

**Detecting
White Dwarf Binaries
with
Gravitational Waves**



Detecting White Dwarf Binary Mergers with Gravitational Waves,

Giona Sala, Chiara Brandenstein, Sebastian Baum, Peter W. Graham,

[arXiv:2510.19913 \[gr-qc\]](https://arxiv.org/abs/2510.19913).

White dwarf binaries (WDBs) are ideal multi-messenger sources, offering detection through multiple channels.

- Electromagnetically:
 - Faint throughout their lifetime;
 - Bright in a potential final detonation;
- Gravitational Waves:
 - Loud in the mid-band frequencies, which will be probed by future space-based detector MAGIS Space.

Outline



- White dwarfs
- Gravitational waves
- Parameter reconstruction
- Merger detection
- Merger rate

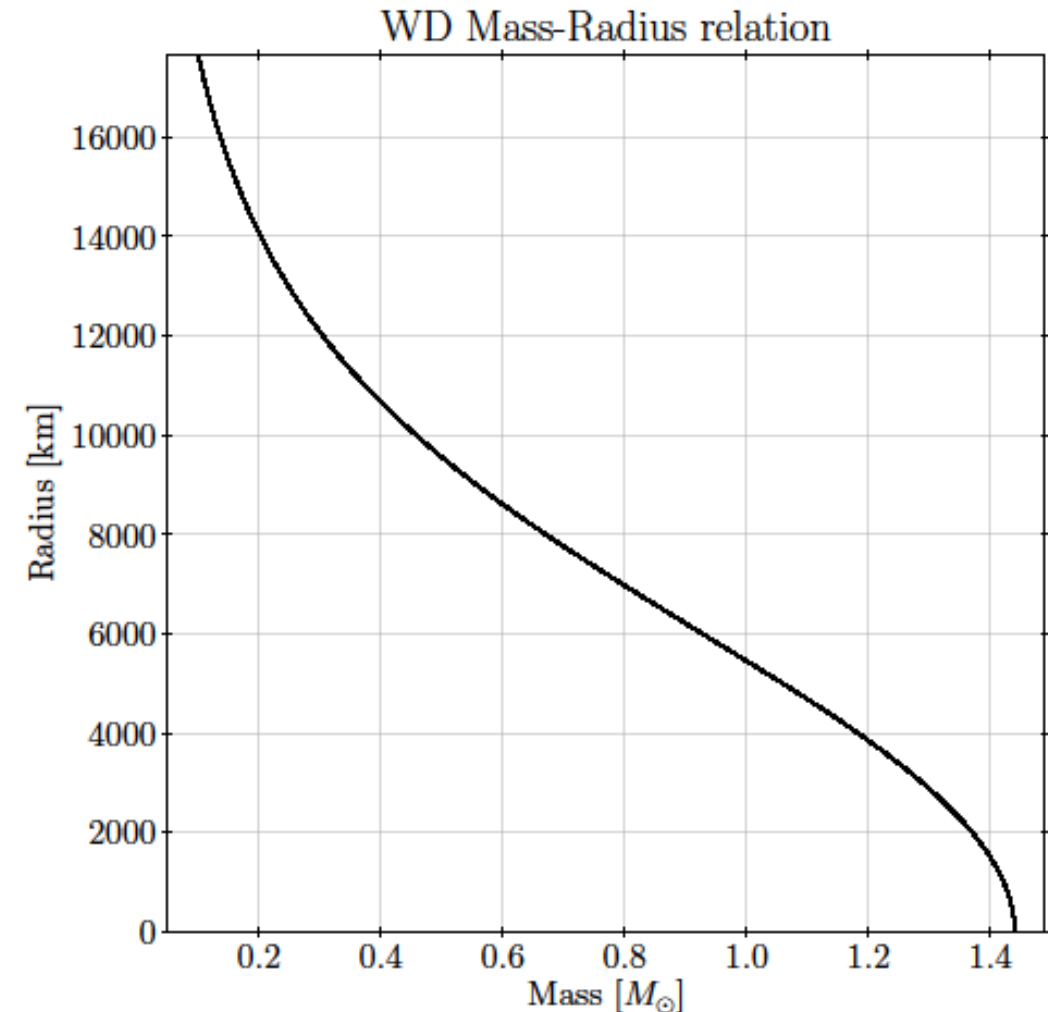
White dwarfs (WDs)

WD properties

Formation and composition:

- Stellar remnants from the collapse of exhaust stars with mass $< 8 M_{\odot}$;
- Low H and He content;
- Hence, very faint;

- Gravitational collapse vs. electron pressure degeneracy;
- The more massive the more compact.
- Collapse or detonation for masses higher than Chandrasekhar mass.



Compact objects

Radius for mass of $1M_{\odot}$:

- Black Hole ~ 3 km

- Neutron Star ~ 12 km

White Dwarf ~ 6000 km $\sim R_{Earth}$

Sun $\sim 7 \cdot 10^5$ km

Supernova Type Ia (SN Ia)

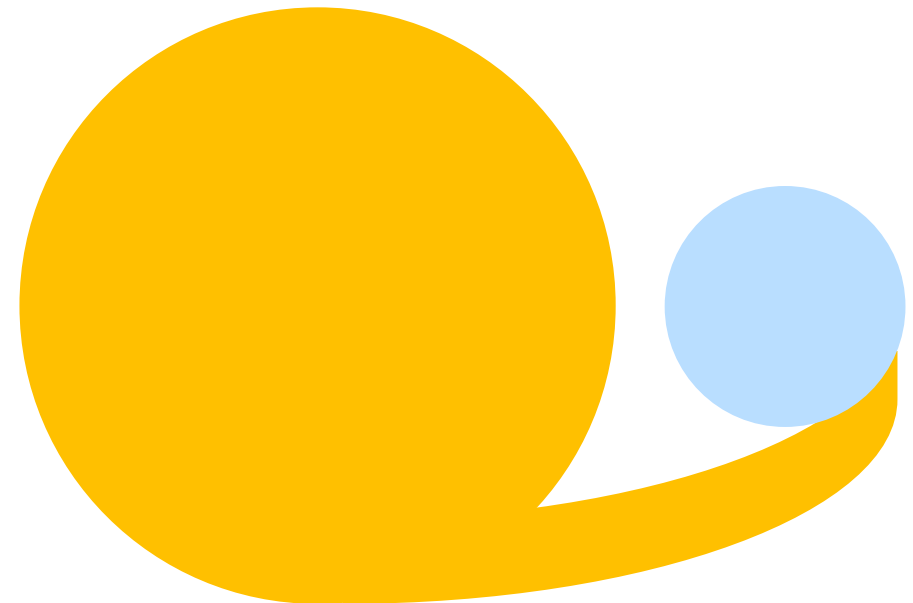
SN Ia are standard candles. They are particularly recognizable due to their distinctive long-lived afterglow and the absence of H and He spectral lines. This characteristic makes WDs perfect candidates for producing them.

Two possible SN Ia progenitors:

- Double Degenerate (DD) channel:

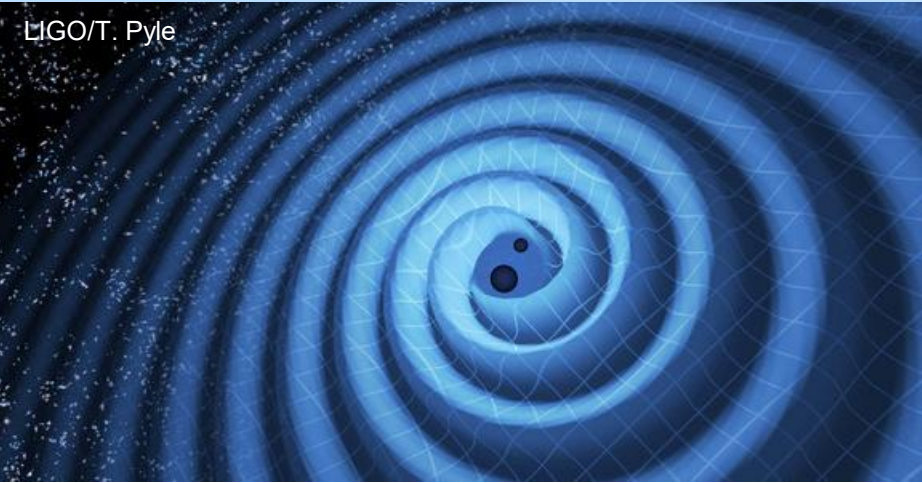


- Single Degenerate (SD) channel:



Gravitational waves (GWs)

GWs from binaries



Chirping:
$$\frac{df_{GW}}{dt} = \frac{96}{5} \pi^{8/3} \mathcal{M}_c^{5/3} f_{GW}^{11/3}$$

Signal or strain: $h_{\mu\nu}(t) = h_+(t)e_{\mu\nu}^+ + h_\times(t)e_{\mu\nu}^\times$

$$h_+(t) = \frac{2\mathcal{M}_c^{5/3} \pi^{2/3} f_{GW}(t)^{2/3}}{d_L} \left[1 + \cos^2 \iota \right] \cos \Phi(t)$$

$$h_\times(t) = \frac{4\mathcal{M}_c^{5/3} \pi^{2/3} f_{GW}(t)^{2/3}}{d_L} \cos \iota \sin \Phi(t)$$

Symbol	Parameter
\mathcal{M}_c	Chirp mass
$q = M_1/M_2$	Mass ratio ($M_1 > M_2$)
d_L	Luminosity distance
Φ_0	Binary phase at t_0
t_0	Time of reference
ι	Inclination angle
ψ	Polarization angle
α	Right ascension
δ	Declination

Merger frequency

$$M_1 = M_2 = 1M_{\odot}$$

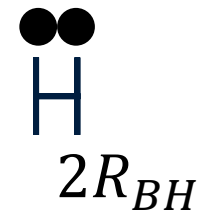
$$\frac{df_{GW}}{dt} = \frac{96}{5} \pi^{8/3} \mathcal{M}_c^{5/3} f_{GW}^{11/3}$$

White Dwarf Binaries:
mass transfer



$$f_{GW} \sim 0.1 \text{ Hz}$$

Binary Black Holes:
impact

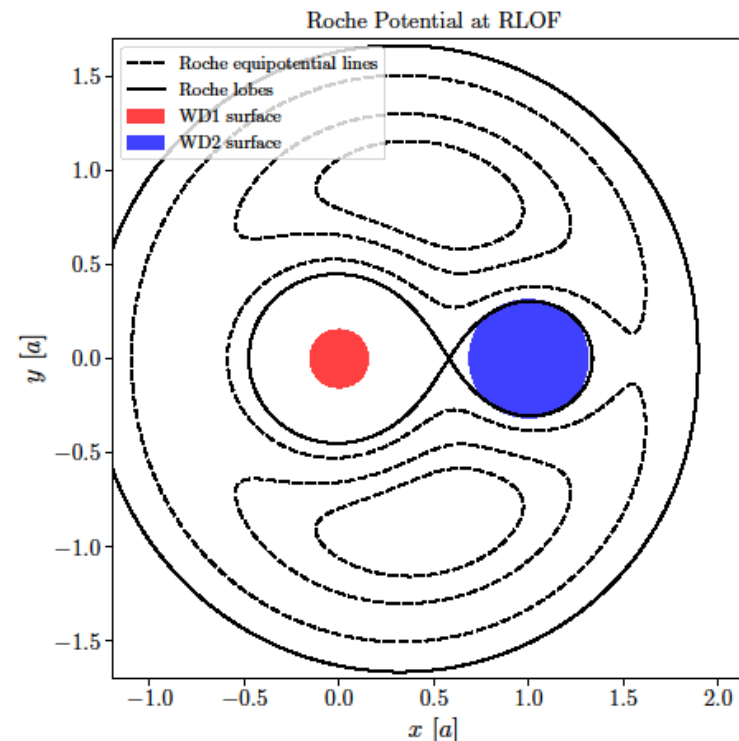
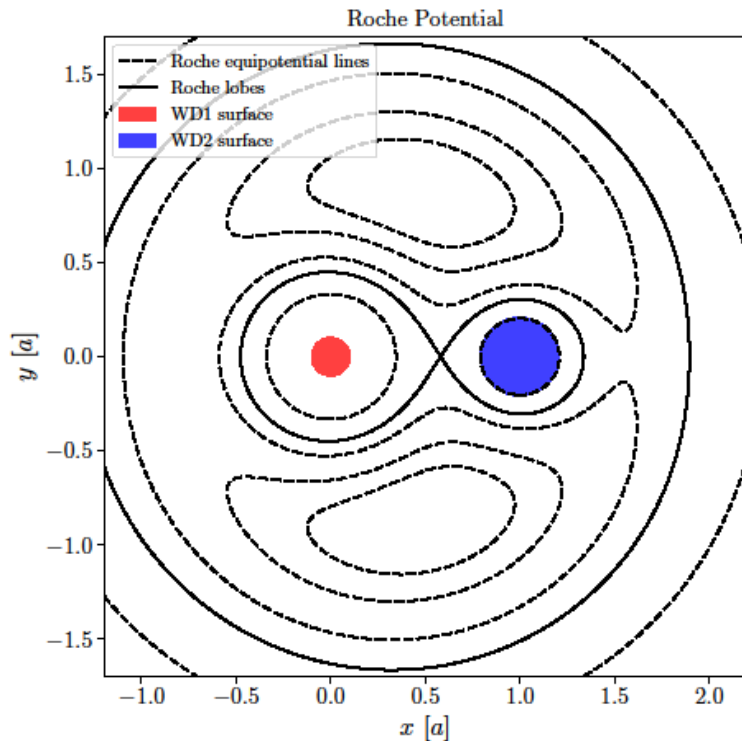


$$f_{GW} \sim 10 \text{ kHz}$$

Roche Lobe Overflow (RLOF)

Mass transfer can happen way before the contact of compact binaries, leading to an earlier merger.

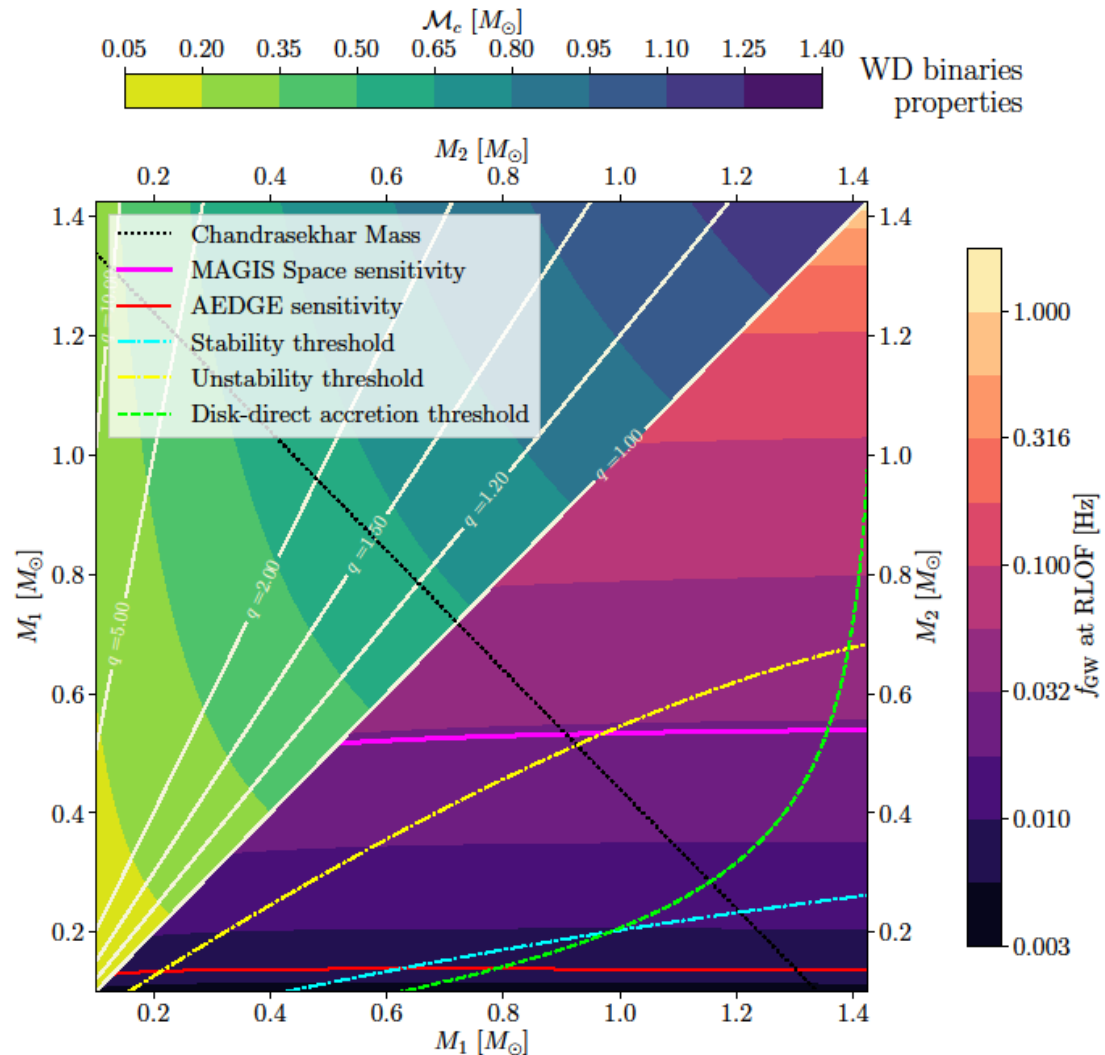
Mass transfer can happen between Roche equipotential lines.



$$\frac{R_{L2}(a)}{a} = \frac{0.49}{0.6 + q_L^{2/3} \ln(1 + q_L^{-1/3})}$$

$$q_L = \frac{M_1}{M_2}$$

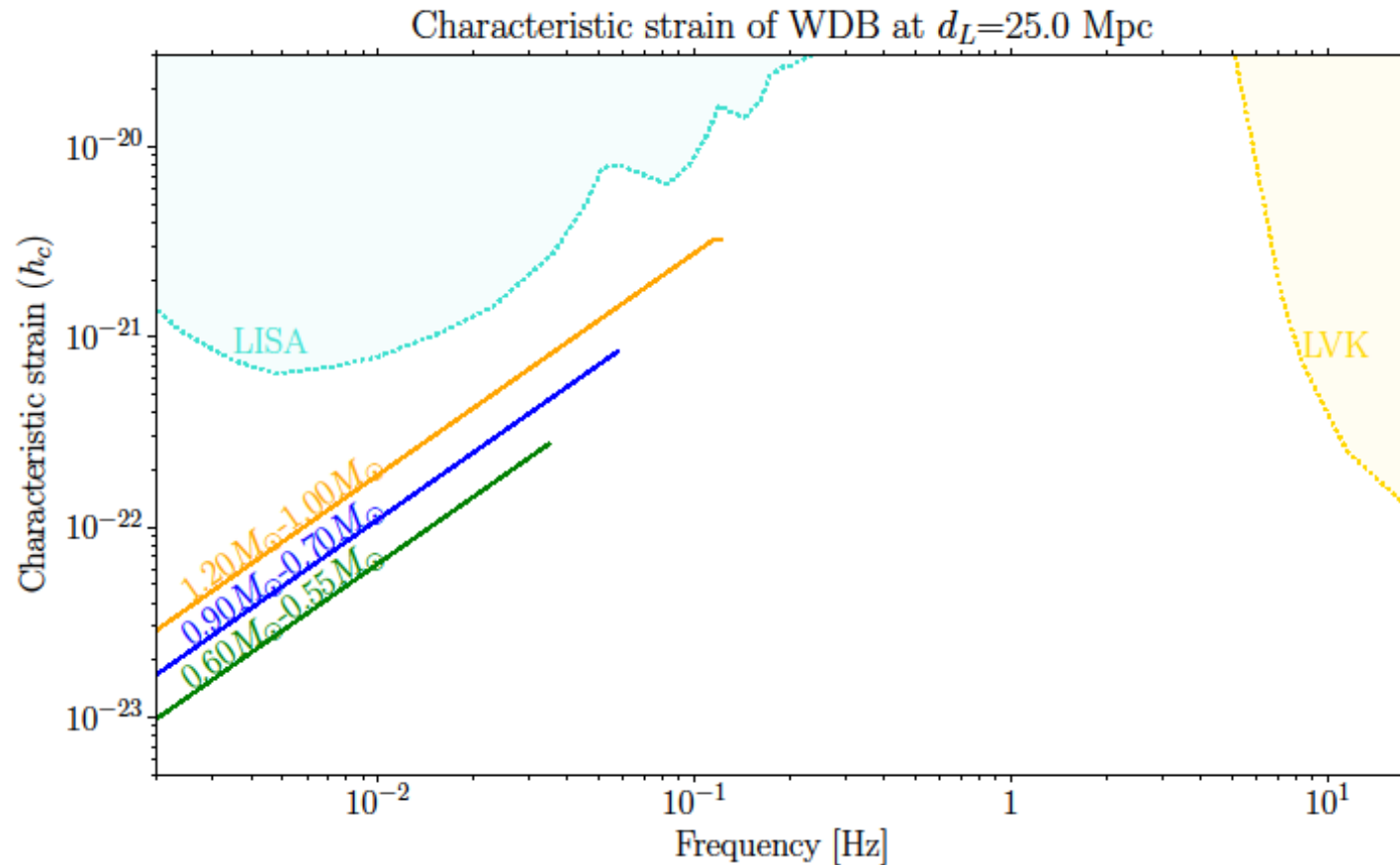
RLOF frequency



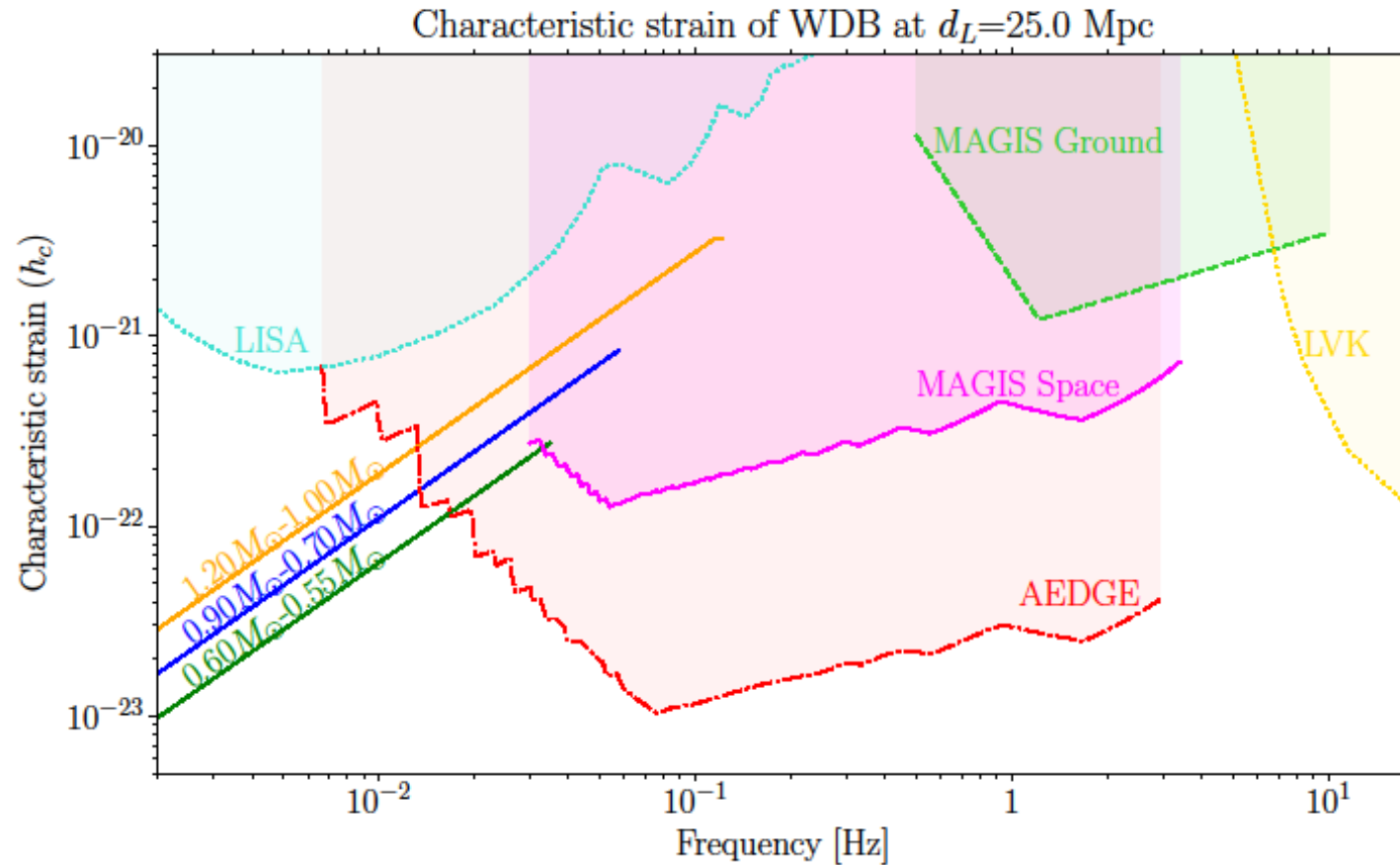
$$\frac{R_{L2}(a)}{a} = \frac{0.49}{0.6 + q_L^{2/3} \ln(1 + q_L^{-1/3})}$$

$$q_L = \frac{M_1}{M_2}$$

Missing mid-band detector



Atom interferometers

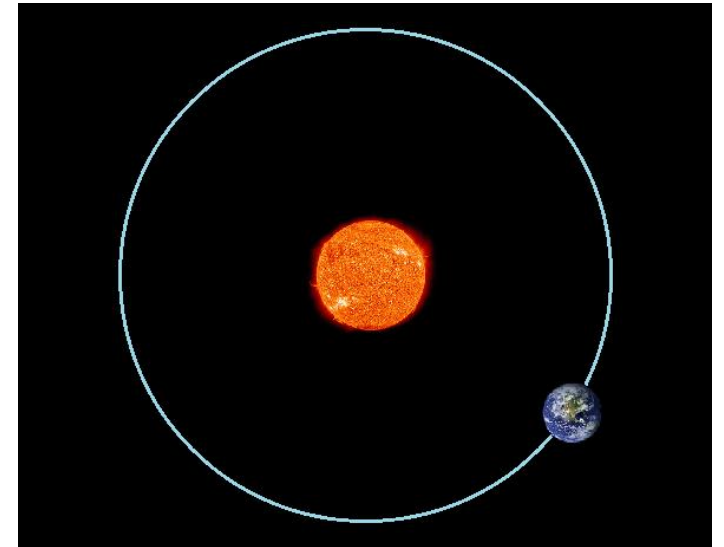


Parameter reconstruction

Signal modelling

Detected strain: $\tilde{h}(f) = e^{i\phi_D} \times \left\{ F_+[t(f)] \times \tilde{h}_+(f) + F_\times[t(f)] \times \tilde{h}_\times(f) \right\}$

- Antenna function $F_{+,\times}$, ϕ_D Doppler phase;
- Long-lived signal integrated over the measurement time, upon RLOF, with code `AIMforGWinFspace`
Baum, Bogorad, Graham, JCAP 05 (2024) or [White Dwarf Binaries GW.git](#);



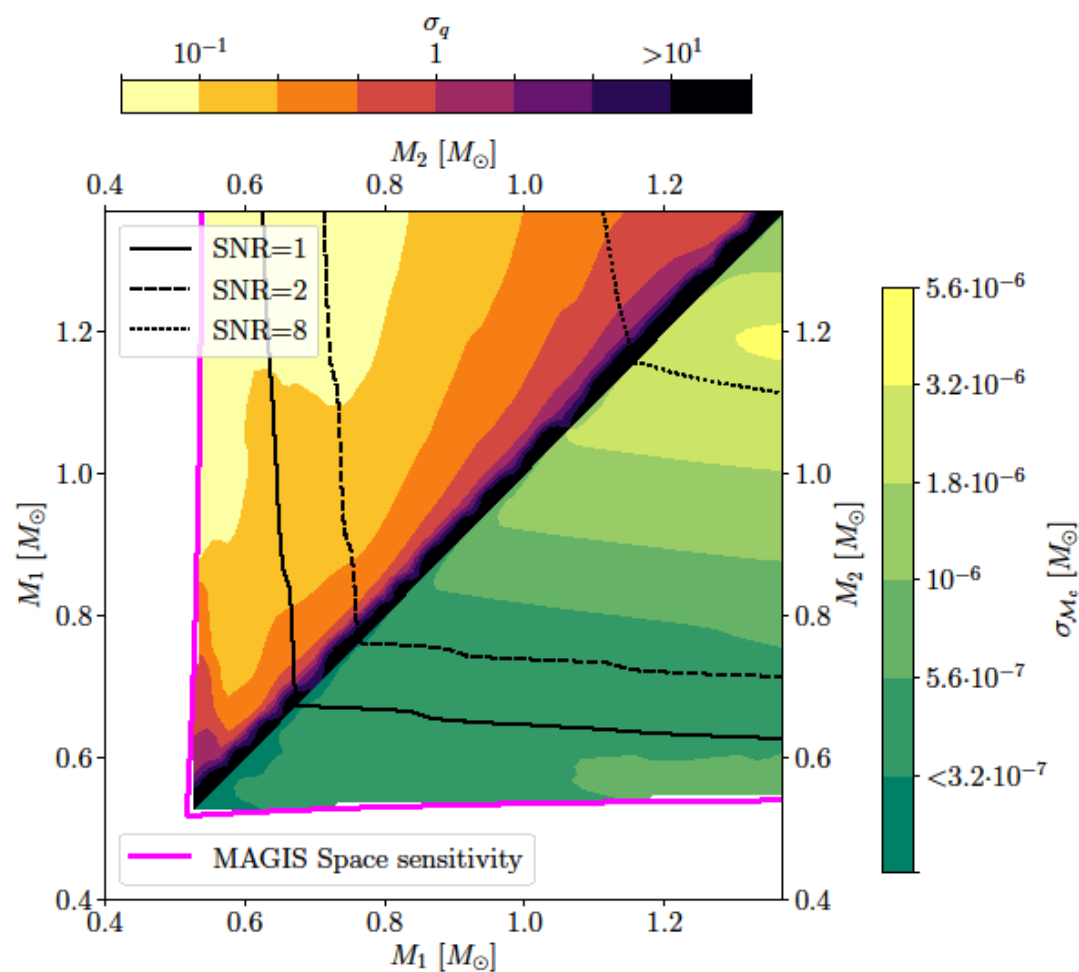
Detected signal evaluated with
Signal-to-noise ratio (SNR) ρ :

$$\rho = \sqrt{\langle h, h \rangle}$$

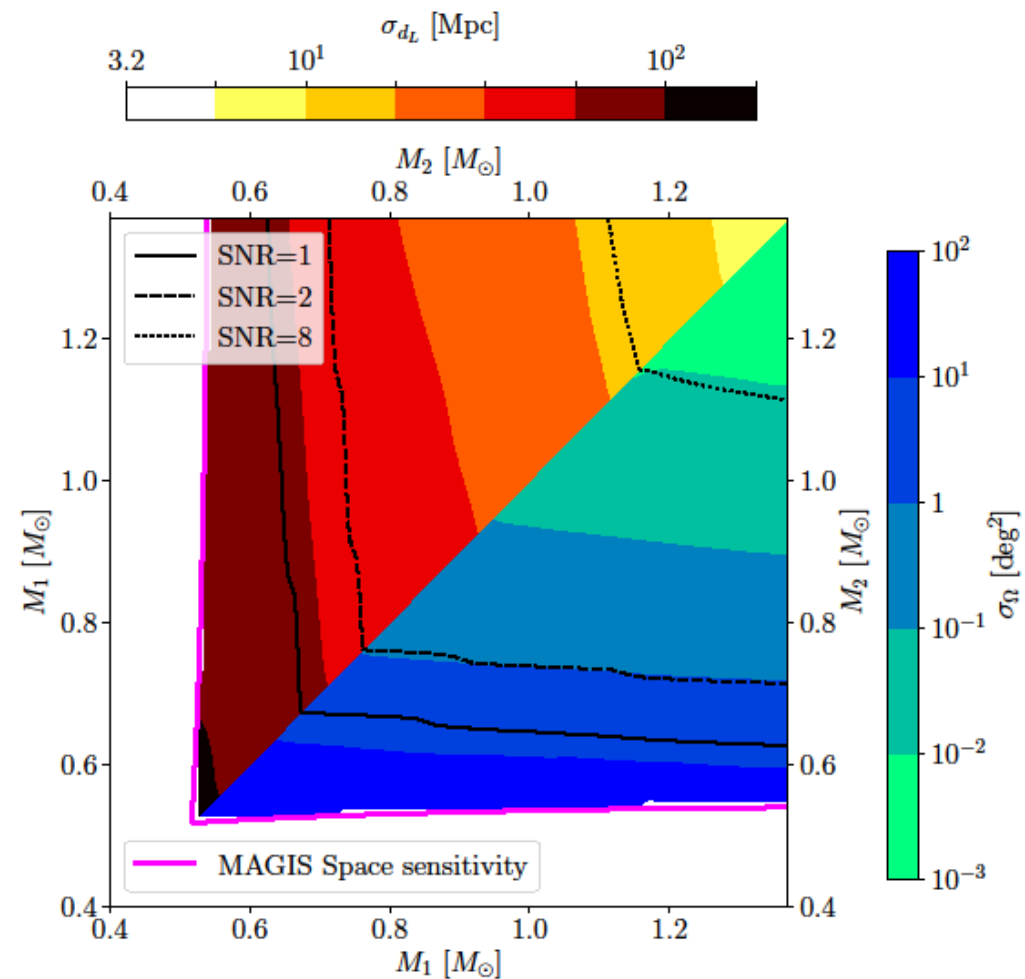
Parameter λ_i reconstruction precision
evaluated with Fisher analysis:

$$\Gamma_{ij} \equiv \left\langle \frac{\partial h}{\partial \lambda_i}, \frac{\partial h}{\partial \lambda_j} \right\rangle$$

Measurement precision



Precise measurement of chirp mass;



Good sky localisation.

Merger detection

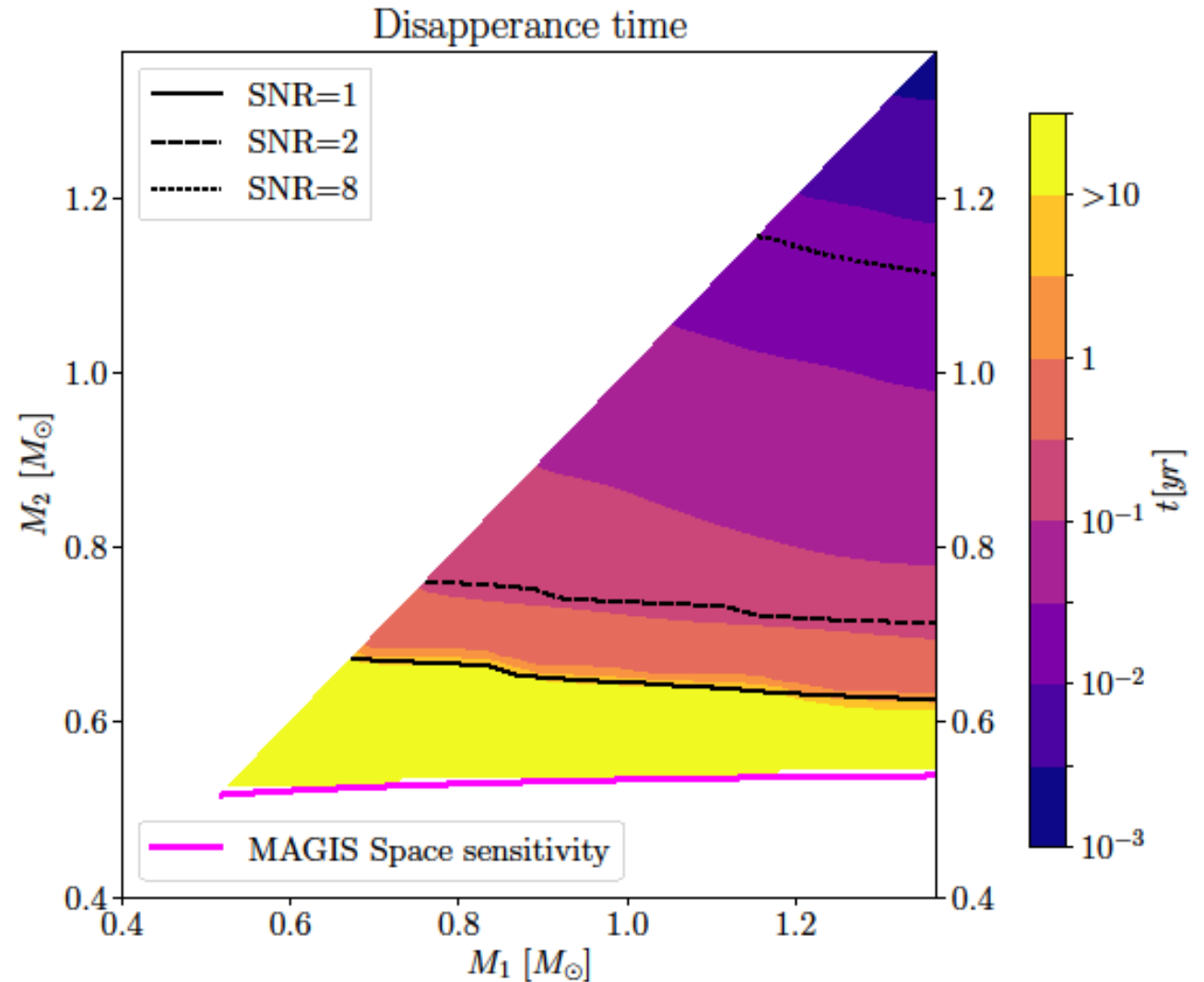
Merger recognition

Can we recognise a merger?

Time needed for WDB to reach SNR of 1 after RLOF.

For massive WDB, the merger can be detected in time for SN Ia to be observed.

$$\mathcal{M}_c \gtrsim 0.9 M_{\odot}$$



Mass transfer

Competing factors:

Before RLOF:

+ GW radiation dominates (point mass approx.)

After RLOF:

+ **GW radiation**

brings the WDs closer together;

± **Mass transfer**

+ Unstable

enhance mass transfer due to greater mass and size difference;

- Stable

angular momentum shift drives WDs apart;

± **Spin-orbit coupling**

exert some torque to synchronise the system.

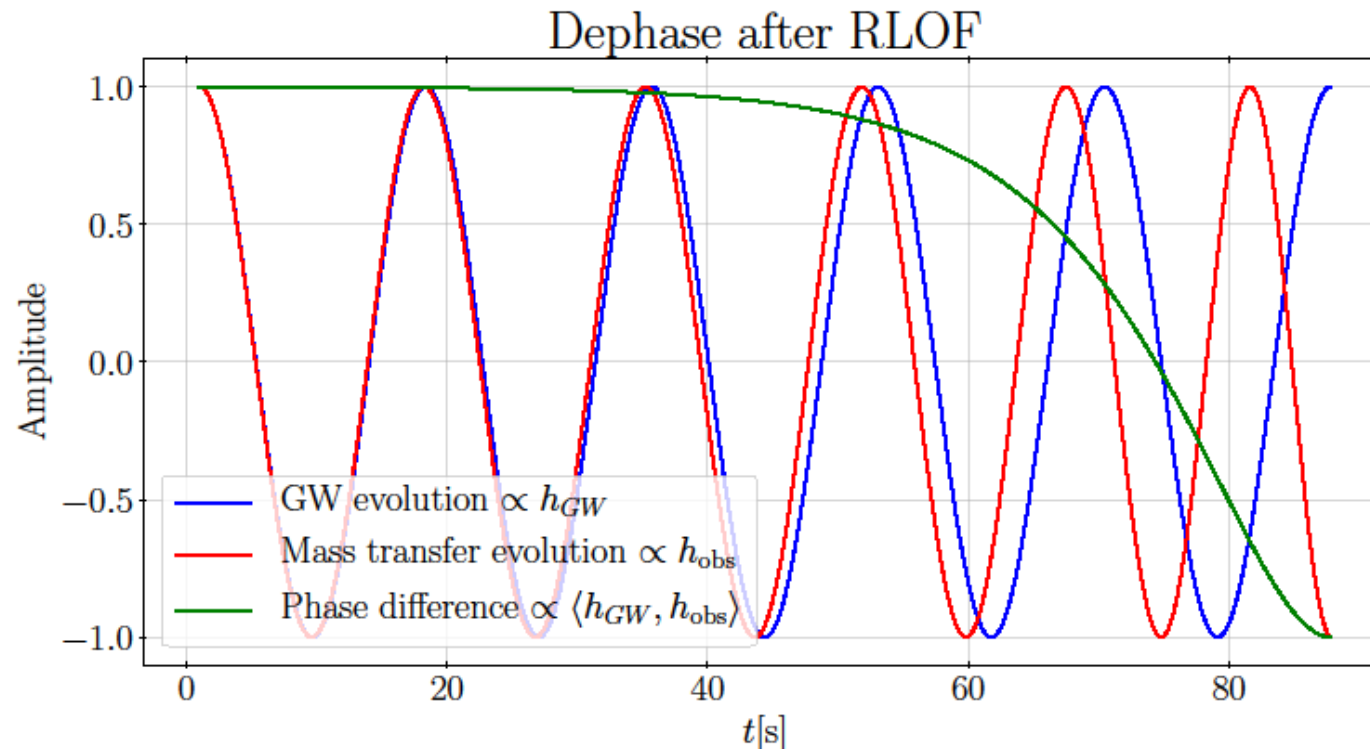


Merger forecast

Can we forecast a merger?

Mass transfer dephases the GW driven evolution of the binary.

$$\langle h_{GW}, h_{obs} \rangle \propto e^{i\Delta\Phi_{obs}(t)}$$

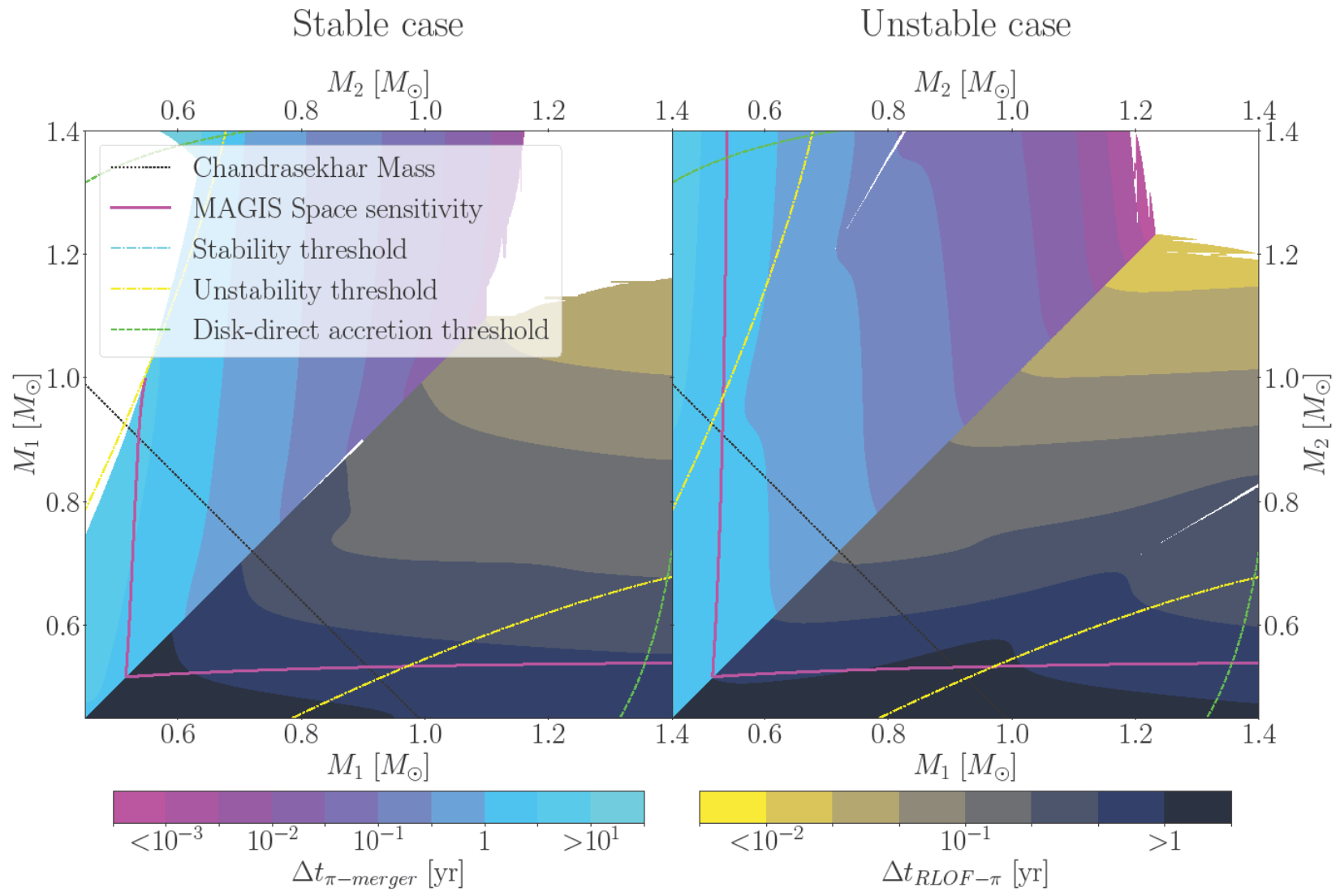


Merger forecast

A phase of 1π can be detected and anticipates a merger

$$\mathcal{M}_c \lesssim 1.0 M_\odot$$

where binaries merge within $\sim 10\text{yr}$



Merger detection

Can we detect WDB mergers and observe their final event?

- SN Ia are long-lived and can be observed within a few months;
- MAGIS Space provides good localisation of WDBs;
- The merger of massive WDBs can be recognised quickly;
- The dephase due to mass transfer can be observed for less massive WDBs.

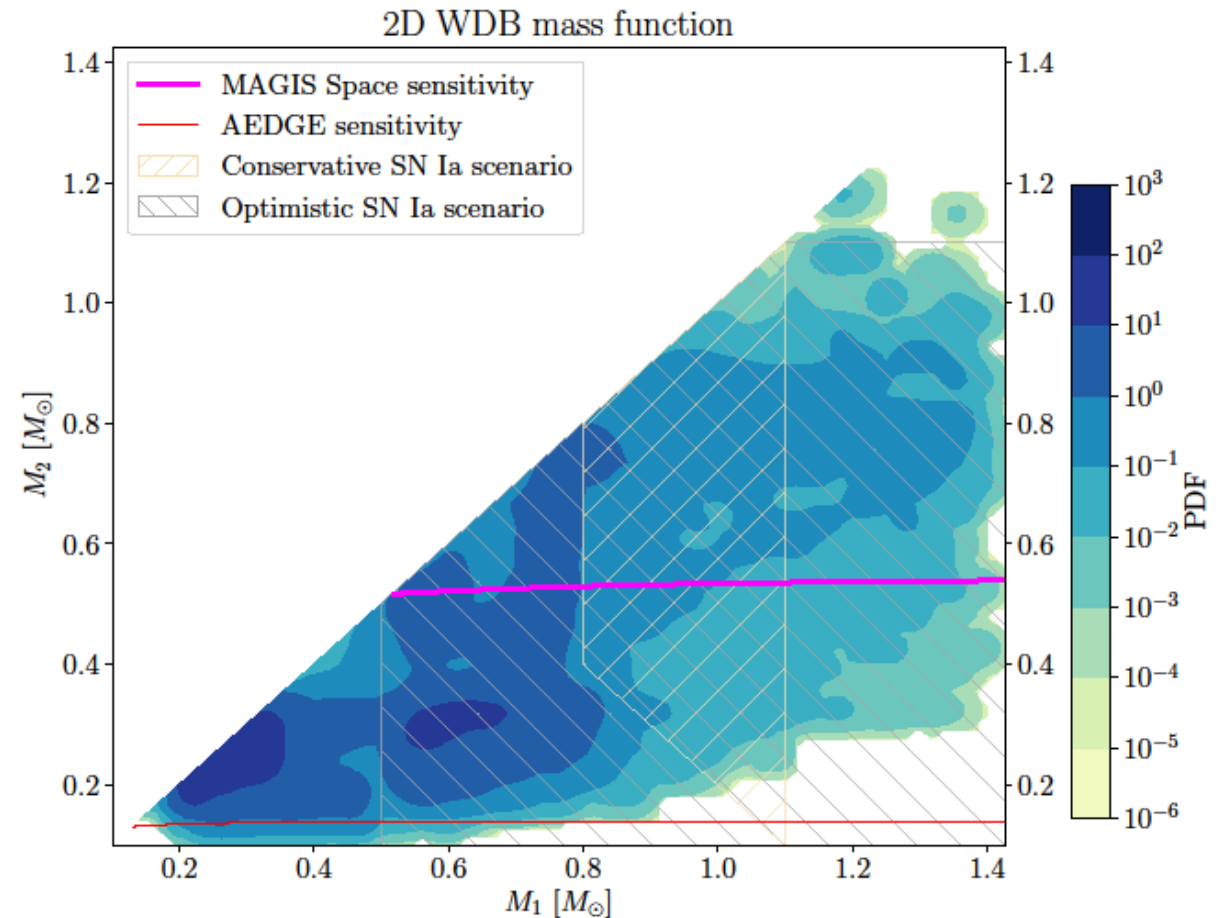
YES!

Merger rate

WDB population

Uncertainties:

- Different WDB population synthesis model, based on star formation history are considered;
- Two scenario for SN Ia detonation:
 - Conservative SN Ia scenario;
 - Optimistic SN Ia scenario.

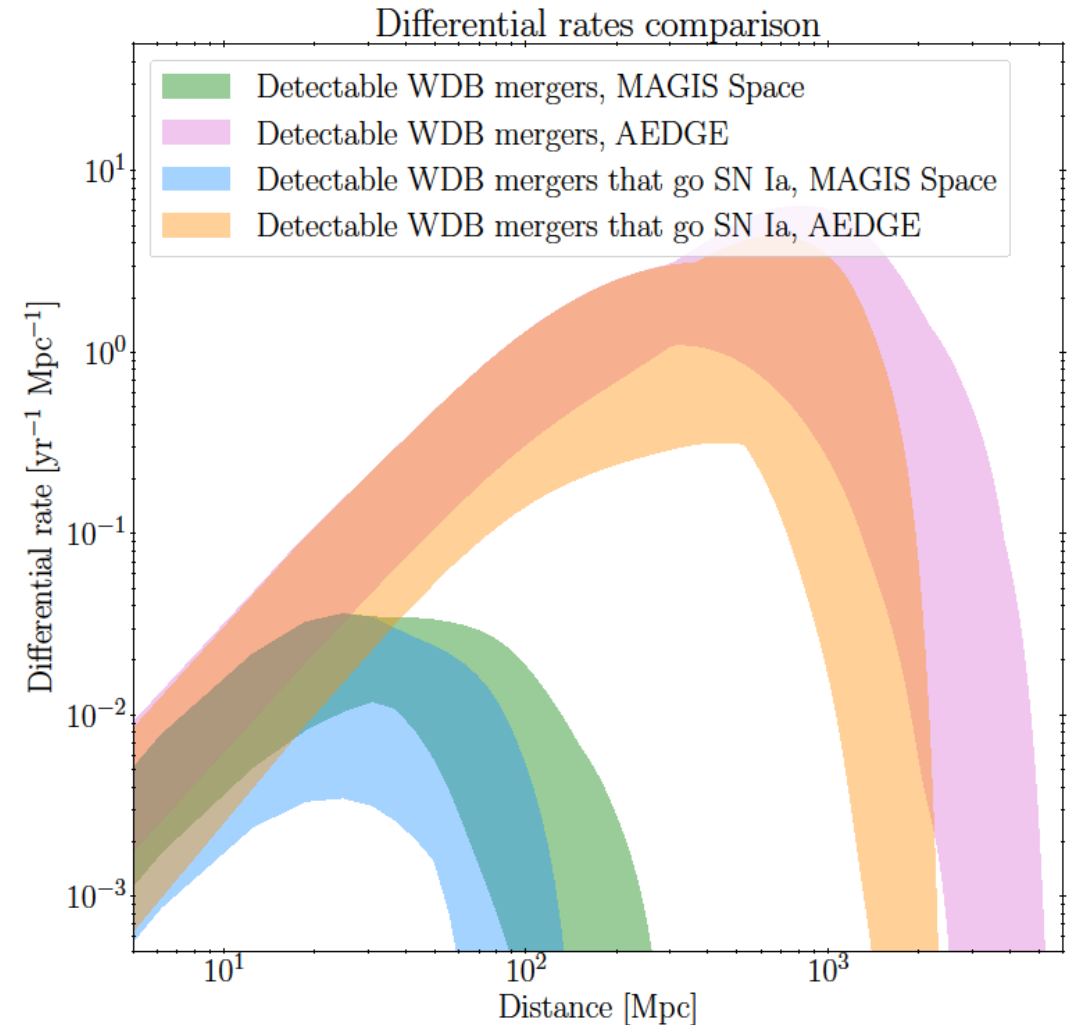


Overall merger rate

Comparison between MAGIS Space and AEDGE with the model approach.

Detectable (SNR>2) rates yearly:

- **MAGIS Space**
 - WDB mergers: 0.56 – 3.41;
 - SN Ia: 0.15 – 1.88;
- **AEDGE**
 - WDB mergers: 771 – 9230;
 - SN Ia: 266 – 4246.



Conclusions



With the space-based atom interferometers we will detect **WDB mergers on a yearly basis** and we will be able to predict and **observe their final event**, or at least their aftermath.

Observing the final stages of WDBs will provide useful insight in understanding WD composition, SN Ia origin and properties, and binary's last stages dynamics.

The absence of SN Ia will still provide useful information (e.g. favour the SD scenario and alternative final event).

Thank you for your attention

Questions?

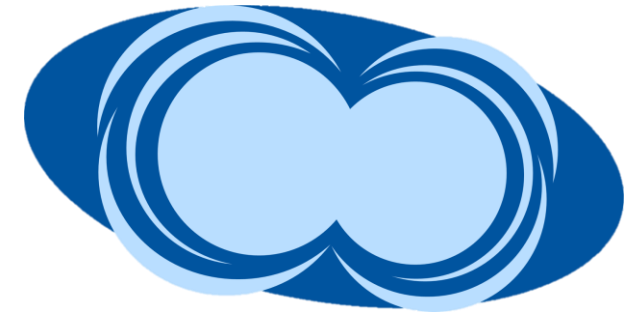
Backup slides

White dwarf binaries (WDBs)

WDB form from two main-sequence stars

Why is the detection of WDBs interesting?

- Detectable GW signature;
- Insight on SN Ia origin;
- Expected to be numerous, but there are large uncertainties on their population;
- Multi-messenger astronomy (e.g. complementary measurement of distance);
- Insight on mass transfer dynamics.



Mass transfer

Competing factors:

Before RLOF:

- GW radiation dominates (point mass approx.)

After RLOF:

+ GW radiation

brings the WDs closer together;

± Mass transfer;

+ Unstable

enhance mass transfer due to greater mass and size difference;

- Stable

angular momentum shift drives WDs apart;

± Spin-orbit coupling

exert some torque to synchronise the system;



$$\frac{\dot{a}}{2a} = -\frac{32 G^3 M_1 M_2 (M_1 + M_2)}{5 c^5 a^4} - \left(1 - 1/q - \sqrt{r_h (1 + 1/q)}\right) \frac{\dot{M}_2}{M_2} + \frac{k M_1 R_1^2 \omega}{\tau_S J_{orb}}$$

Merger rate approaches

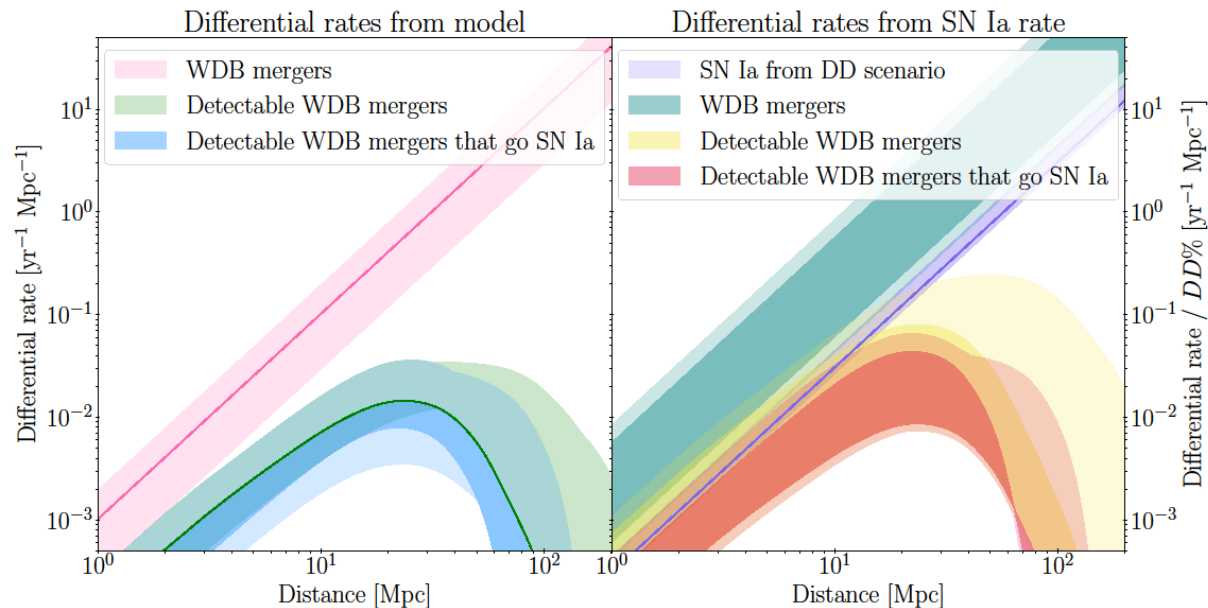
Model approach:

- WDB population synthesis for overall number of WDBs

SN Ia rate approach:

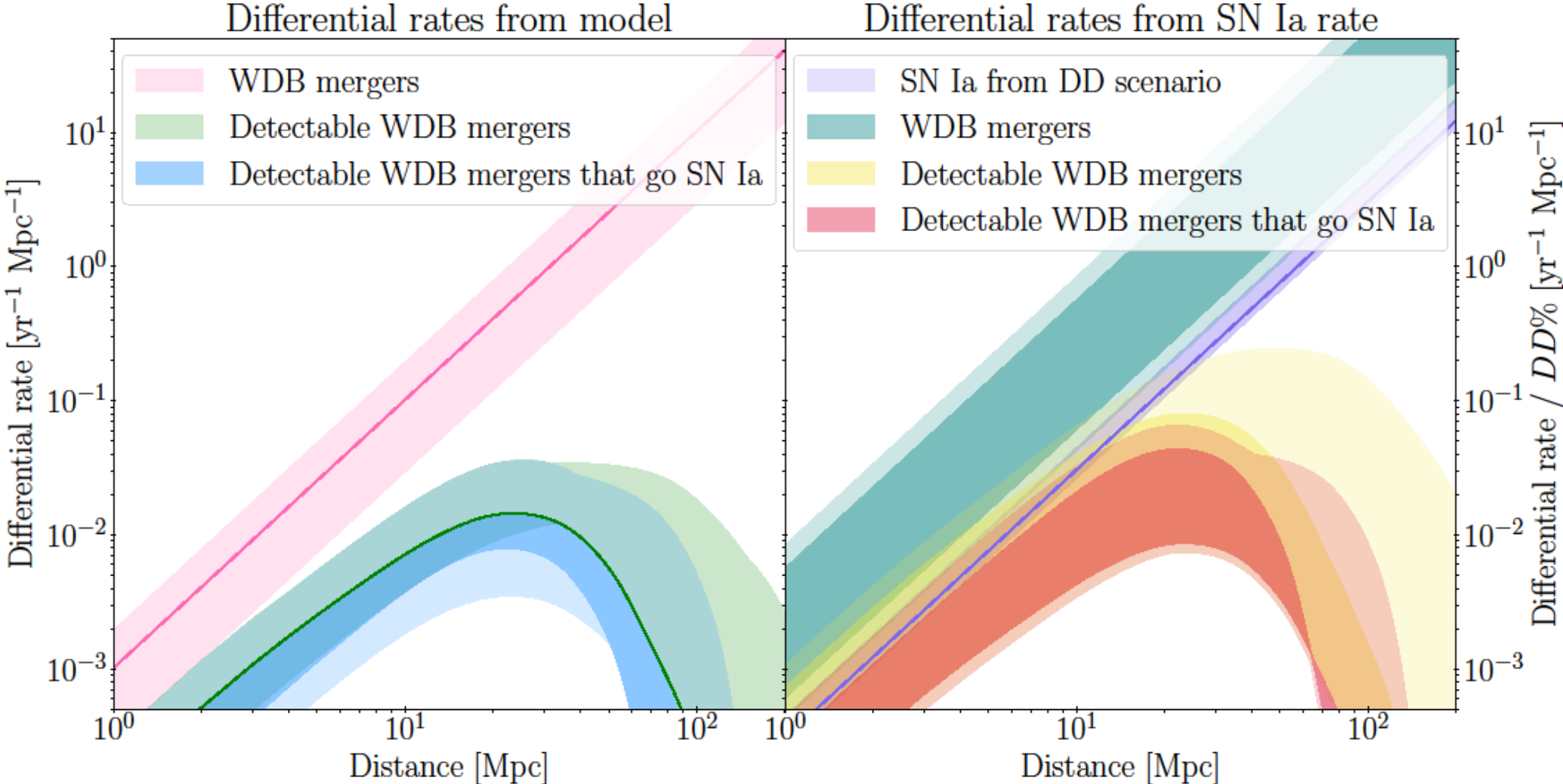
- Observed SN Ia rate + DD case %

$$r_{SN Ia} = 2.43_{-0.32}^{+1.10} \times 10^{-5} \text{yr}^{-1} \text{Mpc}^{-3}$$



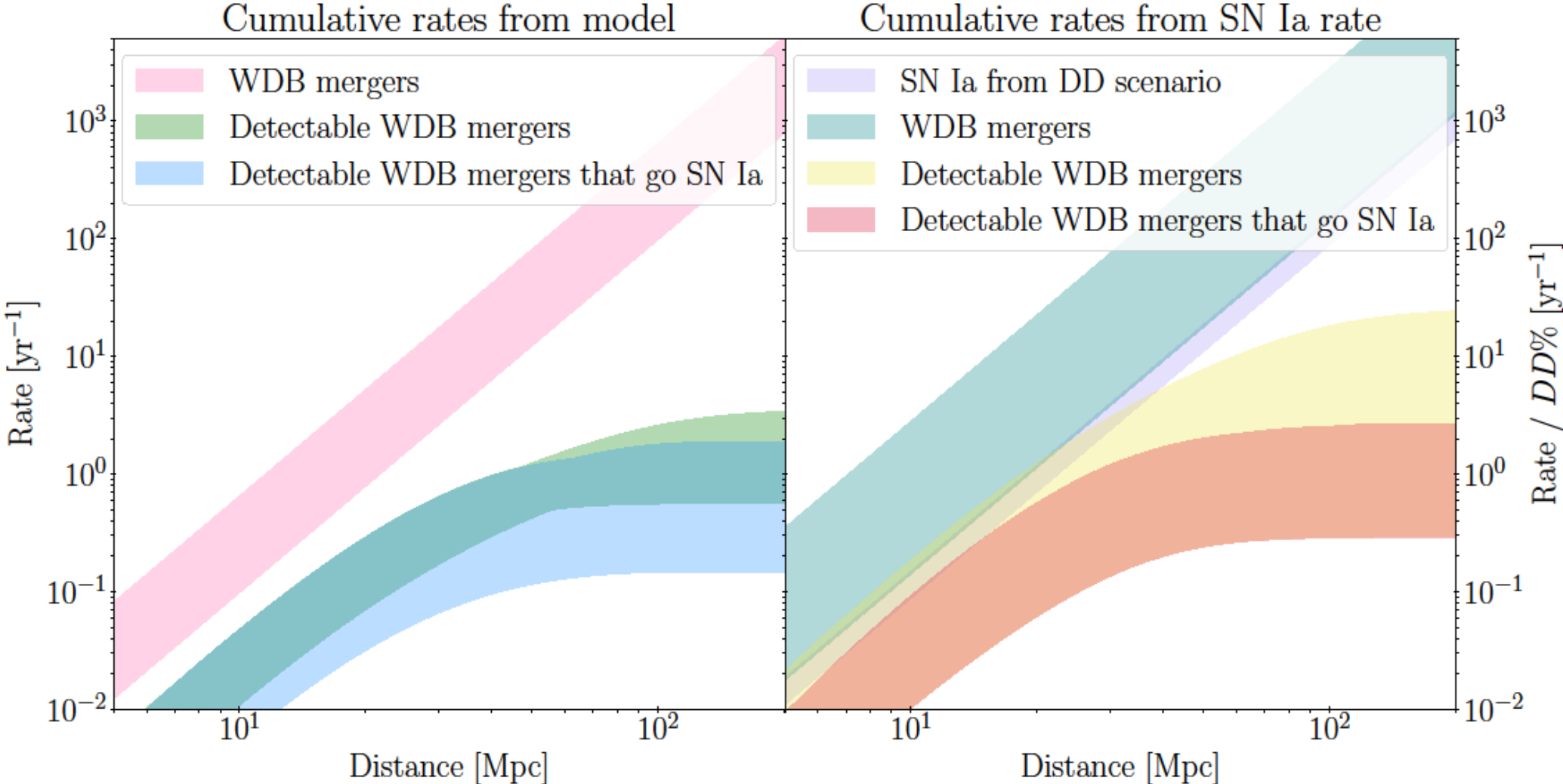
Differential merger rate

MAGIS Space

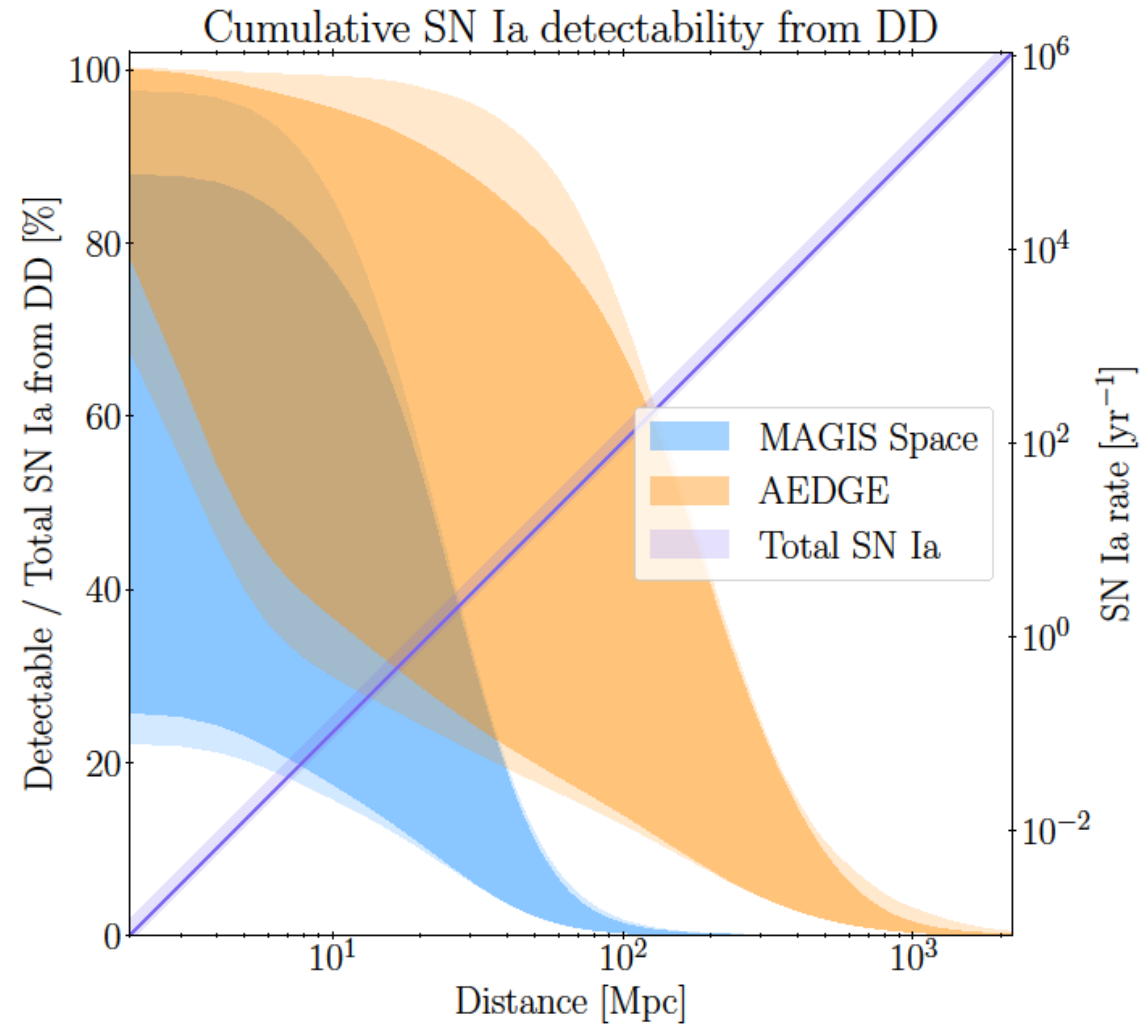


Differential merger rate

MAGIS Space

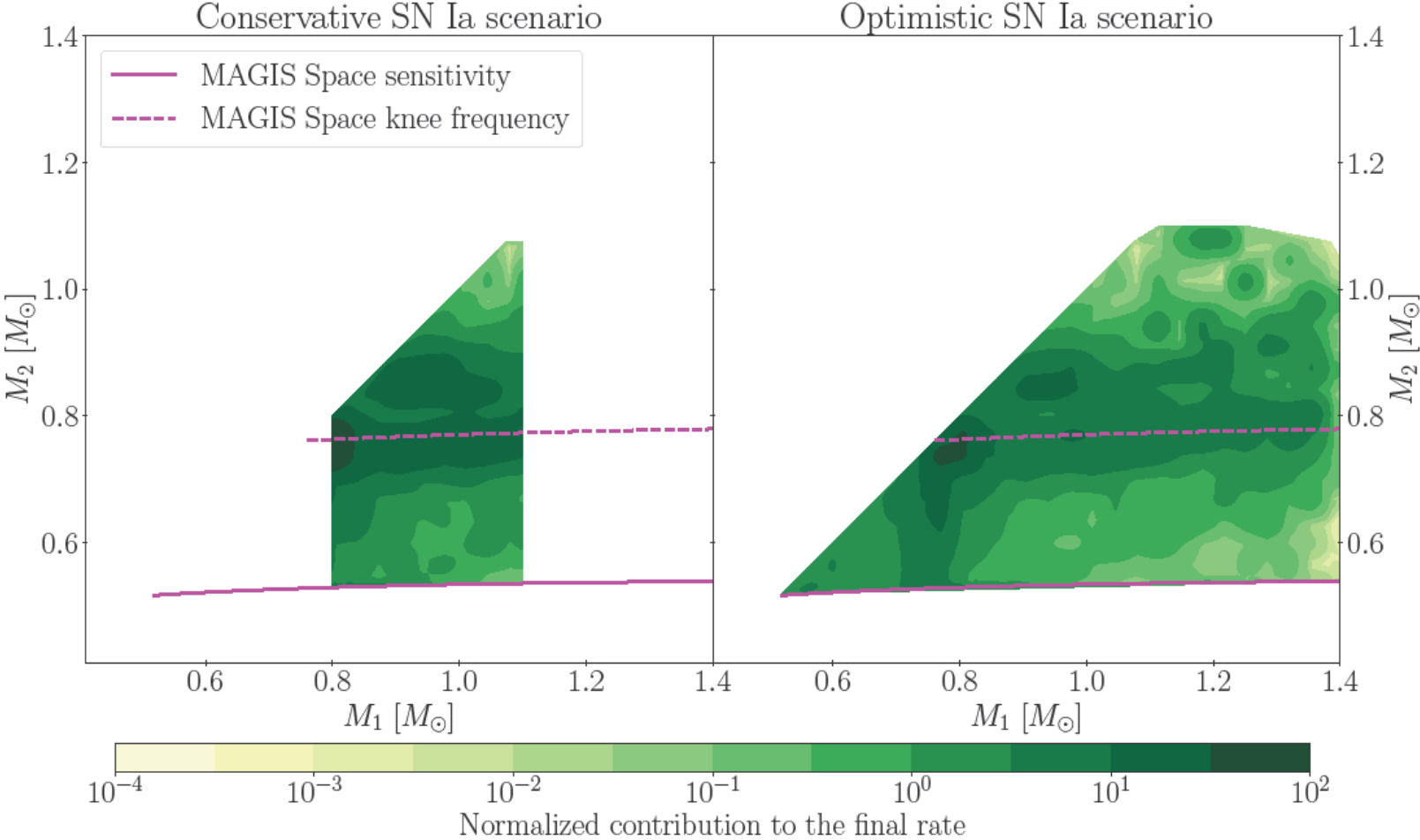


Absent SN Ia observation



Merger rate contribution

MAGIS Space
Fiducial population
synthesis model;



Impact frequency

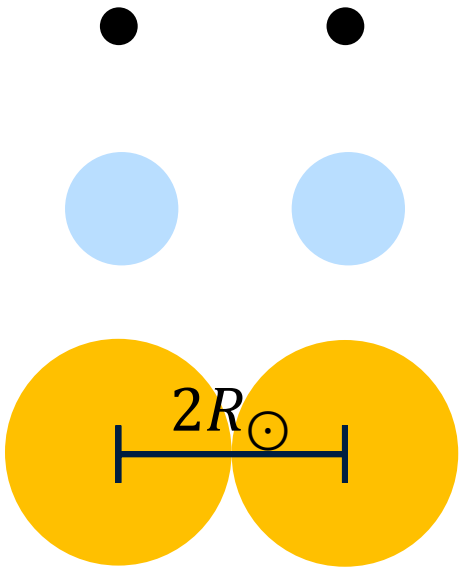
$$M_1 = M_2 = 1M_{\odot}$$

$$f_{GW} = 2f_{orb} = \sqrt{G \frac{M_1 + M_2}{8\pi^2 R^3}} = \sqrt{G \frac{M_{\odot}}{4\pi^2 R^3}}$$

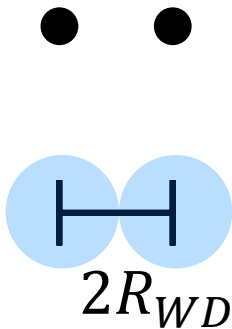
Sun binary impact

WDB impact

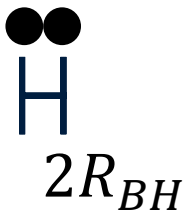
Black Holes impact



$$f_{GW} \sim 10^{-4} \text{ Hz}$$



$$f_{GW} \sim 0.1 \text{ Hz}$$



$$f_{GW} \sim 10 \text{ kHz}$$

Fisher analysis

Parameter precision reconstruction for a representative WDB, with Fisher analysis:

$$\Gamma_{ij} \equiv \left\langle \frac{\partial h}{\partial \lambda_i}, \frac{\partial h}{\partial \lambda_j} \right\rangle$$

Parameter precision:

$$\sigma_i \equiv \sqrt{(\Gamma^{-1})_{ii}}$$

Symbol	Parameter	Value
f_{\max}	Cutoff frequency	$f_{GW,RLOF}$
Δt_{obs}	Observation time	1 yr
d_L	Luminosity distance	25.0 Mpc
Φ_0	Binary phase at t_0	0°
t_0	Time of reference	0 s
ι	Inclination angle	45°
ψ	Polarization angle	135°
α_0	Right ascension	180°
δ_0	Declination	-30°

Frequency after RLOF

We consider two scenarios:

- Stable:

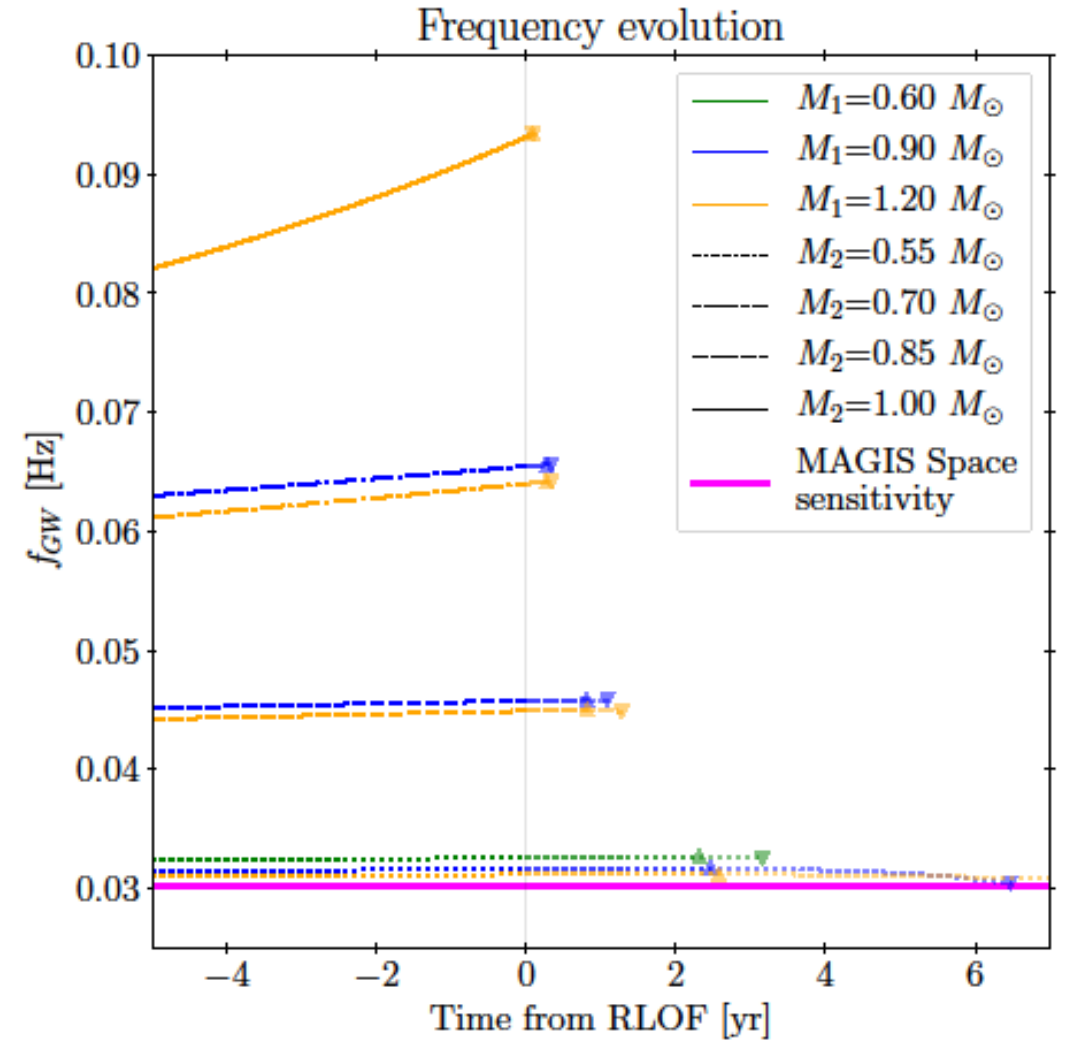
Spin-orbit coupling tends to stabilize the system.

+ Unstable:

Perfect mass transfer with no dissipative torque.

Merger takes place at critical mass transfer

$$- \dot{M}_2 > 0.01 M_{\odot} \text{yr}^{-1}.$$



Atom interferometer

Technology

GW detector

inertial test masses

baseline

LVK

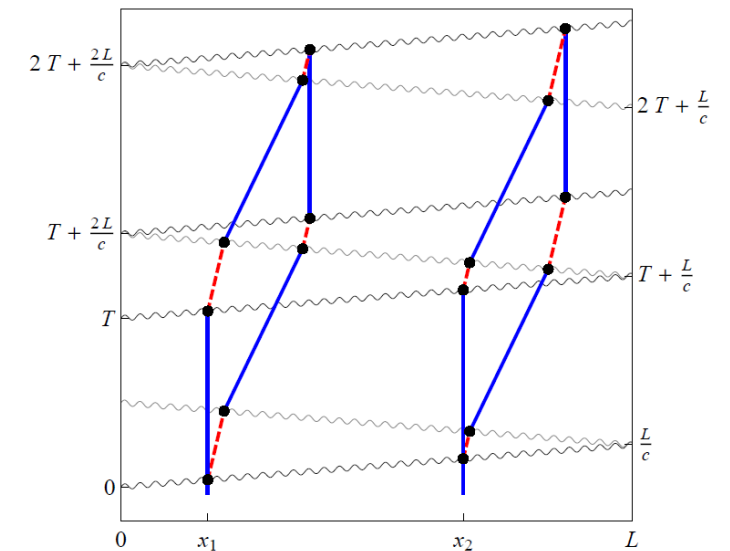
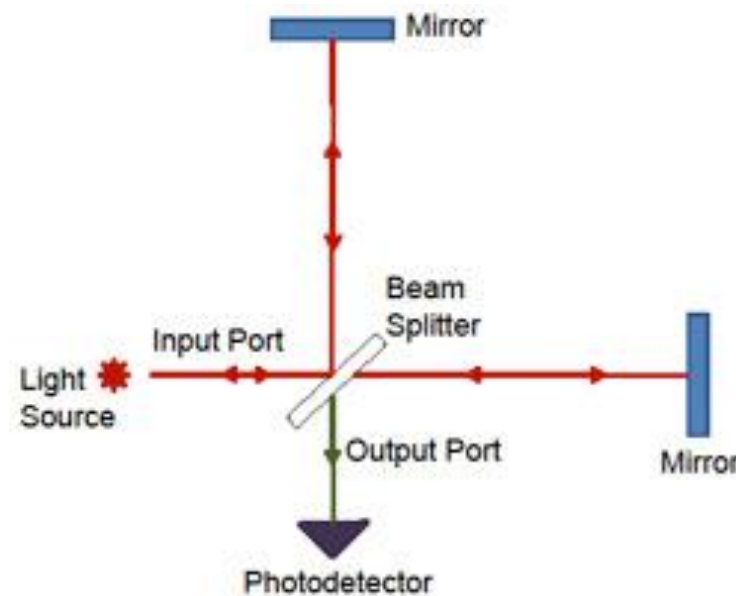
mirrors

laser

Atom interferometer

atoms

laser

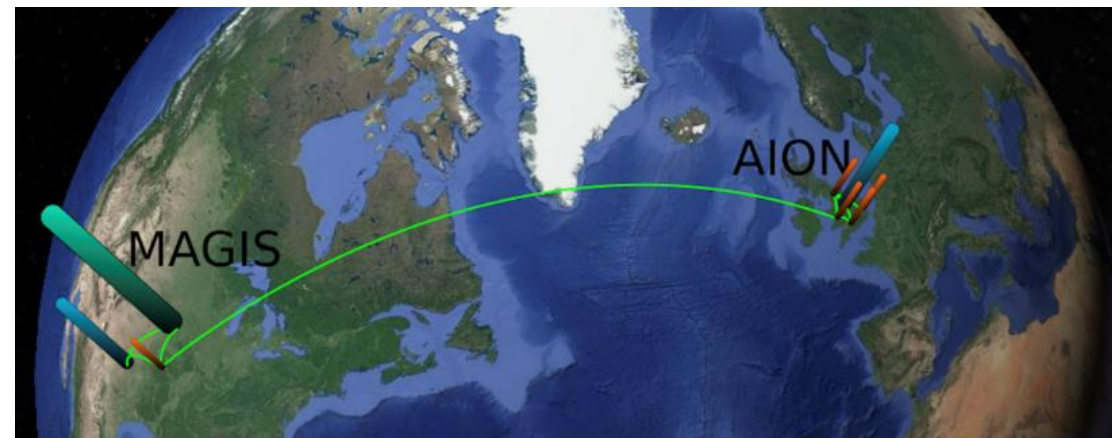
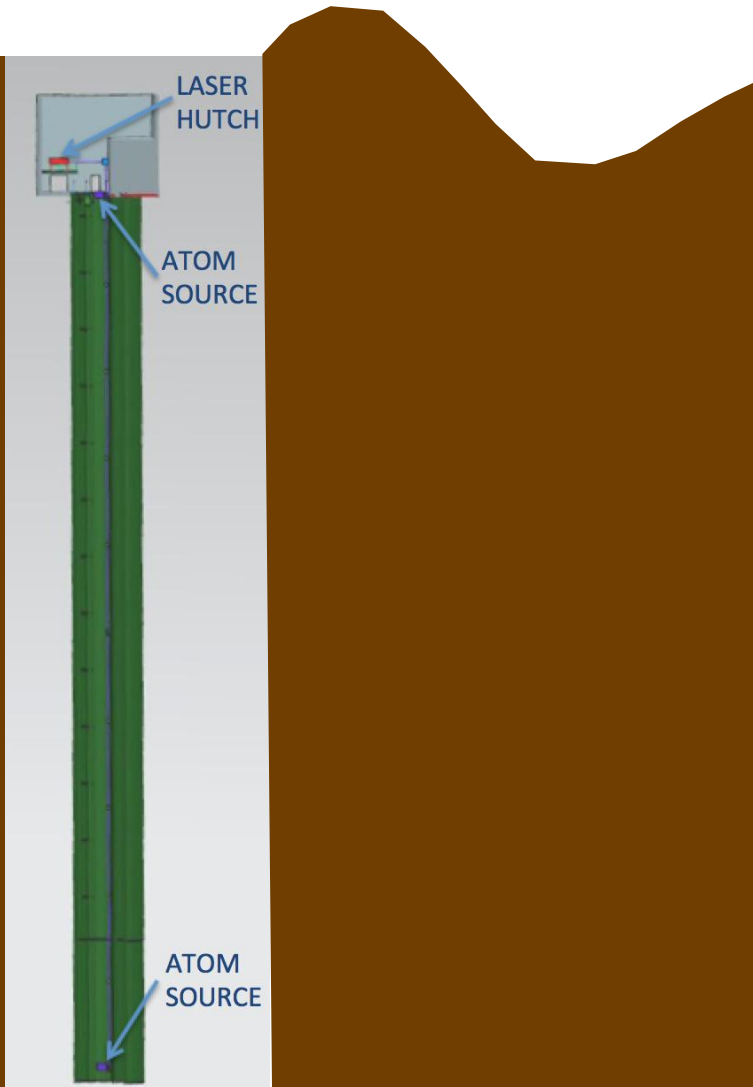


Graham, Hogan, Kasevich, Rajendran PRL 110 (2013)

Ground detector

Current status:

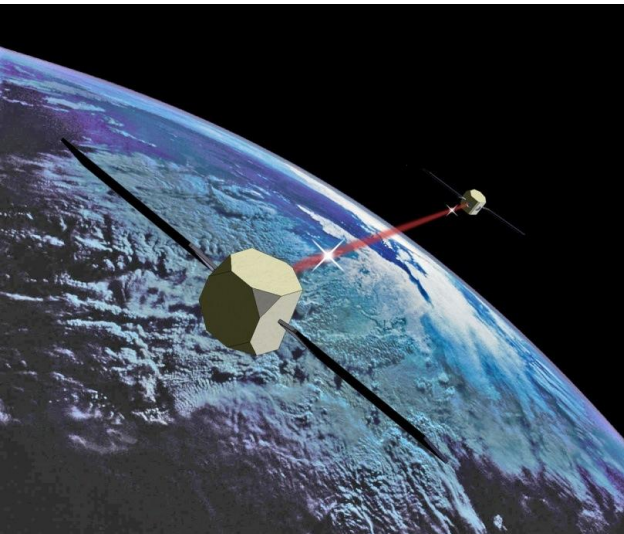
- Vertical configuration, free falling;
 - Longer measurement possible, for good localisation;
- Currently developed in the US (MAGIS) and in the UK (AION);
- 100 m demonstrator version under construction;
- Final version ~ 1 km.



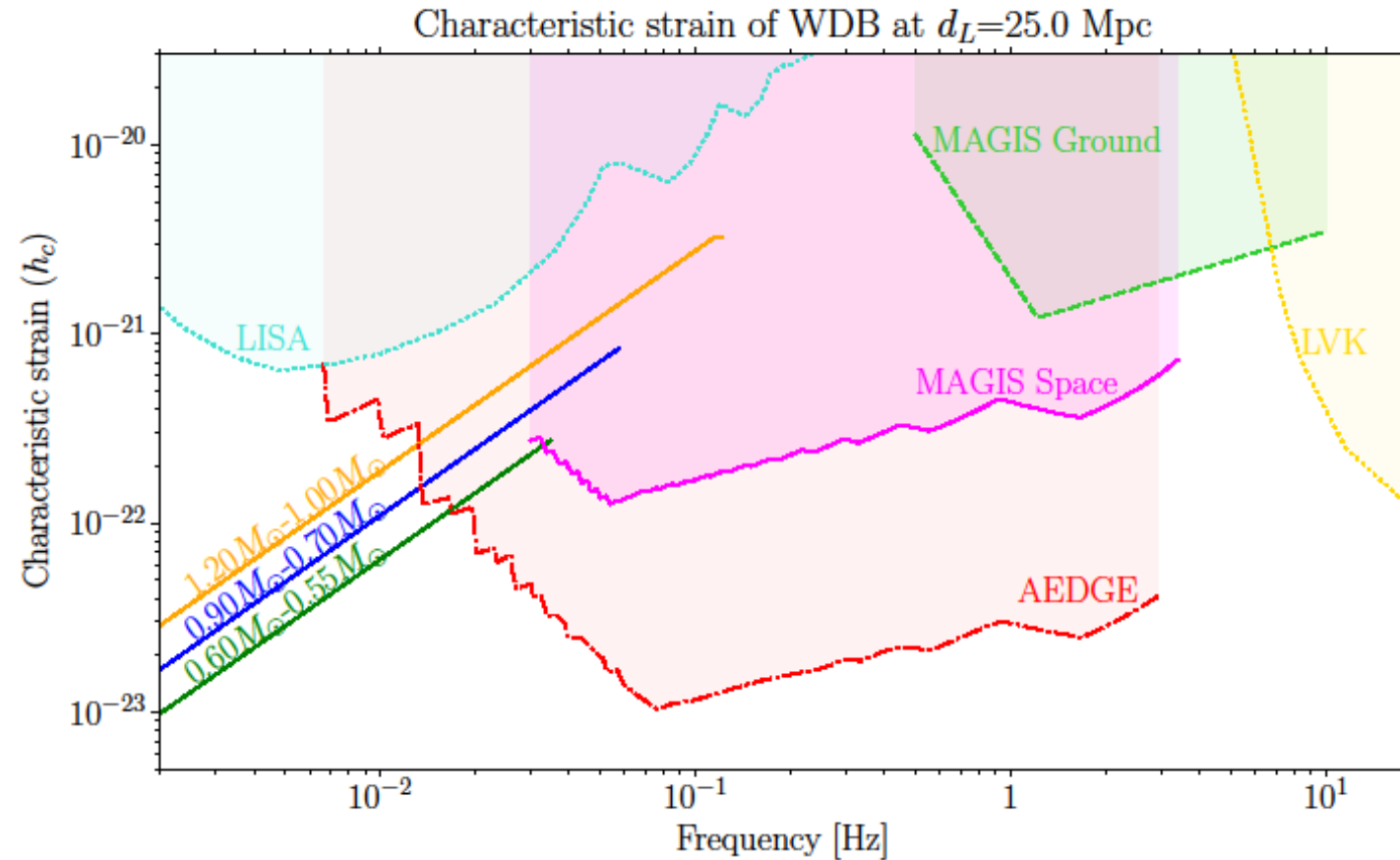
Space detector

Space detector configuration:

- Two satellites trailing each other;
- Orbit around Earth, with radius of $\sim 2 \cdot 10^4$ km;
- US: MAGIS Space, UK: AEDGE.



Giona Sala



GWs detectable signal

Detected strain:
$$\tilde{h}(f) = e^{i\phi_D} \times \left\{ F_+[t(f)] \times \tilde{h}_+(f) + F_\times[t(f)] \times \tilde{h}_\times(f) \right\}$$

- Antenna function $F_{+,\times}$ takes into account the direction of the detector and the incoming GW;
- Signal integrated over the orbit, in frequency space;
- ϕ_D includes the Doppler phase due to the movement of the detector.

