# Probe of Dark Energy at LISA:Standard vs Null Diagonistics

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**Based on arXiv: 2005.07231[astro-ph]**

# Outline

- What is LISA?
- Why Dark Energy?
- Why LISA in Dark Energy?
- What is Standard Diagonistic?
- What is Null Diagonistic?
- Case Studies.... wCDM    CPLCDM   IDE
- Conclusions

What is LISA?

Why Dark Energy?

Why LISA in Dark Energy?

What is Standard Diagonistic?

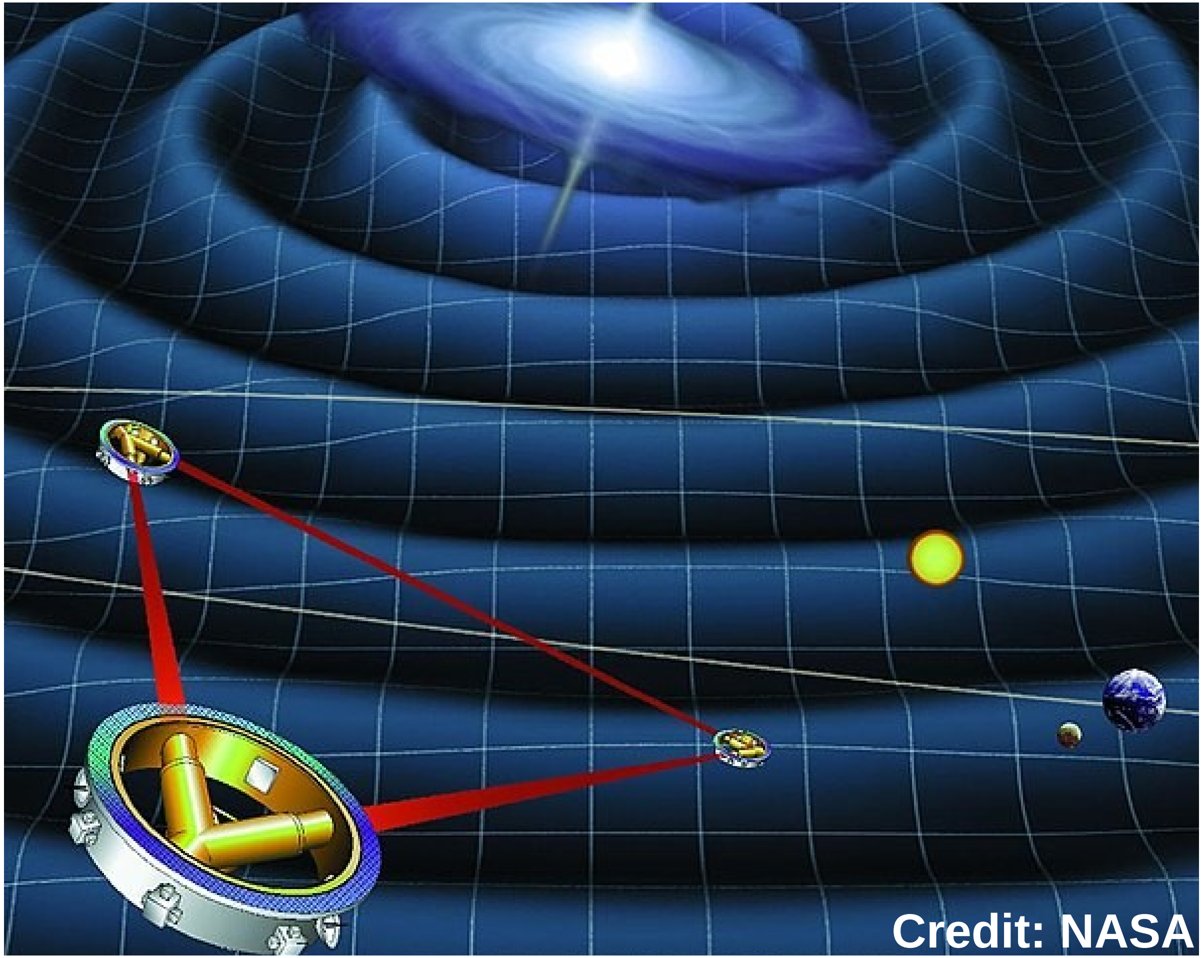
What is Null Diagonistic?

Case Studies.... wCDM CPLCDM IDE

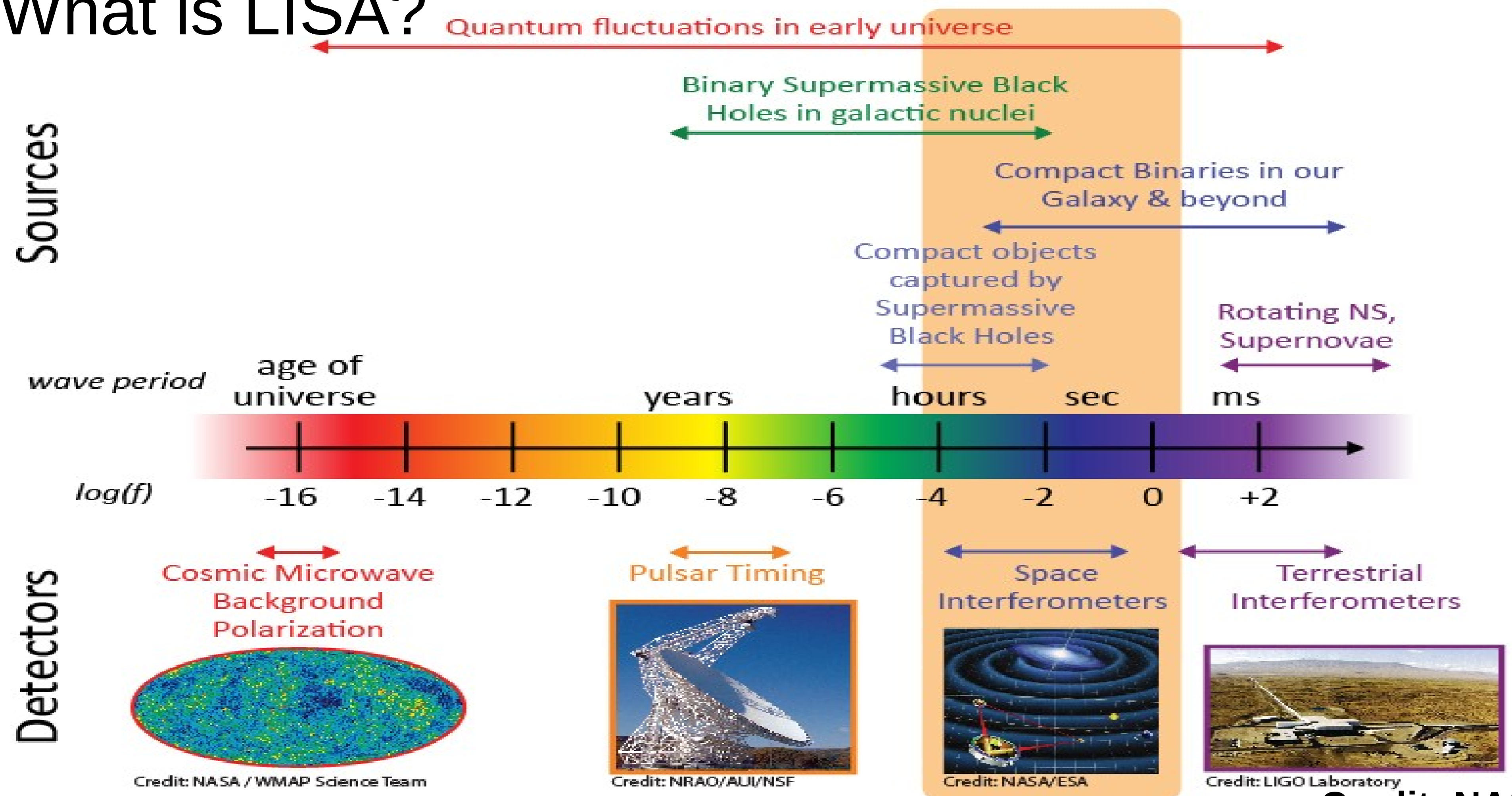
Conclusions

# What is LISA?

- A future GW detector in space.
- Set of three satellites orbitting the sun.
- Distance b/w satellites keep track of the spacetime fluctuations.



# What is LISA?




Credit: NASA

What is LISA?

**Why Dark Energy?**

Why LISA in Dark Energy?

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Case Studies.... wCDM CPLCDM IDE

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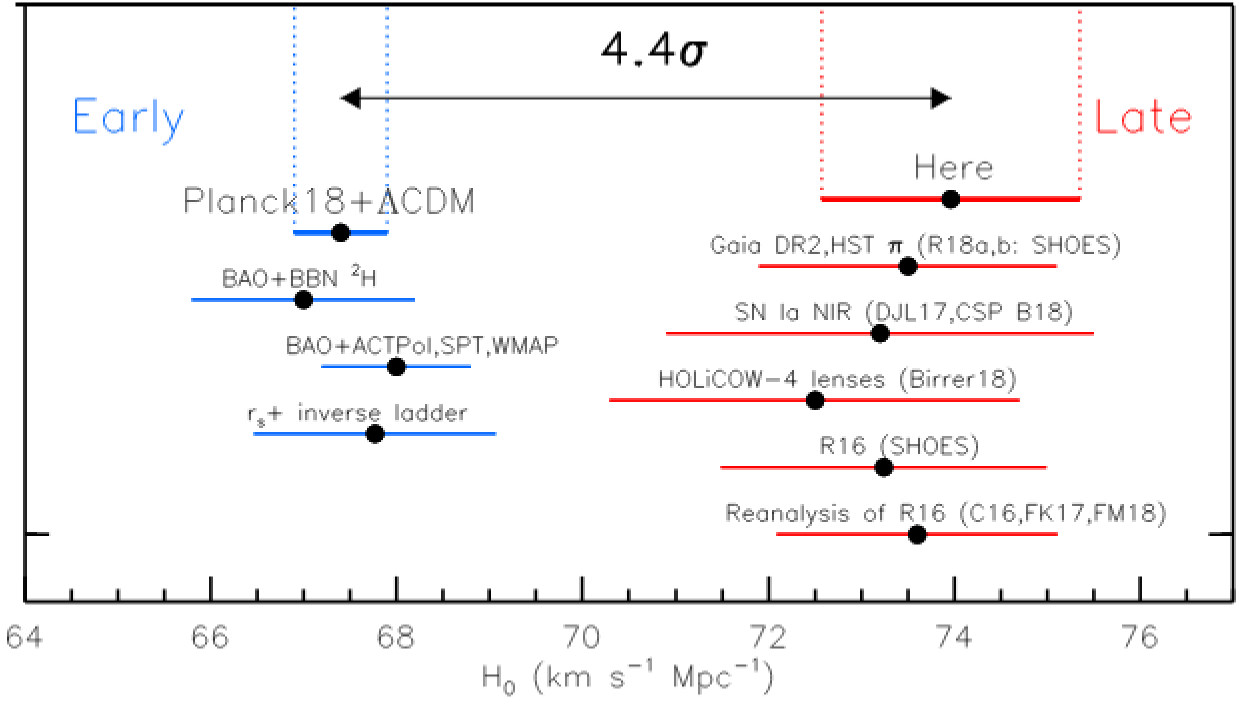
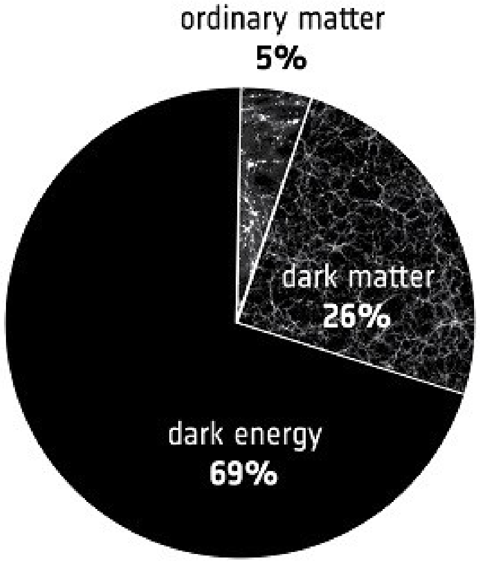
# Why Dark Energy?




Ref. Riess et al. ApJ (2019) arXiv:1903.07603v2 [astro-ph.CO]




**Credit: ESA**

Clearly problems exist in standard cosmology.

What is LISA?

Why Dark Energy?

**Why LISA in Dark Energy?**

What is Standard Diagonistic?

What is Null Diagonistic?

Case Studies.... wCDM CPLCDM IDE

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# Why LISA in Dark Sectors?


- GWs from Supermassive Black Hole Binary (SMBHB) Mergers give an accurate measure of the Luminosity distance.
- Electromagnetic counterparts give the redshift.
- We expect to see such mergers between redshifts 2 and 6. This region has never been probed before.

What is LISA?

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From luminosity distance get *E(x)*.

$$D_L = \frac{cx}{H_0}\int_1^x \frac{dx'}{E(x')}$$

$$x = 1 + z$$

## What is Standard Diagonistic?

$$E(x) = \sqrt{\Omega_{0m}x^{3(1+w_{\rm dm})} + (1-\Omega_{0m})x^{3\left(1+w_0+\frac{w_a(x-1)}{x}\right)}}$$

i. $w_0$CDM: $w_{dm} = 0$ 1 Parameter ($w_0$)

ii. CPLCDM: $w_{dm}=0$; $w=w_0+w_a z/(1+z)$ 2 Parameters( $w_0$ , $w_a$)

iii. IDE: $w = w_0 + w_a z/(1+z)$ 3 Parameters ( $w_0$ , $w_a$, $w_{dm}$)

What is LISA?

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**What is Null Diagonistic?**

Case Studies.... wCDM CPLCDM IDE

Conclusions

- We have used *Om* parameters which is a null diagonostic.

$$Om(x) = \frac{[E(x)]^2 - 1}{x^3 - 1}$$

- Null because these techniques can constrain the EoS parameters while remaining completely agnostic about density parameters

$$\begin{aligned} Om(x_1) &> Om(x_2) \rightarrow \text{phantom} \\ Om(x_1) &< Om(x_2) \rightarrow \text{quintessence} \\ Om(x_1) &= Om(x_2) \rightarrow \Lambda\text{CDM} \end{aligned}$$

# What is Null Diagonistic?

Sahni et al. PRD (2008)
arXiv:0807.3548v3 [astro-ph]

But we require the exact value of the EoS parameters.

So construct

*R*($x_1$, $x_2$, $x_3$, $x_4$) !!

$$R = \frac{Om(x_1) - Om(x_2)}{Om(x_3) - Om(x_4)} = \frac{\frac{x_1^{3(1+w)} - 1}{x_1^3 - 1} - \frac{x_2^{3(1+w)} - 1}{x_2^3 - 1}}{\frac{x_3^{3(1+w)} - 1}{x_3^3 - 1} - \frac{x_4^{3(1+w)} - 1}{x_4^3 - 1}}$$

- We perform a Fisher Matrix forecast analysis since LISA has not flown yet.
- Sources of error – Peculiar velocity of sources, weak lensing, luminosity distance, redshift, Hubble constant.
- We have created a uniform distribution of 100 redshift points for simplicity.
- Unlike the standard case, $R(x_1, x_2, x_3, x_4)$ is a function of four redshifts. Thus we have created a set of four redshift points, keeping in mind $x_1 < x_2 < x_3 < x_4$ to avoid repetition.

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Case Studies.... wCDM CPLCDM IDE

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$$D_L = \frac{cx}{H_0}\int_1^x \frac{dx'}{E(x')}$$

$$Om(x) = \frac{[E(x)]^2 - 1}{x^3 - 1}$$

Om Parametrization

$$R = \frac{Om(x_1) - Om(x_2)}{Om(x_3) - Om(x_4)} = \frac{\frac{x_1^{3(1+w)}-1}{x_1^3-1} - \frac{x_2^{3(1+w)}-1}{x_2^3-1}}{\frac{x_3^{3(1+w)}-1}{x_3^3-1} - \frac{x_4^{3(1+w)}-1}{x_4^3-1}}$$

Case Studies.... wCDM CPLCDM IDE

Standard Parameterization

$$E(x) = \sqrt{\Omega_{0m}x^3 + (1-\Omega_{0m})x^{3(1+w)}}$$

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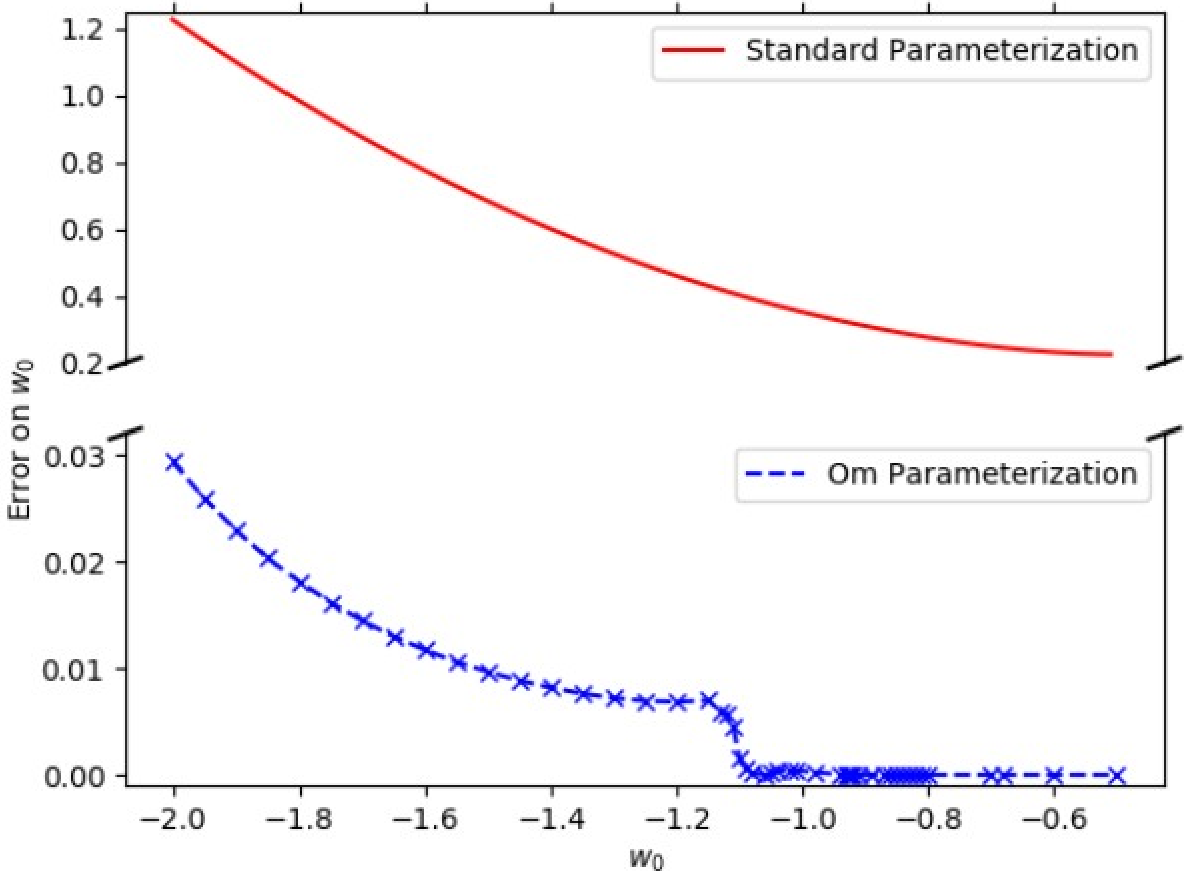
# wCDM Results



$$D_L = \frac{cx}{H_0}\int_1^x \frac{dx'}{E(x')}$$

$$w(z) = w_0 + w_a\left(\frac{z}{1+z}\right)$$

$$Om(x) = \frac{[E(x)]^2 - 1}{x^3 - 1}$$

Om Parametrization

$$R = \frac{Om(x_1) - Om(x_2)}{Om(x_3) - Om(x_4)} = \frac{\frac{x_1^{3(1+w)}-1}{x_1^3-1} - \frac{x_2^{3(1+w)}-1}{x_2^3-1}}{\frac{x_3^{3(1+w)}-1}{x_3^3-1} - \frac{x_4^{3(1+w)}-1}{x_4^3-1}}$$

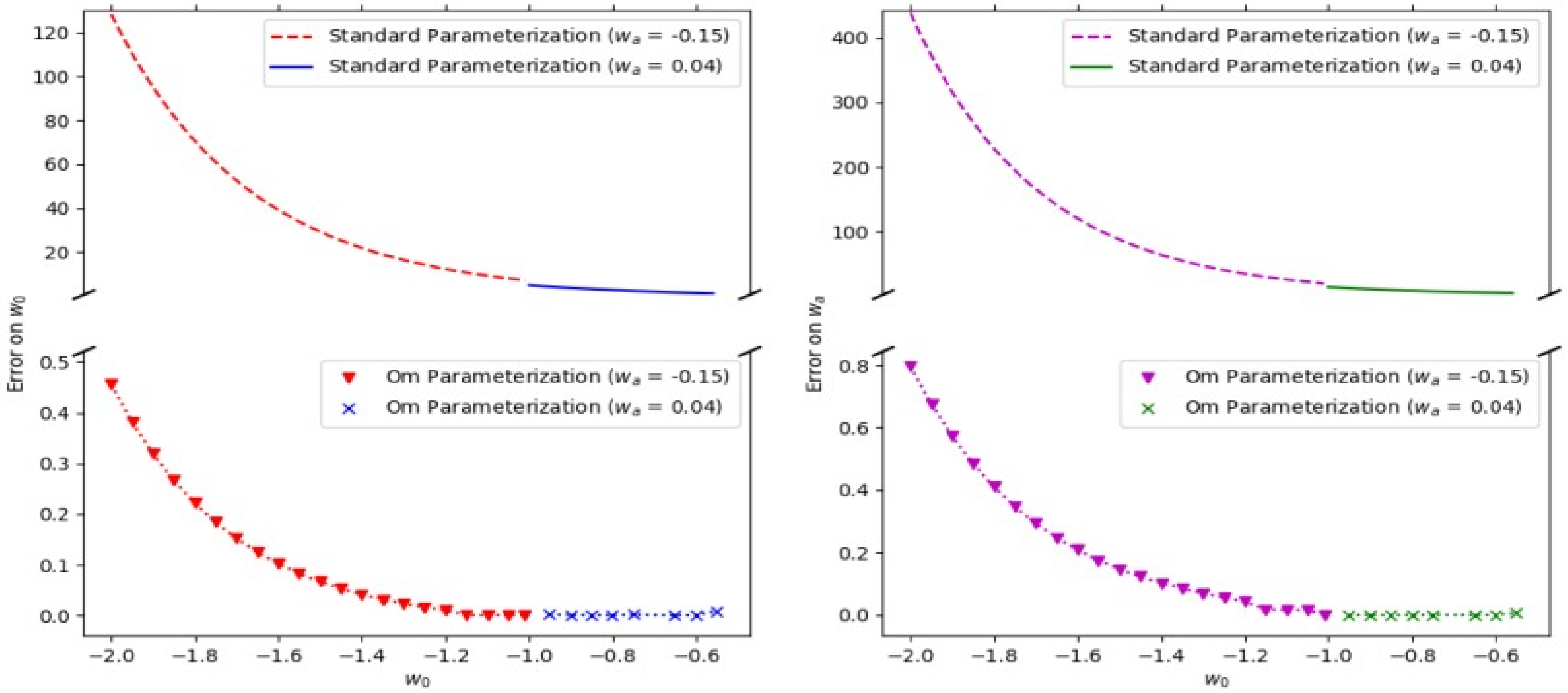
Case Studies.... wCDM CPLCDM IDE

Standard Parameterization

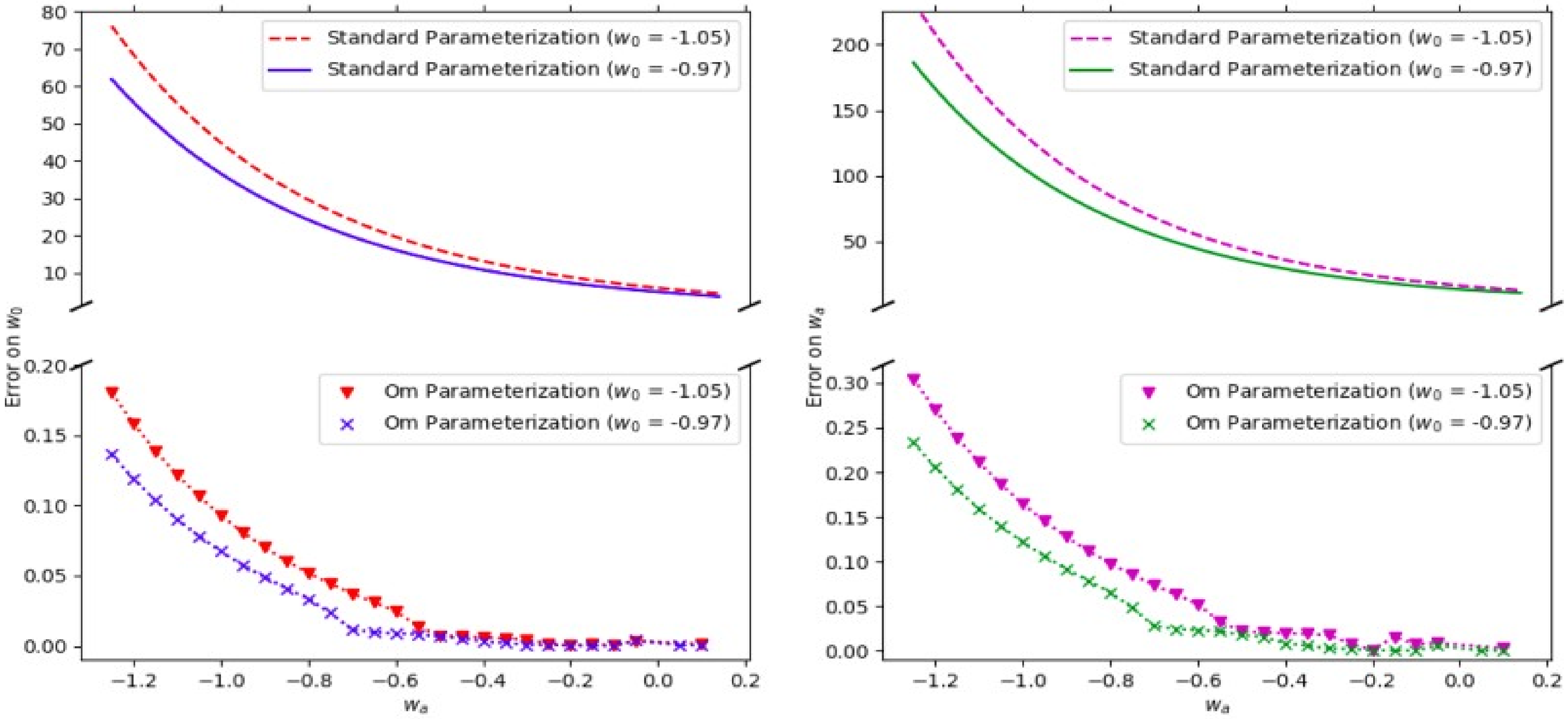
$$E(x) = \sqrt{\Omega_{0m}x^3 + (1-\Omega_{0m})x^{3(1+w)}}$$

Probe of Dark Energy at LISA:Standard vs Null Diagonistics

# CPLCDM Results



# CPLCDM Results



$$D_L = \frac{cx}{H_0}\int_1^x \frac{dx'}{E(x')}$$

$$Om_g(x) = \frac{[E(x)]^2 - 1}{x^{3(1+w_{\rm dm})} - 1}$$

Om Parameterization

$$R_g = \frac{Om_g(x_1) - Om_g(x_2)}{Om_g(x_3) - Om_g(x_4)} = \frac{\frac{x_1^{3(1+w)}-1}{x_1^{3(1+w_{\rm dm})}-1} - \frac{x_2^{3(1+w)}-1}{x_2^{3(1+w_{\rm dm})}-1}}{\frac{x_3^{3(1+w)}-1}{x_3^{3(1+w_{\rm dm})}-1} - \frac{x_4^{3(1+w)}-1}{x_4^{3(1+w_{\rm dm})}-1}}$$

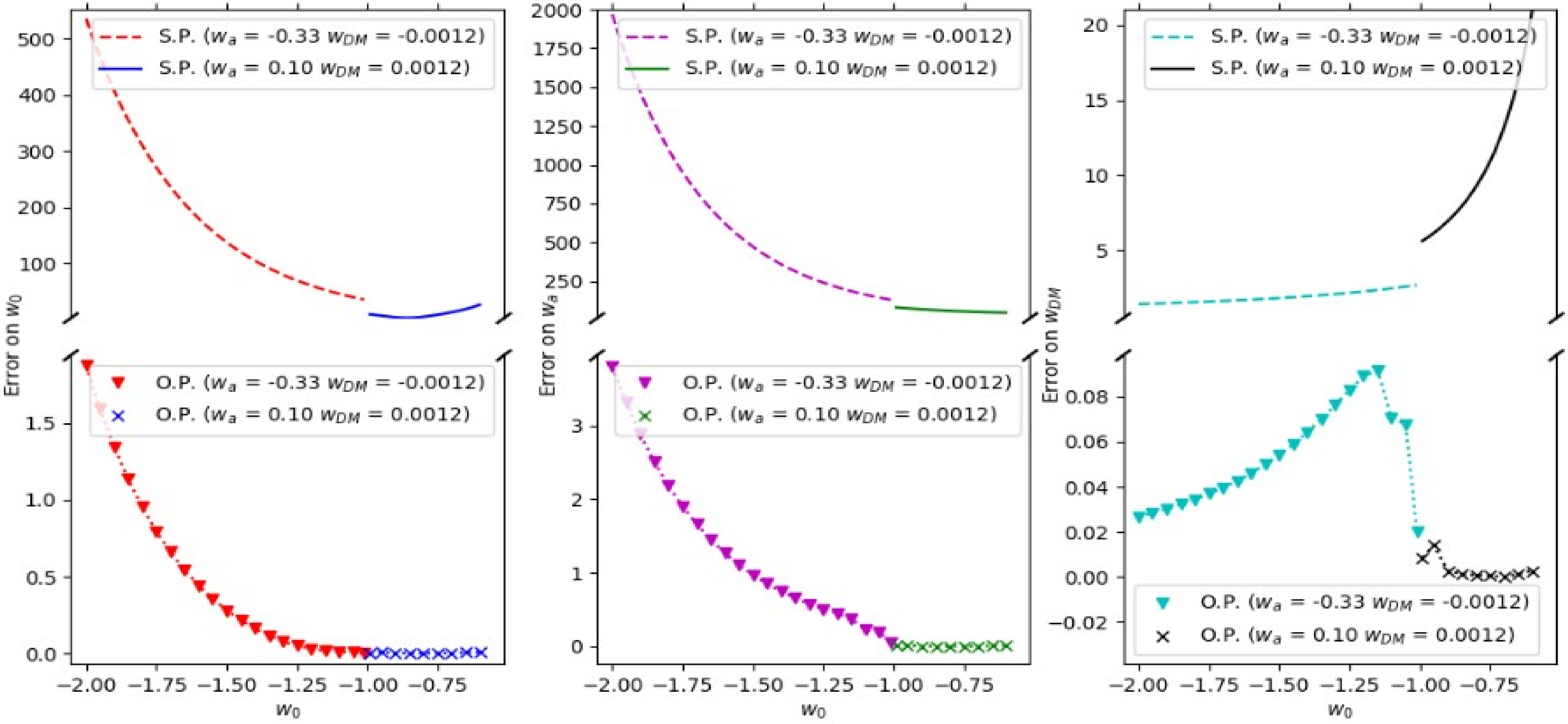
Case Studies.... wCDM CPLCDM IDE

Standard Parameterization

$$E(x) = \sqrt{\Omega_{0m}x^{3(1+w_{\rm dm})} + (1-\Omega_{0m})x^{3(1+w_0+\frac{w_a(x-1)}{x})}}$$

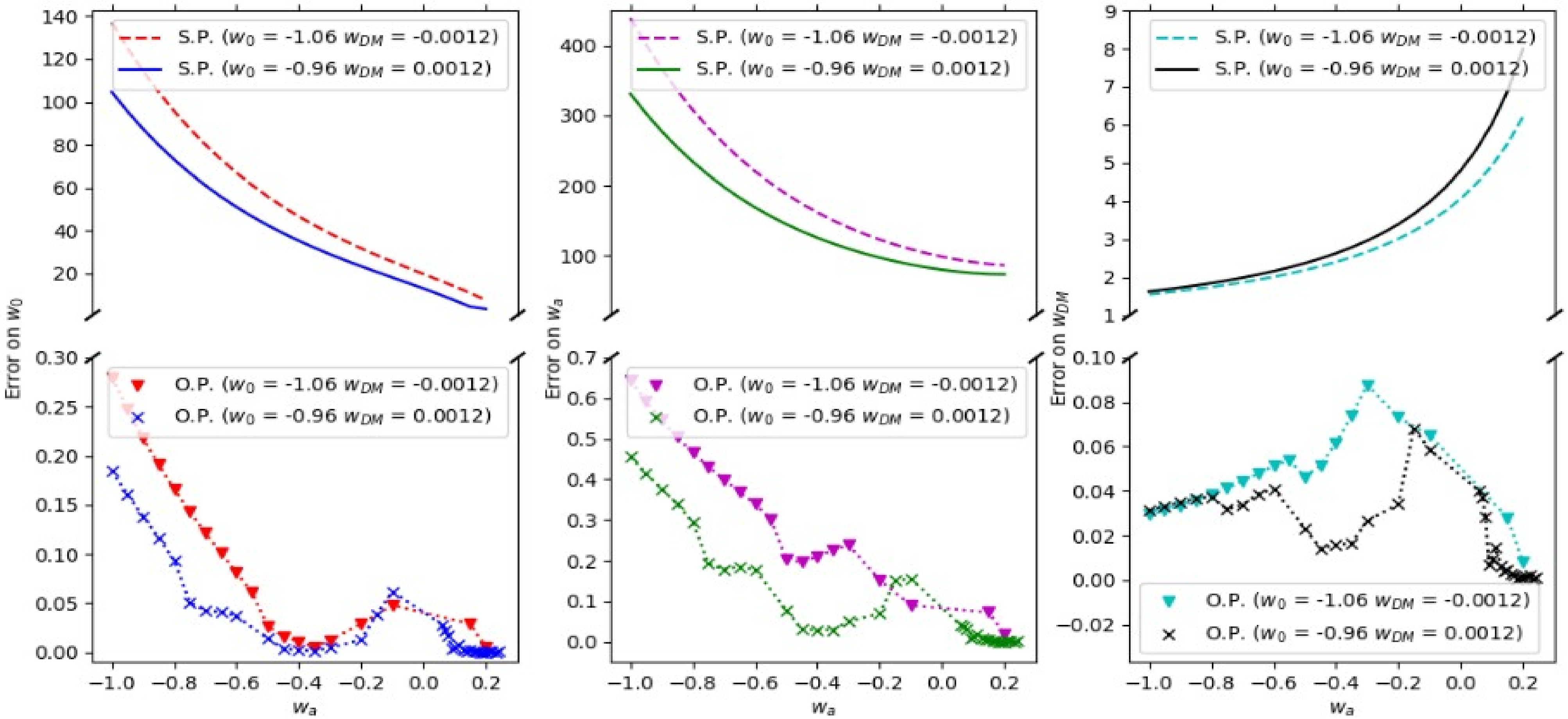
**Probe of Dark Energy at LISA:Standard vs Null Diagonistics**

# IDE Results



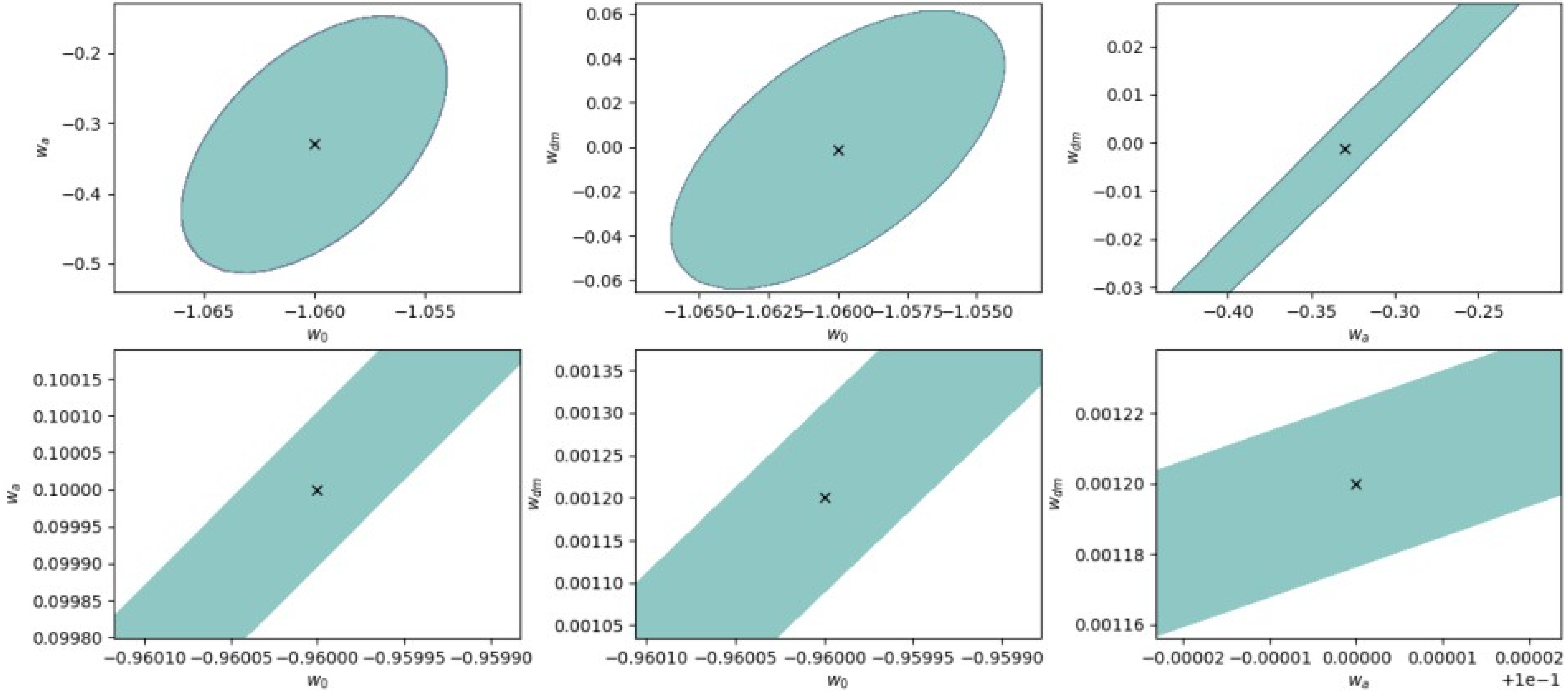

Probe of **Dark Energy at LISA:Standard vs Null Diagonistics**

# IDE Results



S.P. ($w_0$ = -1.06 $w_{DM}$ = -0.0012)
S.P. ($w_0$ = -0.96 $w_{DM}$ = 0.0012)
O.P. ($w_0$ = -1.06 $w_{DM}$ = -0.0012)
O.P. ($w_0$ = -0.96 $w_{DM}$ = 0.0012)
Error on $w_0$
Error on $w_a$
Error on $w_{DM}$
$w_a$

# IDE Results



−0.2
−0.3
−0.4
−0.5
$w_a$
−1.065
−1.060
−1.055
$w_0$
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
$w_{dm}$
−1.0650
−1.0625
−1.0600
−1.0575
−1.0550
$w_0$
0.02
0.01
0.00
−0.01
−0.02
−0.03
$w_{dm}$
−0.40
−0.35
−0.30
−0.25
$w_a$
0.10015
0.10010
0.10005
0.10000
0.09995
0.09990
0.09985
0.09980
$w_a$
−0.96010
−0.96005
−0.96000
−0.95995
−0.95990
$w_0$
0.00135
0.00130
0.00125
0.00120
0.00115
0.00110
0.00105
$w_{dm}$
−0.96010
−0.96005
−0.96000
−0.95995
−0.95990
$w_0$
0.00122
0.00120
0.00118
0.00116
$w_{dm}$
−0.00002
−0.00001
0.00000
0.00001
0.00002
+1e−1
$w_a$

# Summary

. 1-$\sigma$ error on $w_0$, $w_a$ and $w_{dm}$ for phantom fiducial values.

| | | Fiducial Values | | | Error using Stan. Param. | | | Error using $Om$ Param. | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Data | Model | $w_0$ | $w_a$ | $w_{dm}$ | $\Delta w_0$ | $\Delta w_a$ | $\Delta w_{dm}$ | $\Delta w_0$ | $\Delta w_a$ | $\Delta w_{dm}$ |
| Planck | $w_0$CDM | -1 | - | - | 0.34 | - | - | 7.5e-4 | - | - |
| + | CPLCDM | -1.1 | -0.27 | - | 11 | 29 | - | 3.5e-3 | 0.016 | - |
| R16 | IDE | -2.0 | -0.96 | -0.005 | 1800 | 6800 | 1.2 | 6.2 | 11 | 0.014 |
| Planck | $w_0$CDM | -1 | - | - | 0.35 | - | - | 4.8e-4 | - | - |
| + | CPLCDM | -1.05 | -0.15 | - | 7.8 | 22 | - | 6.2e-4 | 0.017 | - |
| BSH | IDE | -1.06 | -0.33 | -0.0012 | 41 | 150 | 2.6 | 5.4e-3 | 0.19 | 0.068 |

1-$\sigma$ error on $w_0$, $w_a$ and $w_{dm}$ for non-phantom fiducial values.

| | | Fiducial Values | | | Error using Stan. Param. | | | Error using $Om$ Param. | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Data | Model | $w_0$ | $w_a$ | $w_{dm}$ | $\Delta w_0$ | $\Delta w_a$ | $\Delta w_{dm}$ | $\Delta w_0$ | $\Delta w_a$ | $\Delta w_{dm}$ |
| Planck | $w_0$CDM | -1 | - | - | 0.34 | - | - | 7.5e-4 | - | - |
| + | CPLCDM | -0.97 | 0.03 | - | 4.5 | 13 | - | 0.0018 | 9.1e-4 | - |
| R16 | IDE | -0.92 | 0.05 | 0.004 | 7.0 | 58 | 5.9 | 0.013 | 0.006 | 0.001 |
| Planck | $w_0$CDM | -1 | - | - | 0.35 | - | - | 4.8e-4 | - | - |
| + | CPLCDM | -0.97 | 0.04 | - | 4.5 | 13 | - | 8.2e-4 | 5.1e-4 | - |
| BSH | +IDE | -0.96 | 0.10 | 0.0012 | 7.4 | 75 | 6.0 | 4.6e-3 | 0.010 | 9.3e-3 |

# Conclusion

- LISA gives lower errors in non-phantom region compared to the phantom region.

- Om parameterization is much more efficient in measuring EoS parameters with errors nearly two orders of magnitude less than standard parameterization.

Thanks for listening...

For questions, comments, discussions you may write to me at baralpratyusava@gmail.com