連星系内での非球対称な恒星風の降着

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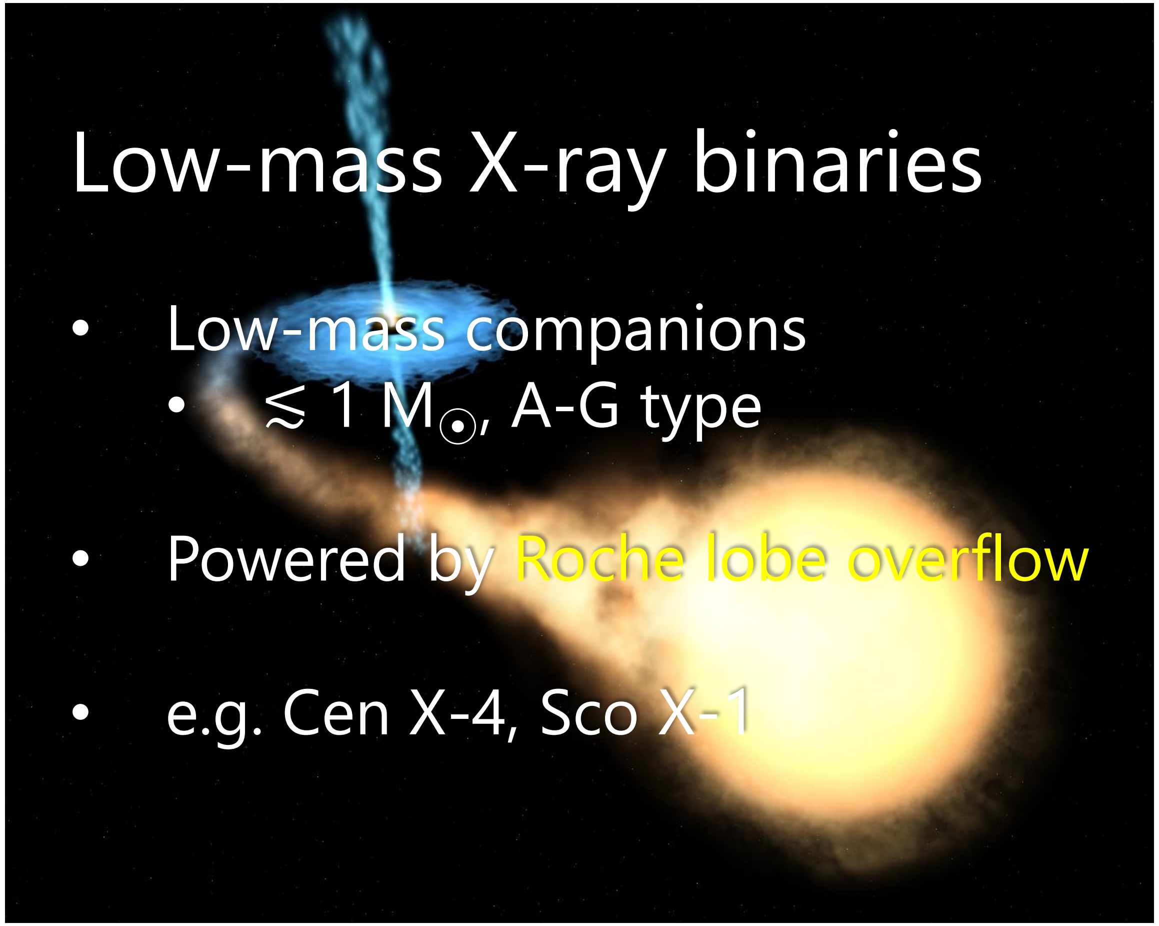
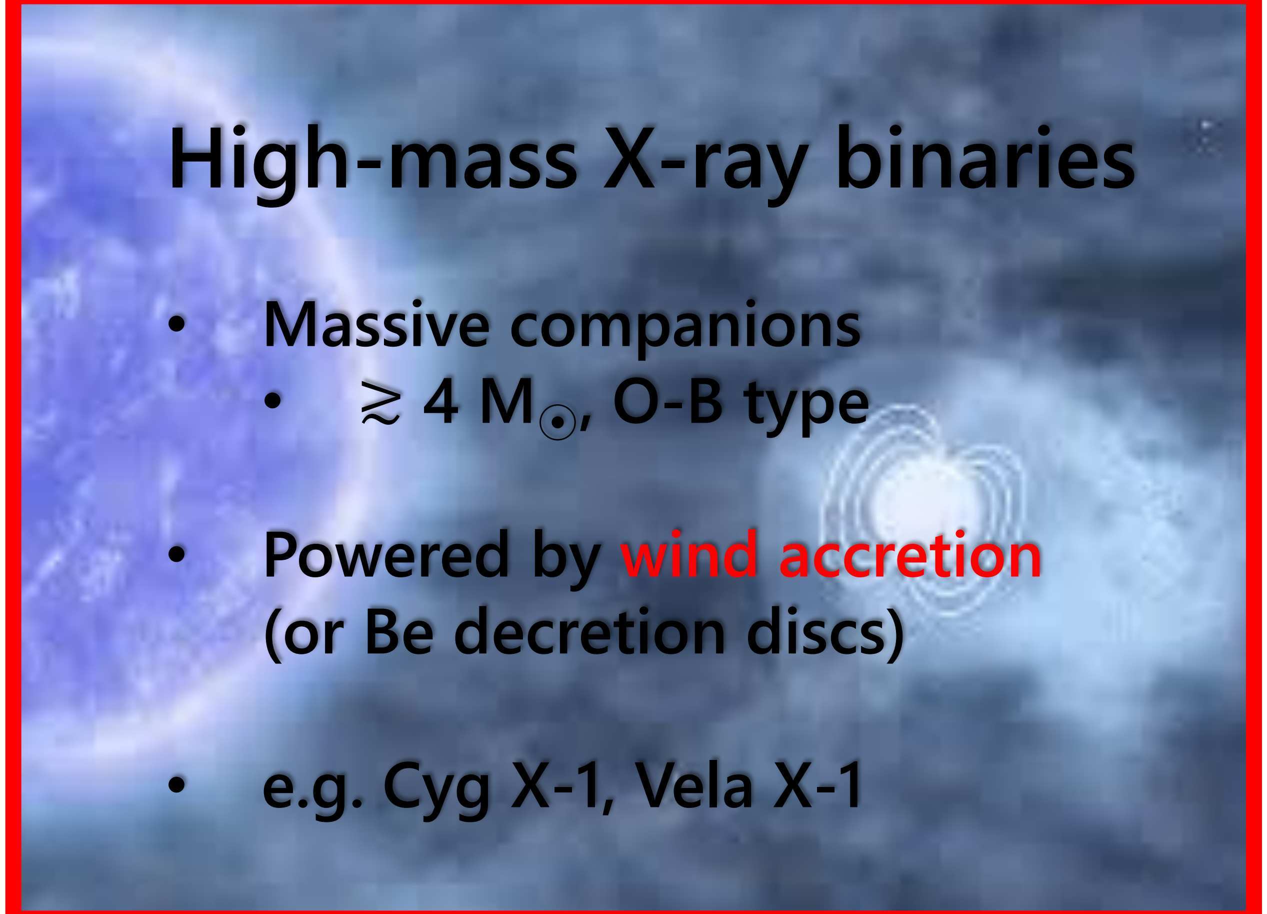
About X-ray binaries

X-ray binaries are binaries that consists of a compact object (neutron star or black hole) and a normal star



Low-mass X-ray binaries

- Low-mass companions
  - $\lesssim 1\ M_\odot$, A-G type
- Powered by Roche lobe overflow
- e.g. Cen X-4, Sco X-1

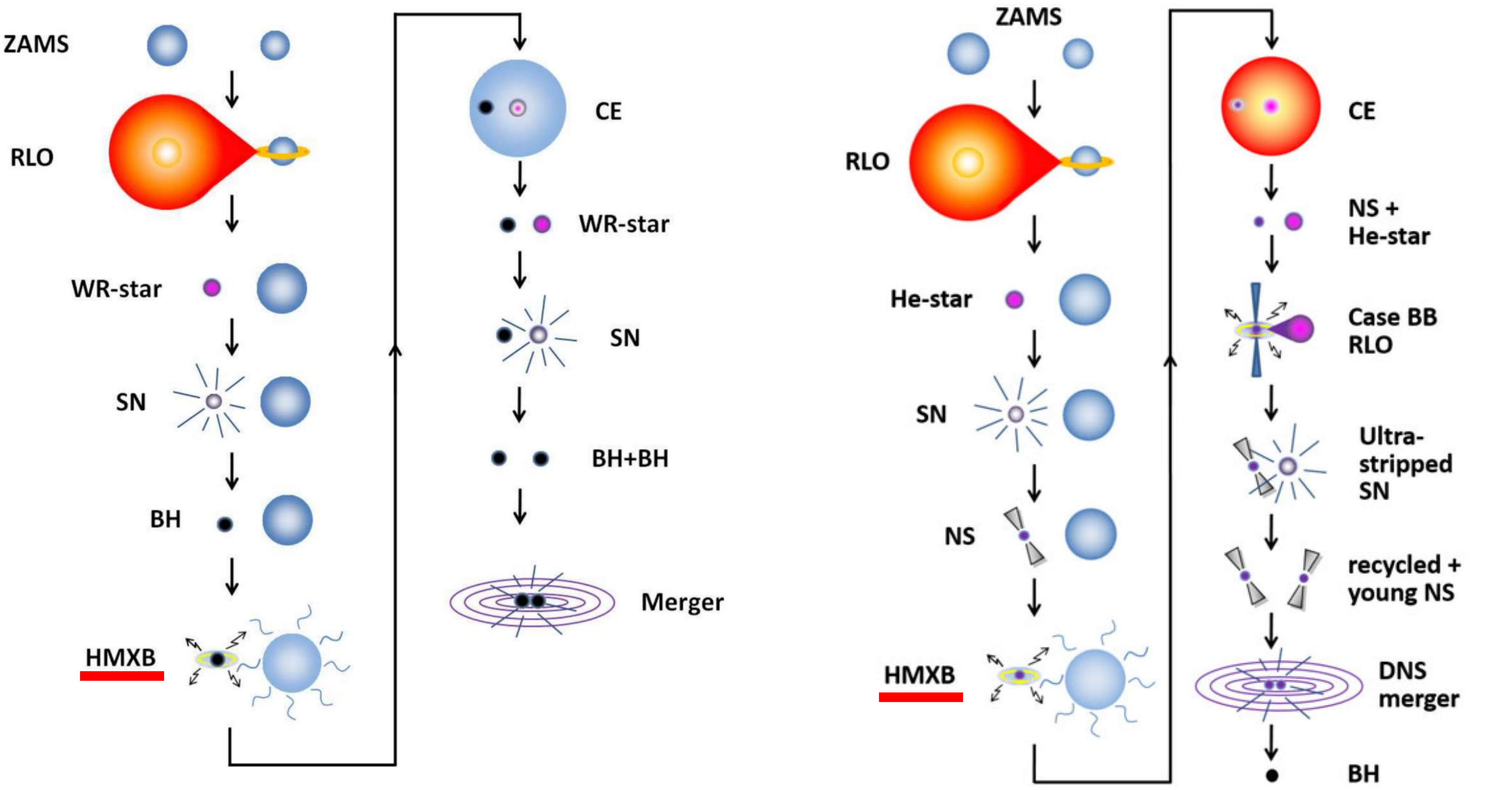


High-mass X-ray binaries

- Massive companions
  - $\gtrsim 4\ M_\odot$, O-B type
- Powered by wind accretion (or Be decretion discs)
- e.g. Cyg X-1, Vela X-1

High-mass X-ray binaries (HMXBs)

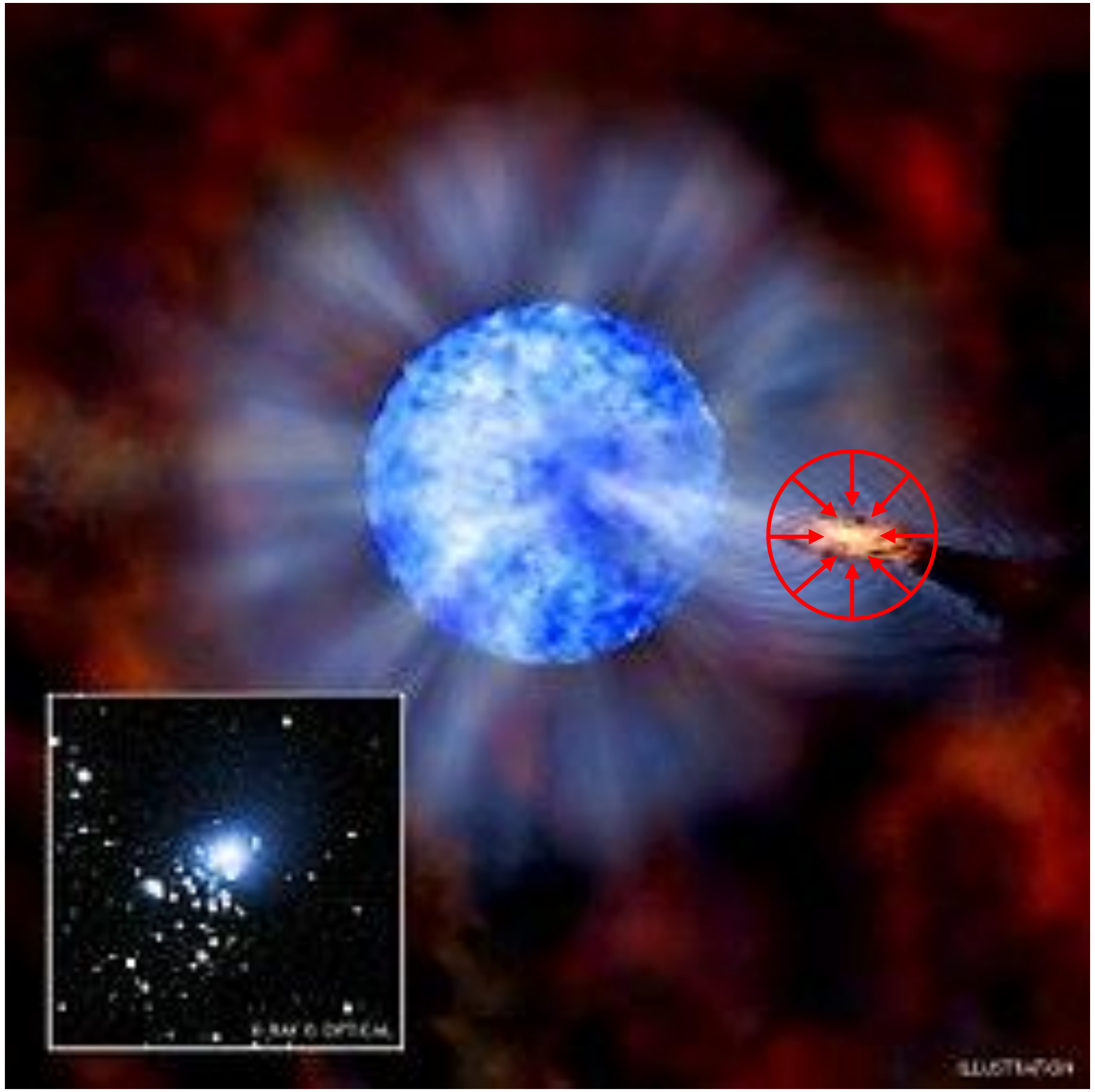
A necessary step towards gravitational wave sources?



Tauris et al. 2017

Wind accretion

Wind accretion can be described by the Bondi-Hoyle accretion picture



Accretion radius

$$R_{\mathrm{Bondi}} \sim \frac{2Gm_2}{v_{\mathrm{wind}}^2}$$

Mass accretion rate

$$\dot{M} \sim \frac{R_{\mathrm{Bondi}}^2}{4a^2}$$

X-ray luminosity

$$L \sim \eta \dot{M} c^2$$

seems simple…

BH-HMXBs

There are only a handful of known HMXBs with black hole companions

Name	P_{orb} (d)	M_{don} ($M_\odot$)	M_{BH} ($M_\odot$)	RL filling factor
Cyg X-1	5.6	40.6±7.7	21.2±2.2	0.997
LMC X-1	3.9	31.8±3.5	10.9±1.4	0.971
LMC X-3	1.7	3.6±0.6	7.0±0.6	>1
MCW 656	~60	~13	4.7±0.9	???
M33 X-7	3.45	~70	~16	0.899
(SS 433)	13	14-18	5-10	???

Known BH-HMXBs have relatively high Roche lobe filling factors

Why are the RL filling factors all so high??
Is there a qualitative difference between high and low RL filling factors??

Wind accretion in close binaries

We discovered that the following 3 effects can be important in close binaries

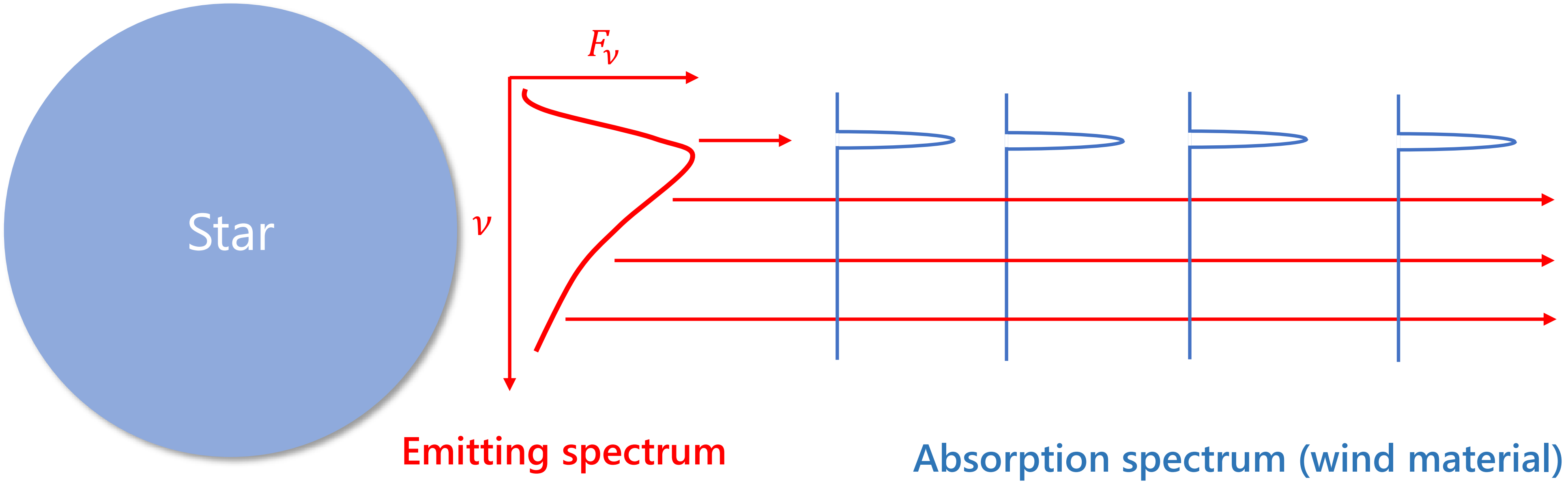
① Wind acceleration zone

② Escape velocity reduction

③ Gravity darkening

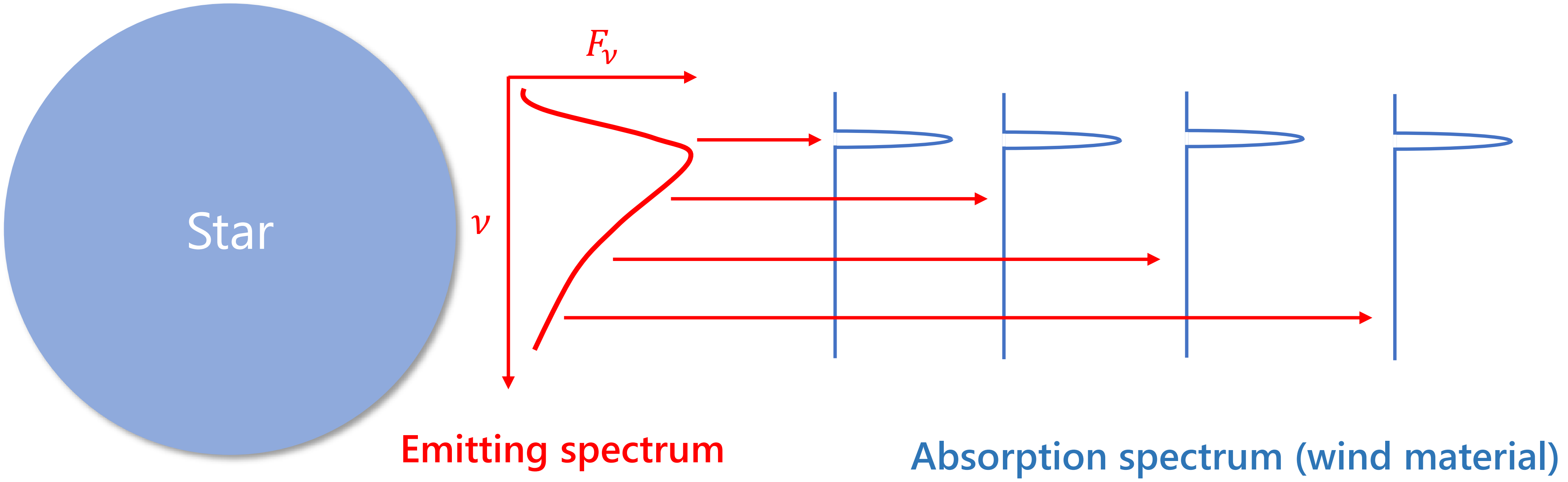
Line-driven winds

- **CAK theory** (Castor, Abbott & Klein 1975)
  - Opacity of UV spectral lines can be very high in an otherwise optically thin wind



Line-driven winds

- **CAK theory** (Castor, Abbott & Klein 1975)
  - Opacity of UV spectral lines can be very high in an otherwise optically thin wind
  - Wind material efficiently captures photons from the stars due to "line deshadowing"



CAK theory (continued)

Cassinelli 1979

Equation of motion

$$v\frac{dv}{dr} = -\frac{GM}{r^2} + \frac{1}{\rho}\frac{dp}{dr} + g_e + g_{\rm L},$$

parameters

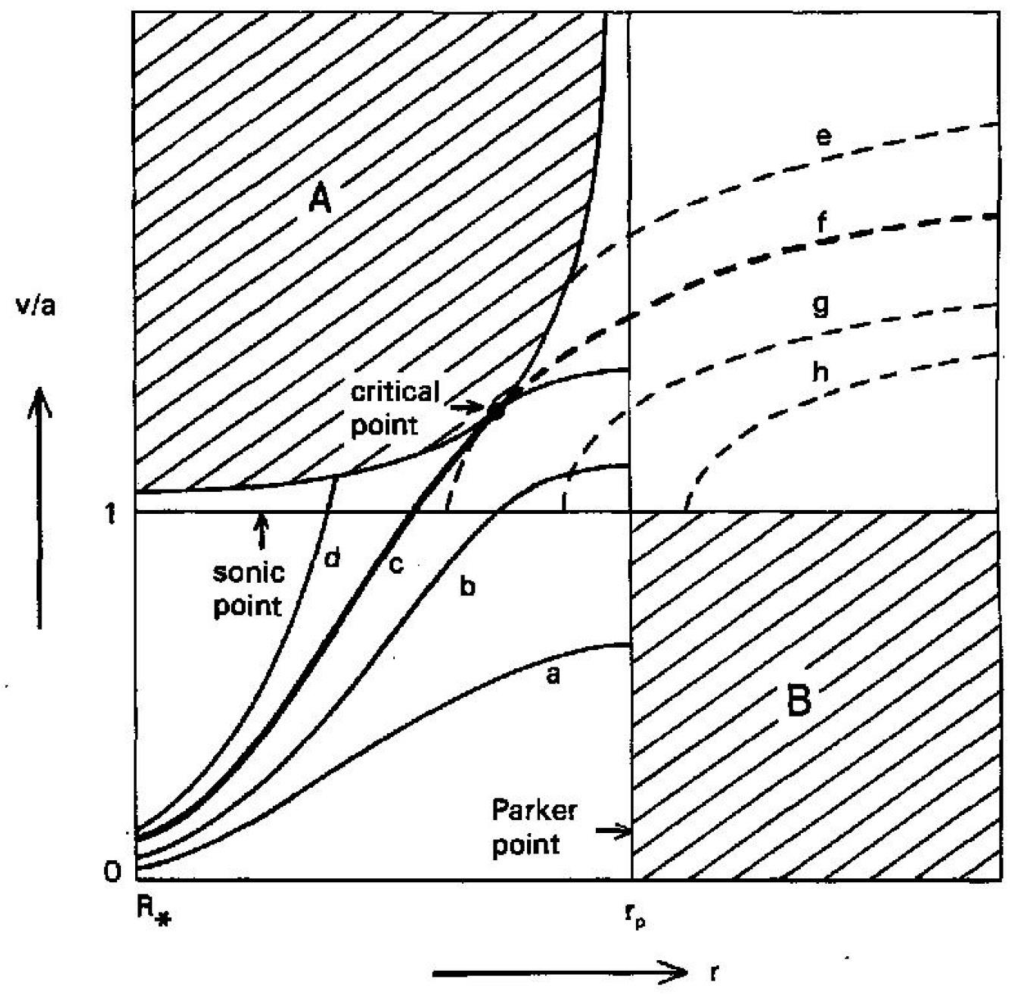
$$g_e = \frac{GM}{r^2}\Gamma \qquad g_{\rm L} = \frac{\sigma_e L}{4\pi r^2 c} k t^{-\alpha},$$

continuum force

line force

$$t \equiv \sigma_e v_{\rm th} \rho \left(\frac{dv}{dr}\right)^{-1},$$

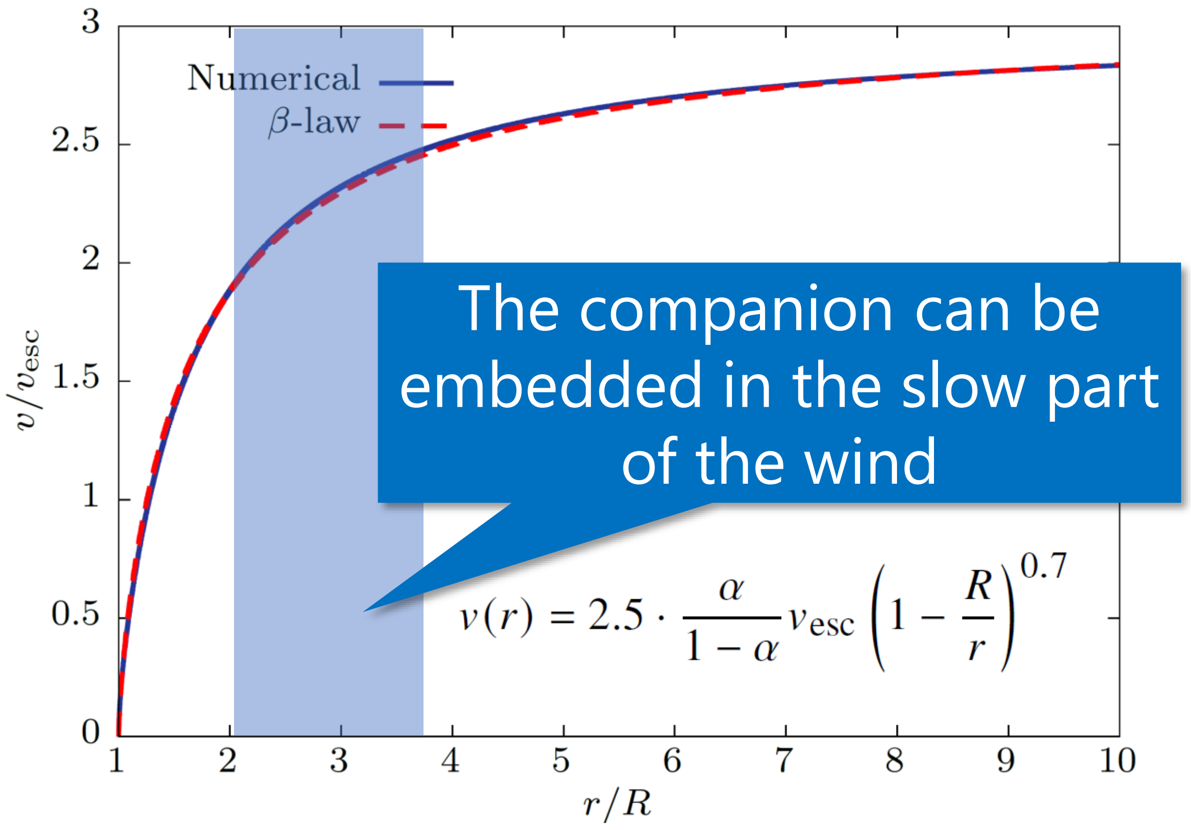
optical depth parameter

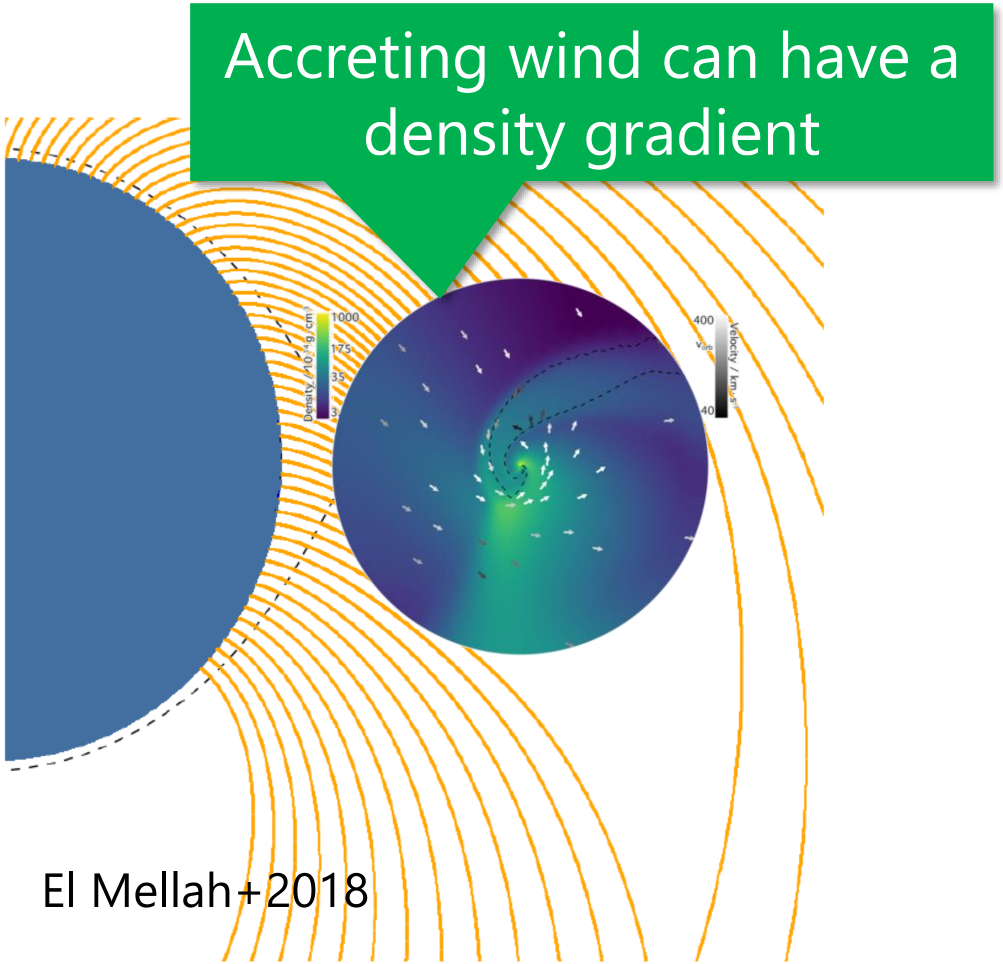


The equations can be analytically solved under certain conditions, otherwise solved numerically through “critical point analysis”

Wind acceleration zone

Winds are not emitted from the stellar surface with fast velocities, but are accelerated over some distance





El Mellah+2018

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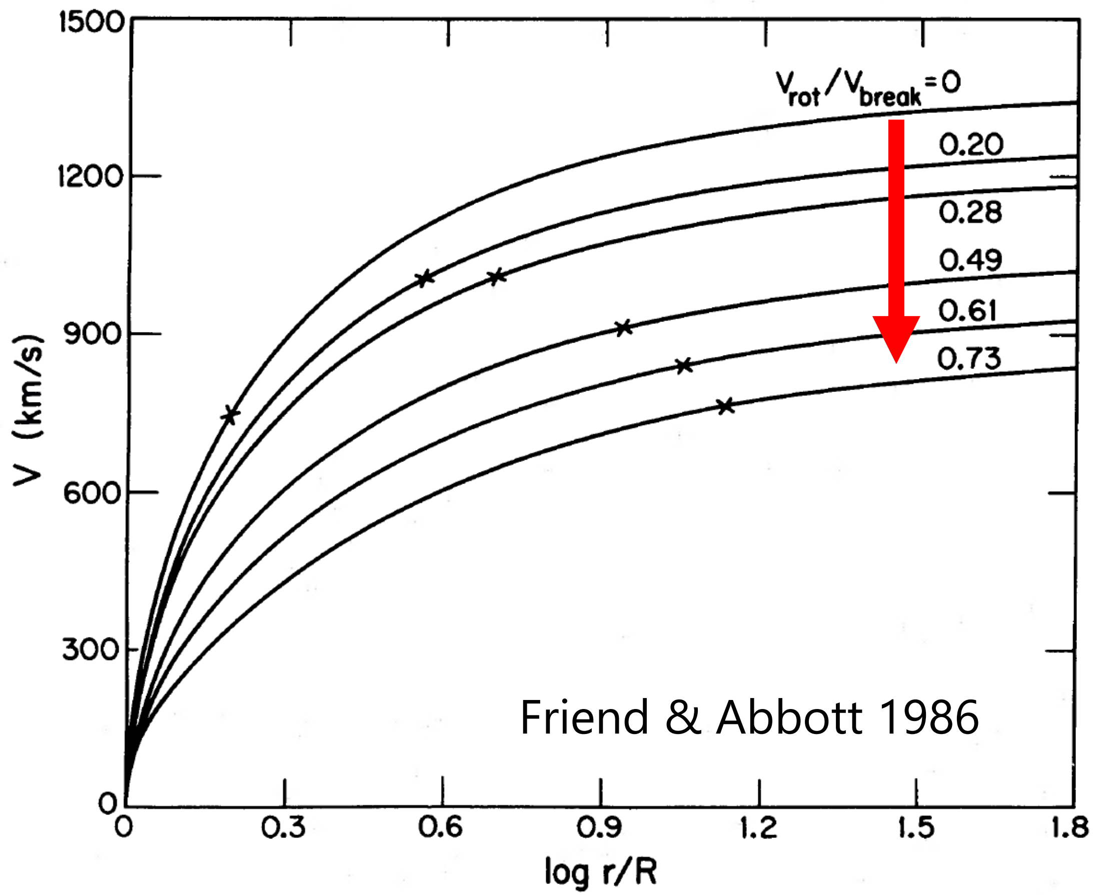
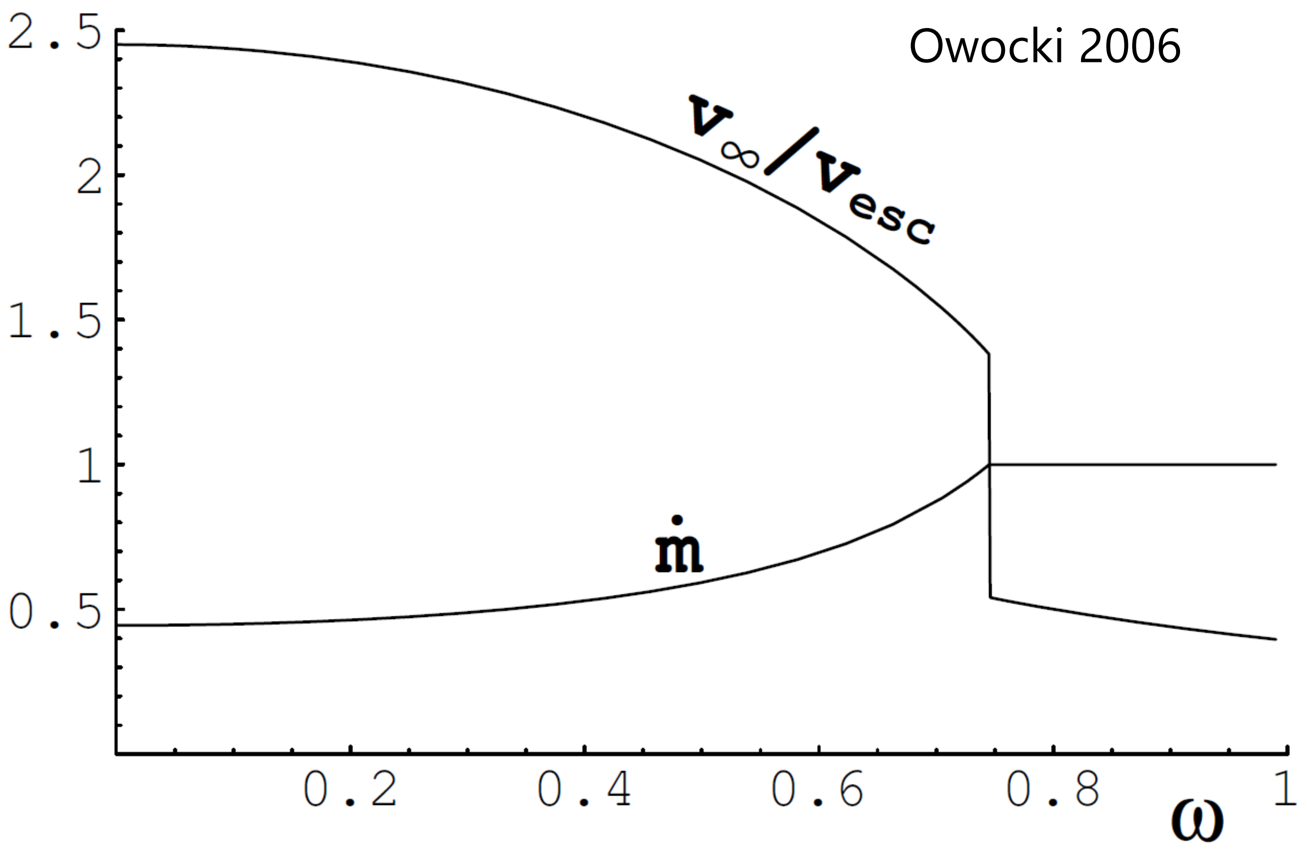
Rotation

Donor stars in close binaries can be rapidly rotating due to tidal locking





Wind is slower for rotating stars

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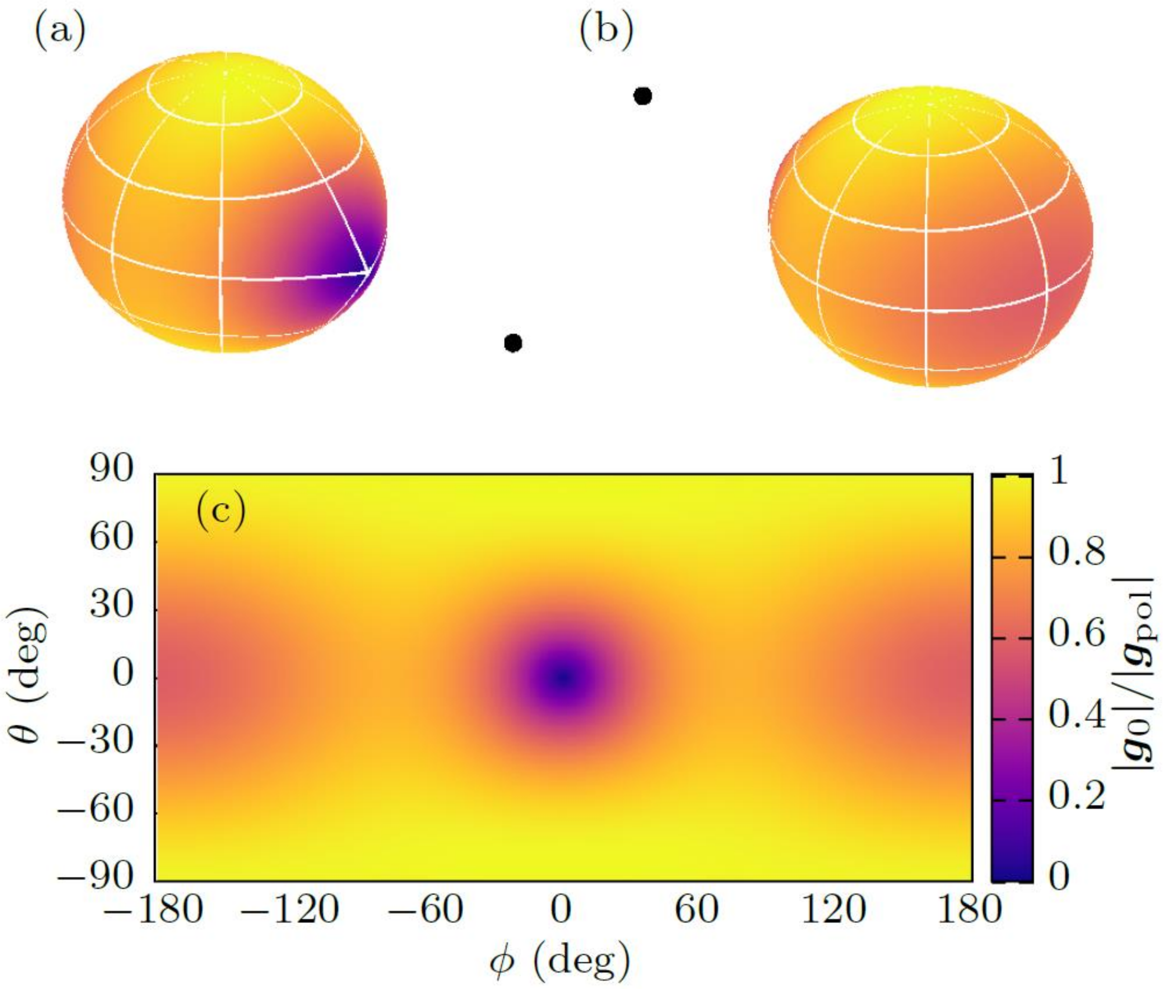
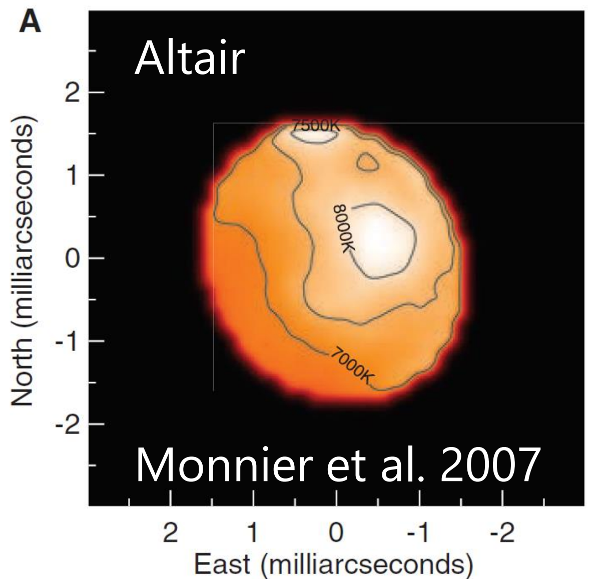
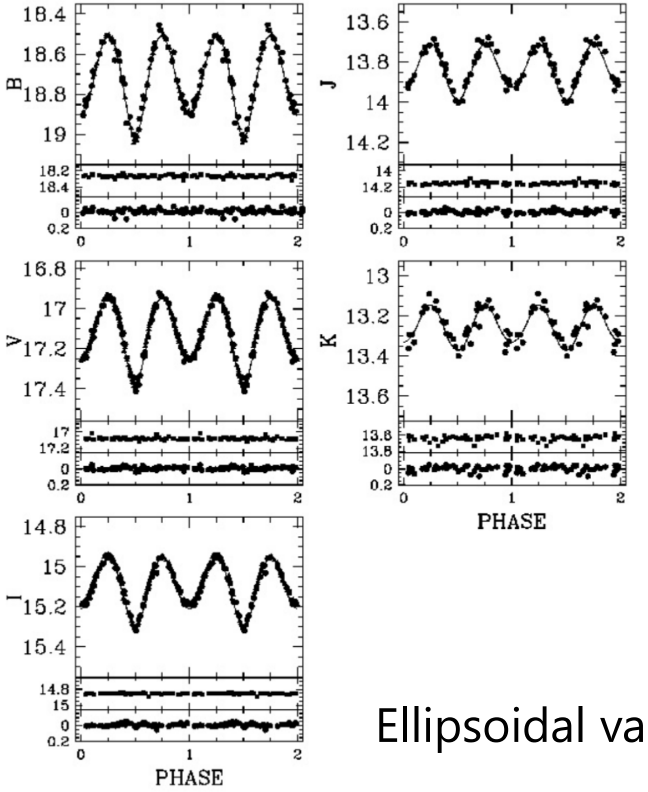
Gravity darkening

Stars can be highly asymmetric in close binaries



Surface gravity distribution





Ellipsoidal variations

Wind accretion in close binaries

We discovered that the following 3 effects can be important in close binaries

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Method

- **Equation of motion for winds in binaries**

$$\frac{d\boldsymbol{v}}{dt} = -\frac{GM_1(1-\Gamma)}{|\boldsymbol{r}-\boldsymbol{r}_1|^2}\boldsymbol{n}_1 - \frac{GM_2}{|\boldsymbol{r}-\boldsymbol{r}_2|^2}\boldsymbol{n}_2$$

$$+ CK_{\mathrm{FDCF}}\left(v_1|\boldsymbol{r}-\boldsymbol{r}_1|^2\boldsymbol{n}_1\cdot\nabla\left[\boldsymbol{n}_1\cdot\boldsymbol{v}\right]\right)^{\alpha}\frac{\boldsymbol{n}_1}{|\boldsymbol{r}-\boldsymbol{r}_1|^2}$$

Line acceleration

$$-\boldsymbol{\Omega}\times(\boldsymbol{\Omega}\times\boldsymbol{r}) - 2\boldsymbol{\Omega}\times\boldsymbol{v},$$

$$C \equiv \frac{\sigma_e L k}{4\pi c}\left(\frac{\sigma_e v_{\mathrm{th}}\dot{M}}{4\pi}\right)^{-\alpha}$$

$$C = \frac{1+\alpha}{\alpha}\left[\frac{\alpha}{1-\alpha}GM(1-\Gamma)\right]^{1-\alpha}\left(\frac{|g_0|}{|g_{\mathrm{pole}}|}\right)^{1-\alpha},$$

Velocity correction (VC)

$$K_{\mathrm{FDCF}} = \frac{(1+\sigma)^{\alpha+1}-(1+\sigma\mu_*^2)^{\alpha+1}}{(1-\mu_*^2)(\alpha+1)\sigma(1+\sigma)^{\alpha}}$$

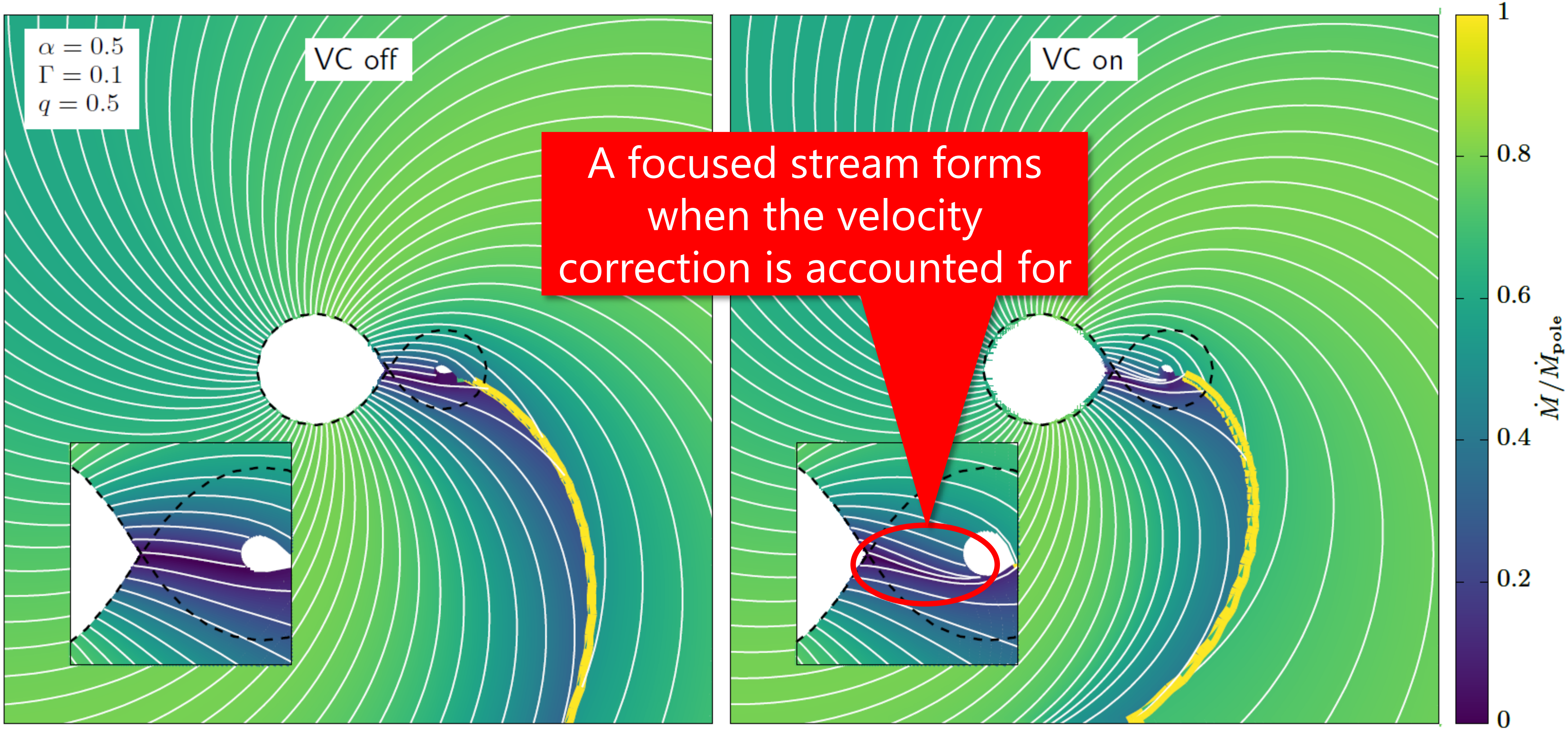
- **Mass-loss rate for line-driven winds**

$$\dot{M} = \frac{k^{\frac{1}{\alpha}}}{v_{\mathrm{th}}}\frac{L_{\mathrm{Edd}}}{c}\Gamma^{\frac{1}{\alpha}}(1-\Gamma)^{1-\frac{1}{\alpha}}\alpha(1-\alpha)^{\frac{1}{\alpha}-1}(1+\alpha)^{-\frac{1}{\alpha}}\left(\frac{|g_0|}{|g_{\mathrm{pole}}|}\right)^{\beta}$$

Gravity darkening (GD)

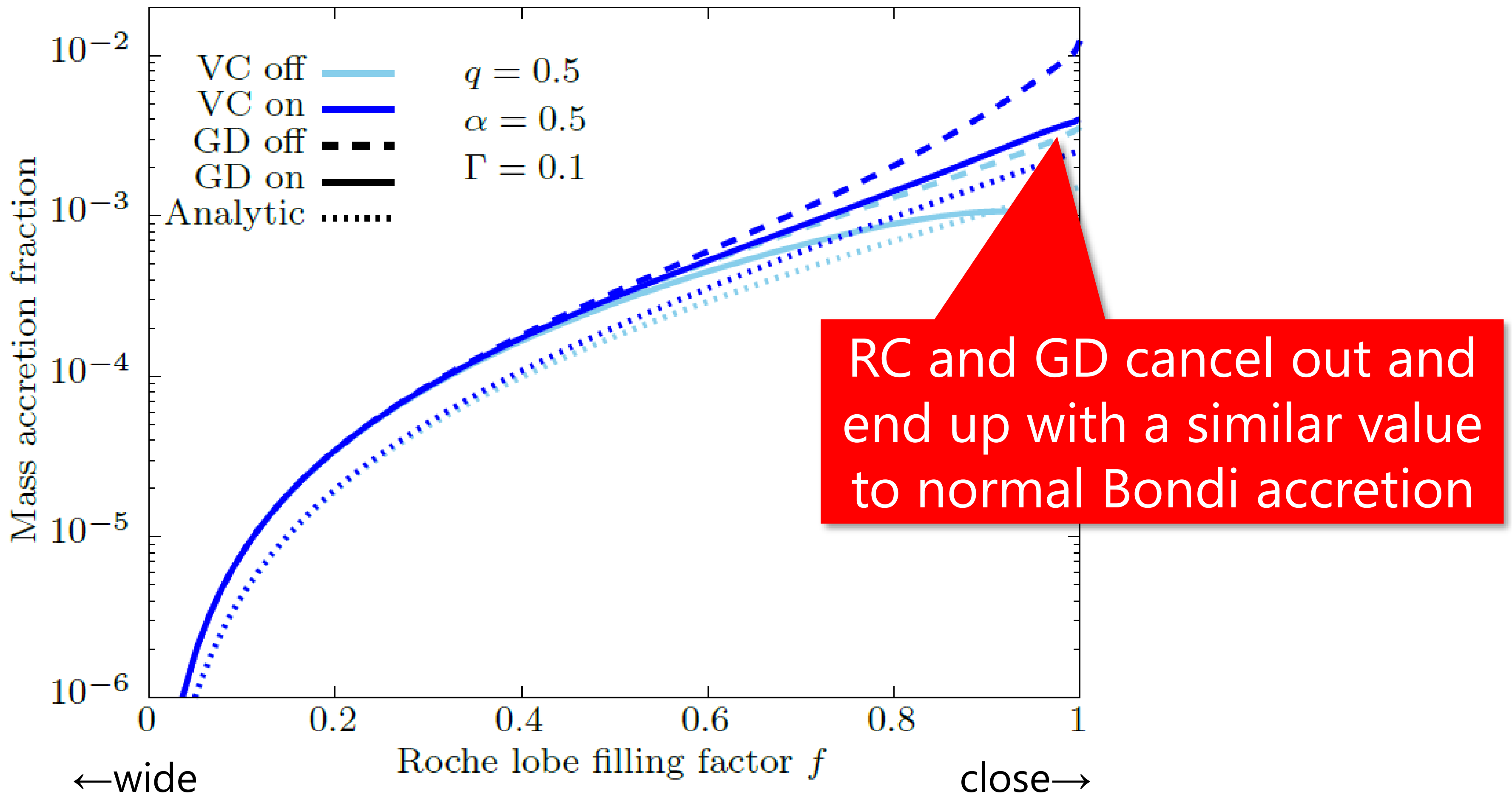
Results – wind streamlines

Wind streamlines for an almost Roche lobe filling case



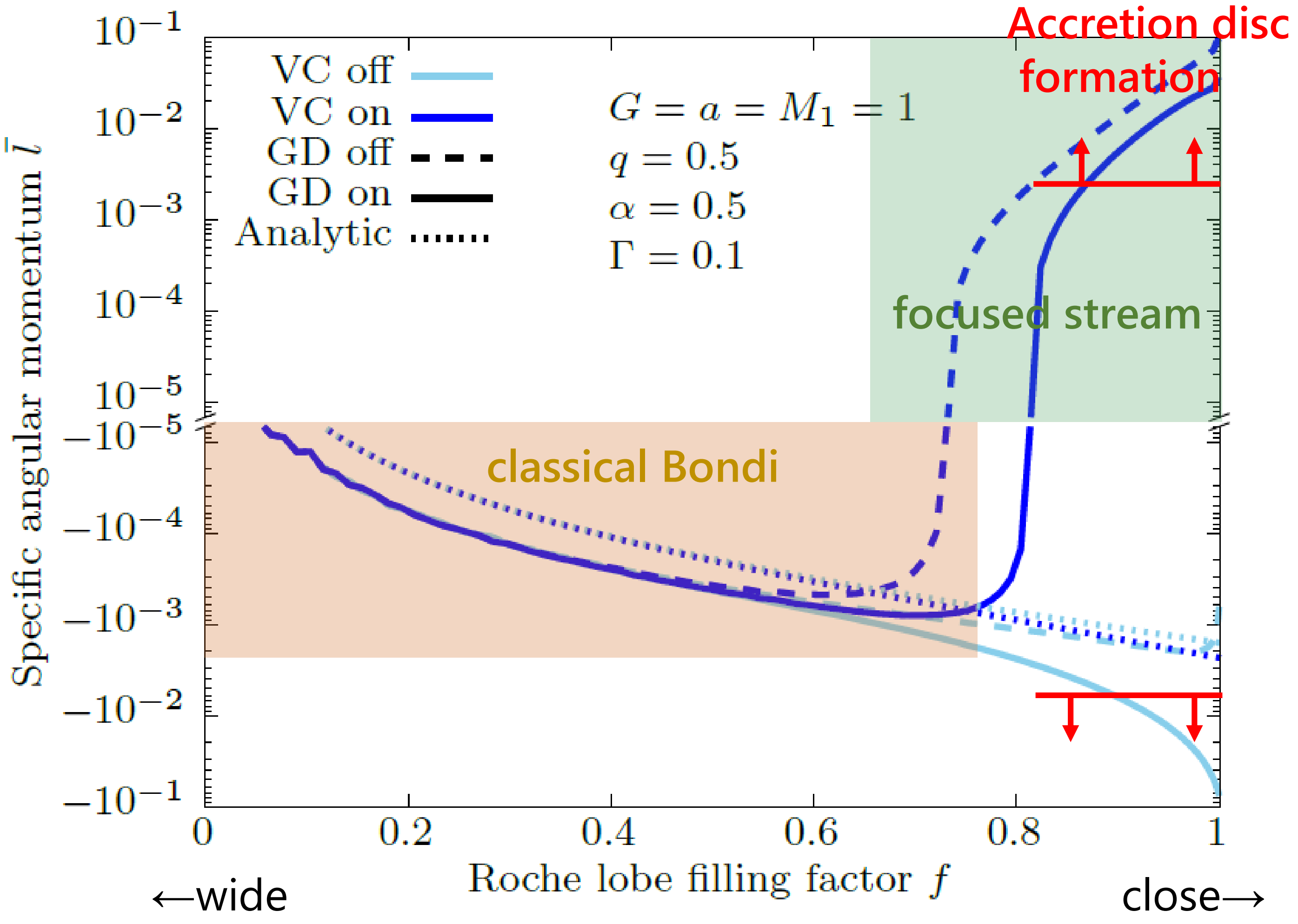
Results – mass accretion rate

Mass accretion rate with the various additional effects switched on/off



Results – angular momentum accretion

Change in accreted angular momentum with the various effects



Conversion formula from my weird units to accretor gravitational units

$$\hat{l} = \bar{l} \cdot \frac{2}{\sqrt{1+q}} \left(\frac{a}{R_{S,2}}\right) \left(\frac{v_{orb}}{c}\right)$$

$$\sim \bar{l} \cdot 730 \frac{(1+q)^{1/6}}{q} \left(\frac{P}{5.6\text{ d}}\right)^{\frac{1}{3}} \left(\frac{m_1}{40\text{ M}_\odot}\right)^{-\frac{1}{3}},$$

ISCO angular momenta

non-rotating BH: $\hat{l} \sim 3.46$

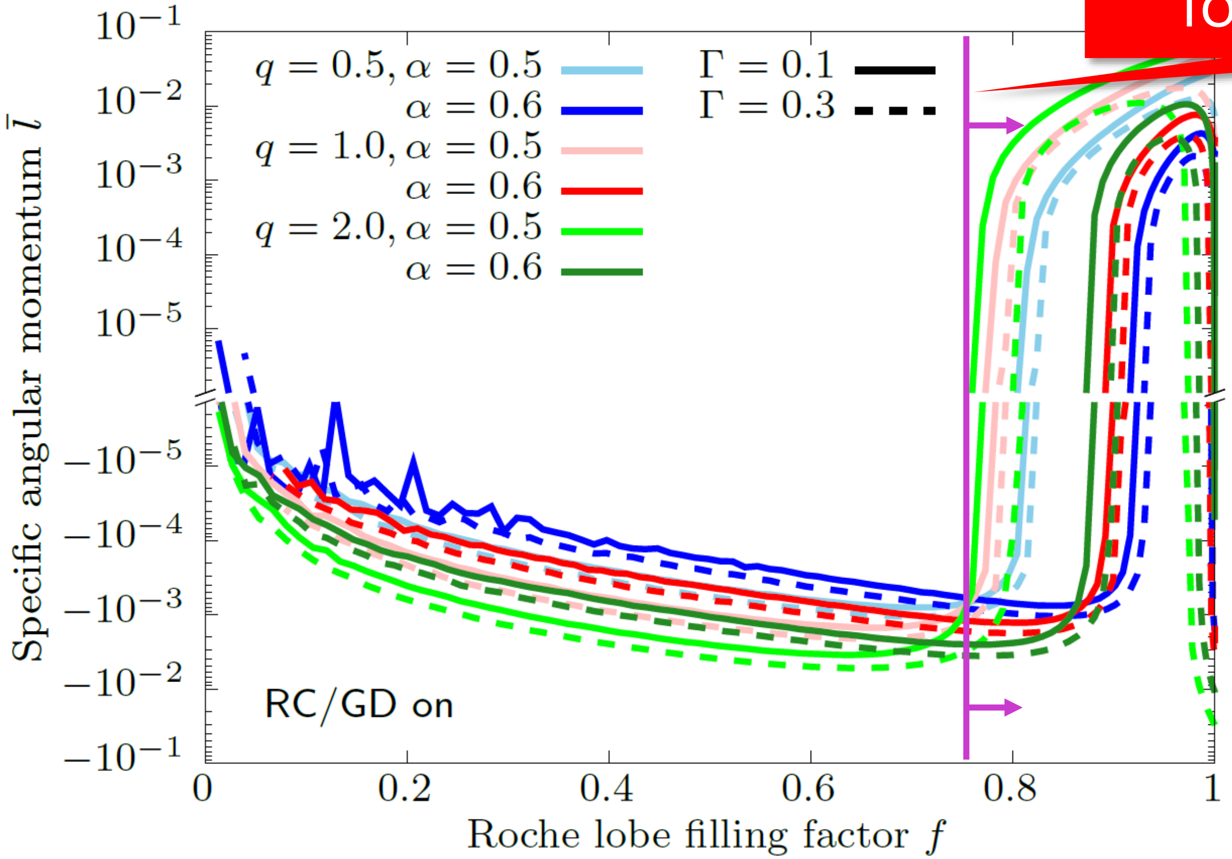
max-rot. BH (prograde): $\hat{l} \sim 1.15$

max-rot. BH (retrograde): $\hat{l} \sim -4.23$

Parameter study

Similar behaviours were found with different wind and binary parameters

Angular momentum



Threshold for accretion disc formation is f>0.8-0.9?

Critical condition for observability!

Conclusions

- X-ray binaries are important intermediate stages of massive binary evolution
- Wind flows in close binaries can be heavily influenced by the following three effects
  - Wind acceleration zone
  - Escape velocity reduction
  - Gravity darkening
- With all the additional effects combined,
  - mass accretion rate is similar to Bondi-Hoyle accretion
  - accreted angular momentum is strongly affected at high RL filling factors
- All observable HMXBs should have f>0.8-0.9