Evolution of X-ray binaries

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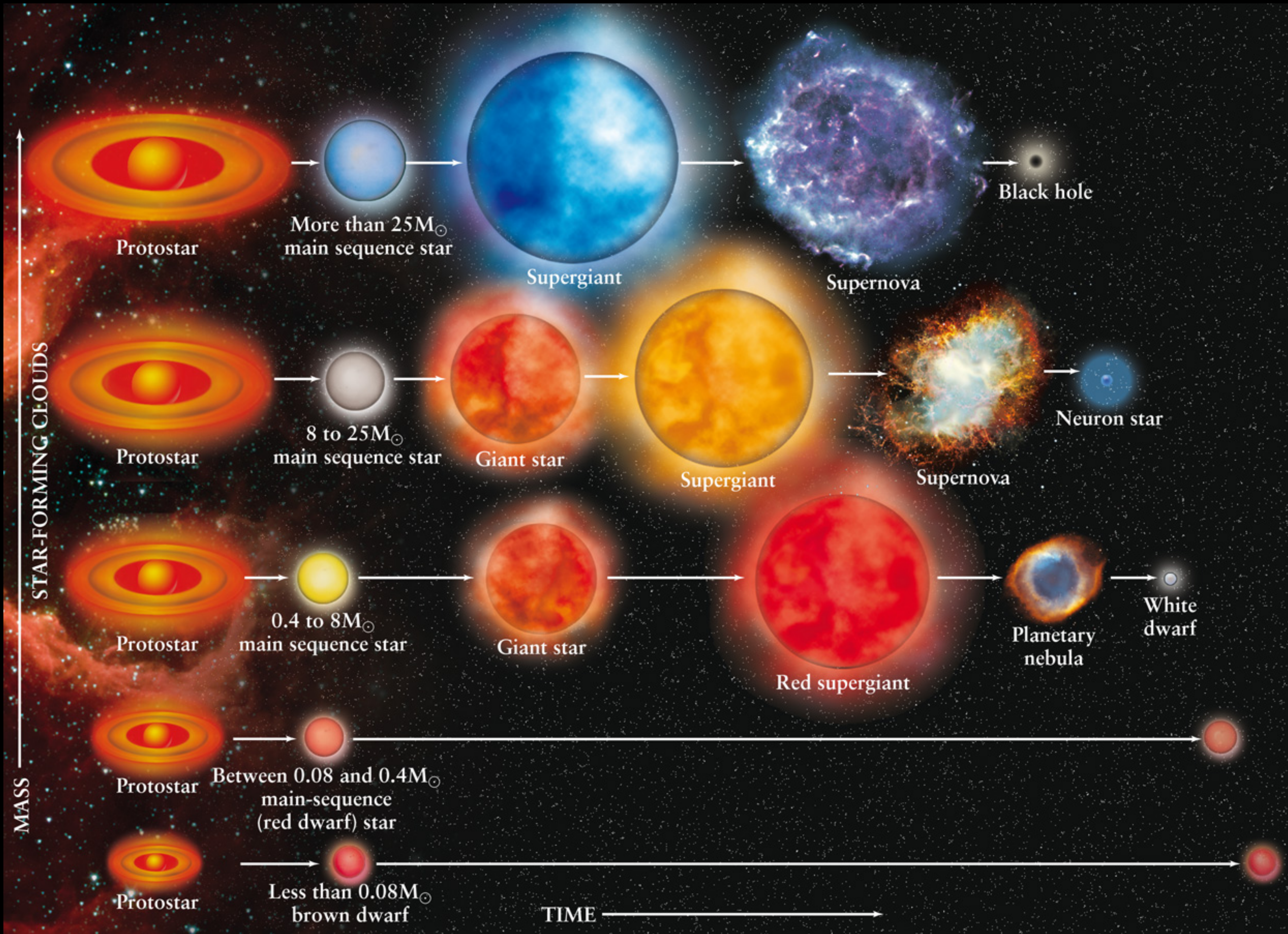

STAR-FORMING CLOUDS
MASS
Protostar
More than 25M$_\odot$
main sequence star
Supergiant
Supernova
Black hole
Protostar
8 to 25M$_\odot$
main sequence star
Giant star
Supergiant
Supernova
Neuron star
Protostar
0.4 to 8M$_\odot$
main sequence star
Giant star
Red supergiant
Planetary
nebula
White
dwarf
Protostar
Between 0.08 and 0.4M$_\odot$
main-sequence
(red dwarf) star
Protostar
Less than 0.08M$_\odot$
brown dwarf
TIME

Evolution of a binary

- Many stars are in binary systems
- Stellar evolution can be significantly altered due to mass loss and mass transfer
- Binary orbit can expand or shrink considerably during the evolution
  - Conservative or non-conservative mass transfer

Conservative mass transfer

- Total mass is conserved
  - $M_{total} = m_1 + m_2 =$ constant
- Total angular moment is conserved
  - Consider only J_{orbit} as $J_{spin} << J_{orbit}$
- Then one can proof that $$\frac{\dot{P}}{P} = \frac{3\dot{m}_1(m_1 - m_2)}{m_1 m_2}$$
- If more massive star transfers mass
  - $dm_1/dt < 0$ and $m_1 > m_2$
  - Then P and a decreases until masses become equal for minimum P and a → **runaway Roche-lobe mass transfer!**
  - If mass transfer continues, then orbit expands again

Non-conservative mass transfer

- General case
- What happens if either mass or angular moment are not conserved?
  - Mass is not conserved when
    - Mass transfer and loss through stellar wind
    - Very rapid Roche-lobe overflow
      - Receiving star cannot accrete all mass and mass is loss through L_2 point
  - Angular moment is not conserved when
    - Magnetic braking through stellar wind
      - Wind is forced to co-rotate at large distance with the rotation of the star

- E.g., wind from primary escapes system
  - $dm_1/dt < 0$, and $dm_2/dt = 0$,

$$\Rightarrow \frac{\dot{P}}{P} = \frac{-2\dot{m}_1}{m_1 + m_2}$$

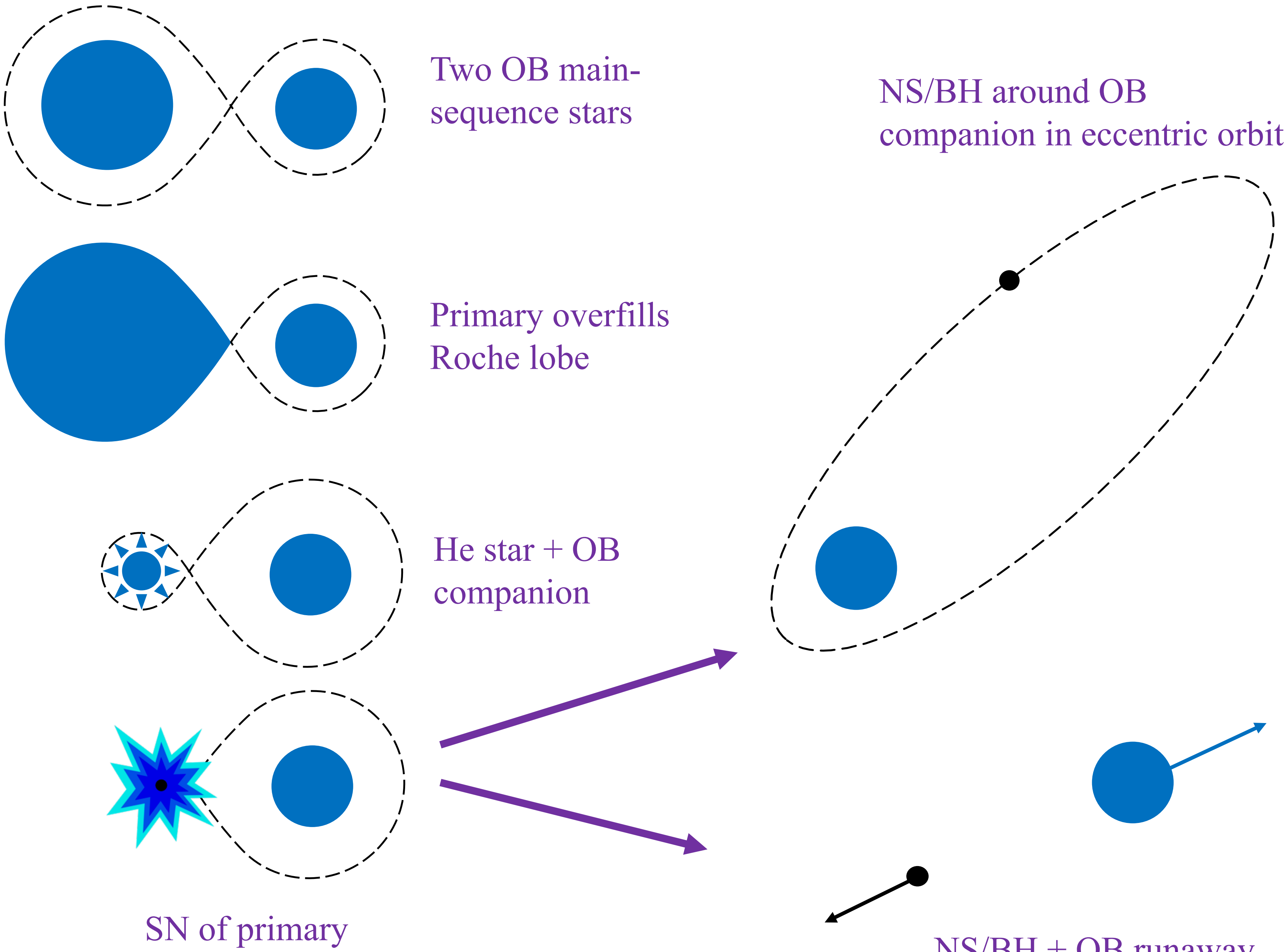
- General case for mass transfer in circular orbits

$$\Rightarrow \frac{\dot{P}}{P} = -\frac{2\dot{m}}{(m_1 + m_2)} - \frac{3\dot{m}_2(m_1 - m_2)}{m_1 m_2} + 3K$$

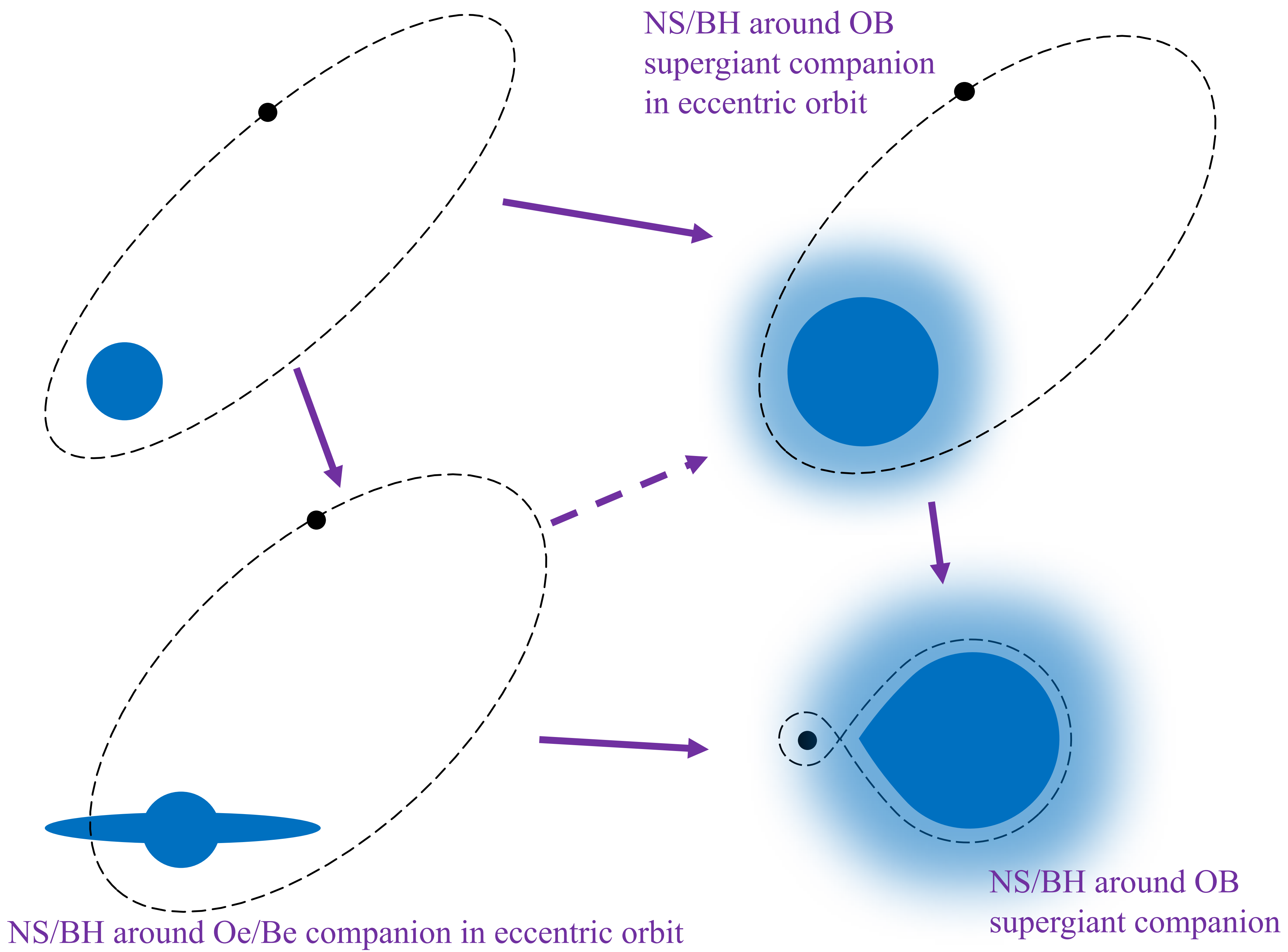
  - With KJ the change in angular moment
  - Conservative mass transfer: $\dot{m} = K = 0$ and $\dot{m}_1 = -\dot{m}_2$
  - Stellar wind loss case: $\dot{m}_2 = K = 0$ and $\dot{m} = \dot{m}_1$

Evolution of a binary

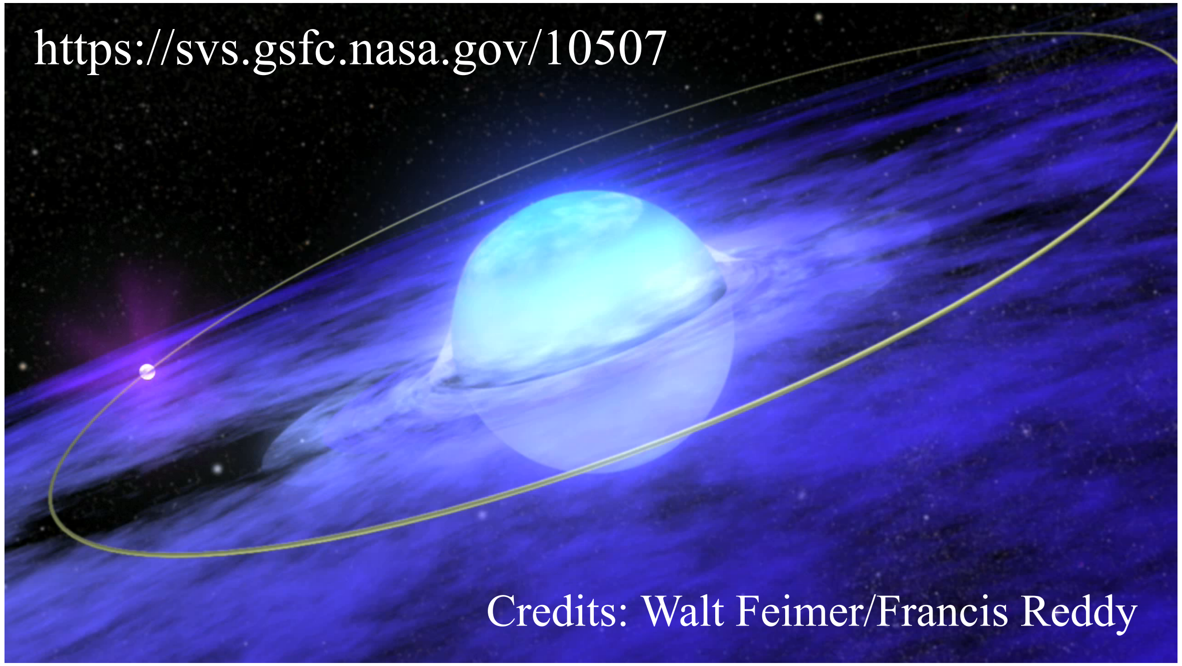
- Many stars are in binary systems
- Stellar evolution can be significantly altered due to mass loss and mass transfer
- Binary orbit can expand or shrink considerably during the evolution
  - Conservative or non-conservative mass transfer
- Evolution of a massive binary
  - Both stars are of O or B spectral type

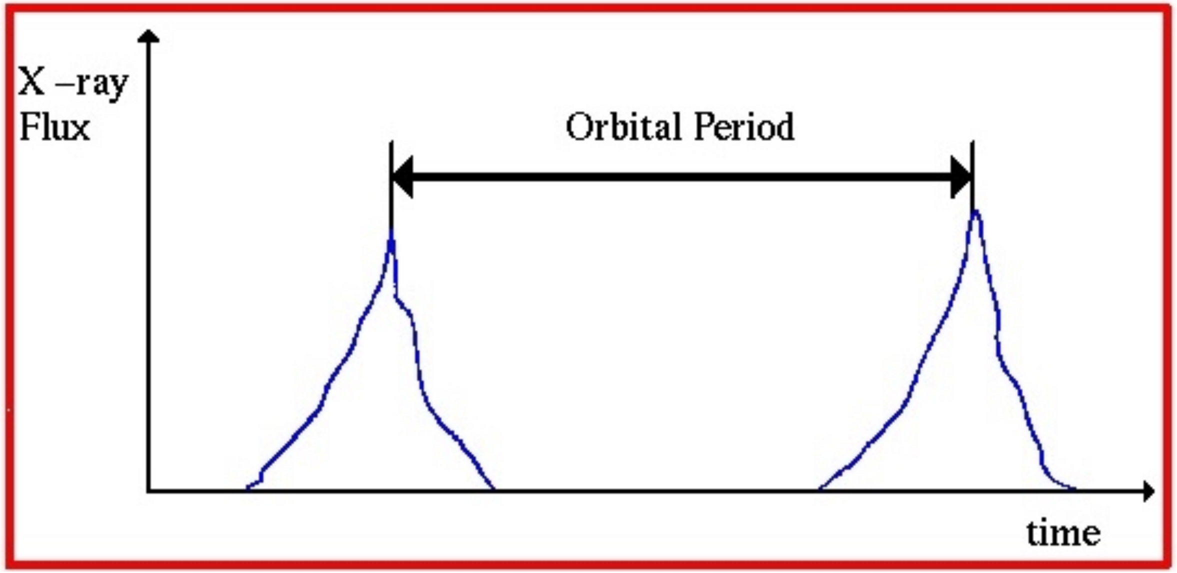

Two OB main-
sequence stars
Primary overfills
Roche lobe
He star + OB
companion
SN of primary
NS/BH around OB
companion in eccentric orbit
NS/BH + OB runaway

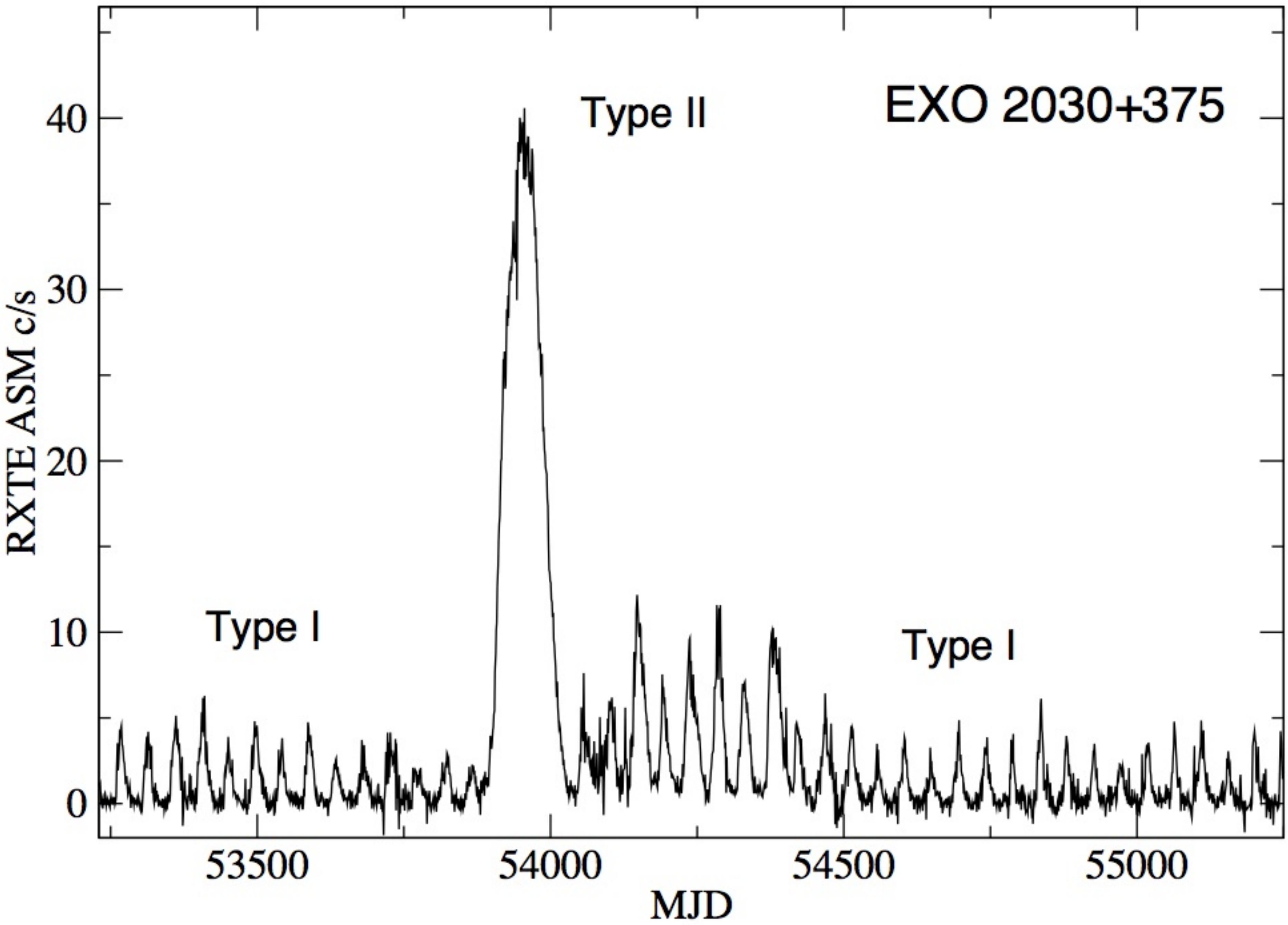

Runaway star zeta Ophiuchi (09.5V)


NS/BH around OB
supergiant companion
in eccentric orbit
NS/BH around Oe/Be companion in eccentric orbit
NS/BH around OB
supergiant companion

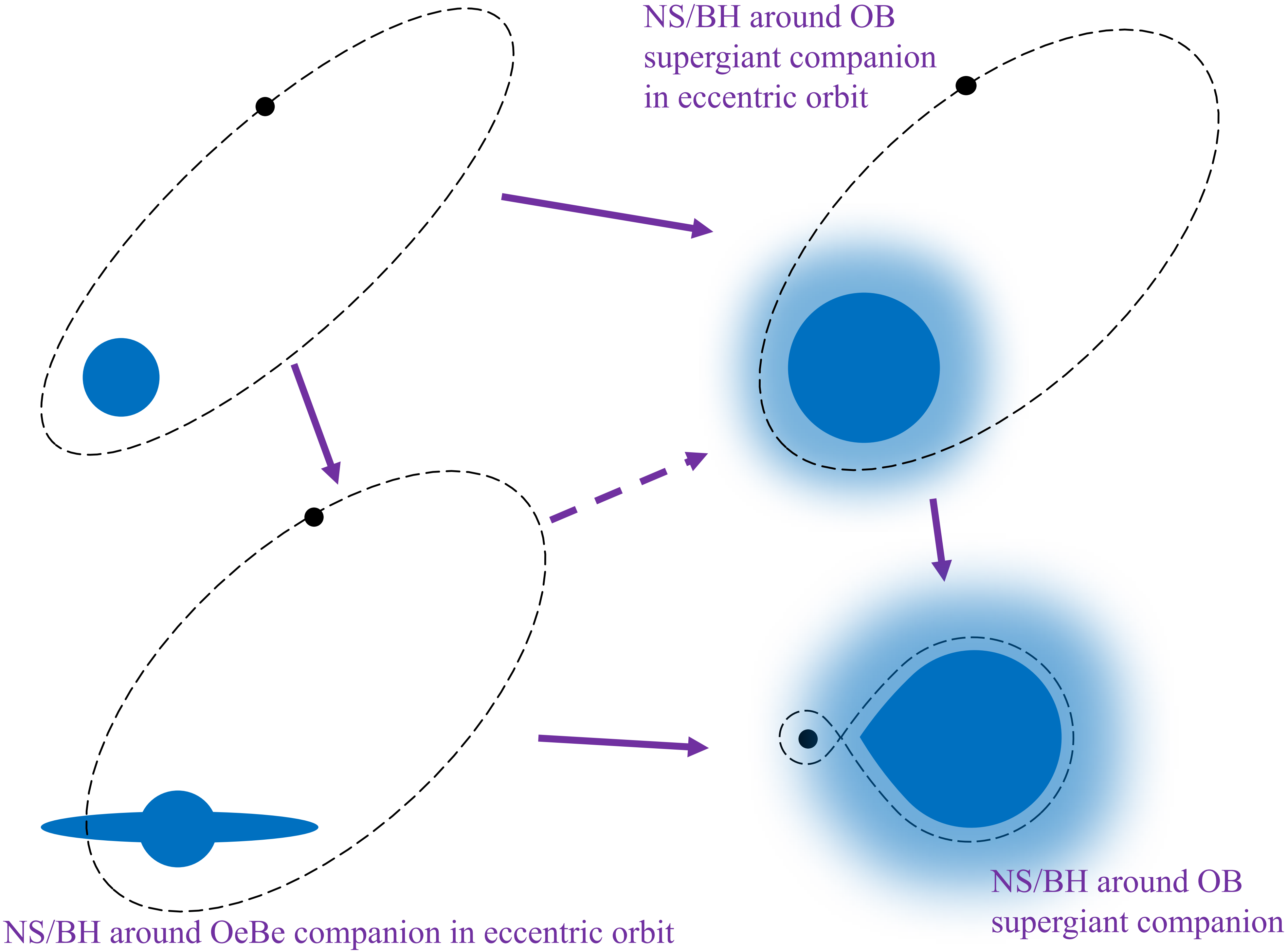
Be/X-ray transients







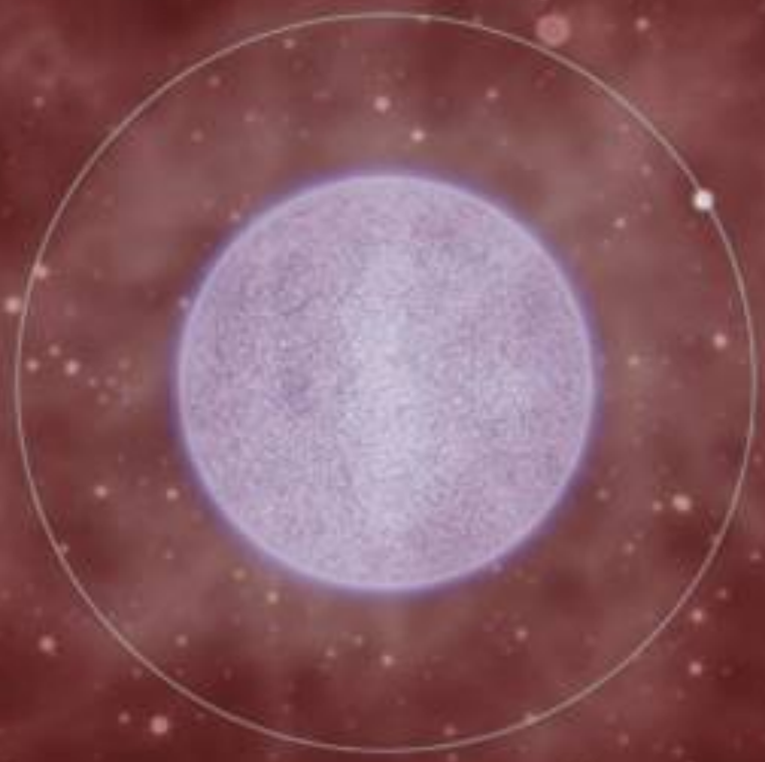
EXO 2030+375
Type II
Type I
Type I
RXTE ASM c/s
MJD
0
10
20
30
40
53500
54000
54500
55000


NS/BH around OB
supergiant companion
in eccentric orbit
NS/BH around OeBe companion in eccentric orbit
NS/BH around OB
supergiant companion

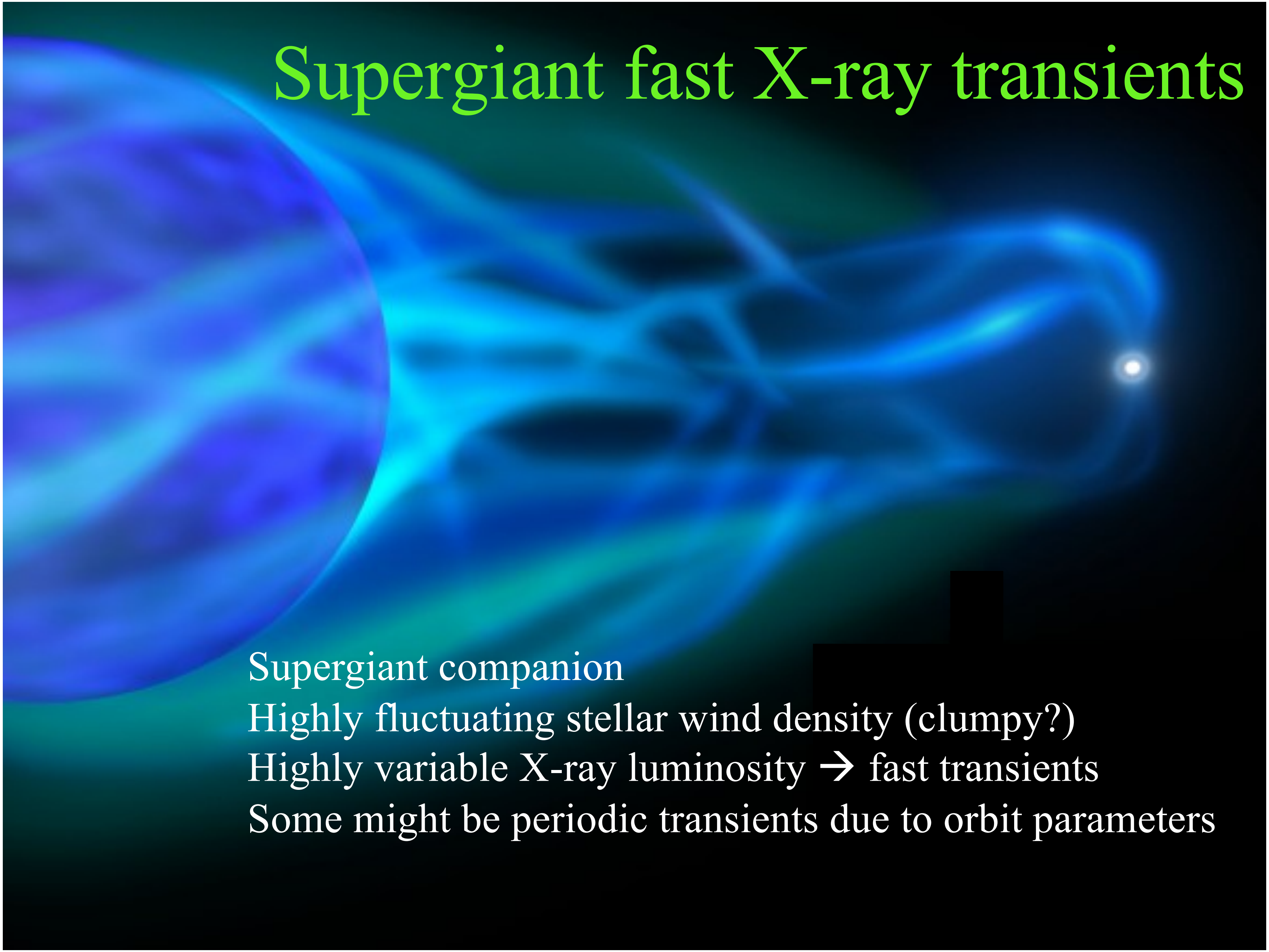
Class of highly obscured systems

Neutron star embedded in outer atmosphere of companion star

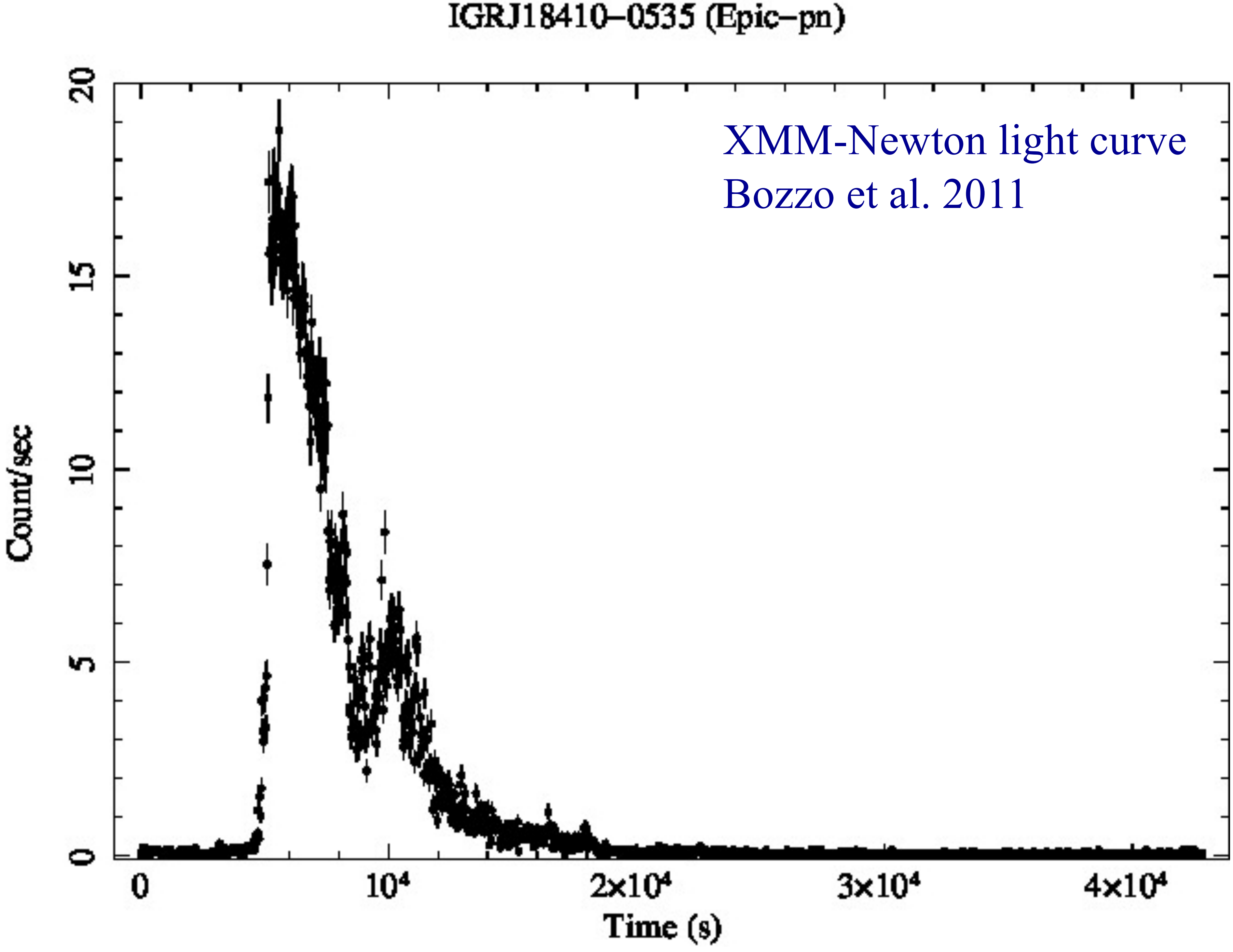
Highly absorbed and best seen at high energies (>5-10 keV)

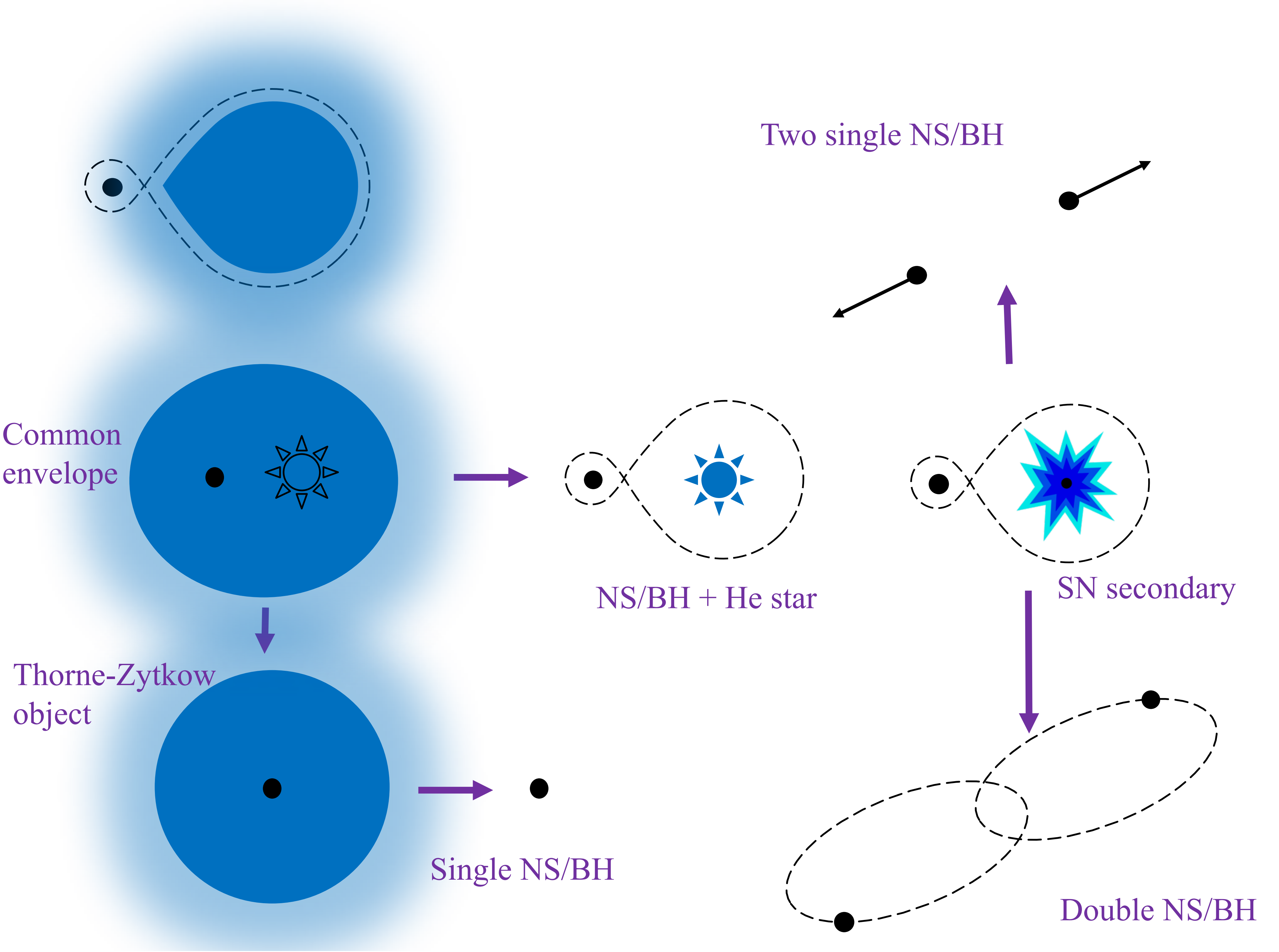


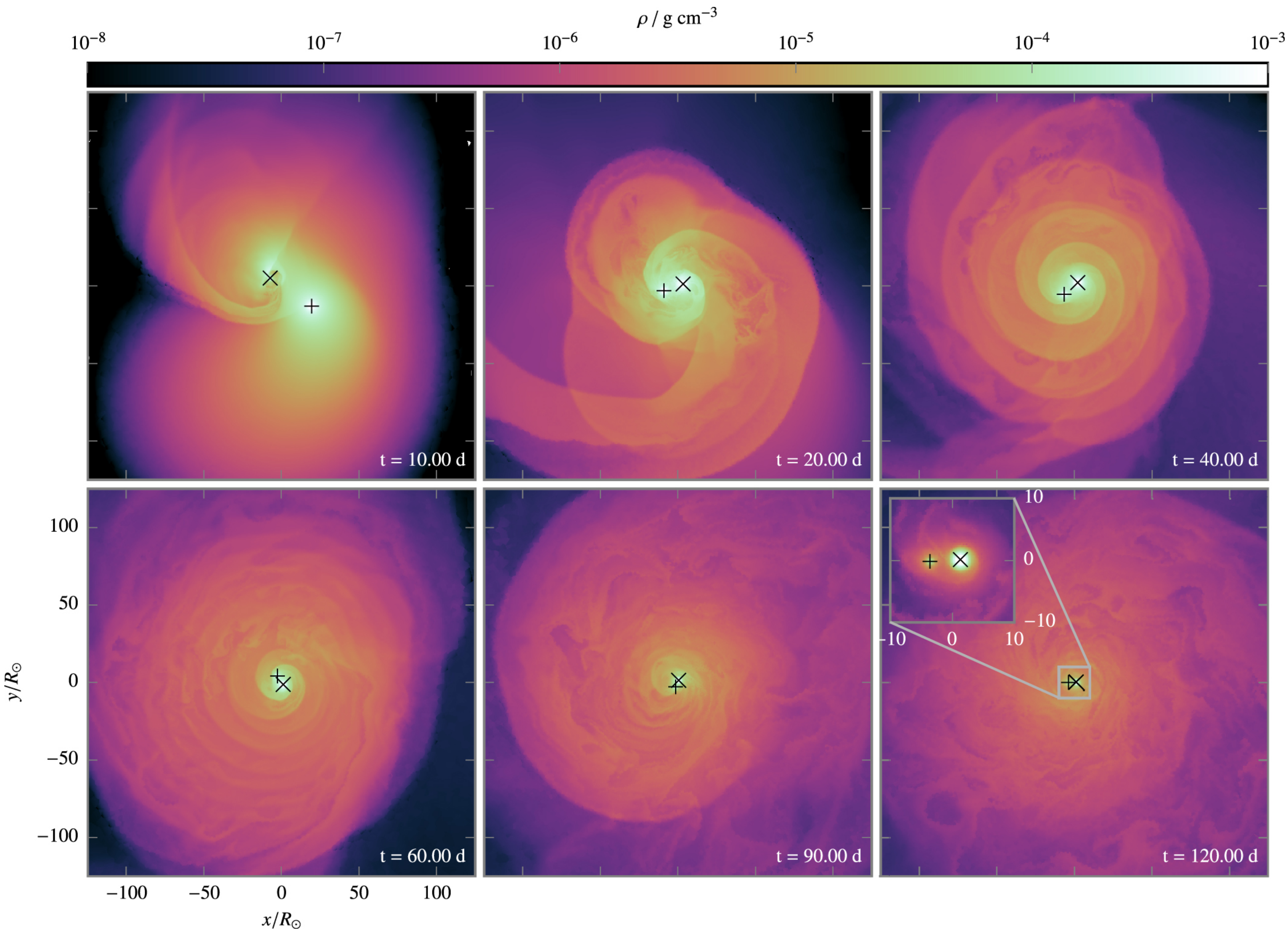
Supergiant fast X-ray transients



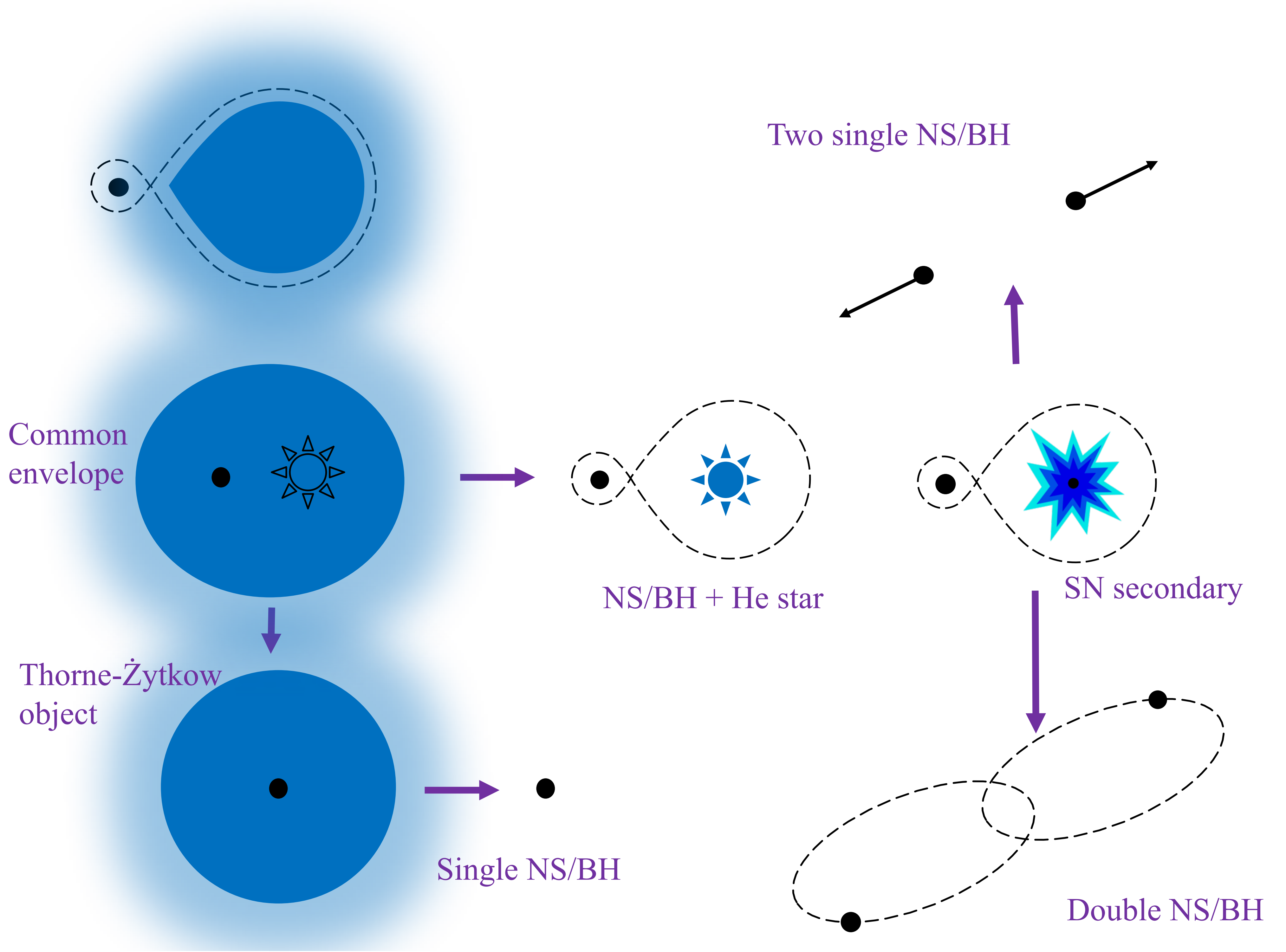
Supergiant companion
Highly fluctuating stellar wind density (clumpy?)
Highly variable X-ray luminosity → fast transients
Some might be periodic transients due to orbit parameters


IGRJ18410−0535 (Epic−pn)
XMM-Newton light curve
Bozzo et al. 2011
Count/sec
Time (s)
0
5
10
15
20
0
10⁴
2×10⁴
3×10⁴
4×10⁴

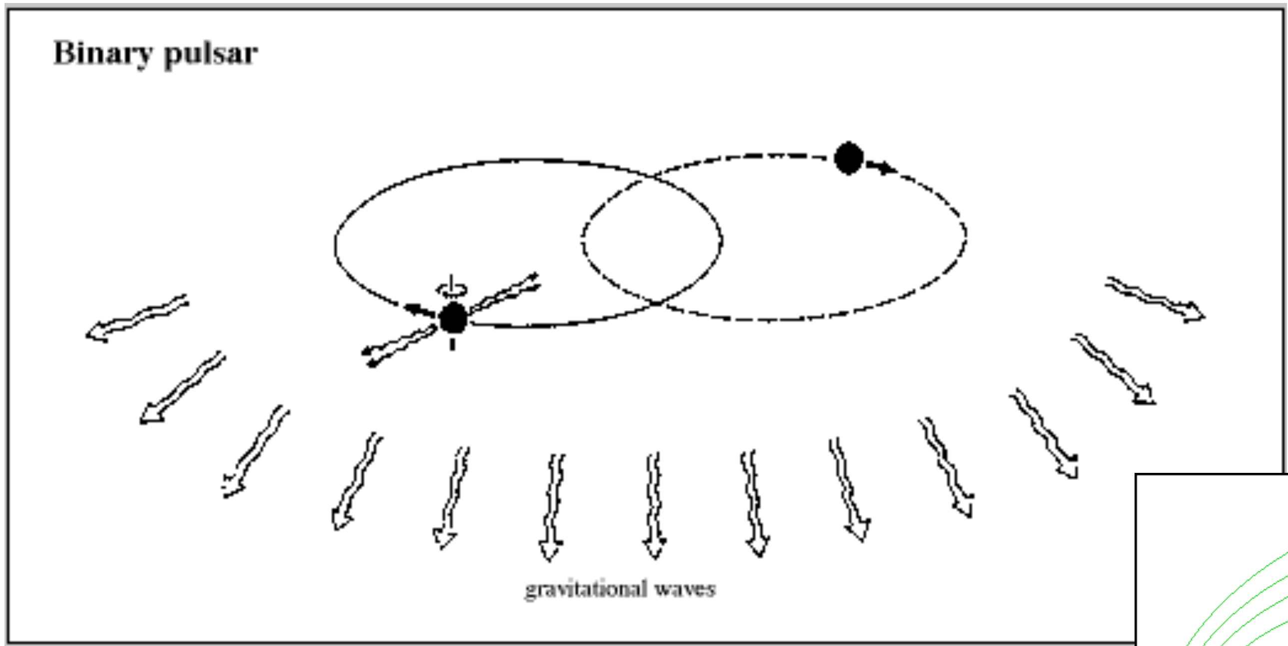

Two single NS/BH
Common envelope
NS/BH + He star
SN secondary
Thorne-Zytkow object
Single NS/BH
Double NS/BH

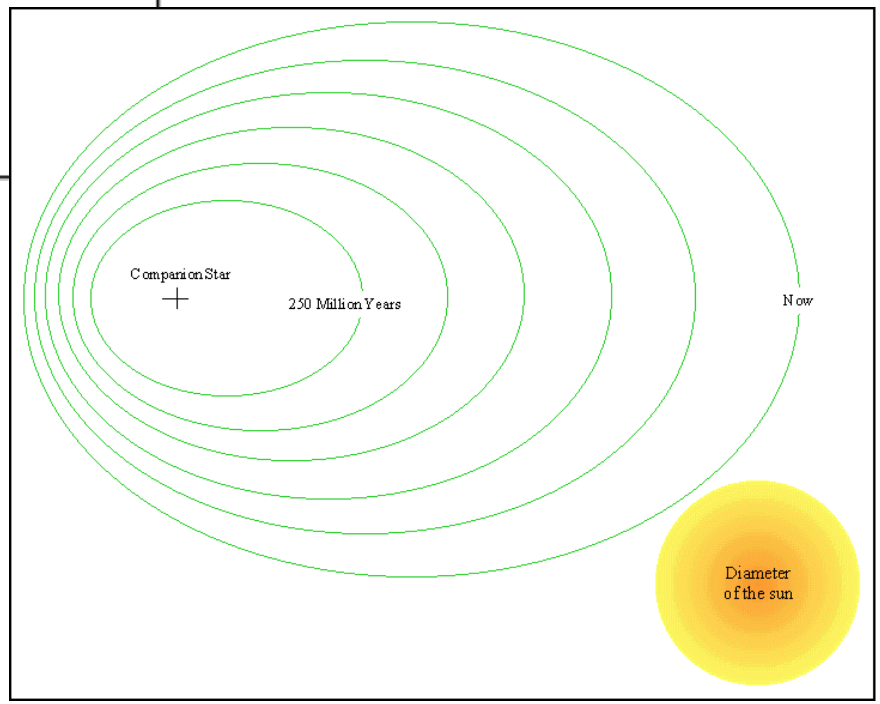


Ohlmann et al. 2016

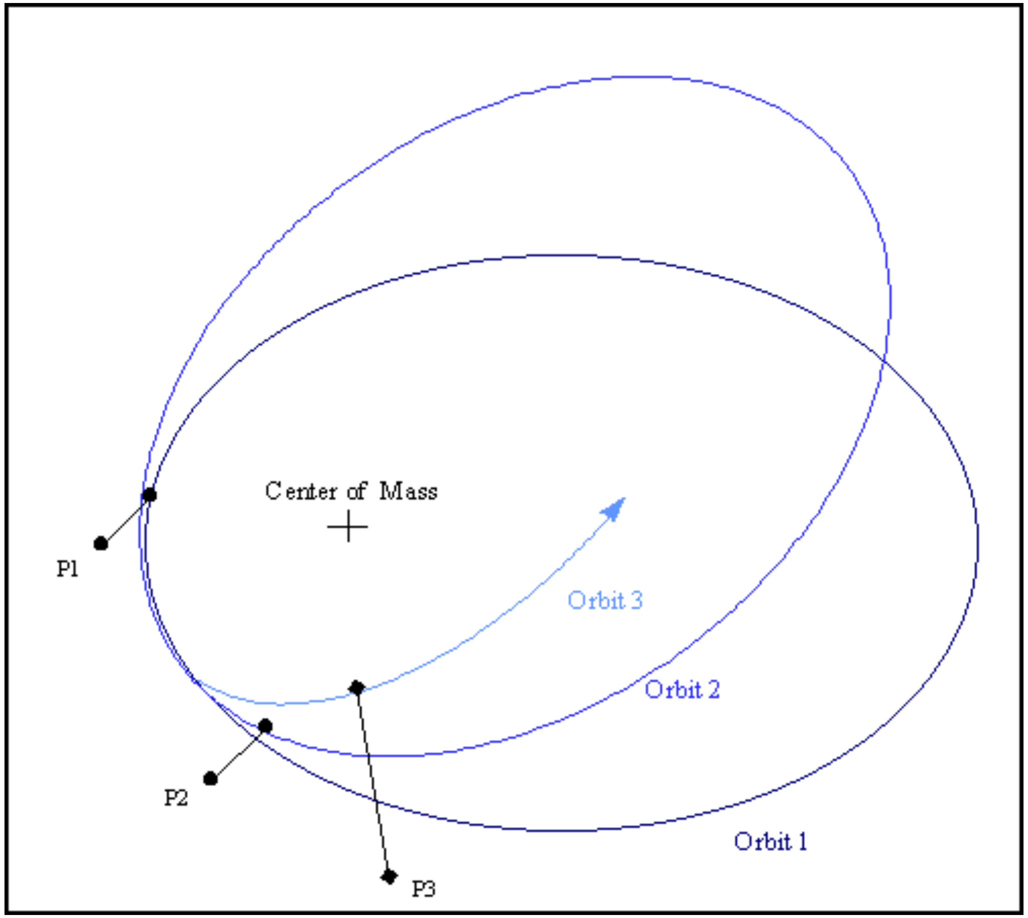

Two single NS/BH
Common envelope
NS/BH + He star
SN secondary
Thorne-Żytkow object
Single NS/BH
Double NS/BH

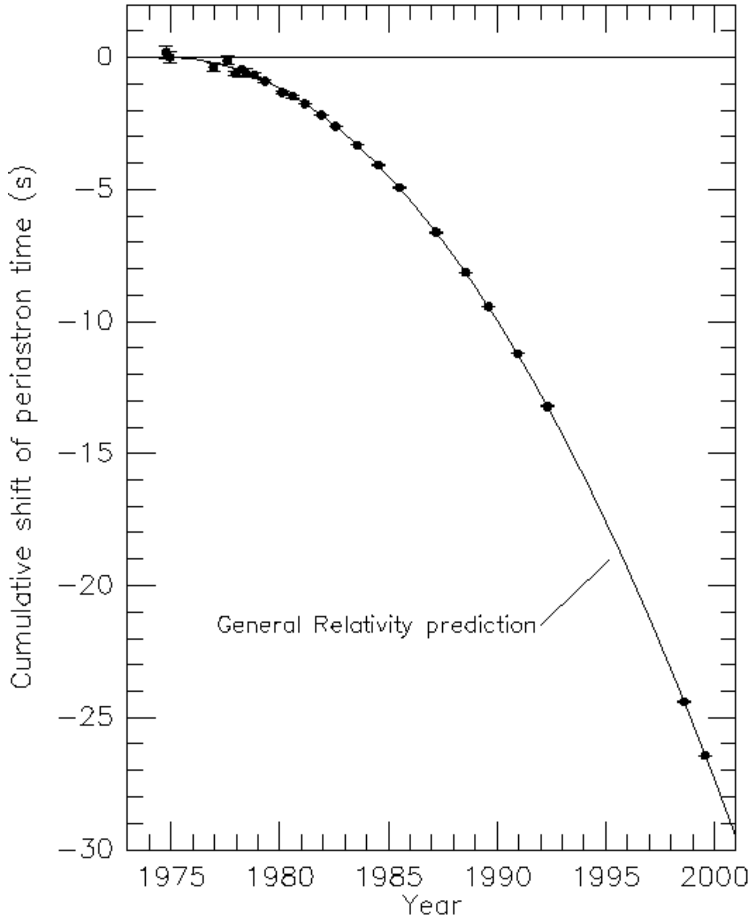
Double neutron star binaries



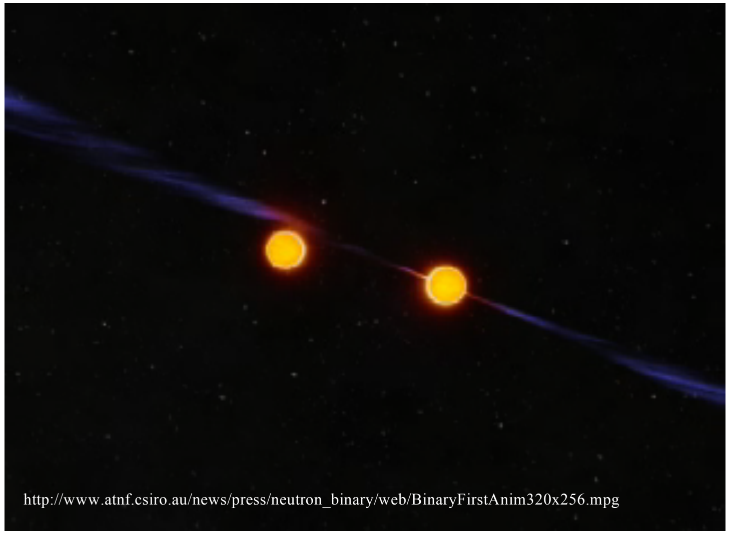


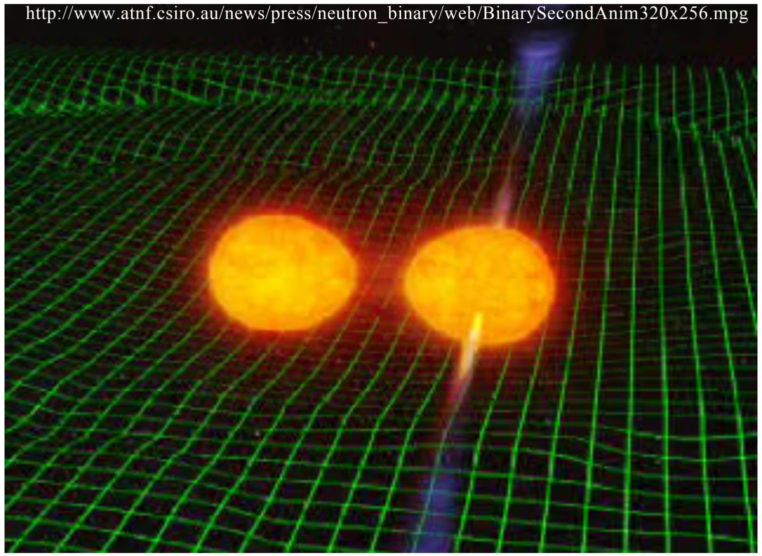
Periastron precession





Merger



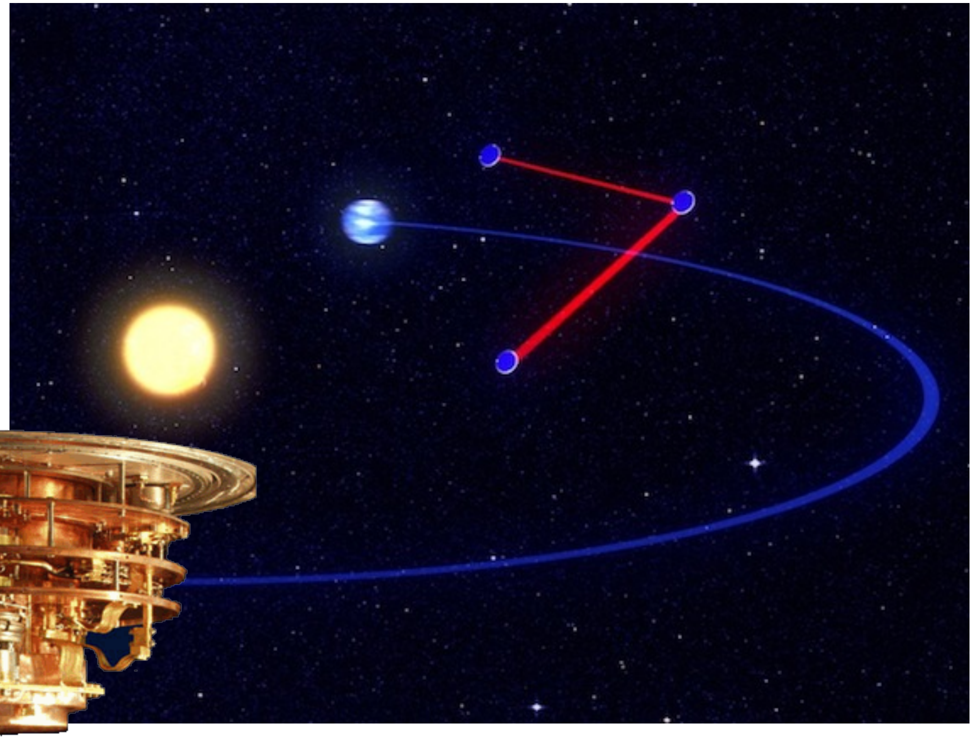


http://www.atnf.csiro.au/news/press/neutron_binary/index.html#animations

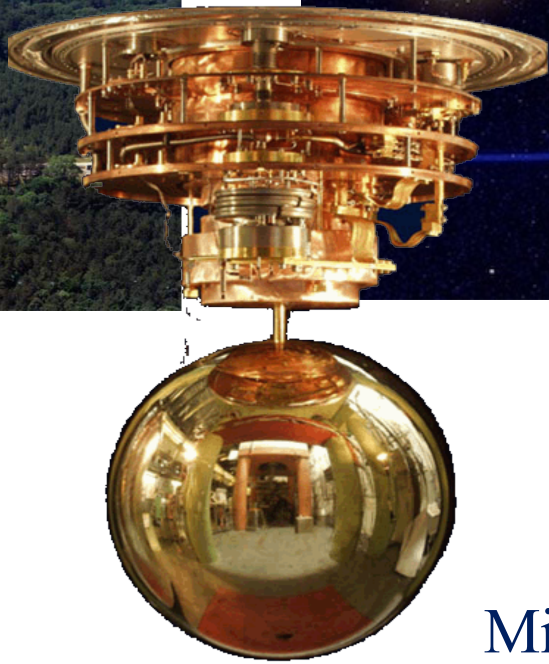
Credit: John Rowe Animation

Gravitational wave detectors

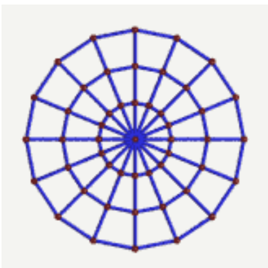
Ligo



eLISA/NGO

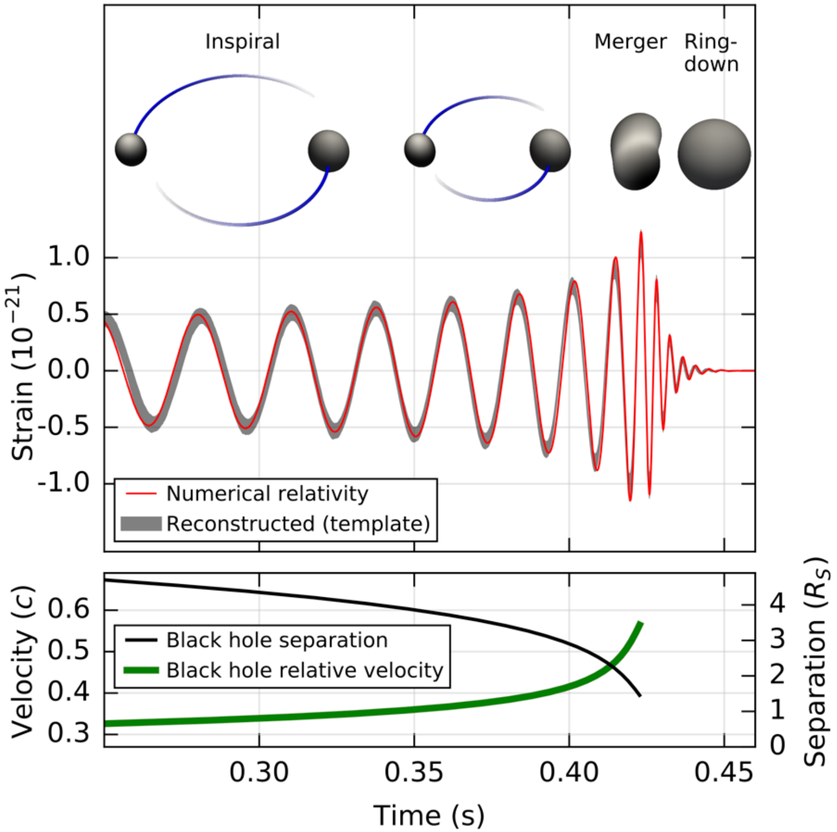


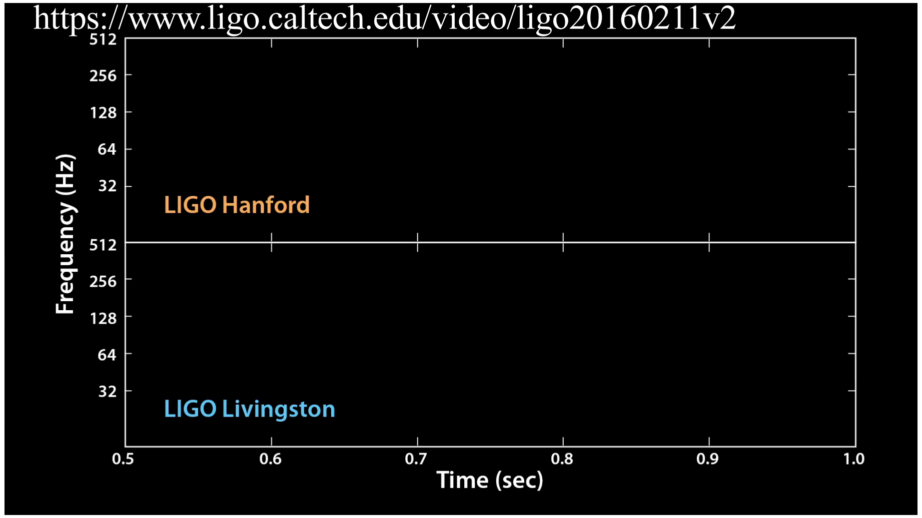
MiniGRAIL

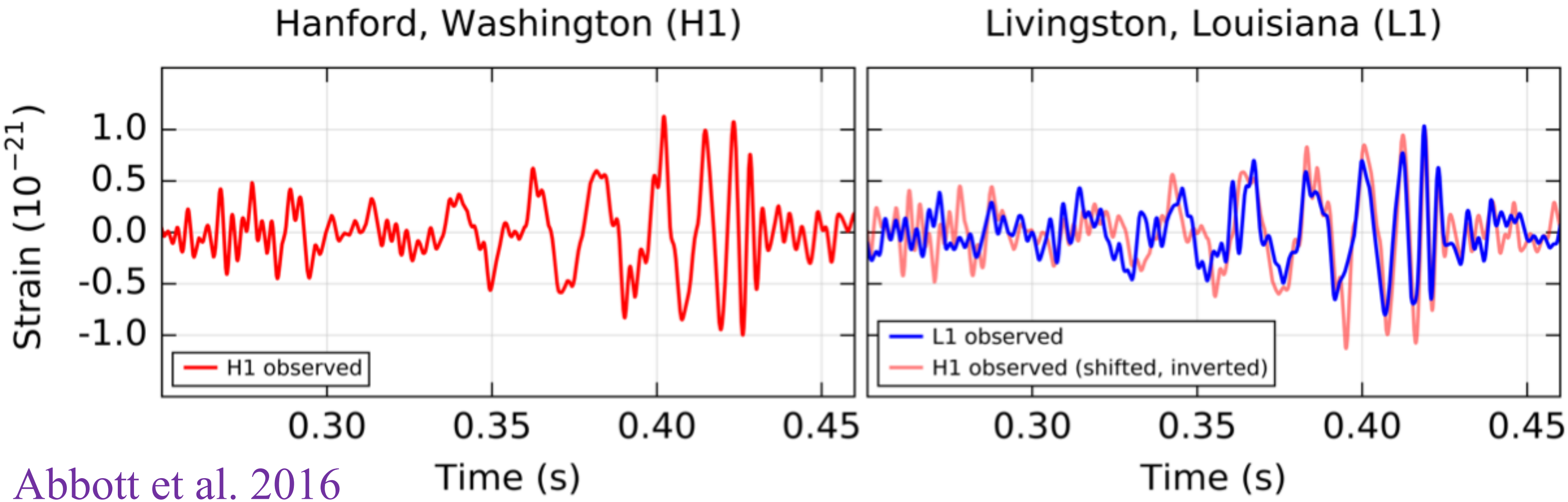


Double black hole binaries

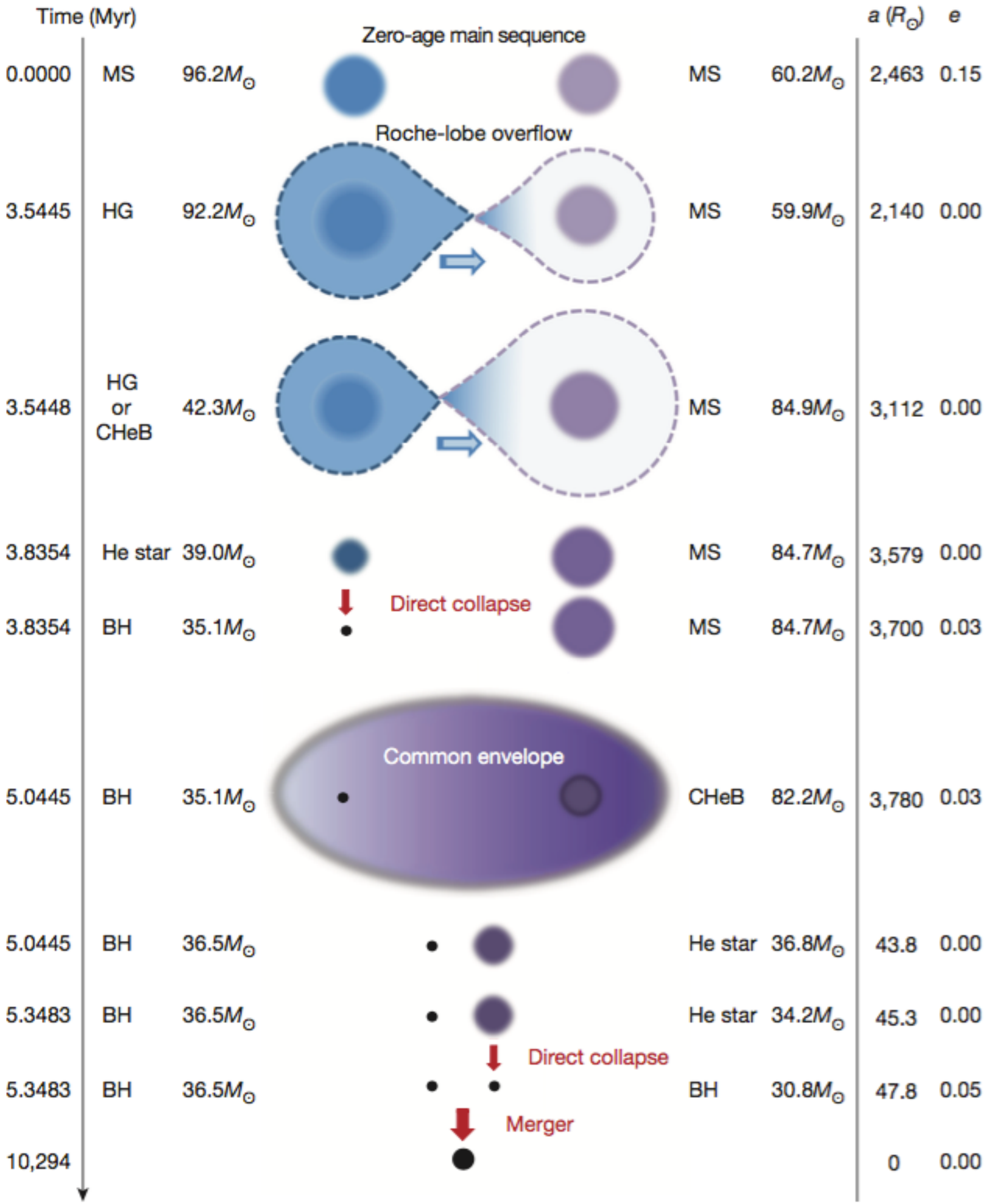
First gravitational wave detection!







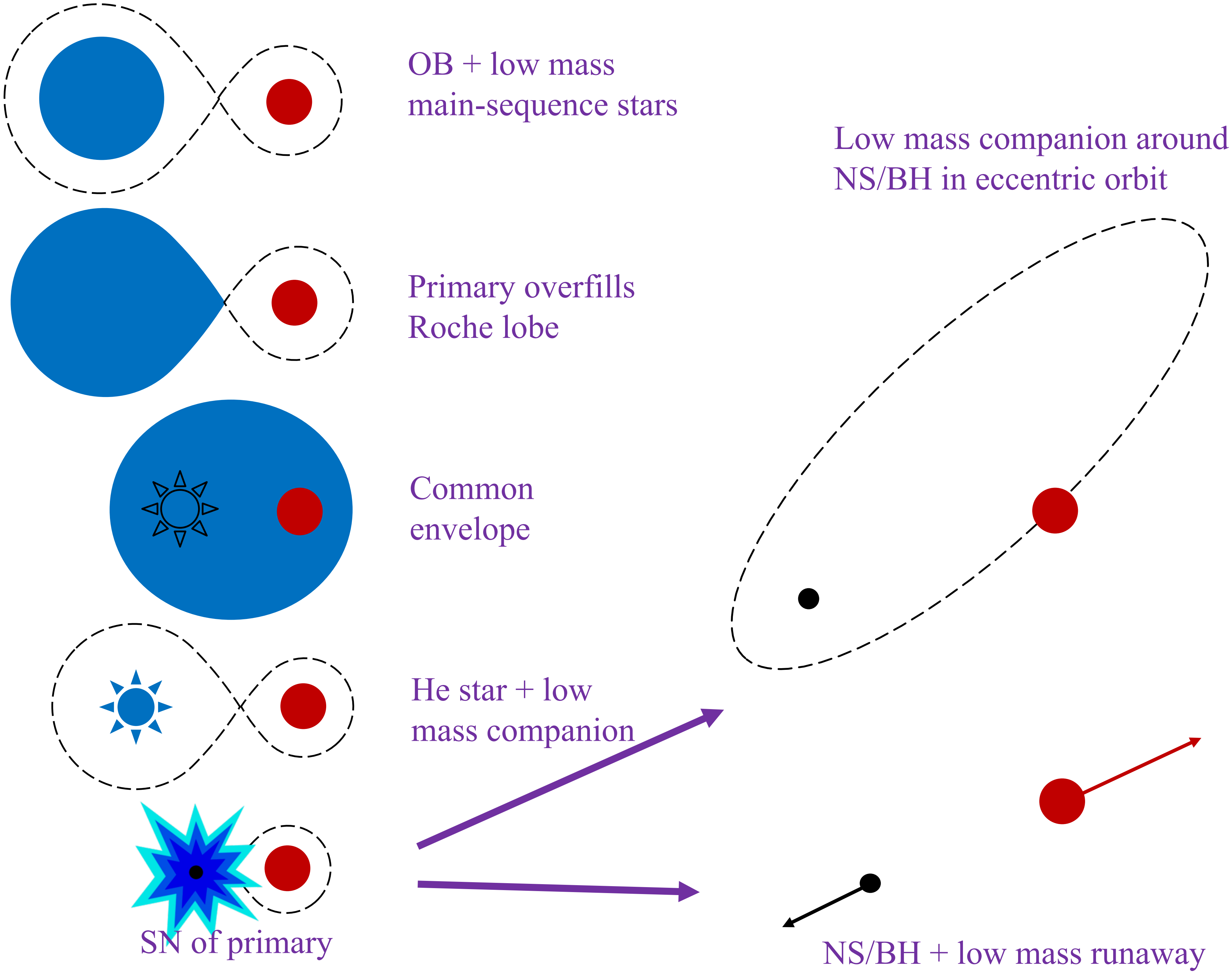
Abbott et al. 2016

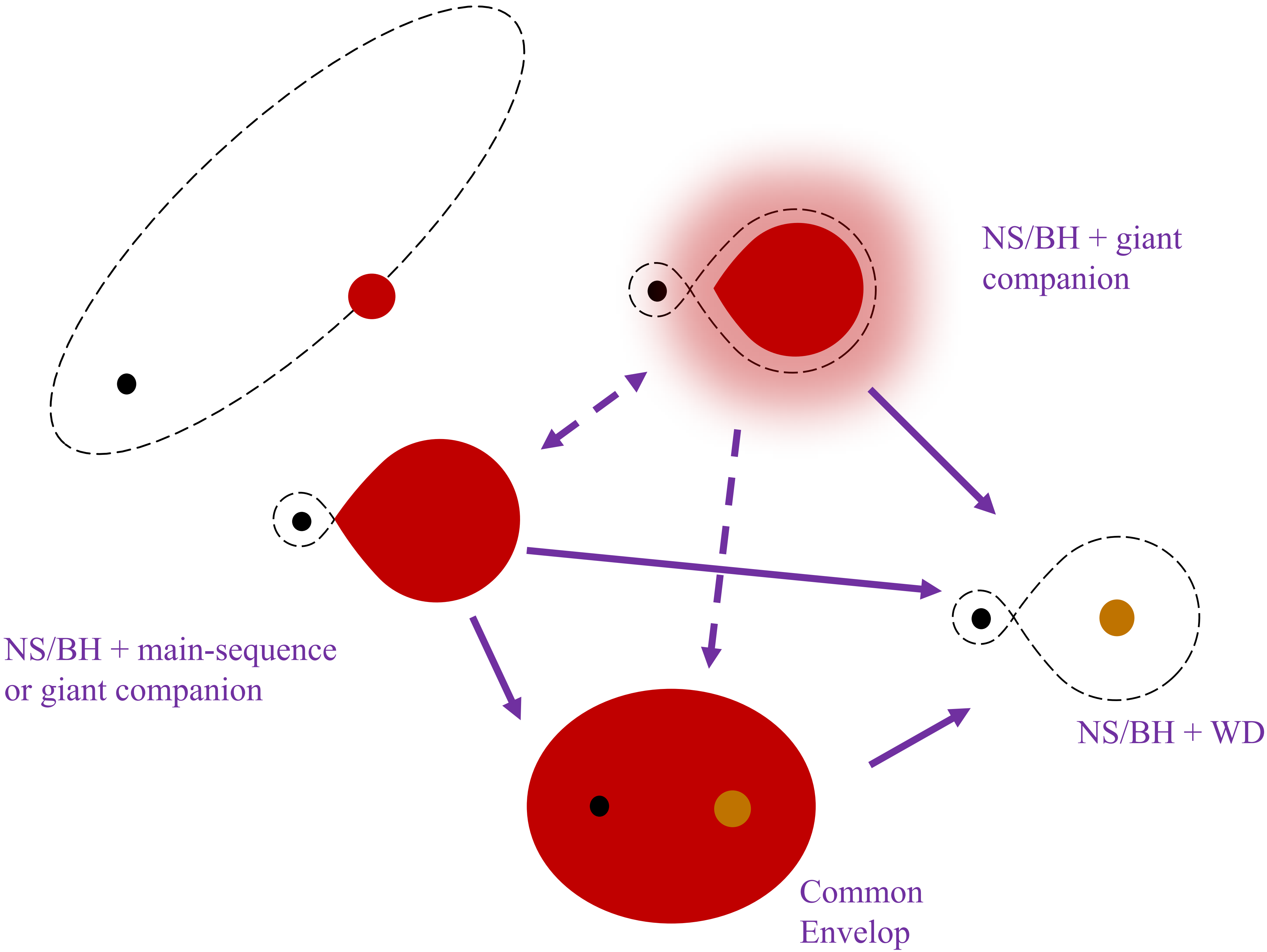


Belczynski et al. 2016

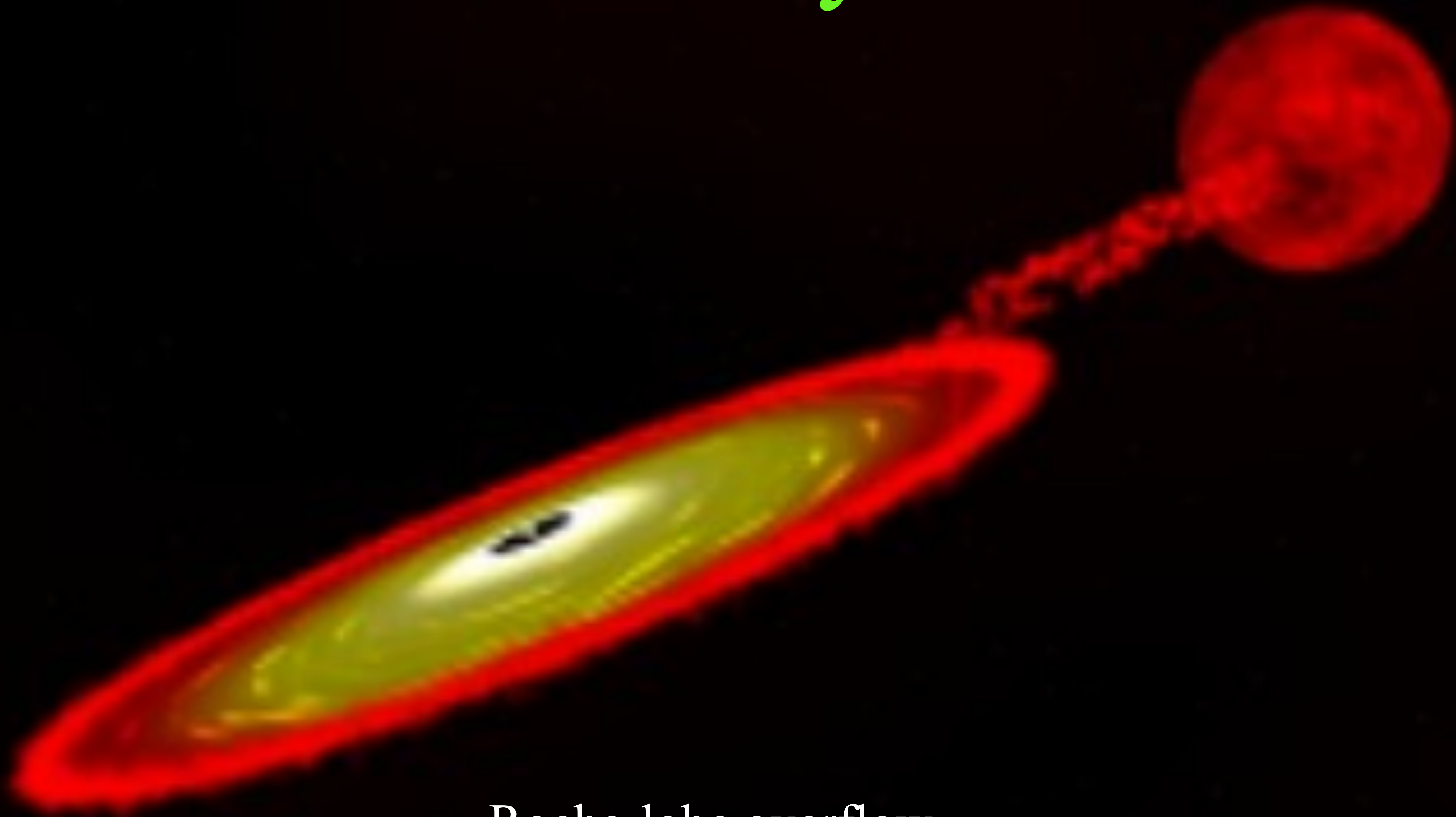
Evolution of a binary

- Many stars are in binary systems
- Stellar evolution can be significantly altered due to mass loss and mass transfer
- Binary orbit can expand or shrink considerably during the evolution
  - Conservative or non-conservative mass transfer
- Evolution of a massive binary
  - Both stars are of O or B spectral type
- Evolution of low-mass binaries
  - One star is massive; other low-mass
  - Both stars are low-mass → we will not discuss them today

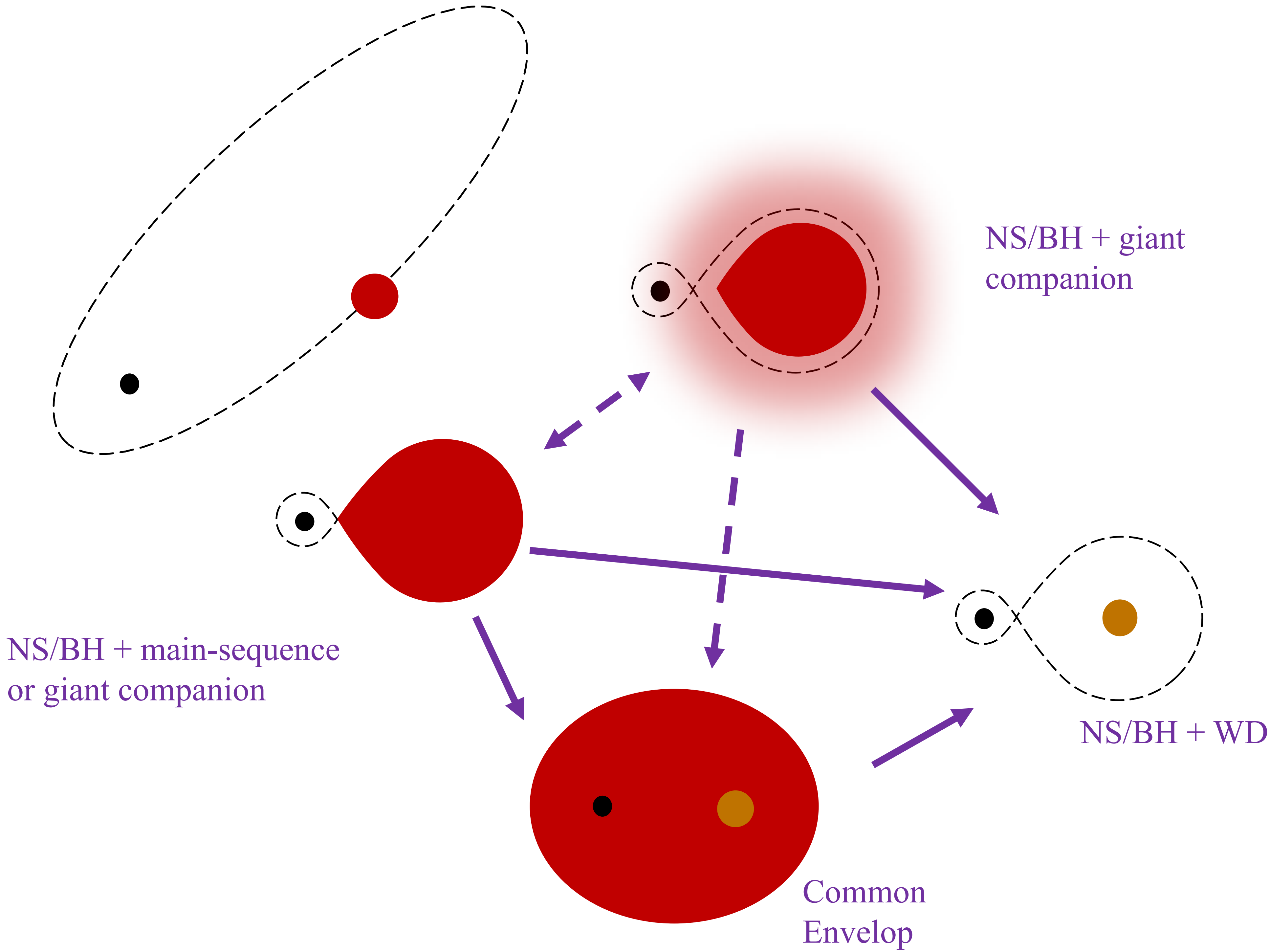

OB + low mass
main-sequence stars
Low mass companion around
NS/BH in eccentric orbit
Primary overfills
Roche lobe
Common
envelope
He star + low
mass companion
SN of primary
NS/BH + low mass runaway


NS/BH + giant
companion
NS/BH + main-sequence
or giant companion
NS/BH + WD
Common
Envelop

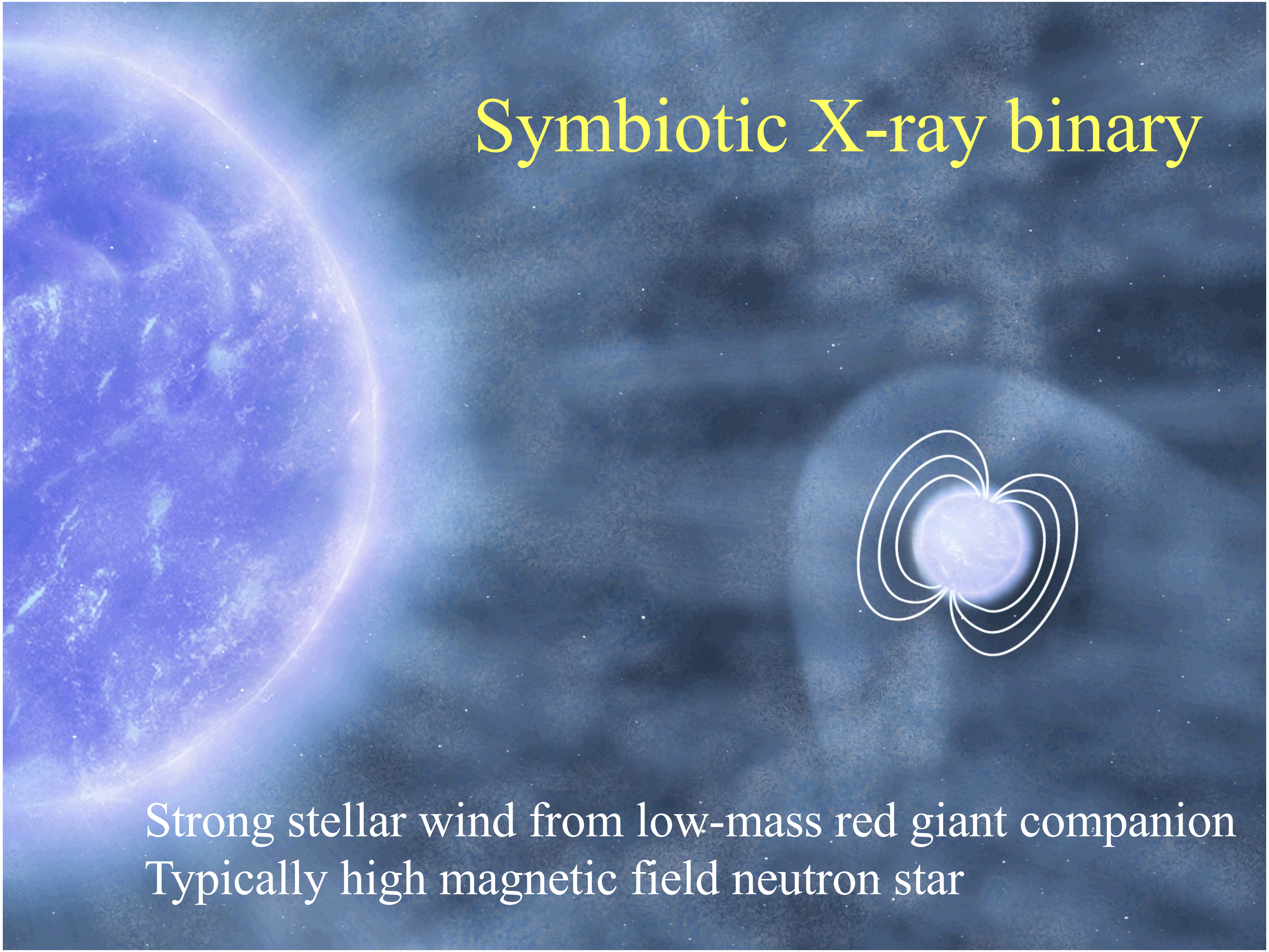
Low-mass X-ray binaries

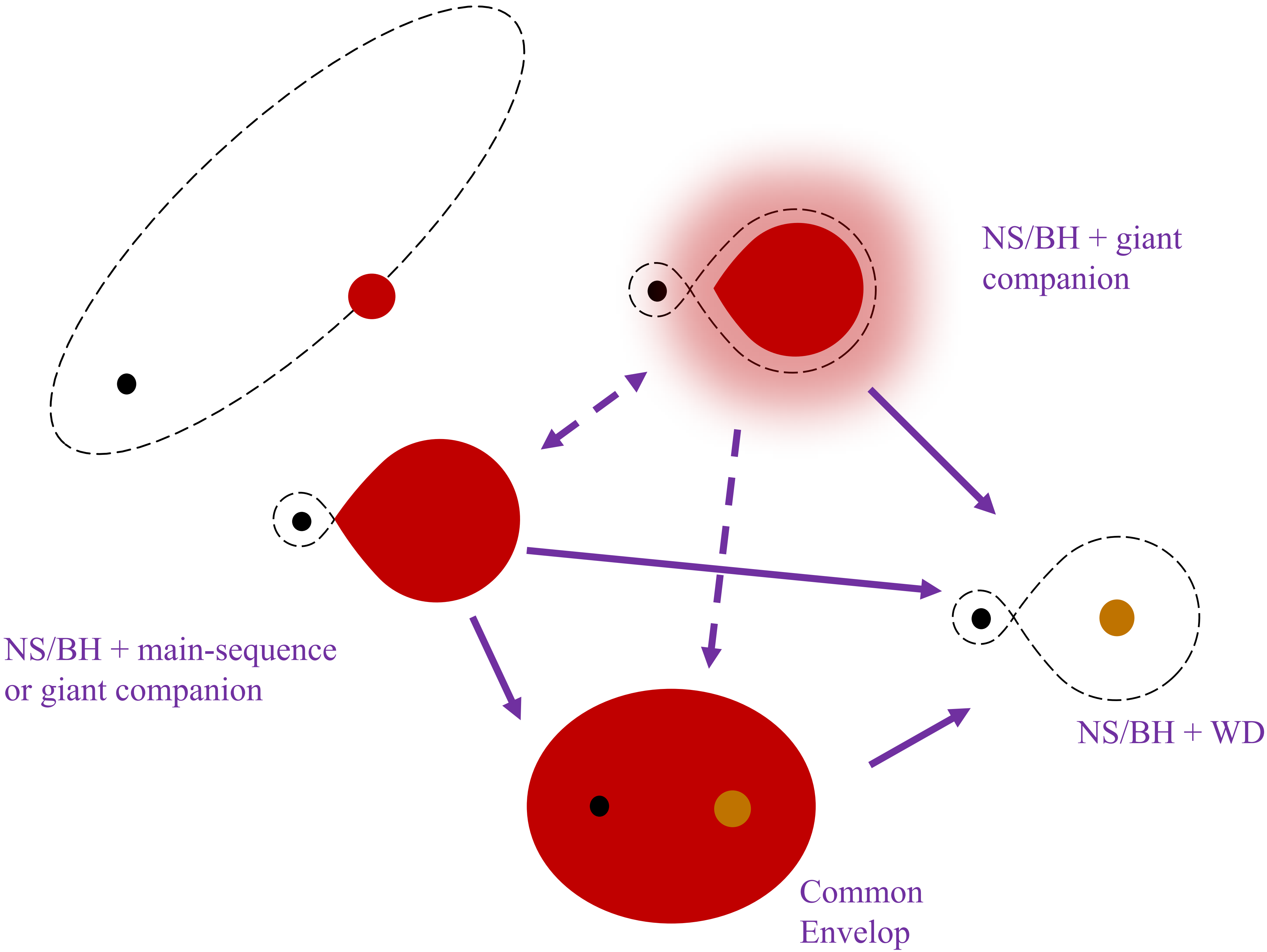


Roche-lobe overflow
Typically normal or white dwarf companion
Typically low magnetic field neutron star



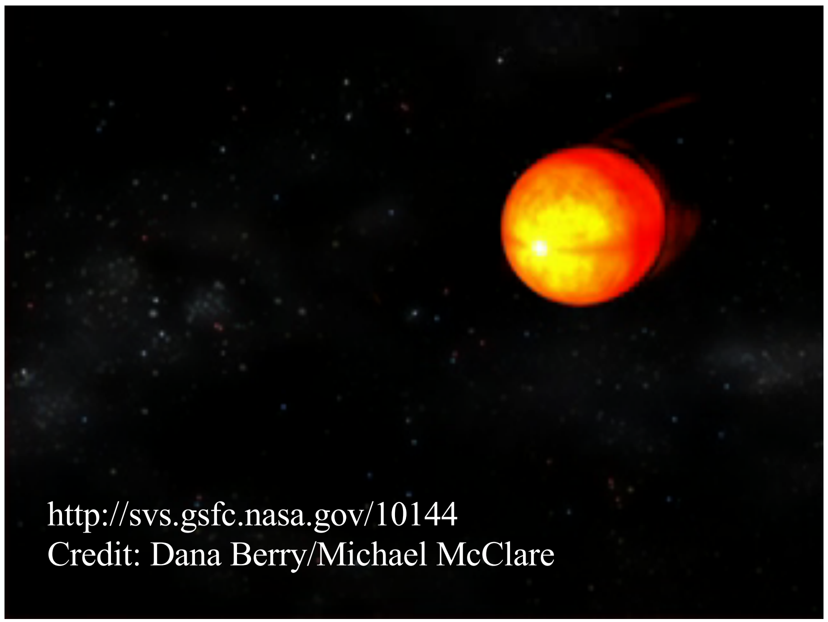
NS/BH + giant
companion
NS/BH + main-sequence
or giant companion
NS/BH + WD
Common
Envelop

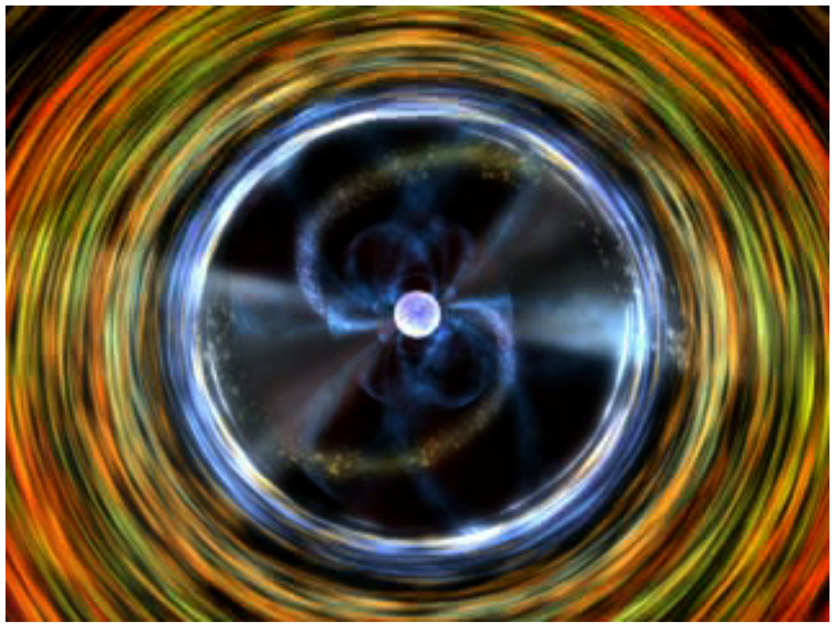

Symbiotic X-ray binary
Strong stellar wind from low-mass red giant companion
Typically high magnetic field neutron star


NS/BH + giant
companion
NS/BH + main-sequence
or giant companion
NS/BH + WD
Common
Envelop

Formation of millisecond radio pulsars

Spinning up the NS
and decreasing magnetic field





- Spin up of star through accretion
- Accretion torque on star is

$$G = \dot{m}R^2\left(\Omega_K(R) - \Omega_*\right) = \dot{m}\sqrt{GMR} \quad \text{if} \quad \Omega_* \ll \Omega_K = \sqrt{\frac{GM}{R^3}}$$

FKR

Angular moment of star

- But also

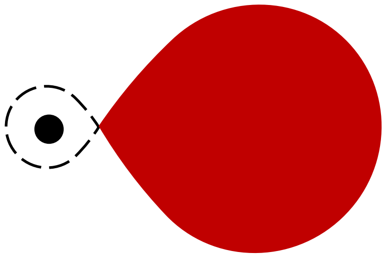
$$G = \frac{dJ}{dt} = \frac{d}{dt}\left(I\Omega_*\right) = I\dot{\Omega}_*$$

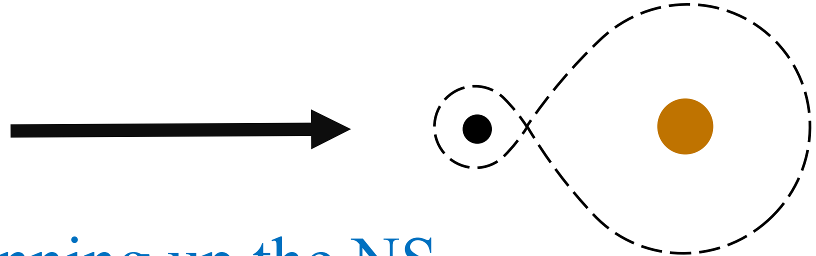
Moment of inertia of neutron star

Integrate this equation to get Ω_* as a function of accreted mass.
Typically, $\Omega_* \sim \Omega_K$ when $\Delta M = 0.1\ M$ for a neutron star.

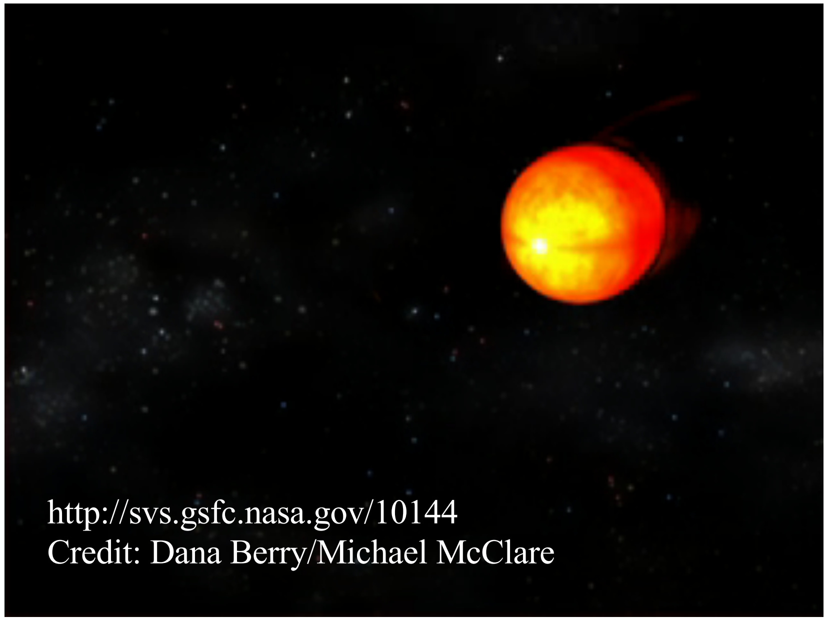
For Eddington accreting sources (~ 10^{-8} solar masses/year) this would only take 10^7 years!

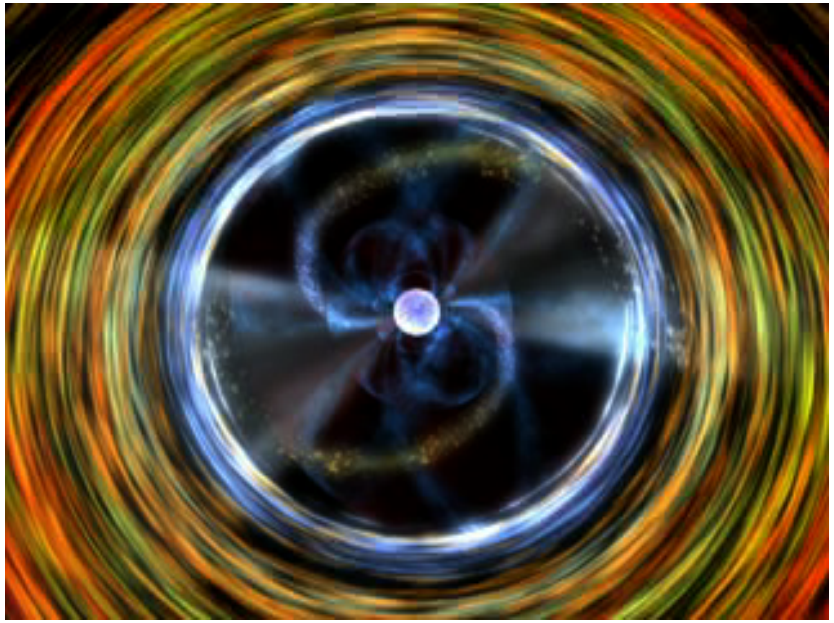
Formation of millisecond radio pulsars





Spinning up the NS
and decreasing magnetic field





Neutron star sound

PSR 0329+54: 0.715 s

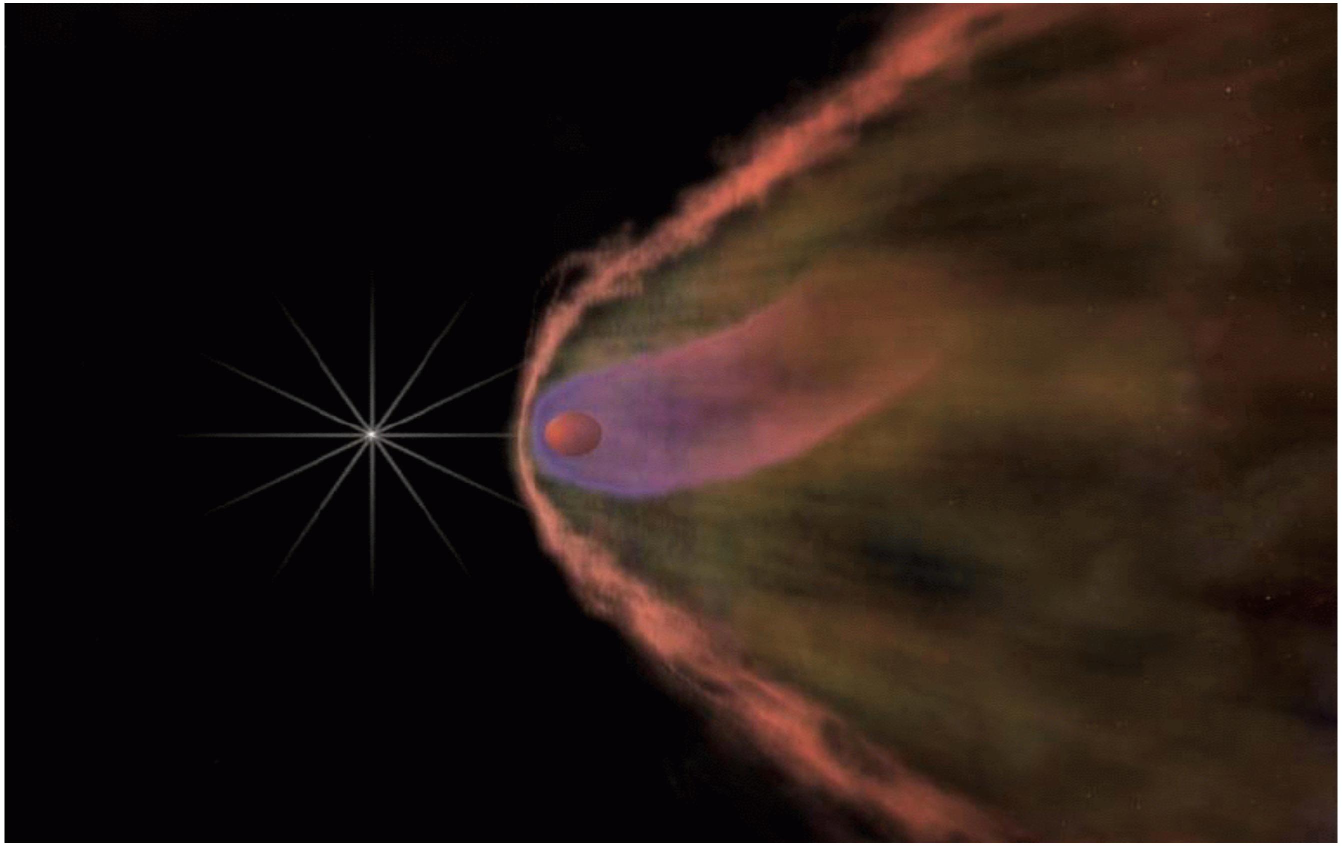
PSR 0833-45: 89.3 ms

PSR 1937+21: 1.56 ms

http://www.jb.man.ac.uk/pulsar/Education/Sounds/

"Black widow" pulsars

- Pulsar wind evaporate companion
  - → Single millisecond pulsar
  - → Planet formation from stellar debris?



Pulsar planets

- PSR B1257+12
  - Discovery of planets in 1992
  - Mass a few Earth mass
  - Orbital periods of 66.6 and 98.2 days