Characterizing the Galactic double white dwarf population

Part I:
Observations and implications to the SN Ia progenitor problem

Na’ama Hallakoun
Weizmann Institute of Science

with

Part I: Dan Maoz, Carles Badenes
Part II: Valeriya Korol, Silvia Toonen

Virtual KITP WD conference, 2021 March 30

Why should we care about double WDs?

- Binary evolution
- Type-Ia supernova progenitors
- Gravitational-wave sources

Why should we care about double WDs?

- Binary evolution
- Type-Ia supernova progenitors
- Gravitational-wave sources

Valeriya's talk

Why should we care about double WDs?

- Binary evolution
- Type-Ia supernova progenitors
- Gravitational-wave sources

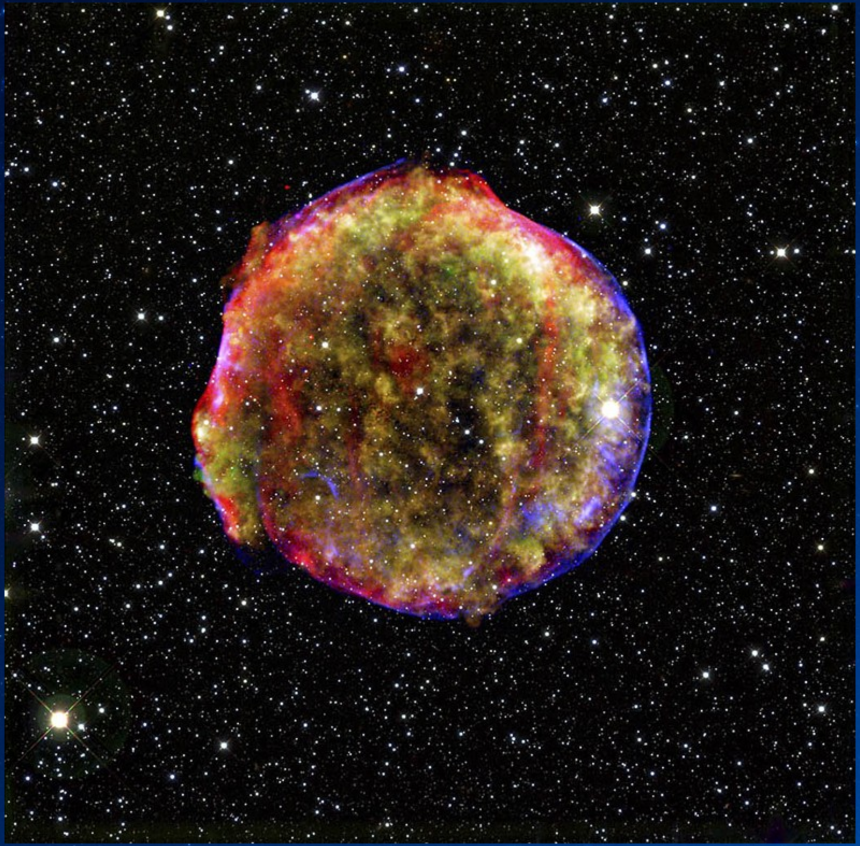
Valeriya's talk

Type-Ia supernovae are important

- Major source of heavy elements
- Standard candles
  - Dark energy

But, nobody knows exactly WHAT is exploding and HOW

Maoz et al. 2014, *ARAA*
Patat & Hallakoun 2019



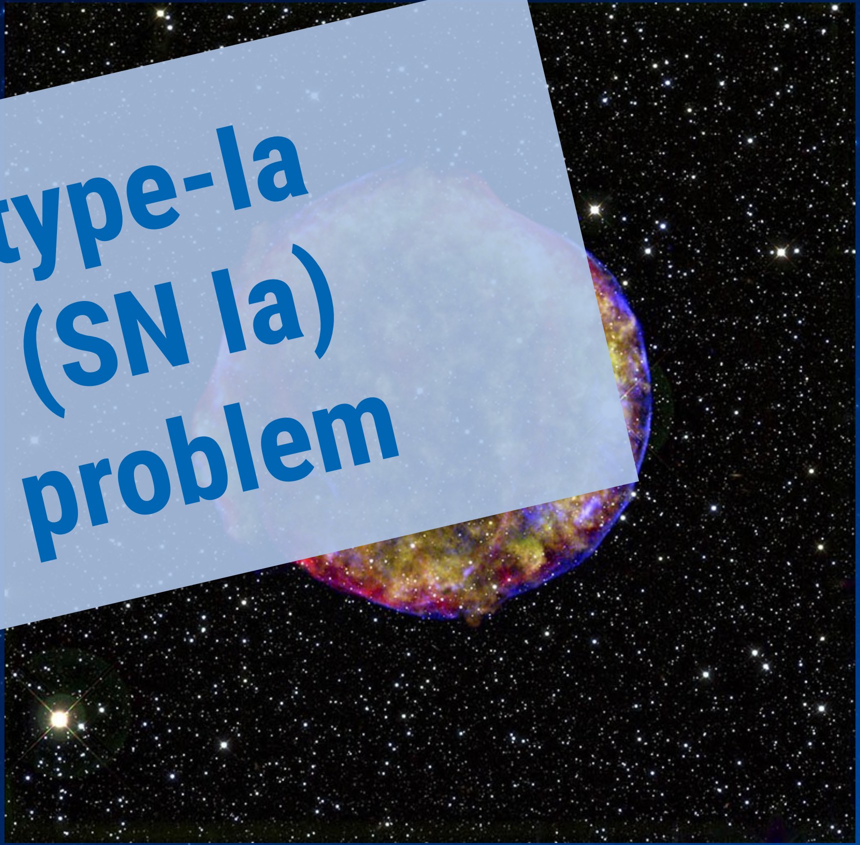
NASA/CXC/SAO; NASA/JPL-Caltech; MPIA, Calar Alto, O. Krause et al.

Type-Ia supernovae are important

- Major source of heavy elements
- Standard candles
  - Dark energy

But, nobody knows exactly WHAT
is exploding and HOW

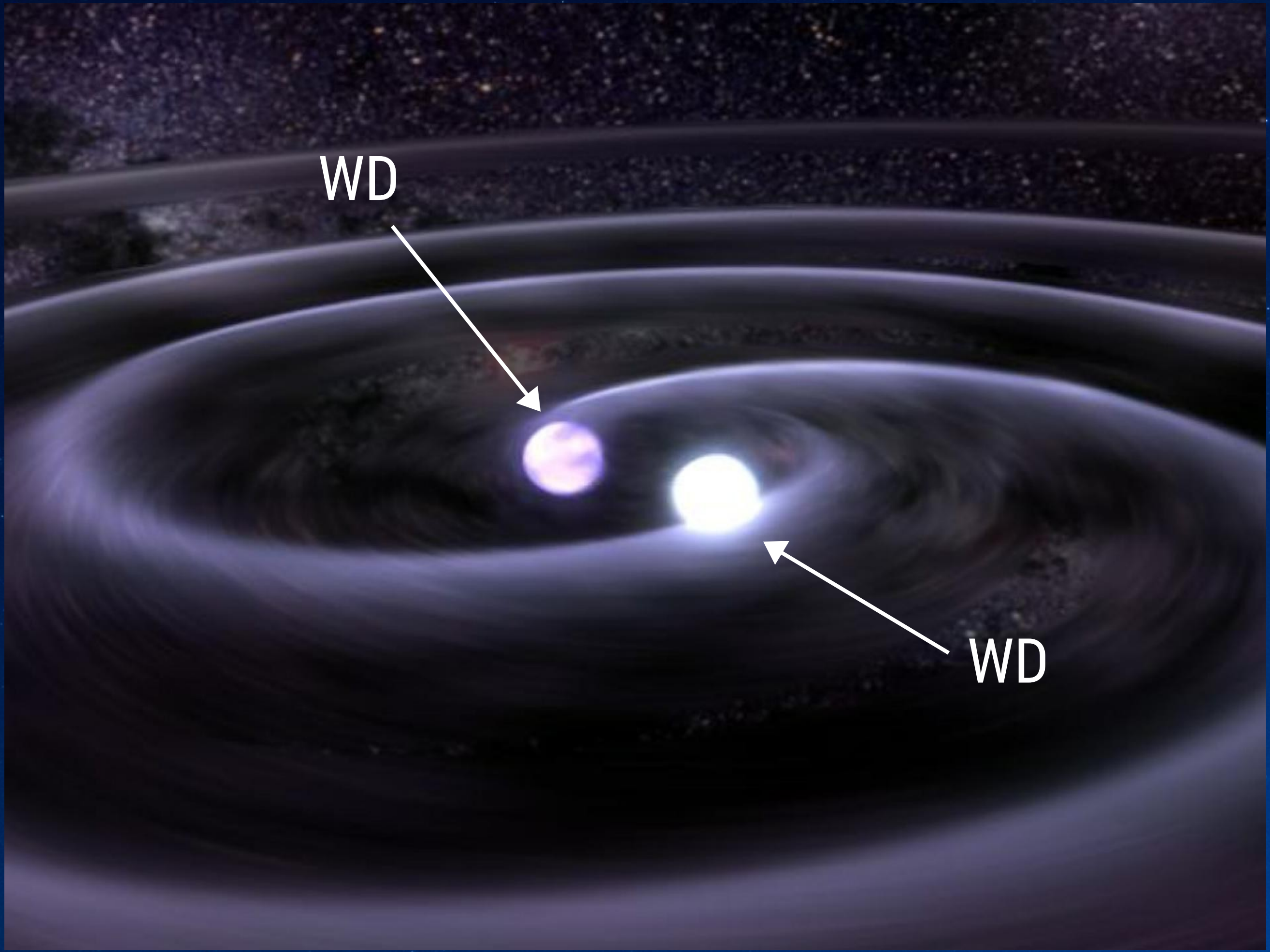
Maoz et al. 2014, *ARAA*
Patat & Hallakoun 2019



NASA/CXC/SAO; NASA/JPL-Caltech; MPIA, Calar Alto, O. Krause et al.

This is the type-Ia supernova (SN Ia) progenitor problem

Double degenerate (DD; Webbink 1984, Iben & Tutukov 1984)



NASA/Tod Strohmayer (GSFC)/Dana Berry (Chandra X-Ray Observatory)

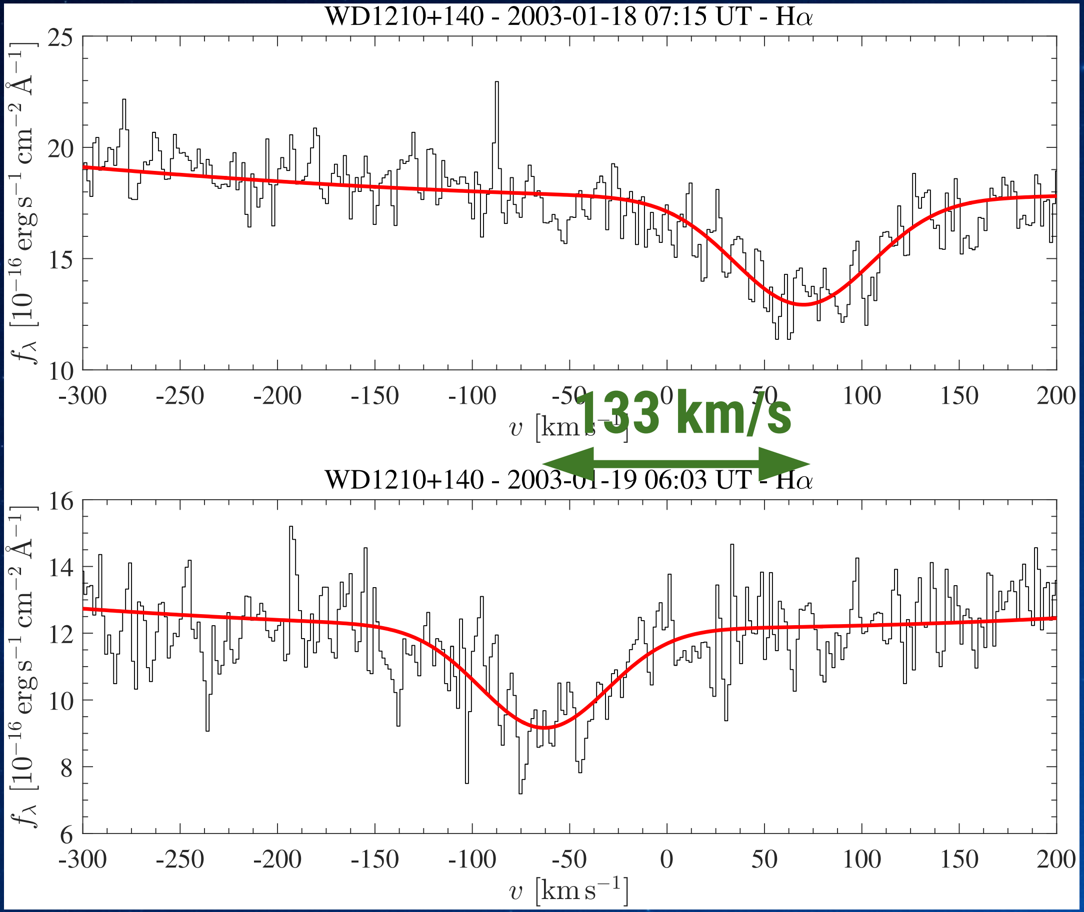
Double degenerate (DD; Webbink 1984, Iben & Tutukov 1984)

NASA/Tod Strohmayer (GSFC)/Dana Berry (Chandra X-Ray Observatory)

If correct, there should be enough close double WD systems to reproduce the Milky Way SN Ia rate

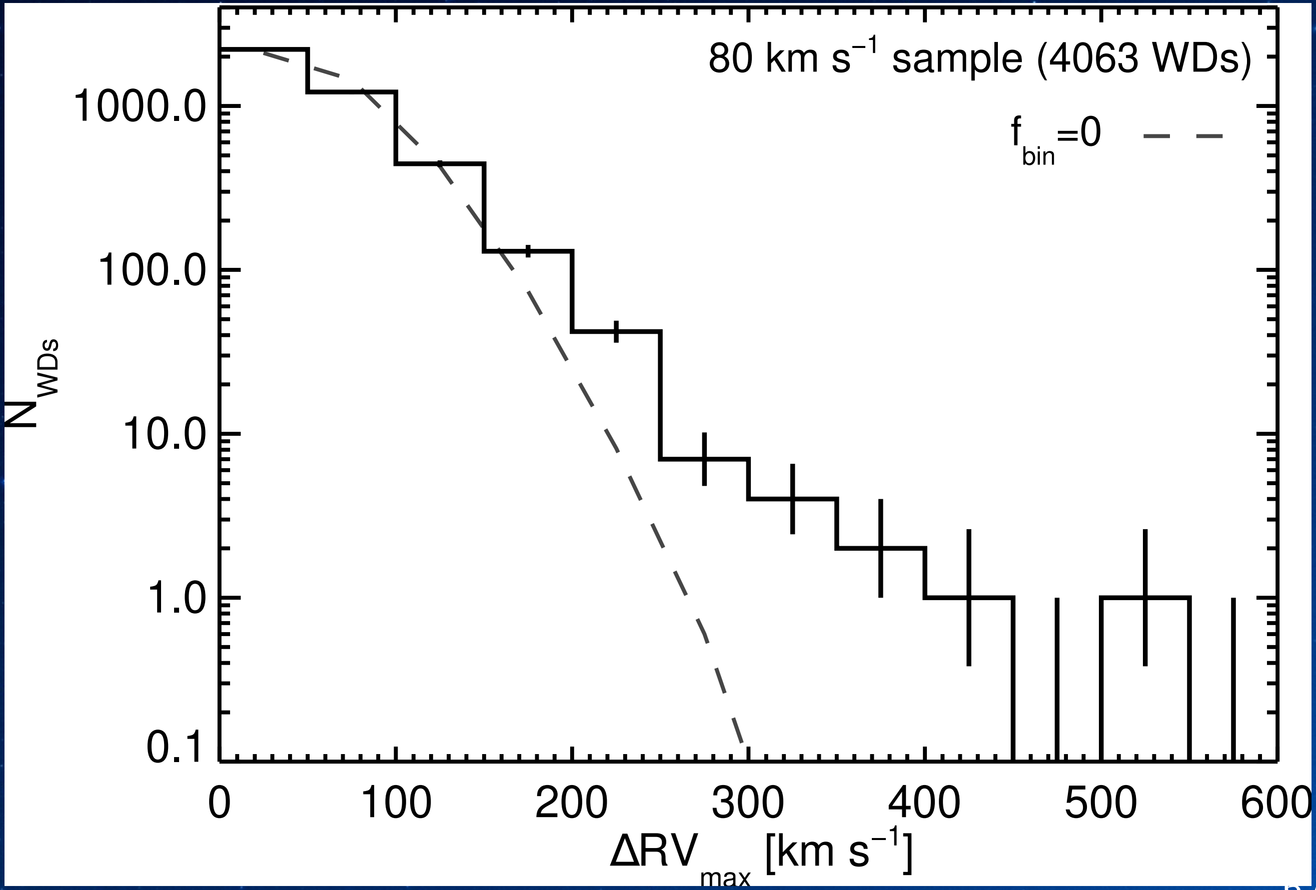
The search for double WDs

An efficient way:
look for radial velocity (RV) variations in WD spectra



The ΔRV_{max} distribution (Maoz et al. 2012)

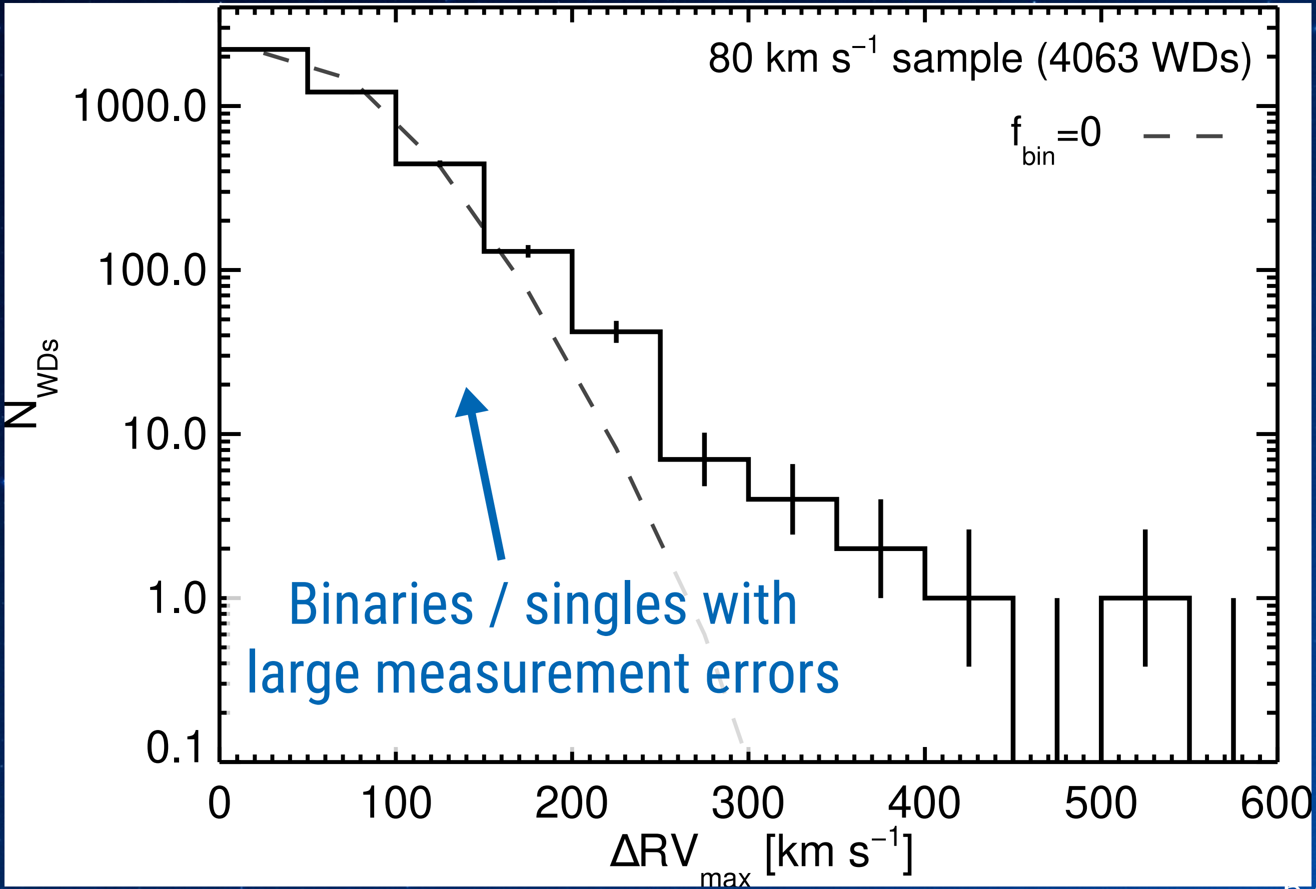
The distribution of maximal observed RV difference per system:



Adapted from Badenes & Maoz 2012

The ΔRV$_{max}$ distribution (Maoz et al. 2012)

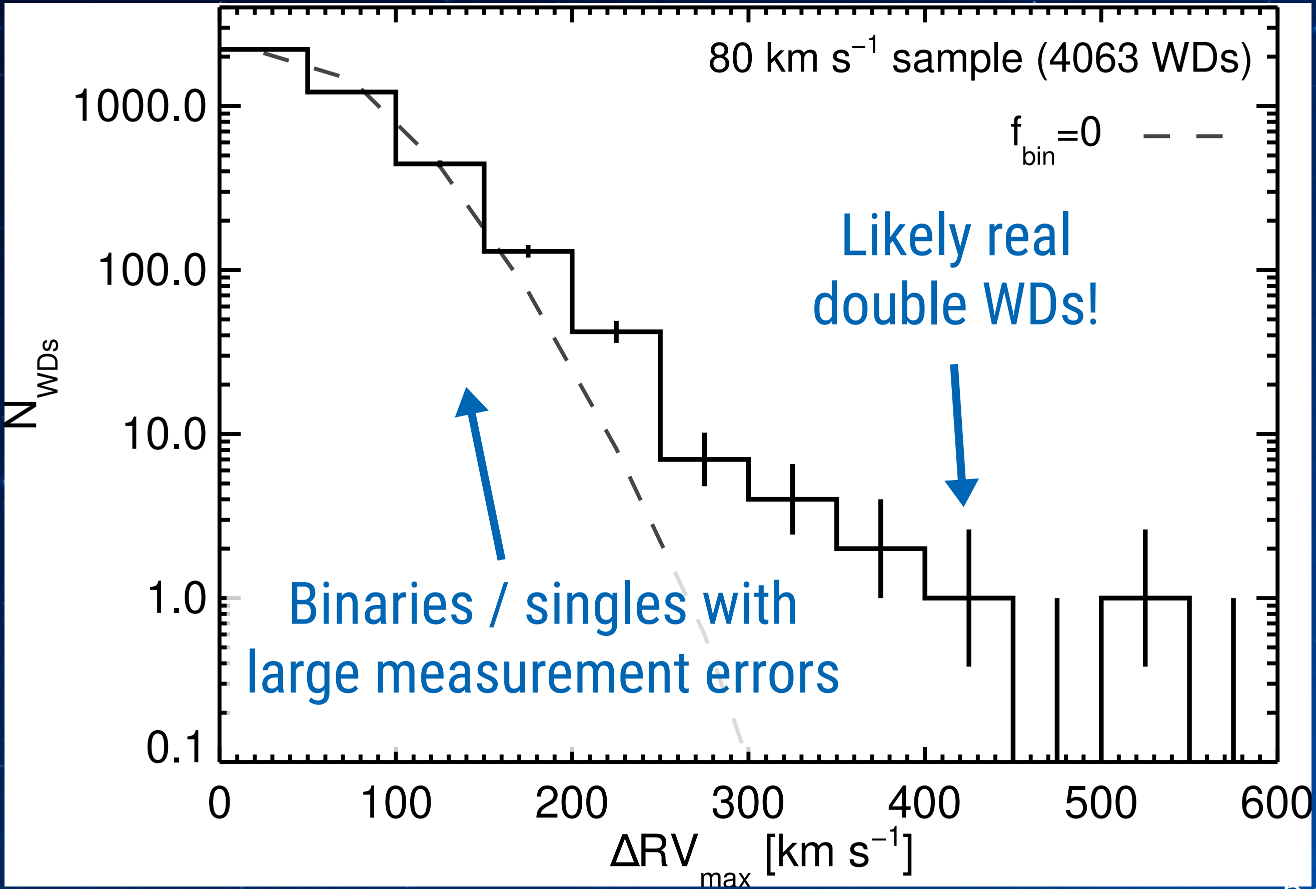
The distribution of maximal observed RV difference per system:



Adapted from Badenes & Maoz 2012

The ΔRV_{max} distribution (Maoz et al. 2012)

The distribution of maximal observed RV difference per system:

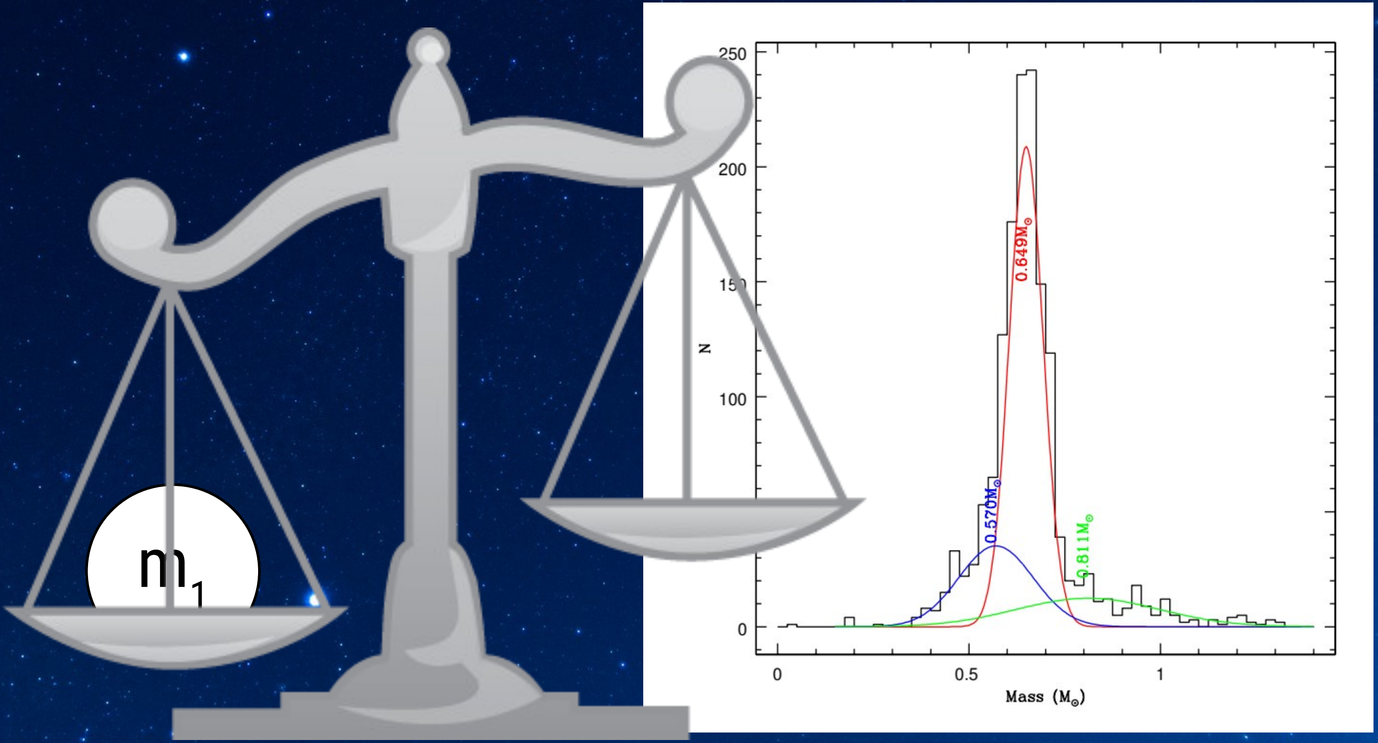


Adapted from Badenes & Maoz 2012

Simulating the local double-WD population

Simulating the local double-WD population

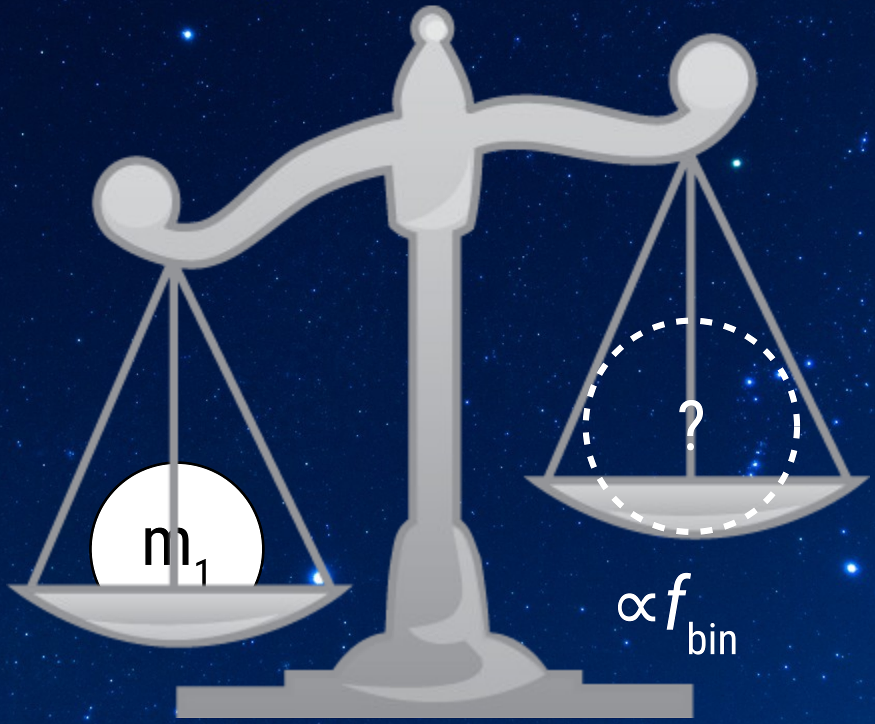
Simulating the local double-WD population



Kepler et al. 2015

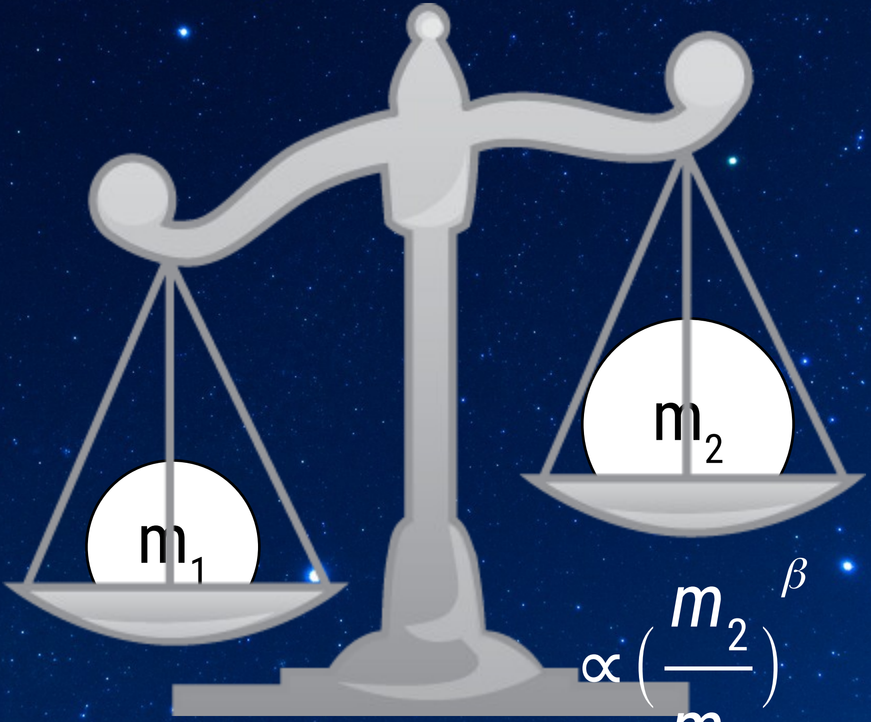
Simulating the local double-WD population

Simulating the local double-WD population



the fraction of all WDs in binaries within *x* AU

Simulating the local double-WD population



$$\propto \left(\frac{m_2}{m_1}\right)^{\beta}$$

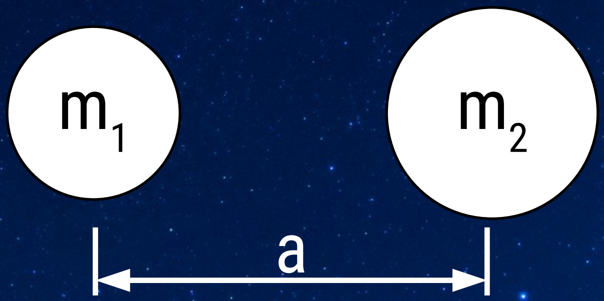
Simulating the local double-WD population

$$\frac{dN}{da_0} \propto a_0^{\alpha}$$

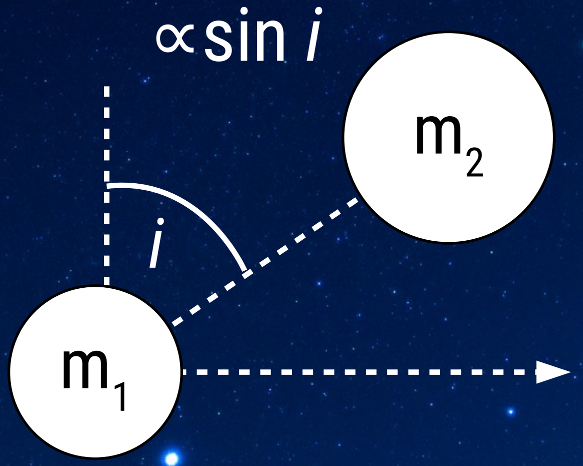
the separation distribution
of double WDs **at birth**

Simulating the local double-WD population

After 10 Gyr of evolution:

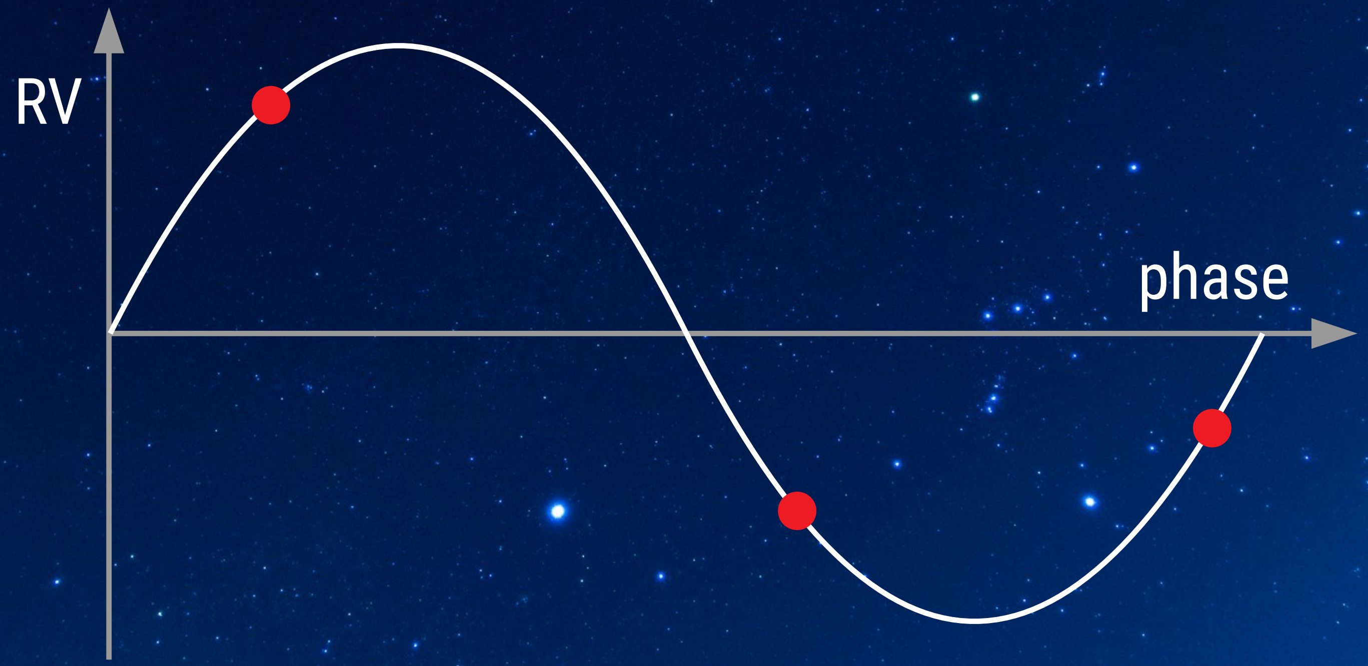


Simulating the local double-WD population

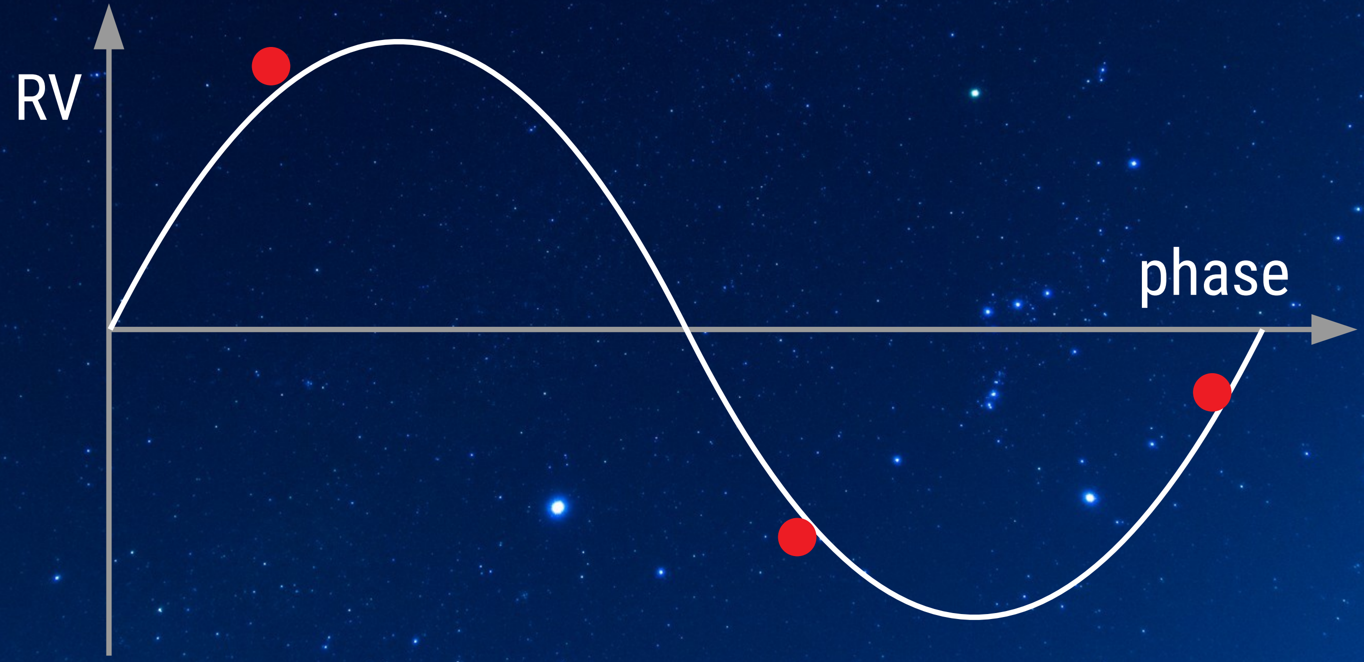


Simulating the local double-WD population

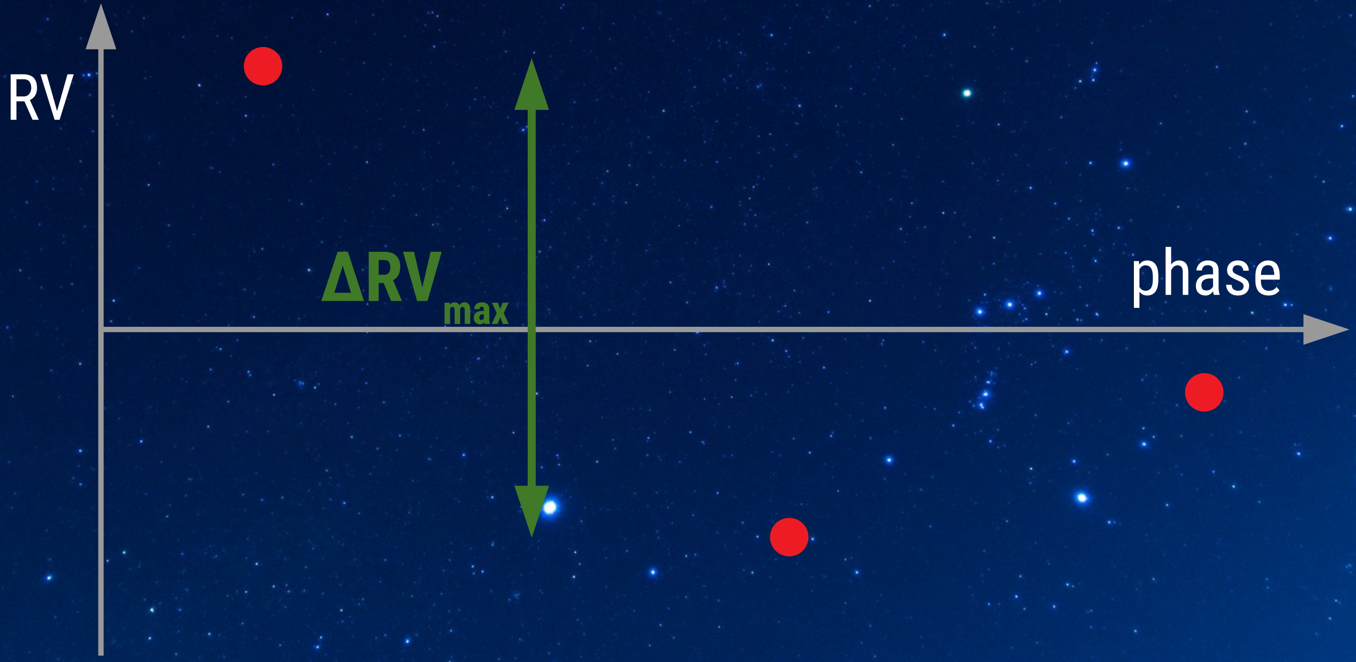
Simulating the local double-WD population



Simulating the local double-WD population

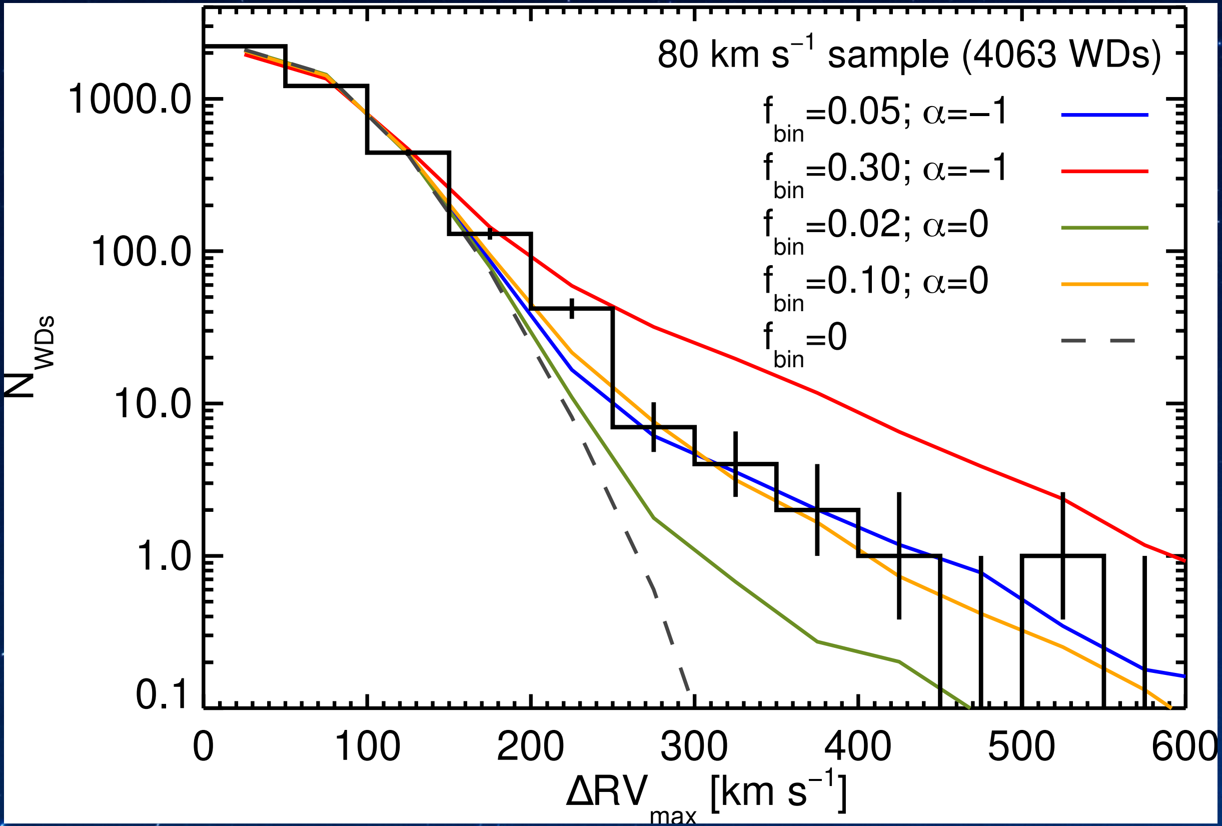


Simulating the local double-WD population



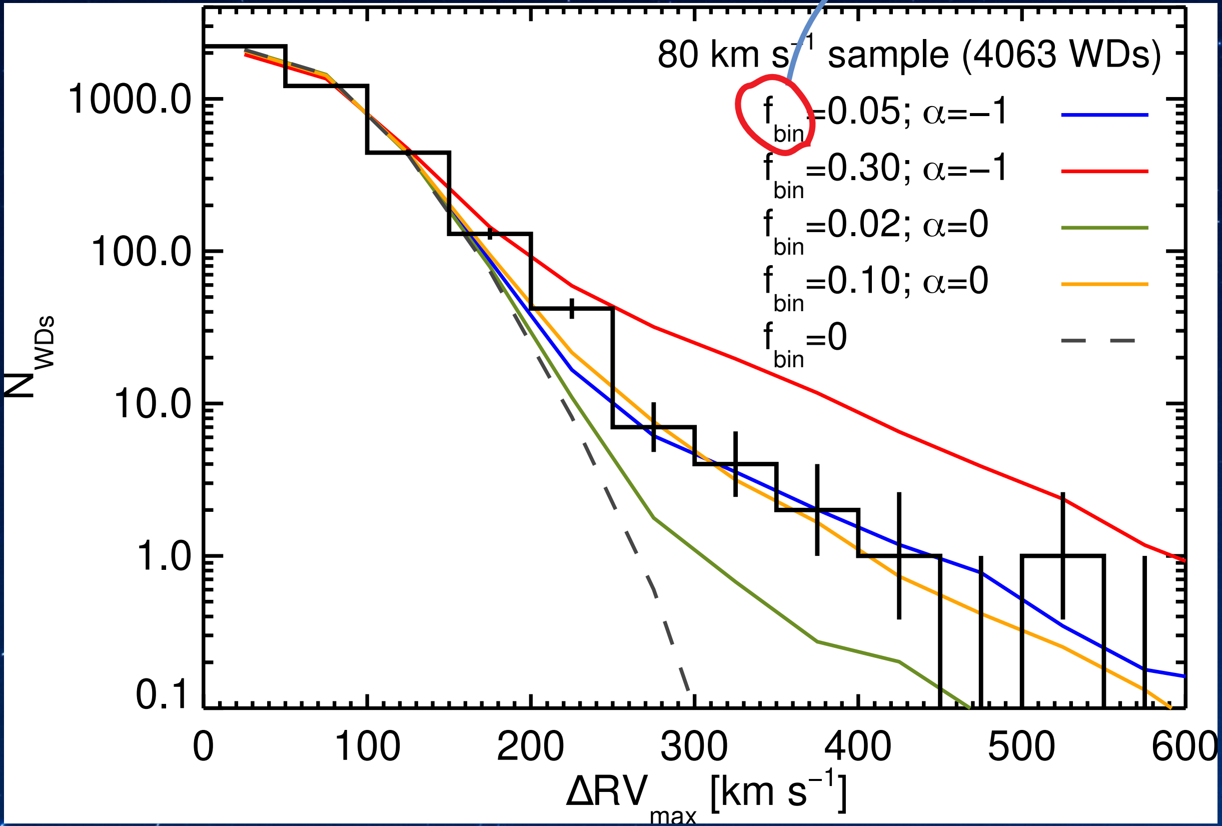
The ΔRV$_{max}$ distribution

Badenes & Maoz 2012



The ΔRV$_{max}$ distribution

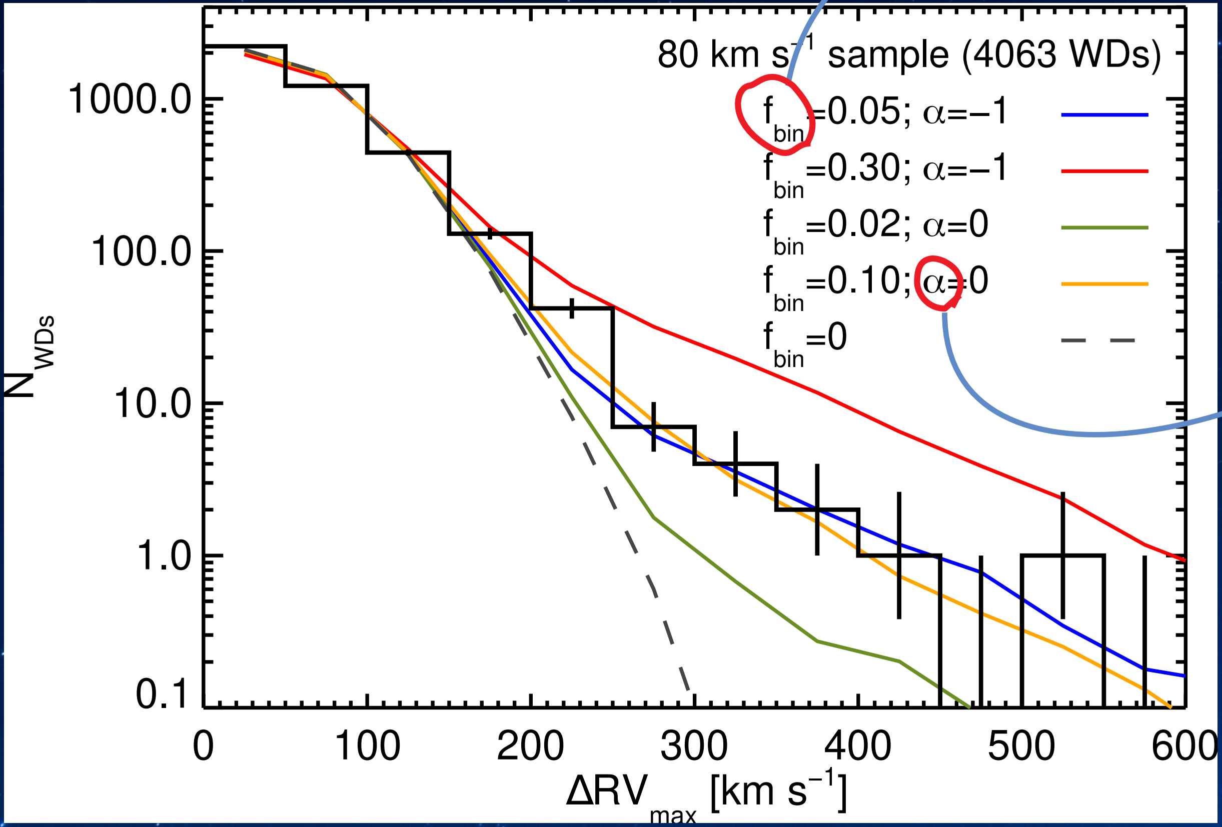
Badenes & Maoz 2012



the fraction of all WDs in binaries within a specific separation

The ΔRV_{max} distribution

Badenes & Maoz 2012

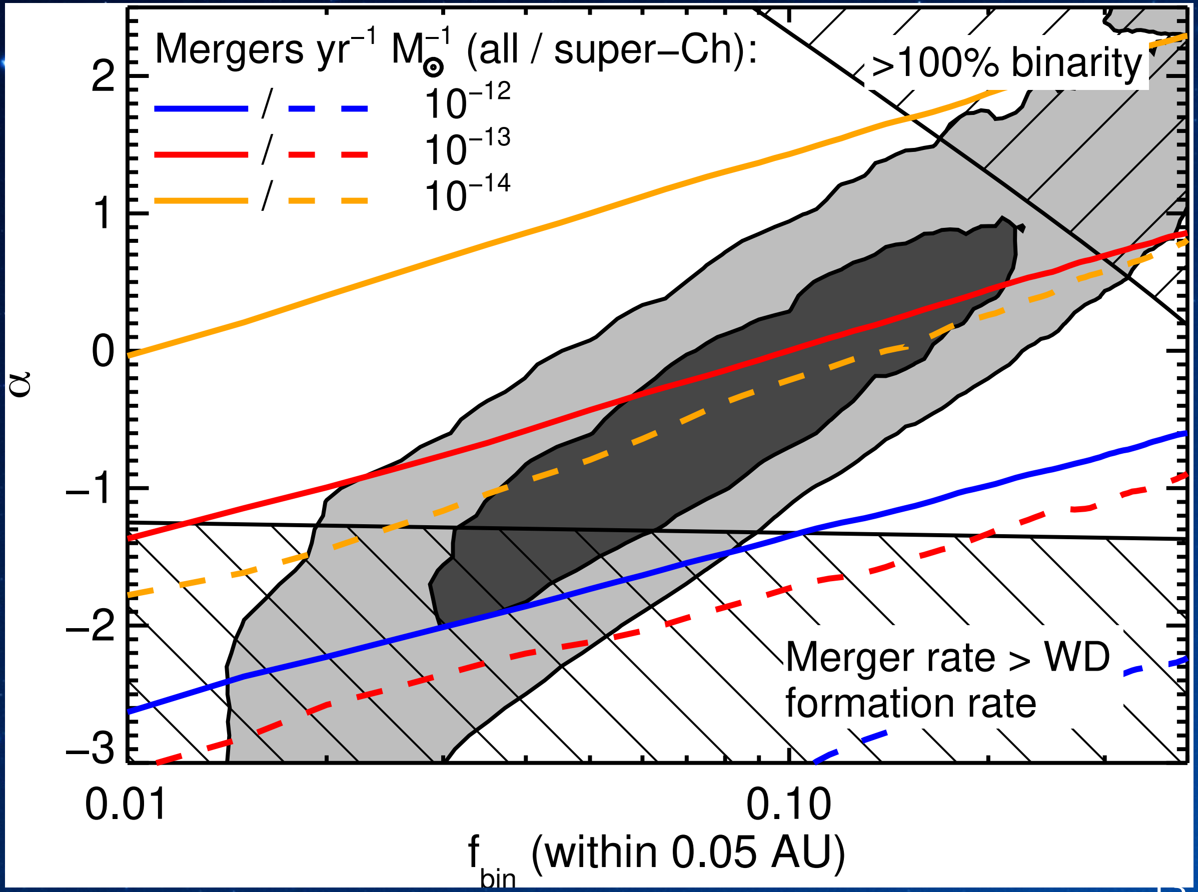


the fraction of all WDs in binaries within a specific separation

$$\frac{dN}{da_0} \propto a_0^{\alpha}$$

the separation distribution of double WDs **at birth**

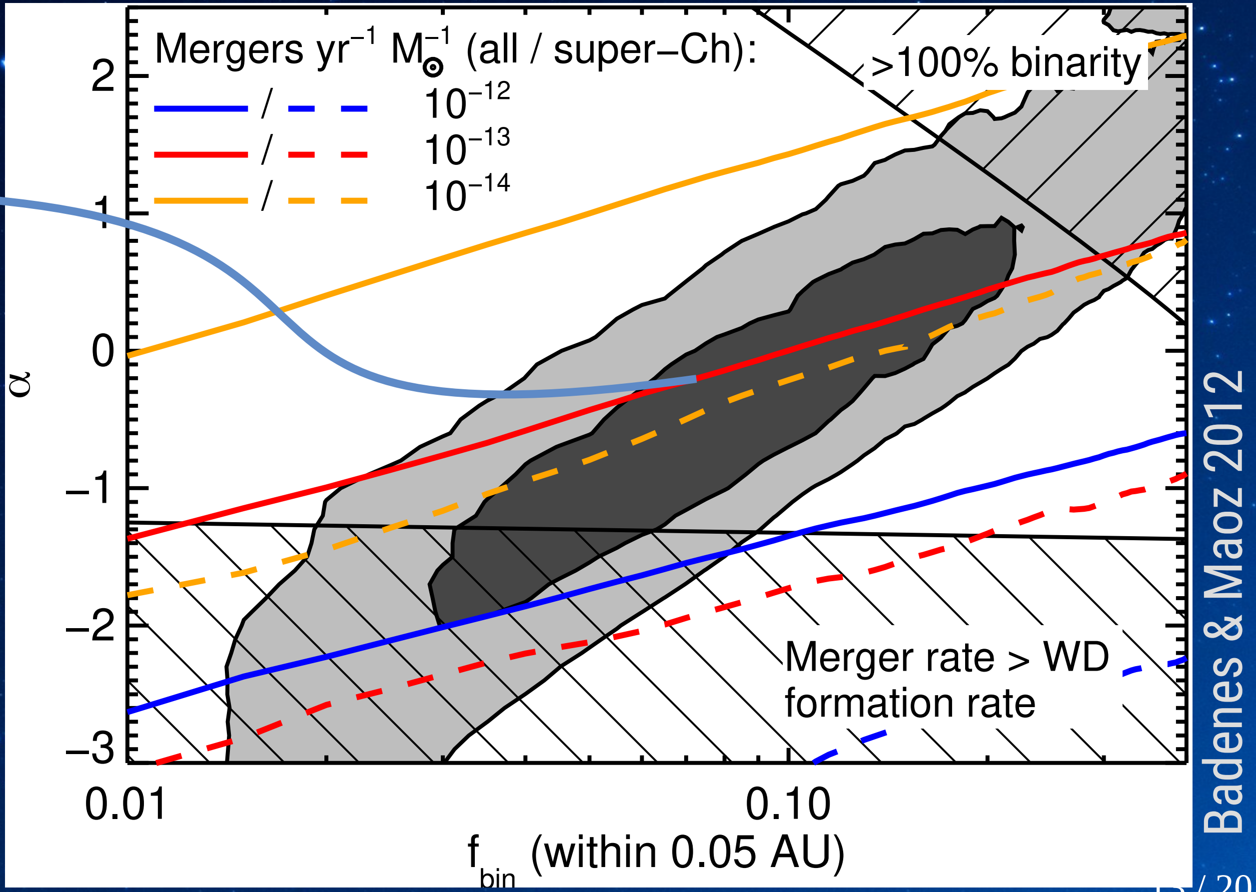
The double-WD population from SDSS



Badenes & Maoz 2012

The double-WD population from SDSS

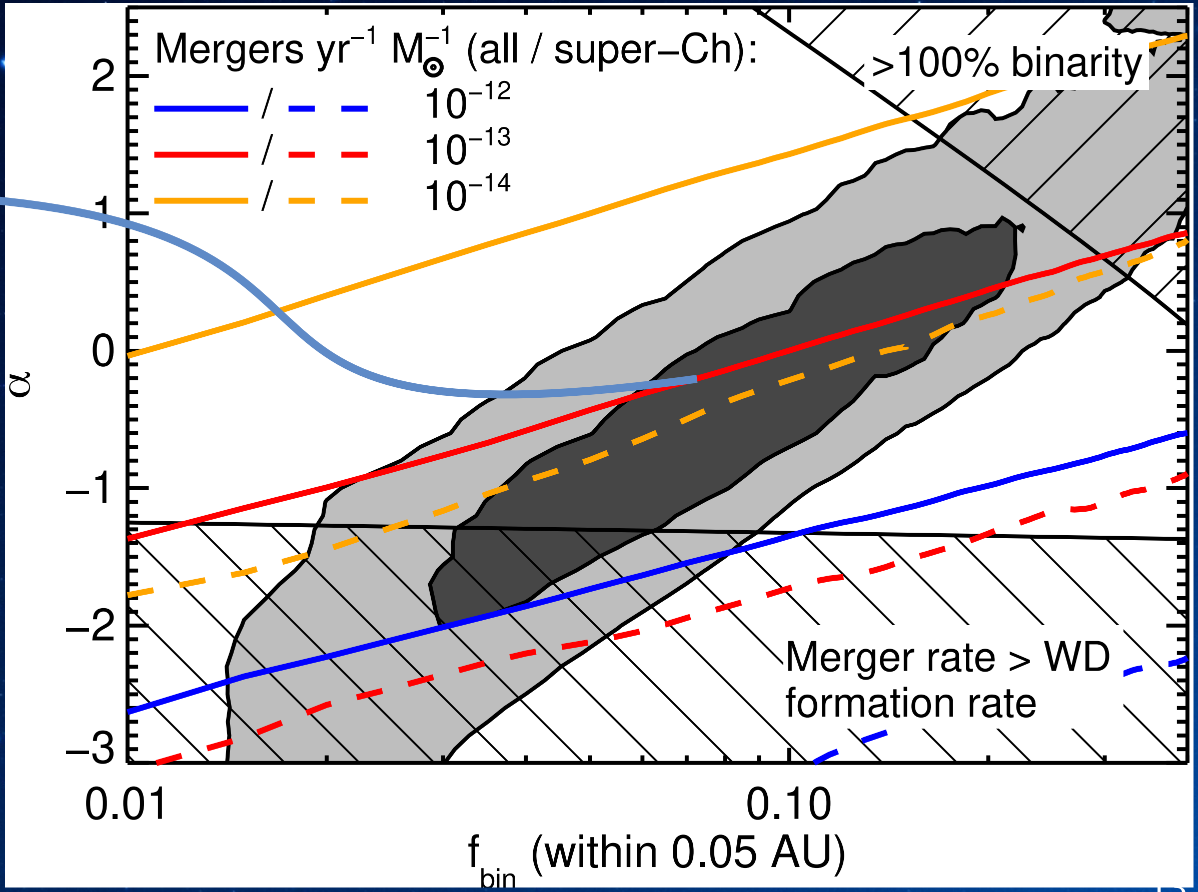
The double-WD merger rate is similar to the SN Ia rate in the Milky Way!



The double-WD population from SDSS

The double-WD merger rate is similar to the SN Ia rate in the Milky Way!

(but uncertain: could be 10x lower or 50x higher)

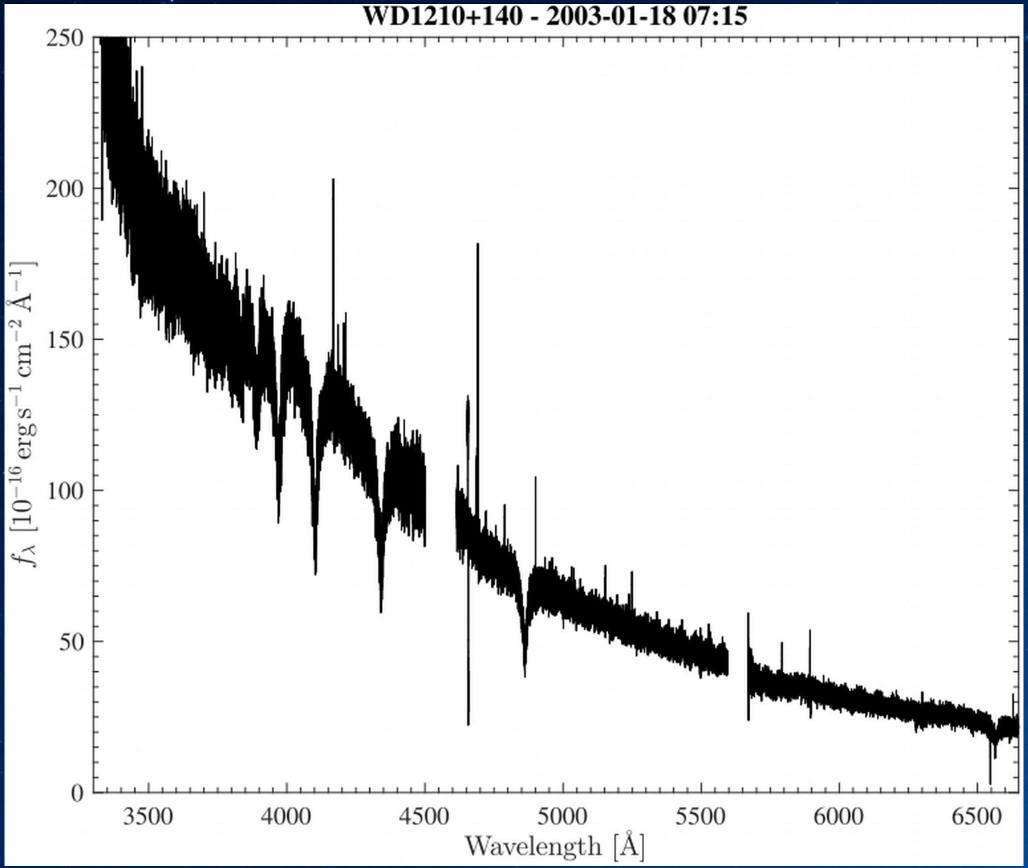


Badenes & Maoz 2012

The SPY sample (the ESO-VLT **S**upernova-Ia **P**rogenitor surve**Y**)

2001-2003, PI: R. Napiwotzki
UVES@VLT

Napiwotzki et al. 2020



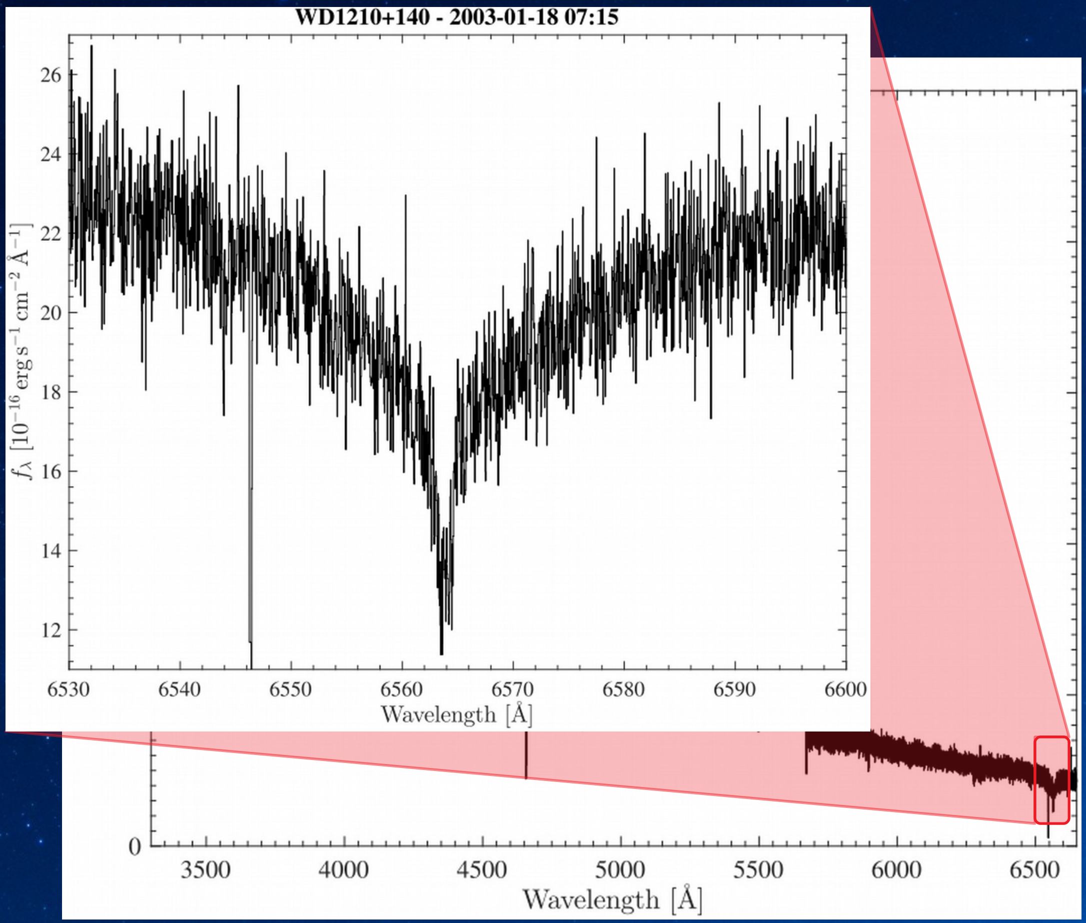
- High resolution (1-2 km s^{-1})
- High S/N
- Multi-epoch
- ~800 WDs

The SPY sample (the ESO-VLT **S**upernova-Ia **P**rogenitor surve**Y**)

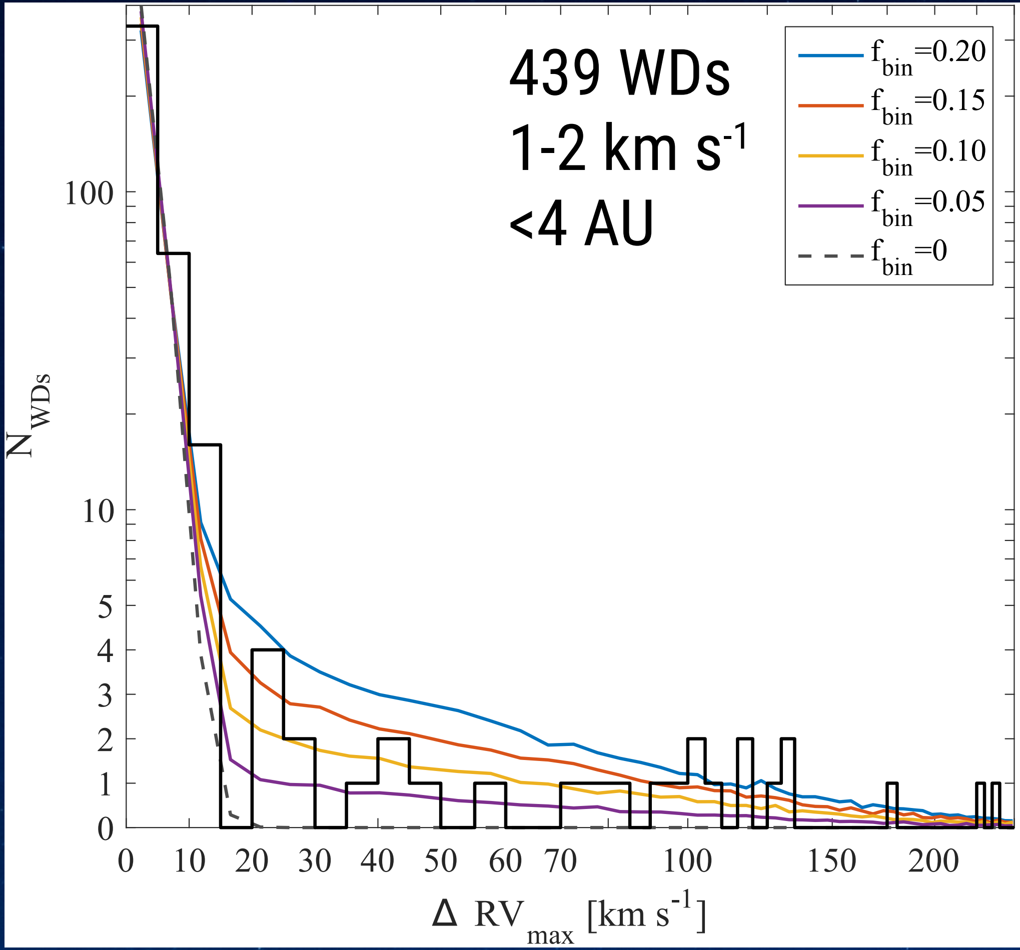
2001-2003, PI: R. Napiwotzki
UVES@VLT

Napiwotzki et al. 2020

- High resolution (1-2 km s^{-1})
- High S/N
- Multi-epoch
- ~800 WDs



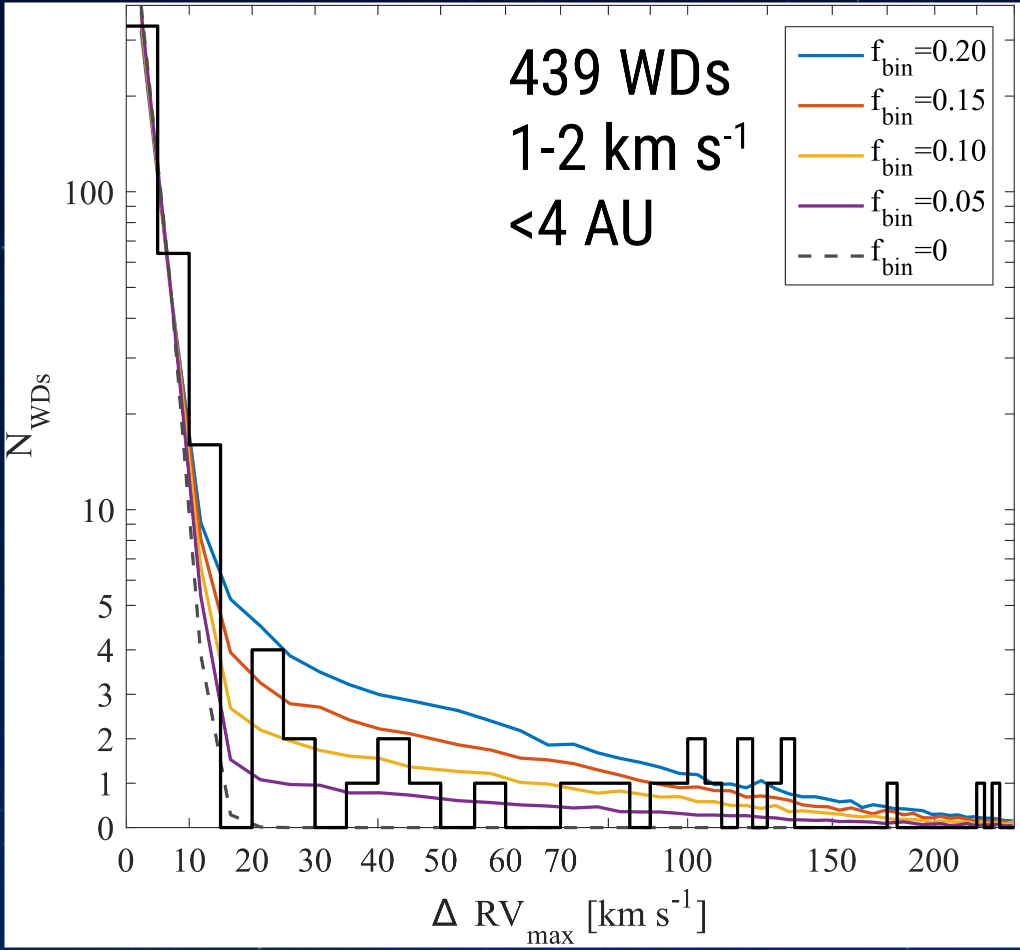
The double-WD population from SPY

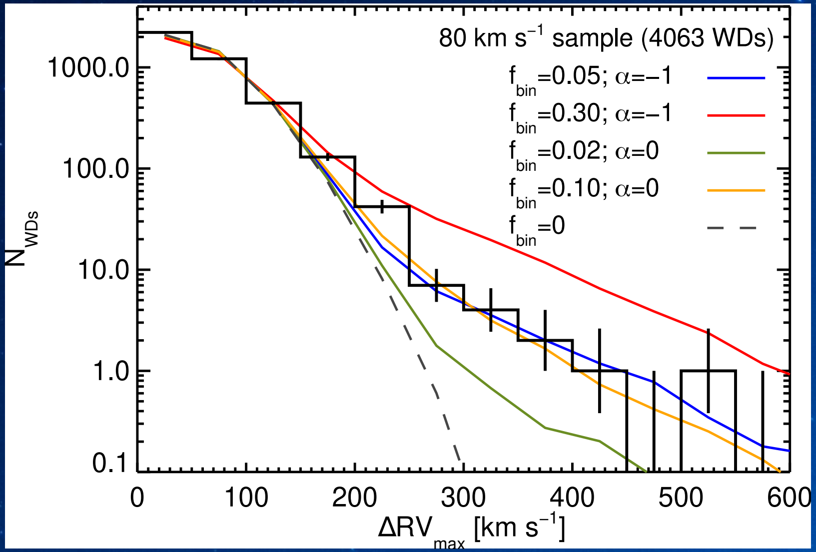


Maoz & Hallakoun 2017

The double-WD population from SPY

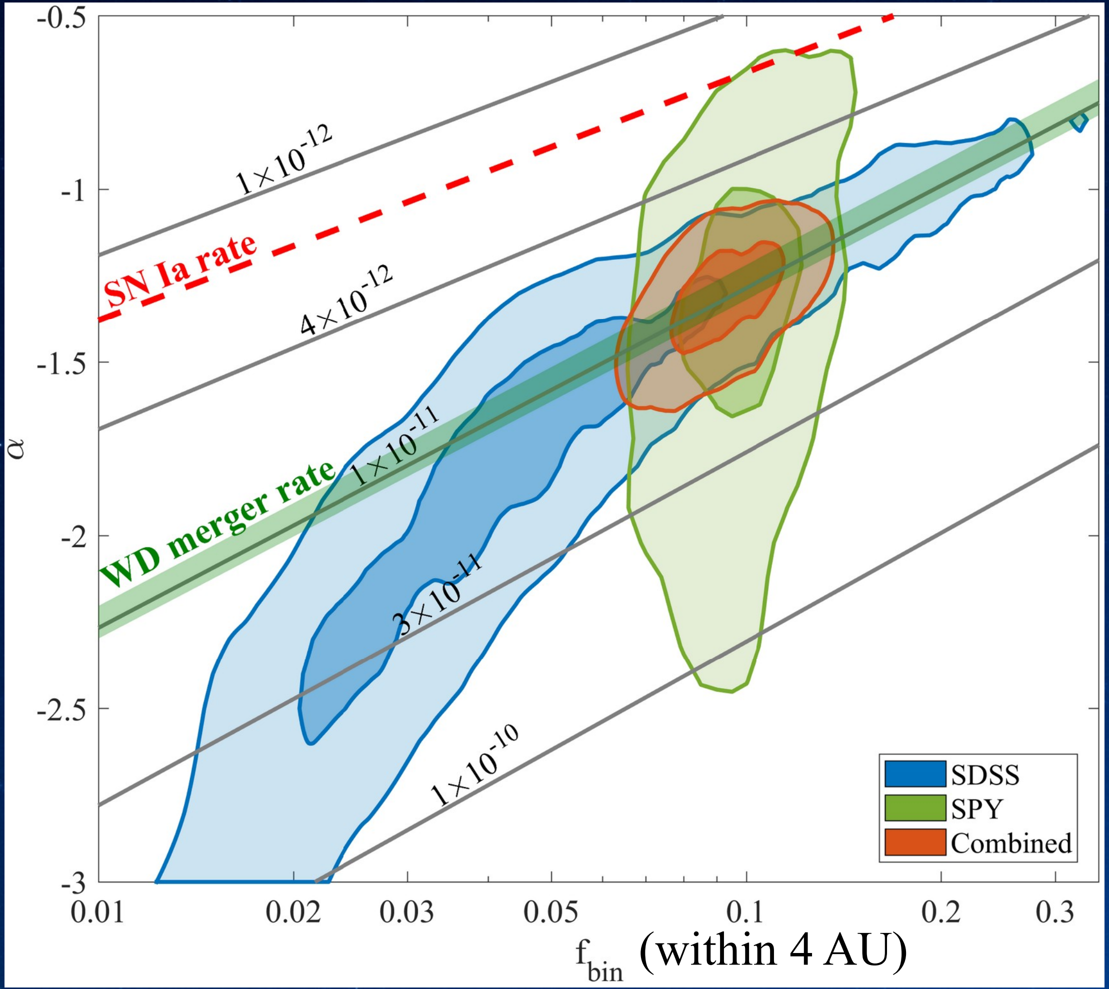
Maoz & Hallakoun 2017





Badenes & Maoz 2012

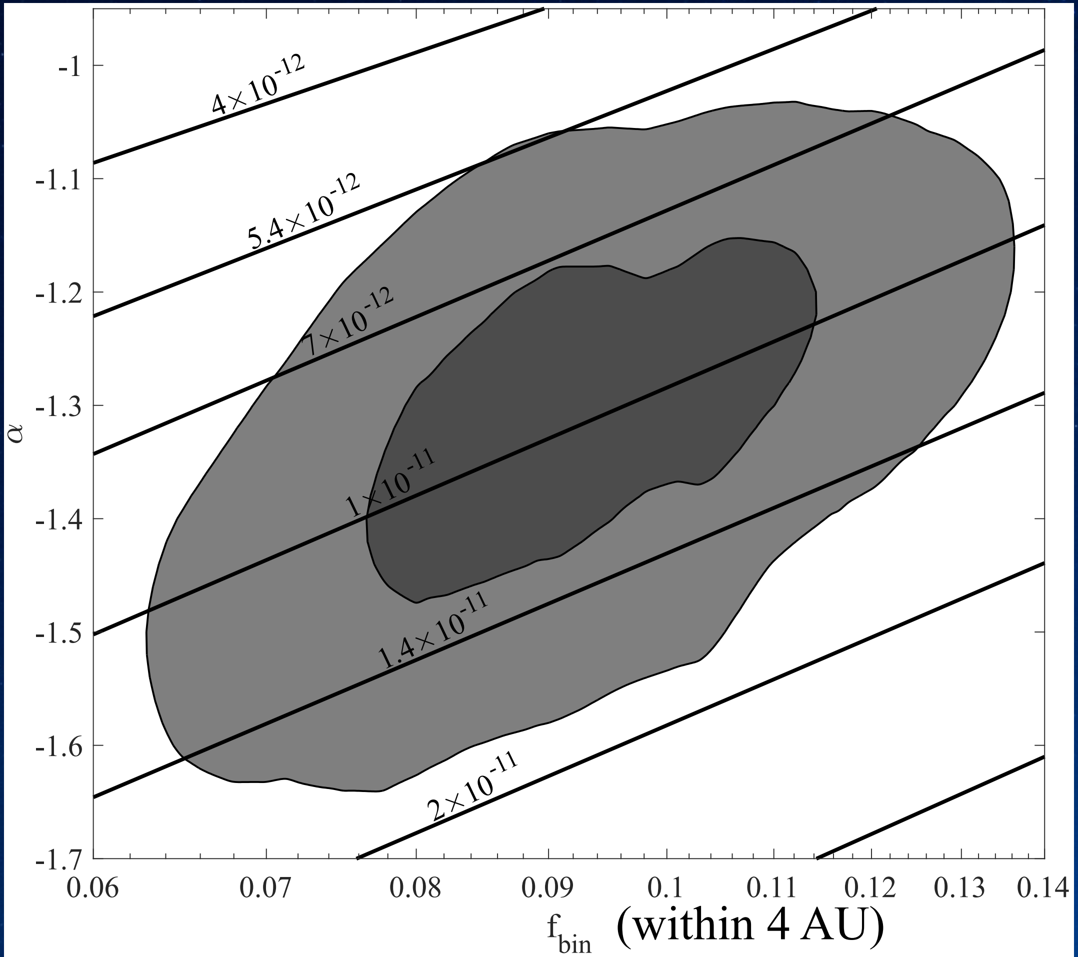
Why not both?



Maoz, Hallakoun, & Badenes 2018

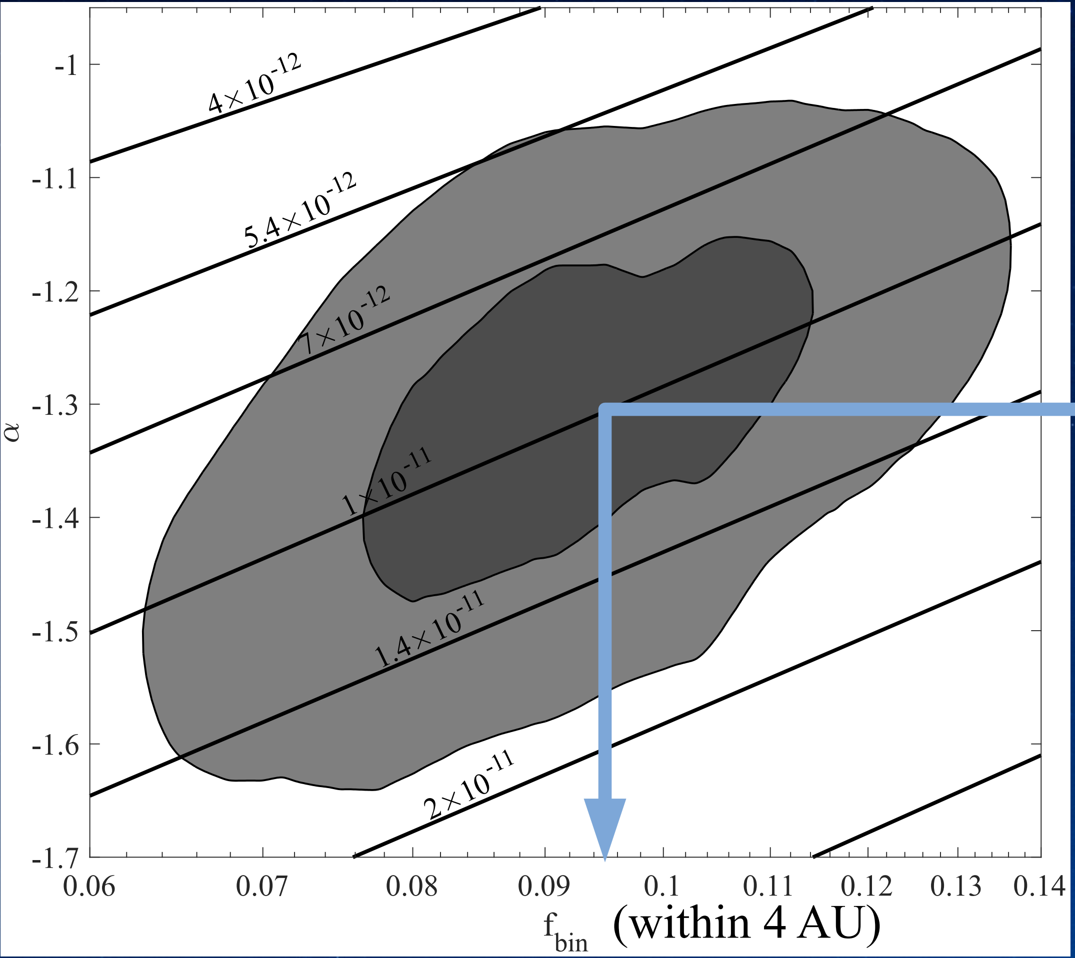
Why not both?

Maoz, Hallakoun, & Badenes 2018



Why not both?

Maoz, Hallakoun, & Badenes 2018



~10%

9.5%±2.0% (+1.0%)

of the WDs are **double WDs** with separations <4 AU

Why not both?

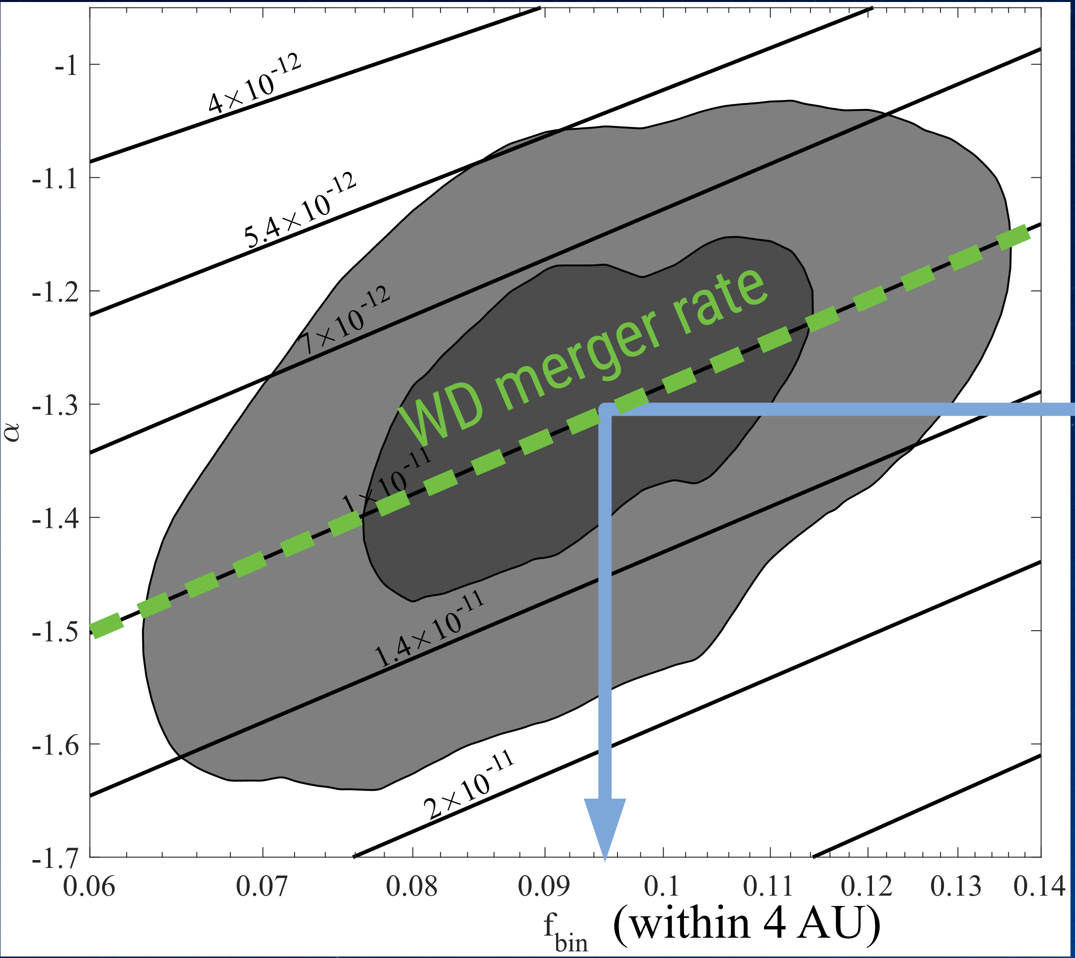
Maoz, Hallakoun, & Badenes 2018

The WD merger rate is

4.5-7

times **higher** than the specific SN Ia rate in the Milky Way

$(9.7 \pm 1.1) \times 10^{-12}$ yr^{-1} WD^{-1}



~10%

9.5%±2.0% (+1.0%)

of the WDs are **double WDs** with separations <4 AU

Why not both?

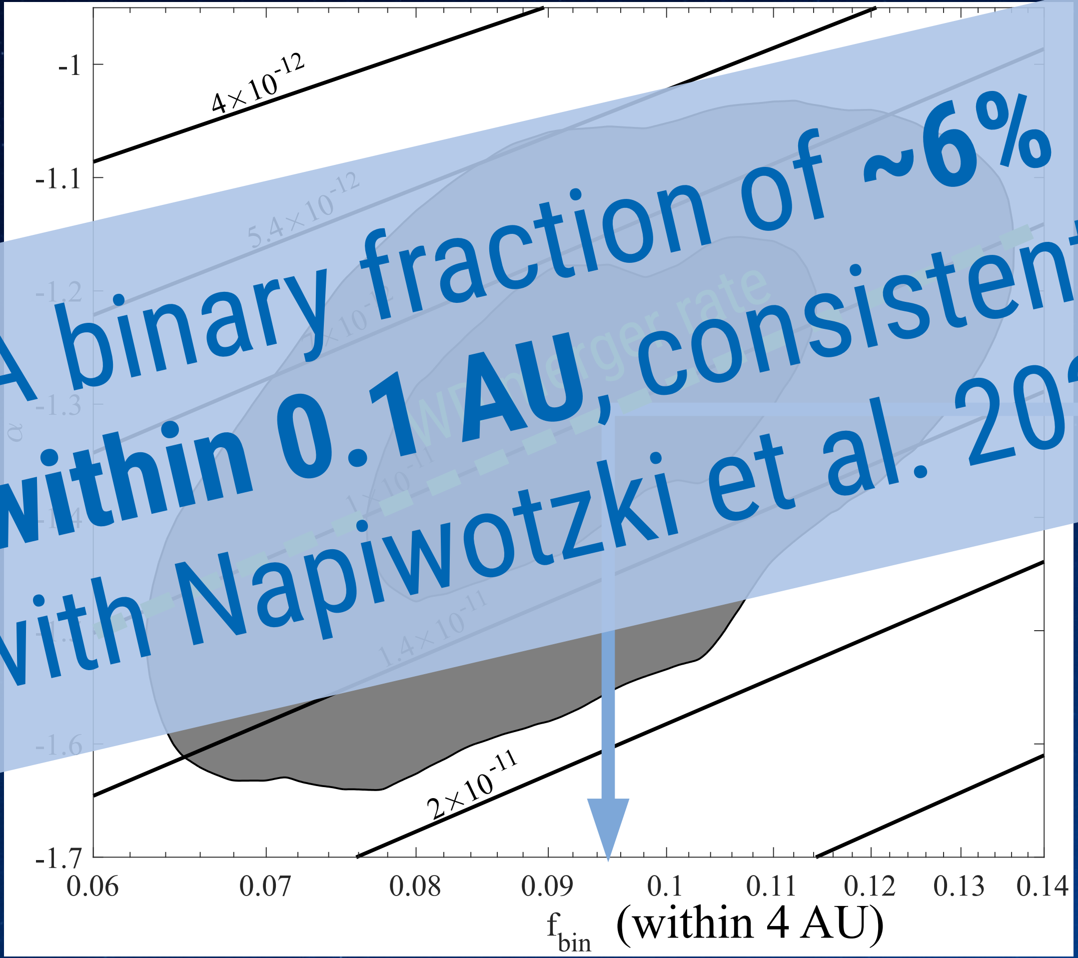
Maoz, Hallakoun, & Badenes 2018

The WD merger rate is

4.5-7

times **higher** than the specific SN Ia rate in the Milky Way

$(9.7\pm1.1)\times10^{-12}$ yr^{-1} WD^{-1}



A binary fraction of **~6% within 0.1 AU**, consistent with Napiwotzki et al. 2020

~10%

.5%±2.0% (+1.0%)

of the WDs are **double WDs** with separations <4 AU

What does it mean?

$\sim 10^{-11}$ yr^{-1} WD^{-1}
WD merger rate

×

$\sim 10^{10}$ yr
Galaxy lifetime

What does it mean?

$\sim 10^{-11}\ \mathrm{yr}^{-1}\ \mathrm{WD}^{-1}$
WD merger rate

×

$\sim 10^{10}\ \mathrm{yr}$
Galaxy lifetime

=

8.5-11%
of WDs have merged

What does it mean?

~10^{-11} yr^{-1} WD^{-1}
WD merger rate × ~10^{10} yr
Galaxy lifetime = 8.5-11%
of WDs have merged

↓

~10^{-11} yr^{-1} WD^{-1}
WD merger rate = ~6 × ~1.7×10^{-12} yr^{-1} WD^{-1}
SN Ia rate

What does it mean?

~15% of double-WD mergers lead to a SN Ia

What does it mean?

~15% of double-WD mergers lead to a SN Ia

~10% of the WDs are merger products

What’s next?

What's next?

97h with UVES on the VLT

following-up double-WD candidates

What's next?

97h with UVES on the VLT + GTC, LBT, SALT...

following-up double-WD candidates

Thanks to help by many more collaborators!
incl. (but not only) Jha, Mannucci, Rebassa-Mansergas...

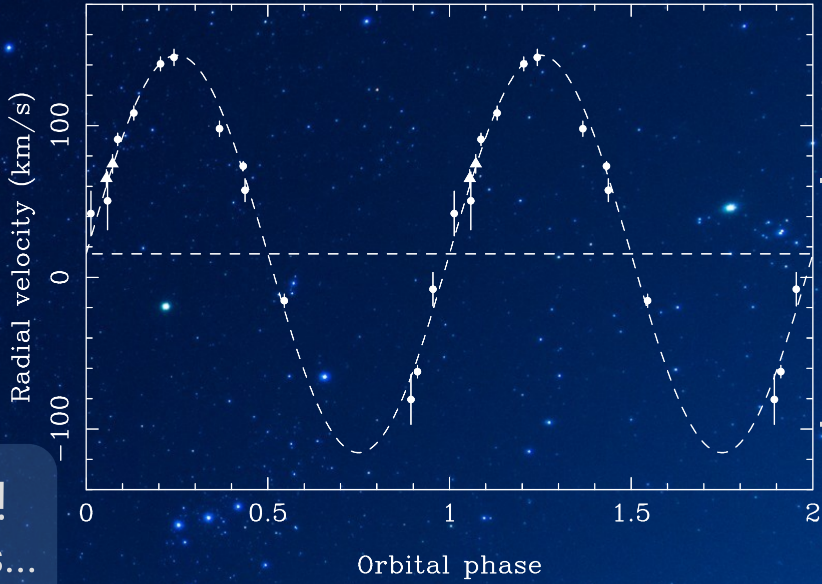
What's next?

97h with UVES on the VLT + GTC, LBT, SALT...

following-up double-WD candidates

Thanks to help by many more collaborators!
incl. (but not only) Jha, Mannucci, Rebassa-Mansergas...

WD1210+140



Nelemans et al. 2005

$P=15.41h$, $M_1=0.23M_\odot$, $M_2 \geq 0.38M_\odot$

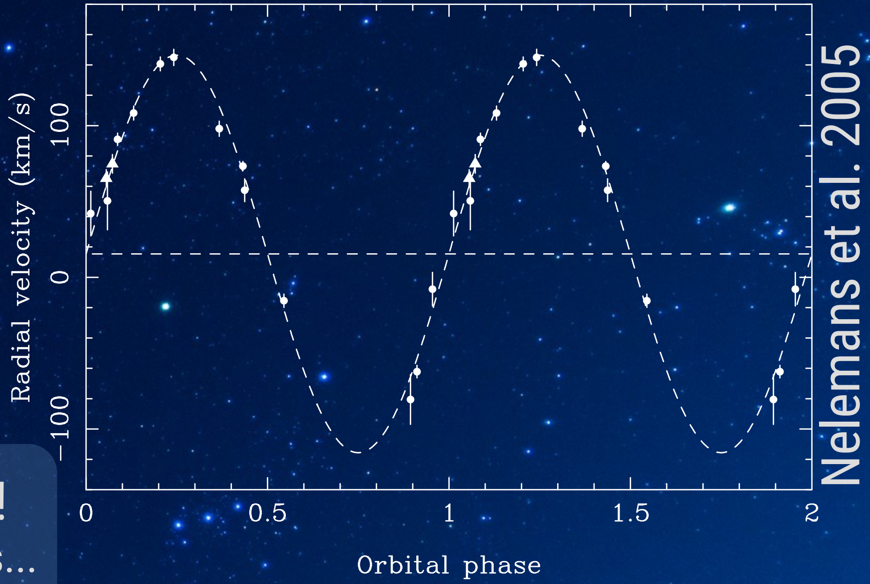
What's next?

97h with UVES on the VLT + GTC, LBT, SALT...

following-up double-WD candidates

Thanks to help by many more collaborators!
incl. (but not only) Jha, Mannucci, Rebassa-Mansergas...

WD1210+140



$P=15.41h$, $M_1=0.23M_\odot$, $M_2 \geq 0.38M_\odot$

SDSS-V during 2020-2025

will get multi-epoch spectra for ~100,000 *Gaia* WDs!

Characterizing the Galactic double white dwarf population

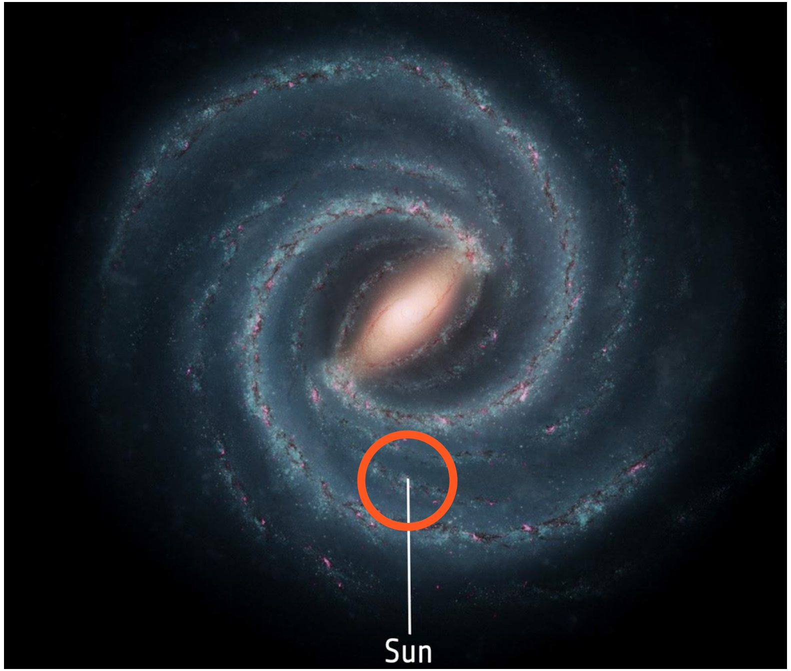
Part II: future observations with LISA

Valeriya Korol, Na'ama Hallakoun and Silvia Toonen

University of Birmingham

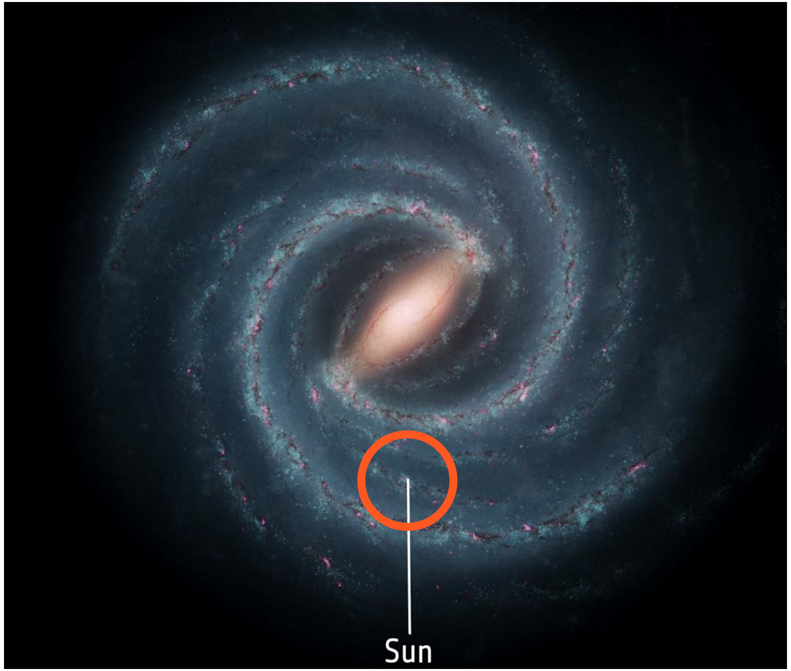
Why LISA will be revolutionary for DWDs?

Observed horizon with optical telescopes now

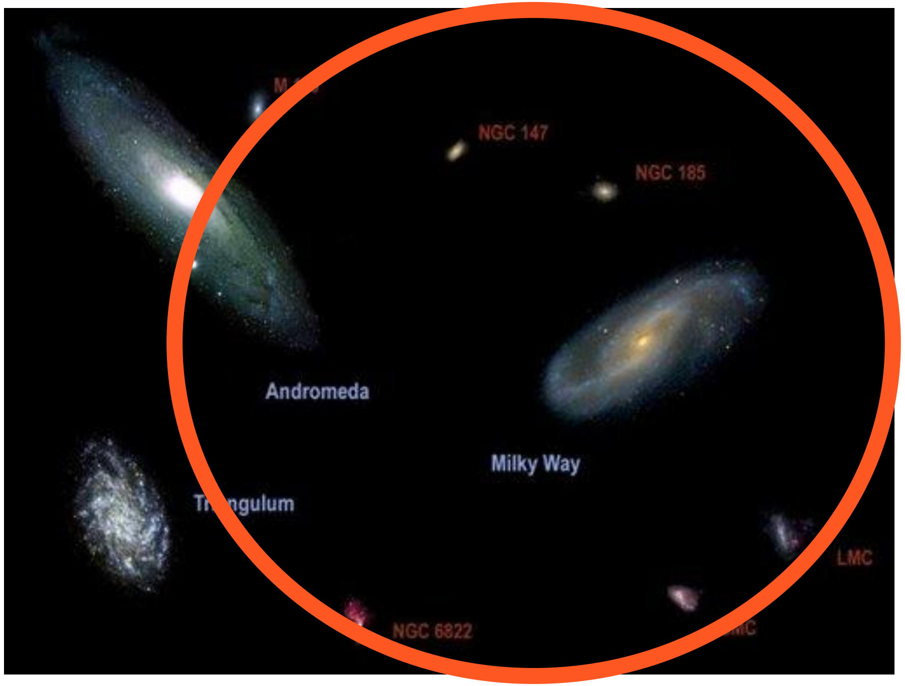


Why LISA will be revolutionary for DWDs?

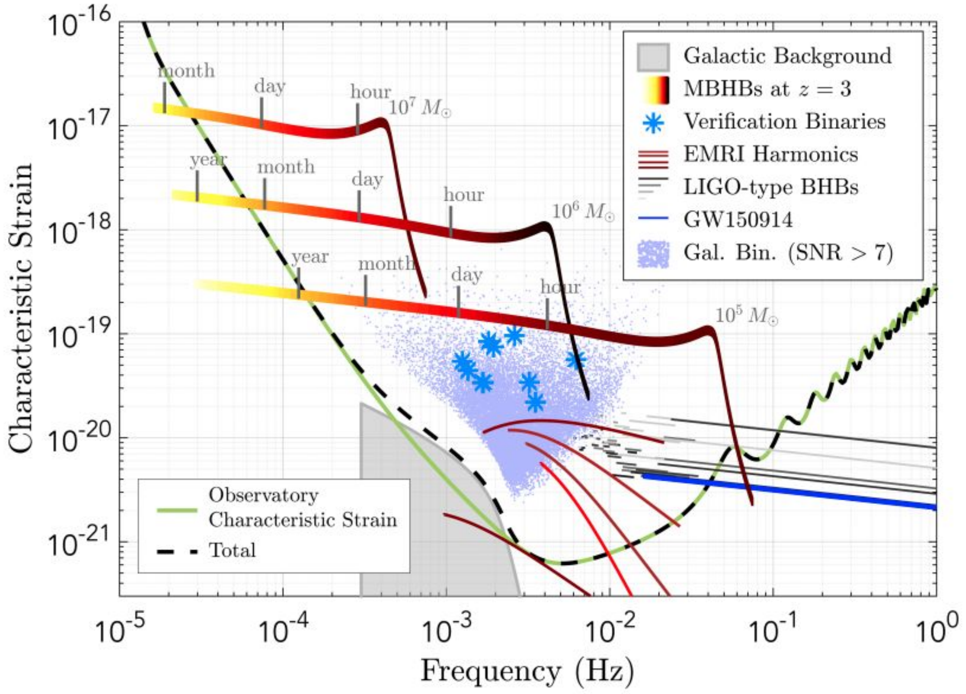
Observed horizon with optical telescopes now



Will be accessible with LISA in 2030's



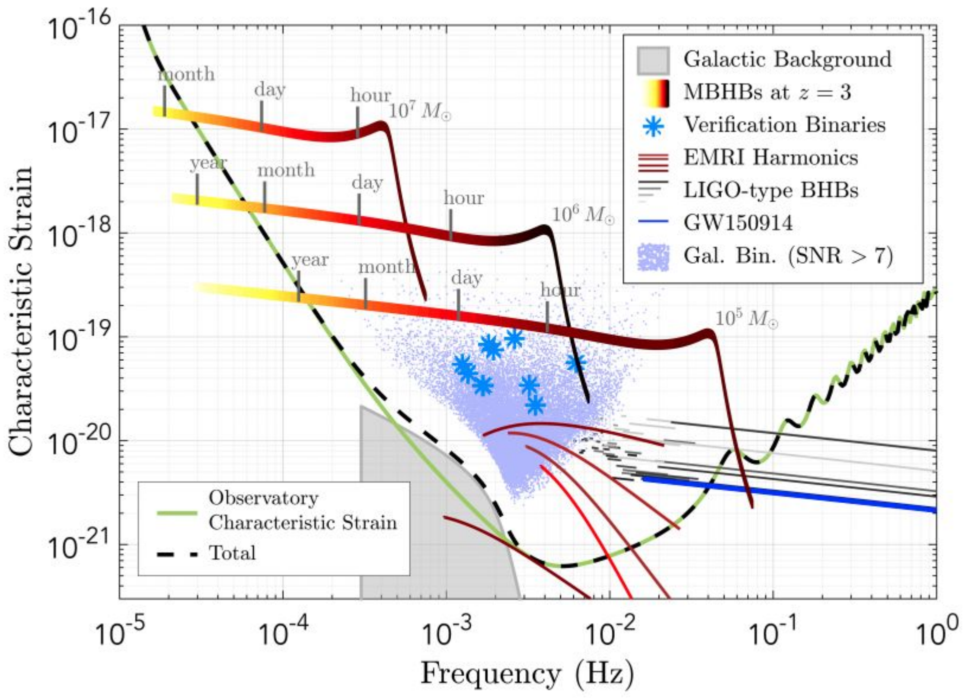
DWDs will dominate the LISA band in number



LISA mission proposal Amaro-Seoane et al. (2017)

https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf

DWDs will dominate the LISA band in number



Gravitational radiation from the DWDs to a good approximation can be treated as a quasi-monochromatic signal with linear drifts in frequency

$$f_{\rm GW}(t) = f_0 + \dot{f}_0 (t - t_0).$$

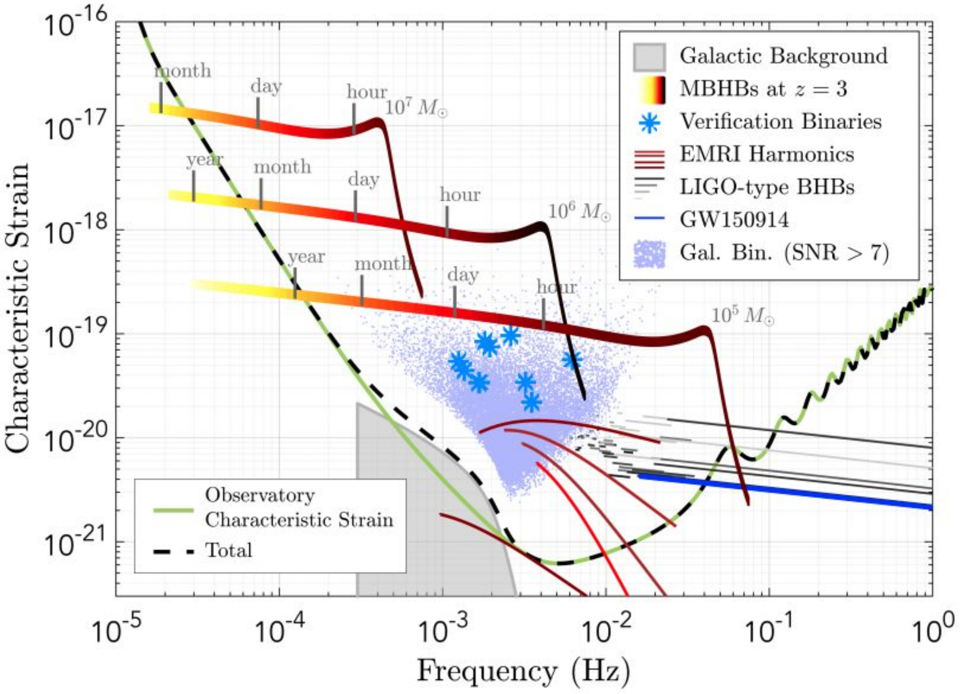
Each of the signals can be described by 8 parameters

$$\{\mathcal{A}, f_0, \dot{f}_0, \lambda, \beta, \iota, \psi, \phi_0\}$$

LISA mission proposal Amaro-Seoane et al. (2017)

https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf

DWDs will dominate the LISA band in number



LISA mission proposal Amaro-Seoane et al. (2017)

https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf

Gravitational radiation from the DWDs to a good approximation can be treated as a quasi-monochromatic signal with linear drifts in frequency

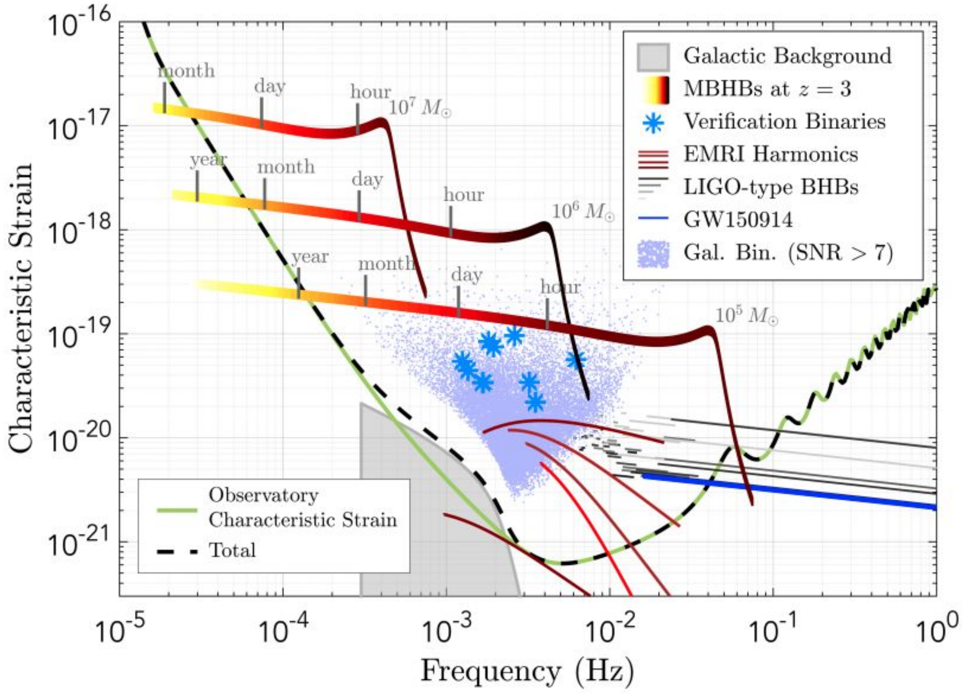
$$f_{\rm GW}(t) = f_0 + \dot{f}_0 (t - t_0).$$

Each of the signals can be described by 8 parameters

$$\{\mathcal{A}, f_0, \dot{f}_0, \lambda, \beta, \iota, \psi, \phi_0\}$$

Angular parameters:
Ecliptic coordinates, inclination, GW polarization, initial orbital phase

DWDs will dominate the LISA band in number



LISA mission proposal Amaro-Seoane et al. (2017)

https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf

Gravitational radiation from the DWDs to a good approximation can be treated as a quasi-monochromatic signal with linear drifts in frequency

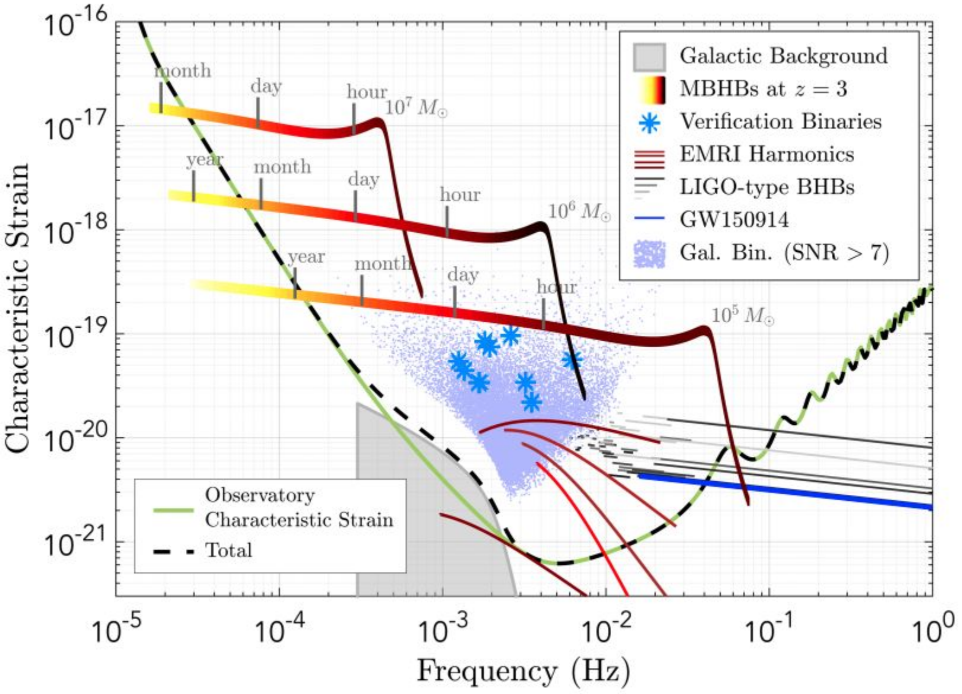
$$f_{\mathrm{GW}}(t) = f_0 + \dot{f}_0 (t - t_0).$$

Each of the signals can be described by 8 parameters

$$\{\mathcal{A}, f_0, \dot{f}_0, \lambda, \beta, \iota, \psi, \phi_0\}$$

GW frequency
2 x orbital frequency

DWDs will dominate the LISA band in number



LISA mission proposal Amaro-Seoane et al. (2017)

https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf

Gravitational radiation from the DWDs to a good approximation can be treated as a quasi-monochromatic signal with linear drifts in frequency

$$f_{\rm GW}(t) = f_0 + \dot{f}_0 (t - t_0).$$

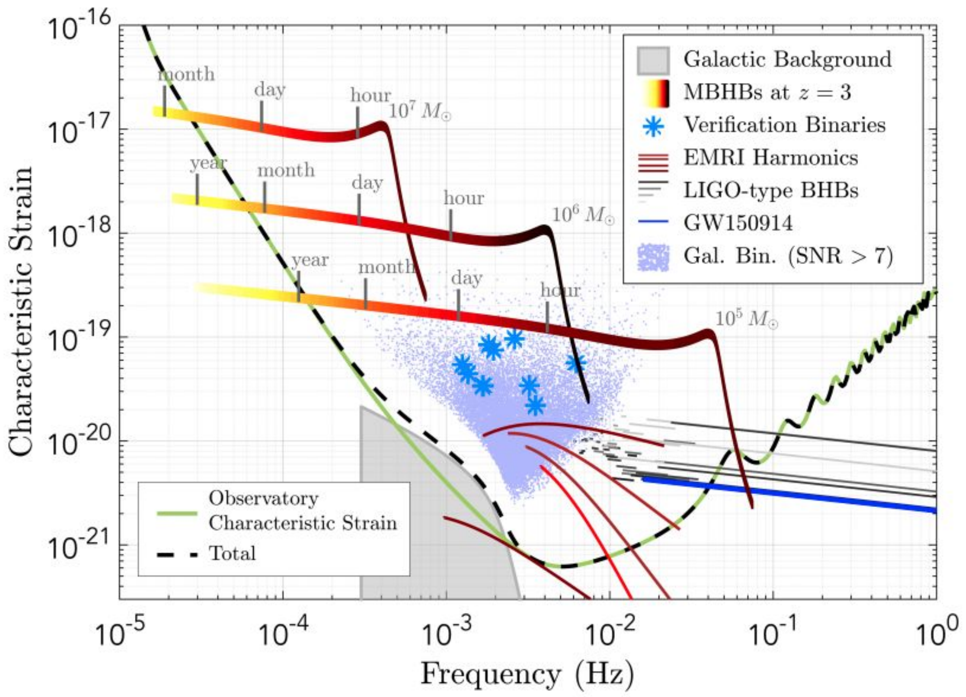
Each of the signals can be described by 8 parameters

$$\{\mathcal{A}, f_0, \boxed{\dot{f}_0}, \lambda, \beta, \iota, \psi, \phi_0\}$$

$$\boxed{\dot{f}_0 = \frac{96}{5} \frac{(G\mathcal{M})^{5/3}}{\pi c^5} (\pi f_0)^{11/3}}$$

$$\boxed{\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}},}$$

DWDs will dominate the LISA band in number



Gravitational radiation from the DWDs to a good approximation can be treated as a quasi-monochromatic signal with linear drifts in frequency

$$f_{\rm GW}(t) = f_0 + \dot{f}_0(t - t_0).$$

Each of the signals can be described by 8 parameters

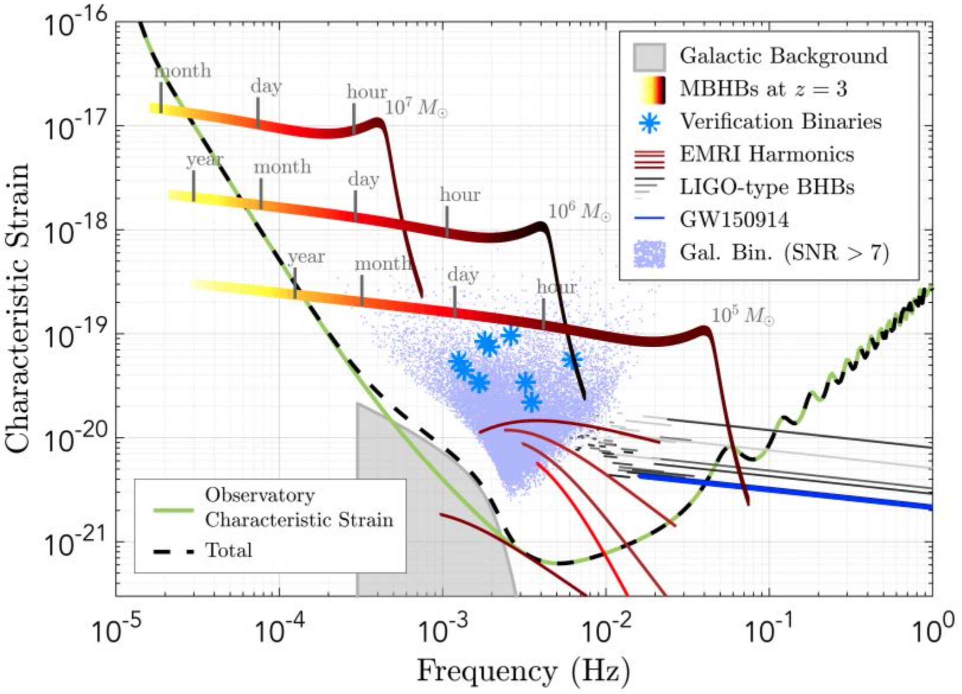
$$\{\mathcal{A}, f_0, \dot{f}_0, \lambda, \beta, \iota, \psi, \phi_0\}$$

$$\mathcal{A} = \frac{2(G\mathcal{M})^{5/3}}{c^4 D}(\pi f_0)^{2/3}$$

LISA mission proposal Amaro-Seoane et al. (2017)

https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf

DWDs will dominate the LISA band in number



Gravitational radiation from the DWDs to a good approximation can be treated as a quasi-monochromatic signal with linear drifts in frequency

$$f_{\rm GW}(t) = f_0 + \dot{f}_0(t - t_0).$$

Each of the signals can be described by 8 parameters

$$\{\mathcal{A}, f_0, \dot{f}_0, \lambda, \beta, \iota, \psi, \phi_0\}$$

We employ DWD population model from Maoz, Hallakoun & Badenes (2018) to sample M_1, M_2 and f.

LISA mission proposal Amaro-Seoane et al. (2017)

https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf

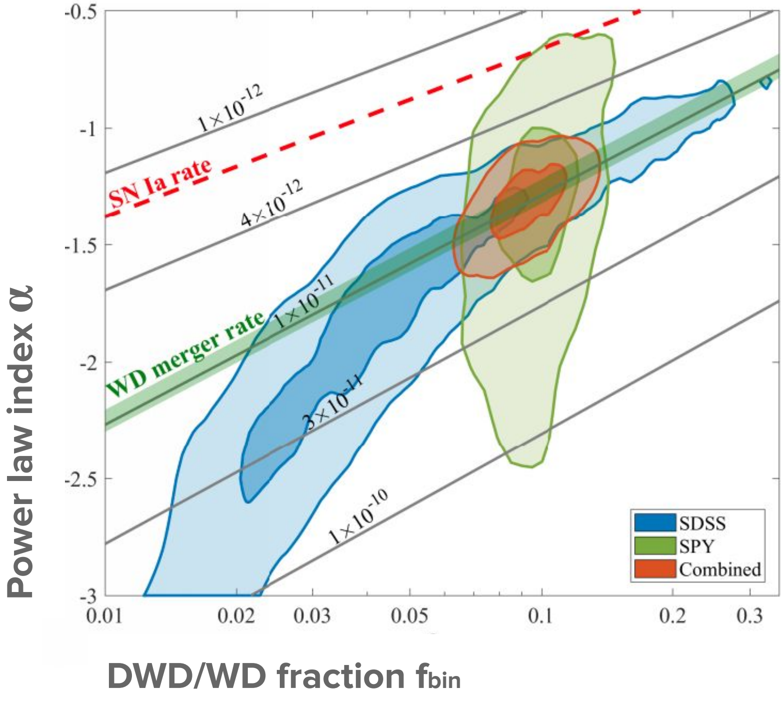
Assembling a model based on SDSS+SPY

Inherent assumptions of the Maoz et al. (2018) model:

- At the time of DWD formation the distribution of separations follows a power law with index α
- Constant star formation rate in the Milky Way disk over the last 10 Gyr

Fit to SDSS+SPY sample:

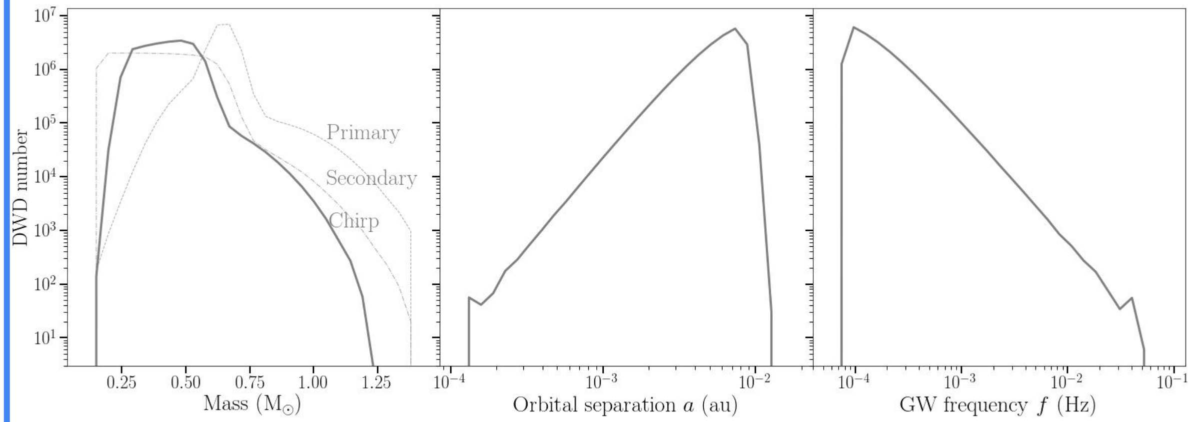
- f_{bin} = 0.095±0.020 for a < 4 au
- α= -1.3 ± 0.15



Maoz, Hallakoun & Badenes (2018)

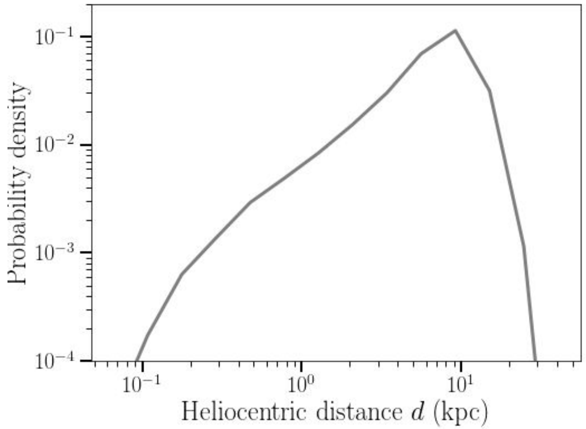
Assembling a model based on SDSS+SPY

Same as in PART I of the talk by Na'ama



Primary masses are drawn from a Gaussian mixture (Kepler et al. 2015) while **secondary masses** are drawn from a flat distribution

Orbital separations are based on the results from SDSS & SPY samples (Maoz et al. 2018) using $\mathbf{f_{bin}}$ **= 0.095** (for a < 4au) and **α = -1.3**



DWD positions in the Milky Way disc are drawn from

$$P(R, z) \propto e^{-R/R_{\rm d}} \, {\rm sech}^2(z/z_{\rm d})$$

and then converted into heliocentric distances (Nelemans et al. 2001)

Total number of DWD in the LISA band $= V_{MWdisc} \times \rho_{WD} \times f_{bin} \approx 4.5 \times 10^6$

- We estimated the Milky Way disc volume to be **$V = 4.5 \times 10^{11}$ pc^3** by integrating the disc stellar density assumed to follow an exponential radial stellar profile with an isothermal vertical distribution (e.g. Nelemans et al. 2004)

$$P(R, z) \propto e^{-R/R_{\rm d}}\, \mathrm{sech}^2(z/z_{\rm d})$$

- We adopt **$\rho_{wd} = 4.49 \times 10^{-3}$ pc^{-3}** estimated based on Gaia DR2 within 20 pc by Hollands et al. (2018)

- We obtain DWD fraction **$f_{bin} = 0.21\%$** by rescaling $f_{bin} = 9.5\%$ (for a < 4 au Maoz, Hallakoun & Badenes 2018) to the low frequency edge of the LISA band from

$$f_{\mathrm{bin},\, a_{\max}} = \frac{\int_{a_{\min}}^{a_{\max}} N(a, \alpha)\, da}{\int_{a_{\min}}^{4\,\mathrm{au}} N(a, \alpha)\, da}\, f_{\mathrm{bin},\, 4\mathrm{au}}$$

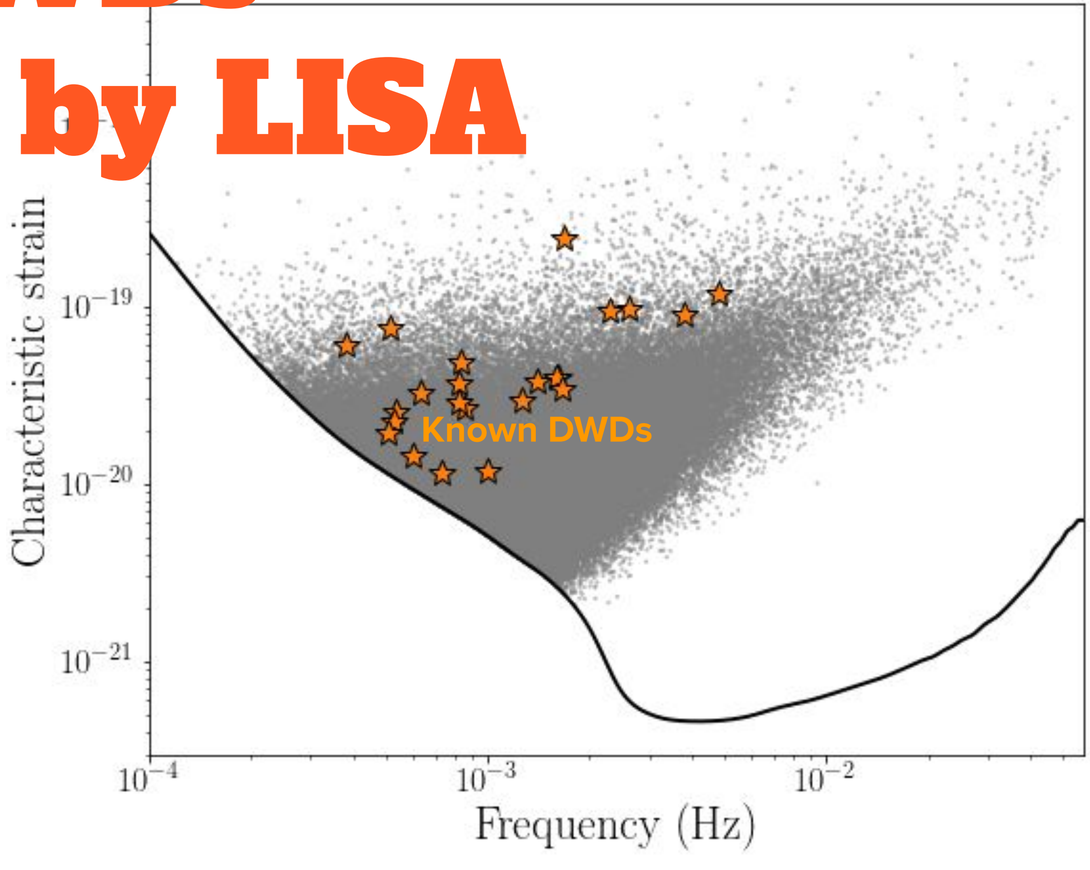
48×10^3 DWDs detectable by LISA

$$\mathrm{SNR} = \mathcal{A}\, F(\iota, \theta, \phi, \psi) \sqrt{\frac{T_{\mathrm{obs}}}{S_{\mathrm{n}}(f)}}$$

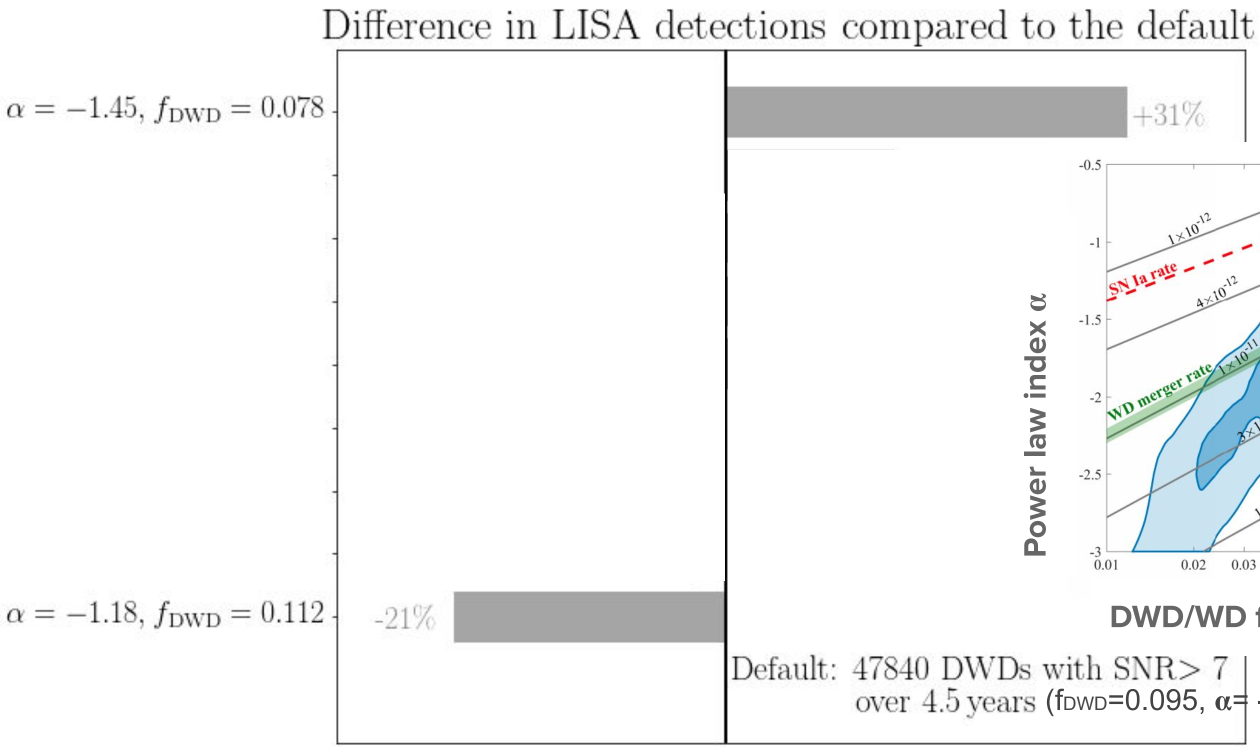
Note: here we have considered an up-to-date LISA's sensitivity requirements and recently updated mission duration of 6 years with 75% duty cycle (i.e. 4,5 years of science operations)

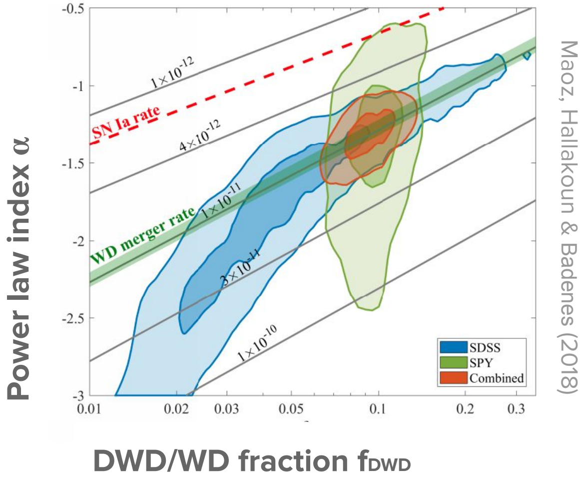
Note: this is only a lower limit!

Korol, Hallakoun & Toonen in prep.



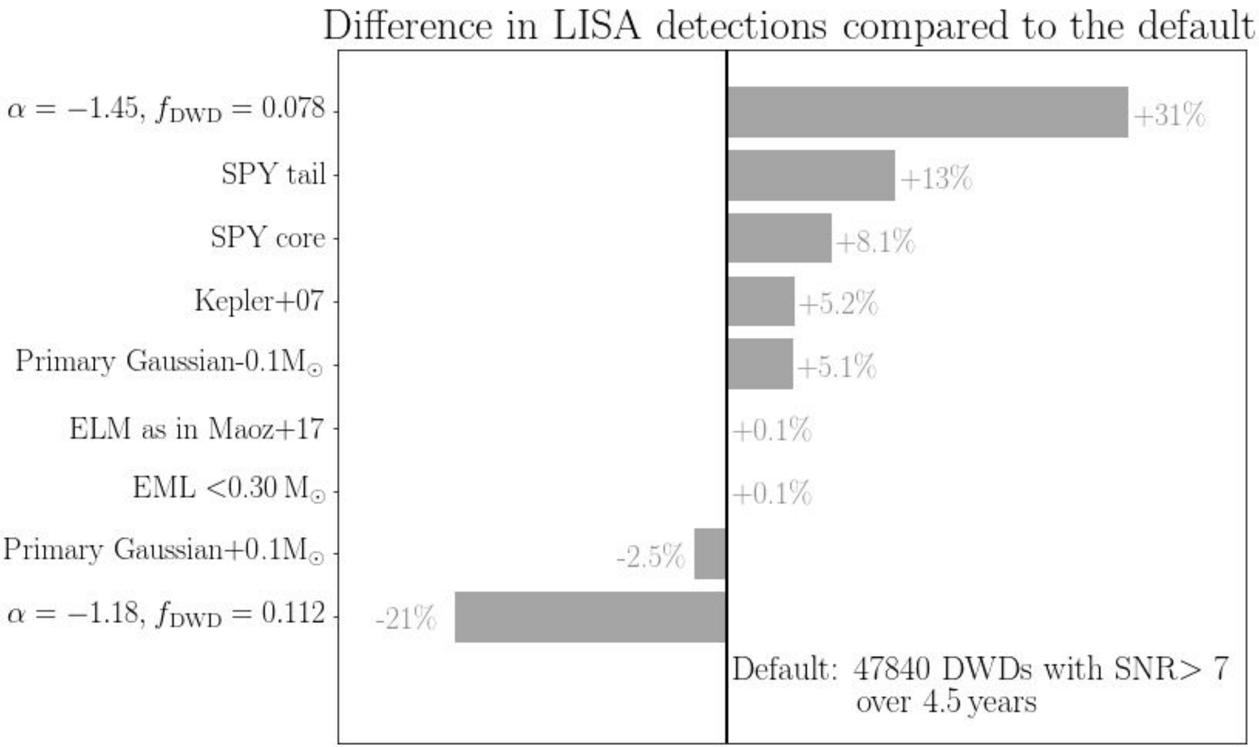
Model variations





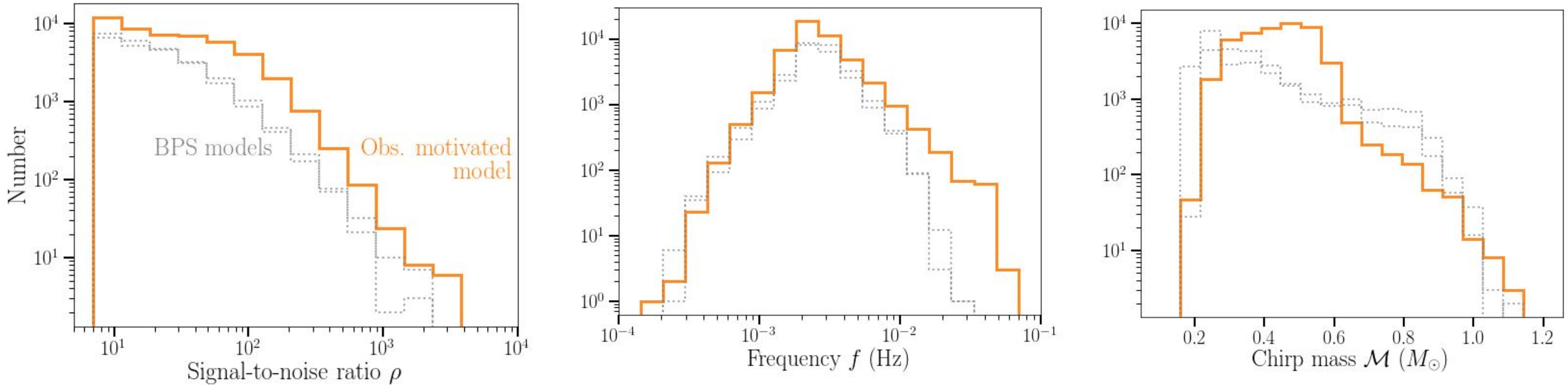
Korol, Hallakoun & Toonen in prep.

Model variations



Korol, Hallakoun & Toonen in prep.

The number of LISA detection is about twice that estimated with BPS models (e.g. Korol et al. 2017)

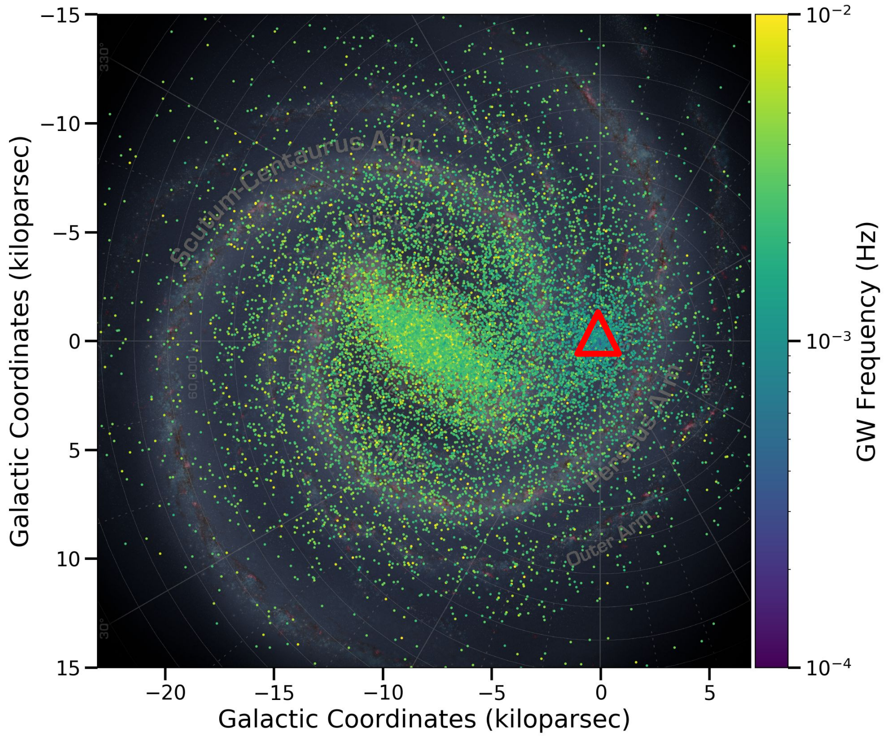


* BPS models are constructed starting from Toonen et al. (2017) and using the same stellar density distribution and constant star formation history as for the obs. motivated model

Korol, Hallakoun & Toonen in prep.

What will we learn from the LISA sample?

GWs of DWDs as Galactic tracers

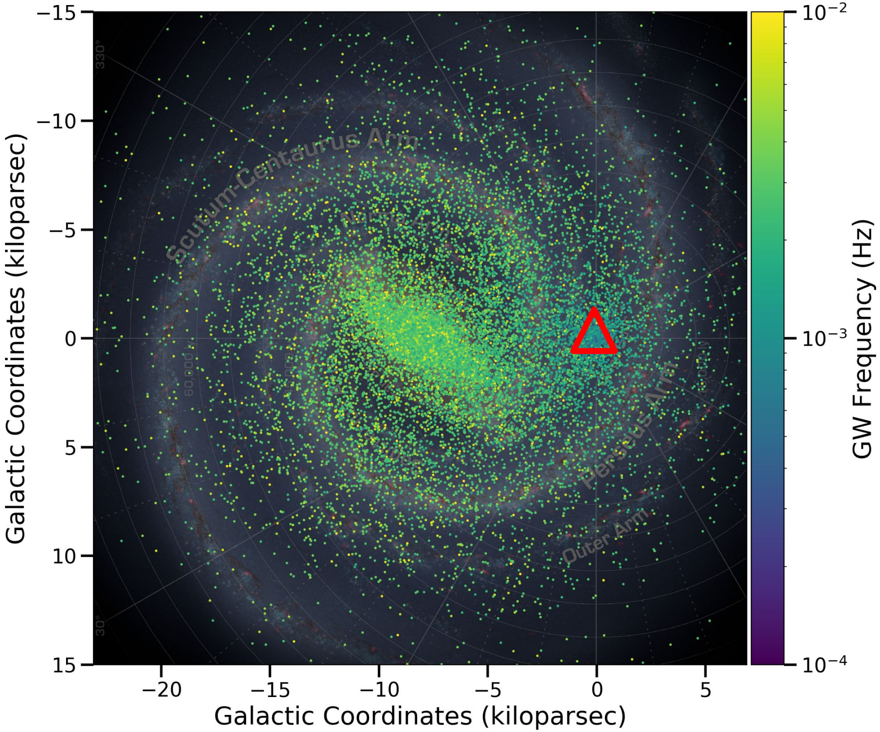


- Numerous and widespread
- Detectability in the Galaxy everywhere
- Measurement of the distance directly from the LISA signal
- Contamination: none

Based on Wilhelm, Korol et al. (2020)

Data: https://figshare.com/articles/dataset/DWD_FullPopulation_Wilhelm_Korol_Rossi_DOnghia_2020/13168464

Milky Way shape unveiled with DWDs



Spatial distribution (in physical and/or Fourier space) of DWDs detectable by LISA yields the measurements of

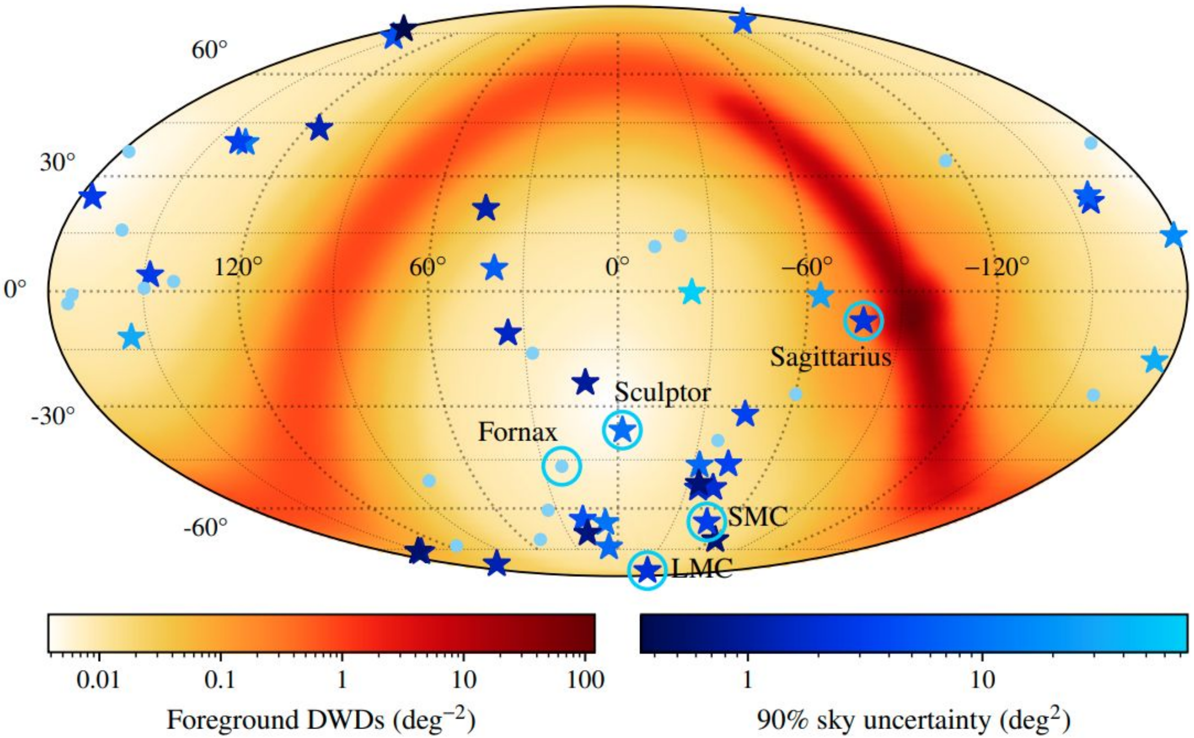
- **Bulge and disc scale radii**, and possibly **disc scale height** (Korol et al. 2019; see also Adams et al. 2012, 2014; Benacquista et al. 2006, Breivik et al. 2019)
- **Bar's lengths, axis ratio** and **orientation** angle (Wilhelm, Korol et al. 2020)

competitive with those based on optical and near-infrared observations.

Based on Wilhelm, Korol et al. (2020)

Data: https://figshare.com/articles/dataset/DWD_FullPopulation_Wilhelm_Korol_Rossi_DOnghia_2020/13168464

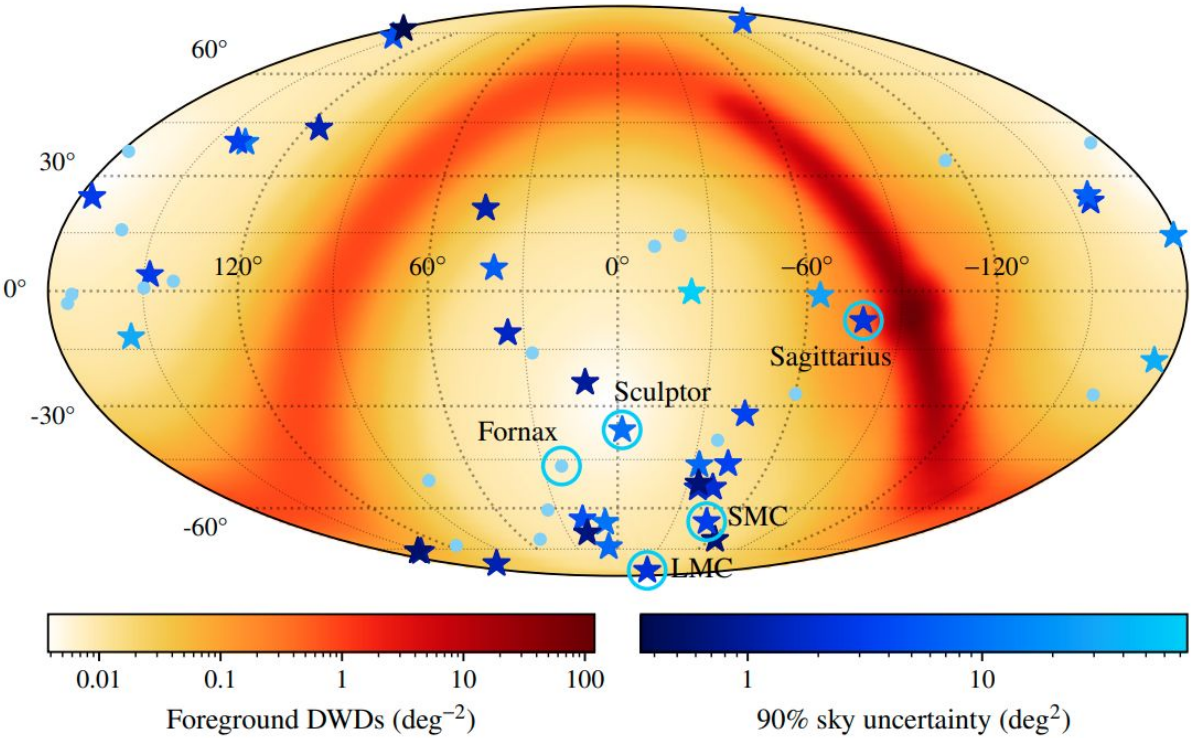
DWDs in Milky Way satellites



Roebber (incl. Korol) et al. (2020)

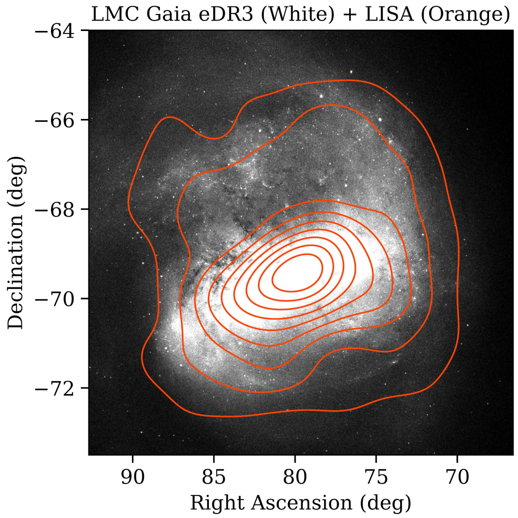
- Satellites with stellar mass > 10^6 $M_\odot$ can shine in GWs (Korol, Toonen et al. 2020)

DWDs in Milky Way satellites



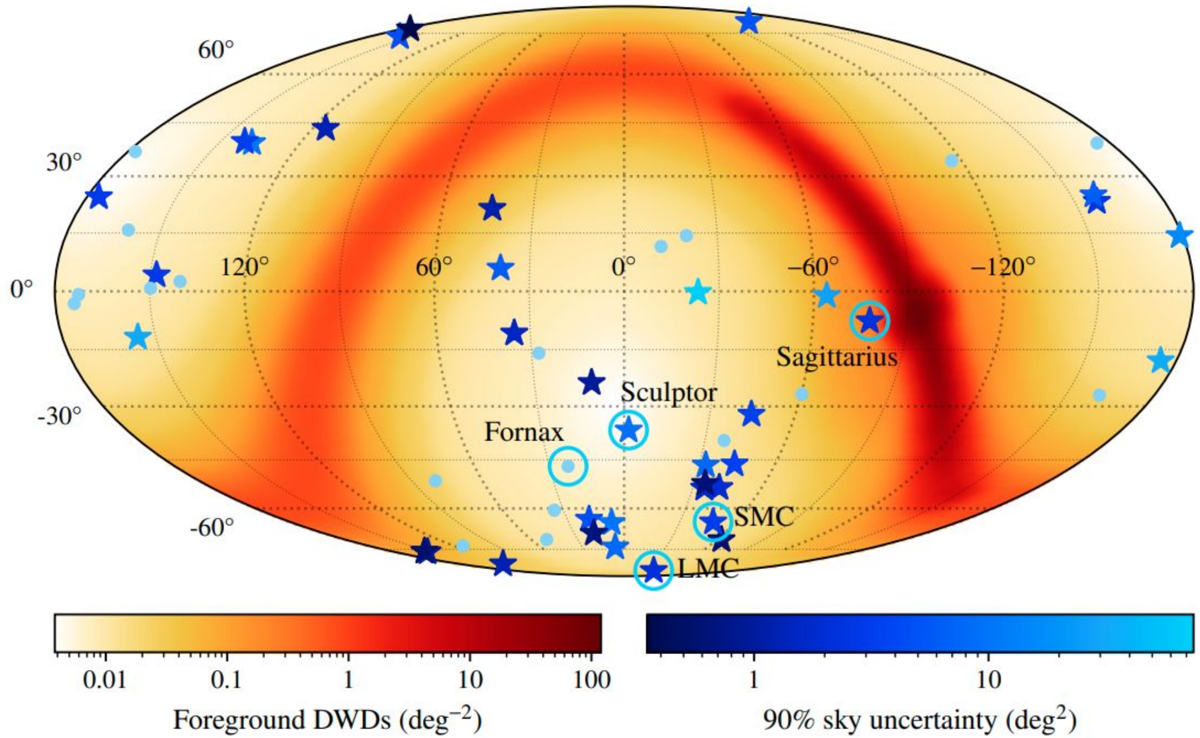
Roebber (incl. Korol) et al. (2020)

- Satellites with stellar mass > 10^6 M☉ can shine in GWs (Korol, Toonen et al. 2020)
- LISA can resolve LMC & SMC



Keim, Korol et al. in prep.

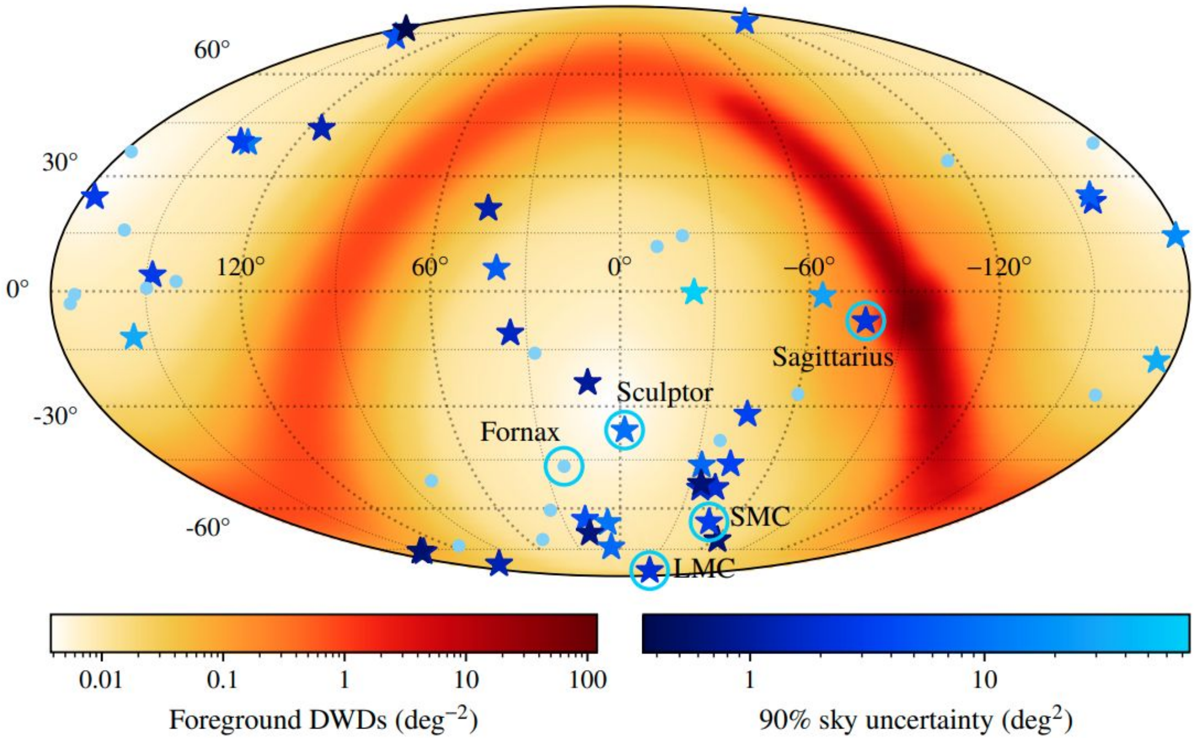
DWDs in Milky Way satellites



Roebber (incl. Korol) et al. (2020)

- Satellites with stellar mass > 10^6 M☉ can shine in GWs (Korol, Toonen et al. 2020)
- LISA can resolve LMC & SMC (Keim, Korol et al., in prep.)
- LISA detections can inform us about the total stellar mass (Korol et al. 2021)

DWDs in Milky Way satellites



Roebber (incl. Korol) et al. (2020)

- Satellites with stellar mass > 10^6 M☉ can shine in GWs (Korol, Toonen et al. 2020)
- LISA can resolve LMC & SMC (Keim, Korol et al., in prep.)
- LISA detections can inform us about the total stellar mass (Korol et al. 2021)
- Discovery of satellites inaccessible to electromagnetic observatories (Roebber et al. 2020)