The Strong Impact of Cosmic Rays on the ISM Structure and Galactic Outflows

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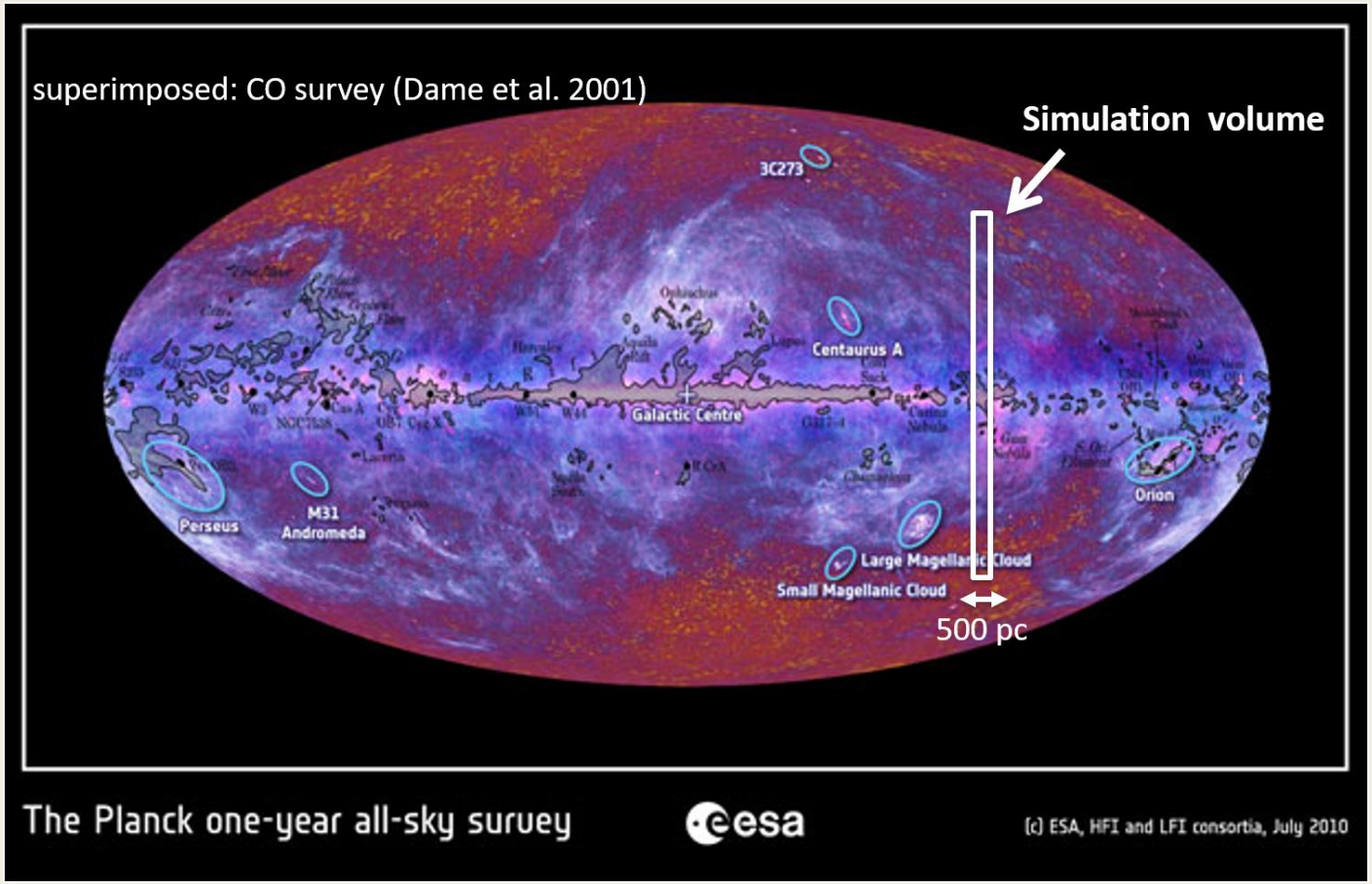
Quang Nguyen Luong & F. Motte, HOBYS Key Program consortium, Herschel SPIRE/PACS/ESA consortia. XMM-Newton: ESA/XMM-Newton



- MHD AMR code FLASH4 (Fryxell+00)
- Stratified disk in elongated box
- Tree self-gravity (Wünsch+ in prep.)
- Column density dependent self-shielding and optical depth calculated with *TreeCol* (Clark+ 12, Wünsch & Walch in prep.)
- Time-dependent chemical network with atomic, molecular and metal cooling and heating (Nelson & Langer 97, Glover+ 12)
- Solar neighborhood conditions: $\Sigma_{\mathrm{Gas}} = 10\ \mathrm{M}_{\odot}\ \mathrm{pc}^{-2}$, $Z_{\odot}$

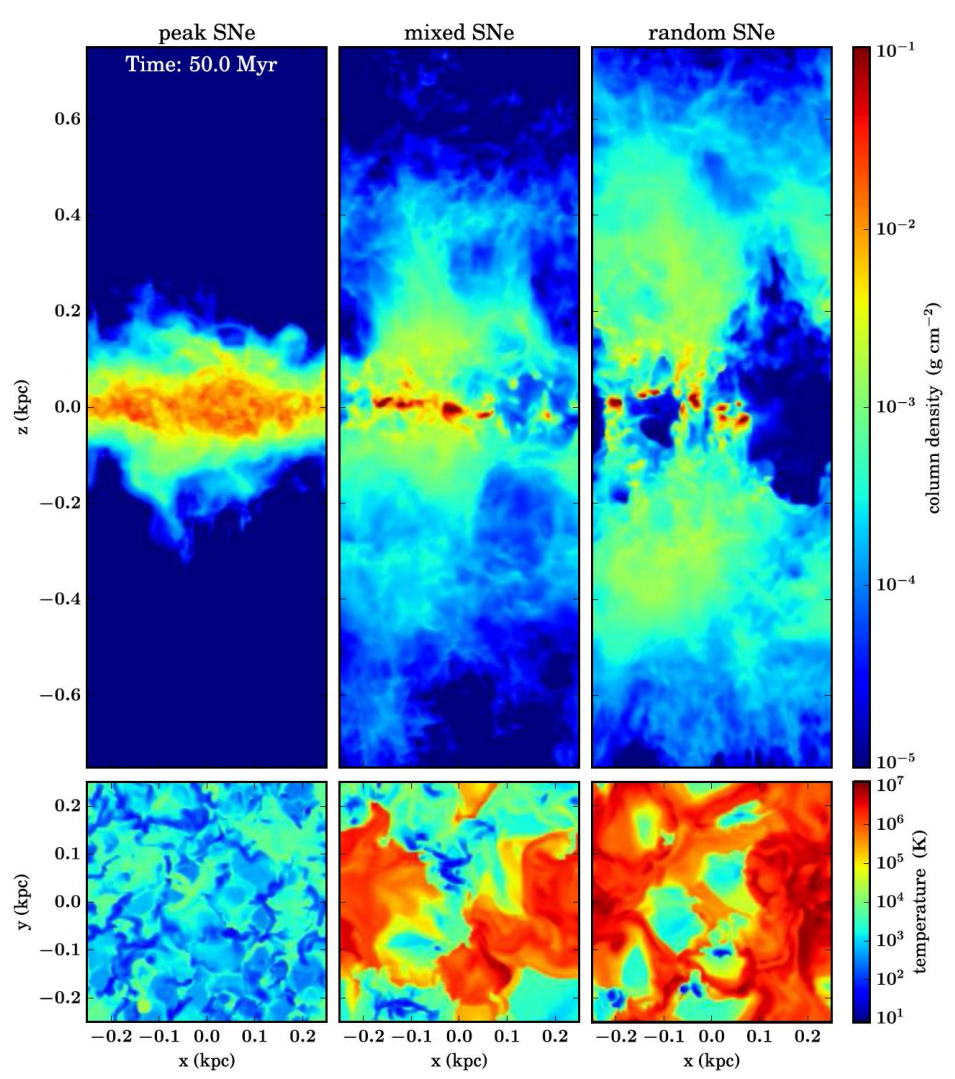
SILCC – Project (https://hera.ph1.uni-koeln.de/~silcc/)
(Walch+ 15, Girichidis+ 16, Gatto+ 16, Peters+ 16, Girichidis+ 18)

See also: Kim & Ostriker 17 (TIGRESS) with ATHENA, Butler+ 17 with RAMSES

The thermal and non-thermal ISM

- **Supernova “feedback”**
  - *Responsible for the two- or three-phase ISM (Walch+ 15, Girichidis+ 16)*
- **Stellar wind “feedback”**
  - *Creates hot wind bubbles and reduces star formation (Gatto+ 16)*
- **Radiation “feedback”**
  - *Changes chemical composition and volume filling factors (Peters+ 16)*
- **Magnetic fields “feedback”**
  - *Delays gravitational collapse and retards star formation (Pardi+ 17, Girichidis+ 18)*
- **Cosmic rays “feedback”**
  - *Drives smooth outflows due to additional pressure gradient (Girichidis+ 16, Girichidis+ 18)*

SN environment from great importance

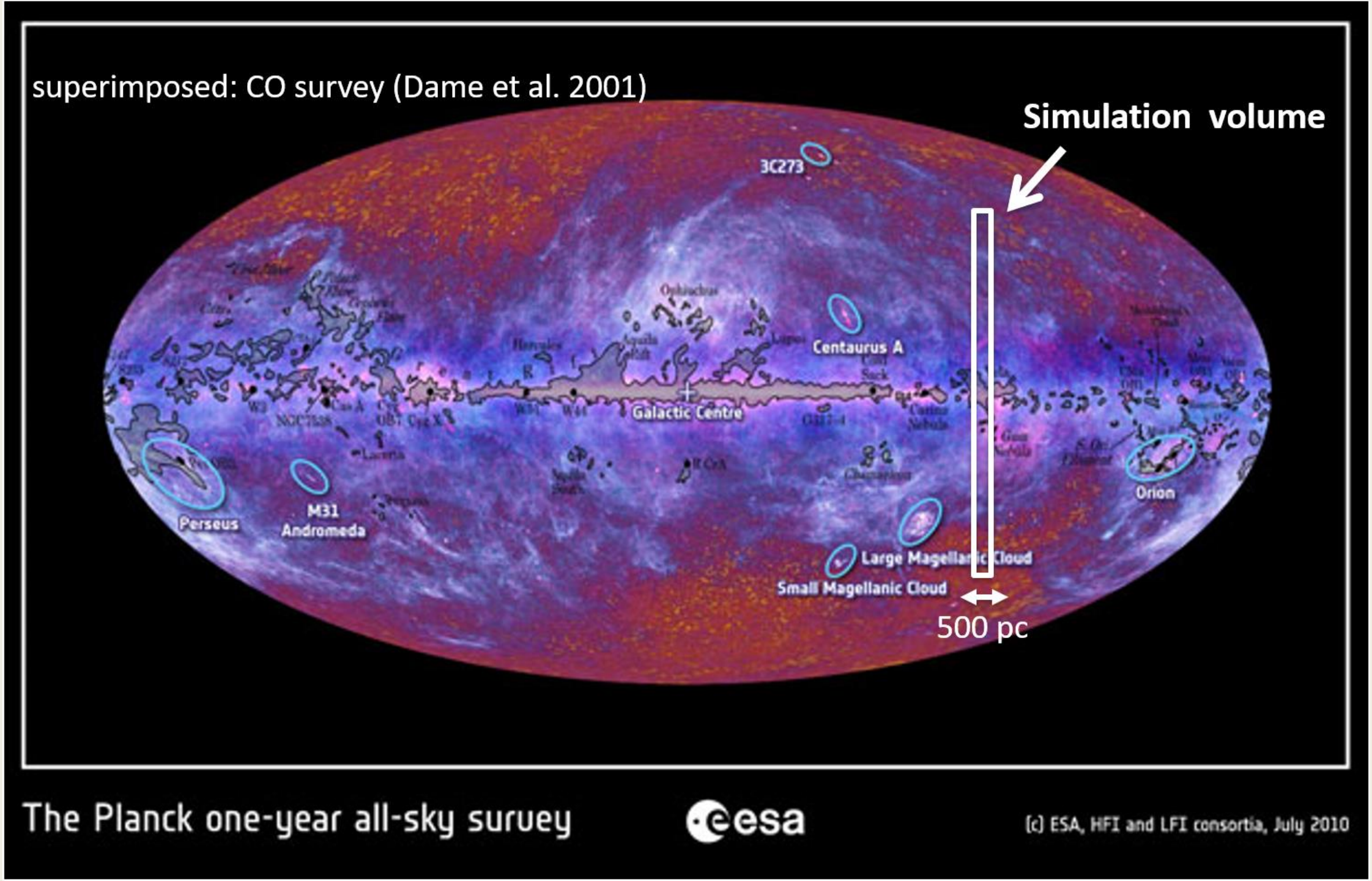


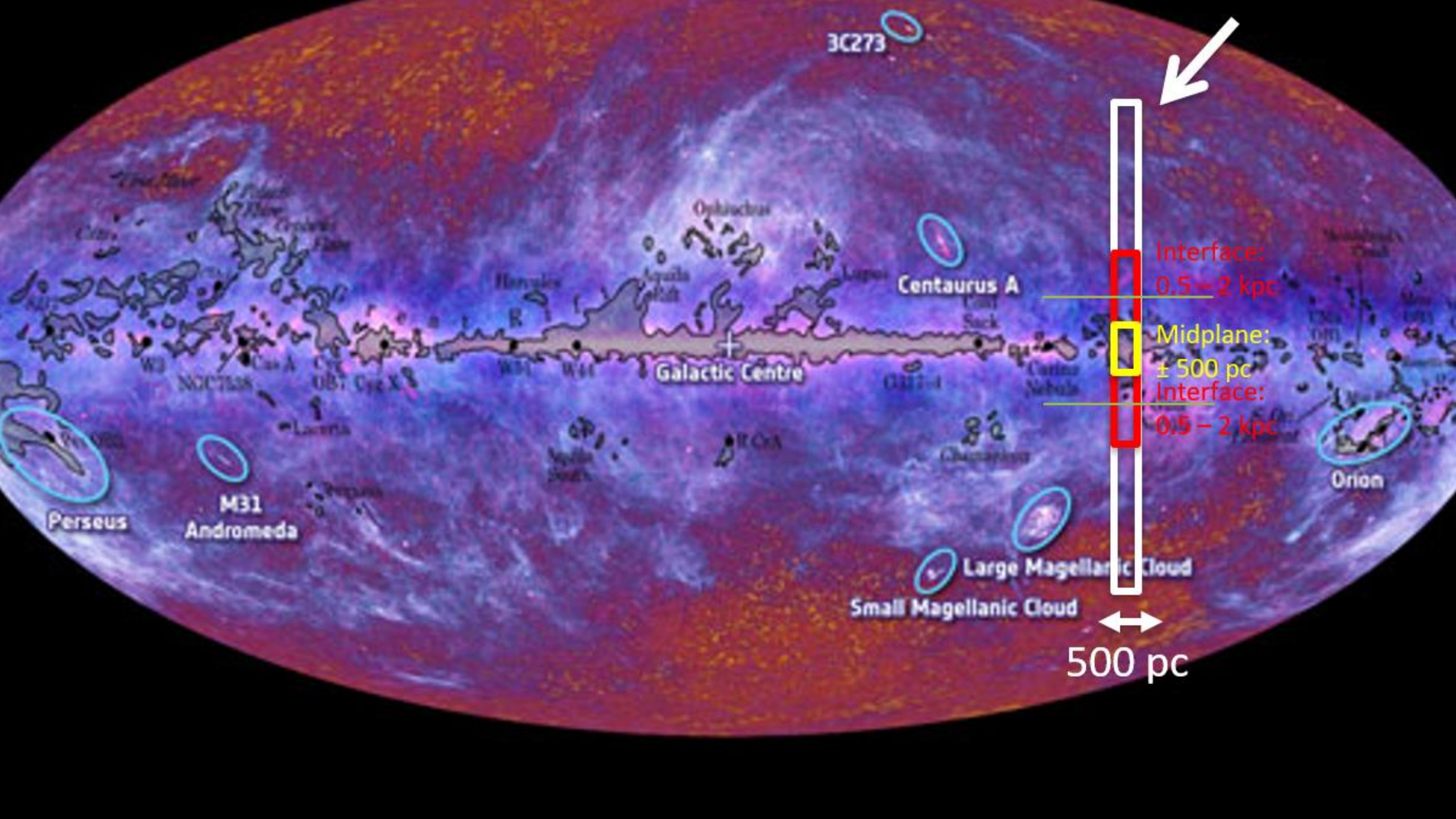
Naab & Ostriker 17

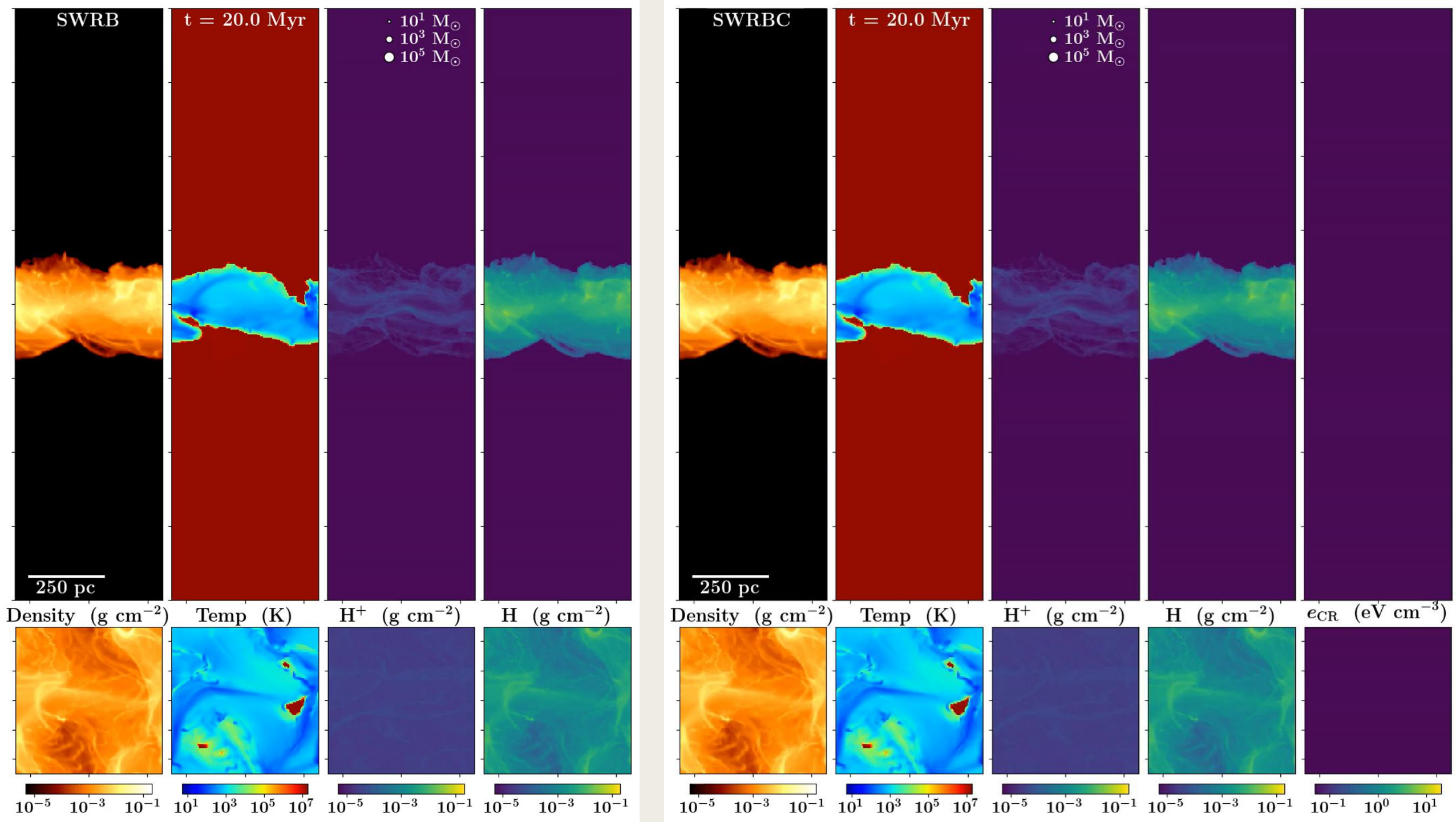
- Ambient SN density determines impact of SN events at fixed rates
- Densities are affected by supernovae, radiation, stellar winds, clustering (and resolution) (Kim & Ostriker 11, Hennebelle & Iffrig 14, Walch+ 15, Girichidis+ 16, Naab & Ostriker 17, Gatto+ 16, Li+ 16)
- <u>Qualitative changes with every process and highly non-linear interactions</u>

Simulations with major physical processes of the thermal and non-thermal ISM

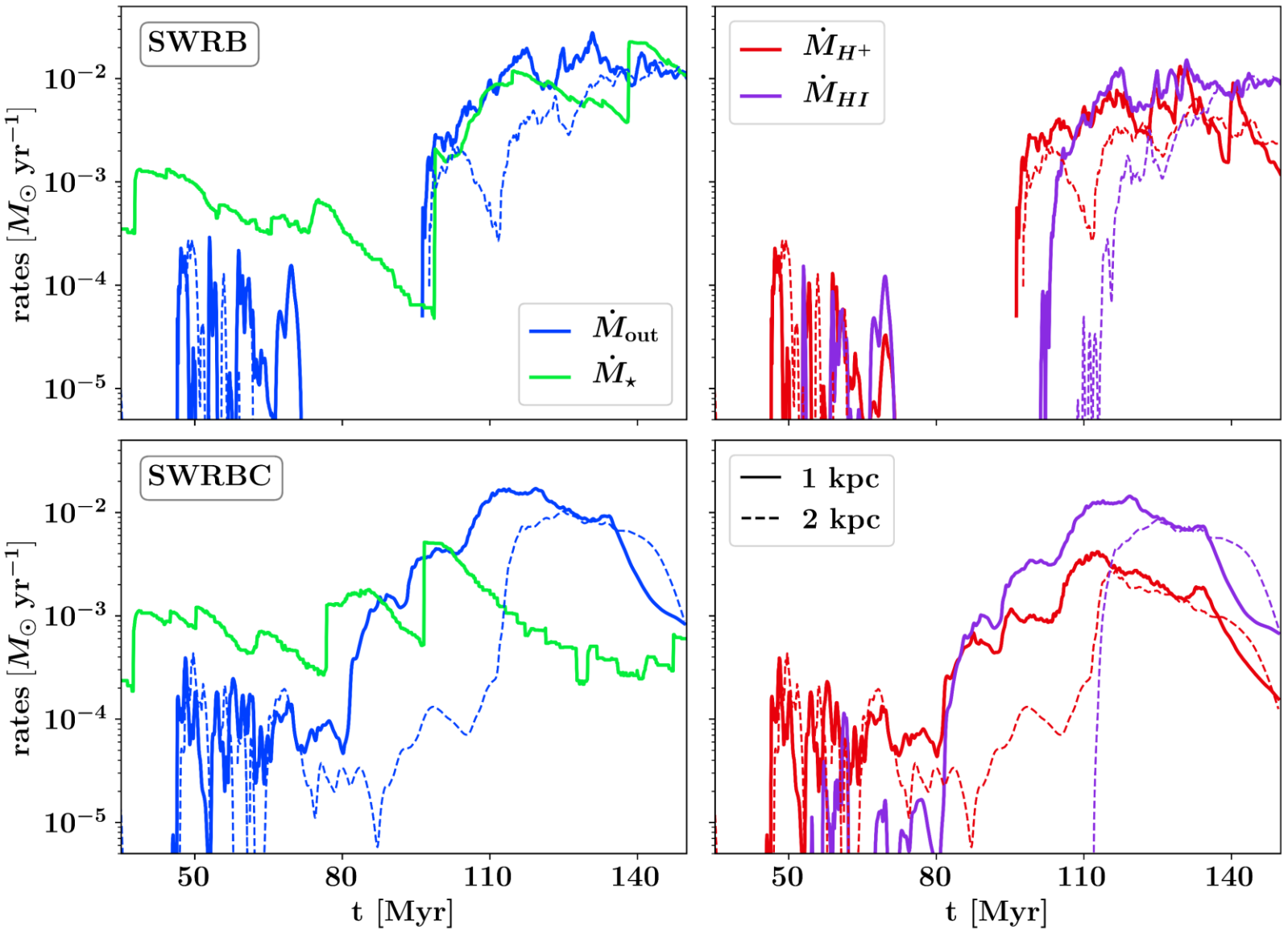
- Stellar feedback via sink particles with subgrid model for stellar clusters/massive stars
  - *Evolution of massive stars (9 - 120 $M_\odot$) via Geneva stellar evolution track (Ekström+ 12)*
- Stellar winds (Puls+ 08) with momentum injection (Gatto+ 16, Haid+ 18)
- Ionizing radiation ($h\nu \geq 13.6$ eV)
  - *Radiative transfer with TreeRay, backward raytracing (Walch & Wünsch in prep.)*
- Supernovae with thermal energy injection (Gatto+ 15)
  - *Terminal momentum injection if Sedov-Taylor phase is not resolved*
- Magnetic fields (Girichidis+ 18) with anisotropic cosmic ray transport
  - *CRs as a relativistic fluid, additional pressure term, anisotropic diffusion and advection, injected with 10% SN energy (Girichidis+ 18)*


superimposed: CO survey (Dame et al. 2001)
Simulation volume
3C273
Centaurus A
Galactic Centre
Perseus
M31
Andromeda
Orion
Large Magellanic Cloud
Small Magellanic Cloud
500 pc
The Planck one-year all-sky survey
esa
(c) ESA, HFI and LFI consortia, July 2010


3C273
Centaurus A
Galactic Centre
Perseus
M31
Andromeda
Orion
Large Magellanic Cloud
Small Magellanic Cloud
Interface:
0.5 – 2 kpc
Midplane:
± 500 pc
Interface:
0.5 – 2 kpc
500 pc

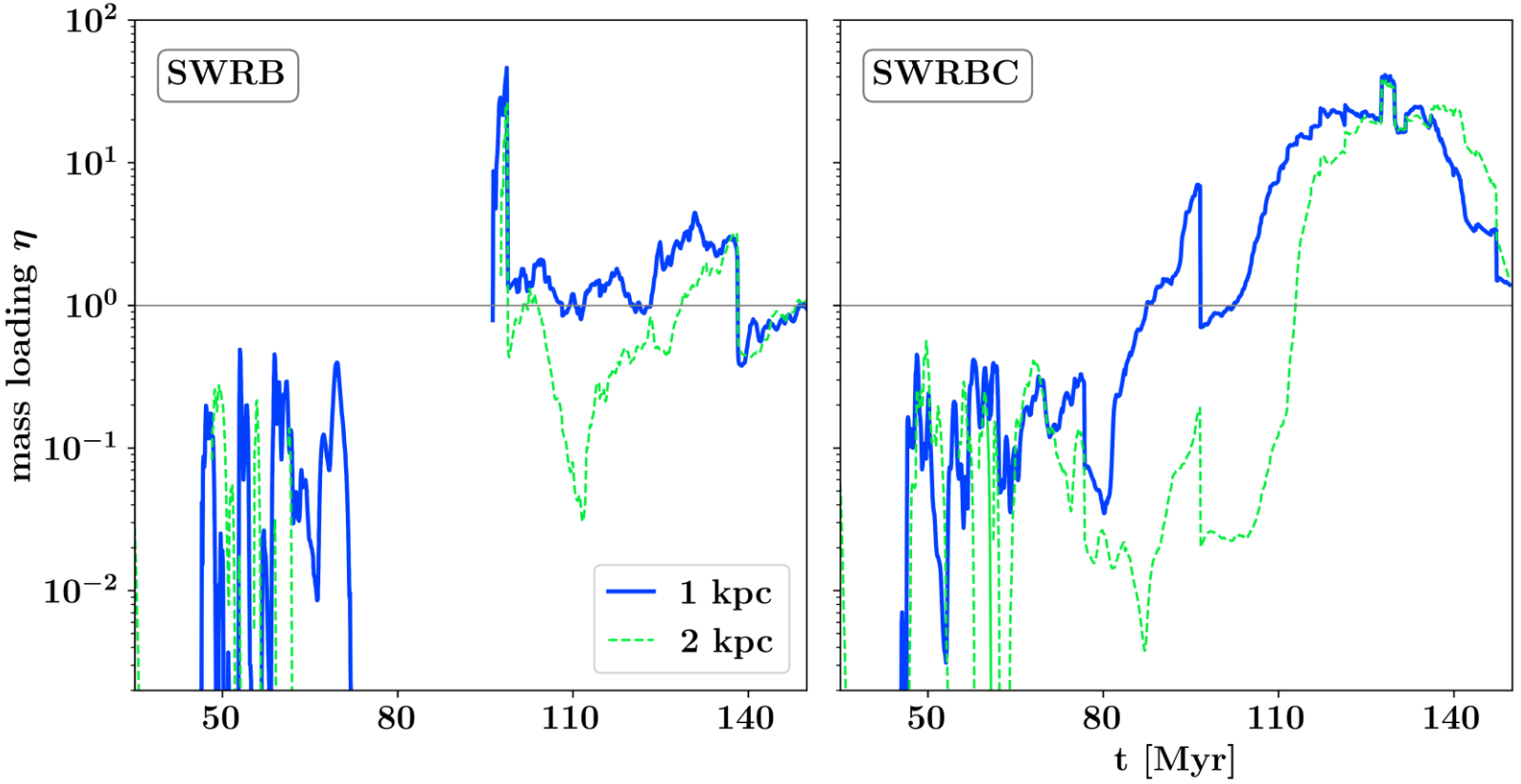

SWRB
t = 20.0 Myr
10^1 M$_\odot$
10^3 M$_\odot$
10^5 M$_\odot$
250 pc
Density (g cm^{-2})
Temp (K)
H$^+$ (g cm^{-2})
H (g cm^{-2})
10^{-5} 10^{-3} 10^{-1}
10^{1} 10^{3} 10^{5} 10^{7}
10^{-5} 10^{-3} 10^{-1}
10^{-5} 10^{-3} 10^{-1}
SWRBC
t = 20.0 Myr
10^1 M$_\odot$
10^3 M$_\odot$
10^5 M$_\odot$
250 pc
Density (g cm^{-2})
Temp (K)
H$^+$ (g cm^{-2})
H (g cm^{-2})
e_{CR} (eV cm^{-3})
10^{-5} 10^{-3} 10^{-1}
10^{1} 10^{3} 10^{5} 10^{7}
10^{-5} 10^{-3} 10^{-1}
10^{-5} 10^{-3} 10^{-1}
10^{-1} 10^{0} 10^{1}

Mass outflow



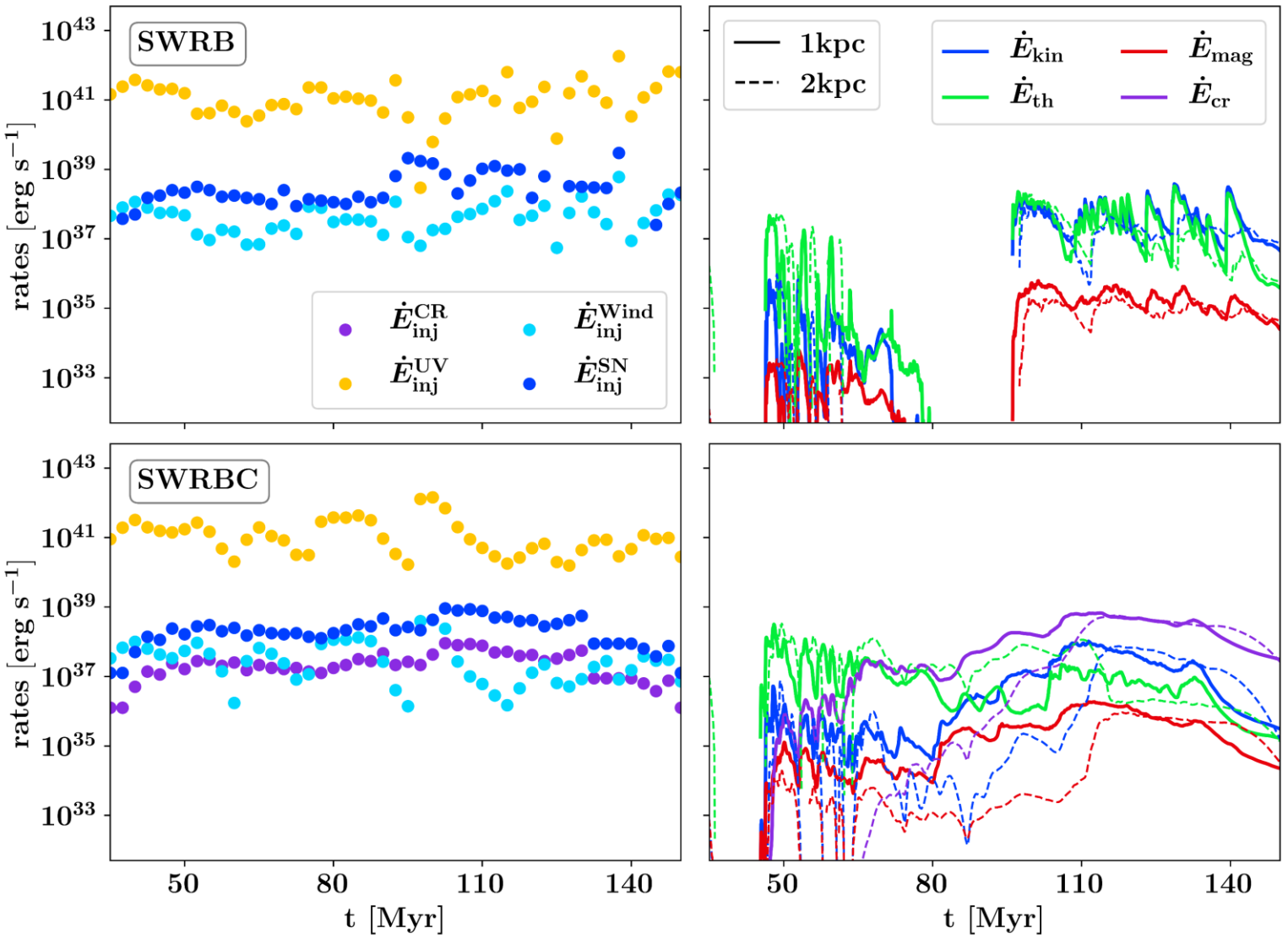
CRs drive more outflow in phases of low star formation with a higher fraction of neutral hydrogen

Mass loading



Mass loading changes with height and is higher with CRs

Energy budget



Midplane energy injection is dominated by radiation, CR subdominant.

But: CR energy flux out of the midplane higher by one order of magnitude than thermal and kinetic energies.

See also: Kim & Ostriker 18

Mass fractions

Midplane:
± 500 pc

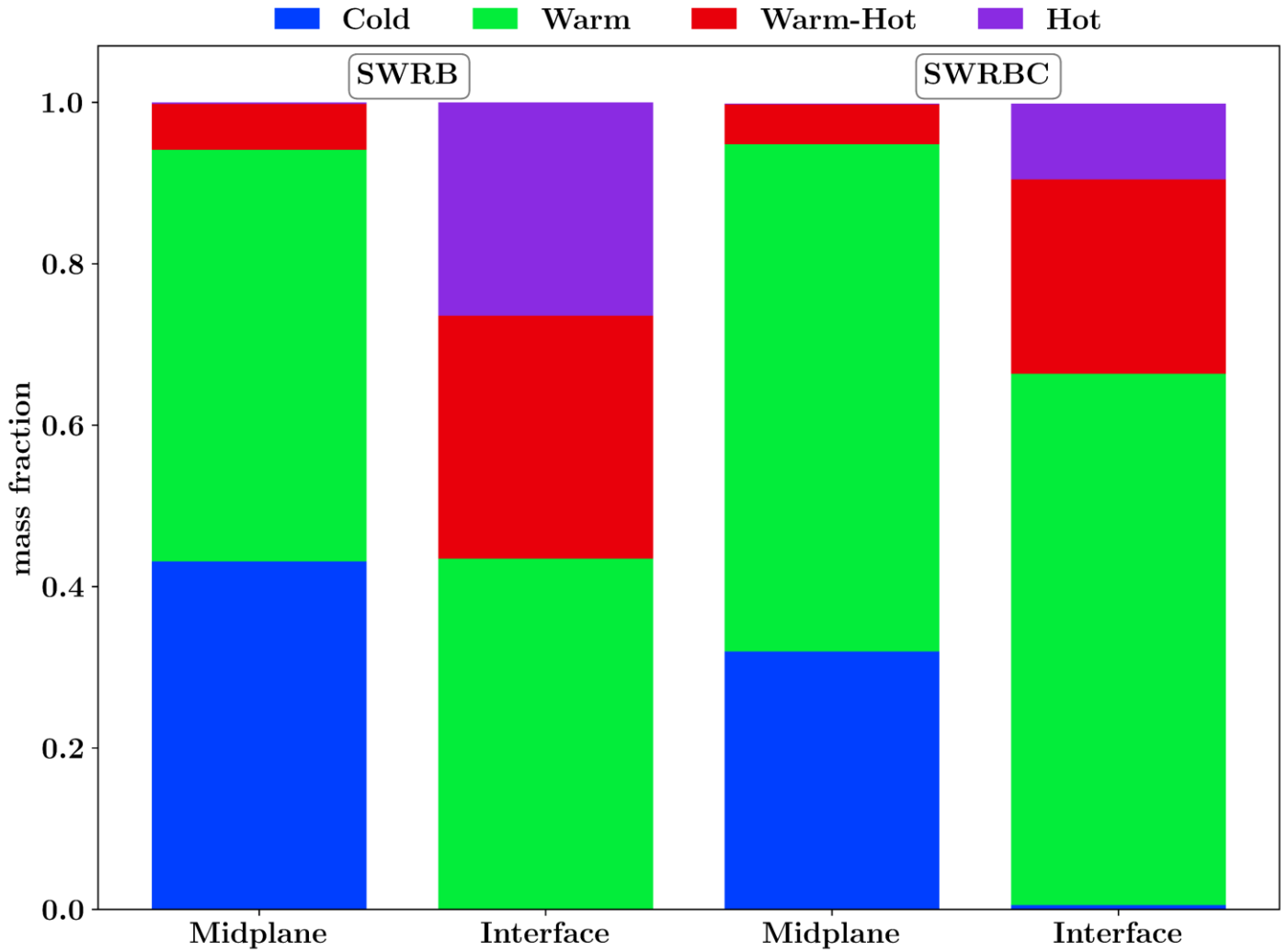
Interface:
0.5 – 2 kpc

Cold:
T < 300 K

Warm:
300 K < T < 8000 K

Warm-Hot:
8000 K < T < 3e5 K

Hot:
T > 3e5 K



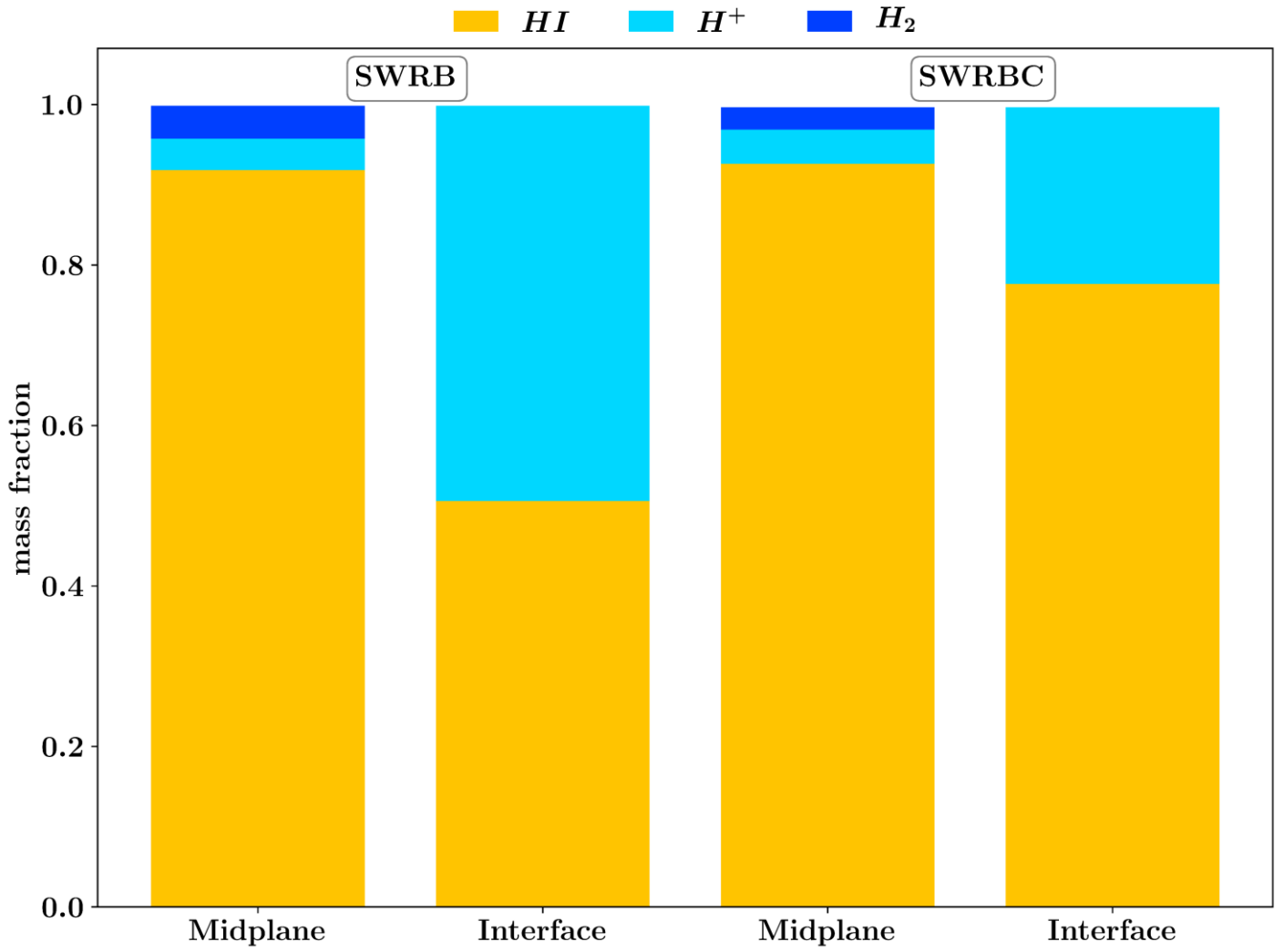
Local ISM (midplane) mostly unaffected by CRs

Disk-halo interface enriched with warm gas in the presence of CRs

Mass fractions

Midplane:
± 500 pc

Interface:
0.5 – 2 kpc



Local ISM (midplane) mostly unaffected by CRs

CR help lifting neutral atomic hydrogen above midplane.

Volume filling fractions

Midplane:
± 500 pc

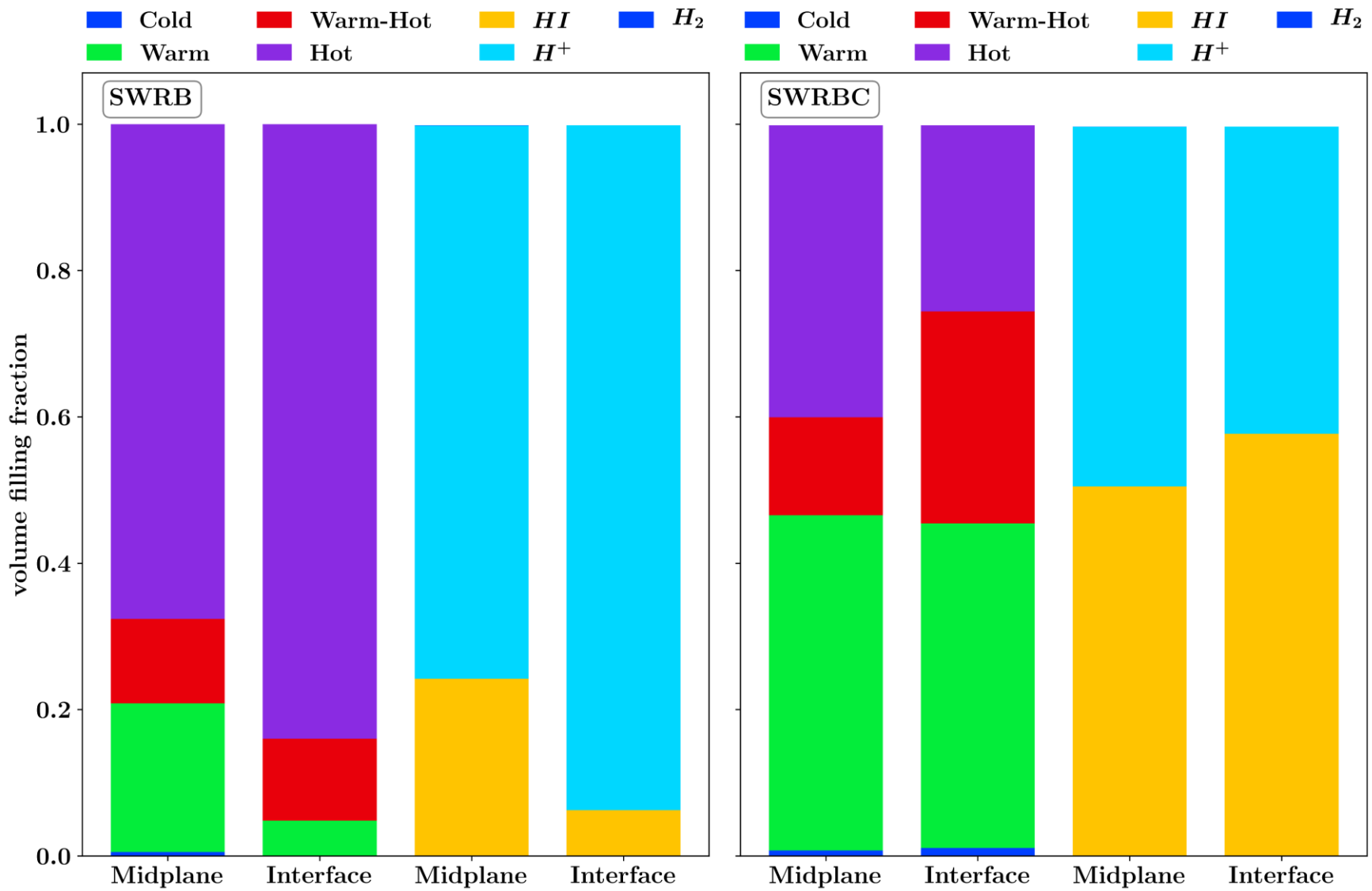
Interface:
0.5 – 2 kpc

Cold:
T < 300 K

Warm:
300 K < T < 8000 K

Warm-Hot:
8000 K < T < 3e5 K

Hot:
T > 3e5 K



Summary

- First simulations with aim for all major thermal and non-thermal components of the ISM
  - *Ionizing radiation* | *supernovae* | *winds* | *magnetic fields* | *cosmic rays*
- **SWRB** gives reasonable three phase ISM structure
- **SWRBC** gives higher outflow rates, smoother outflow structure and plausible CR energy densities
- Caveat: No galactic context
  - *No shear*
  - *Small volume*
  - *No equilibrium state / too short simulated time*