(Astro-)particle and cosmology activities in the Theory Section

Quantum technology seminar, 20/03/2023

Research in the Theory Section

- Torsten Bringmann
- Anders Kvellestad
- Are Raklev

High energy physics

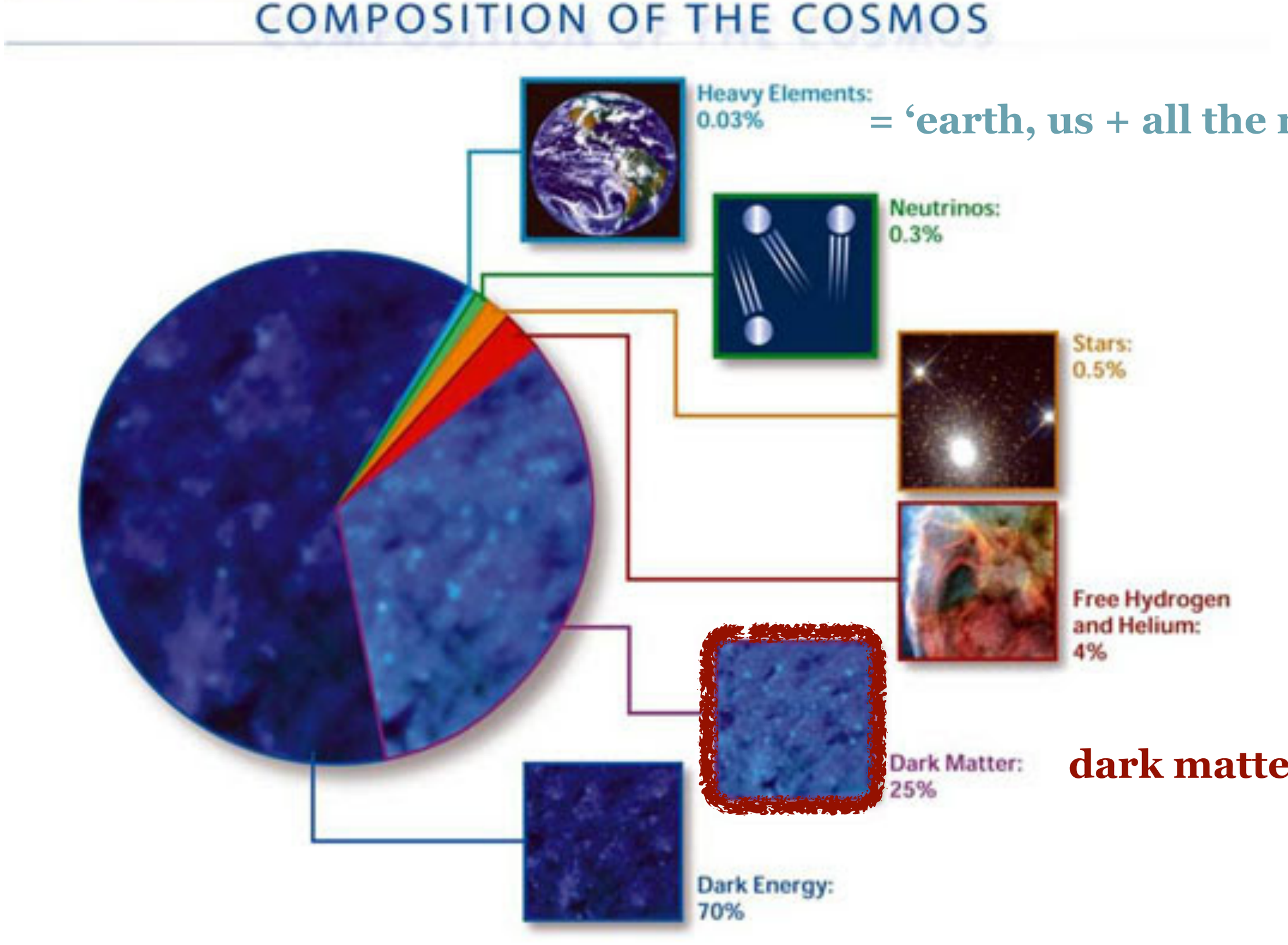
= 'CERN-related research'

particle physics, cosmology, **dark matter**, gravitational waves, **statistical inference**, machine learning, software for theoretical calculations in HEP

- Carsten Lütken
- Johannes Skaar
- Olav Syljuåsen
- Susanne Viefers

Low energy physics

topological phases, high-temperature superconductors, photonics, quantum Hall effect, metamaterials, quantum information theory & cryptography, foundations of quantum mechanics



= 'earth, us + all the rest'

dark matter

We often work with rather <u>fundamental</u> questions…

GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.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/likelihood packages
- 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

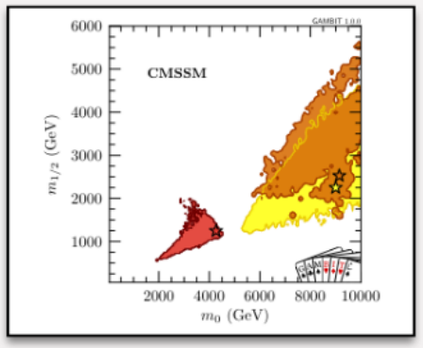
Recent collaborators: P Athron, C Balázs, A Beniwal, S Bloor, T Bringmann, A Buckley, J-E Camargo-Molina, C Chang, M Chrzaszcz, J Conrad, J Cornell, M Danninger, J Edsjö, T Emken, A Fowlie, T Gonzalo, W Handley, J Harz, S Hoof, F Kahlhoefer, A Kvellestad, P Jackson, D Jacob, C Lin, N Mahmoudi, G Martinez, MT Prim, A Raklev, C Rogan, R Ruiz, P Scott, N Serra, P Stöcker , W. Su, A Vincent, C Weniger, M White, Y Zhang, ++

70+ participants in many experiments and numerous major theory codes

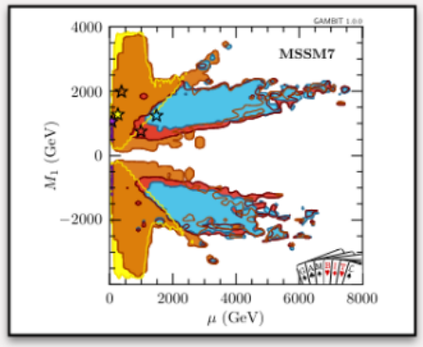
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GAMBIT Collaboration

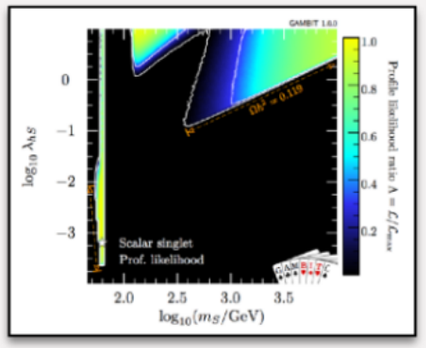
- International collaboration of HEP theorists, experimentalists and software experts
- **A. Kvellestad** (Head), **A. Raklev**, **T. Bringmann**, **C. Chang**, **L. Braseth**, **I. M. Johansson**



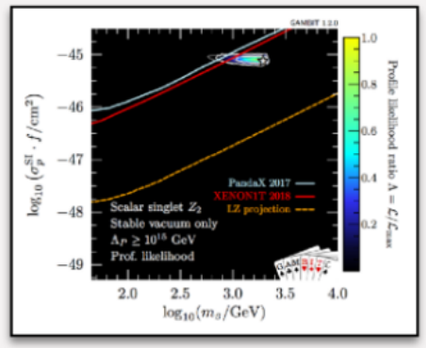
GUT-scale SUSY: 1705.07935



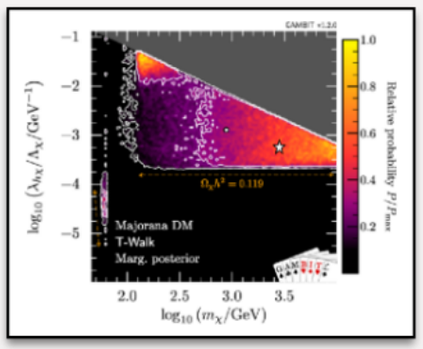
MSSM7: 1705.07917



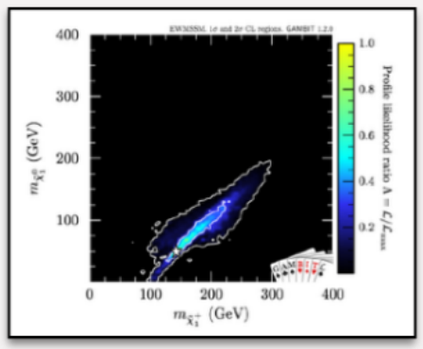
Scalar Higgs portal DM: 1705.07931



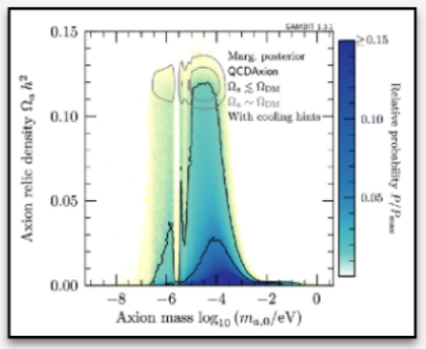
Scalar Higgs portal DM w/ vac. stability: 1806.11281



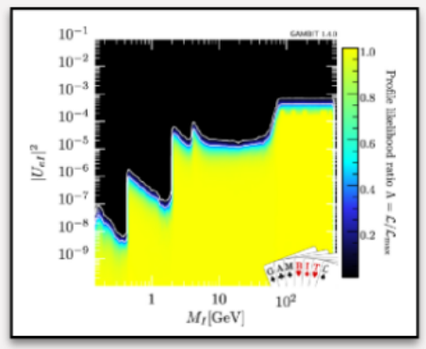
Vector and fermion Higgs portal DM: 1808.10465



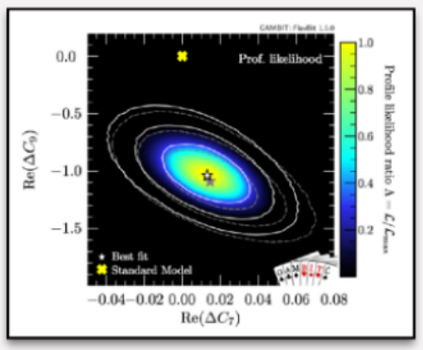
EW-MSSM: 1809.02097



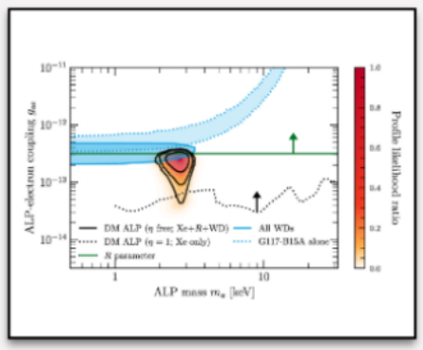
Axion-like particles: 1810.07192



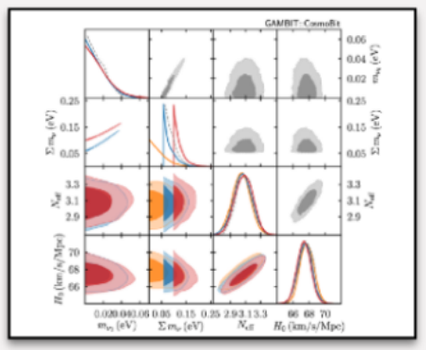
Right-handed neutrinos: 1908.02302



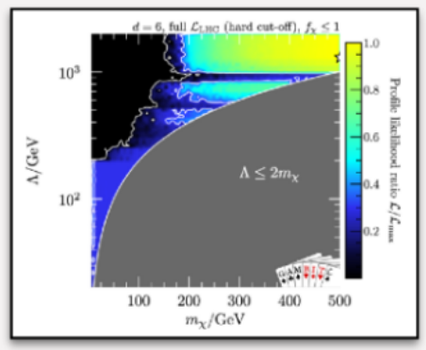
Flavour EFT: 2006.03489



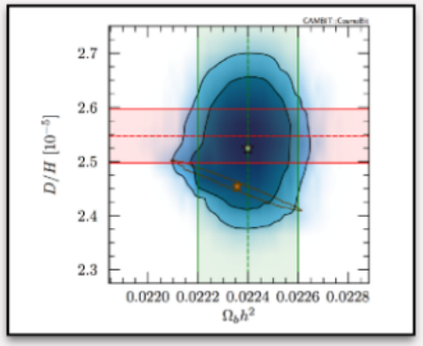
More axion-like particles: 2007.05517



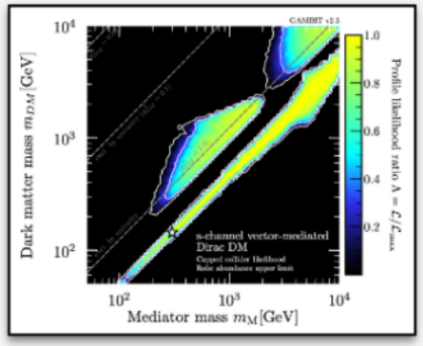
Neutrinos and cosmo: 2009.03287



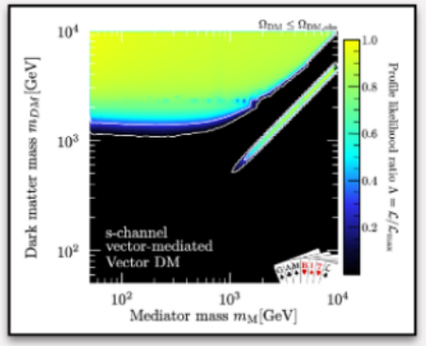
Dark matter EFTs: 2106.02056



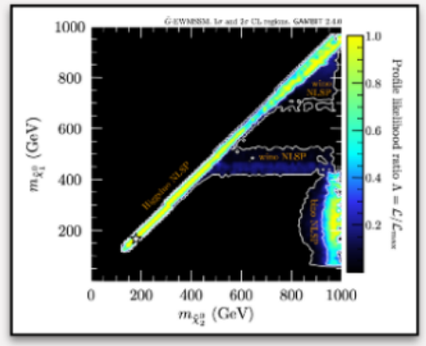
Cosmo ALPs: 2205.13549



Simplified DM, scalar/fermion: 2209.13266



Simplified DM, vector: 2303.08351



EW-MSSM w/ light gravitino: 2303.09082

DarkSUSY: A leading dark matter code

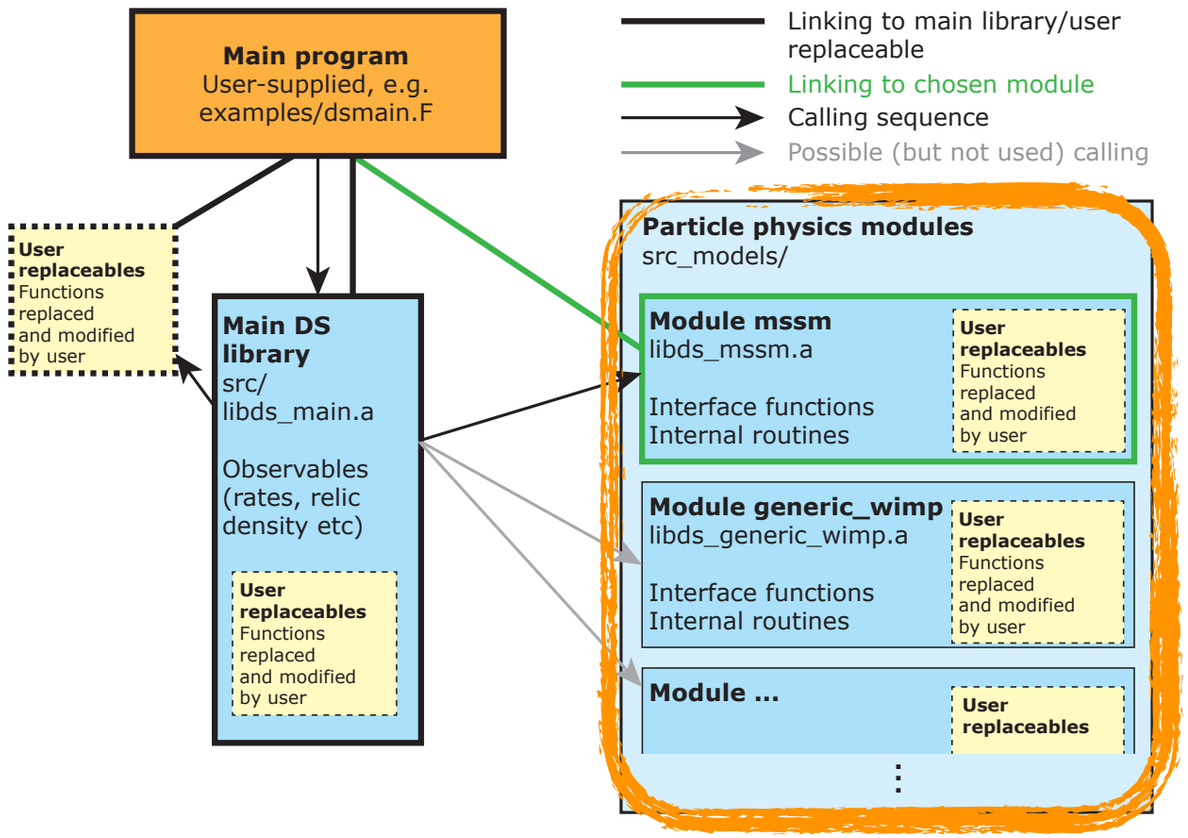


Bringmann, Edsjö, Gondolo, Ullio & Bergström, JCAP '18

http://www.darksusy.org

Since 2018 (v6):
no longer restricted to supersymmetric DM !

- Numerical package to calculate 'all' DM-related observables:
  - *precision relic density & kinetic decoupling*
  - *cosmic ray propagation*
  - *large database of particle yields for generic DM annihilation or decay*
  - *indirect detection rates: gammas, positrons, antiprotons, neutrinos*
  - *direct detection rates*
  - *DM self-interactions*
  - *general dark sector support:*
    $T_{\rm dark}(T_\gamma), \Delta N_{\rm eff}, \ldots$
  - …



most recent new features:

…

v6.2: cosmic-ray upscattered DM

v6.3: freeze-in

v6.4: asymmetric DM

Currently funded projects

- **PLUMBIN'**
  - FRIPRO Fellesløft, collaboration with Dept. of Mathematics
  - **A. Raklev** (PI), **A. Kvellestad** (Co-PI), R. De Bin (Co-PI), **C. Chang**, T. Braun, **T. Klungland**, **L. Braseth** + **master students**

- **Particles, Pandemics and Parameter Spaces**
  - KD *Sustainable Development* project
  - Collaboration with FHI (National Institute of Public Health)
  - **I. M. Johansson**, J. Midtbø, B. F. de Blasio, F, Di Ruscio, **A. Raklev**, **A. Kvellestad**

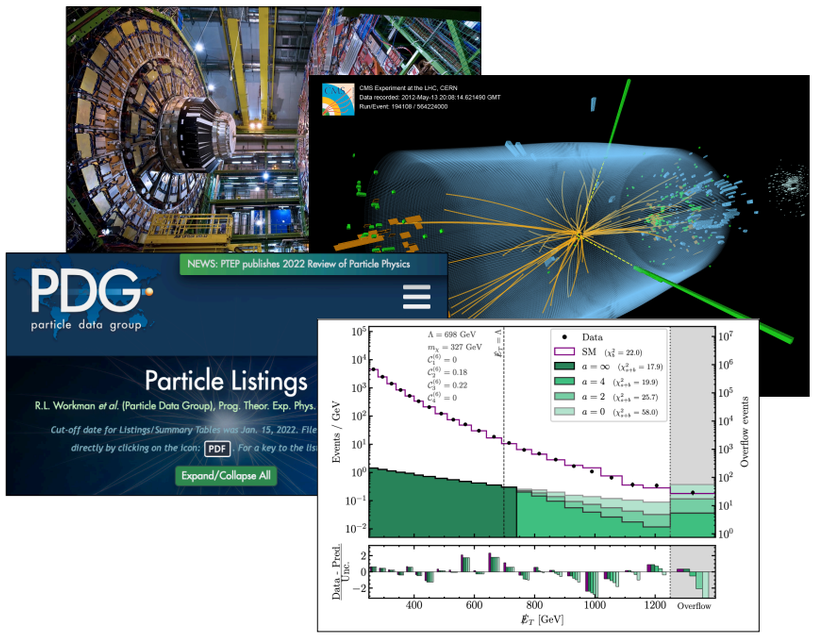
- **Unfolding and uncertainty quantification in nuclear physics**
  - dScience project
  - E. Lima, A. Mjøs, **L. Braseth**, A. C. Larsen, M. Hjorth-Jensen, **A. Kvellestad**

PLUMBIN’

- FRIPRO Fellesløft, collaboration with Dept. of Mathematics
- Overall goal: *Develop solvents for unclogging calculational bottlenecks in high-energy physics*
- **Ongoing work:**
  - Develop a general software framework for fast and precise cross-section computations for collider physics
  - Develop ML-based algorithms for *continual learning* (e.g. on-the-fly training and application of surrogate model on continual stream of input data)
  - Develop ML-based regression tools for fast evaluation of computationally expensive theory predictions
  - Develop sampling algorithms tailored for high-dimensional profile likelihood studies
- **Planned work:**
  - Develop computationally feasible statistical approach to goodness-of-fit tests for many-parameter new physics models
  - Bayesian uncertainty quantification for higher-order theory computations

Particles, pandemics and parameter spaces

- **Collaboration with FHI** (Norwegian Institute of Public Health)
- *Goal:* Tackle computational challenges common to HEP and disease modelling
- *Starting point:* Connect FHI's simulation models to GAMBIT-light

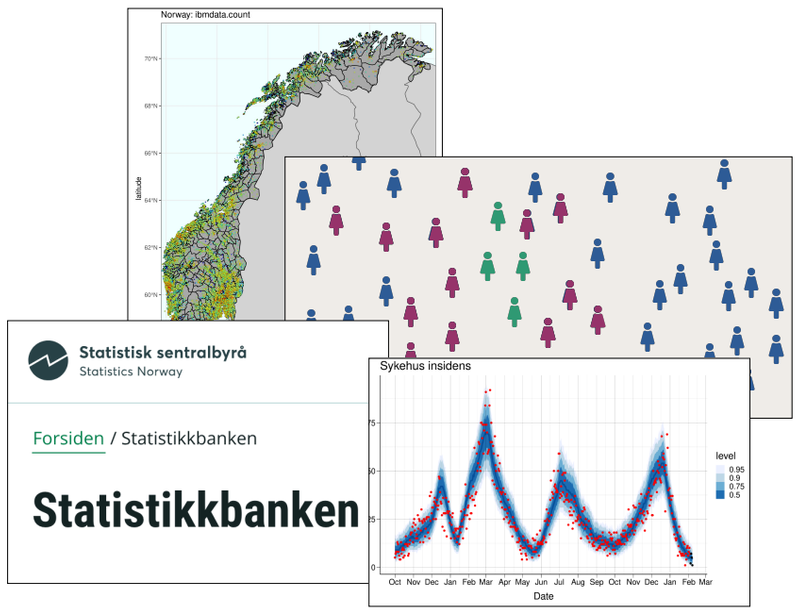


Modelling LHC physics

- Models with many free parameters
- Non-deterministic dynamics (quantum mechanics)
- Each prediction requires expensive Monte Carlo simulations
- *Task:* estimate model parameters, make robust predictions

Modelling outbreaks of infectious diseases

- Model with many free parameters
- Non-deterministic dynamics (people)
- Each prediction requires expensive Monte Carlo simulations
- *Task:* estimate model parameters, make robust predictions



Dark matter production (recent examples)

‘Pandemic dark matter’

Bringmann *et al.* (PRL ’21)

Qualitatively new mechanism to produce dark matter in early universe

(described by the same math as the spread of a disease)



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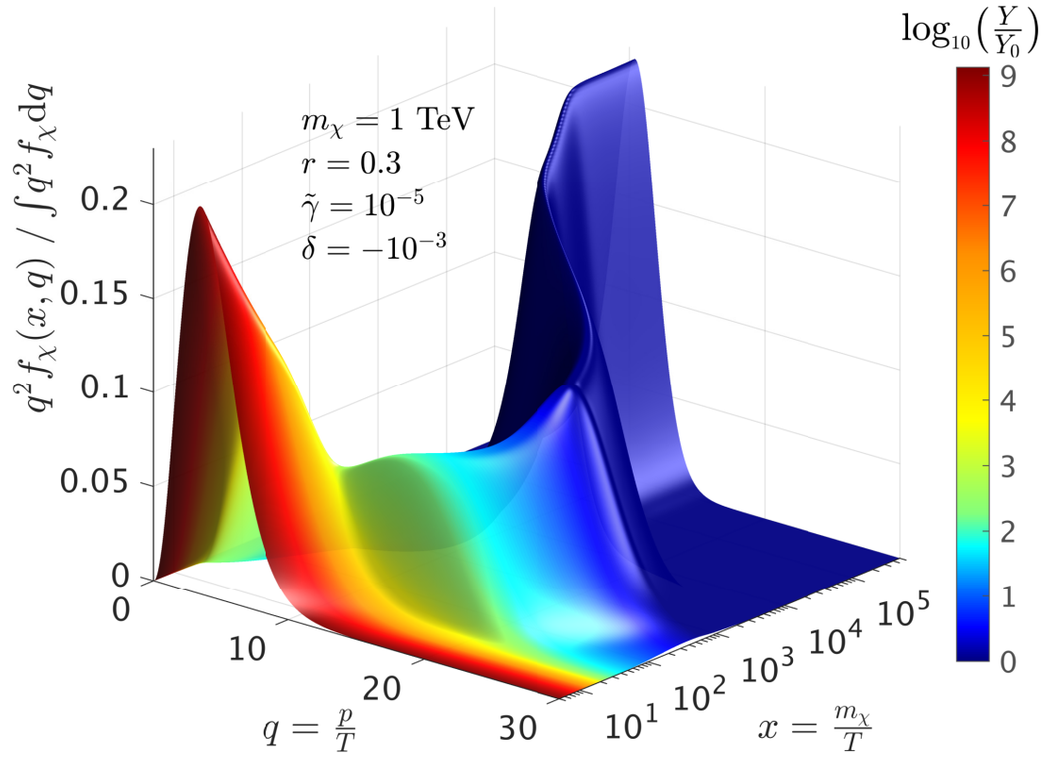
Precision calculations

Binder, Bringmann, Gustafsson & Hryczuk (EPJC ’21)

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

Calculations should match observations in precision!

(Here: pointing out loophole in standard formalism, requiring full solution of Boltzmann equation at phase-space level)



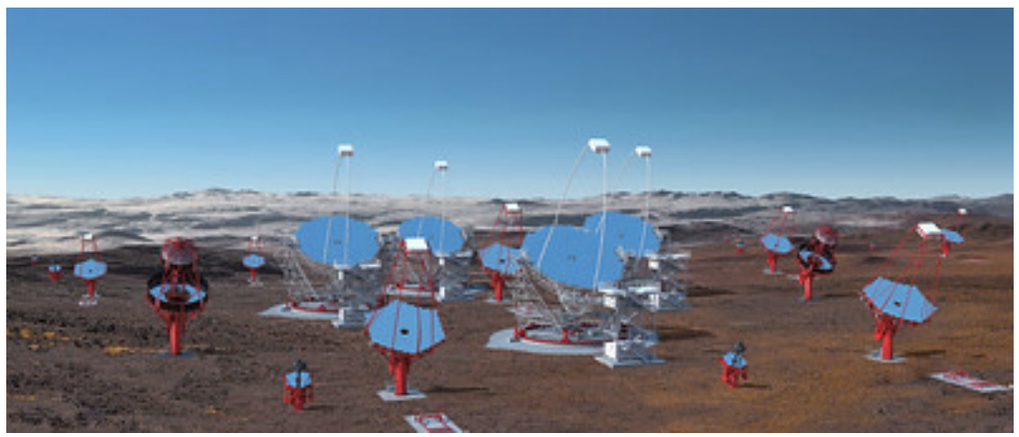
Dark matter detection (recent examples)

DM Searches with gamma rays

Acharyya *et al.* (JCAP '20)

Lead author for one of the 'flagship' consortium publications on CTA prospects for dark matter searches

(looking for signals from annihilating DM particles from the direction of the Galactic Center)



The Cherenkov Telescope Array
— "the future of gamma-ray astronomy"

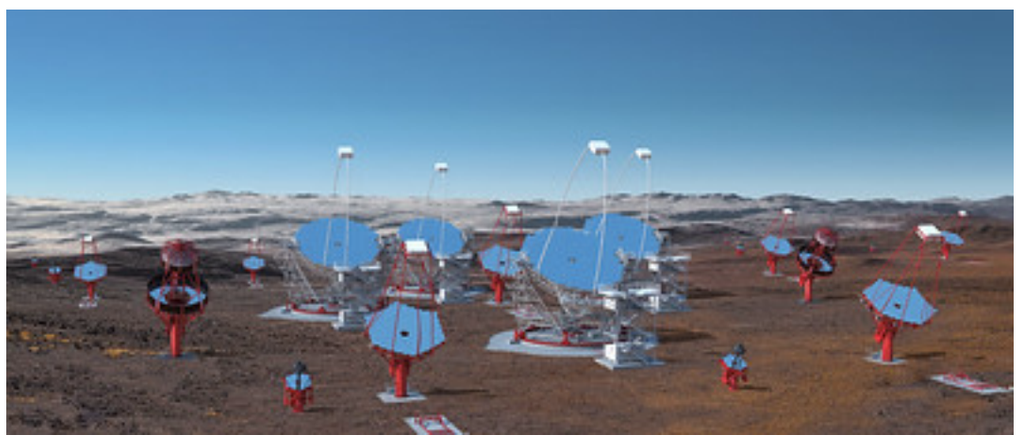
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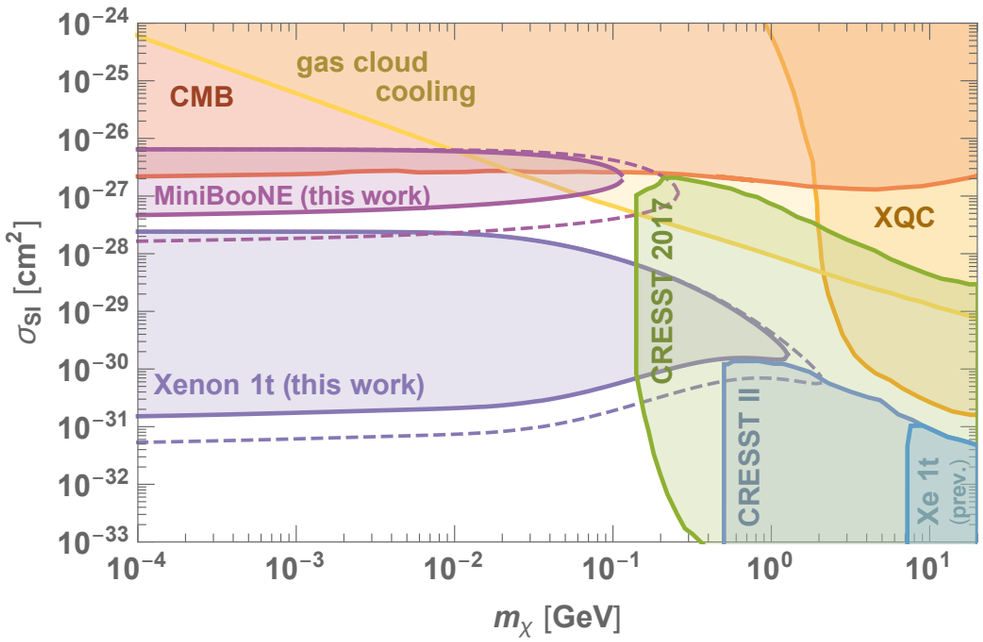
The Cherenkov Telescope Array
— "the future of gamma-ray astronomy"

Direct detection

Bringmann & Pospelov (PRL '19)

New world-leading limits on light dark matter particles

(by re-interpreting existing searches)



Huge international effort — detection of light, low-energy particles requires novel [quantum?] detector ideas!

‘The cosmos as a dark matter lab’ **(long-term interest)**

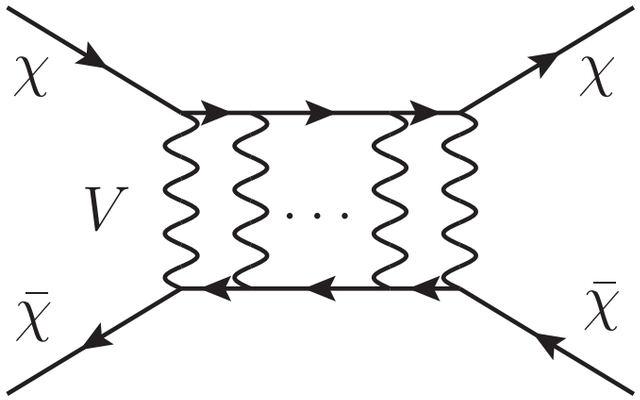
Dark matter particles may be virtually invisible to terrestrial experiments
— but could still leave imprints on cosmological structure formation

‘The cosmos as a dark matter lab’ (long-term interest)

Dark matter particles may be virtually invisible to terrestrial experiments
— but could still leave imprints on cosmological structure formation

E.g. **ETHOS: An Effective Theory of Structure Formation**

with collaborators from Cambridge, MIT, Princeton, … (’16 — ’20)



particle model

input:
masses, spins, coupling constants

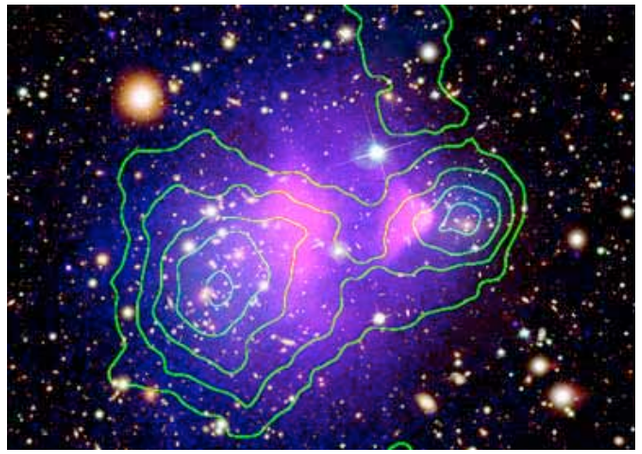
task 1



cosmological simulations

input:
consistent initial conditions, non-gravitational forces between “particles”

task 2



astrophysical observables

input
(for interpretation of data):
output from simulations

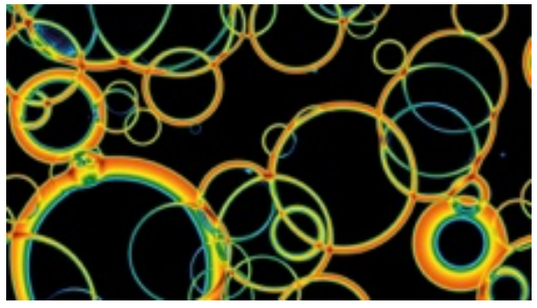
Gravitational waves (relatively new interest)

Are we seeing a dark sector phase transition?

Bringmann *et al.* (JCAP '23)

Recent evidence for nHz GW background can point to new physics!

('Global fit': must take into account complementary constraints from cosmology)



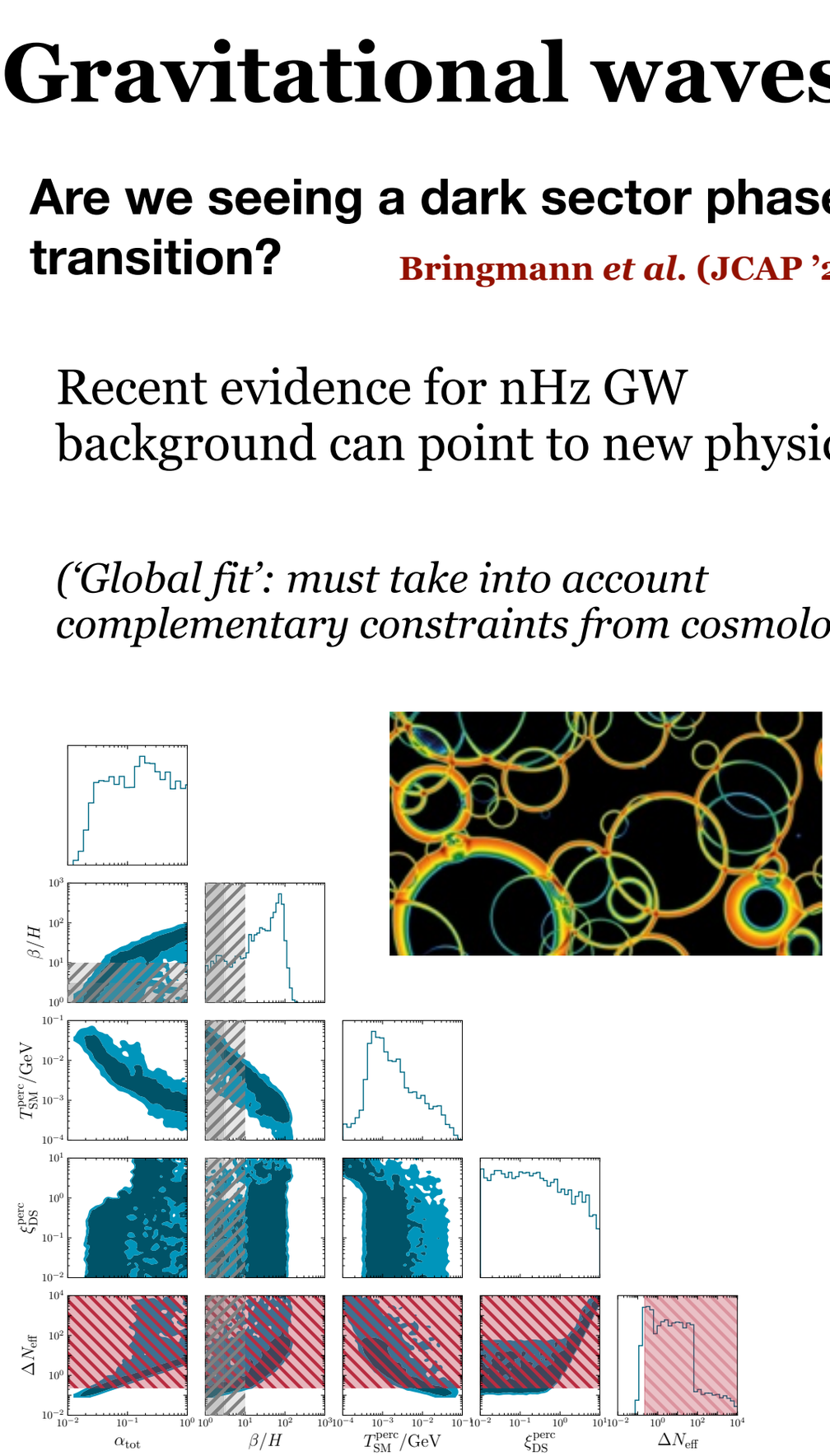
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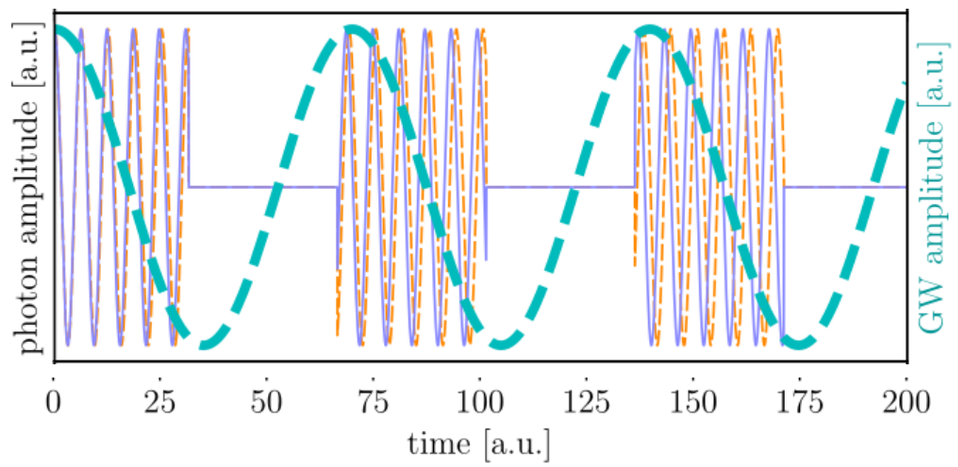
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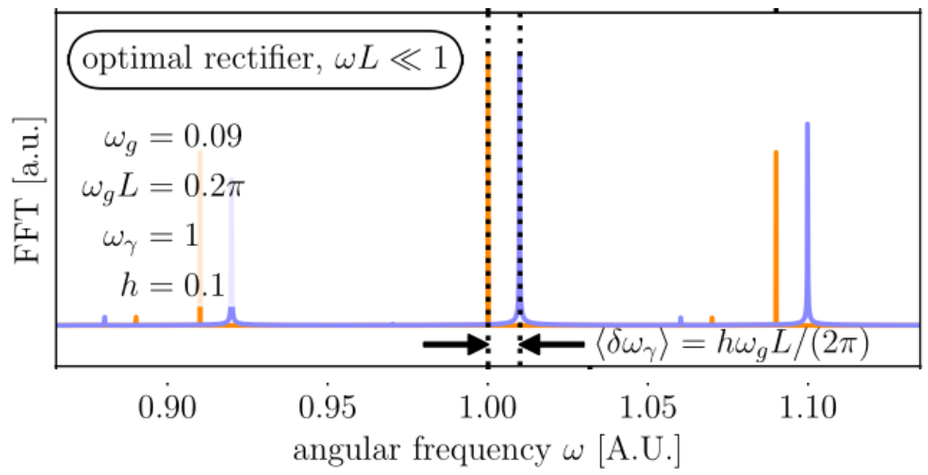


Towards table-top GW detectors ?

Bringmann *et al.* (PRD '23)

Active field of research. One option: look for *tiny* optical frequency modulations due to GHz GWs





*("Atomic clocks as **quantum sensors**": Ramsey spectroscopy to measure $\Delta\omega$)*

Summary (aka wishful thinking list)

- 😉 Quantum computers to run large-scale simulations or scans
- 😉 New types of quantum sensors w/ extreme sensitivities
- 😉 New ideas…

Takk!