

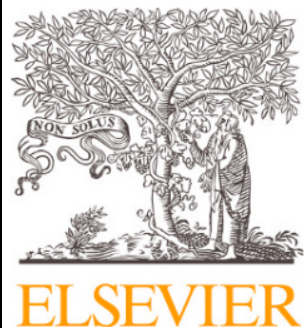
# NEW INSIGHTS ON INTERACTING DARK ENERGY FROM DESI DR2

AFAS 2026

MARCEL VAN DER WESTHUIZEN  
SUPERVISOR: PROF AMARE ABEBE



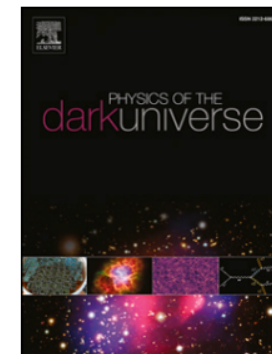
# SEE PAPER FOR DETAILED RESULTS



Contents lists available at [ScienceDirect](#)





## Physics of the Dark Universe

journal homepage: [www.elsevier.com/locate/dark](http://www.elsevier.com/locate/dark)



Full Length Article

Late-time background constraints on linear and non-linear interacting dark energy after DESI DR2

David Figueruelo  <sup>a,b</sup>, Marcel van der Westhuizen  <sup>c,\*</sup>, Amare Abebe  <sup>c,d</sup>,  
Eleonora Di Valentino  <sup>e</sup>


# SCAN FOR PAPER



# OVERVIEW OF BACKGROUND THEORY OF MODELS

Full Length Article

## I. Linear interacting dark energy: Analytical solutions and theoretical pathologies

Marcel van der Westhuizen <sup>a</sup><sup>\*</sup>, Amare Abebe <sup>a,b</sup>, Eleonora Di Valentino <sup>c</sup>


<sup>a</sup> Centre for Space Research, North-West University, Potchefstroom 2520, South Africa

<sup>b</sup> National Institute for Theoretical and Computational Sciences (NITheCS), South Africa

<sup>c</sup> School of Mathematical and Physical Sciences, University of Sheffield, Hounsfield Road, Sheffield, S3 7RH, United Kingdom

Full Length Article

## II. Non-linear interacting dark energy: Analytical solutions and theoretical pathologies

Marcel van der Westhuizen <sup>a</sup><sup>\*</sup>, Amare Abebe <sup>a,b</sup>, Eleonora Di Valentino <sup>c</sup>


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Full length article

## III. Interacting Dark Energy: Summary of models, Pathologies, and Constraints

Marcel van der Westhuizen <sup>a</sup><sup>\*</sup>, Amare Abebe <sup>a,b</sup>, Eleonora Di Valentino <sup>c</sup>

<sup>a</sup> Centre for Space Research, North-West University, Potchefstroom 2520, South Africa

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# Wait a minute...

- Is **dark matter** even real? (Like **yeti**?)
- Is **dark energy** even a thing? (Like **big foot**?)



# Wait a minute...

- Is **dark matter** even real? (Like **yeti**?)
- Is **dark energy** even a thing? (Like **big foot**?)
- **Interactions** between **dark matter** and **dark energy** =  
**love** between **yeti** and **bigfoot**?

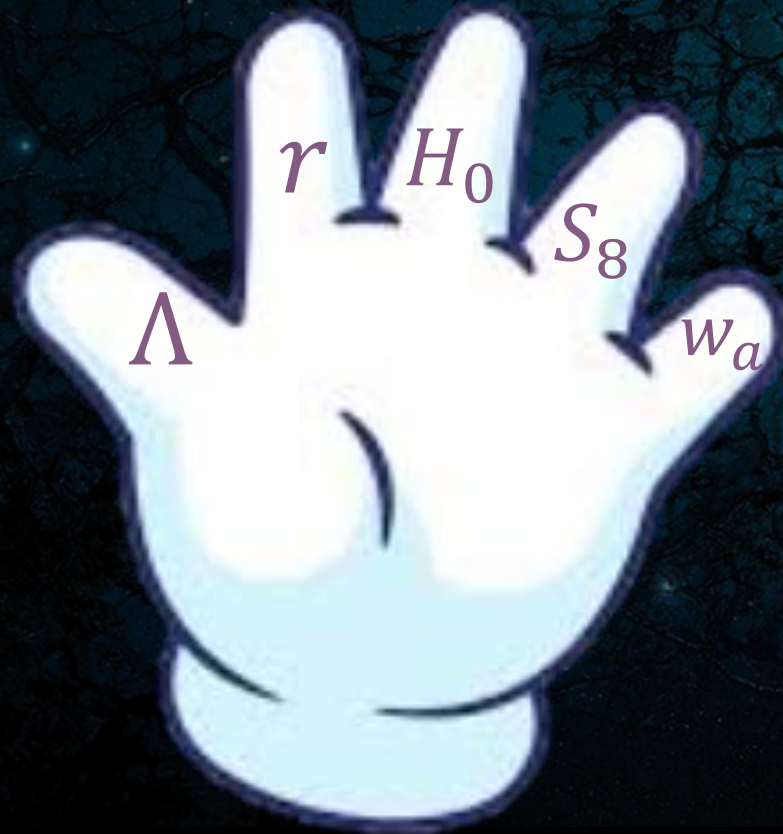


Maybe...

lets look at the argument

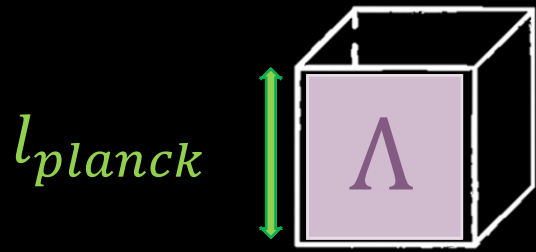


# 1. FIVE REASONS FOR DARK INTERACTIONS BEYOND $\Lambda$ CDM



# 1. COSMOLOGICAL CONSTANT PROBLEM

- Cosmological constant predicted from QM as energy of empty space
- $E \neq 0 \rightarrow \Delta E = 0$  (Violates Heisenberg's uncertainty principle)

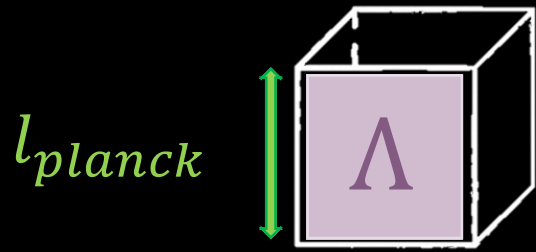


$$\rho_{(\Lambda, \text{predicted})} = \frac{E_{\text{Planck}}}{V_{\text{Planck}}} \approx 10^{114} \text{ Joule} \cdot \text{m}^{-3}$$

$$\rho_{(\Lambda, \text{measured})} = 10^{-10} \text{ Joule} \cdot \text{m}^{-3}$$

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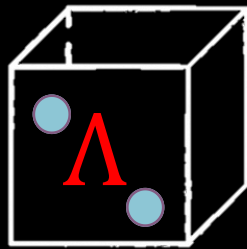
- Comparing the two values gives the **worst prediction in all of physics...**

$$\frac{\rho_{(\Lambda,predicted)}}{\rho_{(\Lambda,measured)}} \approx \frac{10^{114} \text{ Joule} \cdot \text{m}^3}{10^{-10} \text{ Joule} \cdot \text{m}^{-3}} \approx 10^{124}$$

Motivates research for dark energy beyond the cosmological constant.

# 2. COINCIDENCE PROBLEM

- Consider expanding volume with dark energy and dark matter

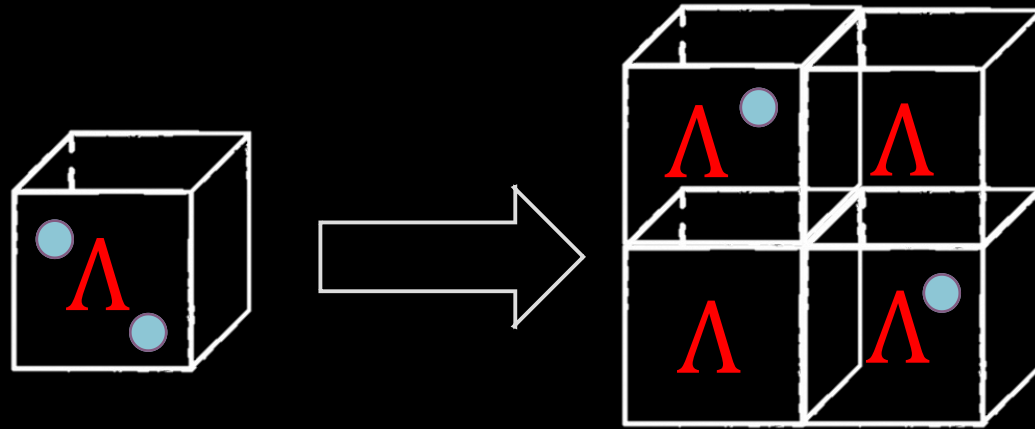


$$r_{\Lambda\text{CDM}} = \frac{\rho_{dm}}{\rho_{\Lambda}} = \frac{2}{1} = 2$$

- DM dilutes fast,  $\rho_{dm} \propto a^{-3}$  and DE remains constant  $\rho_{\Lambda} = \text{constant}$

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$$r_{\Lambda\text{CDM}} = \frac{\rho_{dm}}{\rho_{\Lambda}} = \frac{2}{1} = 2$$

$$r_{\Lambda\text{CDM}} = \frac{\rho_{dm}}{\rho_{\Lambda}} = \frac{2}{4} = 0.25$$

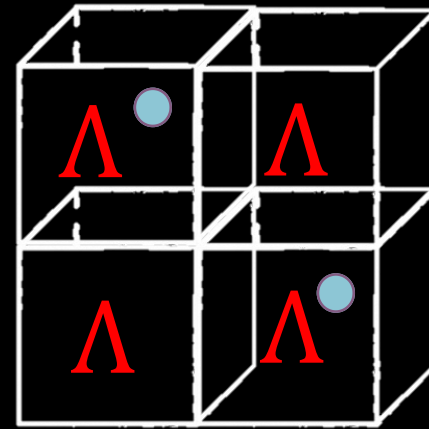
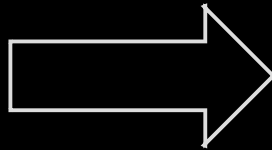
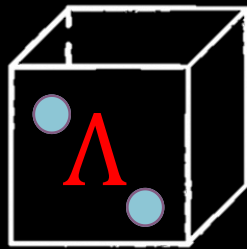
- DM dilutes fast,  $\rho_{dm} \propto a^{-3}$  and **DE remains constant**  $\rho_{\Lambda} = \text{constant}$

# 2. COINCIDENCE PROBLEM

- Consider expanding volume with dark energy and dark matter

$$r_{Planck} = \frac{\rho(dm, Planck)}{\rho(de, Planck)} \approx 10^{95}$$

$$r_{Distant\ Future} = \frac{\rho(dm, Future)}{\rho(de, Future)} \approx 0$$



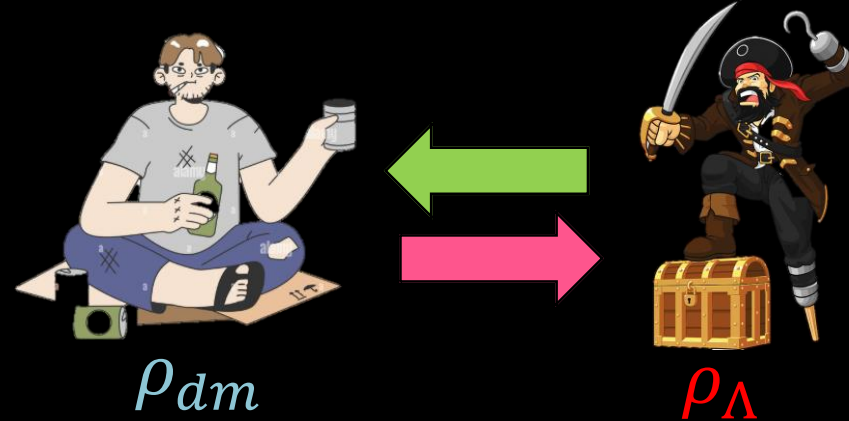
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- DM dilutes fast,  $\rho_{dm} \propto a^{-3}$  and DE remains constant  $\rho_{\Lambda} = constant$
- Why are we alive when the density is approximately equal? ( $r_0 \approx 0.4$ )

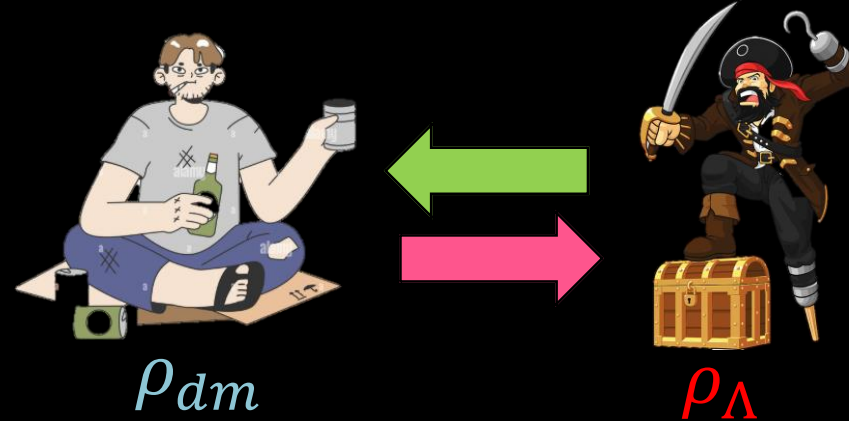
# 2. COINCIDENCE PROBLEM

- Analogy: Imagine you fly past an island.  
half the people are busy drinking away all their money,  
other half have buried their money safely.



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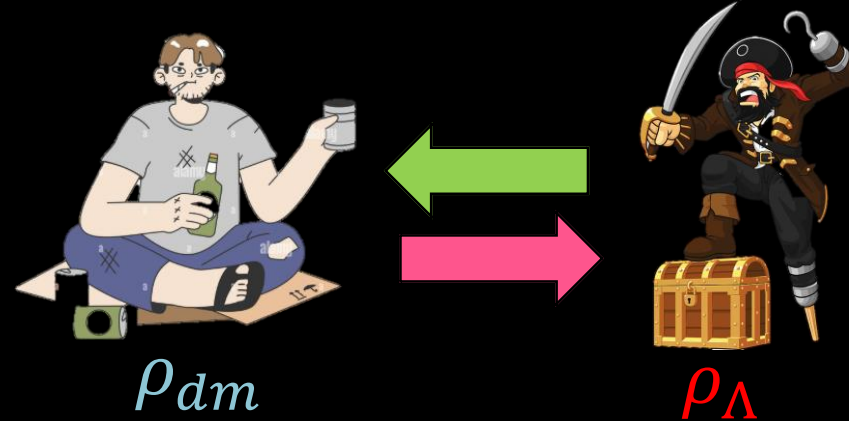
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- You hear this has always been the case for the last 1 000 generations.
- You happen to fly past at a time when both groups have the same amount of money.
- Is this a coincidence?

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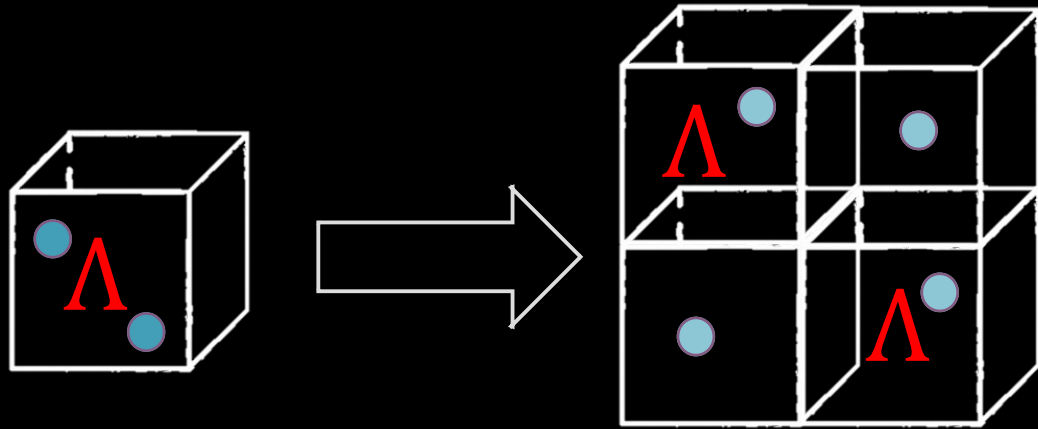


- You hear this has always been the case for the last 1 000 generations.
- You happen to fly past at a time when both groups have the same amount of money.
- Is this a coincidence? Theft? Taxes?

# DARK INTERACTIONS: THE BASIC IDEA

- What happens if dark matter and dark energy decay into each other?

DE  $\rightarrow$  DM  
(Taxing the rich)



$$r_{\Lambda\text{CDM}} = \frac{\rho_{dm}}{\rho_{\Lambda}} = \frac{2}{1} = 2$$

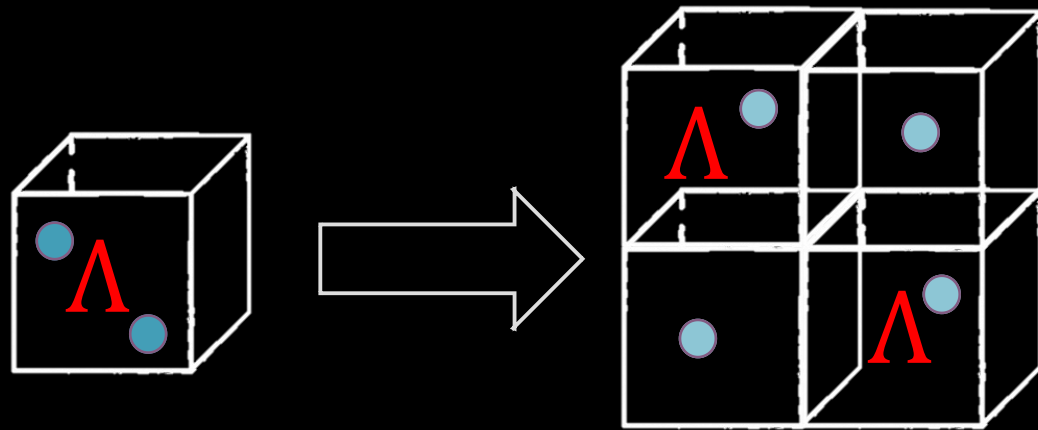
$$r_{\Lambda\text{CDM}} = \frac{\rho_{dm}}{\rho_{\Lambda}} = \frac{4}{2} = 2$$

- If DE decays into DM (iDEDM regime) we alleviate Coincidence Problem

# DARK INTERACTIONS: THE BASIC IDEA

- What happens if dark matter and dark energy decay into each other?

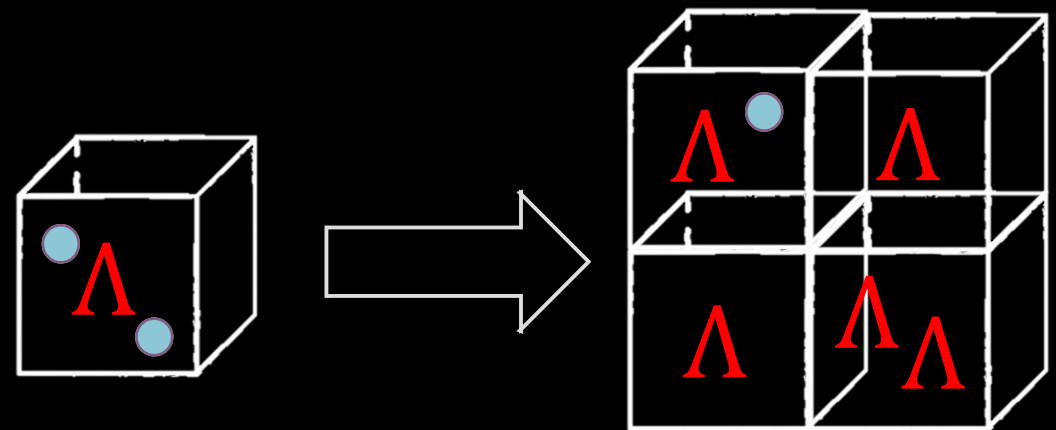
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$$r_{\Lambda\text{CDM}} = \frac{\rho_{dm}}{\rho_{\Lambda}} = \frac{4}{2} = 2$$

DM  $\rightarrow$  DE  
(Taxing the poor)



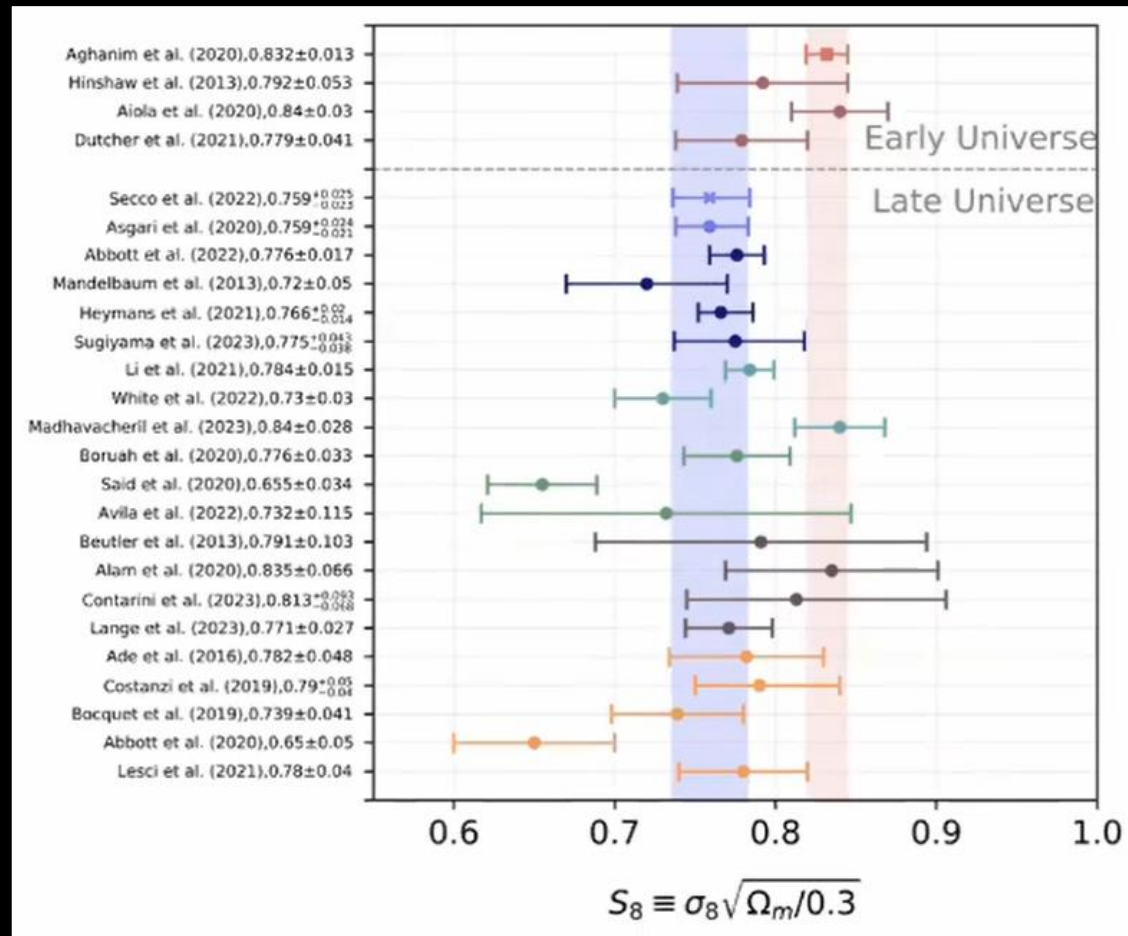
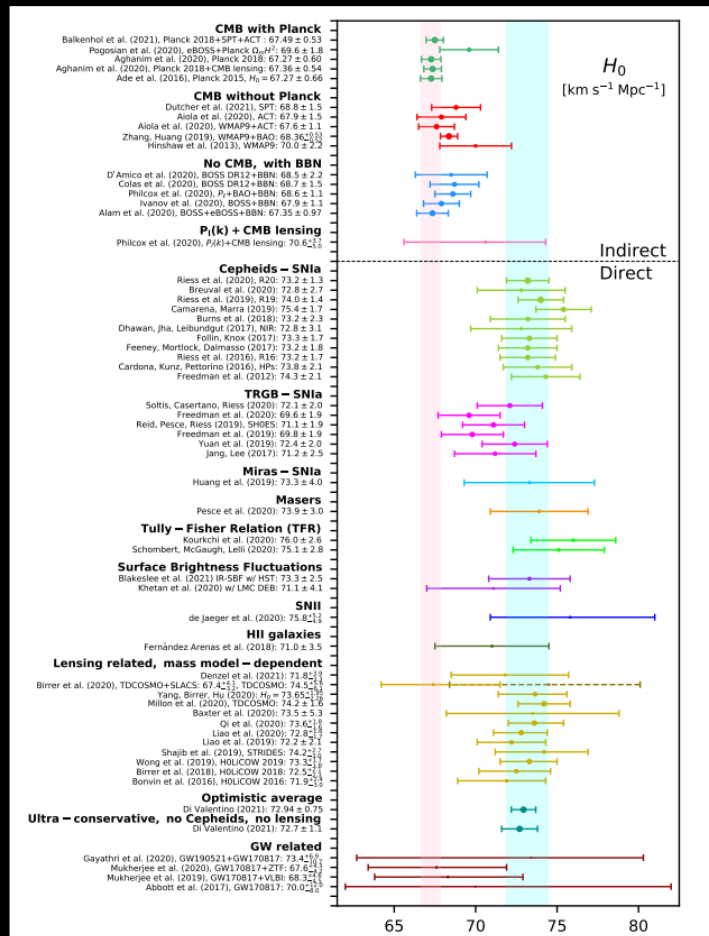
$$r_{\Lambda\text{CDM}} = \frac{\rho_{dm}}{\rho_{\Lambda}} = \frac{2}{1} = 2$$

$$r_{\Lambda\text{CDM}} = \frac{\rho_{dm}}{\rho_{\Lambda}} = \frac{1}{5} = 0.2$$

- If DE decays into DM (iDEDM regime) we alleviate Coincidence Problem
- If DM decays into DE (iDMDE regime) we worsen Coincidence Problem

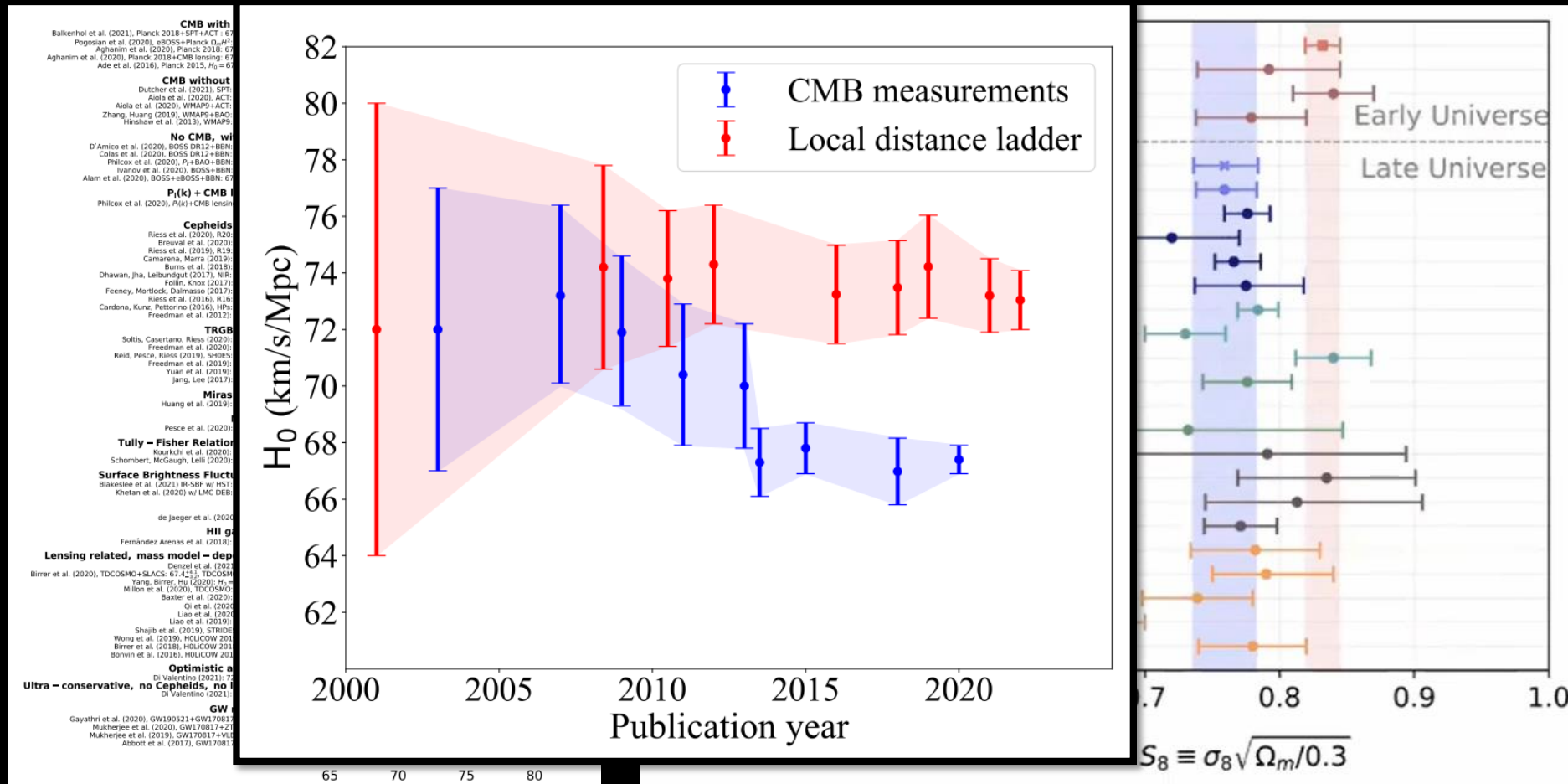
# 3. & 4. THE $H_0$ and $S_8$ TENSION

- Early (CMB) and late time (SN, LSS) measurements of the expansion  $H_0$  and clustering  $S_8$  rates differ by 3 – 5  $\sigma$ , depending on the source



# 3. & 4. THE $H_0$ and $S_8$ TENSION

- Early (CMB) and late time (SN, LSS) measurements of the expansion  $H_0$  and clustering  $S_8$  rates differ by  $3 - 5 \sigma$ , depending on the source



# 3. & 4. THE $H_0$ and $S_8$ TENSION

- **IDE models** introduce **new physics** to address either one or both of these issues. For example

Can interacting dark energy solve the  $H_0$  tension?

Eleonora Di Valentino,<sup>1,2,\*</sup> Alessandro Melchiorri,<sup>3,†</sup> and Olga Mena<sup>4,‡</sup>

Interacting dark energy in the early 2020s: a promising solution to the  $H_0$  and cosmic shear tensions

Eleonora Di Valentino<sup>a</sup>, Alessandro Melchiorri<sup>b</sup>, Olga Mena<sup>c</sup>, Sunny Vagnozzi<sup>d</sup>

Late time interacting cosmologies and the Hubble constant tension

Stefano Gariazzo,<sup>1,\*</sup> Eleonora Di Valentino,<sup>2,†</sup> Olga Mena,<sup>3,‡</sup> and Rafael C. Nunes<sup>4,5,§</sup>

Tale of stable interacting dark energy, observational signatures, and the  $H_0$  tension

Can interacting dark energy with dynamical coupling resolve the Hubble tension

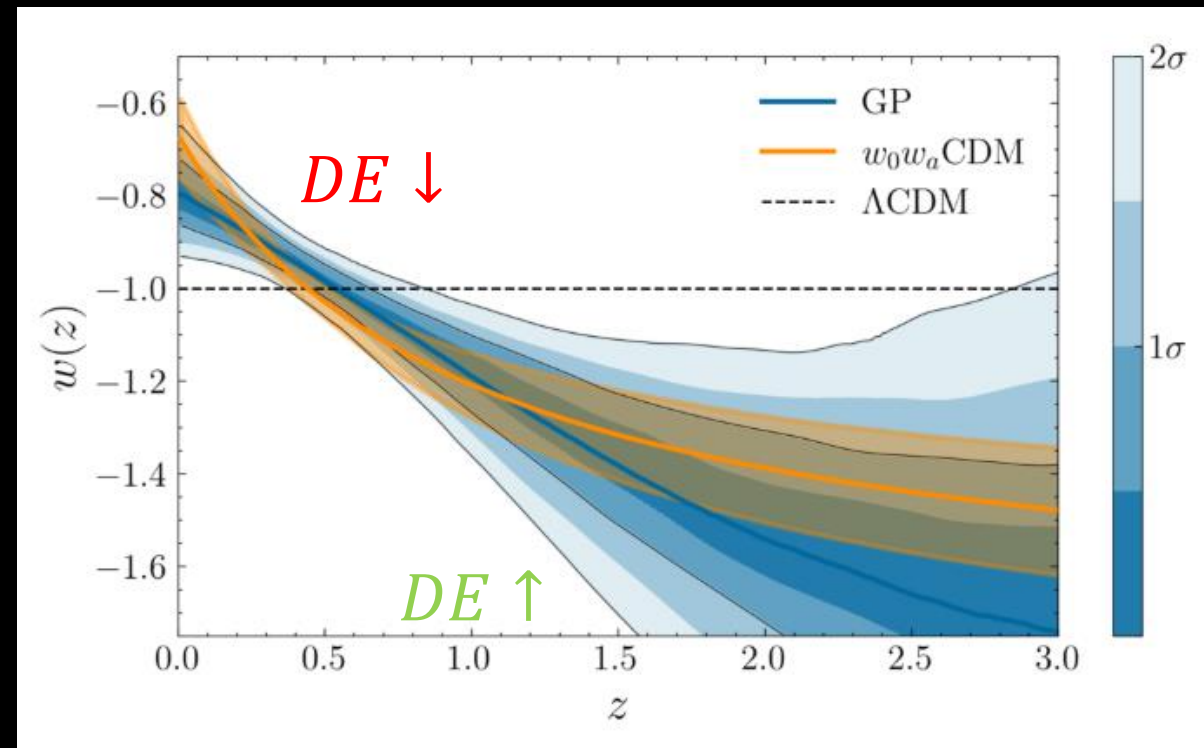
Yan-Hong Yao<sup>\*</sup>

Dark energy-dark matter interactions as a solution to the  $S_8$  tension

Matteo Lucca

# 5. COSMOLOGICAL (NOT SO) CONSTANT

- 2025: DESI collaboration released data on Baryonic acoustic oscillations
- BAO with CMB, SN1a combined prefers **dynamical dark energy** ( $2.8 - 4.2\sigma$ )
- Dark energy **increasing in distant past, decreasing at present?**
- New data released next year...
- IDE models provide a mechanism?



# 5. COSMOLOGICAL (NOT SO) CONSTANT

- **2025:** DESI collaboration released data on Baryonic acoustic oscillations

## Interacting Dark Sectors in light of DESI DR2

Rahul Shah,<sup>1\*</sup> Purba Mukherjee,<sup>1,2†</sup> and Supratik Pal<sup>1‡</sup>

<sup>1</sup>Physics and Applied Mathematics Unit, Indian Statistical Institute, 203 B.T. Road, Kolkata 700 108, India

<sup>2</sup>Centre for Theoretical Physics, Jamia Millia Islamia, New Delhi 110025, India

Phantom crossing or dark interaction?

Sêcloka L. Guedezounme<sup>a</sup> , Bikash R. Dinda<sup>a,b</sup> , Roy Maartens<sup>a,b</sup> 

## Interacting dark energy after DESI DR2: a challenge for $\Lambda$ CDM paradigm?

Supriya Pan,<sup>1,2,\*</sup> Sivasish Paul,<sup>1,†</sup> Emmanuel N. Saridakis,<sup>3,4,5,‡</sup> and Weiqiang Yang<sup>6,§</sup>

## Compartmentalization in the Dark Sector of the Universe after DESI DR2 BAO data

Marcel van der Westhuizen,<sup>1,\*</sup> David Figueruelo,<sup>1,2,†</sup> Rethabile Thubisi,<sup>1,‡</sup>  
Shambel Sahlu,<sup>1,3,§</sup> Amare Abebe,<sup>1,4,¶</sup> and Andronikos Paliathanasis<sup>1,4,5,6,\*\*</sup>

**INTERACTIONS SOLVE ALL PROBLEMS?**

**42**

**INTERACTIONS SOLVE ALL PROBLEMS?**

**42**

**NO, OF COURSE NOT...**

# 3. NEGATIVE ENERGIES

The background is a dark, deep blue color with a complex, branching, and somewhat chaotic pattern that resembles a tree's root system or a network of veins. The pattern is darker in some areas and lighter in others, creating a sense of depth and movement. Scattered throughout the background are numerous small, bright white and light blue dots, similar to stars or distant galaxies, which add to the overall ethereal and mysterious atmosphere of the image.

# CONSERVING THE DARK SECTOR

- In interacting dark energy models, the total dark sector is conserved. Energy lost  $Q$  by DM is gained by DE, and vice versa.

$$\dot{\rho}_{\text{dm}} + 3H\rho_{\text{dm}} = Q \quad ; \quad \dot{\rho}_{\text{de}} + 3H\rho_{\text{de}}(1 + \omega_{\text{de}}) = -Q$$

$Q$  must have units: energy per volume per second

$$\text{Ansatz: } Q \propto \delta H \rho_{\text{dm/de}}$$

$$Q \begin{cases} > 0 & \text{Dark Energy} \rightarrow \text{Dark Matter (iDEDM regime)} \\ < 0 & \text{Dark Matter} \rightarrow \text{Dark Energy (iDMDE regime)} \end{cases}$$

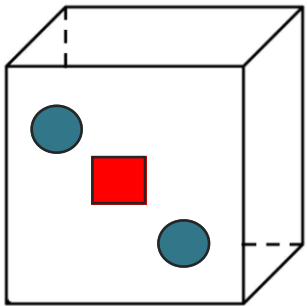
# ENERGY TRANSFER BRAKING MECHANISM

Consider a volume element for a model where  $Q$  is proportional to DE:

Present

Universe expands ( $H > 0$ )

Future



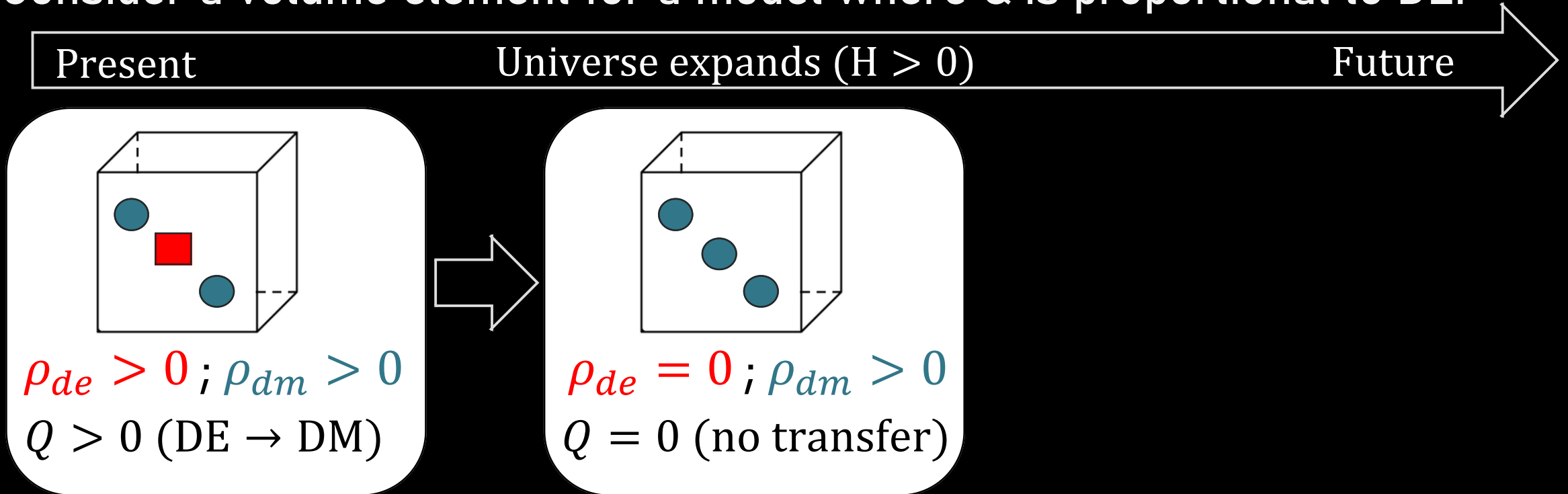
$$\rho_{de} > 0; \rho_{dm} > 0$$

$$Q > 0 \text{ (DE} \rightarrow \text{DM)}$$

$$Q = 3 \underbrace{\delta H}_{> 0 \text{ (iDEDM)}} \rho_{de} \quad \text{[cube]} = \text{volume element} \quad \text{[red square]} = \rho_{de} \quad \text{[blue circle]} = \rho_{dm}$$

# ENERGY TRANSFER BRAKING MECHANISM

Consider a volume element for a model where  $Q$  is proportional to DE:



$Q = 3 \delta \underset{\geq 0}{\underbrace{H}} \rho_{de}$ 

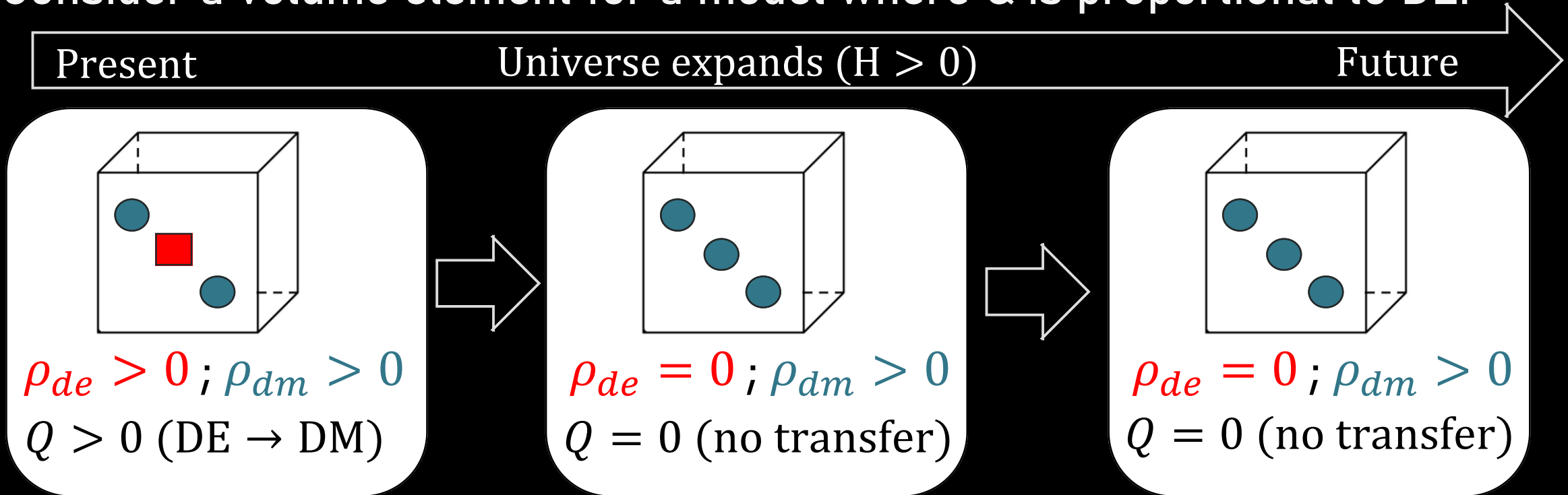
 = volume element
 
 =  $\rho_{de}$ 

 =  $\rho_{dm}$

(iDEDM)

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Consider a volume element for a model where  $Q$  is proportional to DE:



$$Q = 3 \delta \underset{> 0 \text{ (iDEDM)}}{\underbrace{\delta H}} \rho_{de}$$

 = volume element   
  =  $\rho_{de}$    
  =  $\rho_{dm}$

Since there is a braking mechanism, DE never becomes negative!

# NO TRANSFER BRAKING MECHANISM

Consider a volume element for a model where  $Q$  is proportional to DE:



$\rho_{de} > 0 ; \rho_{dm} > 0$   
 $Q < 0$  (DM  $\rightarrow$  DE)

$Q = 3 \underbrace{\delta H}_{\lesssim 0 \text{ (iDMDE)}} \rho_{de}$ 

 = volume element
 

 =  $+\rho_{de}$ 

 =  $+\rho_{dm}$ 

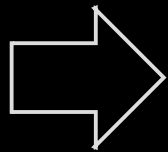
 =  $-\rho_{dm}$

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$Q = 3 \underbrace{\delta H}_{\lesssim 0} \rho_{de}$ 

 = volume element
 

 =  $+\rho_{de}$ 

 =  $+\rho_{dm}$ 

 =  $-\rho_{dm}$



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$\rho_{de} > 0$ ;  $\rho_{dm} > 0$   
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$Q = 3 \delta \underset{\lesssim 0 \text{ (iDMDE)}}{H} \rho_{dm}$     = volume element    =  $+\rho_{de}$     =  $+\rho_{dm}$   
 =  $-\rho_{de}$

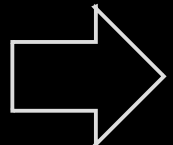
Similar arguments can show negative DE in the past for other models

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 $Q > 0$  (DE  $\rightarrow$  DM)



$\rho_{de} = 0; \rho_{dm} > 0$   
 $Q > 0$  (DE  $\rightarrow$  DM)

$Q = 3 \delta \underset{\lesssim 0 \text{ (iDMDE)}}{H} \rho_{dm}$ 
 = volume element
 
 =  $+\rho_{de}$ 
 =  $+\rho_{dm}$ 
  

 =  $-\rho_{de}$

Similar arguments can show negative DE in the past for other models



# NEGATIVE DARK ENERGY IN PAST...

We thus predict **negative DE densities** in the past if  $\delta < 0$  (DM  $\rightarrow$  DE)

For IDE model  $Q = 3\delta H \rho_{dm}$ , **DE < 0** in past

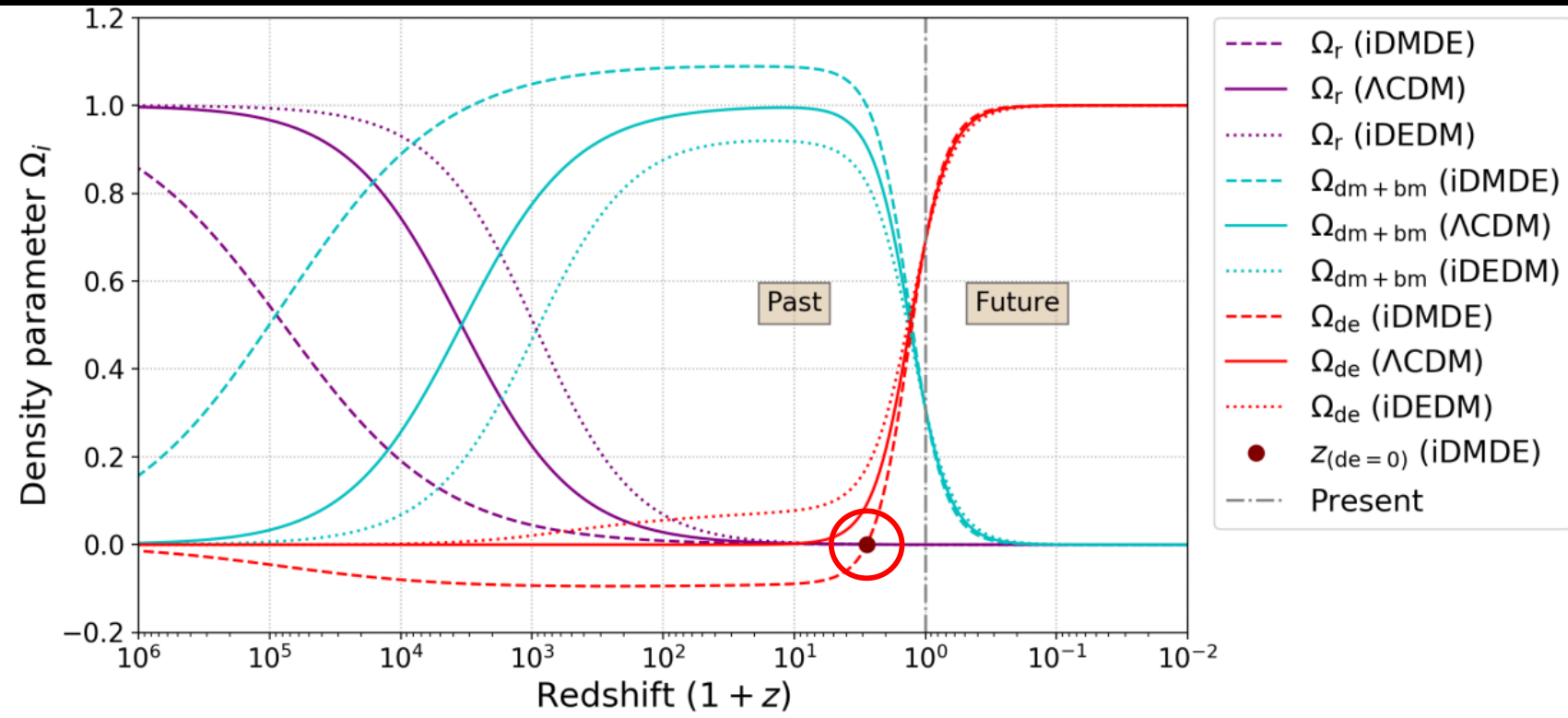
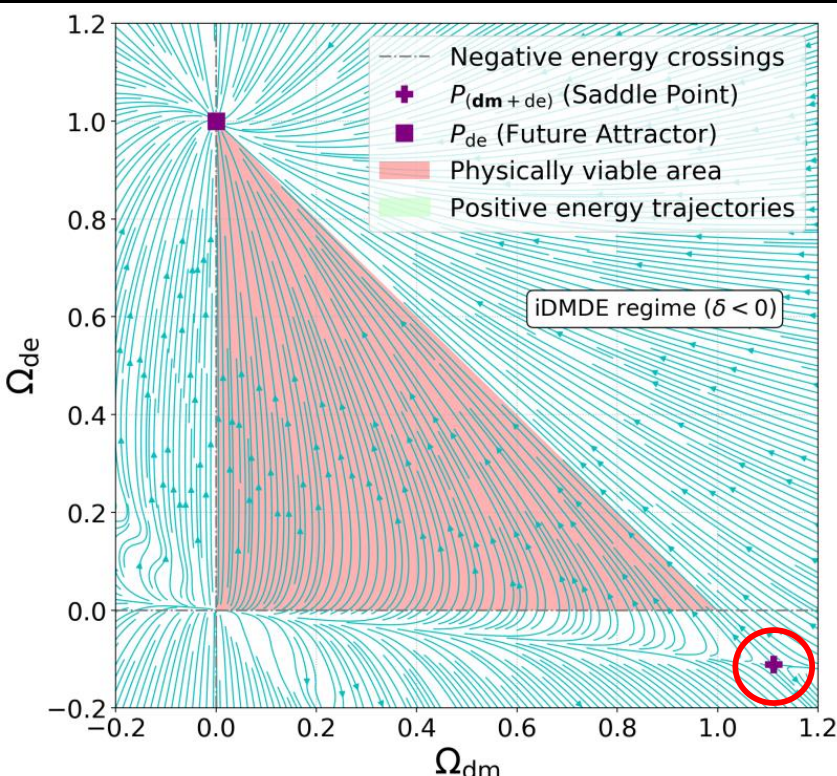
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For IDE model  $Q = 3\delta H \rho_{dm}$ , **DE < 0** in past

Dynamical system analysis

Plotting analytical solutions



# POSITIVE ENERGY CONDITIONS

Similar analysis was done for a total of 8 interactions

Interaction $Q$	$\rho_{\text{dm/de}} > 0$ domain	$\rho_{\text{dm/de}} > 0$ conditions	Example values
$3H(\delta_{\text{dm}}\rho_{\text{dm}} + \delta_{\text{de}}\rho_{\text{de}})$	DE $\rightarrow$ DM	$\delta_{\text{dm}} \geq 0; \delta_{\text{de}} \geq 0; \delta_{\text{dm}}r_0 + \delta_{\text{de}} \leq -\frac{wr_0}{(1+r_0)}$	
$3H\delta(\rho_{\text{dm}} + \rho_{\text{de}})$	DE $\rightarrow$ DM	$0 \leq \delta \leq -\frac{wr_0}{(1+r_0)^2}$	$0 \leq \delta \leq 0.201$
$3H\delta(\rho_{\text{dm}} - \rho_{\text{de}})$	No viable domain	No viable domain	No viable domain
$3H\delta\rho_{\text{dm}}$	DE $\rightarrow$ DM	$0 \leq \delta \leq -\frac{w}{(1+r_0)}$	$0 \leq \delta \leq 0.720$
$3H\delta\rho_{\text{de}}$	DE $\rightarrow$ DM	$0 \leq \delta \leq -\frac{w}{(1+\frac{1}{r_0})}$	$0 \leq \delta \leq 0.280$
$3H\delta \left( \frac{\rho_{\text{dm}}\rho_{\text{de}}}{\rho_{\text{dm}}+\rho_{\text{de}}} \right)$	DE $\leftrightarrow$ DM	$\forall \delta$	$\forall \delta$
$3H\delta \left( \frac{\rho_{\text{dm}}^2}{\rho_{\text{dm}}+\rho_{\text{de}}} \right)$	DE $\rightarrow$ DM	$0 \leq \delta \leq -\frac{w}{r_0}$	$0 \leq \delta \leq 2.575$
$3H\delta \left( \frac{\rho_{\text{de}}^2}{\rho_{\text{dm}}+\rho_{\text{de}}} \right)$	DE $\rightarrow$ DM	$0 \leq \delta \leq -wr_0$	$0 \leq \delta \leq 0.388$

FINDING OBSERVATIONAL POSTERiors PREDICTS BEHAVIOUR



# **5. OBSERVATIONAL CONSTRAINTS**

# LATE TIME BACKGROUND CONSTRAINTS

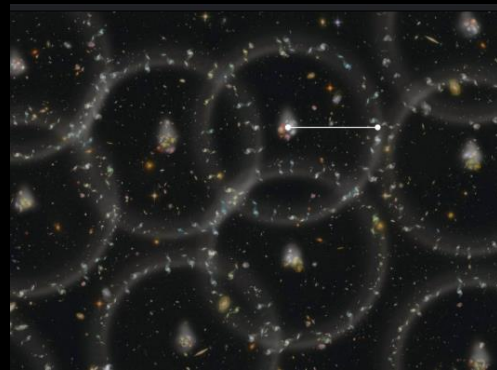
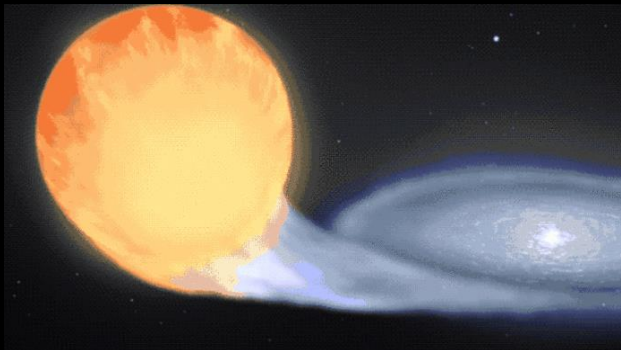
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# LATE TIME BACKGROUND CONSTRAINTS

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- Used analytical  $H(z)$  describing background expansion for all models

We used combinations of four datasets:

1. Pantheon+ Type Ia supernova data, calibrated with SHOES Cepheid data.
2. DESI DR2 Baryon Acoustic Oscillation data.

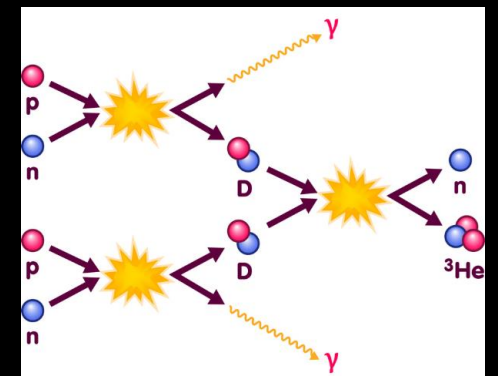
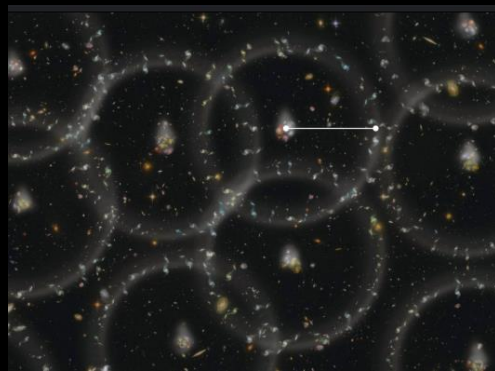
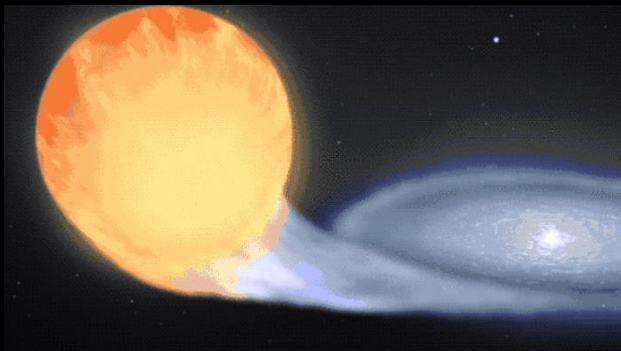


# LATE TIME BACKGROUND CONSTRAINTS

- We constrained 8 IDE models using public MCMC code **MontePython**
- Used analytical  $H(z)$  describing background expansion for all models

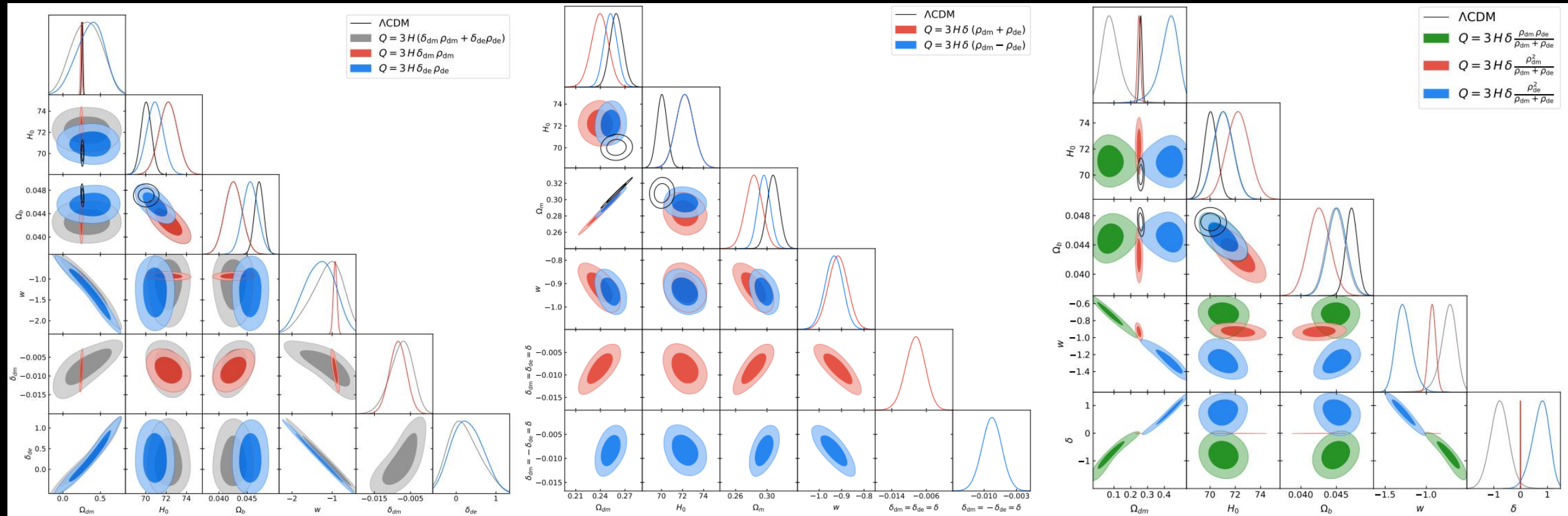
We used combinations of four datasets:

1. Pantheon+ Type Ia supernova data, calibrated with SHOES Cepheid data.
2. DESI DR2 Baryon Acoustic Oscillation data.
3. Cosmic Clock measurements.
4. Big Bang Nucleosynthesis as a prior on  $\Omega_b h^2 = 0.02218 \pm 0.00055$   
(same prior is used in the DESI DR2 papers to break degeneracy in  $H_0 r_d$ )



# LATE TIME BACKGROUND CONSTRAINTS

- Our analysis resulted in the following corner plots for 8 IDE models
- Check our paper for a closer look at these and posterior Tables



The background of the slide is a deep blue, almost black, space filled with a complex network of dark, branching filaments and filaments, resembling a cosmic web or a dense forest of stars. Scattered throughout are numerous small, bright white and blue points of light, some appearing as distant galaxies or stars. The overall effect is one of vastness and intricate structure.

# **6. STATISTICAL ANALYSIS AND COSMOLOGICAL IMPLICATIONS**

# IDE HAS BETTER STATISTICAL FIT

In all cases, where possible:

Model / Kernel $Q$	Pantheon+ & DESI DR2		Pantheon+, DESI DR2, CC & BBN	
	$\Delta\chi^2$	$\Delta\text{AIC}$	$\Delta\chi^2$	$\Delta\text{AIC}$
$\Lambda\text{CDM}$	–	–	–	–
$3H(\delta_{\text{dm}}\rho_{\text{dm}} + \delta_{\text{de}}\rho_{\text{de}})$	–21.96	–15.96	–17.76	–11.76
$3H\delta(\rho_{\text{dm}} + \rho_{\text{de}})$	–21.94	–17.94	–17.76	–13.76
$3H\delta(\rho_{\text{dm}} - \rho_{\text{de}})$	–21.96	–17.96	–17.74	–13.74
$3H\delta\rho_{\text{dm}}$	–21.94	–17.94	–17.74	–13.74
$3H\delta\rho_{\text{de}}$	–7.52	–3.52	–2.34	+1.66
$3H\delta\left(\frac{\rho_{\text{dm}}\rho_{\text{de}}}{\rho_{\text{dm}}+\rho_{\text{de}}}\right)$	–16.14	–12.14	–10.28	–6.28
$3H\delta\left(\frac{\rho_{\text{dm}}^2}{\rho_{\text{dm}}+\rho_{\text{de}}}\right)$	–21.94	–17.94	–17.76	–13.76
$3H\delta\left(\frac{\rho_{\text{de}}^2}{\rho_{\text{dm}}+\rho_{\text{de}}}\right)$	–15.02	–11.02	–9.46	–5.46

- NB. Perturbation equations and CMB not used yet

# IDE HAS BETTER STATISTICAL FIT

In all cases, where possible:

- For all eight IDE models, improved  $\Delta\chi^2 = \Delta\chi_{IDE}^2 - \Delta\chi_{\Lambda CDM}^2$  fit ( $\Delta\chi^2 < 0$ ).

Model / Kernel $Q$	Pantheon+ & DESI DR2		Pantheon+, DESI DR2, CC & BBN	
	$\Delta\chi^2$	$\Delta AIC$	$\Delta\chi^2$	$\Delta AIC$
$\Lambda$ CDM	–	–	–	–
$3H(\delta_{dm}\rho_{dm} + \delta_{de}\rho_{de})$	–21.96	–15.96	–17.76	–11.76
$3H\delta(\rho_{dm} + \rho_{de})$	–21.94	–17.94	–17.76	–13.76
$3H\delta(\rho_{dm} - \rho_{de})$	–21.96	–17.96	–17.74	–13.74
$3H\delta\rho_{dm}$	–21.94	–17.94	–17.74	–13.74
$3H\delta\rho_{de}$	–7.52	–3.52	–2.34	+1.66
$3H\delta\left(\frac{\rho_{dm}\rho_{de}}{\rho_{dm}+\rho_{de}}\right)$	–16.14	–12.14	–10.28	–6.28
$3H\delta\left(\frac{\rho_{dm}^2}{\rho_{dm}+\rho_{de}}\right)$	–21.94	–17.94	–17.76	–13.76
$3H\delta\left(\frac{\rho_{de}^2}{\rho_{dm}+\rho_{de}}\right)$	–15.02	–11.02	–9.46	–5.46

- NB. Perturbation equations and CMB not used yet

# IDE HAS BETTER STATISTICAL FIT

In all cases, where possible:

- For all eight IDE models, improved  $\Delta\chi^2 = \Delta\chi_{IDE}^2 - \Delta\chi_{\Lambda CDM}^2$  fit ( $\Delta\chi^2 < 0$ ).
- Improved fit in Akaike Information Criterion ( $\Delta AIC < 0$ ) in 7 of 8 cases. ( $AIC = \chi^2 + 2$  d.o.f., so it takes account of 2 or 3 extra parameters introduced)

Model / Kernel $Q$	Pantheon+ & DESI DR2		Pantheon+, DESI DR2, CC & BBN	
	$\Delta\chi^2$	$\Delta AIC$	$\Delta\chi^2$	$\Delta AIC$
$\Lambda$ CDM	–	–	–	–
$3H(\delta_{dm}\rho_{dm} + \delta_{de}\rho_{de})$	-21.96	-15.96	-17.76	-11.76
$3H\delta(\rho_{dm} + \rho_{de})$	-21.94	-17.94	-17.76	-13.76
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$3H\delta\left(\frac{\rho_{dm}^2}{\rho_{dm}+\rho_{de}}\right)$	-21.94	-17.94	-17.76	-13.76
$3H\delta\left(\frac{\rho_{de}^2}{\rho_{dm}+\rho_{de}}\right)$	-15.02	-11.02	-9.46	-5.46

- NB. Perturbation equations and CMB not used yet

# BACKGROUND CONSTRAINTS = DE < 0?

Constrained 8 IDE models with DESI DR2, PANTHEON+ and Cosmic Clocks  
 In all cases, where possible, a preference was found for:

Interaction $Q$	Preferred energy flow	$\rho_{\text{dm,past}}$	$\rho_{\text{dm,future}}$	$\rho_{\text{de,past}}$	$\rho_{\text{de,future}}$
$3H(\delta_{\text{dm}}\rho_{\text{dm}} + \delta_{\text{de}}\rho_{\text{de}})$	DM $\rightarrow$ DE followed by DE $\rightarrow$ DM	+	+	-	+
$3H\delta(\rho_{\text{dm}} + \rho_{\text{de}})$	DM $\rightarrow$ DE	+	-	-	+
$3H\delta(\rho_{\text{dm}} - \rho_{\text{de}})$	DM $\rightarrow$ DE followed by DE $\rightarrow$ DM	+	+	-	+
$3H\delta\rho_{\text{dm}}$	DM $\rightarrow$ DE	+	+	-	+
$3H\delta\rho_{\text{de}}$	DE $\rightarrow$ DM	+	+	+	+
$3H\delta\left(\frac{\rho_{\text{dm}}\rho_{\text{de}}}{\rho_{\text{dm}}+\rho_{\text{de}}}\right)$	DM $\rightarrow$ DE	+	+	+	+
$3H\delta\left(\frac{\rho_{\text{dm}}^2}{\rho_{\text{dm}}+\rho_{\text{de}}}\right)$	DM $\rightarrow$ DE	+	+	-	+
$3H\delta\left(\frac{\rho_{\text{de}}^2}{\rho_{\text{dm}}+\rho_{\text{de}}}\right)$	DE $\rightarrow$ DM	+	+	+	+

# BACKGROUND CONSTRAINTS = DE < 0?

Constrained 8 IDE models with DESI DR2, PANTHEON+ and Cosmic Clocks  
 In all cases, where possible, a preference was found for:

- **Negative DE** (in past for models without transfer braking mechanism)

Interaction $Q$	Preferred energy flow	$\rho_{\text{dm,past}}$	$\rho_{\text{dm,future}}$	$\rho_{\text{de,past}}$	$\rho_{\text{de,future}}$
$3H(\delta_{\text{dm}}\rho_{\text{dm}} + \delta_{\text{de}}\rho_{\text{de}})$	DM $\rightarrow$ DE followed by DE $\rightarrow$ DM	+	+	-	+
$3H\delta(\rho_{\text{dm}} + \rho_{\text{de}})$	DM $\rightarrow$ DE	+	-	-	+
$3H\delta(\rho_{\text{dm}} - \rho_{\text{de}})$	DM $\rightarrow$ DE followed by DE $\rightarrow$ DM	+	+	-	+
$3H\delta\rho_{\text{dm}}$	DM $\rightarrow$ DE	+	+	-	+
$3H\delta\rho_{\text{de}}$	DE $\rightarrow$ DM	+	+	+	+
$3H\delta\left(\frac{\rho_{\text{dm}}\rho_{\text{de}}}{\rho_{\text{dm}}+\rho_{\text{de}}}\right)$	DM $\rightarrow$ DE	+	+	+	+
$3H\delta\left(\frac{\rho_{\text{dm}}^2}{\rho_{\text{dm}}+\rho_{\text{de}}}\right)$	DM $\rightarrow$ DE	+	+	-	+
$3H\delta\left(\frac{\rho_{\text{de}}^2}{\rho_{\text{dm}}+\rho_{\text{de}}}\right)$	DE $\rightarrow$ DM	+	+	+	+

# BACKGROUND CONSTRAINTS = DE < 0?

Constrained 8 IDE models with DESI DR2, PANTHEON+ and Cosmic Clocks  
 In all cases, where possible, a preference was found for:

- **Negative DE** (in past for models without transfer braking mechanism)
- **Sign switching behaviour** (DM to DE at high z, DE to DM at low z)

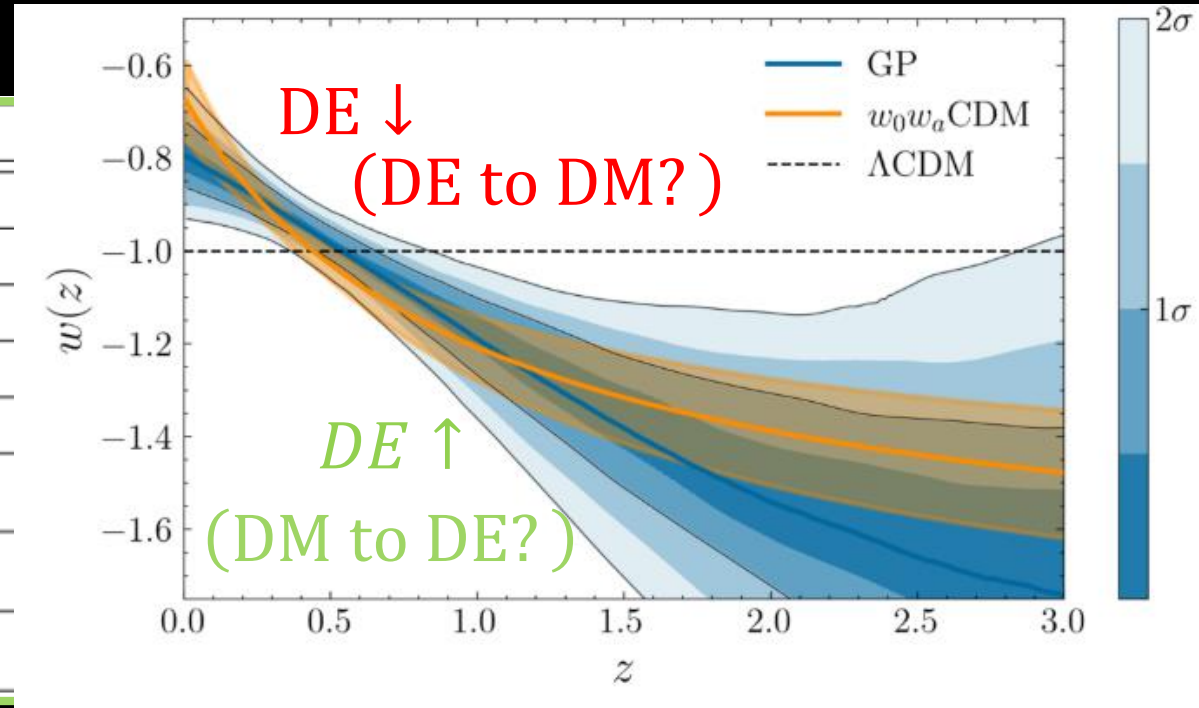
Interaction $Q$	Preferred energy flow	$\rho_{\text{dm,past}}$	$\rho_{\text{dm,future}}$	$\rho_{\text{de,past}}$	$\rho_{\text{de,future}}$
$3H(\delta_{\text{dm}}\rho_{\text{dm}} + \delta_{\text{de}}\rho_{\text{de}})$	DM $\rightarrow$ DE followed by DE $\rightarrow$ DM	+	+	-	+
$3H\delta(\rho_{\text{dm}} + \rho_{\text{de}})$	DM $\rightarrow$ DE	+	-	-	+
$3H\delta(\rho_{\text{dm}} - \rho_{\text{de}})$	DM $\rightarrow$ DE followed by DE $\rightarrow$ DM	+	+	-	+
$3H\delta\rho_{\text{dm}}$	DM $\rightarrow$ DE	+	+	-	+
$3H\delta\rho_{\text{de}}$	DE $\rightarrow$ DM	+	+	+	+
$3H\delta\left(\frac{\rho_{\text{dm}}\rho_{\text{de}}}{\rho_{\text{dm}}+\rho_{\text{de}}}\right)$	DM $\rightarrow$ DE	+	+	+	+
$3H\delta\left(\frac{\rho_{\text{dm}}^2}{\rho_{\text{dm}}+\rho_{\text{de}}}\right)$	DM $\rightarrow$ DE	+	+	-	+
$3H\delta\left(\frac{\rho_{\text{de}}^2}{\rho_{\text{dm}}+\rho_{\text{de}}}\right)$	DE $\rightarrow$ DM	+	+	+	+

# BACKGROUND CONSTRAINTS = DE < 0?

Constrained 8 IDE models with DESI DR2, PANTHEON+ and Cosmic Clocks  
 In all cases, where possible, a preference was found for:

- **Negative DE** (in past for models without transfer braking mechanism)
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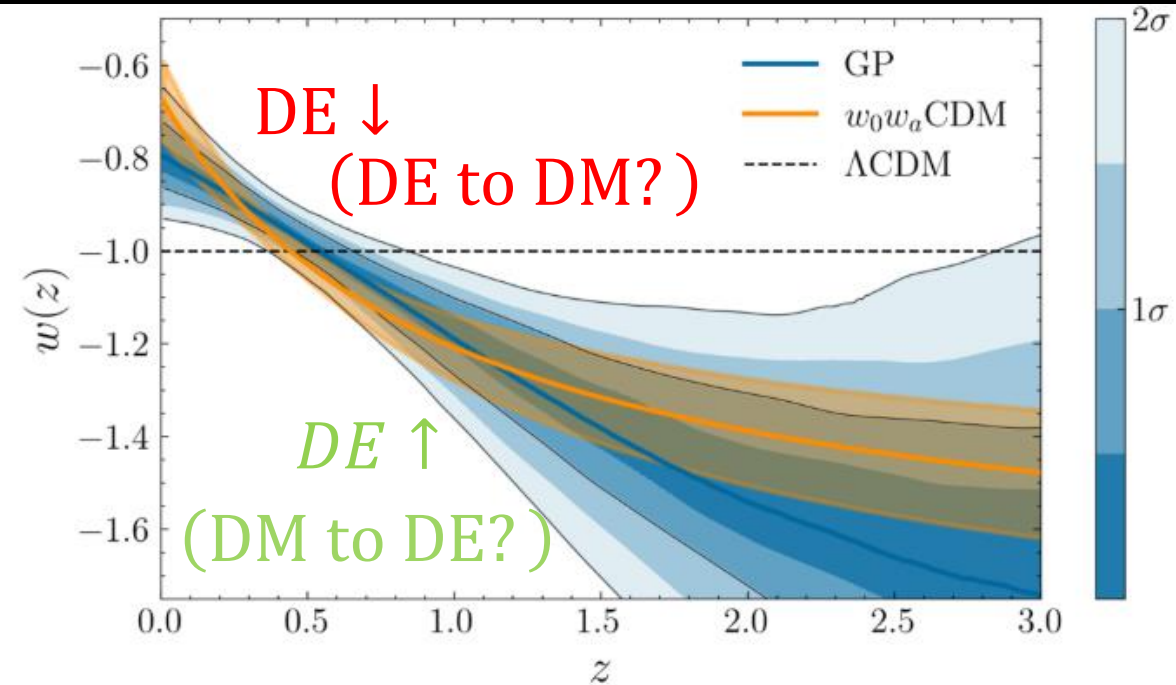
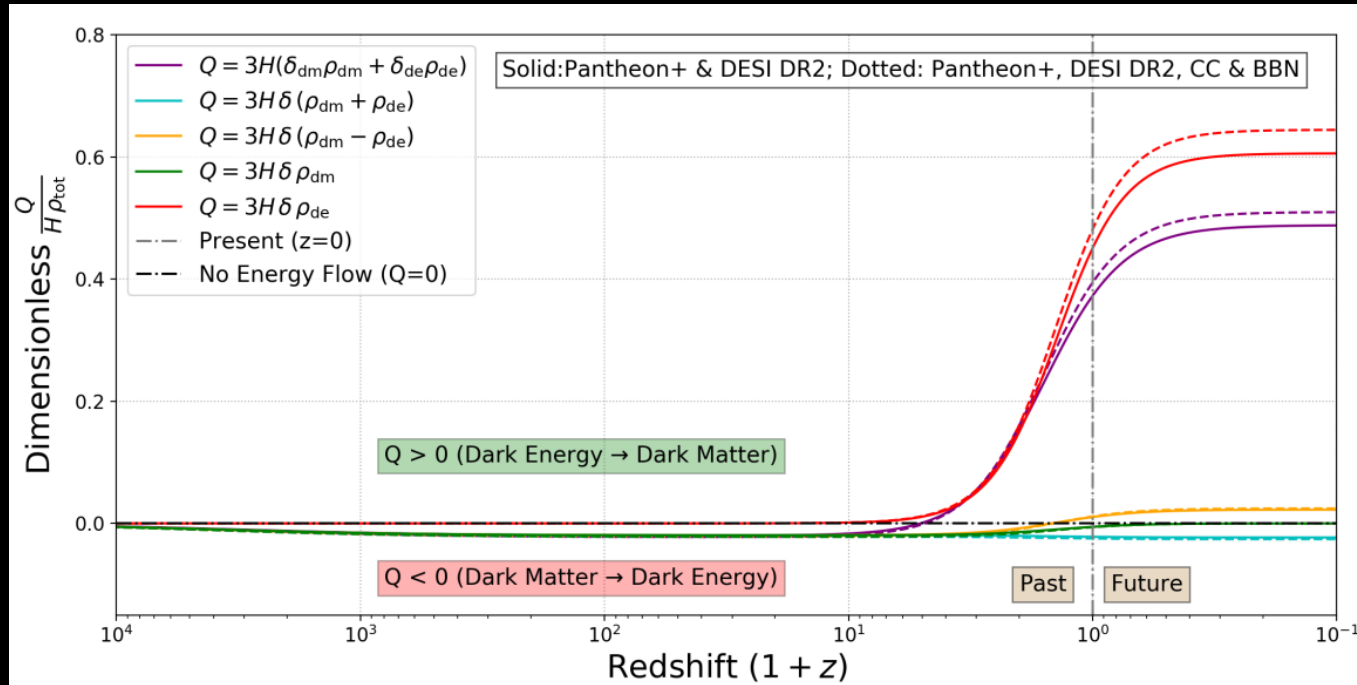
Interaction $Q$	Preferred energy flow
$3H(\delta_{\text{dm}}\rho_{\text{dm}} + \delta_{\text{de}}\rho_{\text{de}})$	DM $\rightarrow$ DE followed by DE $\rightarrow$ DM
$3H\delta(\rho_{\text{dm}} + \rho_{\text{de}})$	DM $\rightarrow$ DE
$3H\delta(\rho_{\text{dm}} - \rho_{\text{de}})$	DM $\rightarrow$ DE followed by DE $\rightarrow$ DM
$3H\delta\rho_{\text{dm}}$	DM $\rightarrow$ DE
$3H\delta\rho_{\text{de}}$	DE $\rightarrow$ DM
$3H\delta\left(\frac{\rho_{\text{dm}}\rho_{\text{de}}}{\rho_{\text{dm}}+\rho_{\text{de}}}\right)$	DM $\rightarrow$ DE
$3H\delta\left(\frac{\rho_{\text{dm}}^2}{\rho_{\text{dm}}+\rho_{\text{de}}}\right)$	DM $\rightarrow$ DE
$3H\delta\left(\frac{\rho_{\text{de}}^2}{\rho_{\text{dm}}+\rho_{\text{de}}}\right)$	DE $\rightarrow$ DM



# BACKGROUND CONSTRAINTS = DE < 0?

Constrained 8 IDE models with DESI DR2, PANTHEON+ and Cosmic Clocks  
 In all cases, where possible, a preference was found for:

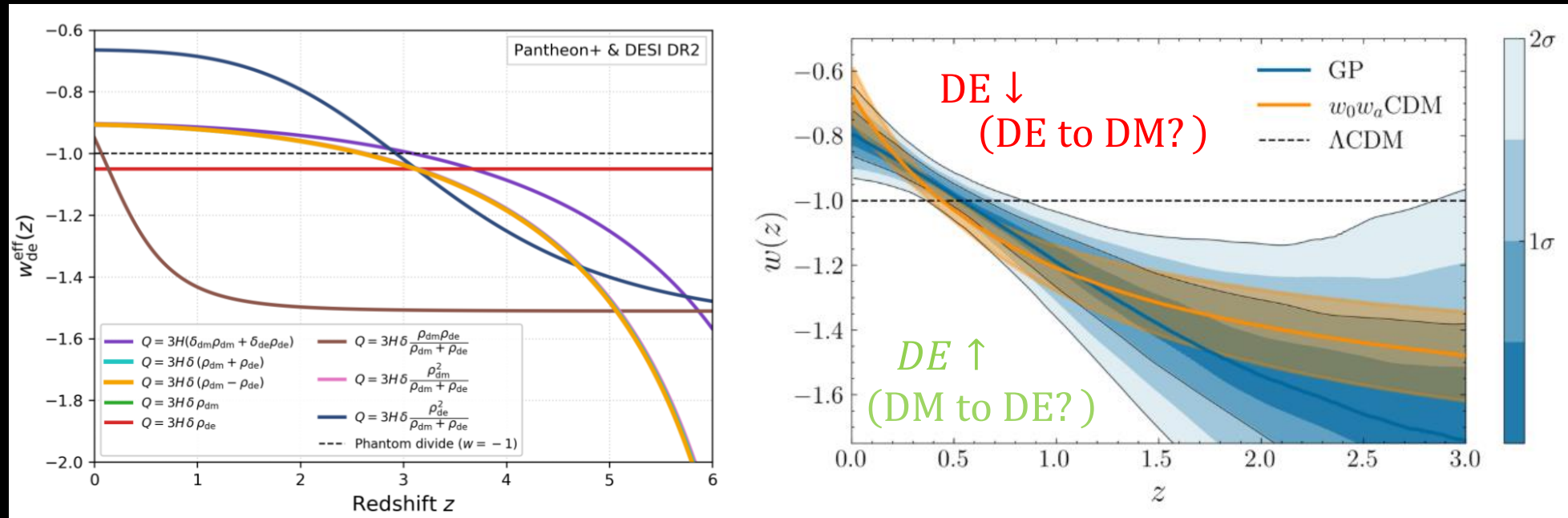
- **Negative DE** (in past for models without transfer braking mechanism)
- **Sign switching behaviour** (DM to DE at high z, DE to DM at low z)



# BACKGROUND CONSTRAINTS = DE < 0?

Constrained 8 IDE models with DESI DR2, PANTHEON+ and Cosmic Clocks  
 In all cases, where possible, a preference was found for:

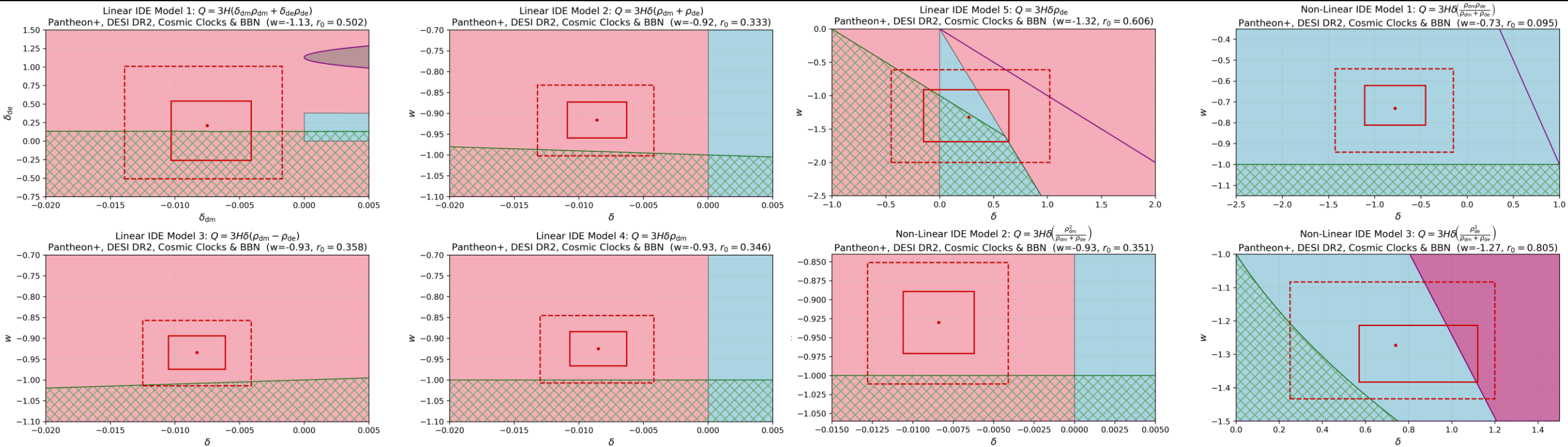
- **Negative DE** (in past for models without transfer braking mechanism)
- **Sign switching behaviour** (DM to DE at high  $z$ , DE to DM at low  $z$ )
- **Phantom crossing** for  $w_{de}^{eff}$  observed when possible



**Dark sector interaction mechanism for dynamical dark energy?**

# IDE PARAMETER SPACE

Be careful about the cost of **new problems** to **solve old problems**



- Blue - Positive DM & DE
- Pink - Negative DM or DE
- Gray - Imaginary energy densities
- Green mesh - Big Rip
- Purple - Undefined DM or DE

# TO ACCEPT OR NOT TO ACCEPT

$$\rho_{de} < 0$$



# TO ACCEPT OR NOT TO ACCEPT



$$\rho_{de} < 0$$

Other negative energy models gained attention:

- $\Lambda_s$ CDM models
- AdS-dS transition

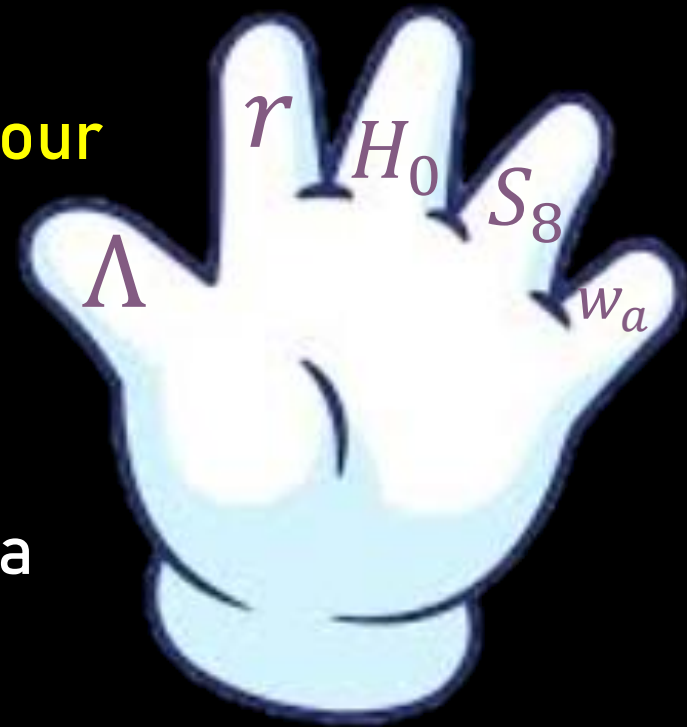
Please feel free to share your thoughts afterwards!



# 6. CONCLUSIONS

# PROMISING BUT PROBLEMATIC

- IDE models relevant for **addressing** key **cosmological problems**
- **Theoretical preference** for small energy flow from **DE to DM**
- **Observational preference** for **sign-switching behaviour** (DM to DE at high  $z$ , DE to DM at low  $z$ )
- May provide **mechanism** for dynamical dark energy
- **Improved  $\Delta\chi^2$  and  $\Delta AIC$**  fit to  $\Lambda$ CDM background data
- Often accompanied by **negative energies**, **perturbation instabilities** or **future singularities**



# FUTURE WORK

- Combine background analysis with **perturbation and stability analysis**
- These models need to be **constrained with more cosmological data**, especially CMB. Can these address tensions?
- These need a more developed **microphysical description**, so that we do not only rely on phenomenological interactions.
- **Rule out IDE models and move on to more promising ideas?**



**THE END**



**QUESTIONS?**

# PERTURBATIONS AND STABILITY

- Perturbations for IDE models often lead to instabilities, and need for choice of DM or DE frame
- Common approach introduce doom factor  $d$

$$d = \frac{Q}{3H\rho_{de}(1+w)} \quad \text{if } \begin{cases} d > 1 & \rightarrow \text{Unstable regime} \\ d < 0 & \rightarrow \text{a priori free of instabilities} \end{cases}$$

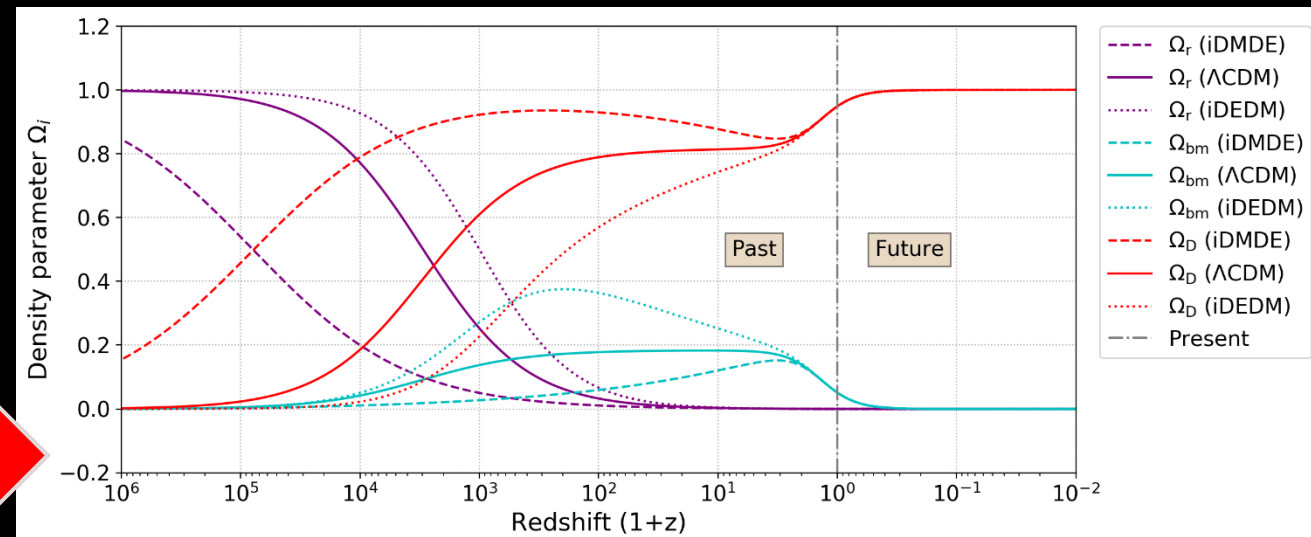
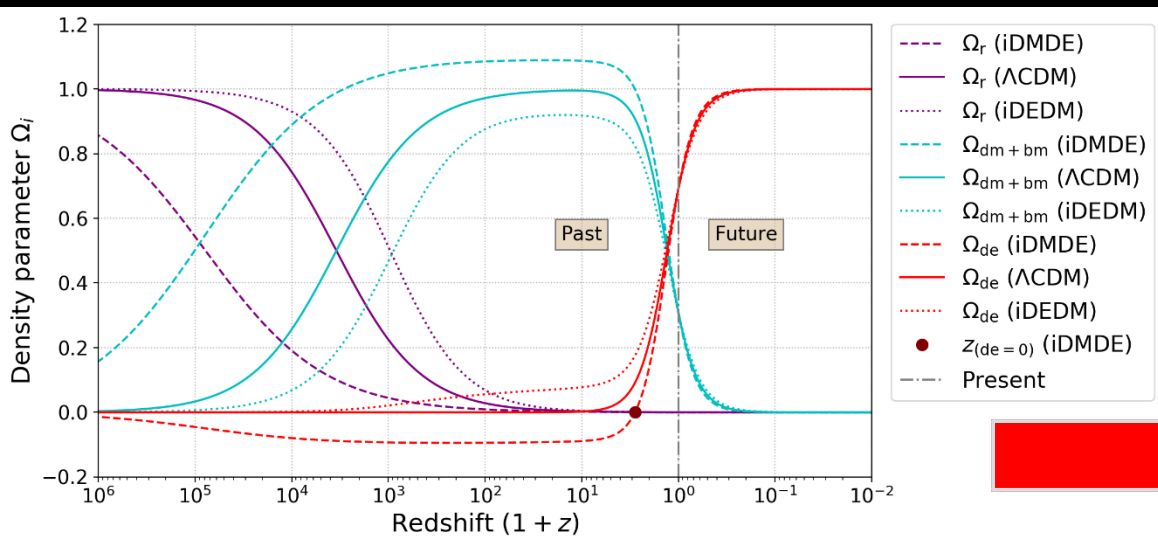
Two safe regimes:

- $Q > 0$  (DE  $\rightarrow$  DM) with  $w < -1$  (Phantom DE)
- $Q < 0$  (DM  $\rightarrow$  DE) with  $w > -1$  (Quintessence DE)

**DETAILS CONSIDERED IN FUTURE WORK**

# AVOIDING NEGATIVE ENERGIES

- **Set priors** to avoid negative energies, i.e. **DE**  $\rightarrow$  **DM**:  $\delta$  [0 ; 0.3]
- Only use **models where DM and DE always positive** .i.e.  $Q \propto \rho_{dm}\rho_{de}$
- Allow that **domain of applicability small**, so pathologies will not occur
- **Non-fluid DE description** i.e. scalar field or holographic principle
- **Conserved total dark sector** i.e. Unified Dark Fluid or Chaplygin Gas



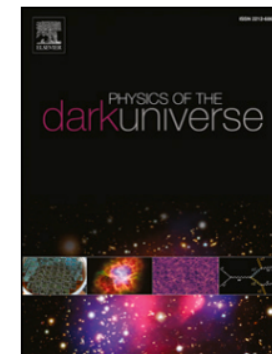
# SEE PAPER FOR DETAILED RESULTS



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## Physics of the Dark Universe

journal homepage: [www.elsevier.com/locate/dark](http://www.elsevier.com/locate/dark)



Full Length Article

Late-time background constraints on linear and non-linear interacting dark energy after DESI DR2

David Figueruelo  <sup>a,b</sup>, Marcel van der Westhuizen  <sup>c,\*</sup>, Amare Abebe  <sup>c,d</sup>,  
Eleonora Di Valentino  <sup>e</sup>


# SCAN FOR PAPER



# OVERVIEW OF BACKGROUND THEORY OF MODELS

Full Length Article

## I. Linear interacting dark energy: Analytical solutions and theoretical pathologies

Marcel van der Westhuizen <sup>a</sup><sup>\*</sup>, Amare Abebe <sup>a,b</sup>, Eleonora Di Valentino <sup>c</sup>


<sup>a</sup> Centre for Space Research, North-West University, Potchefstroom 2520, South Africa

<sup>b</sup> National Institute for Theoretical and Computational Sciences (NITheCS), South Africa

<sup>c</sup> School of Mathematical and Physical Sciences, University of Sheffield, Hounsfield Road, Sheffield, S3 7RH, United Kingdom

Full Length Article

## II. Non-linear interacting dark energy: Analytical solutions and theoretical pathologies

Marcel van der Westhuizen <sup>a</sup><sup>\*</sup>, Amare Abebe <sup>a,b</sup>, Eleonora Di Valentino <sup>c</sup>


<sup>a</sup> Centre for Space Research, North-West University, Potchefstroom 2520, South Africa

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<sup>c</sup> School of Mathematical and Physical Sciences, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, United Kingdom

Full length article

## III. Interacting Dark Energy: Summary of models, Pathologies, and Constraints

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<sup>a</sup> Centre for Space Research, North-West University, Potchefstroom 2520, South Africa

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