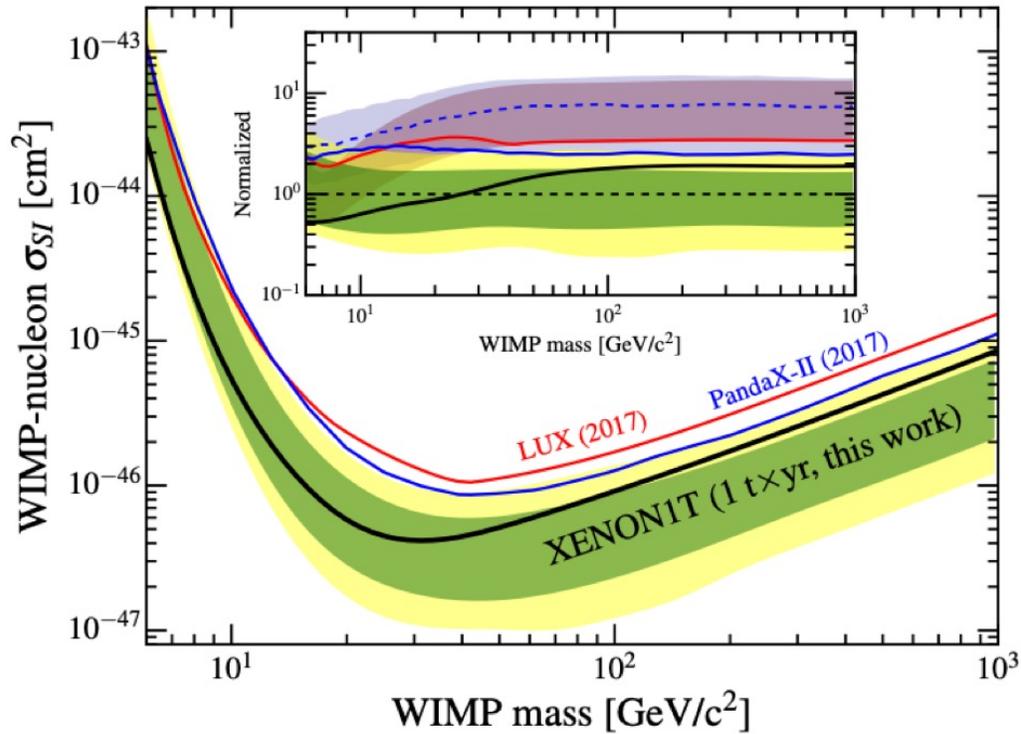
$$\rho_{DM} \simeq 0.3 \text{ GeV/cm}^3$$

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

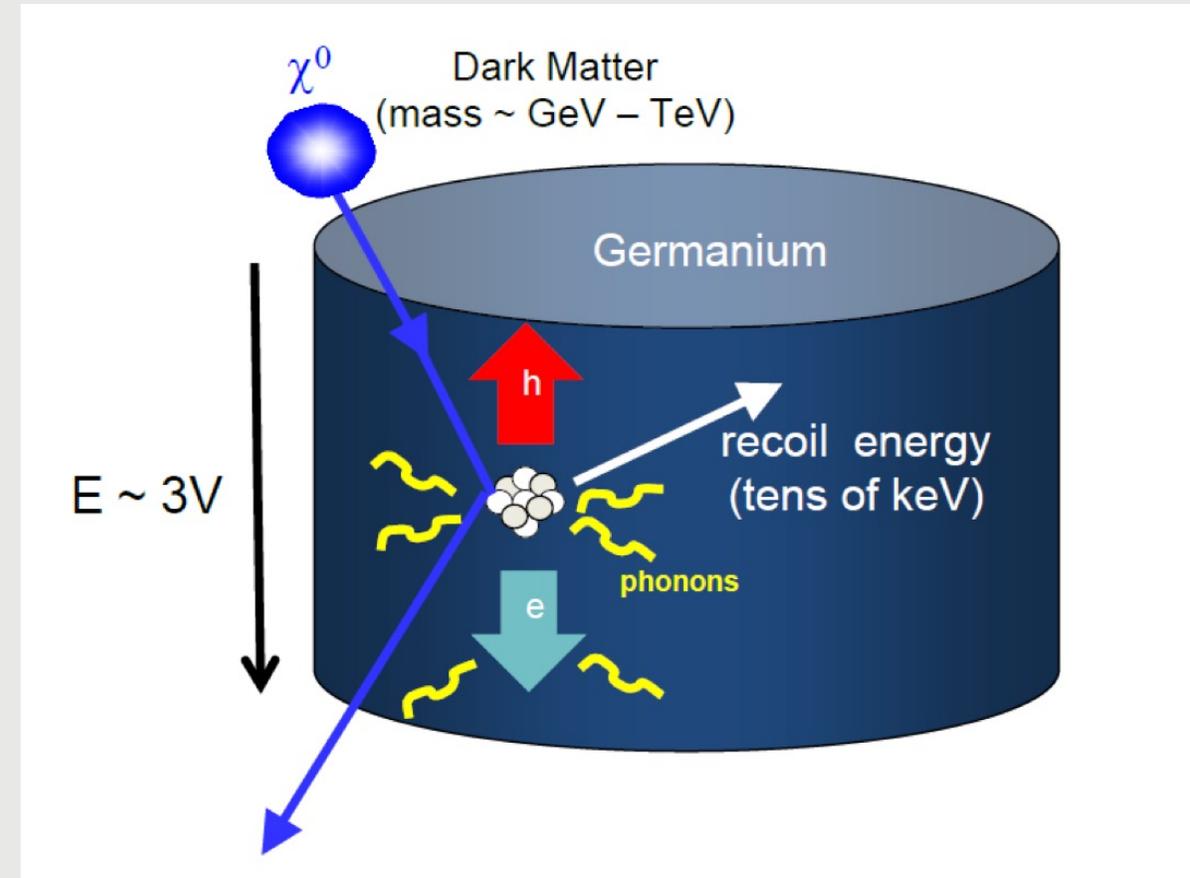
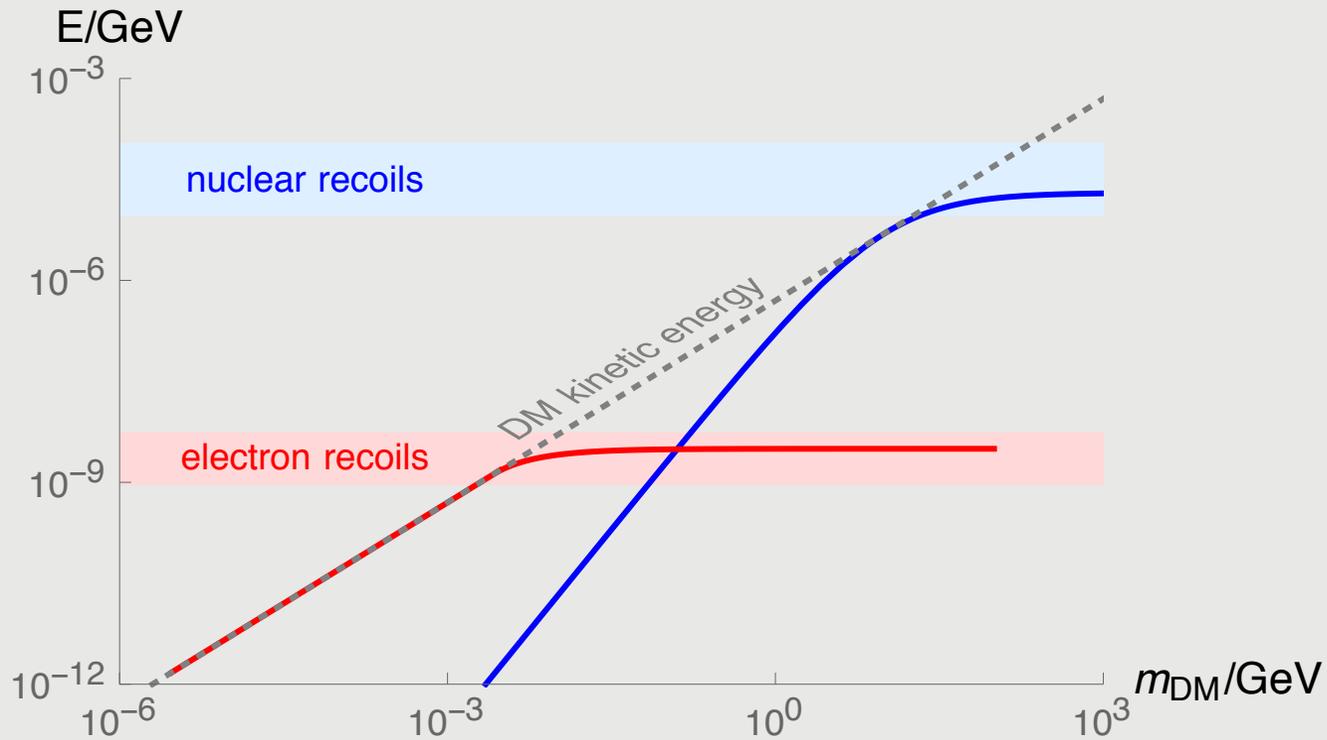


DM SCATTERING ON NUCLEI

Xenon1T 1805.12562



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

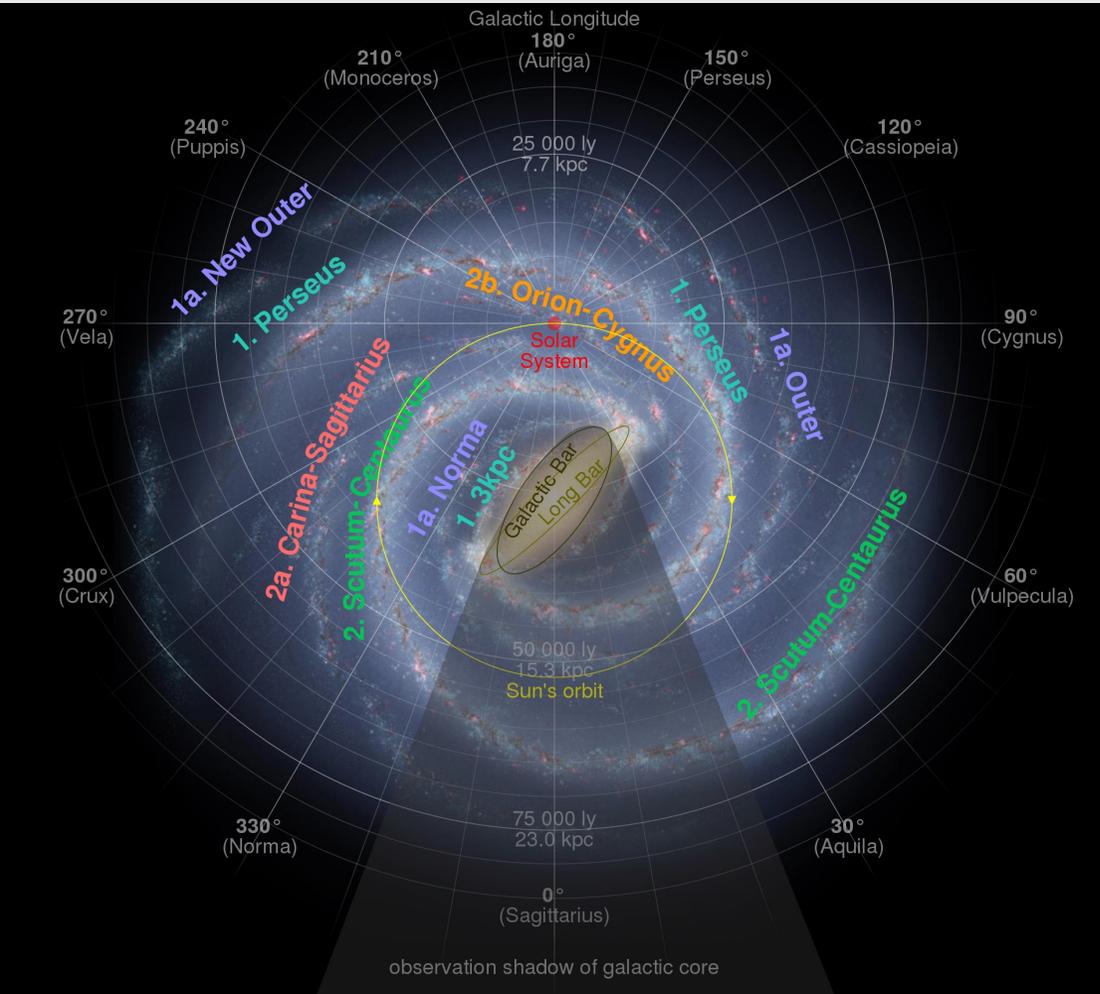


Smaller DM masses, smaller recoil energies.

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

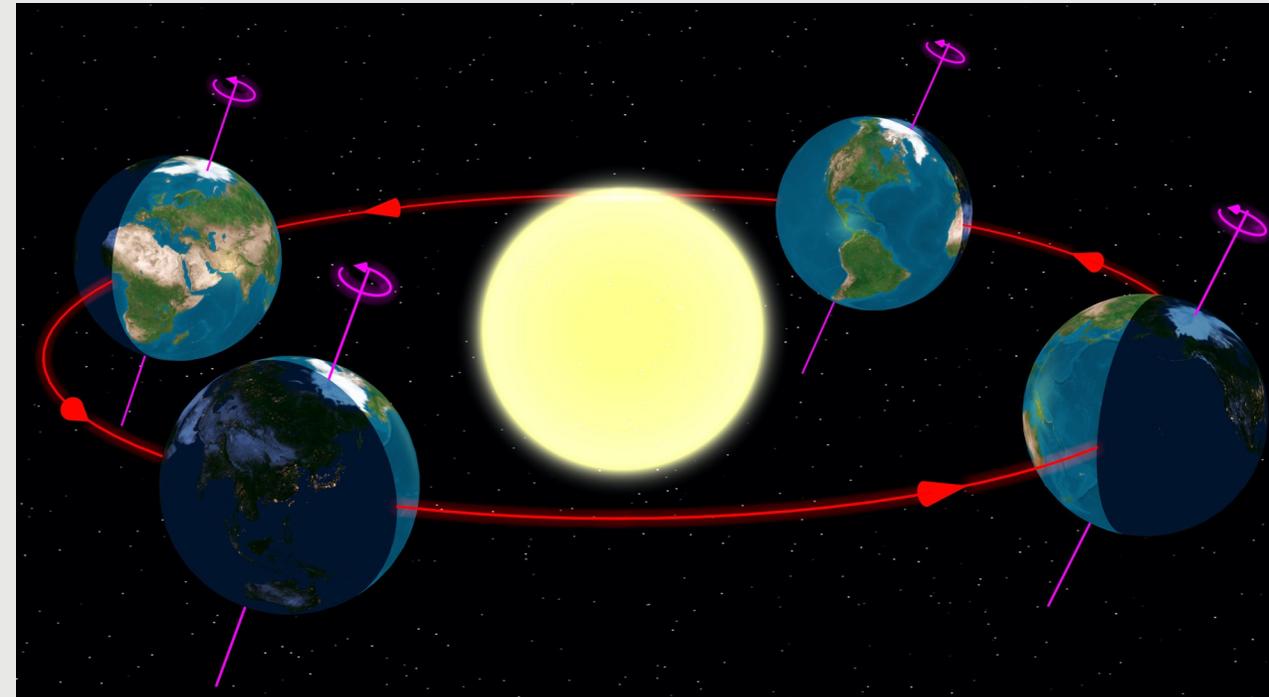
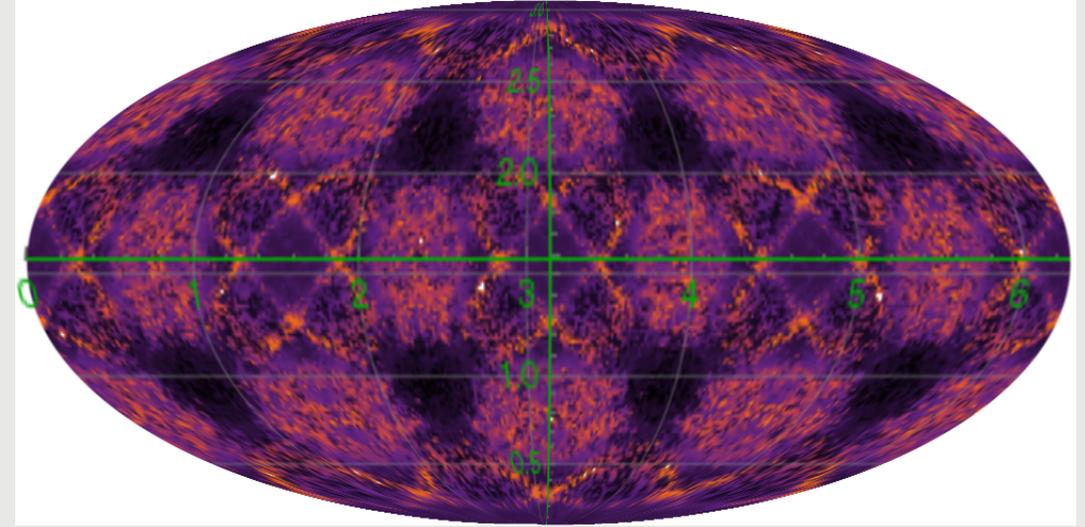
Effects dependent on material properties.

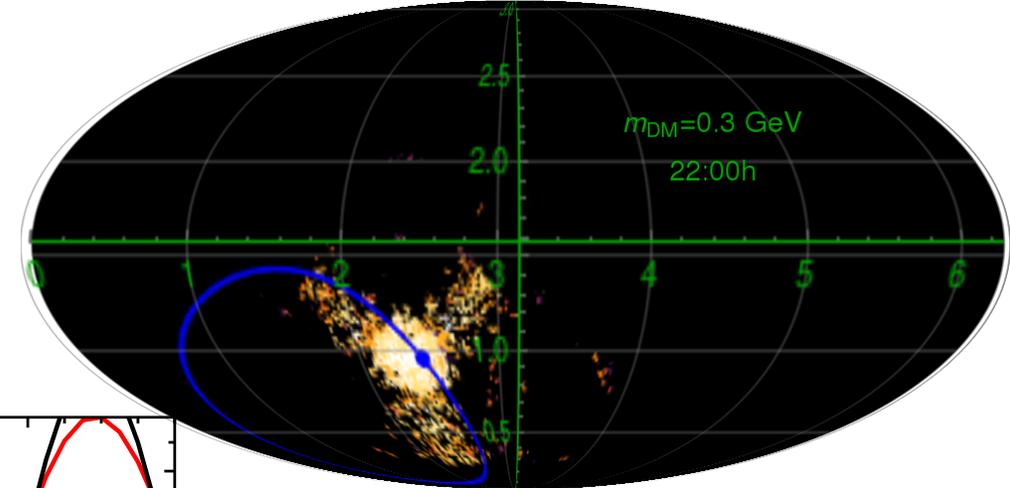
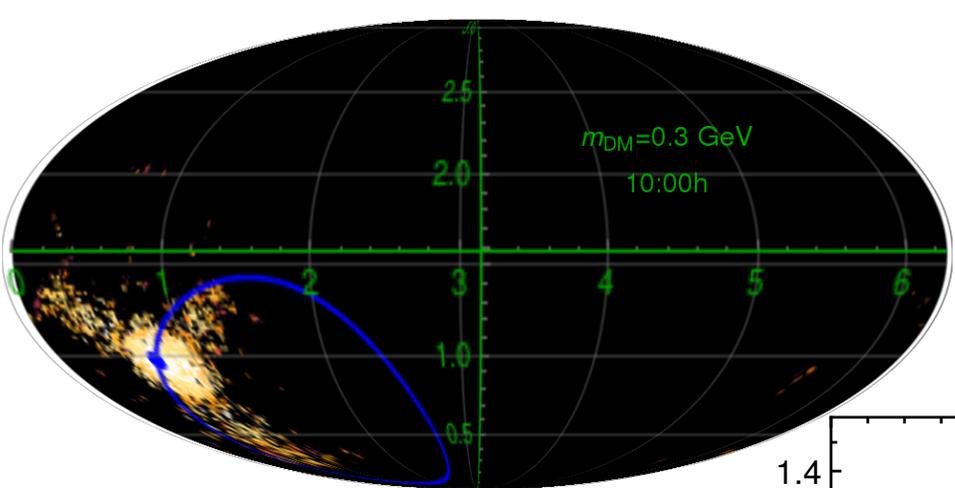
Constant level of recoils
as the Sun moves in the Galaxy.



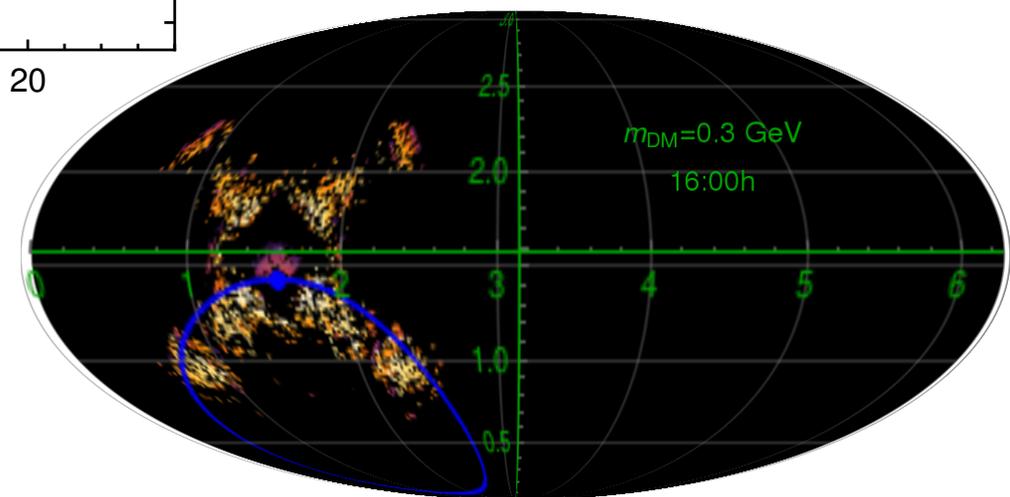
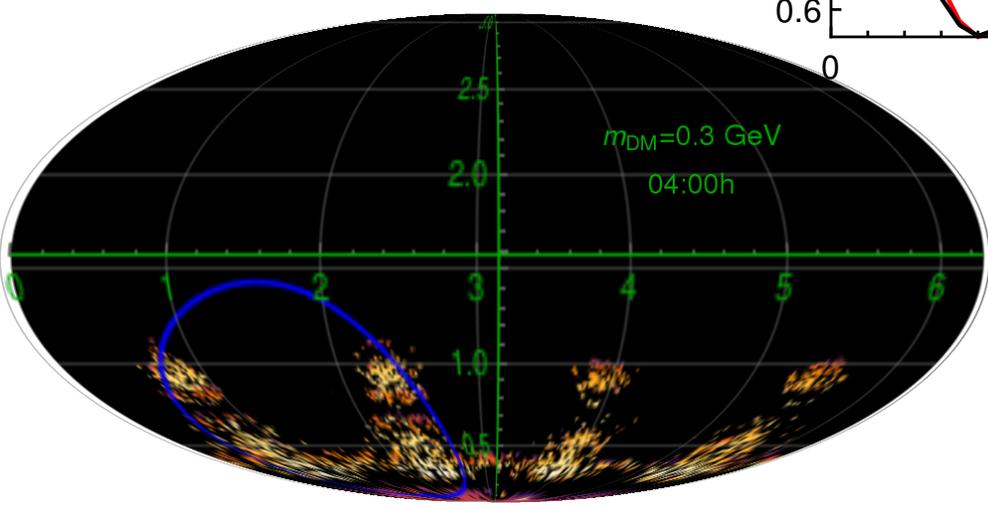
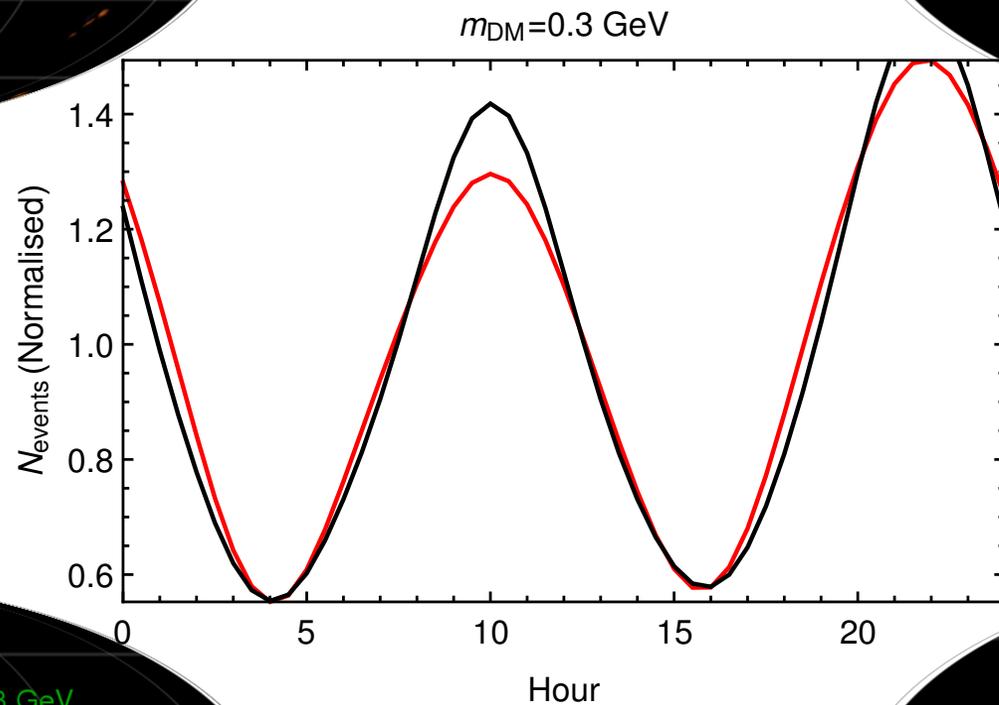
Additional effects from
movement of the Earth

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