# The Origin of LVC's BBHs

Tsvi Piran
The Hebrew University

Zoe Piran 19, Kenta Hotokezaka 17, 18

MMGW2019 YITP, Kyoto

GRB ; TReX

# The Origin of LVC's BBHs

*"What to expect when you are expecting"*

Tsvi Piran
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MMGW2019 YITP, Kyoto

GRB ; TReX

# II. The Origin of BNSs

Nir Shaviv, Paz Beniamini

# III. The Origin of BHNSs

Ehud Nakar

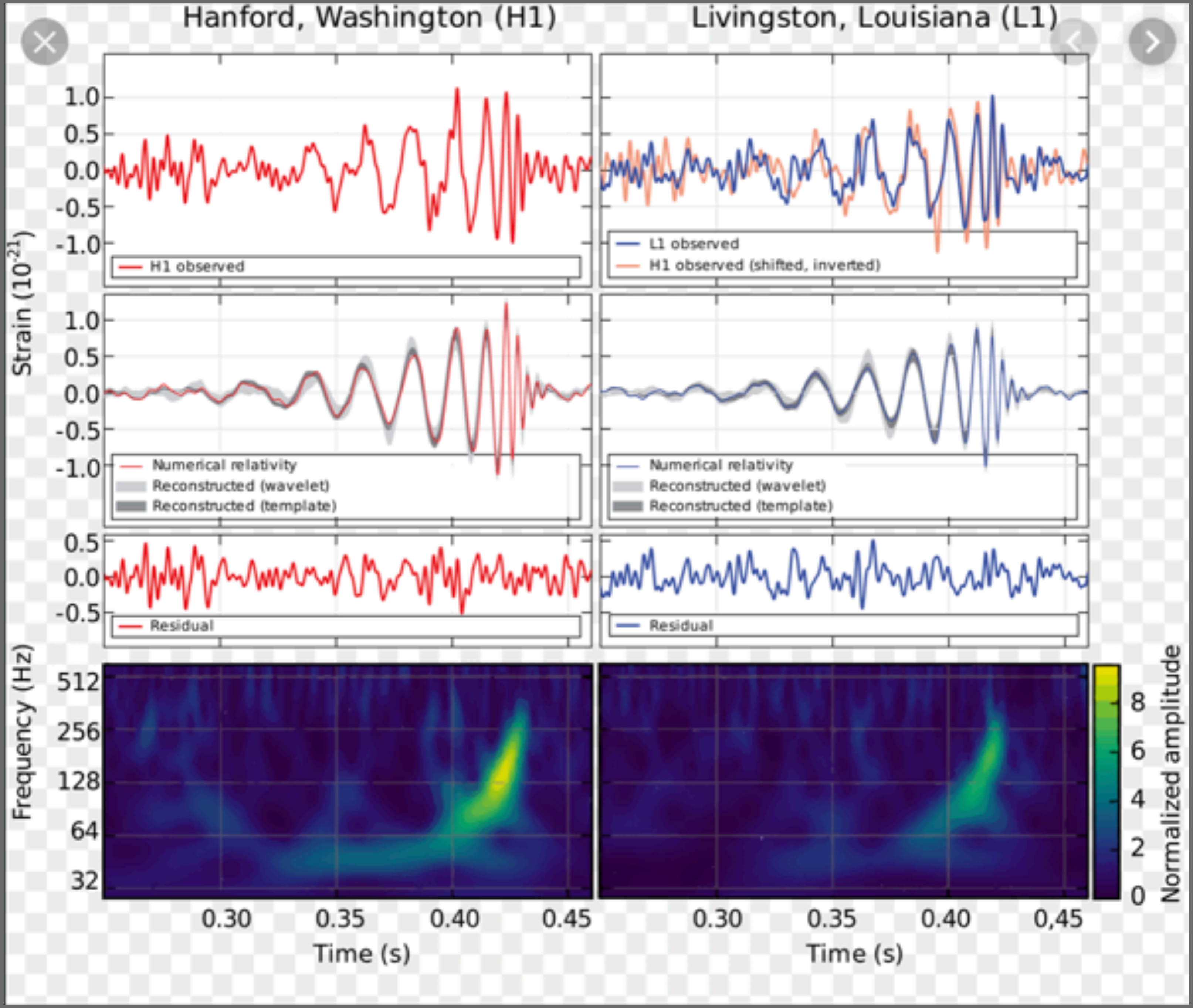
# IV. Why Gravitational Waves?

Bernard Schutz

Origins: From the Big Bang to Planets I-CORE

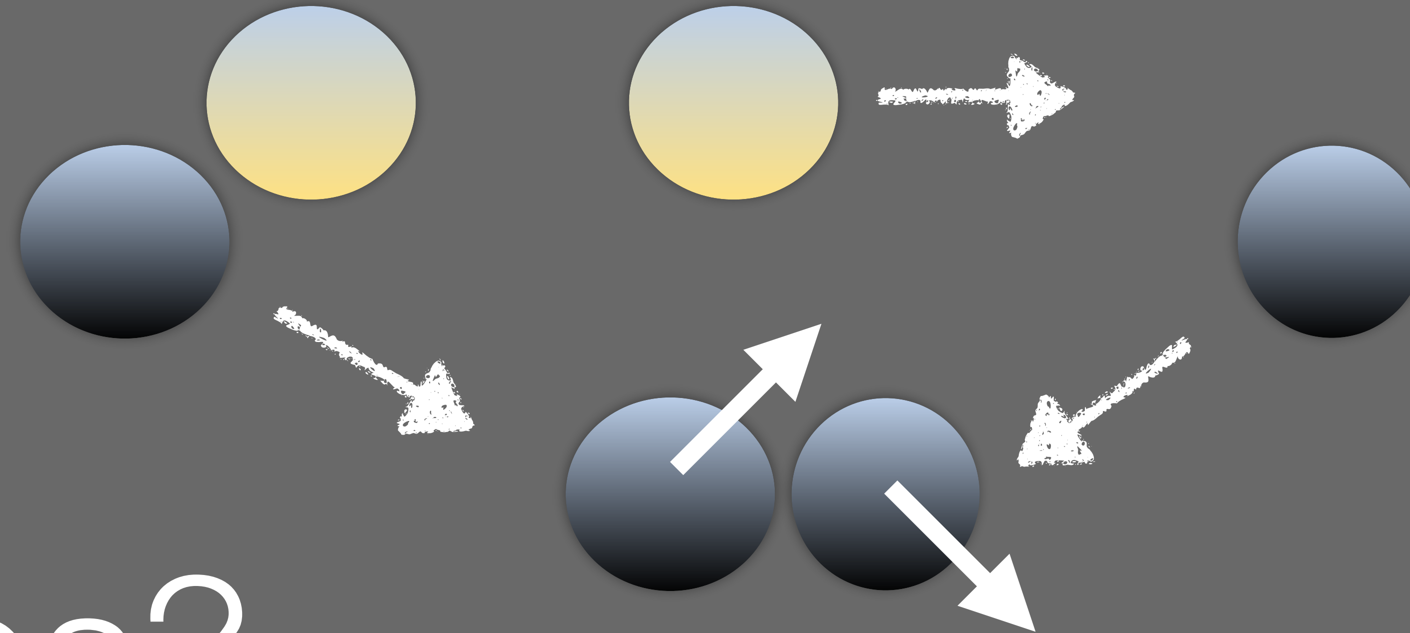
erc GRB ; TReX

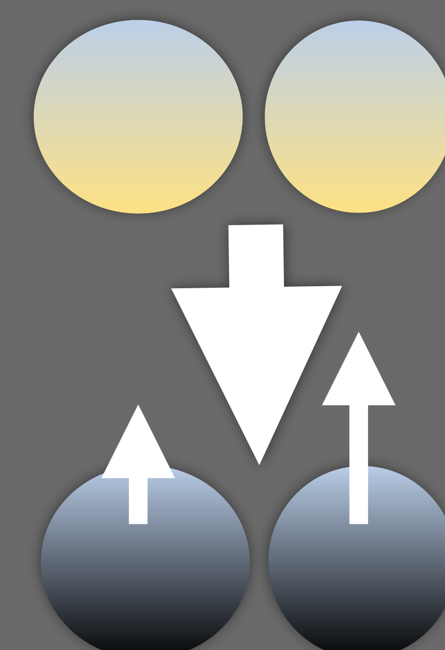
# GW 150914




Who ordered that ?

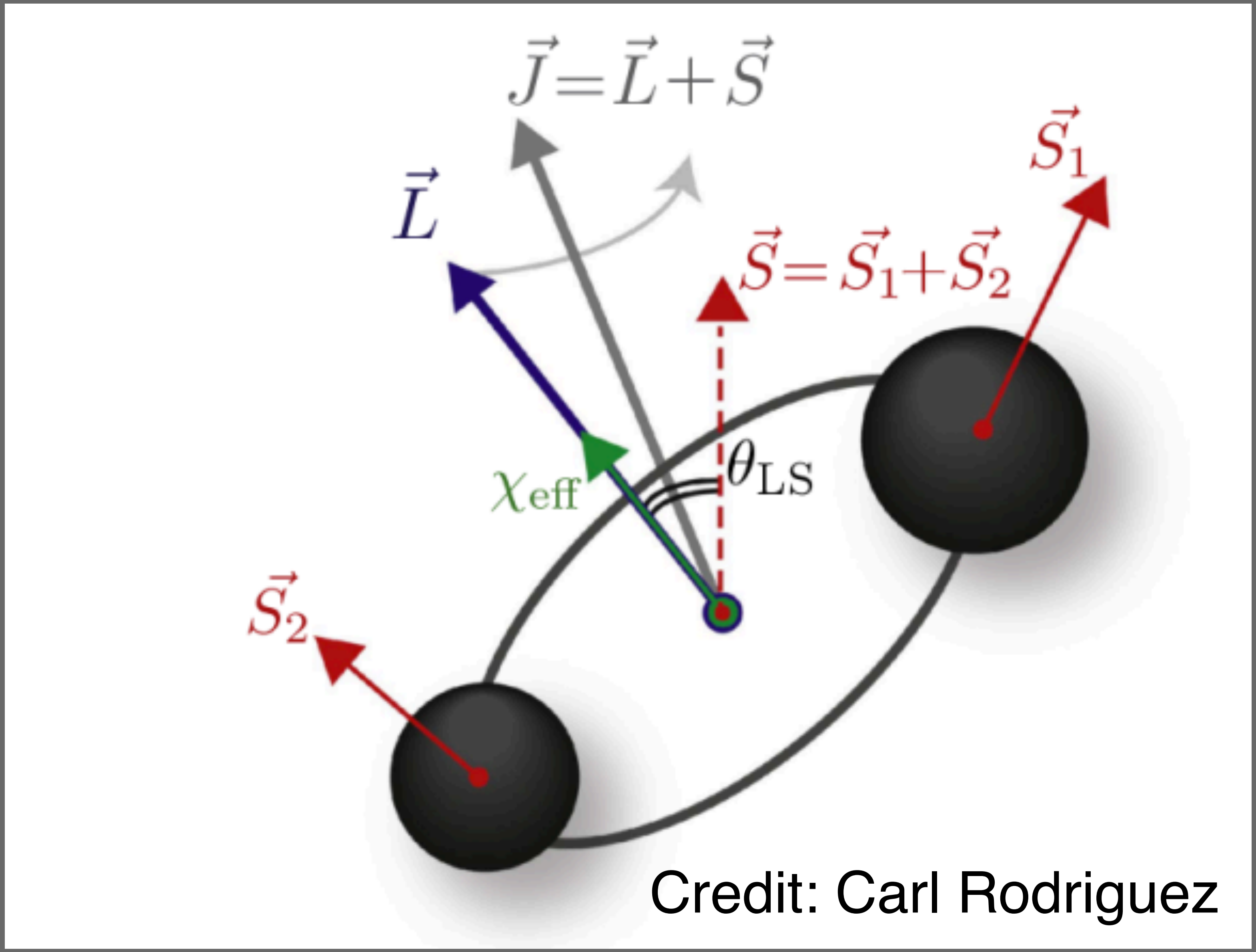
# Capture vs. Field Binaries? Effective Spin - the clue





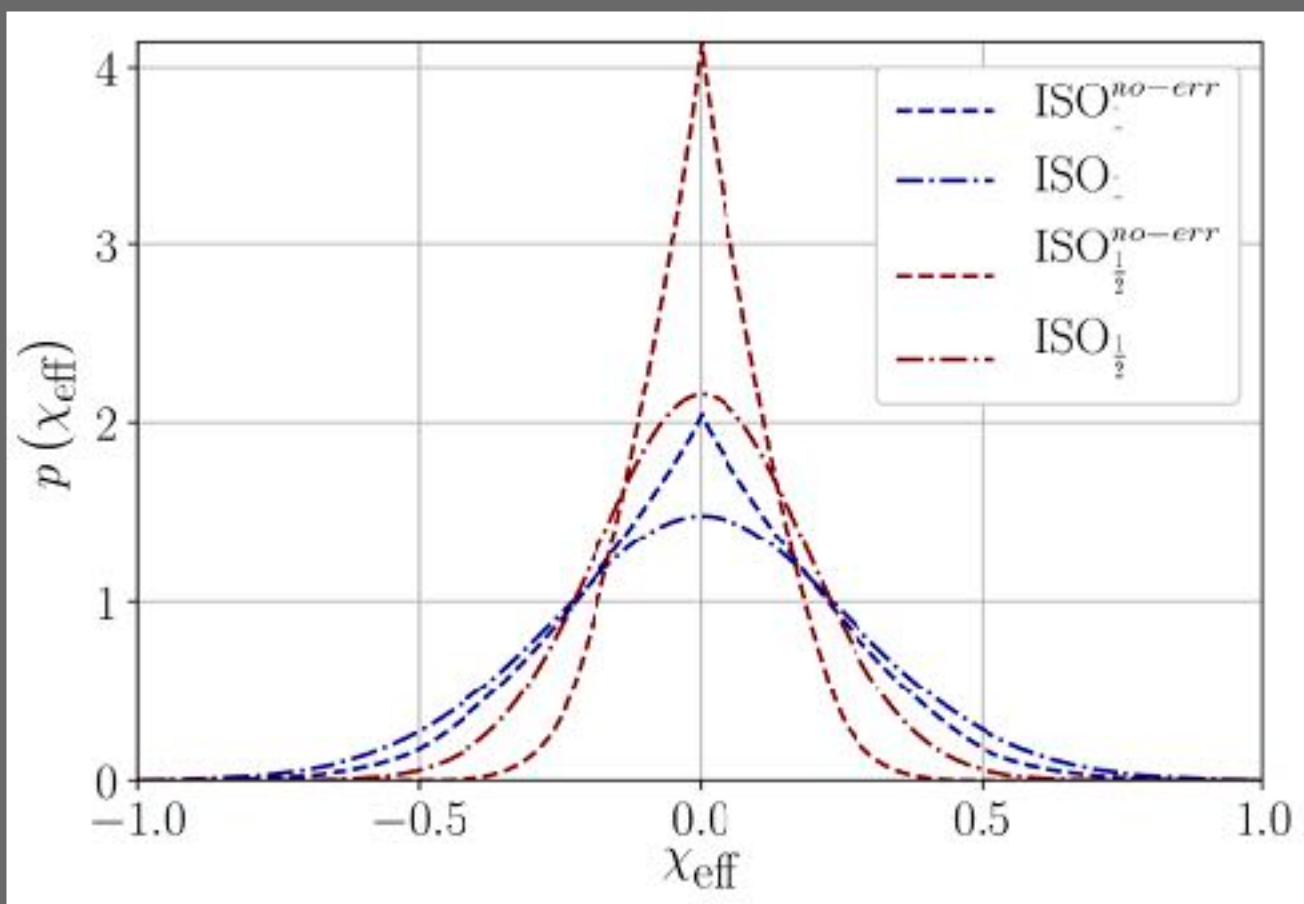
- Capture => Isotropic model
- Field binaries => some high aligned spin events

# The Effective Spin

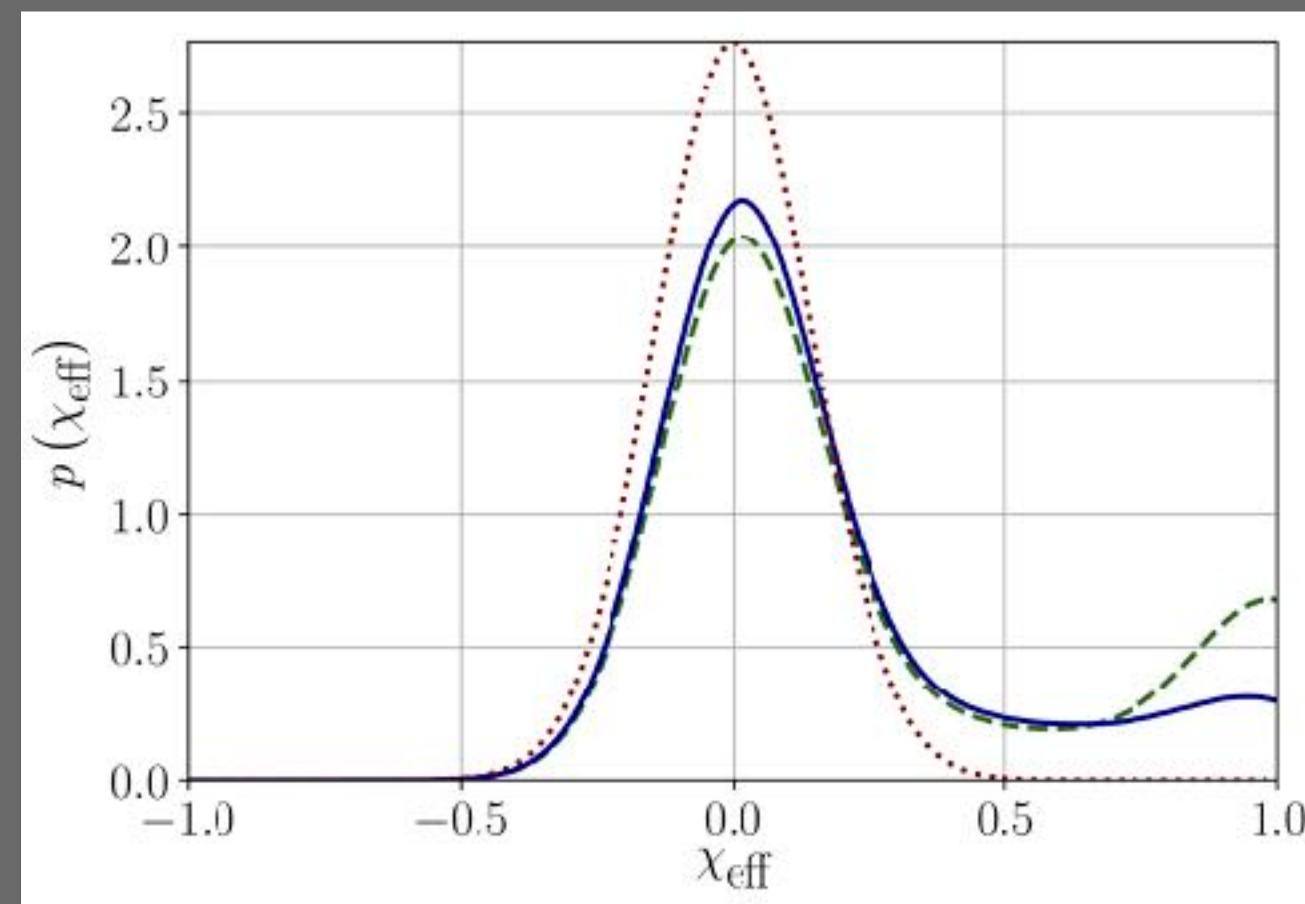



$$\chi_{1,2} = \frac{c}{Gm_{1,2}^2} S_{1,2} \cdot \hat{L}. \qquad \chi_{\rm eff} = \frac{m_1\chi_1 + m_2\chi_2}{M},$$

# Expectations

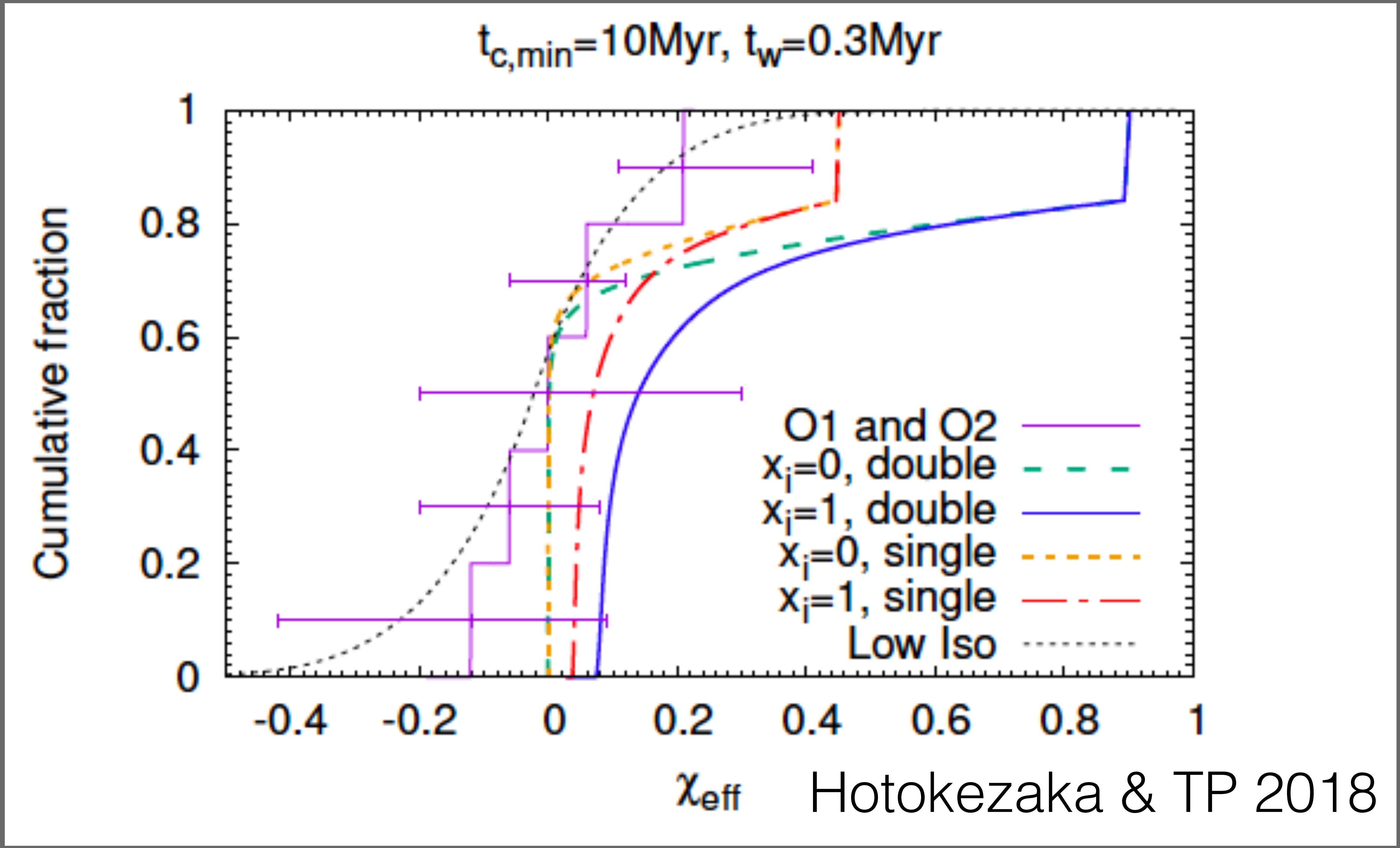



Isotropic



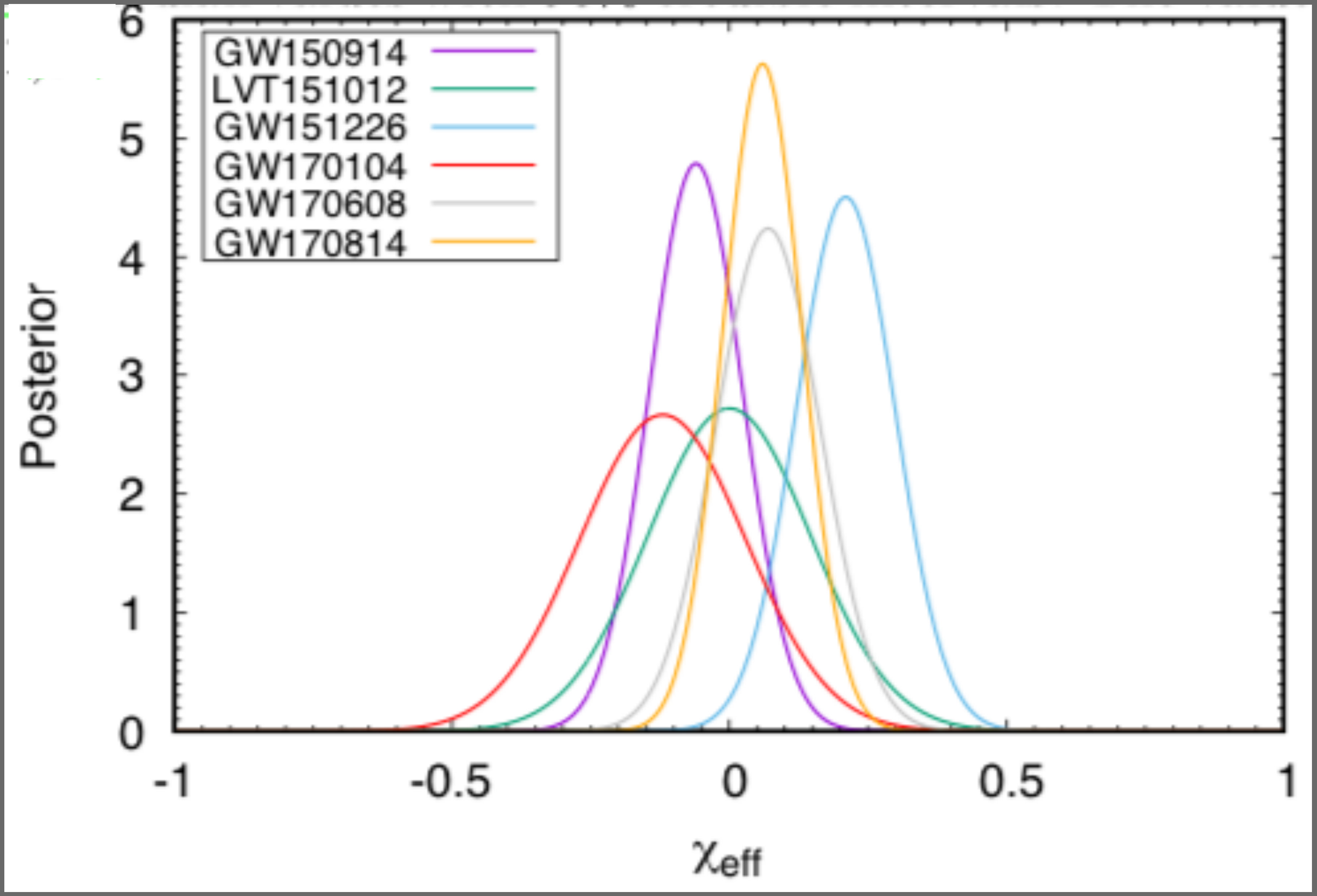

Field Evolution

# Field Evolution?

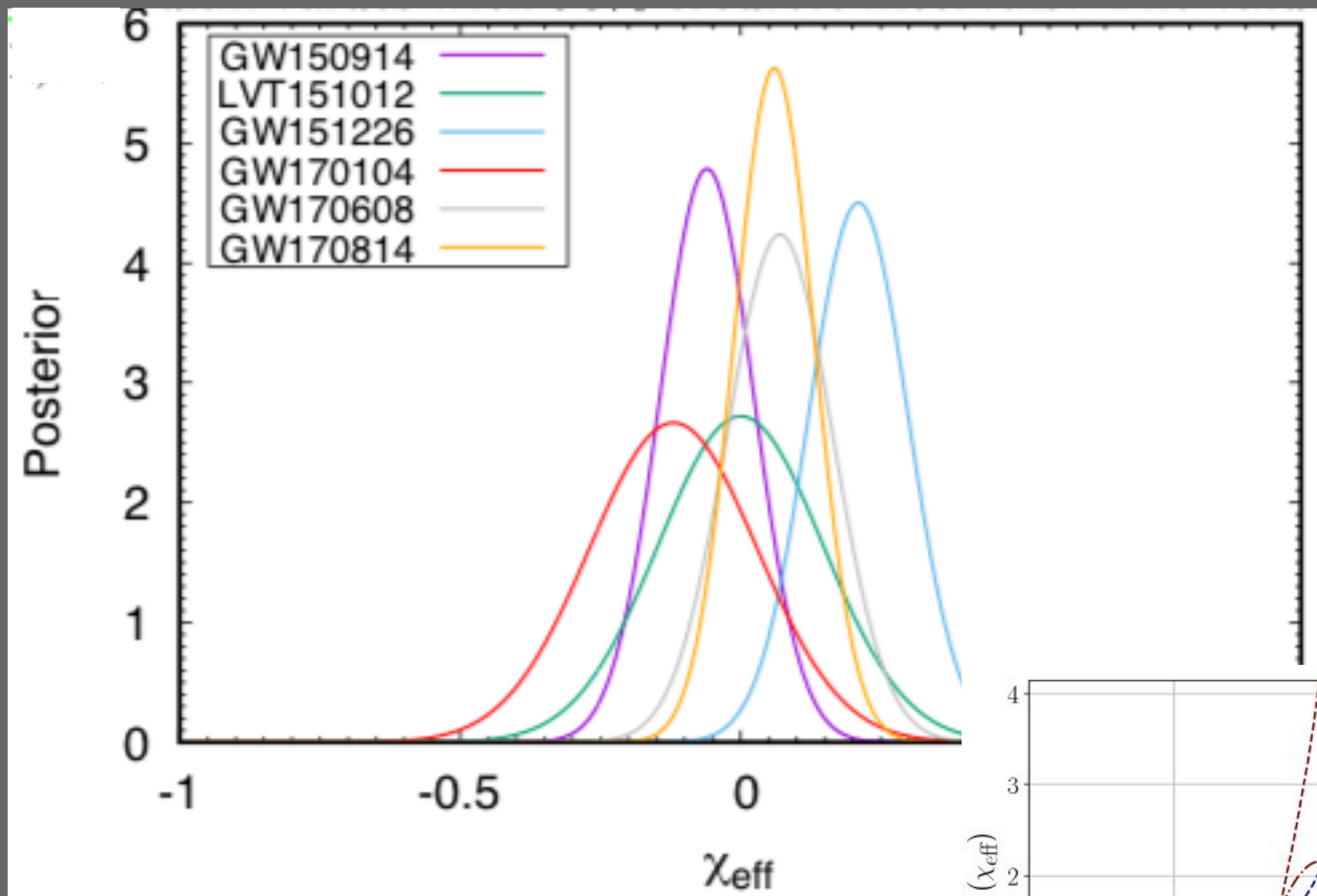


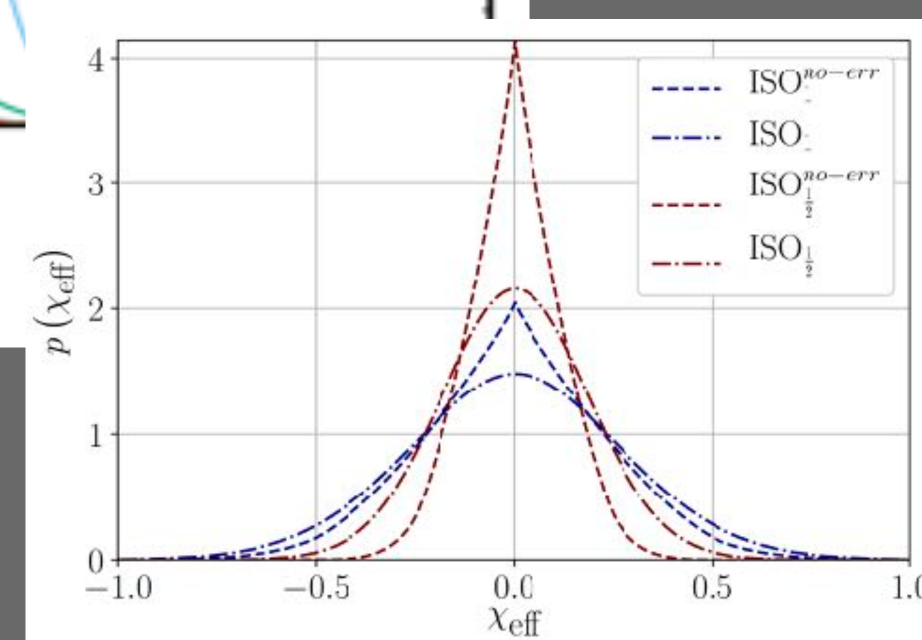

- Isotropic model with low spins fit the data
- ***Field evolution predicts some high spin events***

# The early data



# The early data



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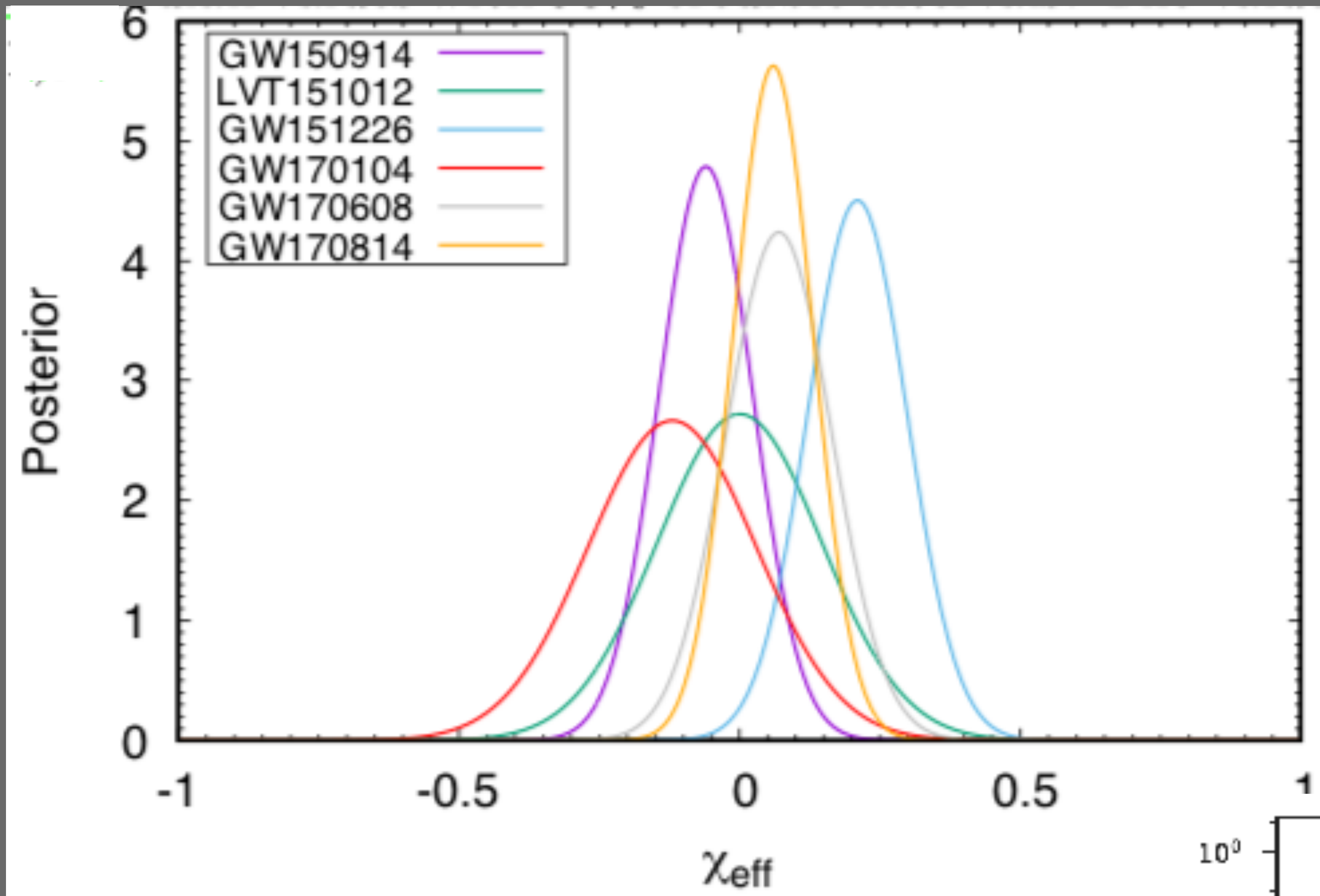
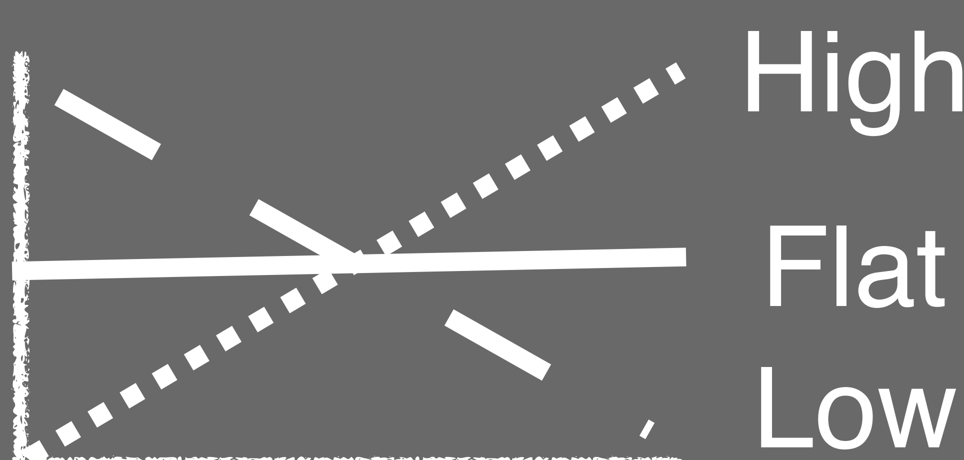
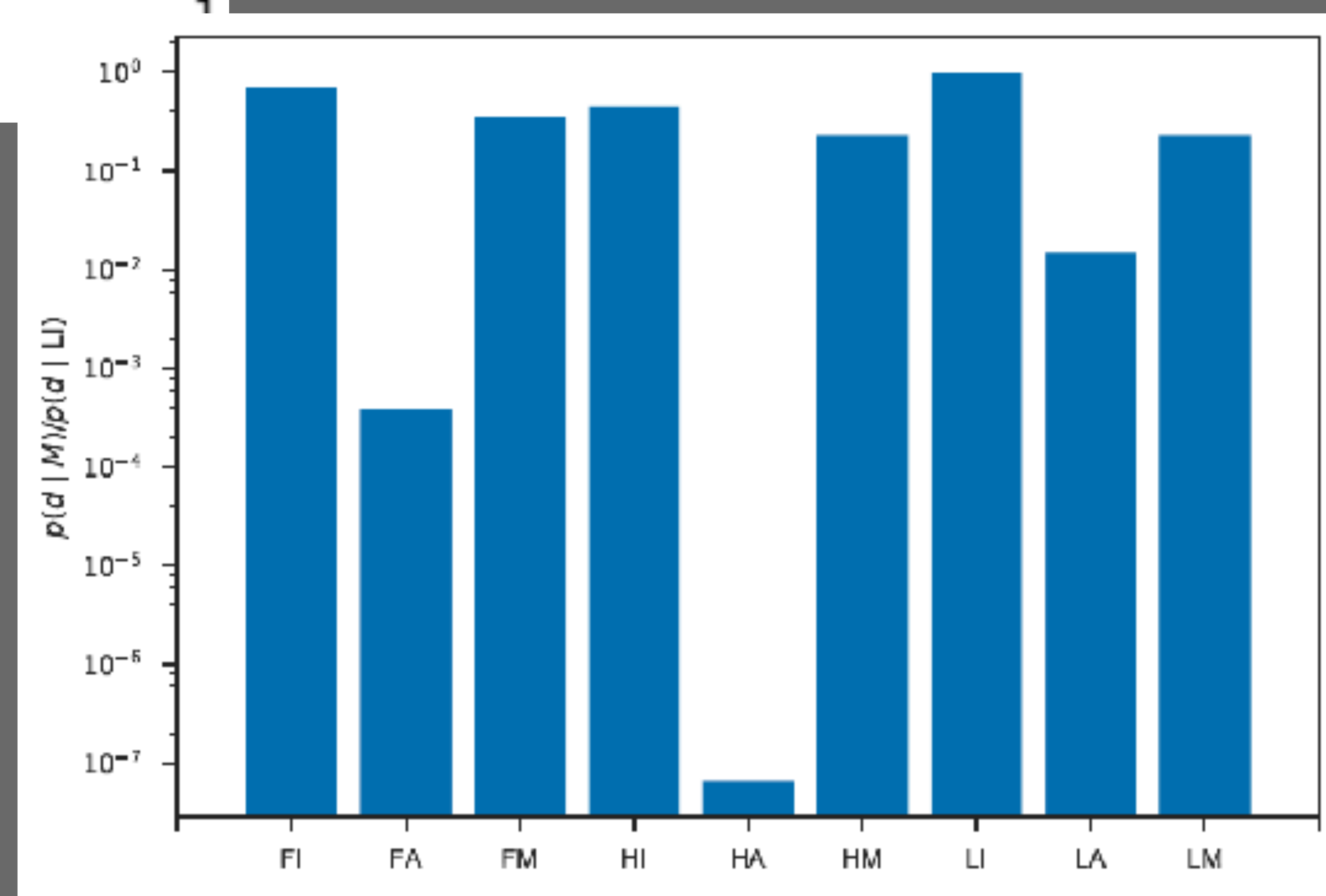


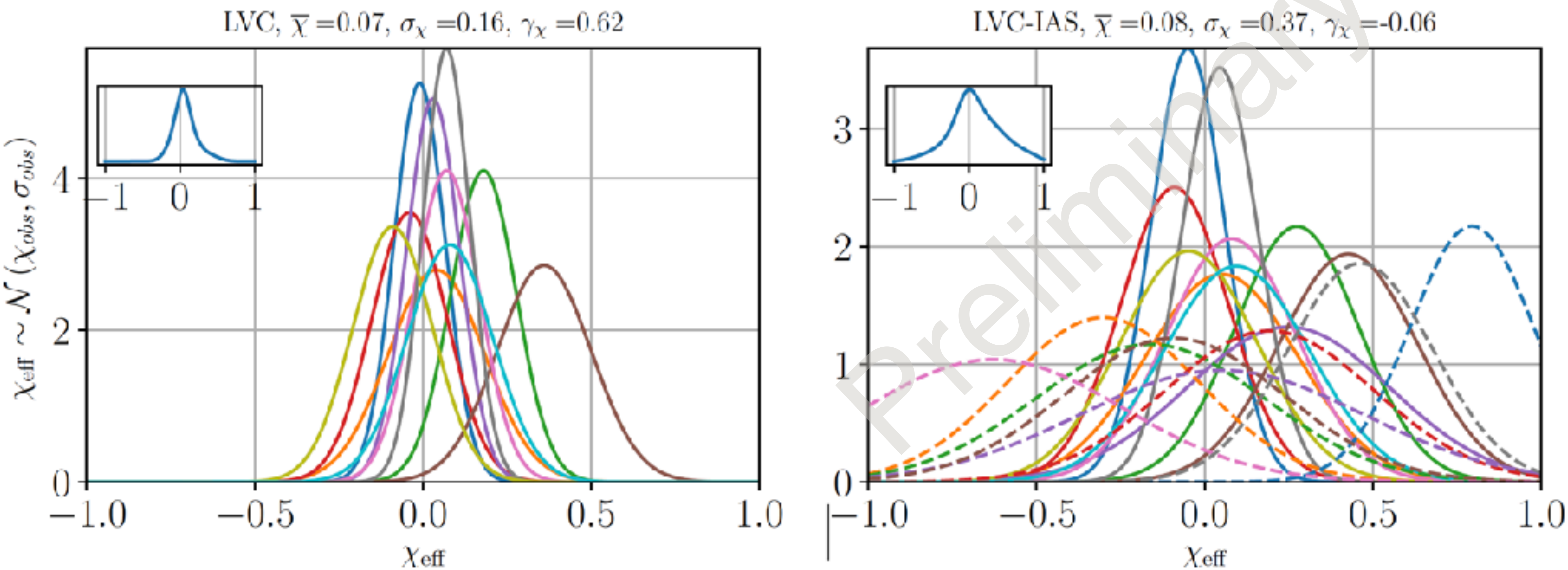

Farr et al., 17 Nature

# Alternative Pipeline

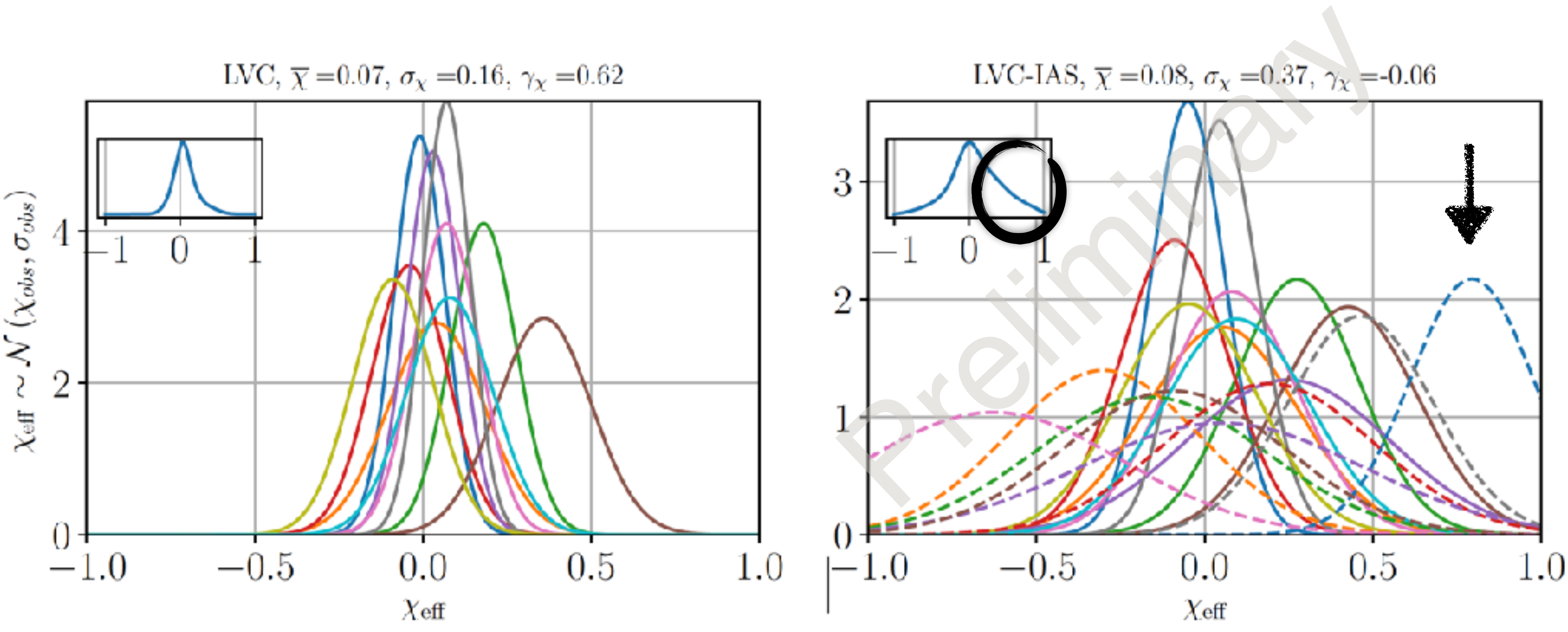
- Discovers additional significant merger events.
- Joint detections have consistent parameters (in spite of different priors).


1. *Venumadhav et al., PRD 19*
2. *Zackay et al., PRD 19*
3. *Venumadhav et al., arXiv 1904.07214*
4. *Zackay talk given at the 13th Amaldi Conference 19*

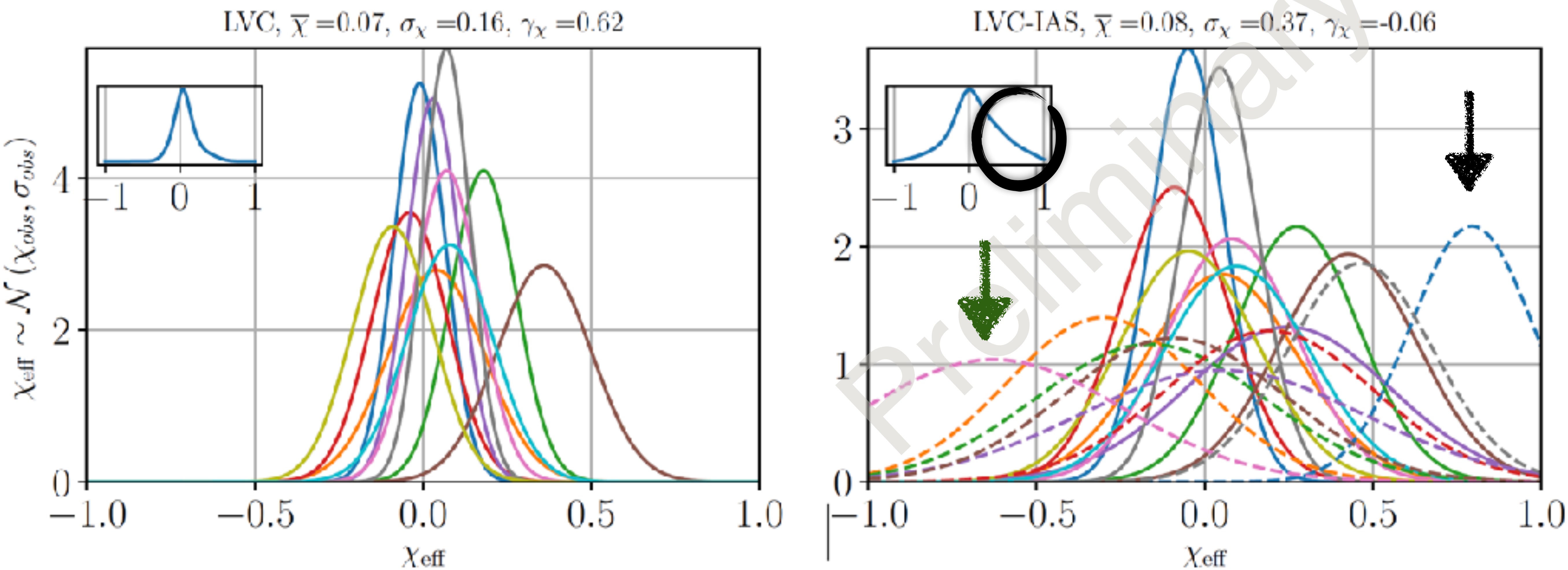
# The Effective Spin Distributions



# The Effective Spin Distributions



# The Effective Spin Distributions



# A Simple Field Evolution Model

# Tidal synchronization + winds

Ignore complications of the common envelope phase.

No Kicks during the collapse

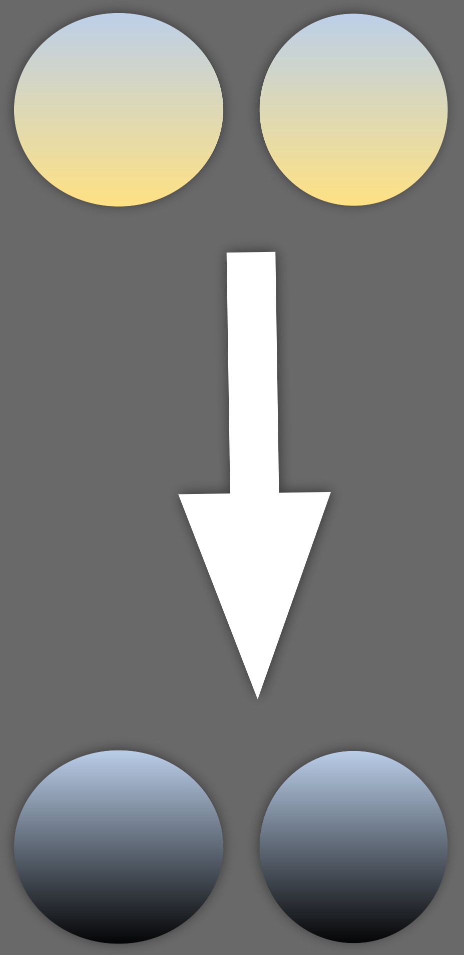
*1. Kushnir et al., MNRAS 2016*

*2. Hotokezaka & TP ApJ 2017*

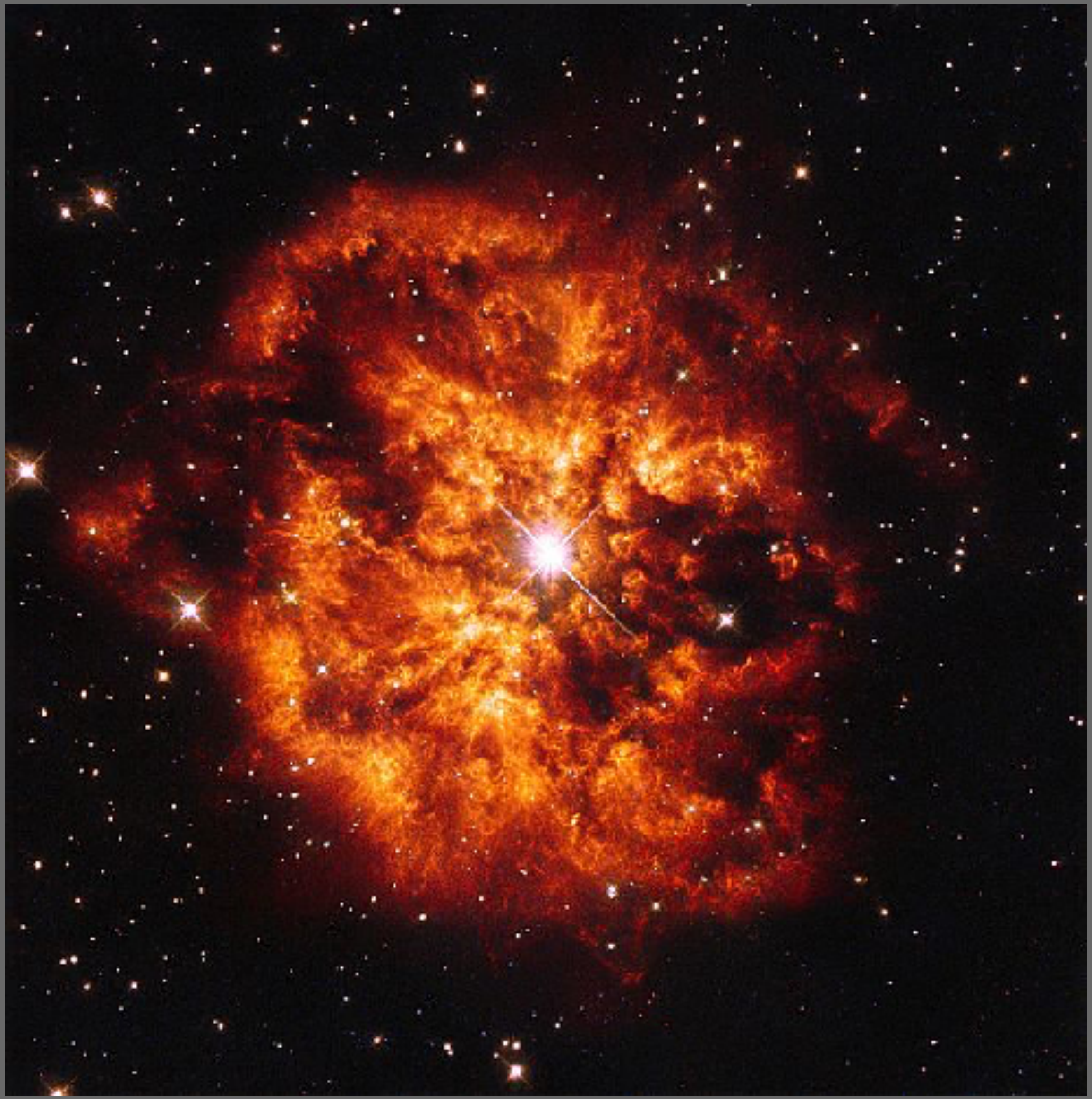
*3. TP & Hotokezaka 2019 in "Jacob Bekenstein - the conservative revolutionary"(Brinks, Mukhanov, Rabinovici, Phua Eds.).*

# Field Binaries?

- Need a short separation for merging in sufficiently short time.

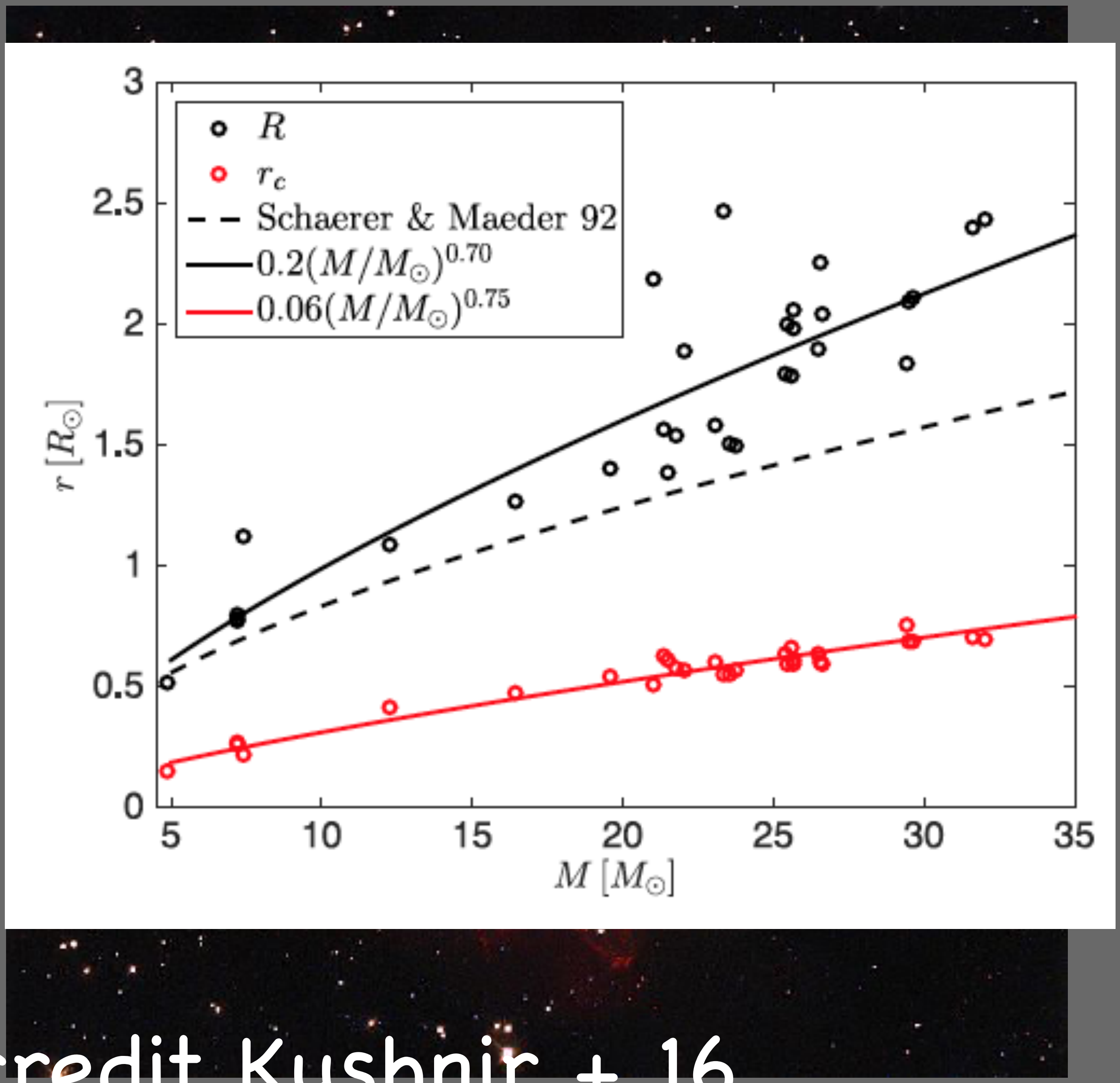


# Wolf Rayet Stars



WR124 loosing its envelope - credit HST

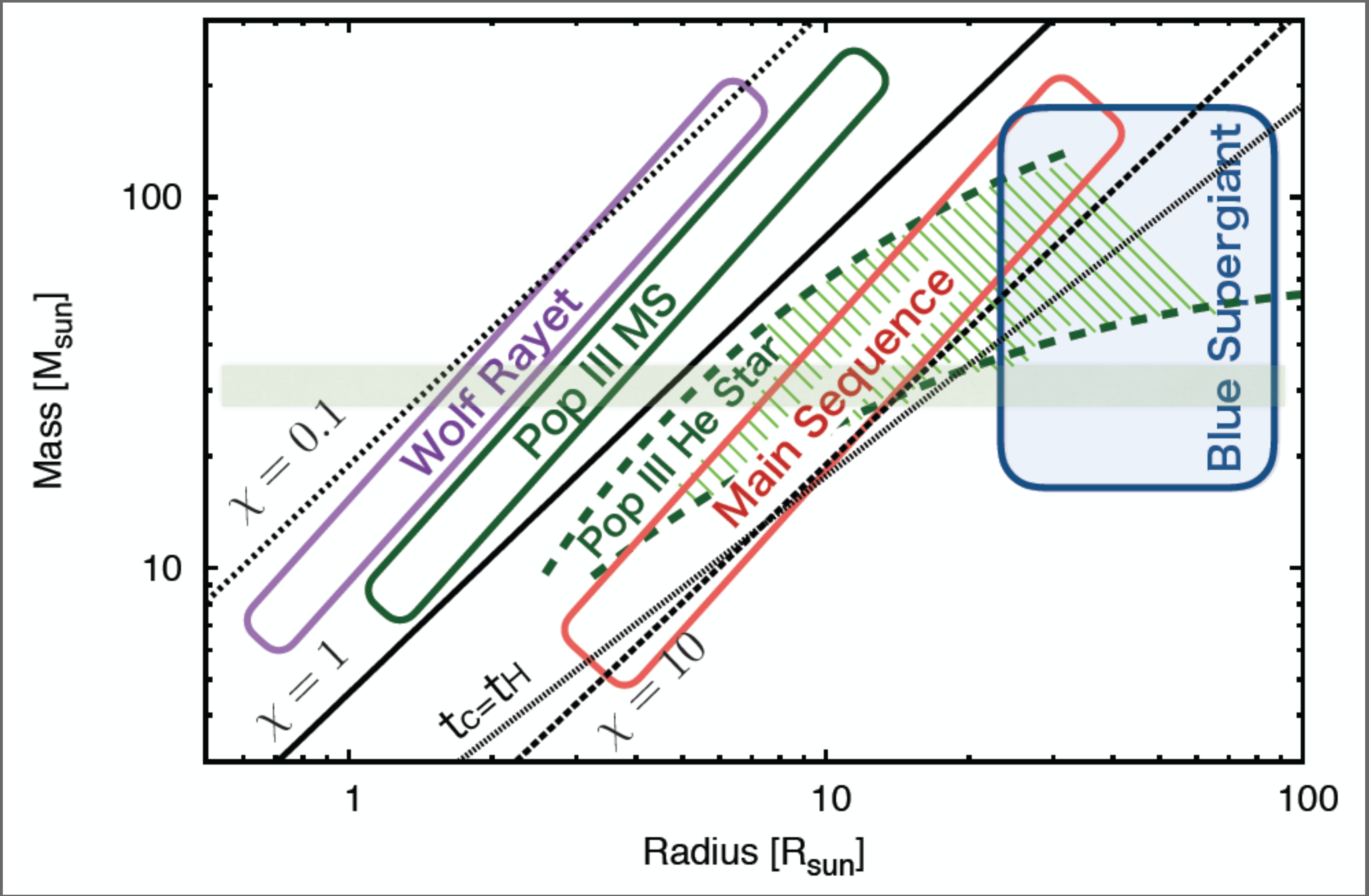
# Wolf Rayet Stars




credit Kushnir + 16

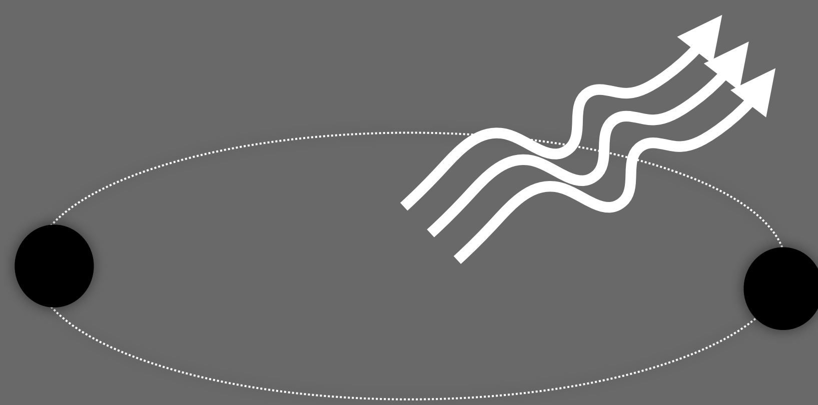
# Population III stars

CR7 a distant Galaxy harboring (possibly) pop III stars - credit ESO VLT



Wolf Rayet
Pop III MS
Pop III He Star
Main Sequence
Blue Supergiant
$\chi = 0.1$
$\chi = 1$
$\chi = 10$
$t_C = t_H$
100
10
1
10
100
Mass [$M_{sun}$]
Radius [$R_{sun}$]

# Gravitational Waves Time Scale

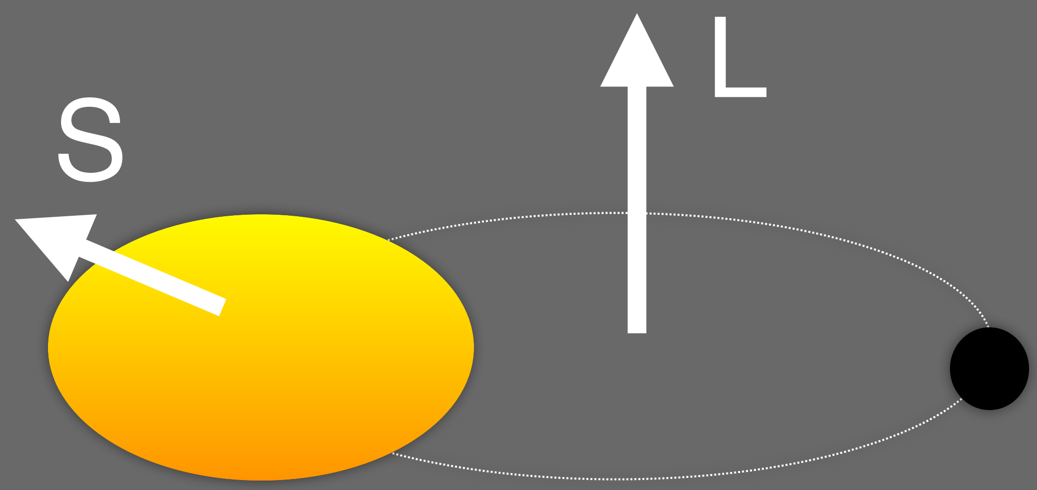


$$t_c = \frac{5}{256}\frac{c^5}{G^3}\frac{a^4}{M^2\mu}$$
$$\approx 10q^2 \cdot \left(\frac{2}{1+q}\right) \cdot \left(\frac{a}{44R_\odot}\right)^4 \cdot \left(\frac{m_2}{30M_\odot}\right)^{-3} \text{Gyr},$$

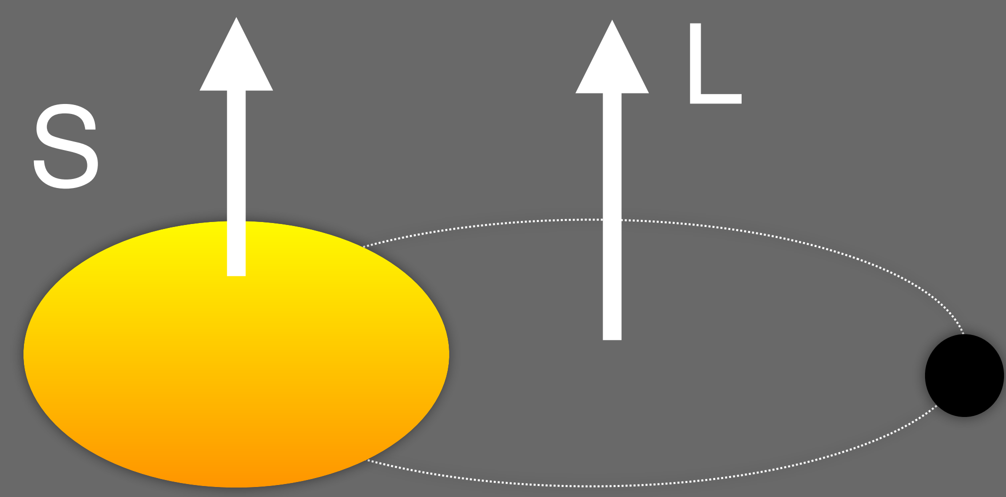
$q \equiv m_2/m_1$

$a \equiv$ Orbital separation

# Synchronization



# Synchronization



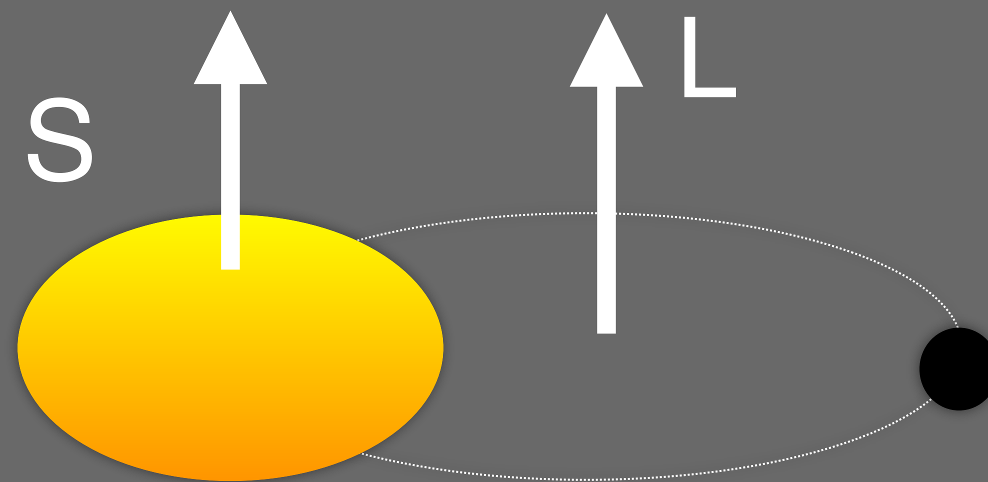

$$t_{syn} \approx 10\ \mathrm{Myr}\ q^{-1/8} \left(\frac{1+q}{2q}\right)^{31/24} \left(\frac{t_c}{1\mathrm{Gyr}}\right)^{17/8}$$

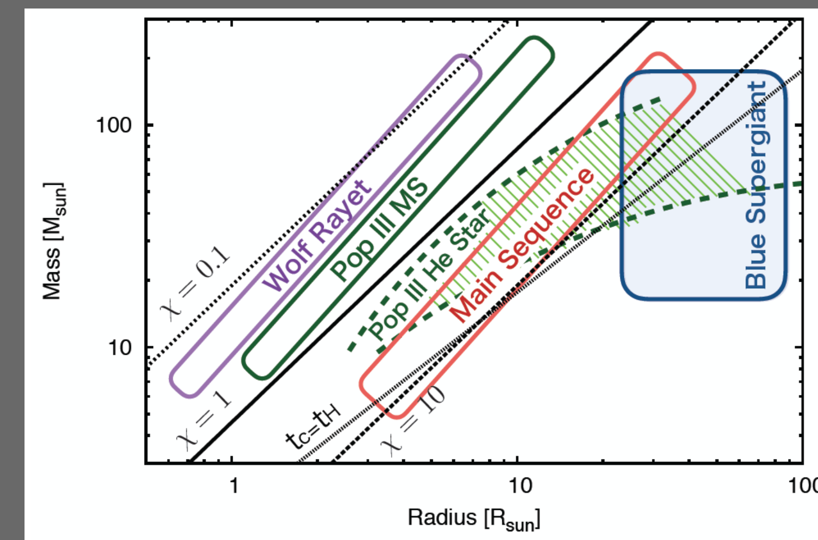
$t_c \equiv$ GW time scale

$$\chi_{syn} \approx 0.5\ q^{1/4} \left(\frac{1+q}{2}\right)^{1/8} \left(\frac{\epsilon}{0.075}\right) \left(\frac{R_2}{2R_\odot}\right)^2 \left(\frac{m_2}{30M_\odot}\right)^{-13/8} \left(\frac{t_c}{1\mathrm{Gyr}}\right)^{-3/8},$$

# Synchronization

$R \sim M^{0.8}$




$$t_{syn} \approx 10\ \mathrm{Myr}\ q^{-1/8}\left(\frac{1+q}{2q}\right)^{31/24}\left(\frac{t_c}{1\mathrm{Gyr}}\right)^{17/8}$$

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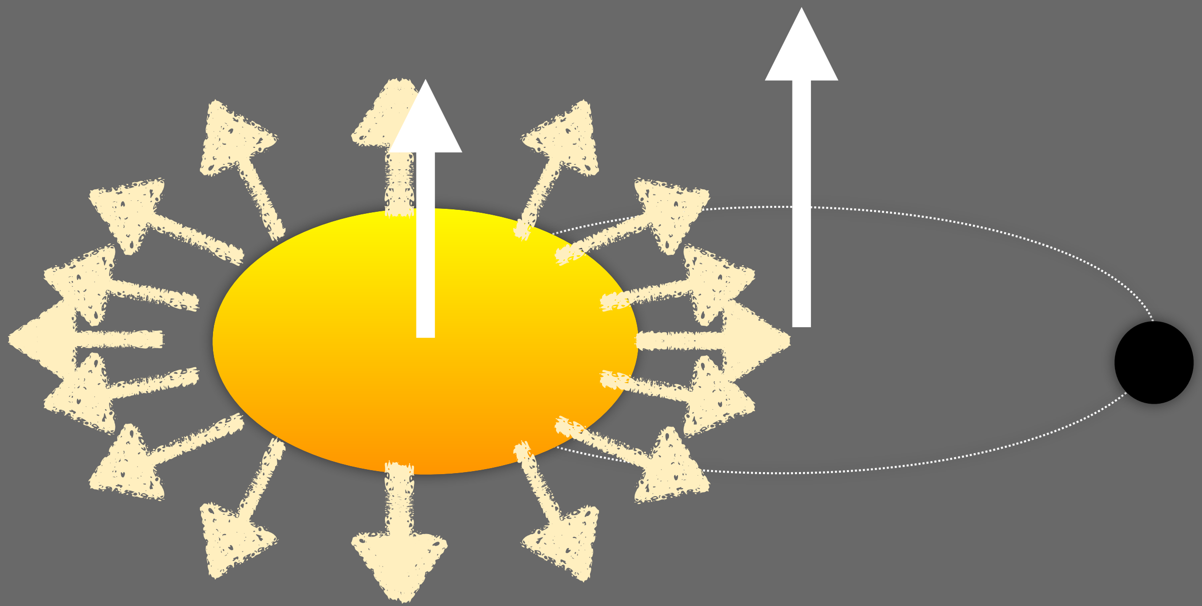
$t_c \equiv$ GW time scale

# Winds

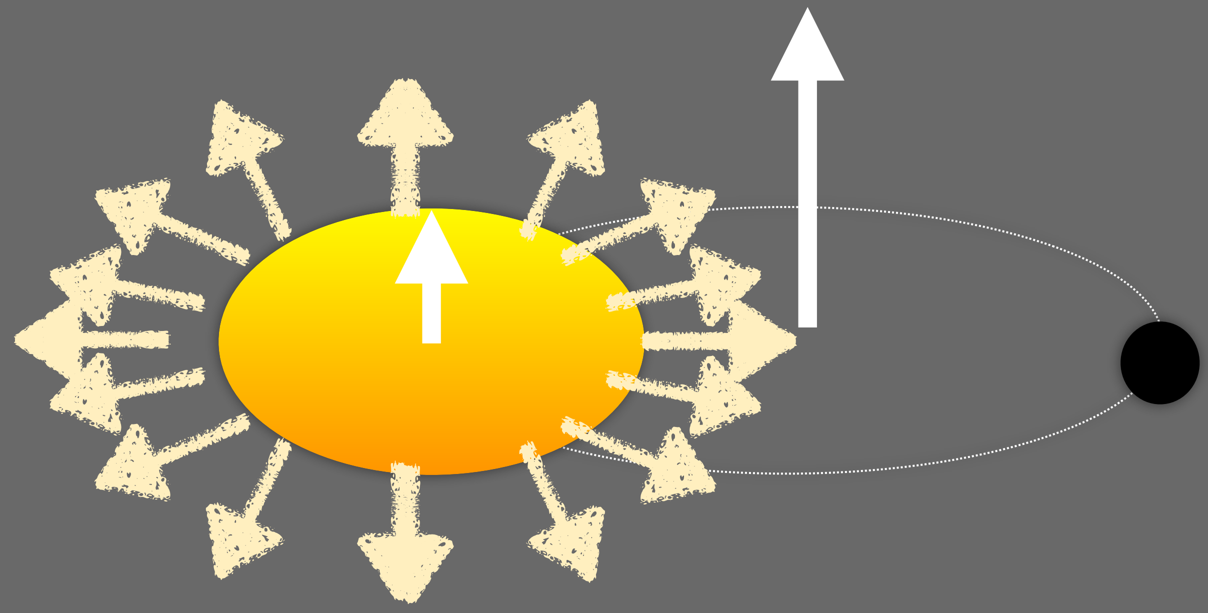


Angular momentum loss due to winds

~$10^{-4}$ to $10^{-6}$ Msun/year

$$t_W \equiv \chi_* / \dot{\chi}_*$$

# Winds



Angular momentum loss due to winds

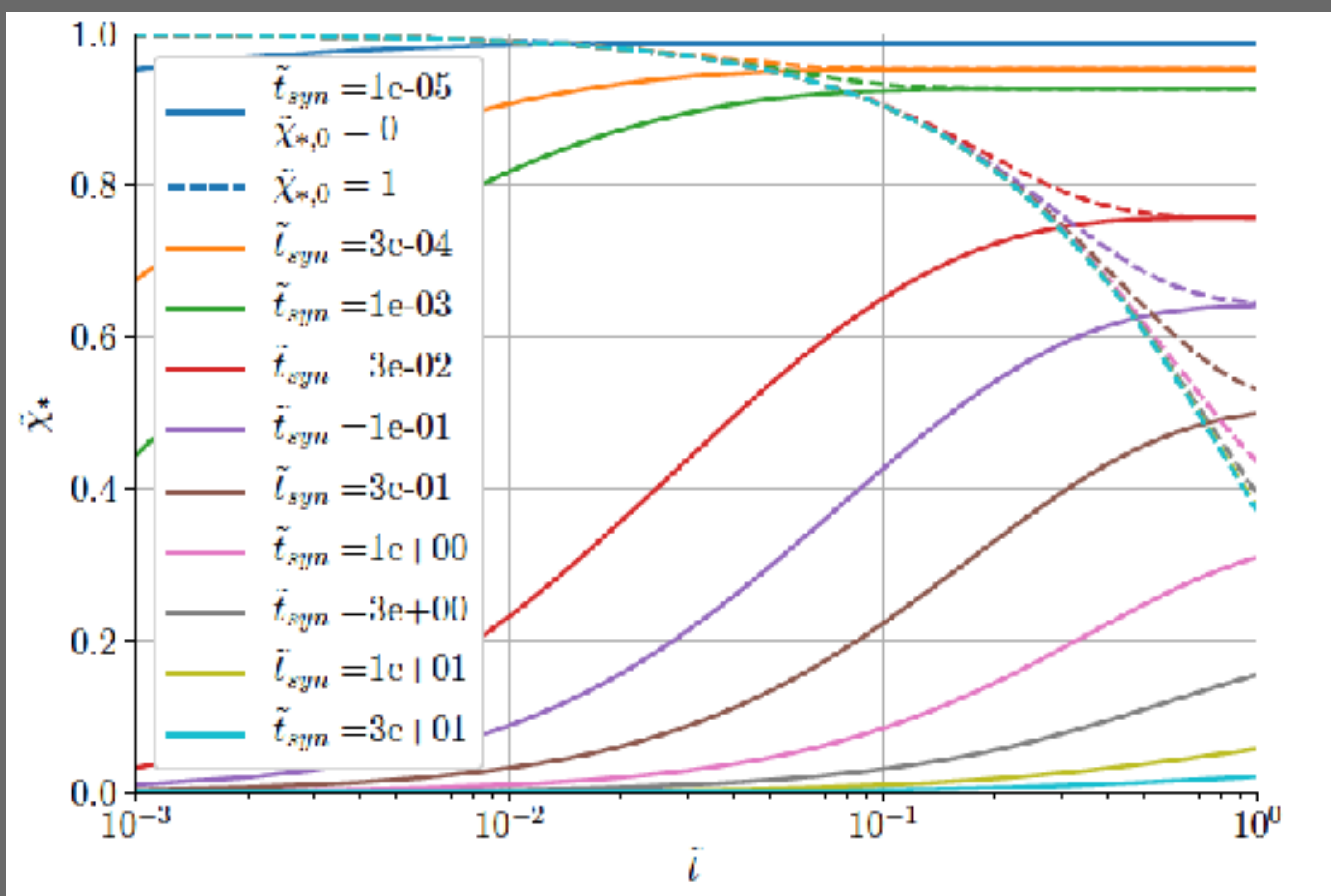
~$10^{-4}$ to $10^{-6}$ Msun/year

$$t_w \equiv \chi_* / \dot{\chi}_*$$

# Tidal locking & Winds

$$\frac{d\tilde{\chi}_*}{d\tilde{t}} = \frac{t_w}{t_{syn}(t_c)}(1-\tilde{\chi}_*)^{8/3} - \tilde{\chi}_* \qquad \tilde{\chi}_* \equiv \chi_*/\chi_{syn}(t_c) \qquad \tilde{t} \equiv t/t_w$$

Tide　　　Wind




$\tilde{\chi} \to 1$ for large $t_w/t_{syn}$

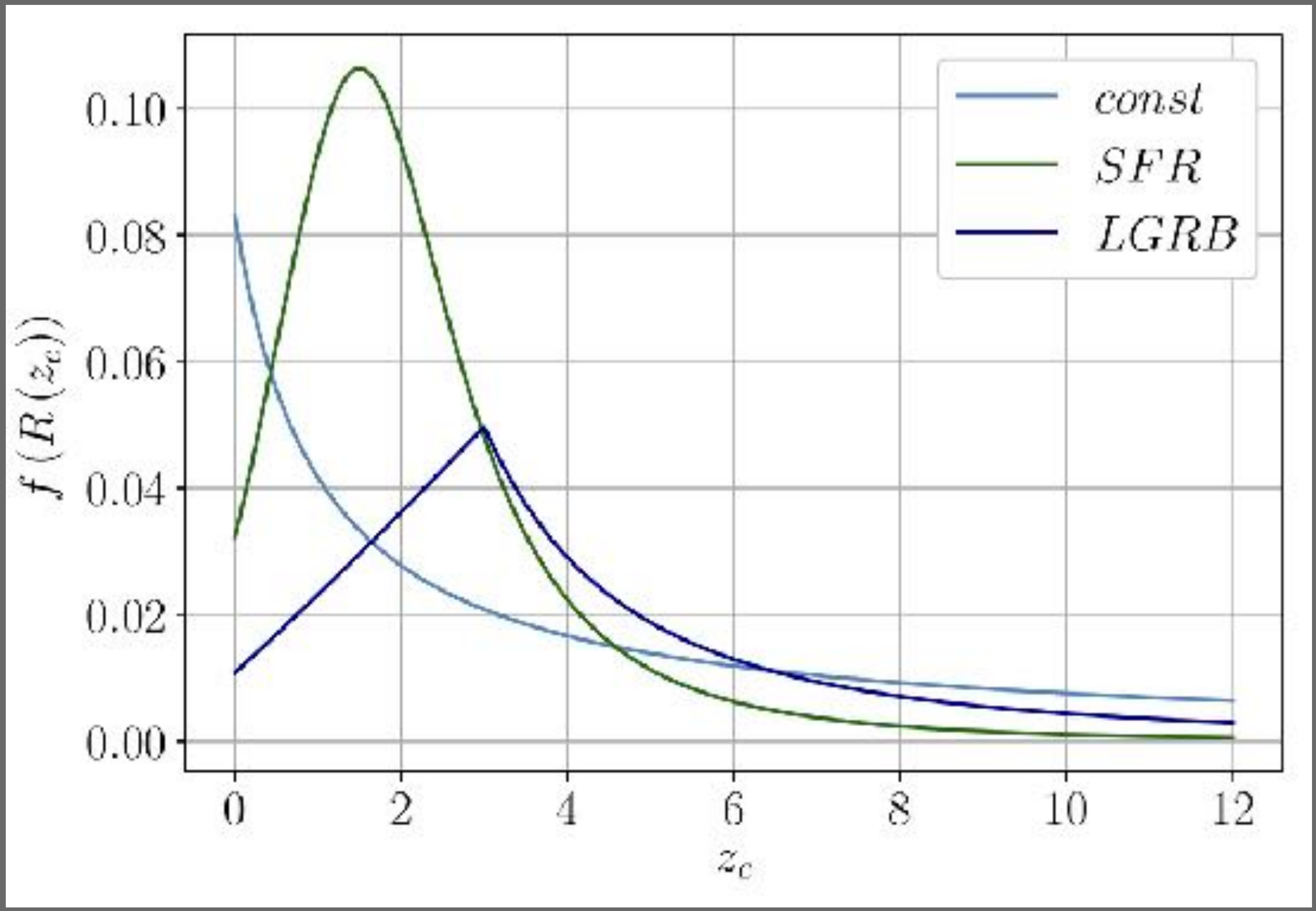
$\tilde{\chi} \to 0$ for small $t_w/t_{syn}$

Small $t/t_w$ : $\tilde{\chi} \to \tilde{\chi}_0$

**All spins are positive**

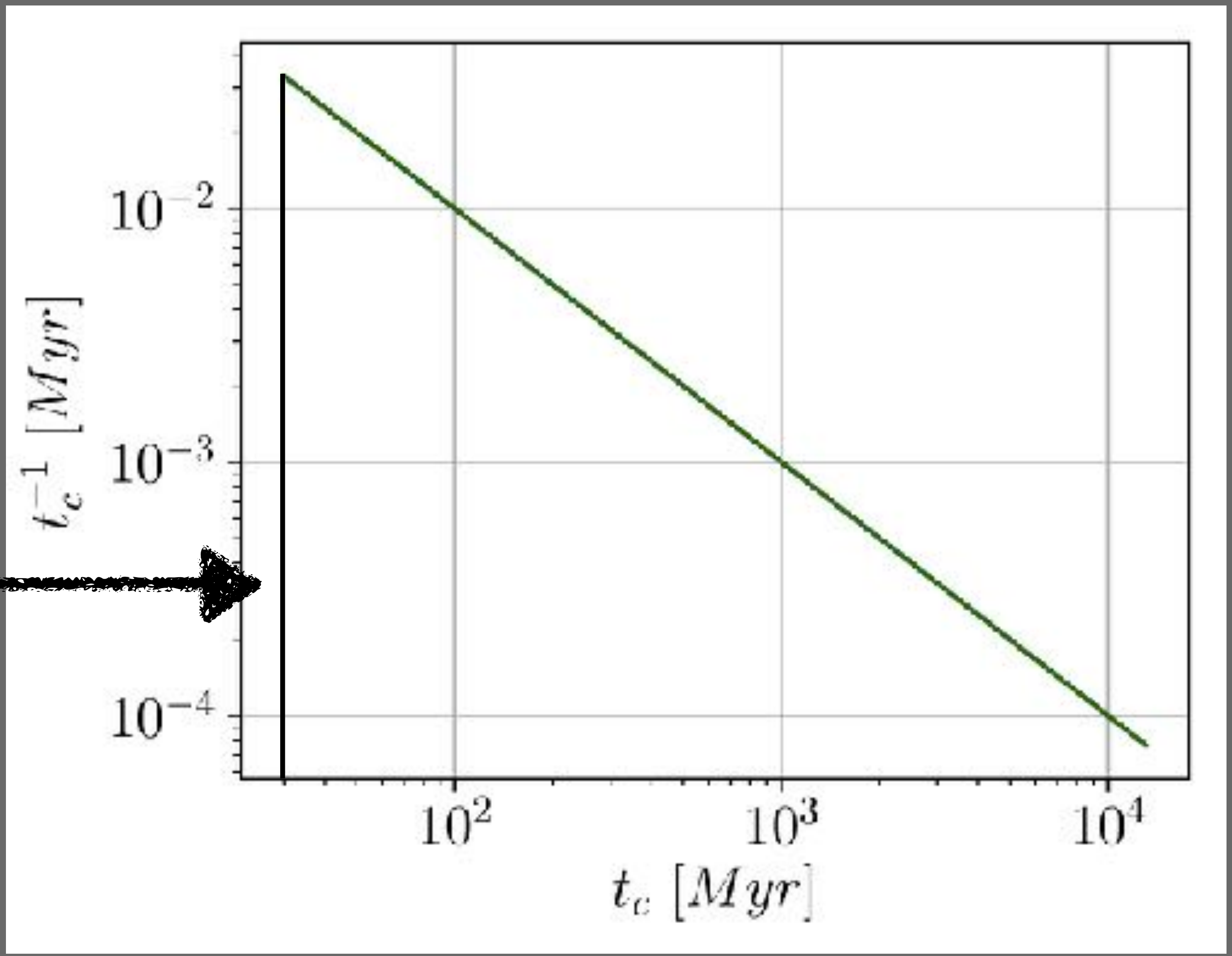
# Source evolution

- Sources follow the SFR, the LGRB rate (massive star formation) or constant.



# Gravitational time delay distribution

- $t_c$ has a $t^{-1}$ distribution with a minimal value $t_{c,min}$



# Further details

- Initial conditions:
  - synchronized ($\chi_0 = \chi_{syn}$)
  - not synchronized ($\chi_0 = 0$).
- Single Aligned (SA) or Double Aligned (DA).
- **For single aligned the other spin is random.**

$$\chi_{\rm eff} = (\chi_{\rm eff,1} + q\chi_{\rm eff,2})/(1+q)$$

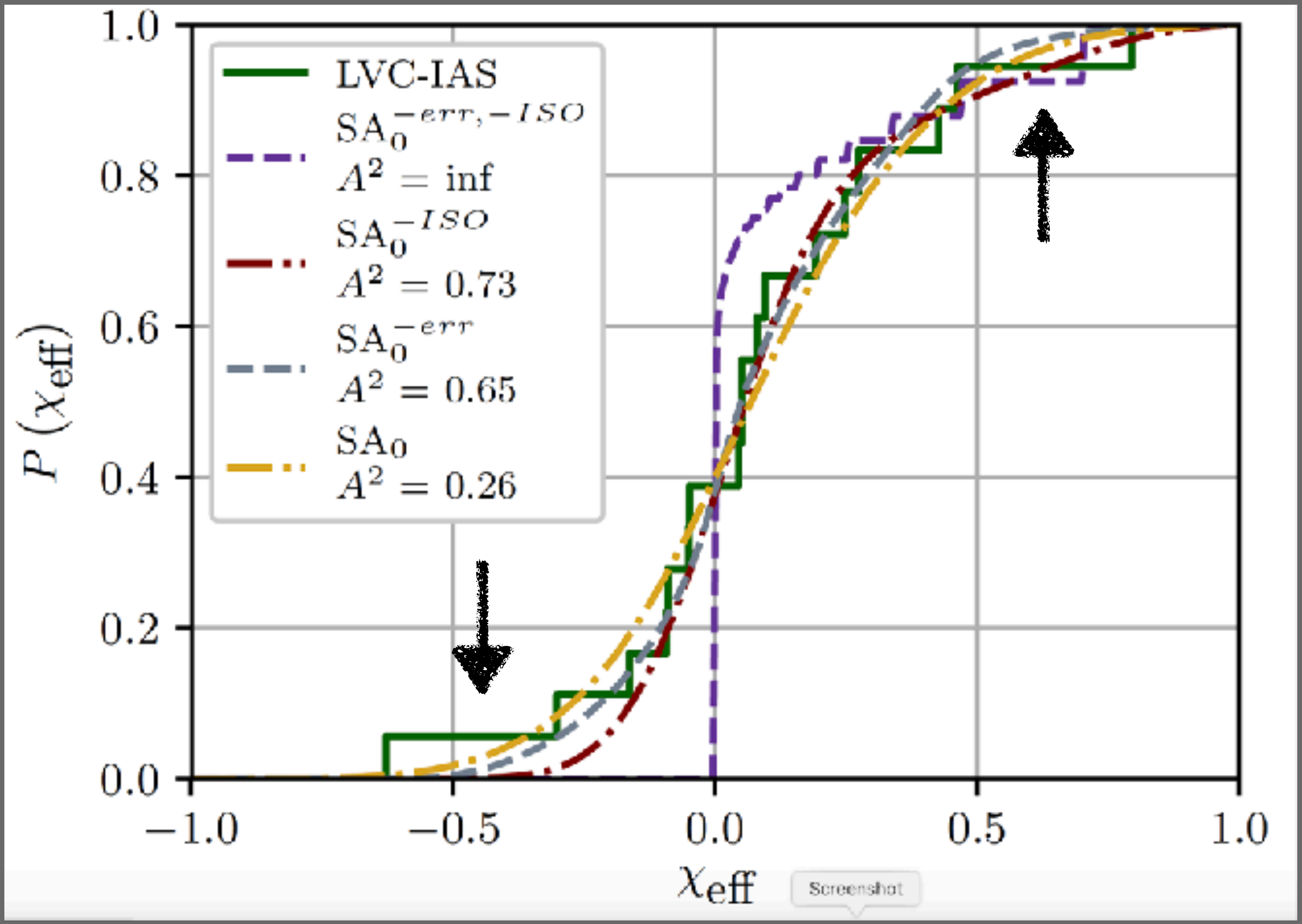
# Measurement errors

- ‘’Measurement” errors are added to the theoretical model:

$$p_{err}(\chi_{\rm eff}) = p(\chi_{\rm eff}; \overline{m}_1, \overline{m}_2) * \varphi(\chi_{\rm eff}; 0, \overline{\sigma}^2_{\chi_{\rm eff}})\ .$$

Model Prediction   Convolution   Gaussian

# Errors + isotropic component



# Model Parameters

- Four free parameters:
  - $t_*$ - Stellar life time = 0.3 Myr (fixed)
  - $t_{c,min}$ - Minimal GW time scale: 5 to 1000 Myr
  - $t_w$ - Wind time: 0.03 to 5 Myr
  - $\chi_0$ - Initial spin (0 or $\chi_{syn}$)

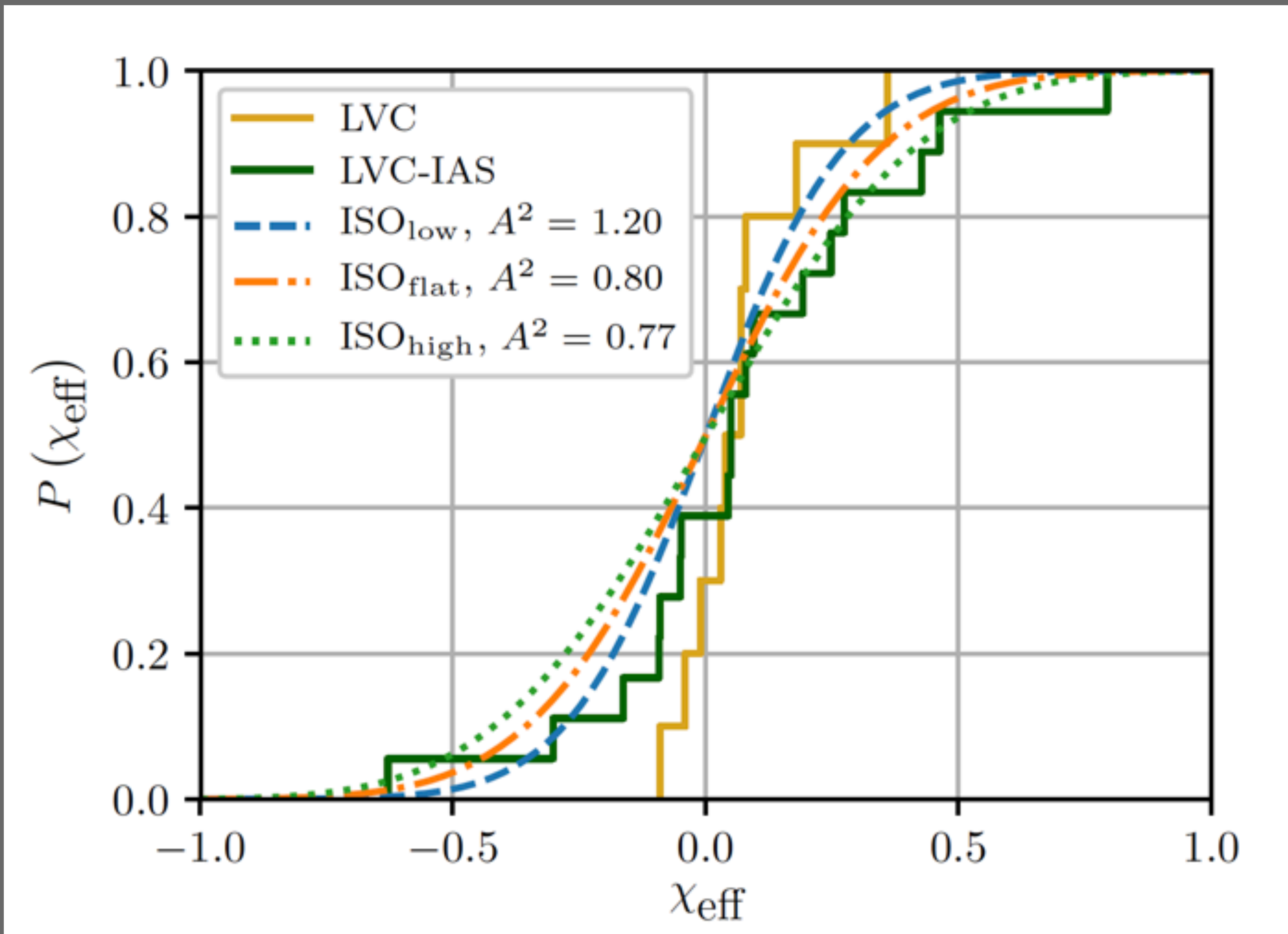
# Statistical test

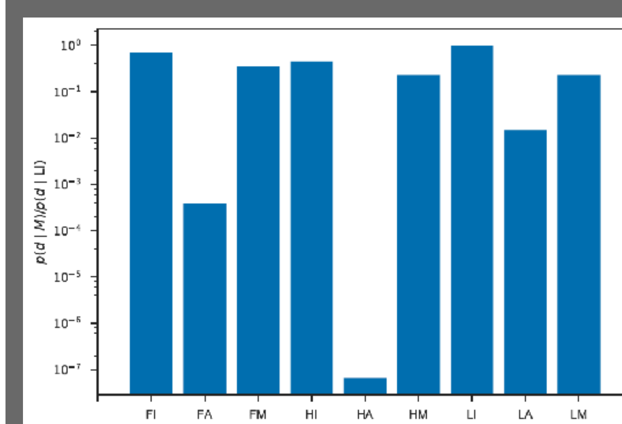
- Models are compared to the data using the **Anderson-Darling** test

| | 99% | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% | 5% | 4% | 3% | 2% | 1% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SA_0, SA_{syn}$ | 0.38 | 0.39 | 0.42 | 0.48 | 0.56 | 0.67 | 0.82 | 1.04 | 1.39 | 2.02 | 2.69 | 2.91 | 3.2 | 3.62 | 4.34 |
| $DA_0, DA_{syn}$ | 0.38 | 0.39 | 0.42 | 0.48 | 0.56 | 0.67 | 0.83 | 1.06 | 1.42 | 2.07 | 2.77 | 3.02 | 3.33 | 3.79 | 4.72 |
| $(SA_{0,syn} + DA_{0,syn})/2$ | 0.38 | 0.39 | 0.42 | 0.48 | 0.55 | 0.67 | 0.82 | 1.05 | 1.4 | 2.05 | 2.74 | 2.98 | 3.28 | 3.71 | 4.49 |
| $ISO_{low}, ISO_{flat}, ISO_{high}$ | 0.38 | 0.39 | 0.42 | 0.48 | 0.56 | 0.67 | 0.83 | 1.05 | 1.4 | 2.02 | 2.66 | 2.87 | 3.12 | 3.5 | 4.13 |

TABLE I. Rejection values of Anderson-Darling test statistic $A^2$ for the different models.

# Results - Isotropic models




| | 99% | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% | 5% | 4% | 3% | 2% | 1% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
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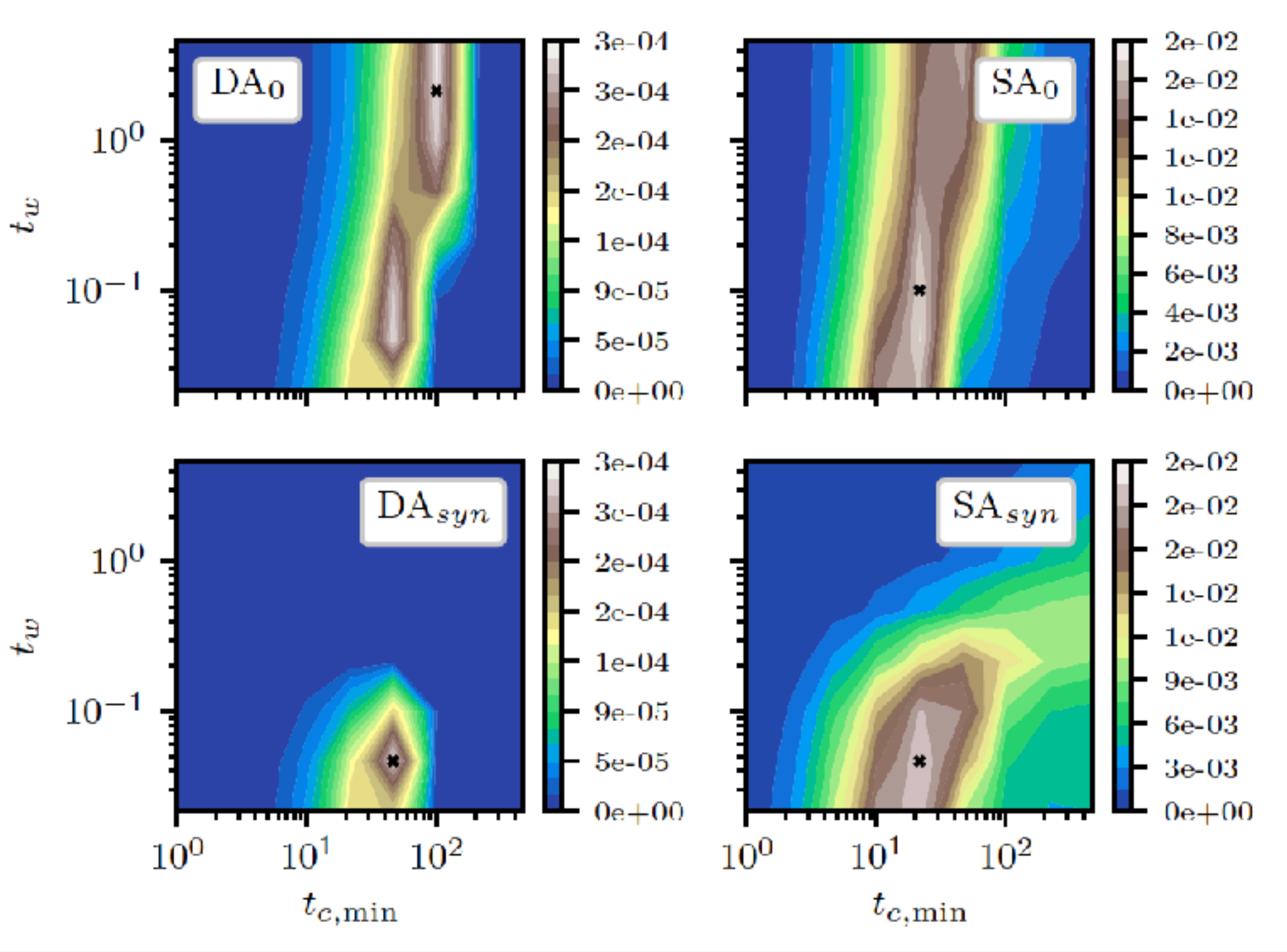
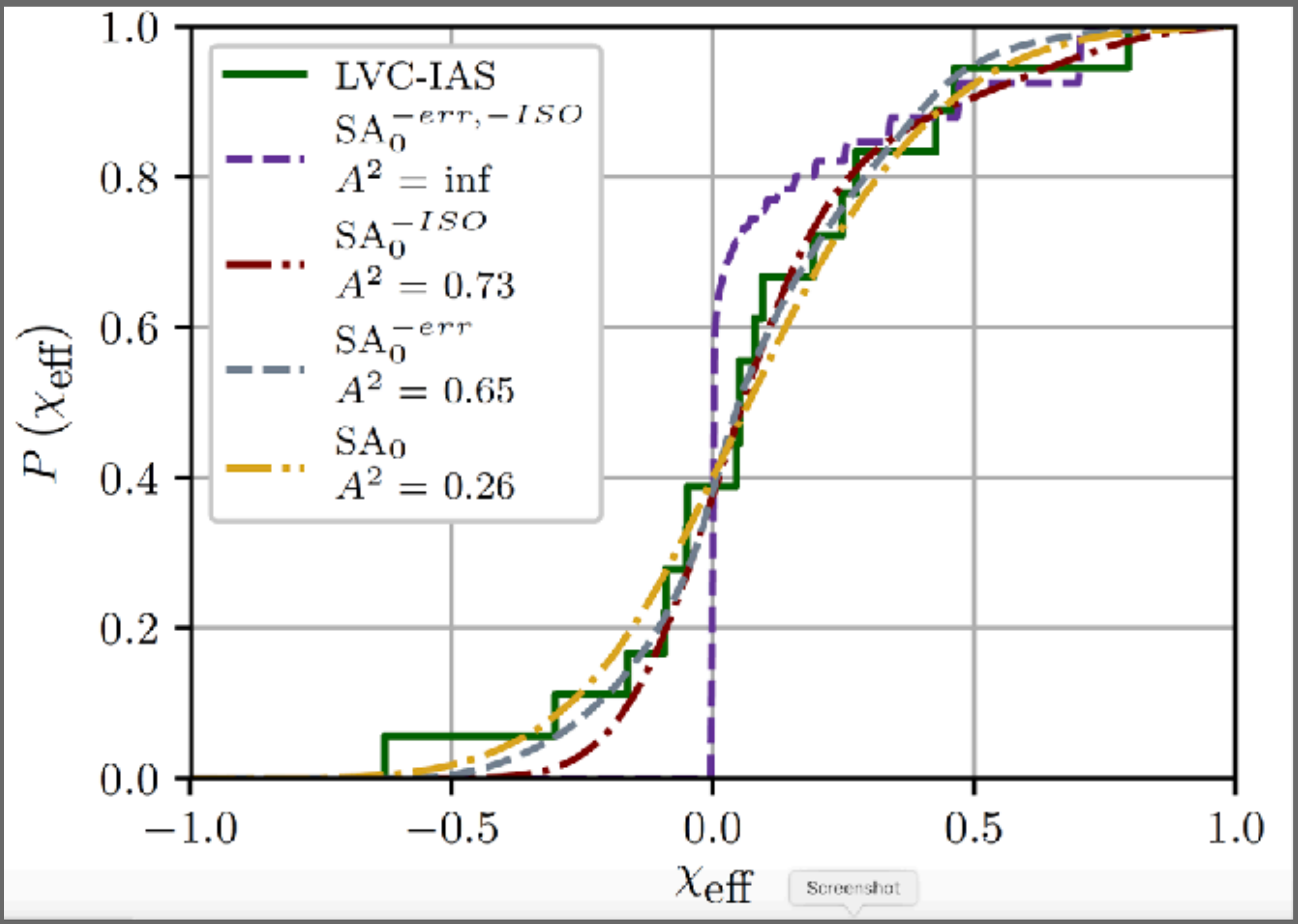
# Results - Field Binaries

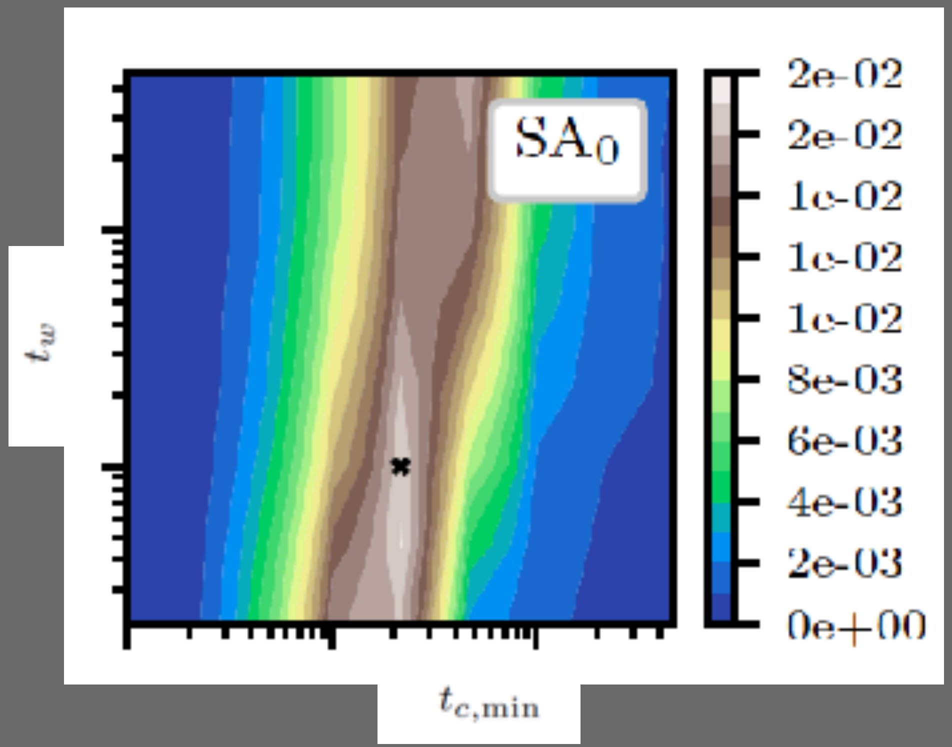


# The Best Model

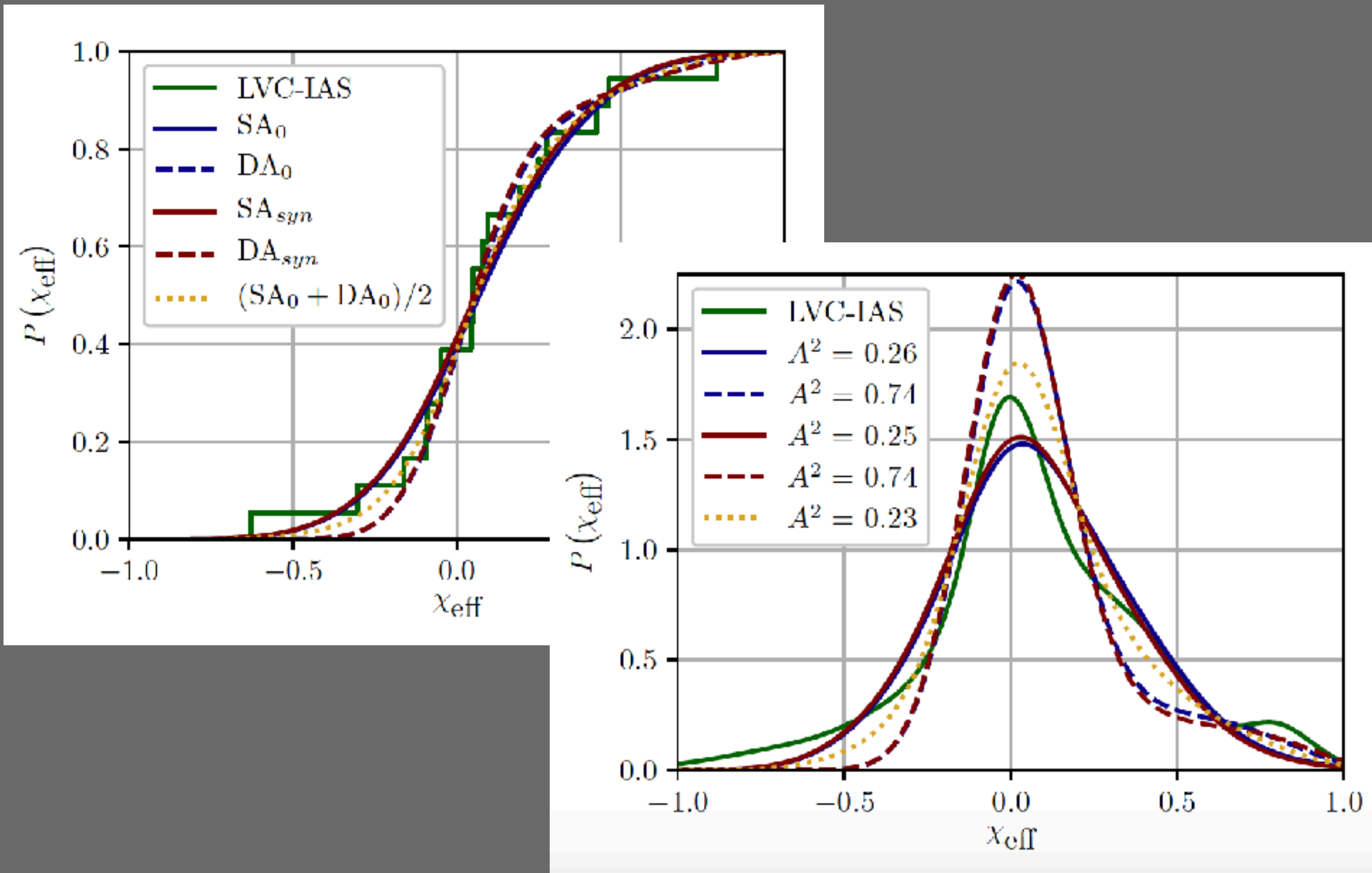
Single Aligned
& $\chi_0$=0

$t_{c,min}$ = 20 Myr
$t_w$ = 0.1-3 Myr

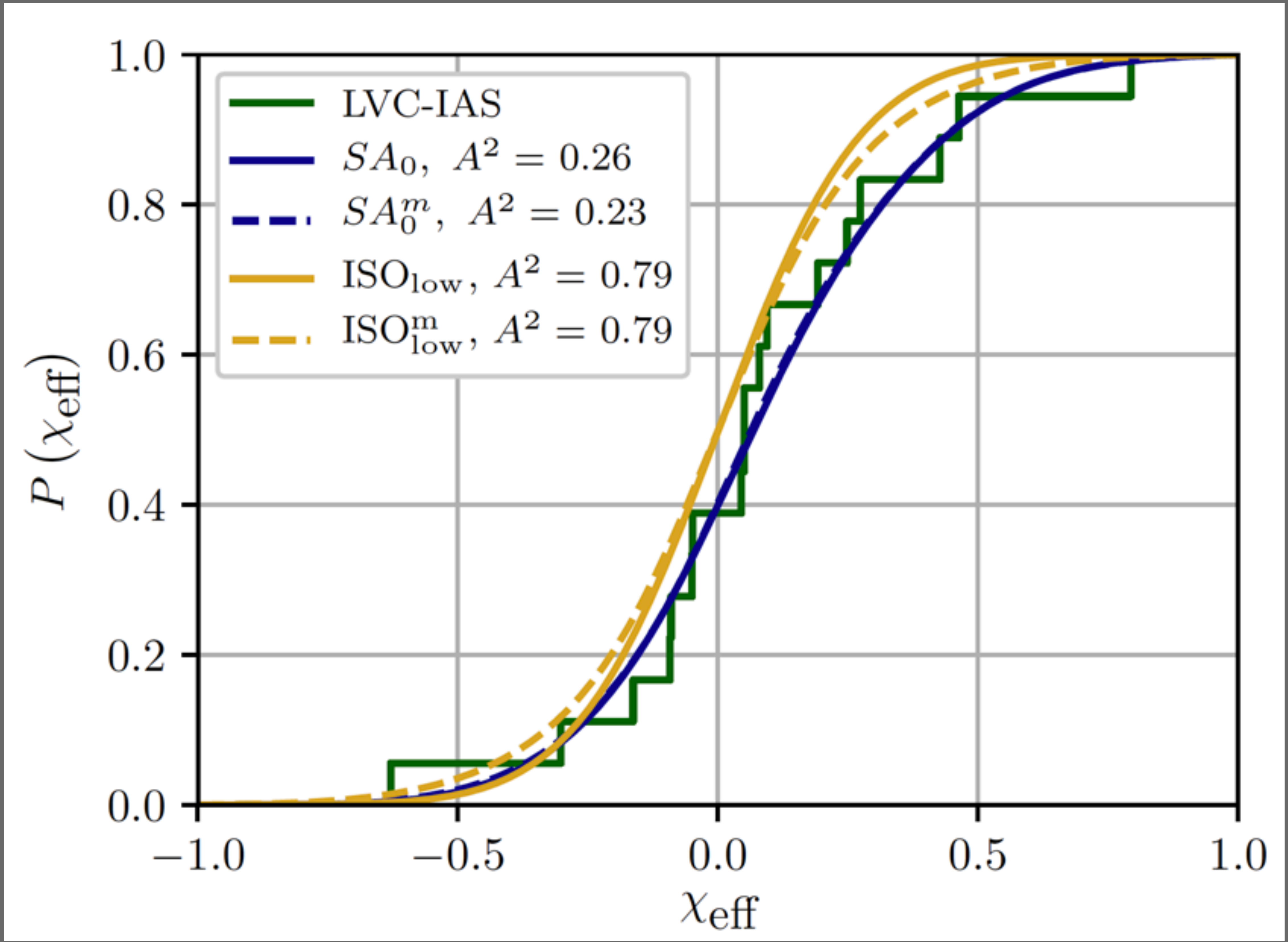


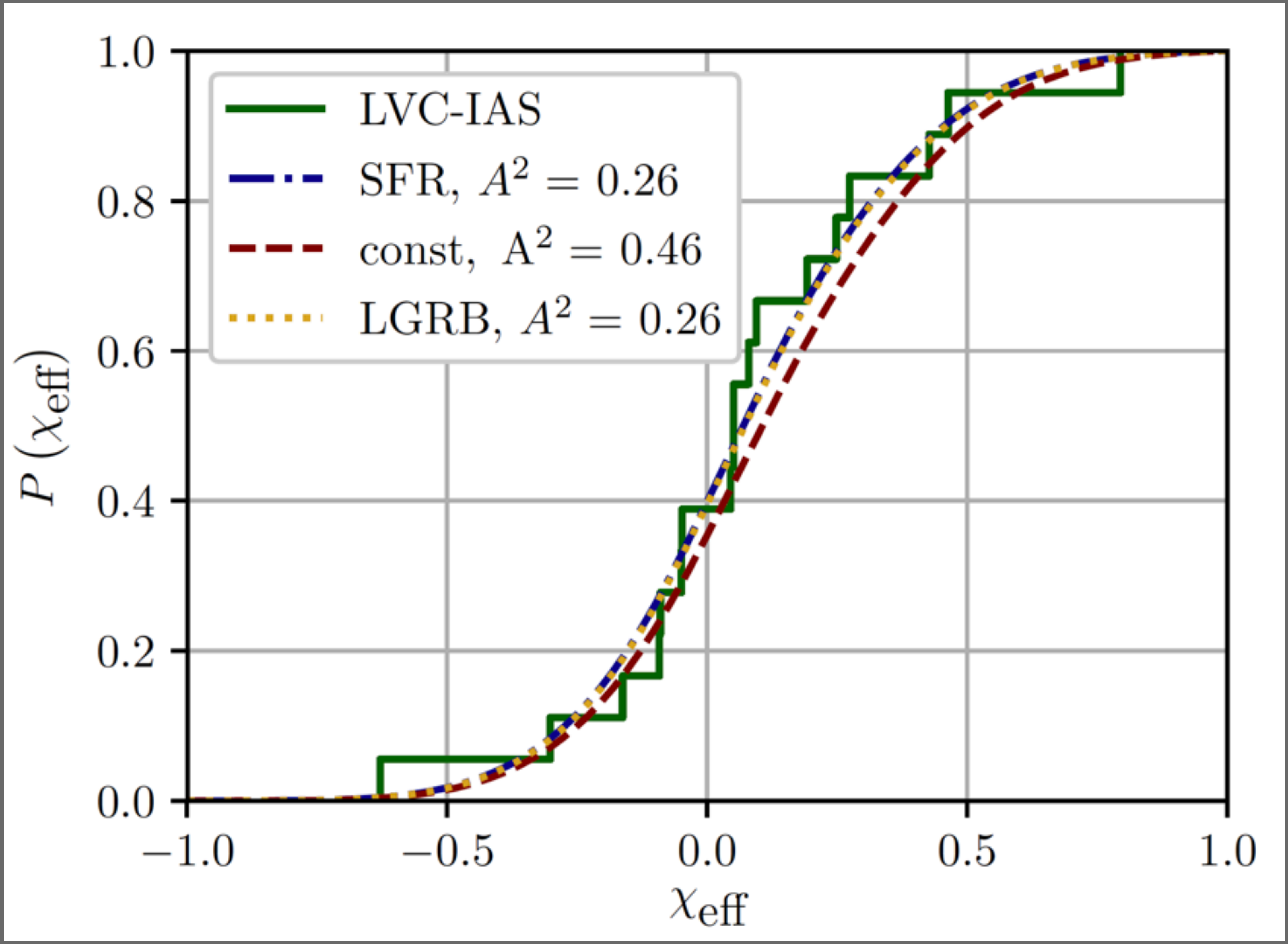
# Other Field Binary Models



# Different masses:



# Different Source Rates



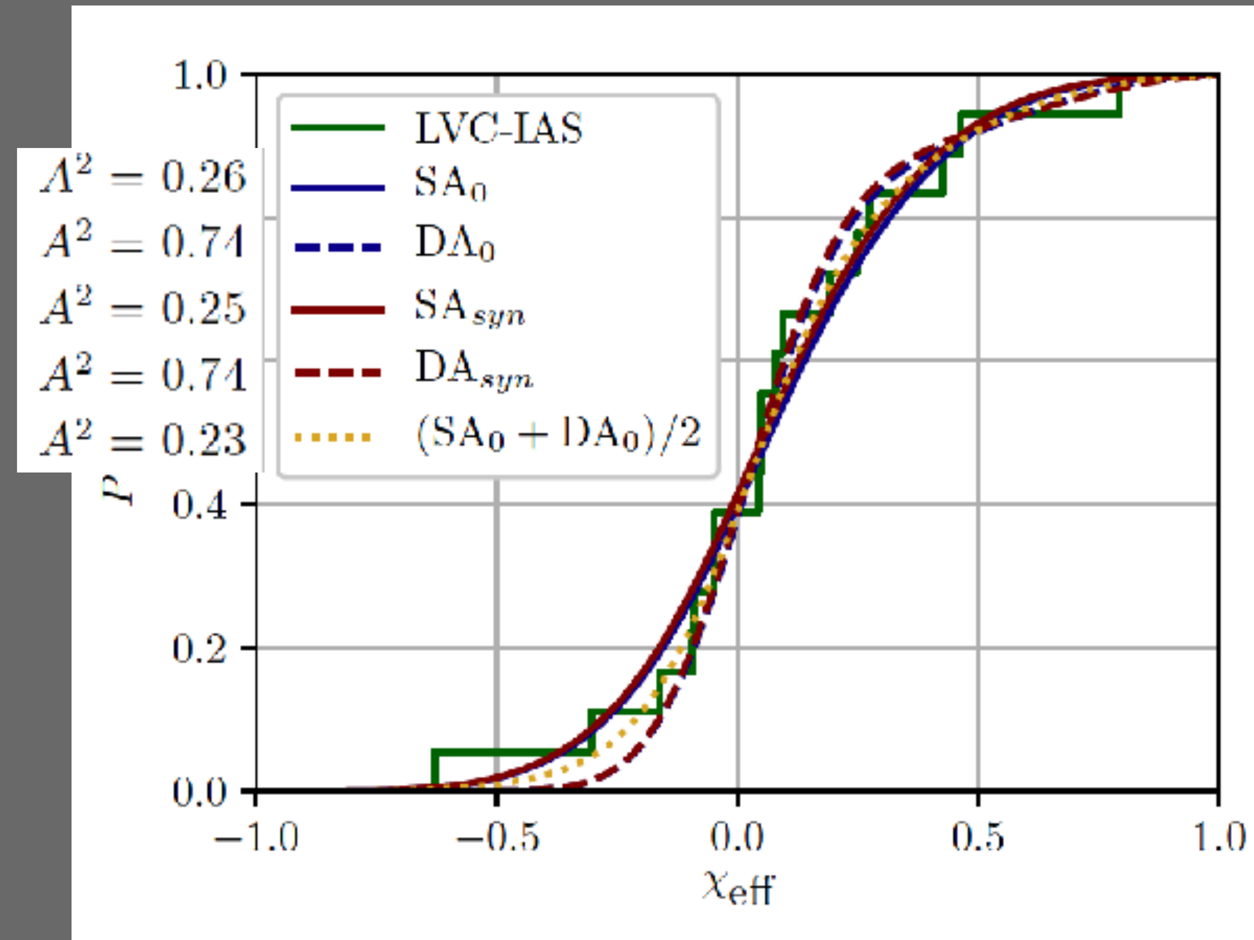
# Conclusions I

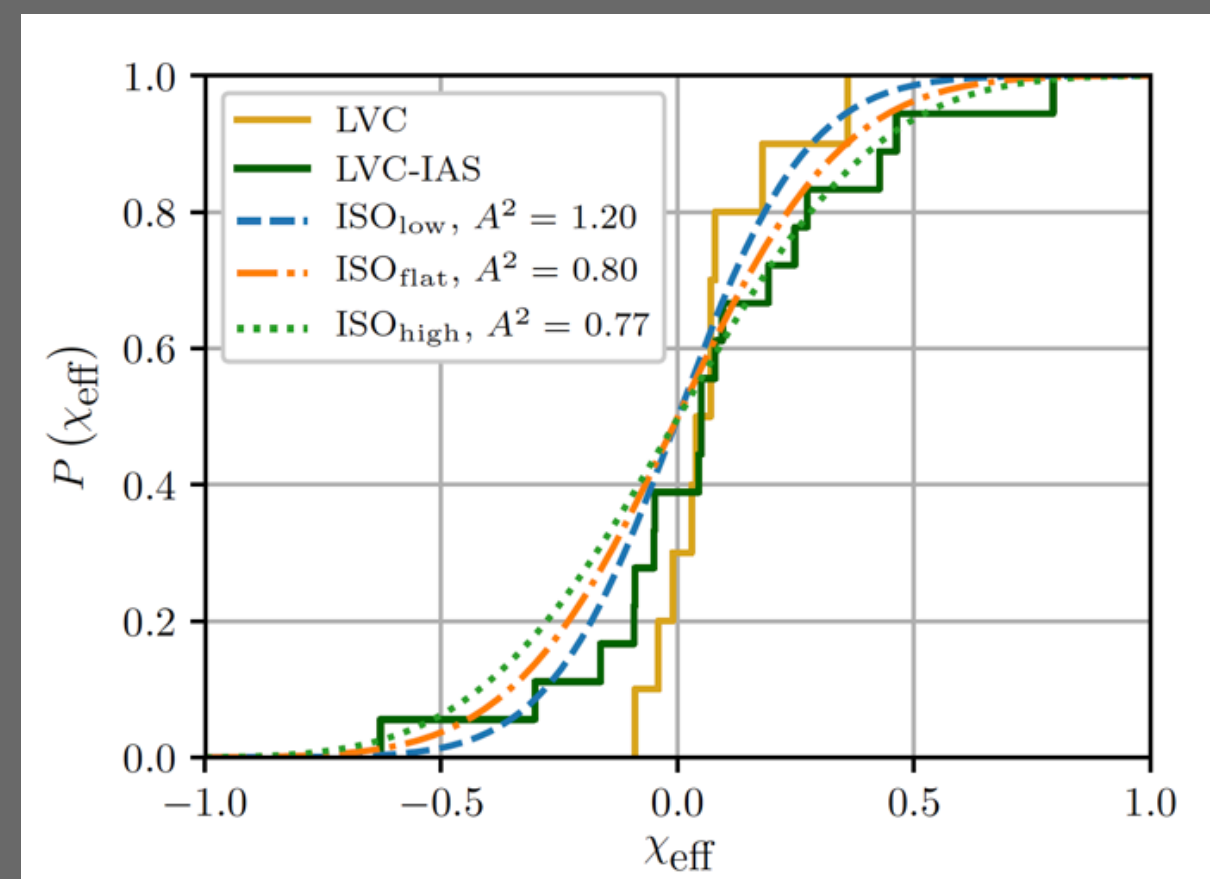
- Single aligned $\chi_0$=0 and Double aligned scenarios fit the data with reasonable physical parameters.

- A possible mixture of these scenarios.

- Removal of uncertain events improves the fit.

- Isotropic distributions are not ruled out but are less favored.



The new results turned the odds in favors of Field Binaries

=> Expect ~10-20% high spins in O3

(see also Romero-Shaw et al. on eccentricity arXiv 1909.05466)

The end,
but not really the end…

# The end,
# but not really the end…

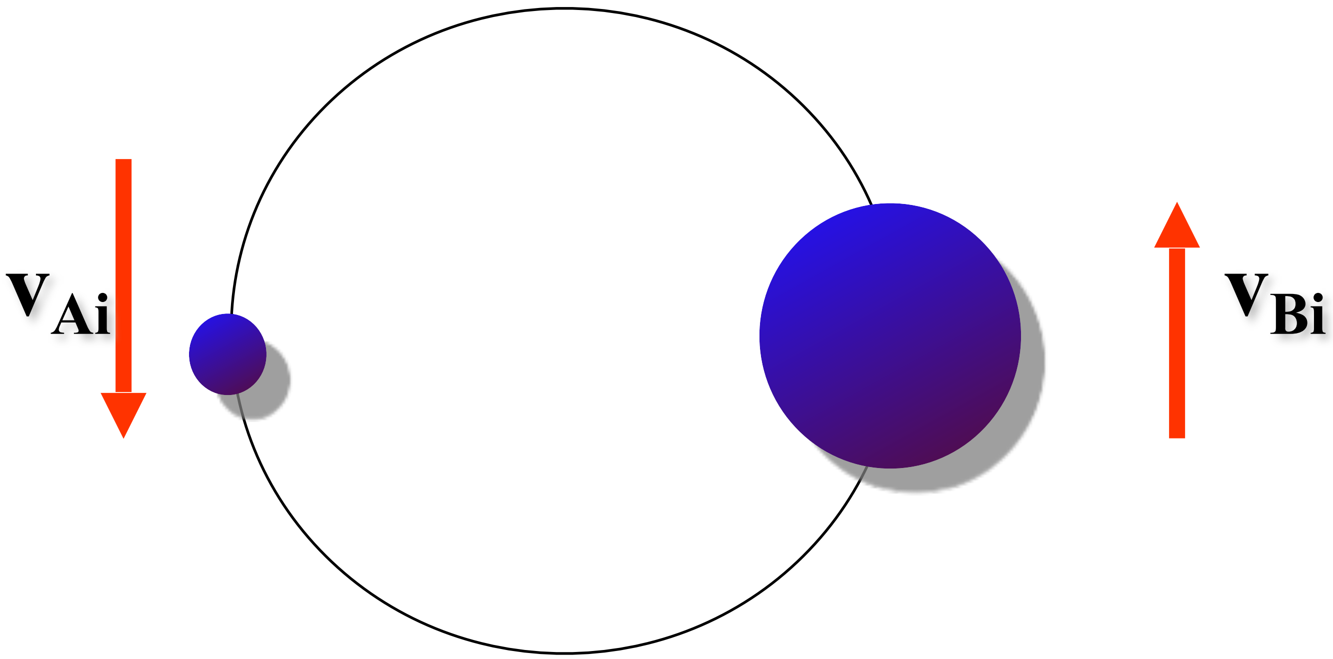
*We all wait eagerly to the O3 results*

# II. The Origin of (galactic) Binary Neutron Stars

The rise and fall of kicks

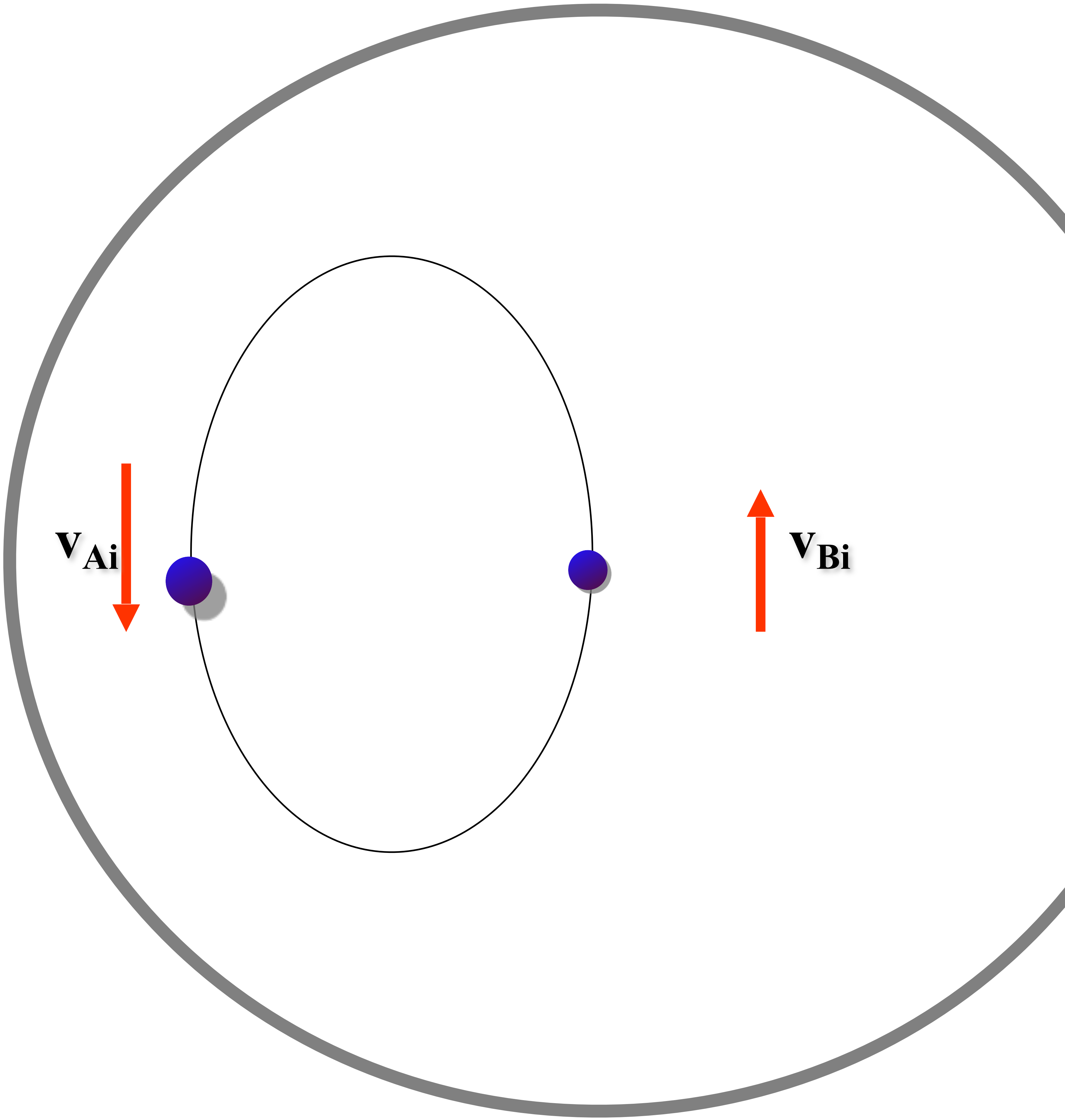
If your theory explains all the observations it must be wrong, because some of the observations are wrong

B. Paczynski




**Because of tidal interaction between A and the progenitor of B the orbit was circular.**

**As mass is lost from B in the orbit becomes elliptical**



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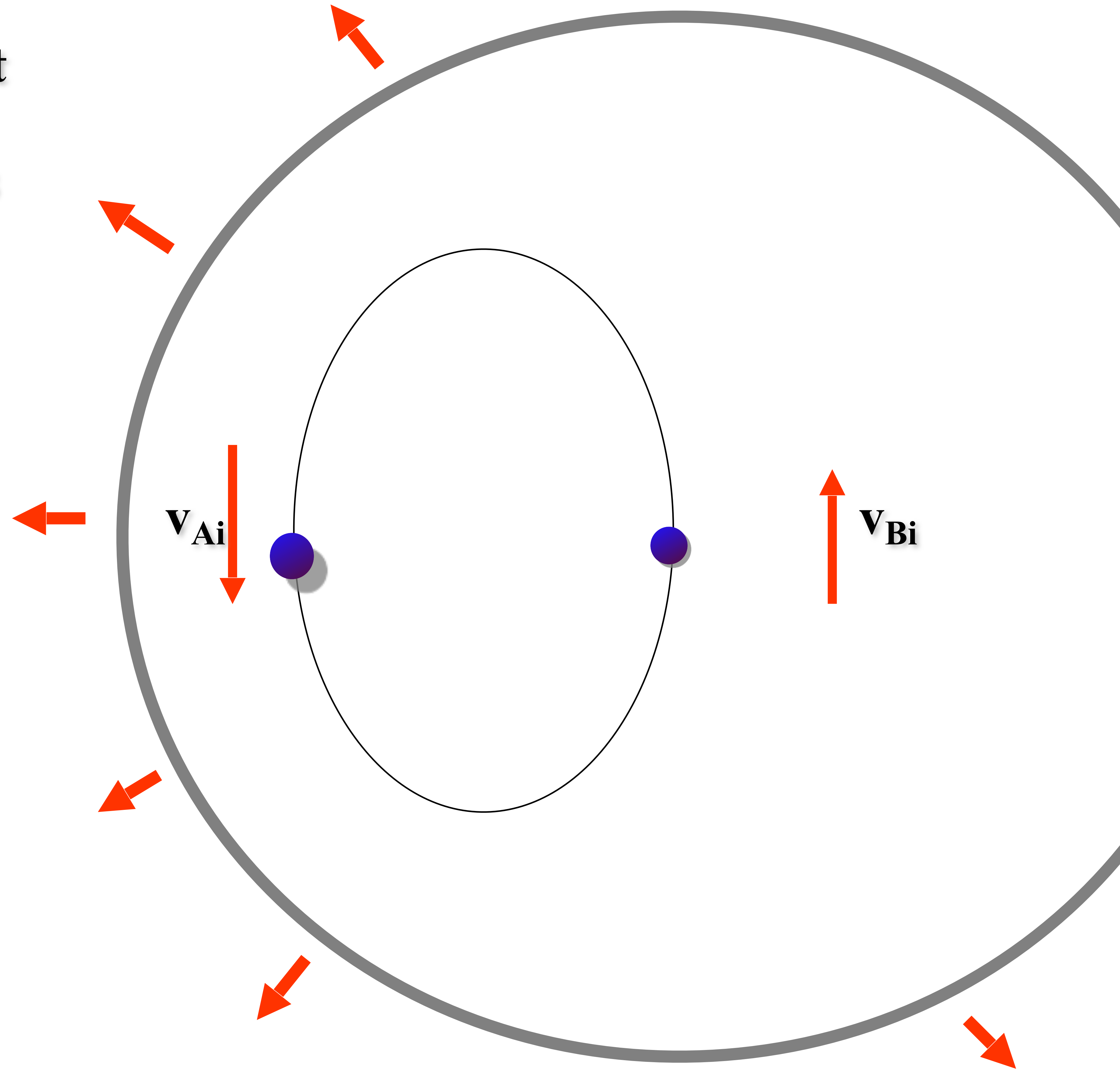

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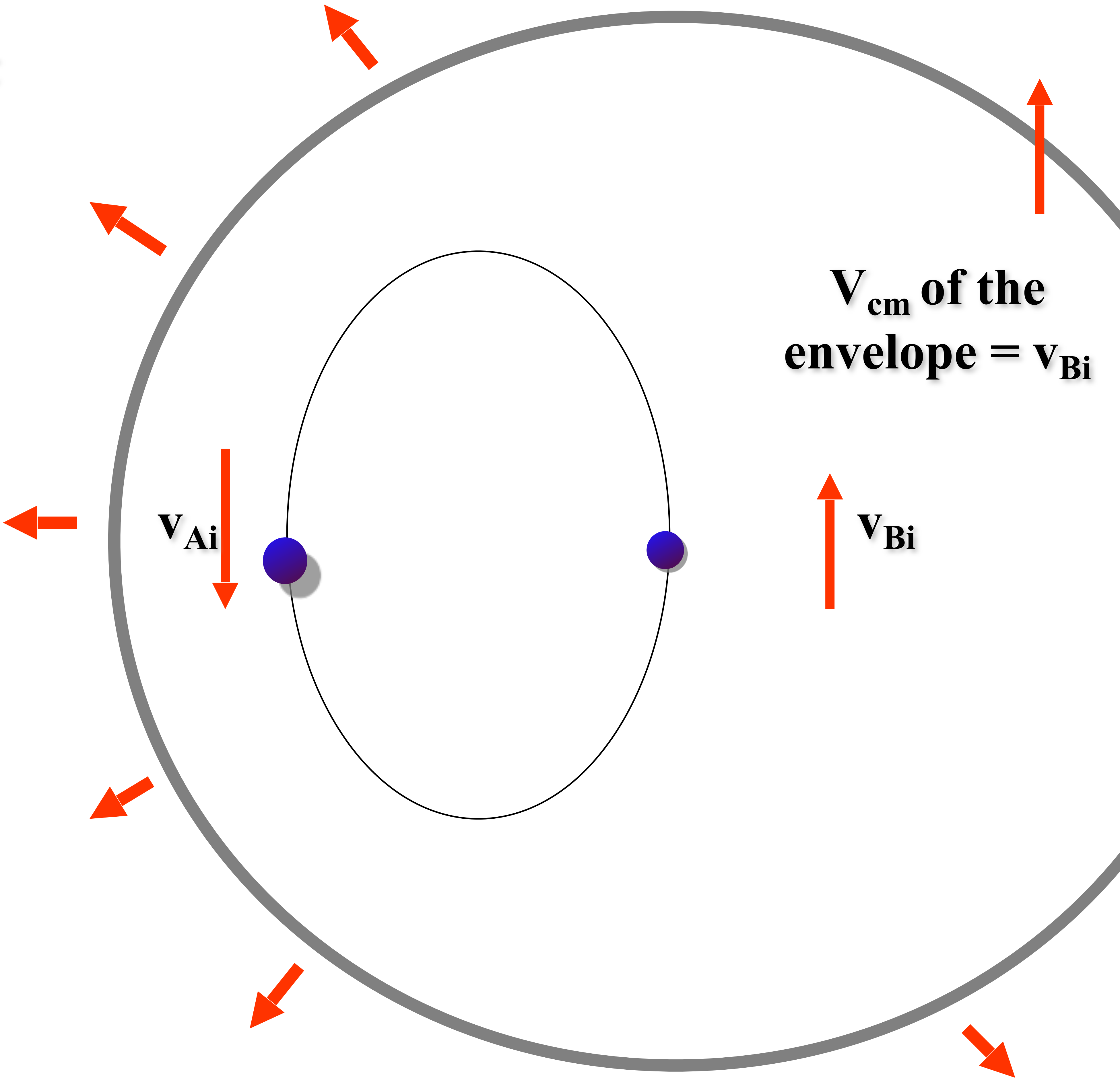
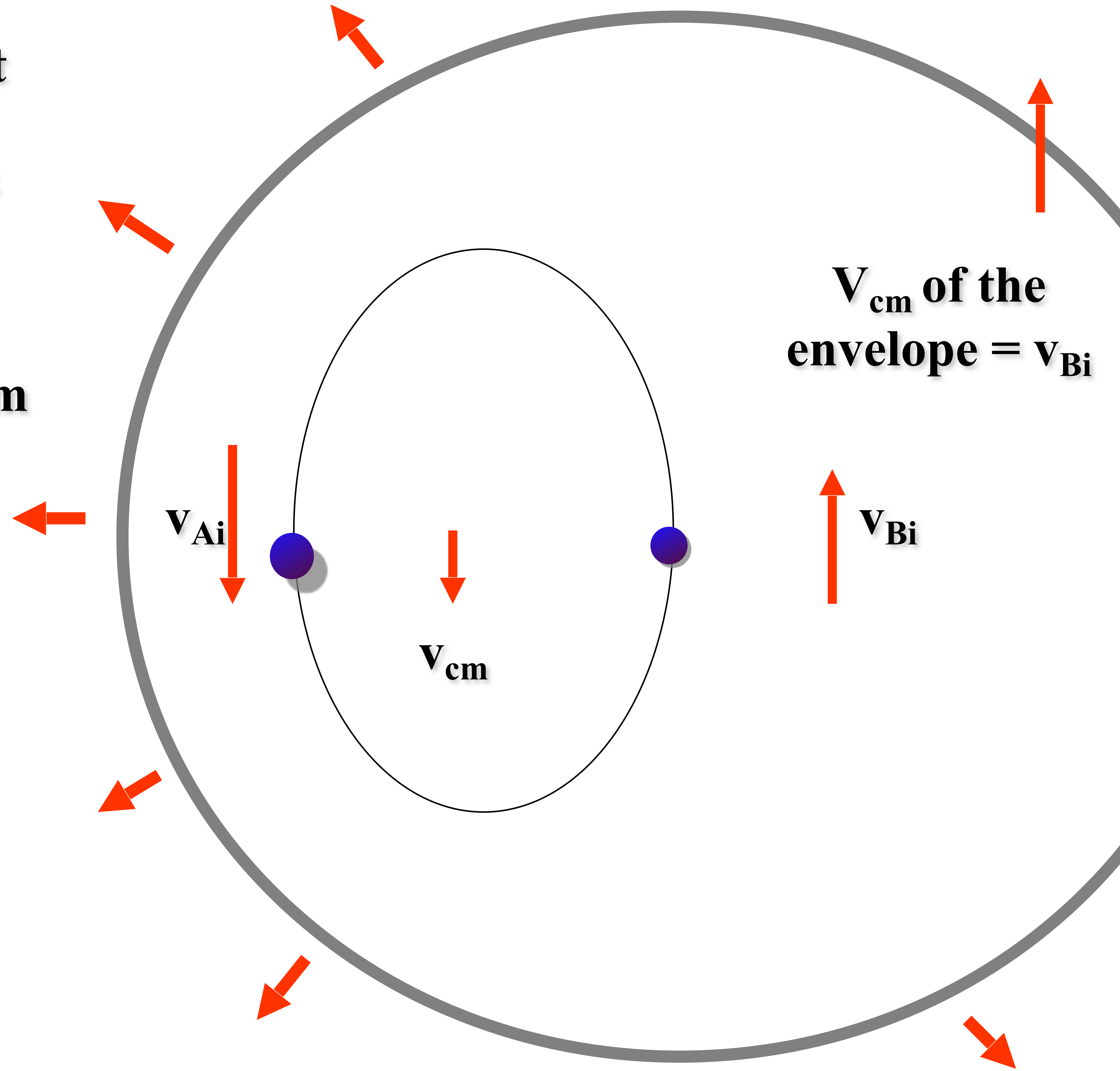


As mass is lost from B in the orbit becomes elliptical

And the system attains a cm velocity



**As mass is lost from B in the orbit becomes elliptical**

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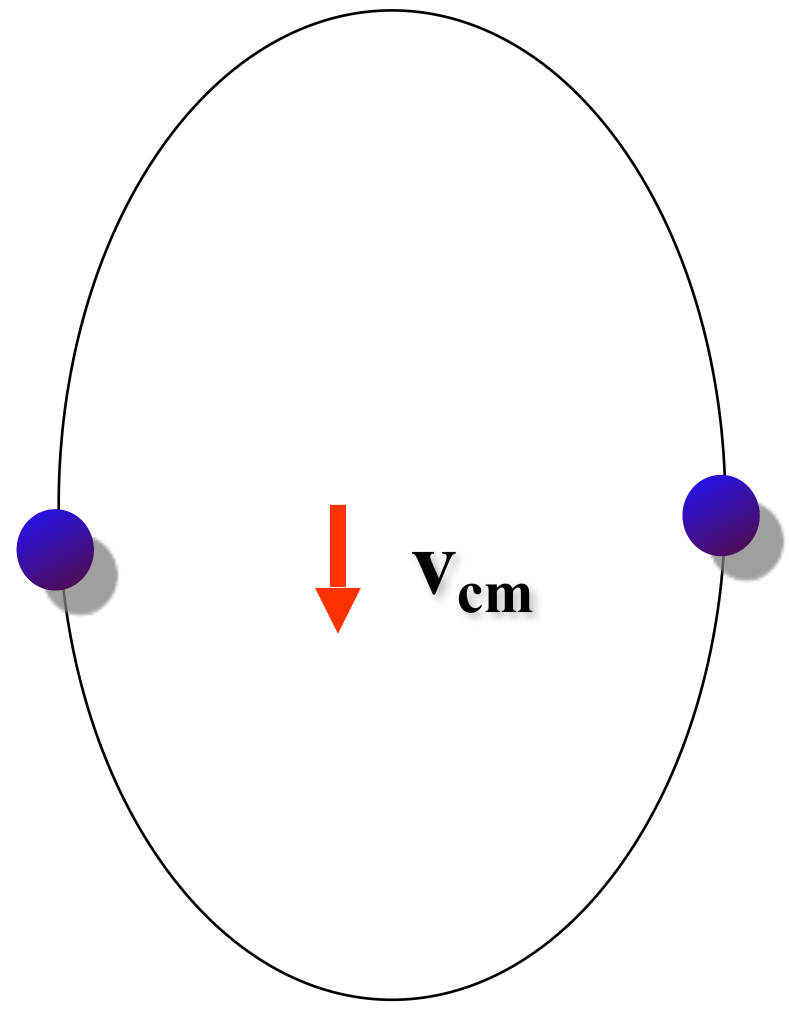

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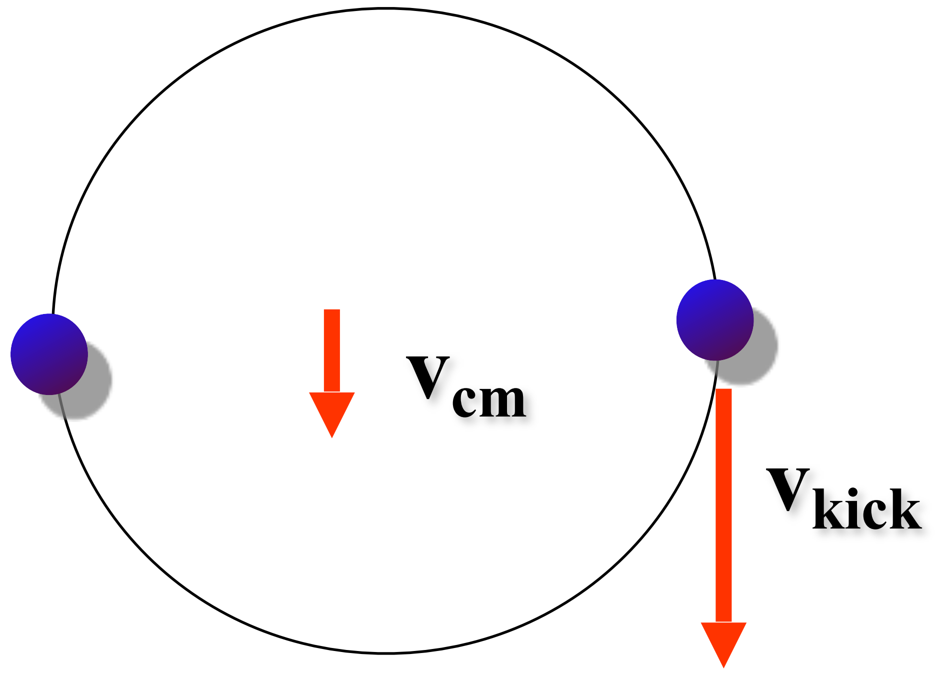
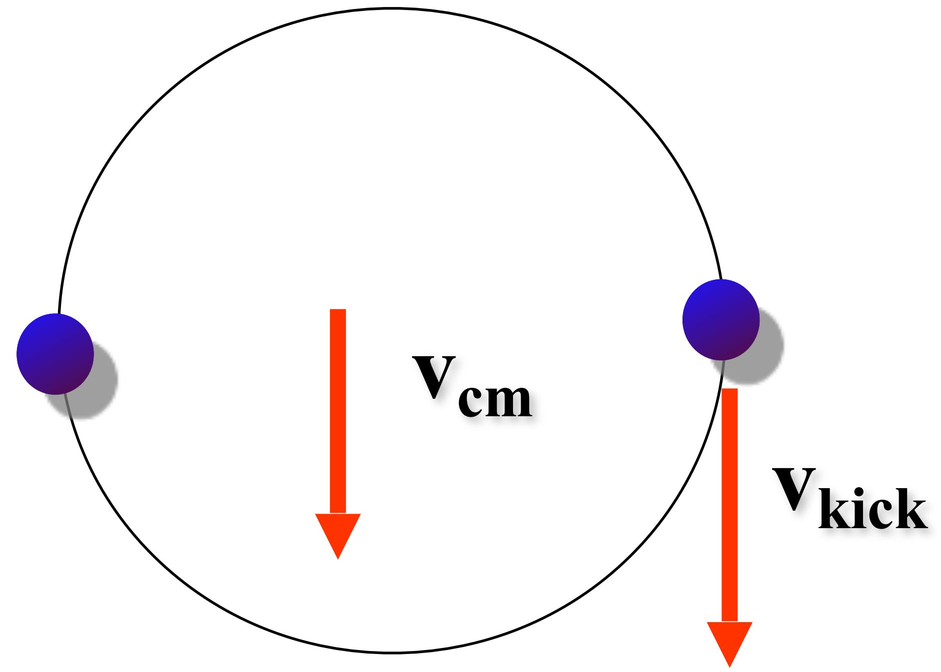


**As mass is lost from B in the orbit becomes elliptical**

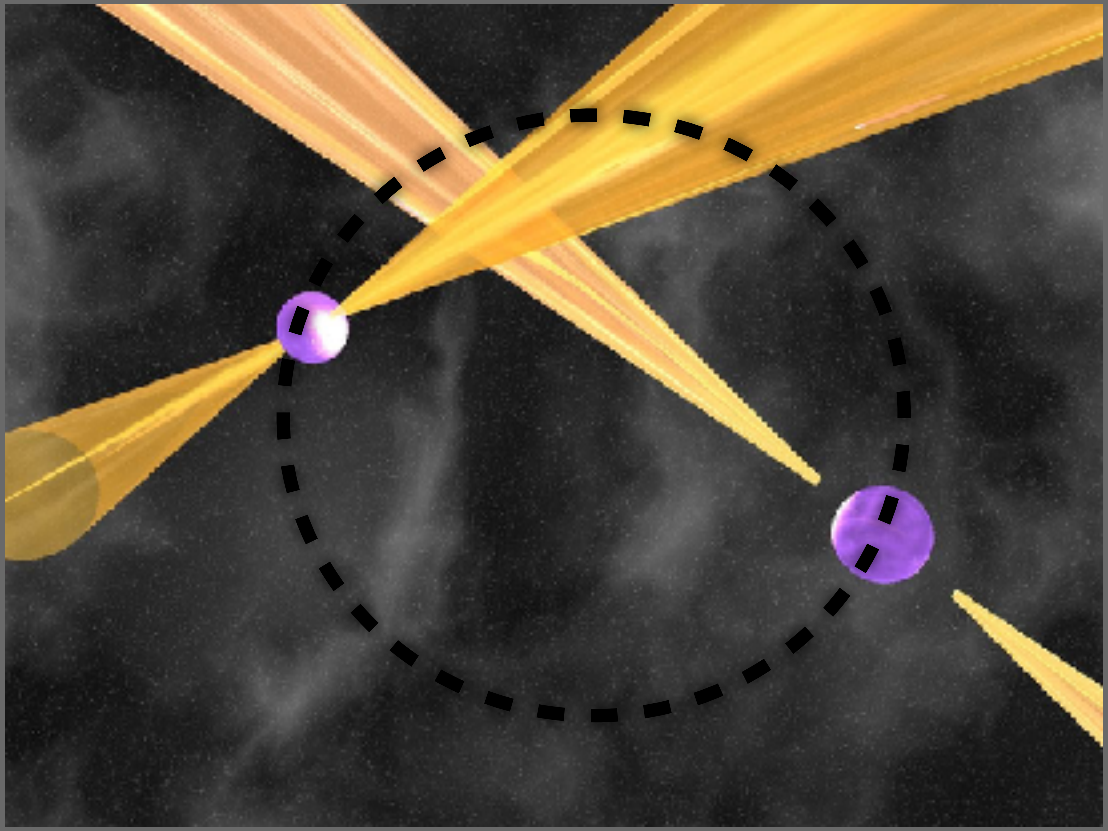
**And the system attains a cm velocity**




**A kick velocity fixed the eccentricity but introduces even larger cm motion**

# J0737-3039 - The Double Pulsar

TP & Shaviv 2005



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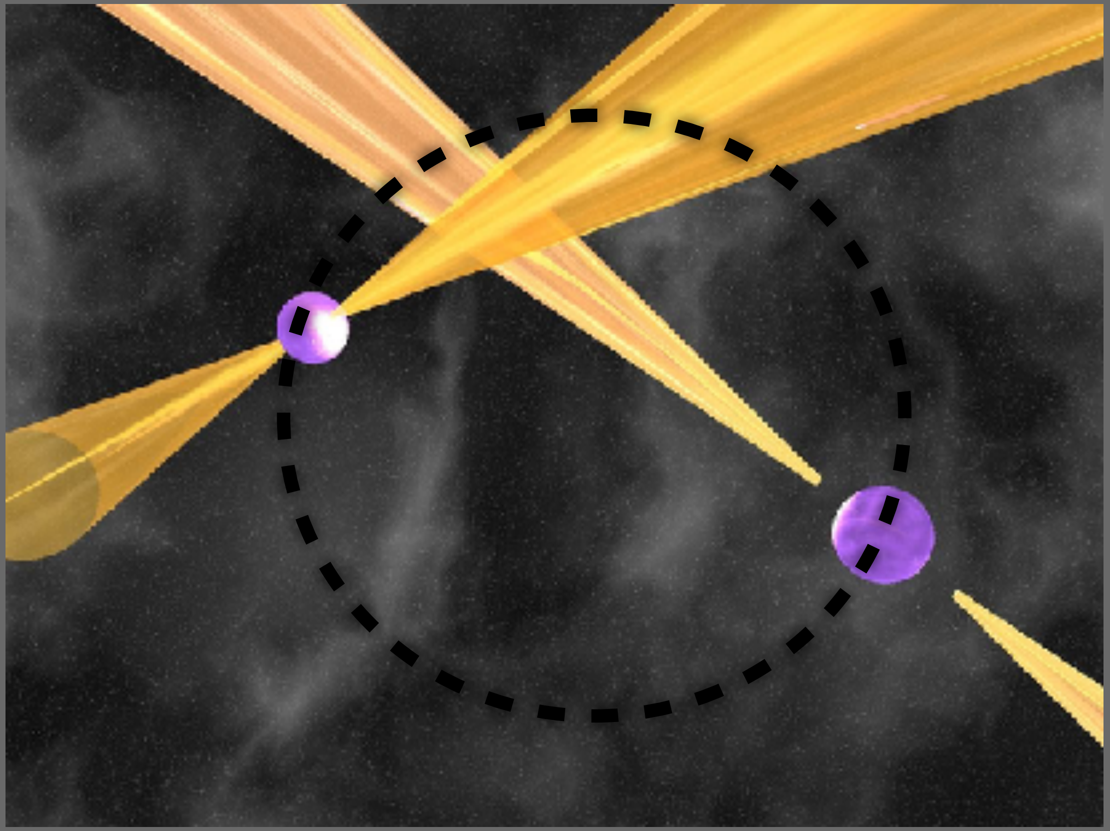
- The orbit of the double pulsar (J0737-3039B) is almost circular and it is in the galactic plane



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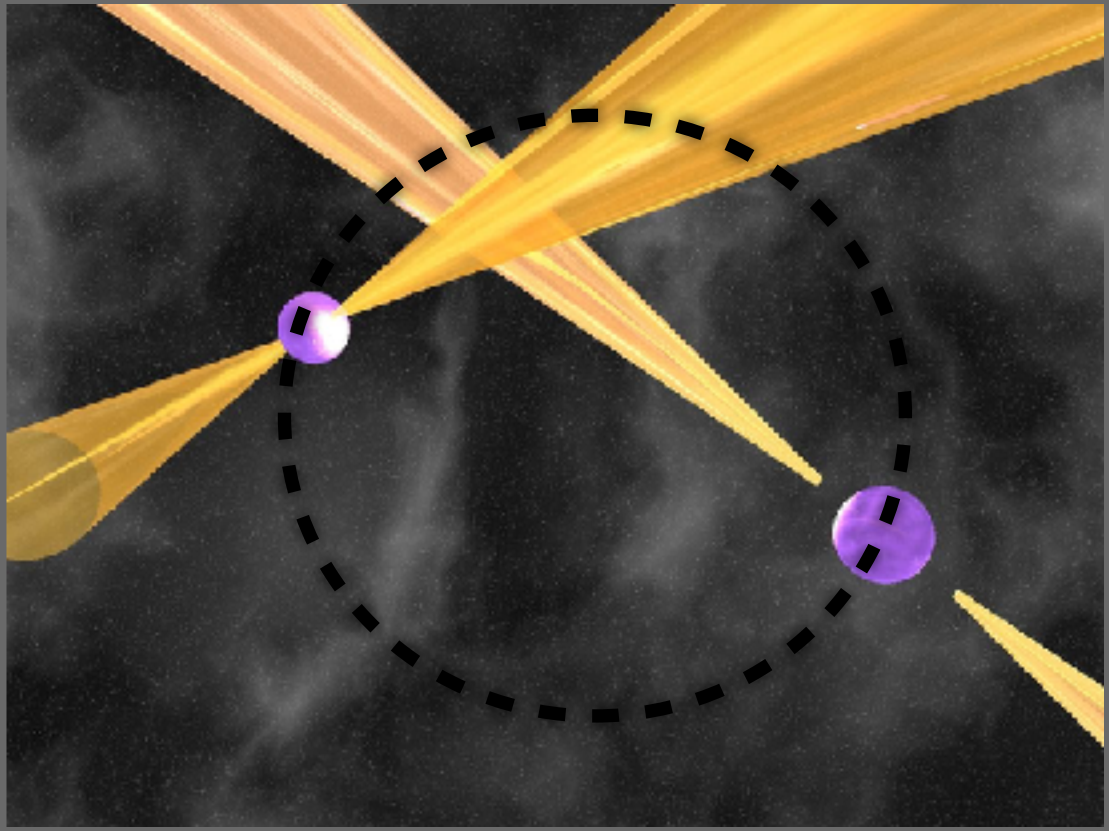

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- ✳The orbit of the double pulsar (J0737-3039B) is almost circular and it is in the galactic plane
- ➡Very low mass ejection (<0.1 $M_{sun}$) and very low peculiar motion
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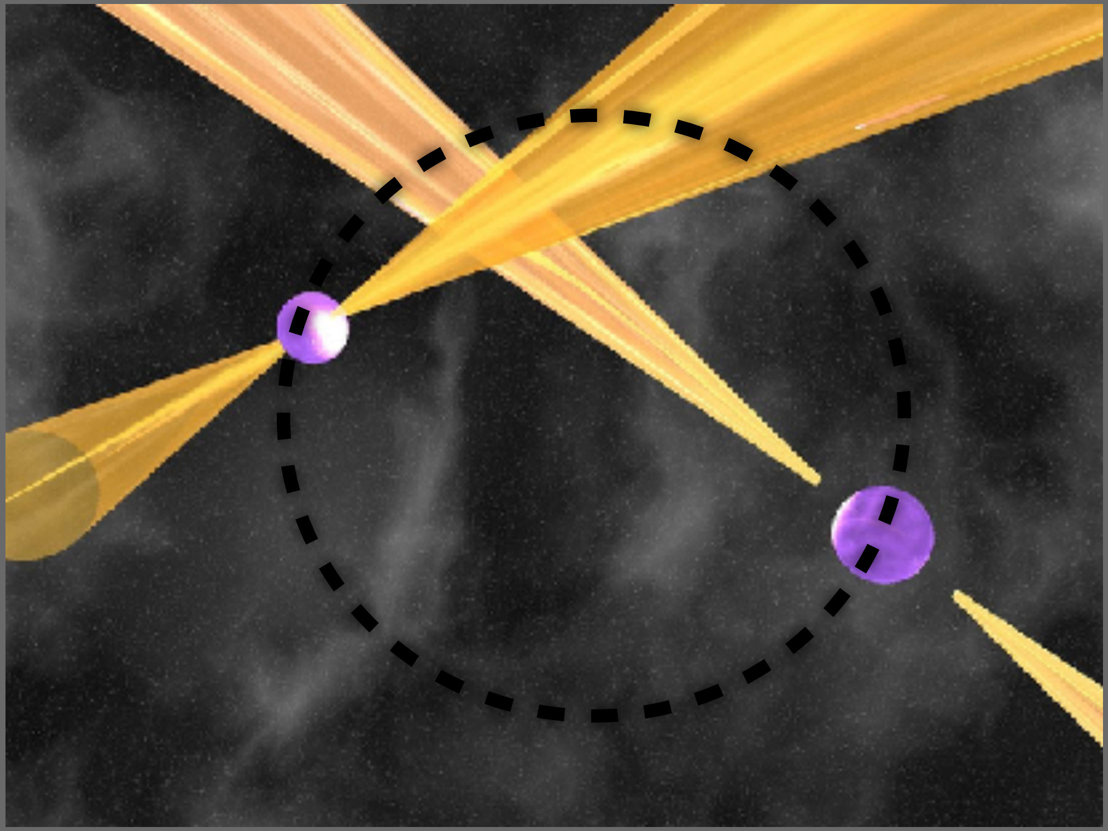
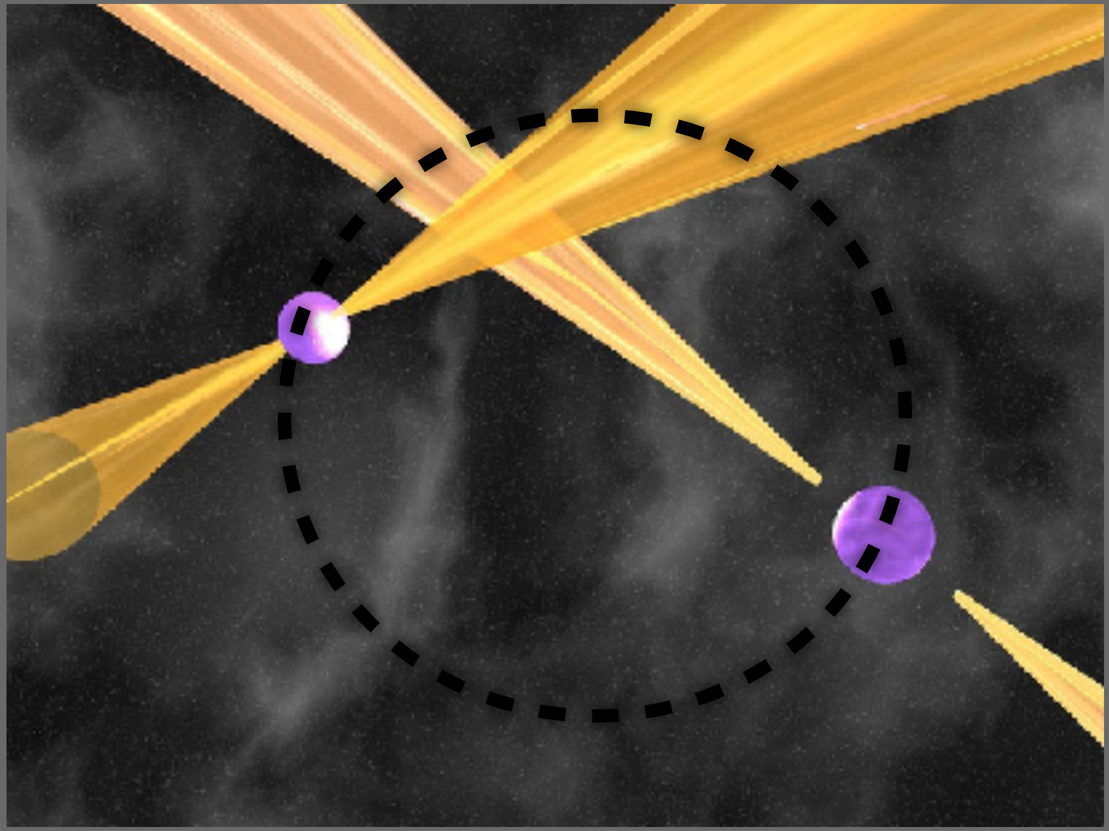


# A remark about binary neutron stars

TP & Shaviv 2005; Dall'Osso, TP & Shaviv 2013,



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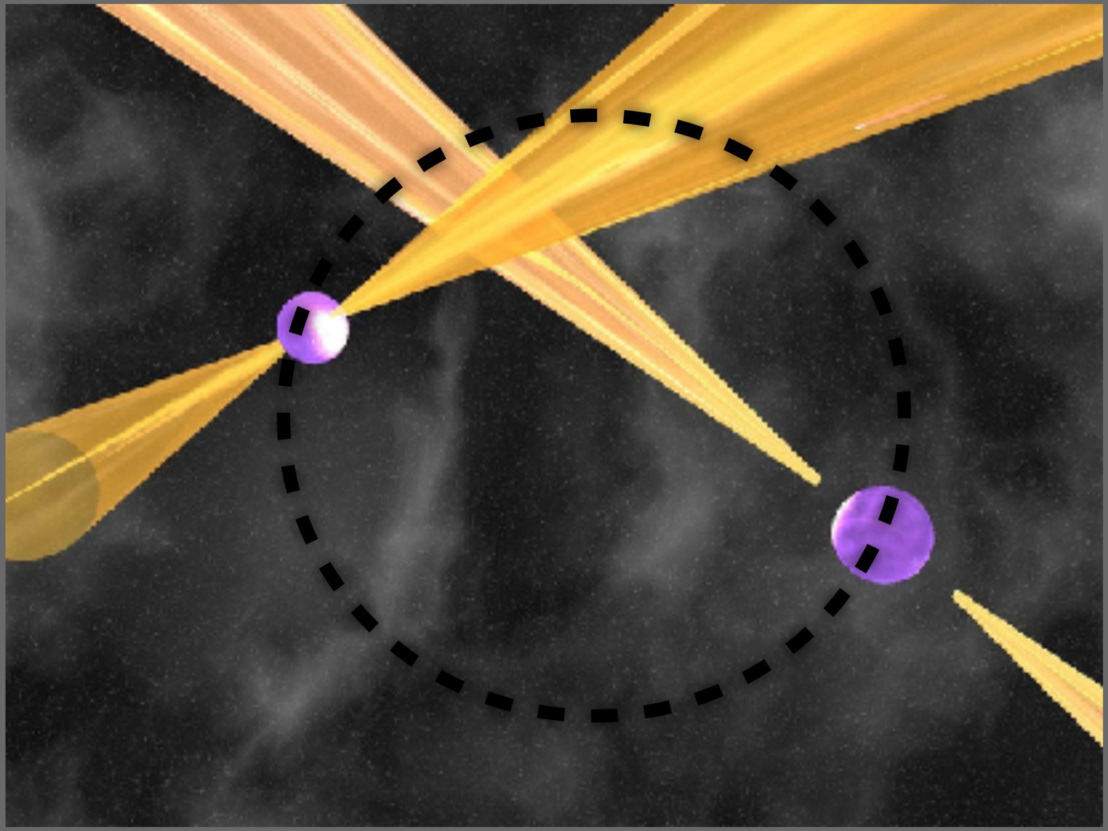

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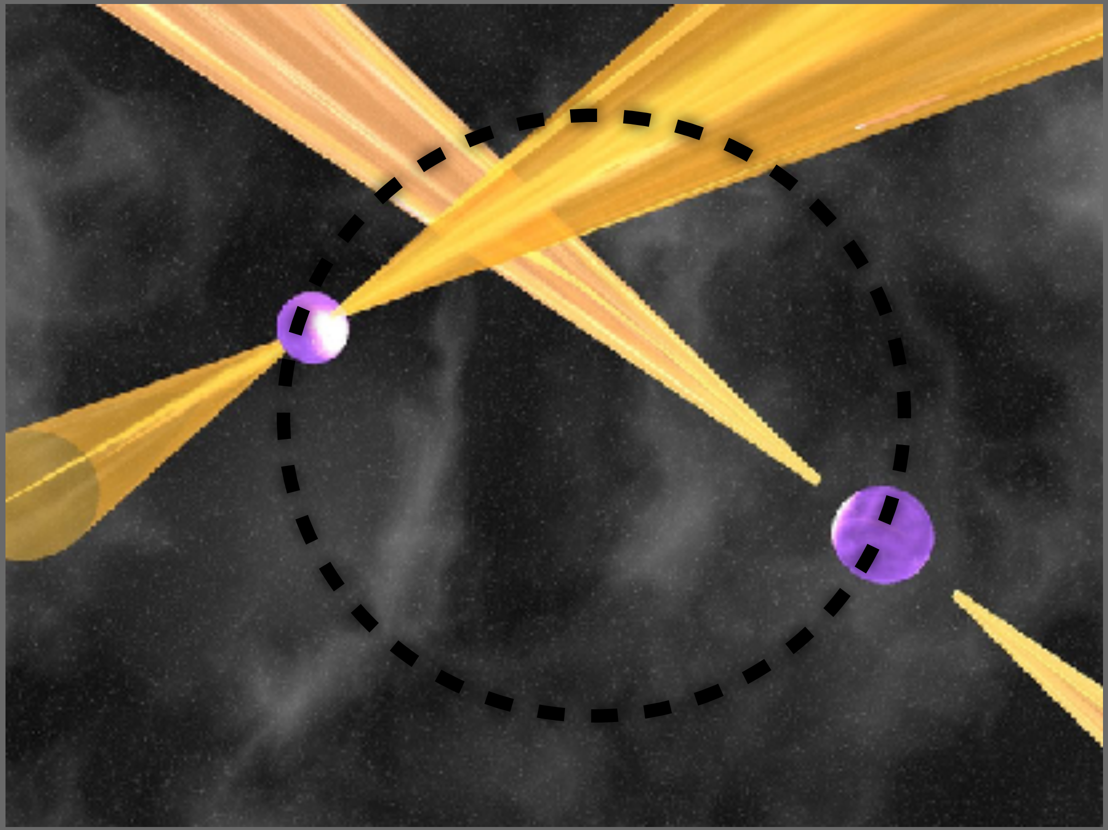

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✳Pulsar observations confirmed a peculiar motion of 10 km/s!

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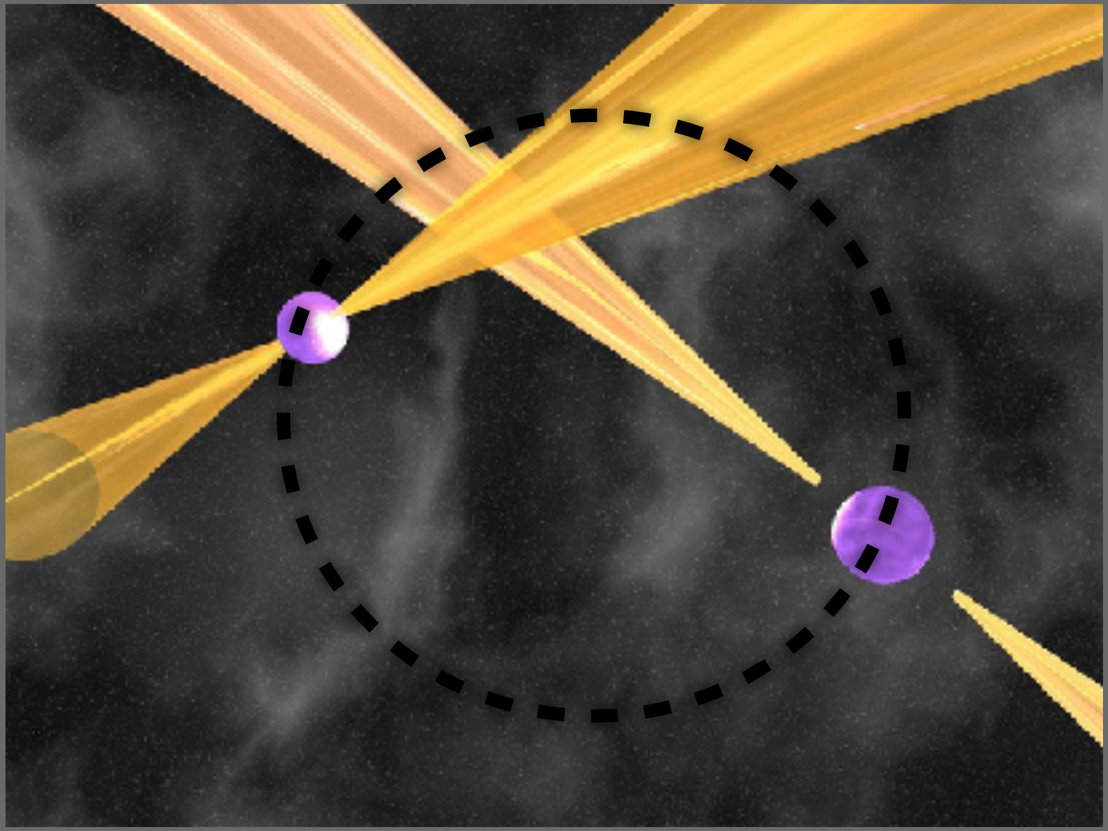
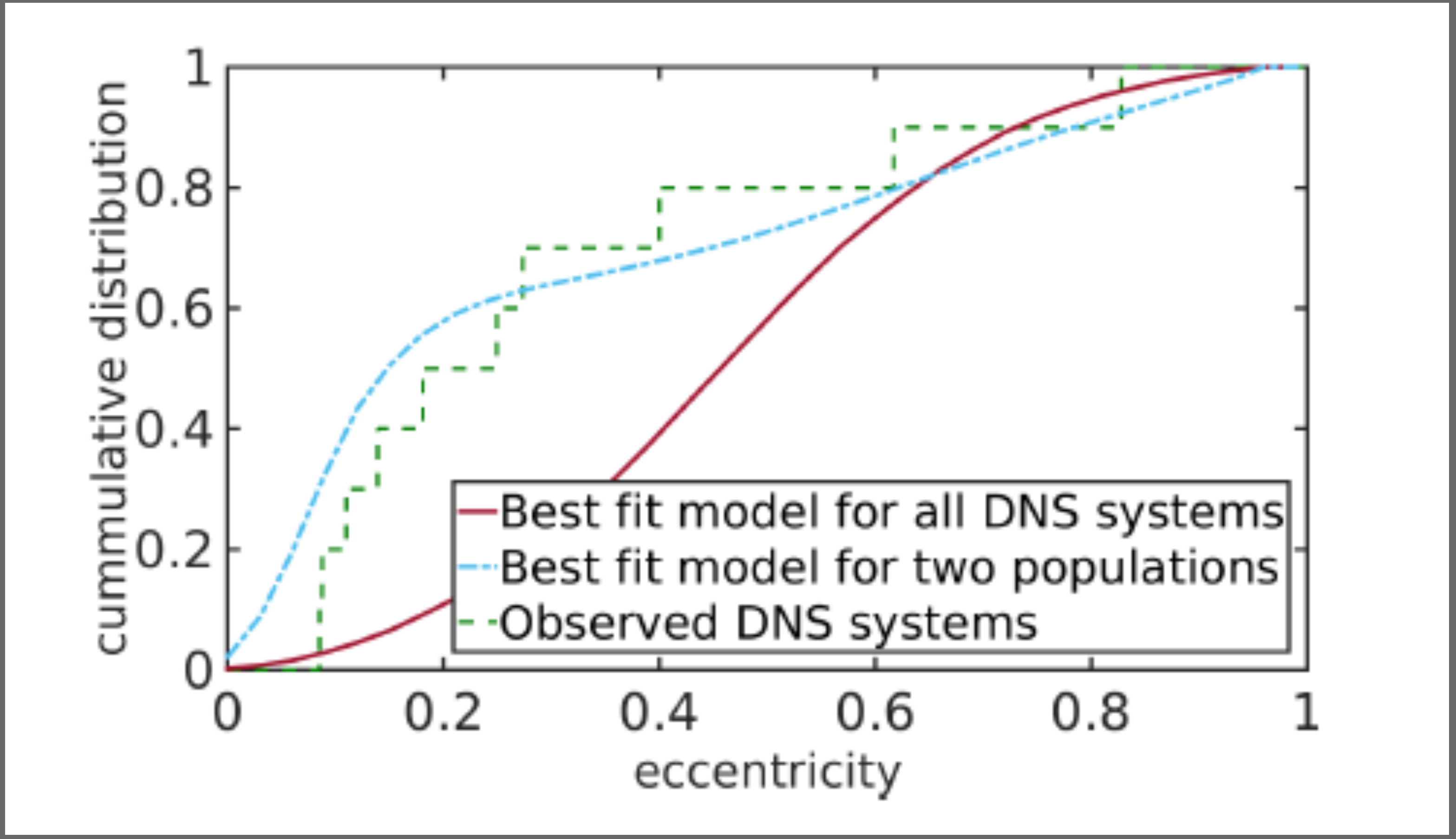
➡**J0737 would not have been ejected from Ret II !**



# The whole Binary pulsar population

Beniamini & TP 2015

- Most (2/3-3/4) observed Galactic binary neutron stars have almost circular orbits and a low peculiar motion.



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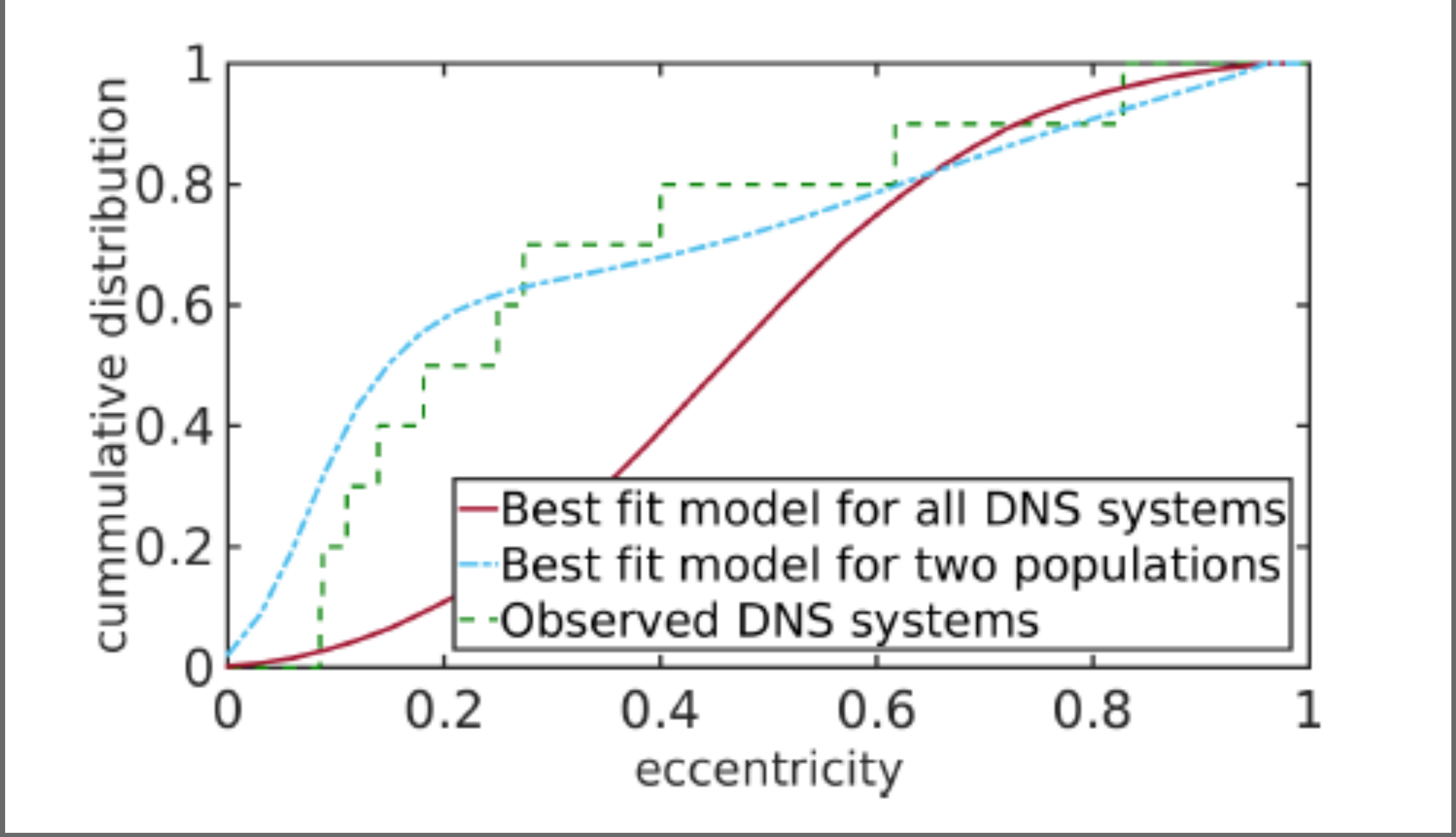
- ✳2/3-3/4 of binary pulsars detected since 2015 satisfy these conditions (almost circular orbit, low peculiar motion)



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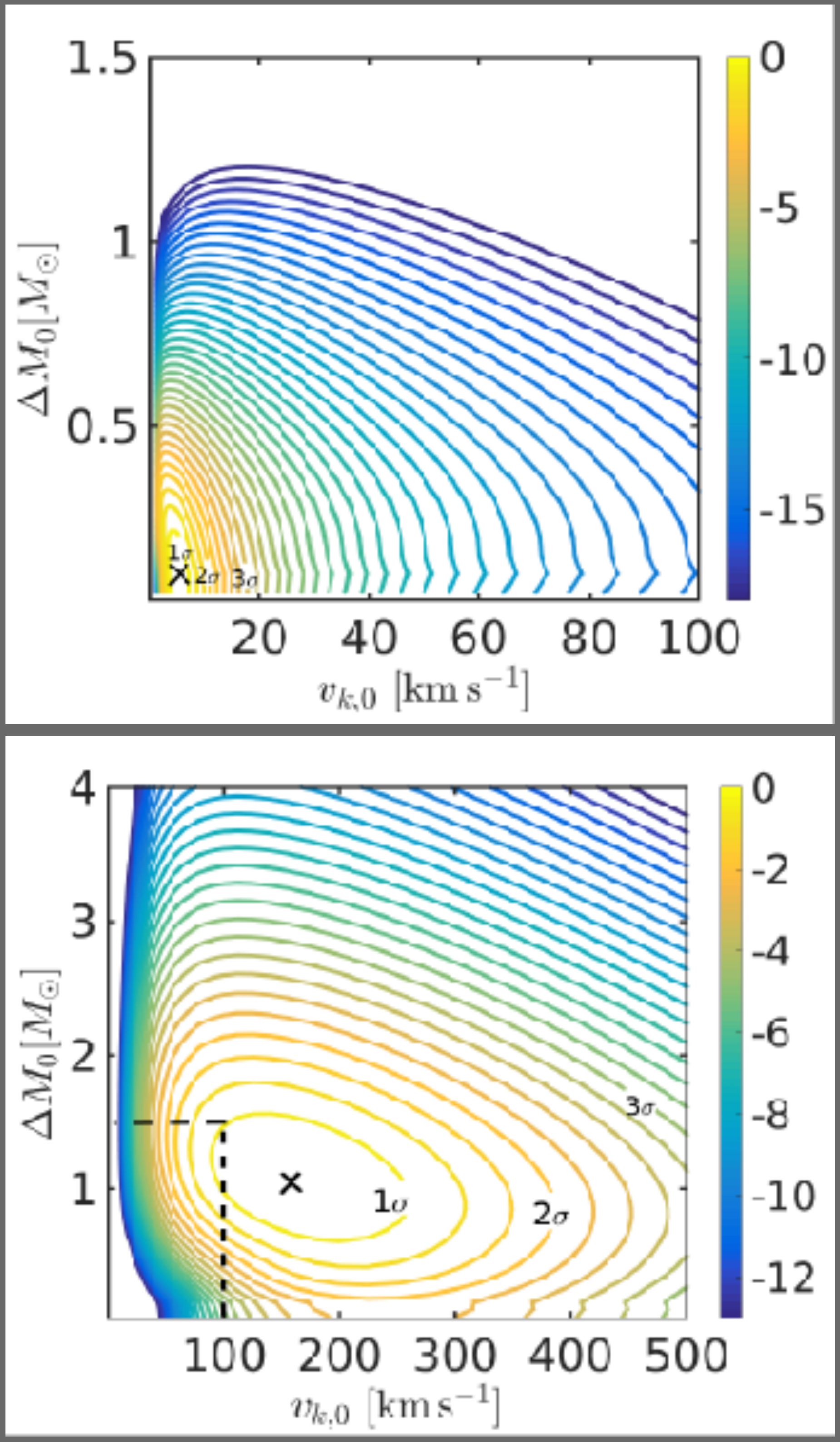

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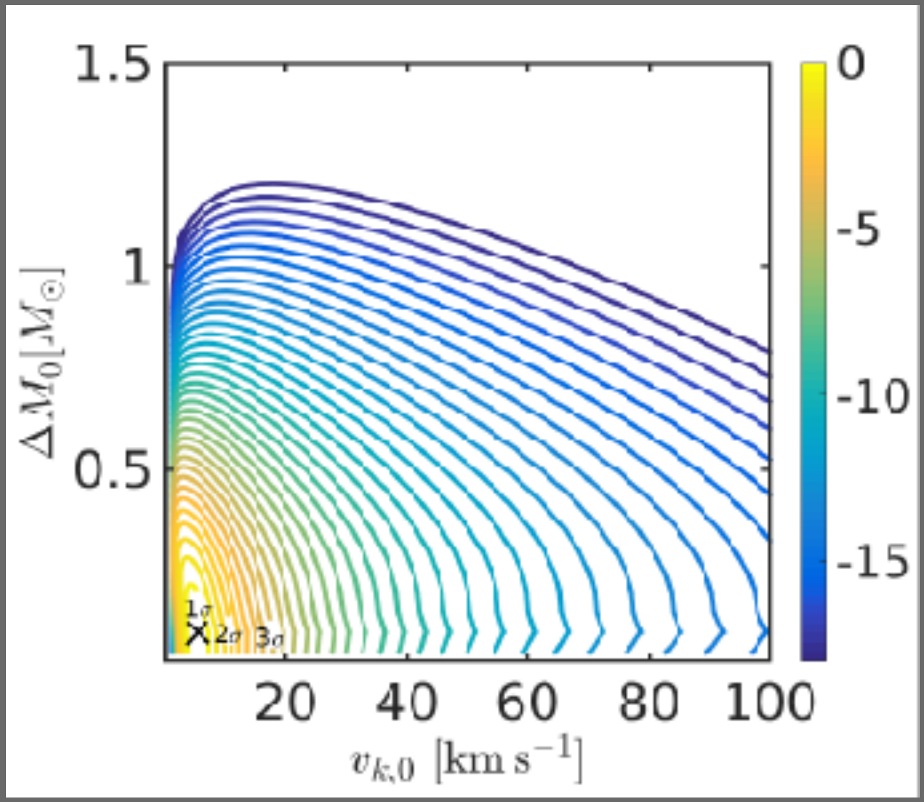


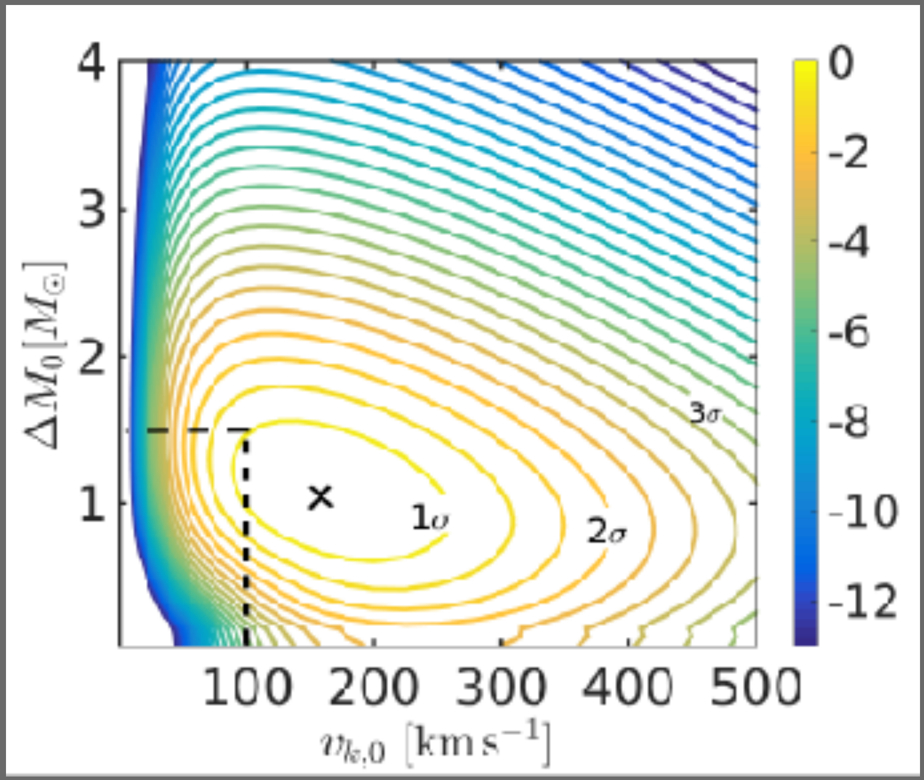

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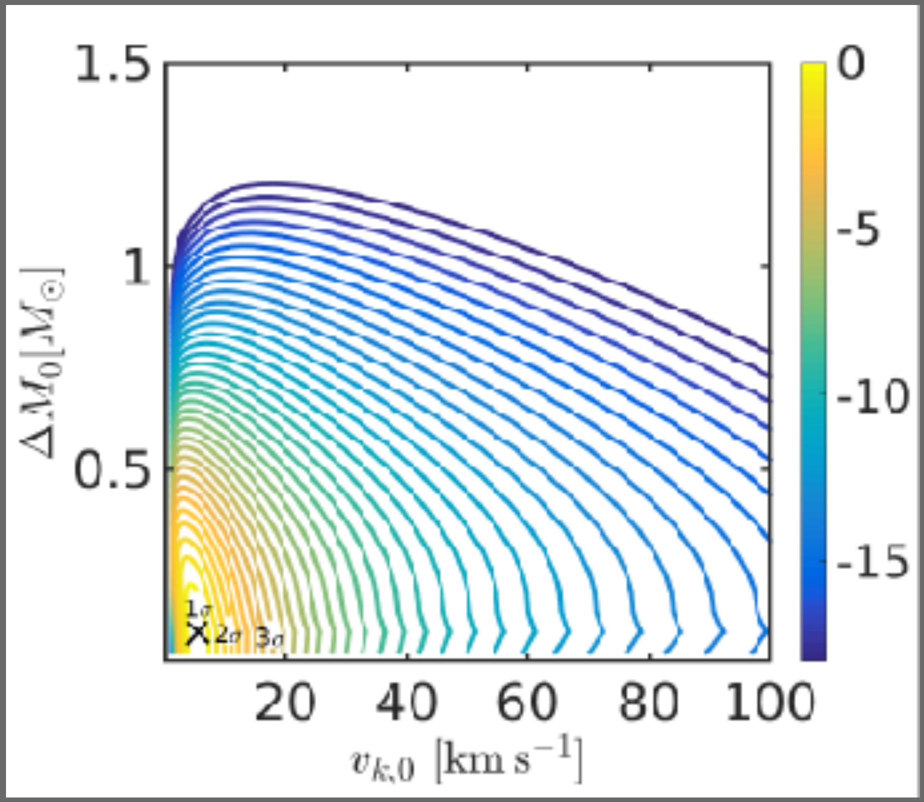
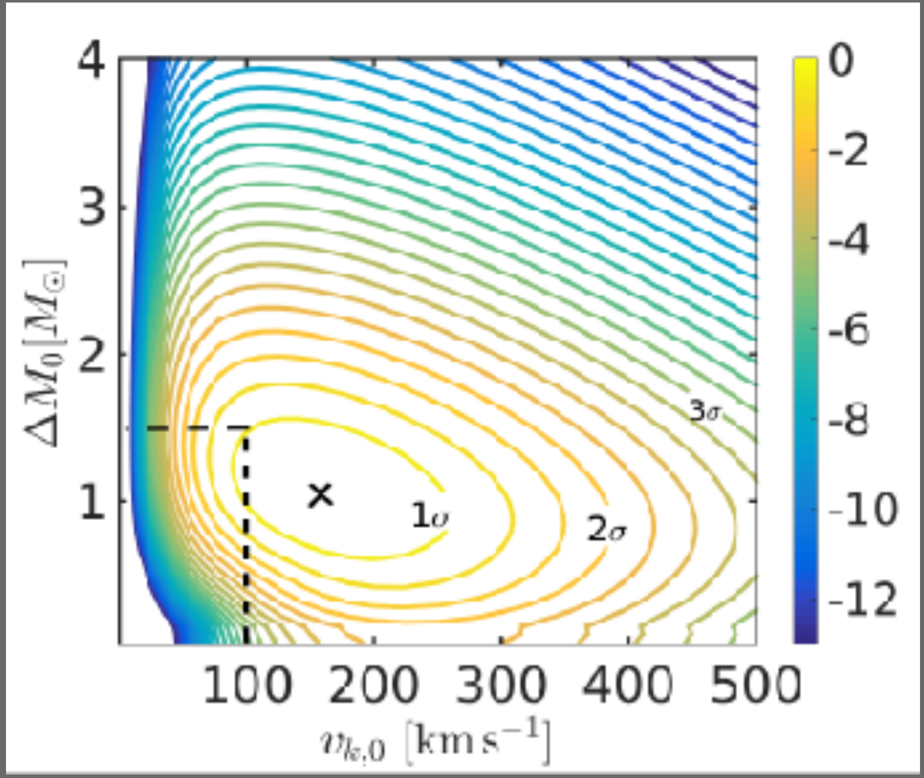
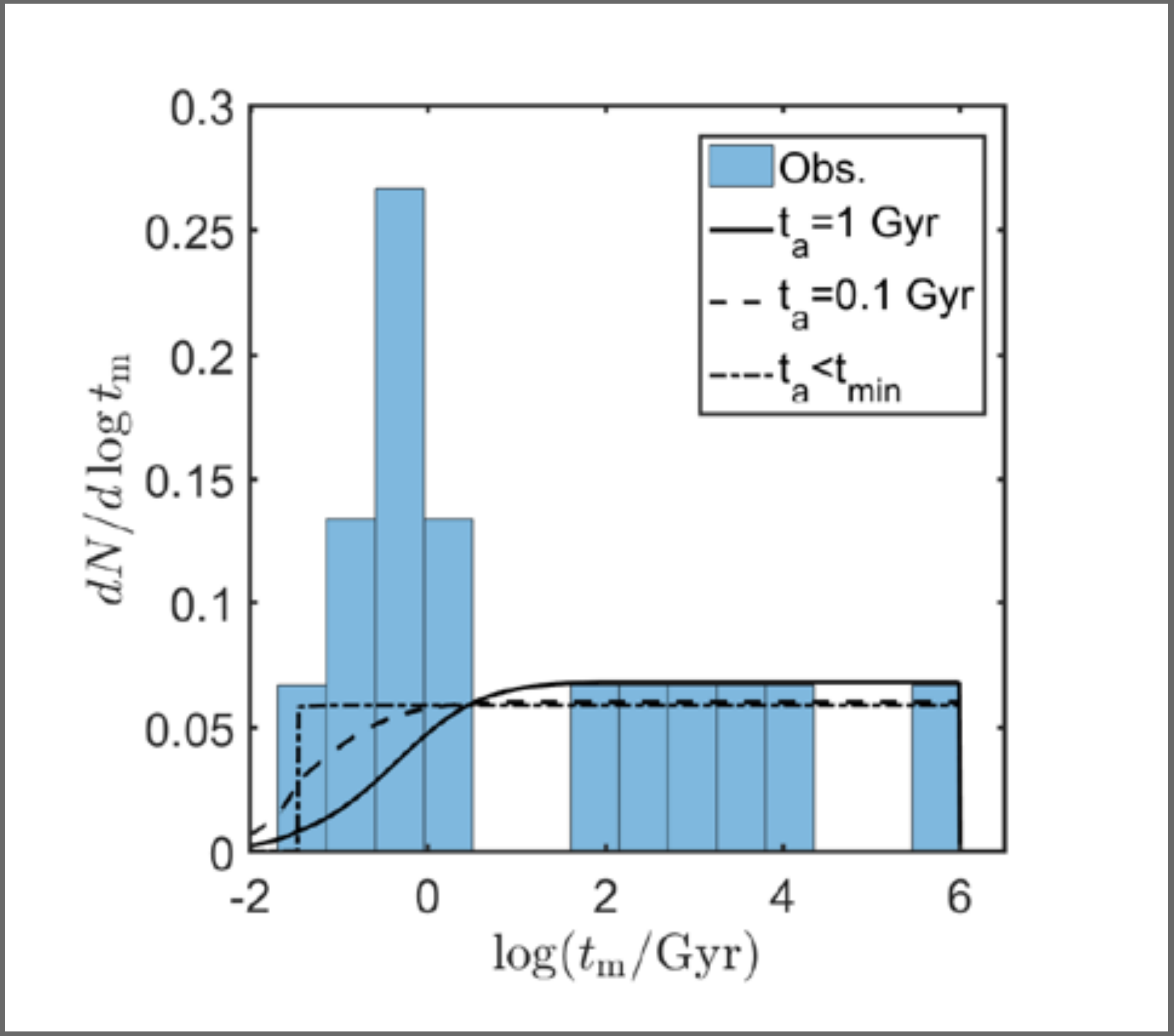
- ✳Most (2/3-3/4) observed Galactic binary neutron stars have almost circular orbits and a low proper motion
- ➡Very low mass ejection (<0.1 $M_{sun}$)
- ➡**NOT formed in a regular SNe**
- ➡**Very low kick velocity**
- ➡**<u>Won't be ejected from a Dwarf Galaxy</u>**



# The GW merger time distribution of Galactic BNS

Biniamini & TP 2019



# The GW merger time distribution of Galactic BNS

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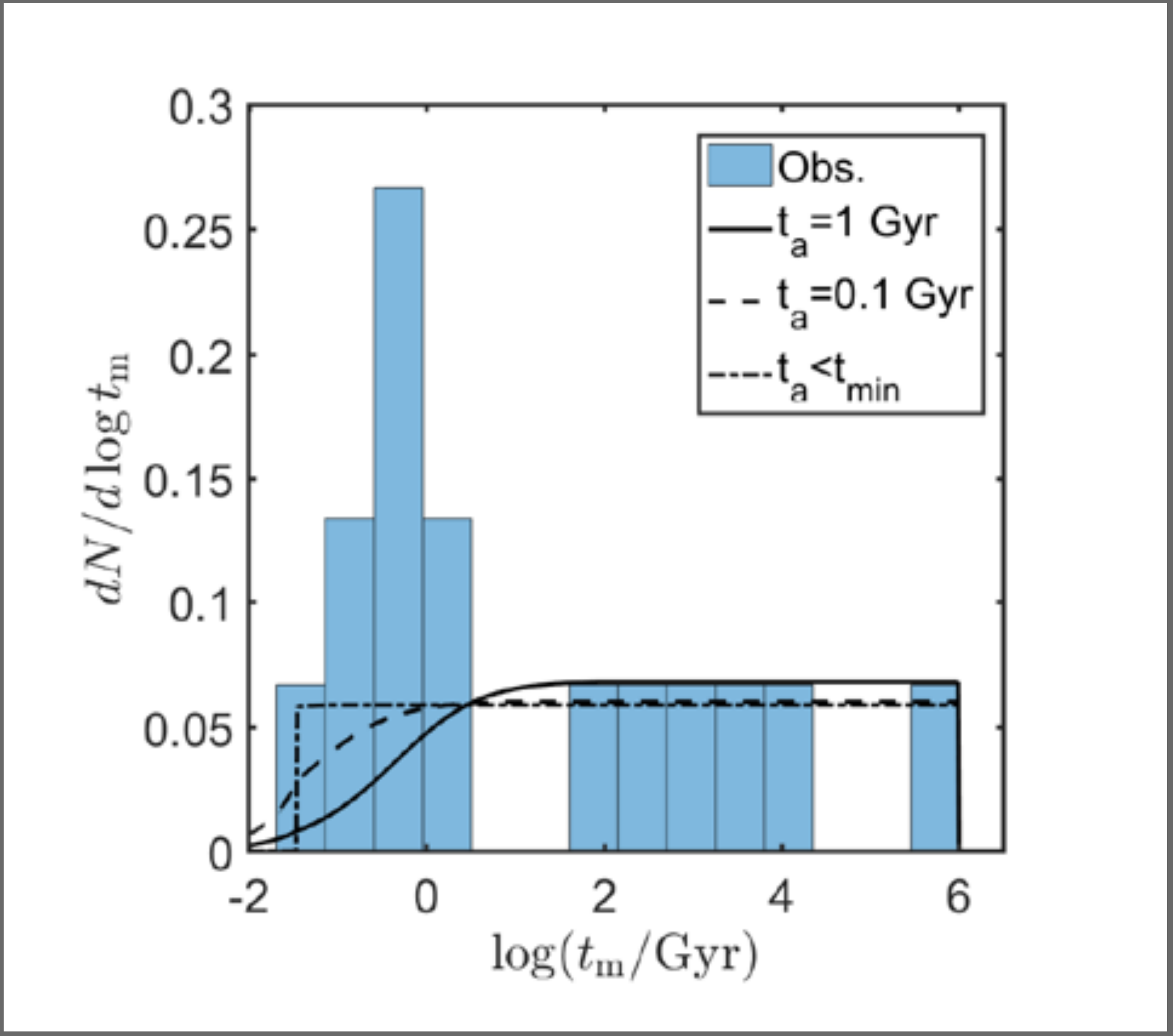
- ✳The Galactic BNS have an excess of “short” merger times.
- ✳Expectation due to pulsar’s life time is a paucity of short mergers.



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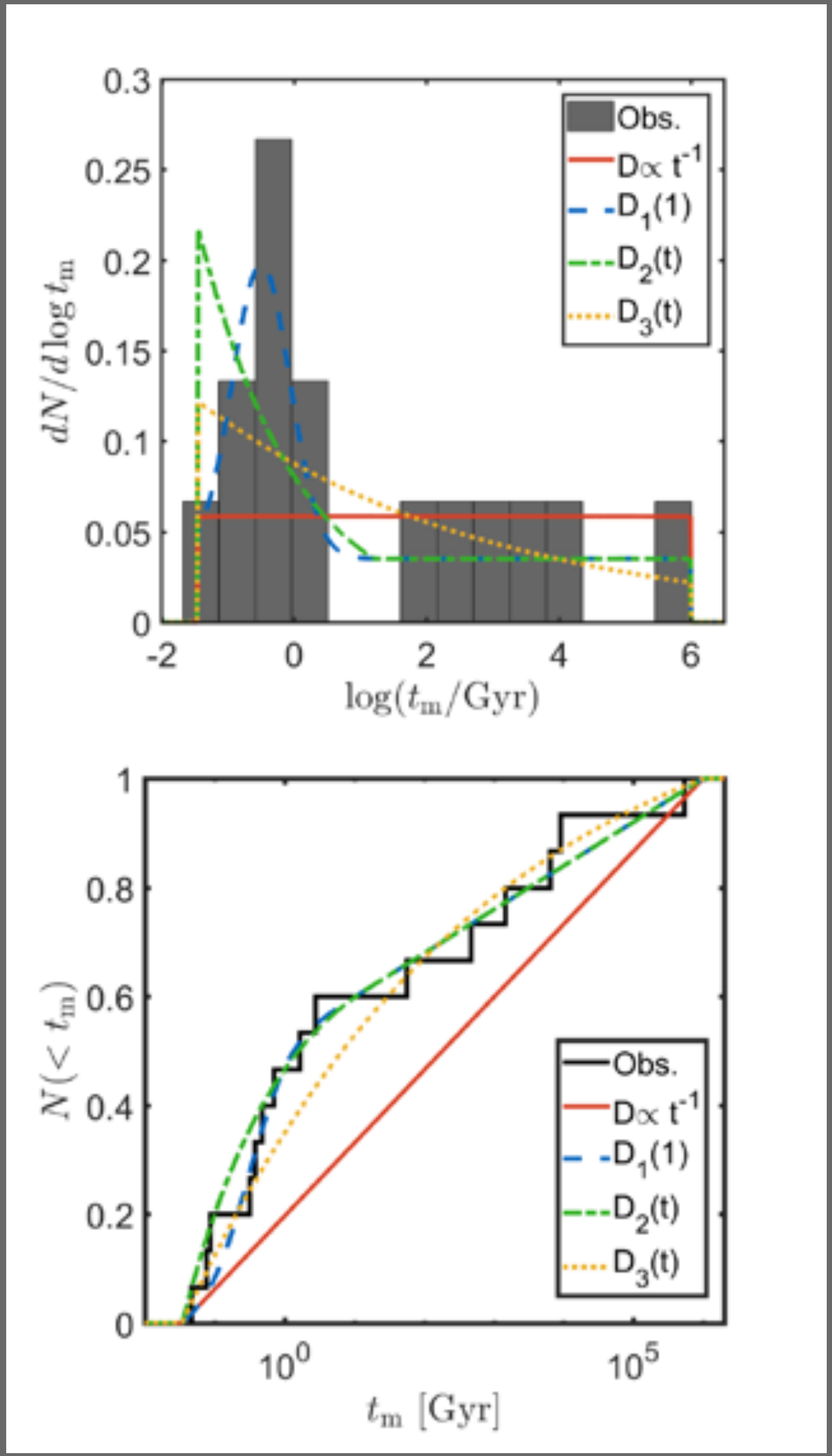

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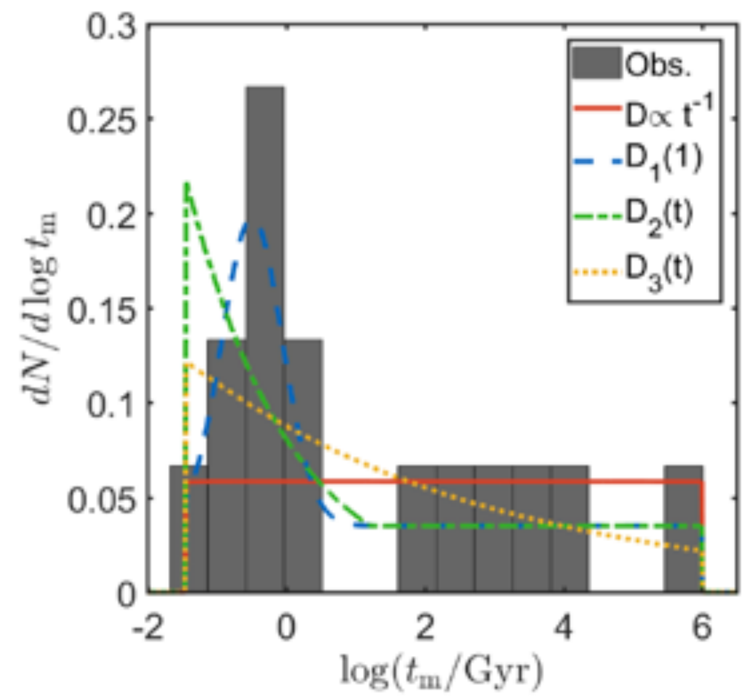
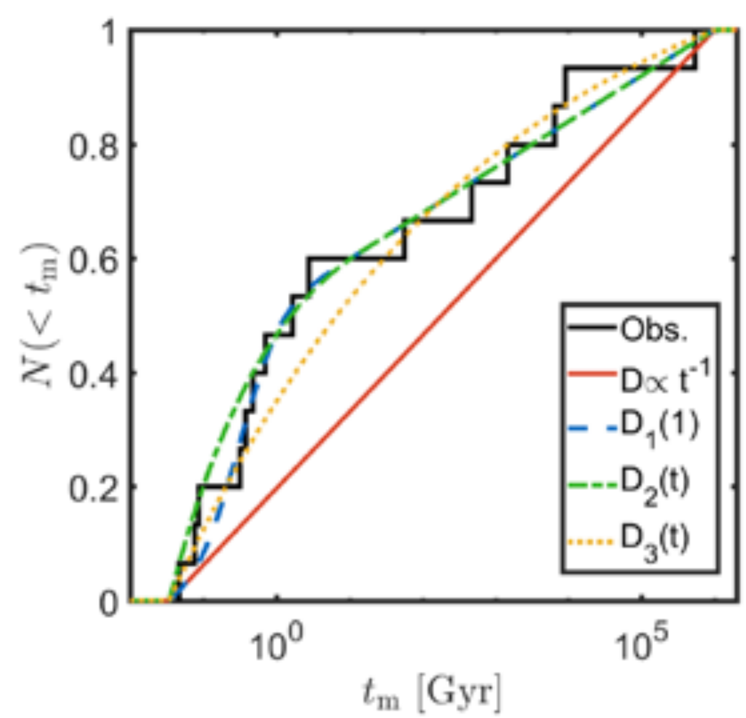
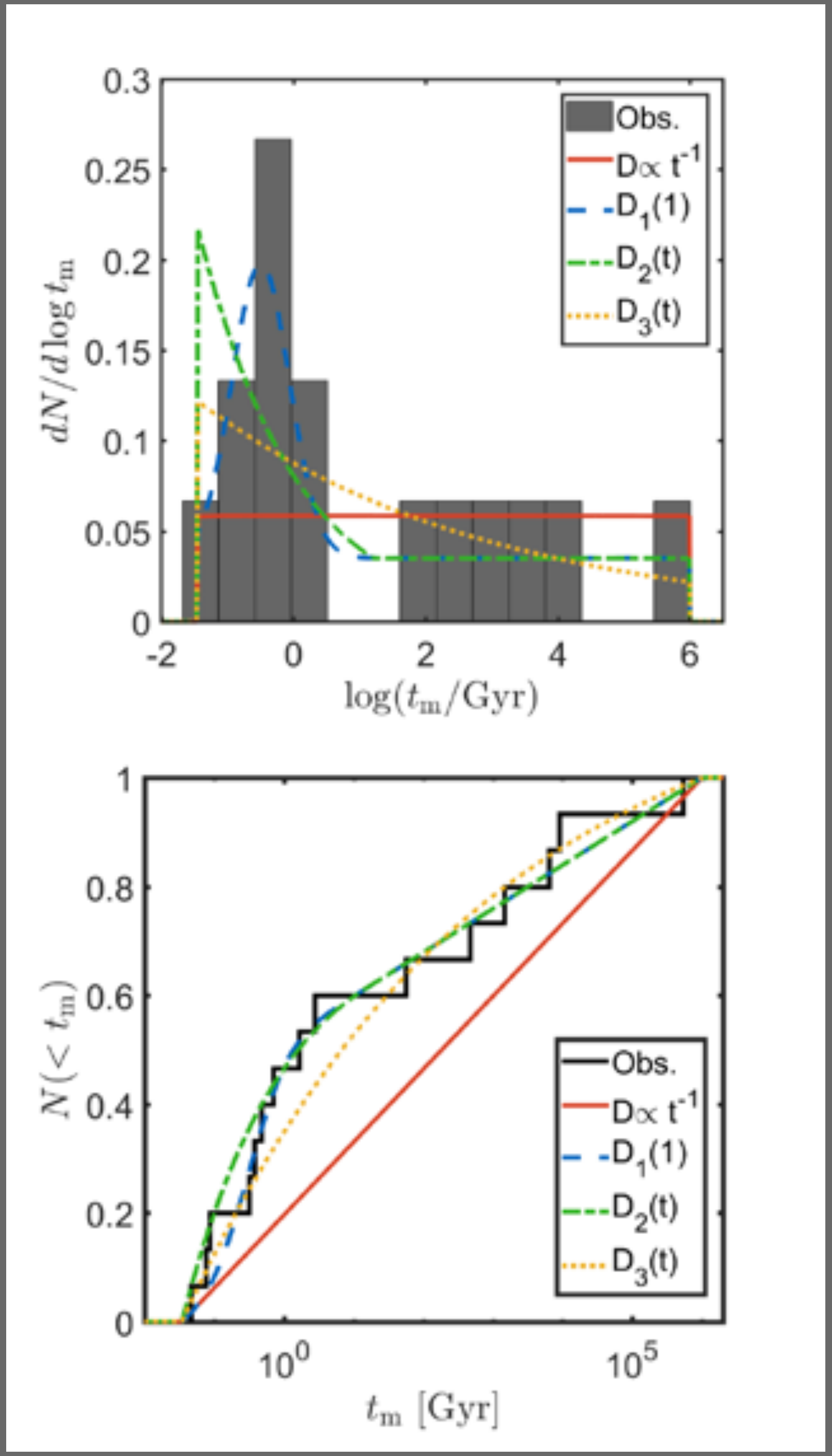


# The GW merger time distribution of Galactic BNS

- ✳The Galactic BNS have an excess of “short” merger times.
- ✳Expectation due to pulsar’s life time is a paucity of short mergers.
- ➡Excess of birth of BNS with short merger times.



# Conclusions II

- Most Galactic BNS form in a unique **rare** (1:100).
- This channel involves very little mass ejections and no kick (might be related to Iair's fast rising - low mass - transients).
- It is likely that both NS are formed in this way.
- A typical binary involving regular SNe is typically disrupted in the second collapse.
- About half of the binaries form with a "short" GW merger time (not $t^{-1}$)

# III. The Origin of BH-NS Binary

- From O1-O3 the rate of BHNS mergers is less than 10% of the rate of NSNS. (see also Kumar + 19).

➡BHNS are more the major sources of r-process or progenitors of sGRBs.

*A pop-synthesis prediction in Kyoto 2013 was the BHNS mergers is > 10 times the NSNS mergers

# A wild speculation?*

- Rarity of BHNS mergers
- Most BHNS binaries are torn apart?

➡Do BNS require a unique evolutionary channel (leading to NS with no mass ejecton) that is rare in the mass range leading to a BHNS?

*I am the only one responsible for this

# Conclusions

- Majority of BBHs progenitors are most likely field binaries (LVC already know if this is correct).

- Majority of BNS are formed in unique evolutionary channel with no kick and little mass ejection.

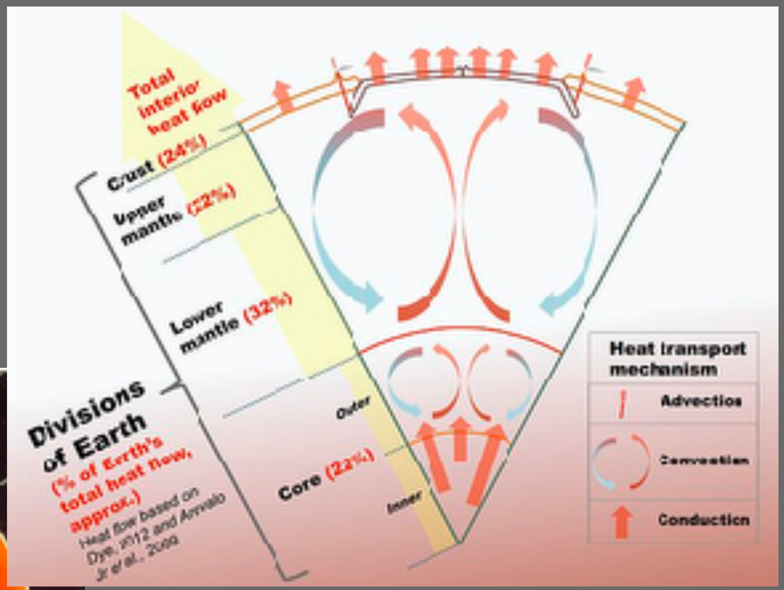
- BHNS are rare and not major contributors to r-process of sGRBs.

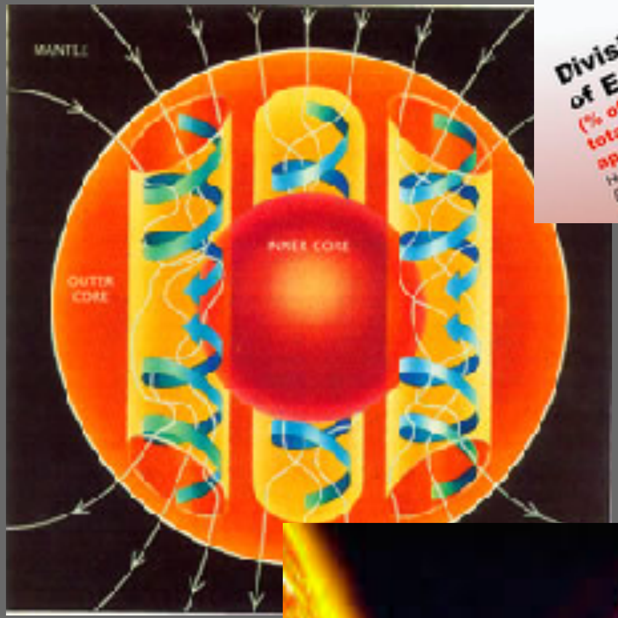
# IV. Why Gravitational Waves?

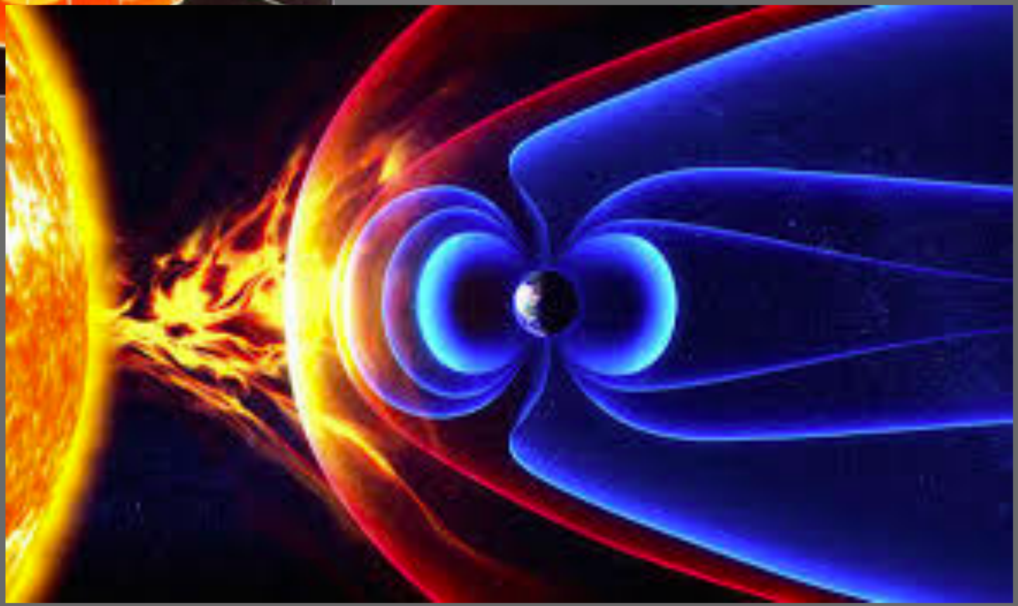
- Is there is a “life motivated reason" for the need of very heavy elements - like Gold, Uranium, Plutonium etc…

# *Yes - for life as we know it on Earth*

- Radioactive U and Th melt the Earth core .
- Enabaling the *magnetic dynamo*!
- The magnetosphere protects the Earth atmosphere from the Solar wind

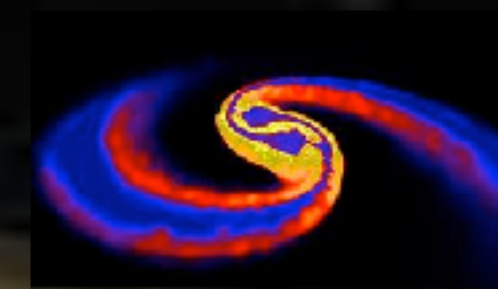


# *Our local merger*

About 1000 Earth masses of Gold + Platimun + Uranium and other heavey metals. Less than 80 Million years before solar system formation!



Is there is a “life motivated reason" for the “local merger” ?

Is the solar system special?

An Open ERC postdoc position

# An Open ERC postdoc position

erc

GRB ; TReX