X-ray binaries: progenitors of NS/BH systems, and gravitational waves

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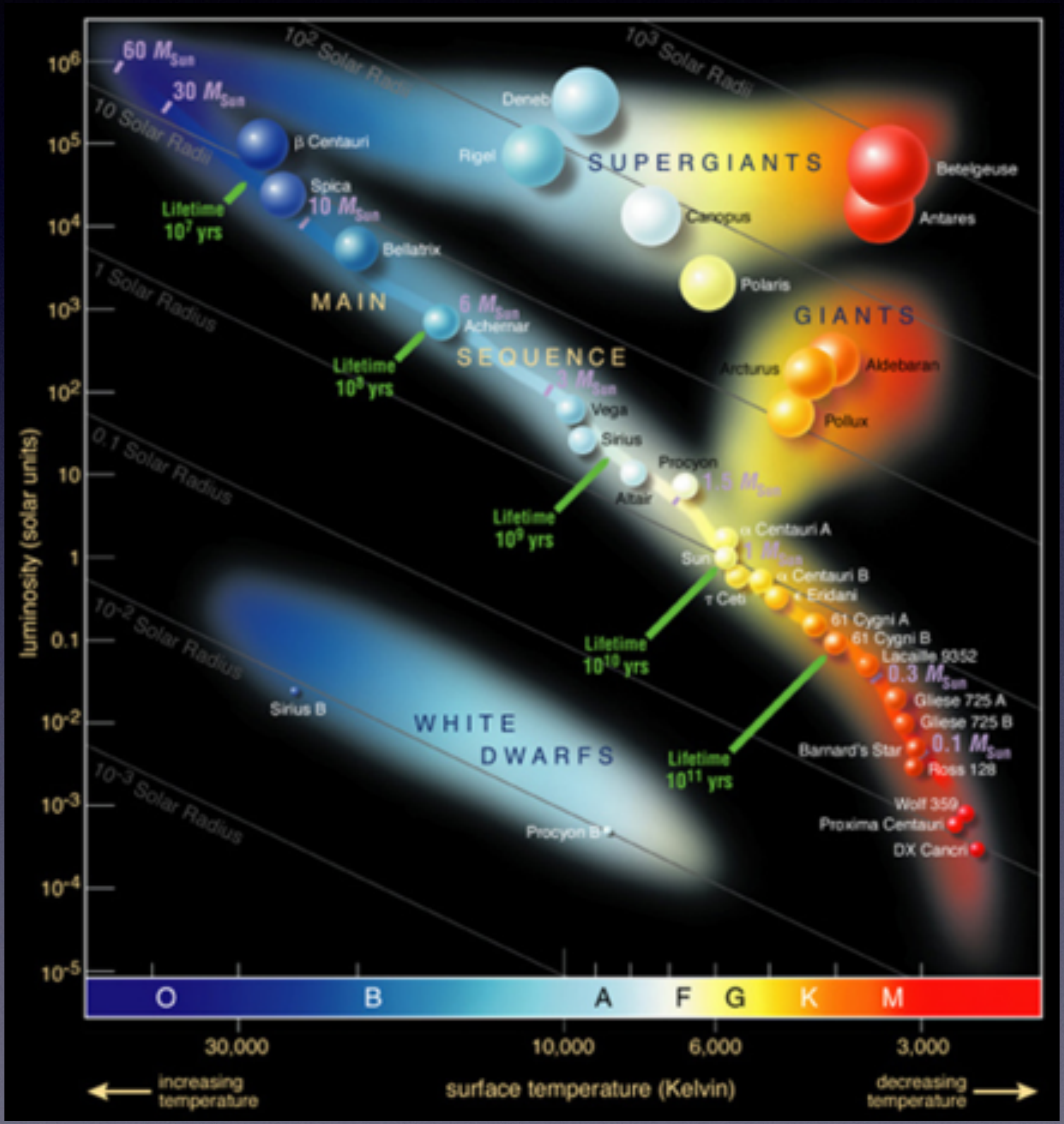
Gravitational Wave Astronomy Meeting
IAP, Paris, Sep 1st, 2016

Stellar evolution

- HR diagramme describes evolution of isolated star
- +70% of massive stars experience a binary interaction in the course of their evolution (Sana+ 2012)



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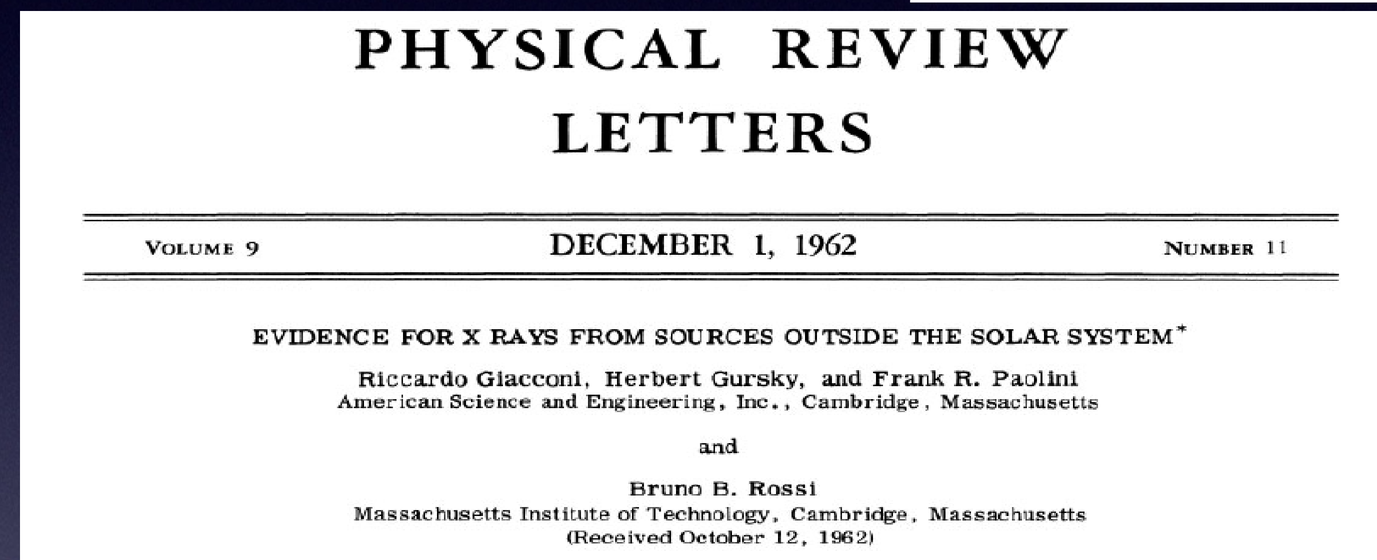
Kick-off of X-ray astronomy

- Discovery of the 1st extra-solar X-ray source: Sco X-1
- Giacconi+1962; Nobel prize of Physics 2002
- Looking forward for the Nobel prize for gravitational waves!



PHYSICAL REVIEW LETTERS

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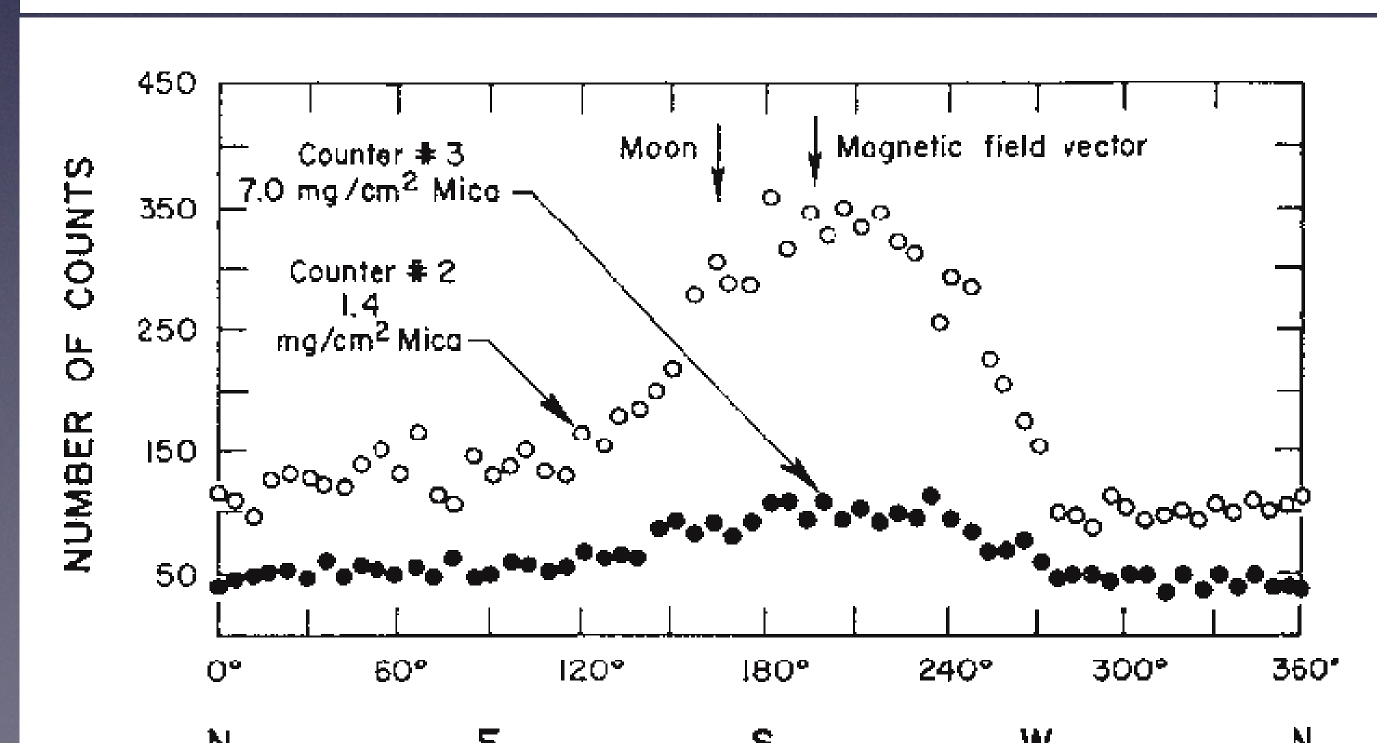
EVIDENCE FOR X RAYS FROM SOURCES OUTSIDE THE SOLAR SYSTEM*

Riccardo Giacconi, Herbert Gursky, and Frank R. Paolini
American Science and Engineering, Inc., Cambridge, Massachusetts

and

Bruno B. Rossi
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received October 12, 1962)

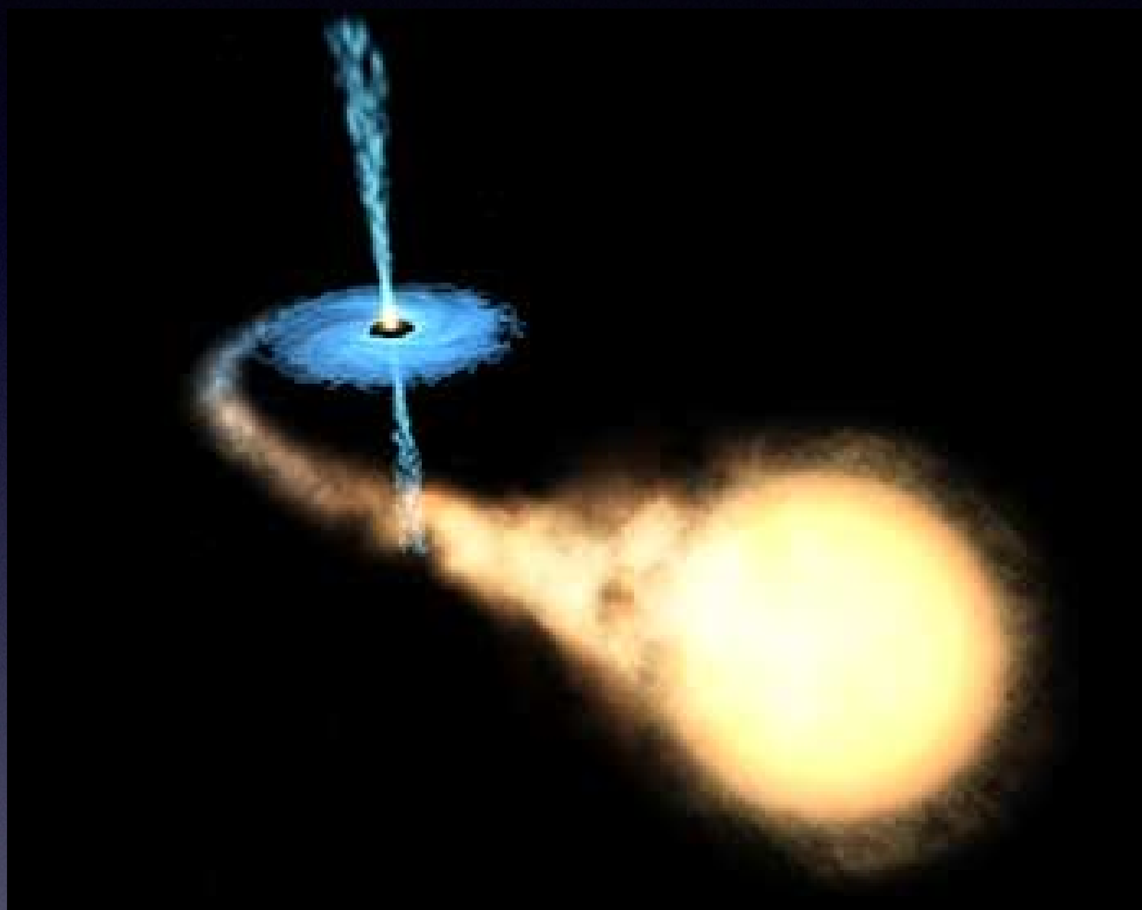


Plan

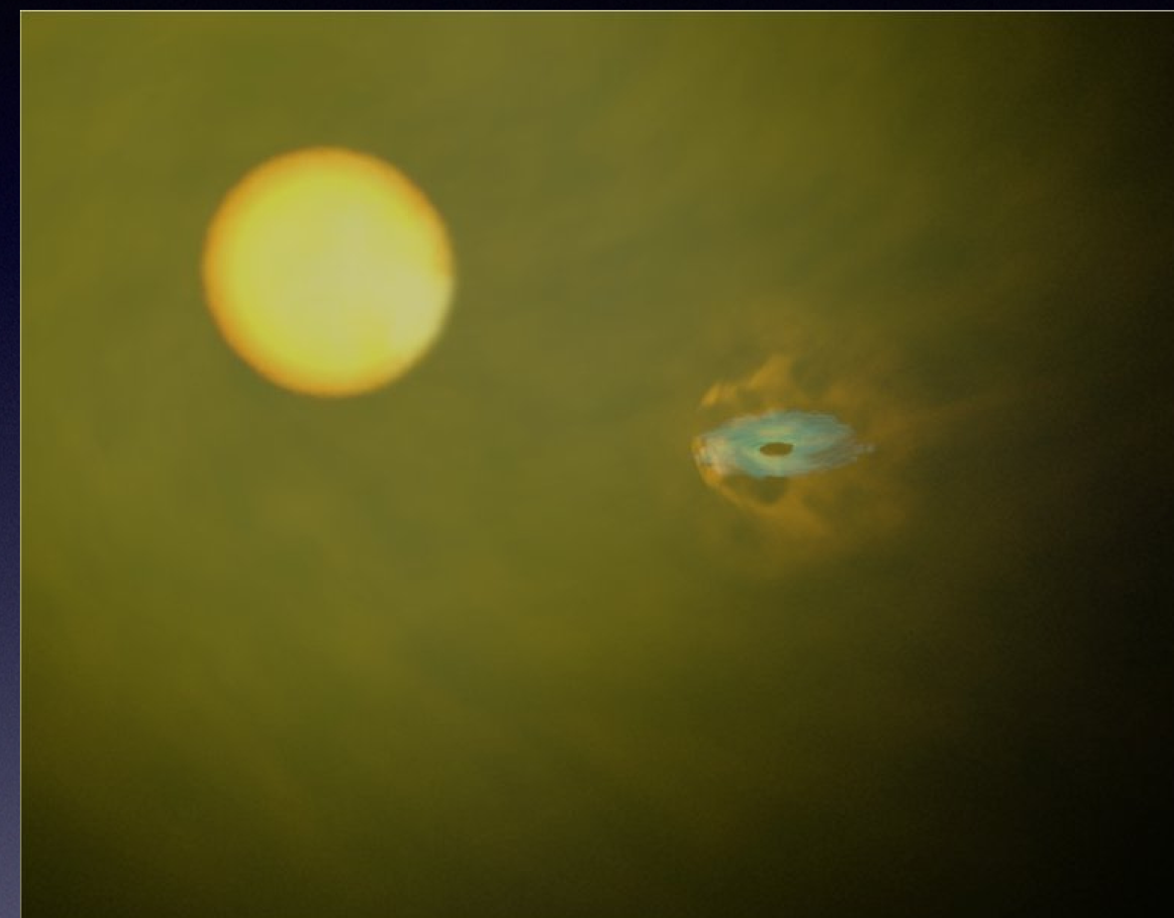
- I. Introduction: binaries, LMXB/HMXB
- II. Evolution
- The INTEGRAL revolution:
  - III. Galactic distribution
  - IV. The best progenitors for merging…
- V. Conclusions

I. Introduction: Binaries, LMXB/HMXB

Galactic X-ray binaries



Low-mass X-ray Binaries (LMXB): Roche lobe overflow



High-mass X-ray Binaries (HMXB): Stellar wind accretion

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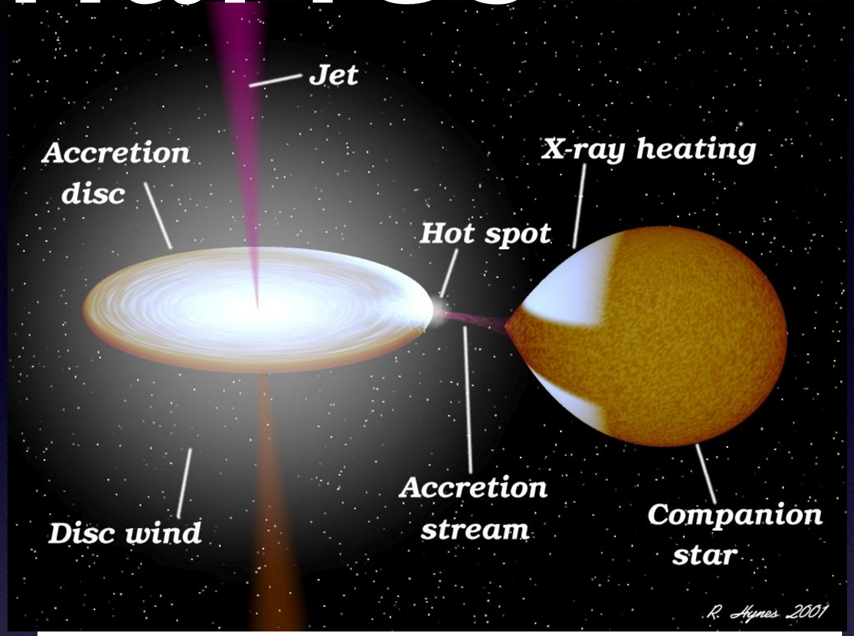
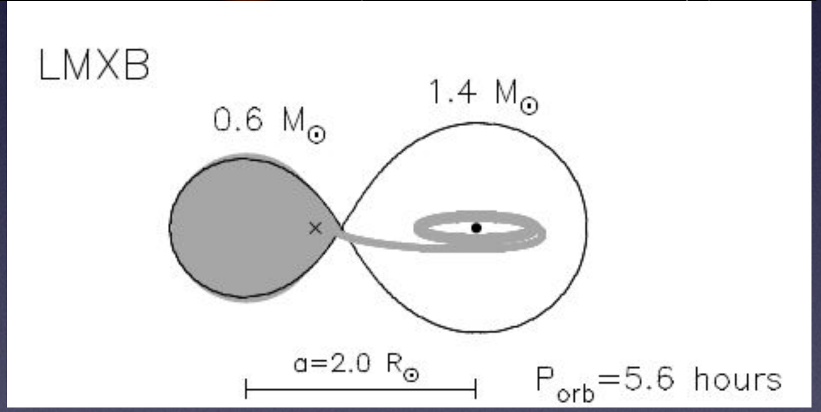
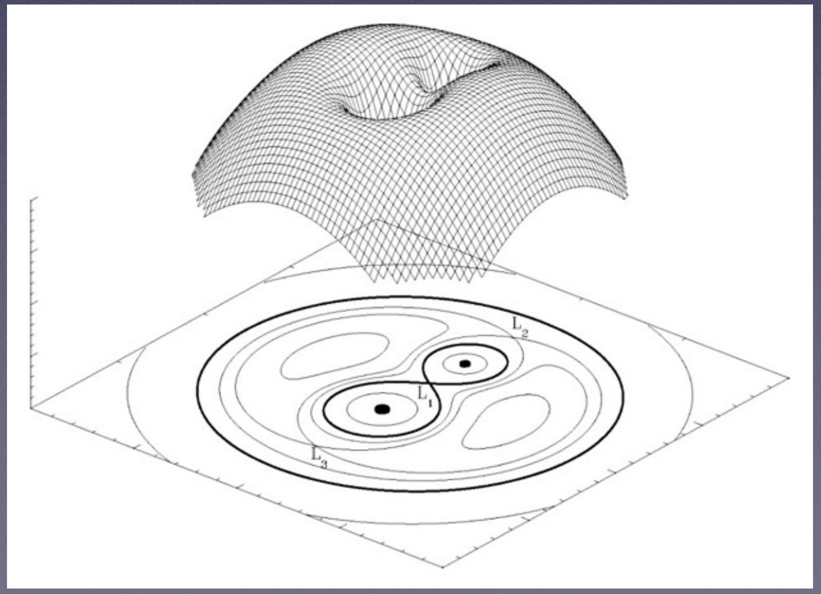
Galactic X-ray binaries

- 300 Galactic X-ray binaries: LMXB + HMXB (Liu+ 2006, 2007)
- 187 LMXB (62%):
  - Companion star later than B ($M<1M_\odot$)
  - Mass transfer: Roche lobe filling (accretion disk)
  - BH/NS LMXBs (Sco X-1…)







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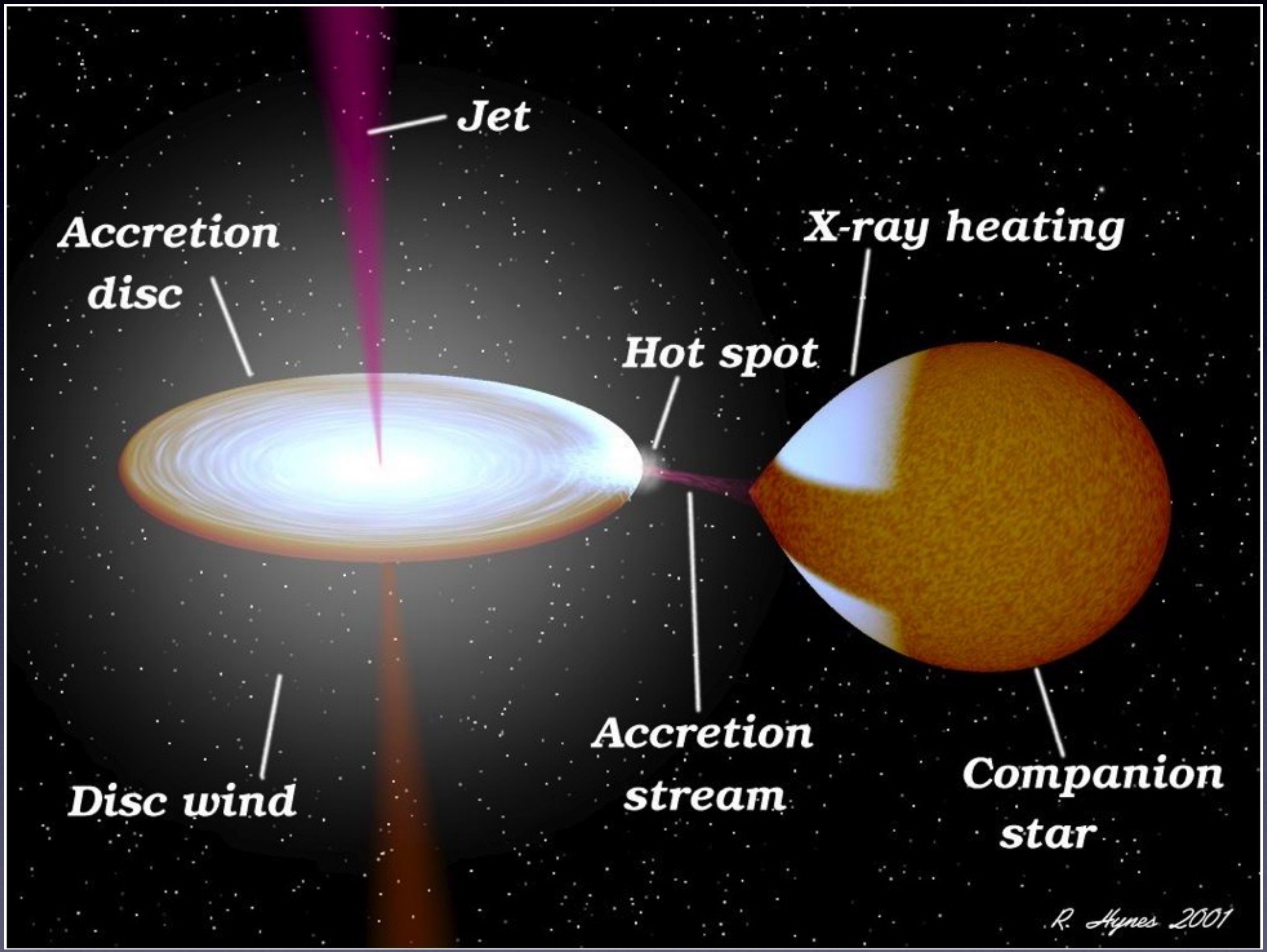
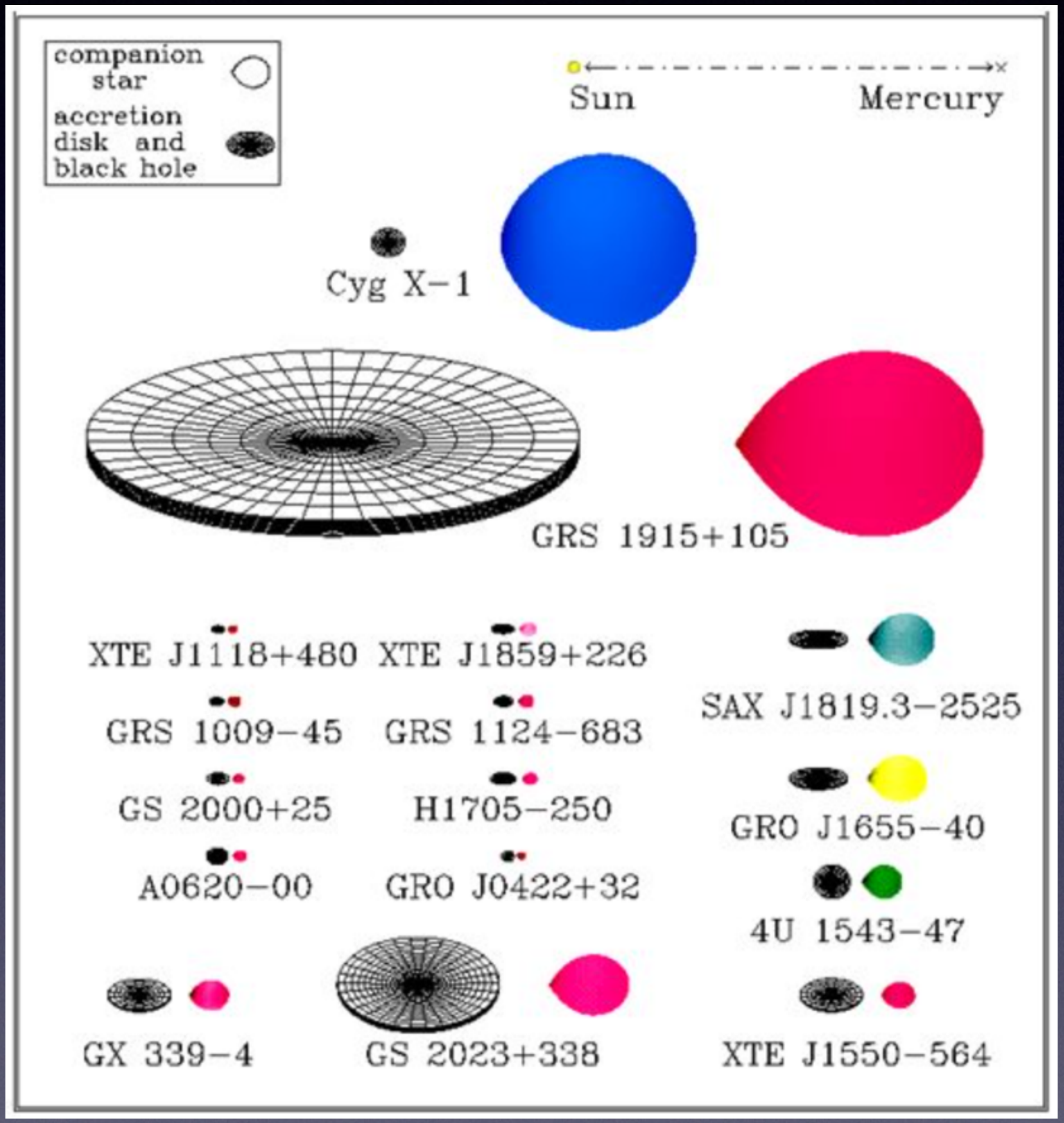
LMXB: Microquasars

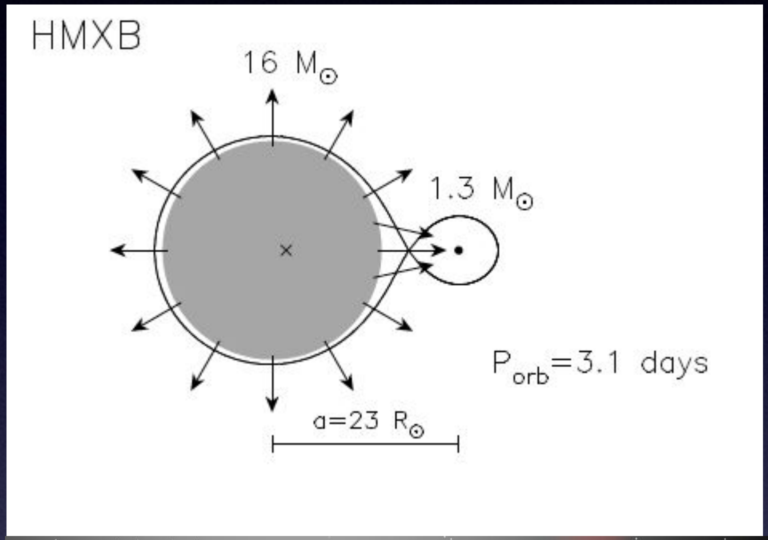


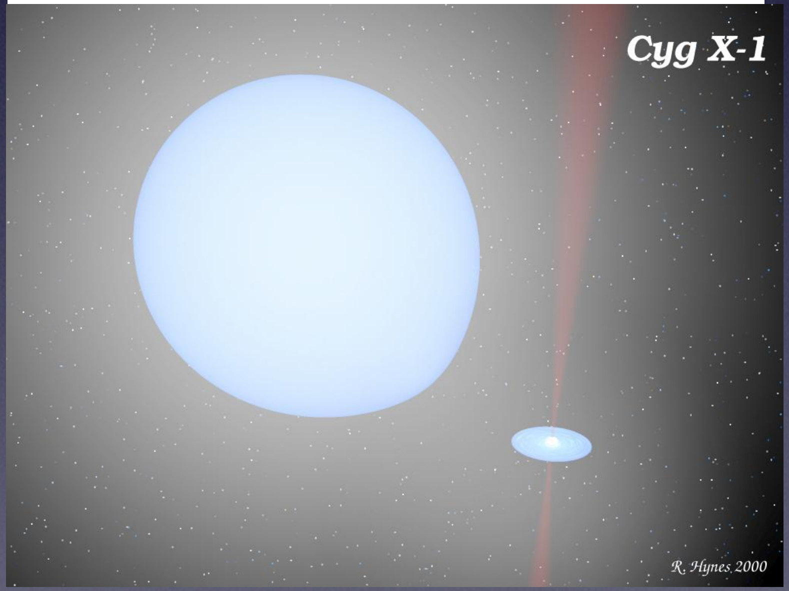


- Observation of flares/outbursts:
  Targets of opportunity multi-wavelength+multi-messengers!

Galactic X-ray binaries

- 114 HMXB (38%):
  - Luminous early-type OB companion (M>10M☼)
  - 2 types depending on mass transfer:
    - **BeXB** (60): direct accretion from circumstellar disk (Be III-V stars)
    - **sgXB** (36): spherical accretion from stellar wind (sg I/II stars)





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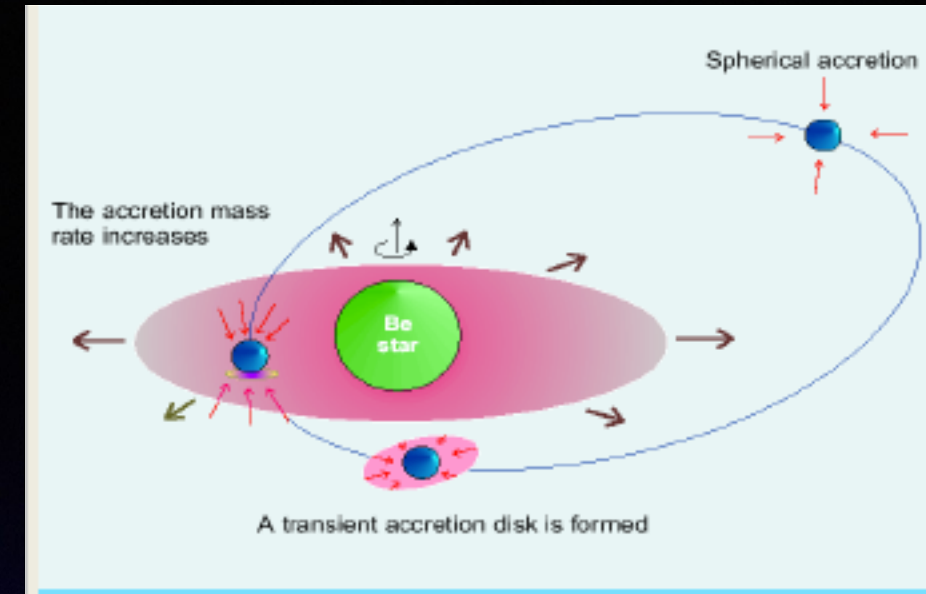
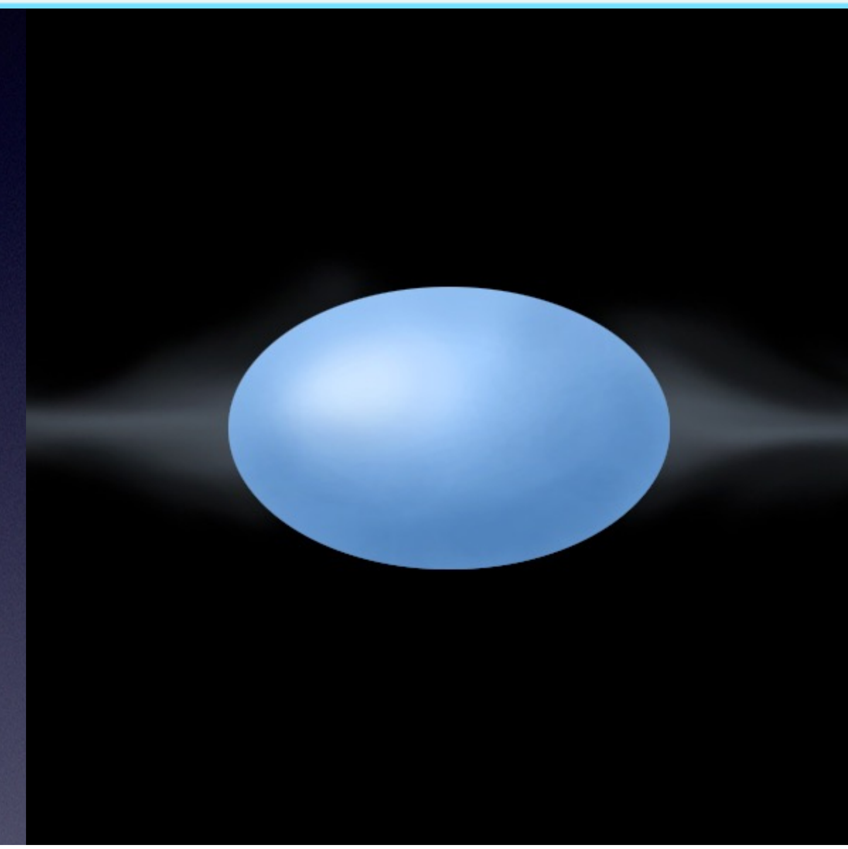
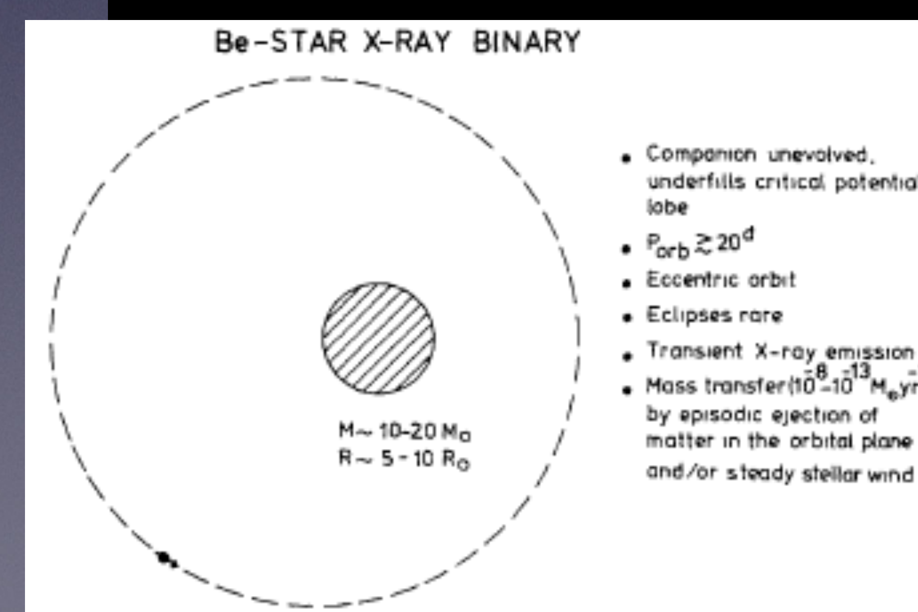
Be X-ray binaries (BeXB)



- Donor: O9-B2e V star with circumstellar «decretion» disc (Coe 2000, Negueruela 2004)
  - low-velocity/high-density wind (10^3km/s, $10^{-7/-6}$M☼/yr): Hα emission line (~disc size)
- NS on wide/eccentric orbit
  - Type I X-ray outbursts (10^{35-37}erg/s): NS crosses disk, last 0.2-0.3 P_{orb}
- ~50 in MW, >35 in SMC





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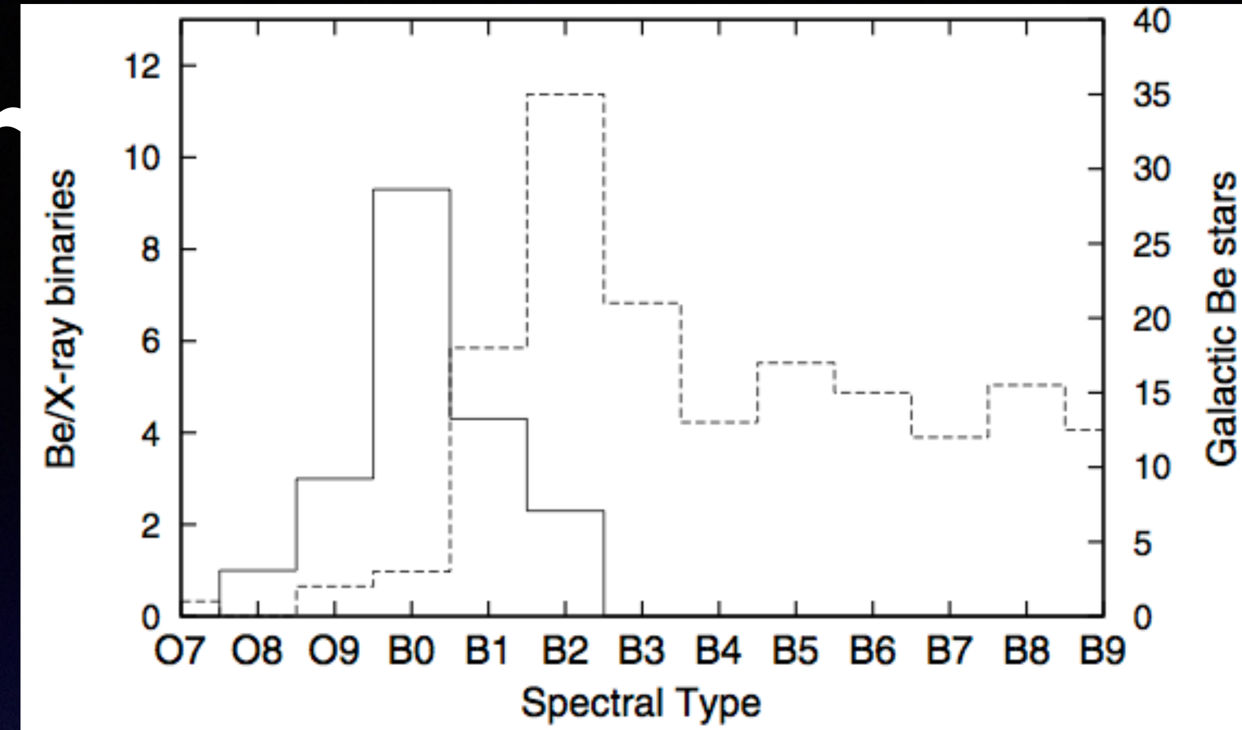
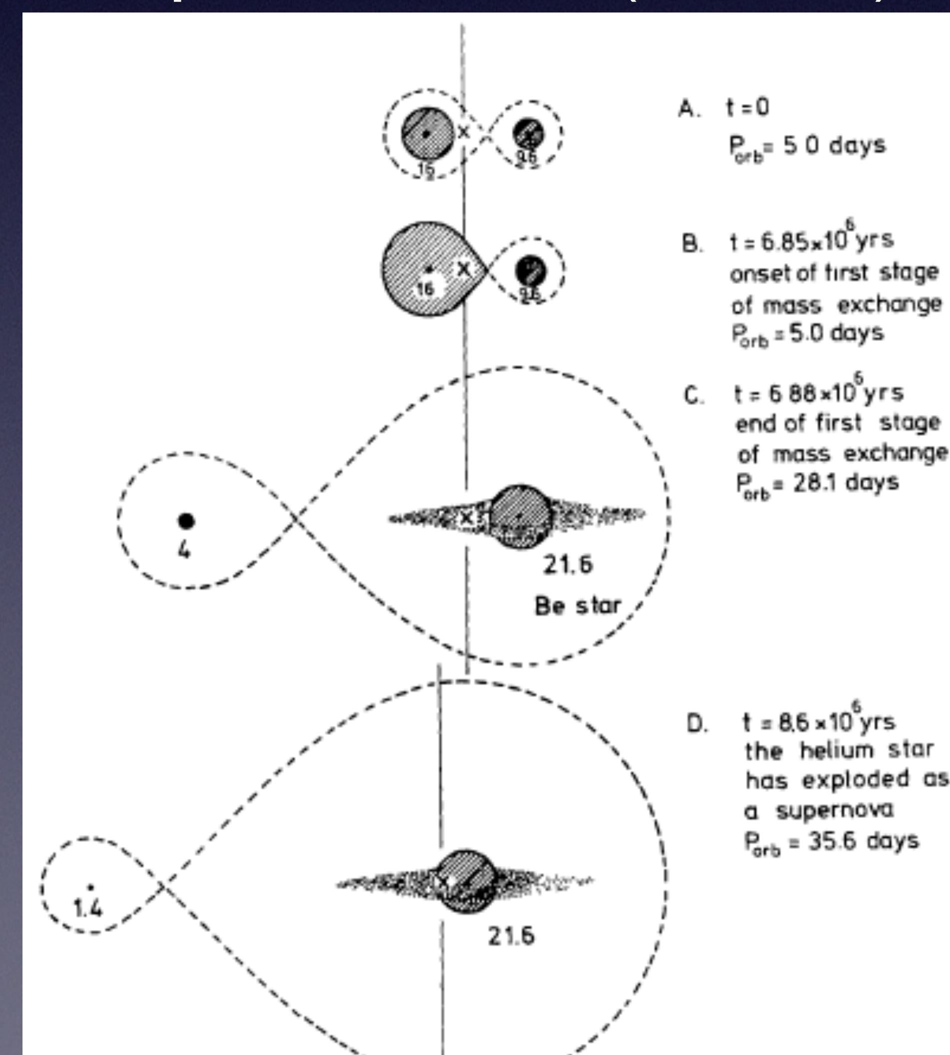
Be X-ray binar
(BeXB)



- BeXB mass distribution:
  - peaks at B0V (~16M☼)
  - low-mass systems (M<10 M☼/B2V+) disrupted by kick (SN)
  - heavier systems (M>22 M☼/O8V-) -> sgXB
- Model of Rejuvenation: mass transfer spins up outer layers of secondary star



Rappaport & van den Heuvel 1982

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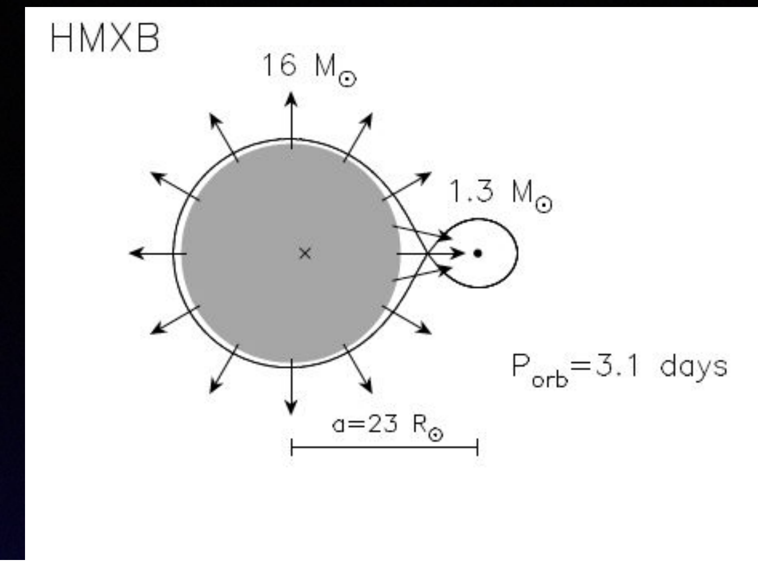
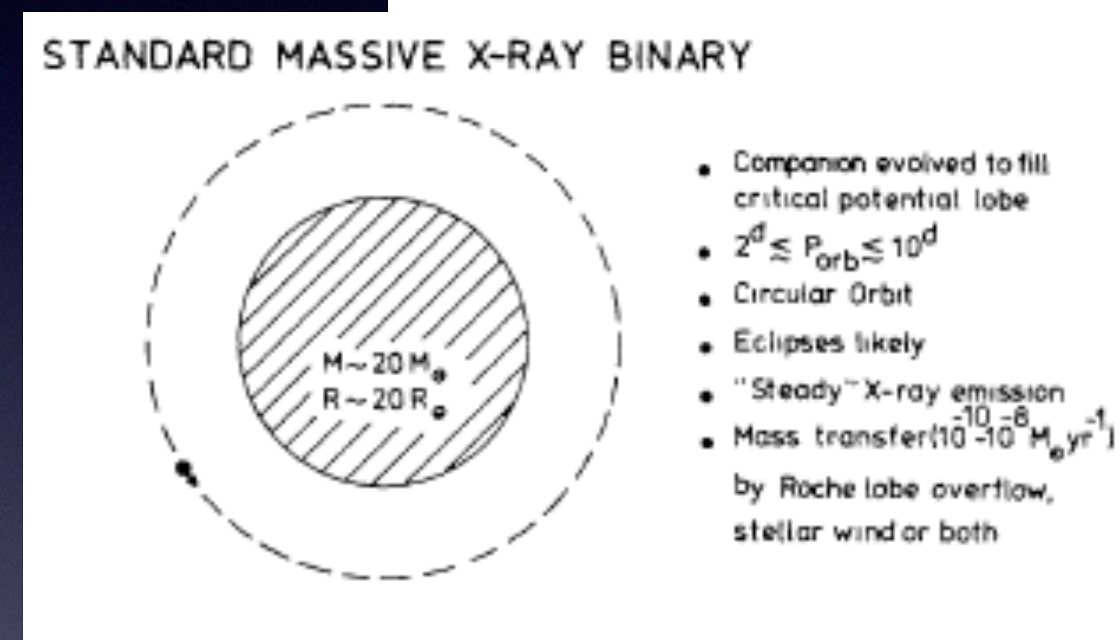
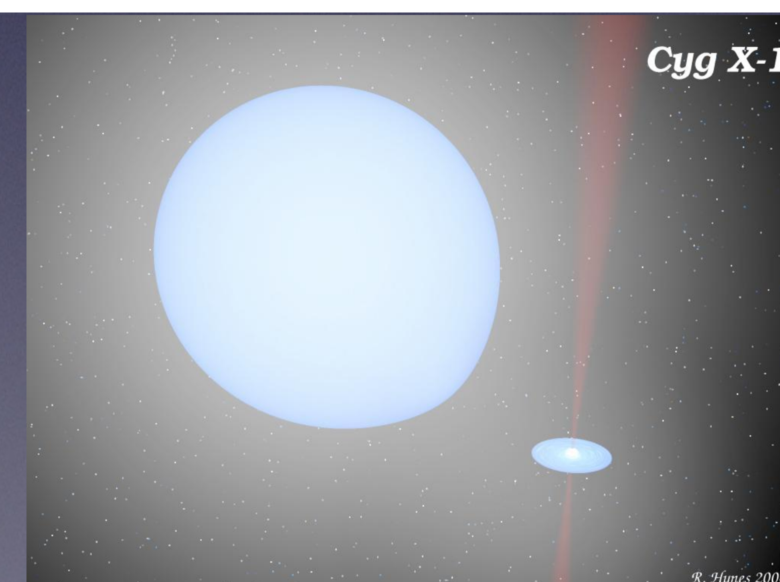
sg X-ray binaries (classical sgXBs)

- Donor: luminous early-type sgOB I/II star ($M>10M_☼$)
- Compact object: NS in ~circular orbit ($L_X \sim 10^{35-36}$ up to 10^{40} erg/s)
- Persistent systems:
  - Spherical accretion from steady stellar wind (~500 to1000 km/s)
  - Beginning Atmospheric Roche Lobe Overflow (Cyg X-1!)
- 18 classical sgXBs: Vela X-1, GX 301-2, 4U 1700-37, 4U 1907+09, OAO 1657-415…







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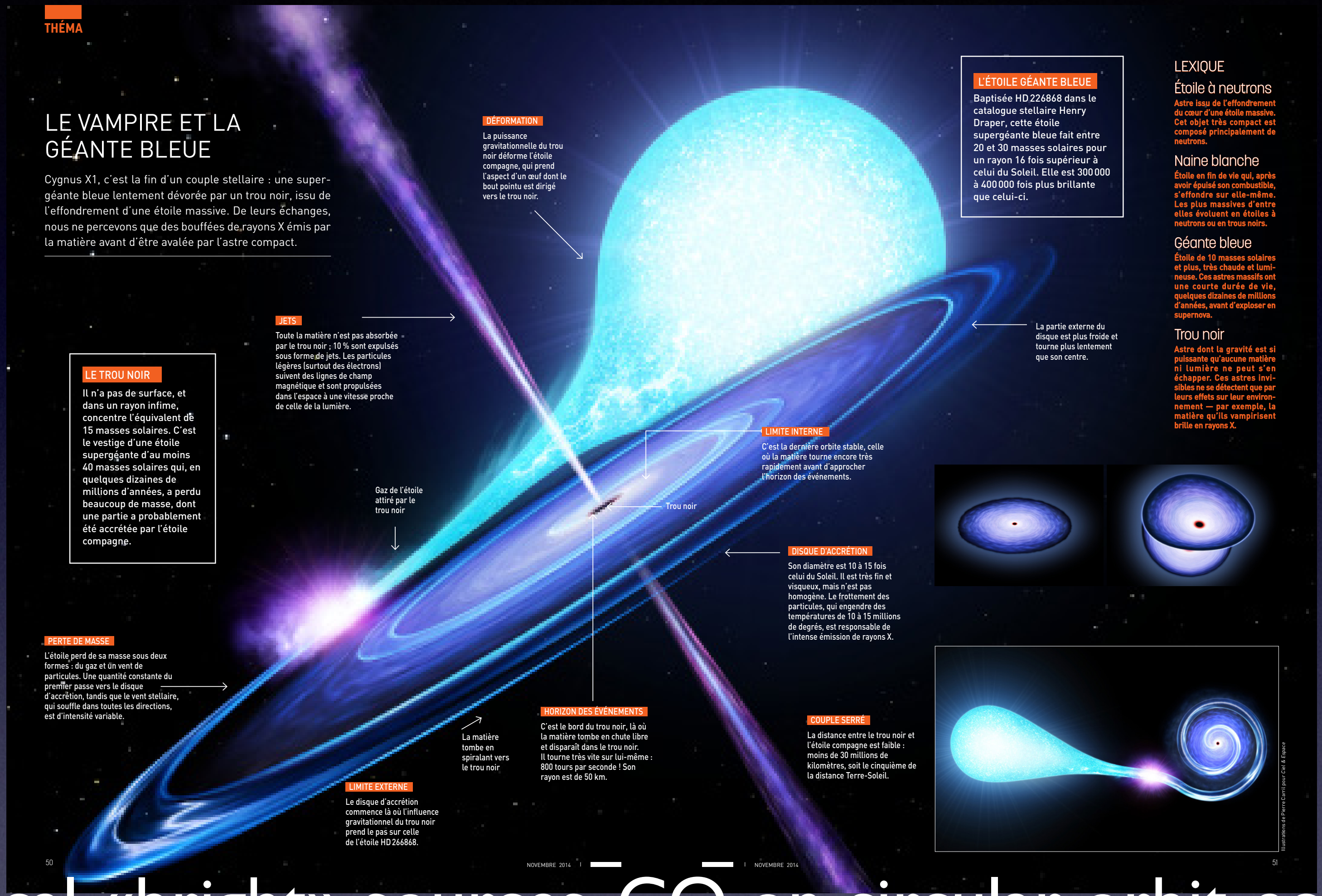
Roche-lobe overflow HMXB: Microquasars



THÉMA

LE VAMPIRE ET LA GÉANTE BLEUE

Cygnus X1, c'est la fin d'un couple stellaire : une supergéante bleue lentement dévorée par un trou noir, issu de l'effondrement d'une étoile massive. De leurs échanges, nous ne percevons que des bouffées de rayons X émis par la matière avant d'être avalée par l'astre compact.

LE TROU NOIR
Il n'a pas de surface, et dans un rayon infime, concentre l'équivalent de 15 masses solaires. C'est le vestige d'une étoile supergéante d'au moins 40 masses solaires qui, en quelques dizaines de millions d'années, a perdu beaucoup de masse, dont une partie a probablement été accrétée par l'étoile compagne.

JETS
Toute la matière n'est pas absorbée par le trou noir ; 10 % sont expulsés sous forme de jets. Les particules légères (surtout des électrons) suivent des lignes de champ magnétique et sont propulsées dans l'espace à une vitesse proche de celle de la lumière.

DÉFORMATION
La puissance gravitationnelle du trou noir déforme l'étoile compagne, qui prend l'aspect d'un œuf dont le bout pointu est dirigé vers le trou noir.

L'ÉTOILE GÉANTE BLEUE
Baptisée HD 226868 dans le catalogue stellaire Henry Draper, cette étoile supergéante bleue fait entre 20 et 30 masses solaires pour un rayon 16 fois supérieur à celui du Soleil. Elle est 300 000 à 400 000 fois plus brillante que celui-ci.

LEXIQUE

Étoile à neutrons
Astre issu de l'effondrement du cœur d'une étoile massive. Cet objet très compact est composé principalement de neutrons.

Naine blanche
Étoile en fin de vie qui, après avoir épuisé son combustible, s'effondre sur elle-même. Les plus massives d'entre elles évoluent en étoiles à neutrons ou en trous noirs.

Géante bleue
Étoile de 10 masses solaires et plus, très chaude et lumineuse. Ces astres massifs ont une courte durée de vie, quelques dizaines de millions d'années, avant d'exploser en supernova.

Trou noir
Astre dont la gravité est si puissante qu'aucune matière ni lumière ne peut s'en échapper. Ces astres invisibles ne se détectent que par leurs effets sur leur environnement — par exemple, la matière qu'ils vampirisent brille en rayons X.

La partie externe du disque est plus froide et tourne plus lentement que son centre.

Gaz de l'étoile attiré par le trou noir

LIMITE INTERNE
C'est la dernière orbite stable, celle où la matière tourne encore très rapidement avant d'approcher l'horizon des événements.

Trou noir

DISQUE D'ACCRÉTION
Son diamètre est 10 à 15 fois celui du Soleil. Il est très fin et visqueux, mais n'est pas homogène. Le frottement des particules, qui engendre des températures de 10 à 15 millions de degrés, est responsable de l'intense émission de rayons X.

PERTE DE MASSE
L'étoile perd de sa masse sous deux formes : du gaz et un vent de particules. Une quantité constante du premier passe vers le disque d'accrétion, tandis que le vent stellaire, qui souffle dans toutes les directions, est d'intensité variable.

La matière tombe en spiralant vers le trou noir

HORIZON DES ÉVÉNEMENTS
C'est le bord du trou noir, là où la matière tombe en chute libre et disparaît dans le trou noir. Il tourne très vite sur lui-même : 800 tours par seconde ! Son rayon est de 50 km.

LIMITE EXTERNE
Le disque d'accrétion commence là où l'influence gravitationnel du trou noir prend le pas sur celle de l'étoile HD 266868.

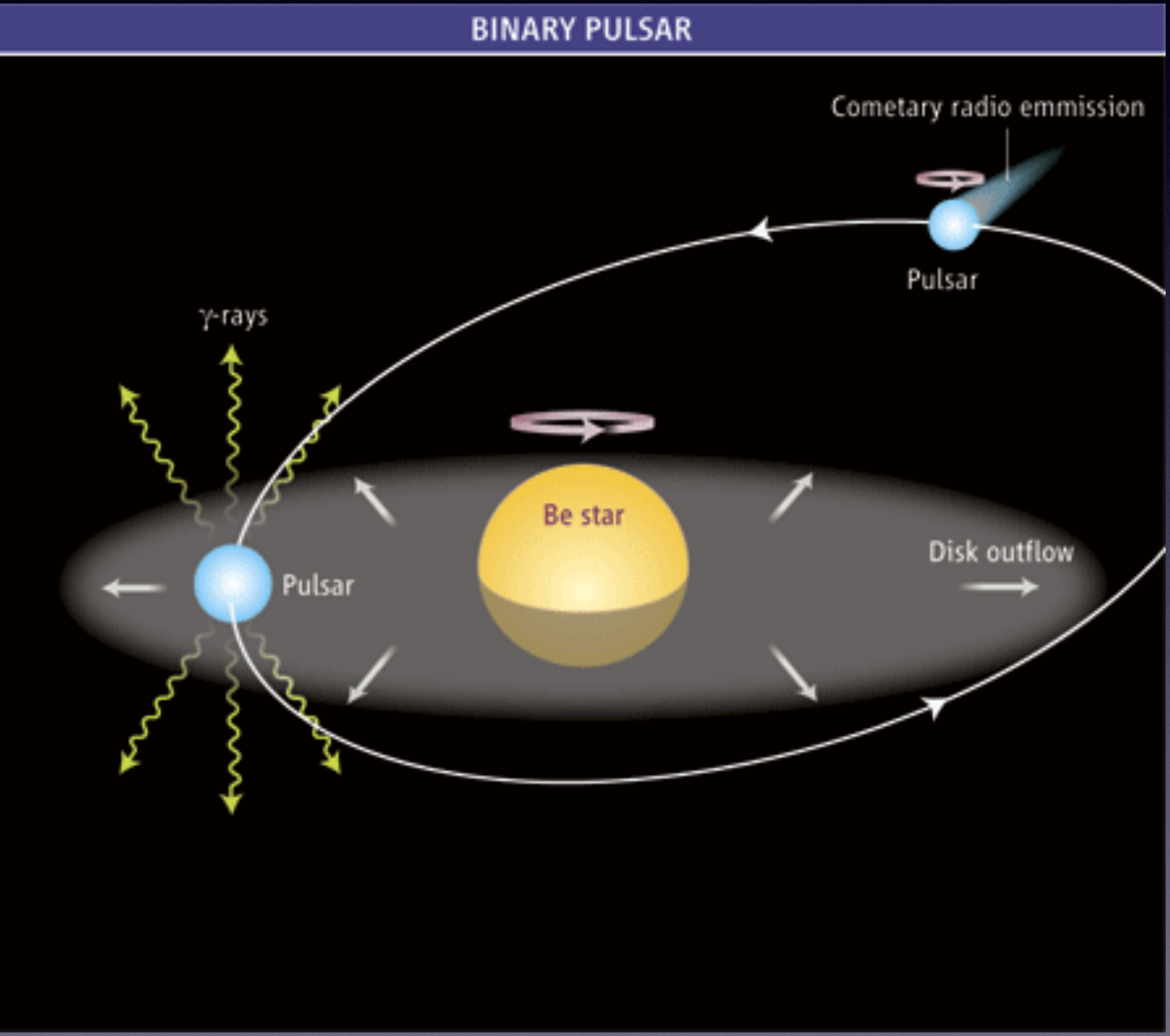
COUPLE SERRÉ
La distance entre le trou noir et l'étoile compagne est faible : moins de 30 millions de kilomètres, soit le cinquième de la distance Terre-Soleil.

Illustrations de Pierre Carril pour *Ciel & Espace*

50 NOVEMBRE 2014 | | NOVEMBRE 2014 51

- Classical «bright» sources, CO on circular orbit, accretion disc: high X-ray luminosity (L_x~10^{38} erg/s) during outbursts
- Cyg X-1: the only HMXB with RLO+stellar wind accretion hosting a confirmed BH!
- Target of opportunity multi-wavelength+multi-messengers!

High Mass Γ-ray Binaries (HMΓB)

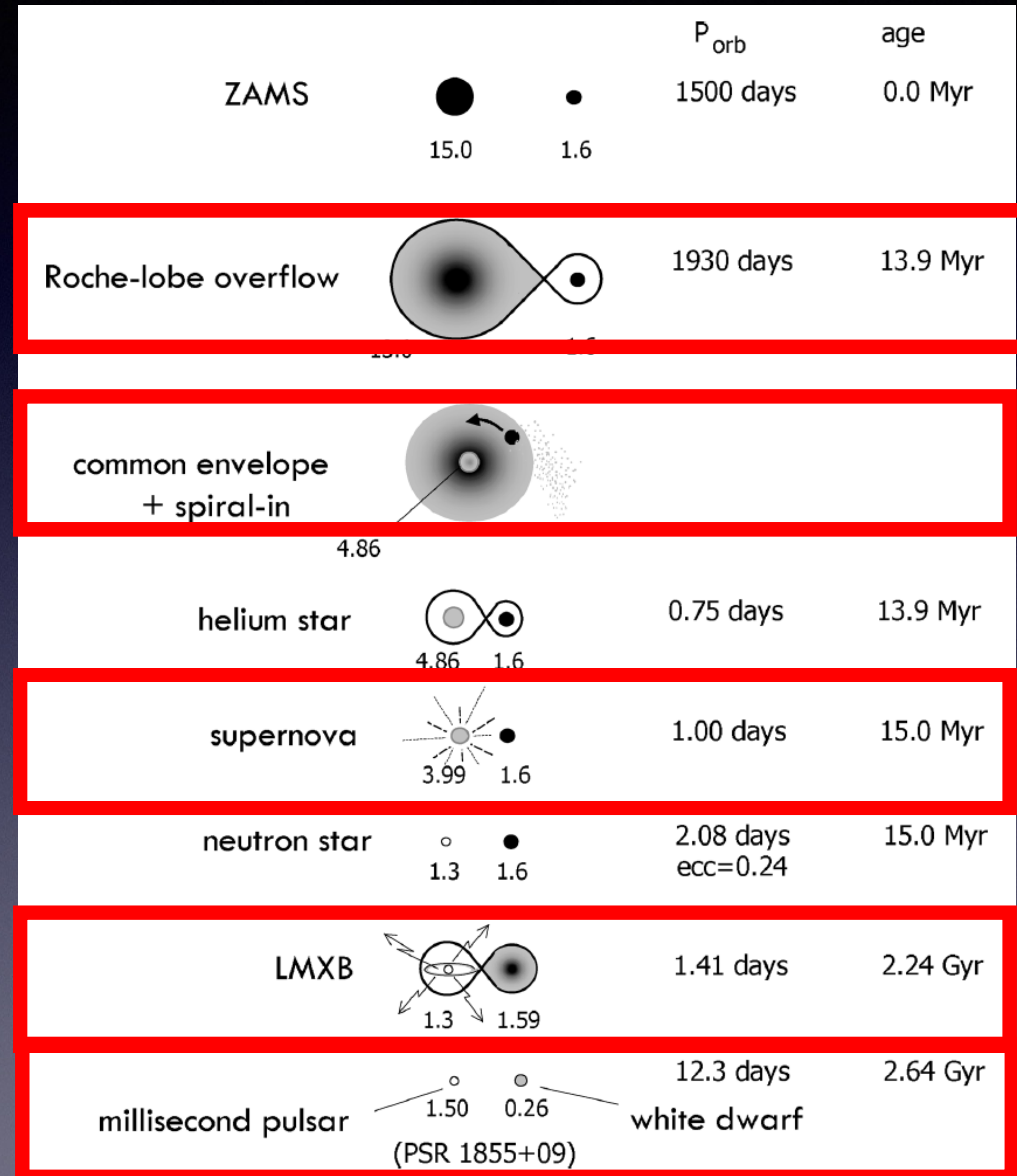


- LSI +61 303
- LS 5039
- PSR B1259-63

II. Evolution

Evolution of LMXB

- Formation -> Roche-lobe overflow
- Go through and survive (?) Common Enveloppe Phase
- After SN, 2nd star evolves
- Short P_{orb}~1d LMXB (while long P_{orb} initial systems!)
- ...end as NS + WD binary systems



Tauris & van den Heuvel 2006

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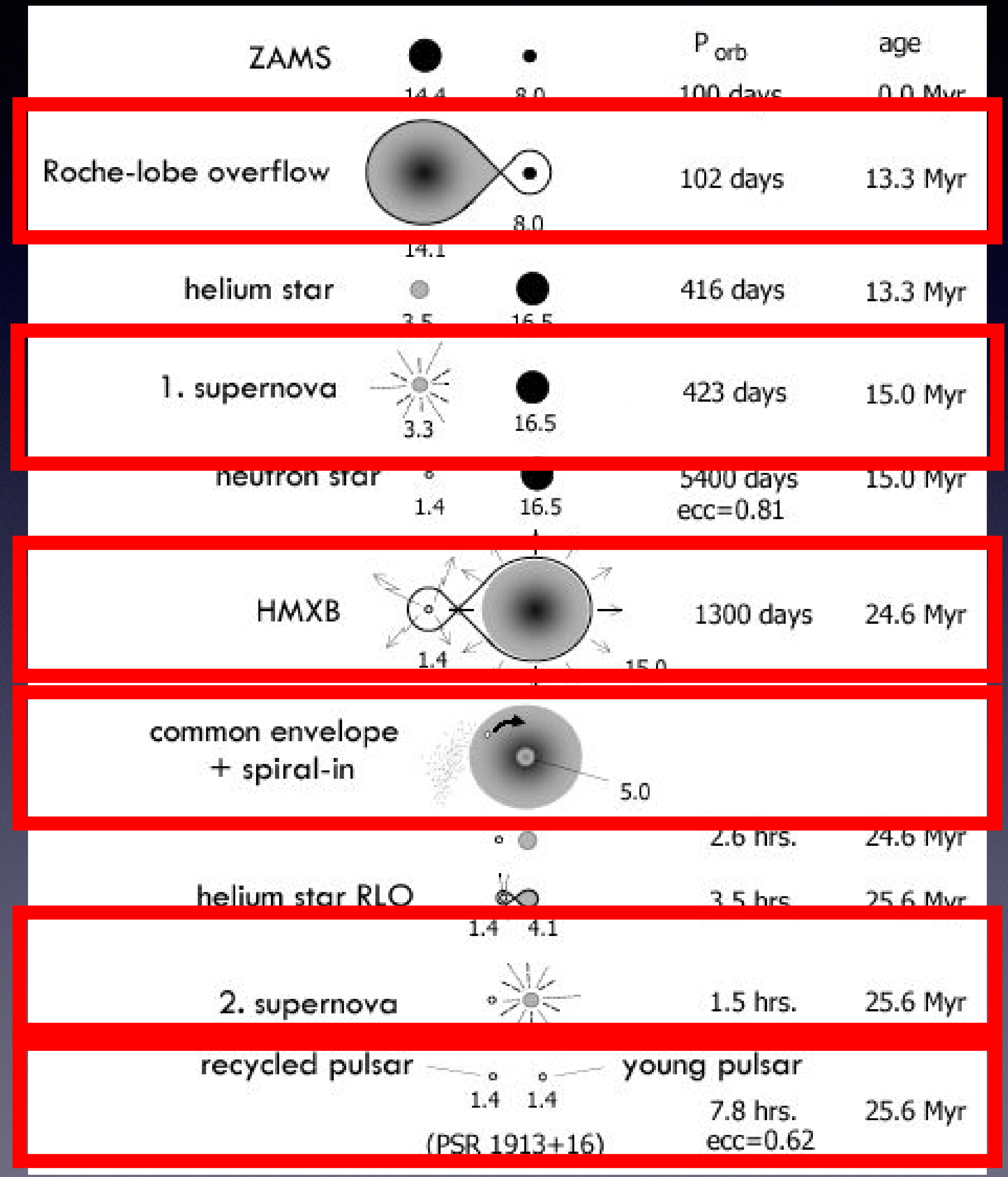
Evolution of HMXB

- Formation -> Roche-lobe overflow
- After 1st SN, 2nd star evolves
- Long P_{orb}~100d HMXB require initial systems with short P_{orb}~10d
- Go through and survive (?) Common Enveloppe Phase
- After 2nd SN, end as close eccentric radio pulsar binary systems (double NS or BH, or NS/BH)



Tauris & van den Heuvel 2006

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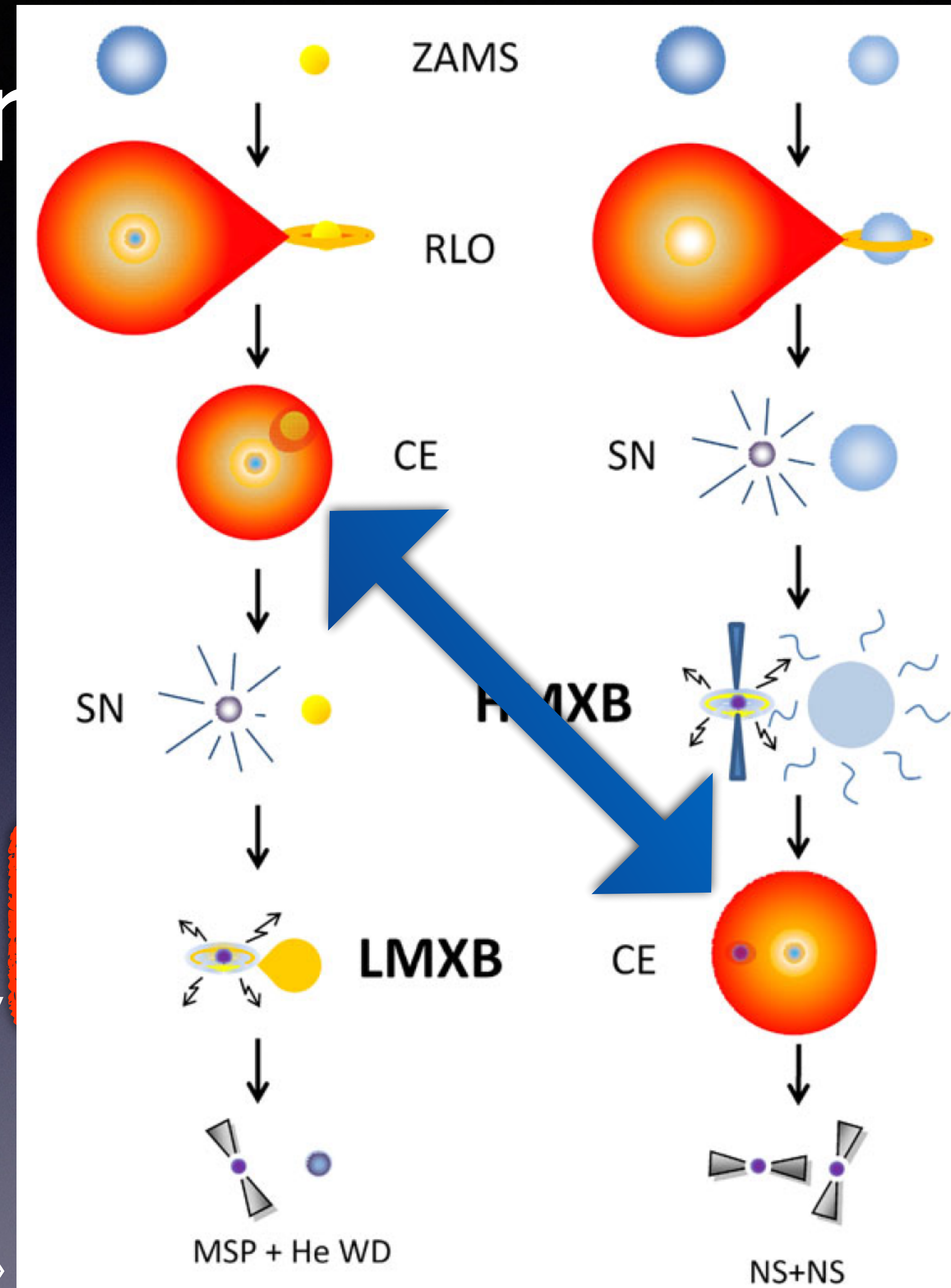
Evolution

- Common enveloppe phase:
  - star radius increases to orbit's size (Paczynski 1976, Webbink 2008)
  - Size of binary's orbit decreases
  - But how much does shrink the orbit, and how many systems do survive? (Ivanova+2013)
  - « classical isolated binary evolution »



Ivanova+2013

The INTEGRAL revolution!

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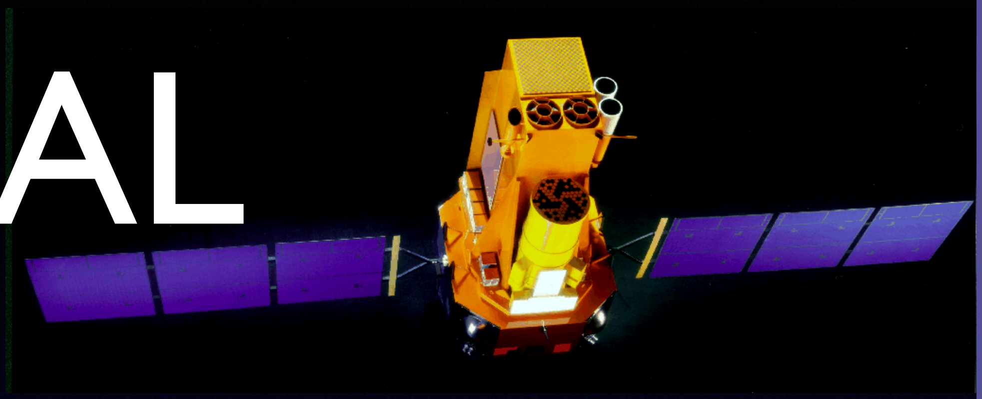
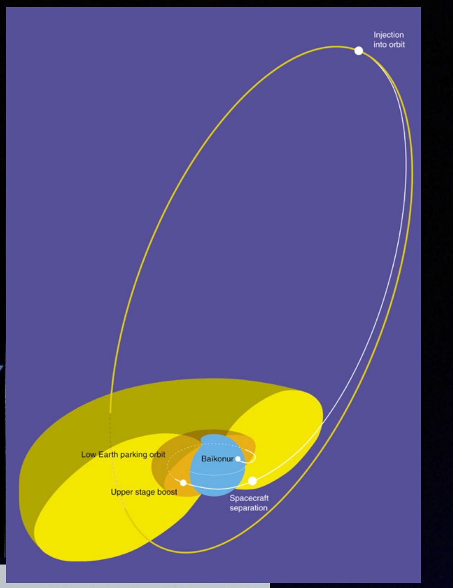
The INTEGRAL legacy

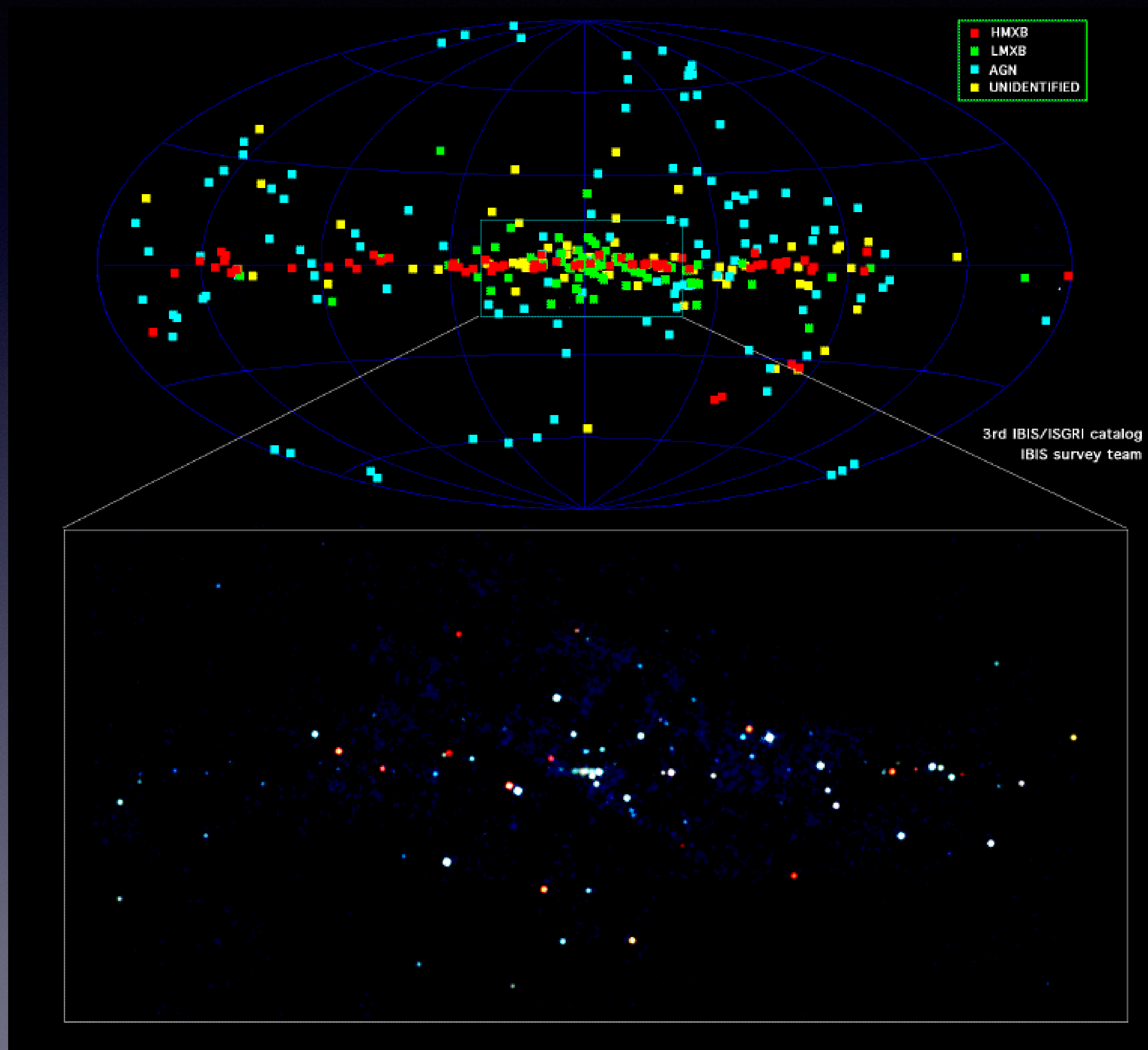




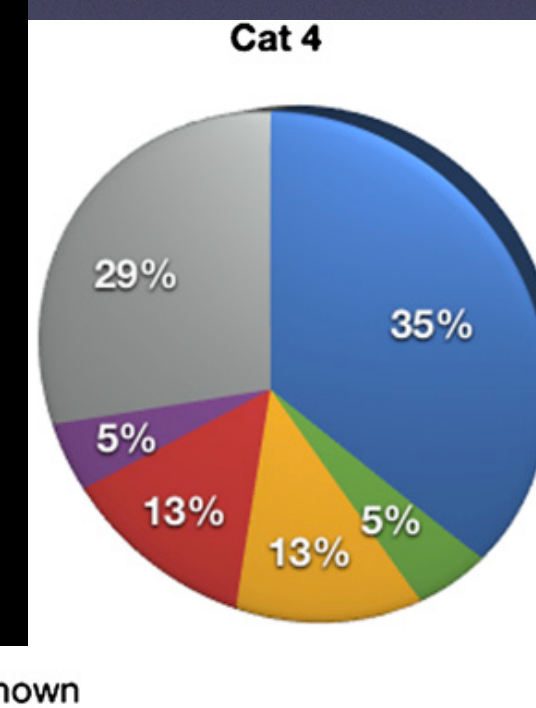
- ESA satellite launched on 17/10/2002 by PROTON rocket on eccentric orbit
- *INTEGRAL* tripled the population of known sgXBs, revealing 3 new categories:
  - obscured (persistent) sgXBs
  - fast transient sgXBs (SFXTs)
  - eccentric transients

- Chaty, AdSpR, 2013

The Milky Way



Bird et al. 2010



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III. Galactic distribution: LMXB vs HMXB

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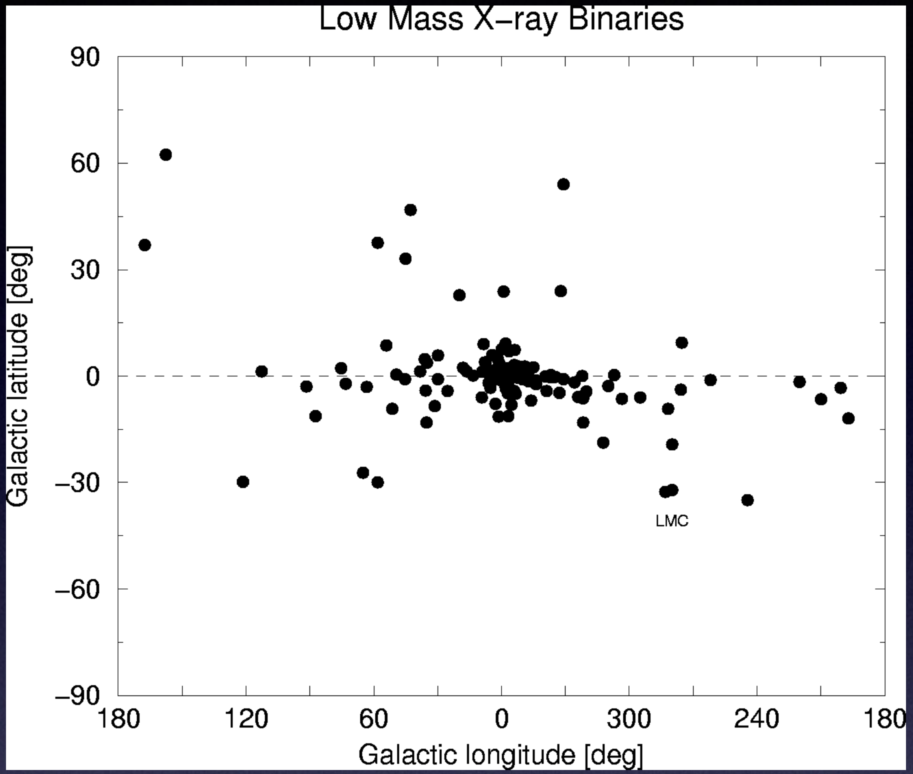
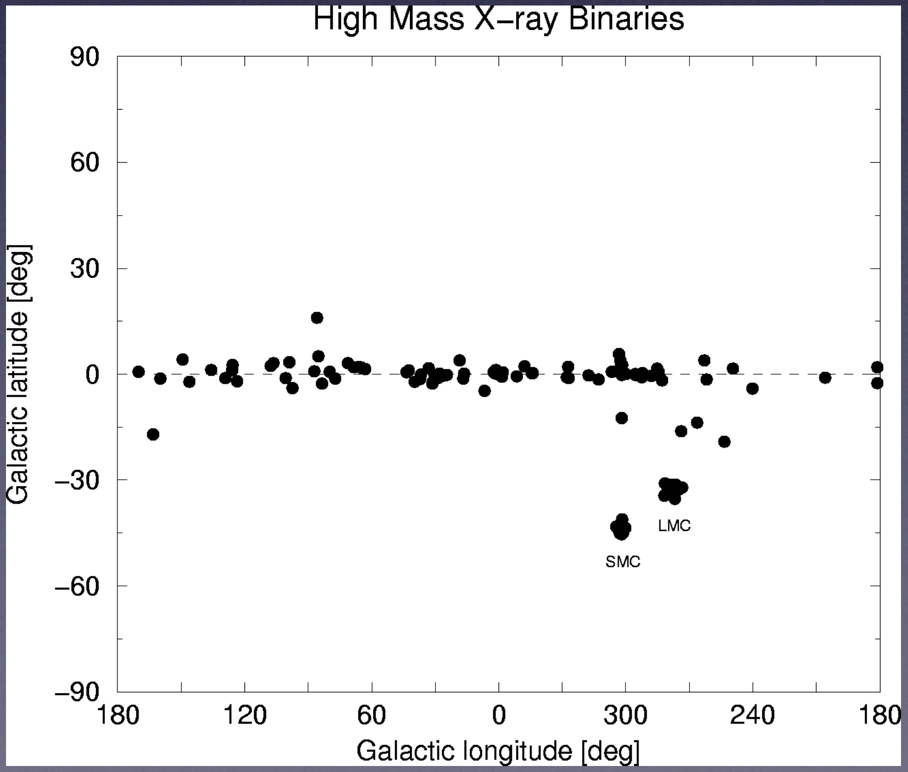
Galactic distribution

- LMXB (old companion stars) in Galactic bulge, migration off the plane (|b|>3-5°)
- HMXB (young companion stars): on Galactic plane, towards tangential directions of spiral arms





Grimm et al. 2002

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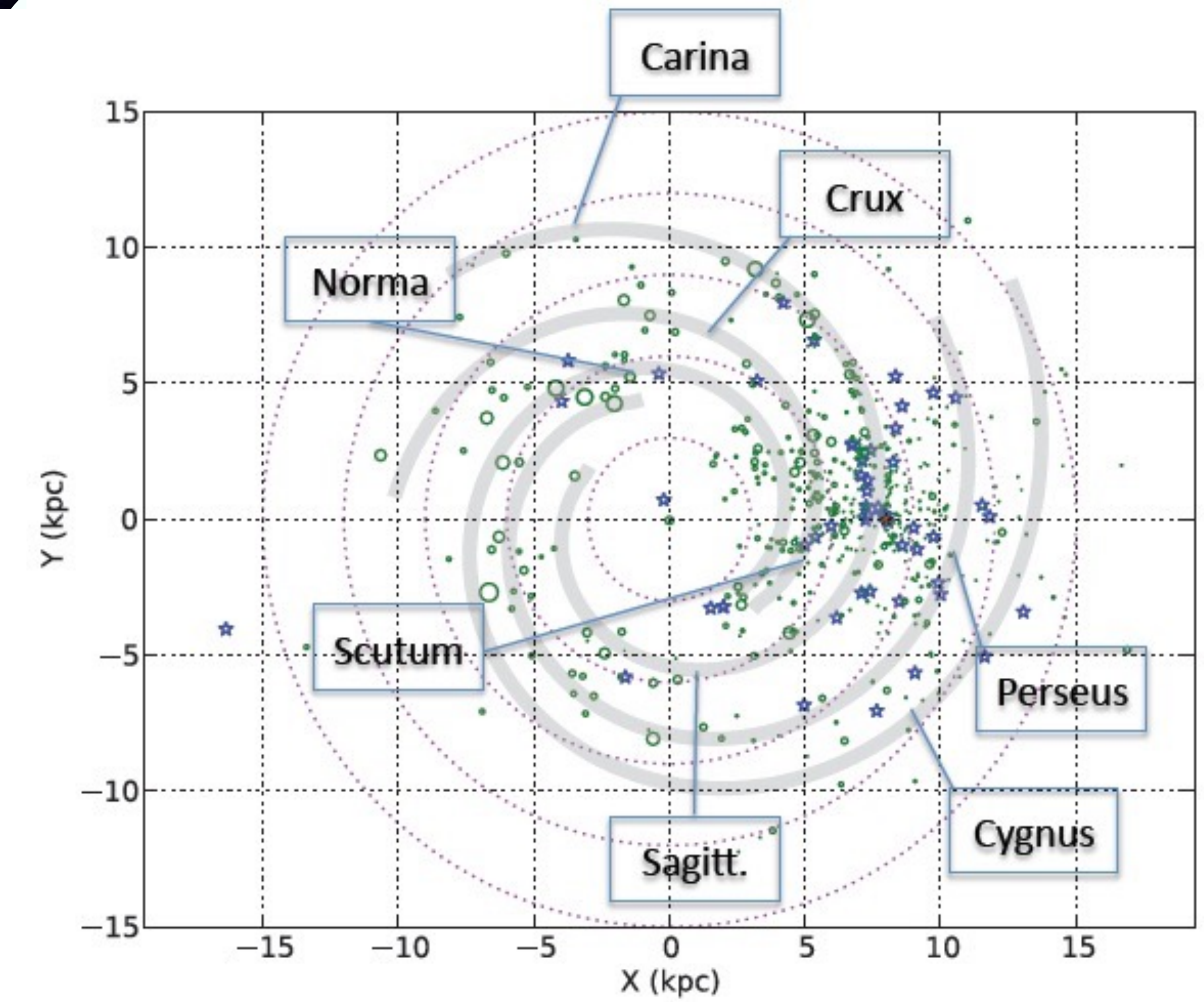
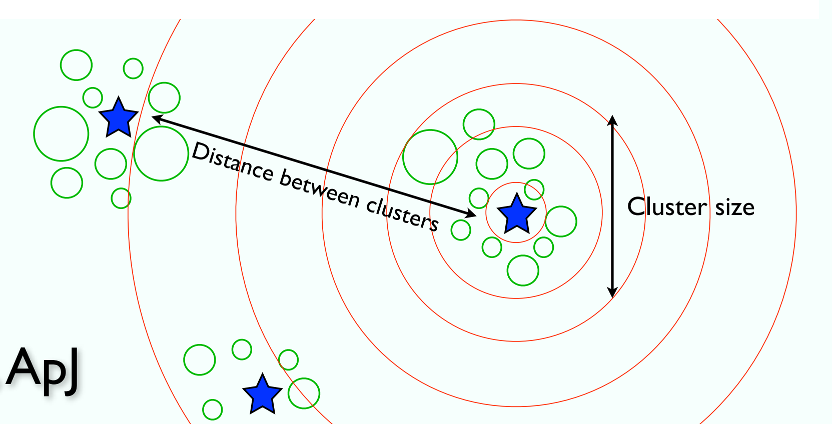
Galactic distribution of HMXB

- Fit (distance, A_V) of 46 HMXB on 4-spiral arm Galactic model
  - HMXB clustered with Star Forming Complexes (Russeil 2003)
  - <size>=0.3 kpc <distance>=1.7 kpc
- HMXB remain close to their birthplace!

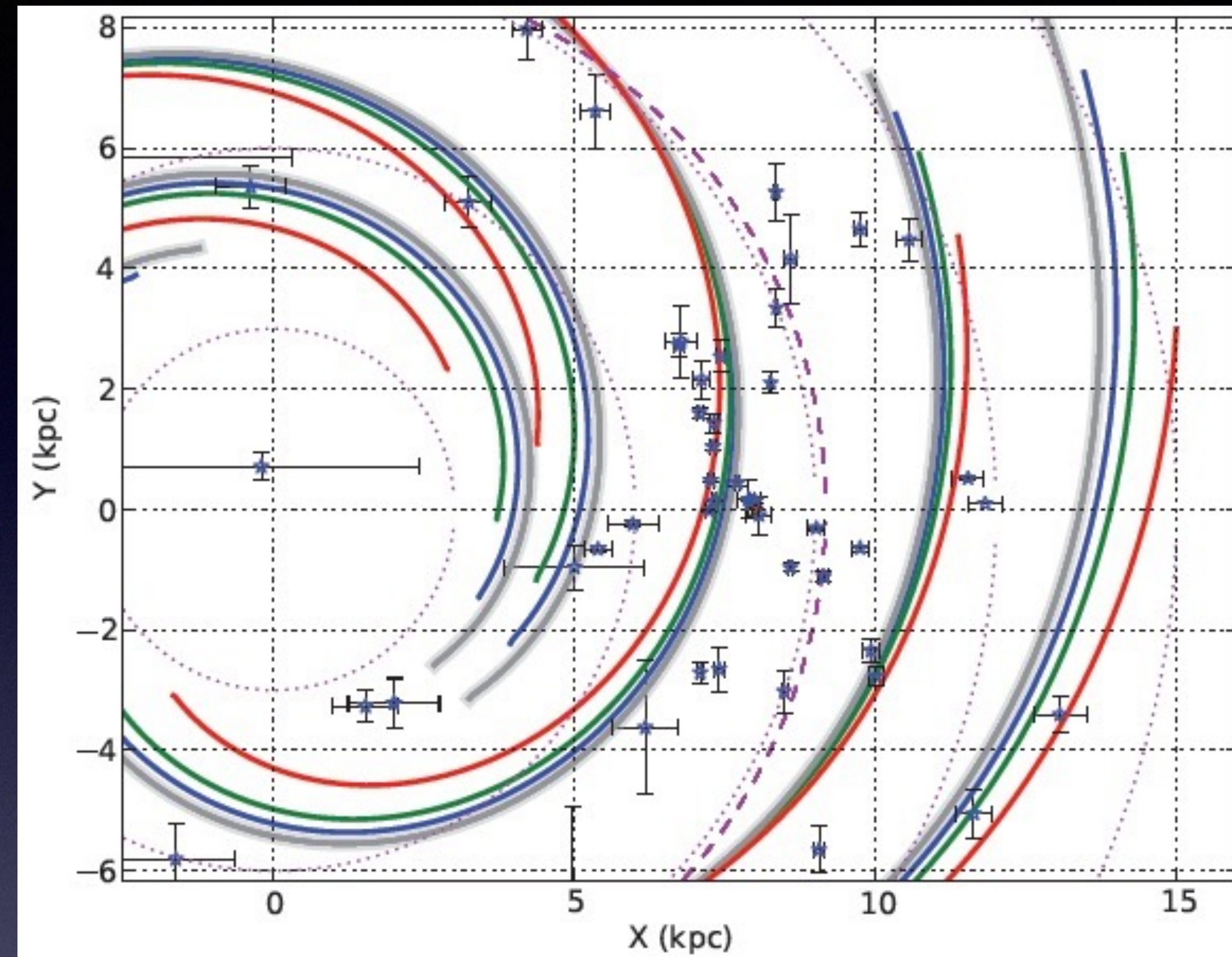




Coleiro & Chaty 2013, ApJ

Galactic distribution of HMXB

- Taking into account the Galactic arm rotation => age, migration distance and kick (50-90 km/s) of Be/sgXB
- HMXB distribution offset by 10^7 yrs wrt spiral arms: ~delay between star birth & Be/sgXB formation
- Kinematic age of sgXB after SN: t~10^6 yrs



SOURCE NAME	AGE (Myr)	MIGRATION DISTANCE (kpc)	UNCERTAINTY
Be			
1A 0535+262	80	0.10	0.30
1A 1118-615	80	0.088	0.56
EXO 0331+530	60	0.25	0.080
GRO J1008-57	40	0.074	0.15
GX 304-1	40	0.048	0.59
H 1417-624	20	0.20	0.39
PSR B1259-63	60	0.037	0.51
RX J0440.9+4431	20	0.011	0.17
RX J1744.7-2713	60	0.10	1.0
Supergiants			
4U 1700-377	80	0.15	0.28
IGR J16465-4507	20	0.087	0.052
IGR J18410-0535	60	0.013	0.11
H 1538-522	20	0.14	0.52

Coleiro & Chaty 2013, ApJ


III. The best progenitors
for merging…
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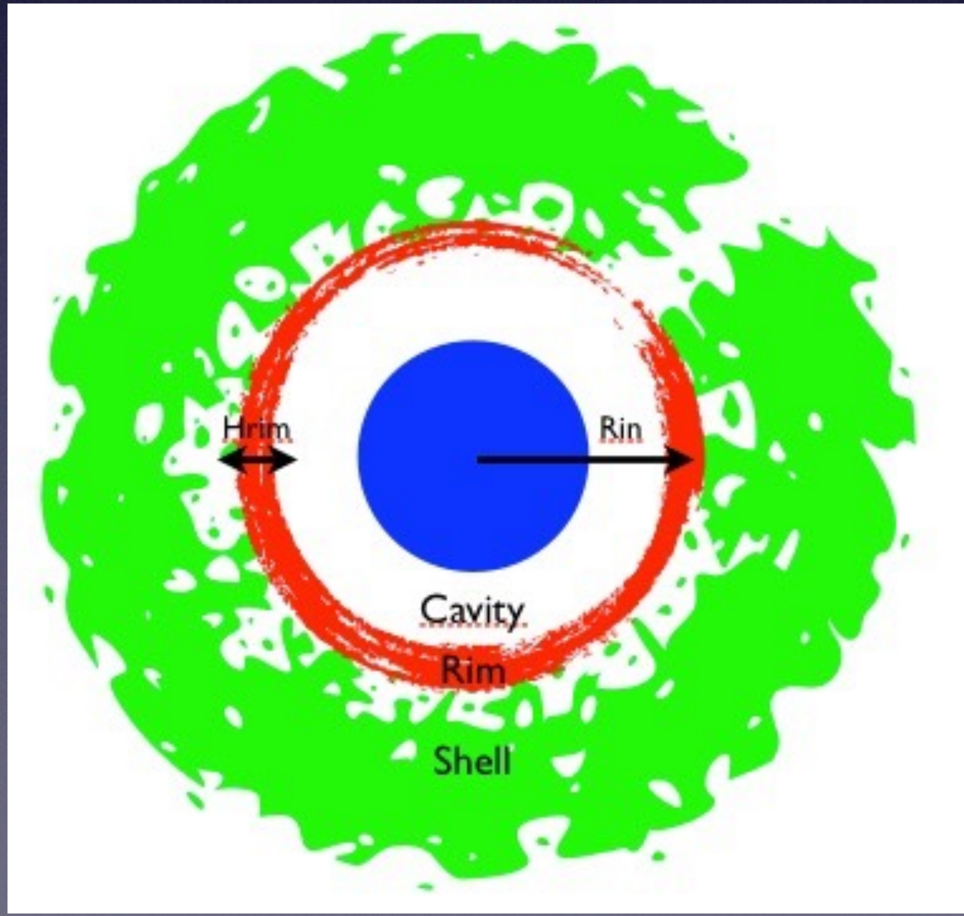
Obscured sgXB:
IGR J16318-4848

- Classical persistent system in transition to RLO, or slow winds
- Stratified circumstellar enveloppe: luminous sgB[e] star: $10^6 L_\odot$, $30M_\odot$, 22 000K, $20R_\odot$=0.1au (ESO/NTT-VLT + *Spitzer* + *Herschel*)
  - $N_H > 10^{24}$ cm^{-2}
  - ~ Herbig Ae/Be models: torus geometry
  - Disk rim: T=5500K, Thickness: ~0.7 R_*
  - Warm dust shell at 900K, $R_d=12R_*=240R_\odot$ (=1au)
- VLTI observations on 03/2015 confirm torus!
- CO orbits within dense equatorial torus



Chaty & Rahoui 2012 ApJ

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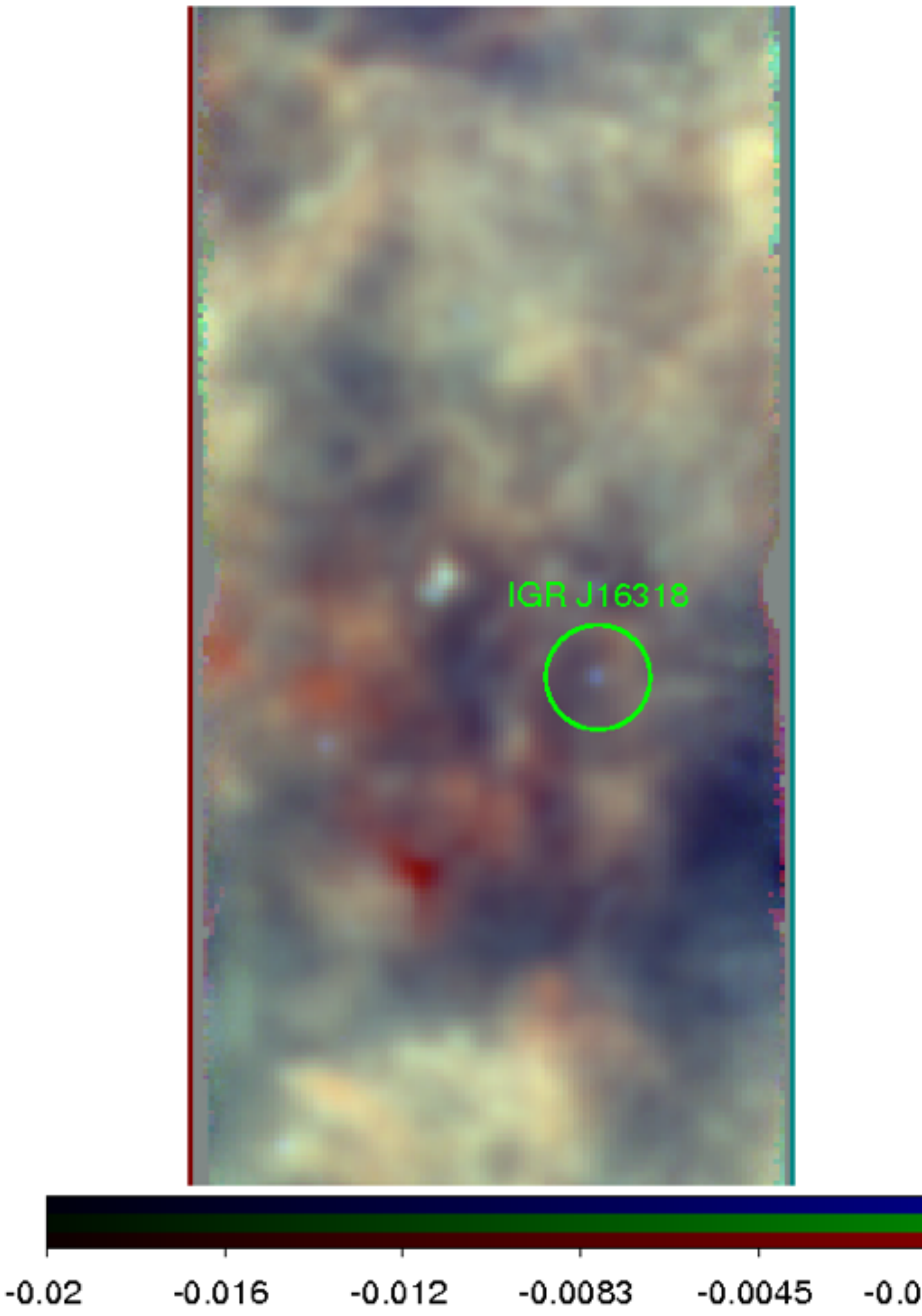
Obscured sgXB:
IGR J16318-4848

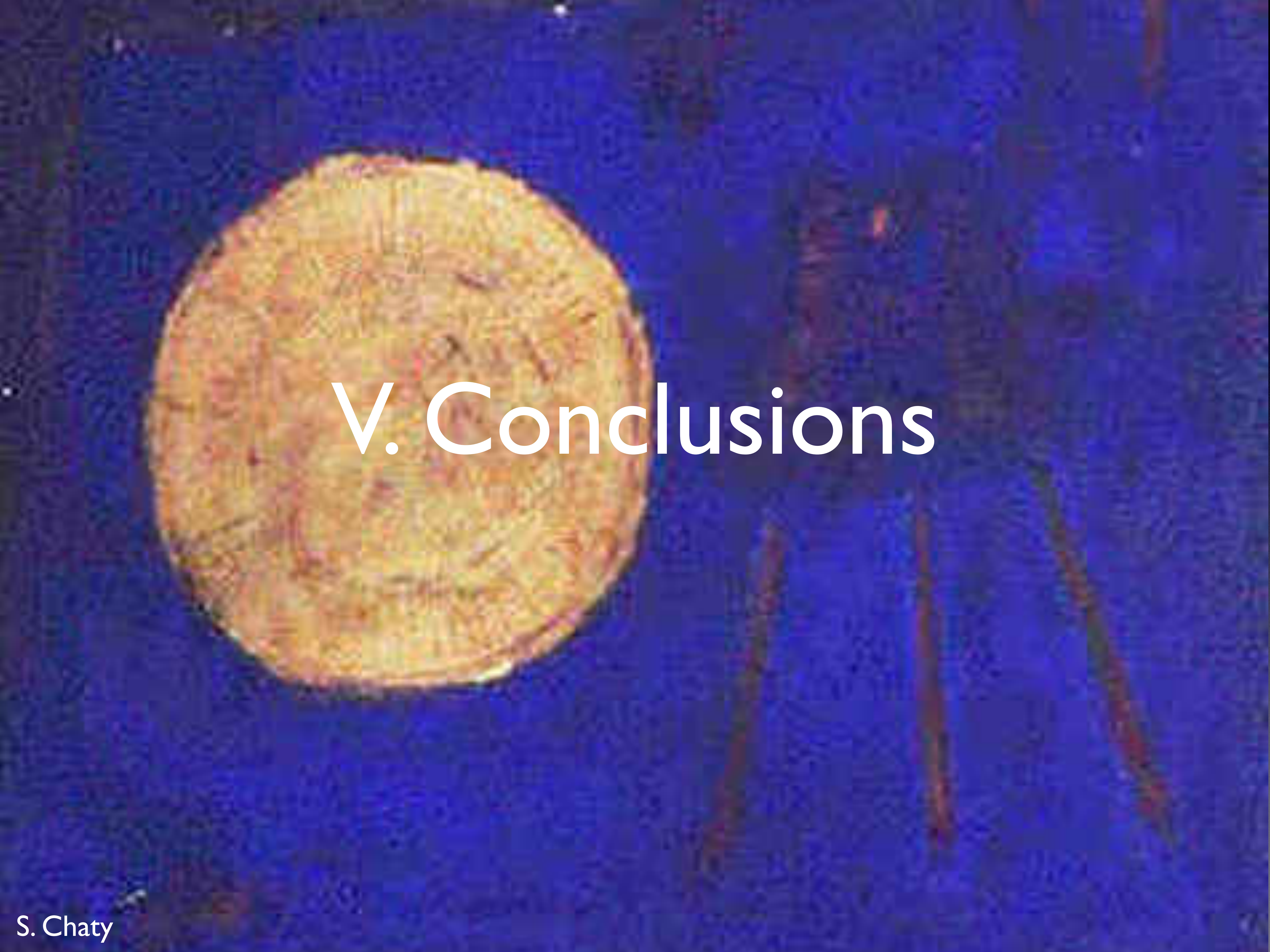
- Evolution: CO orbits within external regions of disk -> become a BH/NS binary
  - Deep spiral-in -> Common Envelope phase
  - sgB[e] -> Hg -> LBV -> luminous WR -> direct collapse to BH, without mass ejection
- Ideal candidate for merging with EM counterparts!



Chaty et al. 2012

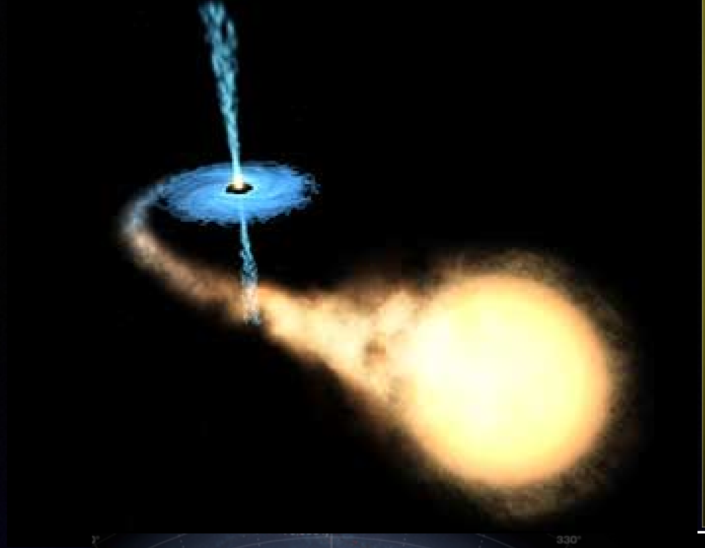
Statistics

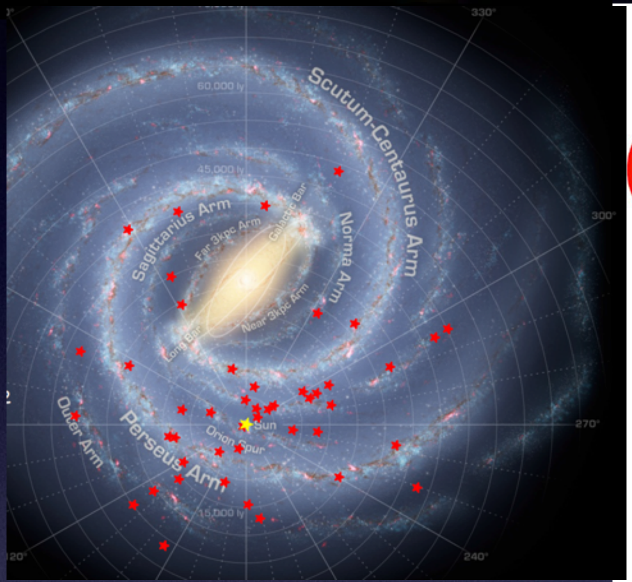
- ~20 000 O stars in Galaxy, 33% (6 600) within double systems evolving through enveloppe stripping (Sana+2012)
- ~50% of these systems (1500) have close orbits, survive natal kicks => ~1 HMXB forms every 7000 yrs
- Large number of sgXB (~30) discovered by *INTEGRAL*, consistent with HMXB lifetime ~10^5 yrs
- sgXB host massive stars, last for ~10 10^6 yrs, produce NS/NS, NS/BH or BH/BH, merge after ~10 10^9 yrs
- We should detect now merging of sgXB formed in early MW, and 100 000s of post-accreting binaries…

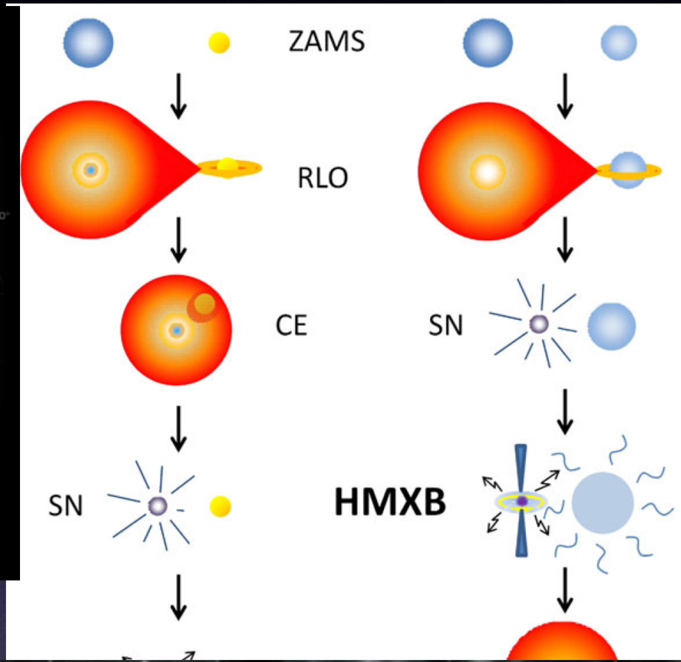


V. Conclusions

Conclusions







- Binaries: LMXB & HMXB
- Evolution: common enveloppe phase
- The INTEGRAL revolution:
  - Galactic distribution: HMXB correlated with SFC
    => age, migration, kick…
  - The best progenitors for merging after the common enveloppe phase!