Variable Galactic Gamma-Ray Sources VII

Barcelona, May 7 2025

O-TYPE RUNAWAY BINARIES WITH COMPACT OBJECTS

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INSTITUTO DE ASTROFISICA DE CANARIAS IAC
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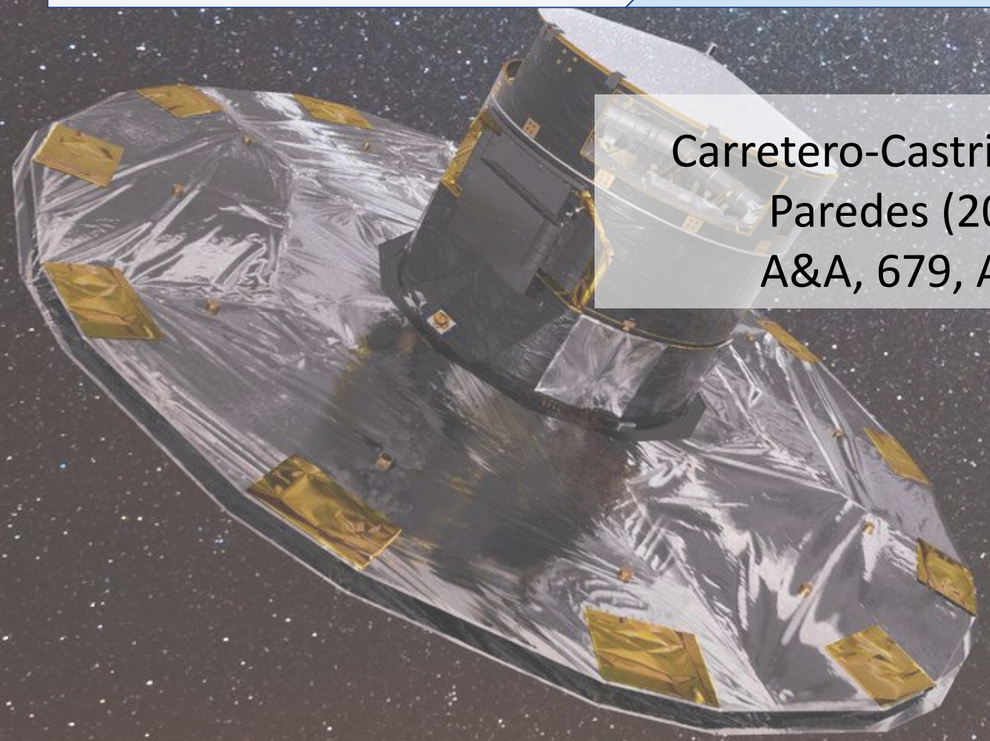
Universidad de La Laguna

CONTEXT

Carretero-Castrillo, Benaglia, Paredes, Ribó (2025) A&A, 694, A250

MASSIVE STARS → RUNAWAY STARS → BOW SHOCKS → BINARIES & DYNAMICAL ORIGINS



Carretero-Castrillo, Ribó, Paredes (2023) A&A, 679, A109

- This talk - Carretero-Castrillo et al. to be submitted

CONTEXT

DISCLAIMER

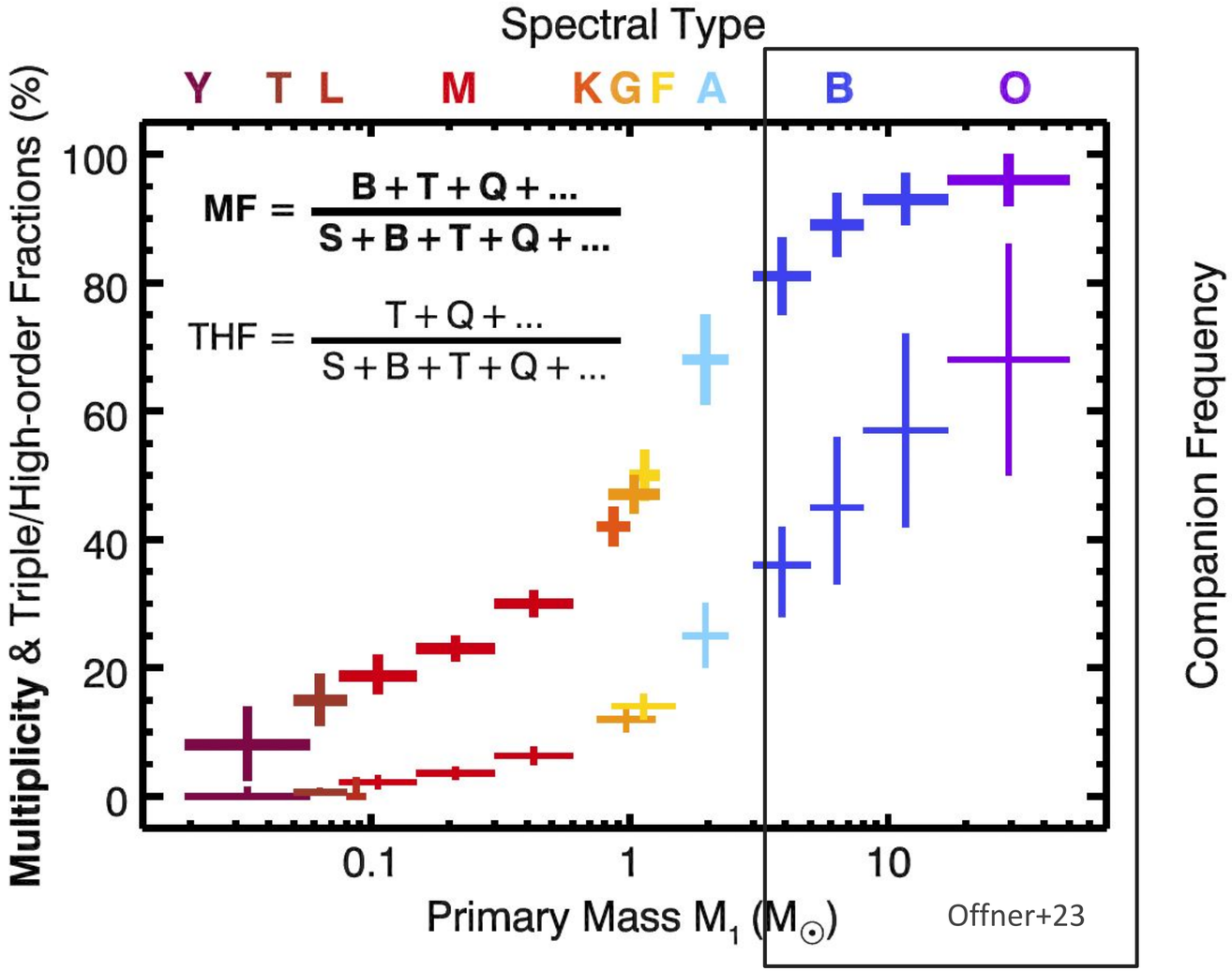
PhD thesis
to be submitted
in approx 10 days

:):

MASSIVE BINARY STARS

- Most massive OB stars are in binaries
- Most are indeed in close binaries and interact at some point during their lives

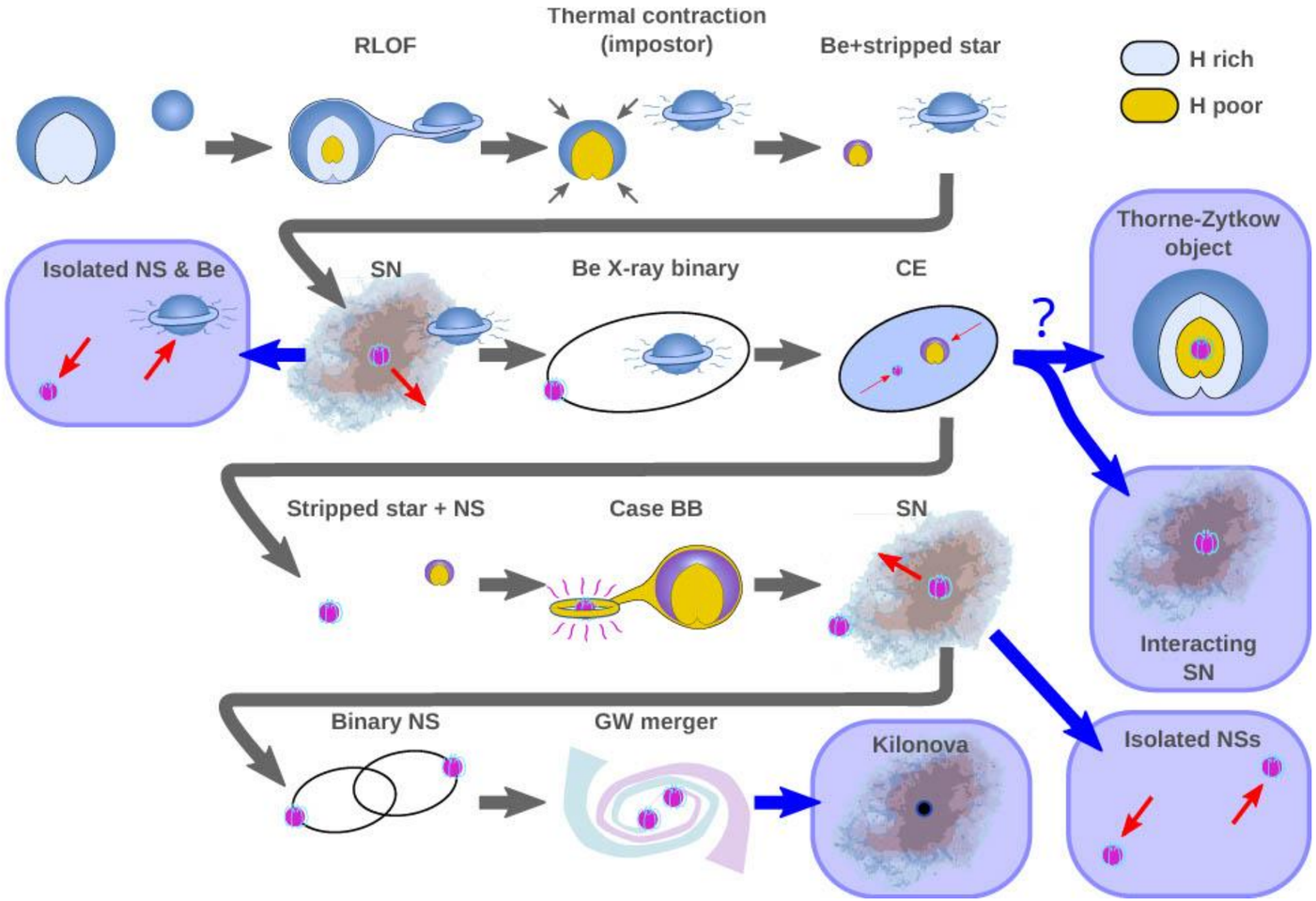
Reviews: Offner+23, Marchant & Bodensteiner (2024)



Multiplicity fraction (%): Number of primaries with at least one companion

MASSIVE BINARY EVOLUTION

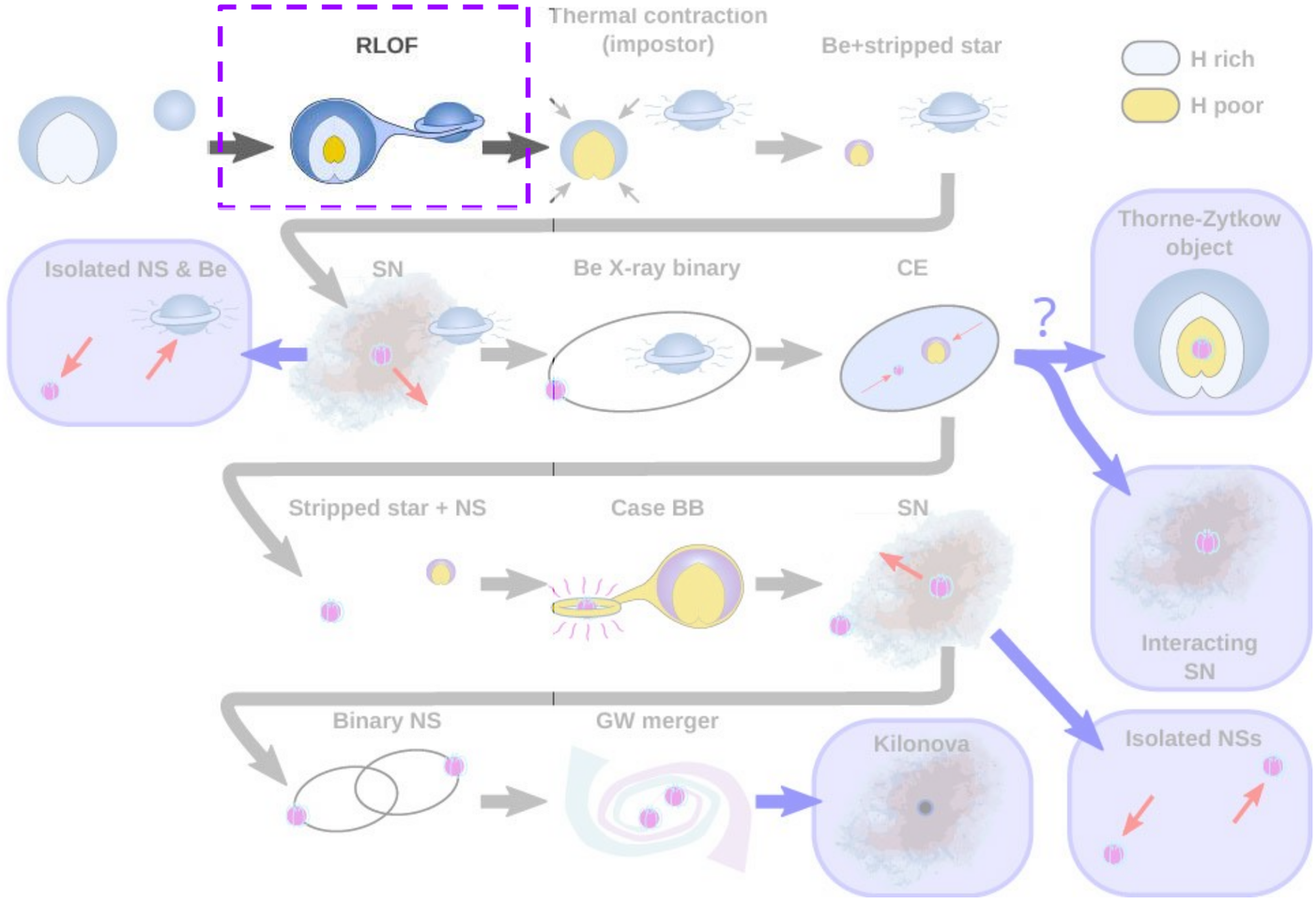
- Most OB stars in close binaries → interaction processes that modify their evolution



Marchant & Bodensteiner (2024)

MASSIVE BINARY EVOLUTION

- Most OB stars in close binaries ⟶ interaction processes that modify their evolution
- During mass transfer, the companion star can be spun-up by gaining mass and angular momentum



Marchant & Bodensteiner (2024)

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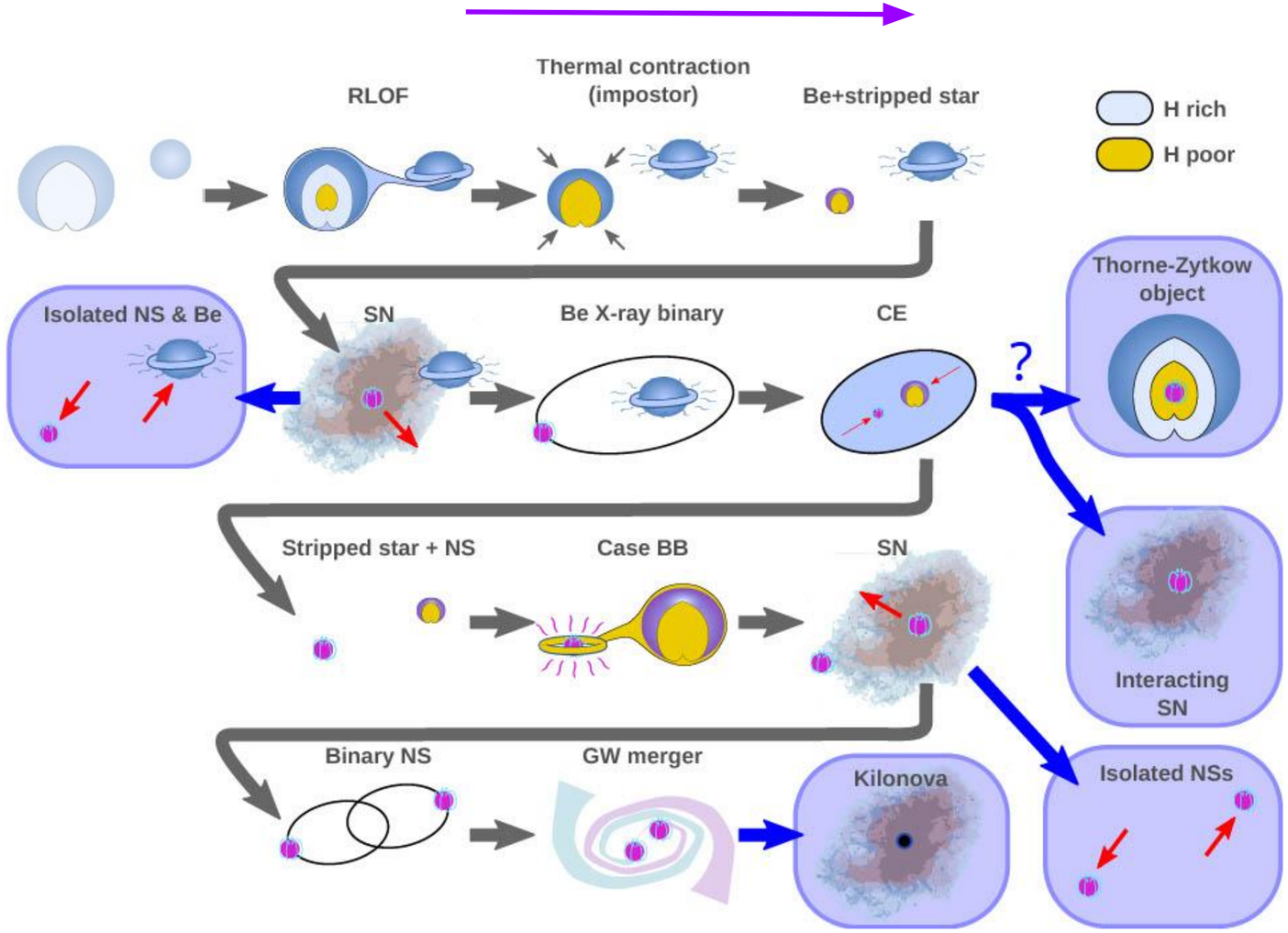
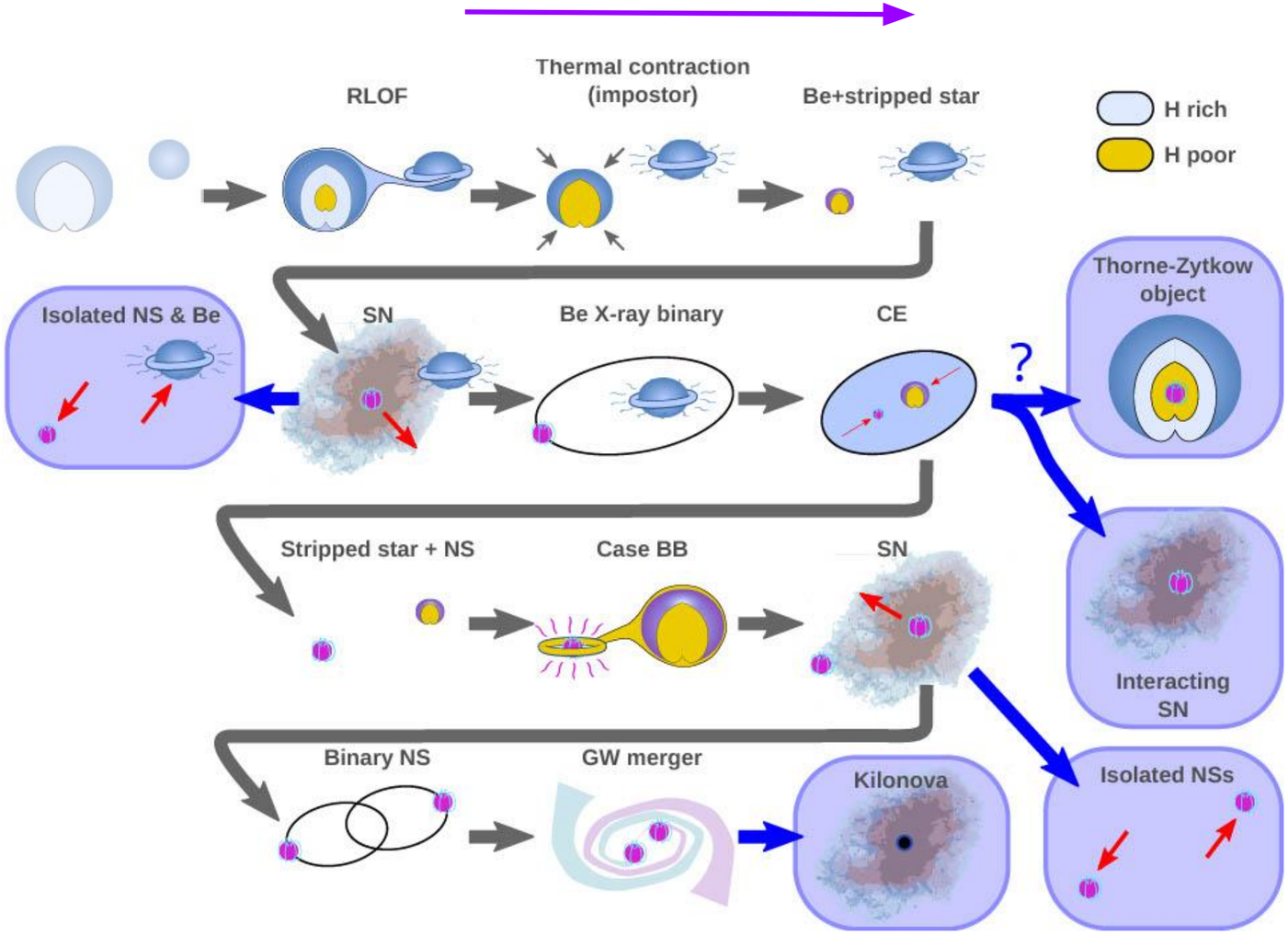


Marchant & Bodensteiner (2024)

MASSIVE BINARY EVOLUTION

- Most OB stars in close binaries → interaction processes that modify their evolution
- During mass transfer, the companion star can be spun-up by gaining mass and angular momentum
- Fast rotators typically defined as those with projected rotational velocities $v \sin i > 200$ km s^{-1}

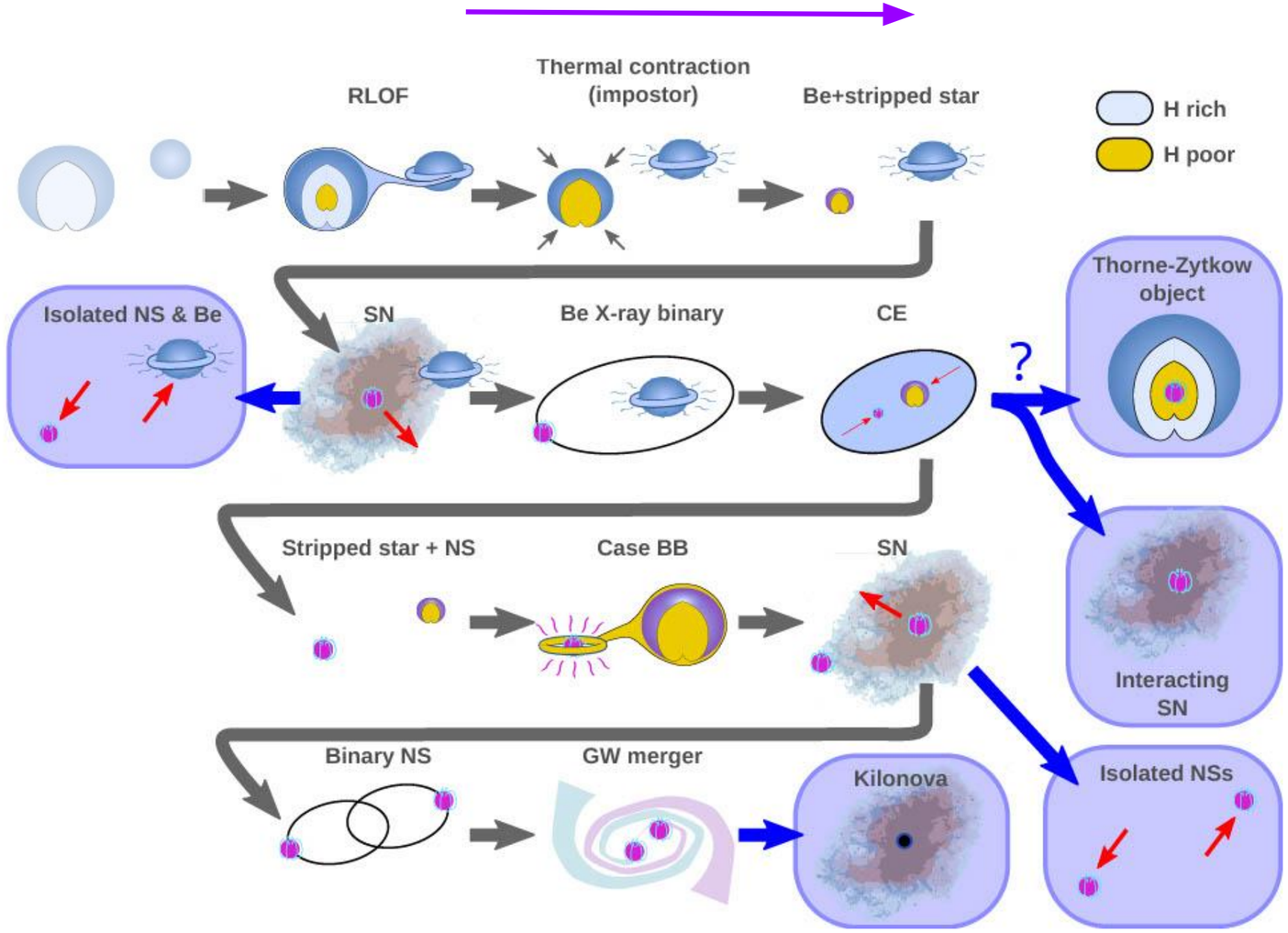


Marchant & Bodensteiner (2024)

MASSIVE BINARY EVOLUTION

- Most OB stars in close binaries → interaction processes that modify their evolution
- During mass transfer, the companion star can be spun-up by gaining mass and angular momentum
- Fast rotators typically defined as those with projected rotational velocities $v \sin i > 200$ km s^{-1}
- Simulations and observations connect fast rotation with post-binary interaction products

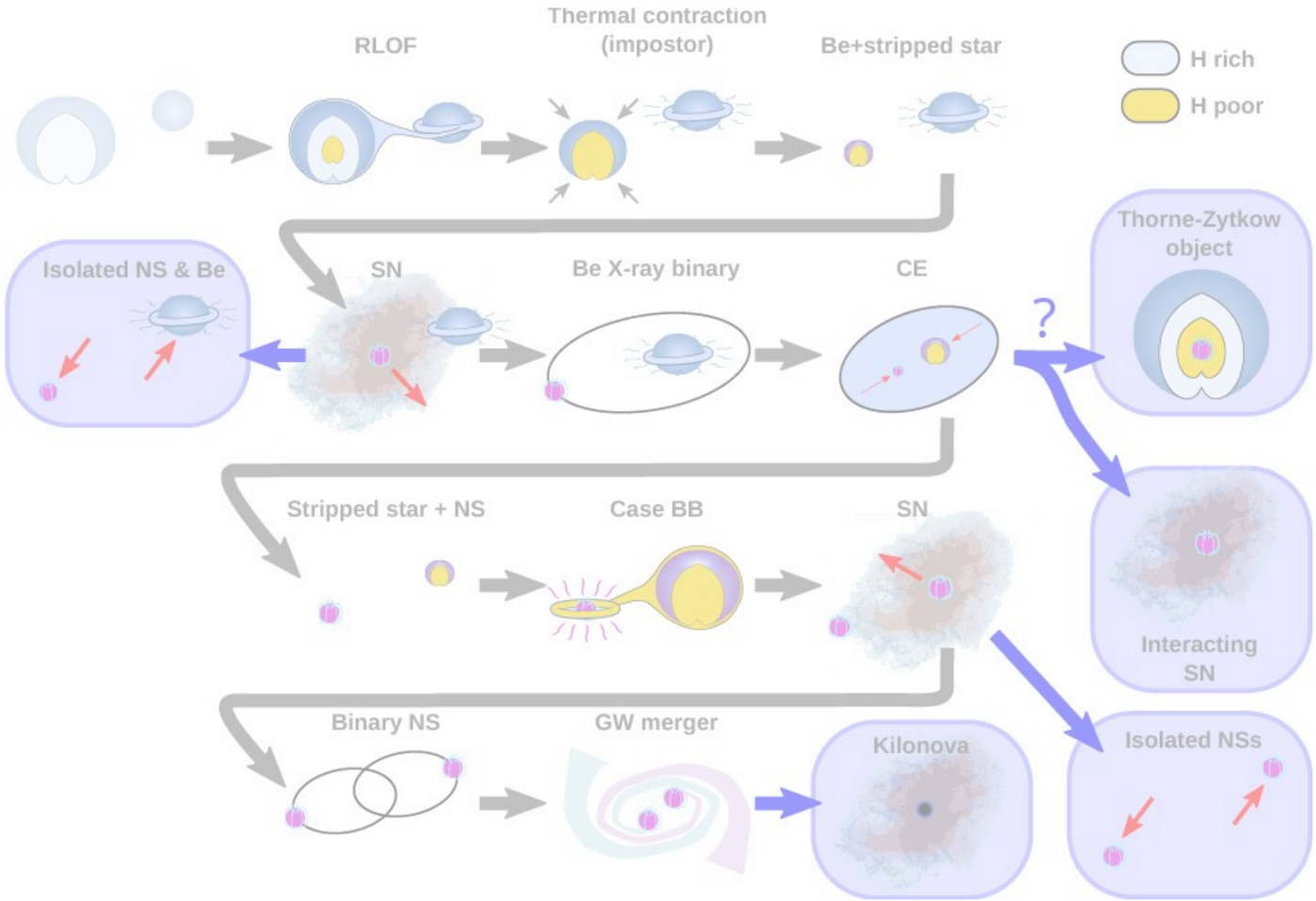
de Mink+13, Holgado+22, Britavskiy+23



Marchant & Bodensteiner (2024)

MASSIVE BINARY EVOLUTION

FAST ROTATION ↔ POST-BINARY INTERACTION PRODUCTS

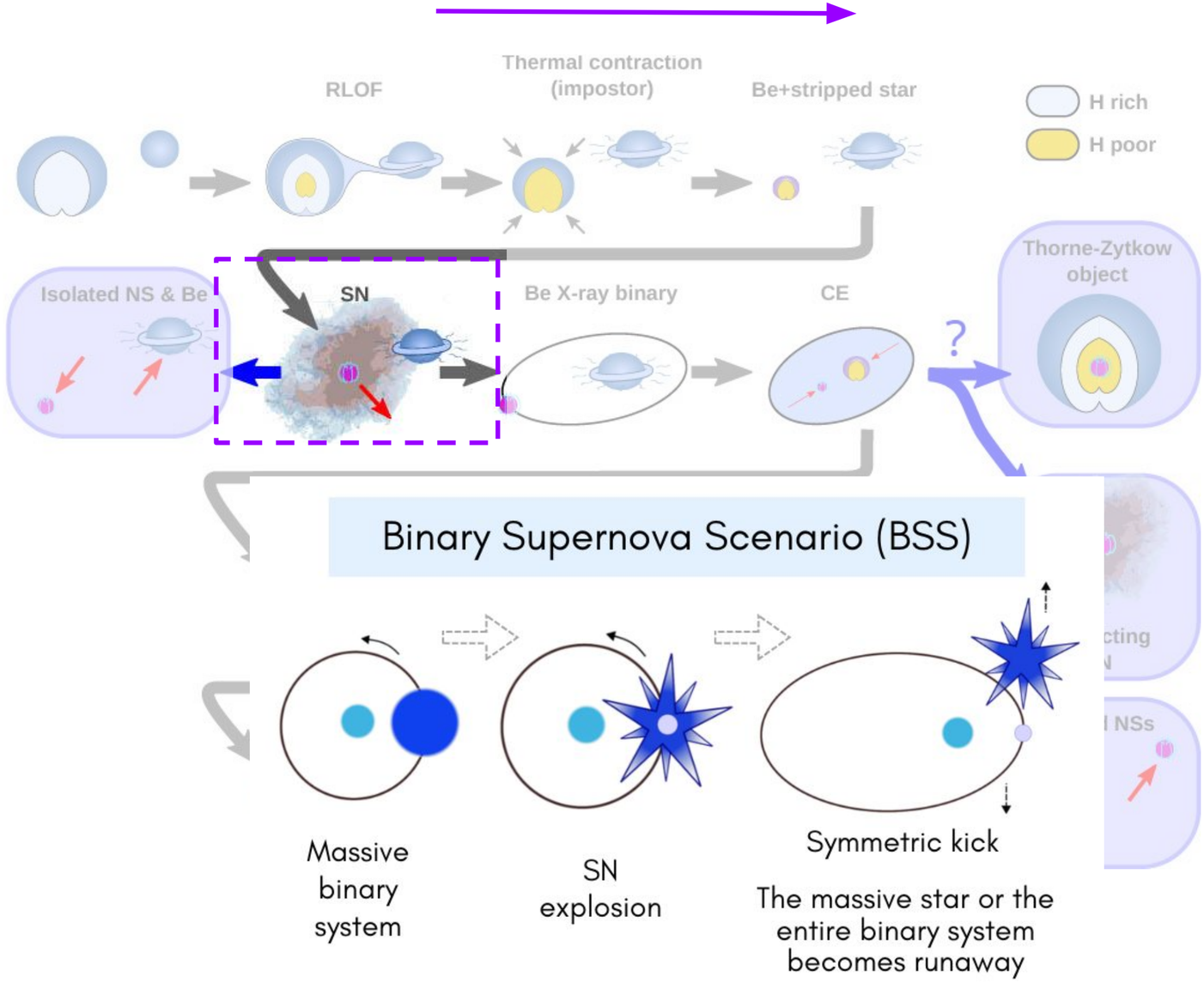


Marchant & Bodensteiner (2024)

MASSIVE BINARY EVOLUTION

FAST ROTATION ↔ POST-BINARY INTERACTION PRODUCTS

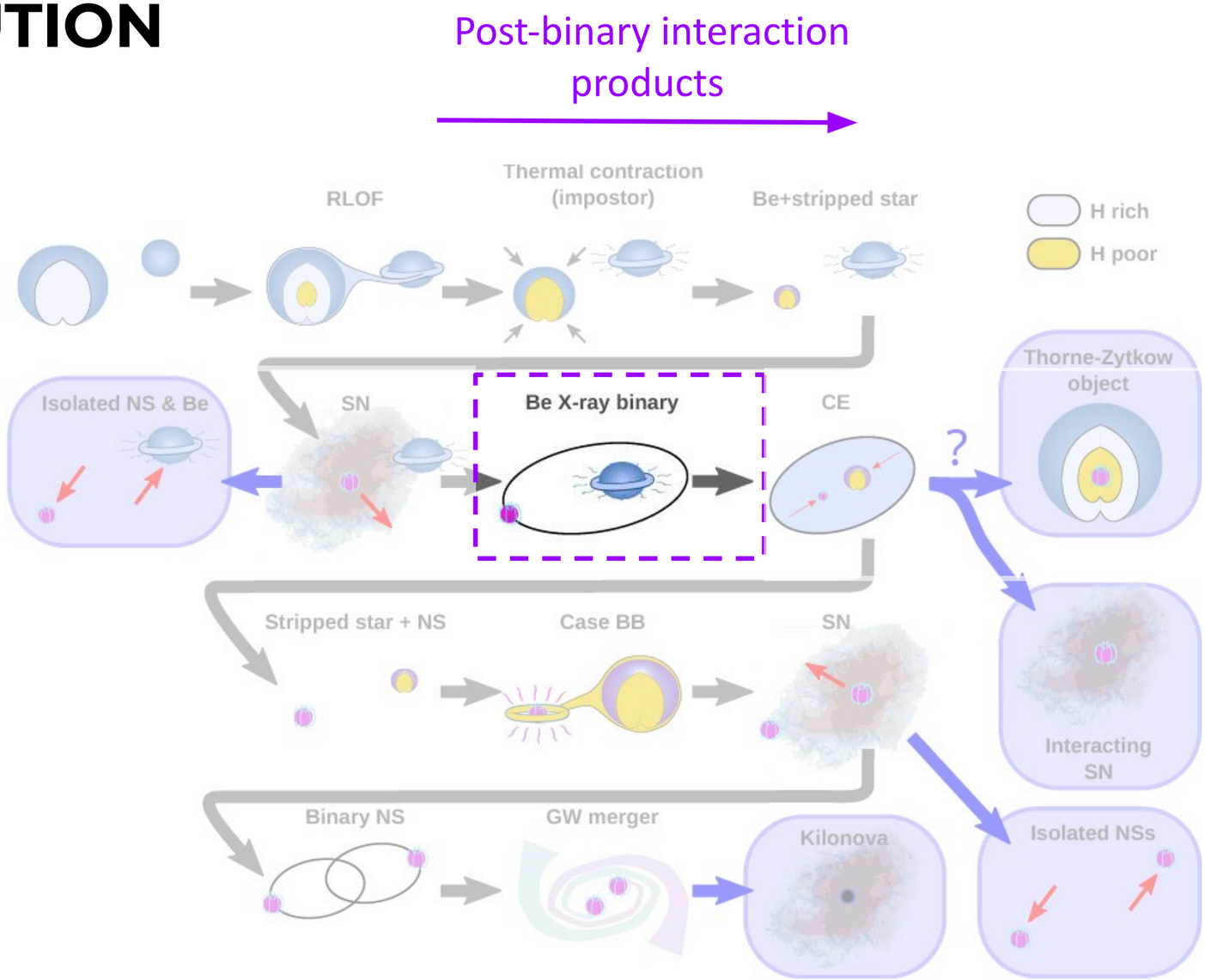
- Another phase in which the binary may experience a SN explosion → may become runaway (BSS)
- Fast rotation and runaway velocities ↔ post BSS runaway products



MASSIVE BINARY EVOLUTION

FAST ROTATION ↔ POST-BINARY INTERACTION PRODUCTS

- Another phase in which the binary may experience a SN explosion → may become runaway (BSS)
- Fast rotation and runaway velocities ↔ post BSS runaway products
- If the binary system remains bound: post-binary interaction products with compact objects (e.g., HMXBs, gamma-ray binaries)



Marchant & Bodensteiner (2024)

RUNAWAY GAMMA- AND HIGH-MASS X-RAY BINARIES

- **3** out of 4 **gamma-ray binaries** with available space velocities **are runaways**

Gamma-ray Binary System	Spectral Type	Orbital Period (days)	Distance (kpc)	Peculiar Velocity (km s^{-1})	
LS 5039	O6.5 V	3.9	2.0	142 ± 40	(1)
LS I +61 303	B0 Ve	26.5	2.7	16	(2)
PSR B1259−63	O9.5 Ve	1236.7	2.3	26 ± 8	(3)
HESS J0632+057	B0 Vpe	315.0	1.9	–	
1FGL J1018.6−5856	O6 V	16.5	4.4	45^{+30}_{-9}	(4)
LMC P3	O5 III	10.3	LMC	–	
PSR J2032+4127	B0 Vpe	17670.0	1.8	–	
4FGL J1405−6119	O6.5 III	13.7	7.7	–	
HESS J1832−093	O6 V	86.3	6.7	–	

Runaway systems

(1) Moldón+12, (2) Wu+17 (3) Miller Jones+18, (4) Marcote+18

Carretero-Castrillo, Ribó, Paredes (2023) A&A, 679, A109

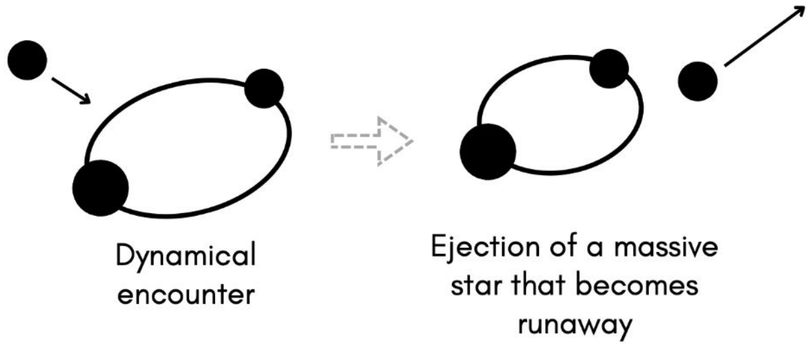
Runaway HMXBs/GRBs

- LS 5039
- Vela X-1
- 4U 1700-377
- **IGR J08408-4503/LM Vel**
- Cyg X-1
- **SAX J2103.5+4545** (Be)
- V 0332+53 (Be)

DYNAMICAL ORIGINS OF RUNAWAY STARS

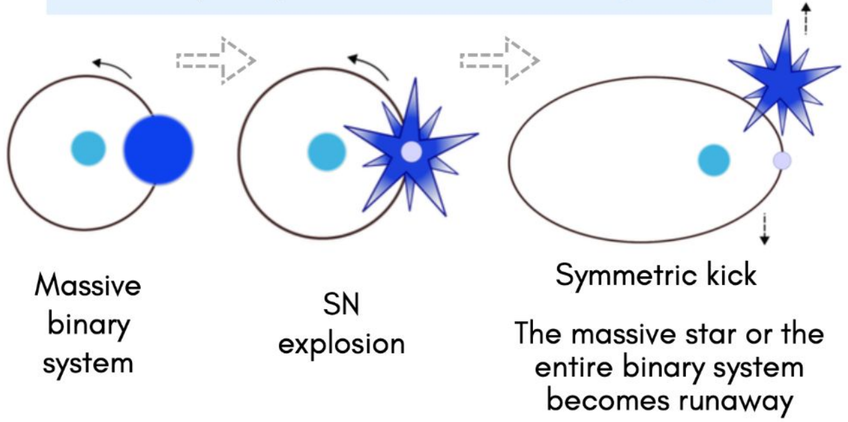
Poveda+67

Dynamical Ejection Scenario (DES)



Binary Supernova Scenario (BSS)

Blaauw (1961)



The understanding of the massive runaway star population and their dynamical origins requires the combined analysis of:

- Space velocity
- Rotational velocity
- Binarity

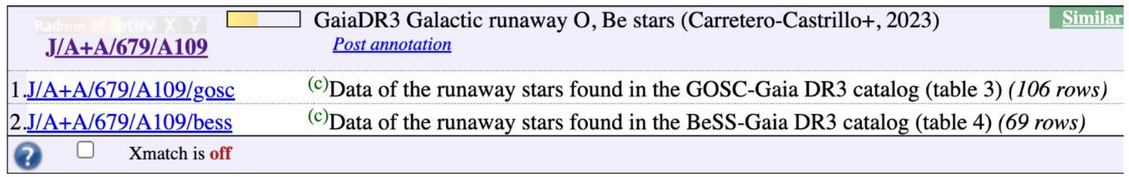
DATA

GOSC-*Gaia* DR3

Carretero-Castrillo+23

- 417 O-type stars:
  - 311 normal stars
  - 106 runaway stars

Runaway catalogs available at VizieR:
[J/A+A/679/A109](J/A+A/679/A109)



IACOB project

Simón-Díaz & Herrero (2014)

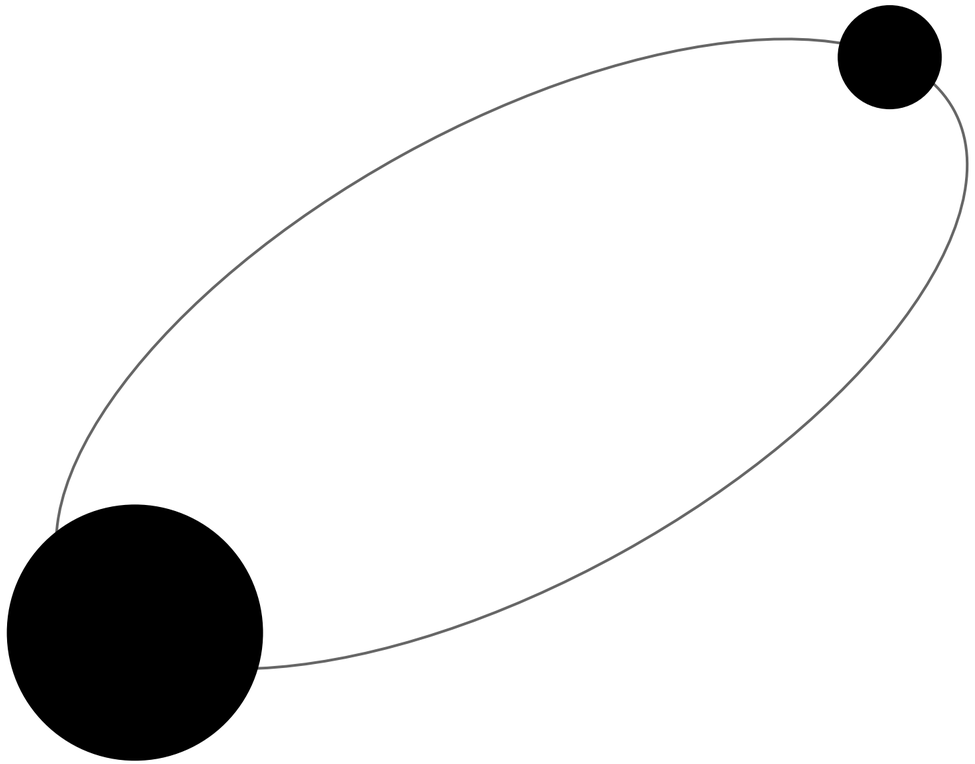
- Spectroscopic database for Galactic OB-type stars
- We use both public and private *v* sin *i* measurements and binarity (LS, SB1, SB2) information

IACOB Spectroscopic database

➔ Likely single (LS)
➔ SB1
➔ SB2

research.iac.es/proyecto/iacob/iacobcat/

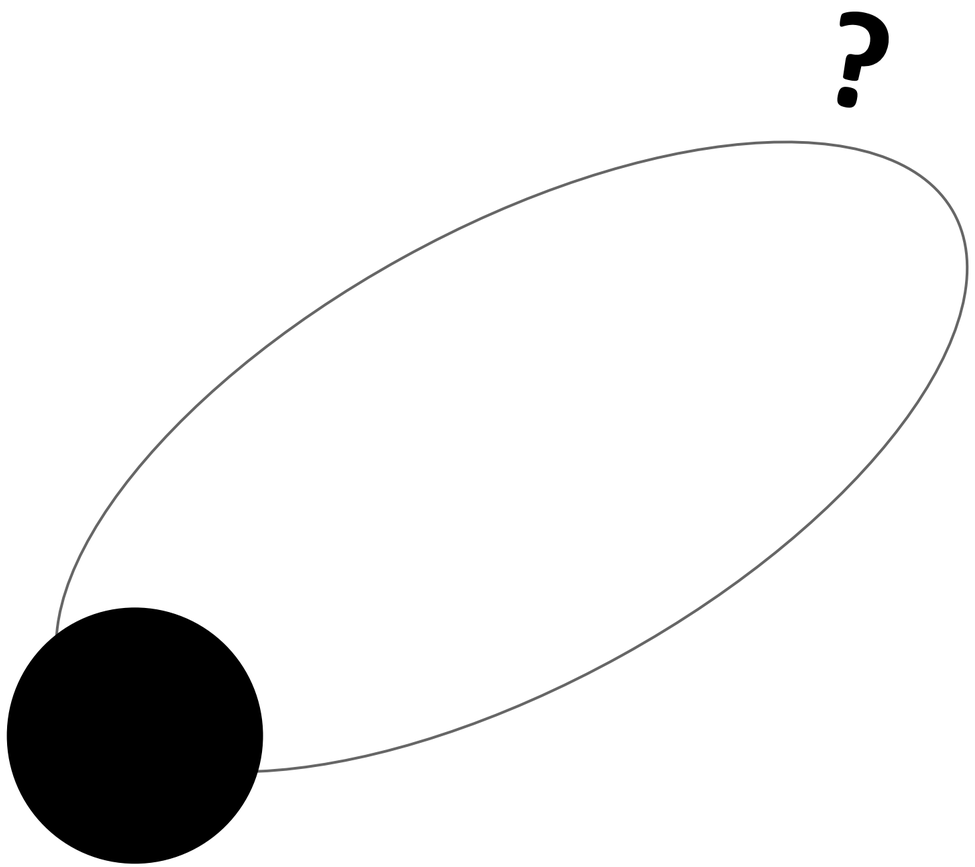
SB1 and SB2 binaries



SB2 binary

- Two visible lines in the spectra

SB1 and SB2 binaries



SB2 binary

- Two visible lines in the spectra

SB1 binary

- Only **one** visible line in the spectra

Unseen companions →

- ★ Main-sequence stars
- ★ Stripped helium stars
- ★ Triple systems
- ★ Compact objects:
  - ○ BH
  - ○ NS

CROSS-MATCH OF THE CATALOGS

GOSC-*Gaia* DR3

Carretero-Castrillo+23

IACOB project

Simón-Díaz & Herrero (2014)

*65 SB2 systems excluded

Rotation sample

- **214** O-type stars with available *v* sin *i* :
  - 136 normal stars
  - 78 runaway stars

> 3 spectroscopic epochs

Rotation LS-SB1 subsample

- **168** O-type stars with *v* sin *i* + binarity information:
  - 103 normal stars
  - 65 runaway stars

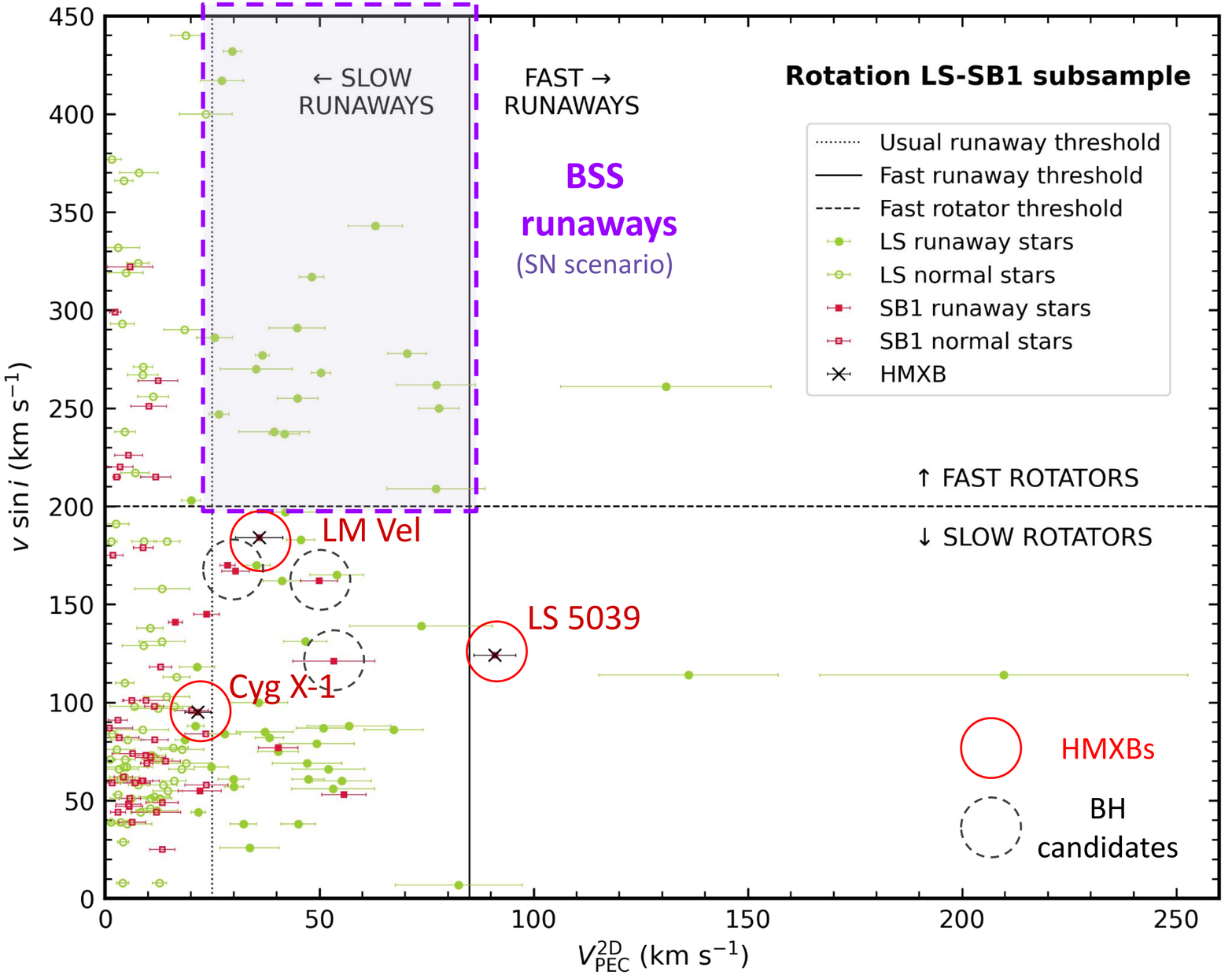
Largest observational samples of O-type stars with accurate runaway classification ever studied in the Milky Way in terms of *v* sin *i* and binarity

RESULTS

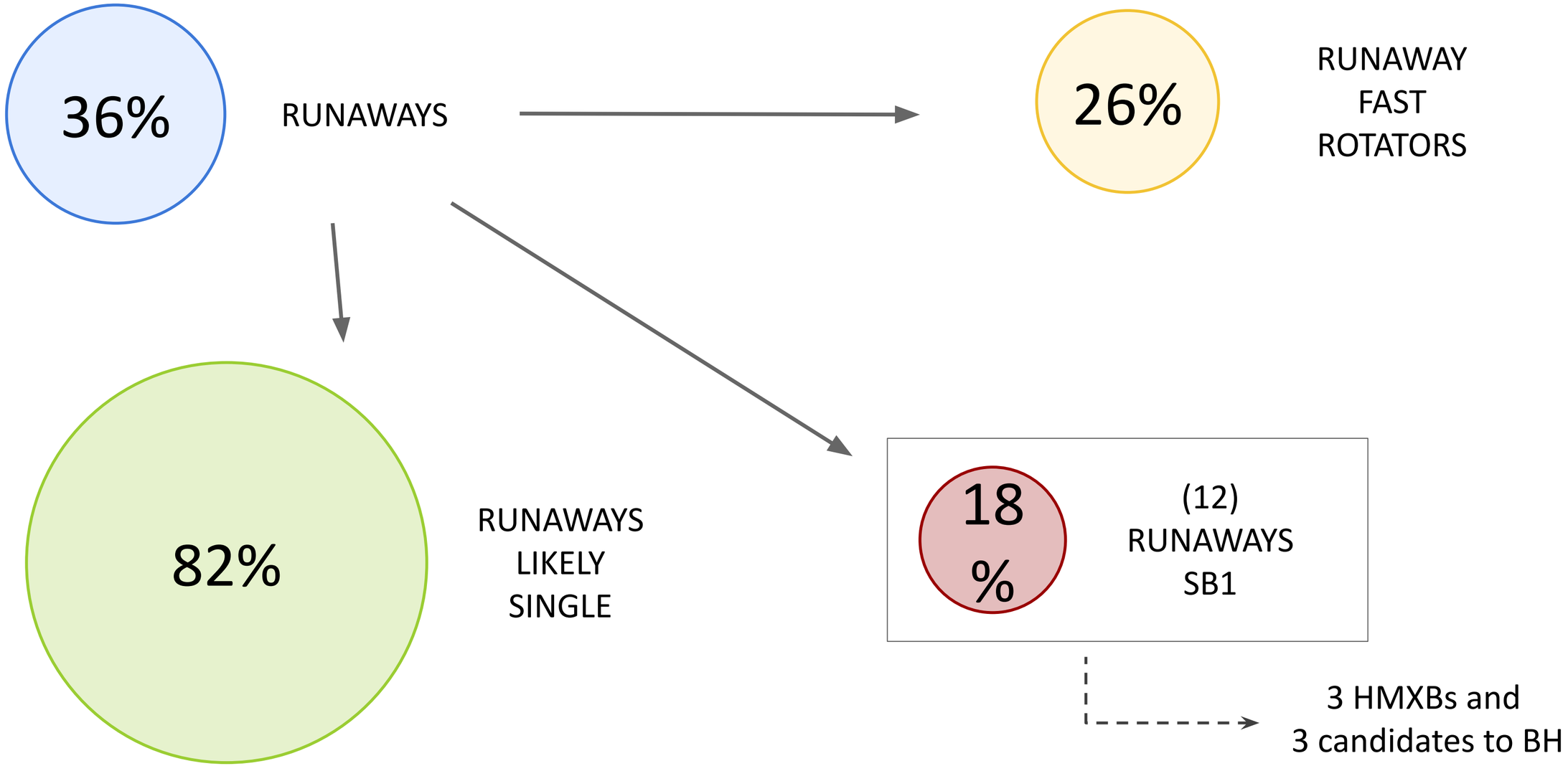
- Most (82%) runaways are likely single LS
- All fast-rotating runaways are LS
- As predicted by simulations, most binaries are disrupted after SN explosions → **HMXBs and gamma-ray binaries rare systems**

  Renzo+19, Wagg+25
- **12 SB1 runaway** systems that are interesting possibilities to host COs
  - 3 are known HMXBs Fortin+23
  - 3 candidates to host a BH

    Mahy+22, Britavskiy+23



RESULTS


36%
RUNAWAYS
26%
RUNAWAY
FAST
ROTATORS
82%
RUNAWAYS
LIKELY
SINGLE
18
%
(12)
RUNAWAYS
SB1
3 HMXBs and
3 candidates to BH

RESULTS - SB1 RUNAWAYS

- Multi-wavelength search in different surveys, instruments, and literature
- Detected multi-wavelength (non-thermal) emission → only from the known HMXBs
- SB1 runaways are interesting systems to monitor

Mahy+22

VLA
VLASS
MeerKat

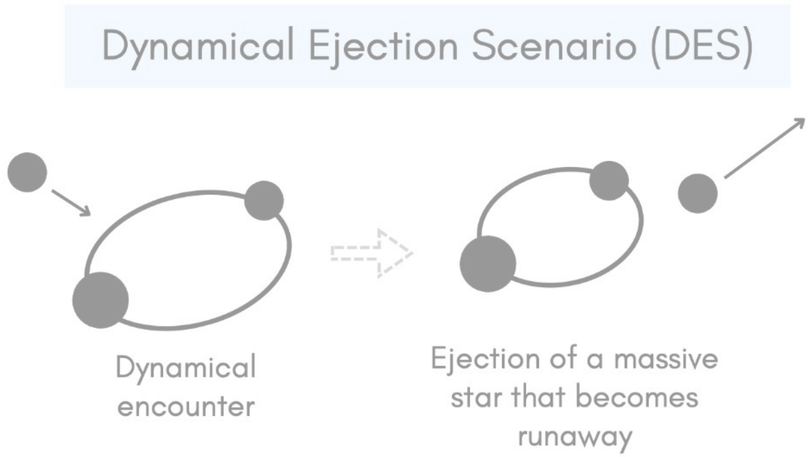
RASS
eRosita
XMM
Swift
Chandra

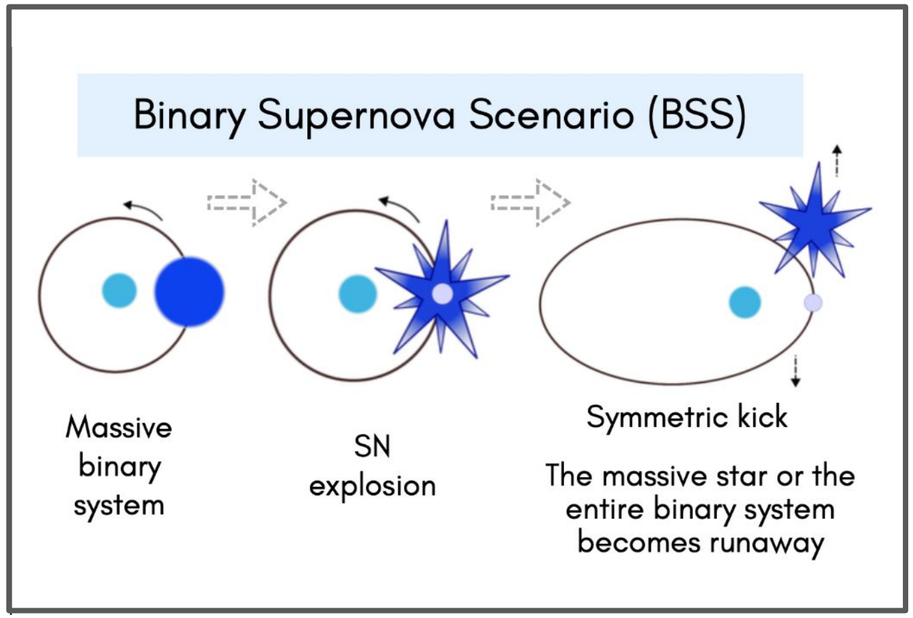
Fermi
IACTs
HAWC
LHAASO

GOSC Name	P_{orb} (d)	e	Radio	X-rays	Gamma rays
LS 5039/ V479 Sct	3.91	0.254	Detected	Detected	HE VHE UHE
HD 94 024	2.46	0.000		Not detected	
HD 76 968				Detected†	
HD 46 573	10.65	0.595	<151 μJy	Not detected	
HD 130 298	14.63	0.457		Not detected	
HD 12 323	1.93	0.000	<187 μJy		
HDE 326 775			<62 μJy	Detected†	
LM Vel	9.54	0.599		Detected	
HD 75 211	20.45	0.340	<110 μJy	Detected†	
Cyg X-1	5.60	0.023	Detected	Detected	HE UHE
HD 105 627	4.34	0.084	<370 μJy	Detected†	
HD 164 438	10.25	0.282			

Refs. Radio: Marti+98, Lacy+20, Goedhart+24, Braes & Miley (1971); X-rays Motch+97, Evans+14, Webb+23, Bowyer+65. Gamma rays: Paredes+00, Aharonian+05, Alfaro+25, Zanin+16, LHAASO Coll+25
†Freund+24: coronal origin from the massive star

RESULTS - DYNAMICAL ORIGINS OF RUNAWAY HMXBS





Observational analysis in kinematics and binarity

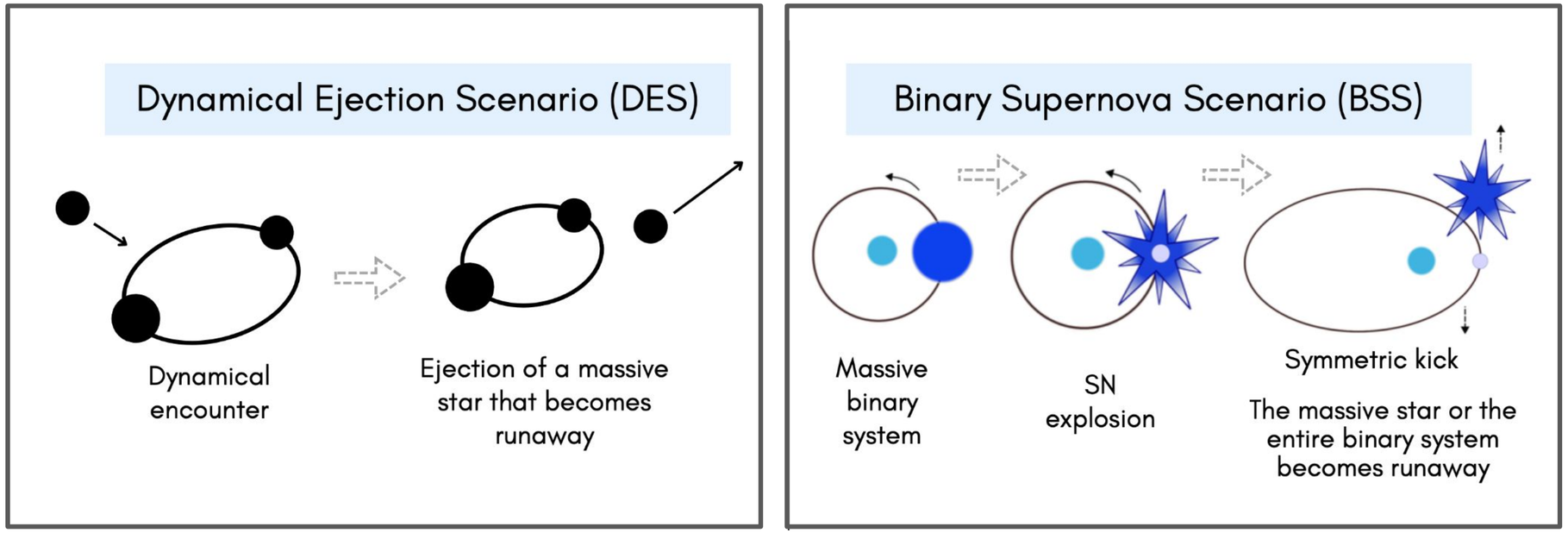
+

Predictions of simulations in runaway production mechanisms

→

- LM Vel ↔ BSS
- Cyg X-1 ↔ BSS

RESULTS - DYNAMICAL ORIGINS OF RUNAWAY HMXBS



Observational analysis in kinematics and binarity

+

Predictions of simulations in runaway production mechanisms

→

- LM Vel ↔ BSS
- Cyg X-1 ↔ BSS
- LS 5039 ↔ DES + BSS

CONCLUSIONS

Large observational study of rotation and binarity of Galactic O-type runaway stars

Carretero-Castrillo et al. to be submitted (UB + IAC)

	%
Runaways	36
Run. fast rotators	26
Run. likely single	82
Runaways SB1	18

12 SB1 runaway systems

↓

3 HMXBs

(Cyg X-1, LM Vel, LS 5039)

3 candidates to host a BH

<u>Multi-wavelength search</u>

No new non-thermal emission findings

Observational study

(kinematics and binarity)

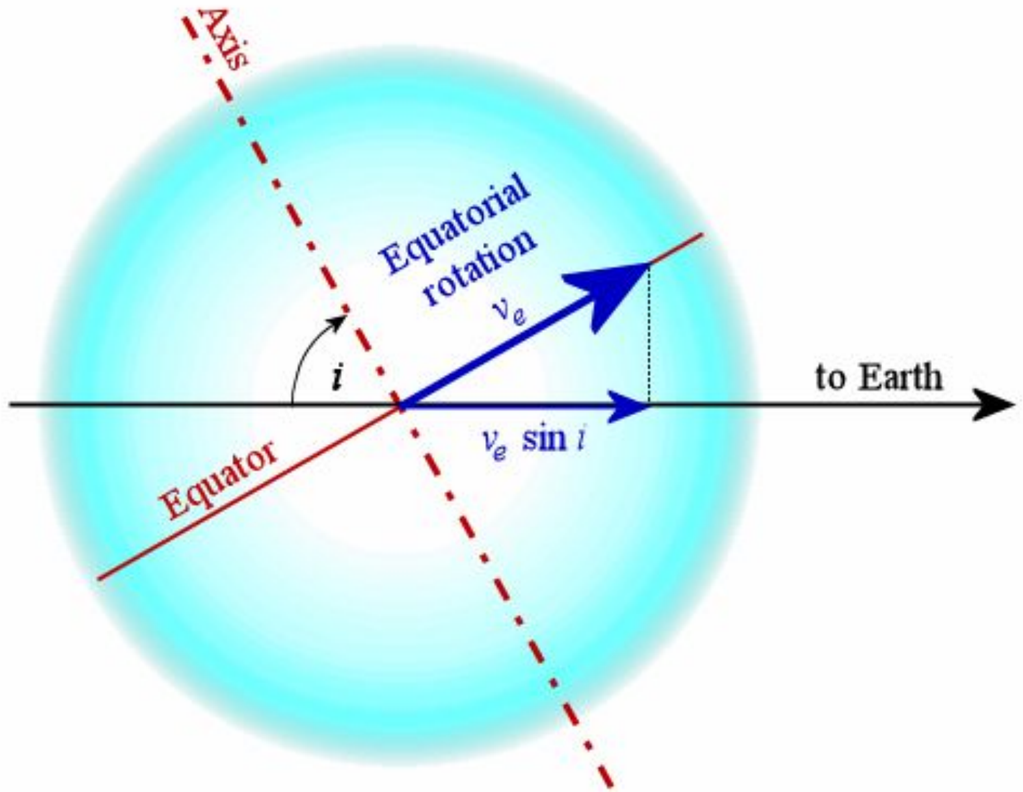
+

simulations predictions

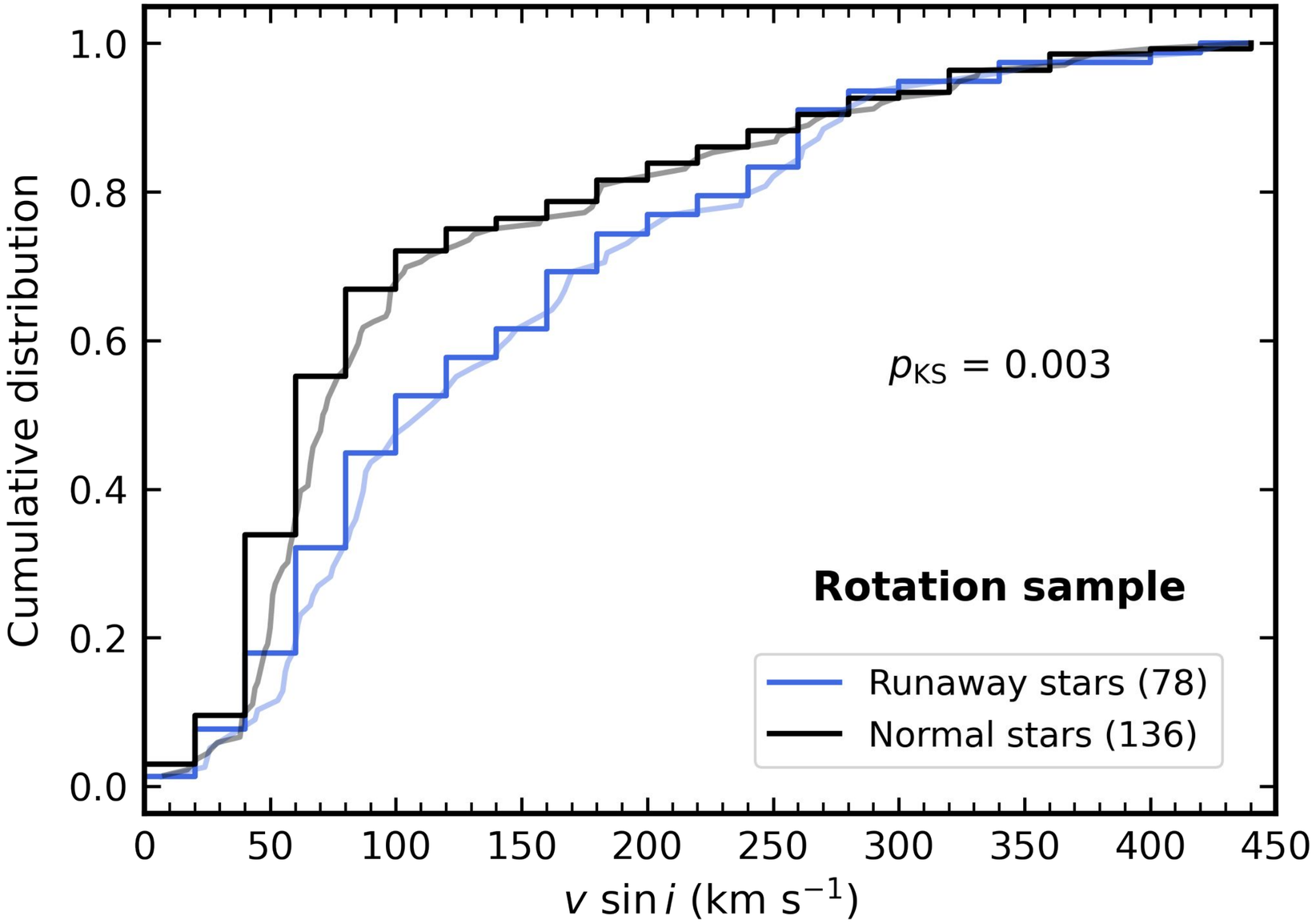
- LM Vel ↔ BSS
- Cyg X-1 ↔ BSS
- LS 5039 ↔ DES + BSS

BACKUP

- Stellar rotation: angular motion of a star around its axis
- Projected rotational velocity: the one measured since the star can have an inclination with respect to the observer’s line of sight



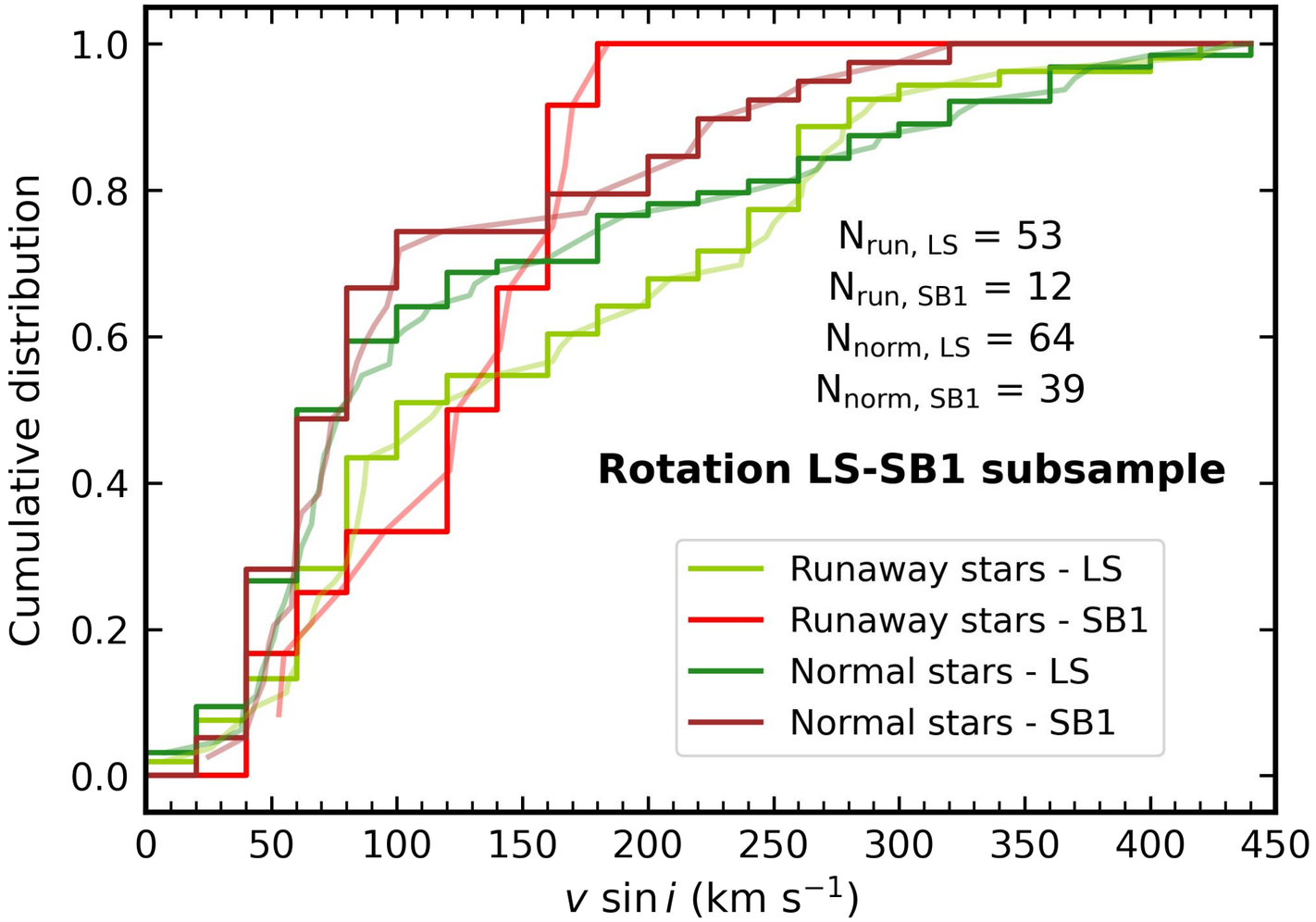
BACKUP - CDFs


1.0
0.8
0.6
0.4
0.2
0.0
Cumulative distribution
0
50
100
150
200
250
300
350
400
450
$v \sin i$ (km s^{-1})
p_{KS} = 0.003
Rotation sample
Runaway stars (78)
Normal stars (136)

BACKUP - CDFs

KS tests

	N	Run-LS	Run-SB1	Norm-LS	Norm-SB1
Run-LS	53	-	9%	6%	7%
Run-SB1	12	9%	-	21%	7%
Norm-LS	64	6%	21%	-	70%
Norm-SB1	39	7%	7%	70%	-



BACKUP - RUNAWAY DYNAMICAL ORIGINS