## Introduction

In **colliding-wind binary (CWB) systems**, the supersonic winds of two stars collide, forming a **wind-collision region (WCR)** delimited by two shocks. Such systems are expected to produce a nonthermal distribution of energetic particles via **diffusive shock acceleration (DSA)** at the collisionless shocks. Interacting with the environment, relativistic electrons and/or protons are in turn expected to produce $\gamma$-rays. Test-particle Monte Carlo simulations suggest that the energy put into nonthermal protons is non-negligible. Their backreaction on the shock itself therefore has to be taken into account. We perform **Monte Carlo simulations** of particle acceleration, obtaining the background from **MHD simulations** of an archetypal CWB system. We further take into account the **feedback** of the accelerated protons **on the local shock structure**, where the particles are injected. Global changes to the system are neglected here. Our approach allows the injection efficiency of DSA in the considered system be obtained from the simulations in a locally self-consistent way.

## MHD simulations of colliding wind binaries

Being interested in studying particle acceleration in CWBs, we obtain the initial background from MHD simulations of such systems.

- Used code: CRONOS [1,2]
- The influence of the stellar magnetic field on wind acceleration is considered
- The magnetic field and the plasma (fluid) evolve solving the MHD equations
- The wind collision region forms when the two winds collide

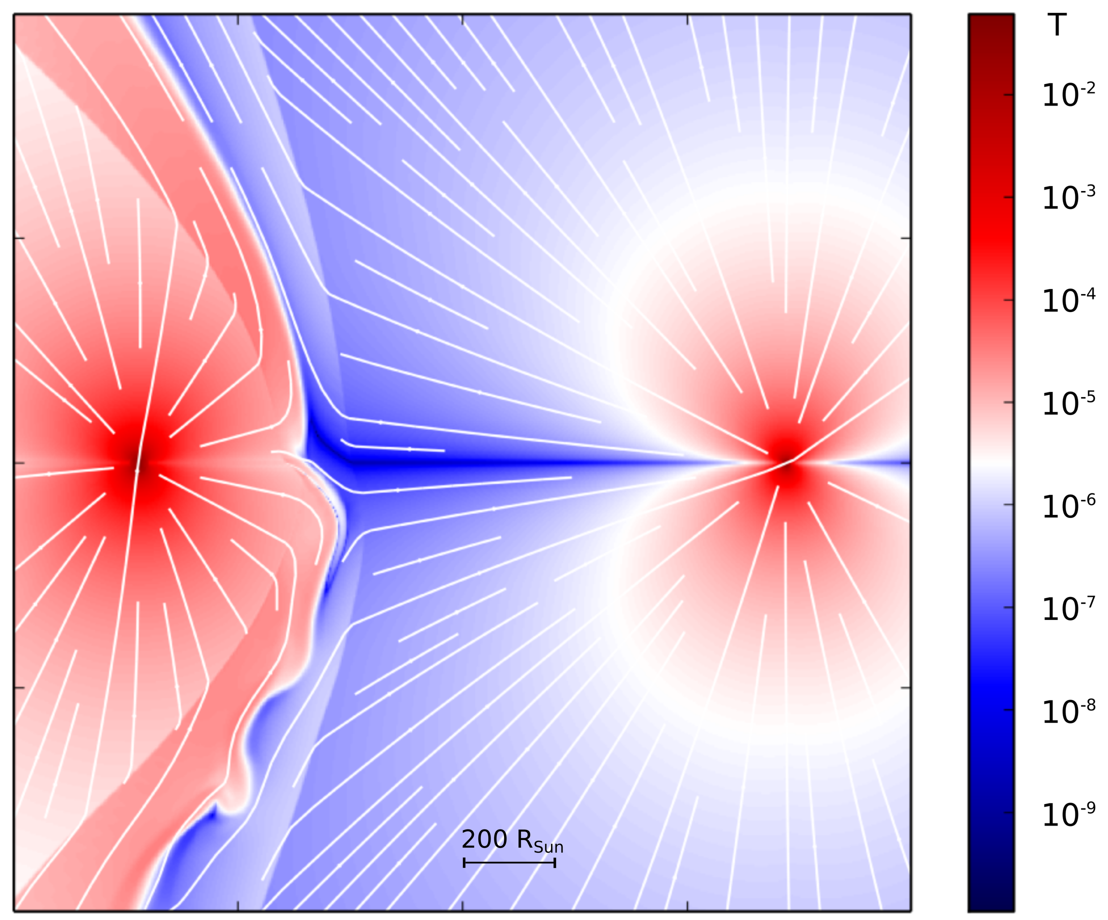


Fig. 6: Intensity of magnetic field at the $y$-$z$ plane.

## Monte Carlo simulations of particle acceleration

Monte Carlo simulations allow to simulate single particles representing the protons of the winds. These are scattered by the background and can be accelerated via Fermi acceleration.

- Full trajectory calculation
- Large angle scattering
- Mean time between scatterings: $t_c = \eta r_g / v$
  - $r_g$ gyroradius
  - $v$ particle speed
  - $\eta = 1$ proportionality factor (highly turbulent medium) [3]
- Particles injected close to the selected shock
- Spectra recorded at the corresponding shock front

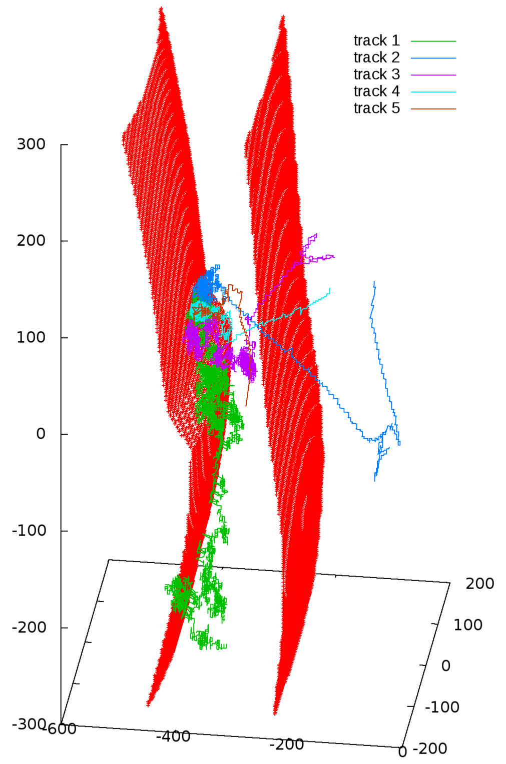

Fig. 7: Particles moving and being scattered in the simulation box.

## Semi-analytical method for nonlinear shock modification

The semi-analytical approach of Amato and Blasi [4] computes the shock modification caused by the accelerated protons.

- Conservation of momentum flux
- The pressure of accelerated protons modifies the flow velocity of the incoming plasma
- Formation of a subshock and a shock precursor
- Two compression ratios: $r_{Sub}$ and $r_{Tot}$, smaller and higher than the unmodified compression ratio, respectively

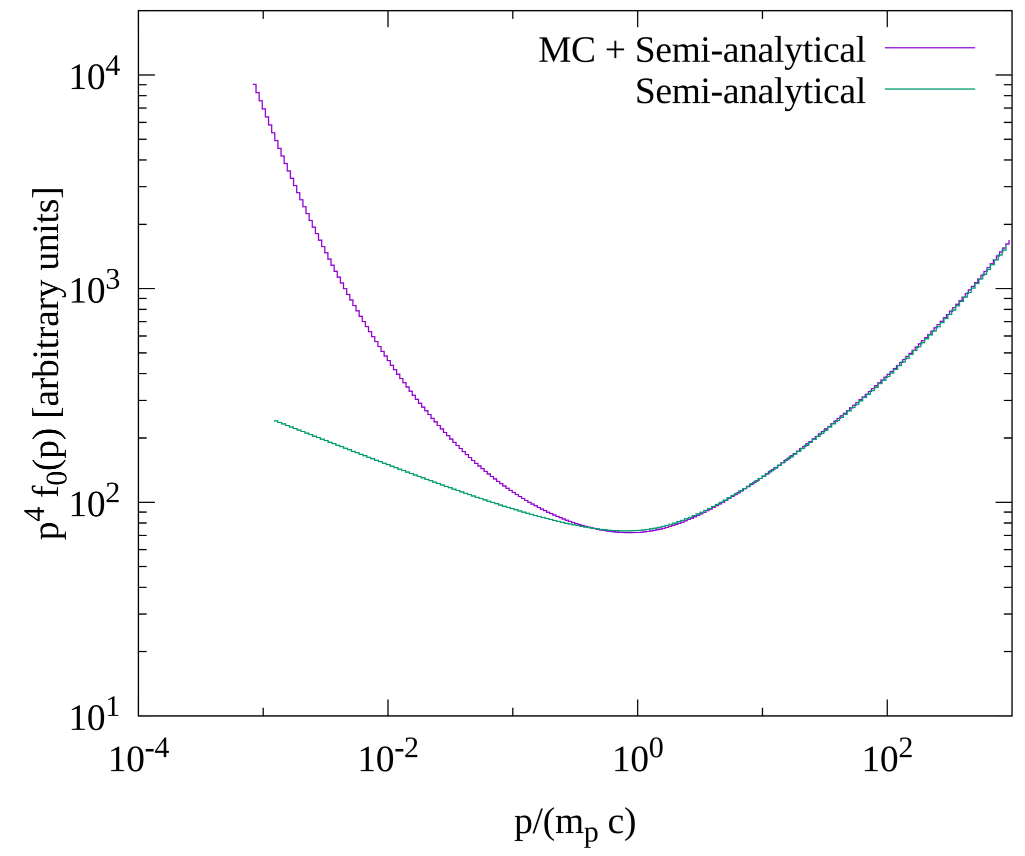


Fig. 8: Example of nonthermal particle distribution of a modified shock.

emanuele.grimaldo@uibk.ac.at

## System

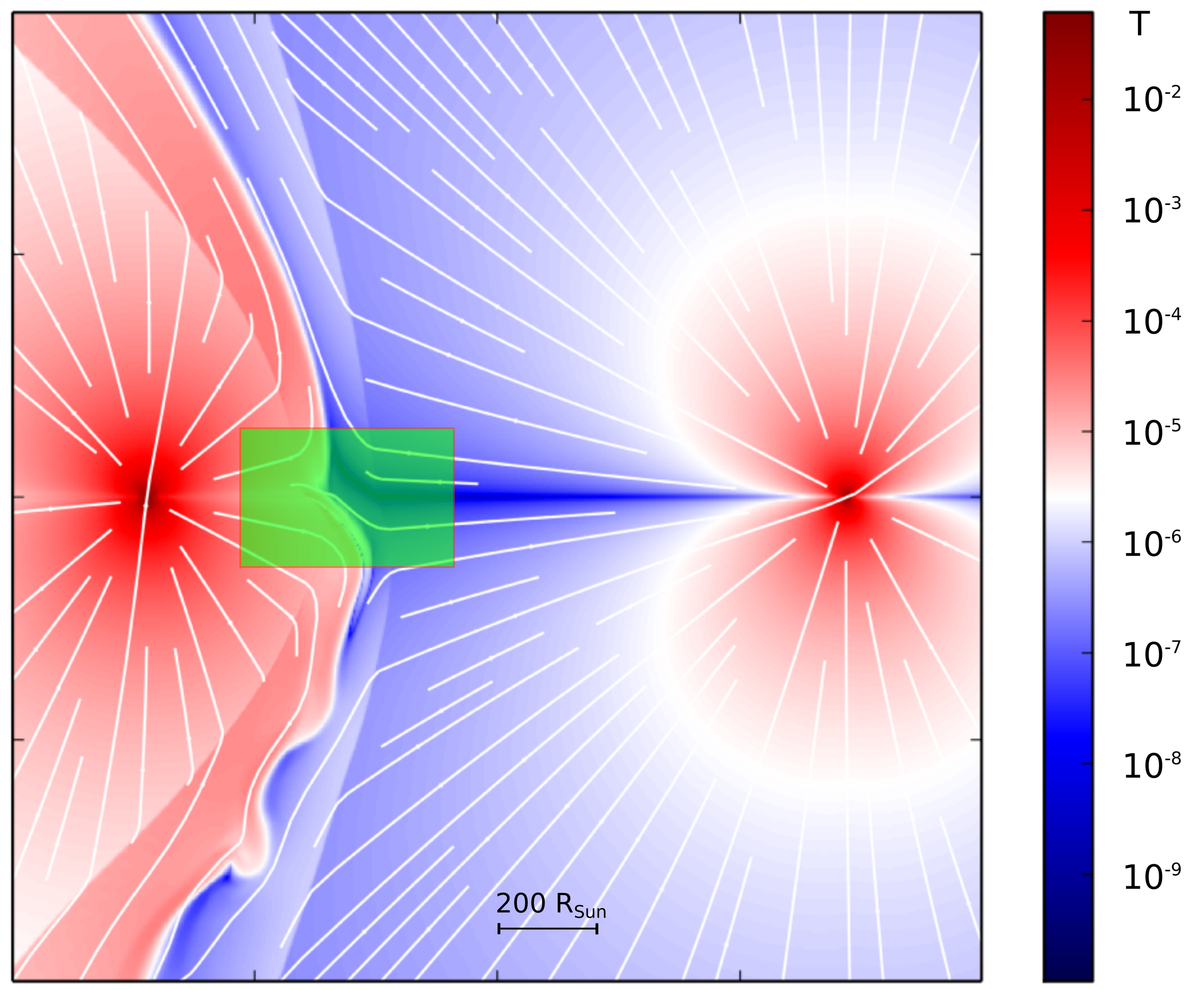


Fig. 7: Intensity of magnetic field at the $y$-$z$ plane. Highlighted region: simulation box for Monte Carlo shock acceleration simulations.

- **OB star** (left) and **WR star** (right)
- Stellar separation: $R = 1440 R_{\odot}$
- **Parameters of the system** [5]:

| Star | $M_*$ [$M_\odot$] | $R_*$ [$R_\odot$] | $T_*$ [K] | $L_*$ [$L_\odot$] | $\dot{M}$ [$M_\odot$ yr$^{-1}$] | $v_\infty$ [km s$^{-1}$] | $B_*$ [G] |
|---|---|---|---|---|---|---|---|
| OB | 30 | 20 | 23000 | $10^5$ | $10^{-6}$ | 4000 | 100 |
| WR | 30 | 10 | 40000 | $2.3 \times 10^5$ | $10^{-5}$ | 4000 | 100 |

- $M_*$ stellar mass
- $R_*$ stellar radius
- $T_*$ effective temperature
- $L_*$ luminosity
- $\dot{M}$ mass loss rate
- $v_\infty$ terminal velocity of wind
- $B_*$ surface magnetic field

## Results

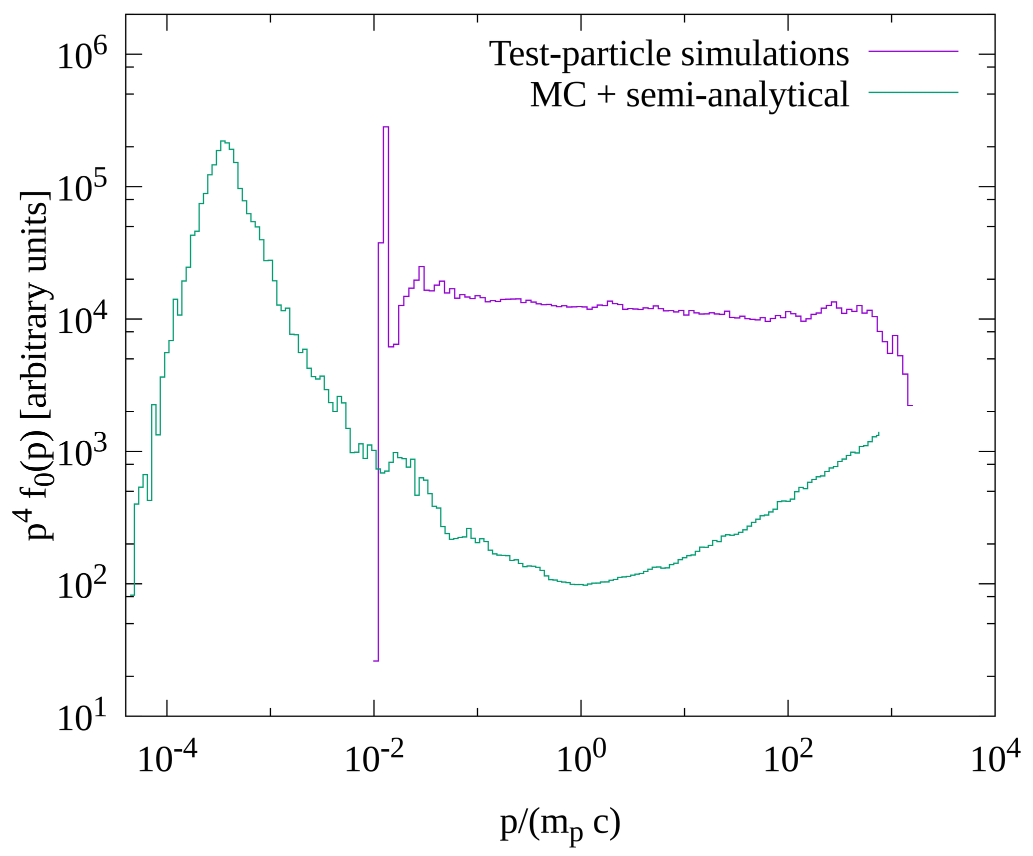


Fig. 8: Spectra of accelerated protons with the test-particle approach and the nonlinear approach.

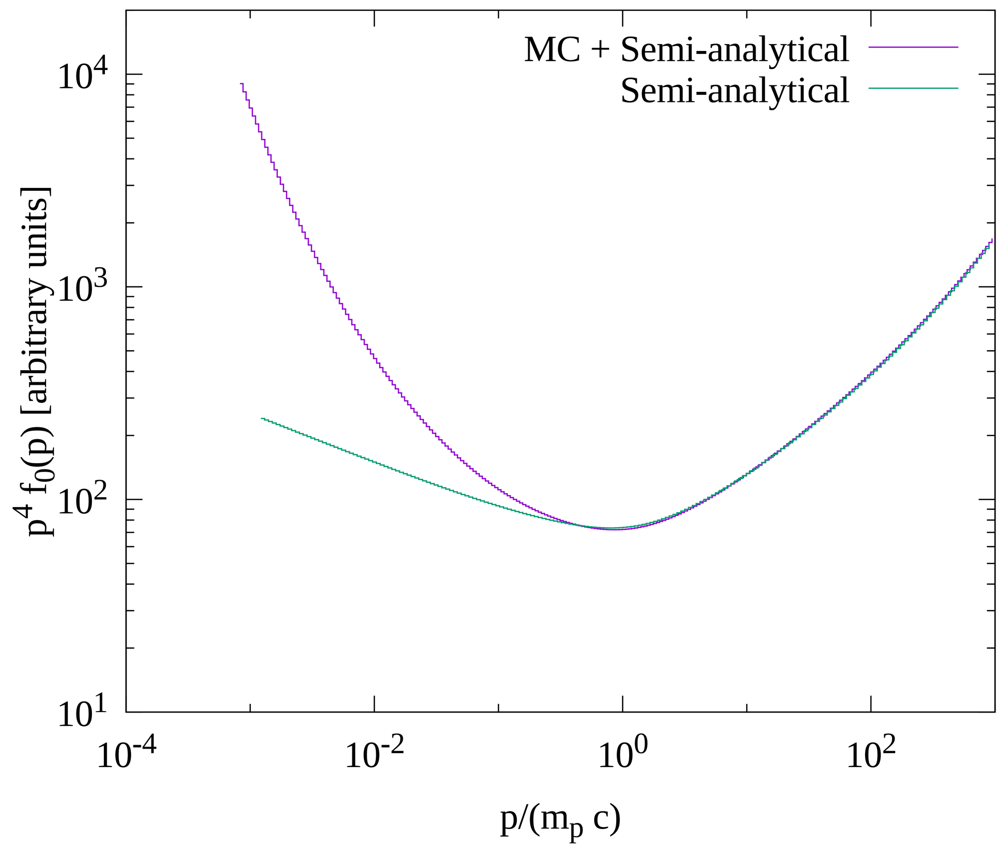


Fig. 9: Nonthermal tail of the particle distribution obtained with the purely semi-analytical method and the semi-analytical combined with MC.

| Method | Subshock compression ratio $r_{Sub}$ | Total compression ratio $r_{Tot}$ | Fraction of thermal protons injected $\eta_0$ |
|---|---|---|---|
| MC + SA | 2.1 | 94 | $\approx 7 \cdot 10^{-3}$ |
| SA | 3.4 | 80 | $\approx 4 \cdot 10^{-4}$ |

## Discussion

Comparison of purely semi-analytical and Monte Carlo + semi-analytical methods:

- Purely semi-analytical method: $\eta_0$ set "by hand". Only particle with momentum greater than an certain multiple of the thermal momentum of the downstream plasma can take part in DSA.
- Monte Carlo method: $\eta_0$ not prescribed. Thickness of the shock considered infinitesimal, scattering law needed.
- Present work: maximal momentum is set at $p_{max} = 10^3\ m_p c$.
- Despite very different fractions of injected particles at low momenta, the accelerated protons modify the shock in such a way that the relativistic part of the nonthermal tails of the proton distribution coincide. This happens because most of the pressure of accelerated particles, which modifies the shock structure, is exerted in the relativistic regime.

Comparison of test-particle and nonlinear methods:

- With test-particle Monte Carlo simulations, the energy in the accelerated protons is unrealistically high (see also [6]).
- The Monte Carlo method combined with the semi-analytical one yields a solution which conserves energy and momentum fluxes.
- Both normalization and spectral shape are clearly different in the two cases, with possible observable consequences.

emanuele.grimaldo@uibk.ac.at

## Conclusions and Outlook

We presented a method for simulating particle acceleration at the shock fronts of a colliding wind binary system. This combines three different simulations, taking advantage of their strengths, in order to obtain proton spectral energy distributions as realistic as possible. We show that the combining Monte Carlo simulations and the semi-analytical model with the same maximal energy yields similar results for the high-energy part of the spectra. This despite a difference in the fraction of thermal particles injected in the acceleration process between the Monte Carlo method (where no prescription is needed) and the semi-analytical prescription.

The comparison of test-particle and nonlinear simulations applied to an archetypal CWB system highlights appreciable differences in both normalization and spectral shape of the nonthermal tail of the proton distribution. Our simulations suggest that the flow velocity of the winds can be modified by the accelerated protons. A caveat is therefore necessary, since the spectra obtained here cannot consider the global changes of the wind structure.

Future work will test models of real systems, aiming at obtaining predictions for $\gamma$-ray fluxes.

## References


- [1] R. Kissmann et al., *Local turbulence simulations for the multiphase ISM*, *MNRAS* **391** (2008) 1577-1588
- [2] R. Kissmann et al., *Colliding-wind Binaries with strong magnetic fields*, *ApJ* **831** (2016) 121
- [3] D. C. Ellison, M. G. Baring and F. C. Jones, *Acceleration rates and injection efficiencies in oblique shocks*, *ApJ* **453** (1995) 873
- [4] E. Amato, P. Blasi, *A general solution to non-linear particle acceleration at non-relativistic shock waves*, *MNRAS* **364** (2005) L76-L80
- [5] K. Reitberger et al., *High-energy particle transport in three-dimensional hydrodynamic models of colliding-wind binaries*, *ApJ* **782** (2014) 96
- [6] E. Grimaldo, A. Reimer and R. Kissmann, *Combined magnetohydrodynamic-Monte Carlo simulations of proton acceleration in colliding wind binaries*, *AIP Conf. Proc.* **1792** (2017) 040031
- [7] M. G. Baring, D. C. Ellison and F. C. Jones, *The injection and acceleration of particles in oblique shocks-A unified Monte Carlo description*, *ApJ* **409** (1993) 327-332


## Acknowledgements


- E. G. and A. R. acknowledge financial support from the Austrian Science Fund (FWF), project P 24926-N27.
- E. G. would like to thank Elena Amato for fruitful discussions, and Felix Niederwanger for his constructive contributions.