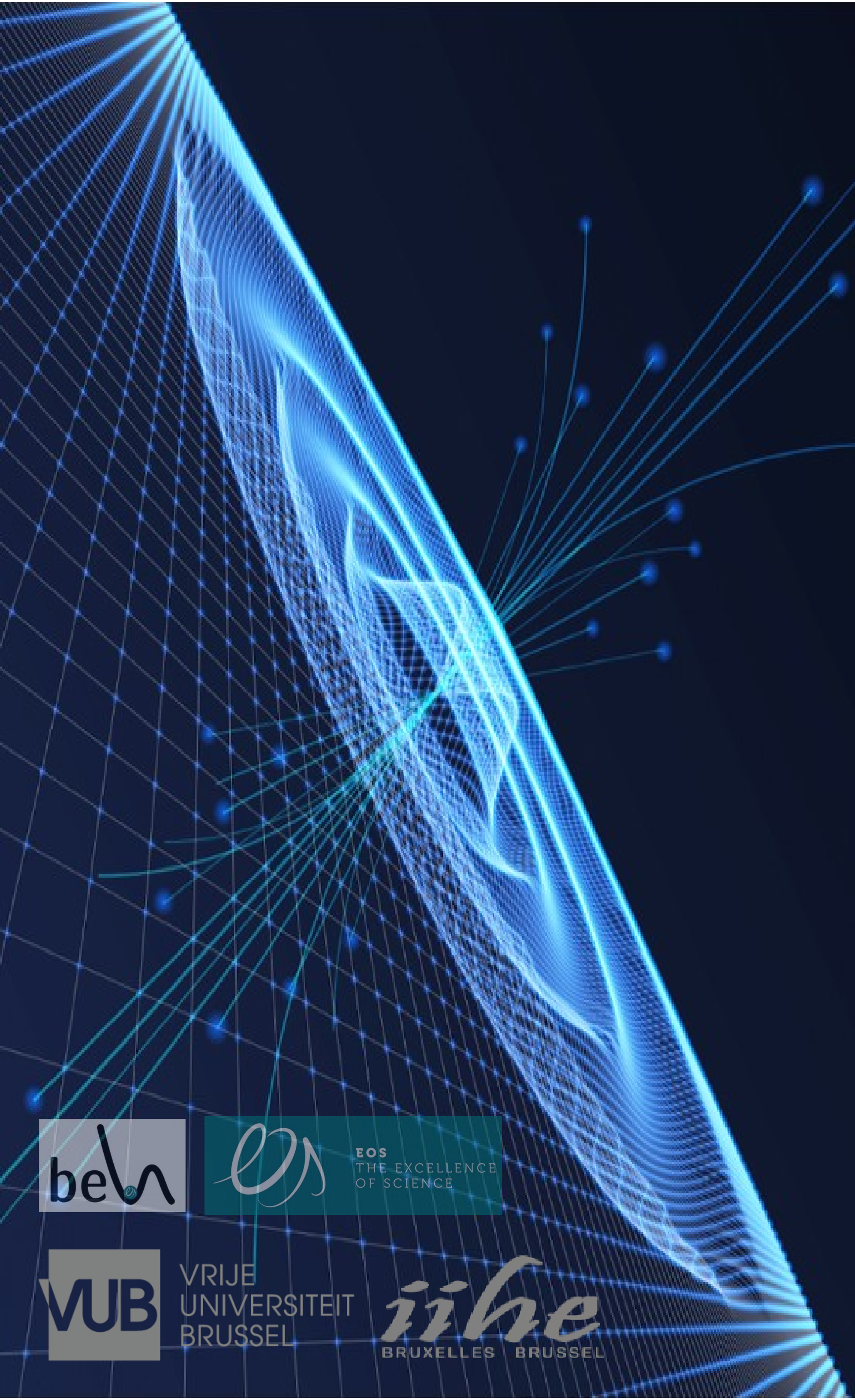


The Dark Universe Introduction

Steven Lowette
Vrije Universiteit Brussel – IIHE

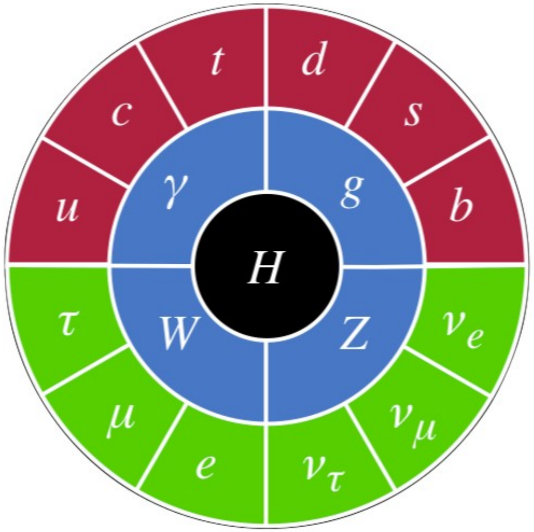
9 March 2023
Symposium – Brussels Town Hall
A decade of discoveries in High Energy Physics

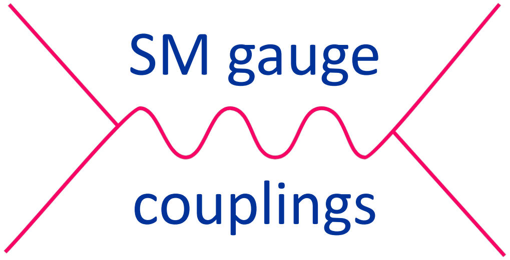
EOS
THE EXCELLENCE
OF SCIENCE

VUB VRIJE
UNIVERSITEIT
BRUSSEL

iihe
BRUXELLES BRUSSEL

The Dark Sector

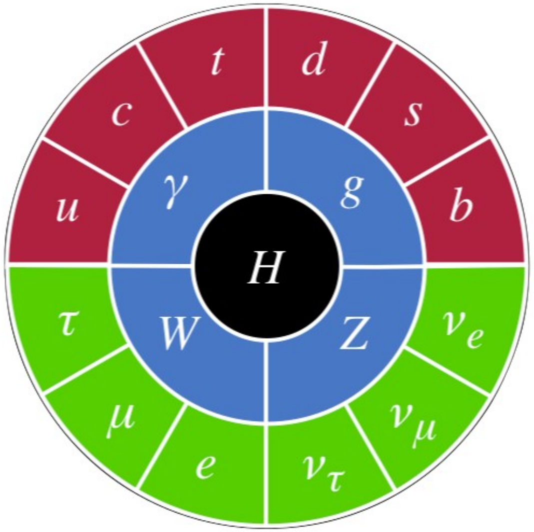




SM gauge

couplings

The Dark Sector

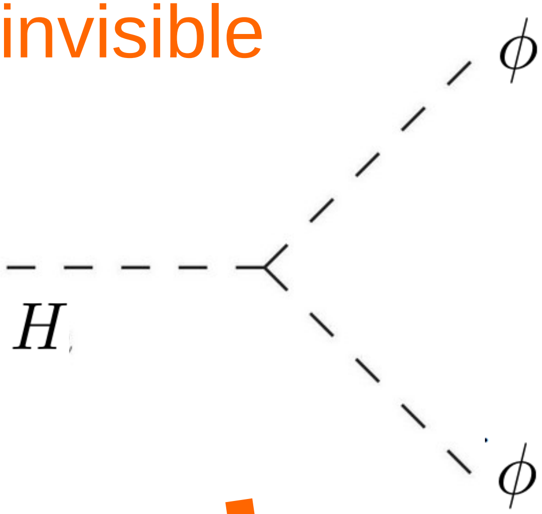


portal coupling

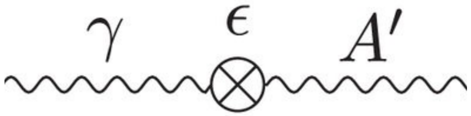
$H^\dagger H \phi^\dagger \phi$	*H* portal
$F_{\mu\nu} X^{\mu\nu}$	vector portal
$H L N_R$	neutrino portal

The Dark Sector: example signatures

H → invisible



dark photon



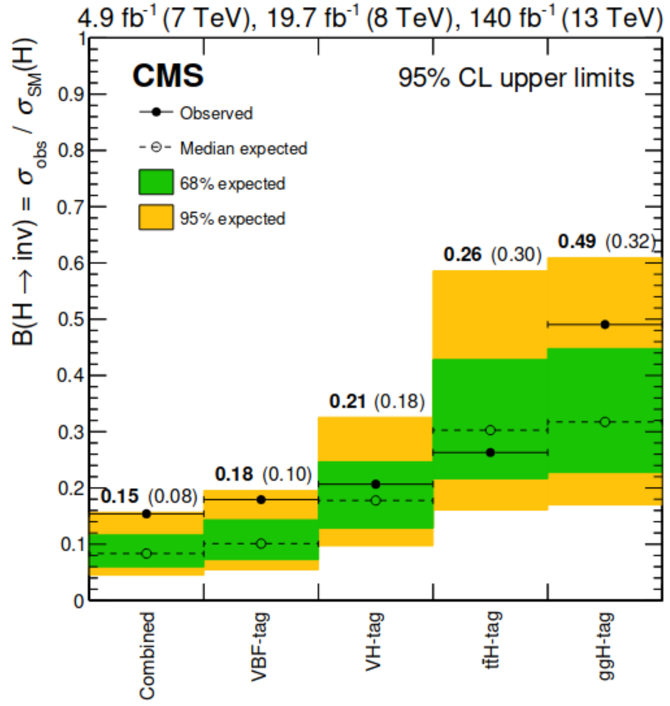
$H^\dagger H \phi^\dagger \phi$ *H* portal

$F_{\mu\nu} X^{\mu\nu}$ vector portal

$H^\dagger H \phi^\dagger \phi$: H → invisible

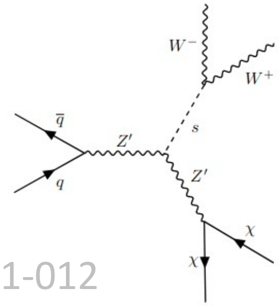
- Hϕϕ vertex arises from simplest H portal model
  - H can decay to invisible particles ($m_\phi < m_H/2$)
  - would not affect other H property measurements
- broad LHC search program
  - in all H production modes
- incredible precision reached:
  - BR (H → invisible) < 0.15% (0.08%)

obs. (exp.) 95% C.L. limit



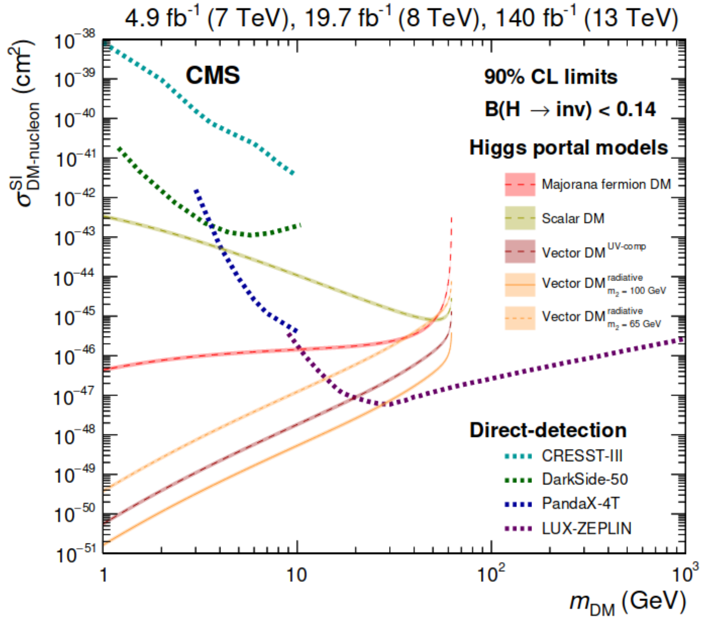
arXiv:2303.01214

- strong constraints on dark matter – nucleon scattering cross sections
- extra scalars may alter the electroweak phase transition
  → electroweak baryogenesis



- also complex dark-H signatures probed

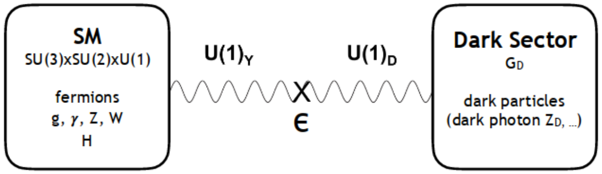
CMS-PAS-EXO-21-012



arXiv:2303.01214

$F_{\mu\nu}X^{\mu\nu}$: dark photons

- dark photon from new U(1) symmetry
  - vector portal: kinetic mixing with regular photon



SM
SU(3)xSU(2)xU(1)
fermions
g, γ, Z, W
H

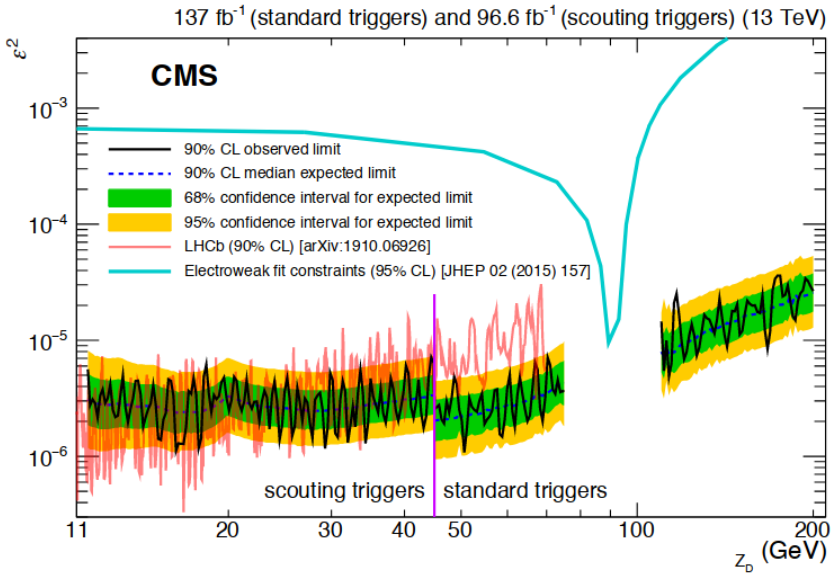
$U(1)_Y$ $U(1)_D$
X
ϵ

Dark Sector
G_D
dark particles
(dark photon Z_D, ...)

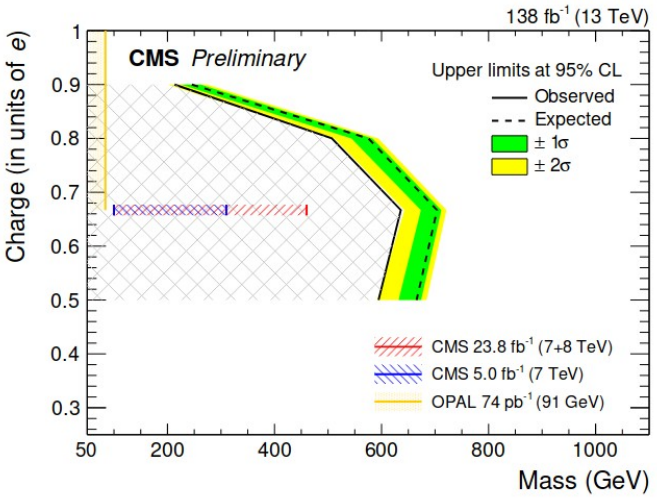
- CMS search for $\mu^+\mu^-$ resonance
  - first time using special triggers to access low mass
- also NA62

- millicharges ~ mixing ϵ
  - unique search for fractionally charged particles
  - milliQan: dedicated new experiment searching for millicharged particles

PRL 124 (2020) 13, 131802



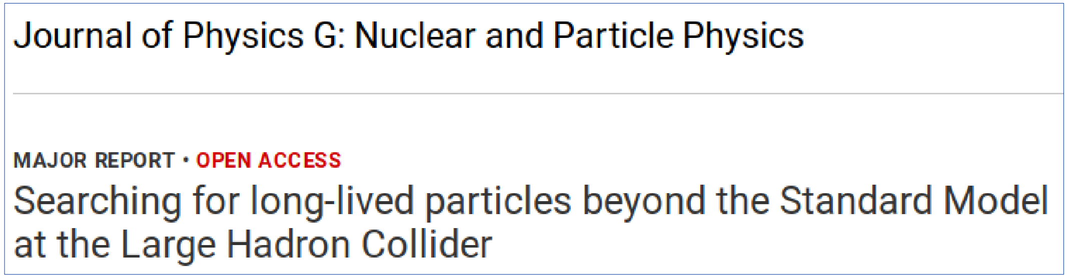
CMS-PAS-EXO-19-006



Next frontiers: long-lived particles

- new long-lived particles are a prediction in many dark sector models
- rich experimental frontier
  - new simulations, trigger developments, reconstruction, unusual backgrounds,…

arXiv:1903.04497

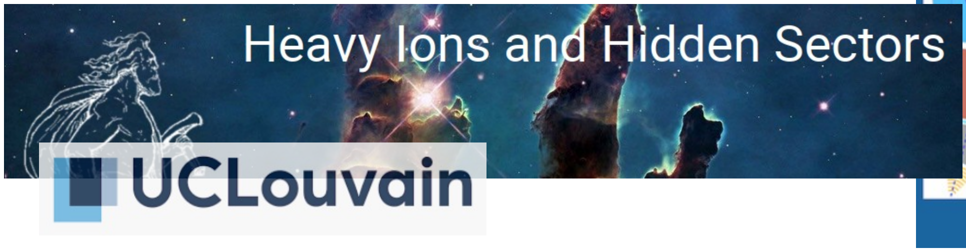


Journal of Physics G: Nuclear and Particle Physics

MAJOR REPORT • OPEN ACCESS

Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider

- activities
  - displaced leptons from compressed spectrum (JHEP 11 (2020) 112)
  - low-mass H-portal scalar in $H \to ss \to \mu^+\mu^- K^+K^-$ (JHEP 01 (2020) 115, ongoing)
  - strongly interacting dark matter (JHEP 11 (2015) 108, Eur.Phys.J.C 82 (2022) 3, 213)
  - 6-quark dark matter (arXiv:1708.08951, ongoing)
  - freezin dark matter and cosmology (JHEP 09 (2018) 037)
  - new physics with heavy ions (arXiv:1812.07688, PRL 124 (2020) 8, 081801)
  - …



The Dark Universe

11:00

The Dark Universe -- Chair: Steven Lowette

Speakers: Aqeel Ahmed (Vrije Universiteit Brussel) , Iason Baldes (Paris) , Steven Lowette (Vrije Universiteit Brussel)

Introduction

Speaker: Steven Lowette (Vrije Universiteit Brussel)

The BEH mechanism at high temperature: a link to matter production ¶

Speaker: Iason Baldes

Dark Side of the Universe

Speaker: Aqeel Ahmed (Vrije Universiteit Brussel)

Aqeel Ahmed

- Max-Planck-Institute für Kernphysik – Heidelberg
- with the VUB pheno group from 2018-2020
- collider signatures of naturalness → dark matter

Iason Baldes

- Ecole Normale Supérieure – Paris
- with the ULB pheno group from 2018-2022
- link to cosmology → electroweak baryogenesis

DARK SIDE OF THE UNIVERSE

Aqeel Ahmed

Max-Planck-Institut für Kernphysik — Heidelberg

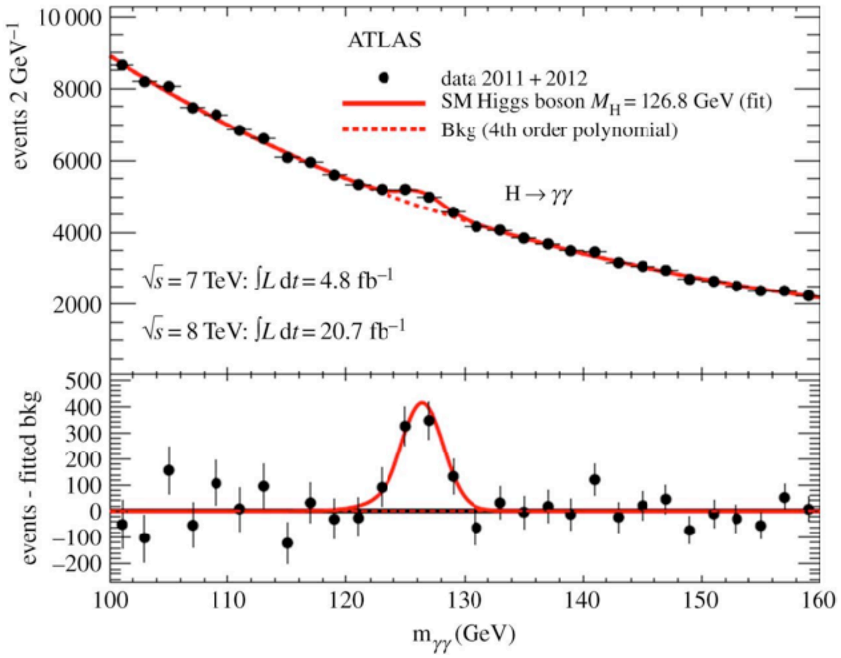
A Decade of Discoveries in High-Energy Physics, Brussels — March 09, 2023

former postdoc (2018–2020) at VUB VRIJE UNIVERSITEIT BRUSSEL

A DECADE OF DISCOVERIES

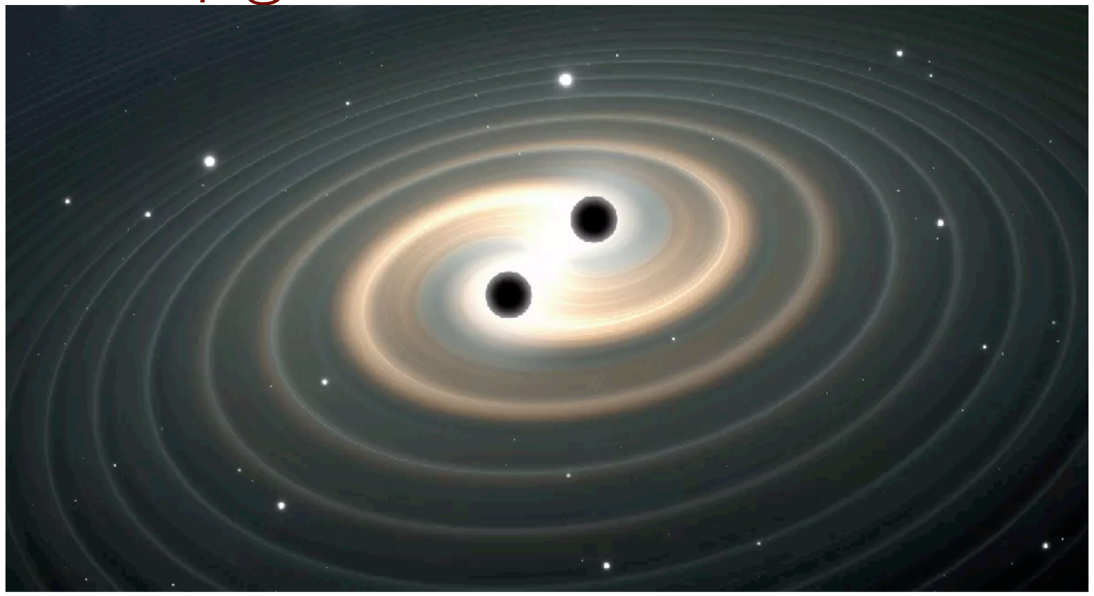
- *Discovery of the H boson* at CERN

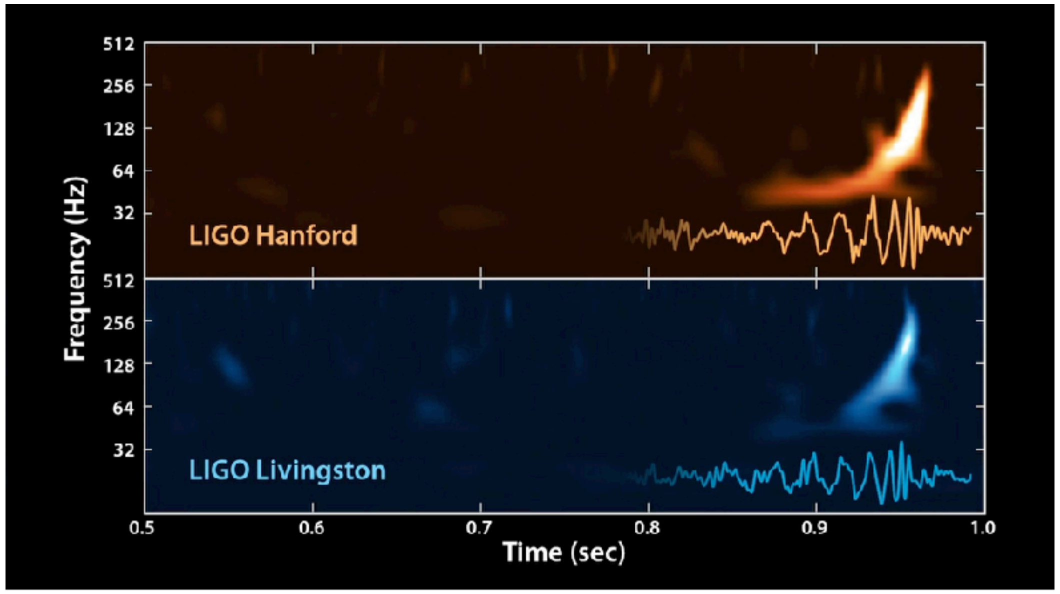
morning session



- *Detection of gravitational waves* at LIGO/VIRGO

see also Baldes' talk
and afternoon session

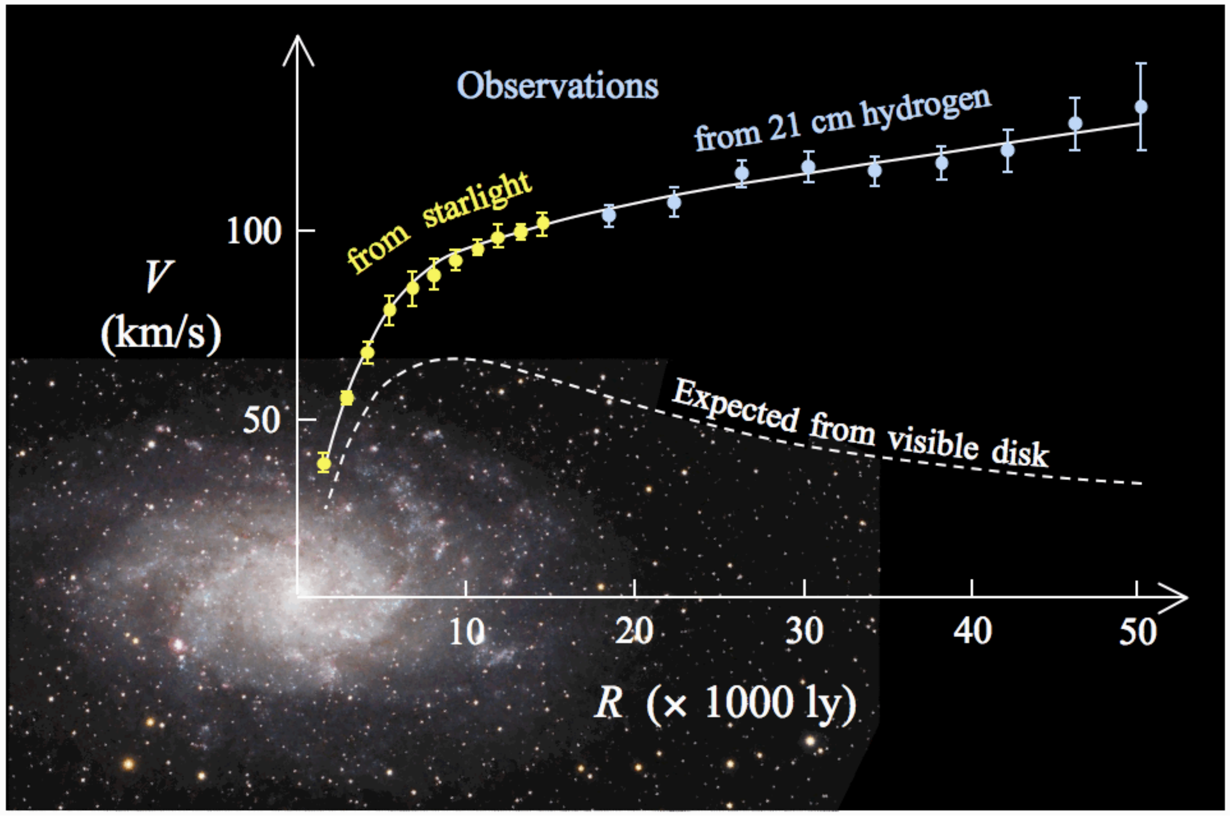




- Dark matter: No breakthrough discovery but enormous progress on theoretical and experimental fronts.

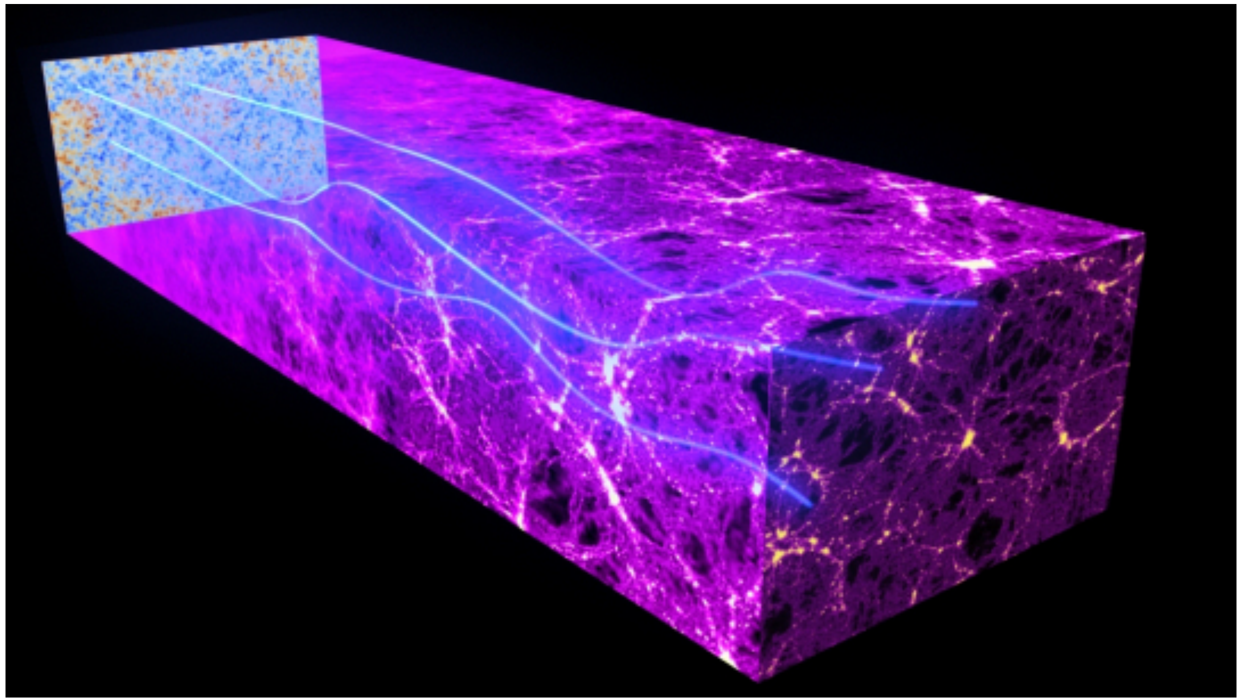
DARK MATTER: EVIDENCE

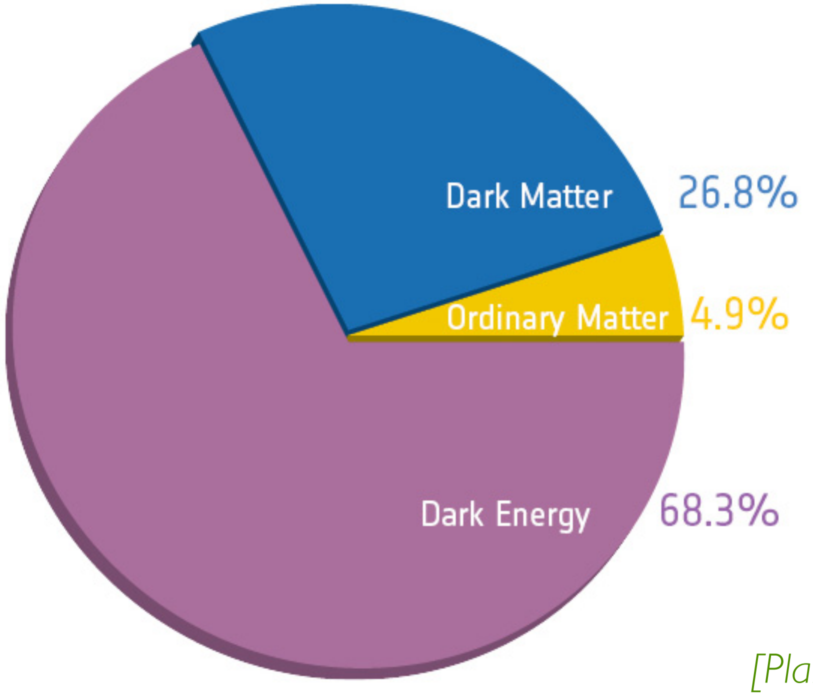
Galatic rotation curves



Cluster collisions

Gravitational lensing of CMB





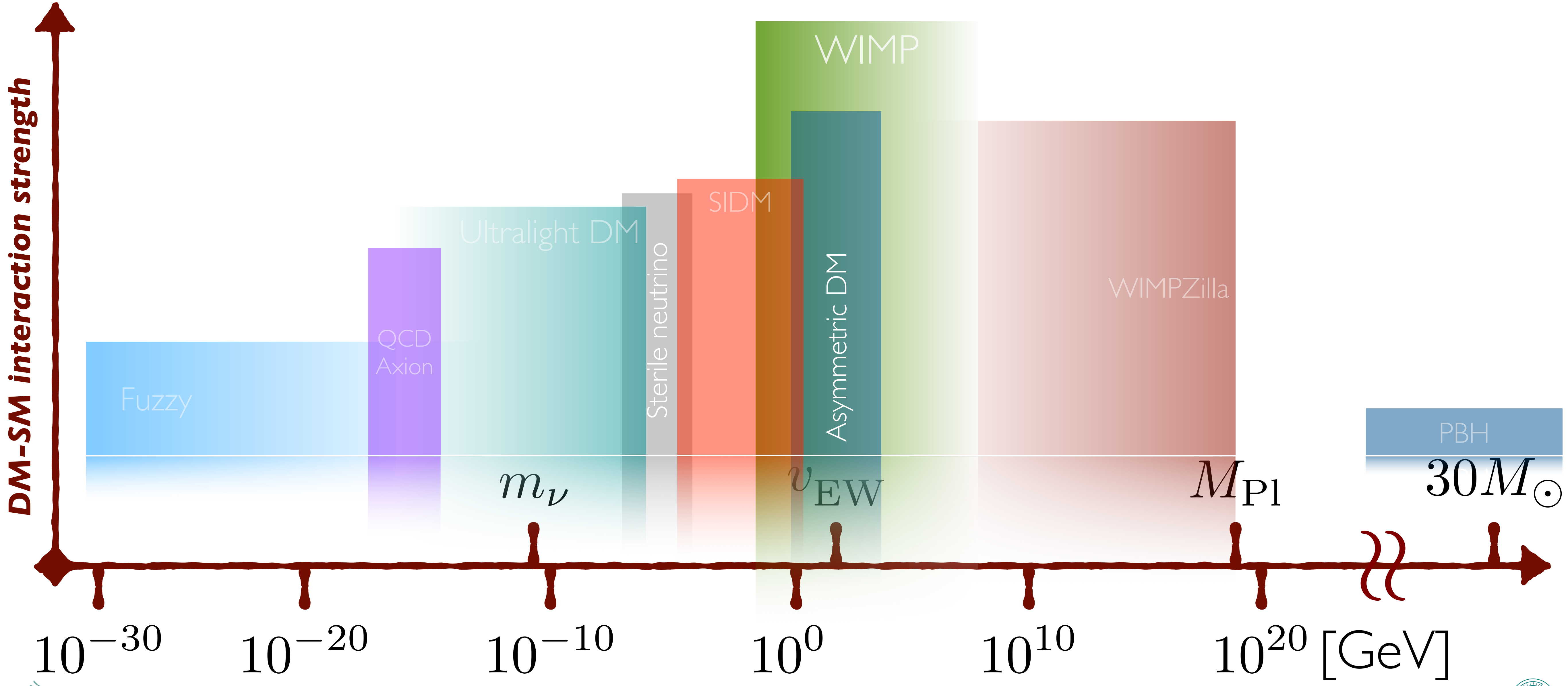
[Planck Satellite]

DARK MATTER: WHAT WE KNOW

- Dark matter is:
  - *Massive* (as it interacts with gravity)
  - *Stable* (at cosmological scales)
  - (electrically) *Neutral*
  - *Cold (non-relativistic)*
  - *Clumps to form halos*
  - *Relic abundance* $\Omega_{\mathrm{DM}}h^2 = 0.12(12)$ *[Planck, 2018]*
- No evidence of non-gravitational interactions b/w DM and SM

WHAT DARK MATTER CAN BE?

- DM mass:
  - particle state, $m_{\rm DM} \in [10^{-30},\ 10^{19}]$ GeV
  - composite state, e.g. Primordial Blackholes, $m_{\rm DM} \sim \mathcal{O}(10)\, M_\odot$



PLAN

I. WIMP DM and its current status

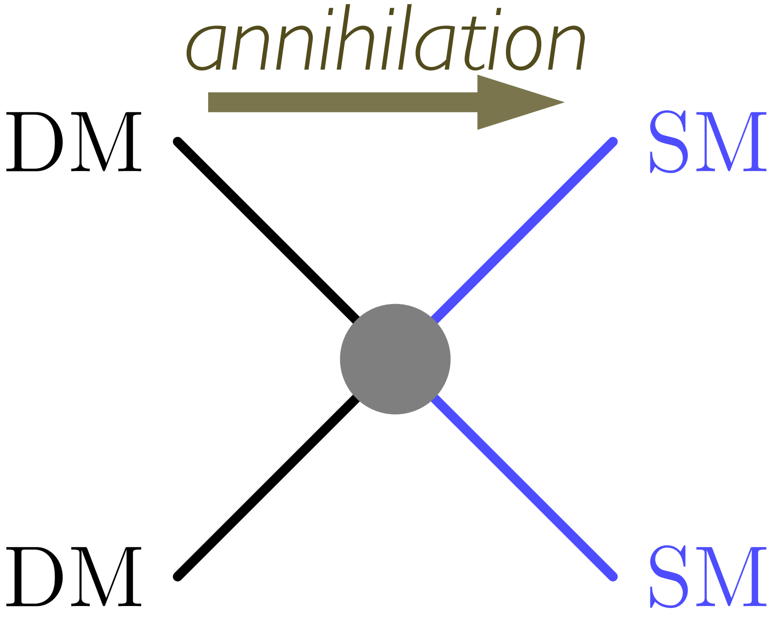
II. DM model building beyond the WIMP paradigm:

- Theoretical ideas
- Experimental prospects

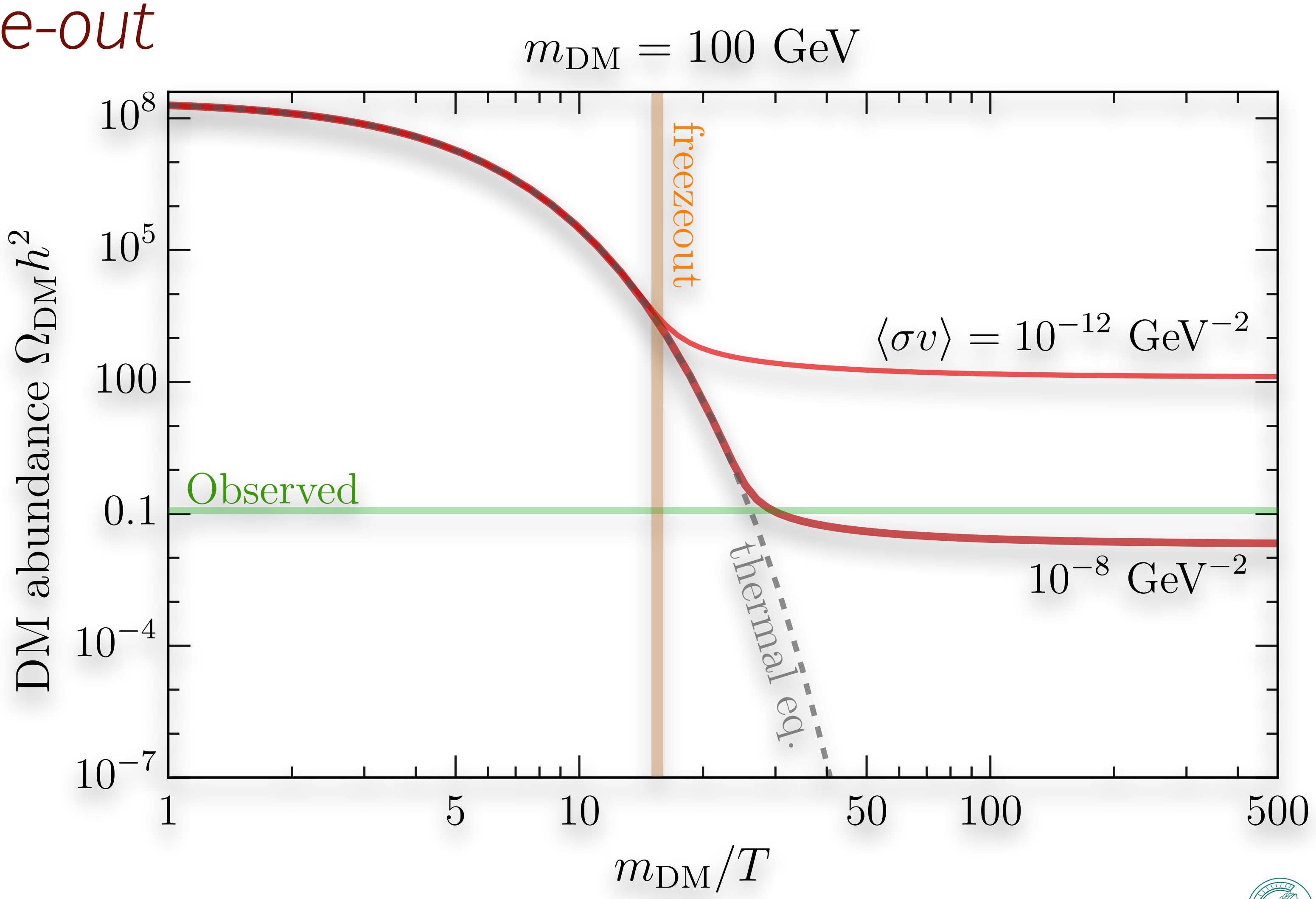
III. Conclusions

WIMP DM

- DM mass $m_{\rm DM} \sim m_{\rm EW} \sim \mathcal{O}(100)\,\mathrm{GeV}$
- DM-SM interaction strength $\sim G_F$
- DM-SM are in thermal equilibrium at high temperatures
- Production via *thermal freeze-out*

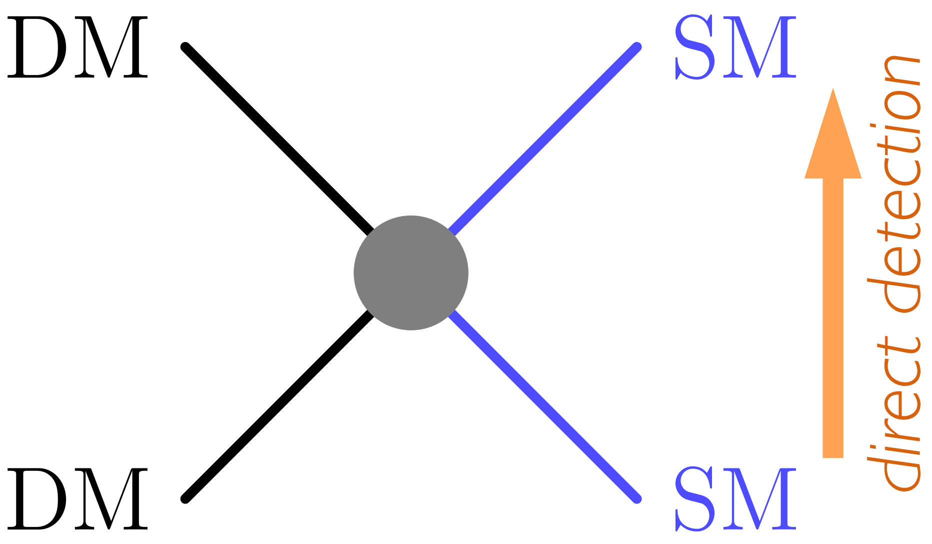


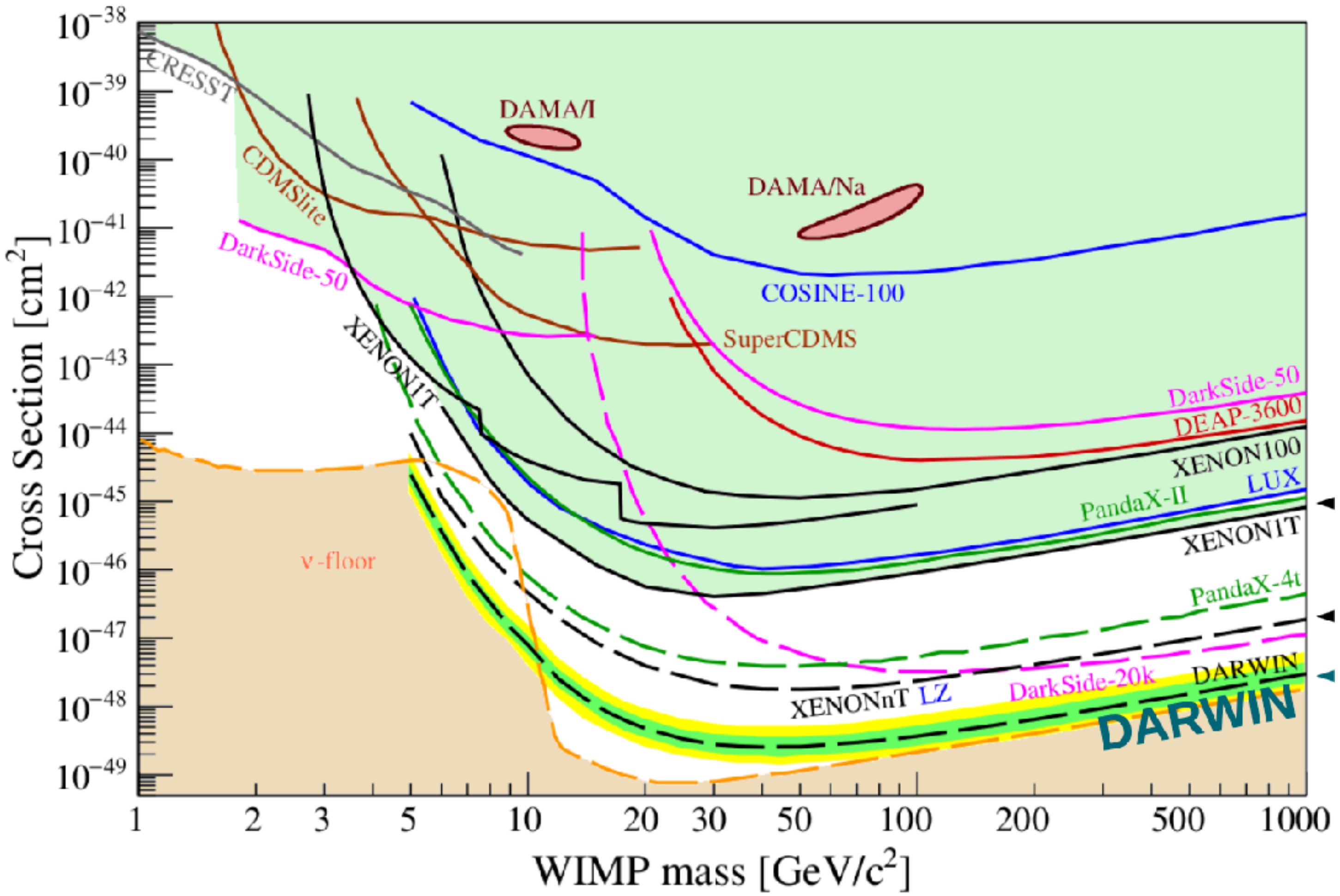
$$\Omega_{\rm DM}h^2 \sim 0.12\left(\frac{m_{\rm DM}}{20\,T}\right)\frac{10^{-8}\,\mathrm{GeV}^{-2}}{\langle\sigma v\rangle}$$



WIMP DETECTION

- WIMP DM at experiments:
  - Direct detection, e.g. *XENON, LZ*, …

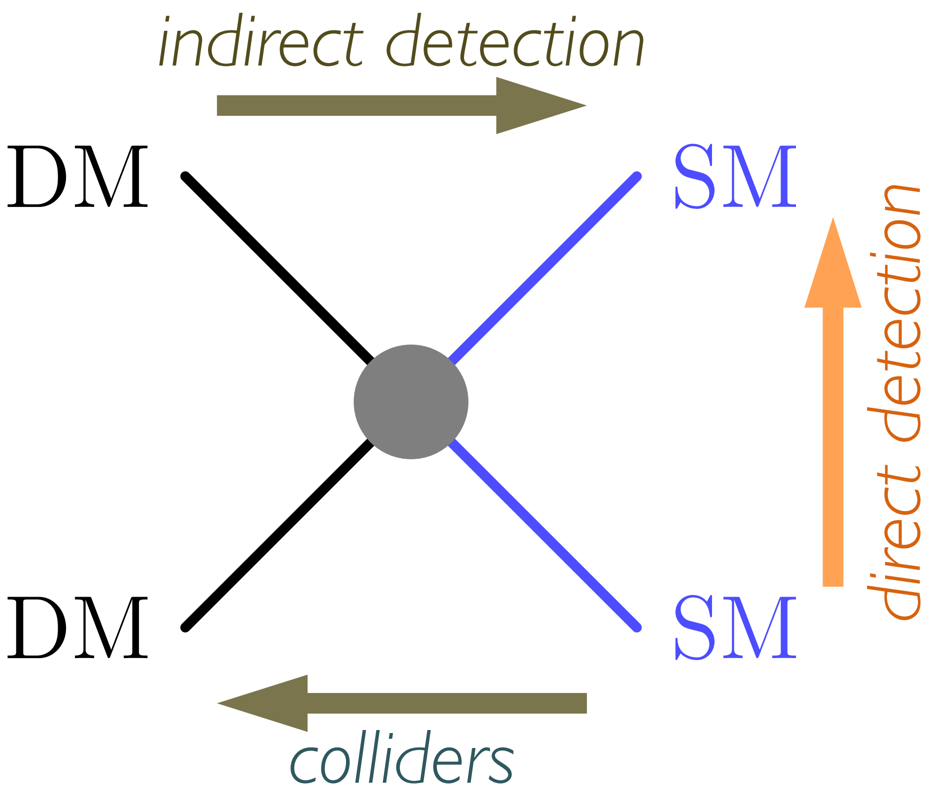




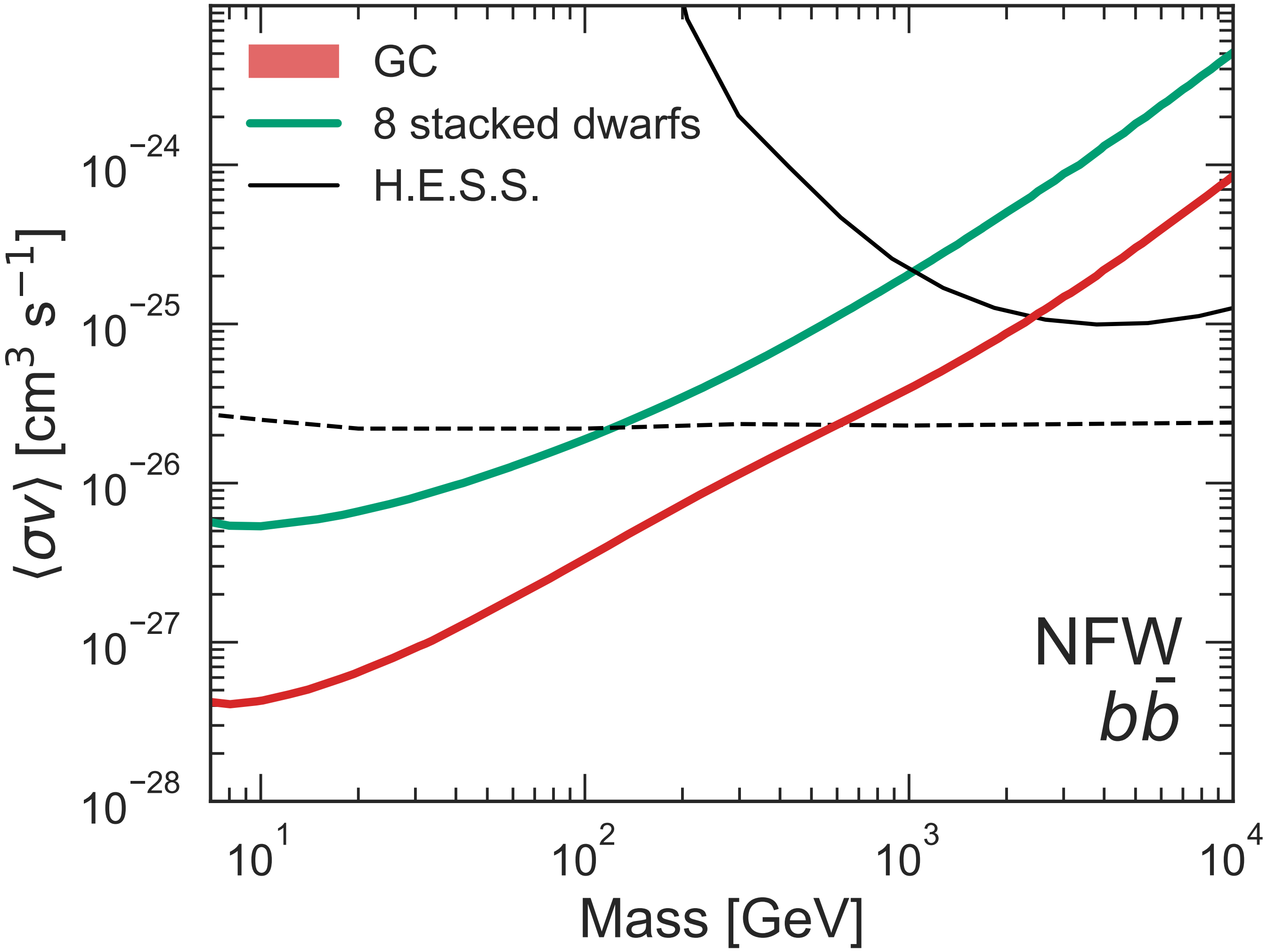
WIMP DETECTION

- WIMP DM at experiments:
  - Direct detection, e.g. *XENON, LZ, …*
  - *Indirect detection, e.g. Fermi gamma-ray space telescope, AMS, …*
  - *Collider experiments, e.g. LHC, future colliders*

see Steven's slides

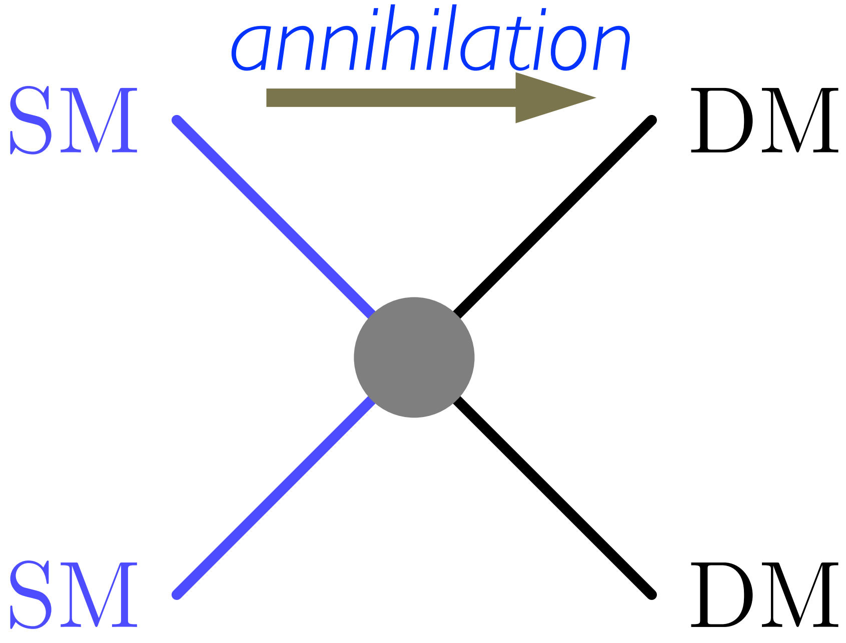


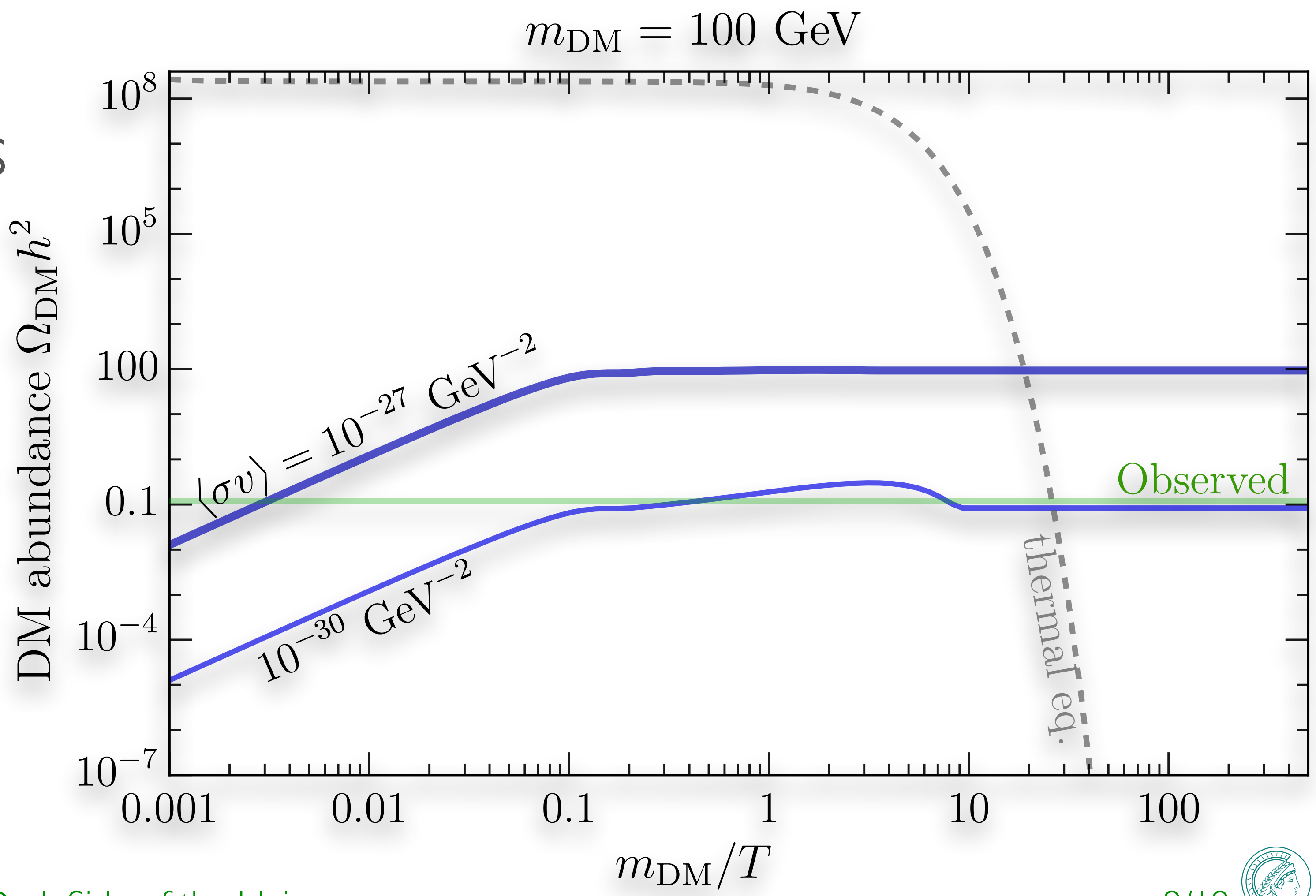
[Abazajian et al., 2020]



FREEZE-IN DM

- Freeze-in DM is one of the main alternatives to WIMP DM:
  - *Out of thermal equilibrium* with the SM
  - Initial abundance is negligible
  - Produced via SM annihilations
  - DM-SM feeble interactions

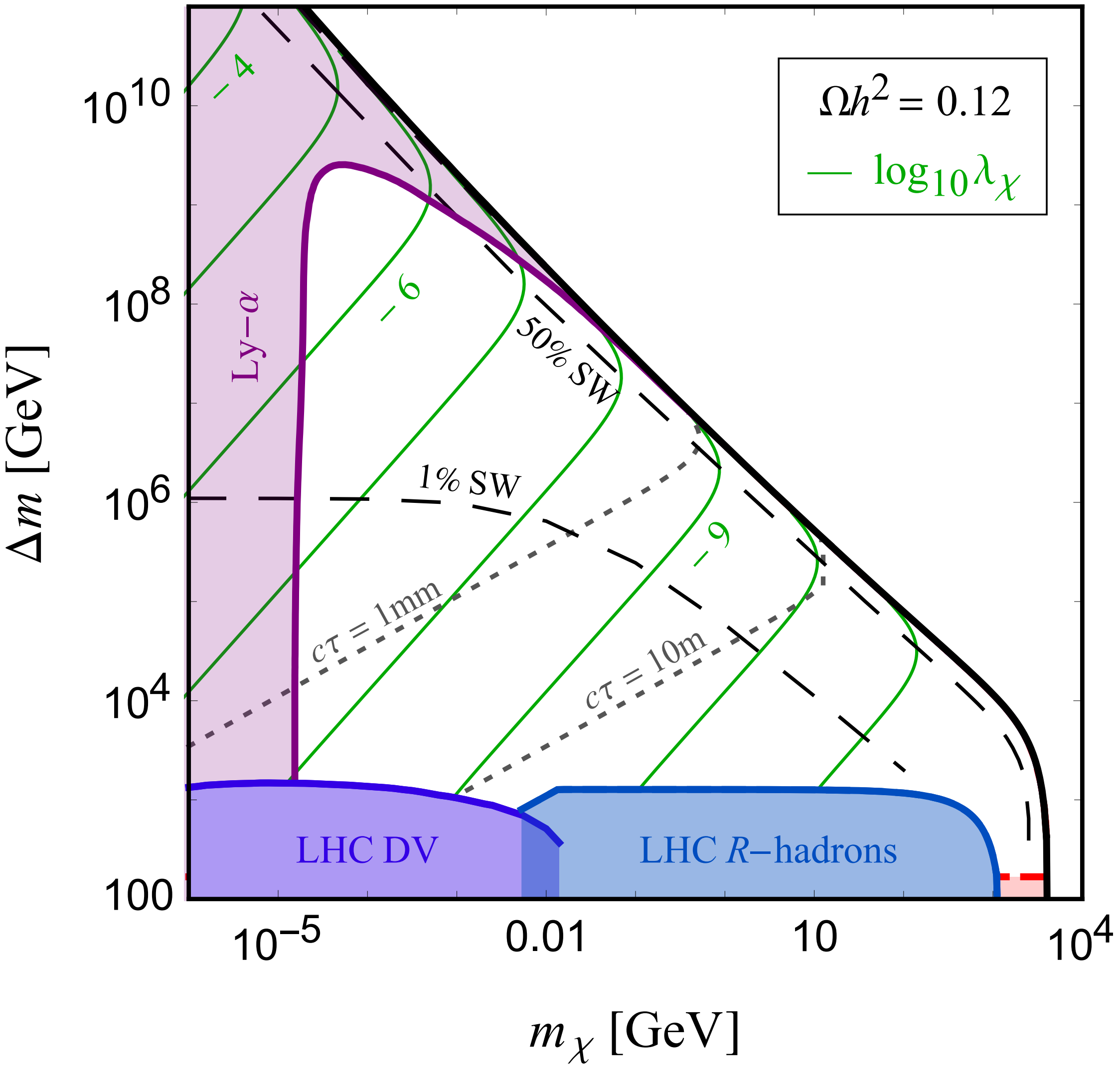


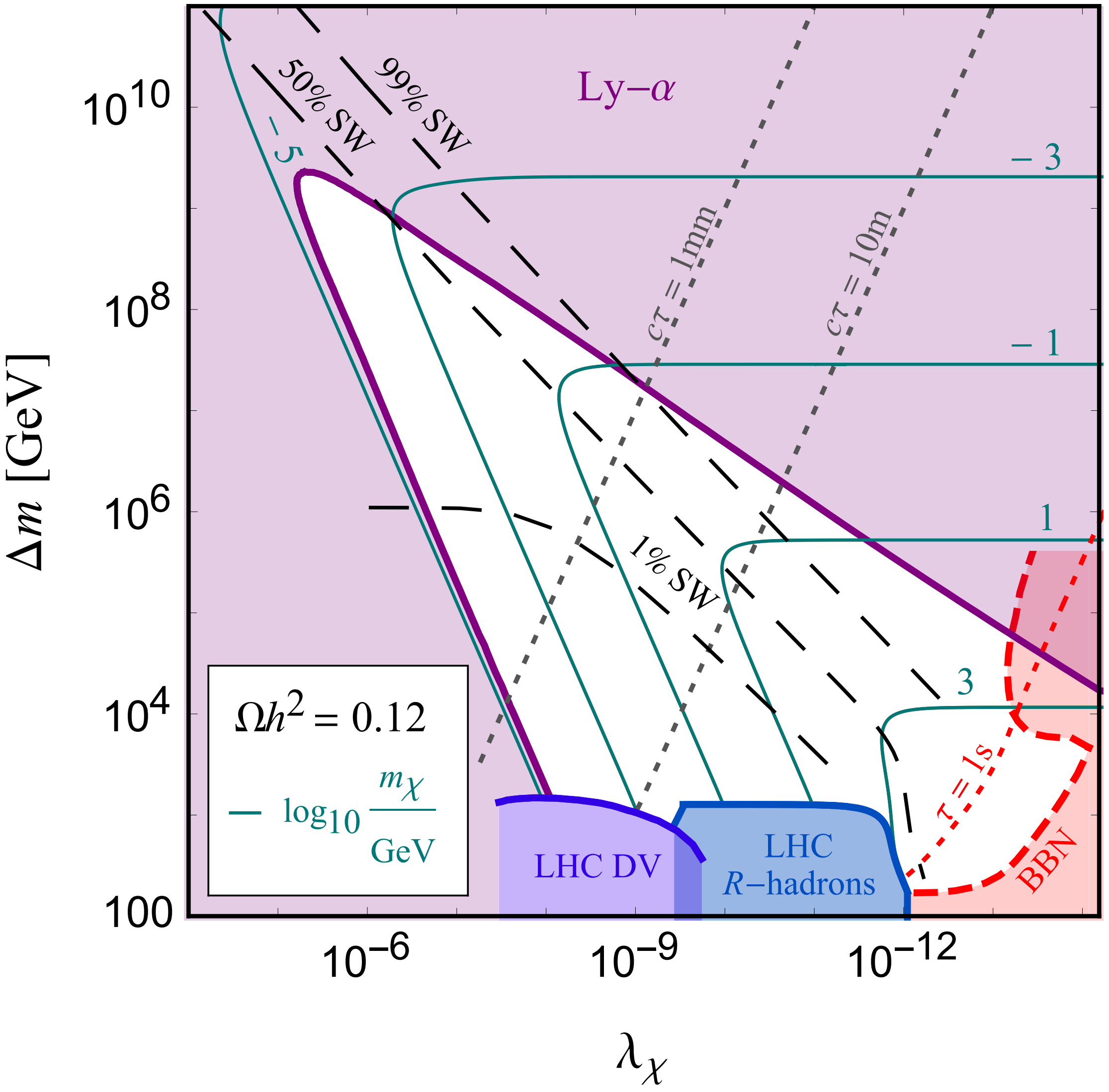


FREEZE-IN SIGNATURES

- Freeze-in DM can have its imprints in
  - Astrophysics and *cosmological data;*
  - Collider signals, e.g. long-lived particles through mediators/portals

[Lopez-Honorez et al., 2021-22,+…]





MISALIGNMENT MECHANISM: AXION DM

- Axions solve the strong CP problem

$$\mathcal{L} = \left(\frac{a}{f_a} - \bar{\theta}\right)\frac{\alpha_s}{8\pi} G^{\mu\nu a}\widetilde{G}^a_{\mu\nu}$$

$$\boxed{m_a^2 = \Lambda_{\rm QCD}^4/f_a^2}$$

- Axion DM can be produced via the misalignment mechanism and behave as cold DM

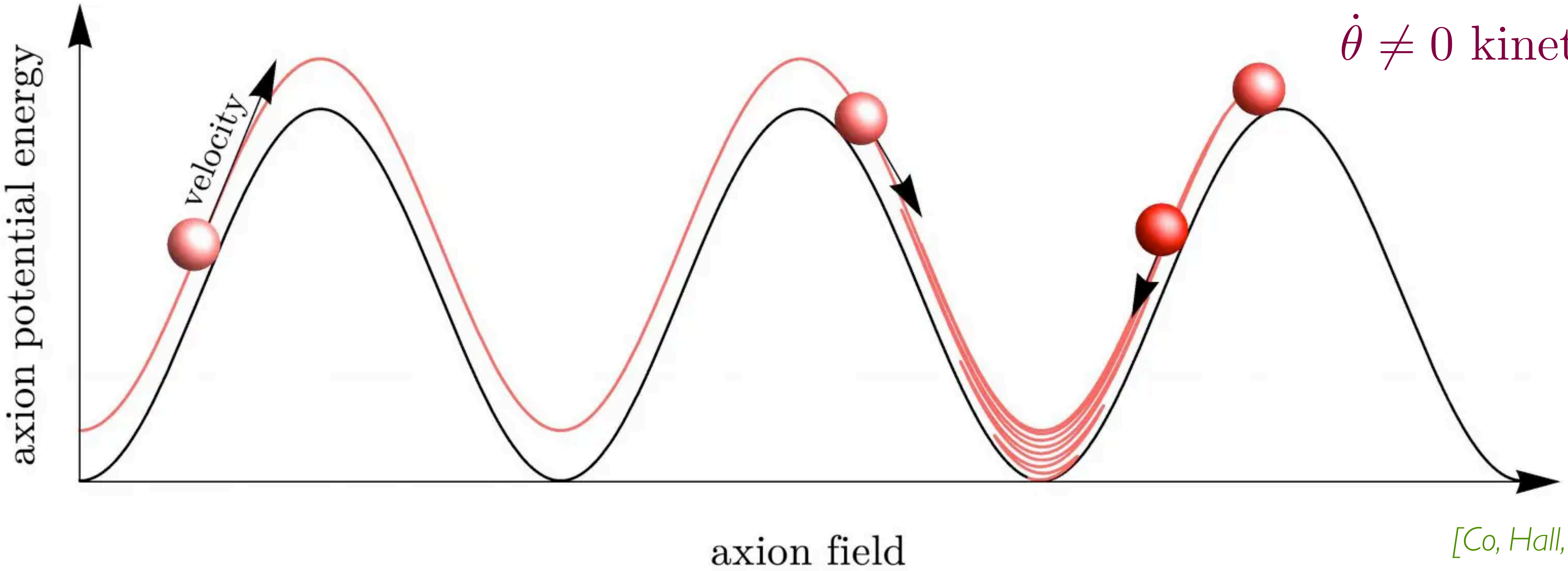
$$\Omega_a h^2 \sim 0.12\left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6}\langle\theta_i^2\rangle$$

$$\boxed{\theta \equiv a/f_a}$$

- Several recent developments for axion DM production, e.g. kinetic misalignment, …

$\dot{\theta} = 0$ misalignment

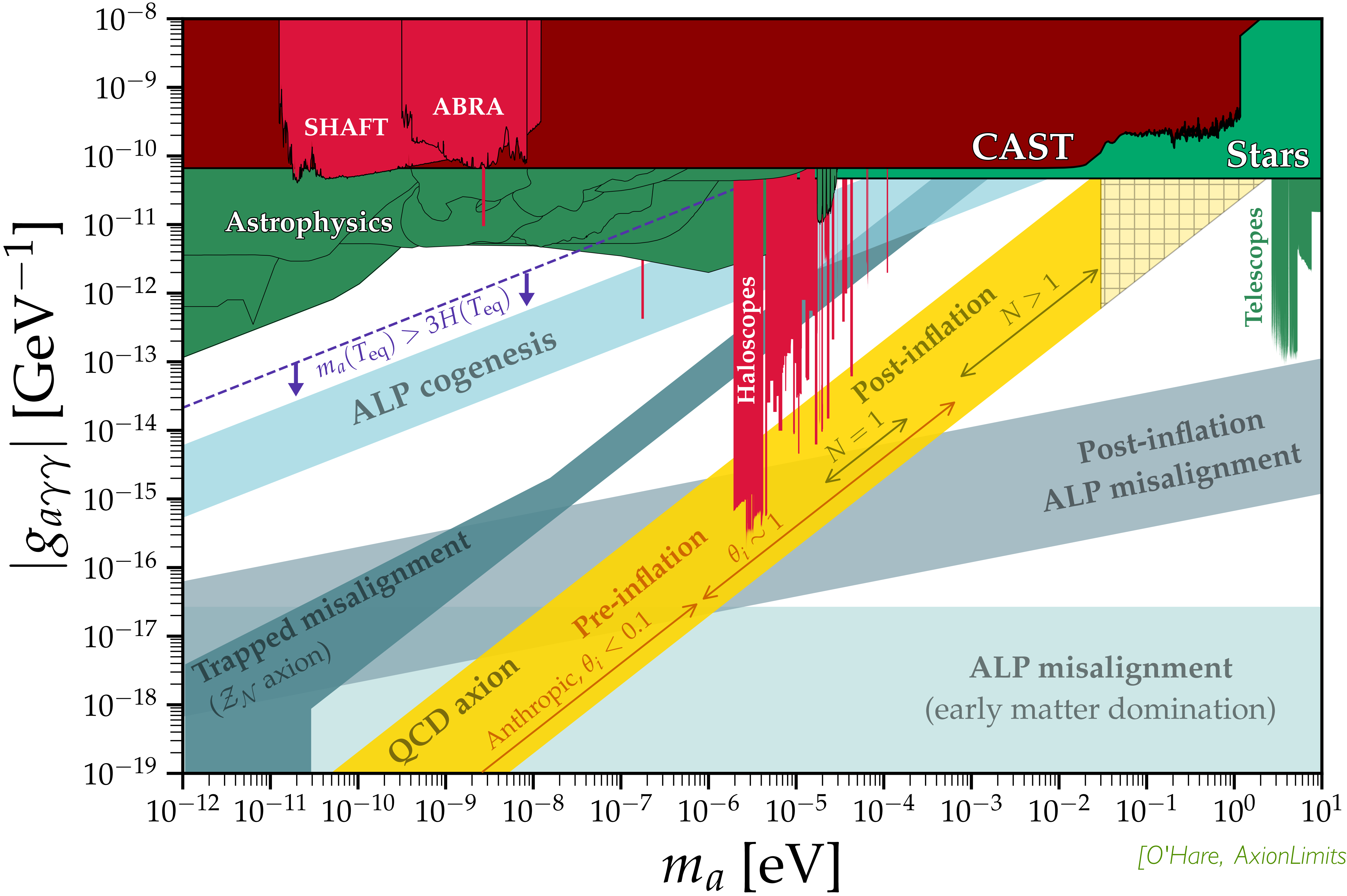
$\dot{\theta} \neq 0$ kinetic misalignment



[Co, Hall, Harigaya, 2020,+…]

AXION DM SEARCHES

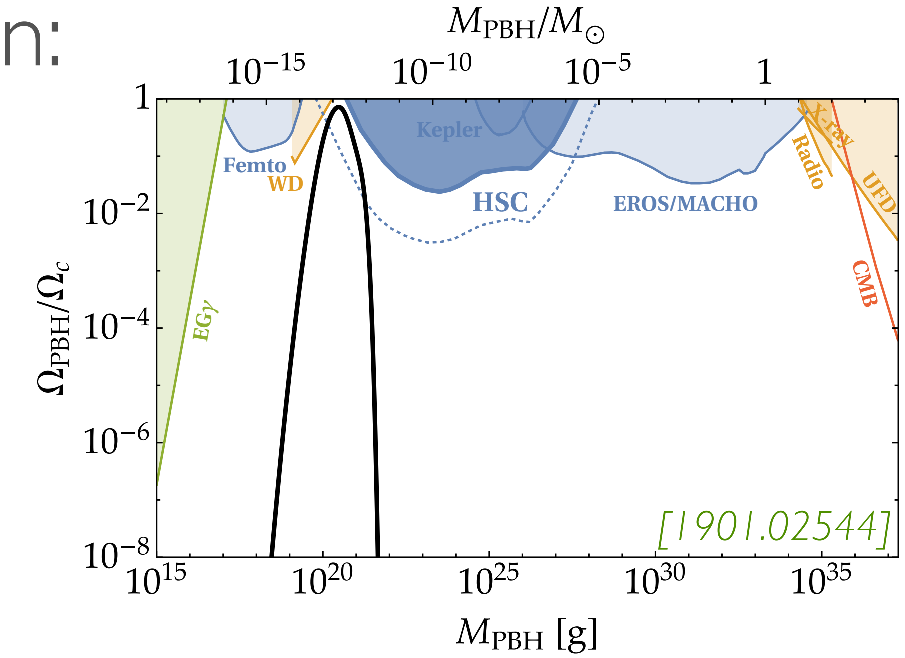
$$\Omega_a h^2 \sim 0.12 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6} \langle \theta_i^2 \rangle \qquad g_{a\gamma\gamma} \sim \mathcal{O}(1)\,\frac{\alpha_{\mathrm{EM}}}{2\pi f_a}$$



[O'Hare, AxionLimits@github]

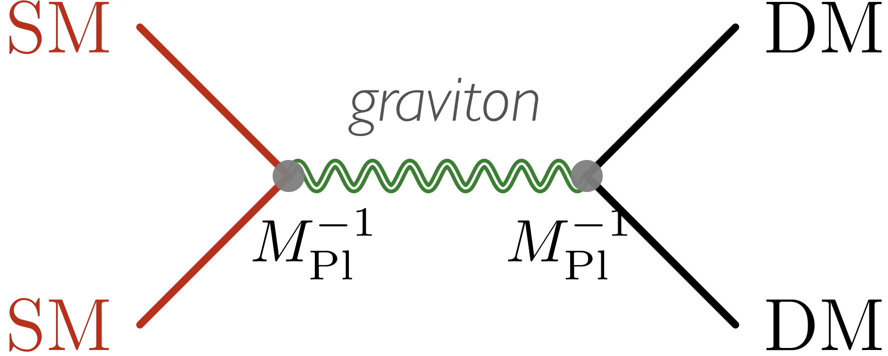
GRAVITATIONAL DARK MATTER

- Nightmare scenario: DM only interacts gravitationally!
- Mechanisms for gravitational DM production:
  - Primordial black holes (PBH) as DM



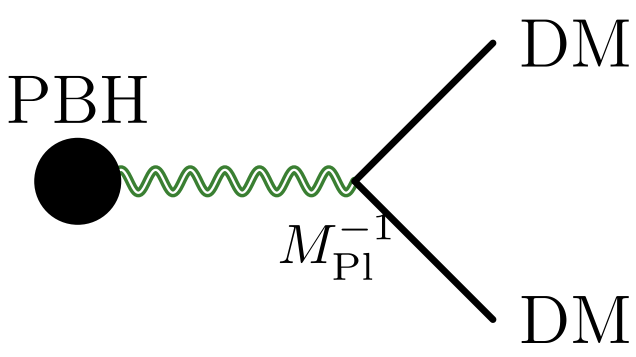
[1901.02544]

  - Freeze-in via graviton portal

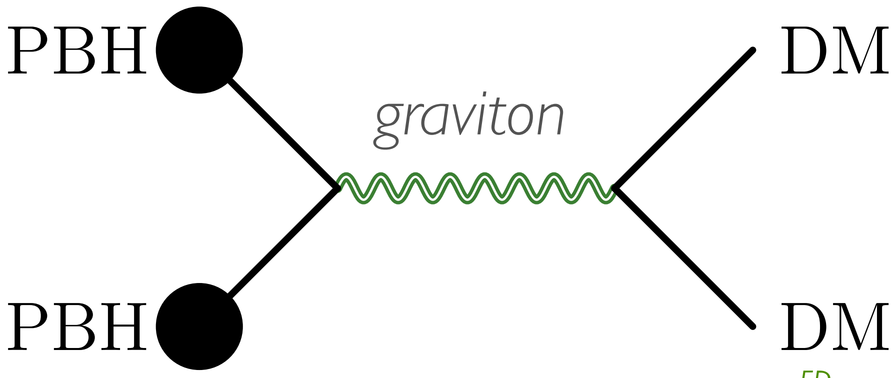


[Garny, Sandora, Sloth 2015; A.A., Grzadkowski, Socha 2019+…]

  - PBH decay/scattering



[Hooper et al, 2019; Baldes et al. 2020+…]



[Bernal, Zapata 2020; +…]

GRAVITATIONAL PARTICLE PRODUCTION

- DM from gravitational particle production due to quantum fluctuations

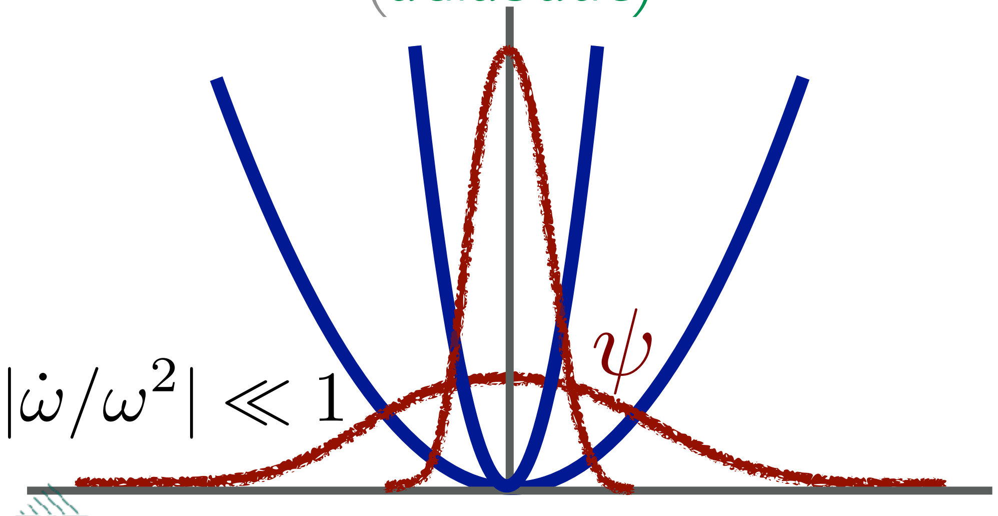
  [Schrodinger 1939; Parker 1969 ; Zeldovich, Starobinsky 1972; Ford 1987; +…]

- Rapid expansion in the early universe (during and after inflation) leads to non-adiabatic production of quantum excitations from the background fields.

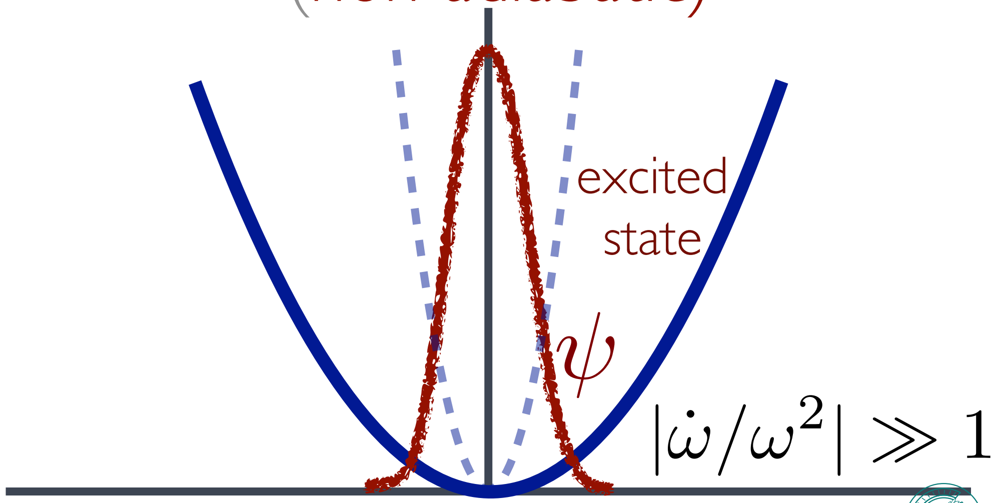
- Analogy: 1D hormonic oscillator with time-dependent frequency

$$\boxed{\ddot{x}(t) + \omega^2(t)x(t) = 0}$$

slow frequency change
(adiabatic)



fast frequency change
(non-adiabatic)



GRAVITATIONAL DARK MATTER

- Why gravitational production of dark matter?
  - An unavoidable consequence of the rapid expansion of the Universe
  - DM number density is tied with inflationary observables; Hubble scale H_I, reheating temperature $T_{\rm rh}$, inflaton potential $V(\phi)$, etc.
  - Besides gravity, no other interaction is required
  - Gravitational DM production is sensitive to inflationary and reheating dynamics so it may be a probe into early universe cosmology.

[Graham, Mardon, Rajendran 2015,
A.A., Grzadkowski, Socha, 2020+…]

EARLY UNIVERSE COSMOLOGY

- Inflation: de Sitter solution
- Reheating: non-standard cosmology

$$w = \rho_\phi / p_\phi : [-1/3, 1]$$

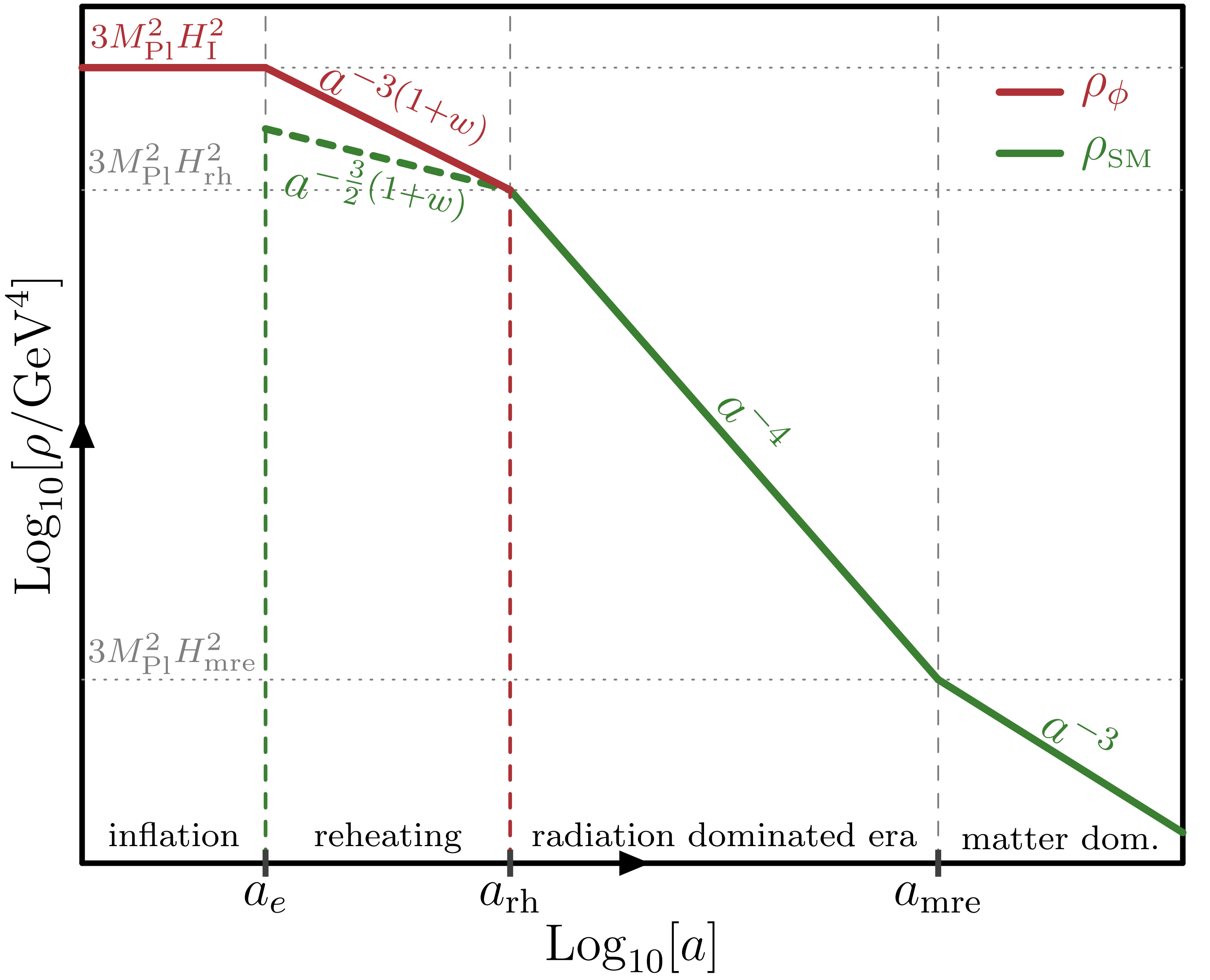
- Standard cosmological evolution after reheating

$$\boxed{\rho(a) = 3 M_{\rm Pl}^2 H^2(a)}$$

$$H(a) = \begin{cases} H_{\rm I}, & a \leq a_e \\ H_{\rm I} \left(\dfrac{a_e}{a}\right)^{\frac{3(1+w)}{2}}, & a_e < a \leq a_{\rm rh} \\ H_{\rm rh} \left(\dfrac{a_{\rm rh}}{a}\right)^{2}, & a_{\rm rh} < a \end{cases}$$

[A.A., Grzadkowski, Socha, 2020]

Evolution of the energy density $\rho(a)$



$$\gamma \equiv \sqrt{\frac{H_{\rm rh}}{H_{\rm I}}}$$

Reheating

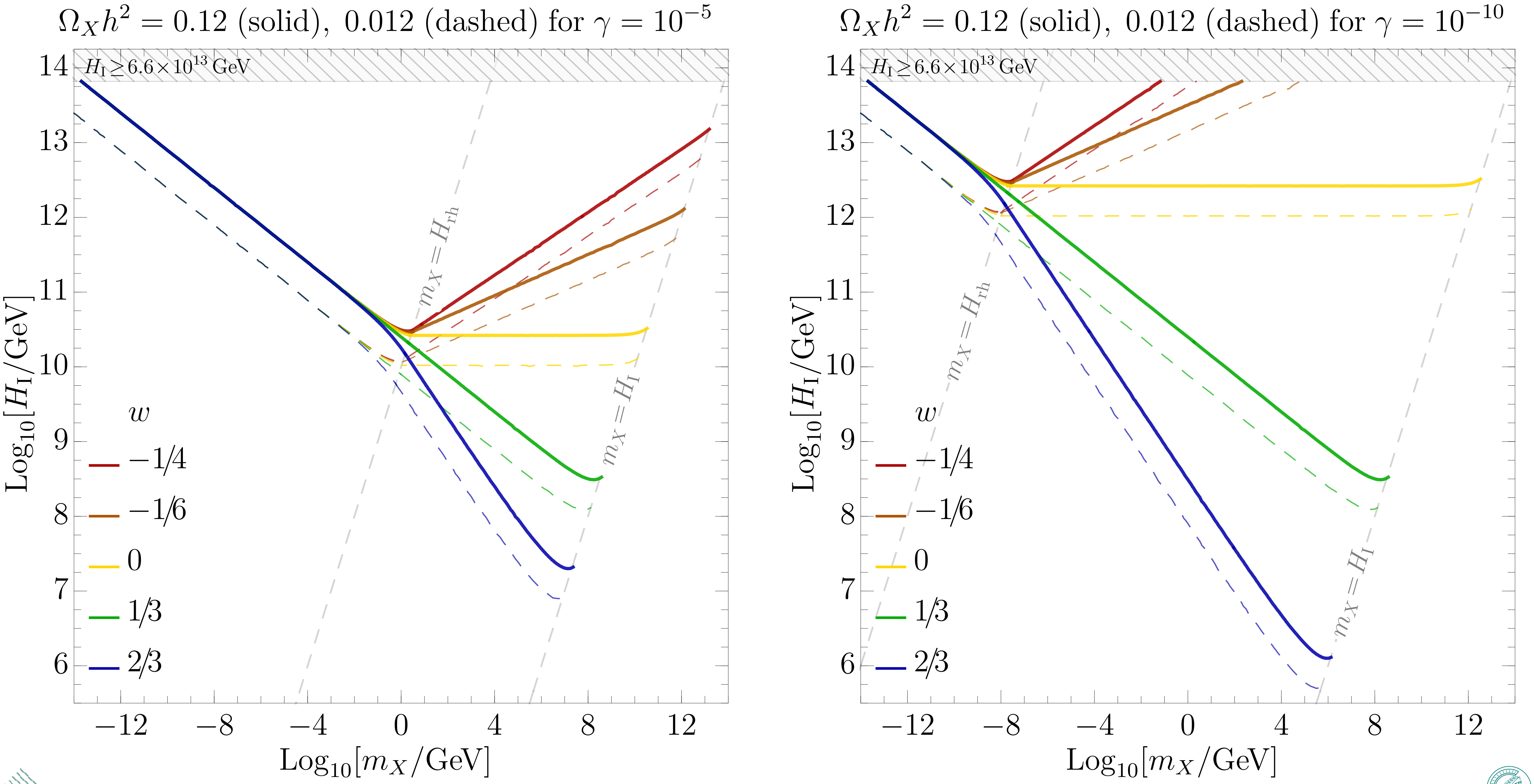
$$10^{-18} \leq \gamma \leq 1$$

$T_{\rm rh} \gtrsim 10\,\mathrm{MeV}$

DARK PHOTON DM

$$\Omega_X h^2 \approx 0.12 \times \begin{cases} \left(\frac{m_X}{0.33\mathrm{GeV}}\right)^{\frac{2w}{1+w}} \left(\frac{H_\mathrm{I}}{3.3\times 10^{10}\mathrm{GeV}}\right)^{\frac{5+w}{2(1+w)}} \left(\frac{10^{-5}}{\gamma}\right)^{\frac{3w-1}{1+w}}, & H_\mathrm{rh} \leq m_X < H_\mathrm{I} \\ \left(\frac{m_X}{2\times 10^{-14}\mathrm{GeV}}\right)^{1/2} \left(\frac{H_\mathrm{I}}{6.6\times 10^{13}\mathrm{GeV}}\right)^{2}, & m_X < H_\mathrm{rh} \end{cases}$$

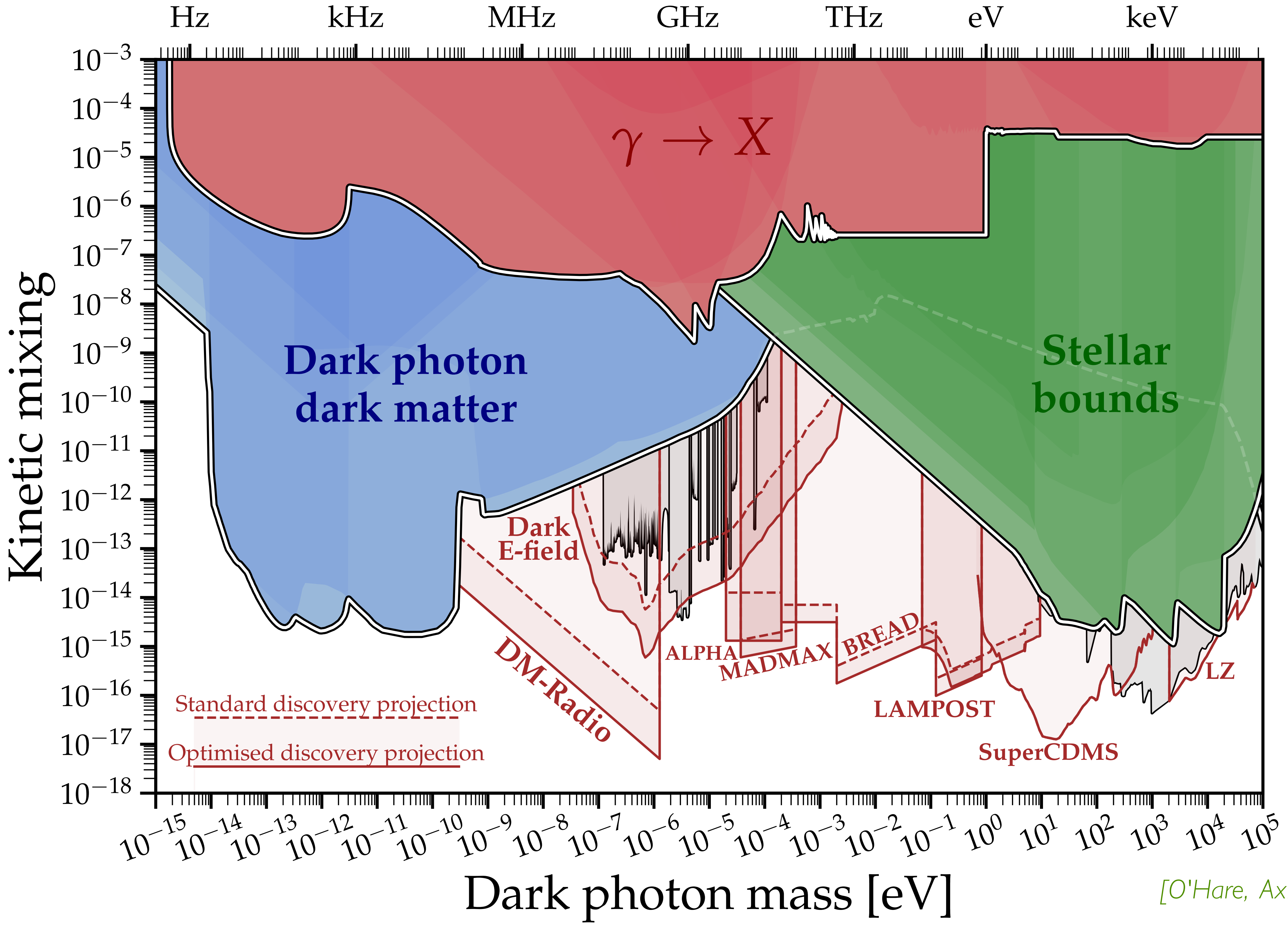
[A.A., Grzadkowski, Socha, 2020]


$\Omega_X h^2 = 0.12$ (solid), 0.012 (dashed) for $\gamma = 10^{-5}$

$\Omega_X h^2 = 0.12$ (solid), 0.012 (dashed) for $\gamma = 10^{-10}$

DARK PHOTON SEARCHES

- Gravitational dark photon DM can be detected if $\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu}$



[O'Hare, AxionLimits@github]

CONCLUSIONS

- Simplified WIMP DM models are in tension with ever-strengthening experimental bounds.

- Significant progress has been made on freeze-in DM, gravitationally produced DM, axion DM, PBHs, ...

- Early universe cosmology, e.g. inflation/reheating dynamics, can play a significant role in non-thermal DM production.

- The search for DM remains a well-motived task for BSM physics for the coming decades.

Thank you!

The BEH mechanism at high temperature – a link to matter production –

Iason Baldes

2018-2019:ULB EoS, 2019-2022: ULB F.R.S.-FNRS,

2022-: LPENS

CosmoChart

Horizon 2020, grant agreement No 101002846

European Research Council

Established by the European Commission

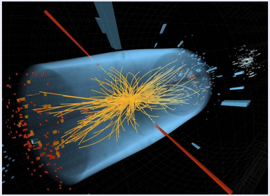
LPENS

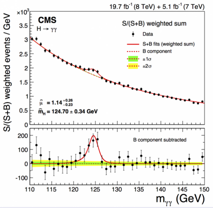
LABORATOIRE DE PHYSIQUE
DE L'ÉCOLE NORMALE SUPÉRIEURE

A Decade of Discoveries in High Energy Physics
Brussels, 9 March 2023

The SM H boson and its mass

Following the 2012 discovery



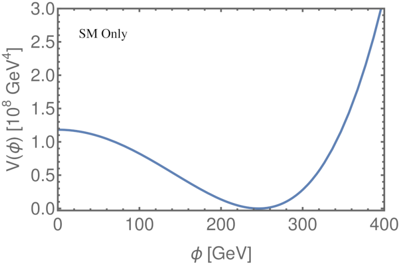


The mass is now also precisely measured:

$$m_h = 125.25 \pm 0.17\ \mathrm{GeV}$$

[PDG Avg. of ATLAS/CMS results]

SM H Potential

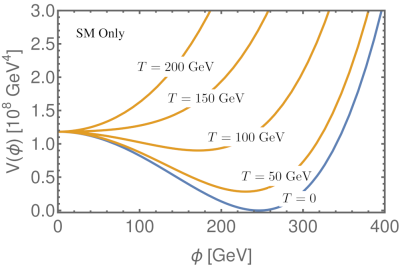


$$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \phi \end{pmatrix} \qquad V(\phi) = -\frac{1}{2}\mu_H^2\phi^2 + \frac{1}{4}\lambda_H\phi^4$$

All the parameters are known:

$\sqrt{2}\mu_H = m_h = 125$ GeV [LHC] $\qquad v_{\mathrm{EW}} = \sqrt{\frac{m_h^2}{2\lambda_H}} = 246$ GeV [Muon decay]

At finite temperature

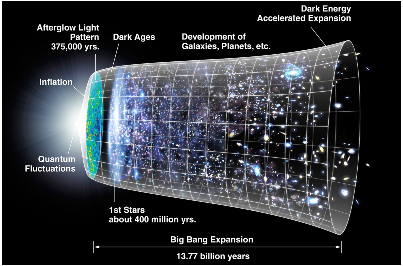


$$V(H) \approx -\frac{1}{2}\mu_H^2\phi^2 + \frac{1}{4}\lambda_H\phi^4 + \frac{1}{2}c_H T^2\phi^2$$

The thermal mass coefficient is related to other SM couplings:

$$c_H \approx \left(\frac{\lambda_H}{2} + \frac{3g_2^2}{16} + \frac{g_Y^2}{16} + \frac{y_t^2}{4}\right) \approx 0.4$$

Cosmological Puzzles



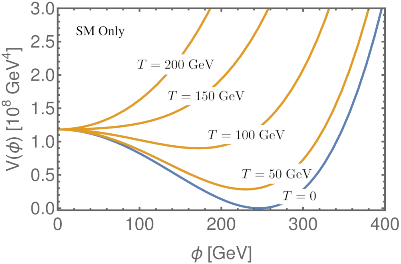
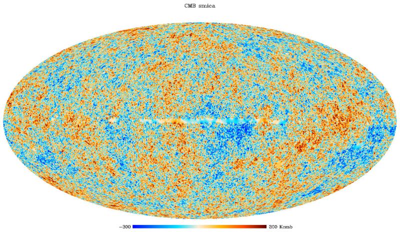


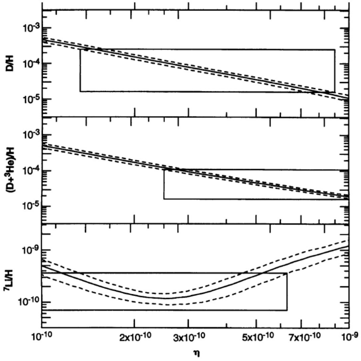
Image: NASA/Wikipedia

Cosmological puzzles which could be related to the SM H boson

- Dark Energy
- Inflation
- Dark Matter
- Baryon Asymmetry → Ordinary Matter Density

The matter-antimatter asymmetry





CMB in agreement with BBN:

$$Y_B \equiv \frac{n_b - n_{\bar{b}}}{s} = (0.86 \pm 0.02) \times 10^{-10}$$

Baryogenesis

Sakharov Conditions

1. B violation
2. C and CP violation
3. Departure from thermal equilibrium (or spontaneously broken CPT)

SM + FLRW

1. (B+L) violation present in symmetric phase at $T \gtrsim 100$ GeV from non-perturbative EW sphaleron process.
2. CP violation observed in quark sector.
3. Can be driven by expansion.

Electroweak baryogenesis - basic picture

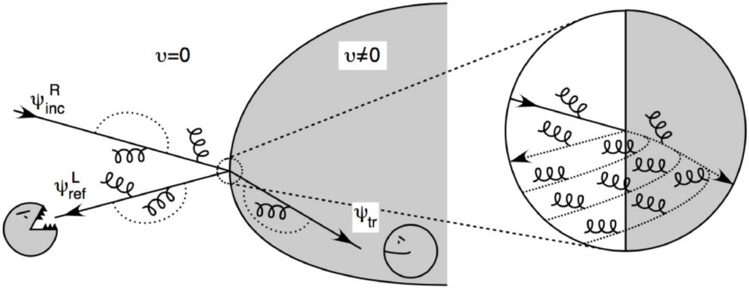
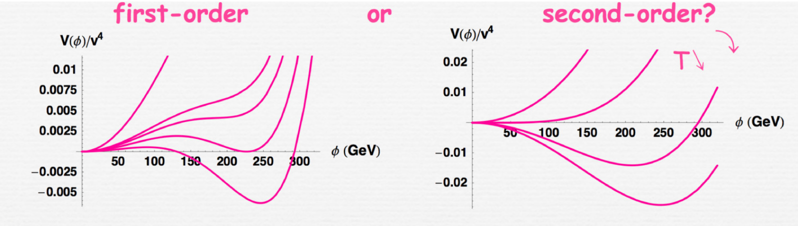


Image from - Gavela, Hernandez, Orloff, Pène, Quimbay [hep-ph/9406289]

- CP violating collisions with the bubble walls lead to a chiral asymmetry.
- Sphalerons convert this to a Baryon Asymmetry.
- This is swept into the expanding bubble where sphalerons are suppressed.

Electroweak baryogenesis - Requirements



Electroweak baryogenesis requires:

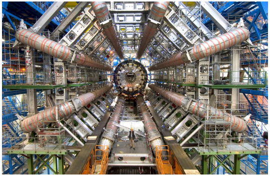
- A strong first order phase transition ($\phi_n / T_n \gtrsim 1$)
- Sufficient CP violation

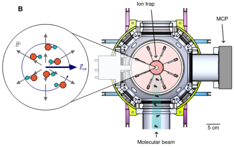
However in the SM:

- The H boson mass is too large
- Quark masses are too small

We require new EW-scale physics!

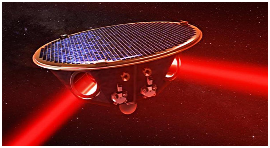
Experimental signatures

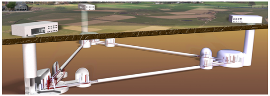




BSM Experimental signatures for EWBG

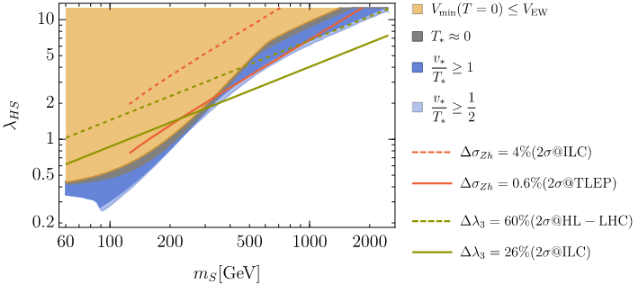
1. Collider signals associated with $V(H)$ modificiation.
2. Electric Dipole Moments associated with low scale CP violation.
3. Gravitational waves from the strong FOPT.





Singlet model

First order EW Phase Transition from a singlet - Choi, Volkas '93 + ...



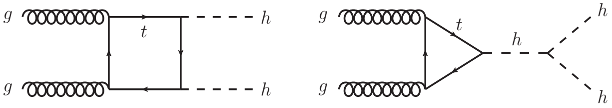
- Beniwal et al, 1702.06124

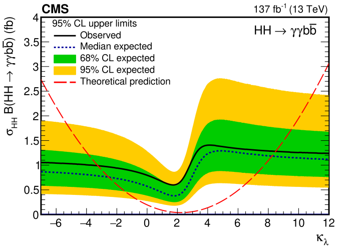
Modification of h^3 coupling

$$\lambda_3 \approx \frac{m_h^2}{2v_{\mathrm{EW}}} + \frac{\lambda_{HS}^3 v_{\mathrm{EW}}^3}{24\pi^2 m_S^2}$$

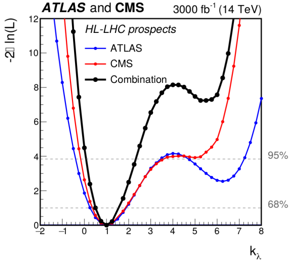
Collider signatures - Triple h coupling

SM: $V(h) = \frac{1}{2} m_h^2 h^2 + \lambda_H v_{\mathrm{EW}} h^3 + \frac{1}{4} \lambda_H h^4$ with $v_{\mathrm{EW}} = \sqrt{\frac{m_h^2}{2\lambda_H}} = 246$ GeV.





- 2011.12373

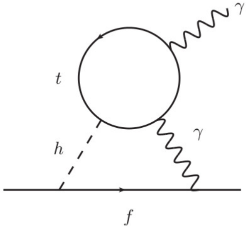


- 1902.00134

Measuring the cubic term is long term challenge.

Some, but not all, singlet models returning a strong FOPT can be excluded by HL-LHC.

Electron EDM constraint



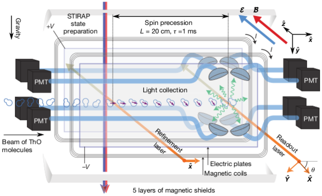
$$\frac{i}{2} d_e (\bar{e}\sigma^{\mu\nu}\gamma_5 e) F_{\mu\nu}$$

Rough estimate of the EDM - Glioti, Rattazzi, Vecchi, 1811.11740.

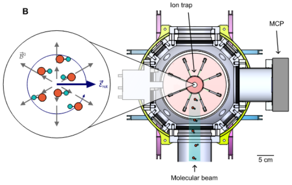
$$|d_e| \sim 10^{-29}\ e\,\mathrm{cm}\,\theta_{\mathrm{CP}} \left(\frac{50\ \mathrm{TeV}}{\Lambda}\right)^2 \qquad 1-\mathrm{loop}$$

$$|d_e| \sim 10^{-29}\ e\,\mathrm{cm}\,\theta_{\mathrm{CP}} \left(\frac{2.5\ \mathrm{TeV}}{\Lambda}\right)^2 \qquad 2-\mathrm{loop}$$

Experimental searches - EDMs

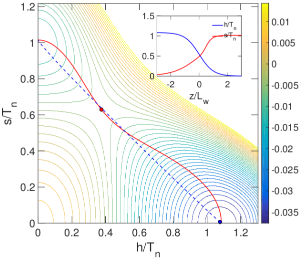


ACMEII (ThO): $|d_e| < 1.1 \times 10^{-29}$ $e\,\mathrm{cm}$ - Nature 562, 355–360 (2018)



Colorado (HfF^+): $|d_e| < 4.1 \times 10^{-30}$ $e\,\mathrm{cm}$ - 2212.11841

Hiding the CP violation



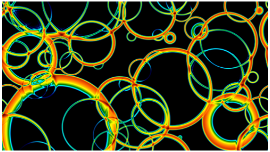
$\mathcal{L} \supset \frac{1}{2}\bar{\chi}\left((\eta P_R + \eta^* P_L)S + m_\chi\right)\chi + y\bar{L}_\tau H_2 P_R \chi + \mathrm{h.c.}$ - from [1] below.

One idea is to hide the CP violation in the dark sector

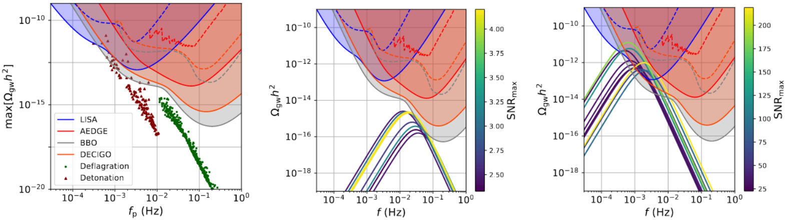
1. "Electroweak baryogenesis from a dark sector",
   Cline, Kainulainen, Tucker-Smith, 1702.08909.
2. "Electroweak Baryogenesis From Dark CP Violation,"
   Carena, Quirós, Zhang, 1811.09719 and 1908.04818.

- eEDM at 3 or 4-loops.

Experimental searches - GWs



From a simulation by Weir et al.



Singlet model - Cline et al. 2102.12490

Strong transitions are detectable by LISA.

LVK searches for PTs have started e.g.:
..., Turbang, ... Mariotti, Sakellariadou, Sevrin et al. 2209.14707

Going beyond EWBG

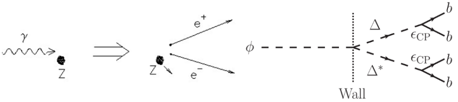
Cosmological PTs are of course of interest beyond EWBG.

- Associated Baryogenesis models not necessarily:
  1. Constrained experimentally by EDMs.
  2. Limited to small γ_{wall} in order to match Y_B.
- Larger range of GW signals possible.

Say we have a phase transition with $\langle \phi \rangle : 0 \to v_\phi$

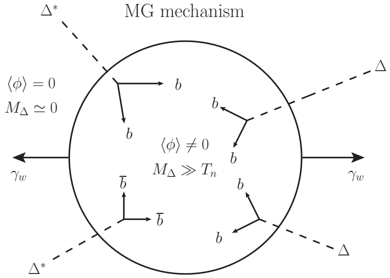
- Incoming quanta $E \sim \gamma_{\text{wall}} T \gg v_\phi$: can produce massive states
- Non-adiabatic transitions $\sigma \to S$, with $M_S \gg m_\sigma, v_\phi$
- Pair production of heavy particles $\sigma \to S + S$, with $M_S \gg m_\sigma, v_\phi$

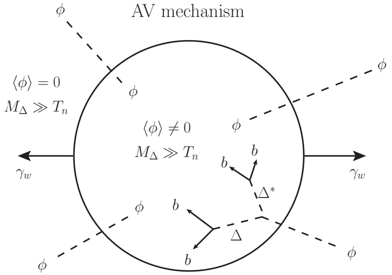
- Azatov, Vanvlasselaer, 2010.02590 Azatov, Vanvlasselaer, Yin 2101.05721



The wall breaks translational symmetry

Going beyond EWBG - Ultra relativistic walls





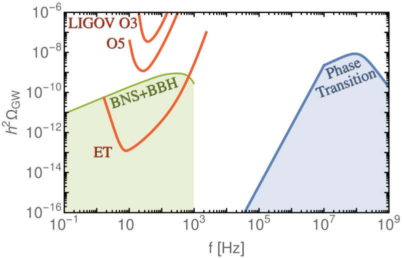
IB, Blasi, Turbang, Mariotti, Sevrin 2106.15602

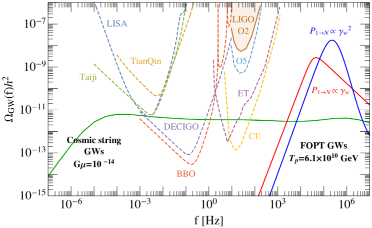
For strong phase transitions with $\langle\phi\rangle \gg T_n$.

The final states are far from equilibrium and can source the baryon asymmetry through their decays.

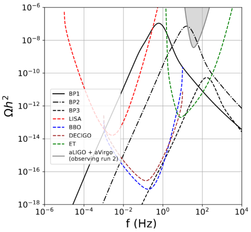
Closely related work: Azatov, Vanvlasselaer, Yin 2106.14913

Going beyond EWBG - GW signals





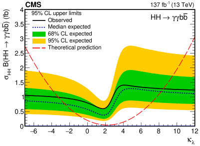
-IB, Blasi, Turbang, Mariotti, Sevrin 2106.15602 - Peisi Huang, Ke-Pan Xie 2206.04691

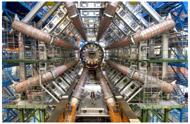


-Dasgupta et al. 2206.07032

Larger range of GW signals possible.

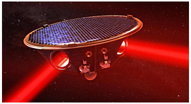
Conclusions

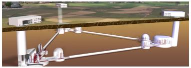




Conclusion

- SM H boson could play a leading role in the early universe
  → possible connections to Inflation, DM, Baryon asymmetry...
- EWBG well motivated, testable
  → now rather constrained baryogenesis mechanism (EDMs).
- But: Beyond the SM EW or other first order PT hardly constrained.
- Exciting interplay of future collider tests and Gravitational waves.



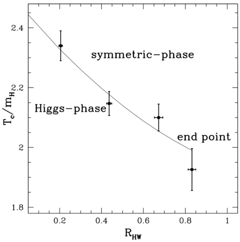


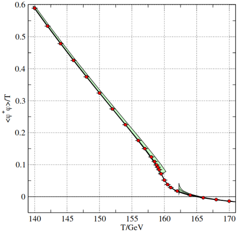
The matter-antimatter asymmetry

Textbook Argument for Baryogenesis

- In a symmetric universe $n_b/s = n_{\bar{b}}/s \approx 10^{-20}$
- The post-inflation causal volume is too small for baryons/antibaryons to be sufficiently separated
- $n_b/s = n_{\bar{b}}/s \approx 10^{-10}$ would be reached at $T \approx 40$ MeV when $M_{H^{-3}} \approx 10^{-7} M_{\odot}$
- Need a mechanism to generate the asymmetry

Electroweak phase transition - Lattice Studies





- Csikor, Fodor, Heitger, hep-ph/9809291, D'Onofrio, Rummukainen 1508.07161

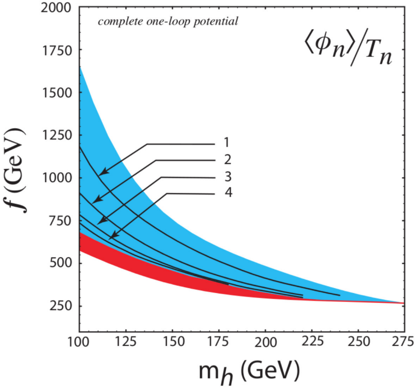
SM with $m_h = 125$ GeV predicts a crossover.
Nevertheless, only the minimum (VEV) of the potential, and the 2nd derivative there (m_h), is known if we allow for BSM physics.

The SM scalar potential can be modified.

Require a modification of the SM Scalar potential

Successful electroweak baryogenesis requires suppressed washout:

$$\frac{\Gamma_{\rm sph}}{V} \sim 10^{1\div 4}\left(\frac{\alpha_W T}{4\pi}\right)^4\left(\frac{2M_W(\phi)}{\alpha_W T}\right)^7 \mathrm{Exp}\left[-\frac{3.2M_W(\phi)}{\alpha_W T}\right] \Rightarrow \frac{\phi_n}{T_n} \gtrsim 1$$



- Delaunay, Grojean, Wells [0711.2511]

$$V(\Phi) = m^2|\Phi|^2 + \lambda|\Phi|^4 + \frac{1}{f^2}|\Phi|^6$$

Other options:

- Singlet models/tree level barriers
- Multi-step transitions
- Thermal barriers from bosonic loops

CPV and The Baryonic Yield

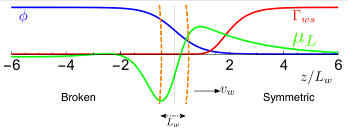


Image from 1706.08534 - Bruggisser, Konstandin, Servant

Diffusion equation

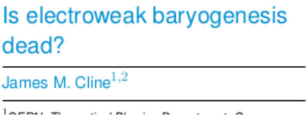
$$\partial_z\, n_B = \frac{3}{2} v_w^{-1} \Gamma_{ws} \left(N_c \mu_L T^2 - \mathcal{A}\ n_B \right)\ , \qquad \Gamma_{ws} = 10^{-6}\ T\ \exp(-a\phi(z)/T)$$

$$\eta_B = \frac{n_B(-\infty)}{s} = \frac{135\ N_c}{4\pi^2 v_w g_* T} \int_{-\infty}^{+\infty} dz\ \Gamma_{ws}\ \mu_L\ e^{-\frac{3}{2}\mathcal{A}\frac{1}{v_w}\int_{-\infty}^{z} dz_0 \Gamma_{ws}}$$

$$\eta_B \sim \frac{\Gamma_{ws}\mu_L L_w}{g_* T} \sim \frac{10^{-8}\mu_L}{T} \quad \text{for} \quad L_w \sim \frac{1}{T}$$

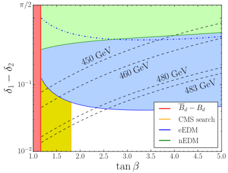
EDMs - Situation 2013-2018

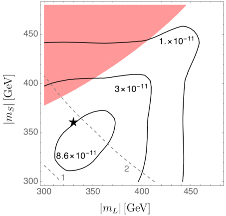
ACME: $|d_e| < 8.7 \times 10^{-29}\ e\,\mathrm{cm}$ (2013) $|d_e| < 9.4 \times 10^{-29}\ e\,\mathrm{cm}$ (2017)

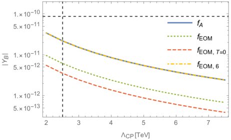


Is electroweak baryogenesis dead?

James M. Cline[1,2]

1. 

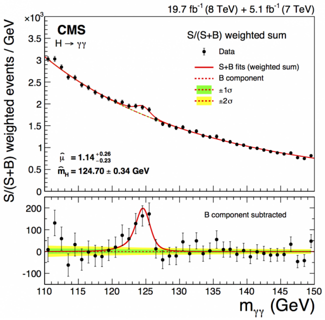
2. 

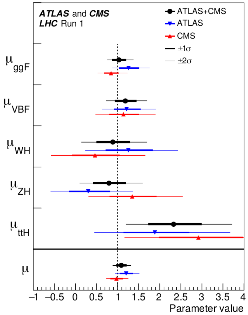
3. 

1. 1611.05874 - Dorsch, Huber, Konstandin, No
2. 1707.02306 - Egana-Ugrinovic
3. 1710.04061 - de Vries, Postma, van de Vis, White

Severe constraint on EWBG!

LHC constraints - Limit on Mixing



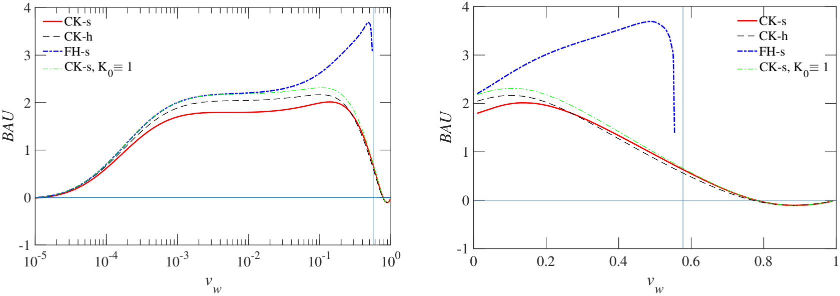


$\mu = 1.09 \pm 0.11$	LHC Run 1	$7 + 8$ TeV	1606.02266
$\mu = 1.10 \pm 0.06$	LHC Run 2	13 TeV	1810.02521

$$\theta \lesssim \mathcal{O}(0.1)$$

But: problem if $v_{\mathrm{wall}} \simeq 1$.

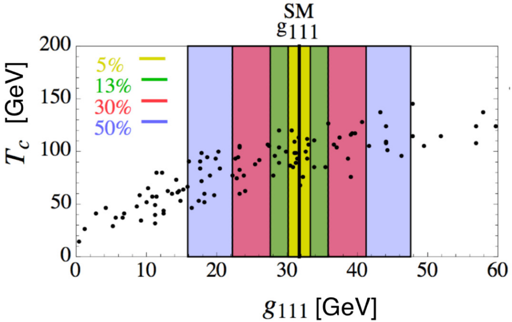
- Less of the plasma is pushed by the wall at high v_{wall}.
- This suppresses the BAU.



From: Cline, Kainulainen 2001.00568

Also see: Dorsch, Huber, Konstandin 2106.06547

Collider signatures - Singlet models difficult to detect



Somewhat optimistically:

$\sim 30 - 50\%$ HL-LHC or TLEP

$\sim 13\%$ ILC

$\sim 3 - 8\%$ 100 TeV pp

- Correlation between T_c and triple Higgs couplings $g_{111}h^3$ in a singlet model. - Profumo, Ramsey-Musolf, Wainwright, Winslow [1407.5342]
- And/or: mixing reducing the signal strength.
  Currently LHC: $\theta \lesssim \mathcal{O}(0.1)$ compatible with singlet models of EWBG.
- And/or: direct searches for heavy singlet states.