Fast quasi-periodic oscillations in magnetic cataclysmic variables

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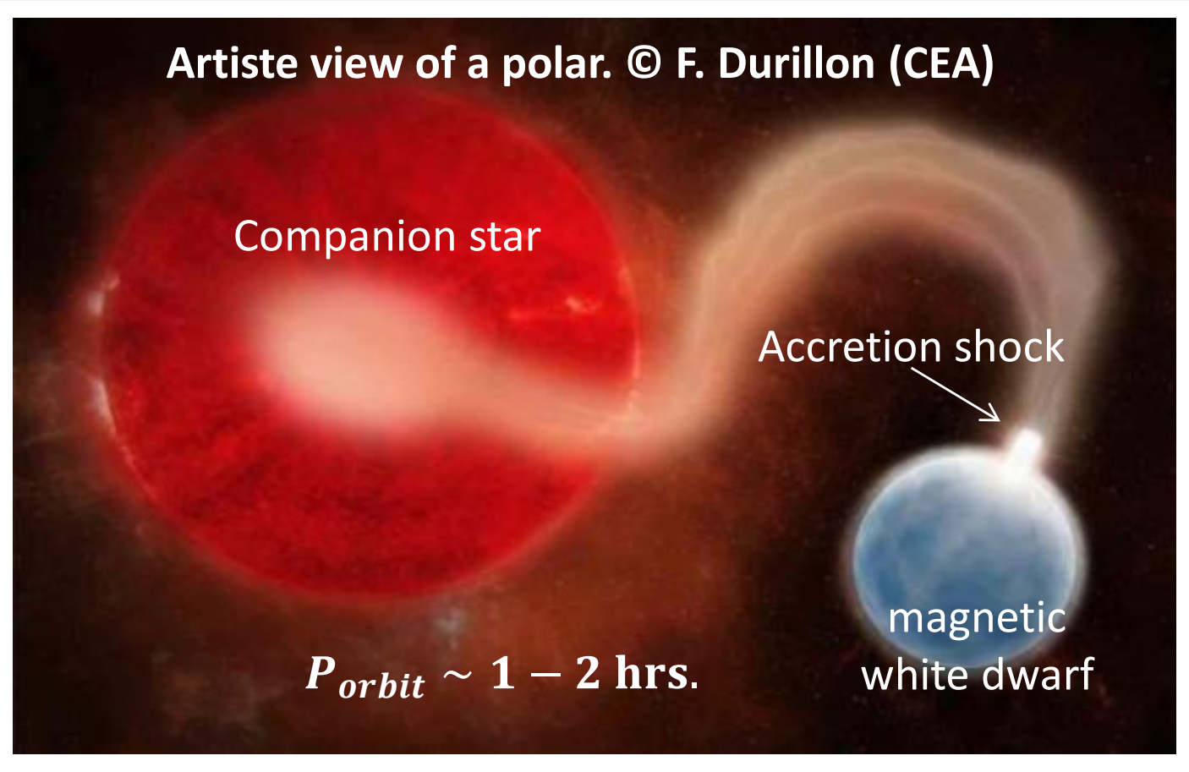
Abstract

Several polars have revealed ~1-Hz quasi-oscillations (QPOs) in the optical, while upper limits only have been derived from XMM-Newton observations. We will review the current observational properties of QPOs in polars and compare them with the radiative properties of our numerical 1D simulations of the structure and dynamics of the post-shock region relevant to the physical parameters of polars exhibiting QPOs (mass, accretion rate, magnetic field). Though large uncertainties exist for these parameters, we will show that the standard model of column instability remains insufficient to account for the observations, thus leaving the origin of QPOs as an opened question. Different solutions, such as a fragmentation of the accretion flow, are proposed, which require 3D simulations.

Accreting magnetic cataclysmic variables : polars



Polars:

Specific sub-class of **magnetic cataclysmic variables** (mCVs) **[Warner, 1995] [Wu, SSR, 2000]** composed of a **magnetic accreting white dwarf** ($B_{WD} > 10$ MG) and a **low-mass companion star** (M-type). The highly magnetized white dwarf prevents the formation of an accretion disk, synchronizes the spin of the white dwarf with the orbital period and induces the **formation of an accretion column.**

Why study those objects ?

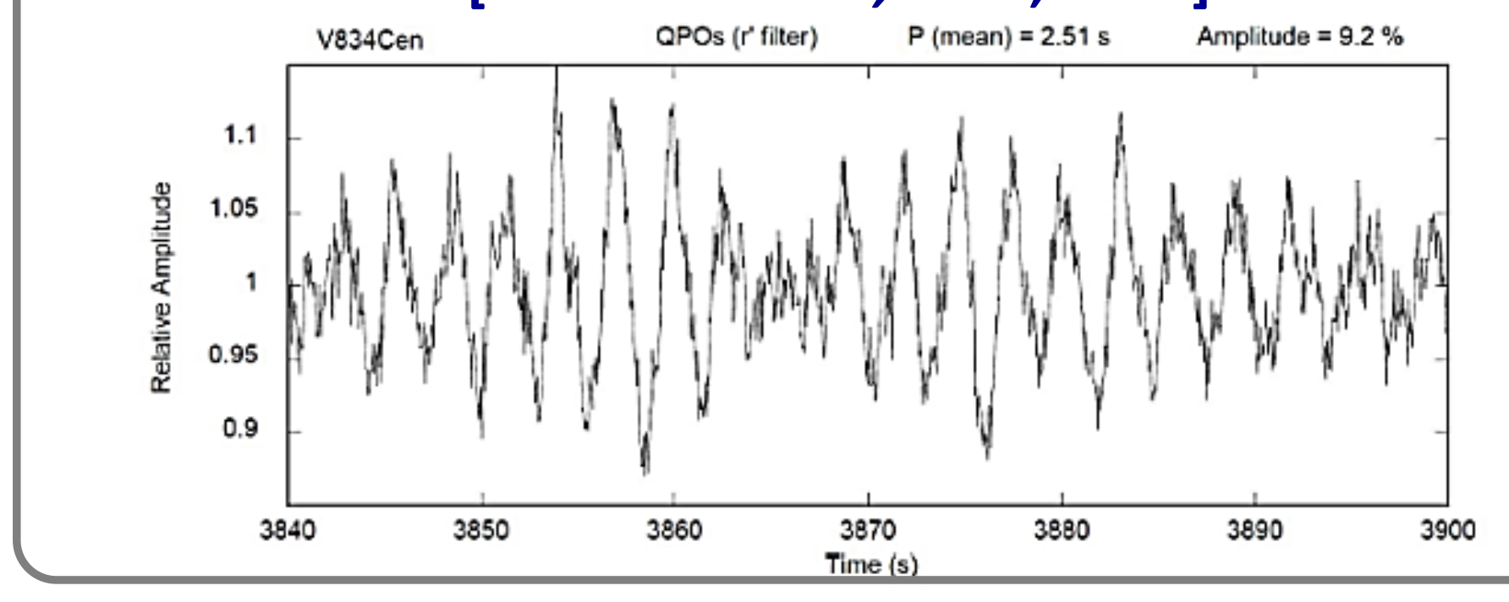
- They provide the best opportunity to study **accretion processes** in high-energy regimes.
- They are an important class of X-ray sources. In recent works **[Perez *et al.*, Nature, 2015]**, magnetic CVs are suggested to be an dominant contributor to the galactic center X-ray emission.
- The CV are potential progenitors of thermonuclear supernovae **[Maoz *et al.*, ARAA, 2014]**.

Five polars show **quasi-periodic oscillations** (QPOs) in their **optical light curve** maybe due to radiative instabilities. **[Langer *et al.*, ApJ, 1981]**

Polars	M_{WD} ($M_\odot$)	B (MG)	$\dot{m}$ (g cm^{-2} s^{-1})	Freq. (Hz)	Opt. amp. (per cent)	Limit X-ray amp. (per cent)
AN UMa	1	29–36	0.2	0.62–0.72	1.3–3.9	25
BL Hyi	1	12–23	1.76	0.2–0.8	1–4	71
EF Eri	0.6–0.92	16–21	6.4	0.3–0.6	1–1.3	58
VV Pup	0.73	31	4.1	0.4–1.2	1.1–1.7	31
V834 Cen	0.66–0.85	23	0.88–1.4	0.26–0.6	0.6–2.1	9

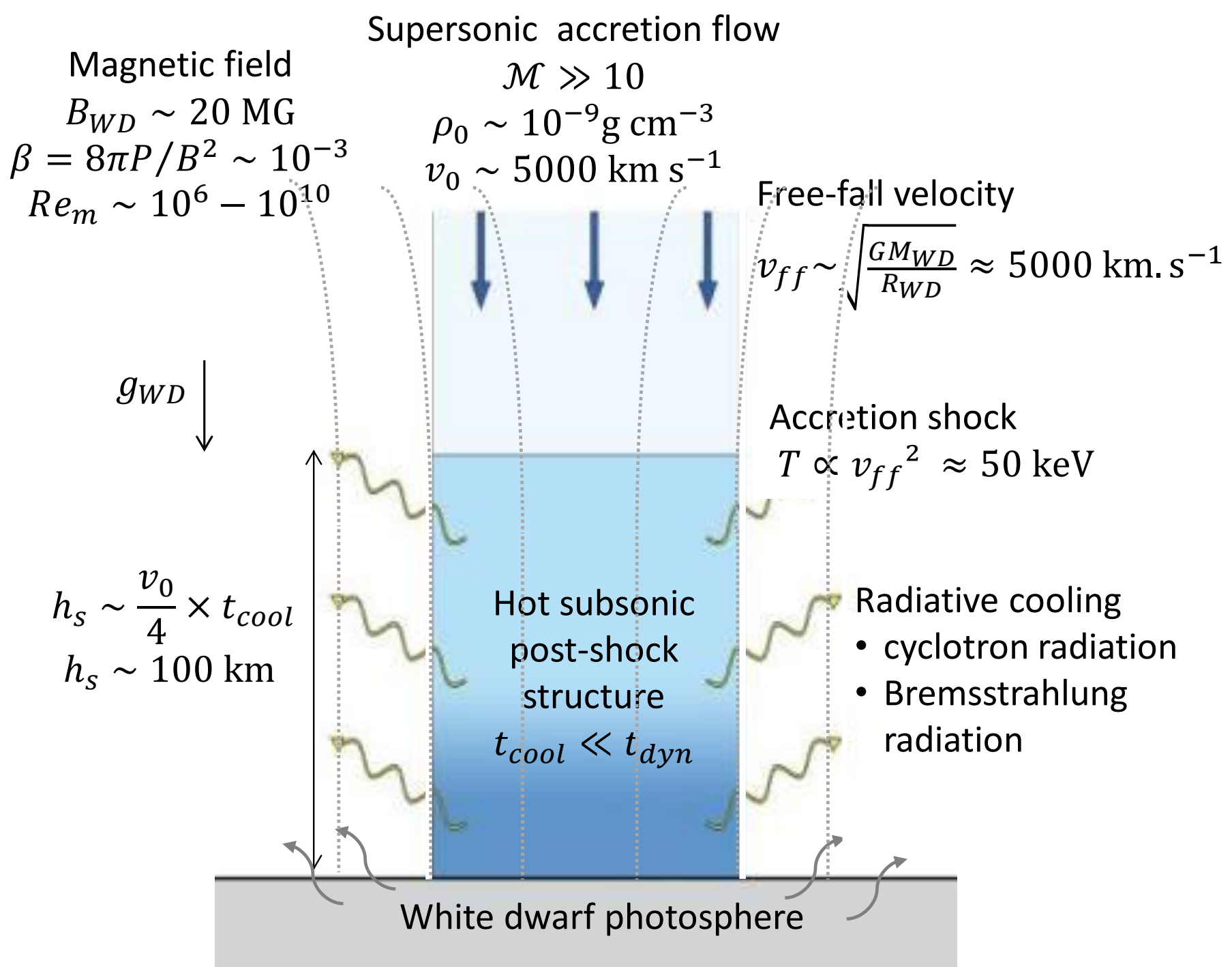
The five Quasi-Periodic Oscillations (QPOs) systems

Observation of the quasi-periodic oscillations in the V834 Cen polar in the optical domain.
[Mouchet *et al.*, A&A, 2017]



Numerical simulations show QPOs in the X-ray domain which are not observed by XMM-Newton **[Bonnet-Bidaud *et al.*, A&A, 2015)] [Busschaert *et al.*, A&A, 2015]** which questions about our understanding of the accretion processes.

Oscillations in the light curve : a complex post-shock structure



The physics of the column depends on :

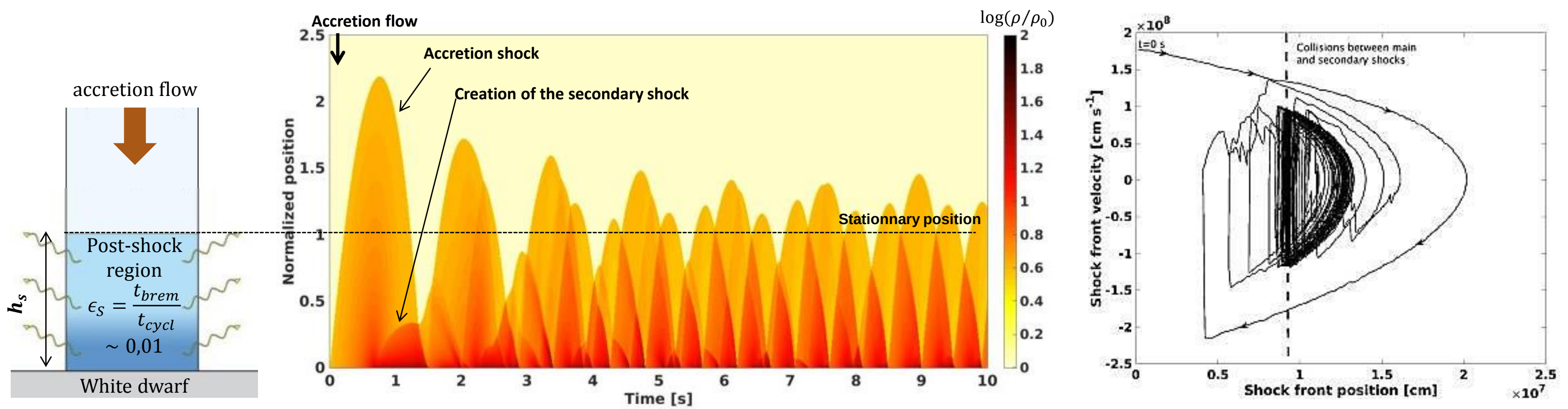
- the white dwarf mass M_{WD}
- the accretion rate $\dot{M}$,
- the magnetic field B_{WD}
- the section of the accretion column S

Radiative cooling :

- Bremsstrahlung cooling (exact) :
$$\Lambda_{brem}(\rho, P) = \Lambda_{0,brem}\ \rho^{1.5} P^{0.5}$$
- Cyclotron cooling (approximation)
$$\Lambda_{cycl}(\rho, P) = \Lambda_{0,cycl}(B_{WD}, S)\ \rho^{-2.35} P^{2.5}$$

ϵ_S parameter :
$$\epsilon_S = t_{brem}/t_{cycl} = \Lambda_{cycl}/\Lambda_{brem} \propto L_{opt}/L_X$$

1D time-dependent simulations with RAMSES code [Teyssier, A&A, 2002]



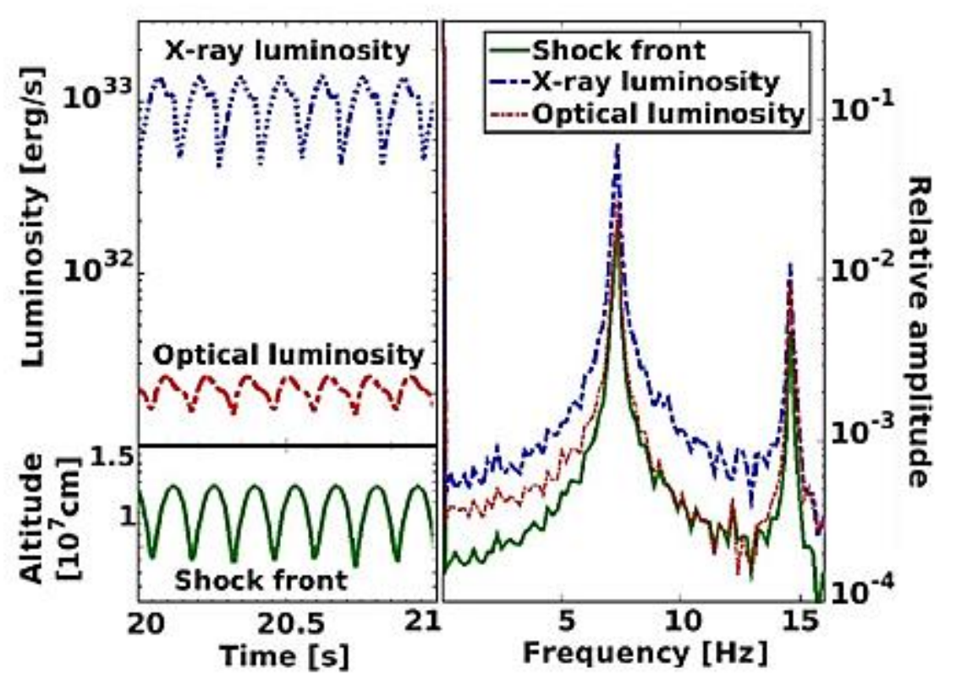
[Van Box Som *et al.*, MNRAS, 2018]

QPOs are due to the development of two radiative instabilities. The secondary shock is fundamental to sustain the accretion shock.

For radiative processes: $\Lambda \sim \rho^2 T^\alpha$
Development of the **cooling instability:**
for $\boldsymbol{\alpha < 1}$
[Chevalier & Imamura, ApJ, 1982]

Secondary shock instability is formed for:
for $\boldsymbol{\alpha < 3/2}$
[Falle, MNRAS, 1981]

The development of the radiative instabilities induces oscillations of the front shock and the luminosities. The X-ray [0.5-10 keV] and the optical luminosities are strongly coupled **[Van Box Som *et al.*, MNRAS, 2018].**

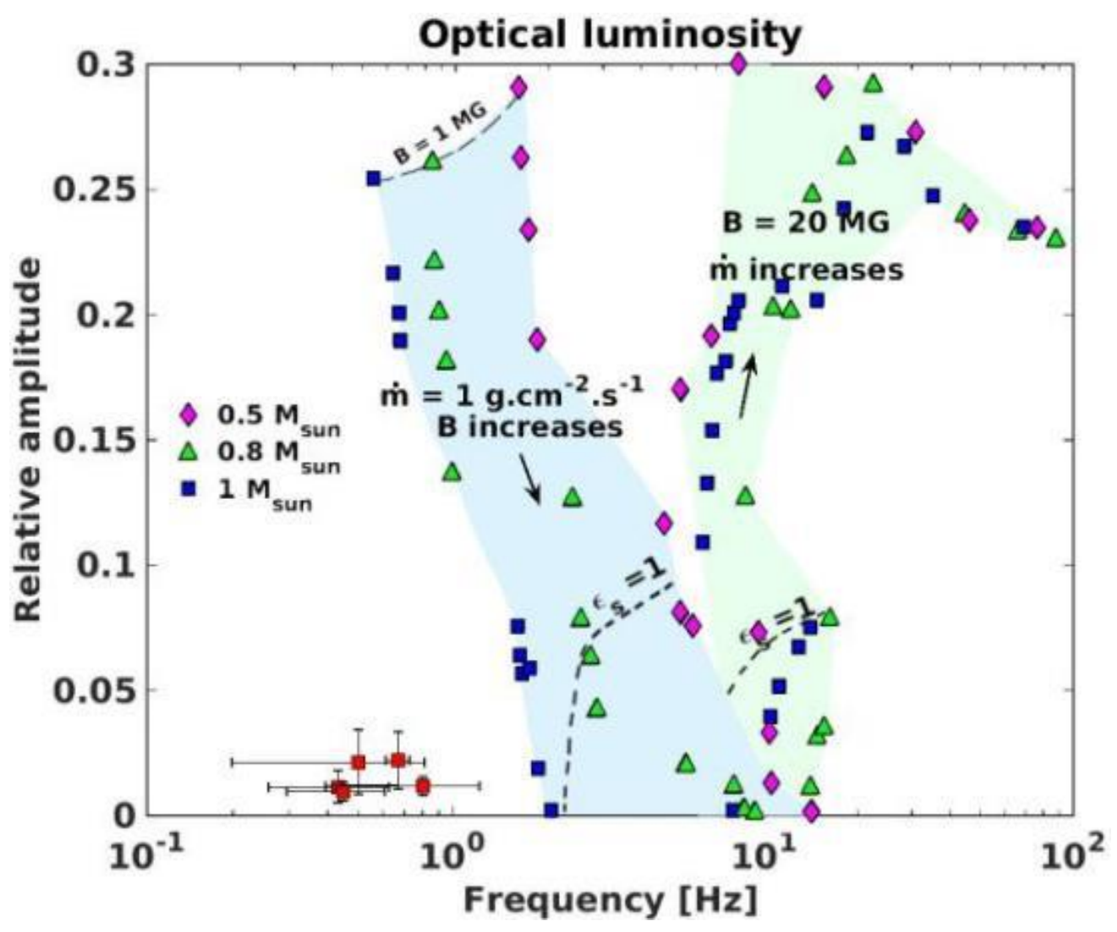


Evolution of the QPOs and application

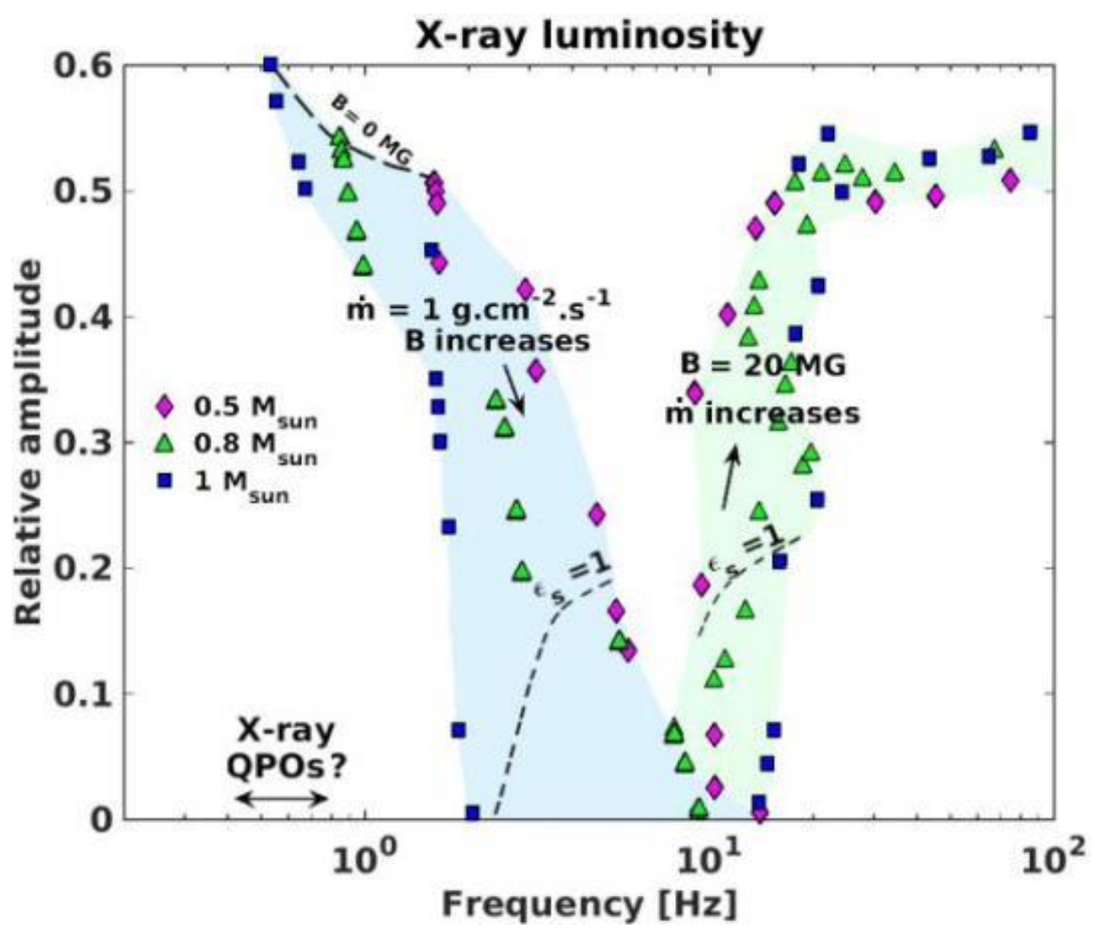
Parametric study of the QPOs

[Van Box Som *et al.*, MNRAS, 2018]
Large parameter space including all parameters of observed QPOs
~ 150 simulations

Models	M_{WD} ($M_\odot$)	B (MG)	$\dot{m}$ (g cm^{-2} s^{-1})	freq. (Hz)	L_X amp. (per cent)	L_{opt} amp. (per cent)
(a)	0.5	0–22	1	1.6–15	0.1–50	0.1–30
(b)	0.8	0–11	1	0.8–9	0.1–53	0.1–20
(c)	1	0–4	1	0.5–2	0.1–60	0.1–20
(d)	0.5	20	0.8–100	9–151	0.1–50	0.1–30
(e)	0.8	20	3–100	6–68	0.1–53	0.1–26
(f)	1	20	7–200	10–87	0.1–54	0.1–30



Optical observed QPOs (red points) are outside the domain covered by the large set of 1D simulations [blue (B variable) and green (mdot variable)].
[Van Box Som *et al.*, MNRAS, 2018]



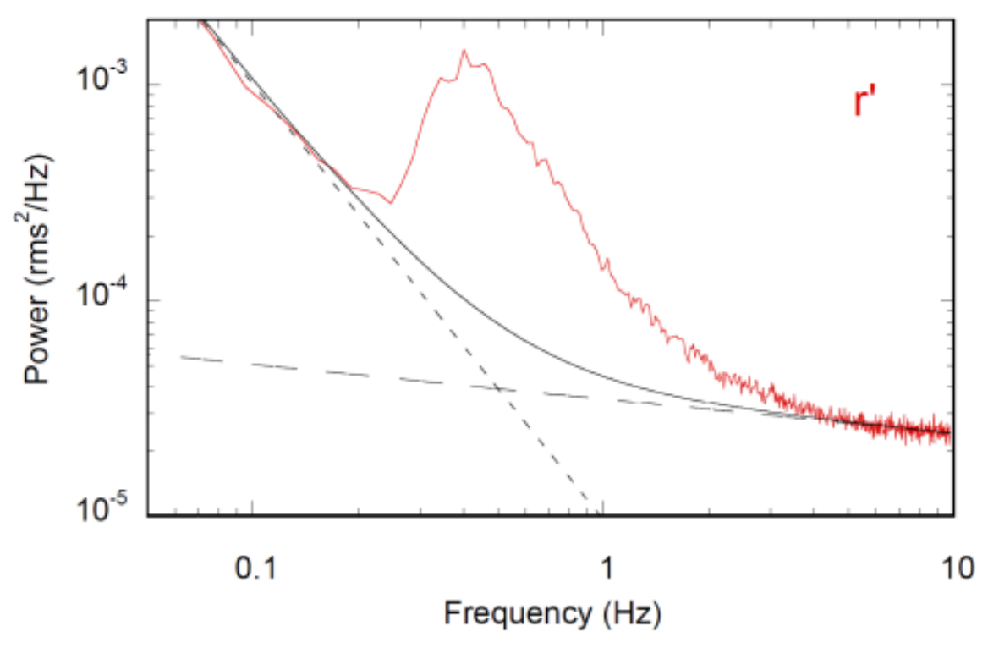
Large QPO amplitude (up to 60%) are predicted in the (1-100Hz) range. No X-ray QPOs, in the range 0.1-5Hz, were detected in XMM-Newton light curves of 24 polars. **[Bonnet-Bidaud *et al.*, A&A, 2015]**

⇒ Matching the observed QPOs with simulations is not possible
⇒ Major problem to interpret QPOs in terms of accretion shock oscillations model

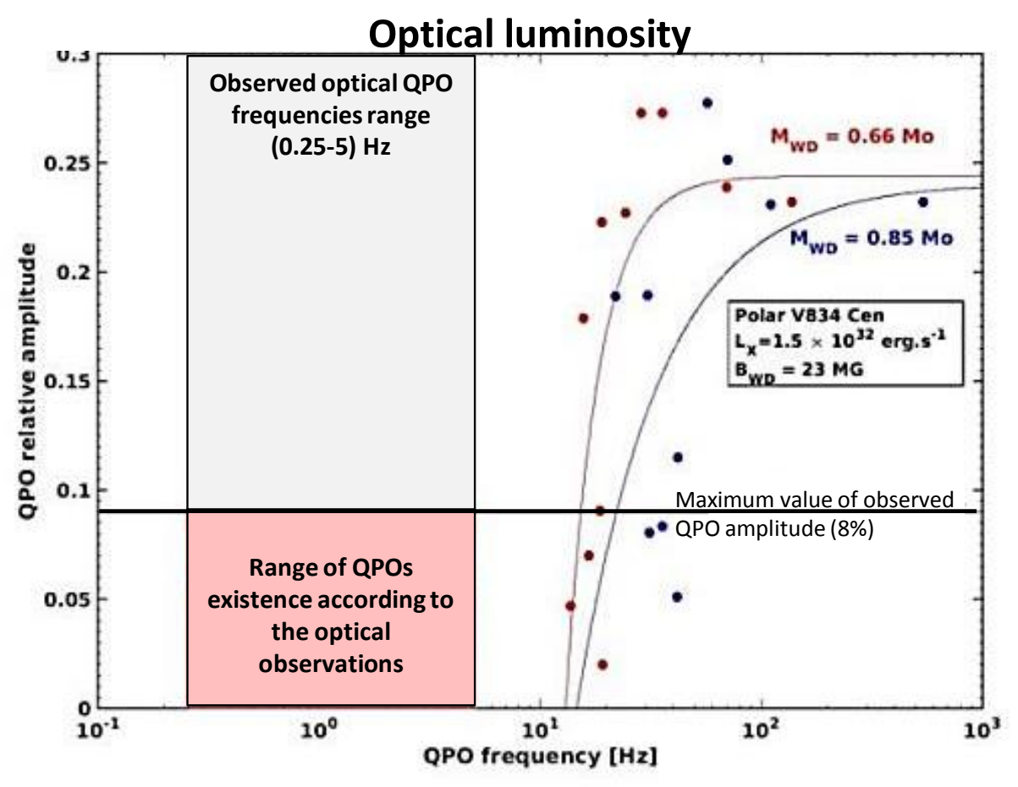
Application to the polar V834 Centauri

New observations of V834 Cen with VLT and Ultracam (0.05s resolution), using 3 filters, reveal strong QPOs (see fig. above) consistent with cyclotron emission. **[Mouchet *et al.*, A&A, 2017]**

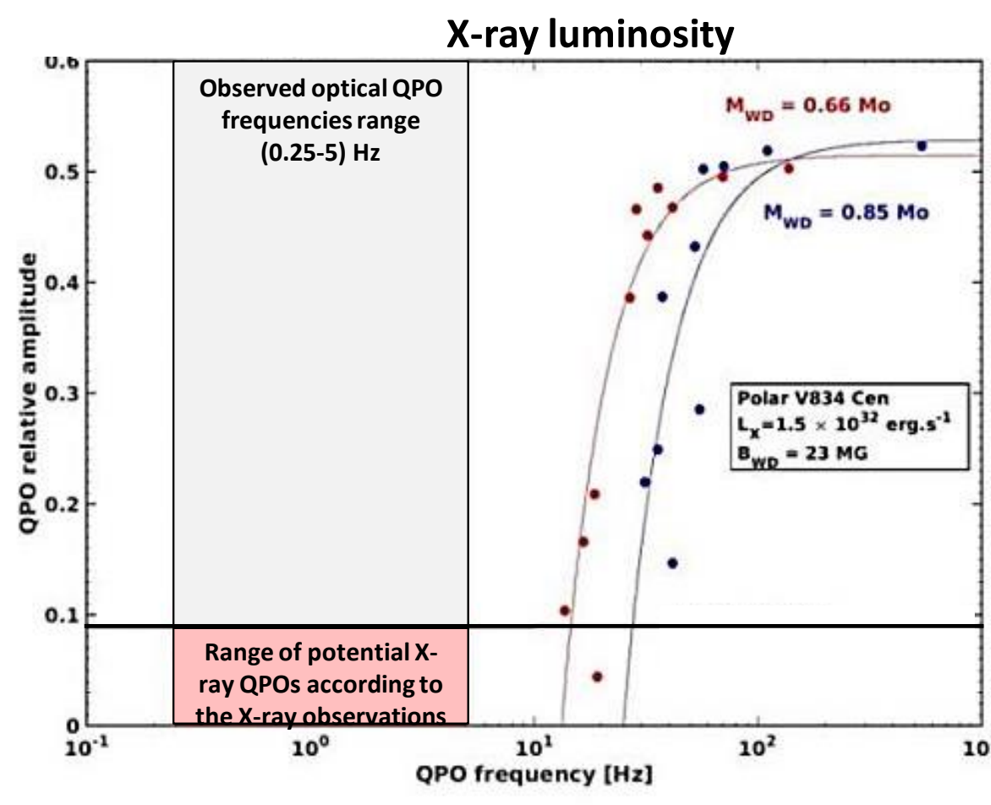
QPO frequency profile (figure to the right) : mean power density spectra of the light curve for the full 5.6h observation are shown in logarithmic scale in the range 0.039 - 9.76 Hz.



Comparison between the oscillations extracted from RAMSES simulations and astronomical QPOs
Numerical set-up for comparison: $B_{WD} = 23$ MG $-$ $L_X = 1.5 \times 10^{32}$ erg. s^{-1}
$M_{WD} = 0.66$ M$_\odot$ & 0.85 M$_\odot$ - Column cross-section evolution : $S = 10^{12} - 10^{17}$ cm^2



Observed amplitudes are reproduced for $\sim 4-5 \times 10^{14}$ cm^2. But the observed frequencies $0.25 - 5$ Hz are smaller than the simulated frequencies $14 - 19$ Hz. **[Mouchet *et al.*, A&A, 2017]**



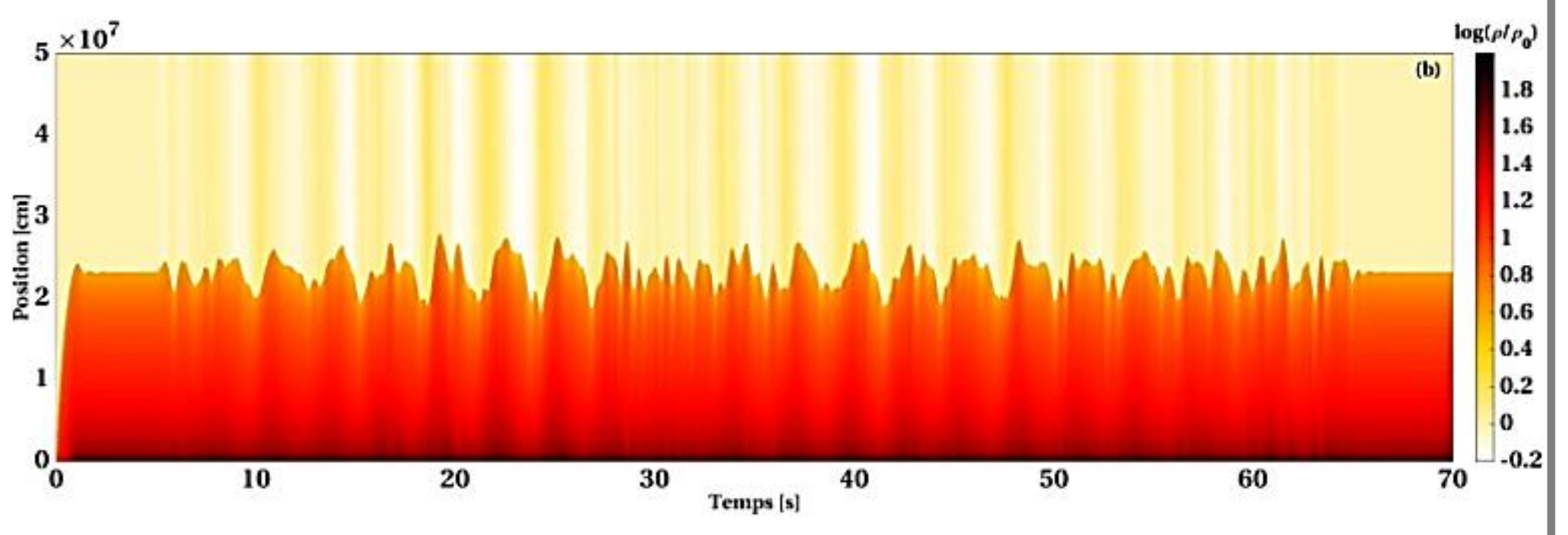
For V834 Cen, from the long (43 ks) XMM-Newton observation, a QPO amplitude upper limit of 9% was derived in the domain 0.1-5 Hz

For V834 Cen, QPOs are observed only in the optical light curve and not in X-ray one (XMM-Newton).
[Bonnet-Bidaud *et al.*, A&A, 2015]

Beyond the standard model : preliminary results

Time variation of the accretion flow in 1D simulations

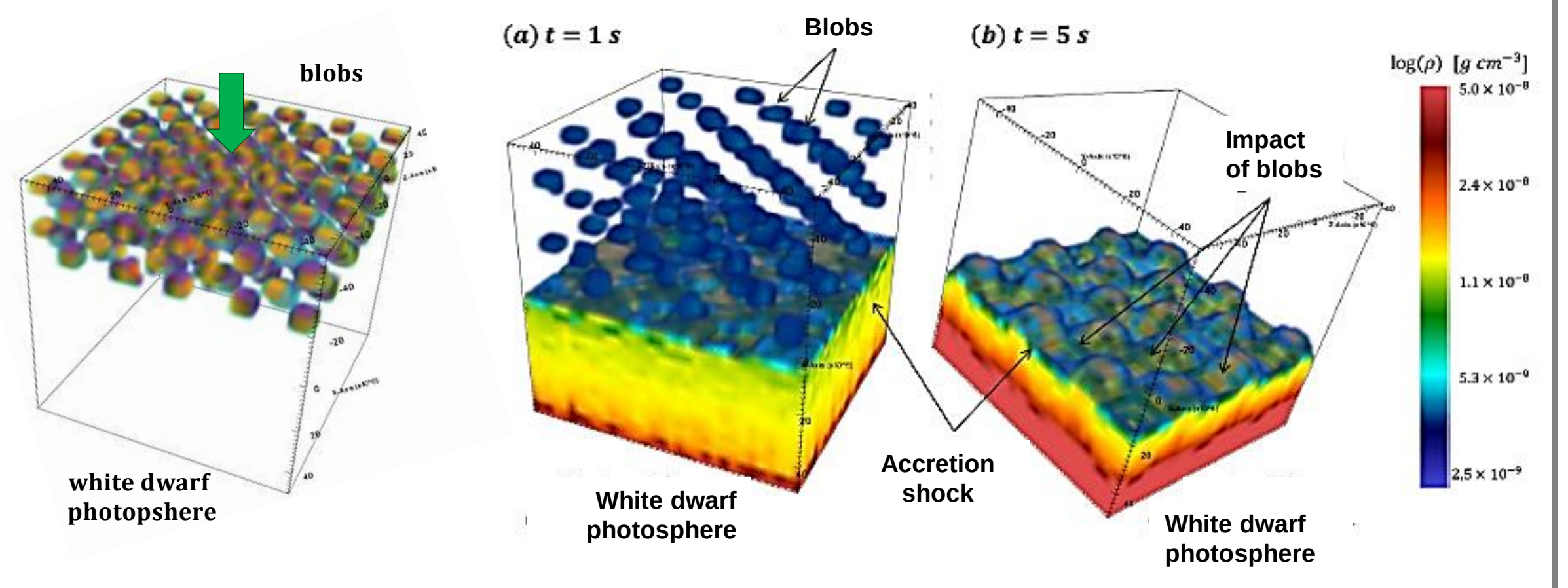
The accretion flow density is determined from the observed QPOs for the polar V834 Centauri. The accretion shock is directly modified by the accretion variation. When the column is stable according to the radiative instability ($\epsilon_S \gg 1$), the synthetic optical luminosity has the same parameters (frequency and amplitude) as the observed QPOs. However the X-ray luminosity is not coherent with the observations.



3D RAMSES MHD simulations with an inhomogeneous accretion model

Time and spatial modulation of the accretion flow
[Hameury *et al.*, MNRAS, 1986]
[Meintjes, MNRAS, 2004]

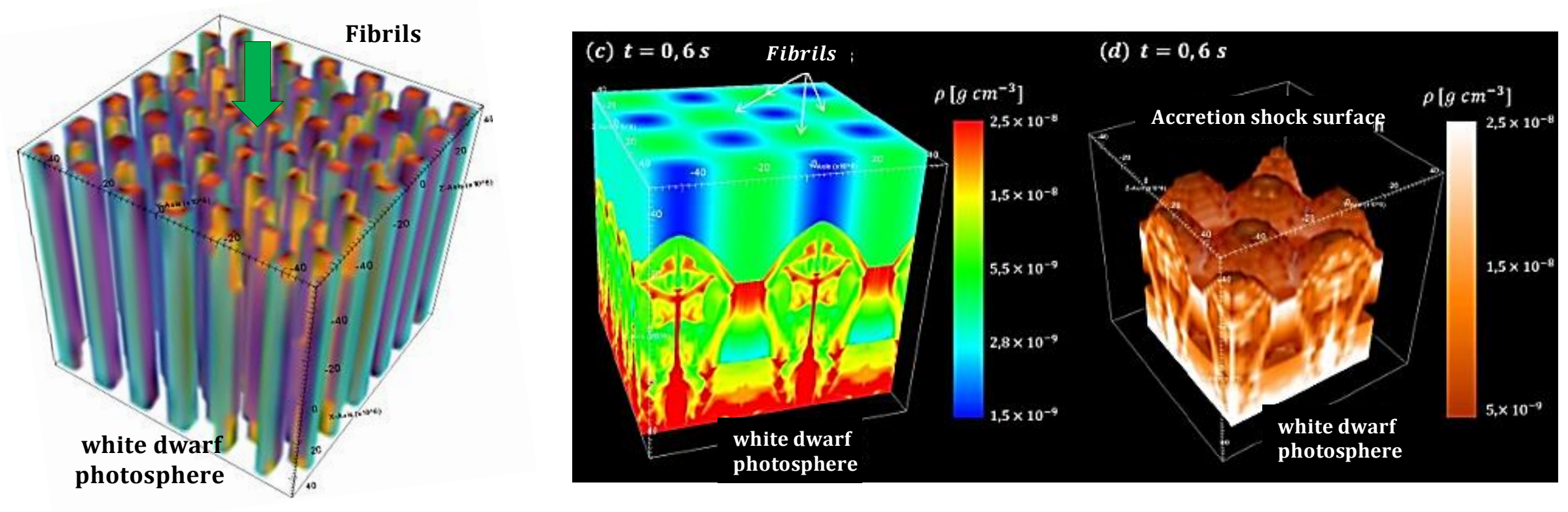
⇒This modulation does not change the global synthetic optical luminosity compared to the homogeneous accretion flow



3D RAMSES MHD simulations with a fibril accretion model

Fracturation of the accretion flow in fibrils, based on the King model
[Frank *et al.*, A&A, 1998]
[King, ApJ, 2000]

⇒The fibrils deeply modify the accretion structure (still in development)



Conclusion et perspectives

- **Modelling of the accretion column with RAMSES**: focus on the effects of high-energy radiative processes and the effects of the gravitational field on the post-shock region dynamics, in particular on the QPOs.
- A well-known polar **V834 Cen** is simulated and the simulations are compared with recent observational data **[Mouchet *et al.*, A&A, 2017].**
- **Large study of the QPO characteristic as a function of the polar parameters : strong inconsistency** between the frequencies of the oscillations extracted from the simulations and the frequencies observed in the optical light curve: questions about our understanding of the accretion processes **[Van Box Som *et al.*, MNRAS, 2018]**. See however **[Bera *et al.*, MNRAS, 2018]** for different prescriptions of the cyclotron luminosity, boundary conditions and initial set-up.
- Study the dynamics of the accretion column in a **new way** in order to explore the models :
  - **Inhomogeneous accretion density :** achieve the observed QPO frequency but questions about the origin of the oscillations in the accretion flow. New observational constraints of the accretion flow are necessary.
  - **Multidimensional simulations with MHD :** Preliminary results give similar behavior for a modulated accretion as for an homogeneous flow while a fragmented accretion of dense fibrils produces transversal motions which destructure the dynamics and geometry of the base of the column (still in development).
  - **Laboratory astrophysics** : Based on the similarity properties of this high-energy environment **[Falize *et al.*, ApJ, 2011],** millimetre-sized models of accretion columns can be produced with powerful lasers and can give us new opportunities to study the radiative accretion processes in laboratory **[Falize *et al.*, HEDP, 2012], [Busschaert *et al.*, New Phys., 2013], [Cross *et al.*, Nature Com., 2016] [Van Box Som *et al.*, HPLSE, 2018].**