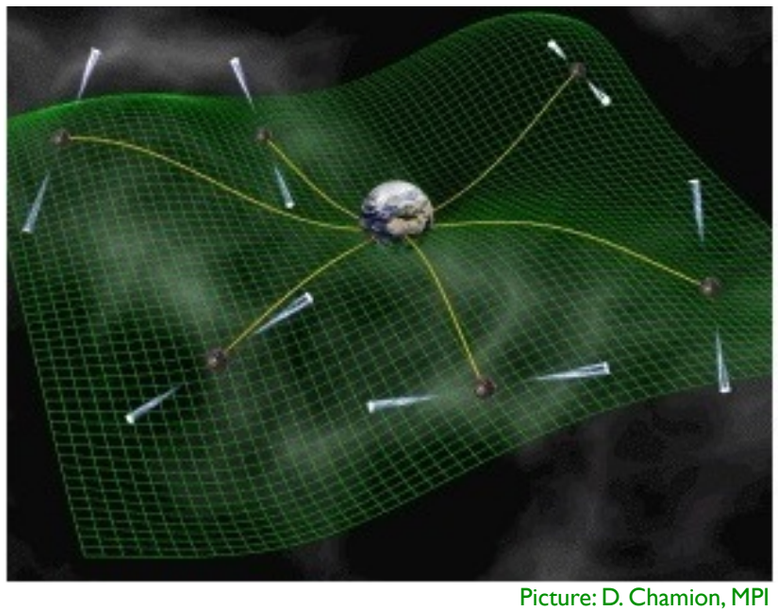
Dark matter and gravitational wave signals

from a phase transition in the early universe

TB, Depta, Konstandin, Schmidt-Hoberg & Tasillo, JCAP '23
Balan, TB, Kahlhoefer, Matuszak & Tasillo, JCAP '25
TB, Konstandin, Matuszak, Schmidt-Hoberg & Tasillo, 2602.09092



Picture: D. Chamion, MPI

TB, Gonzalo, Kahlhoefer, Matuszak & Tasillo, JCAP '24

Picture: NASA

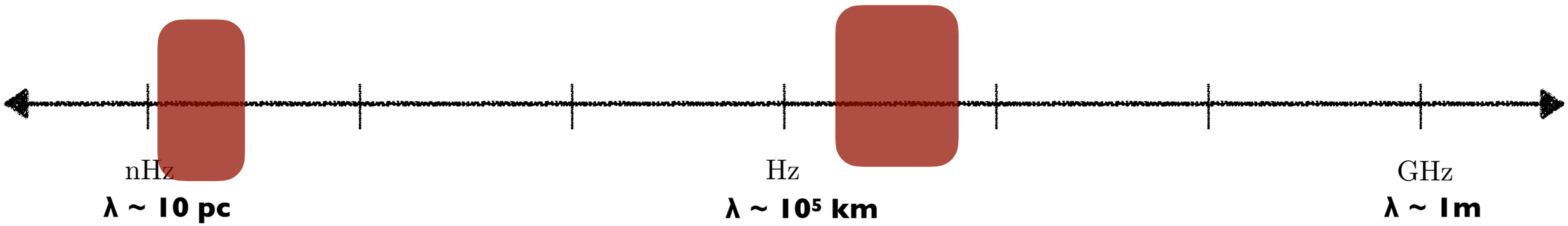
UNTERSTÜTZT VON / SUPPORTED BY
Alexander von HUMBOLDT STIFTUNG

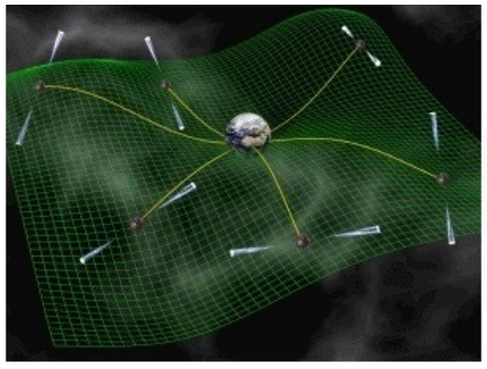
Funded by The Research Council of Norway

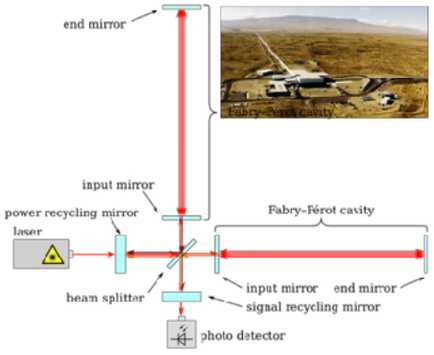
UiO : University of Oslo (Torsten Bringmann)

Gravitational waves: current status

- Confirmed observations in two frequency ranges







- Stochastic BG:
  - SMBH mergers ?
  - New physics ?

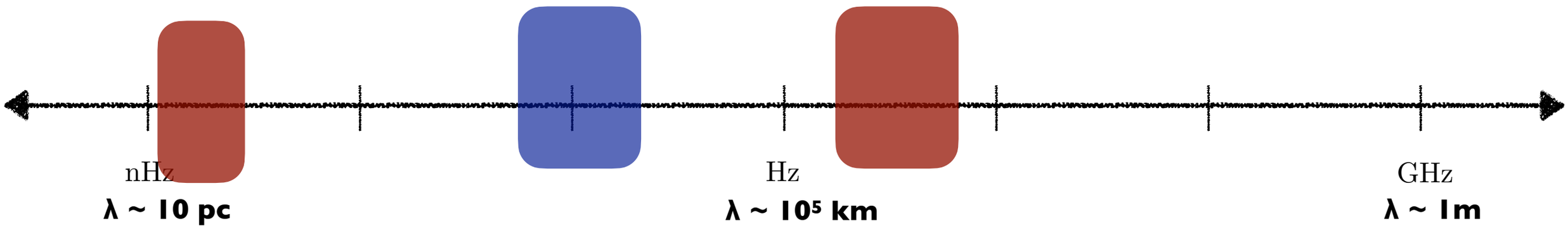
See e.g. talk by C. Gordon

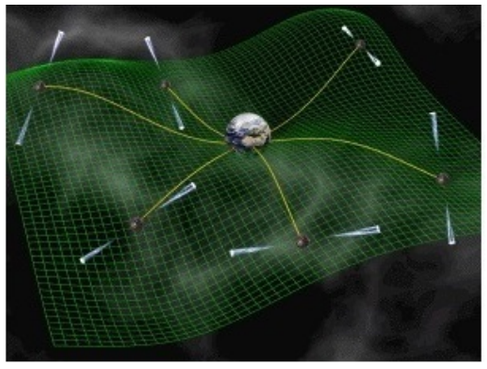
- Individual mergers:
  - BH-BH
  - BH-NS
  - NS-NS

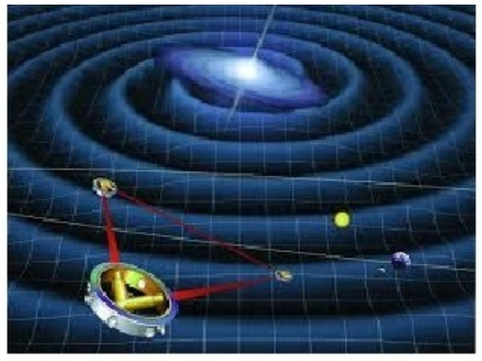
See talks by J. Powell, H. Takahashi, …

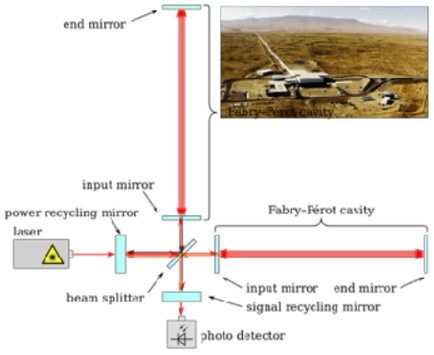
Gravitational waves: looking ahead

- Confirmed observations in two frequency ranges









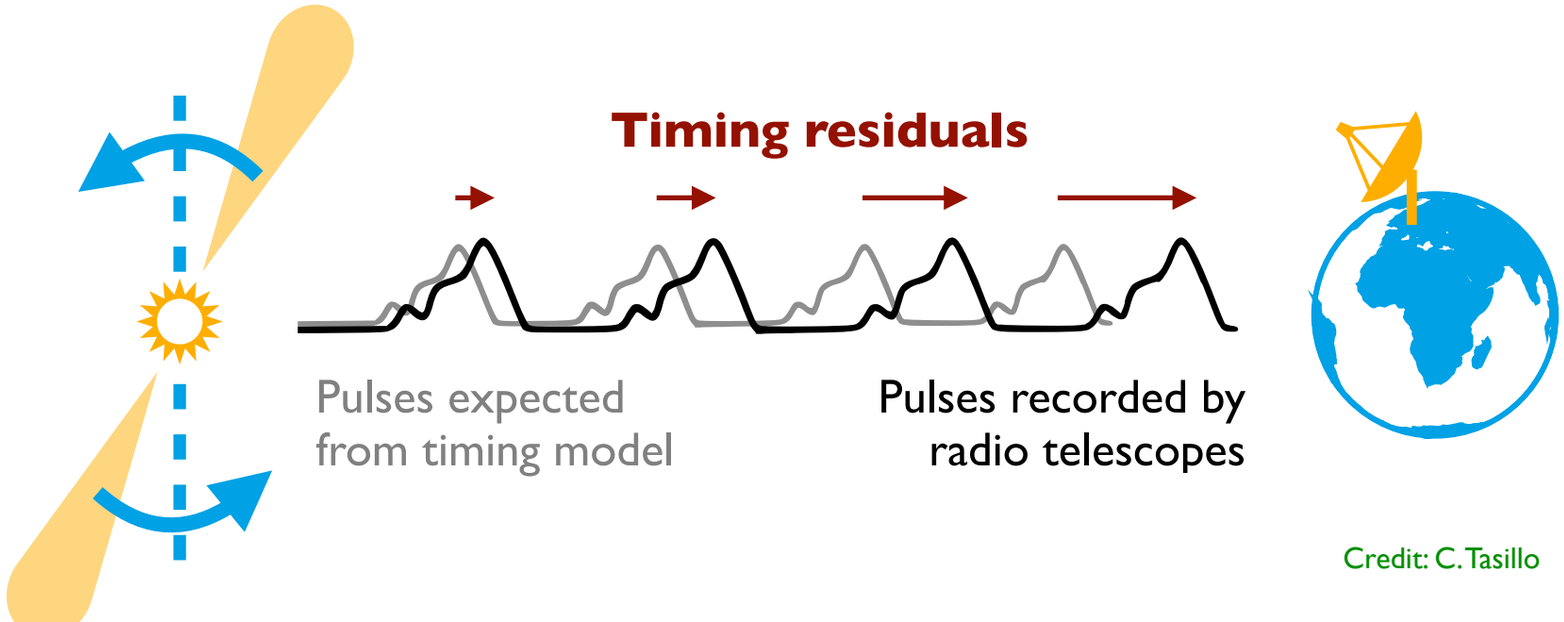
- ESA has formally adopted the LISA mission
  - construction has begun, launch scheduled in 2035

➡ *Large potential to probe new physics*

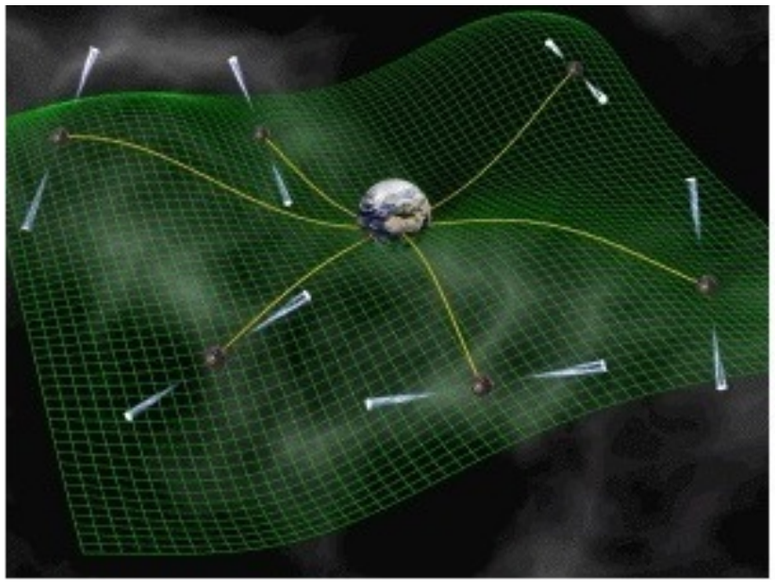
+ massive planned upgrades for ground-based detectors: Einstein telescope, Cosmic Explorer, …

The nHz gravitational wave background

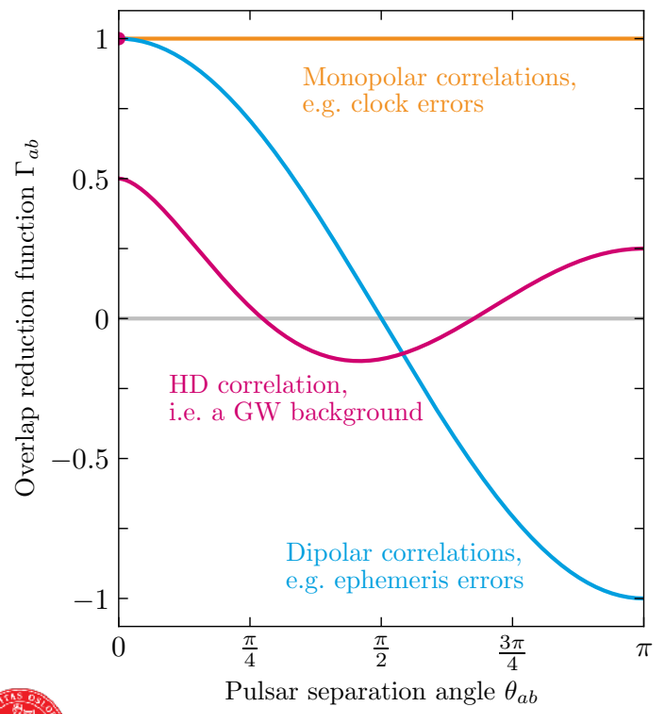
- Pulsar timing arrays (PTAs)



Credit: C. Tasillo

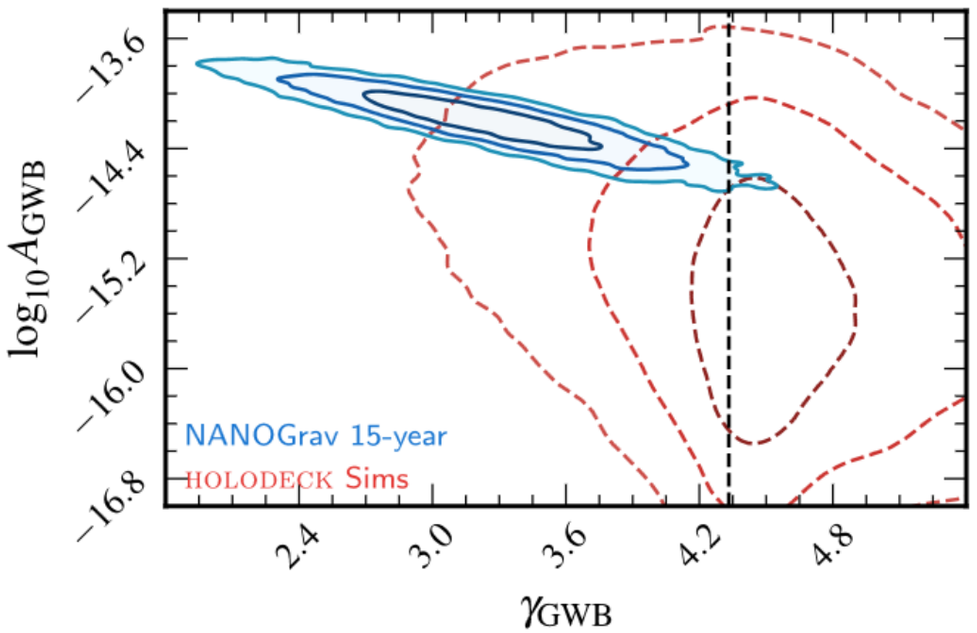


- Common red noise due to GWs



- Discovery w/ 15 year data: angular correlation follows characteristic 'Hellings-Downs' curve NANOGrav, ApJL '23

- Can SMBH mergers really explain this ?

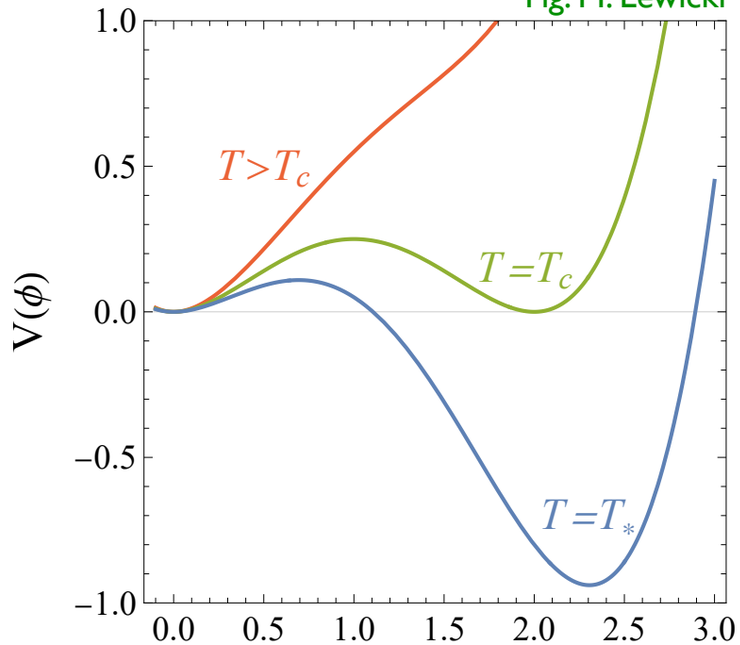


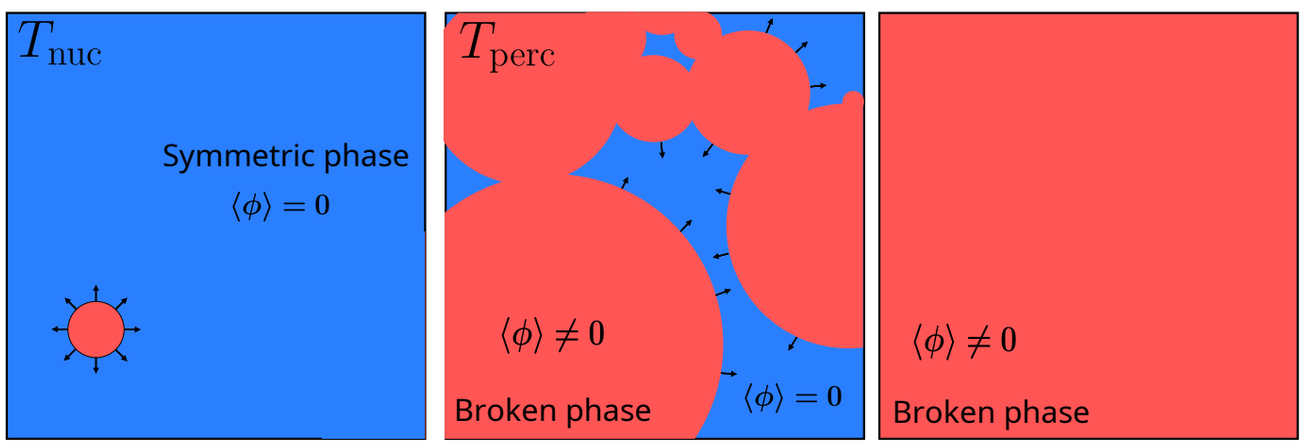
Cosmological phase transitions

- GW signal requires first-order transition
  - Not in the standard model: new physics… !
  - Triggered by temperature corrections to the potential

$$V(\phi, T) = \frac{g_{m^2}}{24}\left(T^2 - T_0^2\right)\phi^2 - \frac{g_m}{12\pi}T\phi^3 + \lambda\phi^4$$

Fig: M. Lewicki

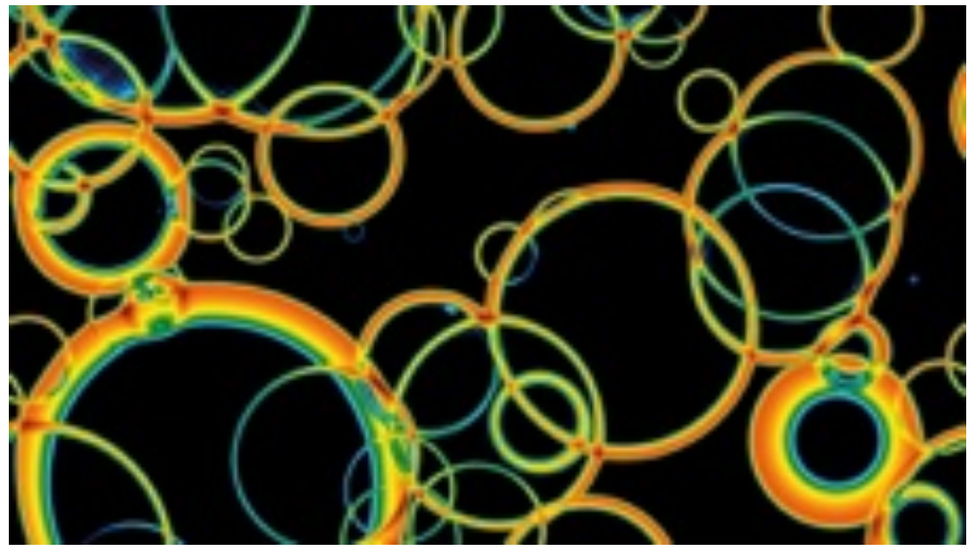




J. Matuszak, '23

- Bubbles of new vacuum phase
  - nucleate spontaneously
  - quickly expand and percolate

- Need numerical simulations
  - highly non-linear dynamics
  - GWs produced through bubble wall collisions, sound waves and plasma turbulence

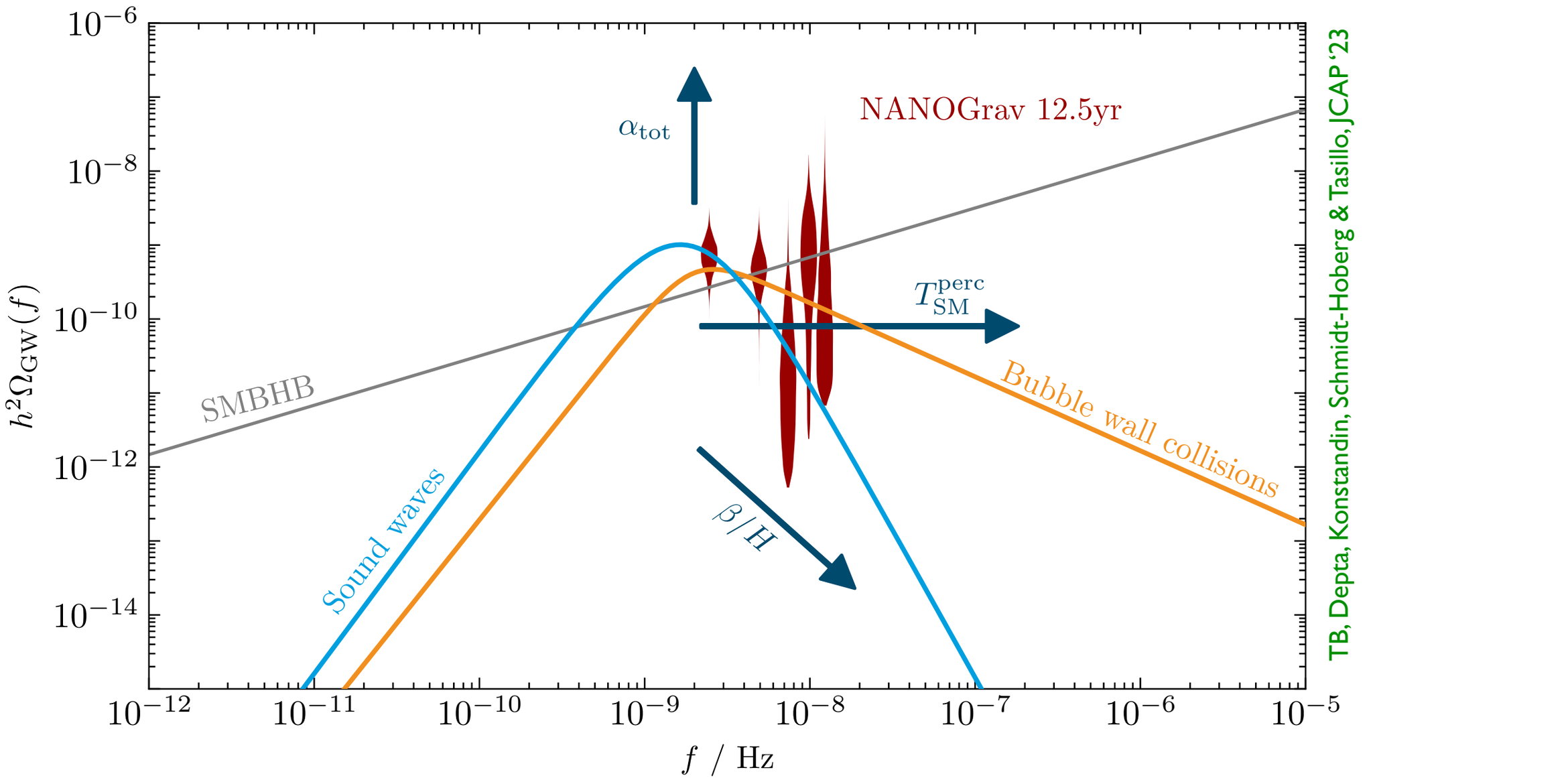


Resulting GW spectrum

- Main phenomenological parameters:
  - nucleation/percolation temperature *T*
  - PT strength α
  - Characteristic scale β (inverse time)

$$\alpha \approx \frac{\Delta V}{\rho_R} \gg 1$$

$$\Gamma \propto e^{-\frac{S_3(T)}{T}} = e^{\beta\,(t-t_0)} \Longrightarrow \frac{\beta}{H} = T\frac{d}{dT}\left(\frac{S_3(T)}{T}\right)\Big|_{T=T_p}$$

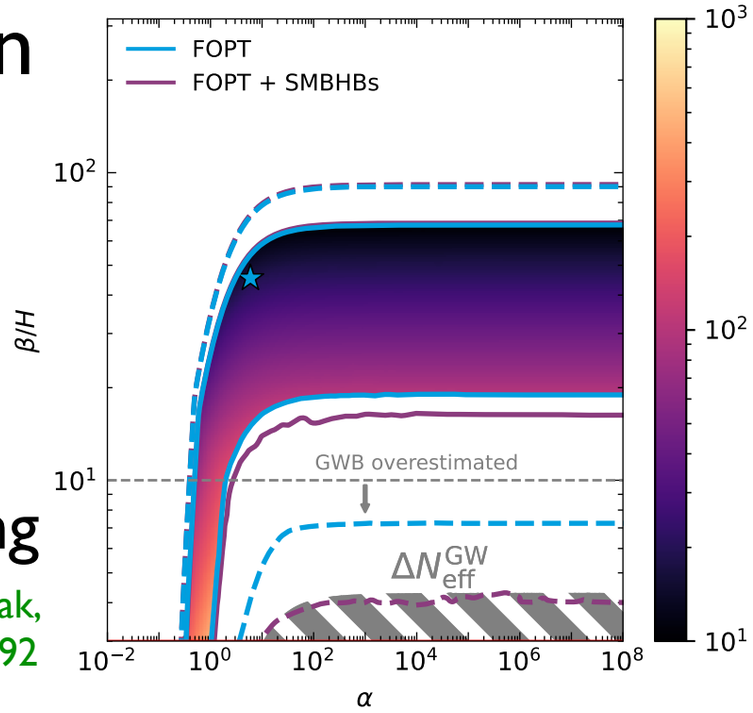


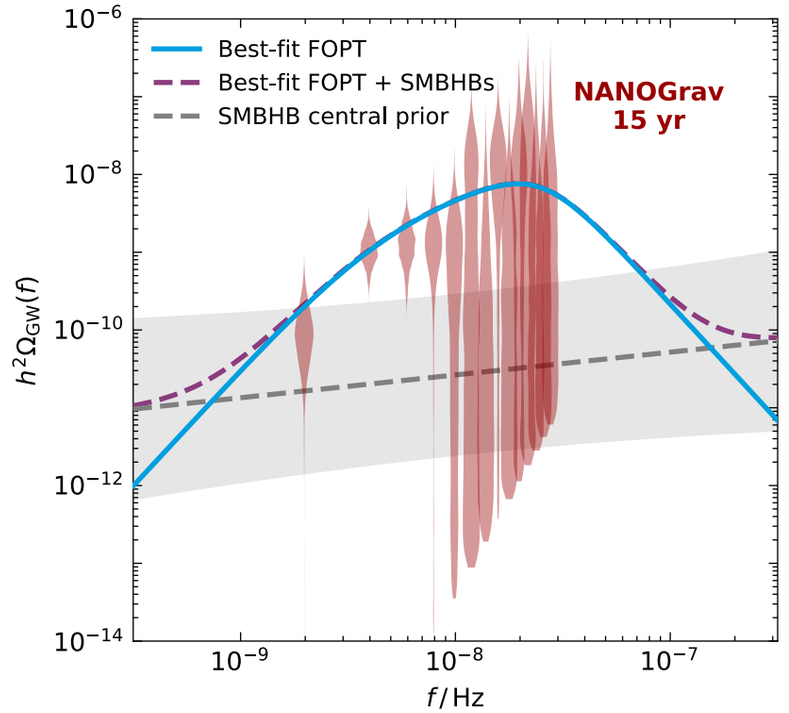
A phase transition as explanation of PTA data ?

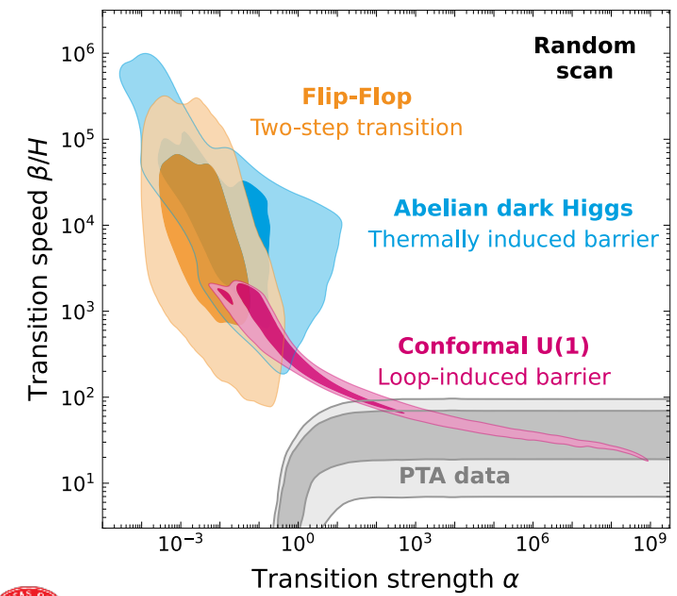
- Requires phase transition (PT) to happen well before BBN
  - Dark sector cannot be completely secluded — TB, Depta, Konstandin, Schmidt-Hoberg & Tasillo, JCAP '23

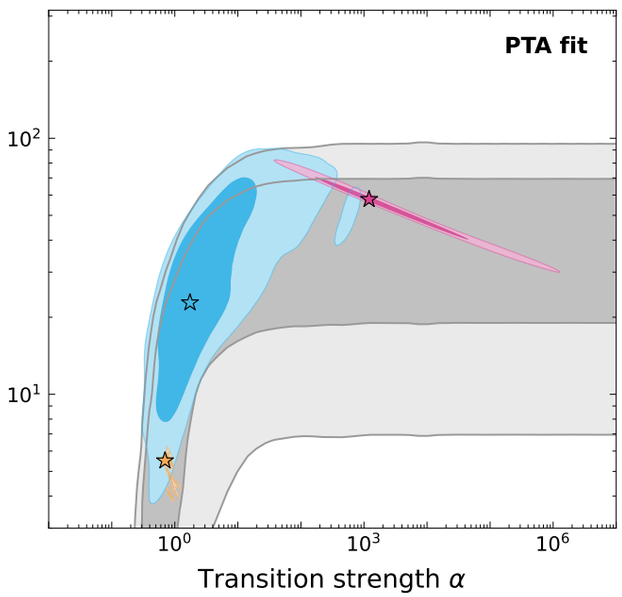
- A PT (still) provides an excellent fit to data
  - Larger T_{reh} compared to 12.5yr data: relaxes BBN constraints, but still very relevant for model-building

TB, Konstandin, Matuszak, Schmidt-Hoberg & Tasillo, 2602.09092







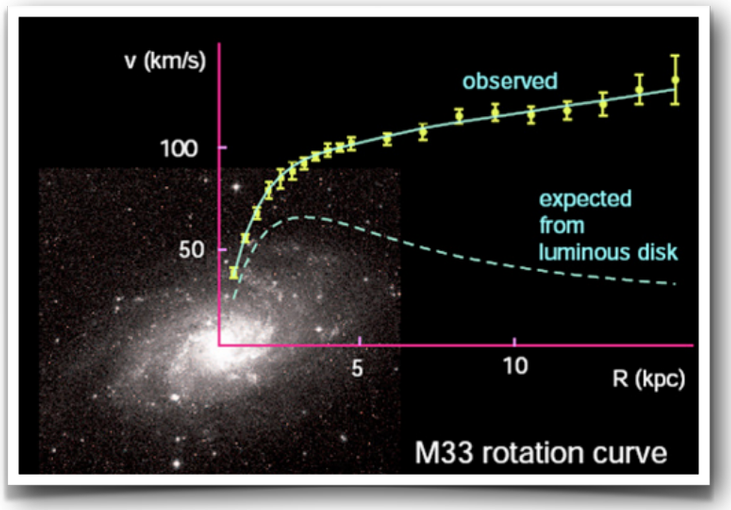


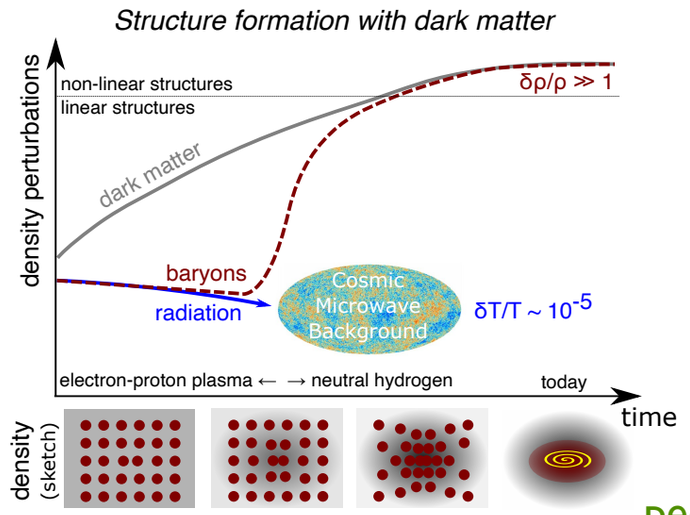
- Various PT models can explain the data well
  - but only conformal models appear to do so without significant tuning of model parameters

Would in principle allow to measure dark sector model parameters !

Dark matter

- Overwhelming evidence on *all* scales
  - galactic scales → … → cosmological scales
    - careful: NO LONGER most compelling argument!
    - modern 'gold standard'





pedagogical DM **review**:
Balacs, TB, Kahlhoefer & White, 2411.05062

- Upshot: we know exactly how much there is…

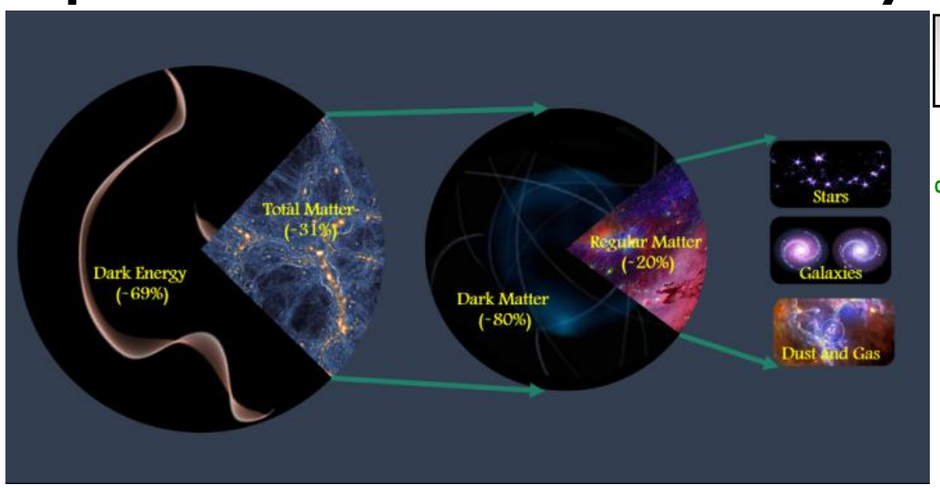
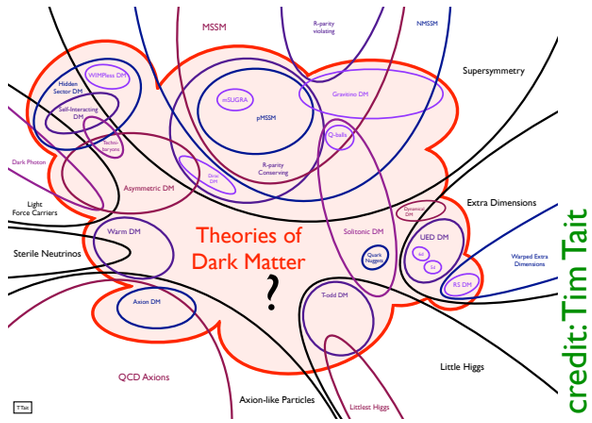


Image credit: M. H. Abdullah

$$\Omega_{\rm CDM} h^2 = 0.1188 \pm 0.0010$$

Ade+ [Planck Coll.], A&A '16

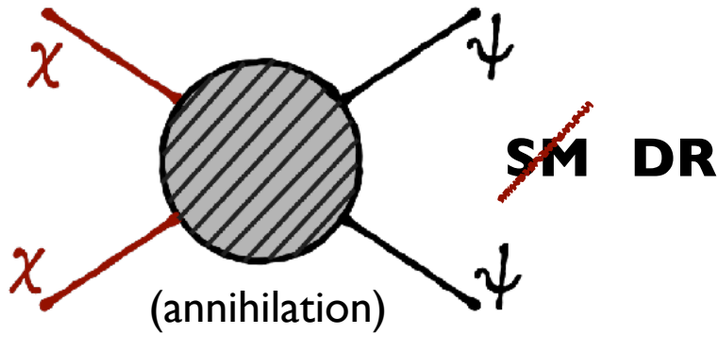


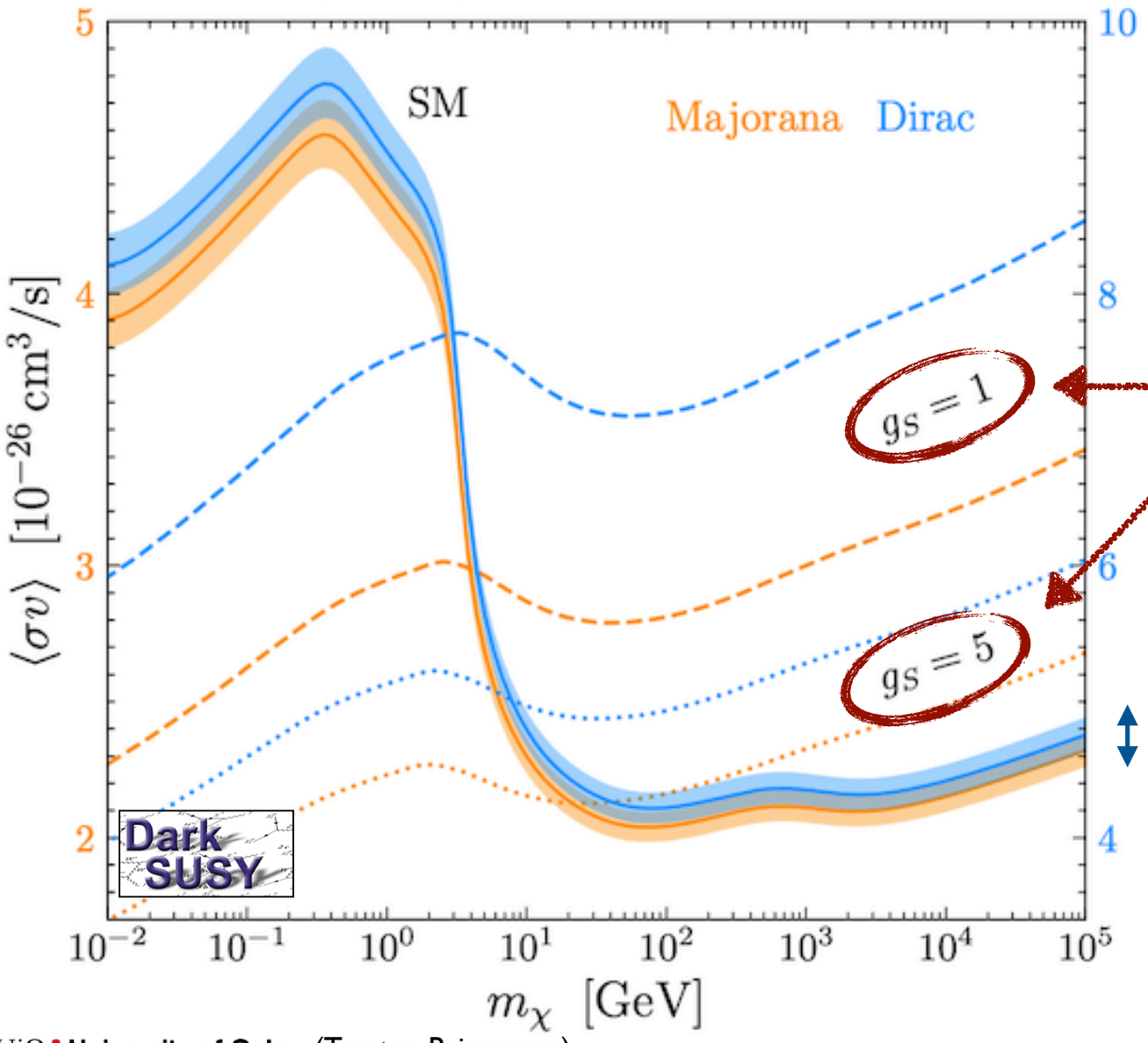
credit: Tim Tait

- …but (still) have no clue what it might be

Freeze-out of 'hidden' dark matter

- Thermal production works equally well for vanilla WIMPs and fully decoupled dark sectors
  - but details need to be implemented correctly for precision treatment





TB, Depta, Hufnagel & Schmidt-Hoberg, PLB '21

dark radiation (DR) degrees of freedom

observational uncertainty on DM abundance

A minimal dark sector model

Balan, TB, Kahlhoefer, Matuszak & Tasillo, JCAP '25

$SU(3)_c \times SU(2)_L \times U(1)_Y$ — $U(1)'$

Standard Model — $\mathcal{L} \supset -\kappa F'_{\mu\nu} F^{\mu\nu}$ — **Dark Sector**

'portal' interactions (kinetic mixing)

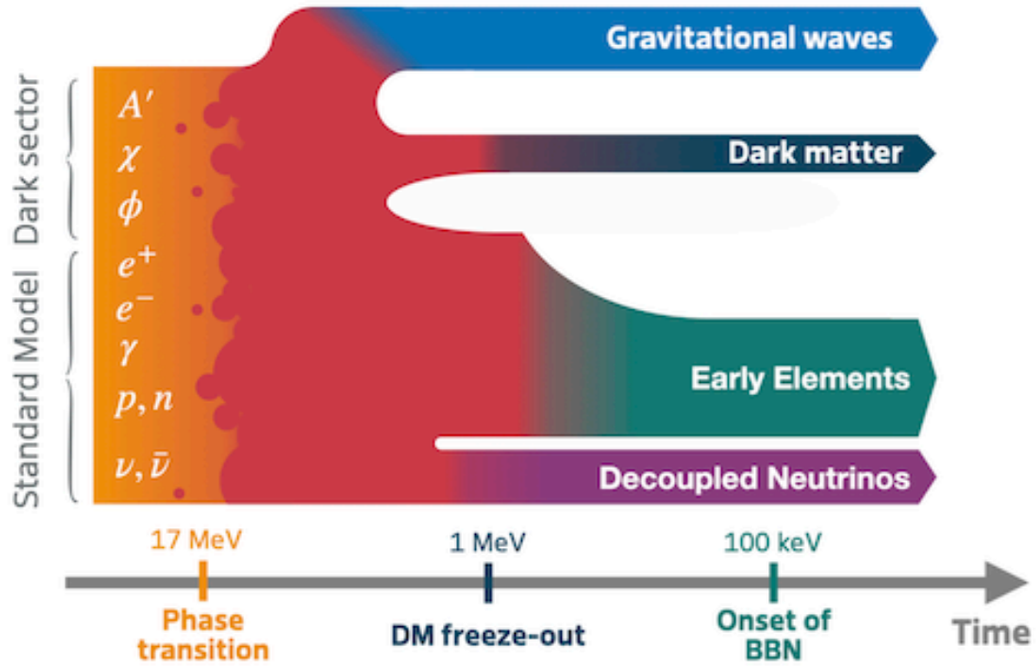
- SM particles
- massless scalar field ϕ
- Chiral fermion pair χ

conformal symmetry

- Quantum and thermal corrections break conformal symmetry

$\langle \phi \rangle \neq 0$ ⇨

- Strong 1st order PT: GWs
- χ becomes massive: dark matter



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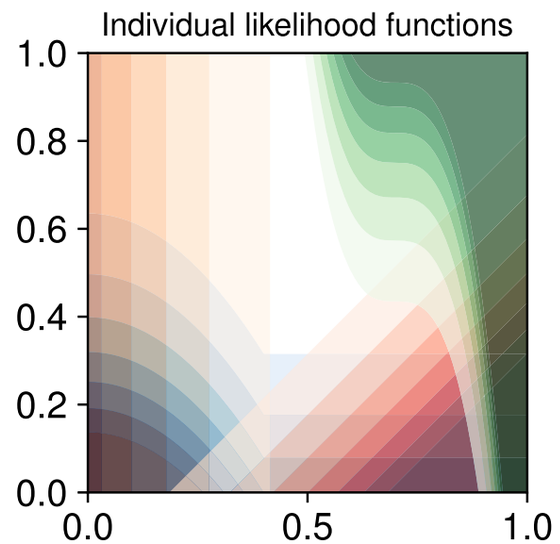
$\langle \phi \rangle \neq 0$ ⇒

- Strong 1st order PT: GWs
- χ becomes massive: dark matter

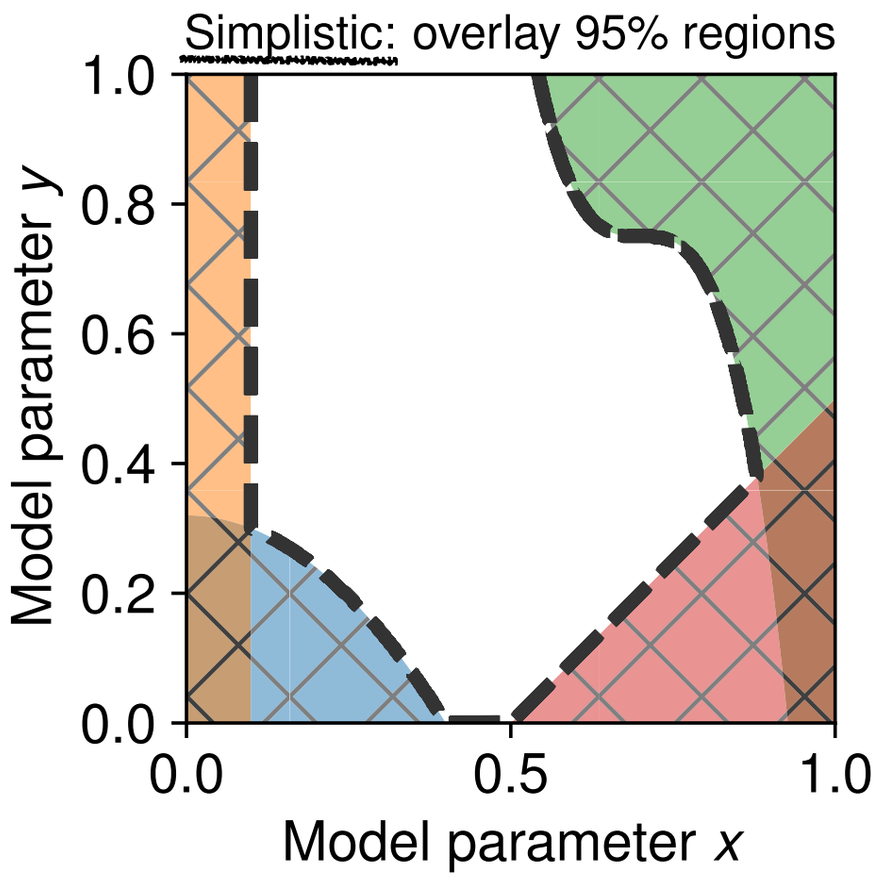
- Dark photon A' has further consequences (cosmology and accelerator searches)
  - Include all constraints in full global fit

Global fits

- Need care when statistically combining multiple experimental constraints
  - Especially for many individual observations…
  - … as well as in the presence of nuisance parameters



$$\mathcal{L}_{\text{total}} = \mathcal{L}_{\text{DD}} \times \mathcal{L}_{\text{ID}} \times \mathcal{L}_{\text{Collider}} \times \dots$$



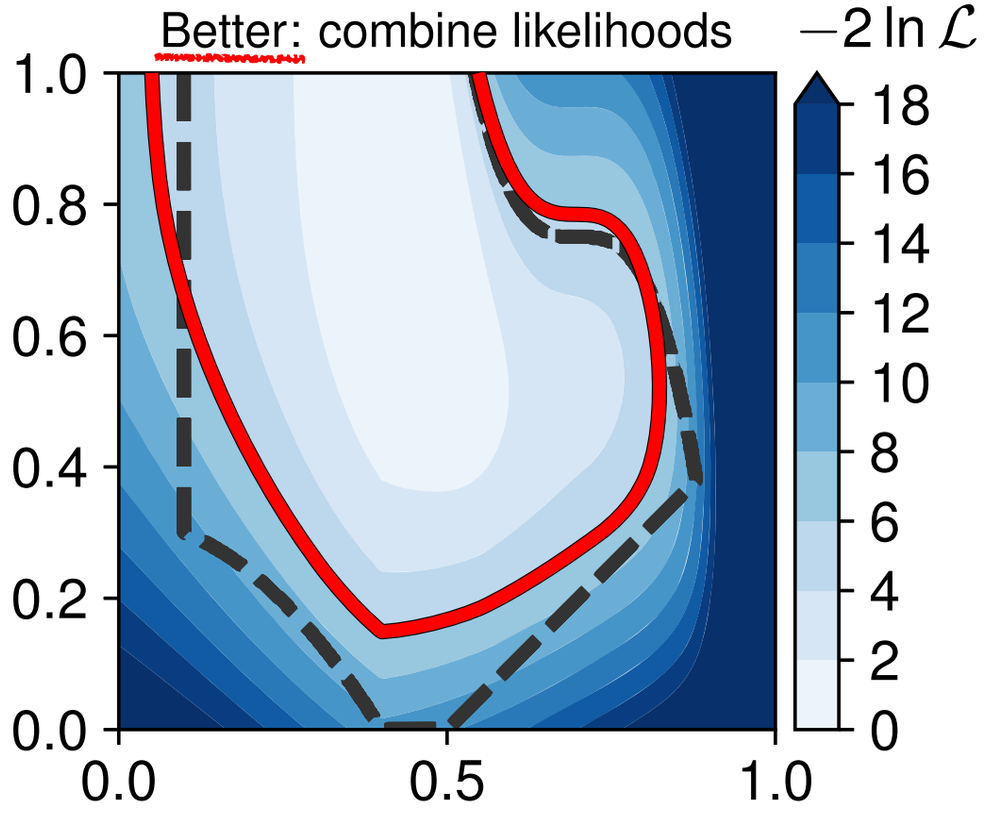
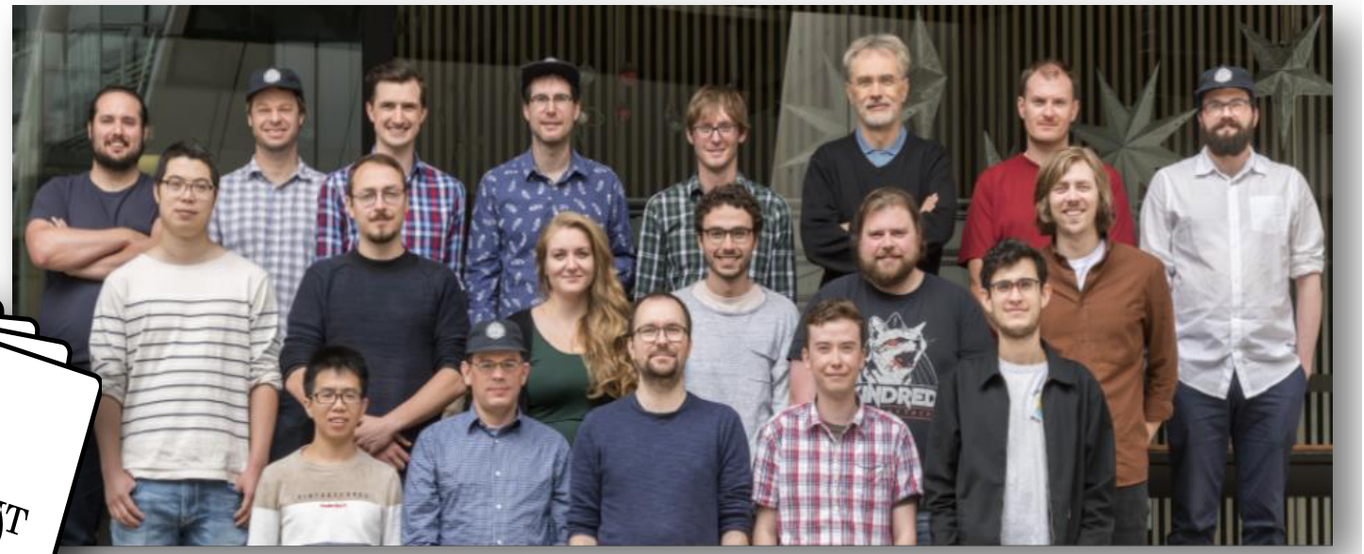


Illustration: AbdusSalam+, RPP '22

GAMBIT: The Global And Modular BSM Inference Tool

gambitbsm.org github.com/GambitBSM EPJC 77 (2017) 784 arXiv:1705.07908

- Extensive model database, beyond SUSY
- Fast definition of new datasets, theories
- Extensive observable/data libraries
- Plug&play scanning/physics/likelihoods
- Various statistical options (frequentist /Bayesian)
- Fast LHC likelihood calculator
- Massively parallel
- Fully open-source



Members of: ATLAS, Belle-II, CLiC, CMS, CTA, Fermi-LAT, DARWIN, IceCube, LHCb, SHiP, XENON

Authors of: BubbleProfiler, Capt'n General, Contur, DarkAges, DarkSUSY, DDCalc, DirectDM, Diver, EasyScanHEP, ExoCLASS, FlexibleSUSY, gamLike, GM2Calc, HEPLike, IsaTools, MARTY, nuLike, PhaseTracer, PolyChord, Rivet, SOFTSUSY, SuperIso, SUSY-AI, xsec, Vevacious, WIMPSim

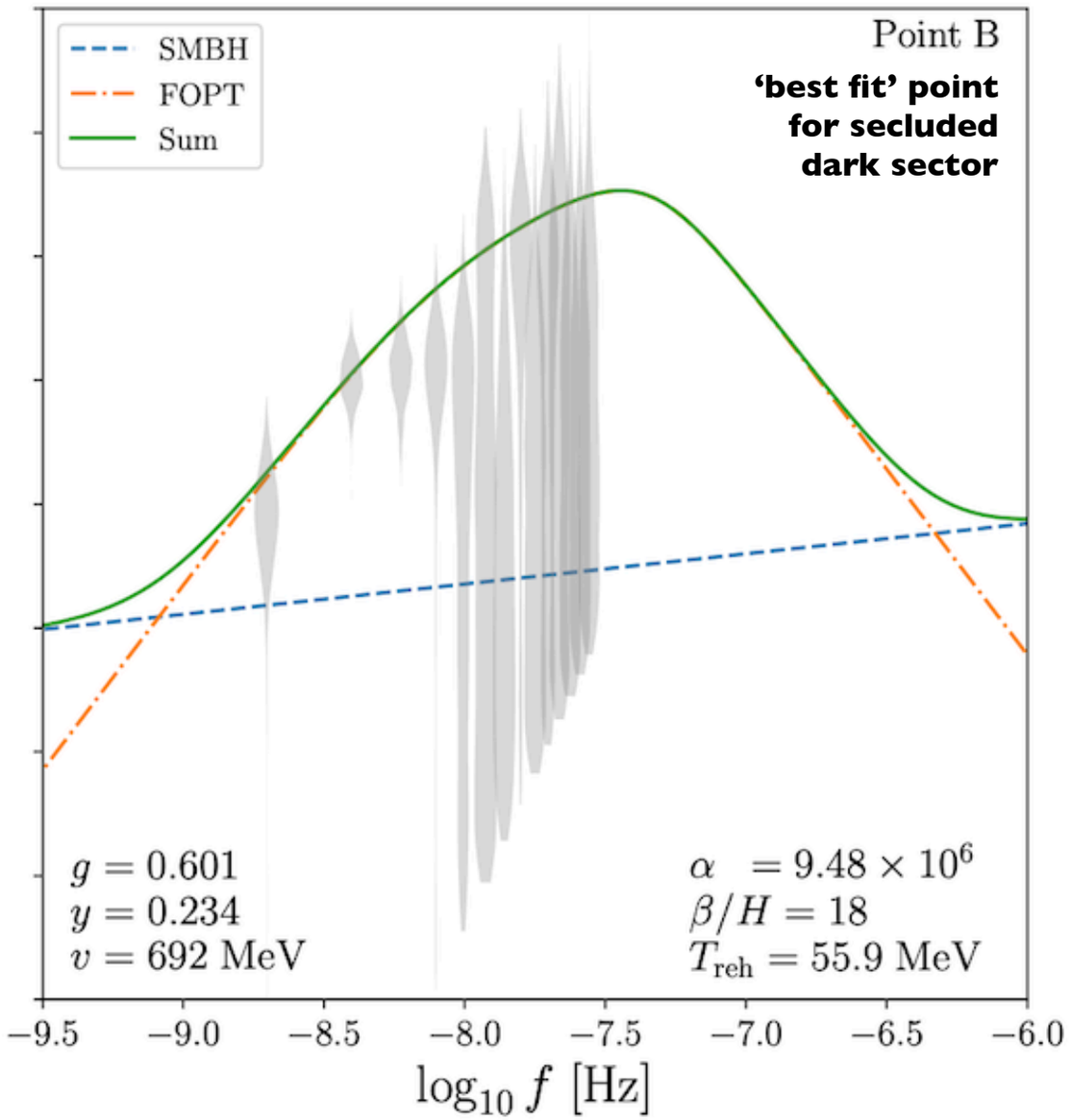
Recent collaborators: P Athron, C Balázs, S Balan, T Bringmann, G Busoni, J Butterworth, C Chang, J M Cornell, B Farmer, A Fowlie, T Gonzalo, W Handley, I-M Johansson, A Jueid, F Kahlhoefer, N P A Kozar, A Kvellestad, M Lucente, S Lee, N Mahmoudi, G D Martinez, J Matuszak, H Pacey, M Palmiotto, M Pitts, T Procter, A Raklev, R R de Austri, P Scott, C Sierra, L Street, P Stoecker, W Su, C Tasillo, A Vincent, M White, L Wu, Y Zhang, P Zhu, J Zuk

80+ participants in many experiments and numerous major theory codes

GAMBIT is a software framework for global fits actively developed over the past decade

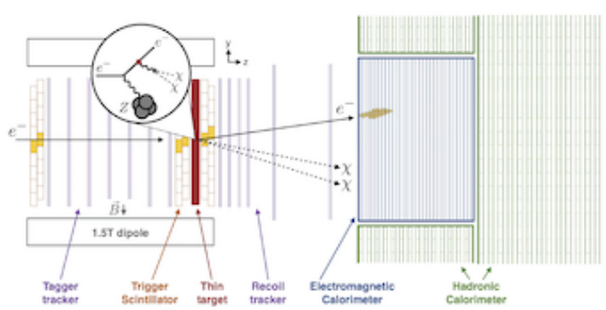
Global fit results

Balan, TB, Kahlhoefer, Matuszak & Tasillo, JCAP '25



- Loud PT on top of astro-physical SMBH merger signal
  - addresses issues with SMBH signal slope and normalization
- 100% of observed dark matter
- Satisfies constraints from BBN, CMB, Bullet cluster, (in)direct searches
- Testable prediction for DMX:

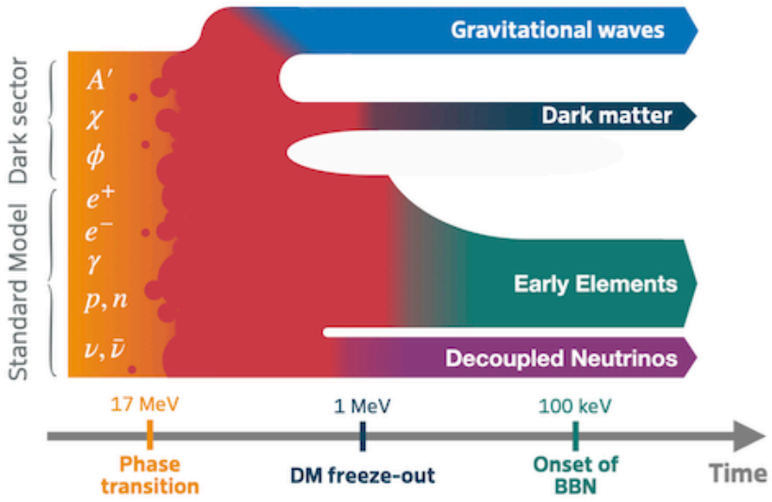
$$m'_A = 100 - 200\,\text{MeV}$$
$$\kappa \simeq 10^{-4}$$

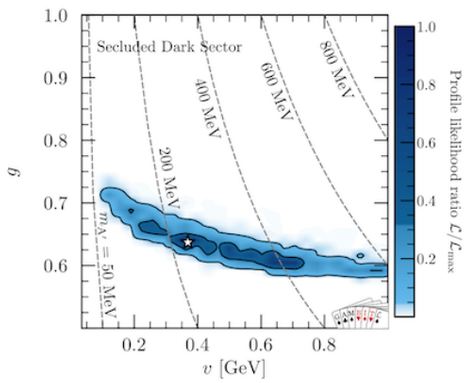


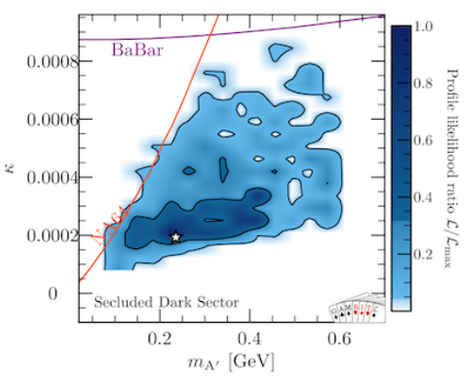
Secluded vs coupled dark sector

Balan, TB, Kahlhoefer, Matuszak & Tasillo, JCAP '25

- NB: Thermalization requires κ within experimental reach



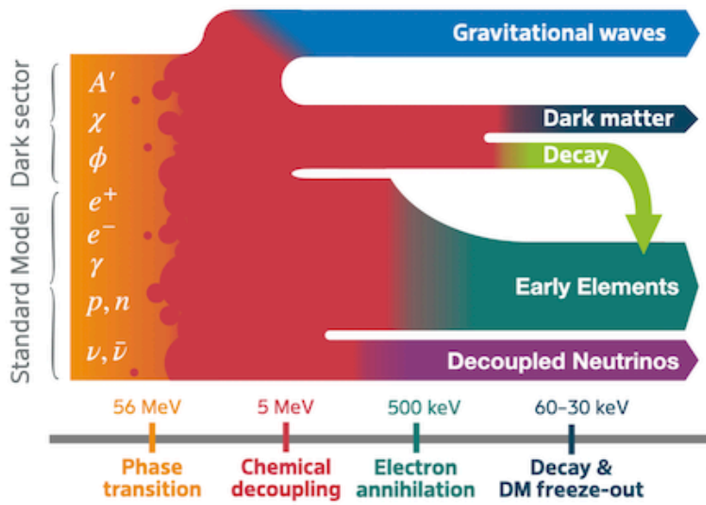


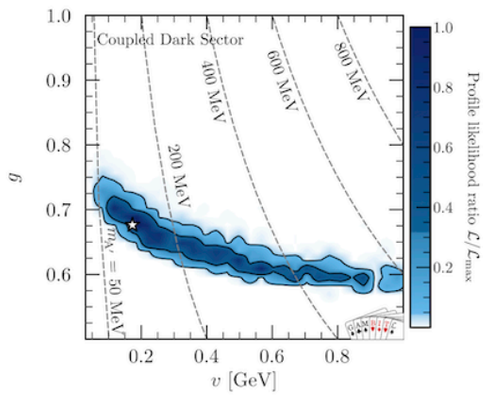


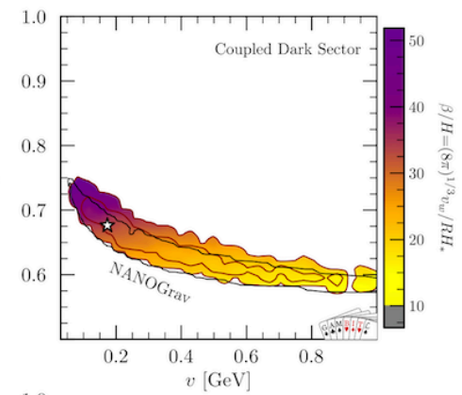
extend model by adding dim-6 operator for

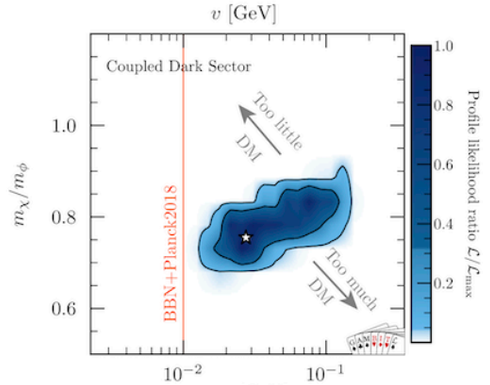
$\phi \to e^+ e^-$

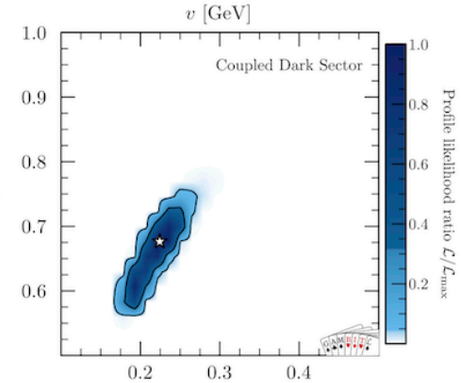
- … but even $\kappa = 0$ may be possible





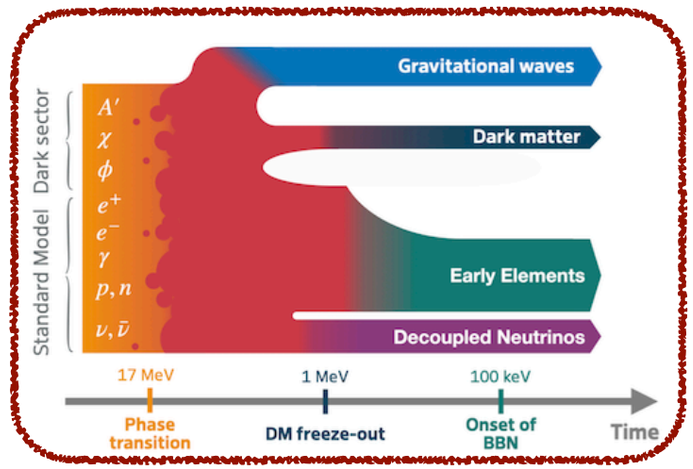


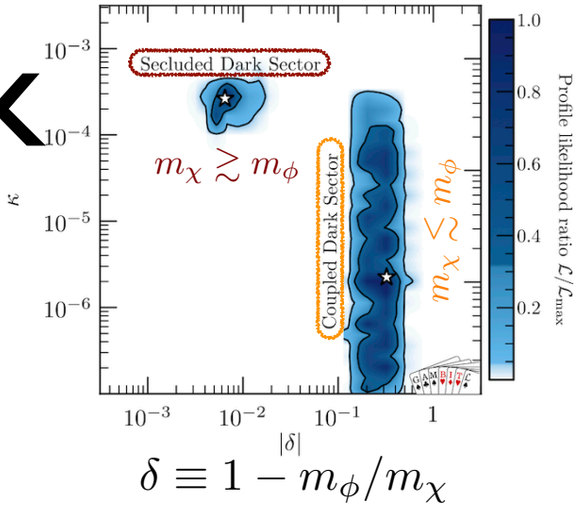


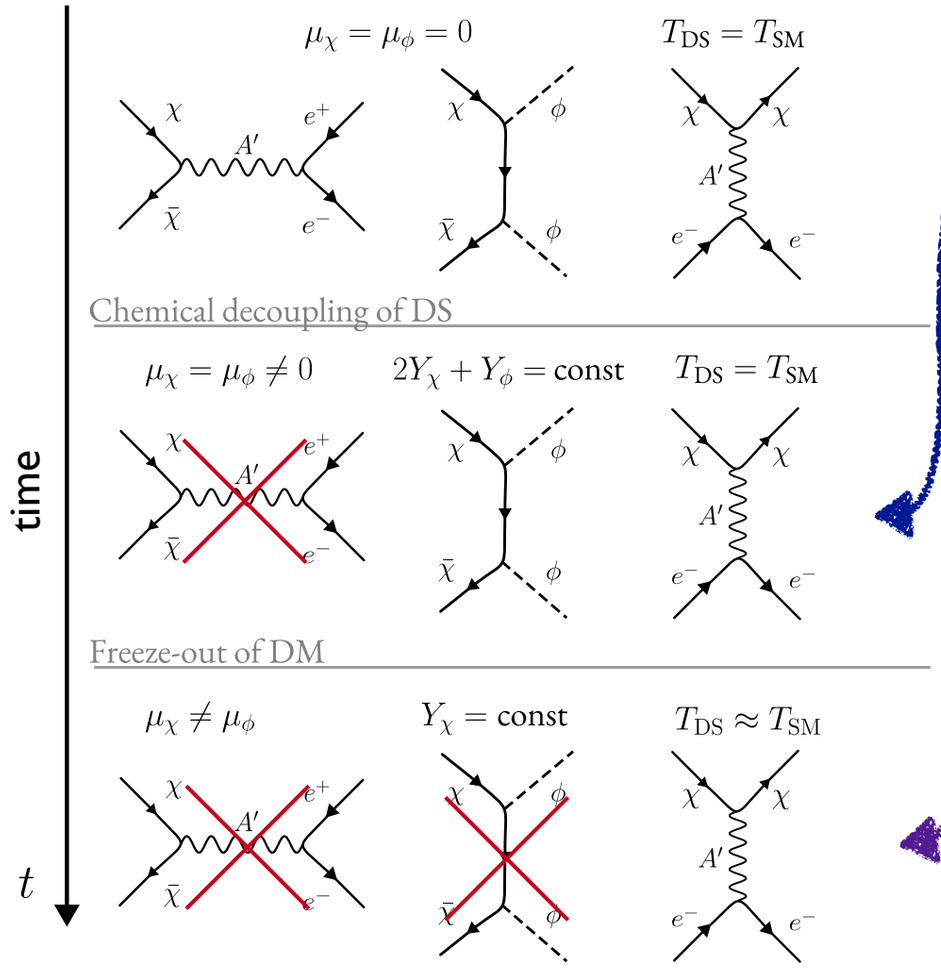


DM production: a closer look

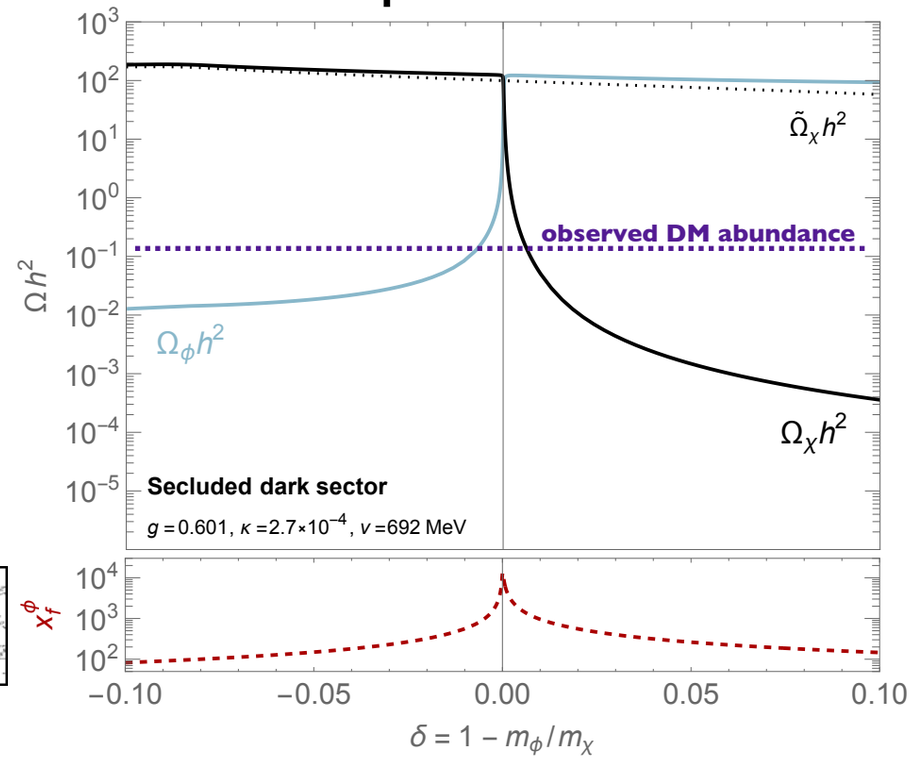
- In the secluded sector case, the scalar must be slightly lighter than the DM particle





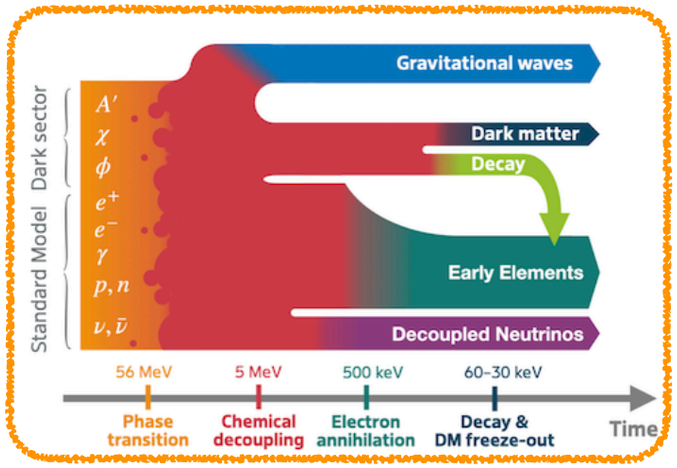


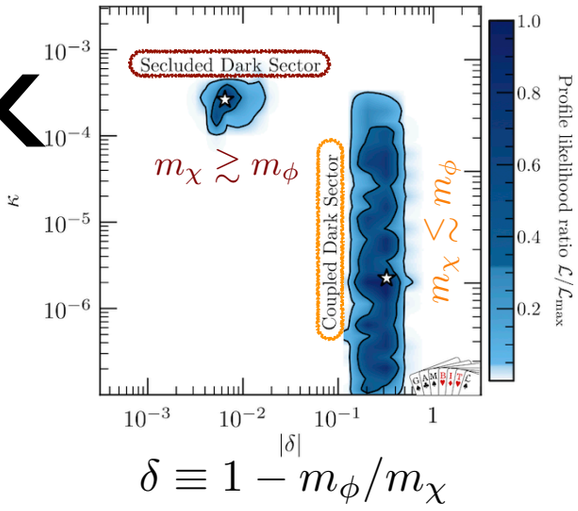
- first step: determines total dark sector content
- second step: $\phi\phi \leftrightarrow \chi\chi$ quickly depletes the heavier species

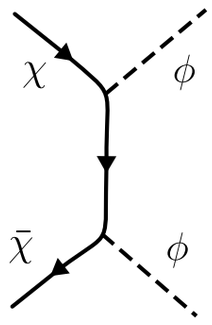


DM production: a closer look

- In the coupled sector case, the scalar must be a bit heavier than the DM







- ϕ in eq. with SM during entire freeze-out process
- Large Yukawas and $m_\chi \sim 100\,\mathrm{MeV}$

  ⇒ $(\sigma v)_{v\to 0} \gg 3 \cdot 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$

- only way to avoid full DM depletion: 'forbidden' annihilation

D'Agnolo & Ruderman, PRL '15

$m_\phi > m_\chi$ ⇒ $\langle \sigma v \rangle \sim (\sigma v)_{v\to 0} \times e^{-(m_\phi - m_\chi)/T_{\mathrm{f.o.}}}$

So… is 'vanilla' freeze-out really impossible in this kind of scenario ?

A LISA miracle ?

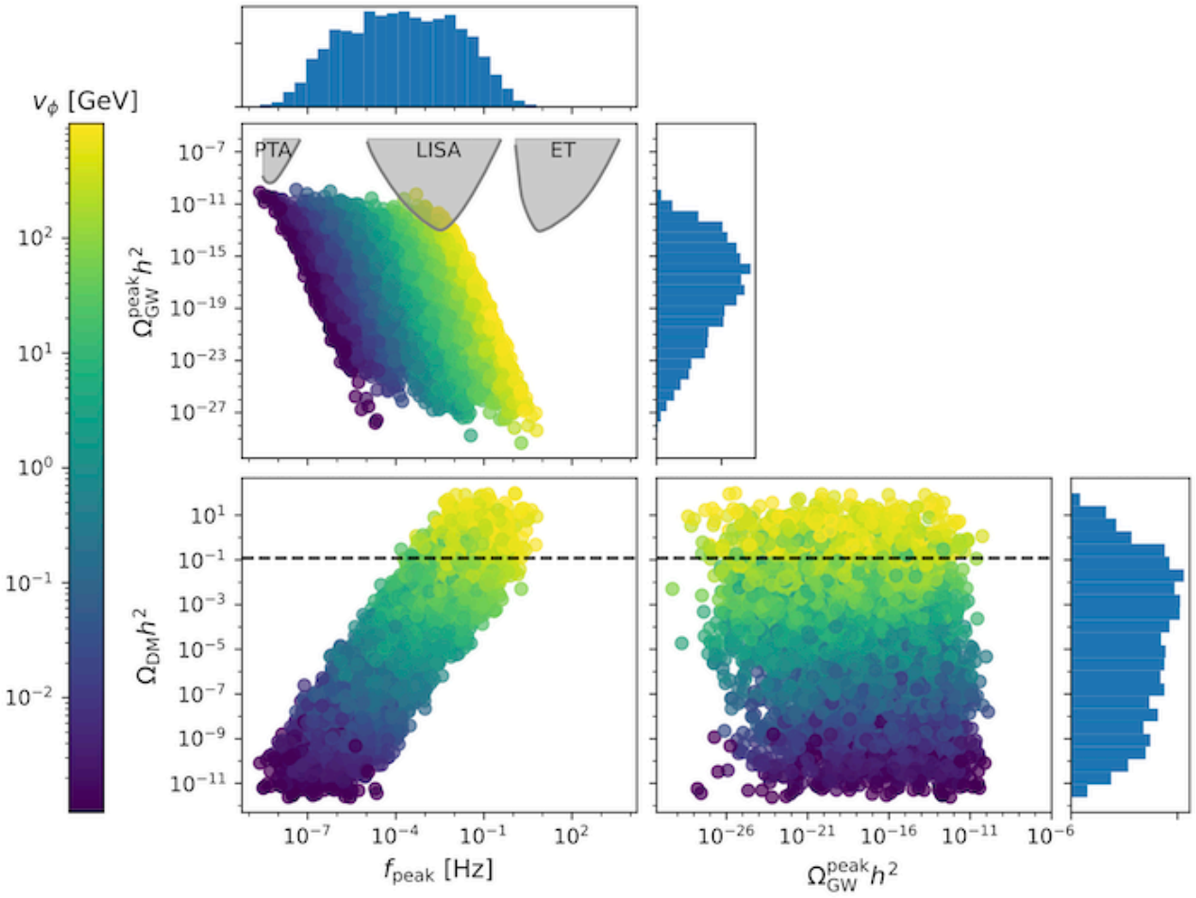
TB, Gonzalo, Kahlhoefer, Matuszak & Tasillo, JCAP '24

$$\mathcal{L} = |D_\mu \Phi|^2 - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + \mu^2 \Phi^* \Phi - \lambda (\Phi^* \Phi)^2 + \chi_L^\dagger i \not{D} \chi_L + \chi_R^\dagger i \not{D} \chi_R - y \Phi \chi_L^\dagger \chi_R - y \Phi^* \chi_R^\dagger \chi_L$$

- scalar field charged under U(1)'
- (Chiral) dark matter fermion

  ⟹ (after PT) mass & thermal freeze-out

- Result: striking correlation between GW peak frequency and DM abundance



- Why ??
  - strong PT + large GW signal

$$g \sim \lambda \sim \mathcal{O}(1) \rightsquigarrow m_\phi \sim v_\phi$$

  - (vanilla) freeze-out

$$m_\chi \gtrsim m_\phi, m_{A'} \rightsquigarrow y \gtrsim 0.1$$

$$\langle \sigma_{\rm ann} v \rangle \sim \frac{y^4}{m_{\rm DM}^2} \sim \frac{y^2}{v_\phi^2} \stackrel{!}{=} 10^{-8} \text{GeV}^{-2}$$

$$\rightsquigarrow v_\phi \sim \text{TeV}$$

  - $f_{\rm peak} \simeq 10\,\text{mHz} \left(\frac{\beta/H}{100}\right) \left(\frac{T_{\rm p}}{1\,\text{TeV}}\right)$

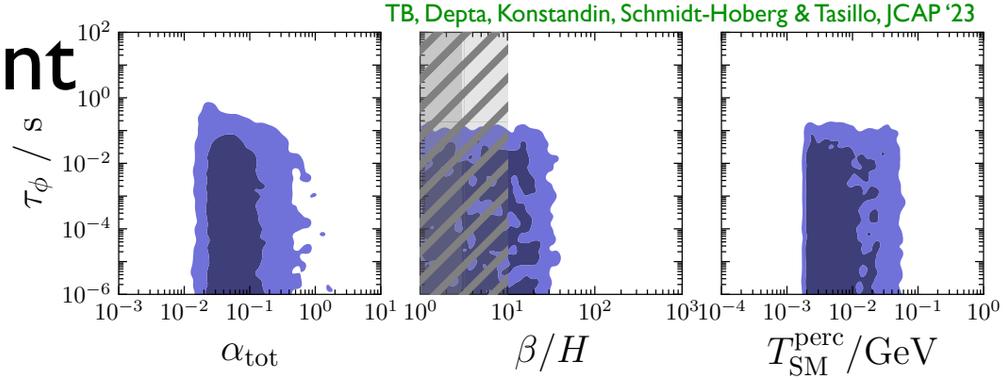
$$\sim 10\,\text{mHz} \left(\frac{v_\phi}{1\,\text{TeV}}\right)$$

for (not too strong) supercool PT

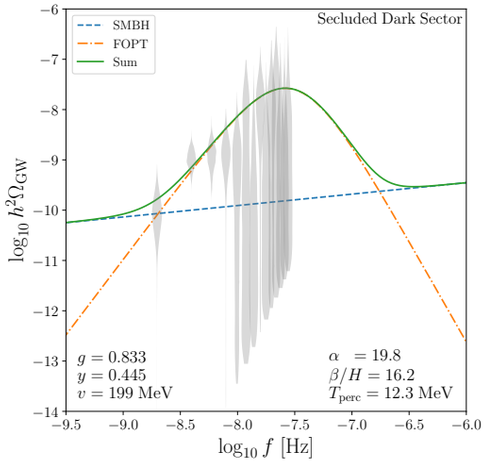
Conclusions

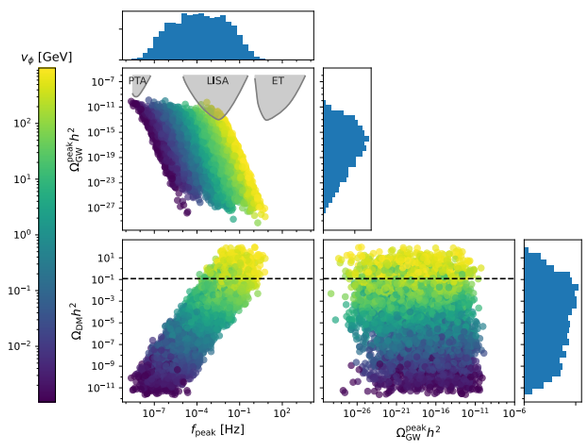
- The ***nHz*** GW background is consistent with a dark sector phase transition
  - but only if the dark sector is not 'too' dark !

TB, Depta, Konstandin, Schmidt-Hoberg & Tasillo, JCAP '23



- A simple conformal model explains both the GW signal and the cosmological dark matter
  - Testable with beam dump experiments !





- The observation of a ***mHz*** signal might more generically indicate thermal dark matter production in a secluded dark sector
  - … the WIMP miracle in disguise?

Thanks for listening!

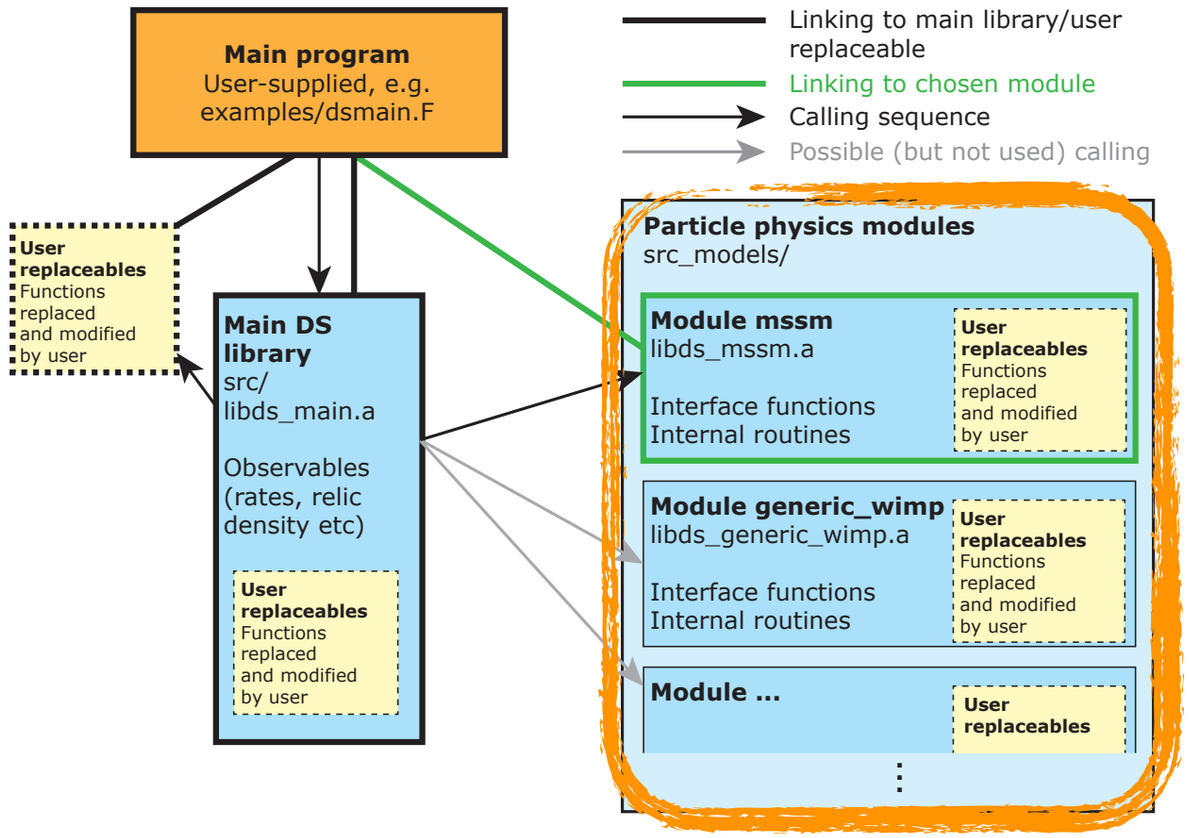
DarkSUSY

TB, Edsjö, Gondolo, Ullio & Bergström, JCAP '18

http://darksusy.hepforge.org

Since version 6: no longer restricted to supersymmetric DM !

- Numerical package to calculate 'all' DM related quantities:
  - *relic density + kinetic decoupling* **(also for $T_{\rm dark} \neq T_{\rm photon}$)**
  - *generic SUSY models + laboratory constraints implemented*
  - *cosmic ray propagation*
  - particle yields for generic DM annihilation or decay
  - *indirect detection rates: gammas, positrons, antiprotons, neutrinos*
  - *direct detection rates*
  - …



since 6.1: DM self-interactions

since 6.2: 'reverse' direct detection
(also Q^2 -dependent scattering!)

since 6.3: freeze-in