Electroweak Phase Transition in a Vector Dark Matter Scenario

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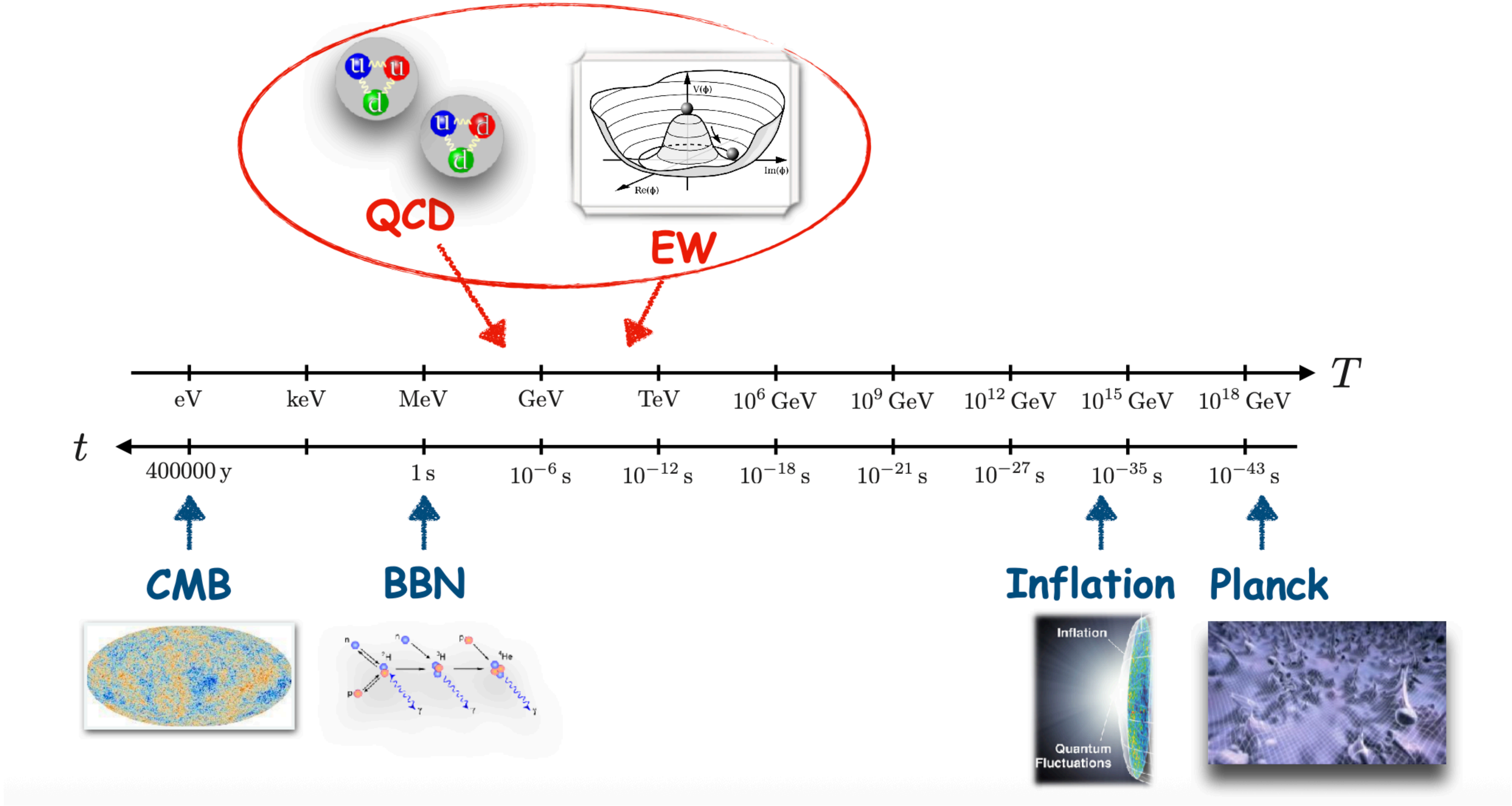
Thermal History of the Universe

Phase transitions are important events in the evolution of the Universe

- the SM predicts two of them (QCD confinement and EW symmetry breaking)

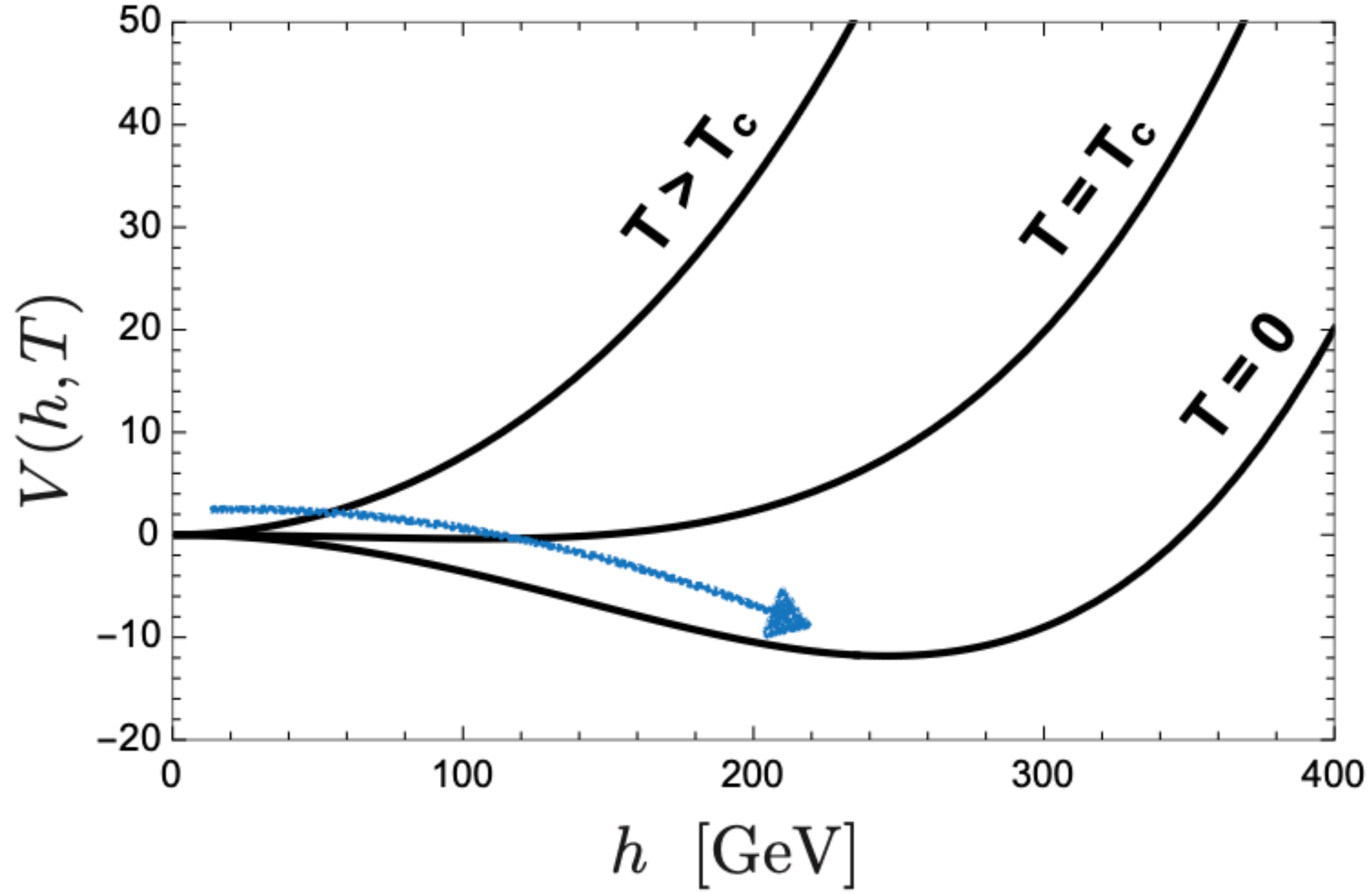


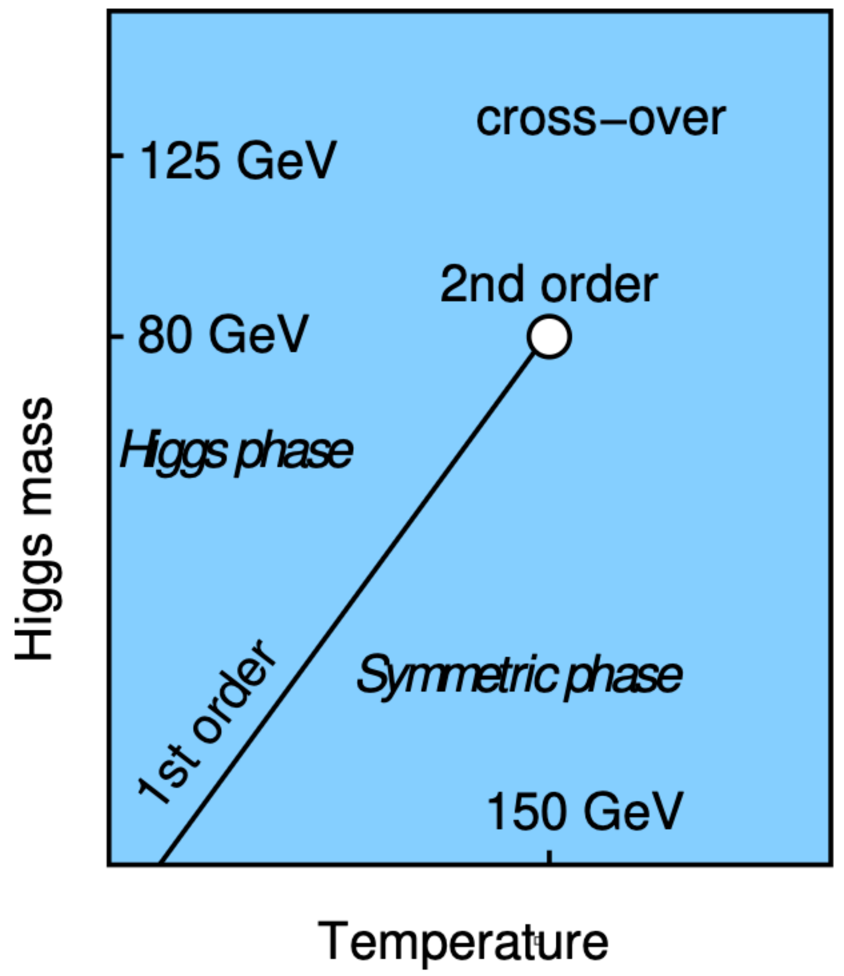
Phase Transition in the SM

In the SM the QCD and EW PhT are extremely weak

→ the two phases are smoothly connected (cross over)

- no barrier is present in the effective potential
- the field gently "rolls down" towards the global minimum when $T < T_c$
- no strong breaking of thermal equilibrium
- no distinctive experimental signatures





Phase Transition Beyond the SM

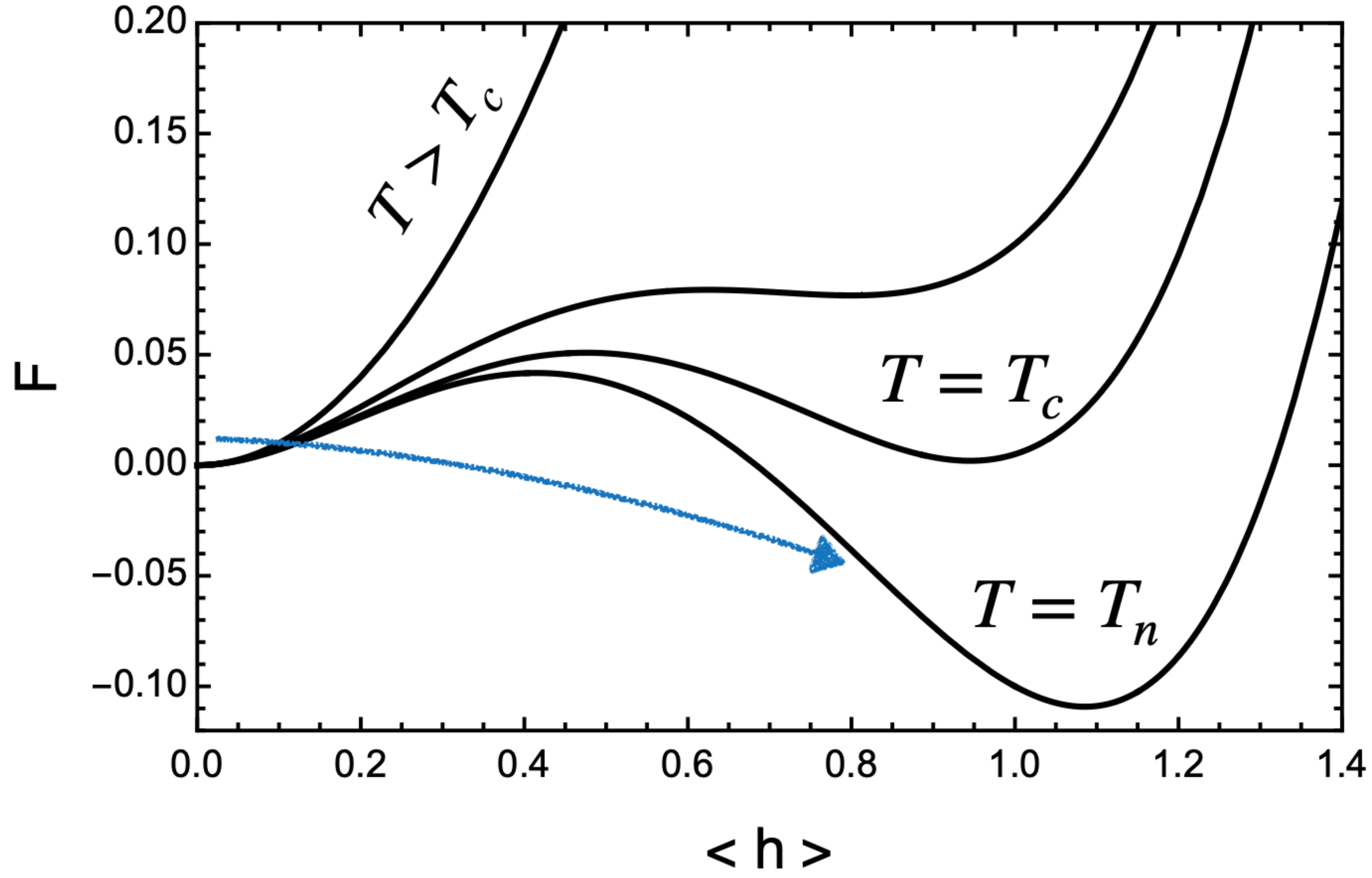
New physics may provide **first order** phase transitions

- a barrier in the potential may be generated from tree-level deformations, thermal or quantum effects

- the field tunnels from false to true minimum at

  $T = T_n < T_c$

- the transition proceeds through bubble nucleation
- significant breaking of thermal equilibrium
- interesting experimental signatures (eg. gravitational waves)

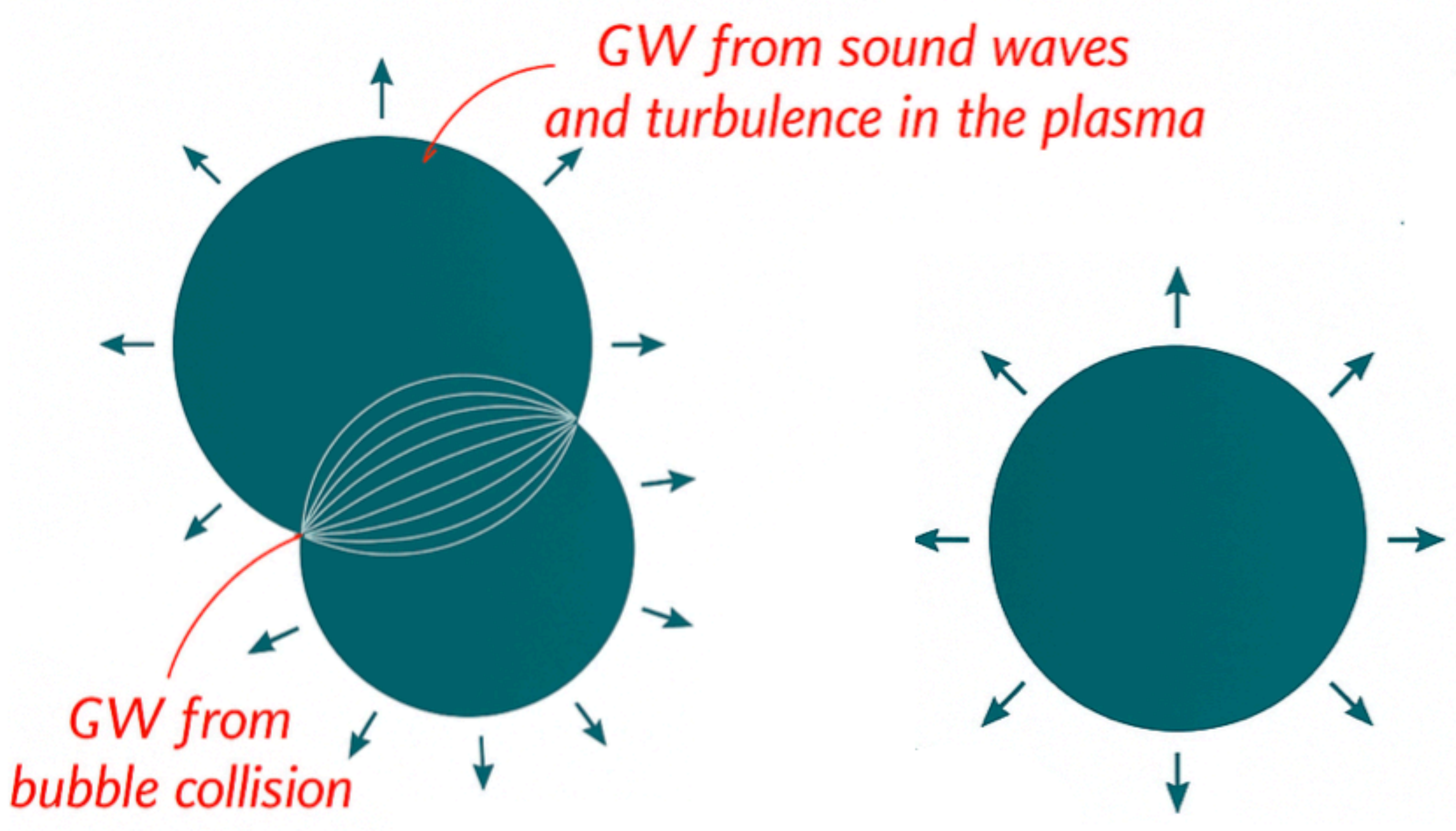


How does phase transition source GW?

- First-order phase transition: proceeds via bubble nucleation similar to boiling water

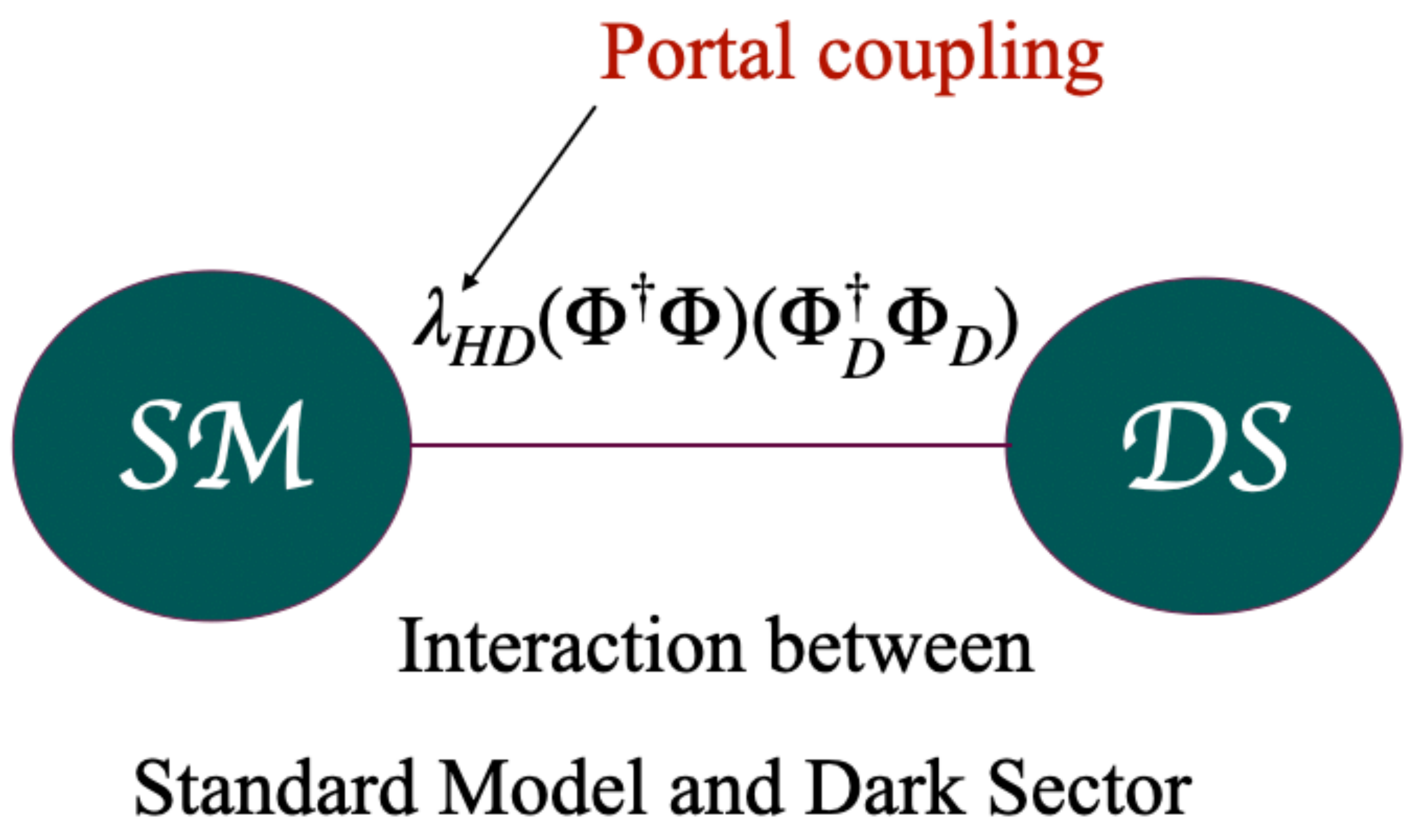
- GWs then sourced from
  - sound waves in the plasma
  - collisions of bubbles
  - turbulence in plasma

$$h^2\Omega_{GW} \simeq h^2\Omega_{col} + h^2\Omega_{sw} + h^2\Omega_{turb}$$



Dark $SU(2)$ Model

- We consider an extension of the SM with a $SU(2)_D$ gauge symmetry under which all the SM particles are singlets

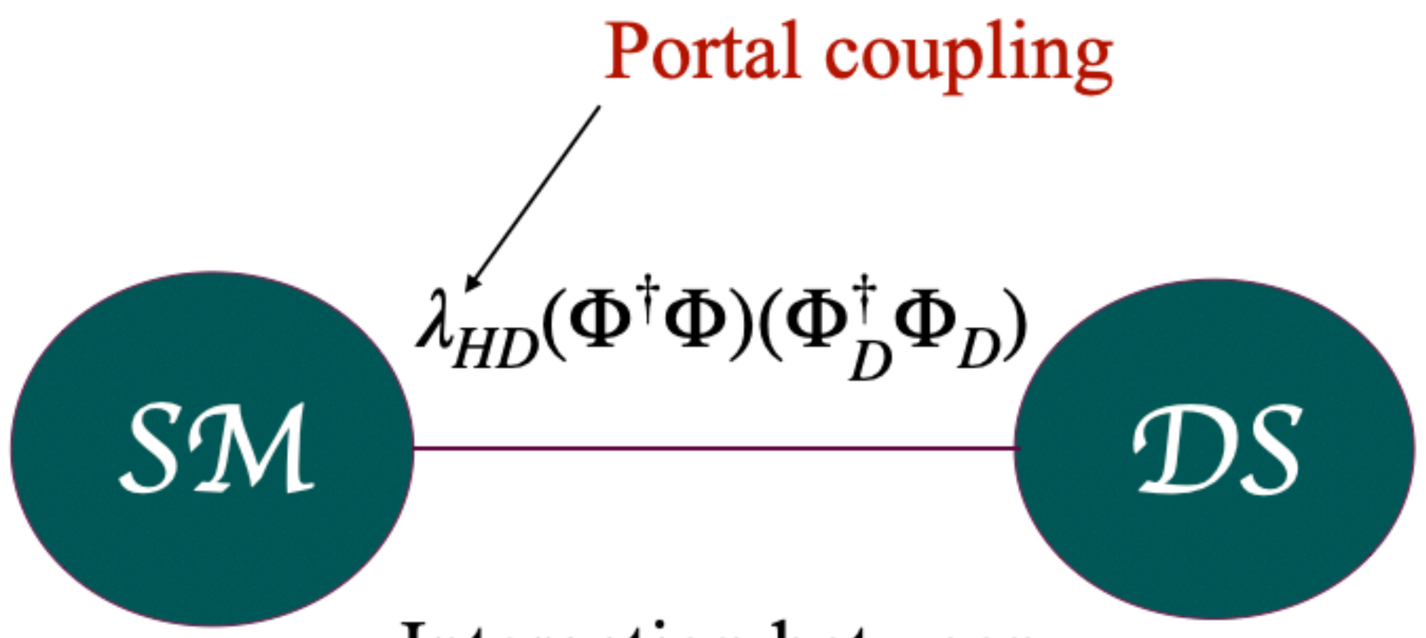


- We introduce a scalar doublet that breaks the $SU(2)_D$ symmetry via a Higgs mechanism in the dark sector.
- The custodial $SO(3)$ symmetry in the $W^\mu_{1,2,3}$ component space ensures that three spin-one particles are stable and mass-degenerate with a common mass $m_{V_D} = g_D v_D/2$
- Custodial symmetry prevents the decay of the gauge bosons, due to the fact that they are $SO(3)$ singlets

Dark $SU(2)$ Model

- The Lagrangian density of the model $\mathscr{L}_{SM} + \mathscr{L}_D$:

$$\mathscr{L} = \mathscr{L}_{\rm SM} - \frac{1}{4} F_D^{\mu\nu} F_{\mu\nu}^D + (D_\mu \Phi_D)^\dagger (D^\mu \Phi_D) + \mu_D^2 (\Phi_D^\dagger \Phi_D)$$
$$- \lambda_D (\Phi_D^\dagger \Phi_D)^2 - \lambda_{HD} (\Phi^\dagger \Phi)(\Phi_D^\dagger \Phi_D)$$

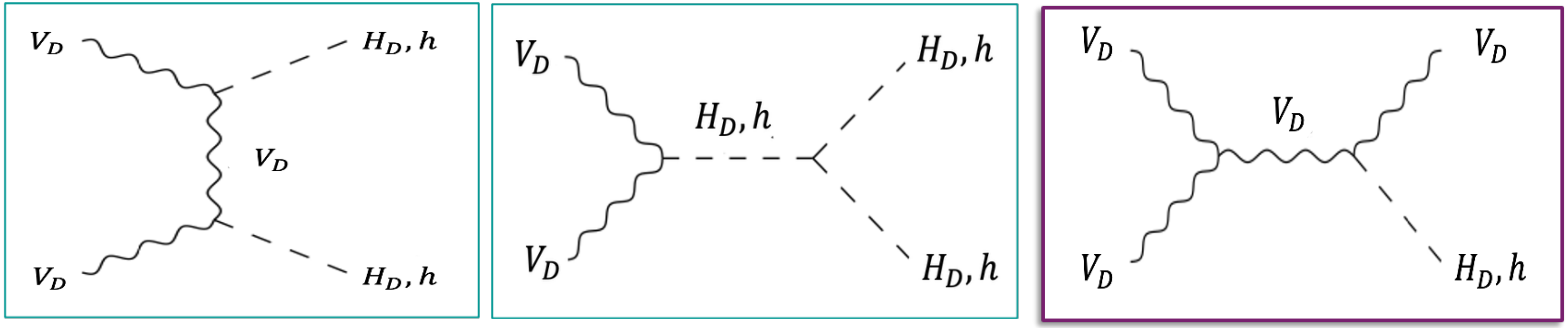


Interaction between Standard Model and Dark Sector

- Φ and Φ_D are $SU(2)_L$ and $SU(2)_D$ doublets respectively
- $\mathscr{L}_D$ is invariant under an $SO(4)$ symmetry, which is broken to the custodial $SO(3)$ symmetry by the VEV of Φ_D
- This custodial symmetry makes dark matter particles stable
  $\longrightarrow$ viable dark matter candidate
- Phase transition analysis is performed using the effective potential (tree-level + loop corrections + thermal corrections)

DM annihilation

- Some examples of DM annihilation diagrams are:



- The annihilation channel on the right exhibits a unique characteristic because it involves one DM particle in the final state, which is not possible with ordinary models based on Z_2 symmetry

Scan of Parameter Space

Random scan on the four free parameters g_D, m_{V_D}, m_{H_D} and θ_S:

- m_{V_D} and m_{H_D} logarithmically from 10 MeV to 100 TeV

  $m_{V_D} \longrightarrow$ dark matter mass

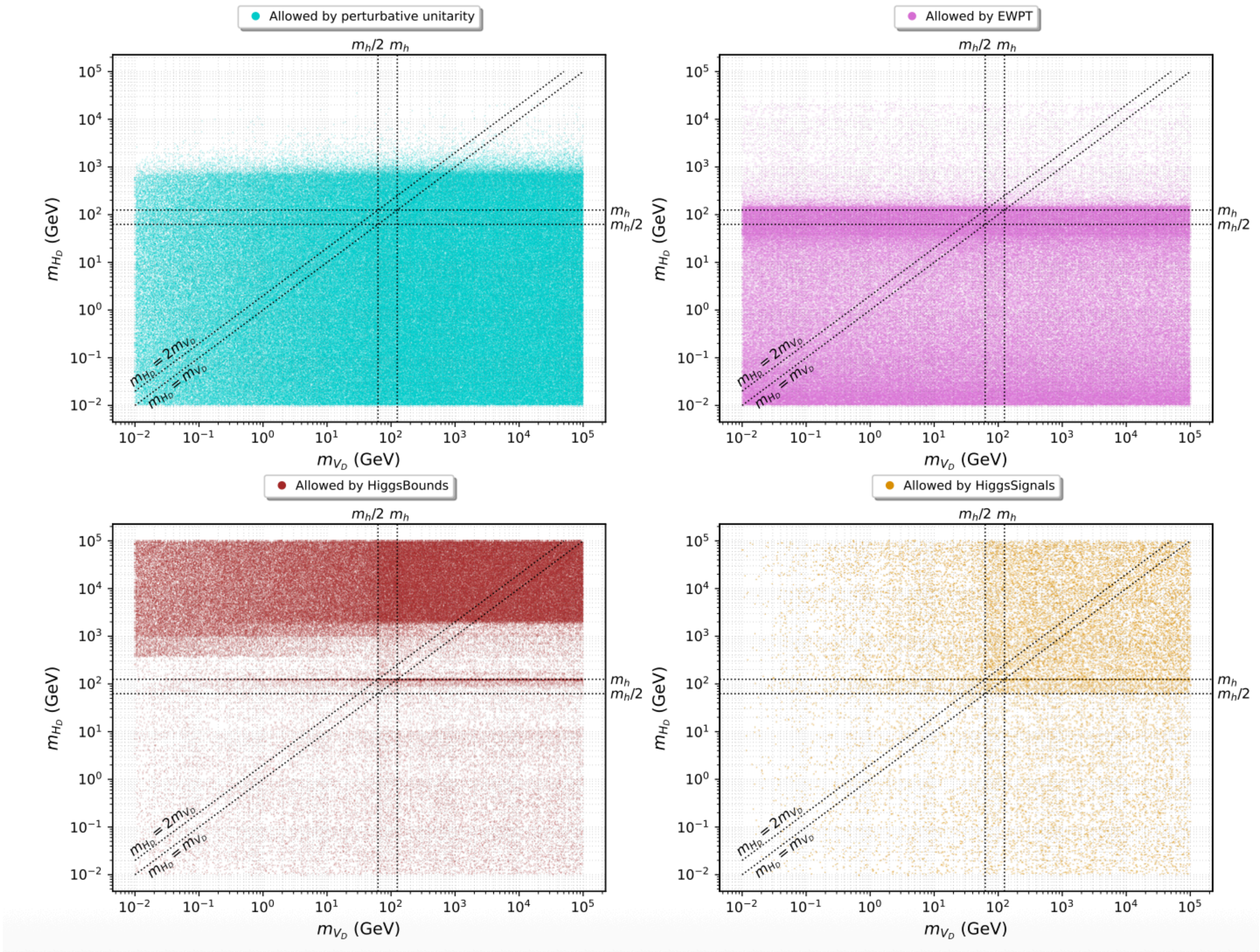
- g_D logarithmically from 10^{-4} to 4π :

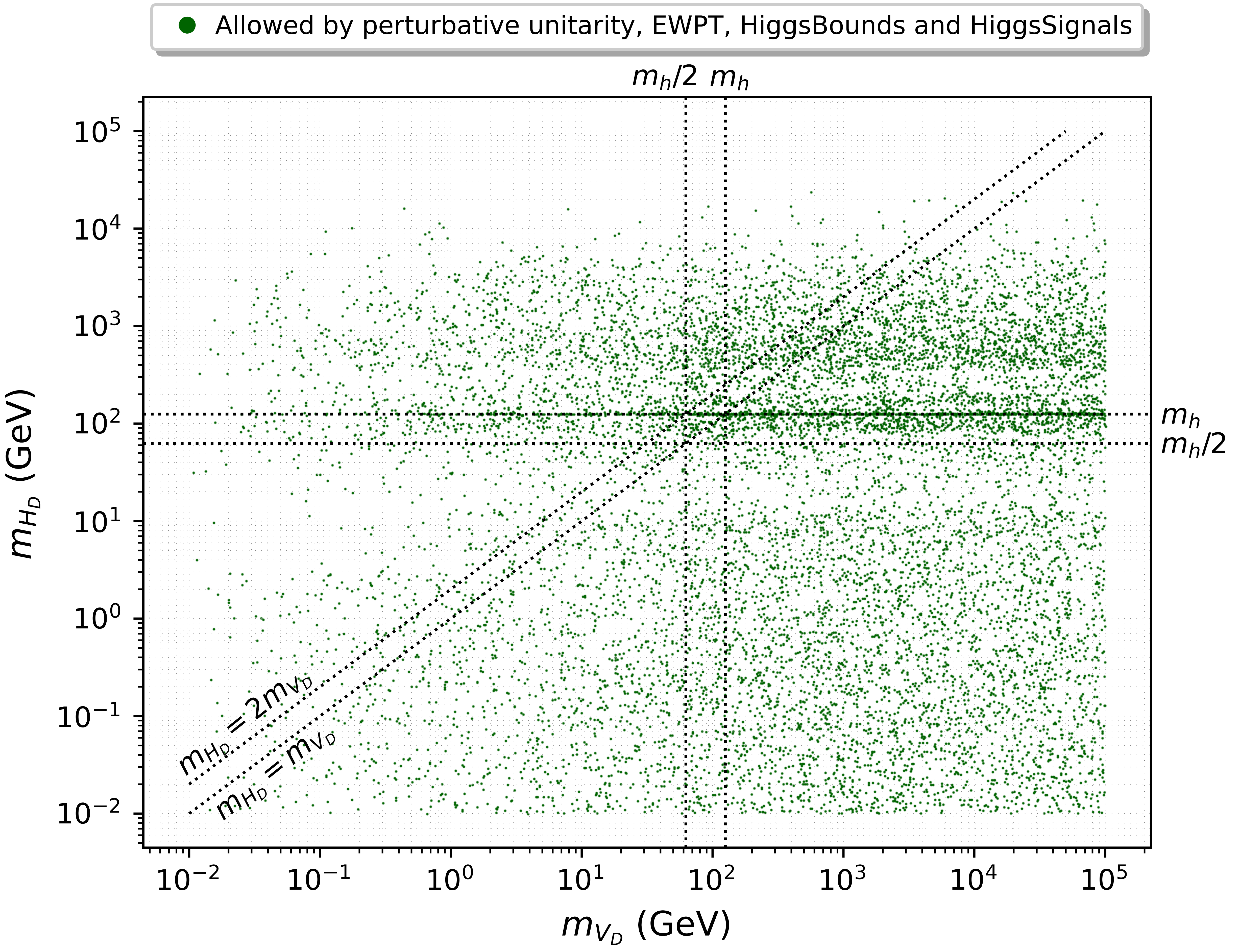
  $\longrightarrow$ $SU(2)$ dark gauge coupling

- $cos\theta_S$ linearly from 0 to 1

  $\theta_S \longrightarrow$ mixing angle between two scalars

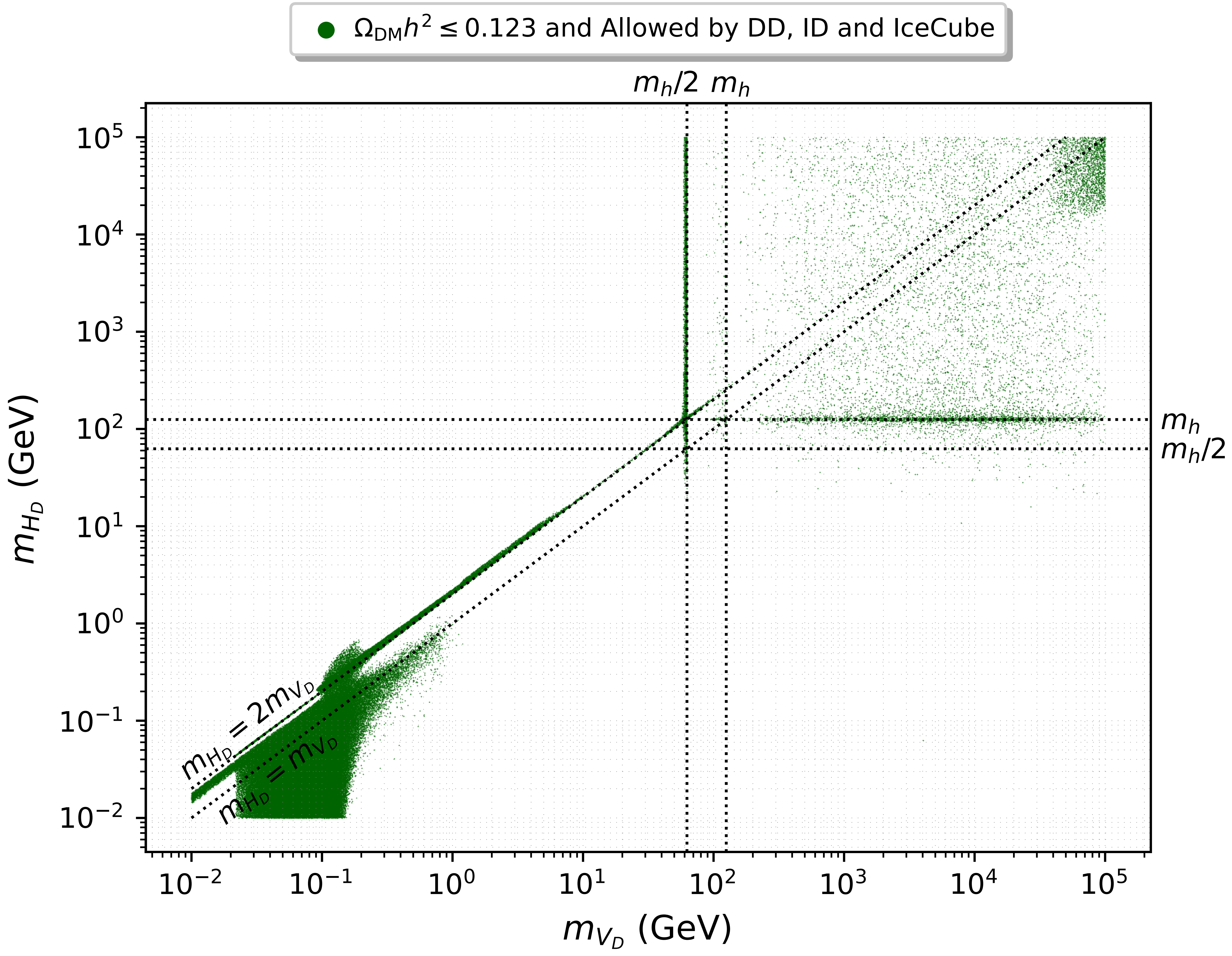
The Parameter Space: Theoretical and Collider Constraints





- The surviving parameter points are shown with different colours
- PU and EWPO strongly limit the highest values achievable for the H_D mass ($m_{H_D} \lesssim O(10^4 GeV)$)

The Parameter Space: Cosmological and Astrophysical Constrains



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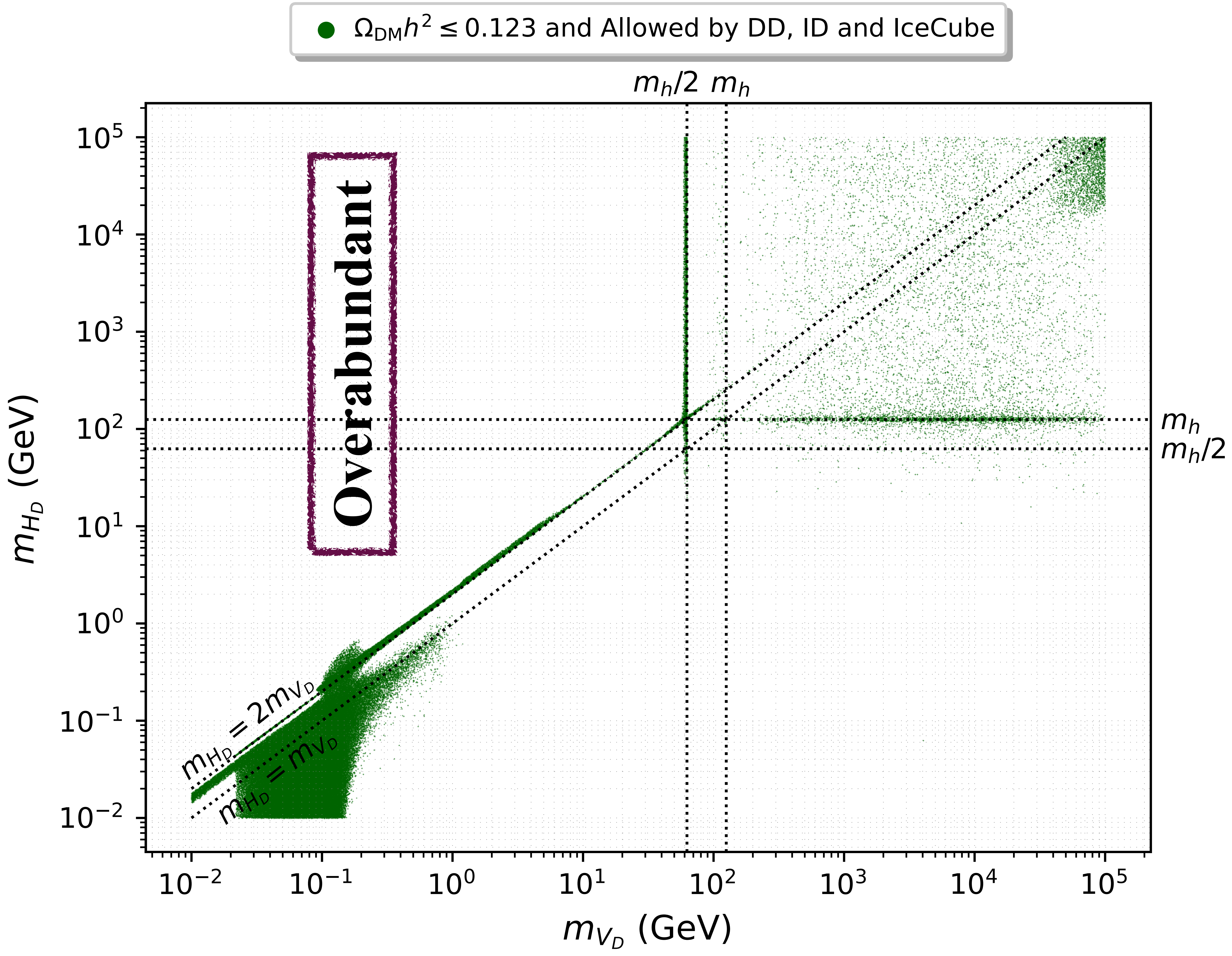

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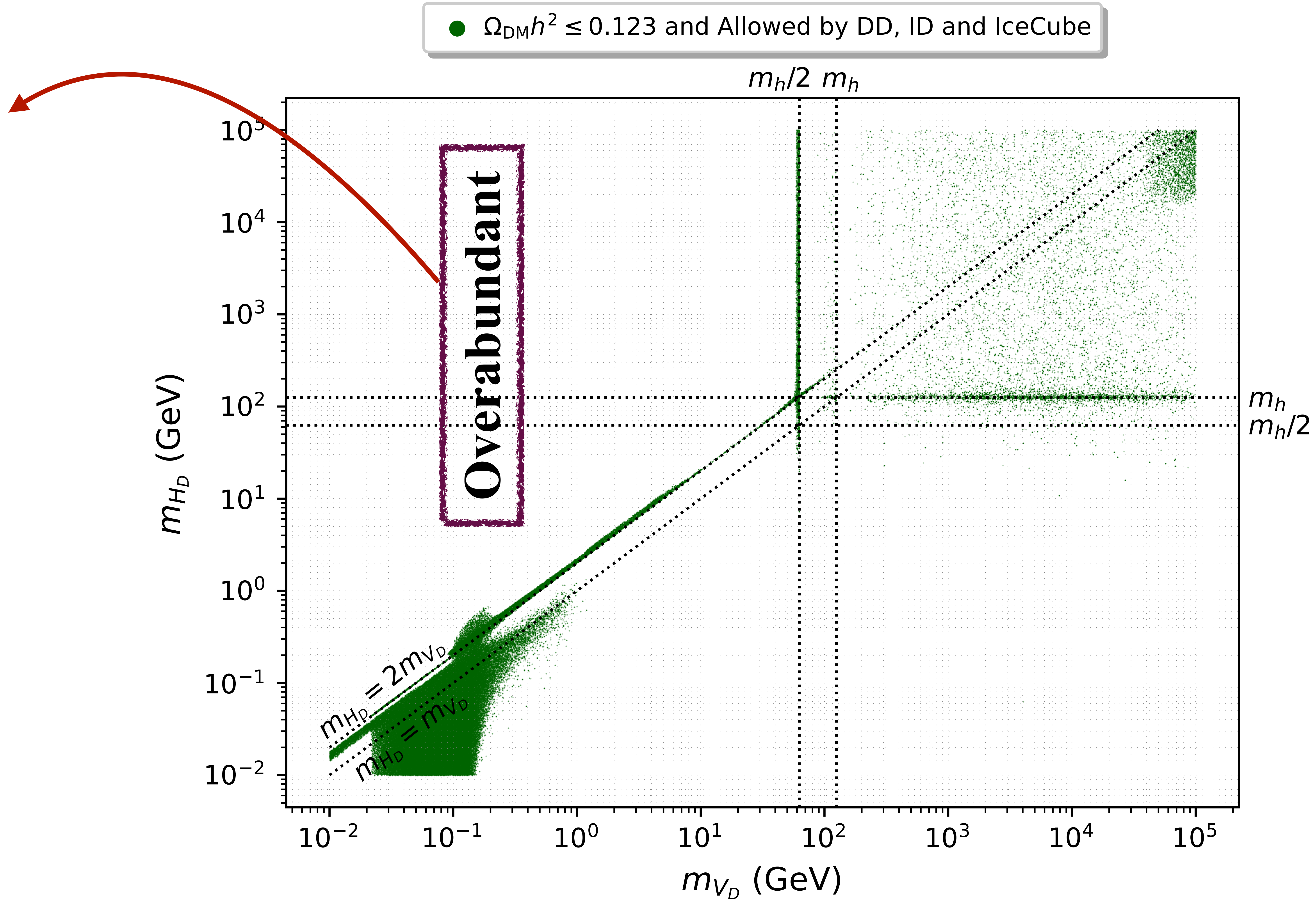

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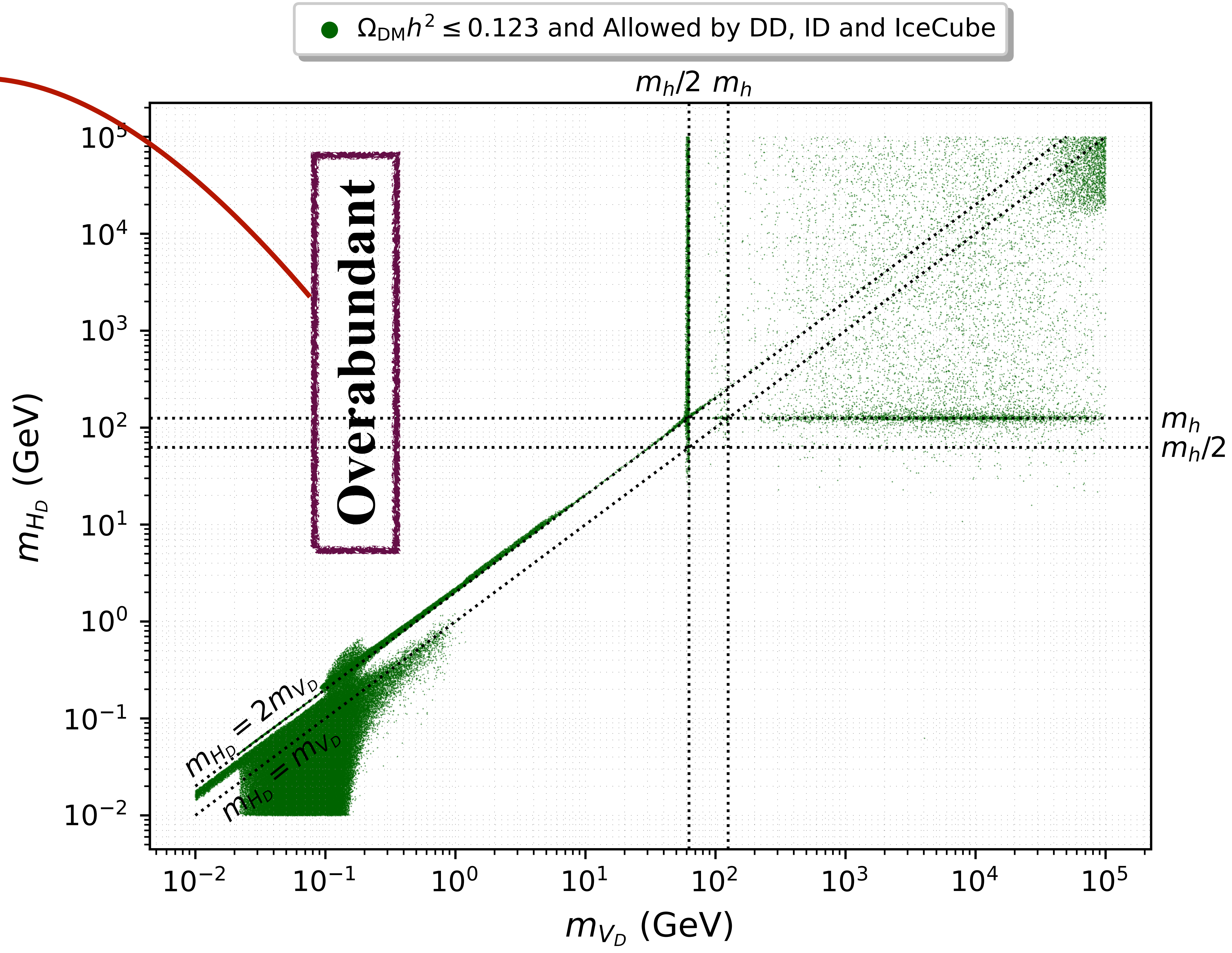
Excluded due to too high relic abundance



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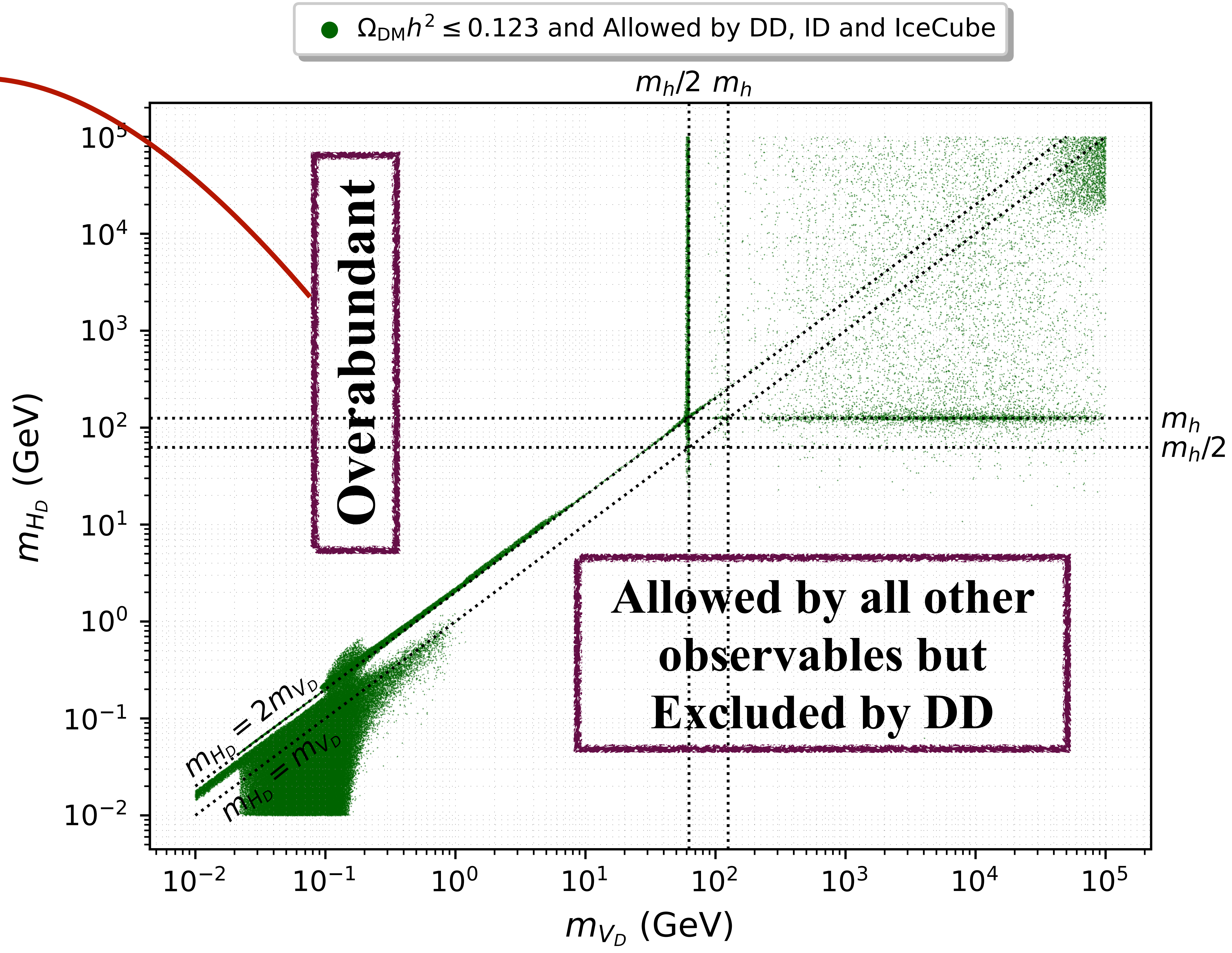

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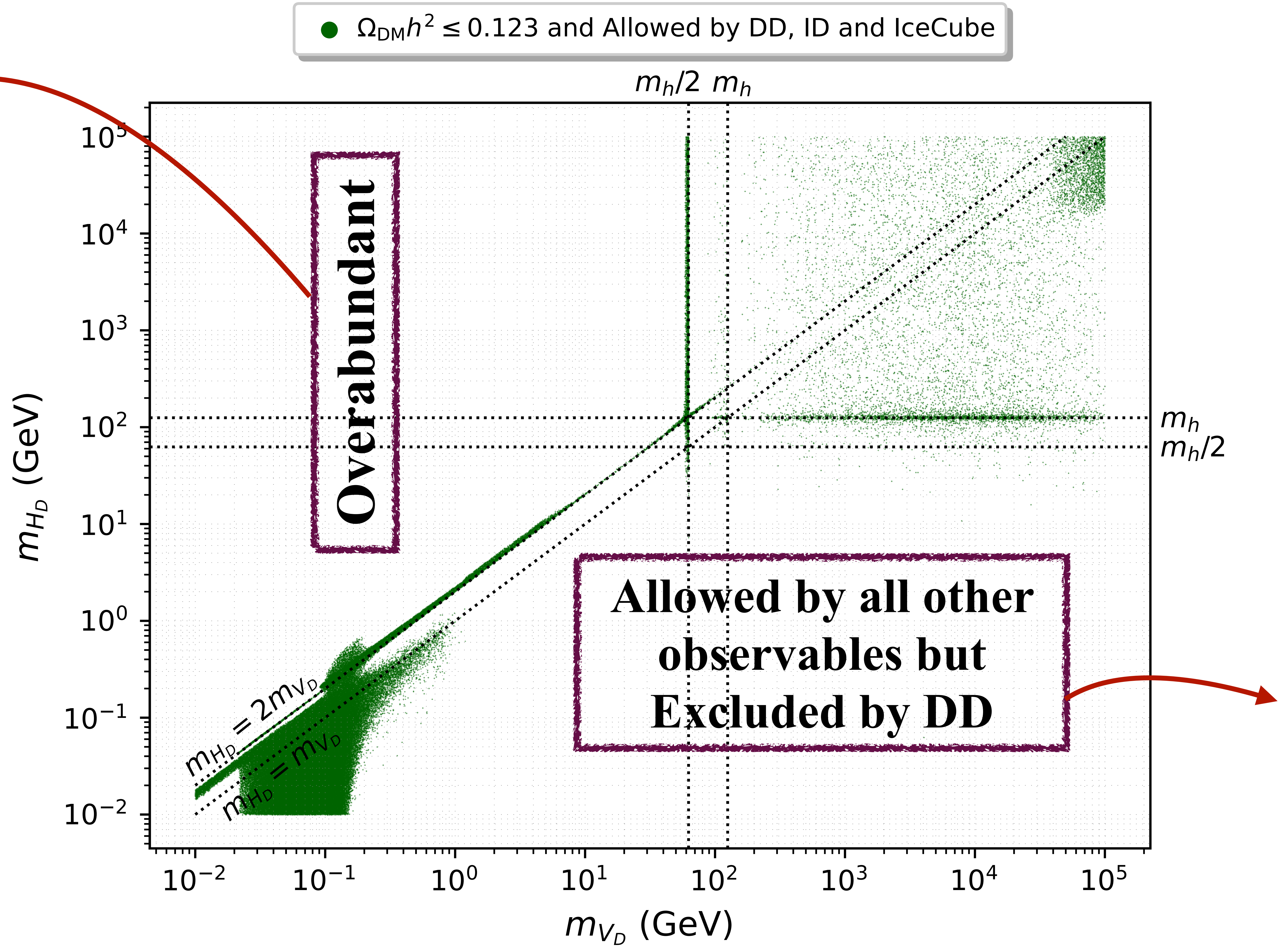

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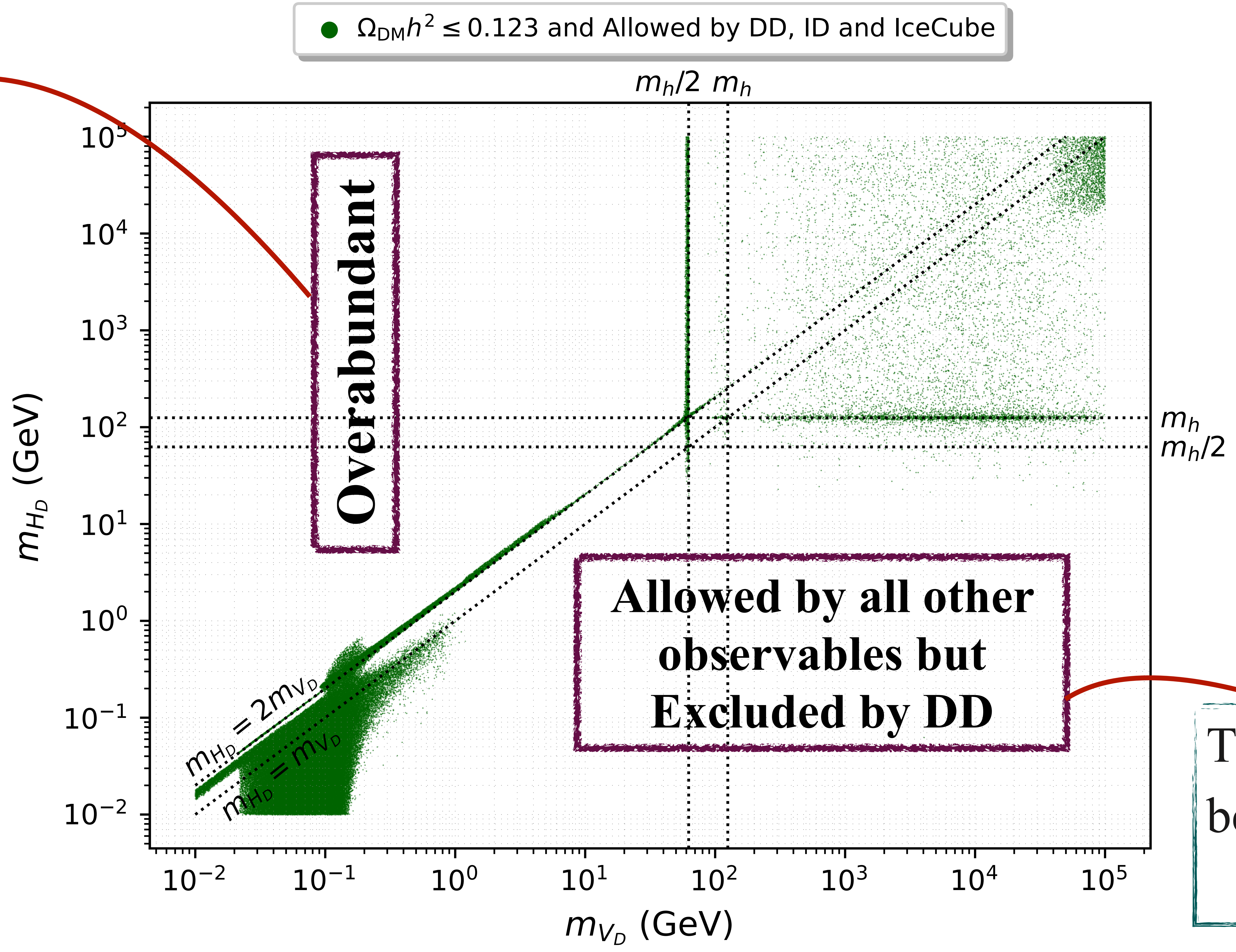

The direct detection constraints being by far the strongest

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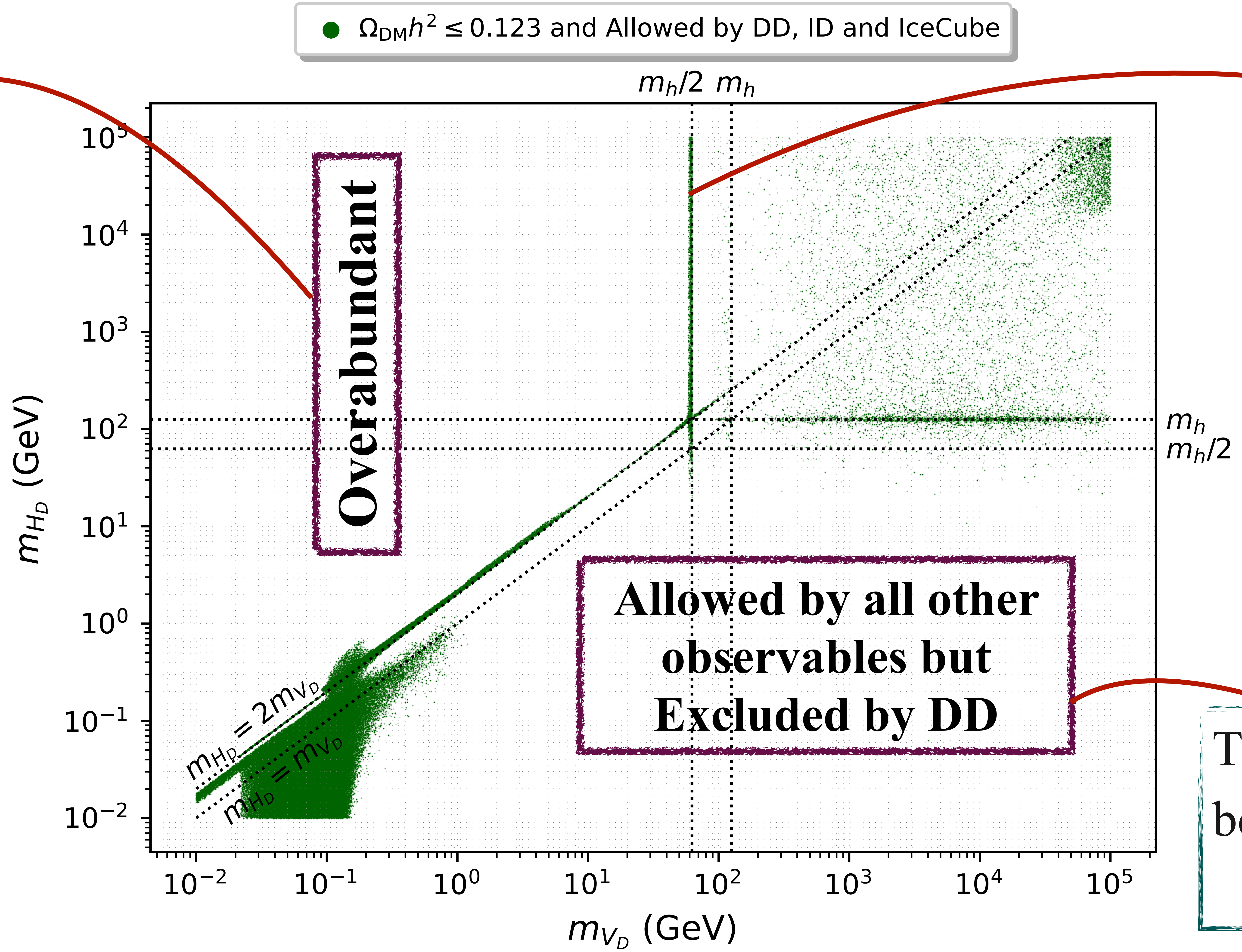

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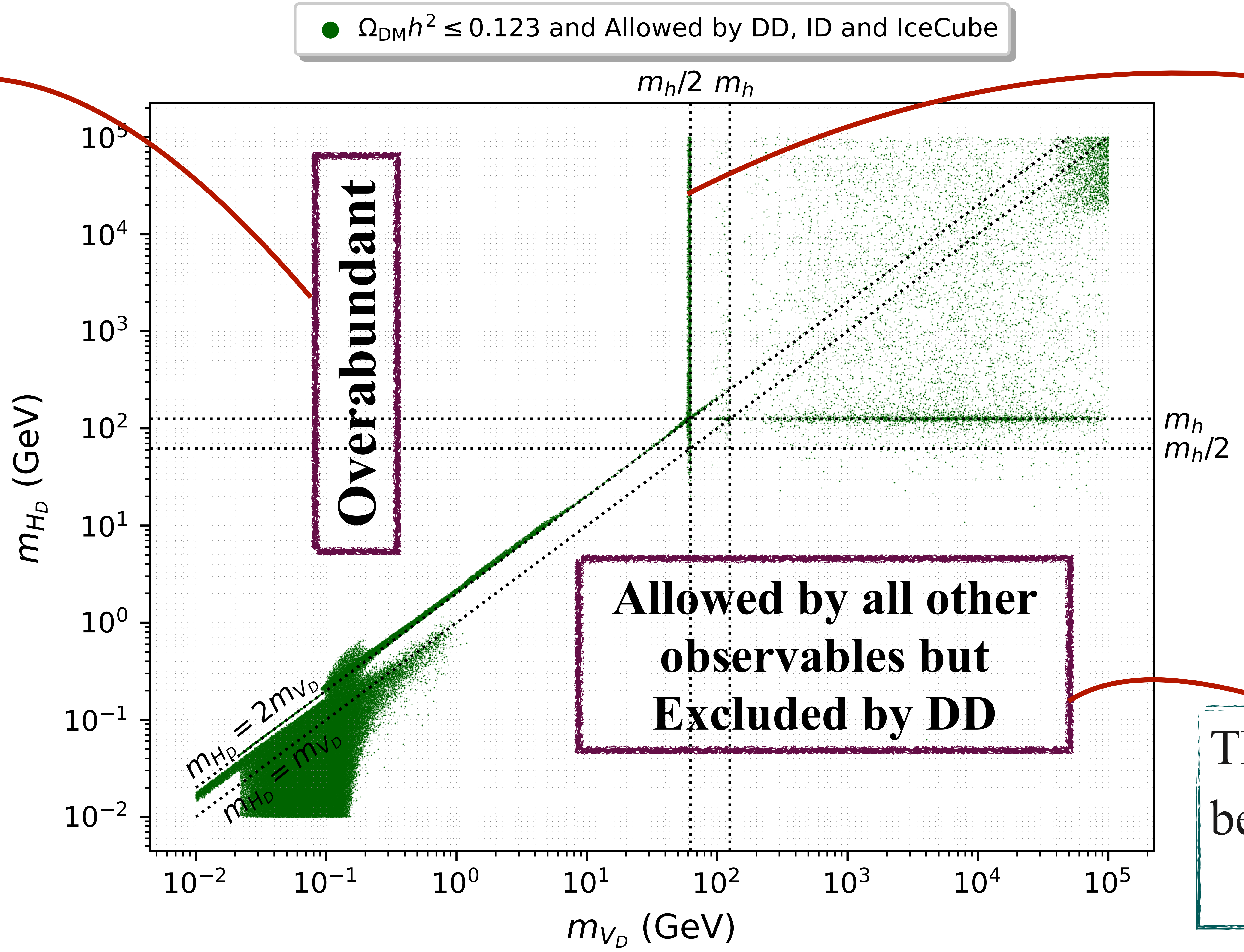

Annihilation proceeds through h resonance.

The direct detection constraints being by far the strongest

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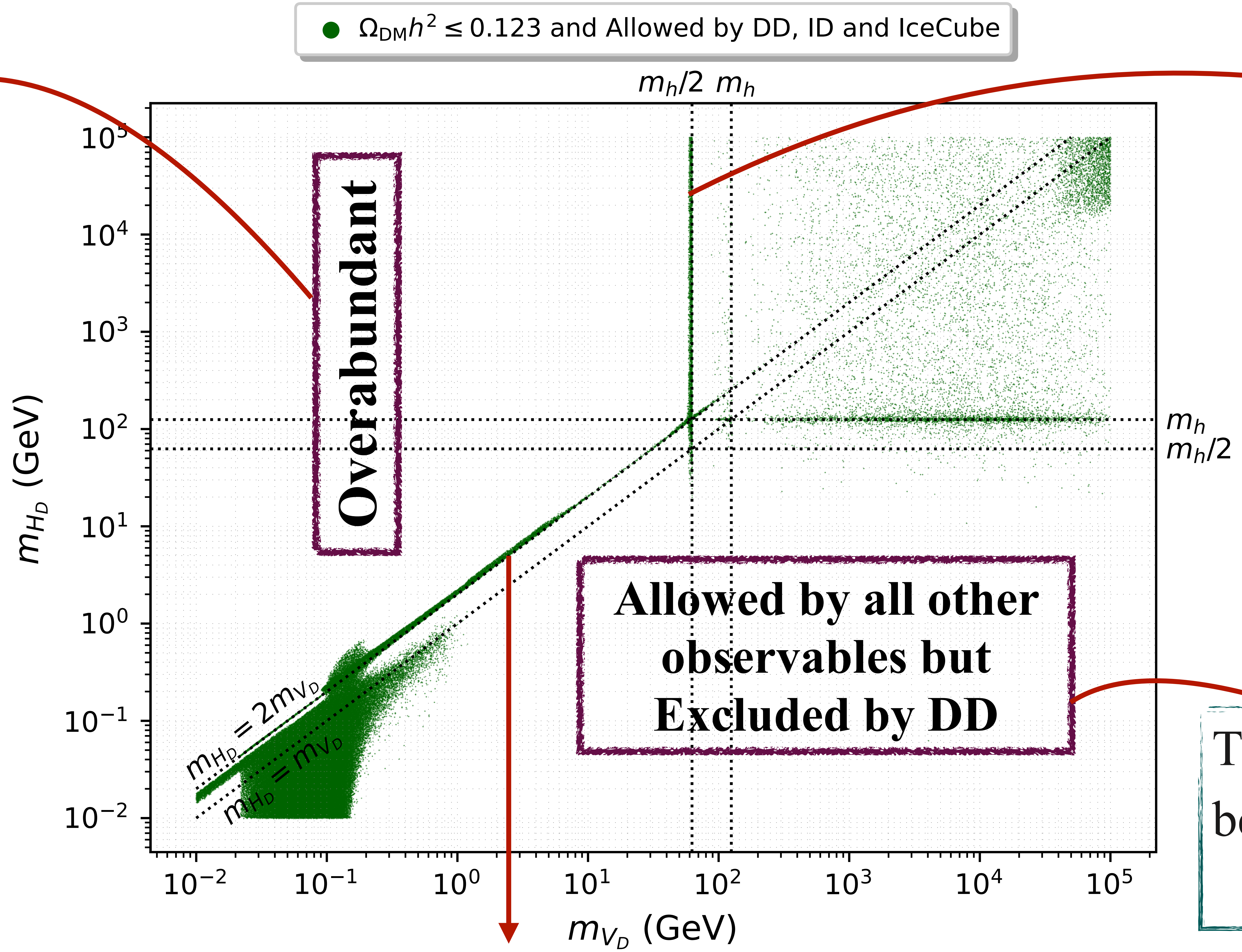

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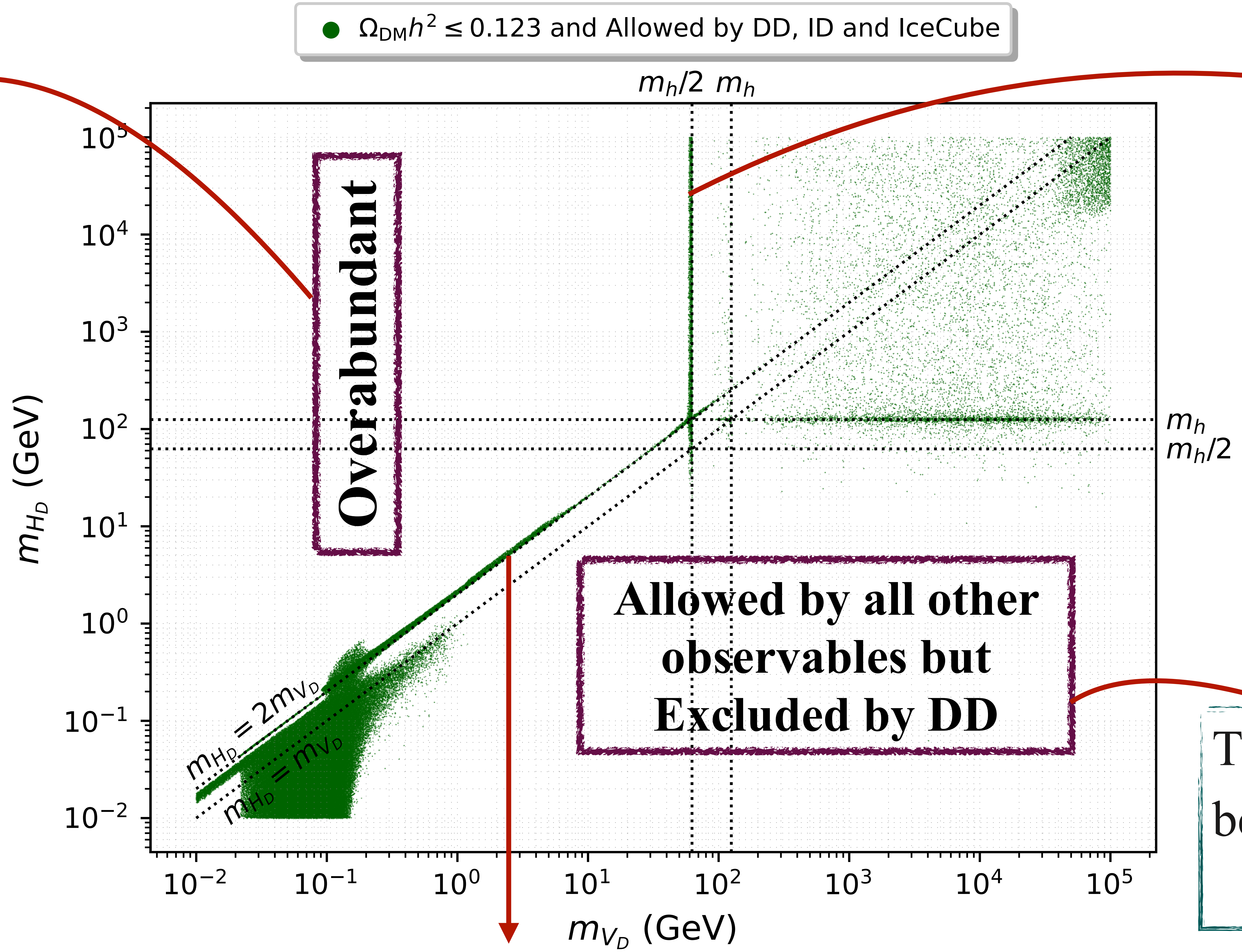

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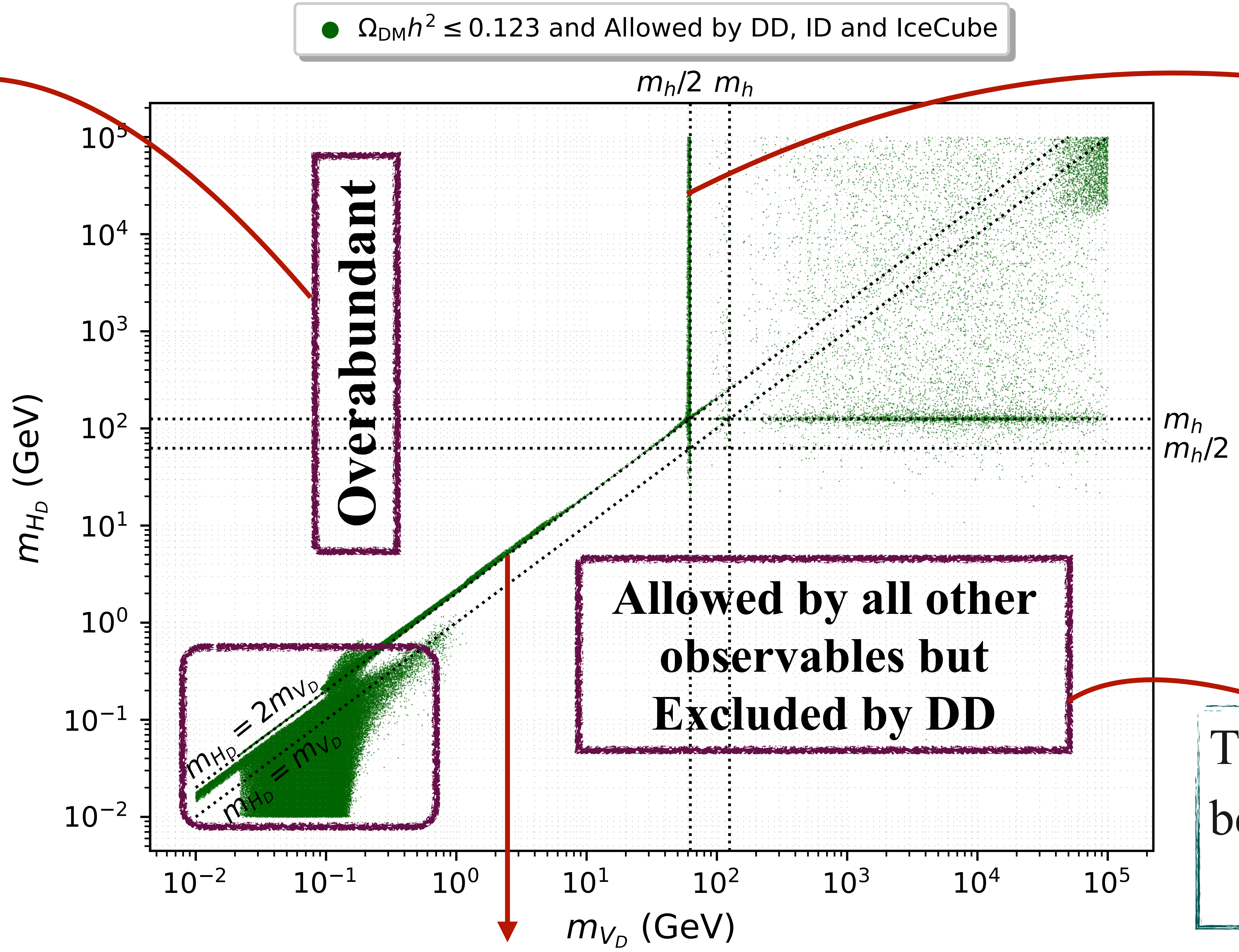

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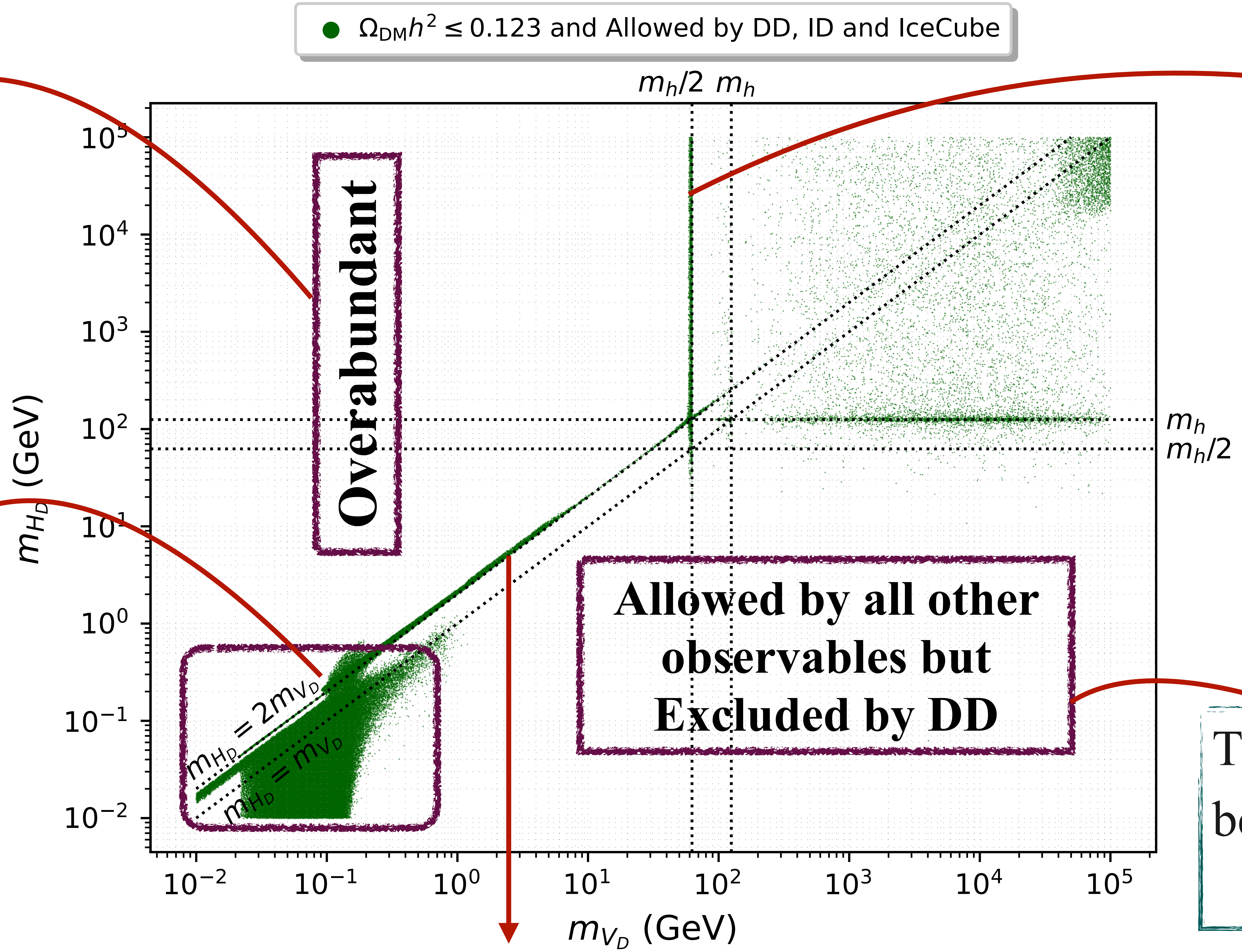

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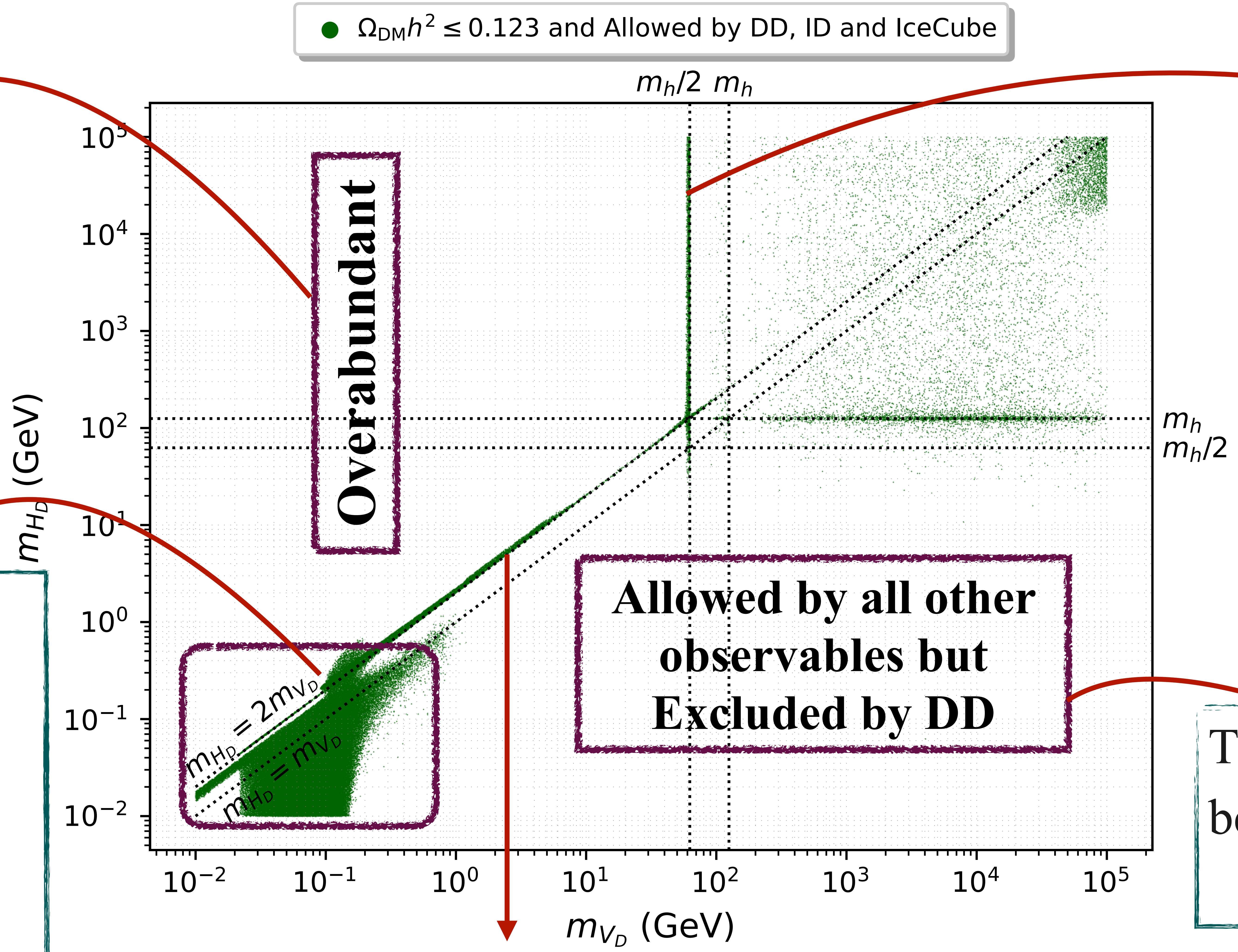

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Annihilation proceeds through h resonance.

Allowed due to

- feature resonances
- large interferences between processes
- not sensitive to DD, ID and IC

The direct detection constraints being by far the strongest

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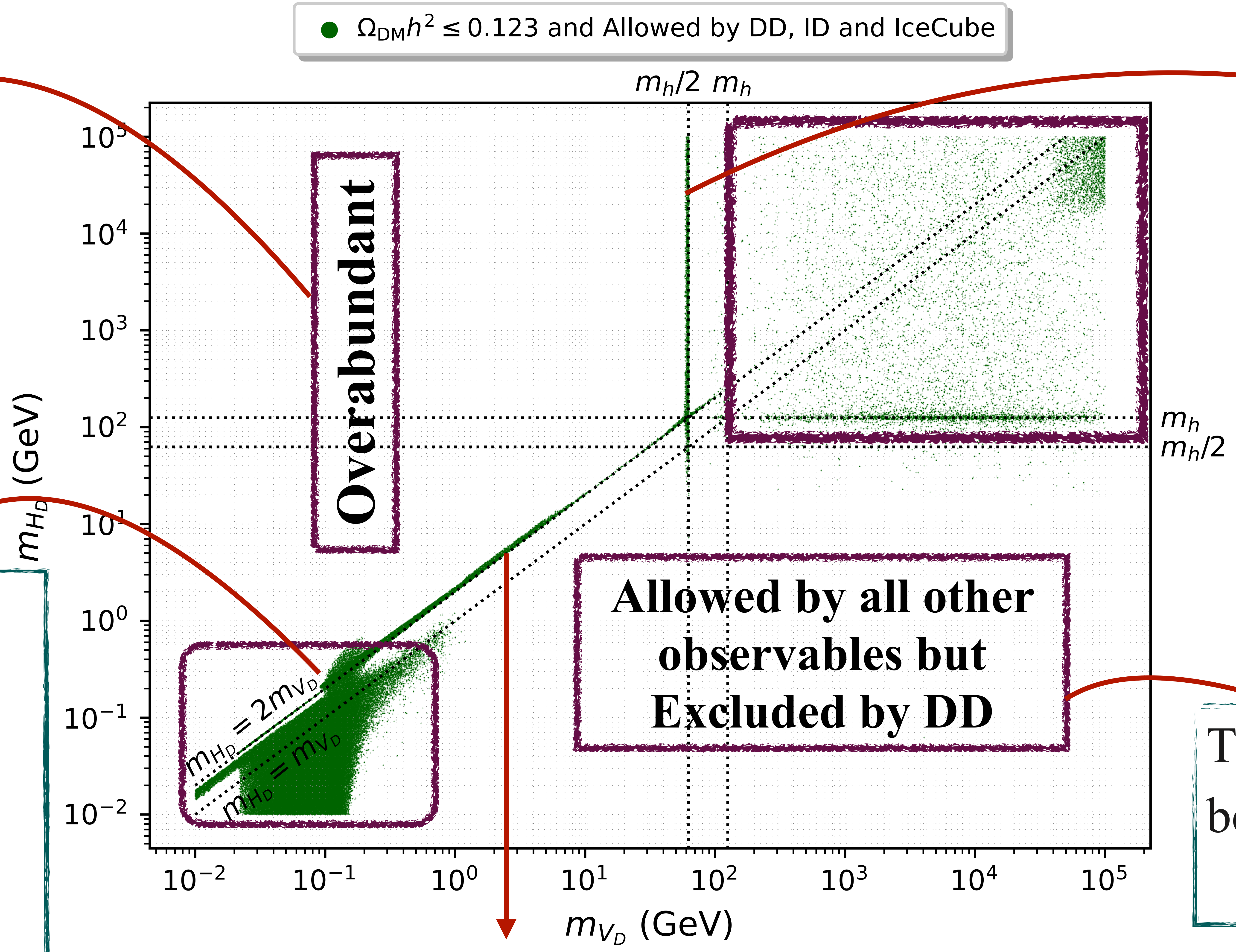

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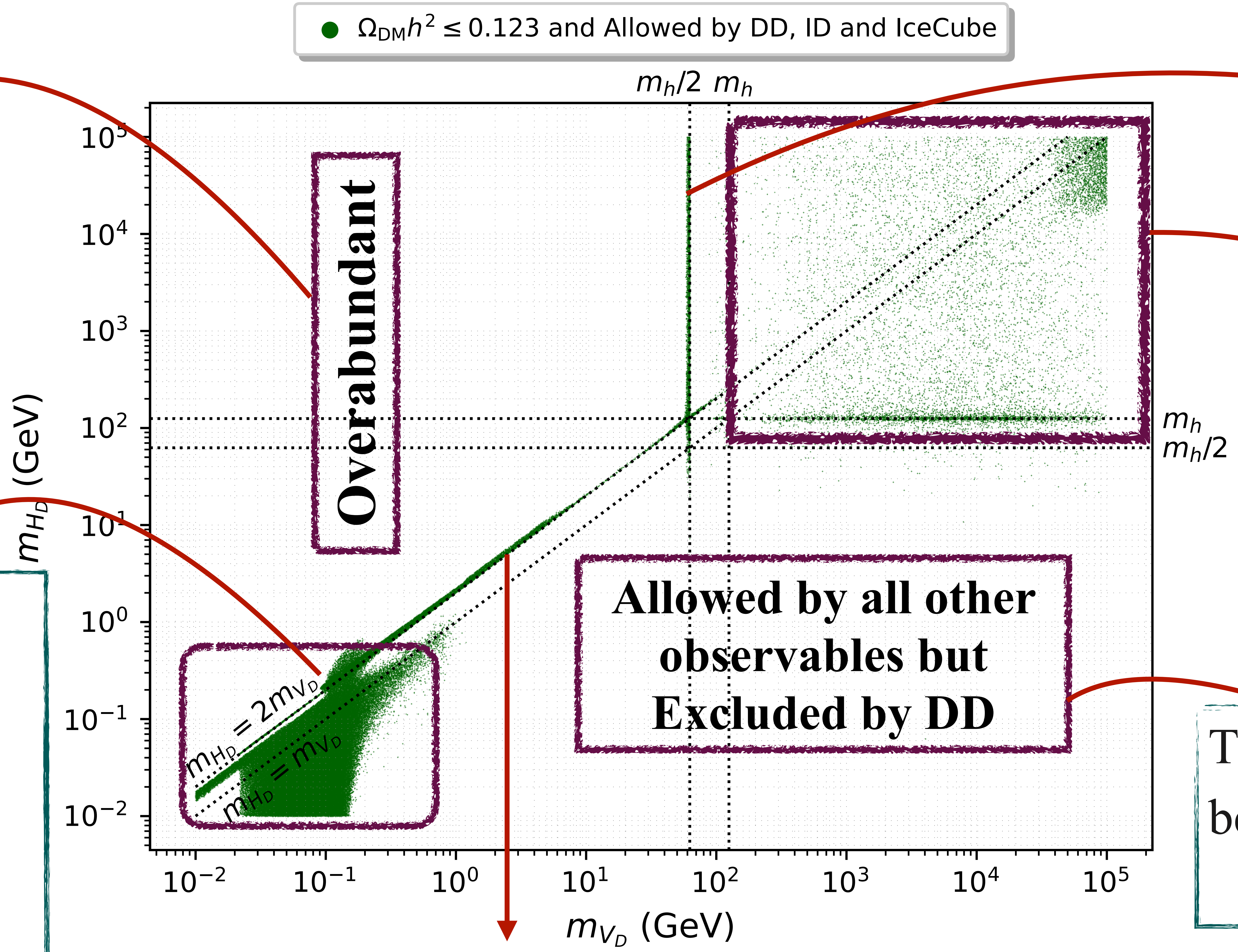

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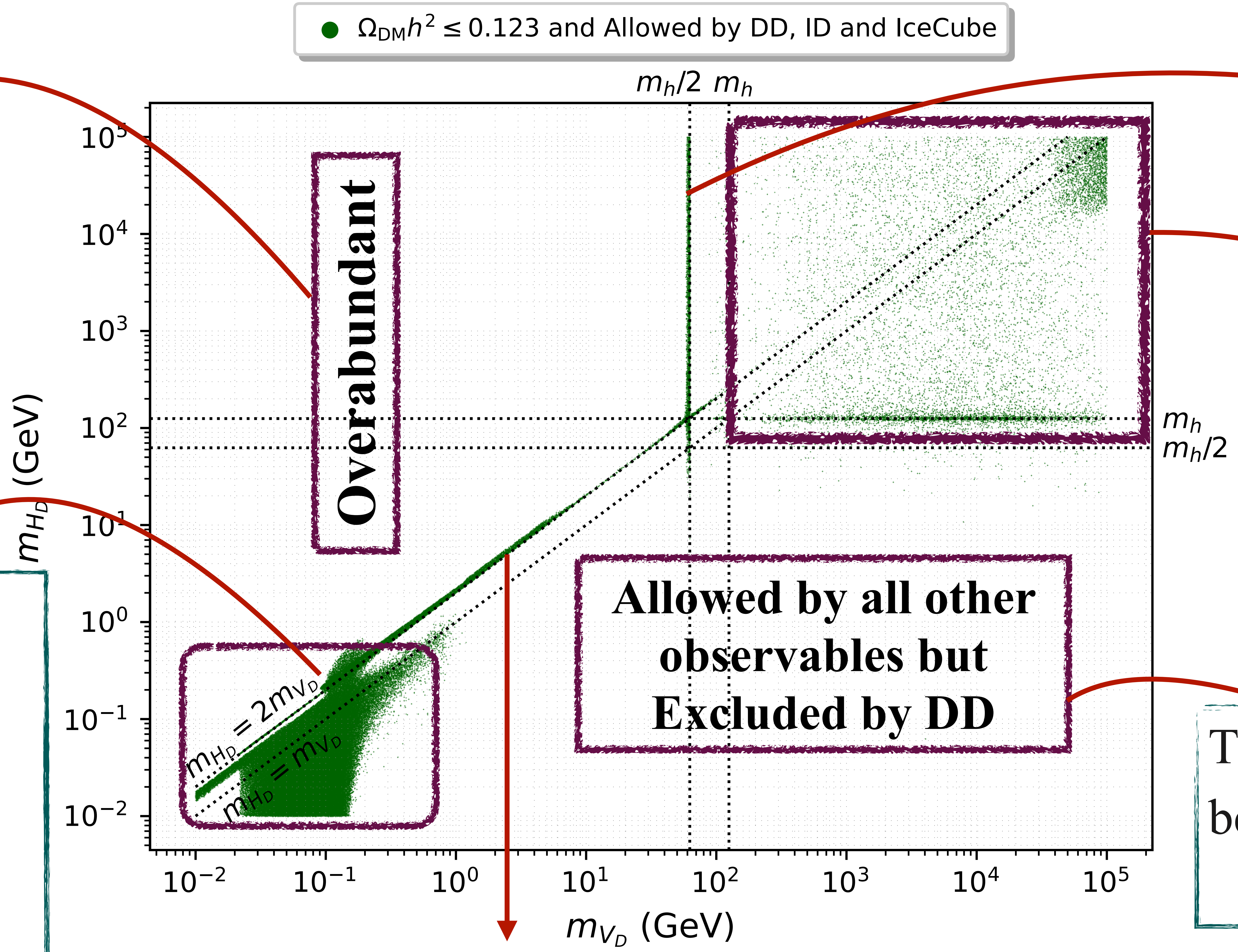


Annihilation proceeds through h resonance.

- Non-resonant
- Not sensitive to DD, ID and IC

Allowed due to
- feature resonances
- large interferences between processes
- not sensitive to DD, ID and IC

The direct detection constraints being by far the strongest

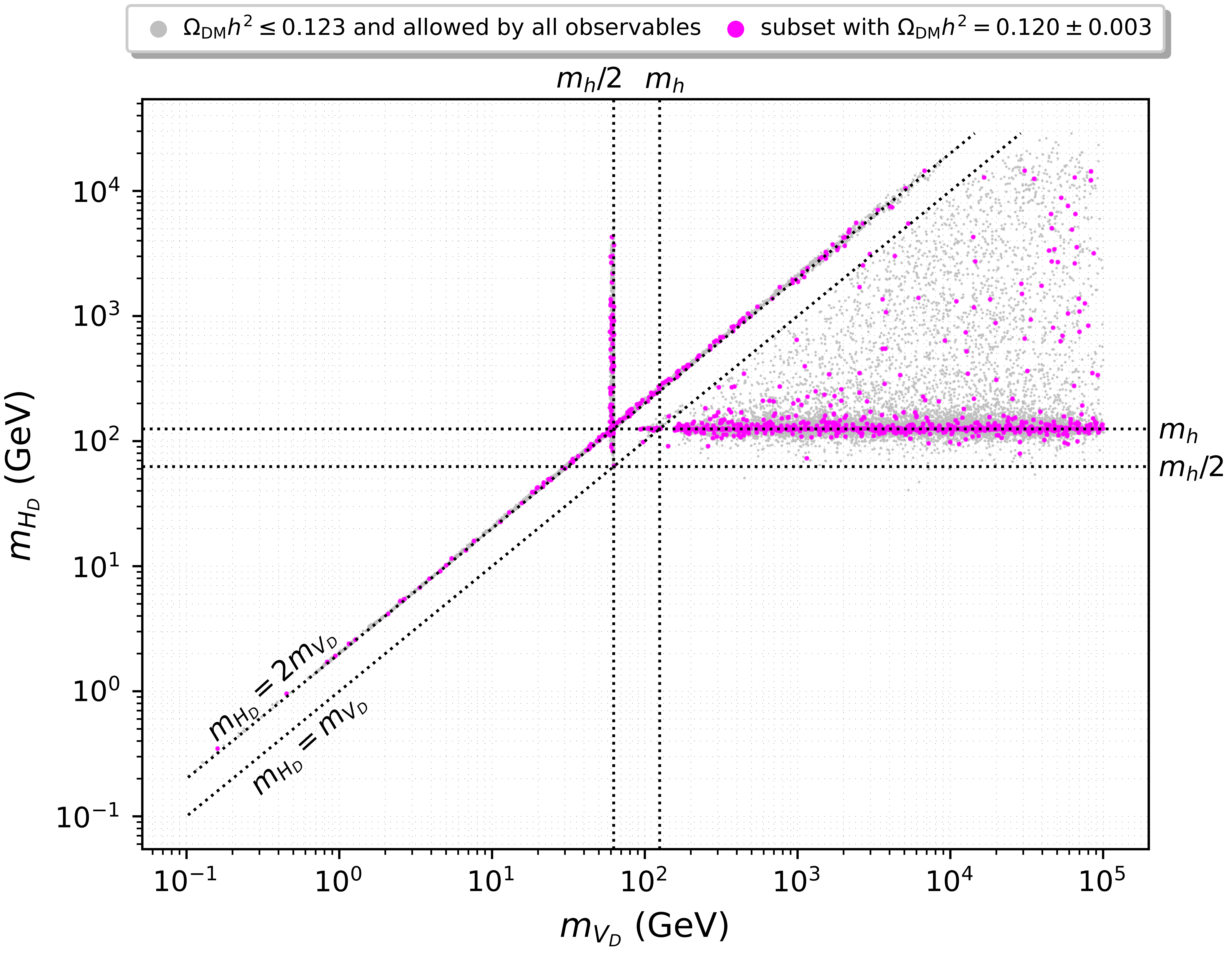
Annihilation proceeds through H_D resonance

The Parameter Space: Combined Constraints

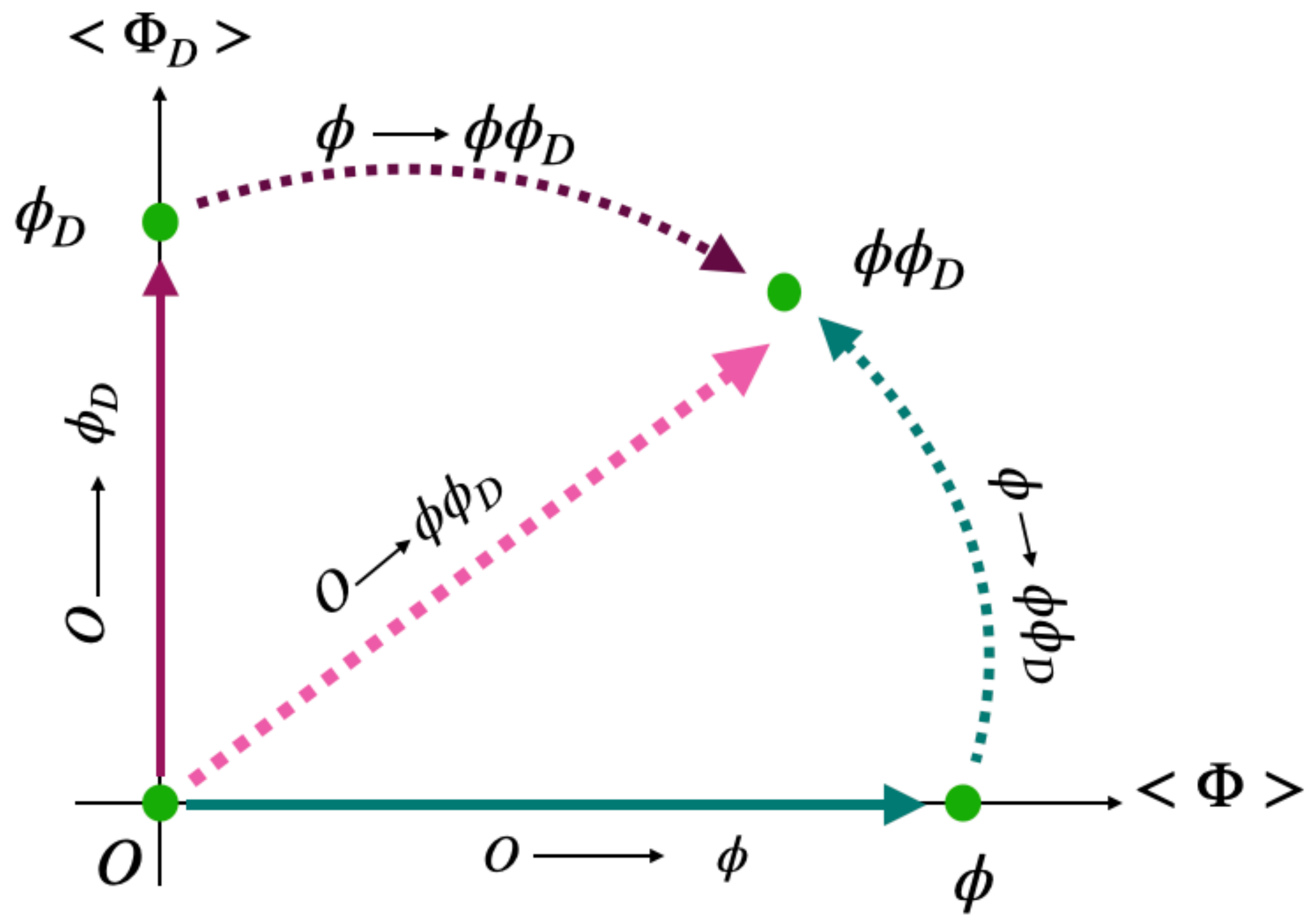
- The combination of all theoretical, cosmological, astrophysical and collider constraints

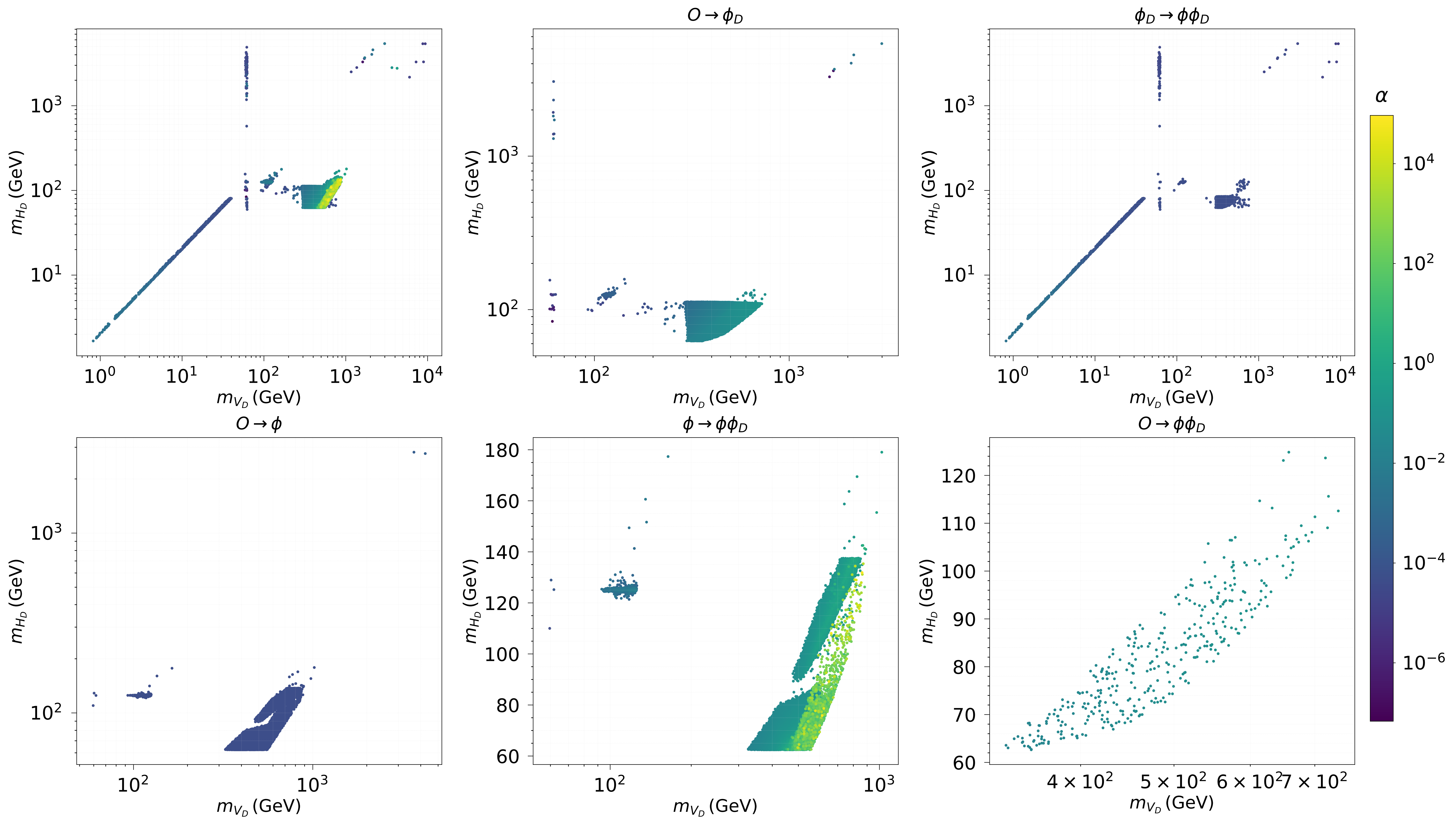
- Grey points leads to underabundant
- Magenta points leads to correct relic density

- The region with higher density of points is less constrained by collider observables



The Parameter Space: Phase Transition Results





- Different PT patterns
- Direct transitions from symmetric phase are weak

- The strongest phase transitions are obtained for the second step ($\phi \to \phi\phi_D$) of a two step PT$\longrightarrow \alpha \geq 1$

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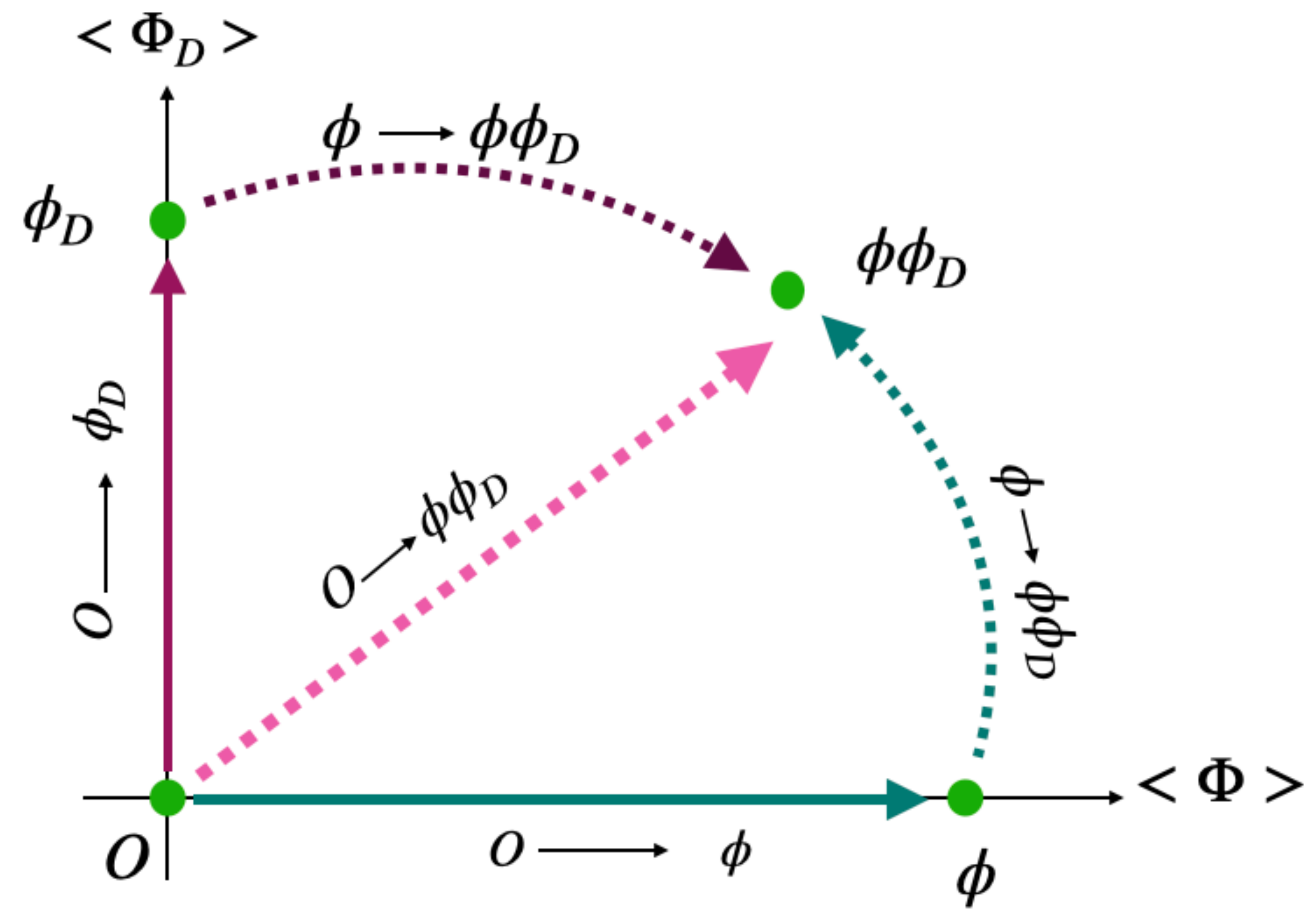

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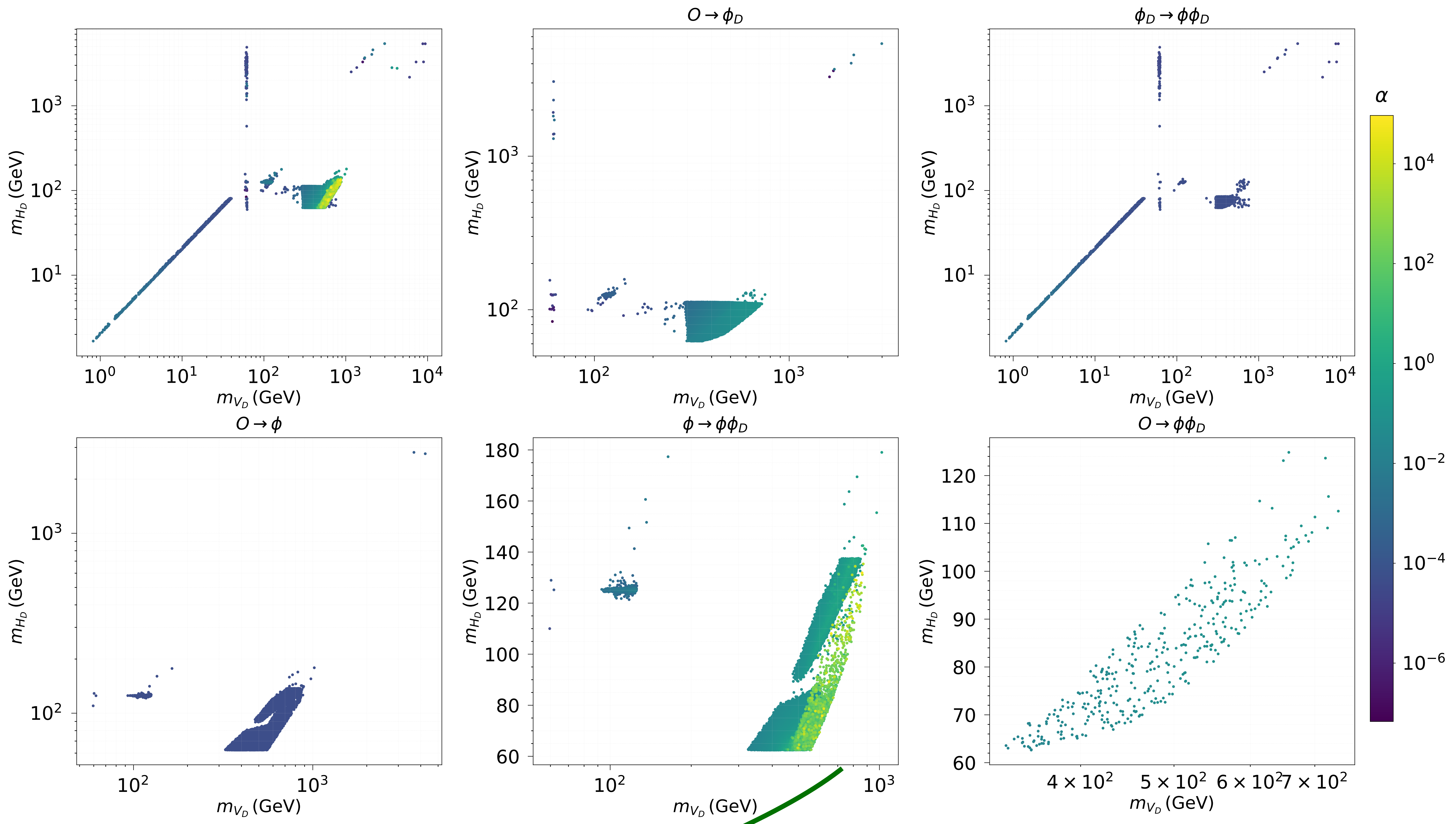

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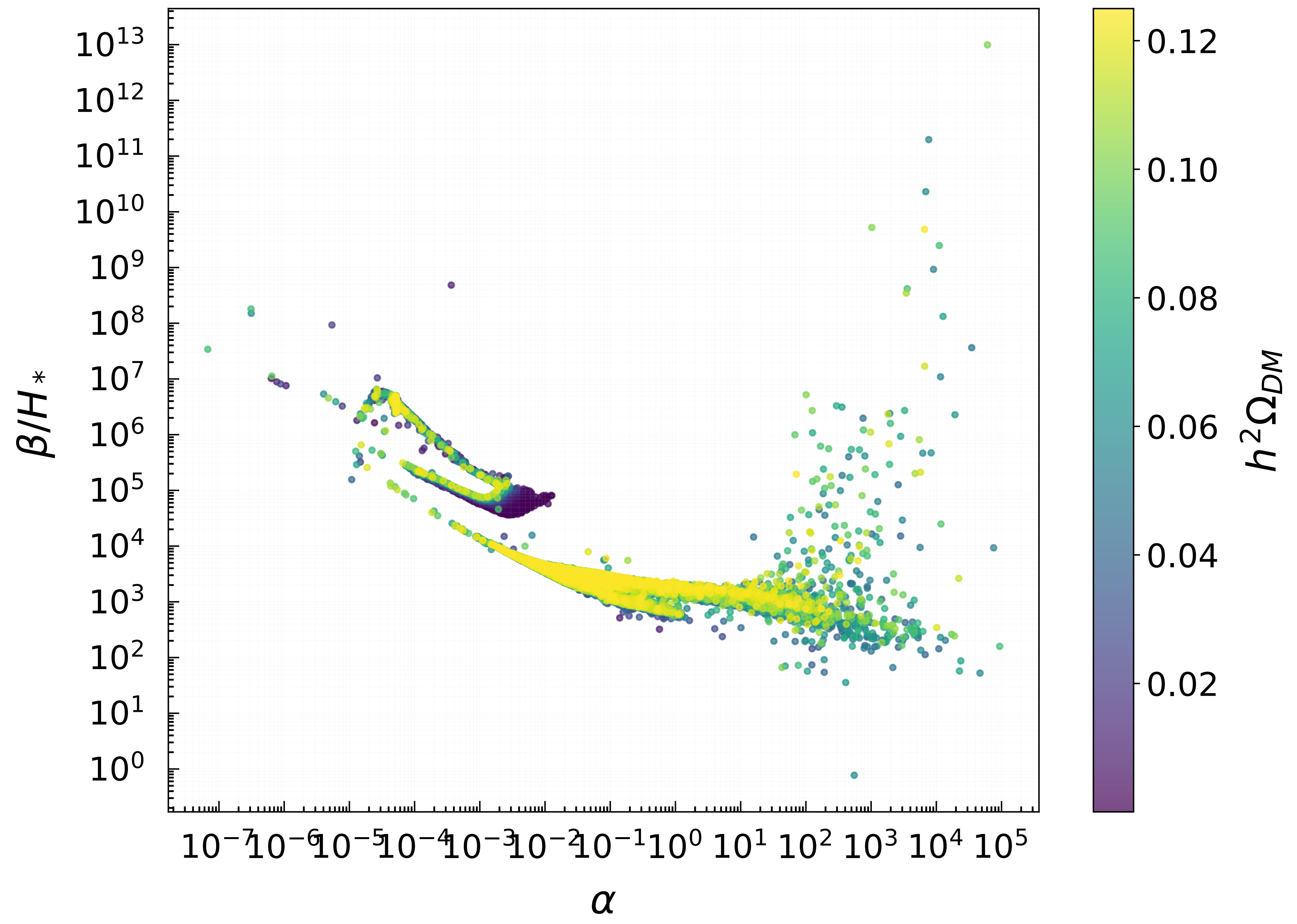
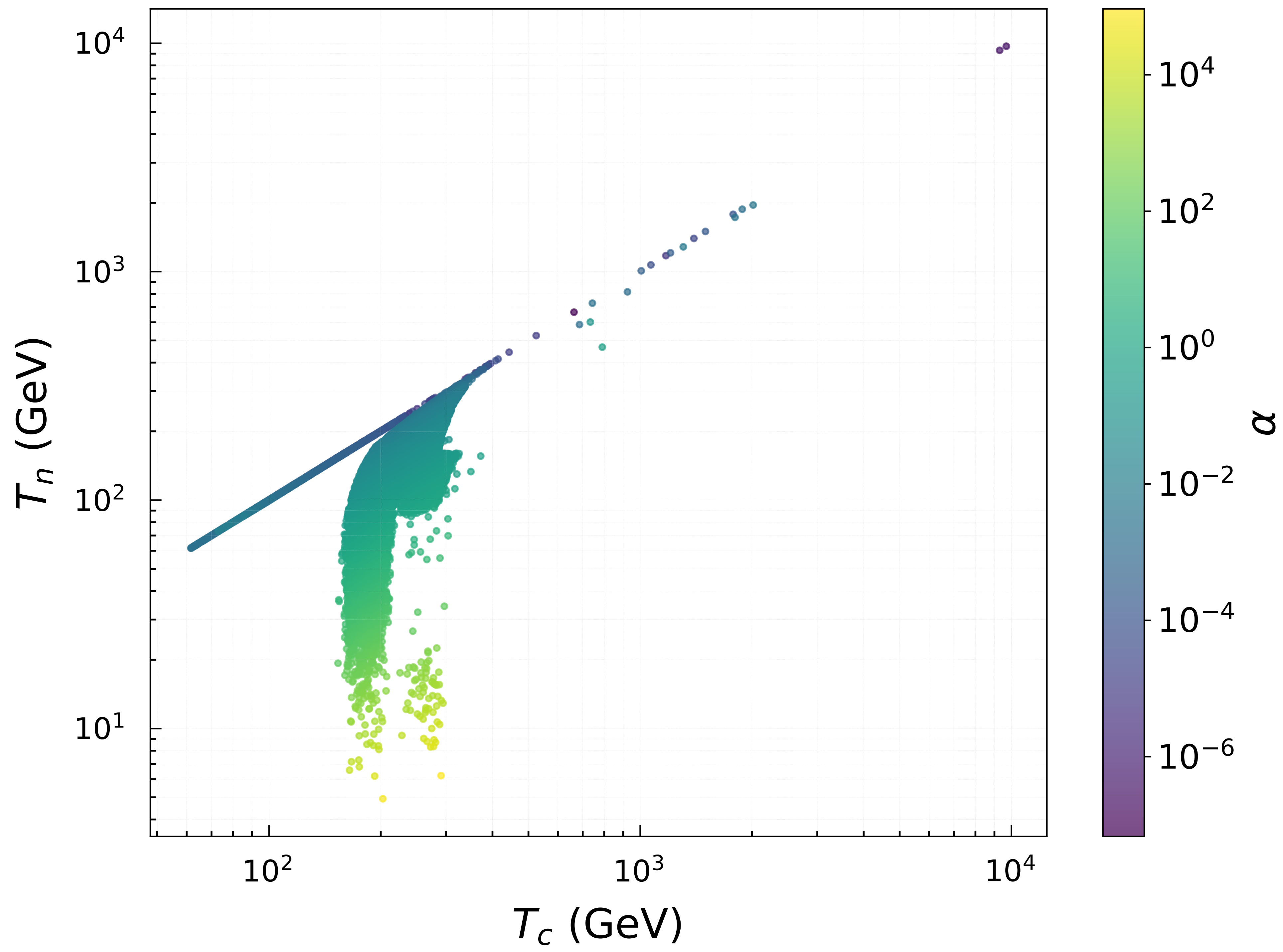




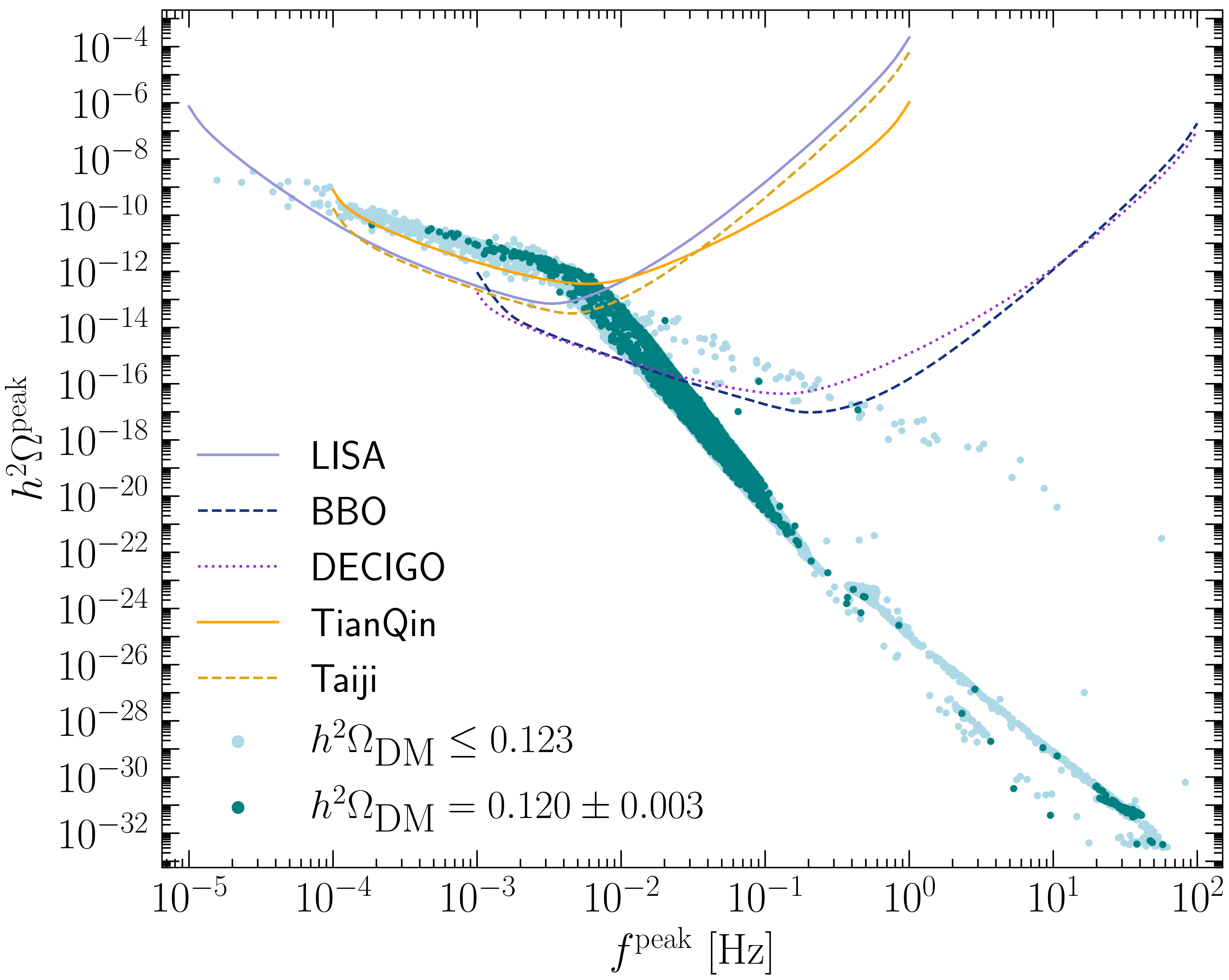
- The correlations between the phase-transition parameters

→ the slower the phase transition (smaller β/H_*), the stronger (larger α) it is

→ more T_n deviates from the line $T_n = T_c$

→ the slower is the phase transition, the bigger is the PT strength α

Gravitational-Wave Signal



- The sensitivity curves of future gravitational wave detectors are shown.
- Significant number of points can potentially be detected by these five GW detectors.
- Large part of these (dark) points also provide a DM abundance that matches the Planck observations.

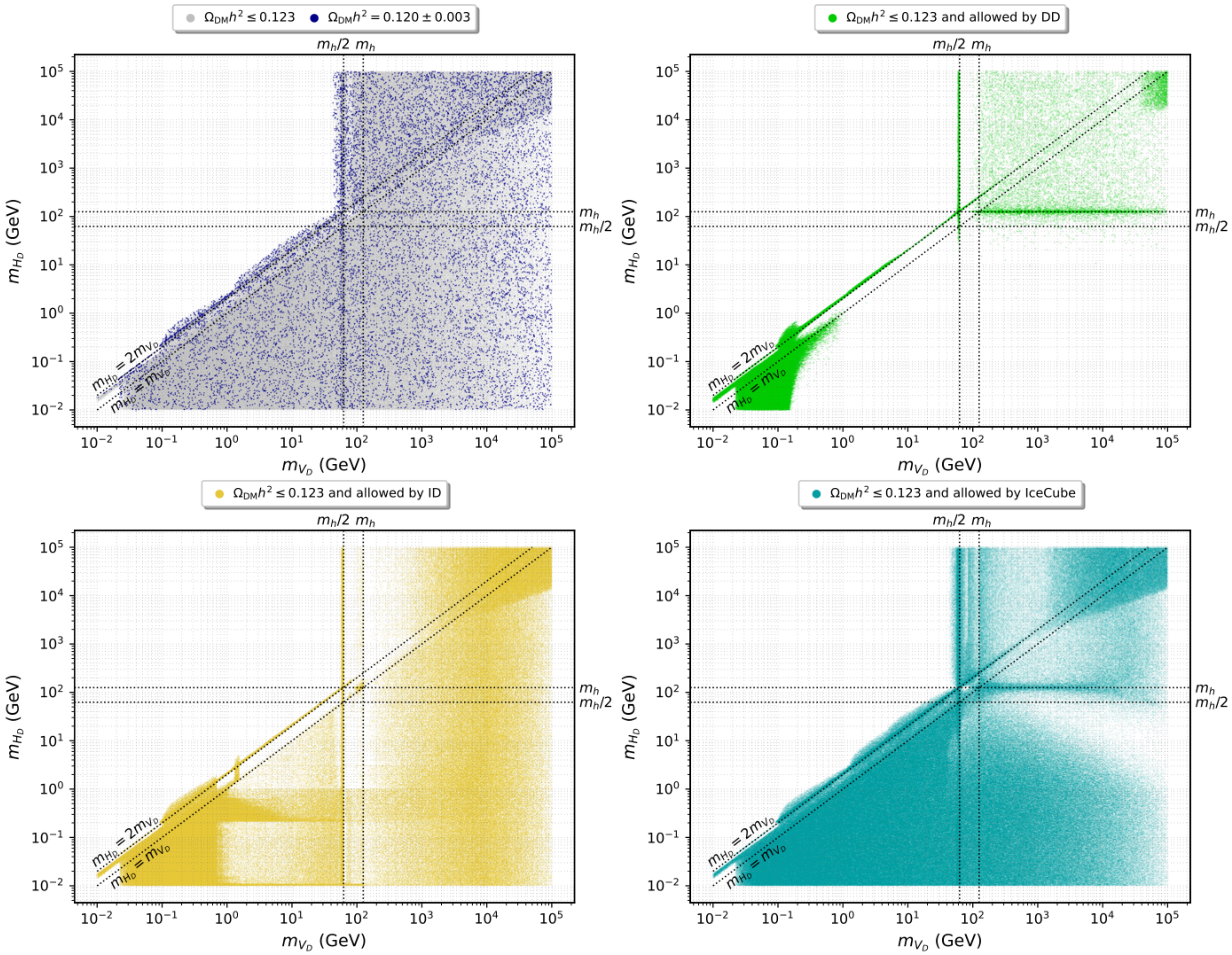
Conclusions

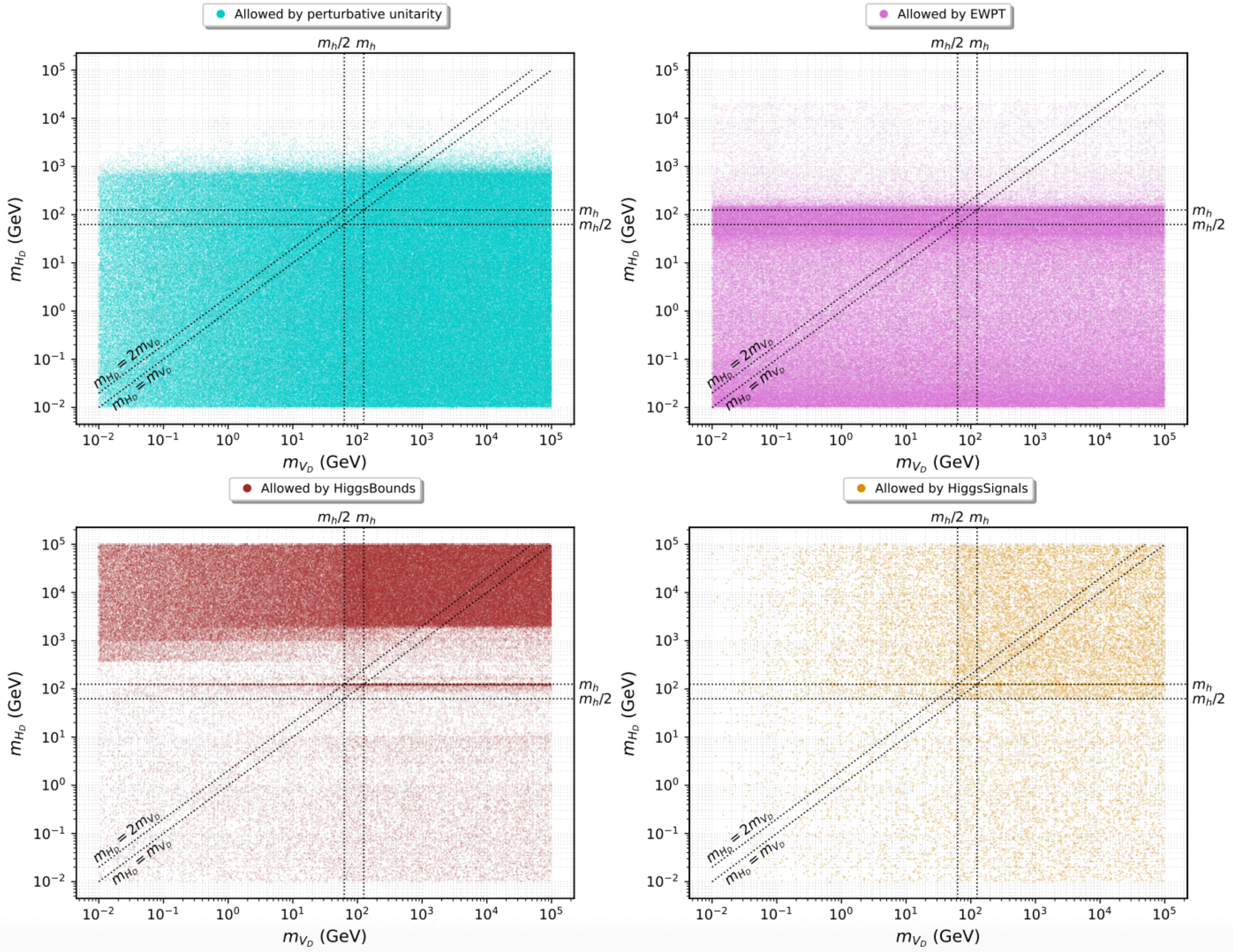
- Studied an extension of the SM with a new dark $SU(2)$ gauge group
- Custodial symmetry makes the dark gauge bosons stable $\rightarrow$ viable dark matter candidates
- Tested against collider and astrophysical constraints $\rightarrow$ identified allowed parameter space
- Found regions consistent with DM abundance and strong first-order phase transitions
- Predicted stochastic GW signals detectable by LISA, DECIGO, BBO, TianQin, and Taiji
- Gravitational waves provide a powerful probe of this scenario, complementing collider searches

Thank You

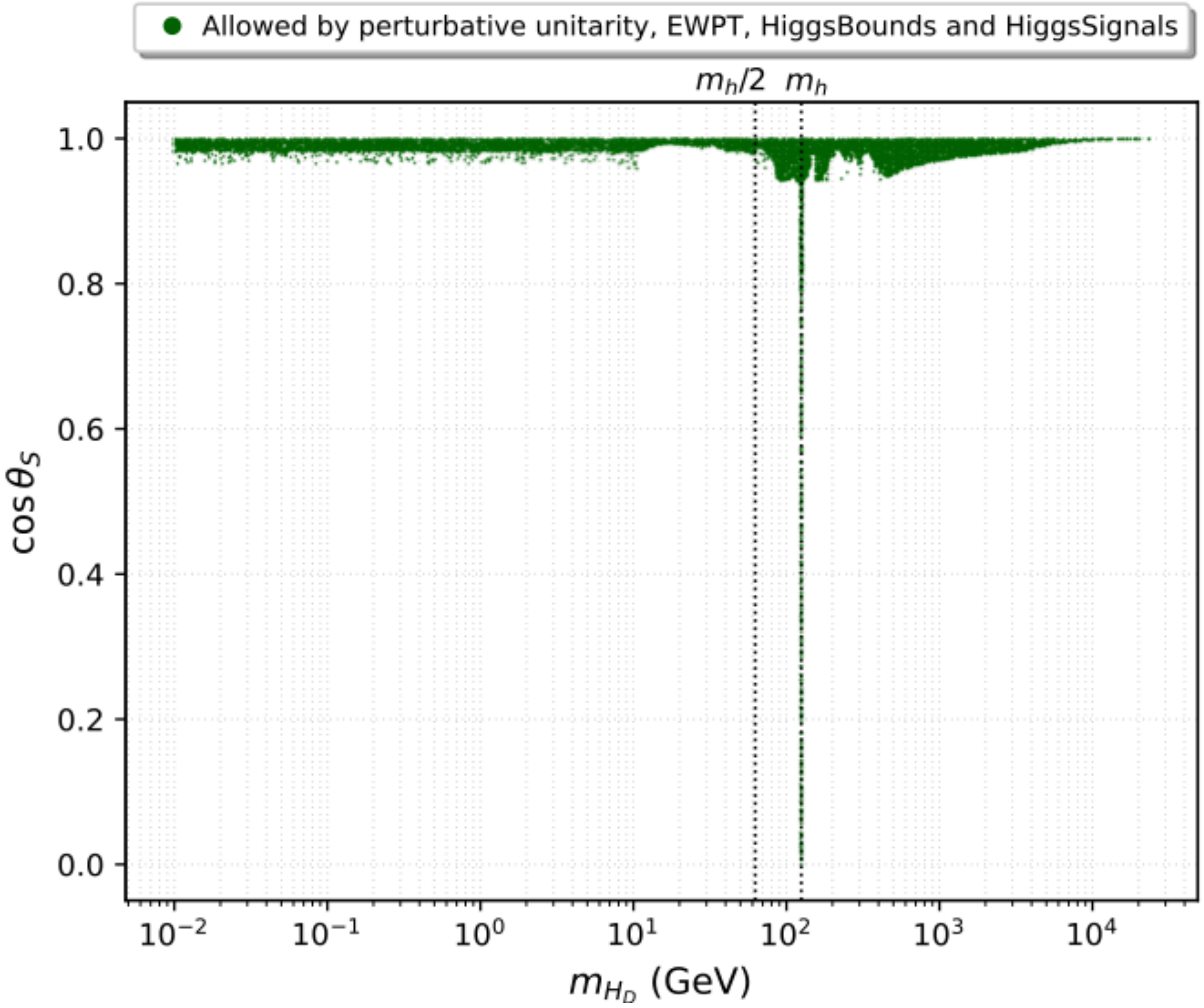
Any questions?

Backup slides


$\Omega_{\rm DM}h^2 \leq 0.123$
$\Omega_{\rm DM}h^2 = 0.120 \pm 0.003$
$\Omega_{\rm DM}h^2 \leq 0.123$ and allowed by DD
$\Omega_{\rm DM}h^2 \leq 0.123$ and allowed by ID
$\Omega_{\rm DM}h^2 \leq 0.123$ and allowed by IceCube
$m_h/2$ m_h
m_h
$m_h/2$
$m_{H_D} = 2m_{V_D}$
$m_{H_D} = m_{V_D}$
m_{H_D} (GeV)
m_{V_D} (GeV)
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}



Allowed by perturbative unitarity
Allowed by EWPT
Allowed by HiggsBounds
Allowed by HiggsSignals
$m_h/2$ m_h
m_h
$m_h/2$
$m_{H_D} = 2m_{V_D}$
$m_{H_D} = m_{V_D}$
m_{H_D} (GeV)
m_{V_D} (GeV)



Allowed by perturbative unitarity, EWPT, HiggsBounds and HiggsSignals
$m_h/2$
m_h
1.0
0.8
0.6
0.4
0.2
0.0
$\cos\theta_S$
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
m_{H_D} (GeV)