Constraining cosmological parameters in FLRW metric with lensed GW+EM signals

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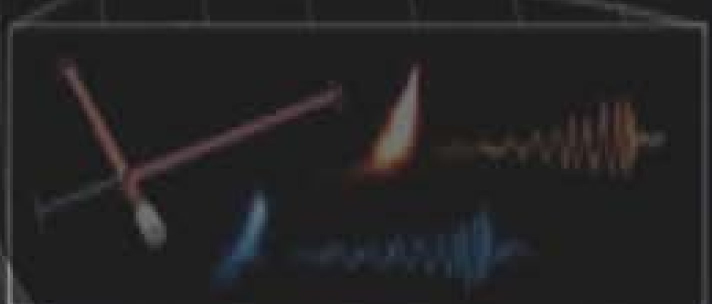
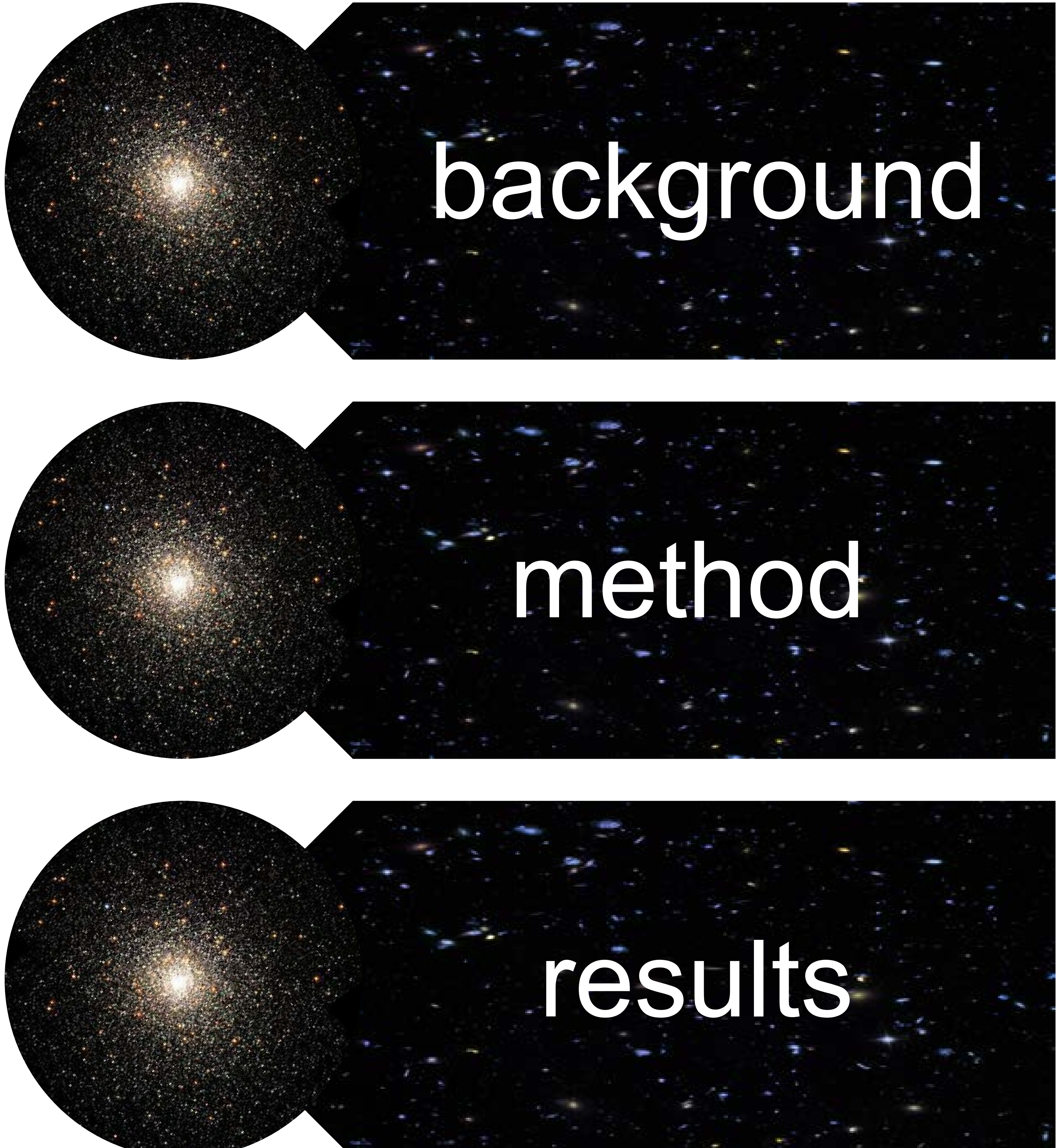
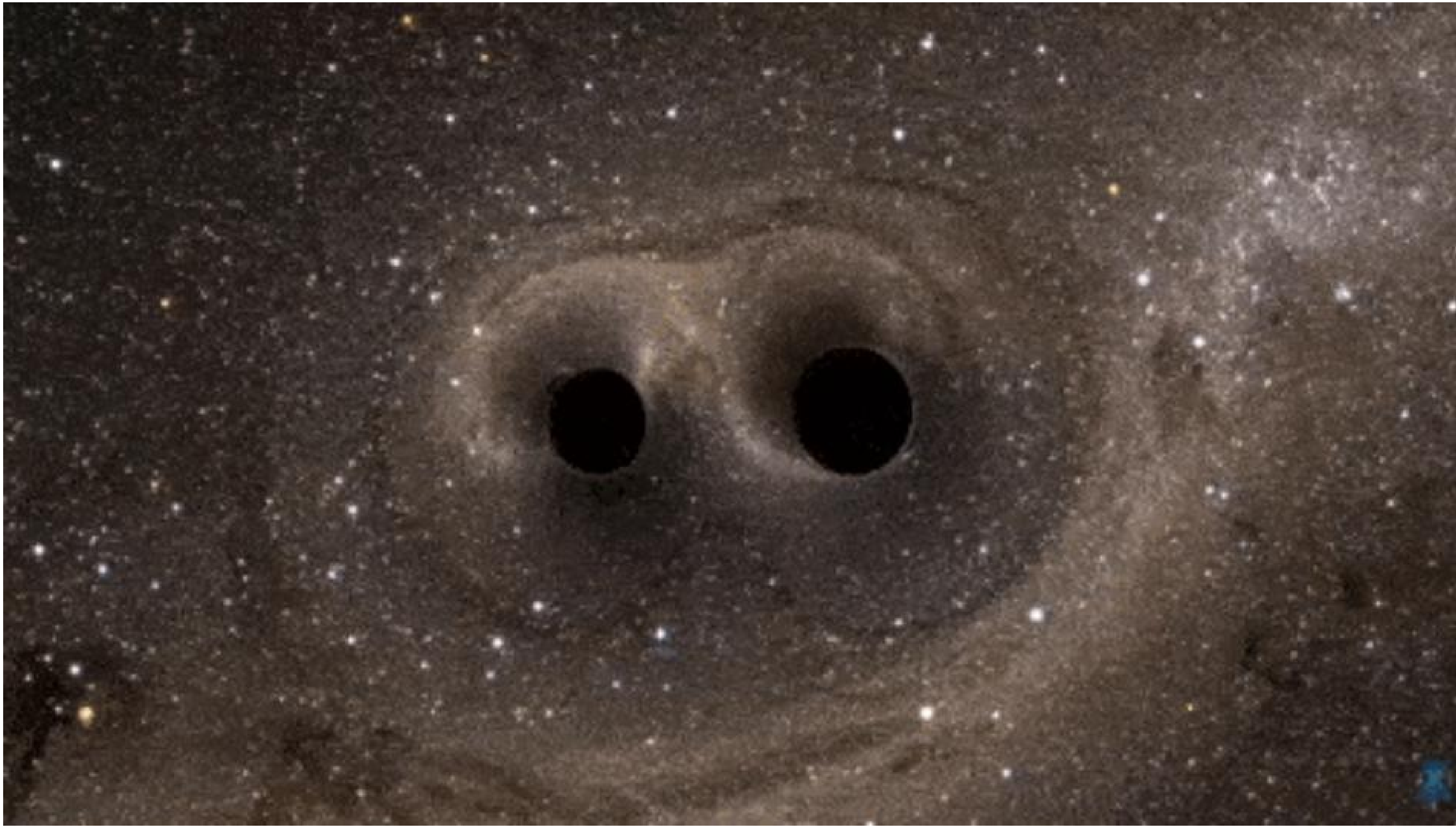
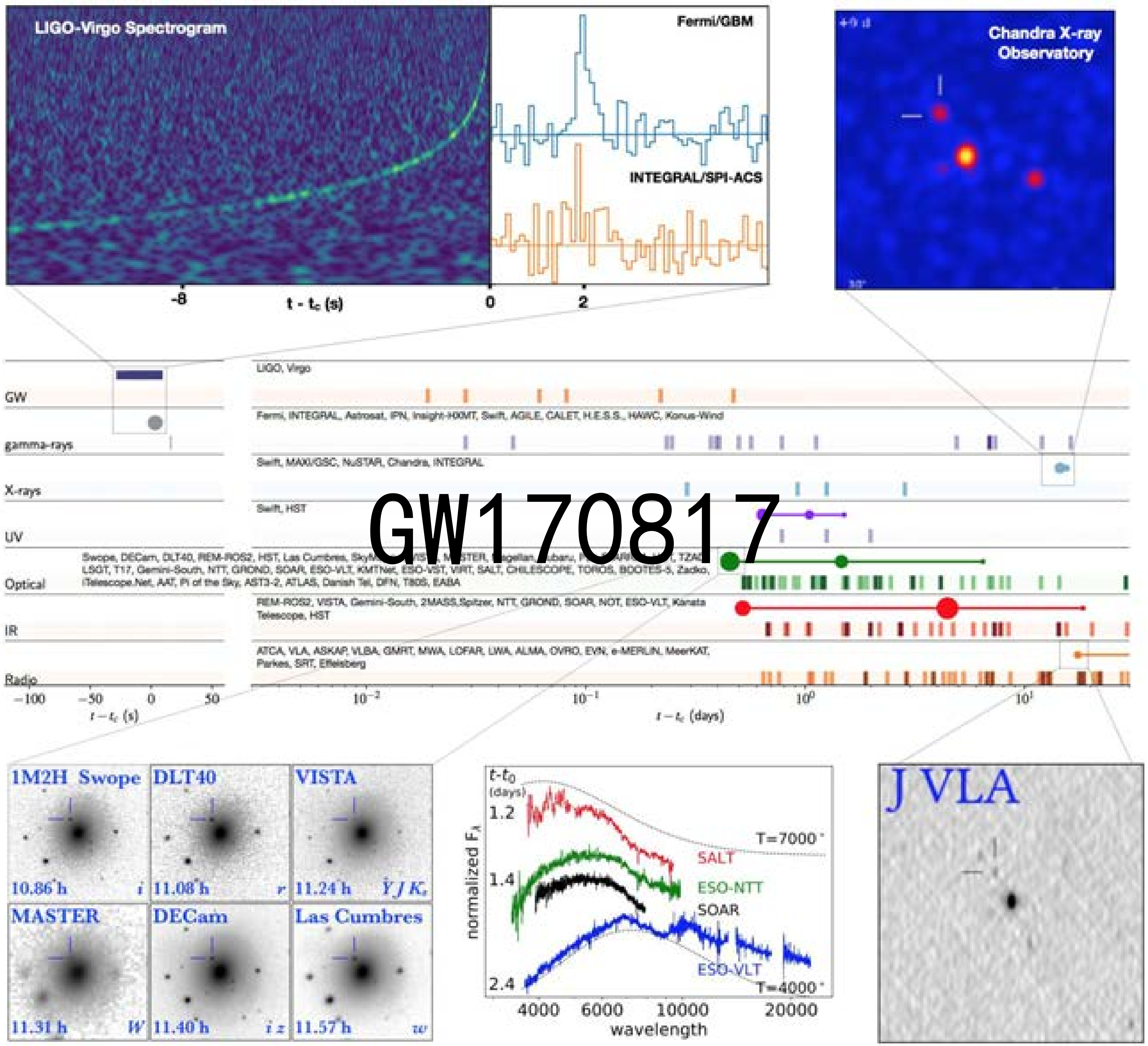



background
method
results



GW150914
B. P. Abbott et al. 2016

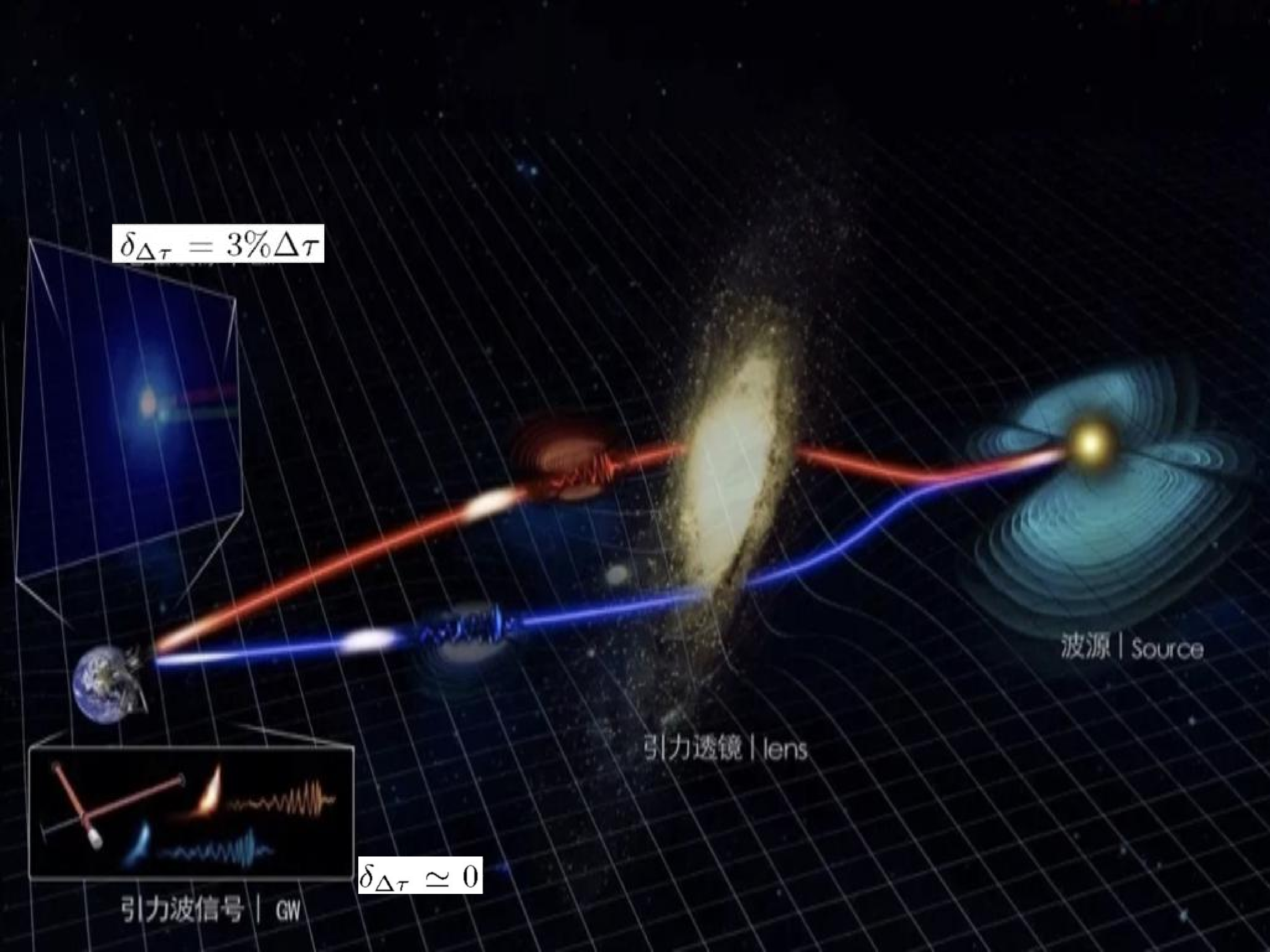
GW170817



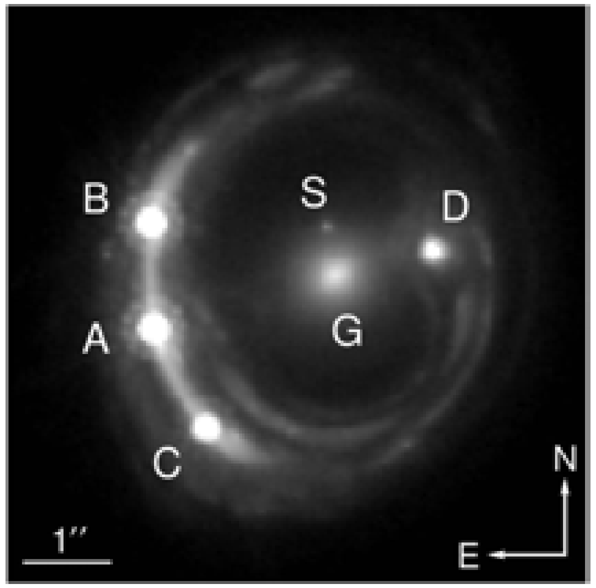
LIGO-Virgo Spectrogram
Fermi/GBM
INTEGRAL/SPI-ACS
t - t_c (s)
Chandra X-ray Observatory
GW
LIGO, Virgo
gamma-rays
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-rays
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t - t_c (s)
t - t_c (days)
1M2H Swope
DLT40
VISTA
MASTER
DECam
Las Cumbres
normalized F_λ
SALT
ESO-NTT
SOAR
ESO-VLT
T=7000
T=4000
wavelength
J VLA

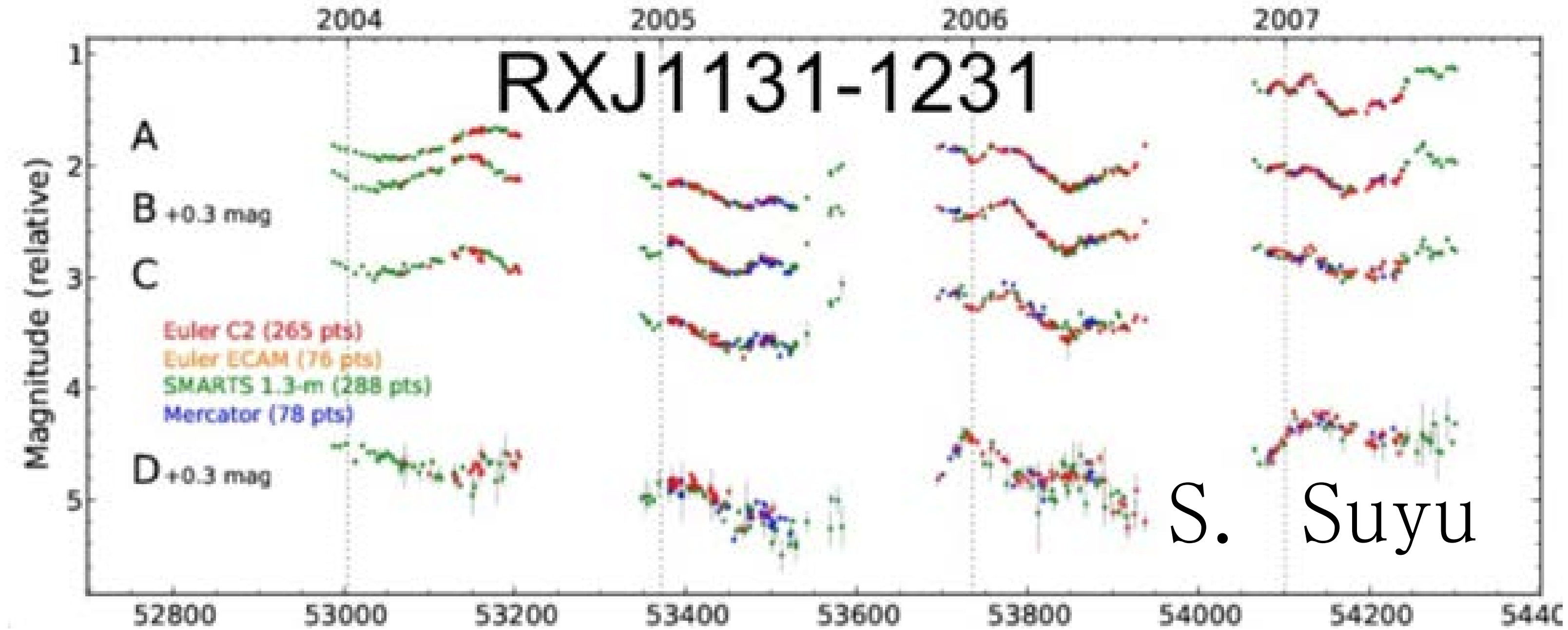
EM

EM+GW

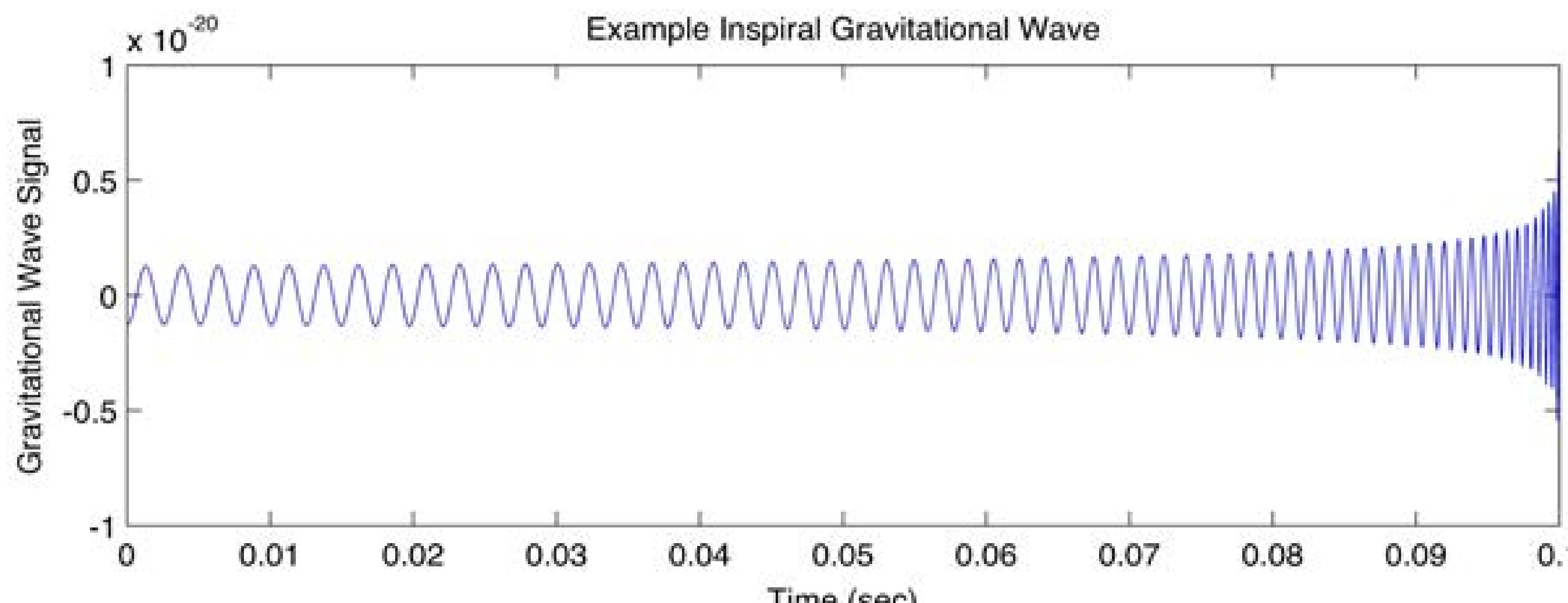

$\delta_{\Delta\tau} = 3\%\Delta\tau$
$\delta_{\Delta\tau} \simeq 0$
波源 | Source
引力透镜 | lens
引力波信号 | GW

EM

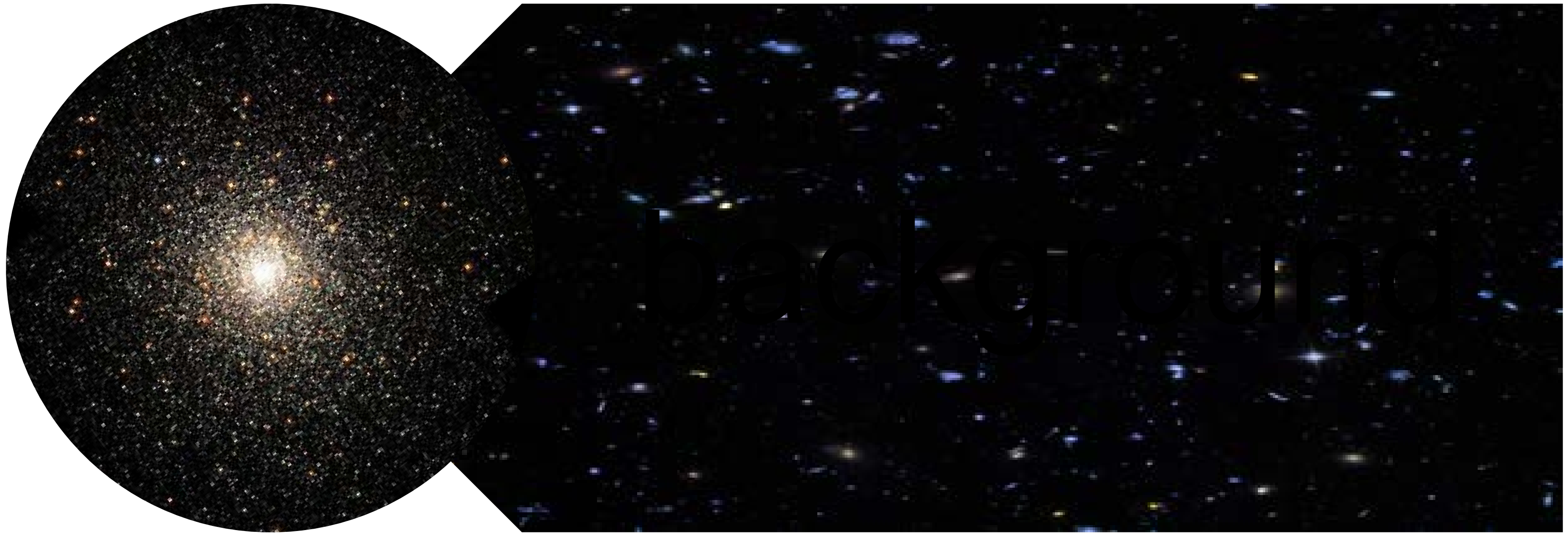

B
S
D
A
G
C
N
E
1″


2004
2005
2006
2007
RXJ1131-1231
A
B +0.3 mag
C
D +0.3 mag
Euler C2 (265 pts)
Euler ECAM (76 pts)
SMARTS 1.3-m (288 pts)
Mercator (78 pts)
Magnitude (relative)
S. Suyu

GW


Example Inspiral Gravitational Wave
x 10^-20
Gravitational Wave Signal
Time (sec)

1. **Ding et al.(2015): ET will detect 50 − 100 lensed GWs per year**
2. **Liao et al.(2017): just 10 such systems can provide a Hubble constant uncertainty of 0.68%**
3. **Fan et al.(2017): lensed GW+EM systems can be used to measure the speed of gravitational waves**
4. **Wei et al.(2017): strongly lensed GW-EM systems can provide stringent constraints on parameters of Dark energy equation of state**


background

method

results

Lens redshift

Source redshift

$$D_{\Delta t} = \frac{D_A(z_l)D_A(z_s)}{D_A(z_l, z_s)}$$

$$D_{\Delta t}(observation) = \frac{\Delta t}{(1+z_l)\Delta\phi}$$

$$\Delta\phi_{i,j} = [\frac{(\theta_i - \beta)^2}{2} - \psi(\theta_i) - \frac{(\theta_j - \beta)^2}{2} + \psi(\theta_j)]$$

Fermat potential difference

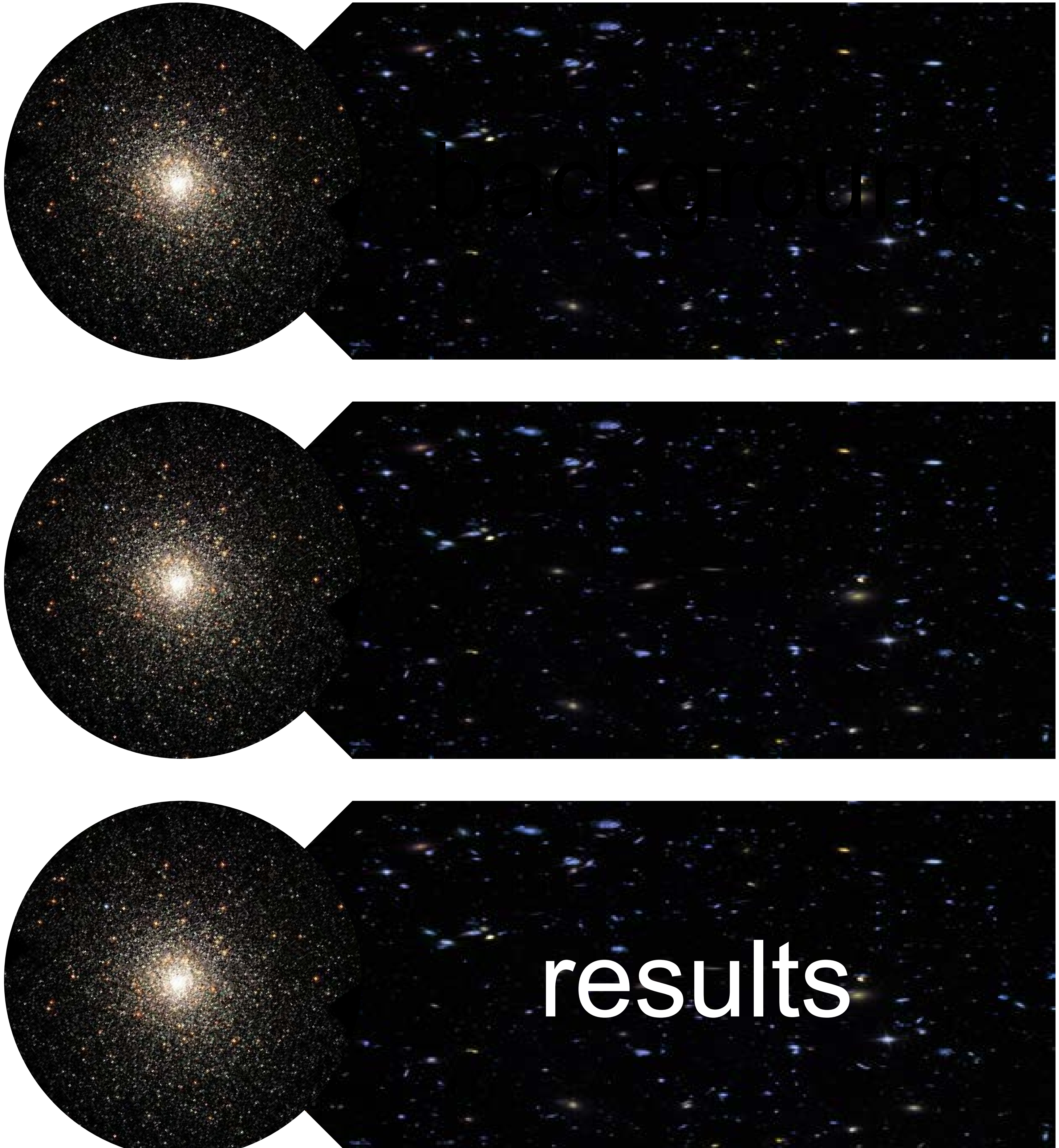
$$\mathrm{D}_{\Delta t}(theory) = \frac{1}{(1+z_l)(T(z_l) - T(z_s))}$$

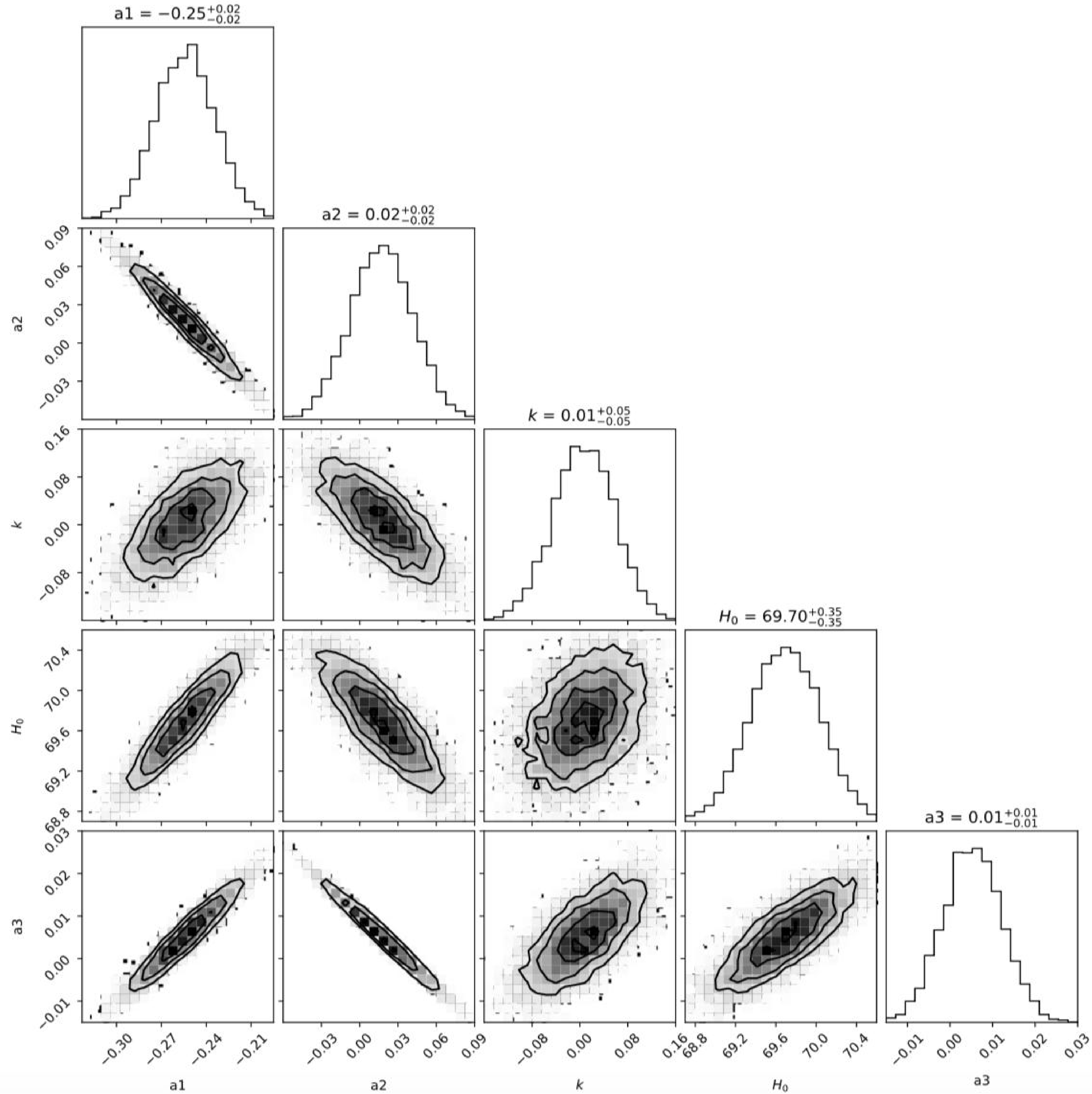
$$\boldsymbol{T(z) = \frac{1}{d(z)}\sqrt{1 - kd(z)^2}}$$

$$d(z) = z + a1z^2 + a2z^3 + a3z^4$$

$$D_{\Delta t}\ \textbf{(observation)} = D_{\Delta t}\textbf{(theory)}$$

observed quantities (z_l , z_s , Δt, $\Delta\varphi$, D_L) → **theoretical values**(k, $d(z)$, $H0$)


background
results



a1 = −0.25$^{+0.02}_{-0.02}$
a2 = 0.02$^{+0.02}_{-0.02}$
k = 0.01$^{+0.05}_{-0.05}$
H_0 = 69.70$^{+0.35}_{-0.35}$
a3 = 0.01$^{+0.01}_{-0.01}$
a1
a2
k
H_0
a3

https://arxiv.org/abs/1901.10638

	No.	$a1$	$a2$	$a3$	k	H_0
lensed quasar	300	$-0.24^{+0.04}_{-0.04}$	$0^{+0.06}_{-0.06}$	$0.01^{+0.03}_{-0.02}$	$0^{+0.05}_{-0.06}$	$69.86^{+0.53}_{-0.53}$
lensed GW+EM	10	$-0.25^{+0.02}_{-0.02}$	$0.02^{+0.02}_{-0.02}$	$0.01^{+0.01}_{-0.01}$	$0.01^{+0.05}_{-0.05}$	$69.7^{+0.35}_{-0.35}$

Summary

- ***Strongly lensed GW-EM systems combine highly accurate time delay from GW signals with redshift and image from EM counterparts.***
- ***In the future, strongly lensed GW-EM systems can be applied to do precision cosmology.***
- ***Establish a complete set of lensed GW-EM numerical simulation is necessary.***

Thank You