CERN Academic Training Lectures: Dark Matter Searches

Lecture 3: WIMPs at Colliders and Searches for Light Dark Matter

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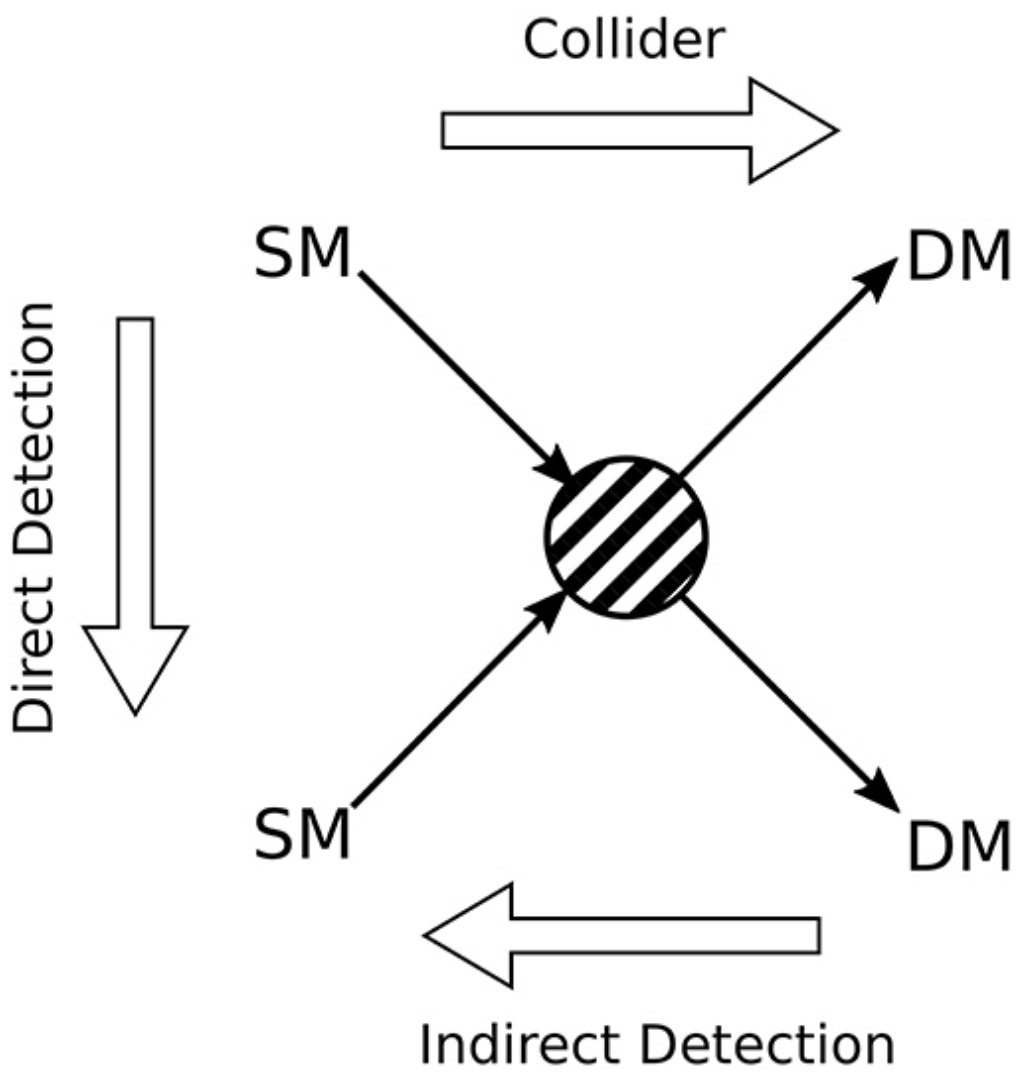
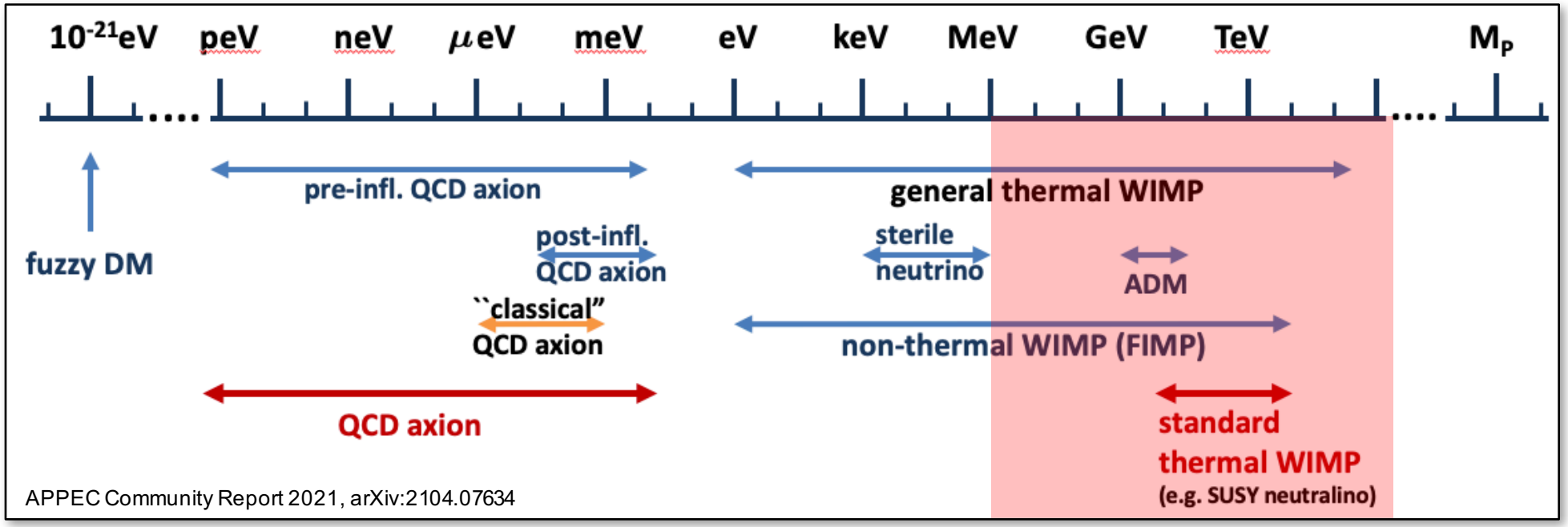
Recap: Dark Matter Searches

- Three main ways to search for evidence of particle DM via non-gravitational interactions
- Indirect: Seek evidence for annihilation or decay products of DM particles trapped in galactic / solar / planetary potential wells
  - X-rays, gamma rays, neutrinos, anti-matter ….
  - May prove DM but not identify particle
- Direct: Seek evidence for DM particle interactions with targets in terrestrial detectors
  - Nucleons, nuclei, electrons, photons …
  - May prove DM but not identify particle
- Accelerator/Collider: Seek evidence for invisible particle production in SM particle collisions
  - May identify particle but cannot prove DM



S. Giagu, https://doi.org/10.3389/fphy.2019.00075

WIMP Searches at Colliders

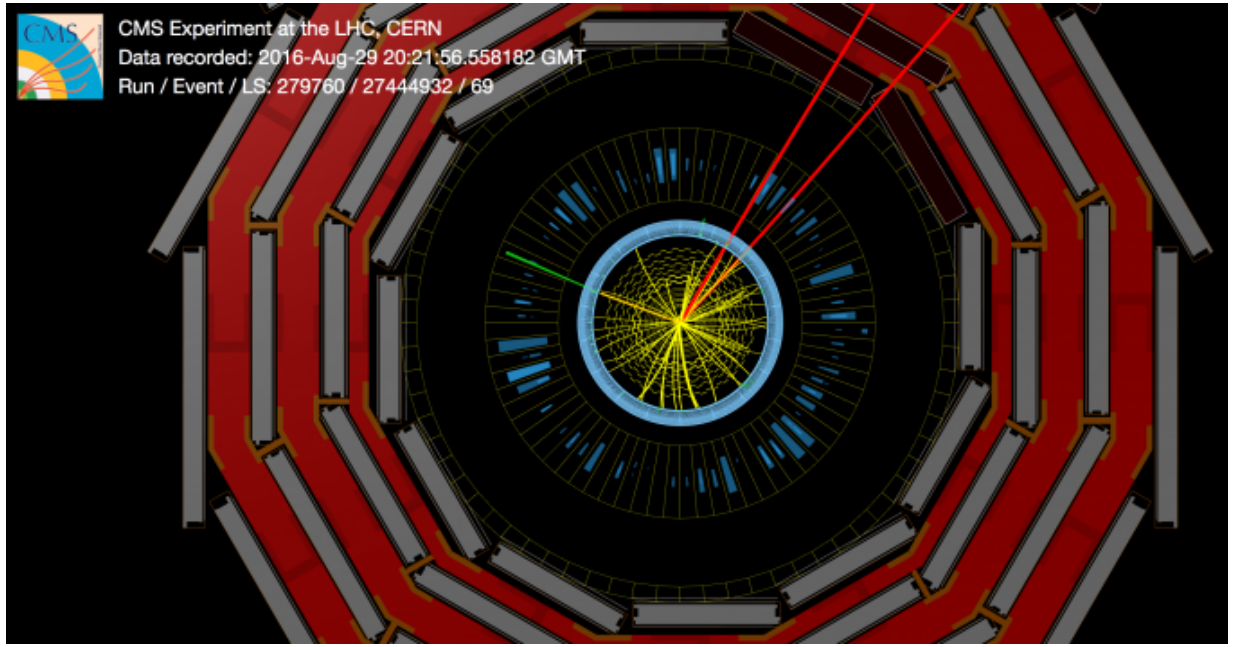


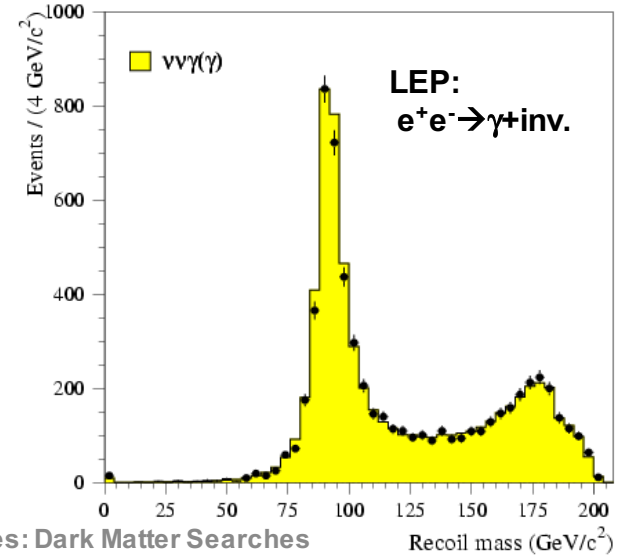
APPEC Community Report 2021, arXiv:2104.07634

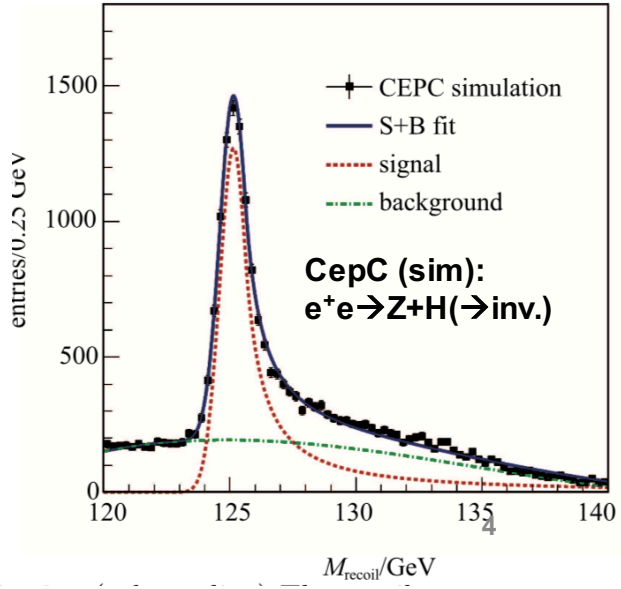
Collider Kinematics

- Central to all DM searches at colliders is missing (transverse) energy
  - Negative vector sum of visible products
  - Lepton colliders (LEP, ILC, CepC, FCC-ee, muon collider): 3-vector E^{miss}
  - Hadron colliders (Tevatron, LHC, FCC-hh): 2-vector E_T^{miss} (MET)
  - Care must be taken with soft particles / unclustered energy
- Lepton colliders further benefit from beam energy constraint:
  - 'Missing mass' / 'recoil mass'

$$m_{\rm rec}^2 = s + m_{\rm vis}^2 - 2\sqrt{s}\sqrt{p_{\rm vis}^2 + m_{\rm vis}^2}$$



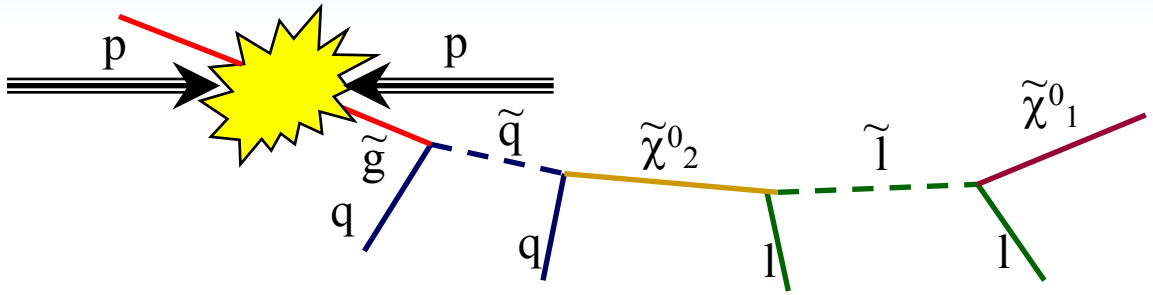


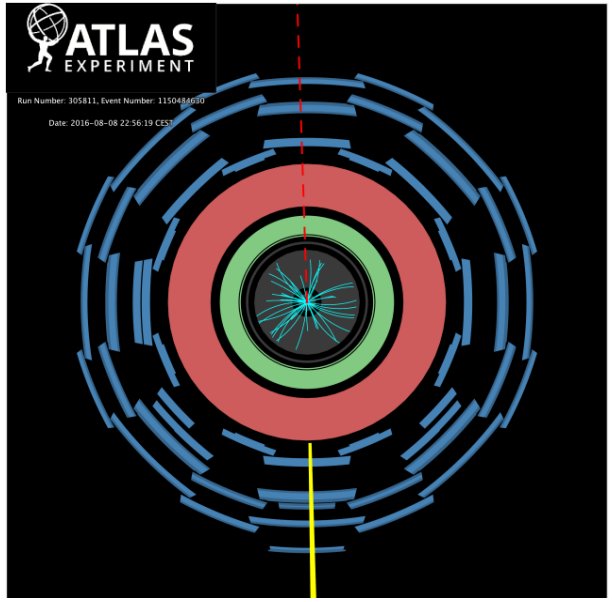


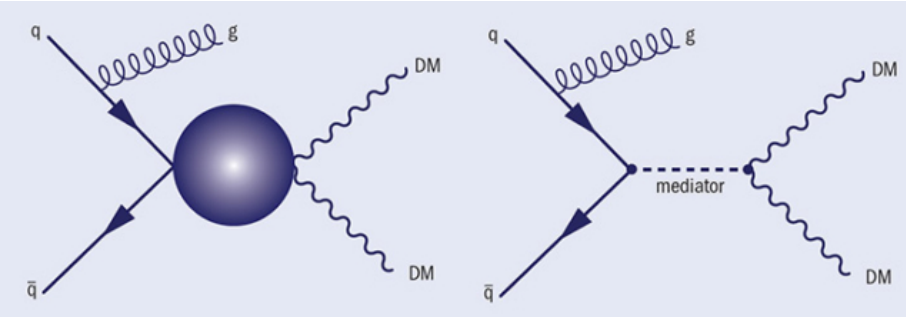
LHC Dark Matter Searches

- Model-dependent searches (e.g. SUSY):
  - Greater reach using (strongly coupled) decay chain → additional final state particles
  - Less inclusive
  - DM signal from R_p-conserving models
  - DM (neutralinos) pair-produced
- Generic DM searches:
  - DM couples to, and recoils against, specified visible final state
  - Simplified model with DM and mediator
  - Parameterisation: m_χ, m_A, g_χ, g_q, $J^{CP}(A)$, $J^{CP}(\chi)$
  - Coupling of mediator to pp enables complementary search for BSM mediator resonance
  - Usually assume DM pair production

See also: https://lpcc.web.cern.ch/content/lhc-dm-wg-dark-matter-searches-lhc







SUSY Search Kinematics

- Model-dependent SUSY searches exploit longer decay chains
- Introduces additional decay constraints on kinematics
- Event selection can exploit endpoints in
  - 'Stransverse' mass m_{T2}

$$m_{\mathrm{T2}} = \min_{\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} = \mathbf{q}_{\mathrm{T}}(1) + \mathbf{q}_{\mathrm{T}}(2)} \left[\max\left(m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}(1), \mathbf{q}_{\mathrm{T}}(1)), m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}(2), \mathbf{q}_{\mathrm{T}}(2)) \right) \right]$$

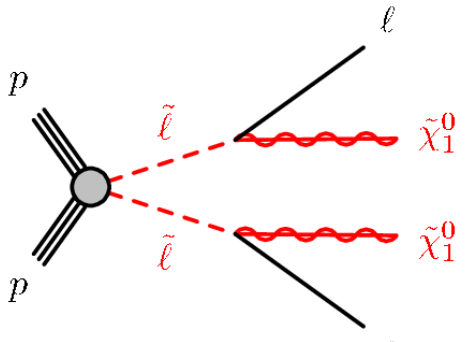
Lester and Summers (1999)

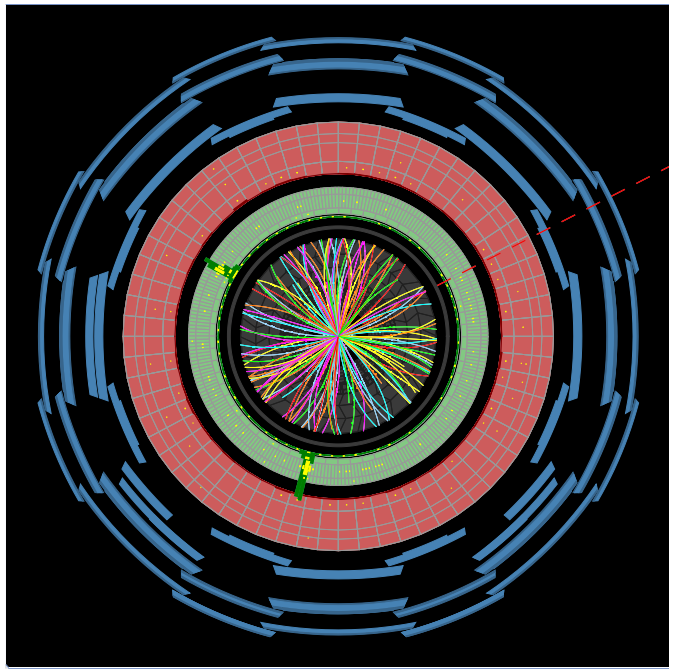
  - 'Contransverse' mass m_{CT}

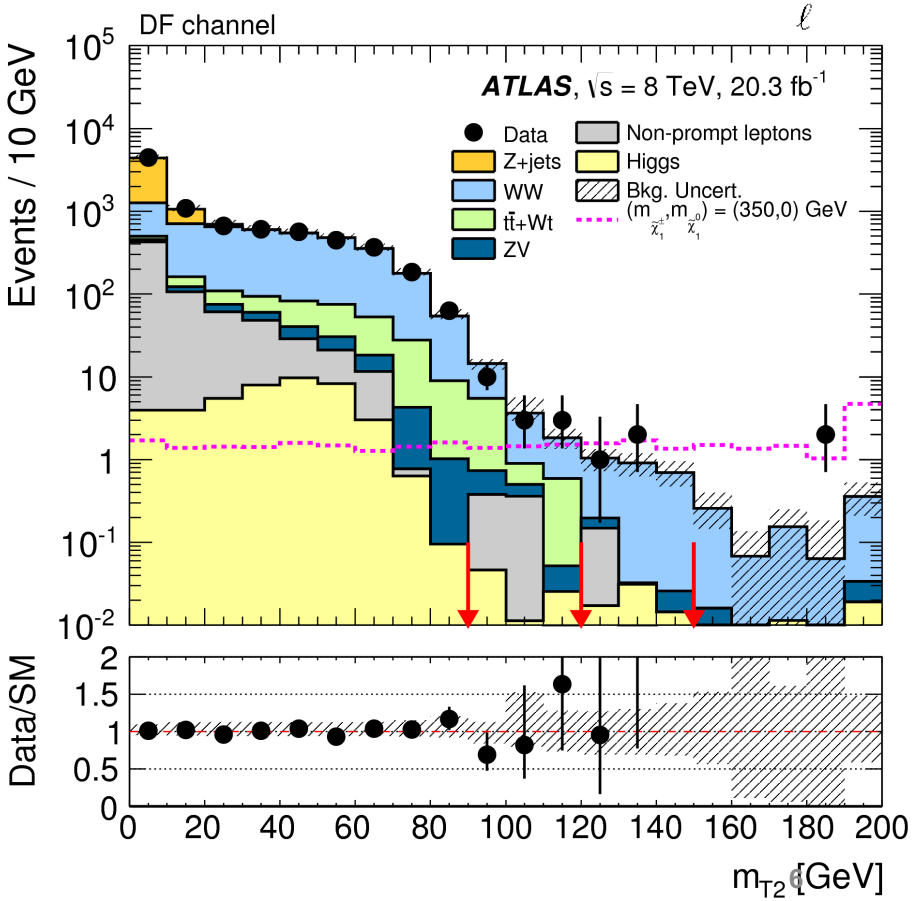
$$m_{\mathrm{CT}}^2 = (E_{\mathrm{T}}(1) + E_{\mathrm{T}}(2))^2 + (\mathbf{p}_{\mathrm{T}}(1) + \mathbf{p}_{\mathrm{T}}(2))^2$$

- Inclusive variables:
  - 'Effective mass'

$$m_{\mathrm{eff}} = \sum_{i=1}^{N} p_{\mathrm{T}}(i) + E_{\mathrm{T}}^{\mathrm{miss}}$$

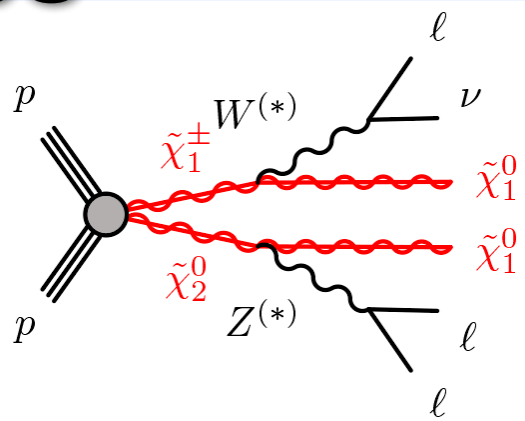


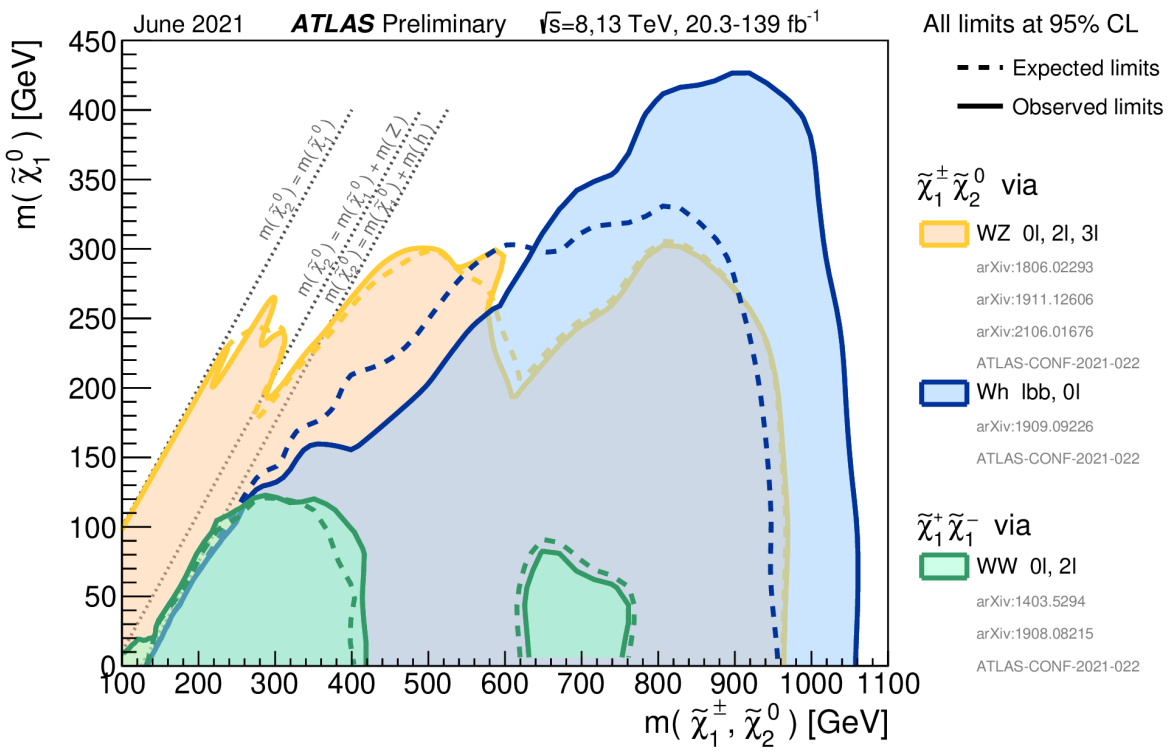


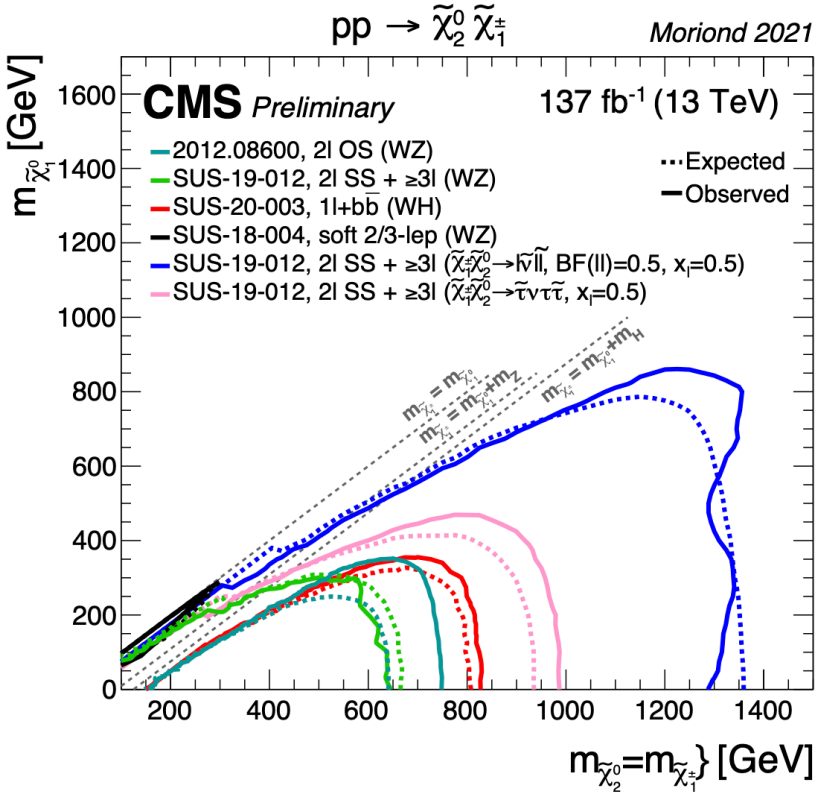


Electroweak SUSY Searches

- $\chi^0_1\ \chi^0_1$ pair production invisible
- Greatest sensitivity for $\chi^0_2\ \chi^{\pm}_1$ production
  - Variety of decay modes, e.g. 3l/2l/0l+MET (WZ), lbb/0l+MET (Wh), slepton
  - Assume mass degenerate χ^0_2 , $\chi^{\pm}_1$
  - Pure wino (AMSB) / higgsino: χ^0_1 degenerate → χ^0_2 , $\chi^{\pm}_1$ products soft

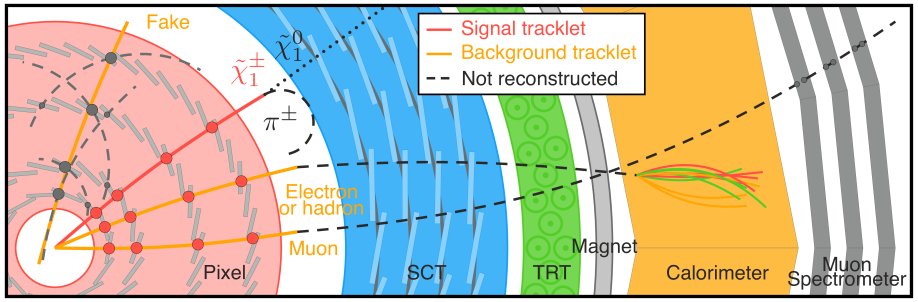


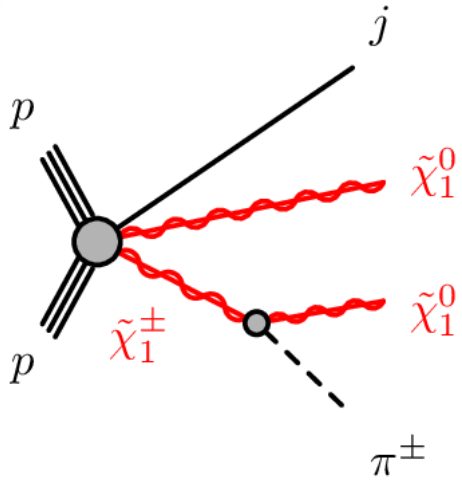




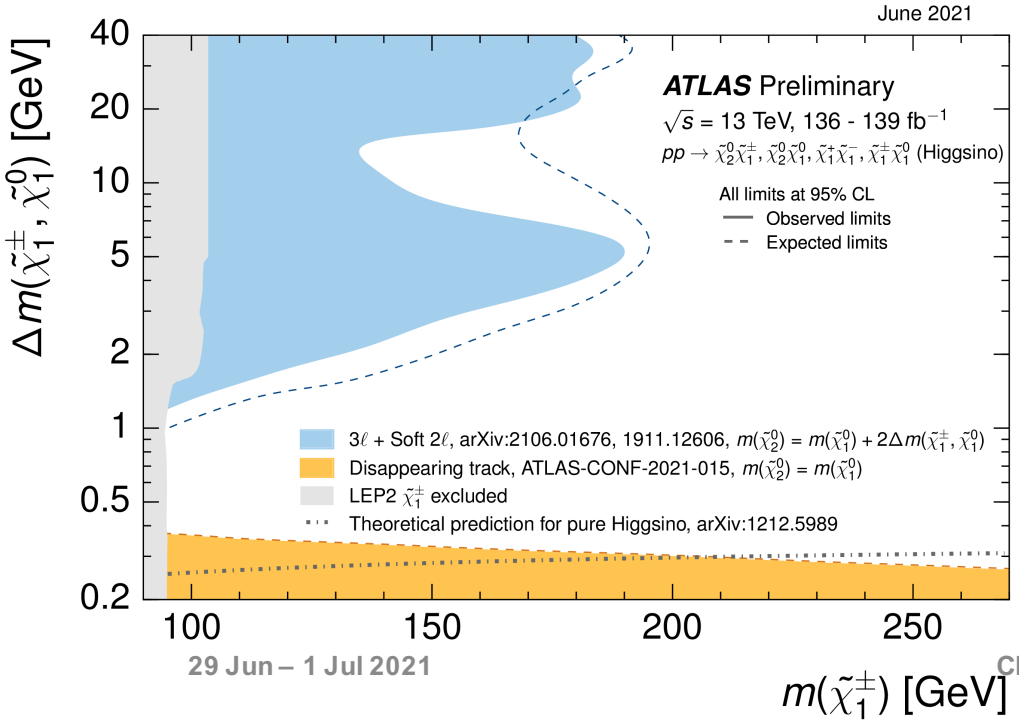
Wino/Higgsino Searches

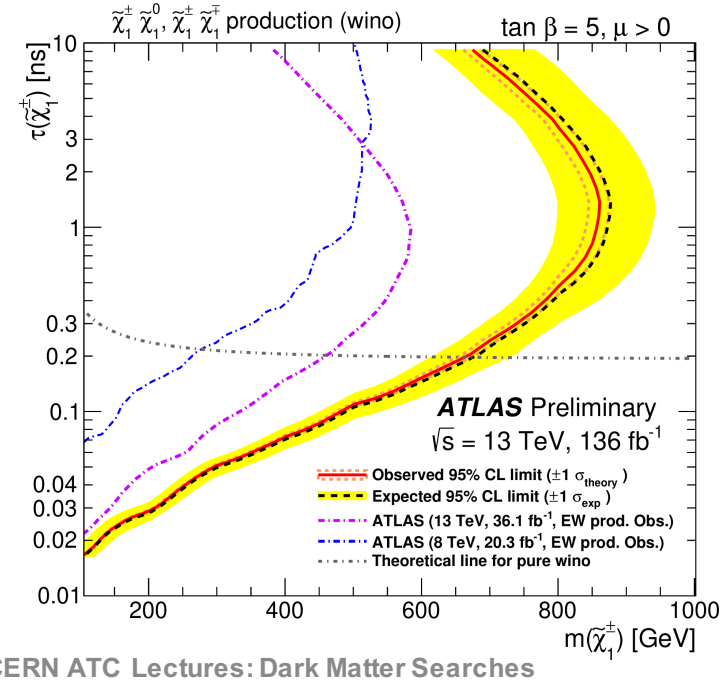
- Small mass splitting creates meta-stable NLSP (phase-space)
  - Dedicated search for disappearing track signatures
  - Also soft lepton signatures (larger mass splitting)

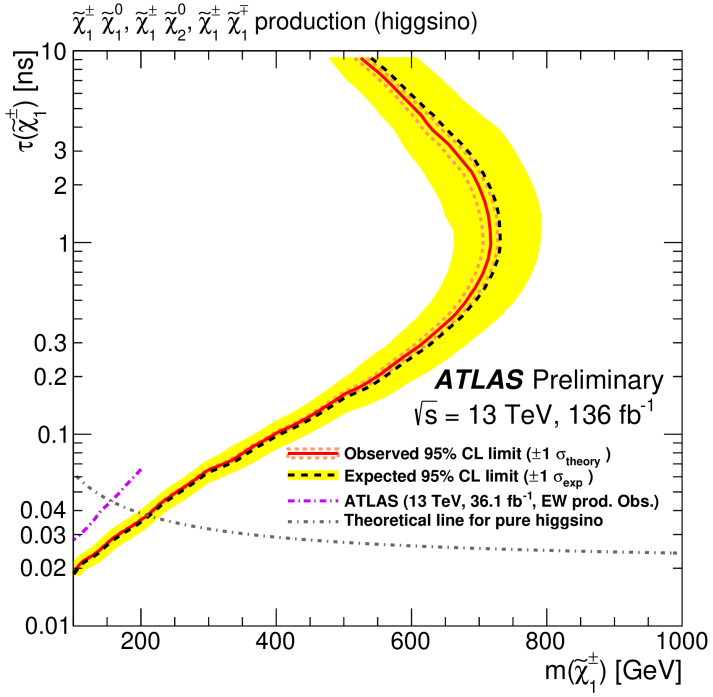




See also https://atlas.cern/updates/briefing/new-higgsino-limits

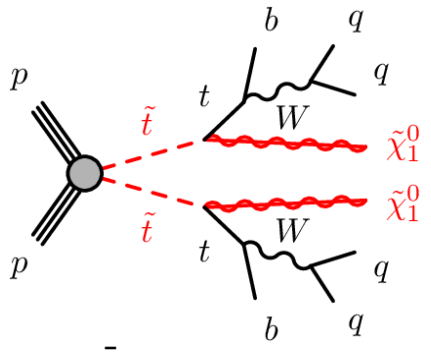


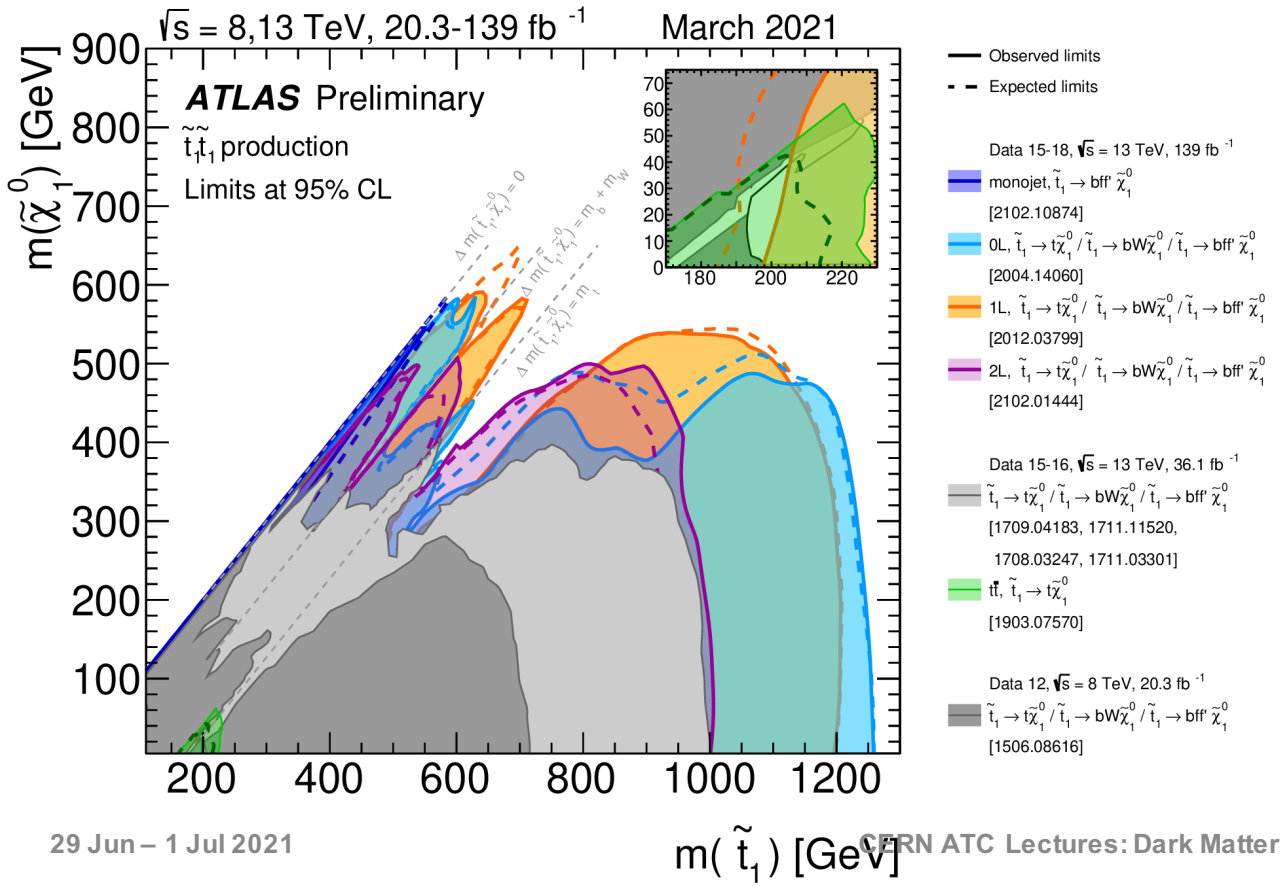


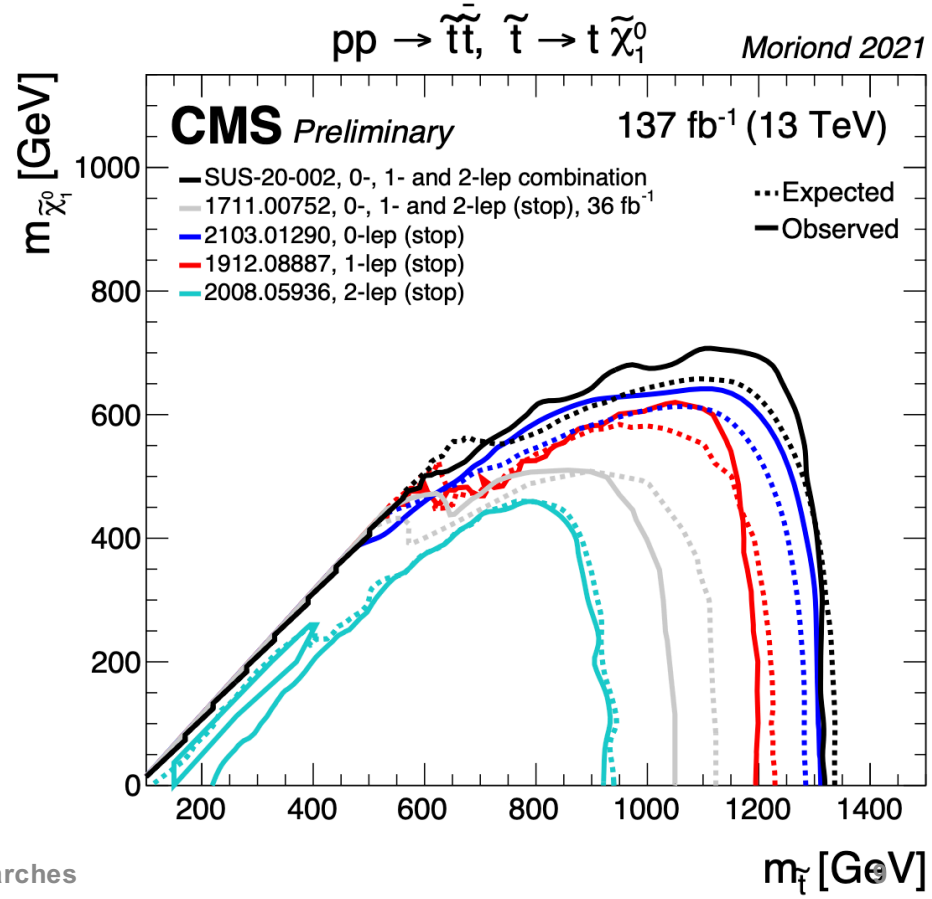


3rd Generation Searches

- Greater reach using strongly produced states
- Stop must be light to solve hierarchy problem
- Mass limits ~ 500-700 GeV for high m(stop)

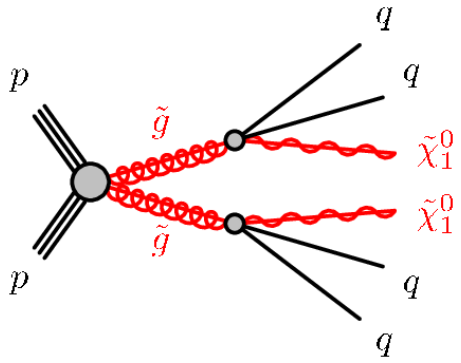


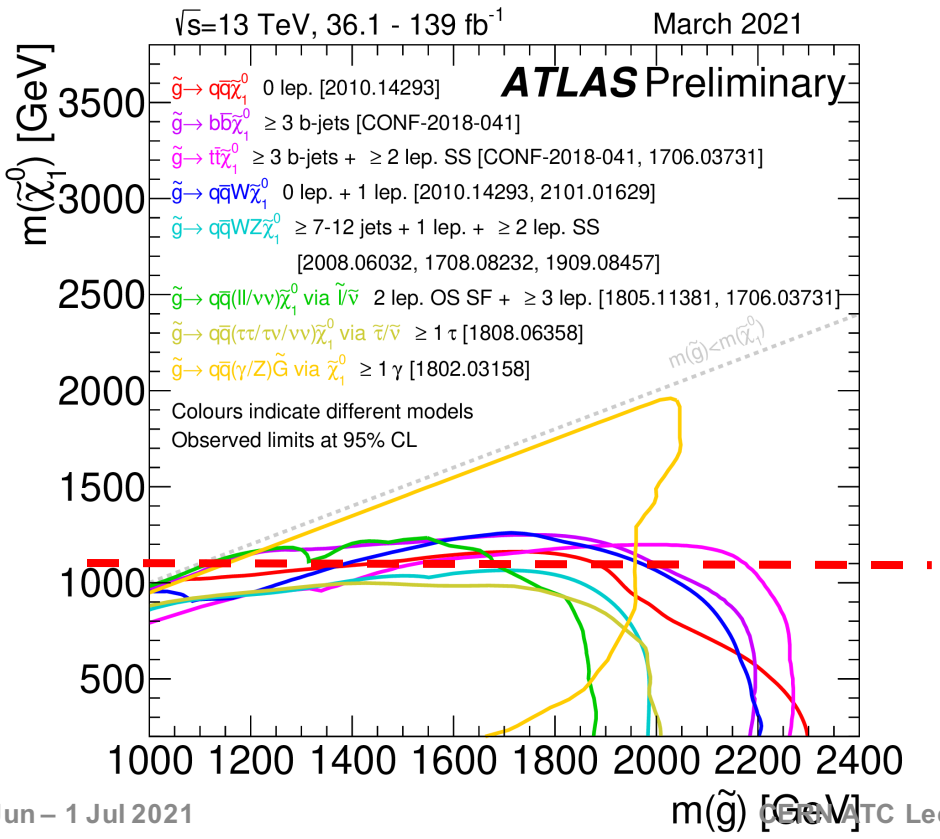


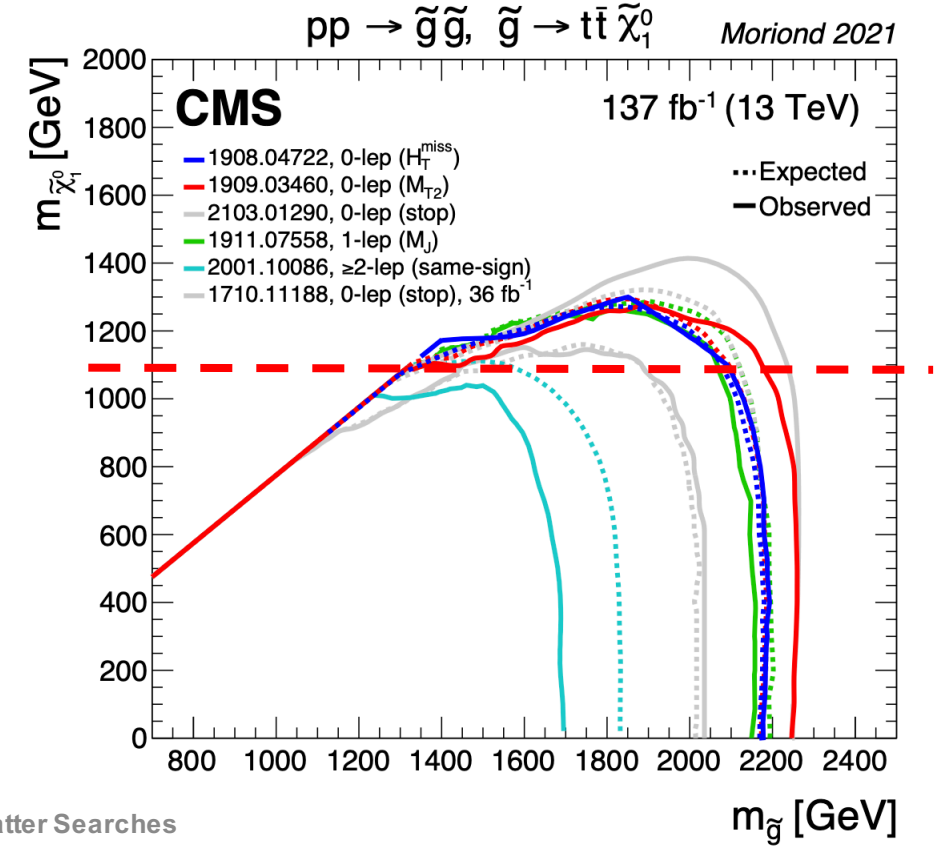


Gluino Searches

- Still greater reach using gluino decays
  - High cross-section,
  - Long decay chains, high (b)-jet multiplicity → low background
  - Gluino mass correlated with stop mass → 'gluino sucks'
  - Mass limits ~ 1000 – 1300 GeV for high m(gluino)

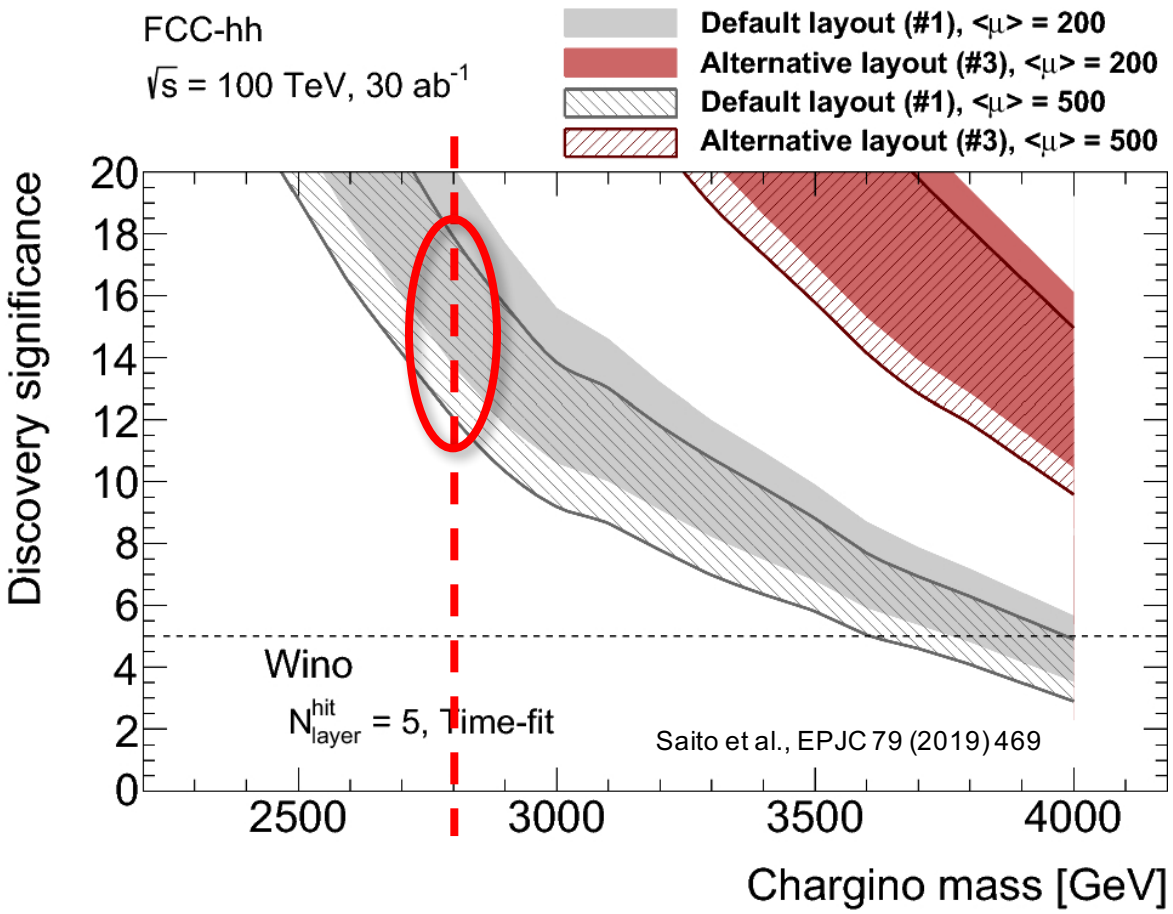


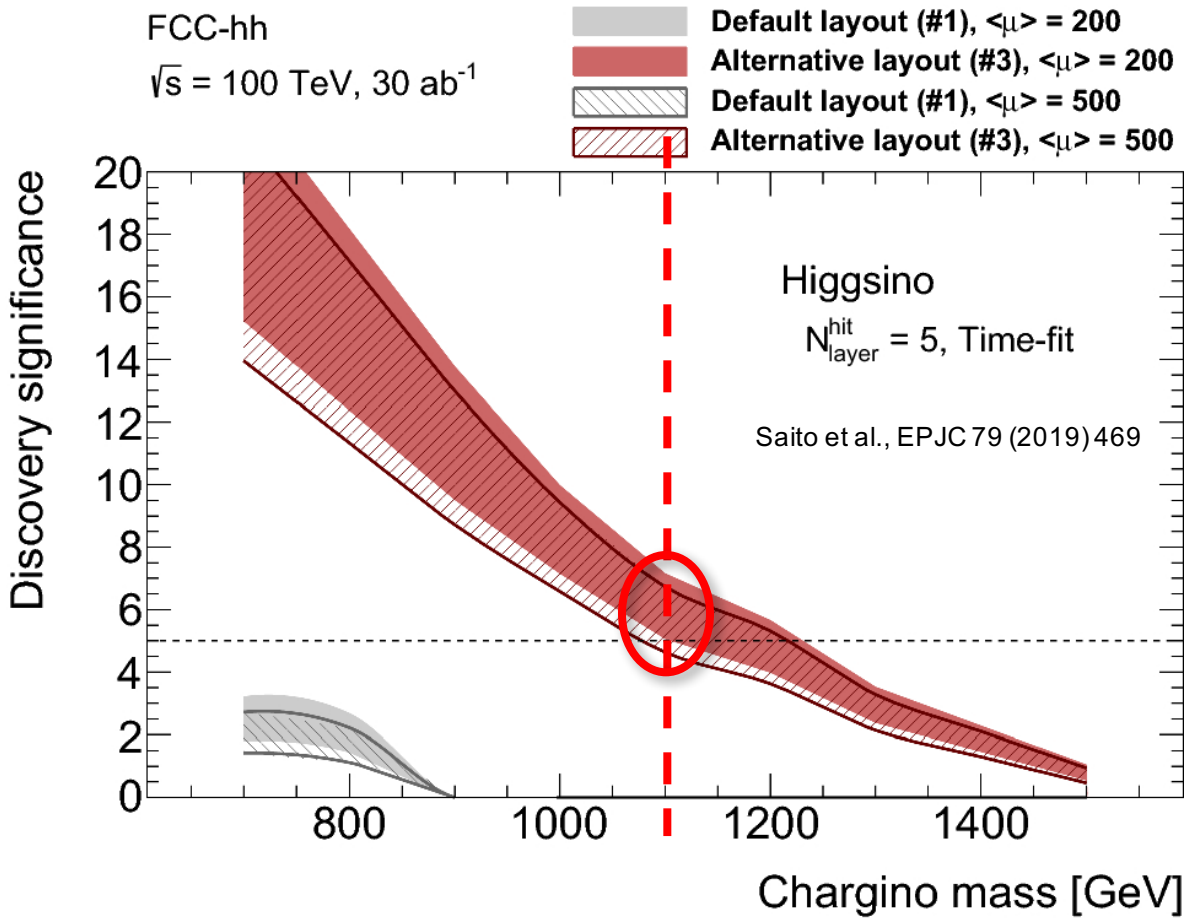




Winos/Higgsinos at FCC-hh

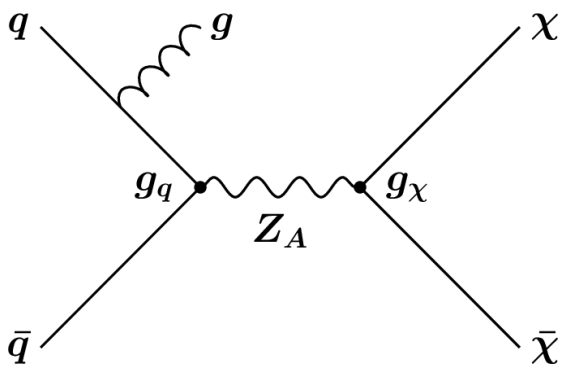
- Disappearing track signature gives possibility for 5σ observation of wino and higgsino DM production at FCC-hh

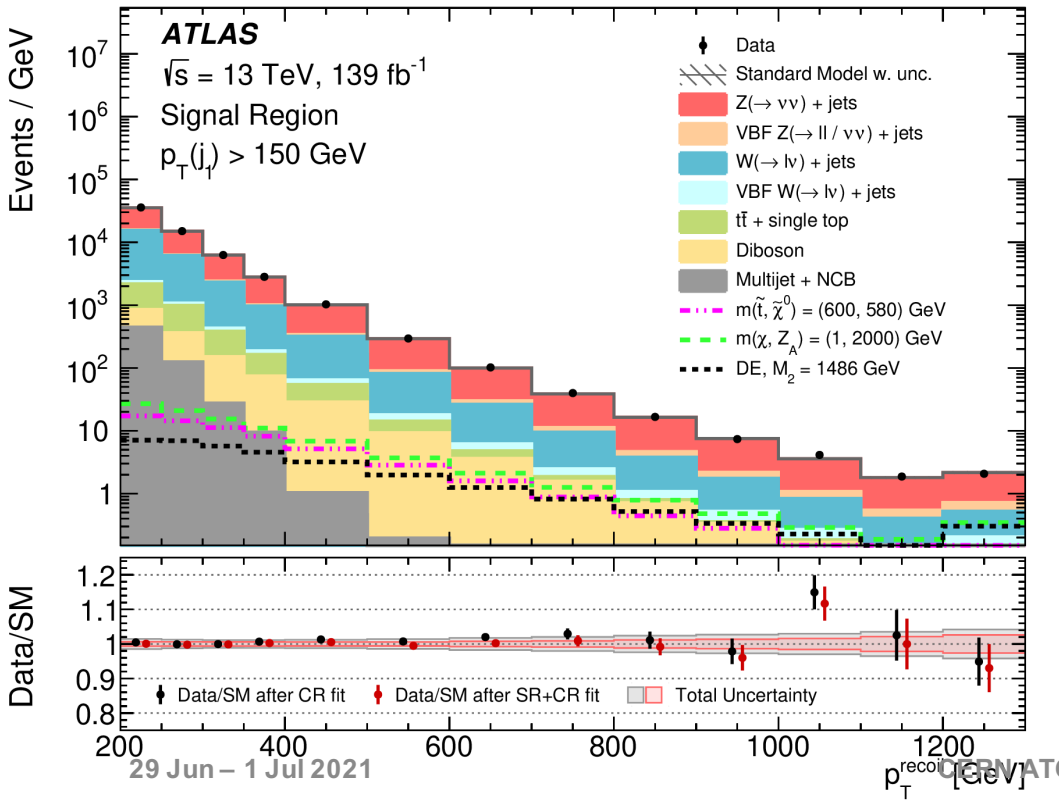


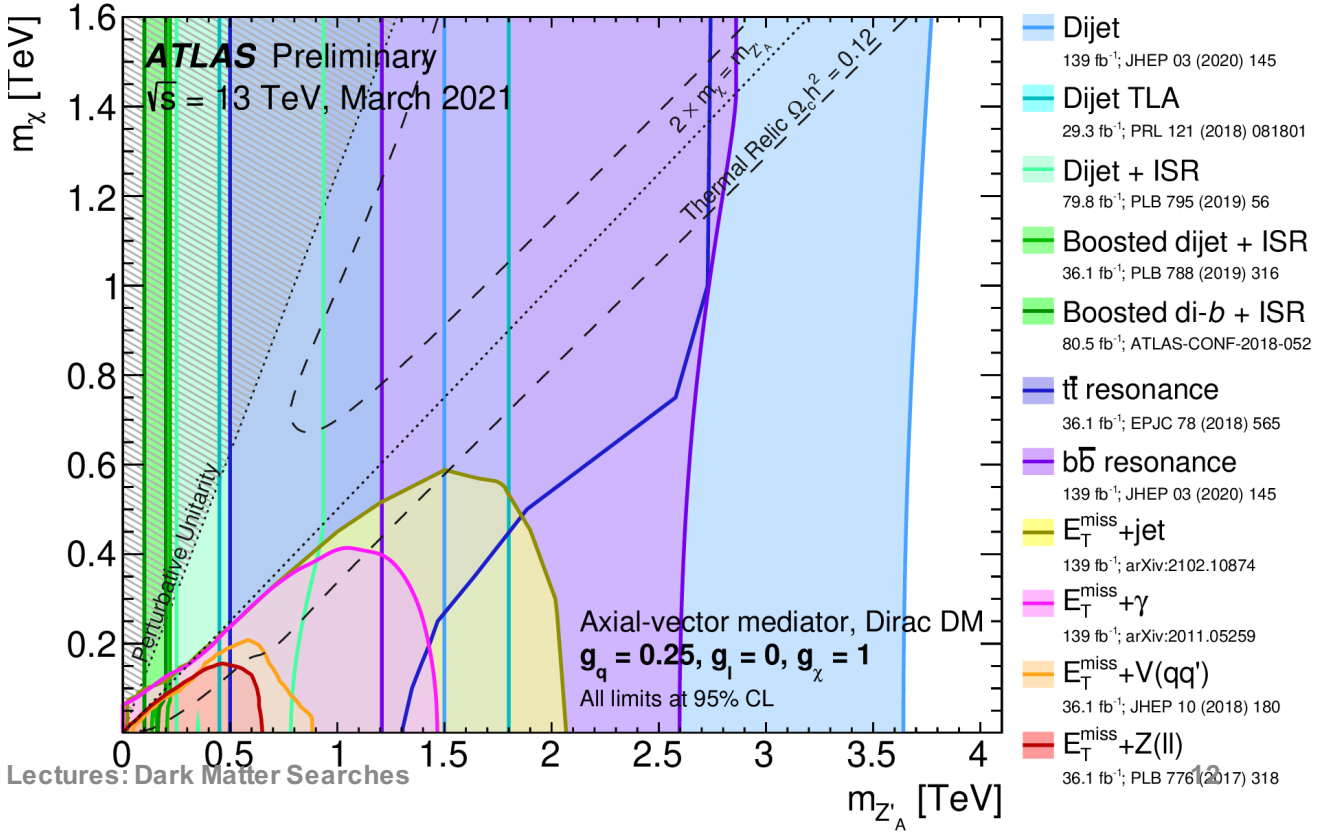


Generic DM Searches: mono-X

- To be produced, DM must couple (in-)directly to quarks/gluons
  - Tag invisible DM events with gluon (jet) + MET (a la LEP)
- Also consider γ/W/Z/H/t/b+MET
- Resonance searches give strong limits unless DM coupling v.large
  - Mediator must couple to qq due to production process

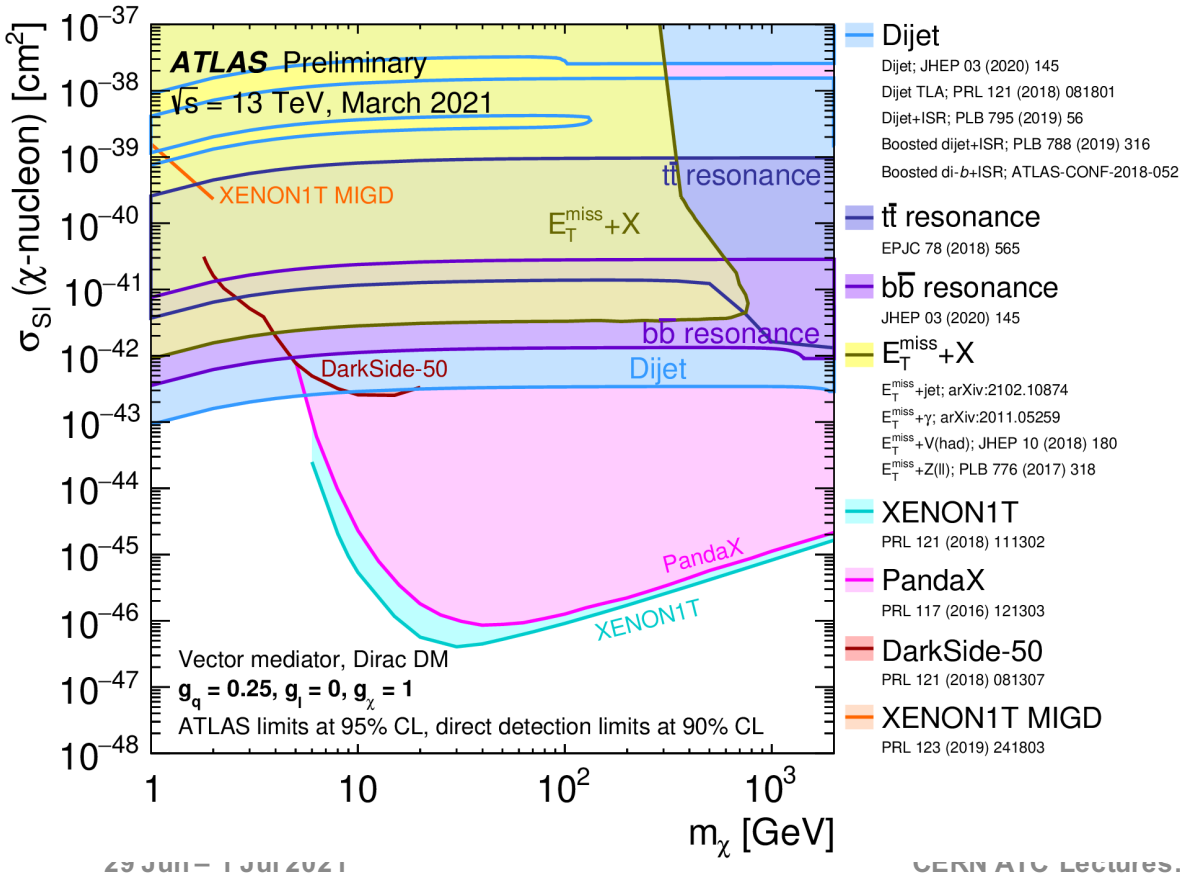


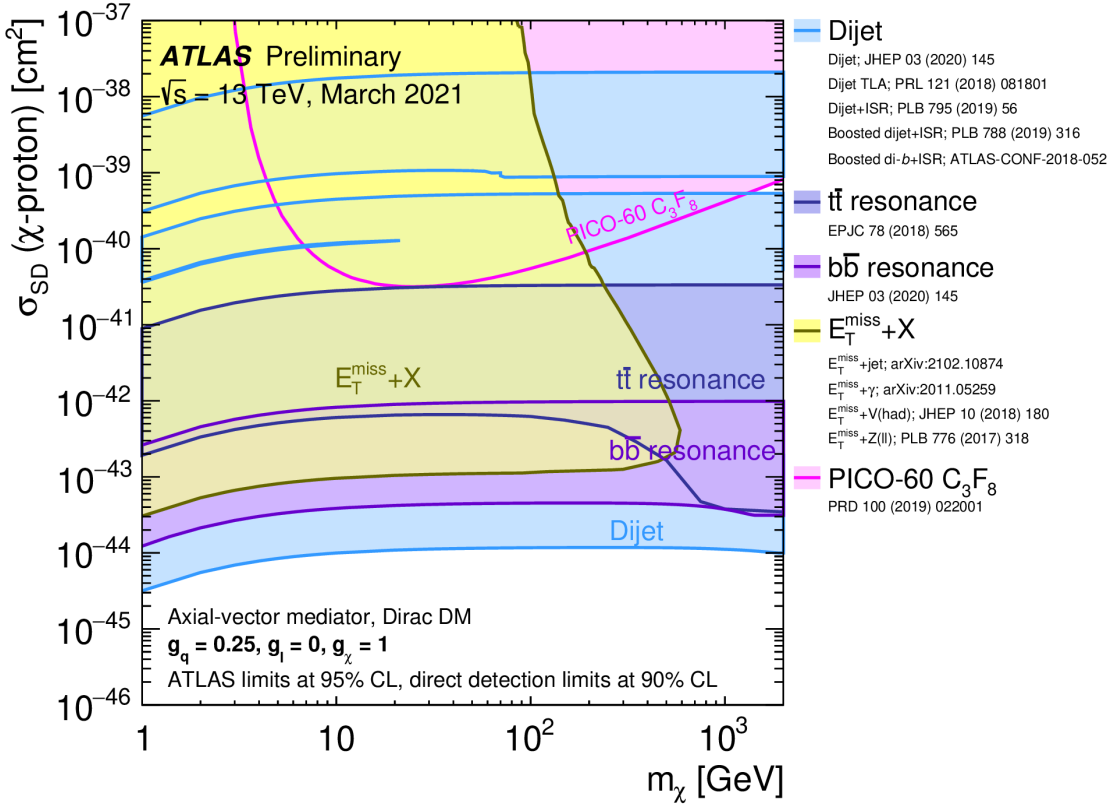




Generic DM Searches

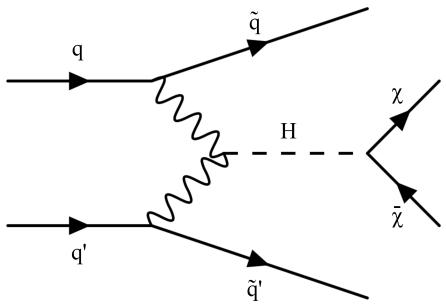
- Within context of specific generic model, can reinterpret mono-X+MET and resonance limits in direct detection parameter space.
  - Highly model-dependent
  - Constraints most powerful for light DM, where direct searches lose kinematic sensitivity



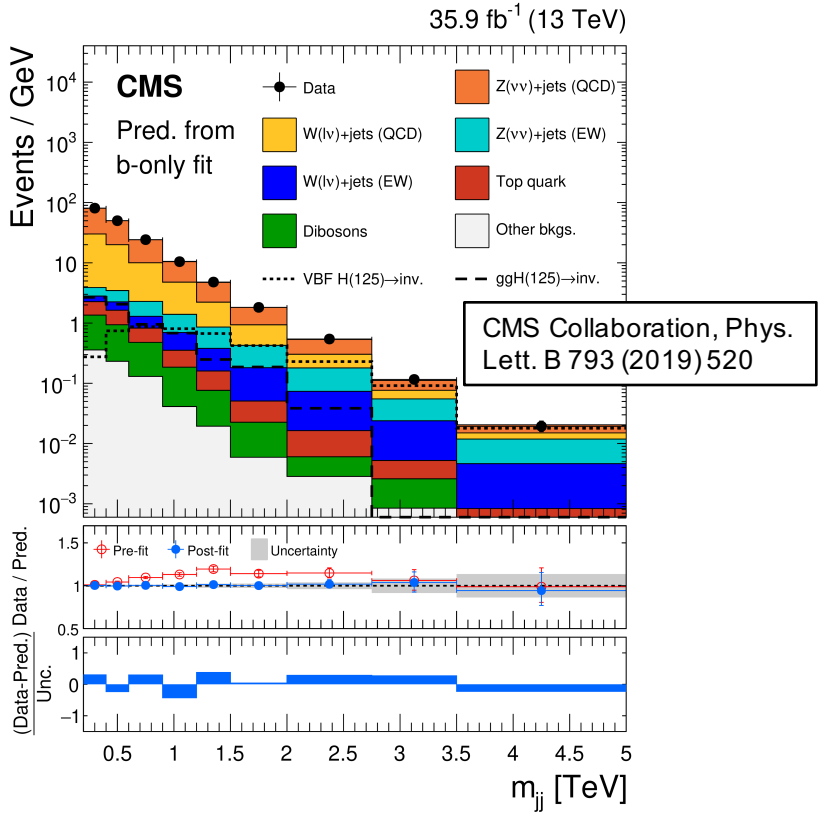


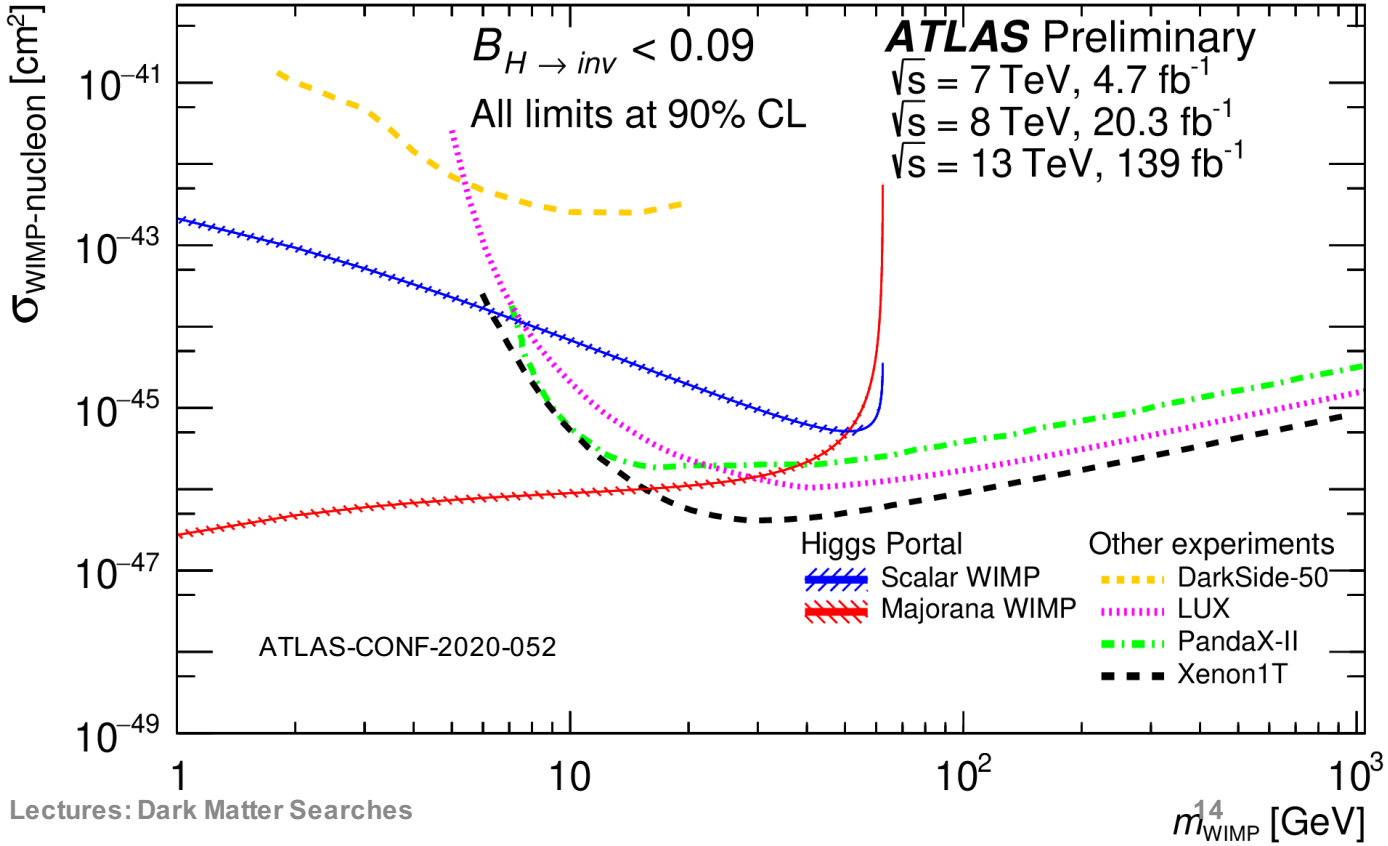
Invisible Higgs Decays

- Direct search for invisible Higgs decays in VBF production mode
  - BR enhanced by decays to DM in higgs portal models
  - Relevant only for $m_\chi < m_H/2$
  - Results model-dependent. Most powerful for low m_χ

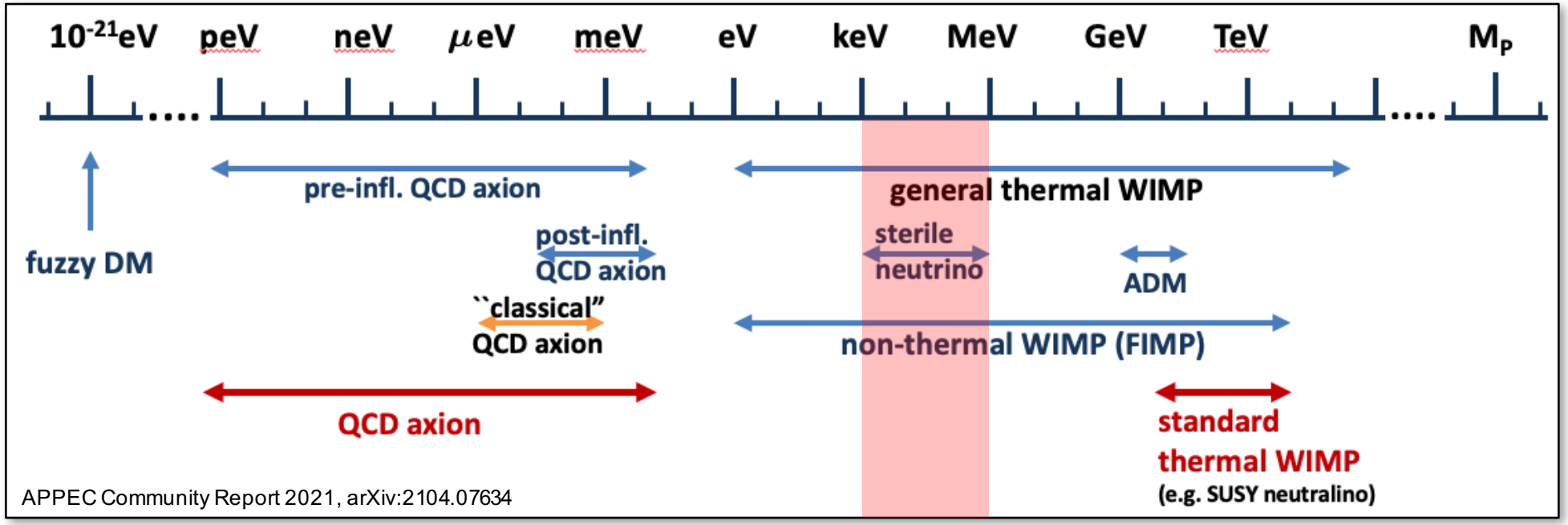


- Higgs coupling combination further strengthens limit (with more assumptions)



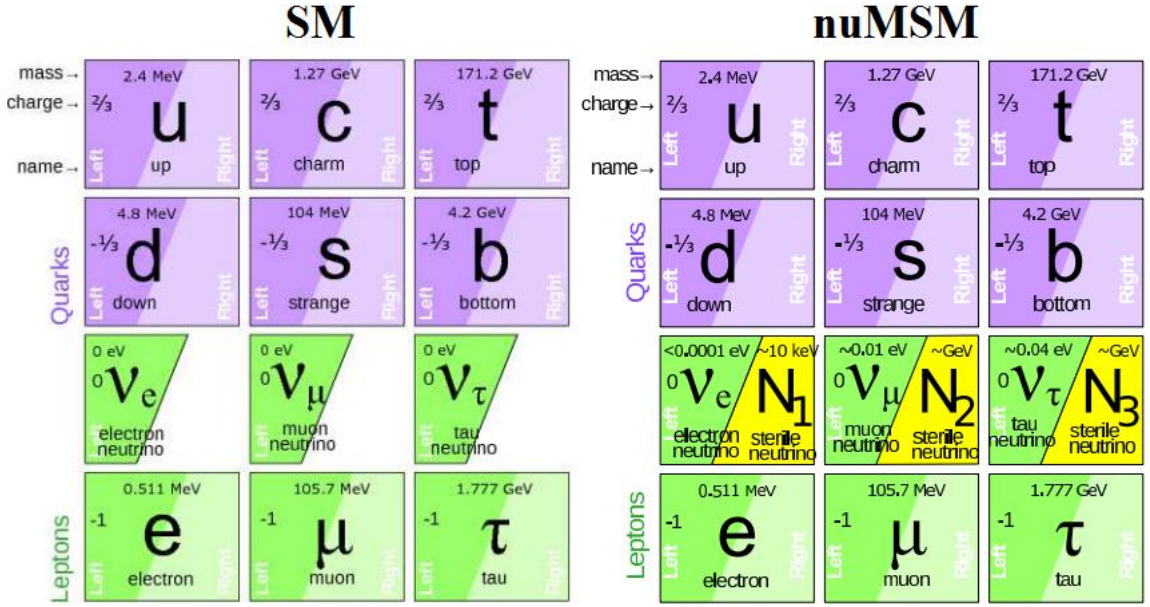


Search for Heavy Neutrino Dark Matter



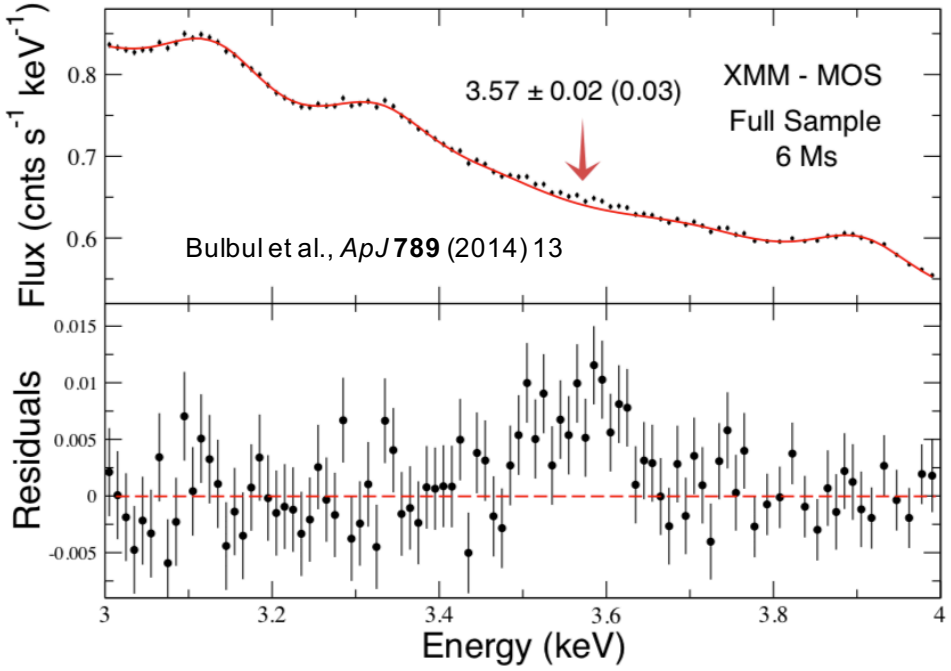
Sterile Neutrino DM

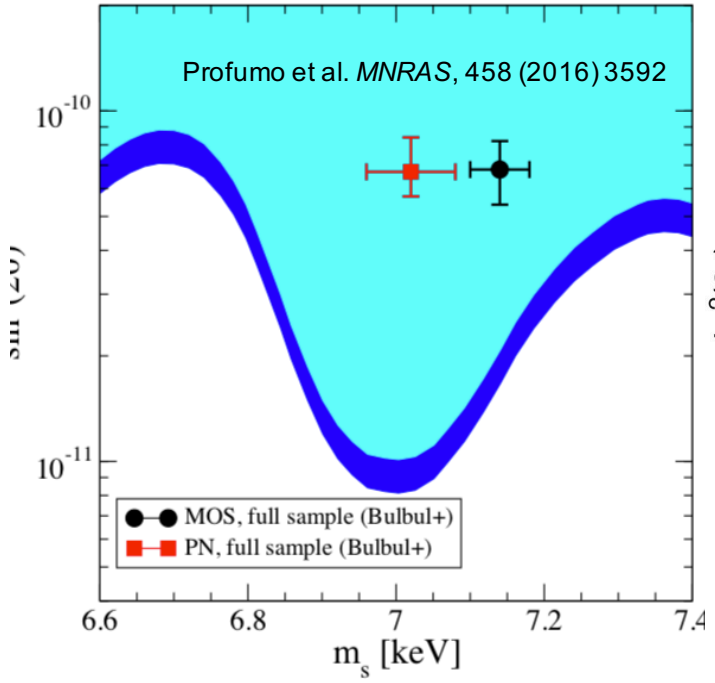
- Heavy LH neutrinos with SM couplings excluded (direct search with t-channel Z)
- RH singlet ν_R mixing with LH SM neutrinos ν_L allowed for small mixing angles θ
- ν_R decays to 3 ν_L (invisible) and $\nu_L+\gamma \rightarrow$ mono-energetic photon signal $E_\gamma=m_{\nu R}/2$.
- Concrete model: νMSM
  - Asaka, Blanchet and Shaposhnikov, Phys. Lett. B 631 (2005) 151
  - Lightest SM ν_R is DM candidate (N_1)
  - Explanation for baryogenesis, ν masses etc.

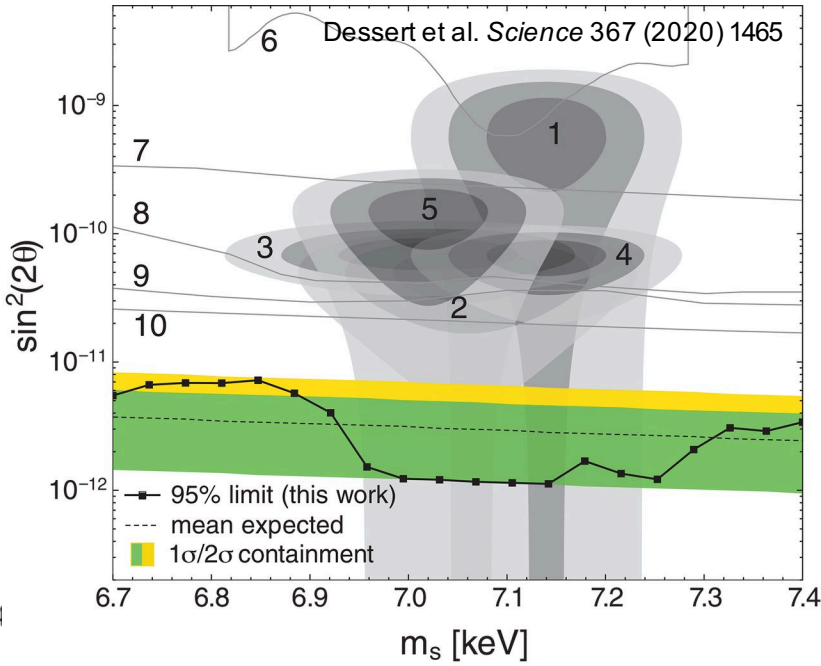


3.5 keV X-Ray Line

- Bulbul et al. (2014 and later) and others claim anomalous mono-energetic 3.5 keV X-ray line in stacked XMM observations of galaxy clusters, and galactic centre.
- Signal not observed in other studies of galaxies, dwarf galaxies (Draco etc.) and stacked XMM blank-sky observations of the MW halo
- High-res calorimetry from XRISM (ex-HITOMI SXS) will be crucial test

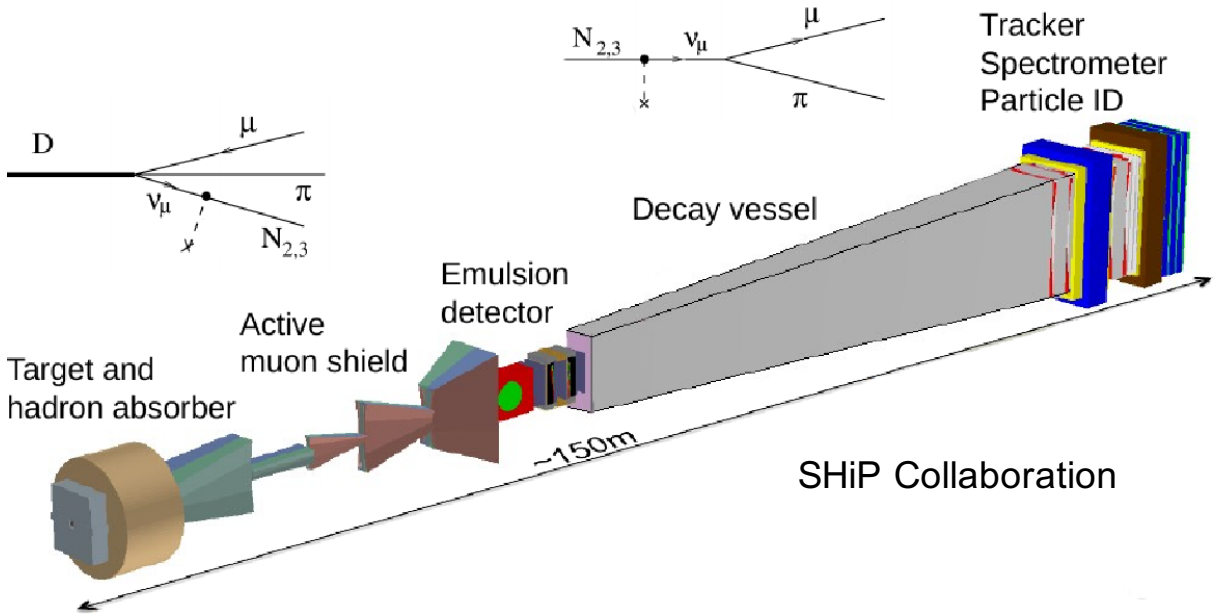


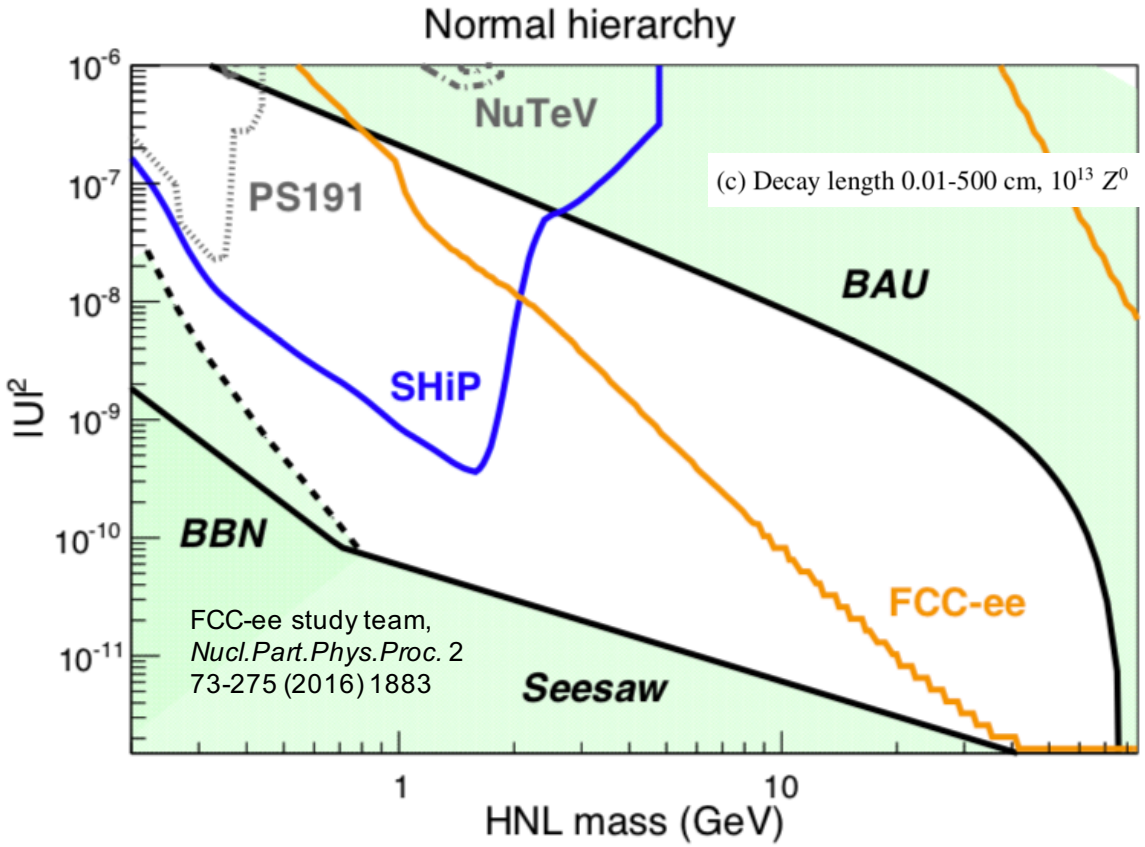




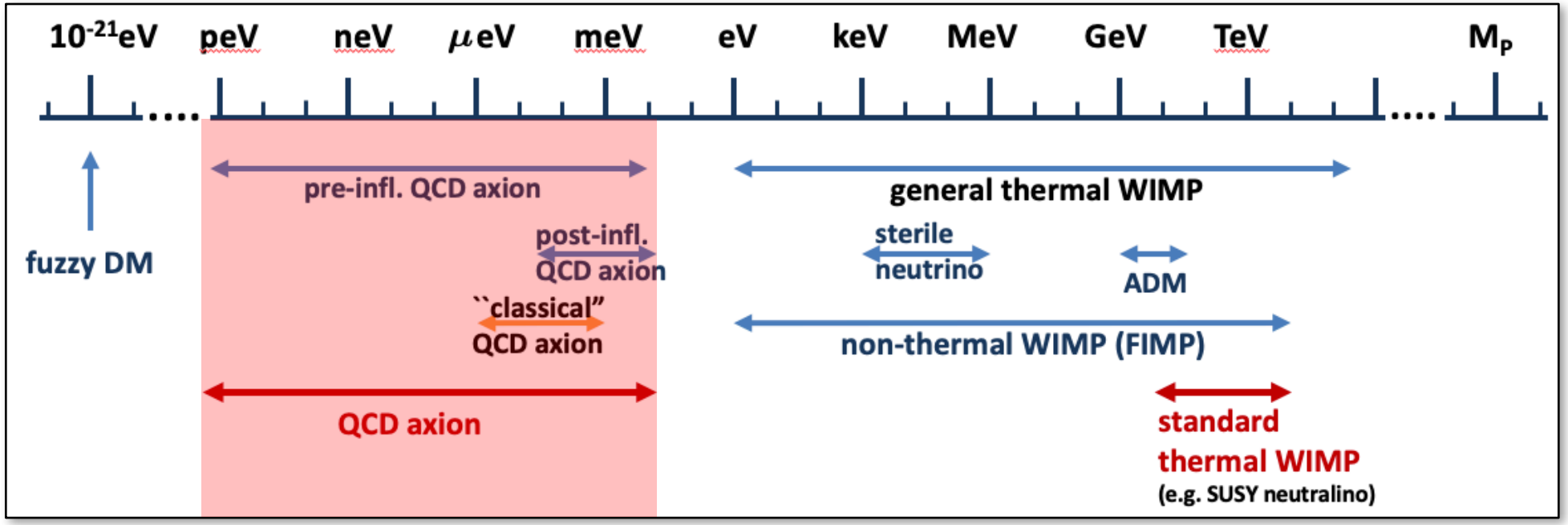
Future Accelerator Searches

- Accelerator searches for production and decay of N_2/N_3
  - SHiP (production in D-decays, displaced vertices)
  - FCC-ee (following earlier searches at LEP)





Searches for Axion and ALP Dark Matter

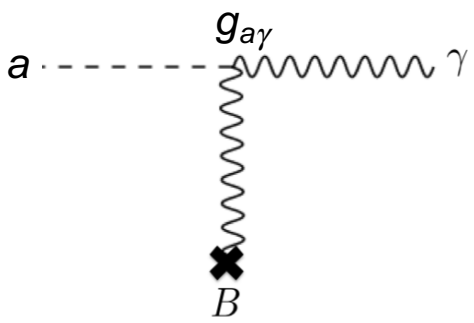


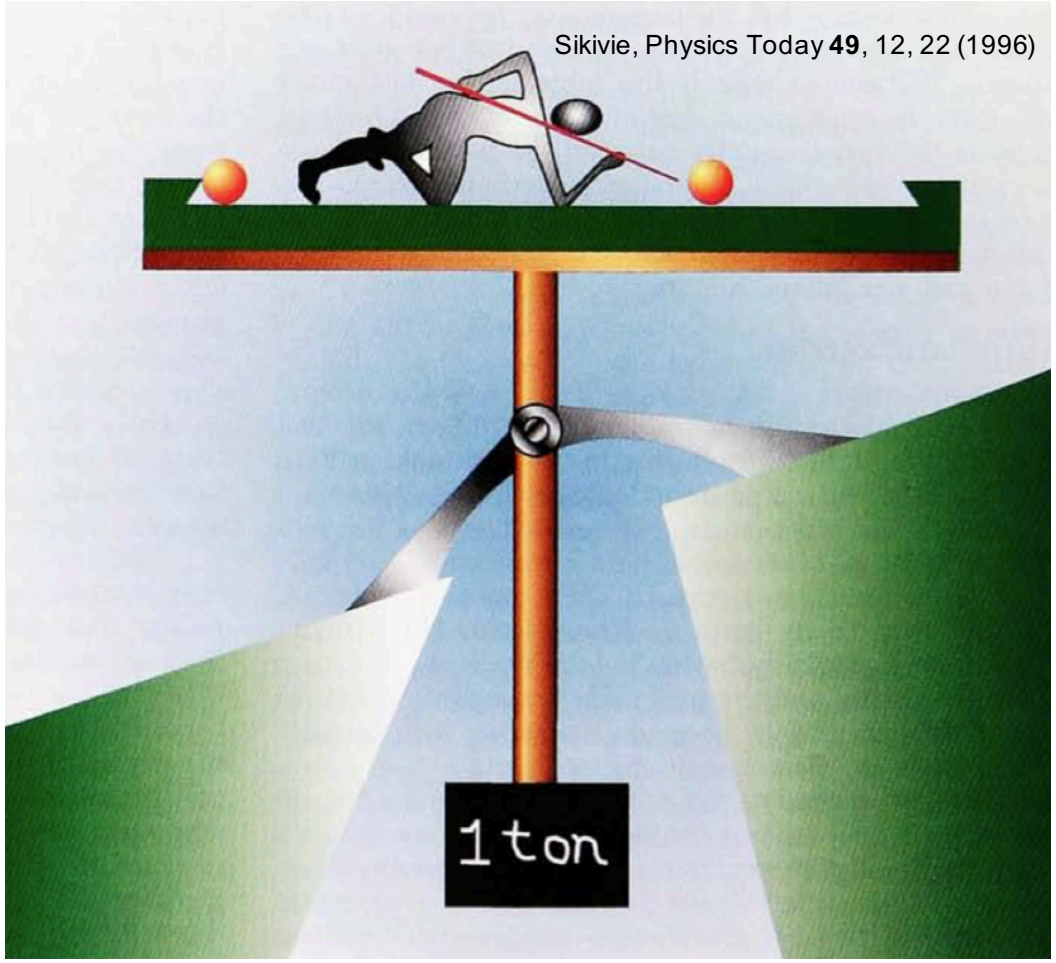
APPEC Community Report 2021, arXiv:2104.07634

Axions and ALPs

- QCD axion consequence of Peccei-Quinn mechanism dynamically explaining CP-conservation in strong interactions
  - PQ symmetry: spontaneously broken global U(1)
  - Axion: pseudo-NG boson from PQ symmetry breaking (a la Higgs mechanism)
- More generically, pseudoscalar boson coupling in similar way to SM fields - ALPs
- Couples at 1-loop to photon, modifying EM interactions
- Search for coupling to strong magnetic field (inverse Primakoff effect)

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a \widetilde{F}_{\mu\nu} F^{\mu\nu} = g_{a\gamma\gamma} a \, \mathbf{E} \cdot \mathbf{B},$$





Sikivie, Physics Today **49**, 12, 22 (1996)

Axion Parameter Space

- Benchmark models:
  - KSVZ: SM quarks uncharged under PQ symmetry → no tree-level axion-quark couplings
  - DFSZ: SM quarks charged under PQ; 2 additional higgs doublets
- Relic density from axion CDM production:
  - PQ symmetry breaking post-inflation: axion formation from topological defects; m_a~25-5000 μeV
  - PQ symmetry breaking pre-inflation: axion formation from vacuum realignment; masses smaller

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Ringwald, Rosenberg, Rybka, PDG 2020

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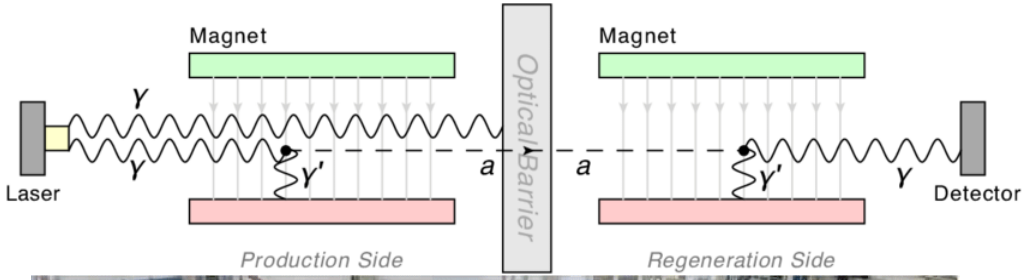
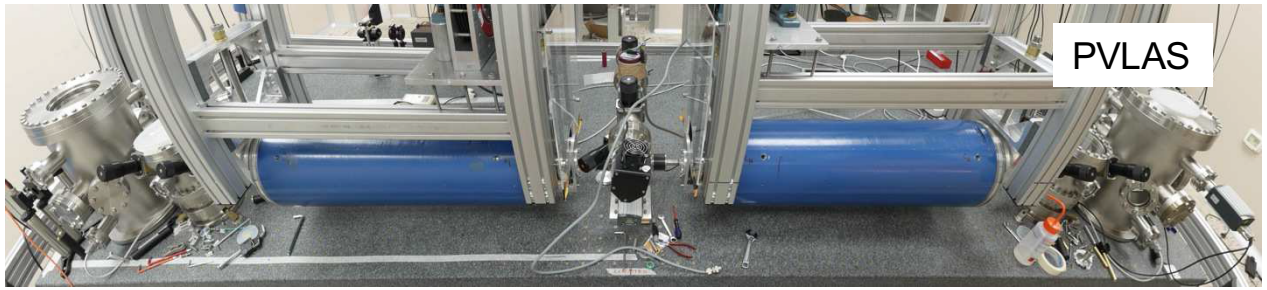
θ_i = vacuum misalignment angle

MADMAX Collaboration, Eur. Phys. J. C 79 (2019) 186

Axion/ALP Searches (non-halo)

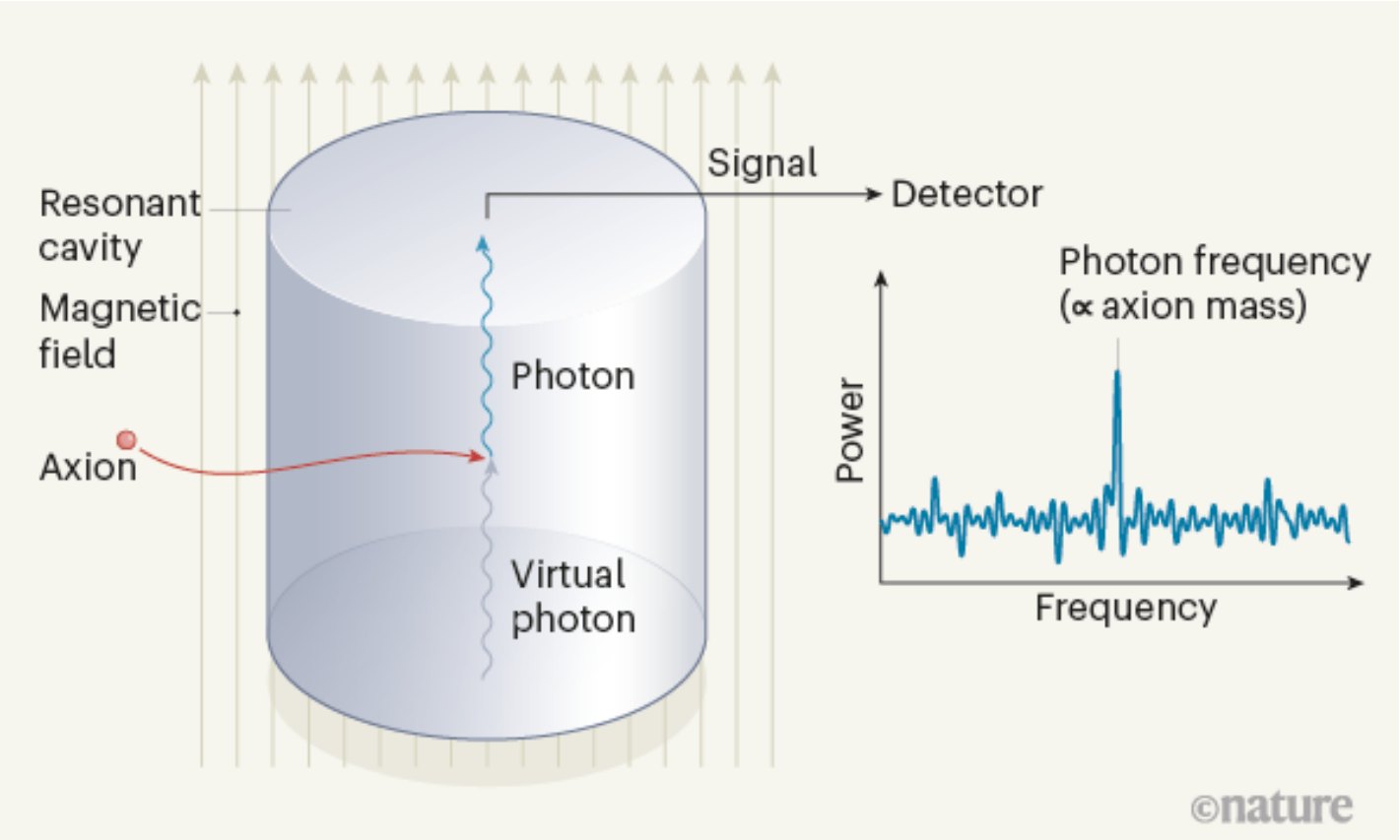
- Rich hunting ground – not solely reliant on cosmological production
- Stellar/solar axions:
  - Strong constraints from stellar cooling
  - Helioscope searches (CAST, IAXO…): photons convert to axions to solar B-field; keV X-rays detected in terrestrial magnet (inverse-Primakoff)
  - Axion-electron scattering in direct WIMP searches
- 'Shining light through walls' (OSQAR, ALPS….)
  - ~ Solar axion (Primakoff) production in lab
- Vacuum birefringence (PVLAS …)





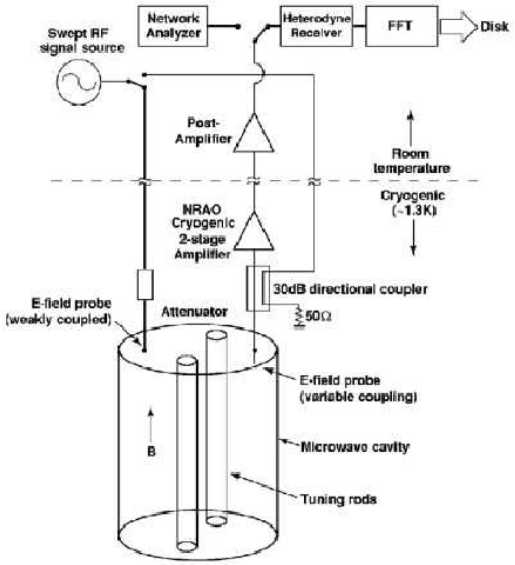
Direct Axion DM Searches

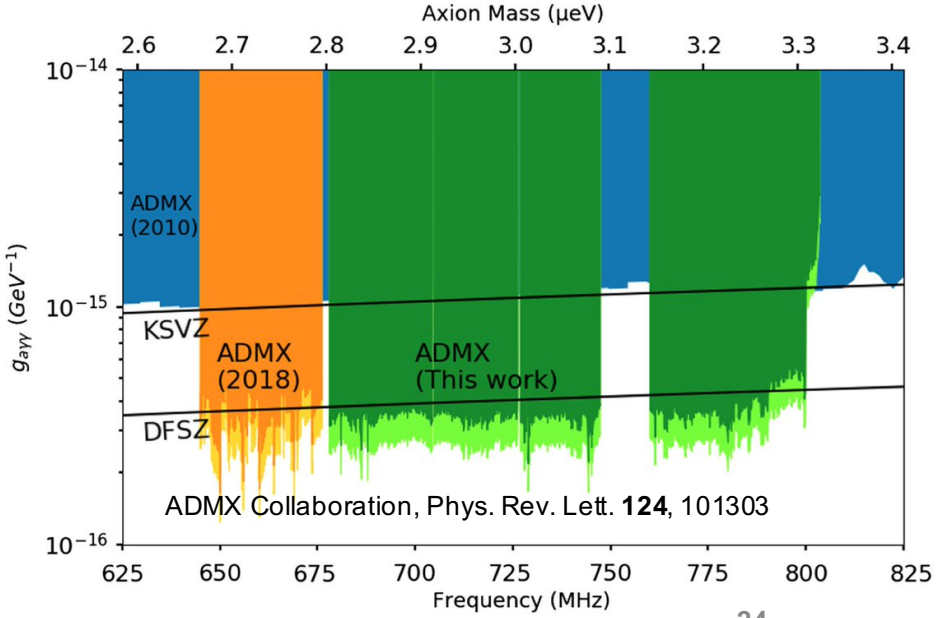
- Main technology: cavity haloscope (Sikivie, 1983)
  - Strong solenoidal magnetic field
  - Dilution fridge
  - Cryogenic radio receiver and amplifier
  - Tunable high-Q microwave cavity
  - CDM axions convert to mono-energetic photons via inverse Primakoff effect
- Narrowband search:
  - Run-time required for scan
  - Easy rescan to confirm signal



ADMX

- Longest running haloscope, U Washington
  - Previous experiments (1980s) at U Florida
- Apparatus:
  - 8T solenoid
  - Mechanically tuned cavity (1 m x 0.5 m ϕ)
  - Cryogenic quantum noise limited SQUID (T_{noise} < 100 mK) + HEMT and Josephson Parametric amplifiers
  - World's lowest noise non-R&D microwave receiver
- First experiment sensitive to KSVZ and DFSZ axions

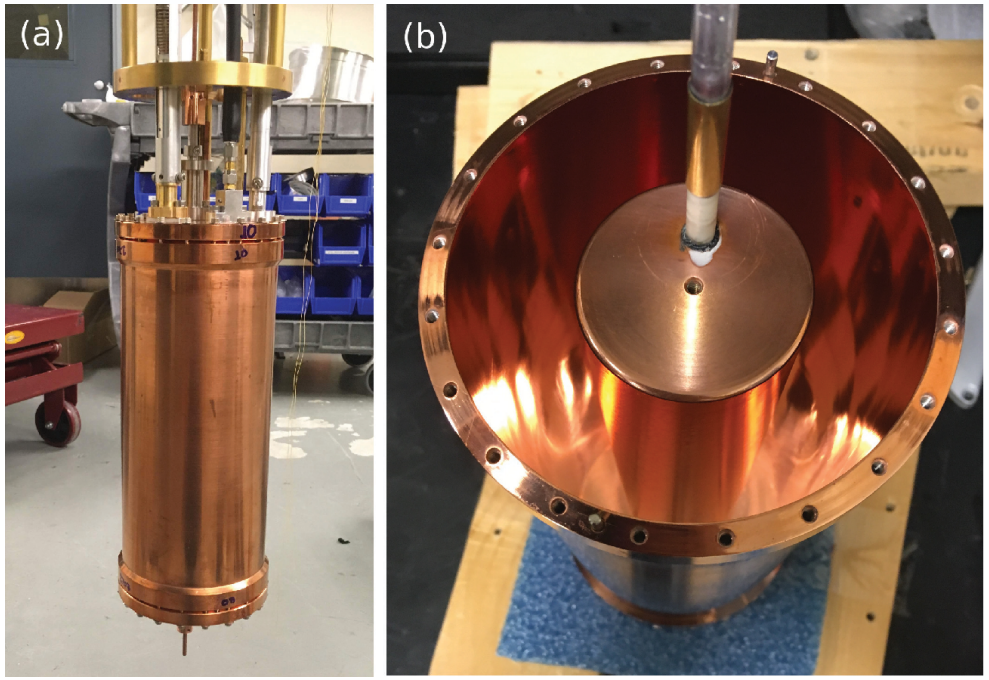


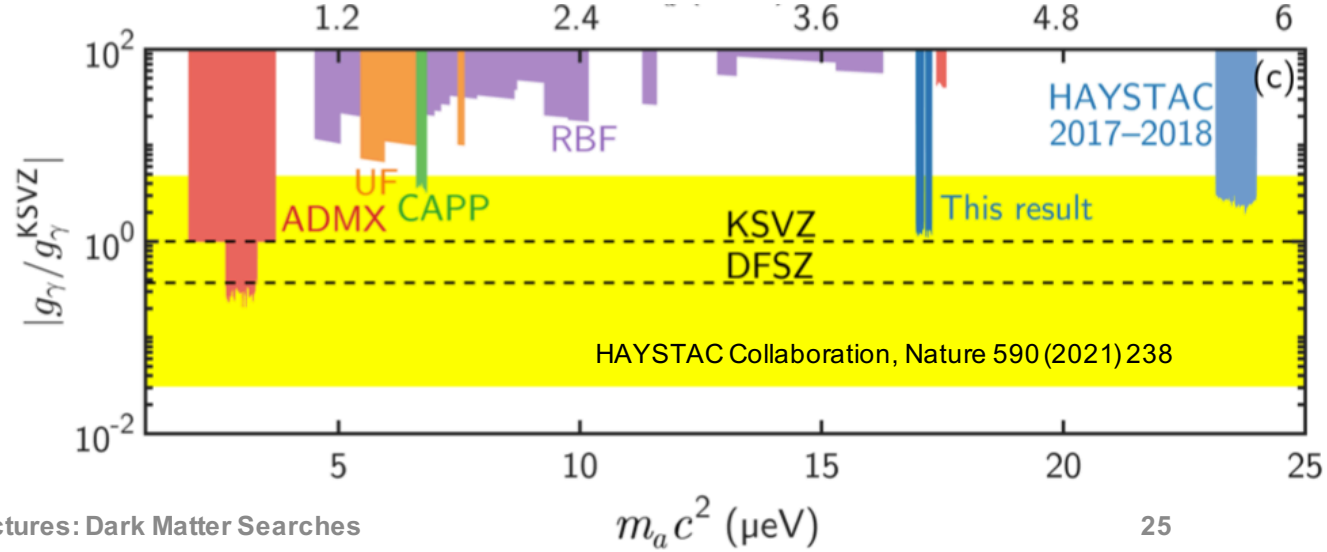


ADMX Collaboration, Phys. Rev. Lett. **124**, 101303

HAYSTAC

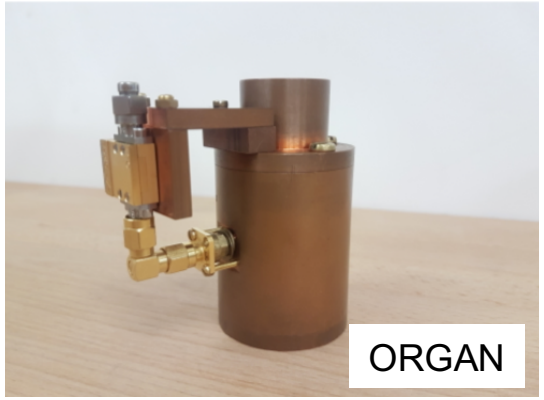
- Yale, previously ADMX-HF
- Targets higher masses / frequencies
  - Smaller cavity (25 cm x 10 cm ϕ)
  - 9T field over smaller volume
  - Josephson Parametric Amplifier
- First run (2017-18) targeted post-inflationary PQ symmetry breaking models: masses ~23-24 μeV
- Latest results (2021) uses squeezed microwave state to exceed quantum noise limit
  - Targets masses ~ 17 μeV



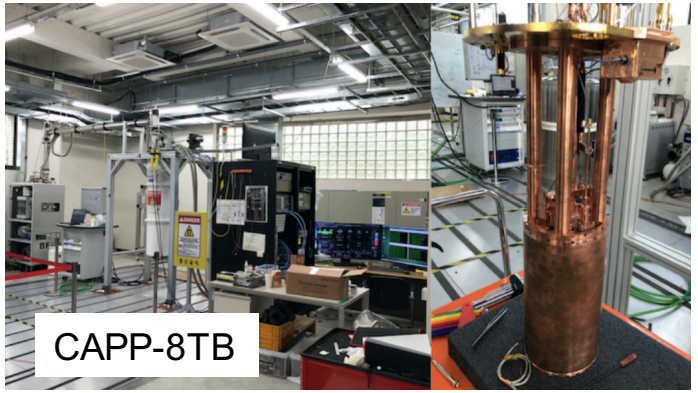


Other Cavity Haloscopes

- New cavity haloscope experiments
  - CULTASK/CAPP (Korea): 8 T B-field with HEMT amplifier
  - ORGAN (Australia): 14 T B-field with JPA and array of thin cavities (c.f. 'pipe organ')
  - CAST-RADES (CERN): 8.8 T B-field with HEMT amplifier
  - KLASH proposal (Frascati): 0.6 T B-field, large volume – targets low mass ~0.2 μeV

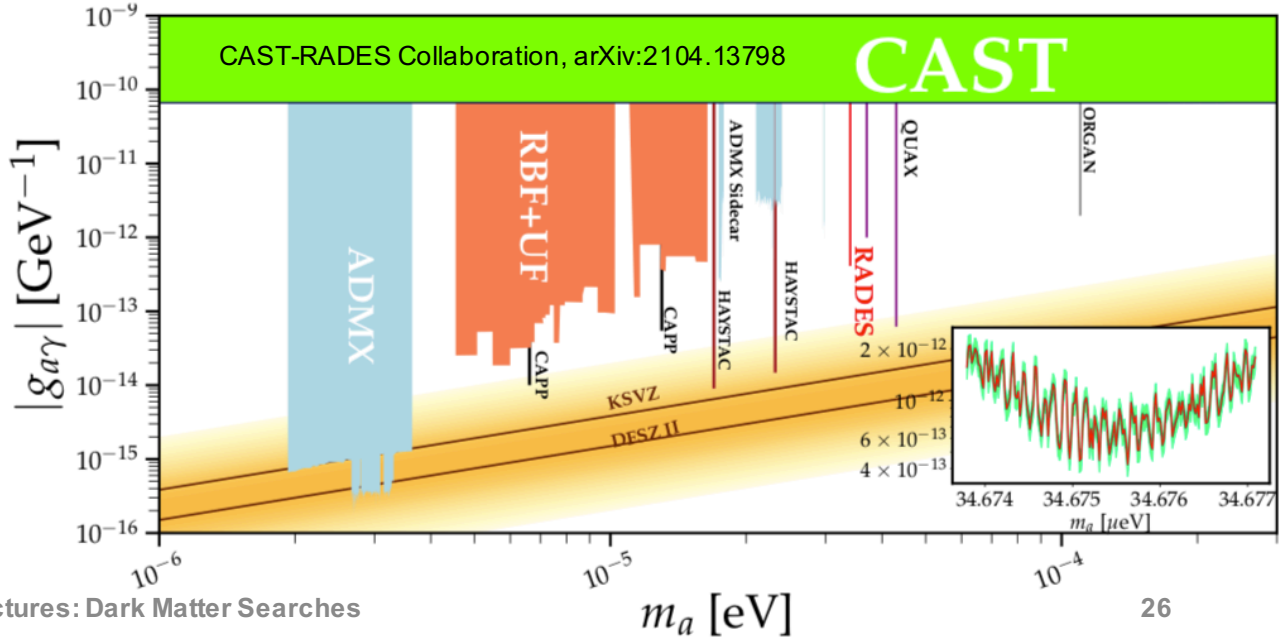


ORGAN Collaboration, arXiv:1706.00209



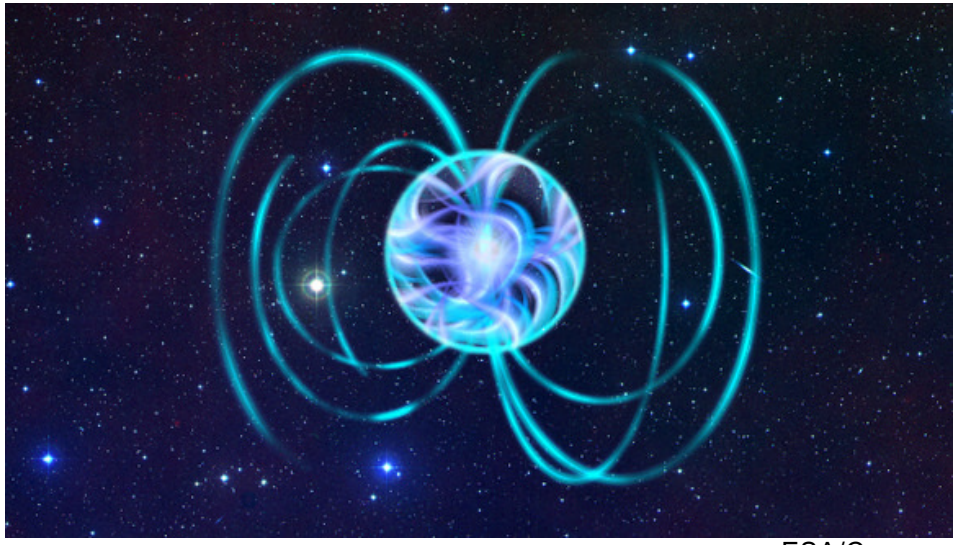
CAPP Collaboration, arXiv:2007.07468

CAST-RADES Collaboration, arXiv:2104.13798

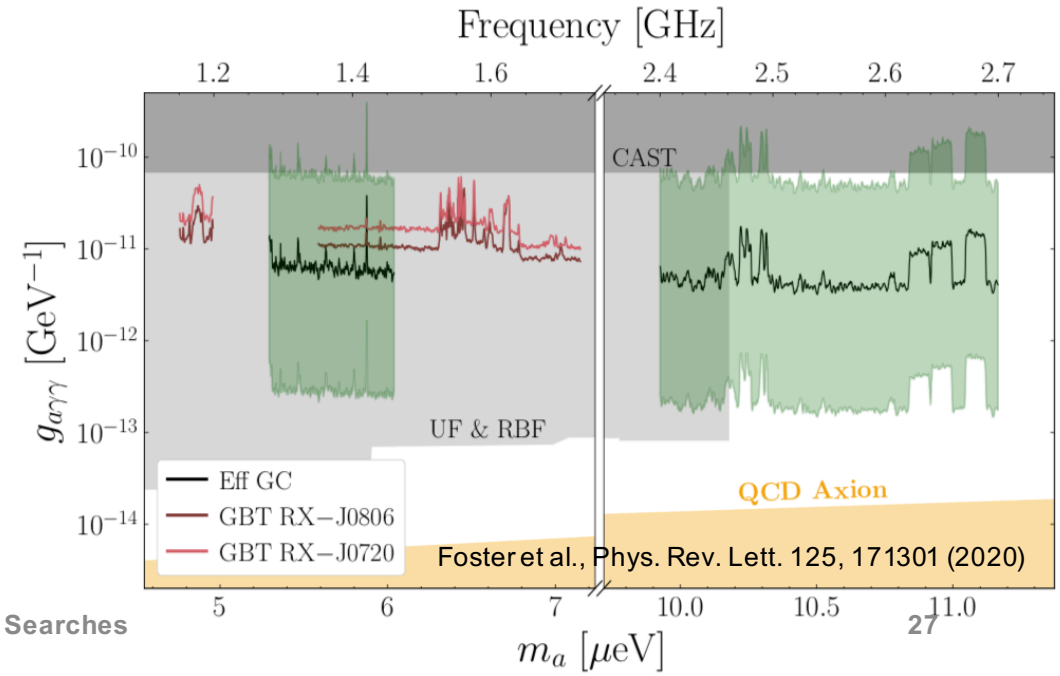


Indirect Axion DM Searches

- Strongest B-fields in known universe generated by neutron stars / magnetars
  - Expect mono-chromatic line from axion-photon conversion (inverse-Primakoff effect as haloscopes)
- Foster et al. (2020): radio-spectroscopy search with Green Bank and Effelsberg telescopes
  - Not yet competitive with haloscopes but promising



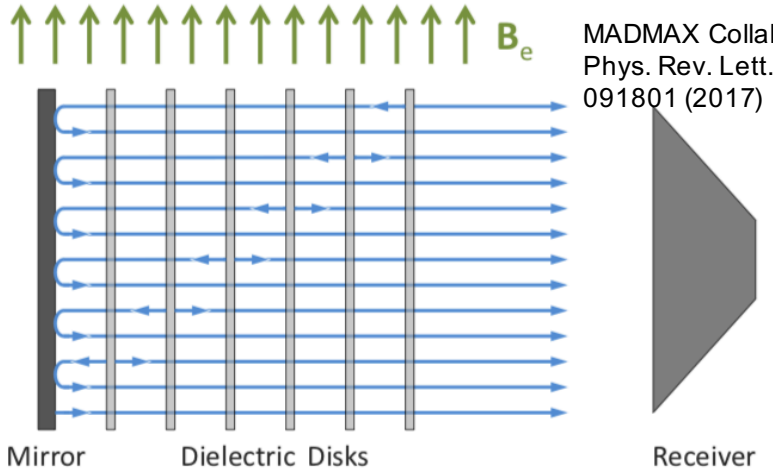
ESA/Carreau



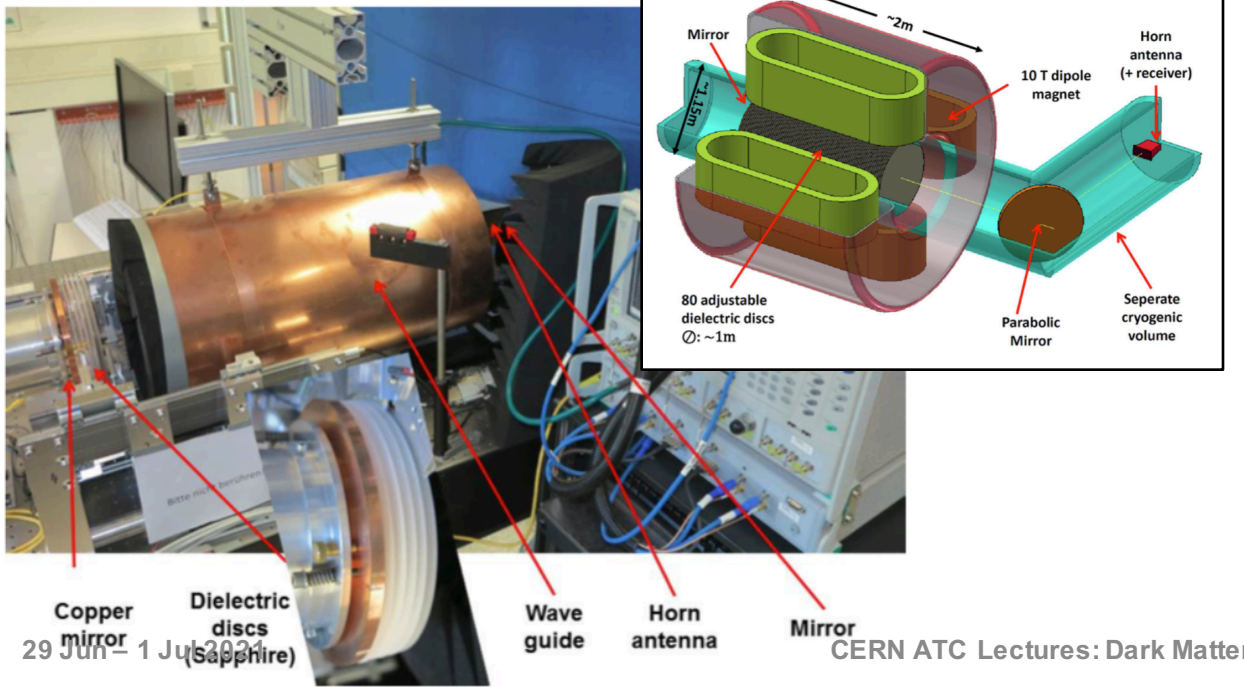
Foster et al., Phys. Rev. Lett. 125, 171301 (2020)

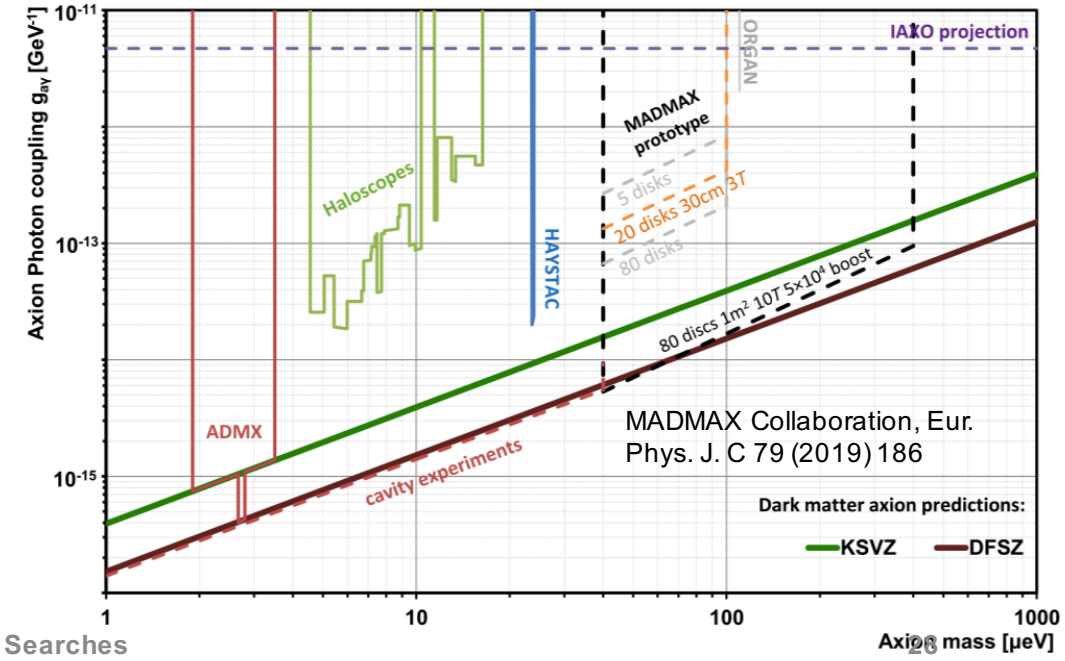
Dielectric Haloscopes

- Cavity haloscope signal ~ volume ~ $1/m_a^3$
- Dielectric haloscope (MADMAX proposal):
  - Axion to photon conversion at permittivity boundary in B-field
  - Coherent enhancement of emission with multiple low loss disks (e.g. $LaAlO_3$) with tunable $\lambda/2$ separation
  - Mirror forms longitudinal cavity. Transverse dimension non-resonant. Signal scales with length.



MADMAX Collaboration, Phys. Rev. Lett. 118, 091801 (2017)

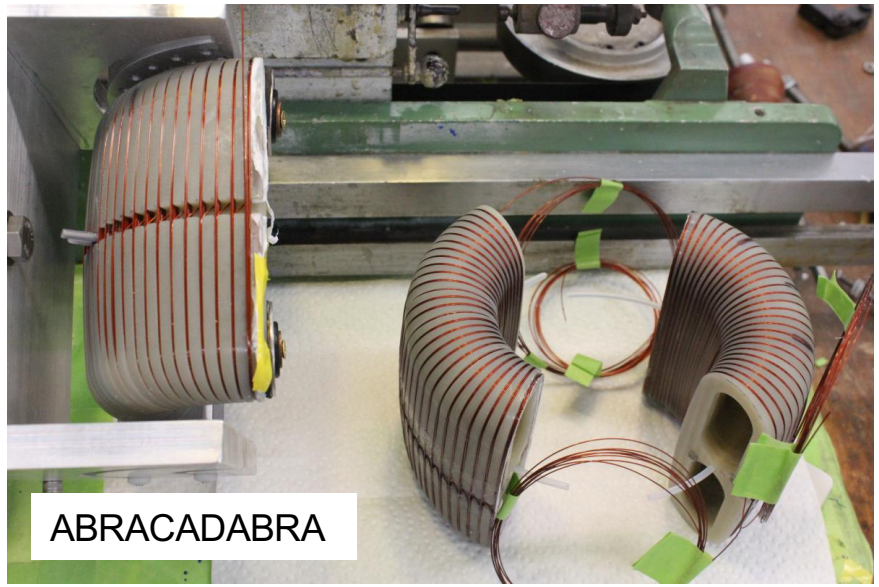


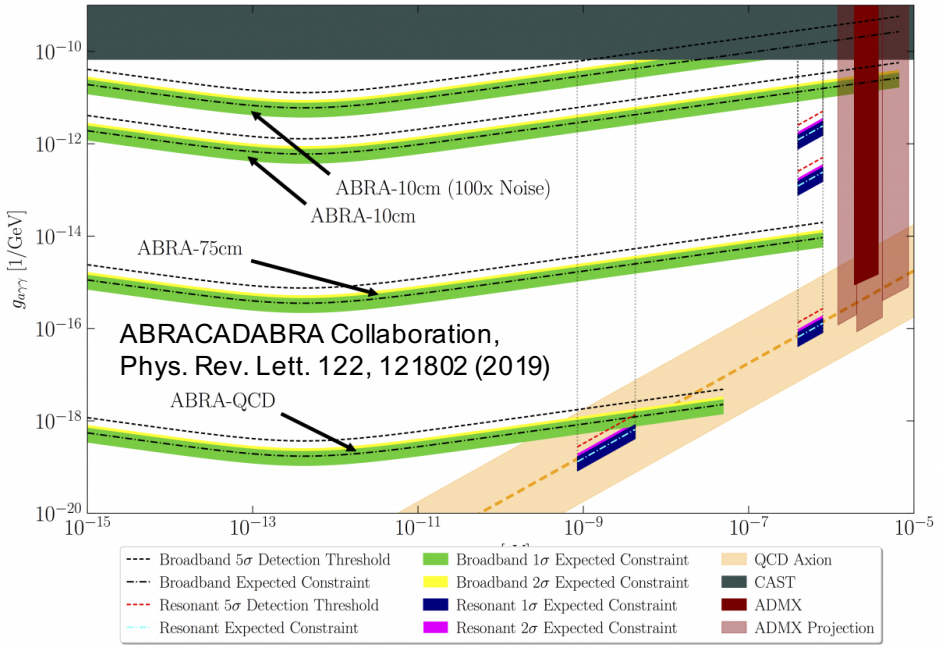


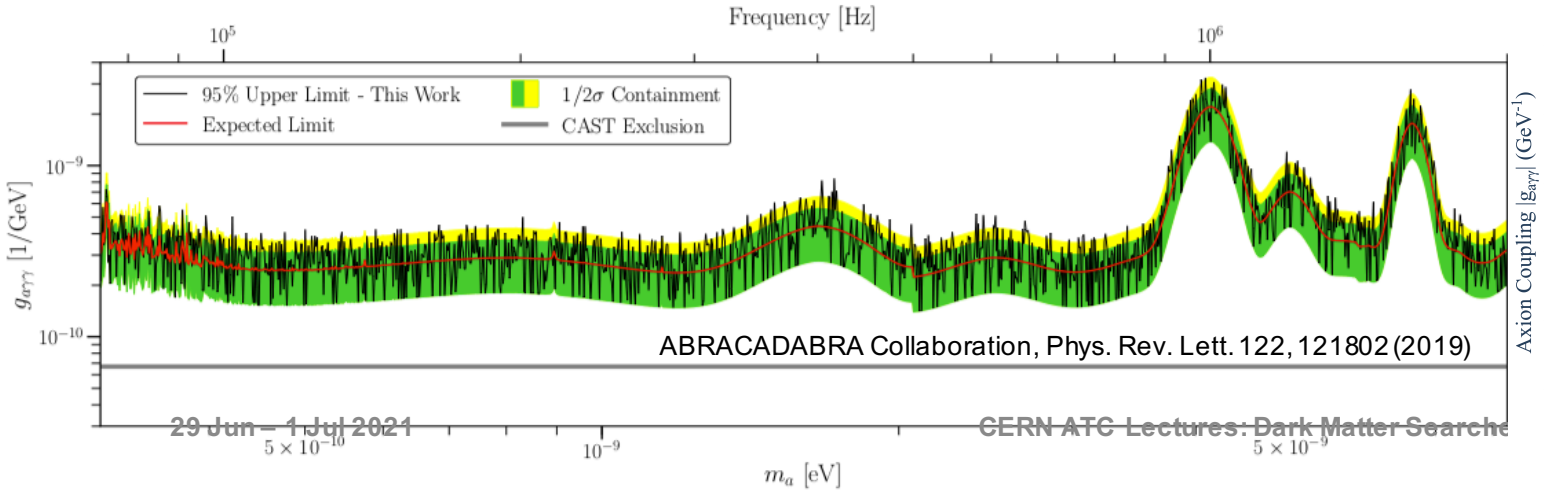
MADMAX Collaboration, Eur. Phys. J. C 79 (2019) 186

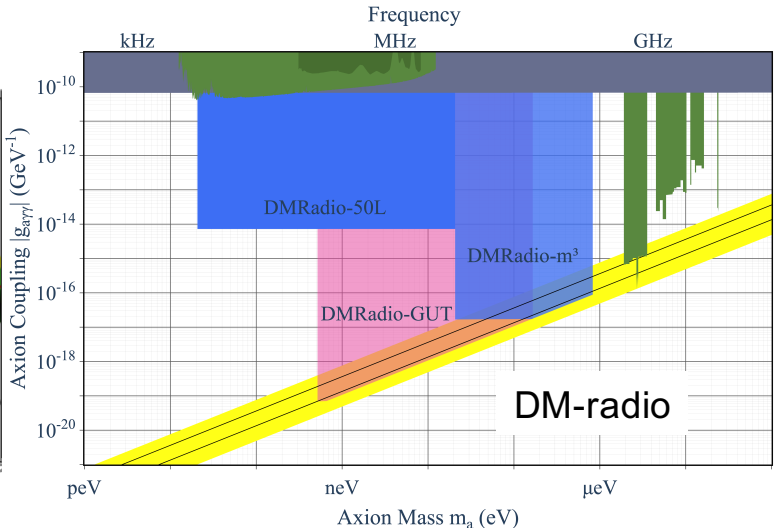
Low Mass Axions: Time-Dependence

- Very low mass axions induce observable time-dependent fields
- ABRACADABRA:
  - Seek AC B-field induced inside static toroidal field cavity with tuned LC circuit
- Similar approach taken by DM-radio



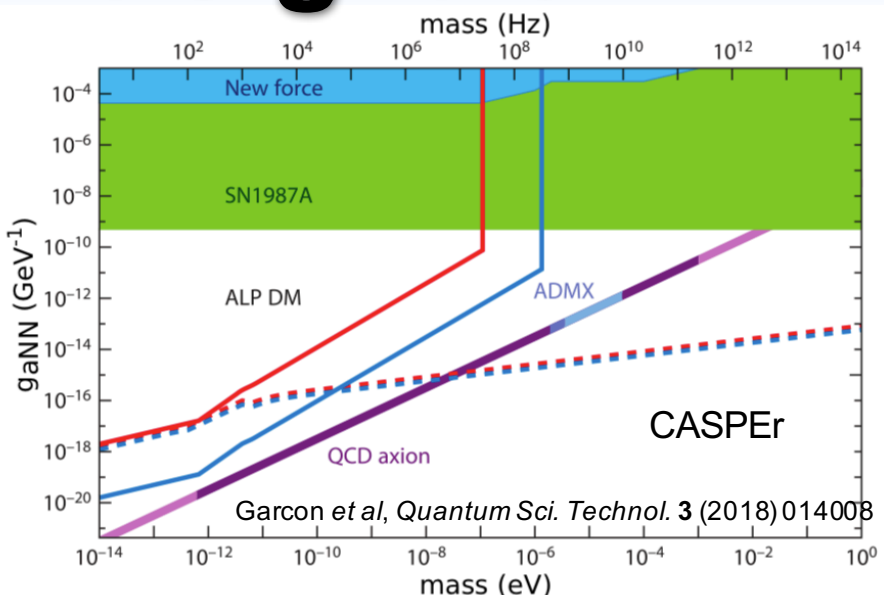




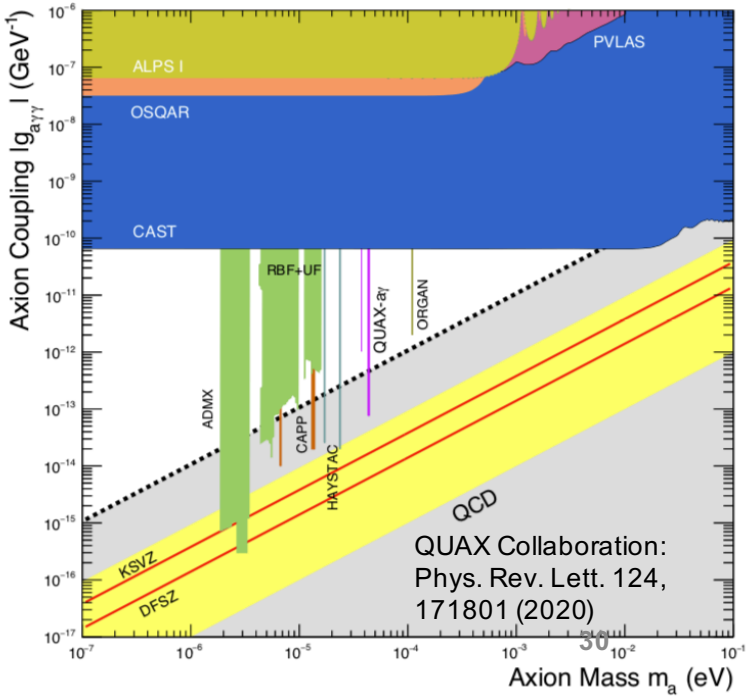


Magnetic Resonant Signals

- For low mass axions/ALPs, oscillating field may give rise to observable signals
- ALP-photon coupling induces pseudo-magnetic field leading to spin-precession in hyper-polarised nuclei (^{129}Xe and ^{3}He)
  - CASPEr-Wind: spin-precession with NMR
- Axion-gluon coupling induces oscillating nuclear EDM
  - CASPEr-Electric: apply static electric field in addition to magnetic field and perform NMR
- Coupling with electron spin induces magnetic resonance in ferromagnetic material in external B-field, with Larmor frequency tuned to axion mass
  - QUAX experiment

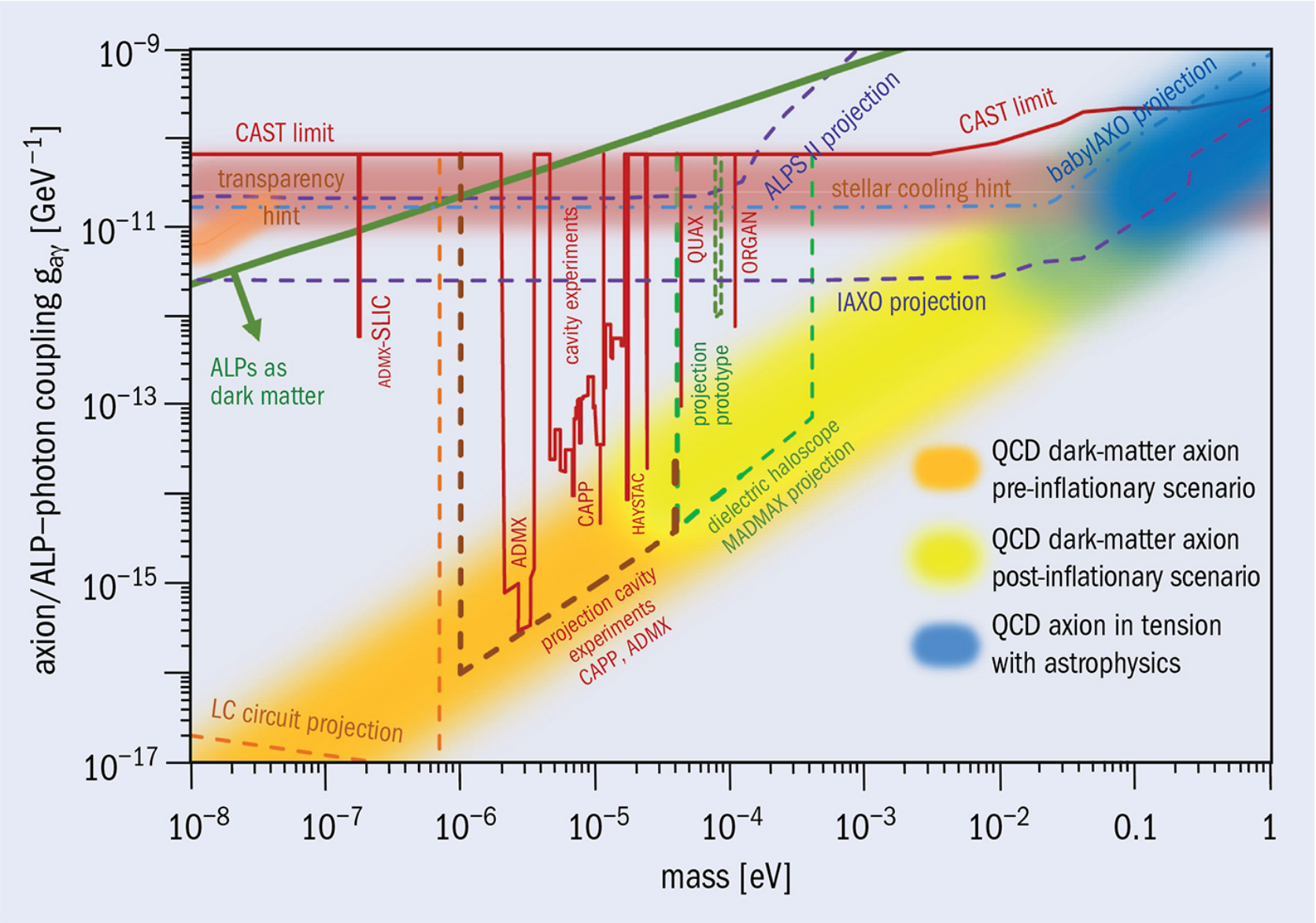


Garcon *et al*, *Quantum Sci. Technol.* **3** (2018) 014008



QUAX Collaboration: Phys. Rev. Lett. 124, 171801 (2020)

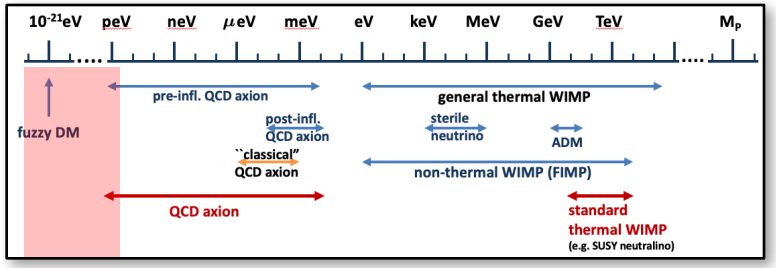
Axion Summary

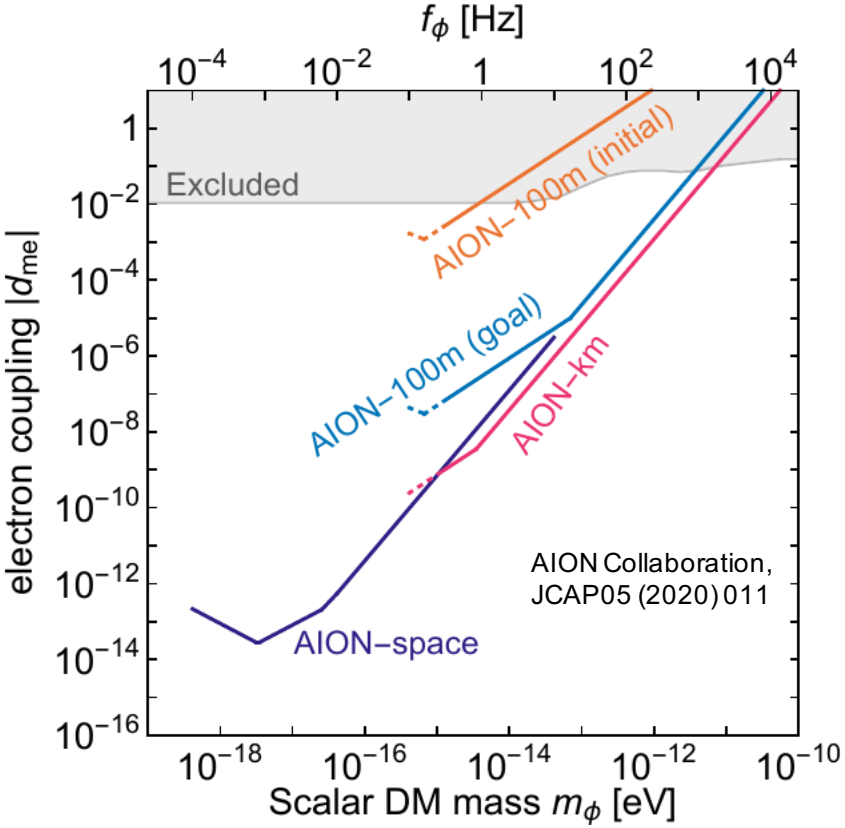


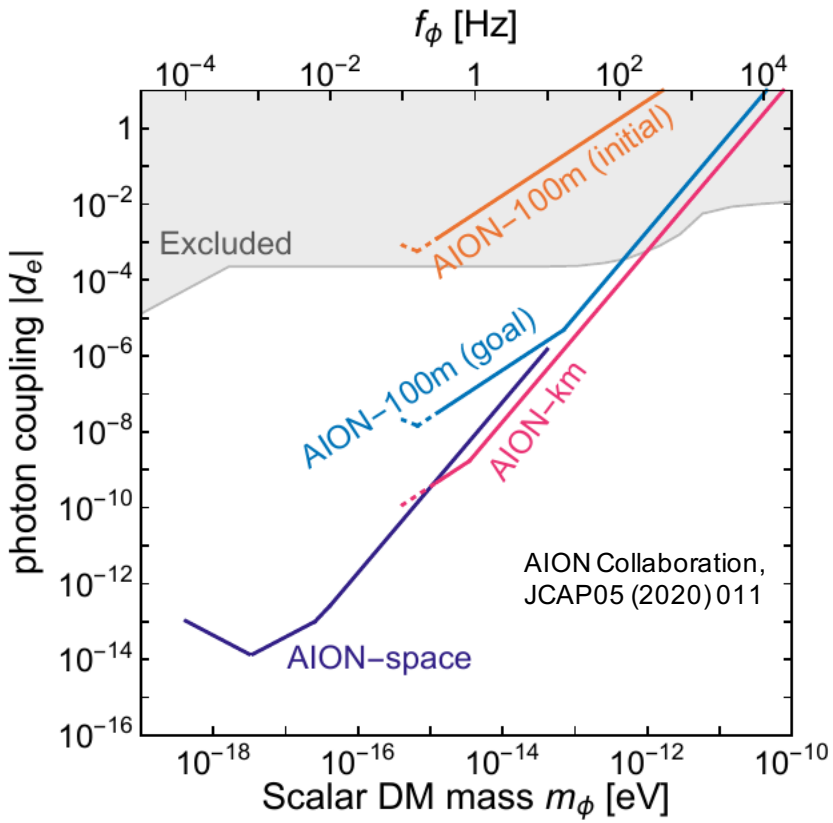
CERN Courier / B. Majorovits

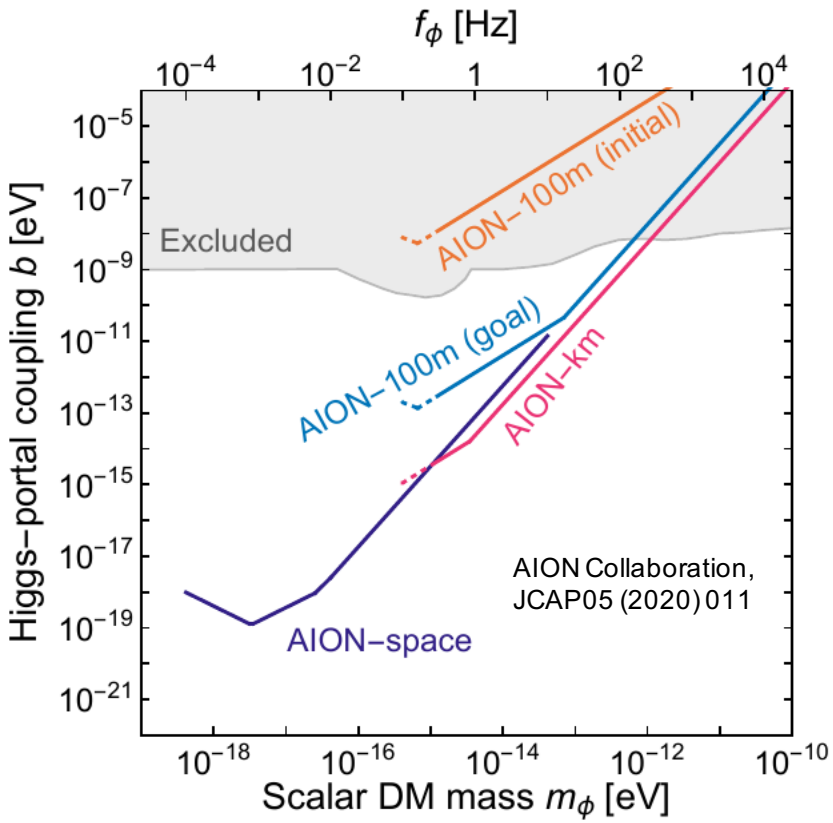
Very Light Dark Matter

- Compton wavelength of DM becomes macroscopic.
- Searches for time varying 'fifth forces' relevant
  - e.g. atom interferometers (MAGIS, AION etc.)
  - Huge potential for future innovation; connections with 'quantum technologies' initiatives









Grand Summary

- Dark matter searches have grown rapidly over past 40 years from somewhat 'niche' area of astroparticle physics to major component of astrophysics, astroparticle and collider physics programmes.
- Range of candidates and interactions has expanded massively.
- No other area of particle physics has similar opportunities for innovation in detector design with potentially low barrier to realisation (e.g. ALPs searches)
- Scientific pay-off potentially immense
- Field has never been in better health

G. Bertone and T. M. P. Tait

Backup

SUSY Summary

ATLAS SUSY Searches* - 95% CL Lower Limits

June 2021

ATLAS Preliminary

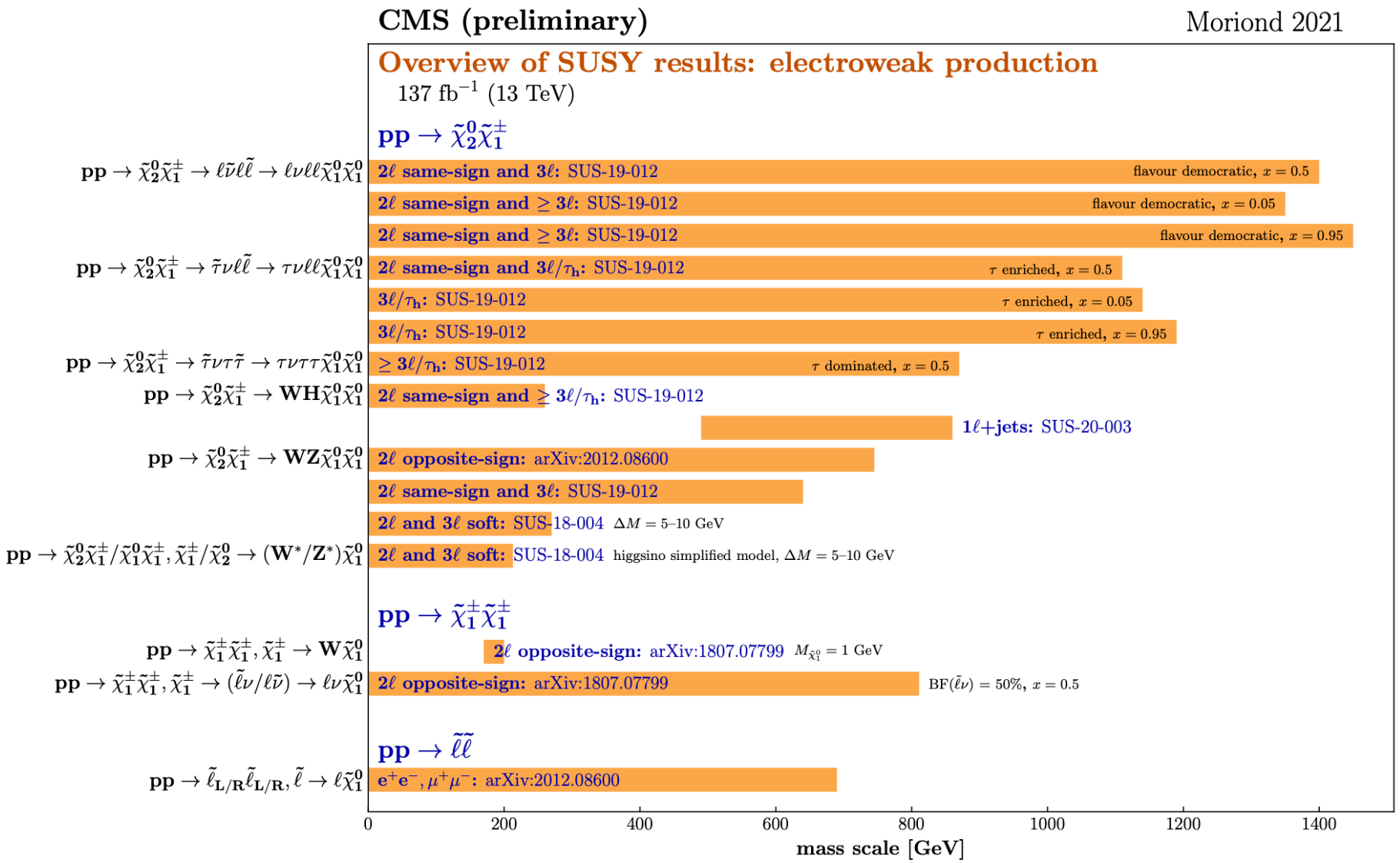
$\sqrt{s}$ = 13 TeV

	Model	Signature			$\int \mathcal{L}\, dt$ [fb^{-1}]	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{q}$ [1×, 8× Degen.] 1.0 1.85	$m(\tilde{\chi}^0_1)$<400 GeV	2010.14293
		mono-jet	1-3 jets	E_T^{miss}	36.1	$\tilde{q}$ [8× Degen.] 0.9	$m(\tilde{q})$-$m(\tilde{\chi}^0_1)$=5 GeV	2102.10874
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{g}$ 2.3	$m(\tilde{\chi}^0_1)$=0 GeV	2010.14293
						$\tilde{g}$ Forbidden 1.15-1.95	$m(\tilde{\chi}^0_1)$=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}W\tilde{\chi}^0_1$	1 e,μ	2-6 jets		139	$\tilde{g}$ 2.2	$m(\tilde{\chi}^0_1)$<600 GeV	2101.01629
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee,\mu\mu$	2 jets	E_T^{miss}	36.1	$\tilde{g}$ 1.2	$m(\tilde{g})$-$m(\tilde{\chi}^0_1)$=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	E_T^{miss}	139	$\tilde{g}$ 1.97	$m(\tilde{\chi}^0_1)$ <600 GeV	2008.06032
		SS e,μ	6 jets		139	$\tilde{g}$ 1.15	$m(\tilde{g})$-$m(\tilde{\chi}^0_1)$=200 GeV	1909.08457
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	E_T^{miss}	79.8	$\tilde{g}$ 2.25	$m(\tilde{\chi}^0_1)$<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$ 1.25	$m(\tilde{g})$-$m(\tilde{\chi}^0_1)$=300 GeV	1909.08457
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	E_T^{miss}	139	$\tilde{b}_1$ 1.255	$m(\tilde{\chi}^0_1)$<400 GeV	2101.12527
						$\tilde{b}_1$ 0.68	10 GeV<$\Delta m(\tilde{b}_1,\tilde{\chi}^0_1)$<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	E_T^{miss}	139	$\tilde{b}_1$ Forbidden 0.23-1.35	$\Delta m(\tilde{\chi}^0_2,\tilde{\chi}^0_1)$=130 GeV, $m(\tilde{\chi}^0_1)$=100 GeV	1908.03122
		2 τ	2 b	E_T^{miss}	139	$\tilde{b}_1$ 0.13-0.85	$\Delta m(\tilde{\chi}^0_2,\tilde{\chi}^0_1)$=130 GeV, $m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2020-031
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}^0_1$	0-1 e,μ	≥ 1 jet	E_T^{miss}	139	$\tilde{t}_1$ 1.25	$m(\tilde{\chi}^0_1)$=1 GeV	2004.14060,2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$ Forbidden 0.65	$m(\tilde{\chi}^0_1)$=500 GeV	2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to\tilde{\tau}_1 b\nu, \tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$ Forbidden 1.4	$m(\tilde{\tau}_1)$=800 GeV	ATLAS-CONF-2021-008
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$ 0.85	$m(\tilde{\chi}^0_1)$=0 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	139	$\tilde{t}_1$ 0.55	$m(\tilde{t}_1,\tilde{c})$-$m(\tilde{\chi}^0_1)$=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}^0_2, \tilde{\chi}^0_2\to Z/h\tilde{\chi}^0_1$	1-2 e,μ	1-4 b	E_T^{miss}	139	$\tilde{t}_1$ 0.067-1.18	$m(\tilde{\chi}^0_2)$=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ	1 b	E_T^{miss}	139	$\tilde{t}_2$ Forbidden 0.86	$m(\tilde{\chi}^0_1)$=360 GeV, $m(\tilde{t}_1)$-$m(\tilde{\chi}^0_1)$= 40 GeV	2006.05880
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	Multiple ℓ/jets		E_T^{miss}	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.96	$m(\tilde{\chi}^0_1)$=0, wino-bino	2106.01676, ATLAS-CONF-2021-022
		$ee,\mu\mu$	≥ 1 jet	E_T^{miss}	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.205	$m(\tilde{\chi}^\pm_1)$-$m(\tilde{\chi}^0_1)$=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		E_T^{miss}	139	$\tilde{\chi}^\pm_1$ 0.42	$m(\tilde{\chi}^0_1)$=0, wino-bino	1908.08215
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	Multiple ℓ/jets		E_T^{miss}	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ Forbidden 1.06	$m(\tilde{\chi}^0_1)$=70 GeV, wino-bino	2004.10894, ATLAS-CONF-2021-022
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	139	$\tilde{\chi}^\pm_1$ 1.0	$m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1908.08215
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		E_T^{miss}	139	$\tilde{\tau}$ [$\tilde{\tau}_L, \tilde{\tau}_{R,L}$] 0.16-0.3 0.12-0.39	$m(\tilde{\chi}^0_1)$=0	1911.06660
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$ 0.7	$m(\tilde{\chi}^0_1)$=0	1908.08215
		$ee,\mu\mu$	≥ 1 jet	E_T^{miss}	139	$\tilde{\ell}$ 0.256	$m(\tilde{\ell})$-$m(\tilde{\chi}^0_1)$=10 GeV	1911.12606
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	≥ 3 b	E_T^{miss}	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	E_T^{miss}	139	$\tilde{H}$ 0.55	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	≥ 2 large jets	E_T^{miss}	139	$\tilde{H}$ 0.45-0.93	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	ATLAS-CONF-2021-022
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	E_T^{miss}	139	$\tilde{\chi}^\pm_1$ 0.66	Pure Wino	ATLAS-CONF-2021-015
						$\tilde{\chi}^\pm_1$ 0.21	Pure higgsino	ATLAS-CONF-2021-015
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$ 2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4	$m(\tilde{\chi}^0_1)$=100 GeV	1710.04901,1808.04095
	$\tilde{\ell}\tilde{\ell}, \tilde{\ell}\to\ell\tilde{G}$	Displ. lep		E_T^{miss}	139	$\tilde{e},\tilde{\mu}$ 0.7	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
						$\tilde{\tau}$ 0.34	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
RPV	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_1, \tilde{\chi}^\pm_1\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_1$ [BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.95 1.55	$m(\tilde{\chi}^0_1)$=200 GeV	2103.11684
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^0_1, \tilde{\chi}^0_1\to qqq$		4-5 large jets		36.1	$\tilde{g}$ [$m(\tilde{\chi}^0_1)$=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}^0_1, \tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	$m(\tilde{\chi}^0_1)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to b\tilde{\chi}^\pm_1, \tilde{\chi}^\pm_1\to bbs$		≥ 4b		139	$\tilde{t}$ Forbidden 0.95	$m(\tilde{\chi}^\pm_1)$=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, $\cos\theta_t$=1	2003.11956
	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2/\tilde{\chi}^0_1, \tilde{\chi}^0_{1,2}\to tbs, \tilde{\chi}^+_1\to bbs$	1-2 e,μ	≥6 jets		139	$\tilde{\chi}^0_1$ 0.2-0.32	Pure higgsino	ATLAS-CONF-2021-007

10^{-1} 1 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

SUSY Summary



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

Generic DM Searches: di-X+MET

- Limits on generic DM models with mediators coupling preferentially to top or bottom quarks can be obtained by modifying 3rd generation SUSY searches