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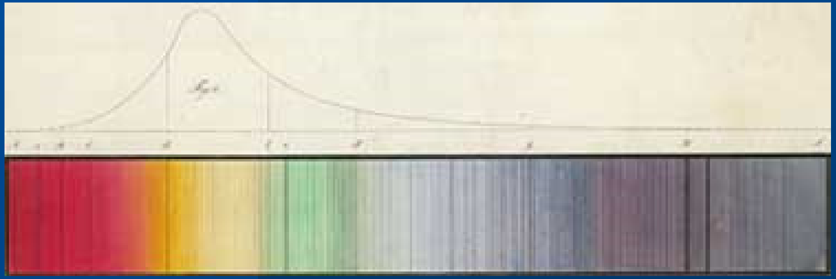
Understanding the magnetic field evolution in supernova remnants

a crucial role of high-performance computing

New tools stimulate essential changes

1609,
Galileo

“Experiment” in Astronomy consists in observations



1850,
Fraunhofer

HPC – new possibilities

2000ths

High performance computing

HPC for Astronomy

related to observations

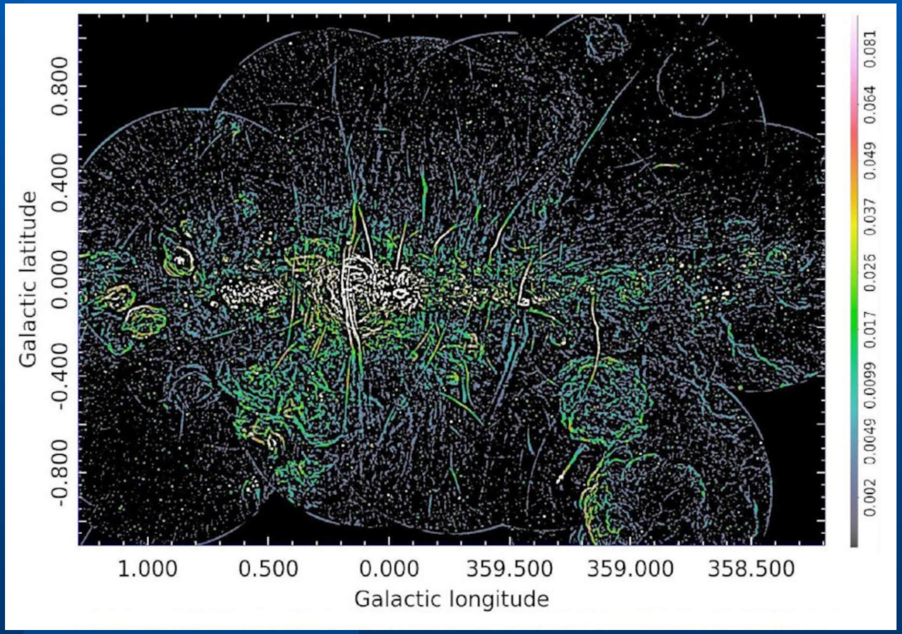
- Data Acquisition: on-fly analysis during observations
- Data Processing: at different levels (raw to end-user)
- e.g. CTA, LOFAR, SKA

numerical experiments

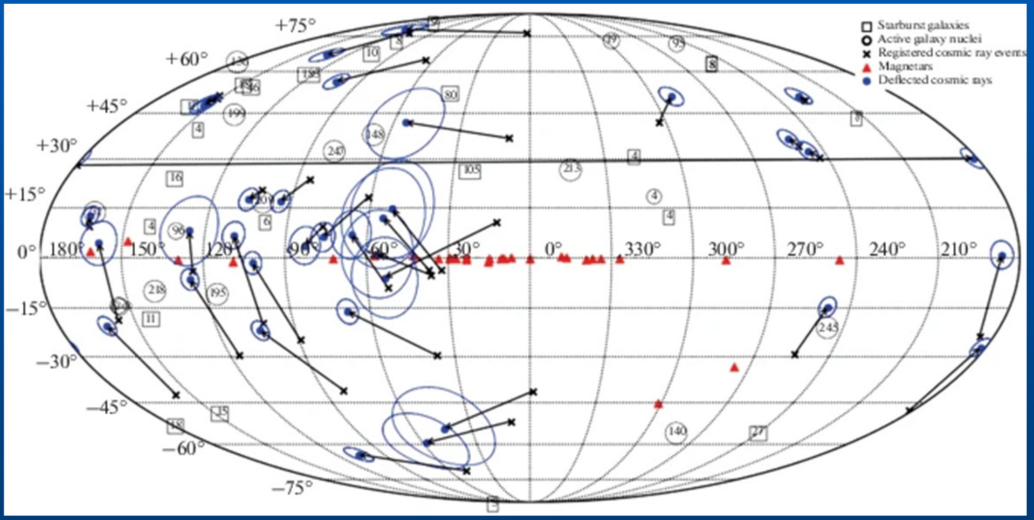
- The experiment in Astronomy is not only observations
- Numerical simulations is a way to set up a controlled experiment as in other branches of science

Magnetic fields in the Universe

MF manifests itself through a number of multi-messenger channels



1.28 GHz MeerKAT image of the Galactic center [Sofue 2023]



Distribution of Cosmic Rays with E > 10^20 eV (crosses), the directions of their entry into the Galactic MF (arrowheads), and the 1σ circles of the deviation in the random Galactic and extragalactic MFs up to 50 Mpc for C nuclei [Hnatyk, Voitsekhovskyi 2020]

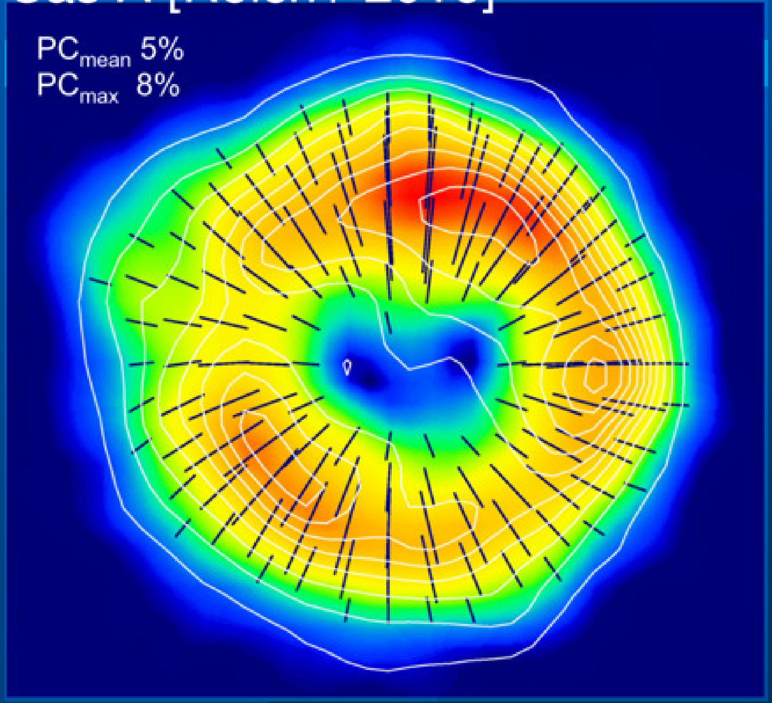
Numerical experiments are crucial

- MF in SNRS: complexity of processes
- The only analytic solution for MF in SNR is known for Sedov shock
- Numerical simulations are the key to study MF in SNRs
- Few examples
  - MF evolution @ different ages of SNRs
  - Dynamical effects of MF
  - 3D structure of MF in SNRs: images and polarization

Evolutionary change in MF structure?

radio polarimetric observations of SNRs:
- young SNRs have preferentially radial orientation of MF
- evolved SNRs have mostly tangential MF

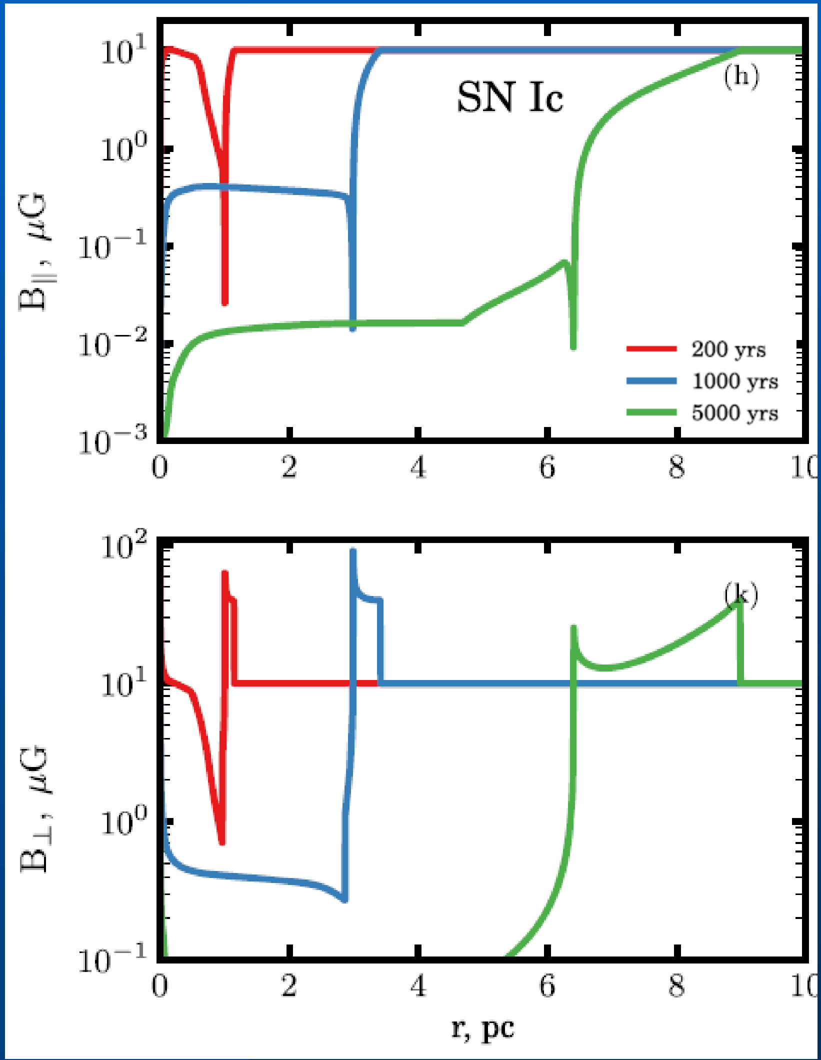
Cas A [Reich+ 2016]



G156.2+5.7 [Reigh+ 1992]

[Milne 1987, Dubner & Giacani 2015]

Numerical results for young SNRs



[Petruk+ 2021]

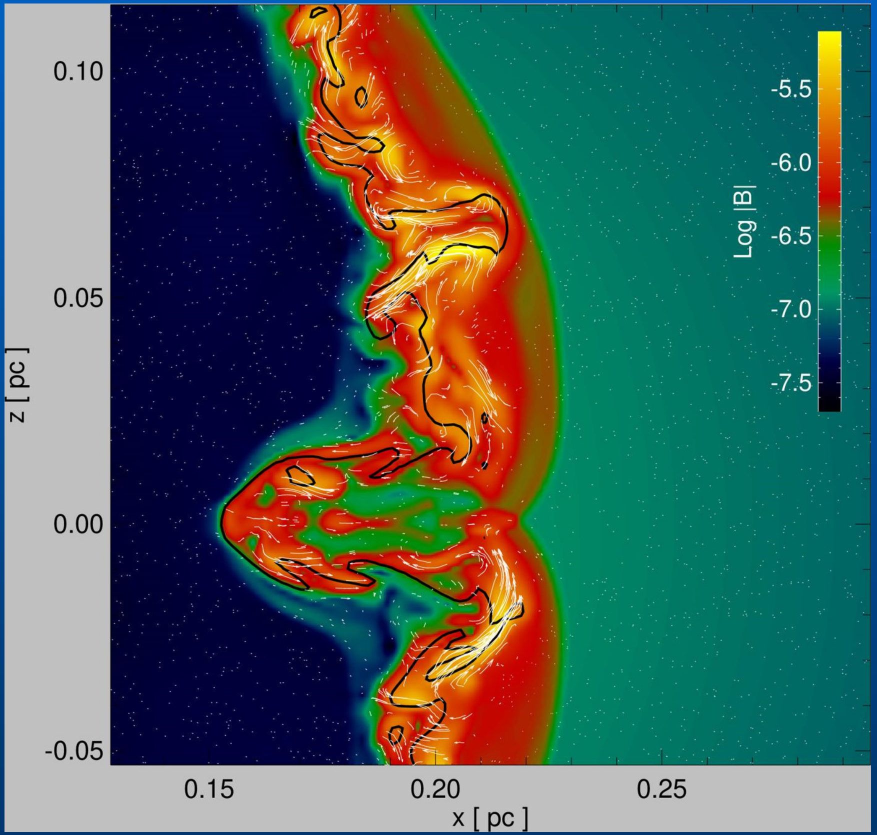
MF in young SNRs:

- Typical *ISMF is not dynamically important* if SNR evolves *adiabatically*
- *Radial MF drops faster* downstream than the tangential component
  - Radial MF may not dominate tangential MF in SNRs if it was not so before the explosion
  - Observed radial polarization patterns in young SNRs should be due to initially dominant radial ISMF
  - Limitations on the rotation of progenitors

Radial polarization patterns

Other suggestion

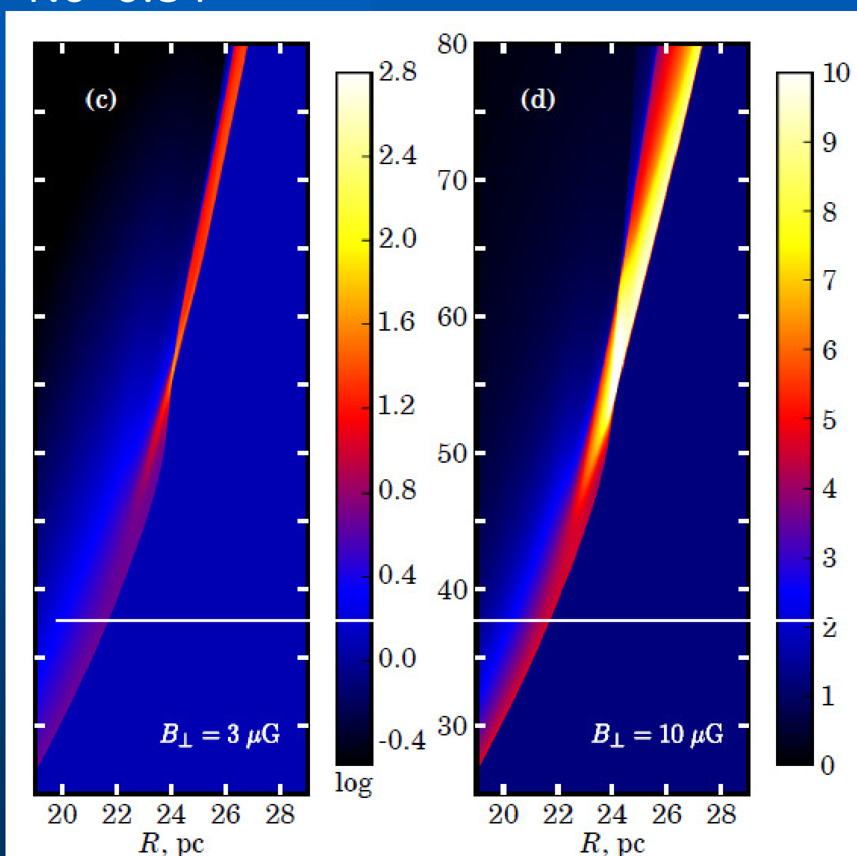
- **Jun & Norman 1996: `fingers`** from the Rayleigh–Taylor instability at the contact disconinuity
- **However,** RT `fingers` are well developed in our 3D simulations. => ***RT is not effective*** to be responsible for the radial MF (they are around CD and have low filling factor)



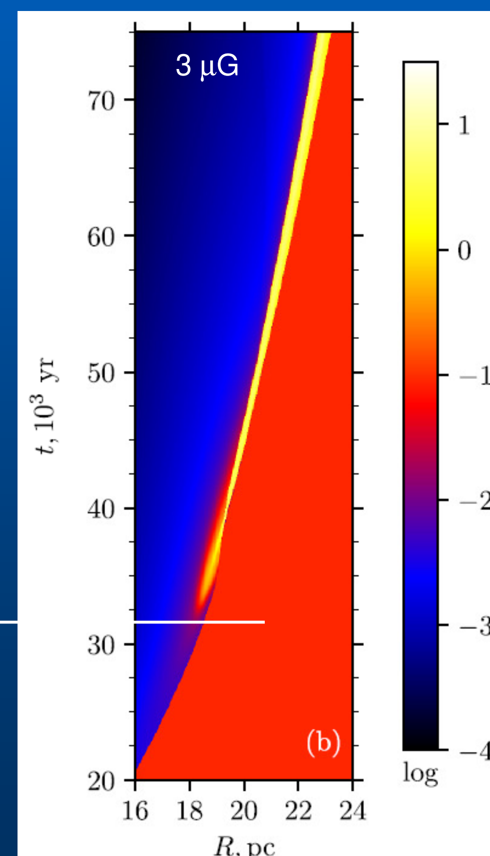
[Orlando+ 2019; Petruk+ 2023]: there are regions with strong radial MF at `fingers` but the overall polarization pattern remains tangential in the model

Evolved SNRs: radiative losses

Density Space-Time Map
N0=0.84



ratio between the magnetic and thermal energy densities

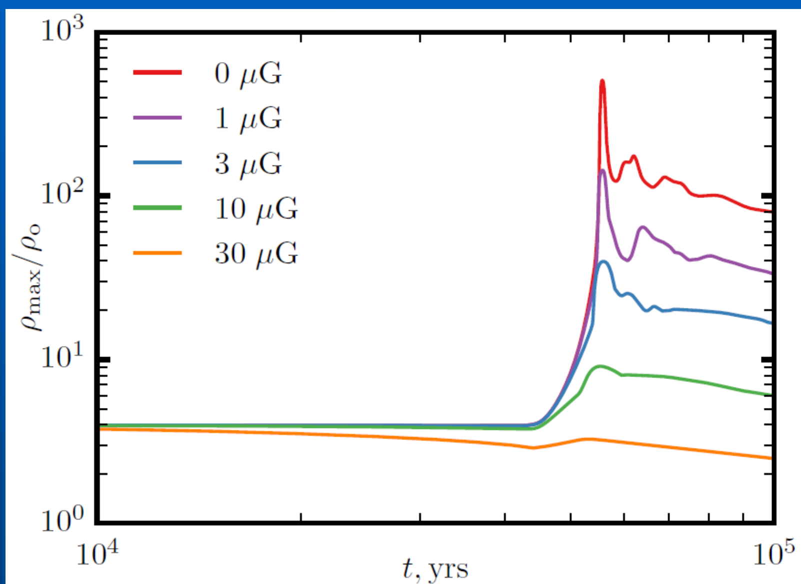


Post-adiabatic shocks: line marks the time when the radiative losses become prominent

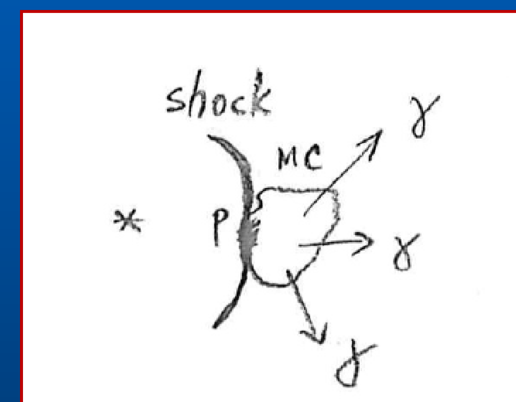
[Petruk+ 2018]

Effect of magnetic field on γ-rays

Post-adiabatic shock compression



Evolved SNRs interacting with molecular clouds (MC): accelerated protons+protons in MC -> γ-rays

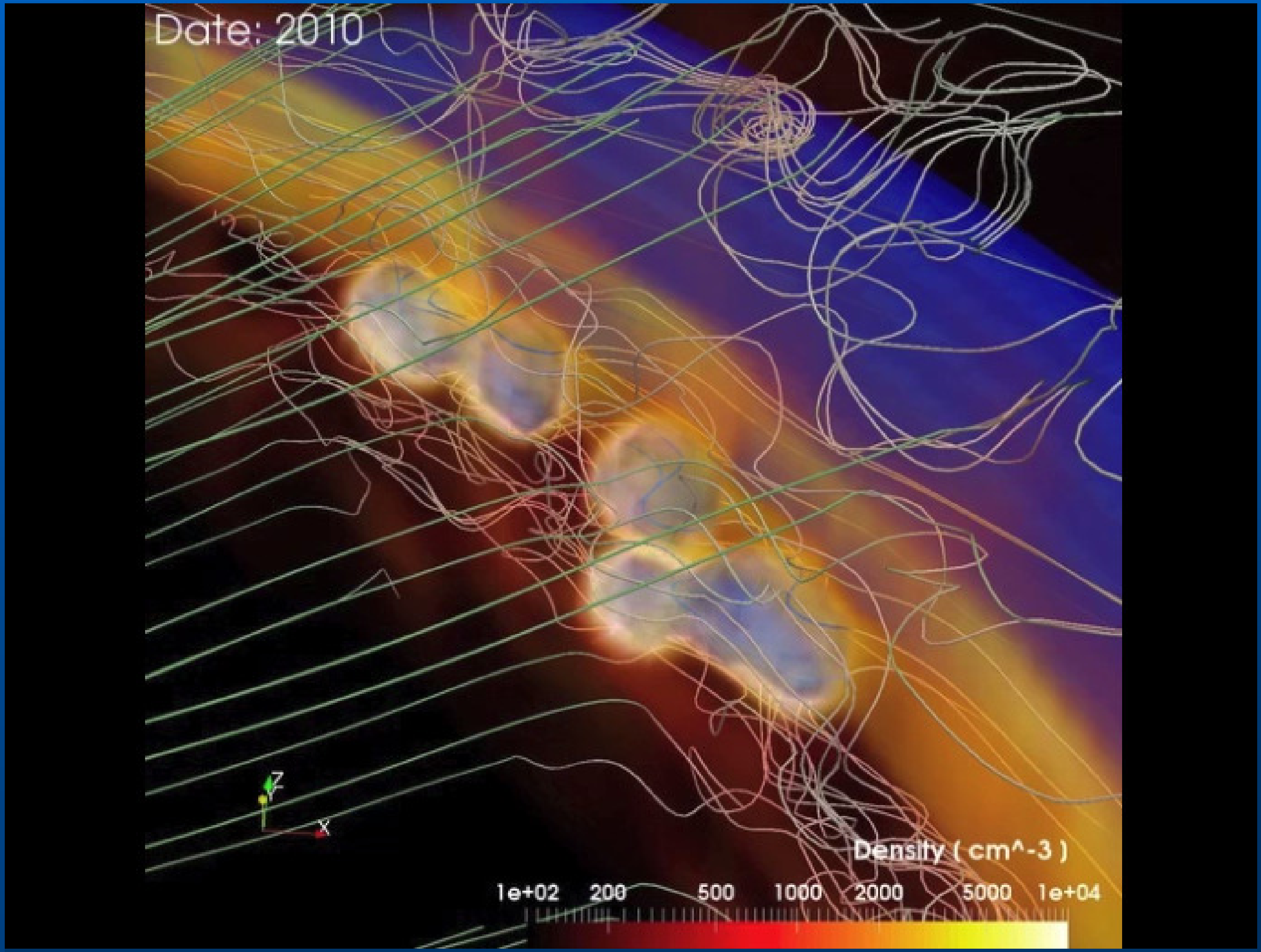


- shock energy goes effectively into the perpendicular MF component
- MF pressure modifies the shock dynamics
- MF limits the shock compression comparing to the HD simulations
- this lowers expected γ-ray flux from interacting SNR-MC

[Petruk+ 2021]

MF prevents the shock to crush clumps

[Orlando+ 2019]



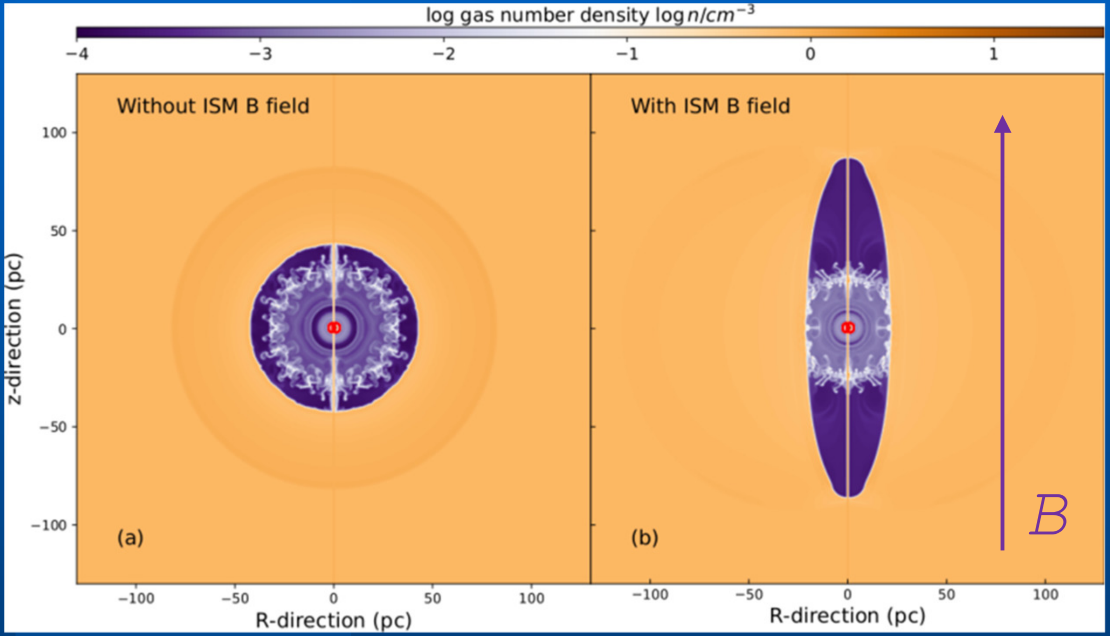
MF acts as an airbag in a car

Dynamical effect on the shape of SNR

- **Typical ISMFs are ineffective to modify the shape of SNRs: $E_B \ll E_{gas}$**
- **The shape is determined by the ISM density distribution: $V \sim \rho^{-1/2}$**
- **However, an indirect effect is possible:**

1. **Stellar winds: $E_B \sim E_{gas}$**
2. **MF shapes the wind and its density**
3. **Wind structure shapes SNR**

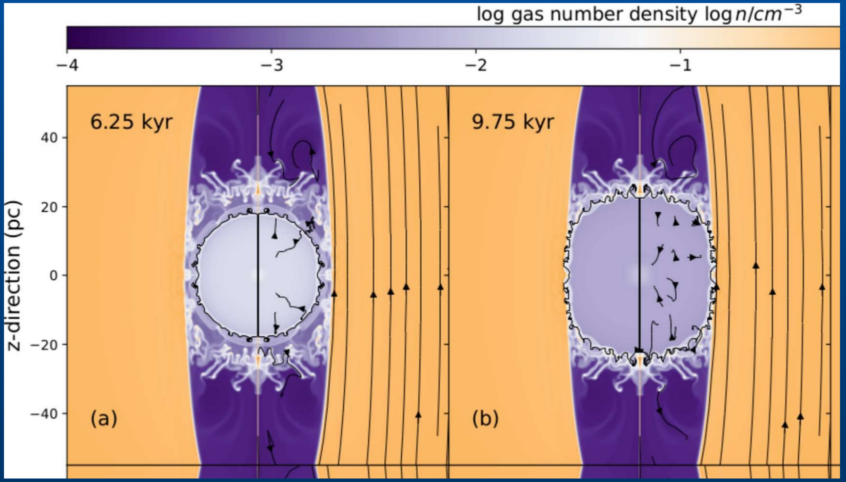
Stellar wind bubble around a Wolf-Rayet star



wind bubble

W49B Chandra, Palomar Observatory, VLA

SNR in the bubble



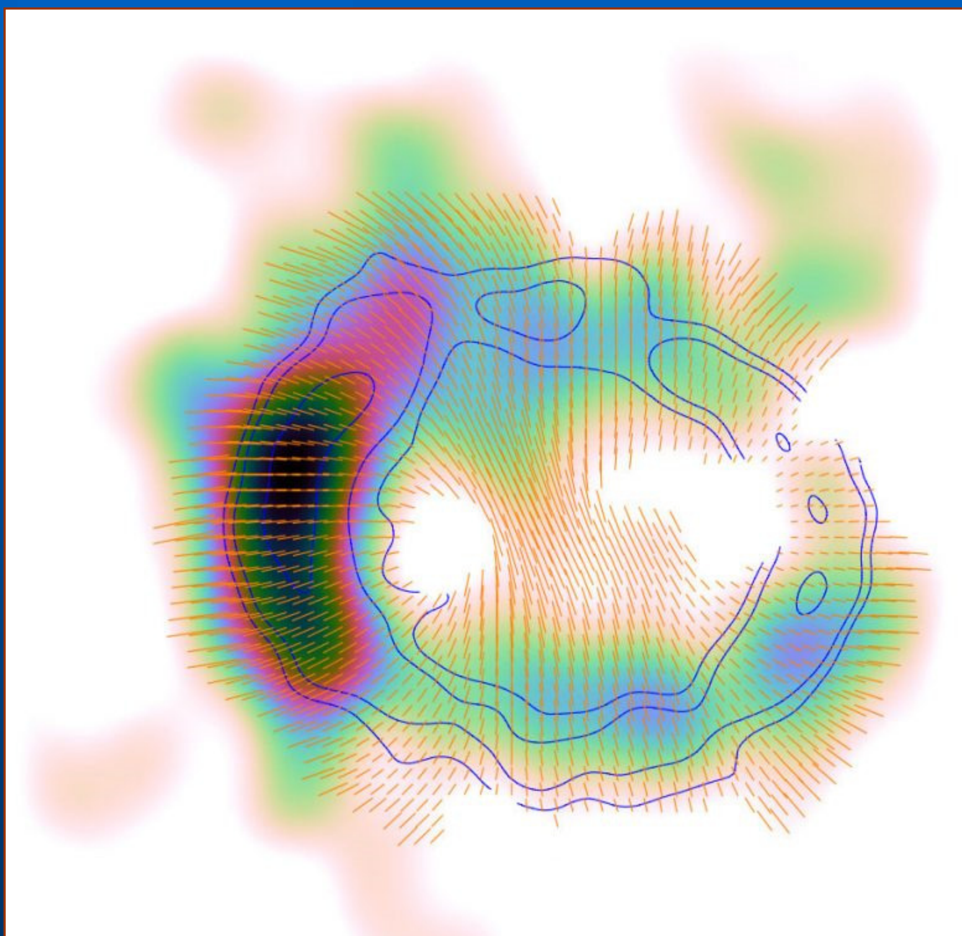
MF in ISM is parallel to the symmetry axis z, B=7 μG. $\beta_{ISM}=P_{ISM}/P_B$=0.05
The evolution of the wind-ISM interaction for the entire star life, 5.4 Myr.

[Meyer+ 2022]

Polarization maps of SNRs

- Radio polarization of SNRs are known since 1950ths
  - 3D structure of the MF vector field
  - Internal Faraday effect
- X-ray polarization since 2022 (IXPE)
  - 3D structure of the MF vector field
  - Internal Faraday effect
  - X-rays from electrons around p_{max}: MF affects the shape of $N_e(p)$

SN1987A: radio polarization



Large Magellanic Cloud
51.4 kiloparsecs (168,000 ly)
closest observed since SN 1604 (Kepler)

ATCA radio telescope

Observations: 10.2015 - 05.2016
22 GHz (1.4 cm)

Polarization fraction ~3%

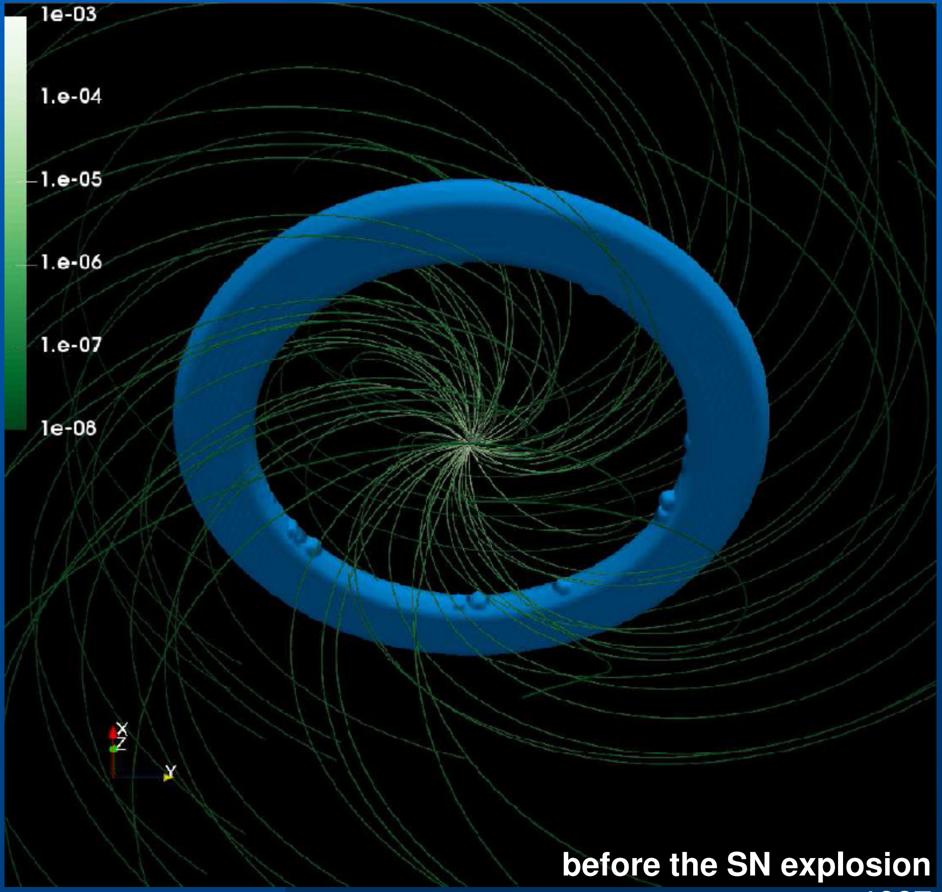
colors: polarized intensity @22 GHz
contours: total intensity @44 GHz
lines: polarization vectors (*B*)

[Zanardo+ 2018]

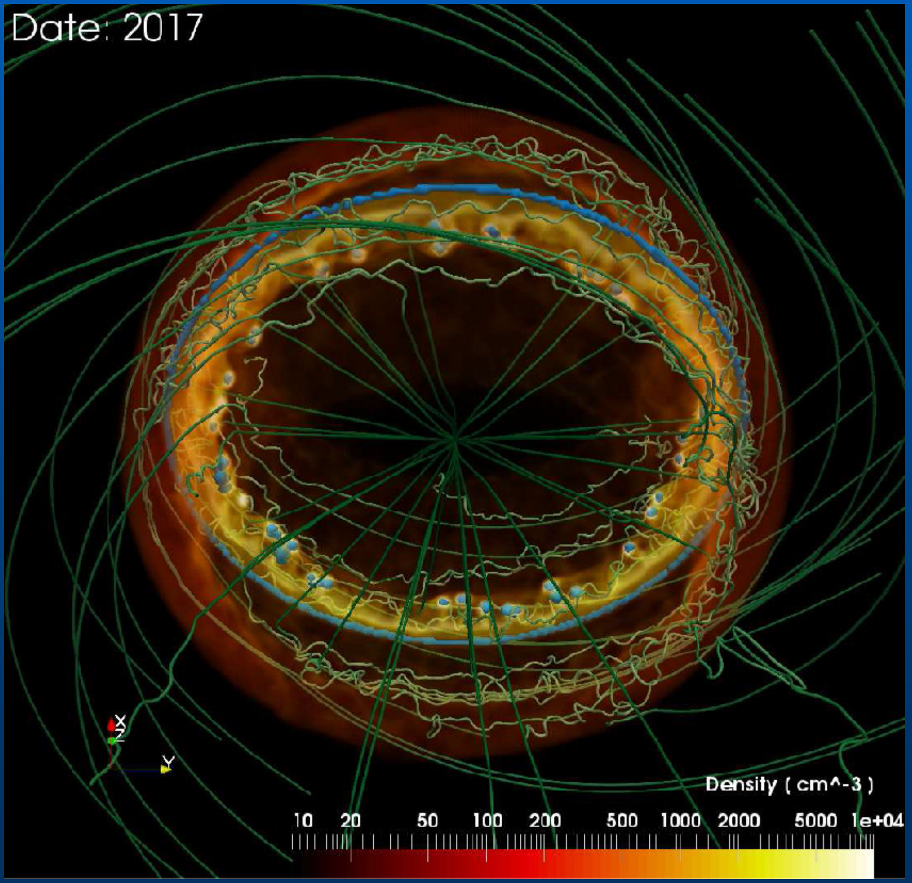
SN 1987A: the first 3-D MHD simulations

MF around the progenitor is the Parker spiral

$$B_r = \frac{A_1}{r^2}, \qquad B_\phi = -\frac{A_2}{r} \sin\theta,$$



before the SN explosion
year 1987



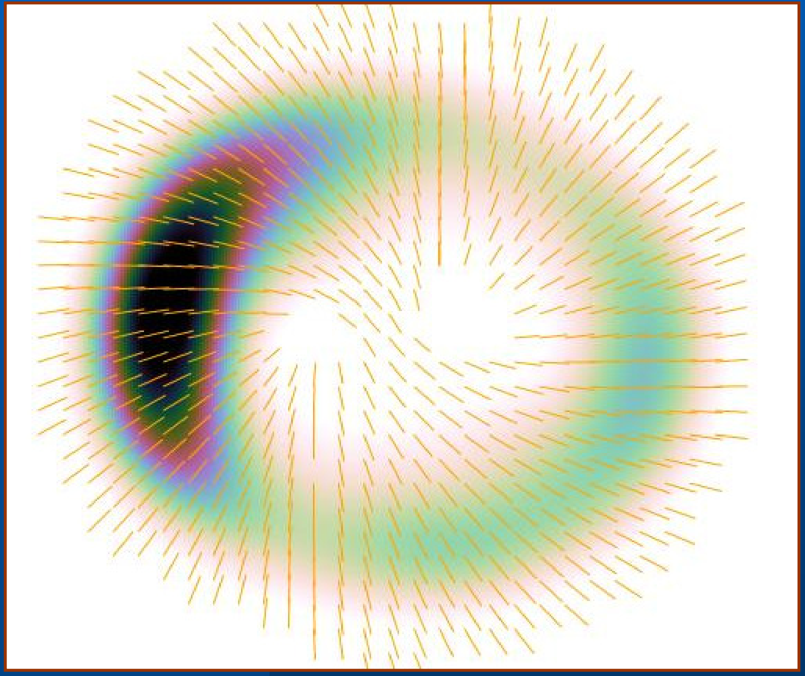
after the SN explosion
year 2017

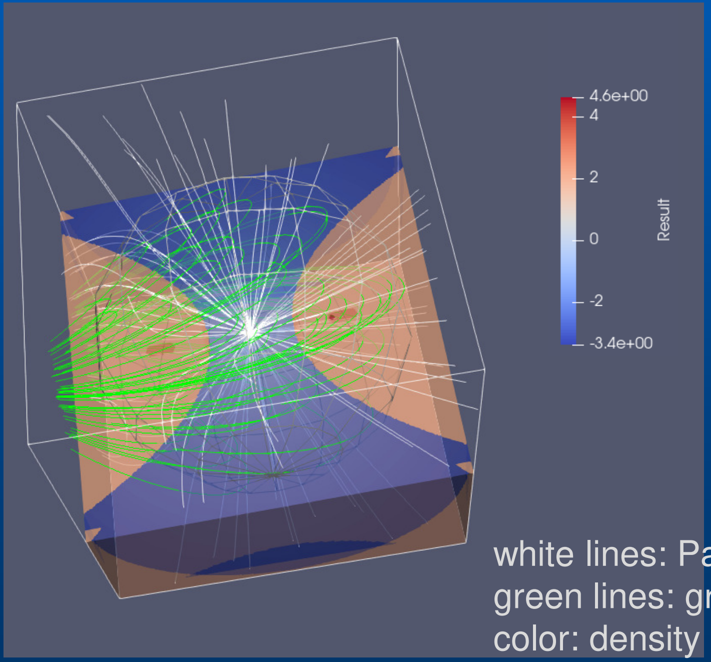
[Orlando+ 2019]

Search for MF to fit the vector pattern

the Parker spiral $B_r = \frac{A_1}{r^2}, \qquad B_\phi = -\frac{A_2}{r}\sin\theta,$

with A_2 quite low, i.e. almost radial field – on the scale of few R





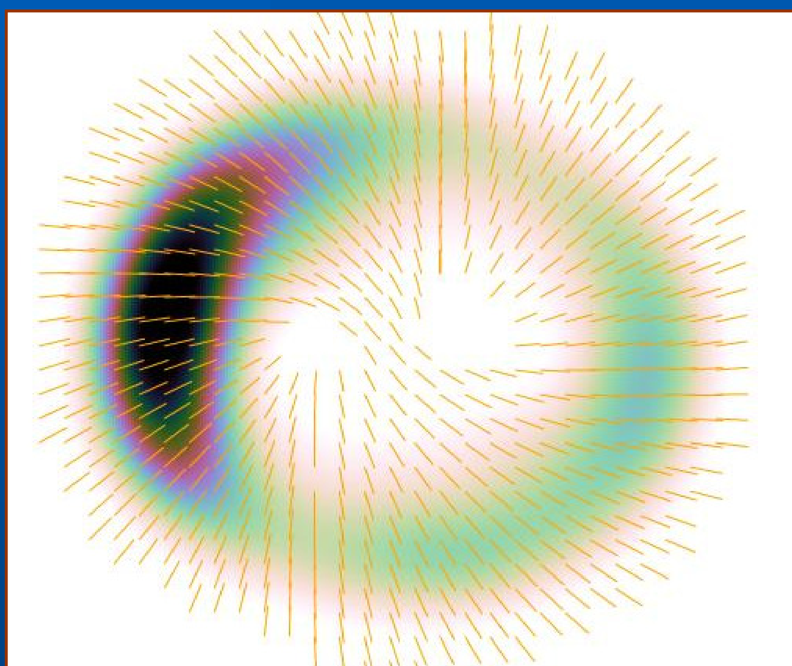
white lines: Parker MF
green lines: grad B with dipole
color: density

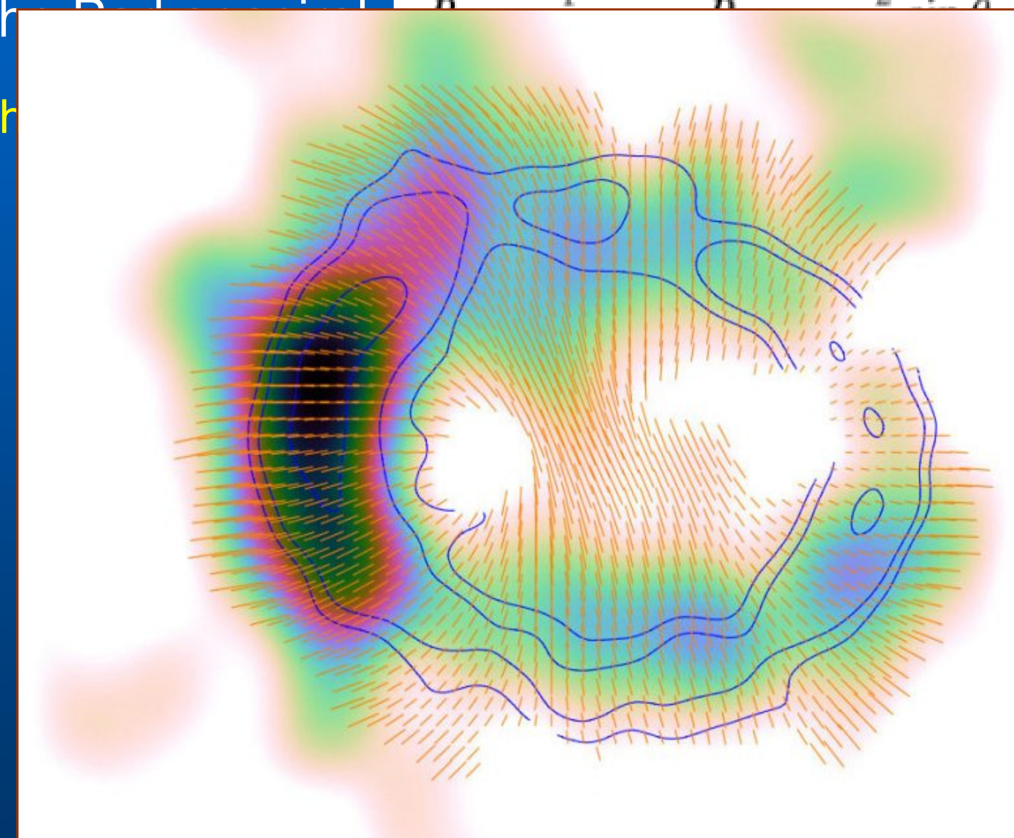
[Petruk+ 2023]

Search for MF to fit the vector pattern

th

with A_2 quite low, i.e. almost radial field – on th





observations

3D MHD model: surface brightness and pattern of polarization vectors recovered

High performance computing

HPC for Astronomy

related to observations

- Data Acquisition: on-fly analysis during observations
- Data Processing: at different levels (raw to end-user)
- e.g. CTA, LOFAR, SKA

numerical experiments

- HPC allows for the first time to set up controlled experiments in Astrophysics

Magnetic fields in SNRs

- **Numerical experiments are crucial**
- **MF evolution @ different ages of SNRs**
  - Young SNRs: radial field is likely a property of ISM
  - Post-adiabatic shocks: MF is dynamically important
- **Dynamical effects of MF**
  - CR acceleration (direction, level of turbulent MF, MF amplification)
  - Prevents crushing small scale clumps
  - Prevents compression (affect gamma-emission in shock-cloud interactions)
  - Not important on large scales inside SNR up to the post-adiabatic era
  - Important for shaping the stellar wind of progenitor -> shape of SNR expanding into the wind
- **Polarization maps of SNRs**
  - radio and X-rays
  - 3D structure of MF vector field is needed