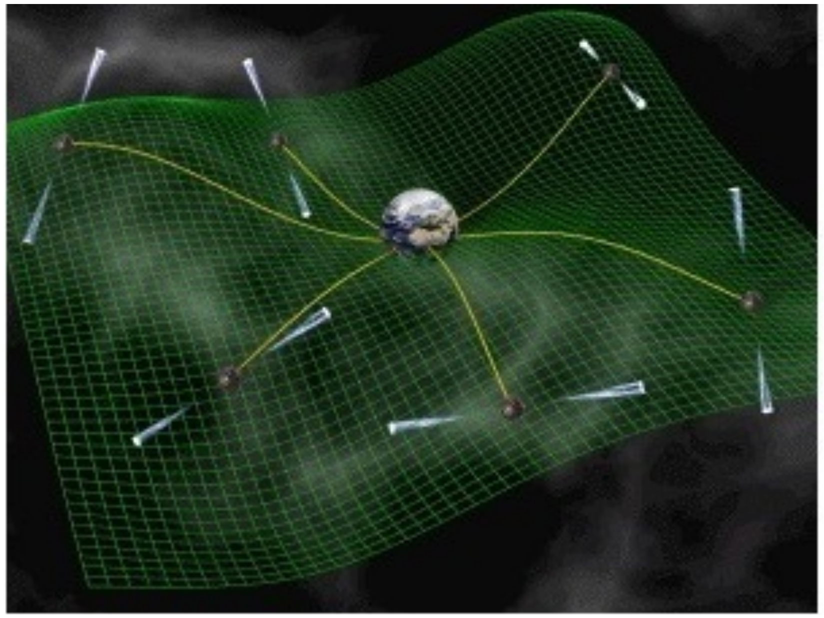
Dark matter and gravitational wave signals

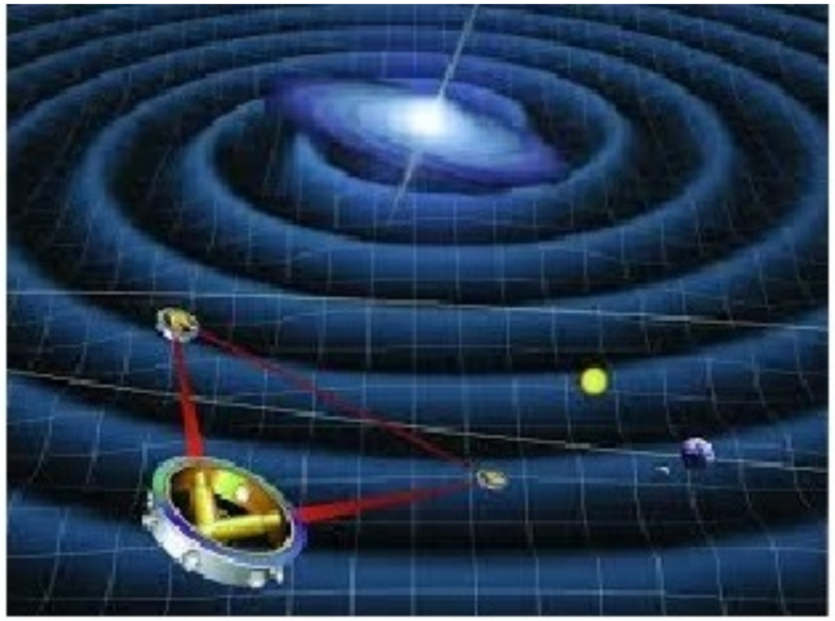
from a phase transition in the early universe

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

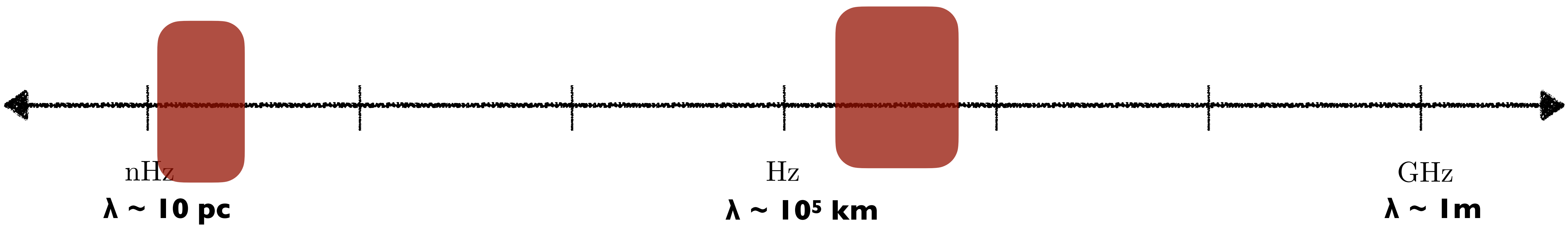
UNTERSTÜTZT VON / SUPPORTED BY Alexander von HUMBOLDT STIFTUNG

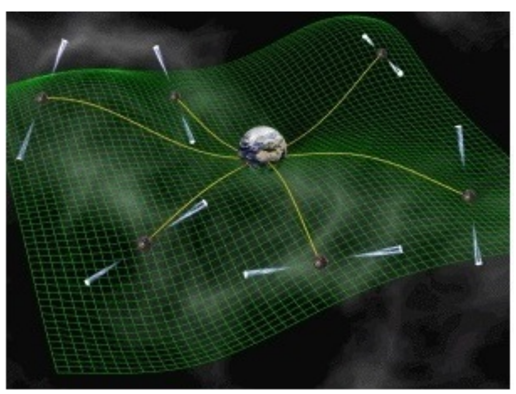
Funded by The Research Council of Norway

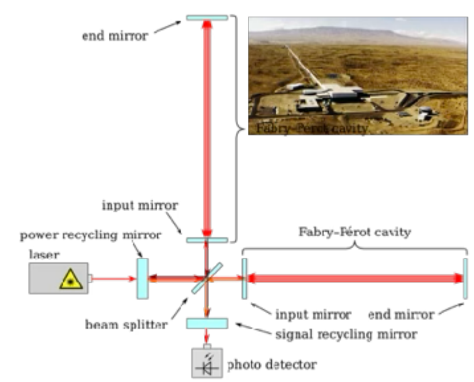
UiO : University of Oslo (Torsten Bringmann)

Gravitational waves: current status

- Confirmed observations in two frequency ranges





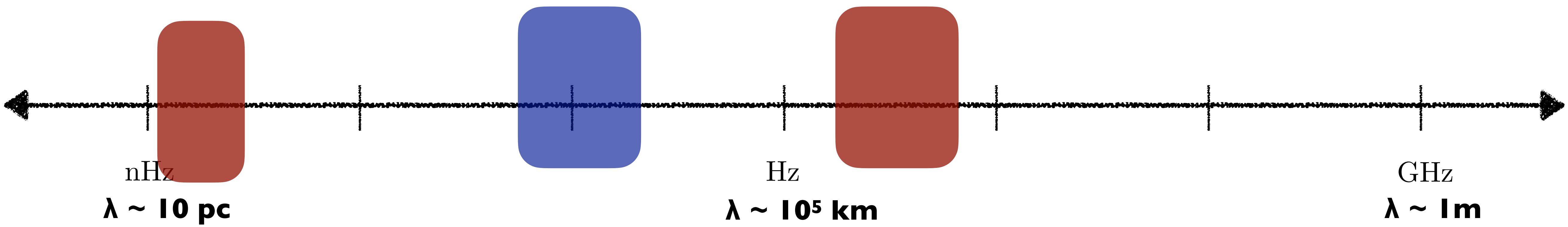


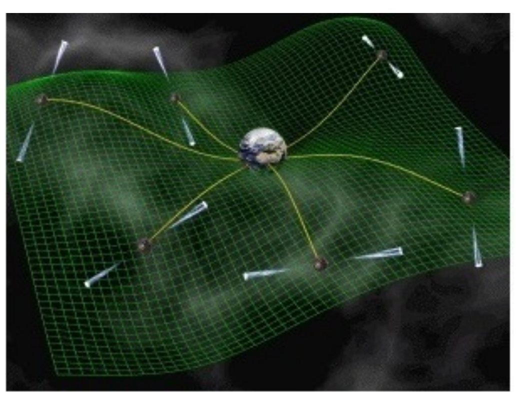
- Stochastic BG:
  - SMBH mergers ?
  - New physics?

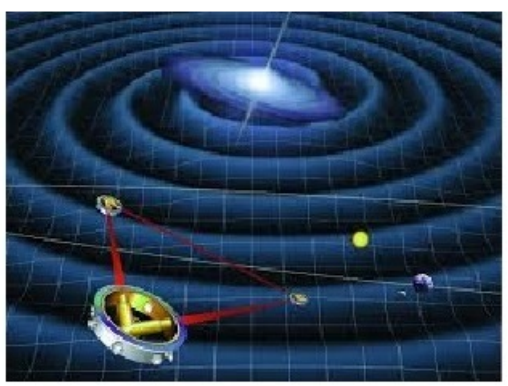
- Individual mergers:
  - BH-BH  **2017 Weiss, Thorne & Barish**
  - BH-NS
  - NS-NS

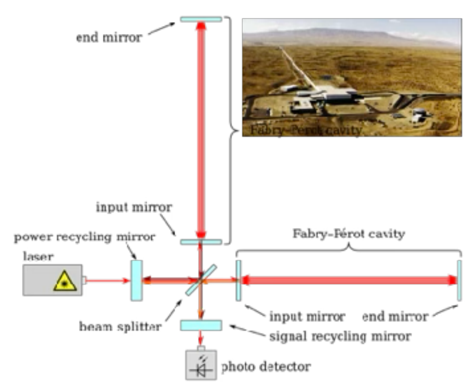
Gravitational waves: looking ahead

- Confirmed observations in two frequency ranges







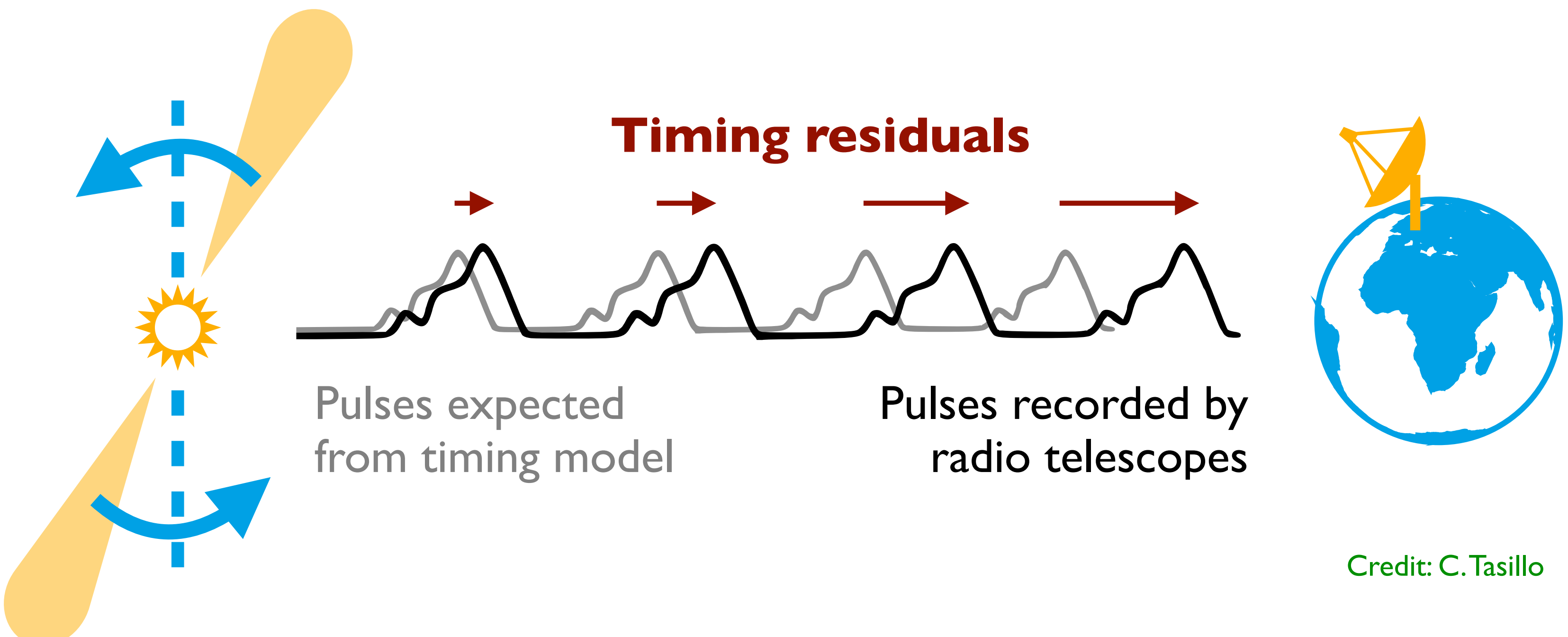


- ESA has formally adopted the LISA mission
  - construction has begun, launch scheduled in 2035

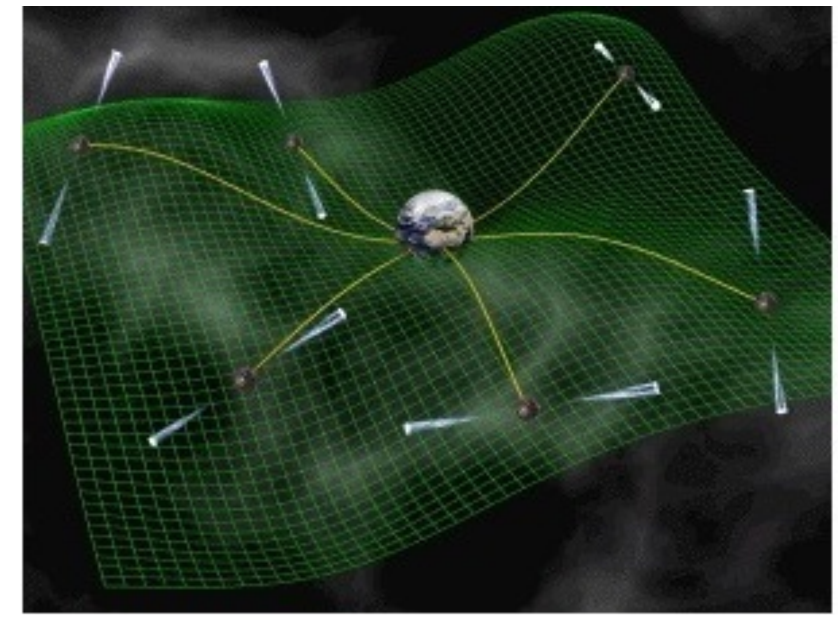
➡ *Large potential to probe new physics*

The nHz gravitational wave background

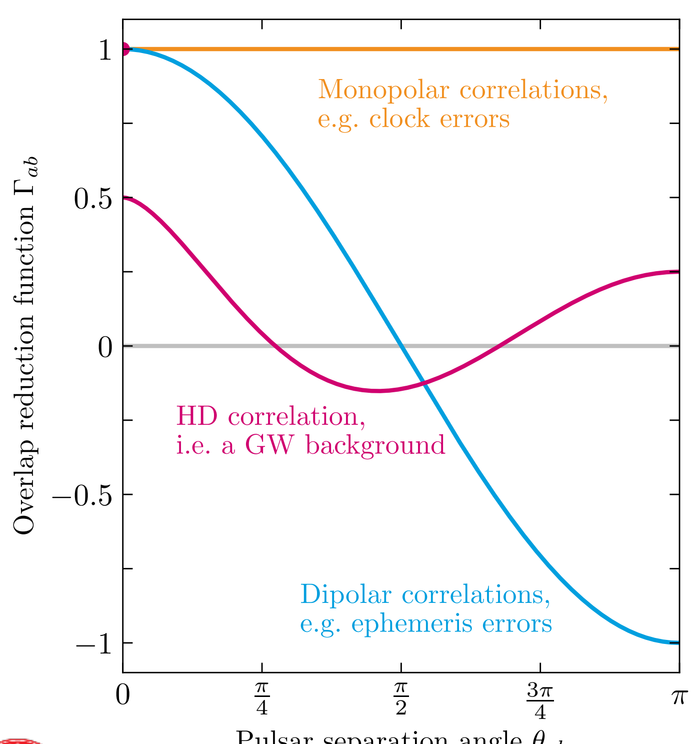
- Pulsar timing arrays (PTAs)



Credit: C. Tasillo

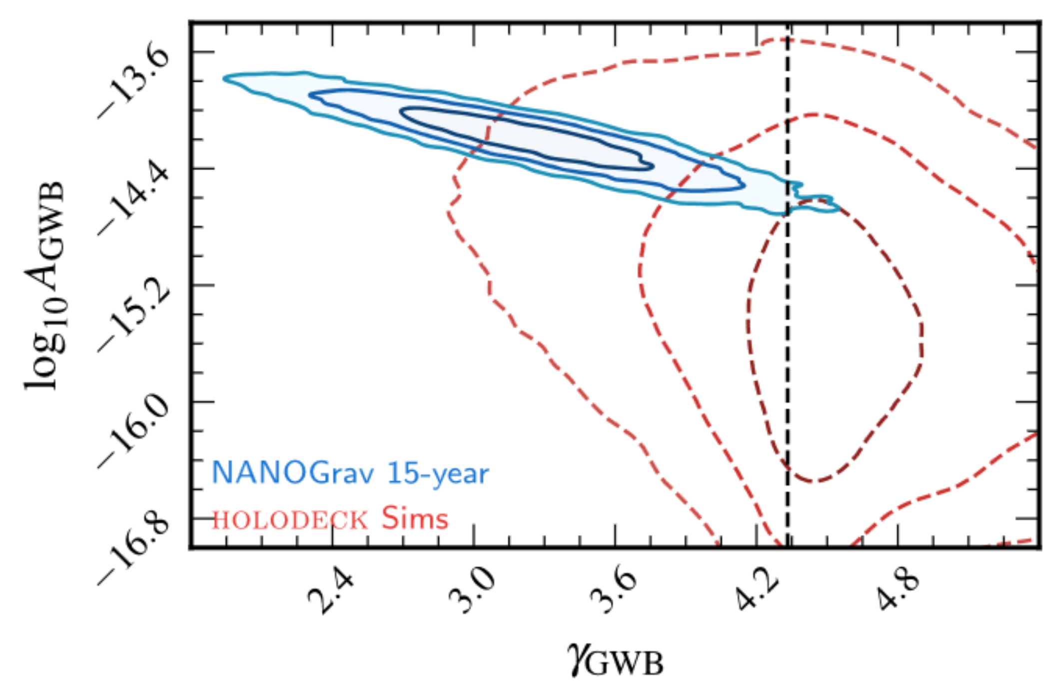


- Common red noise due to GWs



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

- Can SMBH mergers really explain this ?

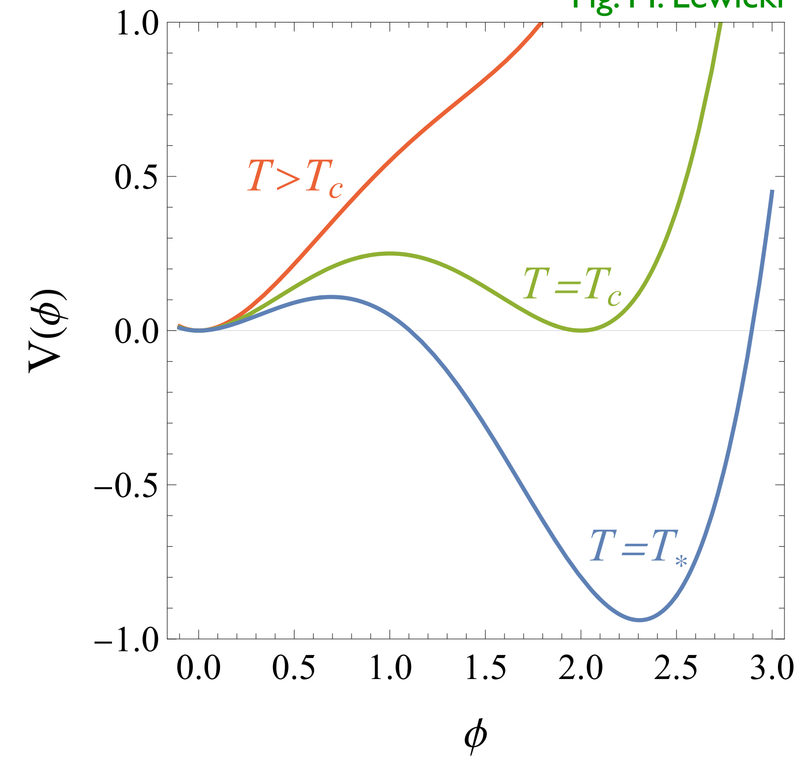


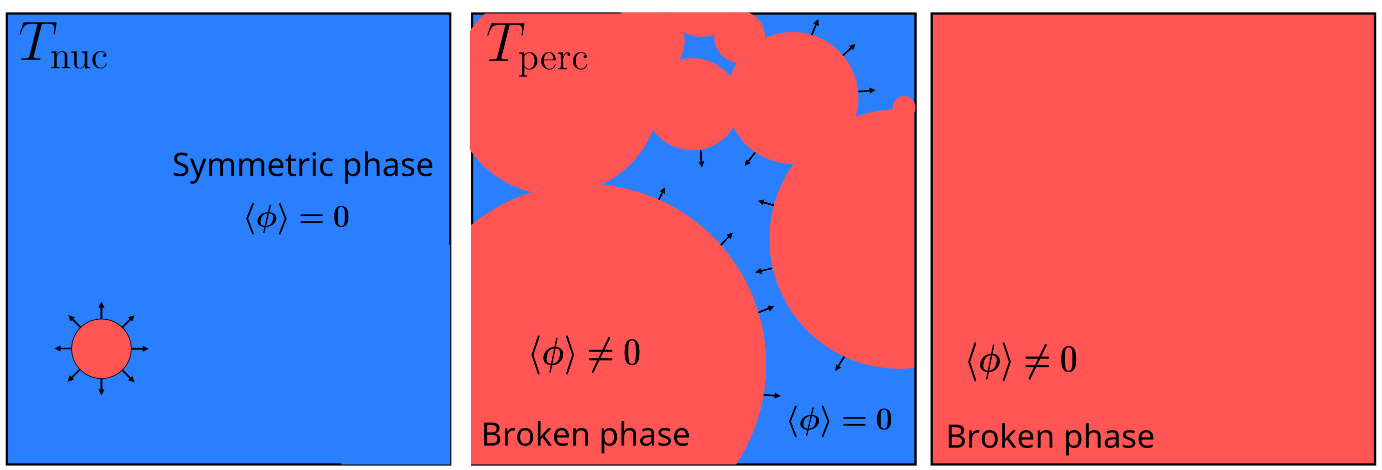
Cosmological phase transitions

- 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

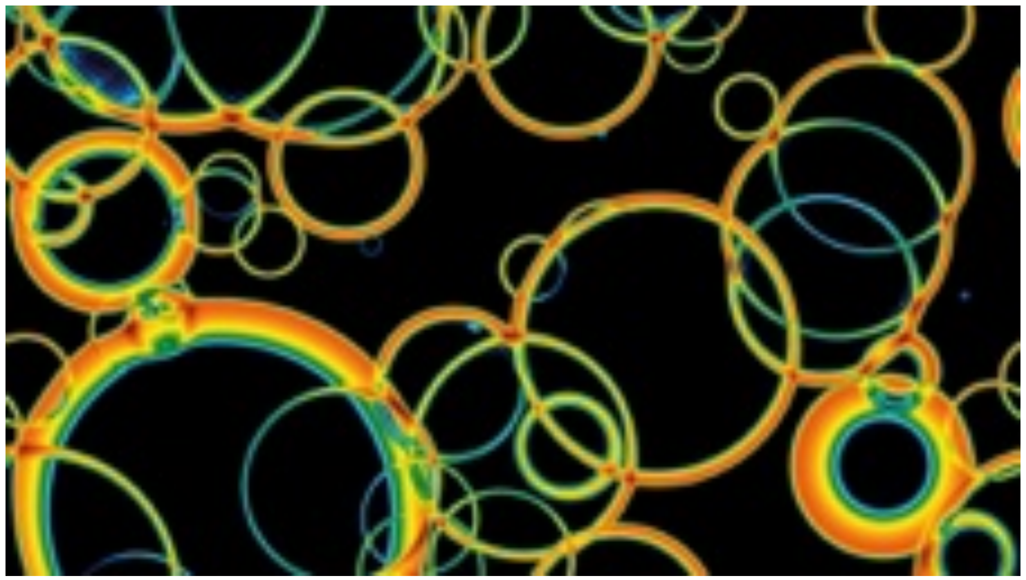




J. Matuszak, '23

- 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

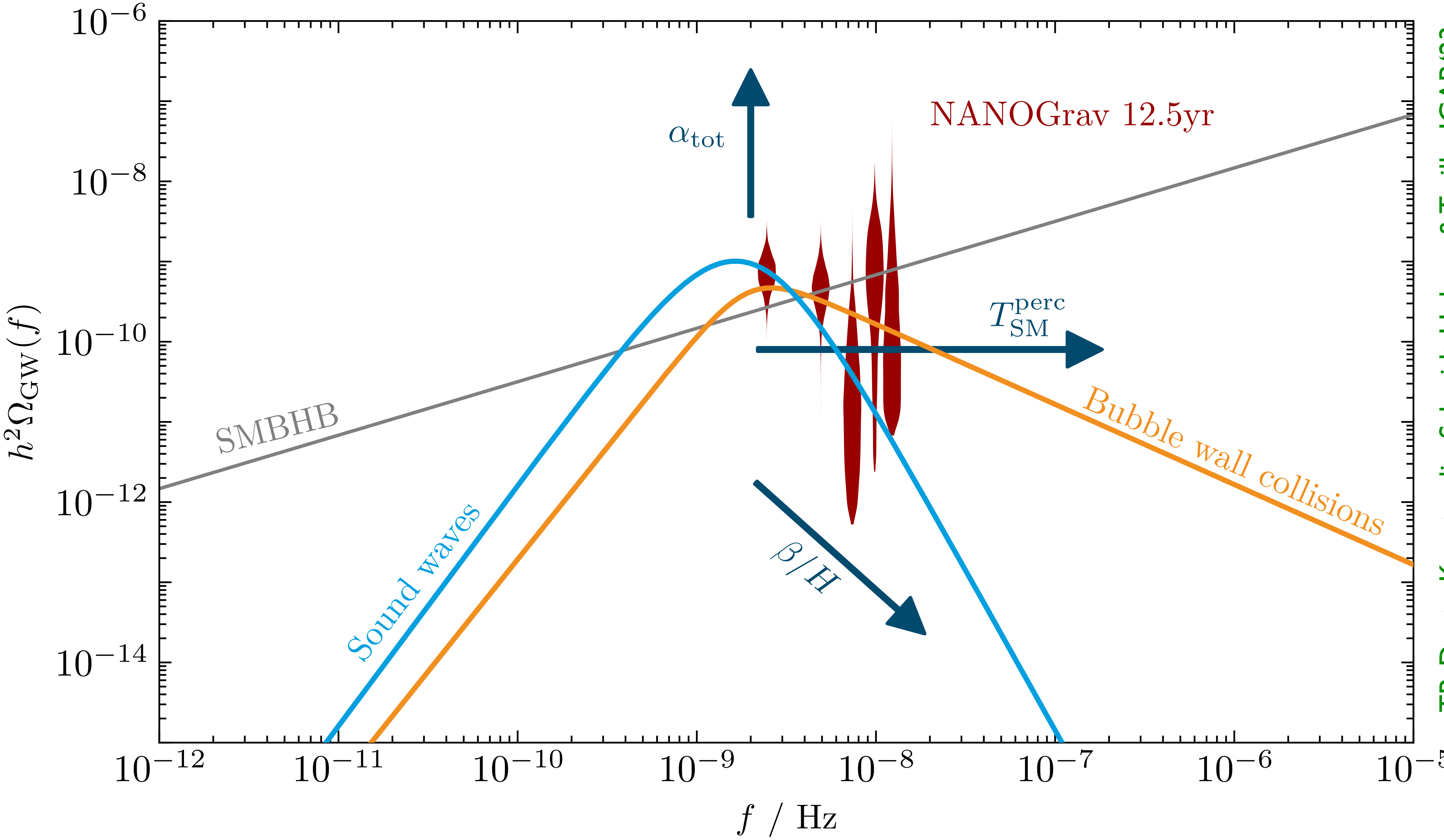


Resulting GW spectrum

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

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

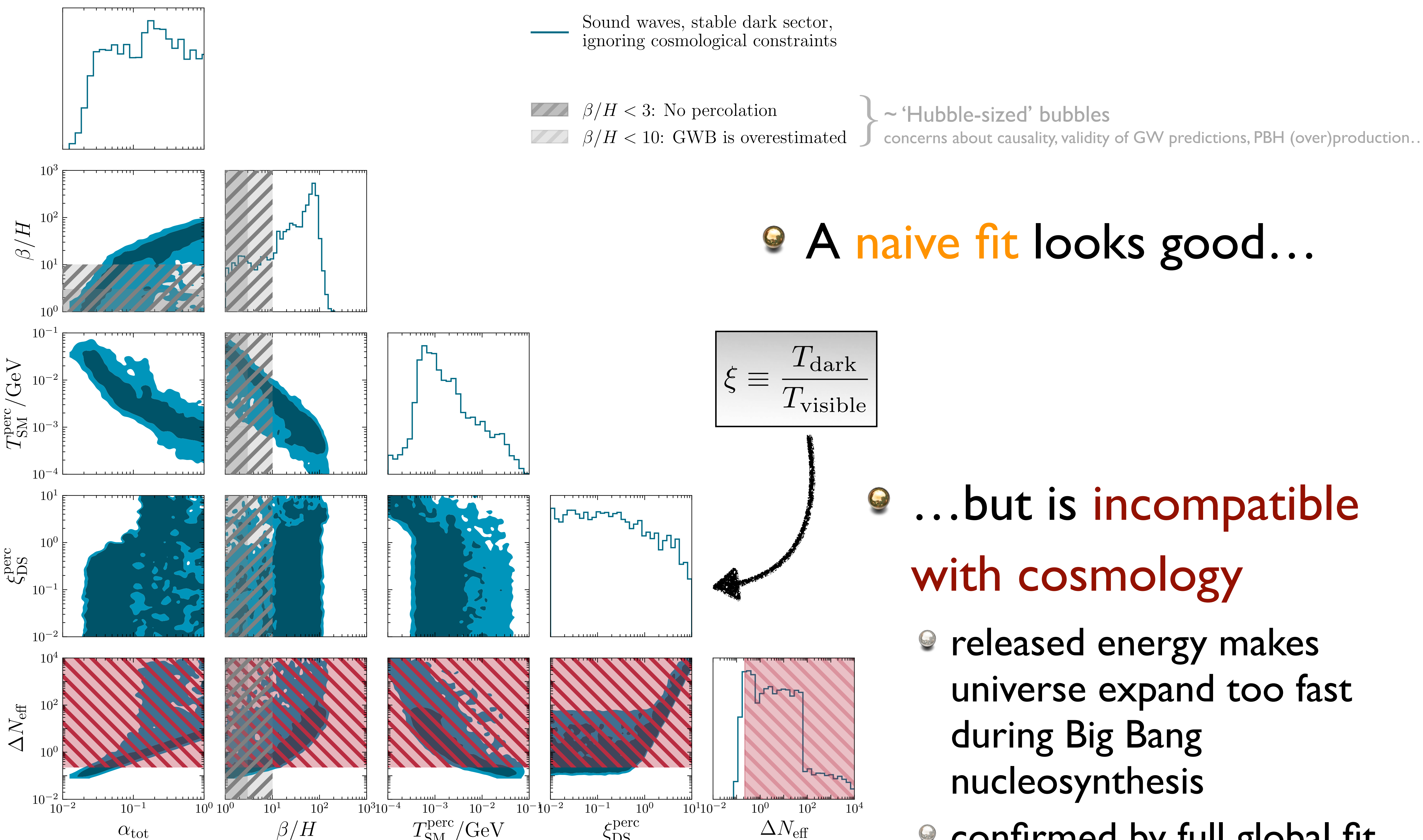
$$\Gamma \propto e^{-\frac{S_3(T)}{T}} = e^{\beta\,(t-t_0)} \Longrightarrow \frac{\beta}{H} = T\frac{d}{dT}\left(\frac{S_3(T)}{T}\right)\Big|_{T=T_p}$$



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

A PT explanation of NANOGrav ?

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



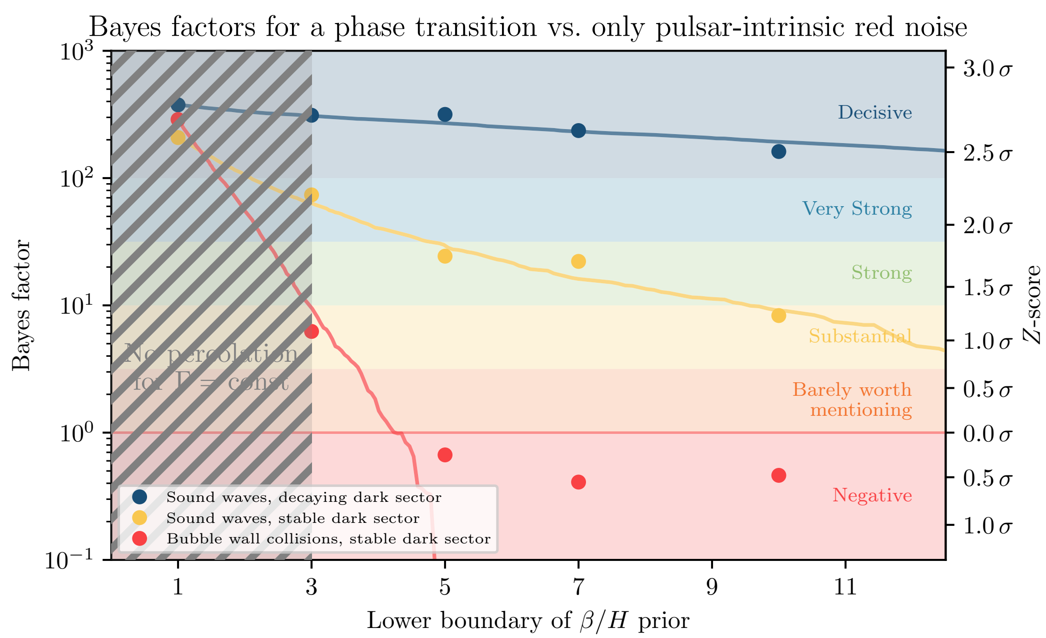
- A naive fit looks good…
- …but is incompatible with cosmology
  - released energy makes universe expand too fast during Big Bang nucleosynthesis
  - confirmed by full global fit

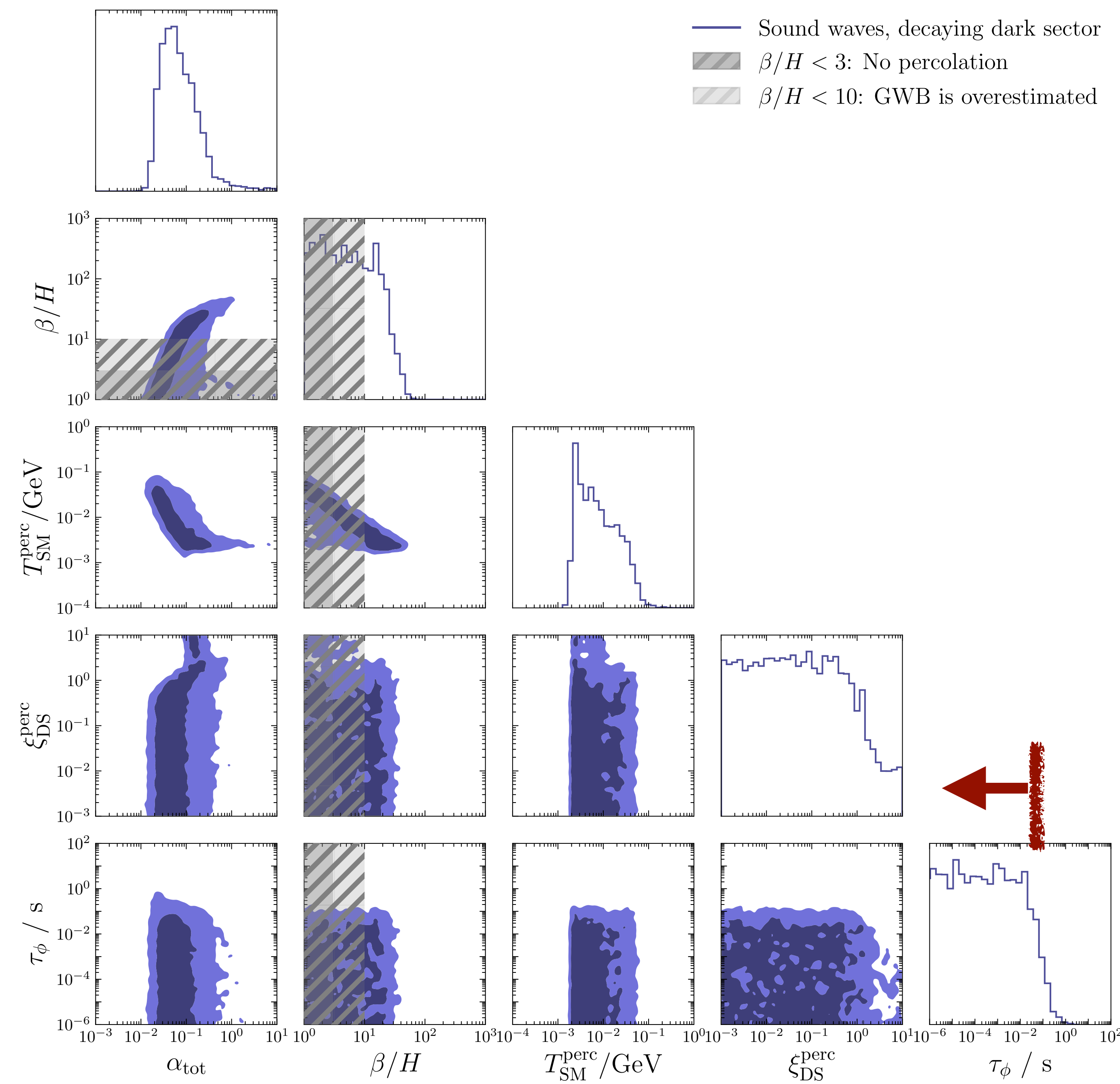
A decaying dark sector

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

- Simplest way out : allow $\phi \to \mathrm{SM}$ decays before BBN

- Problem solved — results in good fit to data



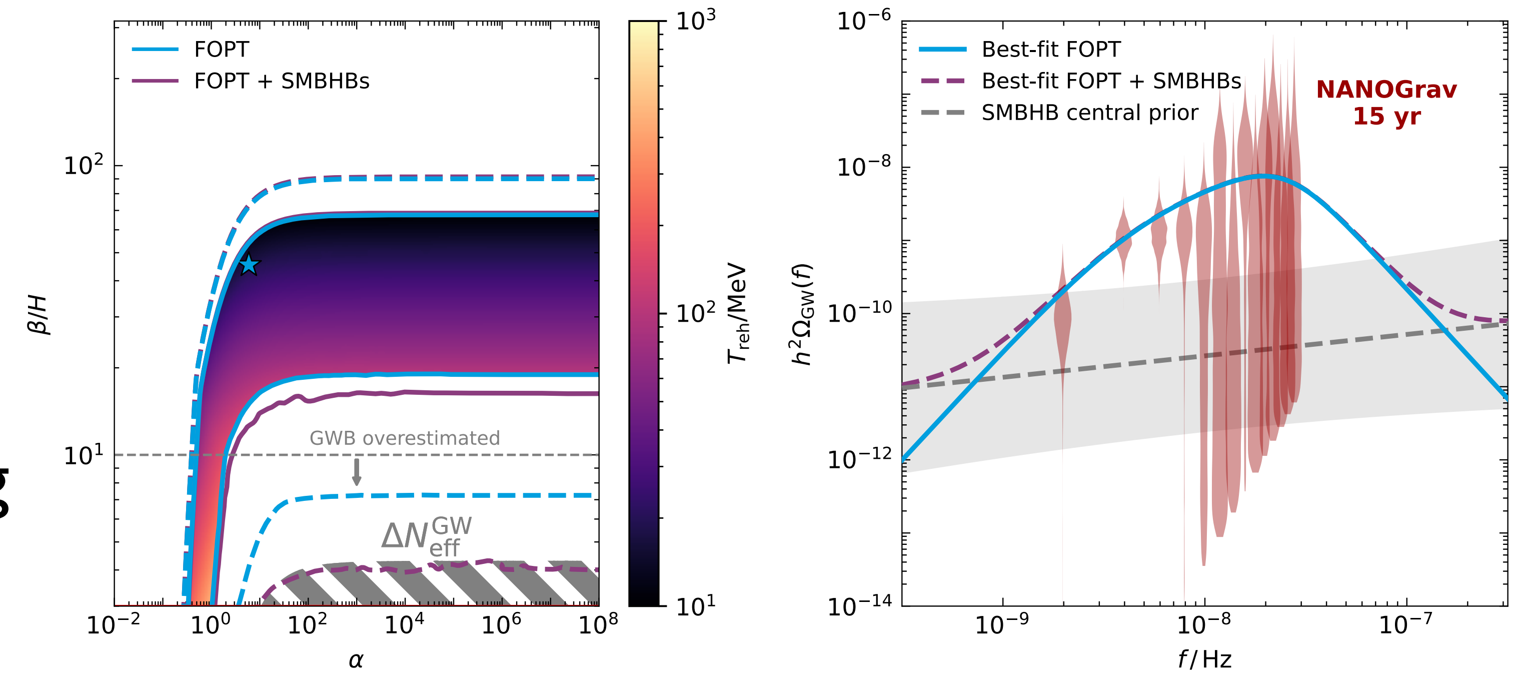


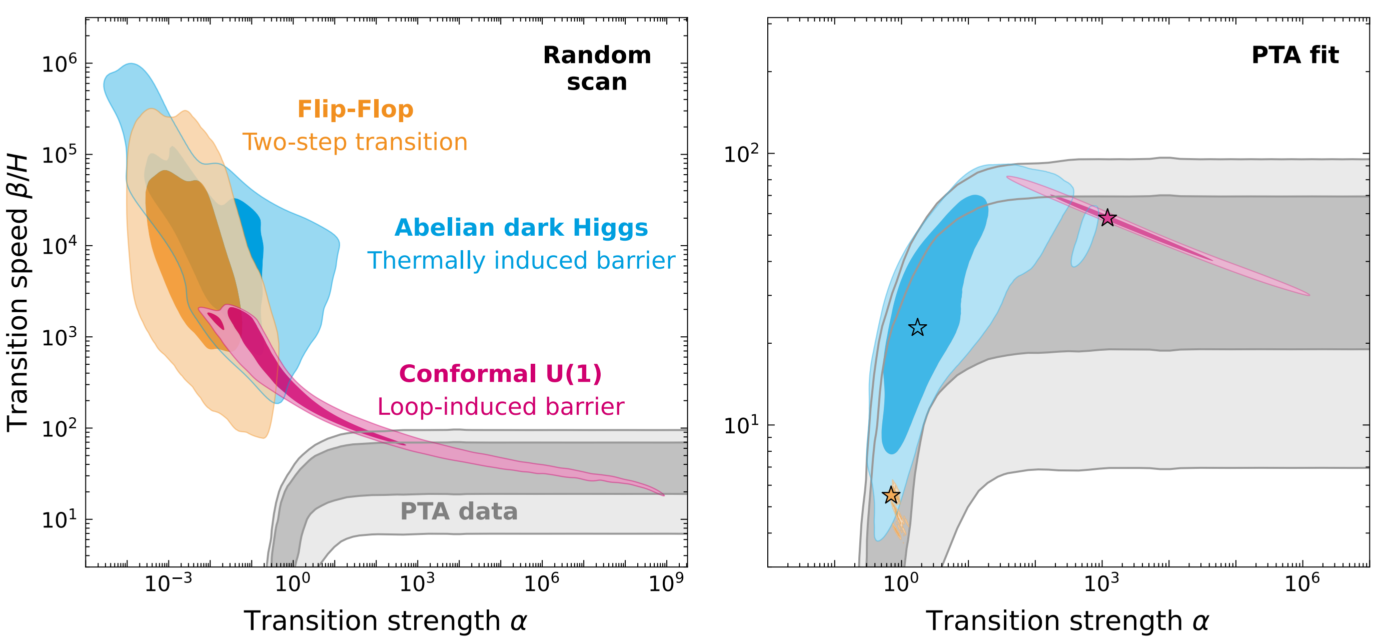
Important generic constraint for any model-building !

Update: 12.5yr → 15 yr data

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

- preferred PT parameters shift towards larger $T_{\rm reh}$
  - Relaxes BBN constraints, but still relevant for model-building





- 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 <u>measure</u> dark sector model parameters !

A minimal dark sector model

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

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

Standard Model

- SM particles

$\mathcal{L} \supset -\kappa A'_{\mu\nu} B^{\mu\nu}$

'portal' interactions
(kinetic mixing)

$U(1)'$

Dark Sector

- massless scalar field ϕ
- Chiral fermion pair χ

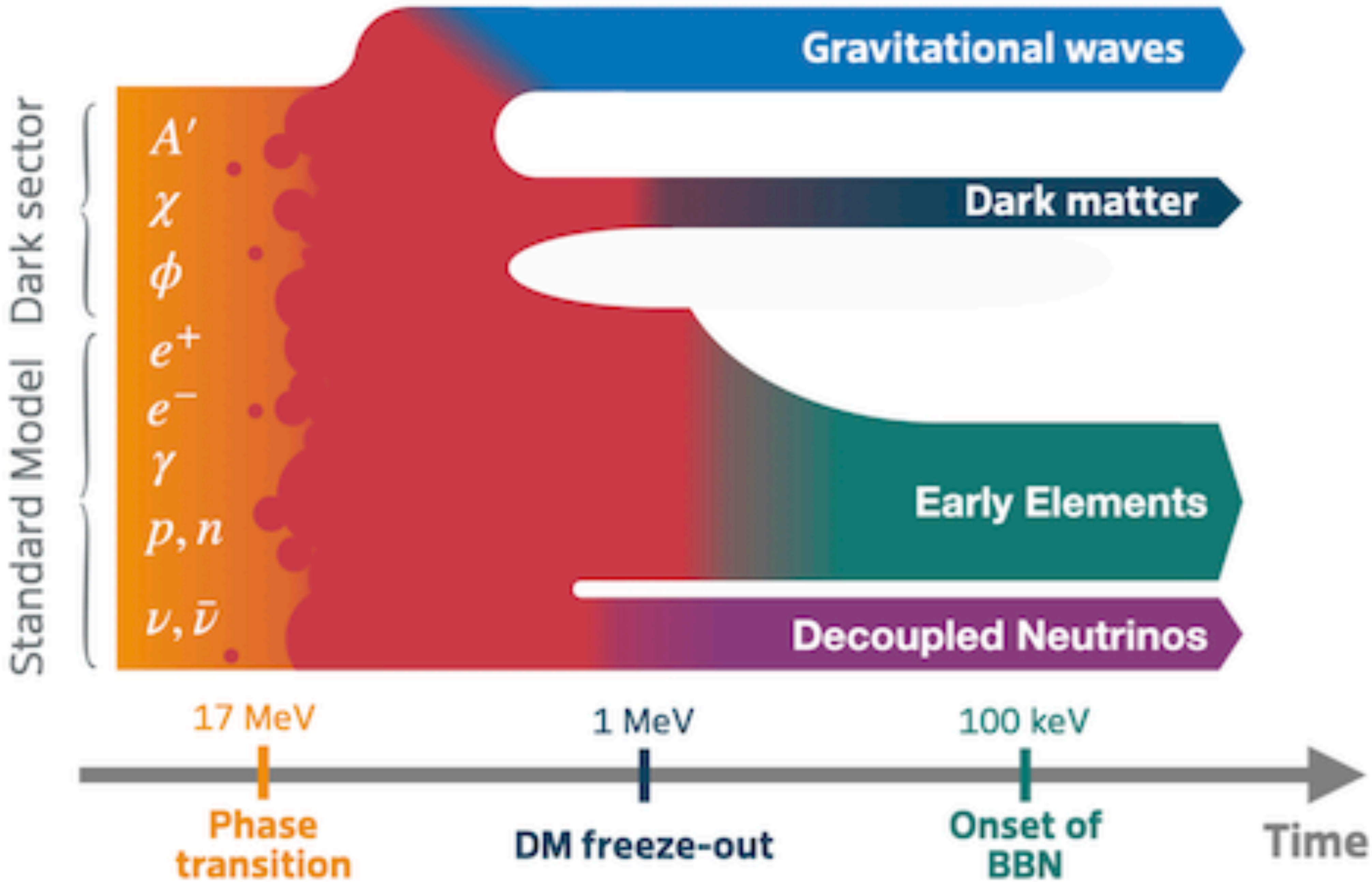
conformal symmetry

- Quantum and thermal corrections break conformal symmetry

$\langle \phi \rangle \neq 0 \Rightarrow$
  - Strong 1st order PT: GWs
  - χ becomes massive: dark matter

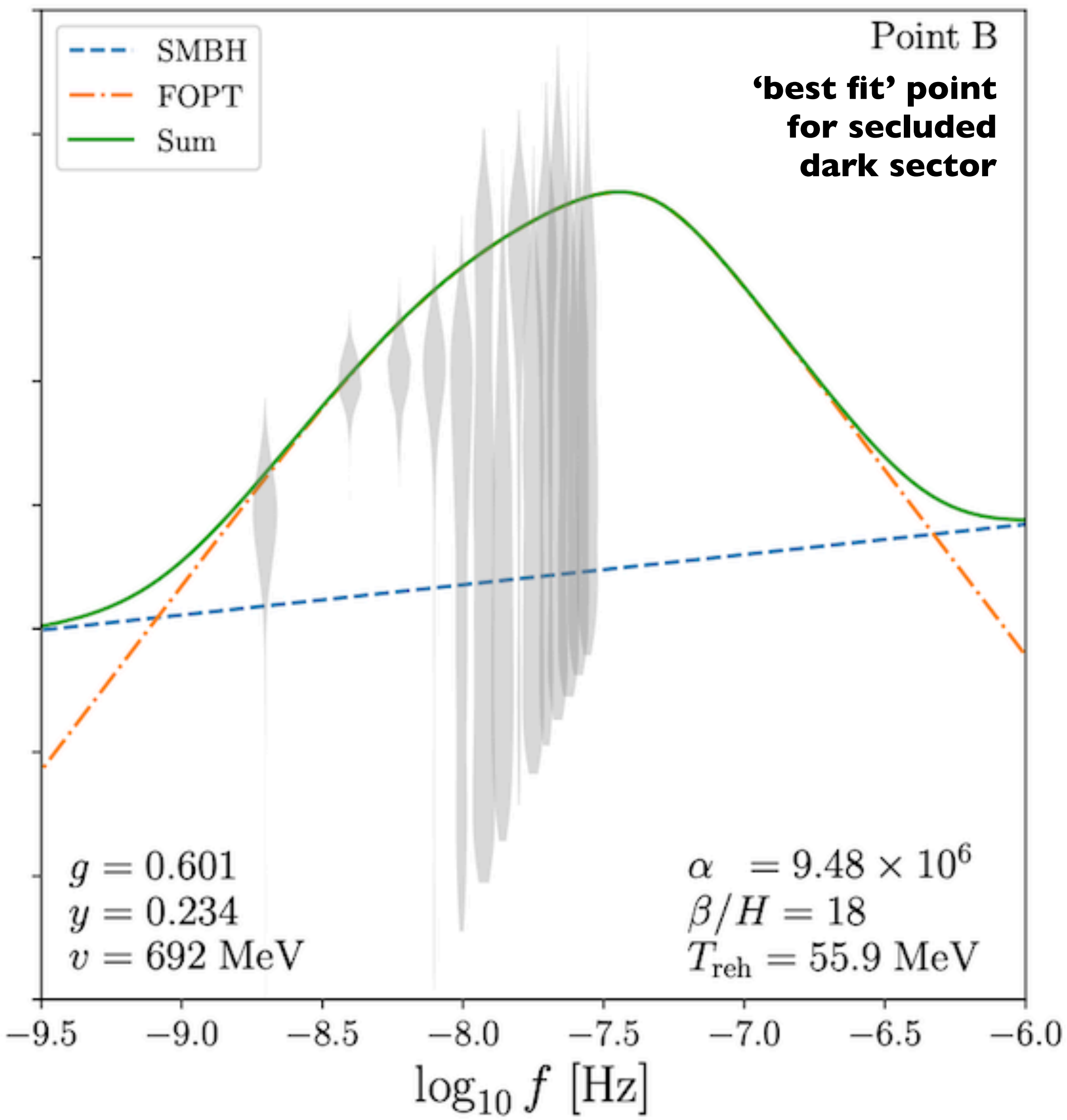
- Dark photon A' has further consequences (cosmology and accelerator searches)
  - Include all constraints in full global fit

Timeline of events



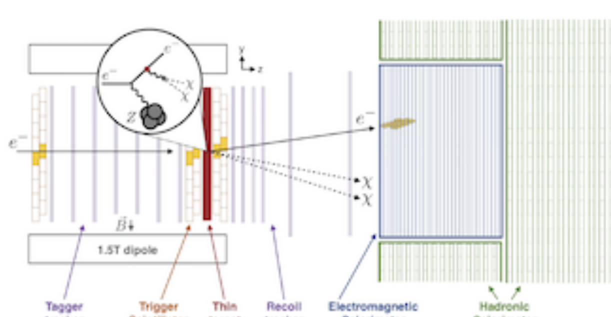
Global fit results

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 LDMX :

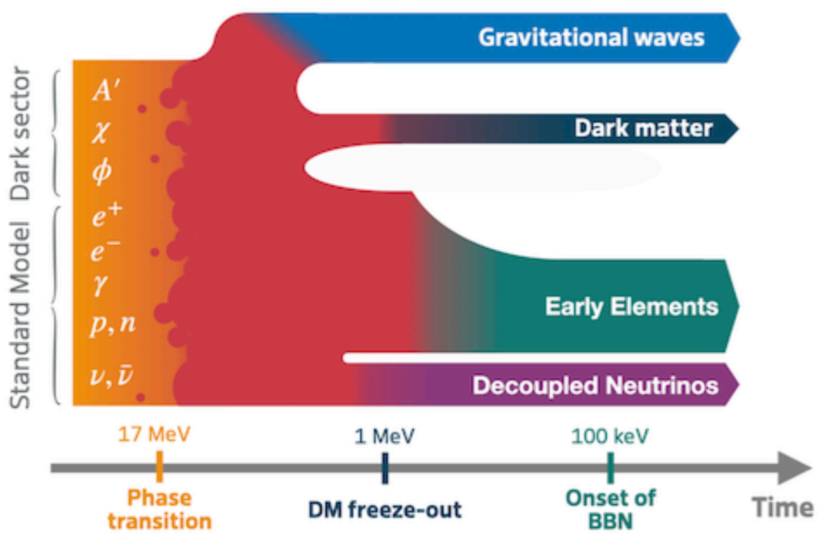
$$m'_A = 100 - 200\,\mathrm{MeV}$$
$$\kappa \simeq 10^{-4}$$

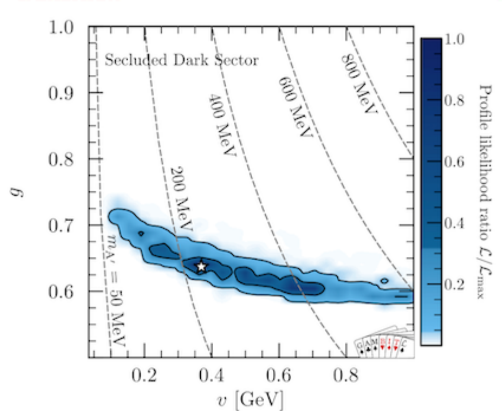


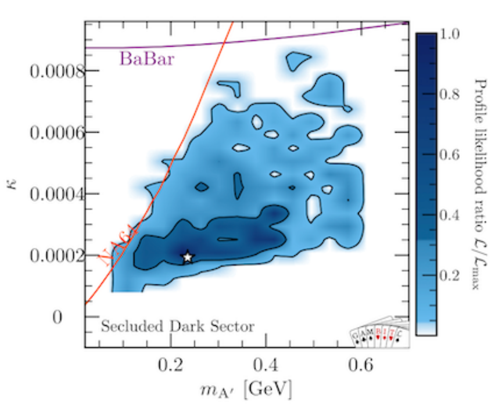
Secluded vs coupled dark sector

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

- NB: Thermalization requires κ within experimental reach

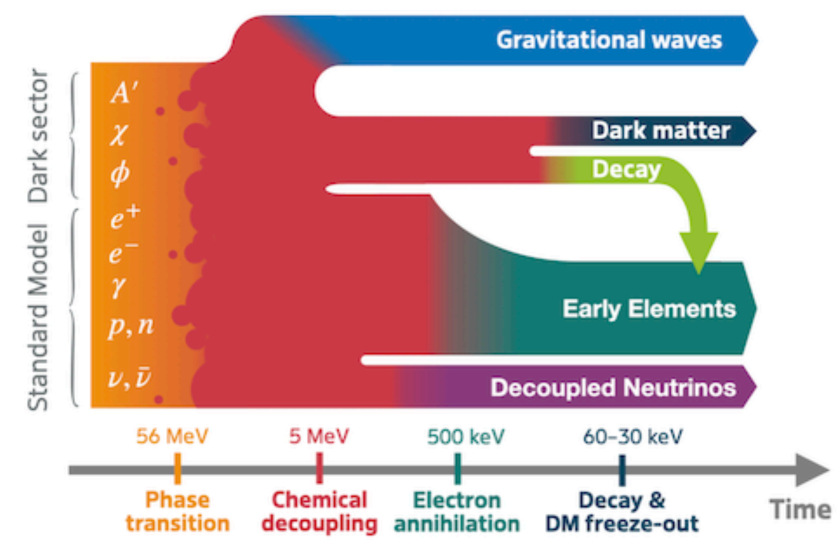


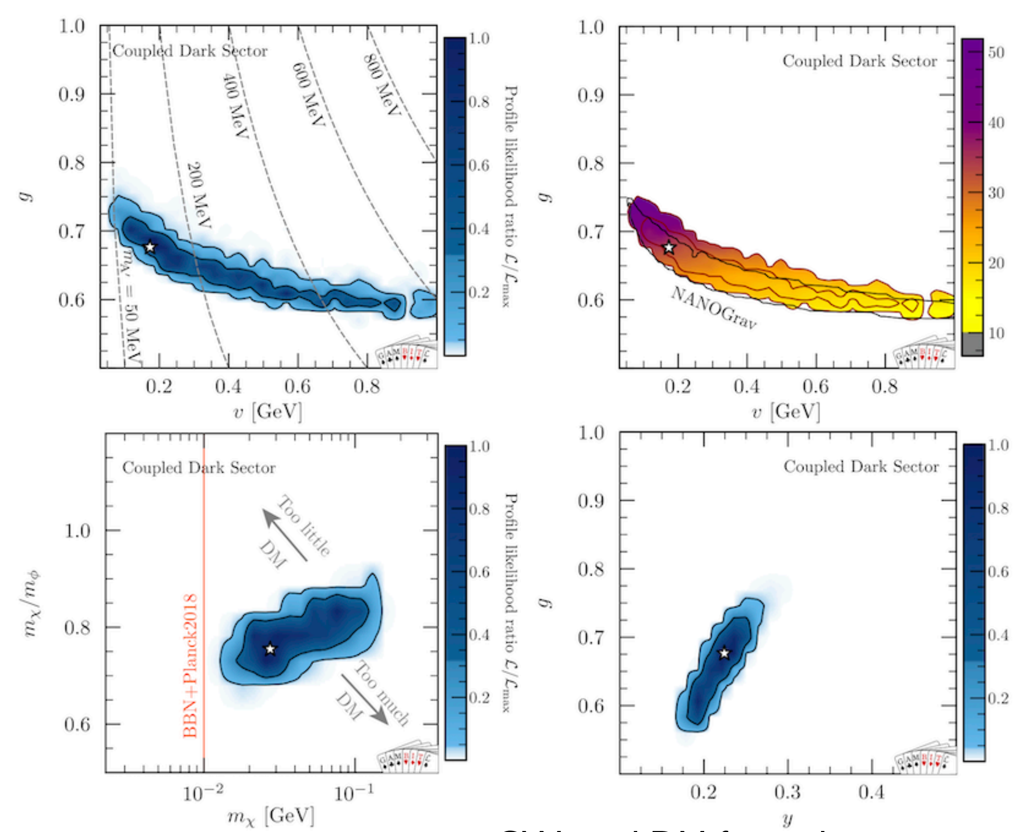




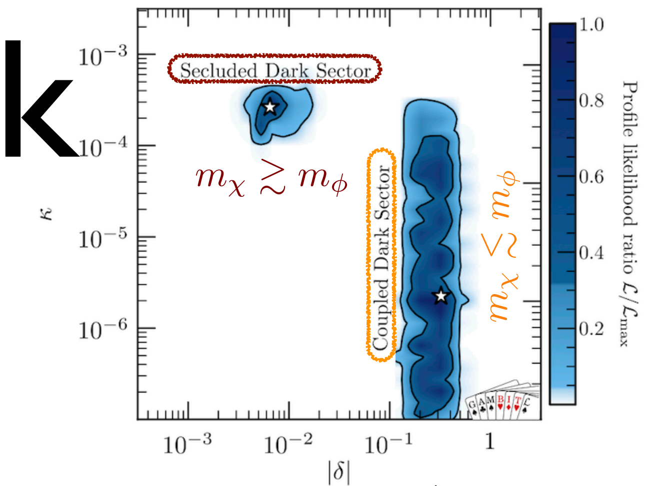
extend model by adding dim-6 operator for $\phi \to e^+ e^-$

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



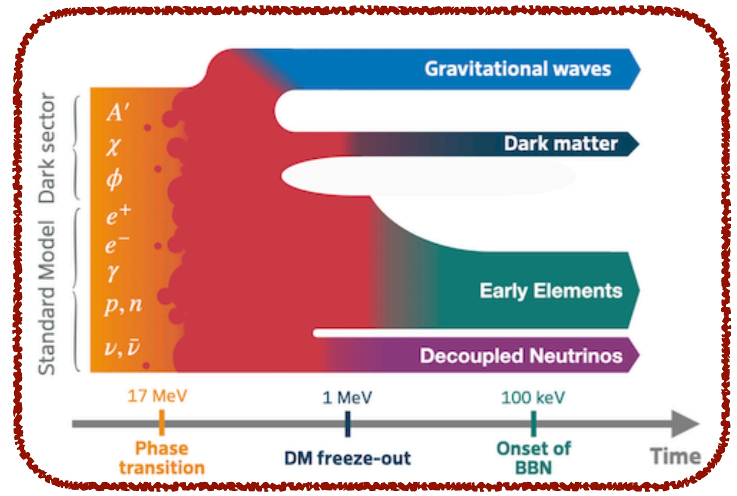


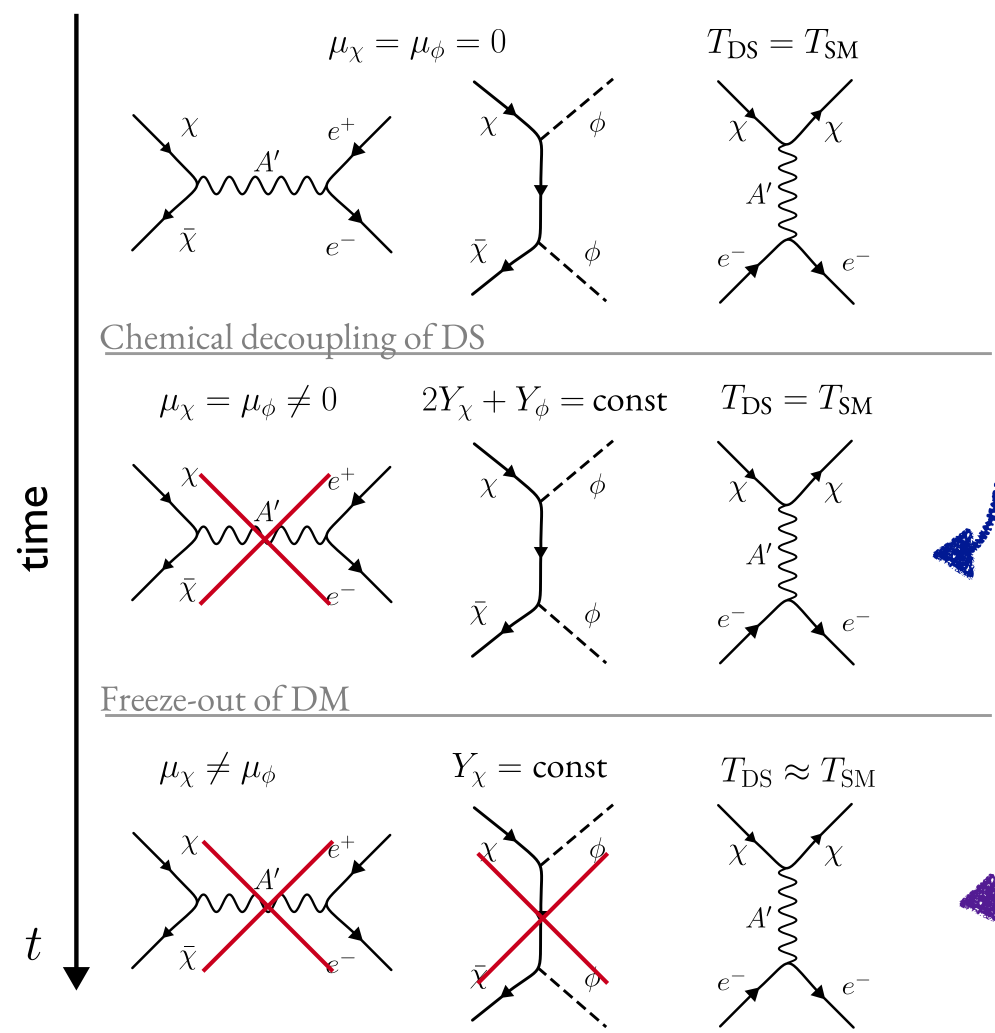
DM production: a closer look



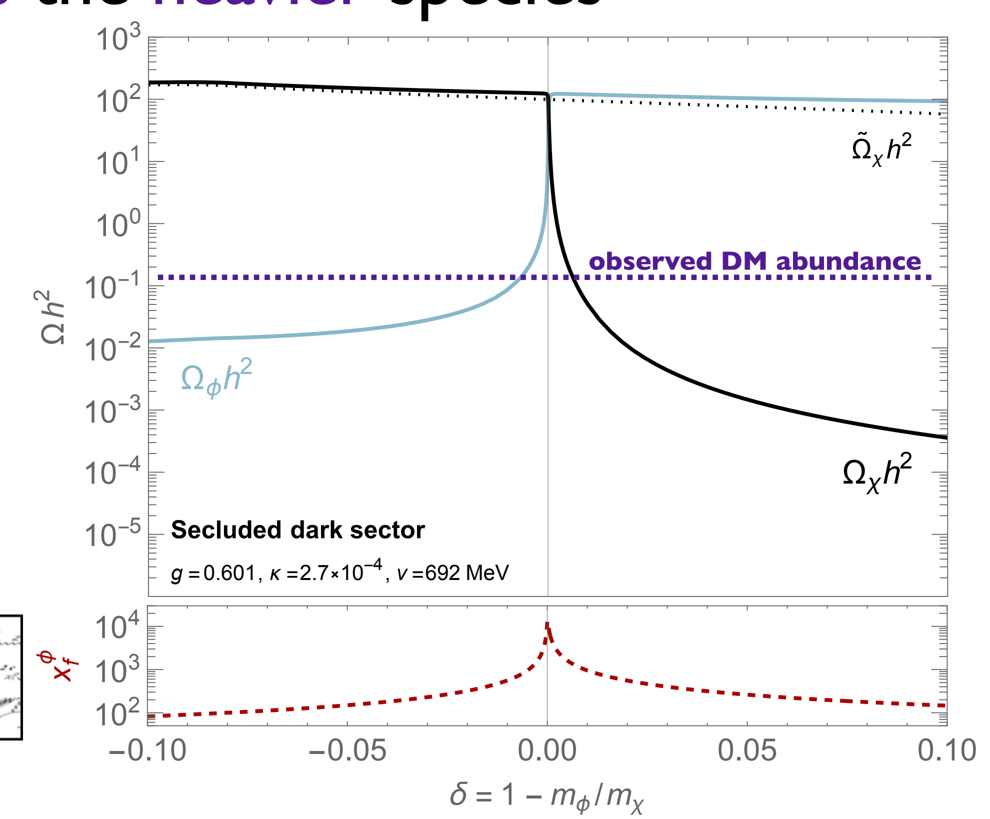
$\delta \equiv 1 - m_\phi/m_\chi$

- In the secluded sector case, the scalar must be <u>slightly</u> lighter than the DM particle



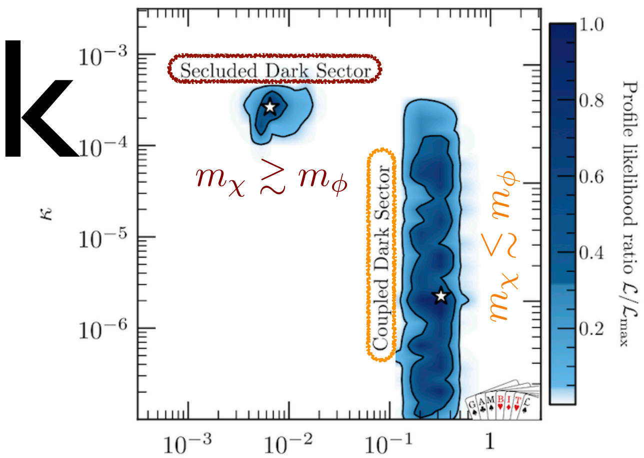


- first step: determines **total** dark sector content
- second step: $\phi\phi \leftrightarrow \chi\chi$
  quickly **depletes** the **heavier** species



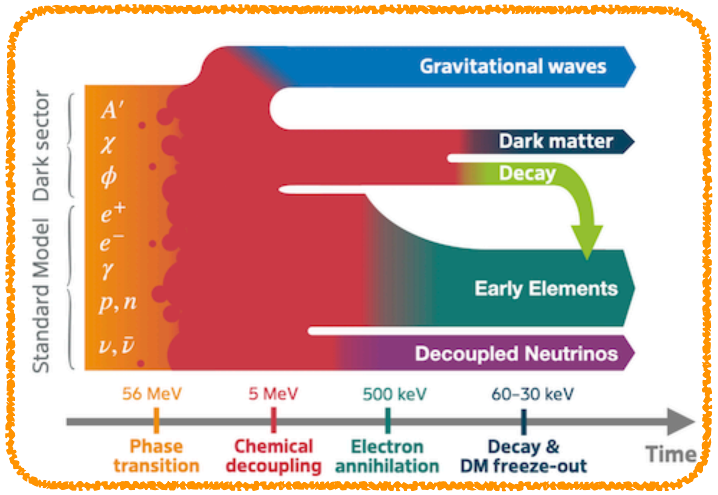
DarkSUSY

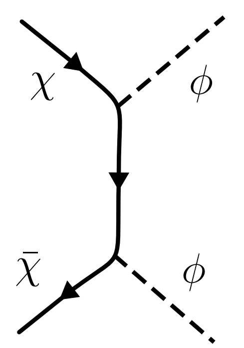
DM production: a closer look



$\delta \equiv 1 - m_\phi/m_\chi$

- 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

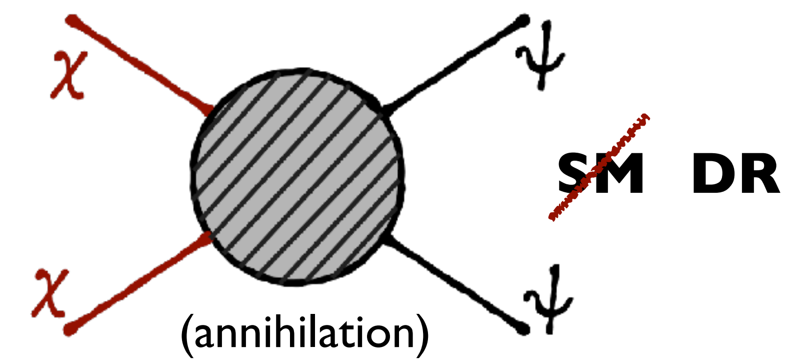
D'Agnolo & Ruderman, PRL '15

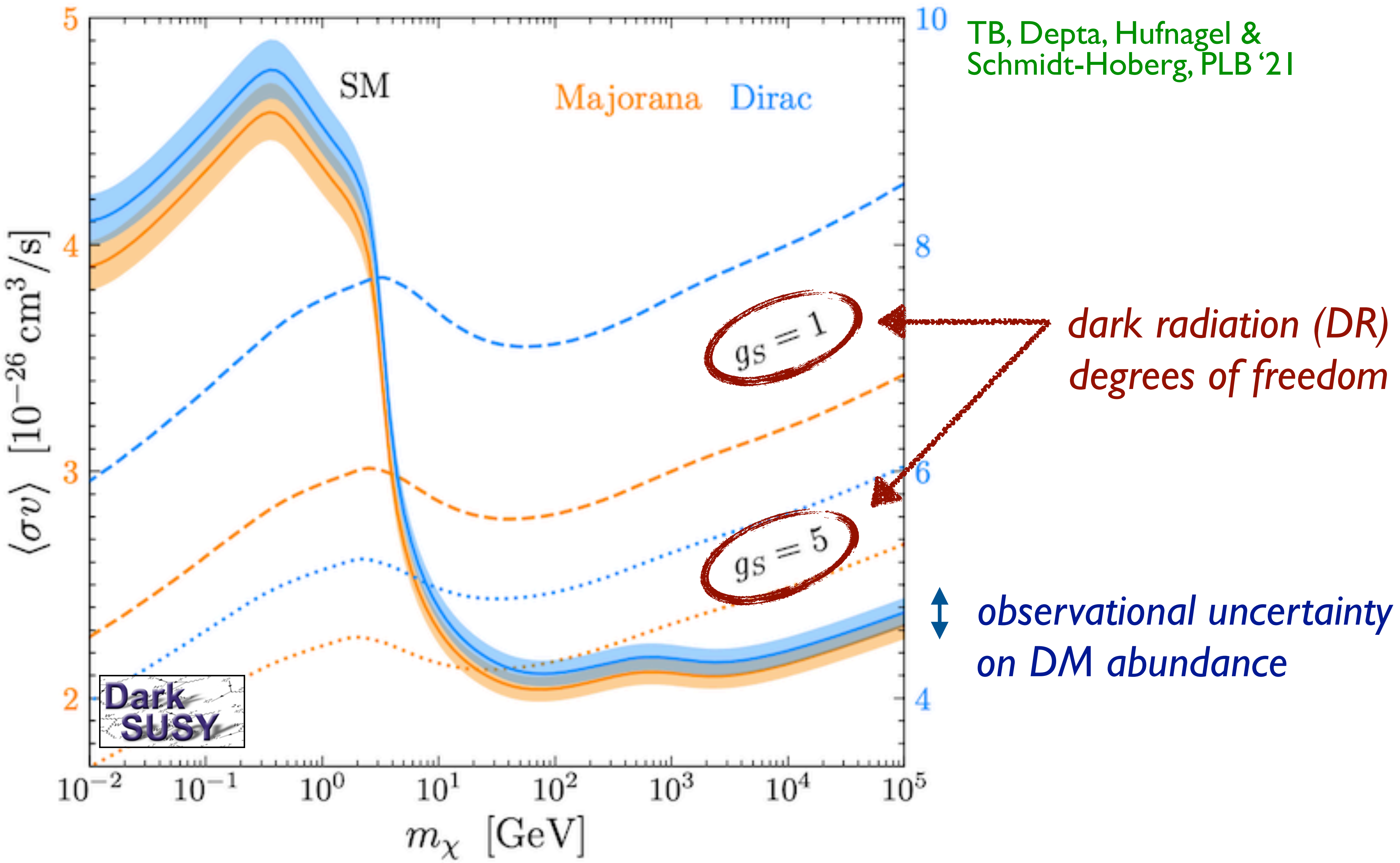
$m_\phi > m_\chi$ ➡ $\langle \sigma v \rangle \sim (\sigma v)_{v\to 0} \times e^{-(m_\phi - m_\chi)/T_{\mathrm{f.o.}}}$

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

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

A concrete model

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

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

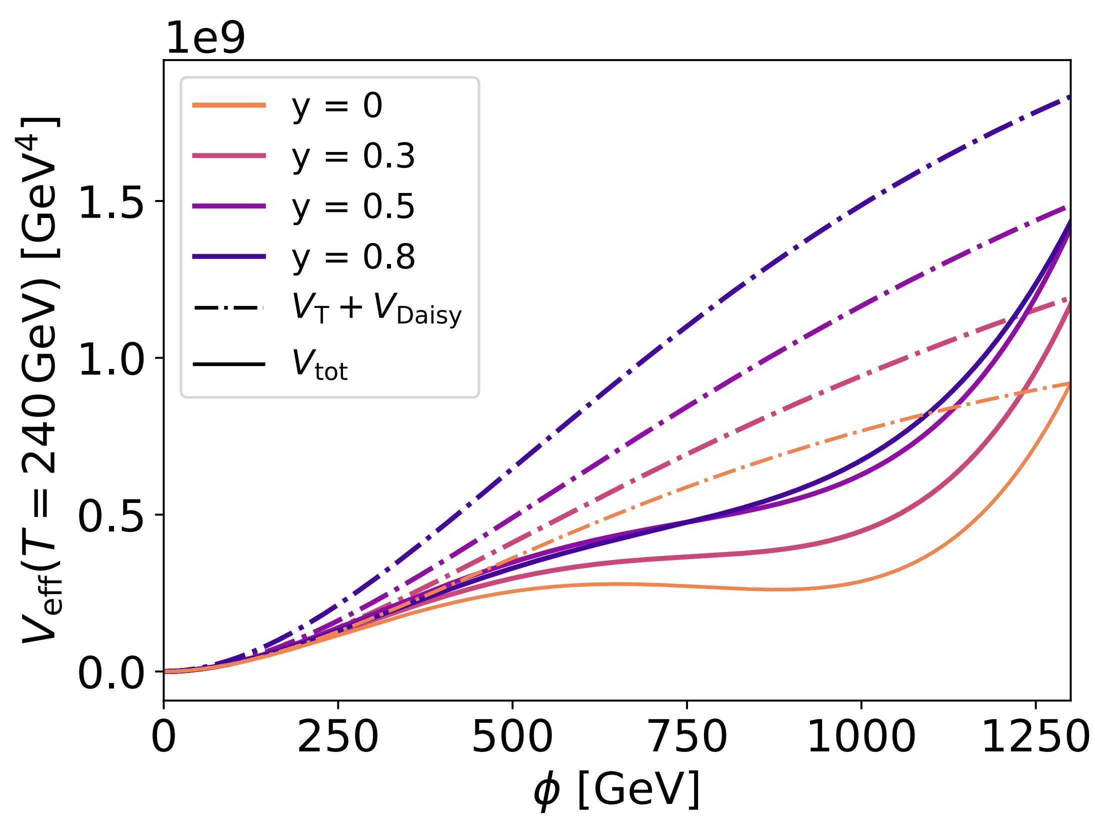
- scalar field charged under U(1)'
- (Chiral) dark matter fermion

after PT → mass & thermal freeze-out

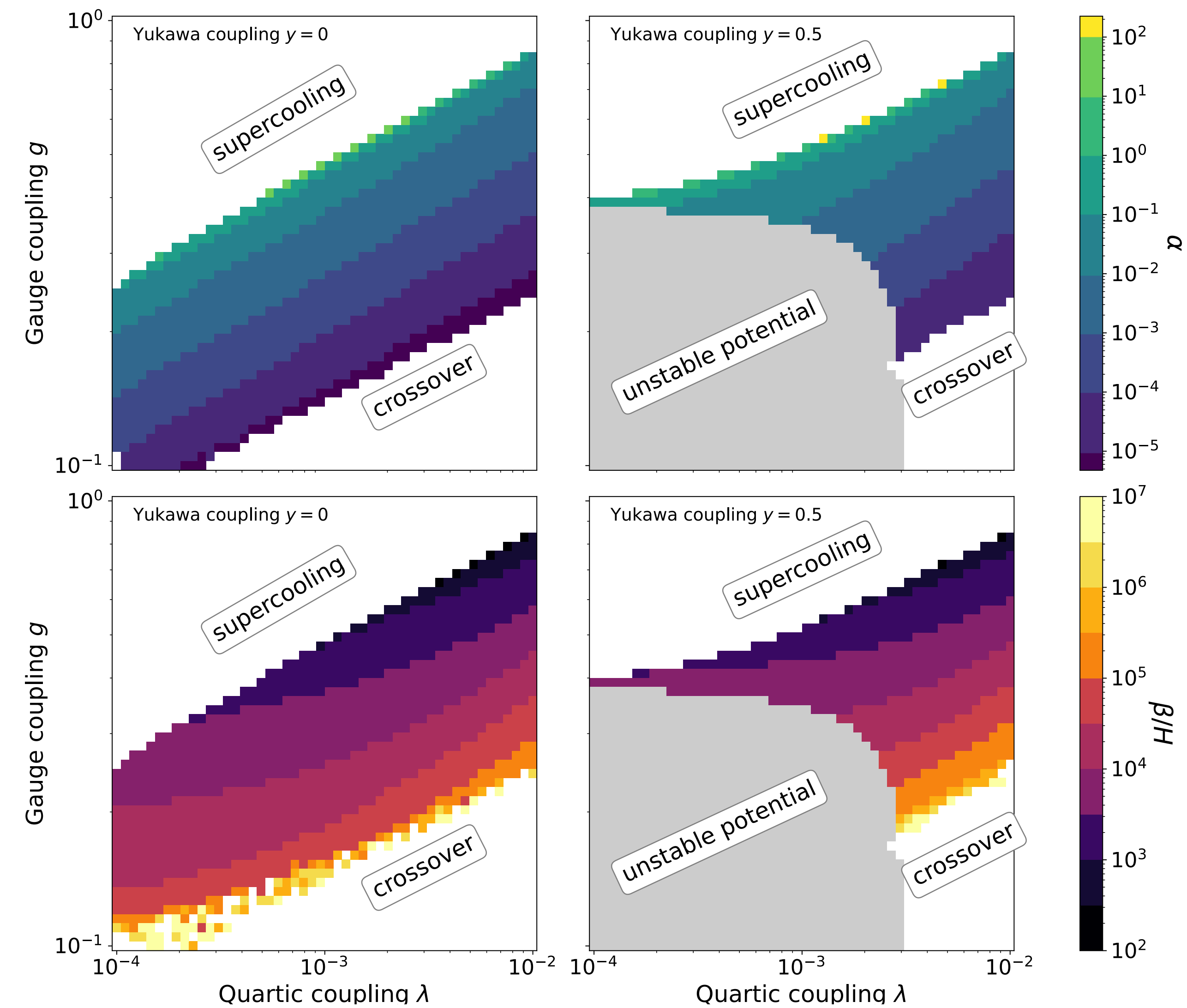
- tree-level masses from SSB:

$$m_\phi^2 = -\mu^2 + 3\lambda v_\phi^2 = 2\lambda v_\phi^2, \quad m_\varphi^2 = 0, \quad m_{A'}^2 = g^2 v_\phi^2, \quad m_\chi^2 = \frac{y^2}{2} v_\phi^2$$

- loop (CW) + thermal corrections:



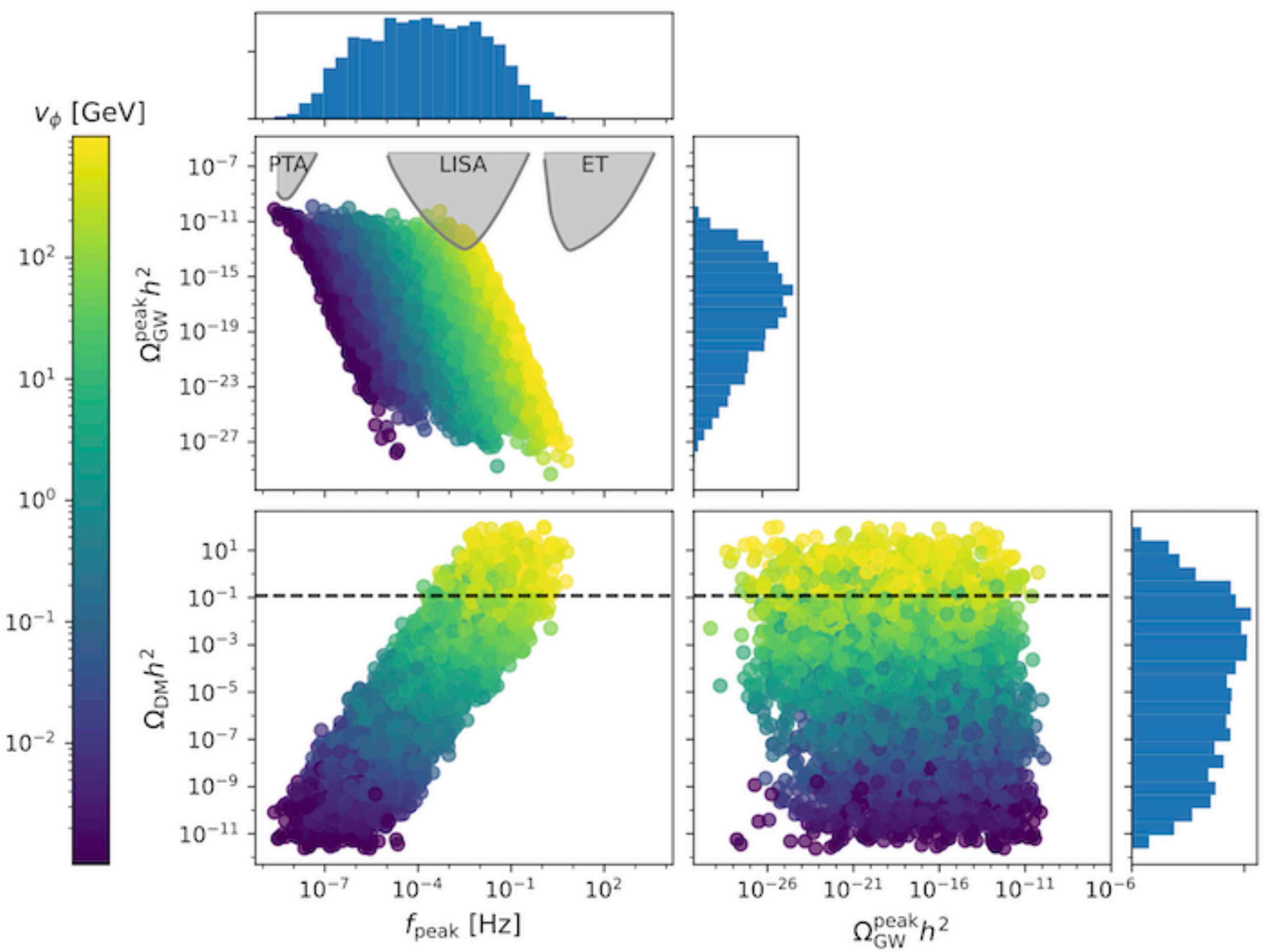
$g = 0.67, \lambda = 0.0035, v_\phi = 1000\,\mathrm{GeV}$ and $T = 240\,\mathrm{GeV}$



A LISA miracle ?

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

- 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

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

    $$\Omega_{\rm DM} \simeq 0.1 \, \frac{10^{-8}\,{\rm GeV}^{-2}}{\langle \sigma_{\rm ann} v \rangle}$$

    $$\langle \sigma_{\rm ann} v \rangle \sim \frac{y^4}{m_{\rm DM}^2} \sim \frac{y^2}{v_\phi^2}$$

    $\rightsquigarrow \quad v_\phi \sim {\rm TeV}$

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

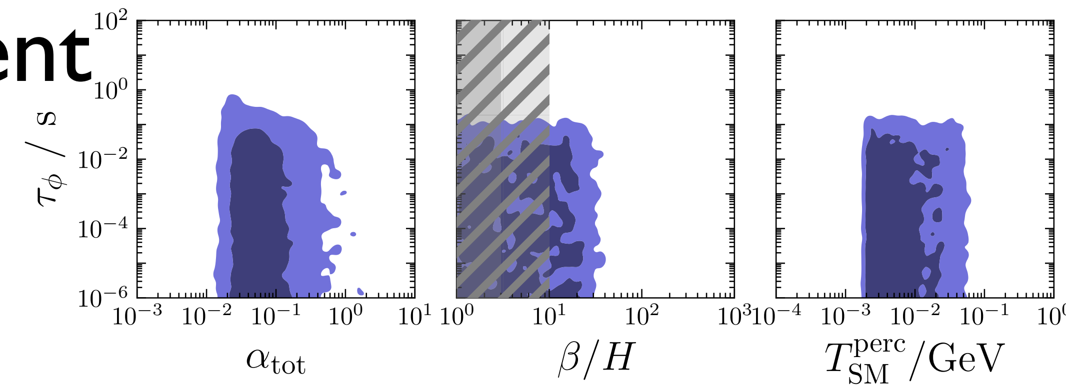
    $$\sim 10\,{\rm mHz} \left(\frac{v_\phi}{1\,{\rm TeV}}\right)$$

    for (not too strong) supercool PT

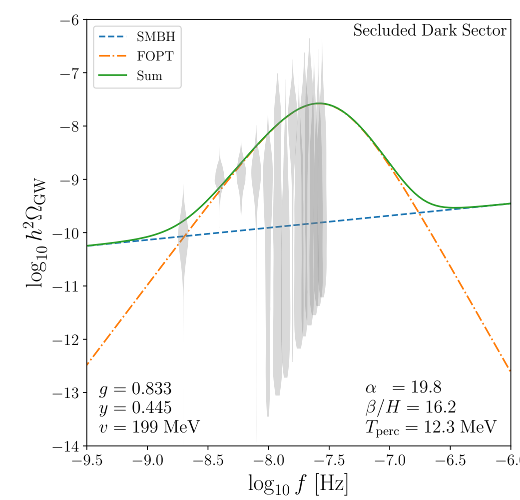
$\square$

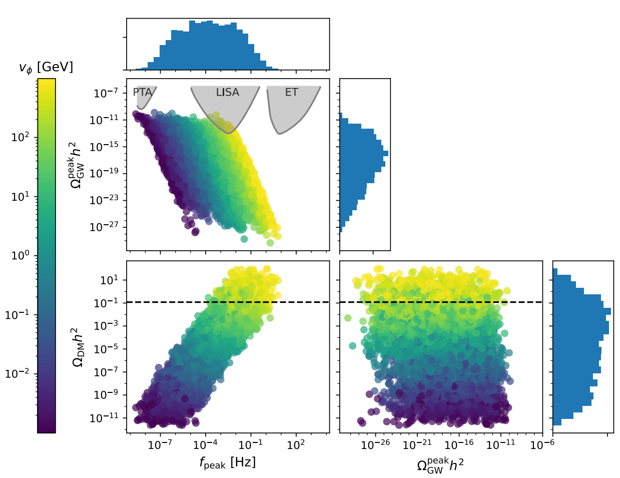
Conclusions

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



- A simple conformal model explains both the GW signal and the cosmological dark matter
  - Testable with beam dump experiments !
    - ⇨ *see LDMX poster by Taylor Gray*





- 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!

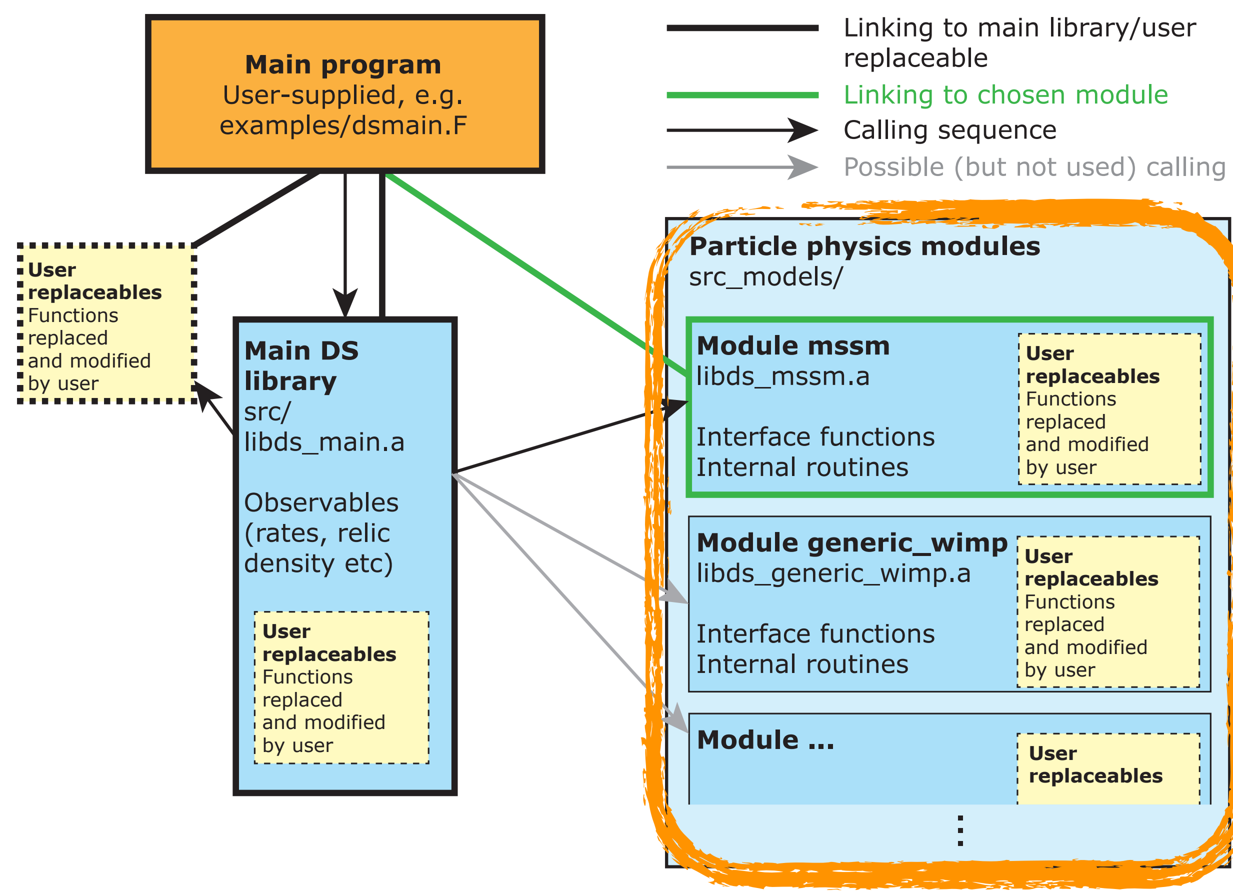
DarkSUSY

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