Feeding supermassive black holes by supernova driven shells

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in cooperation with

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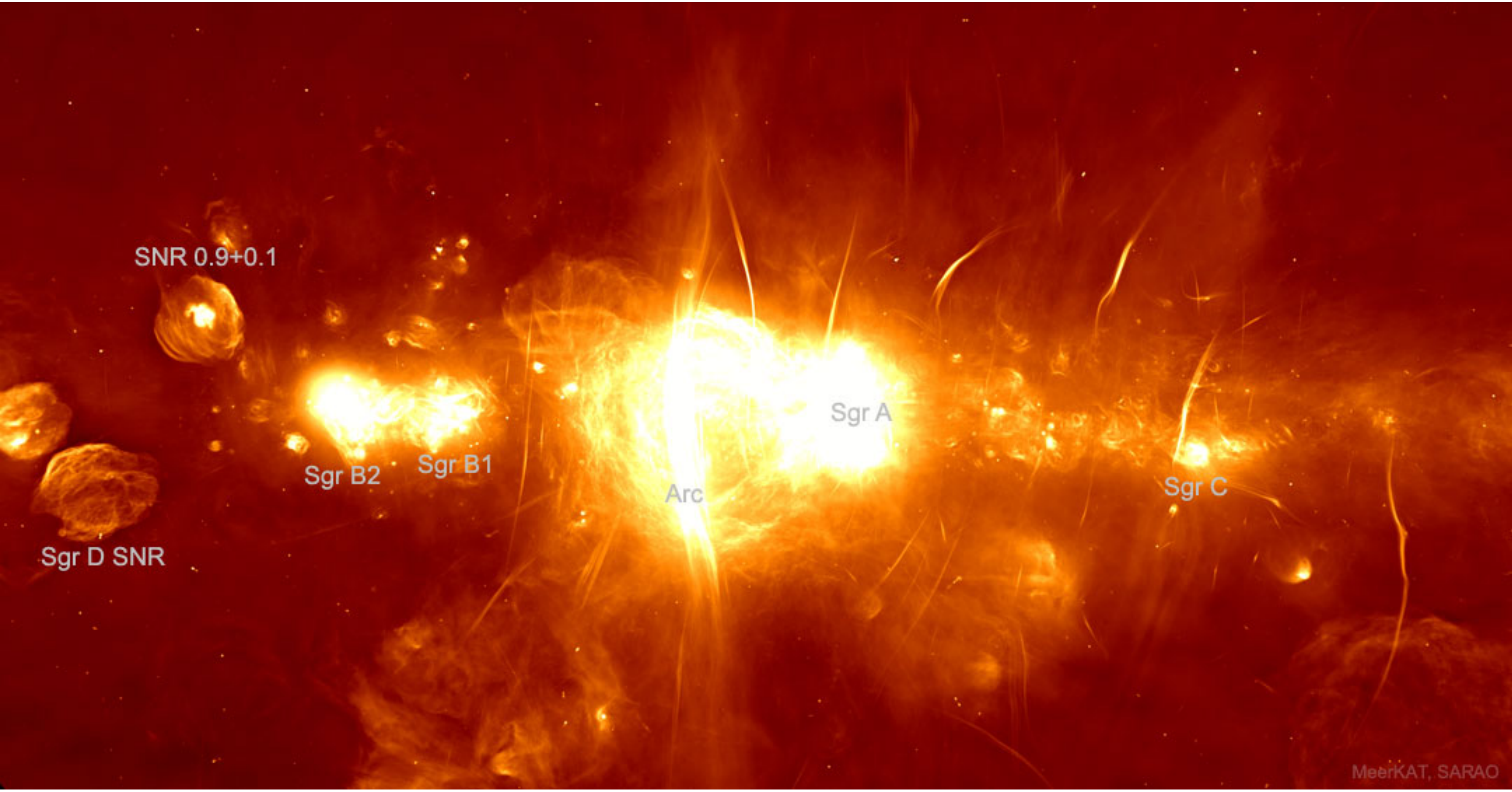
Central Part of the Milky Way

- Kruisen, J.M.D., Longmore, S.N., Elmegreen, B.G., Norman, M., Bally, J., Testi, L., Kennicut Jr., R.C.:
- What controls star formation in the central 500 pc of the Galaxy,
- MNRAS 440, 3370- 3391, 2014;
- and the references there.

Central Part of the Milky Way

- X1 - X2 orbits in the gravitational potential of the bar;
- Large scale outflows: Fermi bubbles;
- Central Molecular Zone:
  100 - 300 pc, 6 -7 10^7 Msun, T = 50 - 500 K;
- Circum Nuclear Disk: 1 - 5 pc;
- Nuclear Star Cluster: a few - 10^7 Msun;
- Accretion disk - feeding - low: 5 10^-9 Msun/yr;
- Supermassive Black Hole: 4 10^6 Msun.

MeerKAT HI in the MW center
Heywood et al. 2019, Nature, 573,235



Central zones

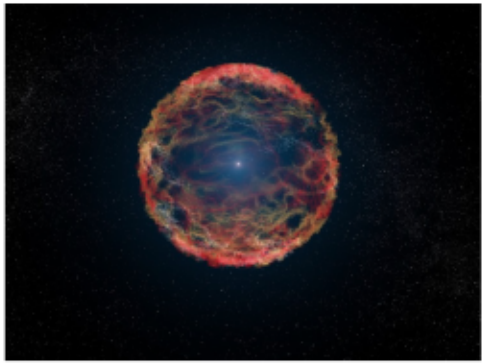
- 100 - 10 pc: Central Molecular Zone;
- 10 - 1 pc: Circum Nuclear Disk;
- 1 - 0.1 pc: Nuclear Star Cluster;
- below 0.1 pc: Accretion disk;
- Supermassive Black Hole: 4 10^6 Msun.

Supernovae inside the Zone: 10 - 1 pc

Do they redistribute the mass and angular momentum?

Can supernova shells feed supermassive black holes in galactic nuclei?

- Supernovae explosions release ~ 10^44 Watts
- The blast wave creates a thin shell expanding in the ISM
- The shell accumulates material
- What happens in the vicinity of a SMBH?

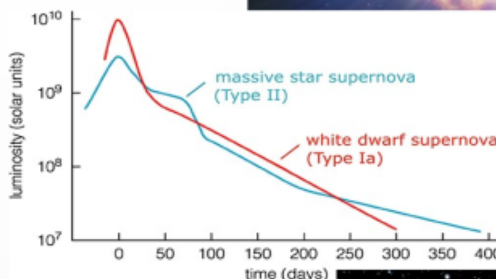


Credit: X-ray: NASA/CXC/SAO/J.Hughes et al, Optical: NASA/ESA/Hubble Heritage Team (STScI/AURA)

Stages of SN evolution

- Explosion (WD or Massive star)

  $M \sim 1\text{-}80\ M_{Sol}$; $E \sim 1\text{-}10 \times 10^{51}$ erg

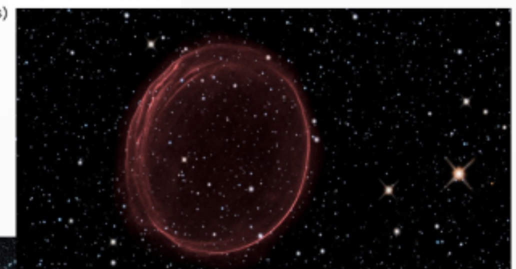


- Free expansion

  Photospheric and Nebular phases

- Sedov-Taylor phase

  Formation of the thin shell



- Snowplough phase

  Keeping the momentum

- Disperse into ISM

  $v_{exp} < c_{ISM}$

FLASH
grid-based hydrodynamical code

- Piecewise Parabolic Methods with time-step controlled by Courant-Friedrichs-Lewy criterion
- equilibrium radiative cooling using prescription of Schure et al. (2009)

1D - 2D - 3D

The Thin Shell Approximation

- Kompaneets (1960), Bisnovatyj-Kogan & Blinnikov (1982);
- Tenorio-Tagle & Palouš (1987), Ehlerová & Palouš (1996), Silich et al. (1996) and others.

FLASH prepares for RING

stellar winds & mass loading

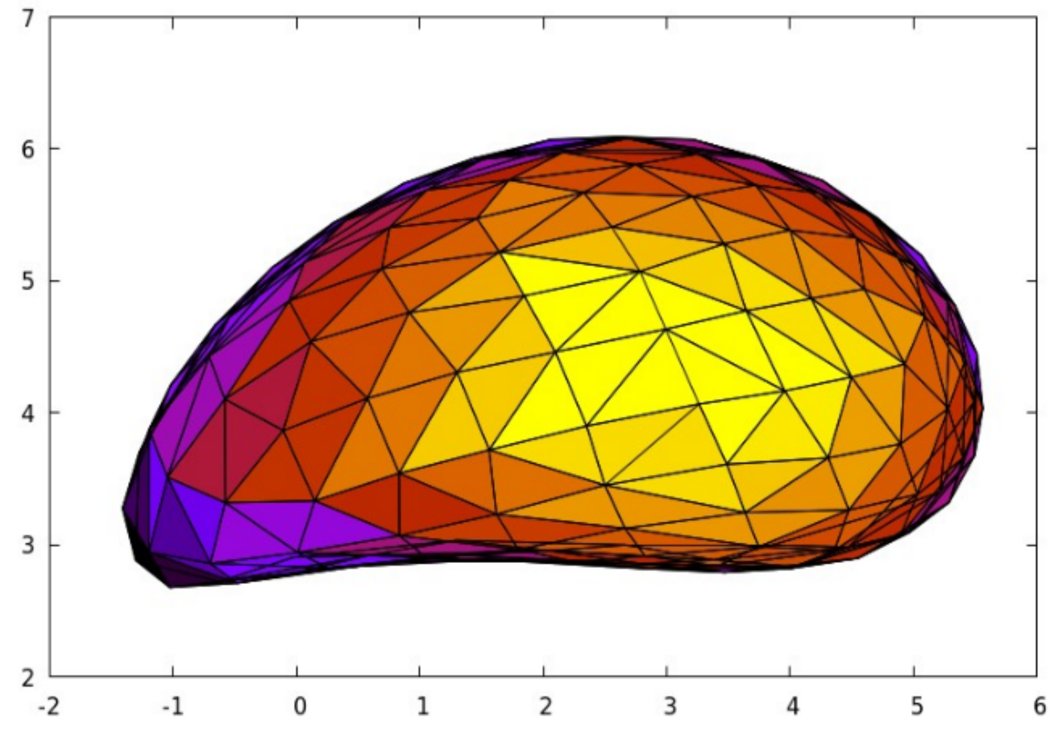
inside of NSC of 0.5 pc radius

sources providing energy and momentum

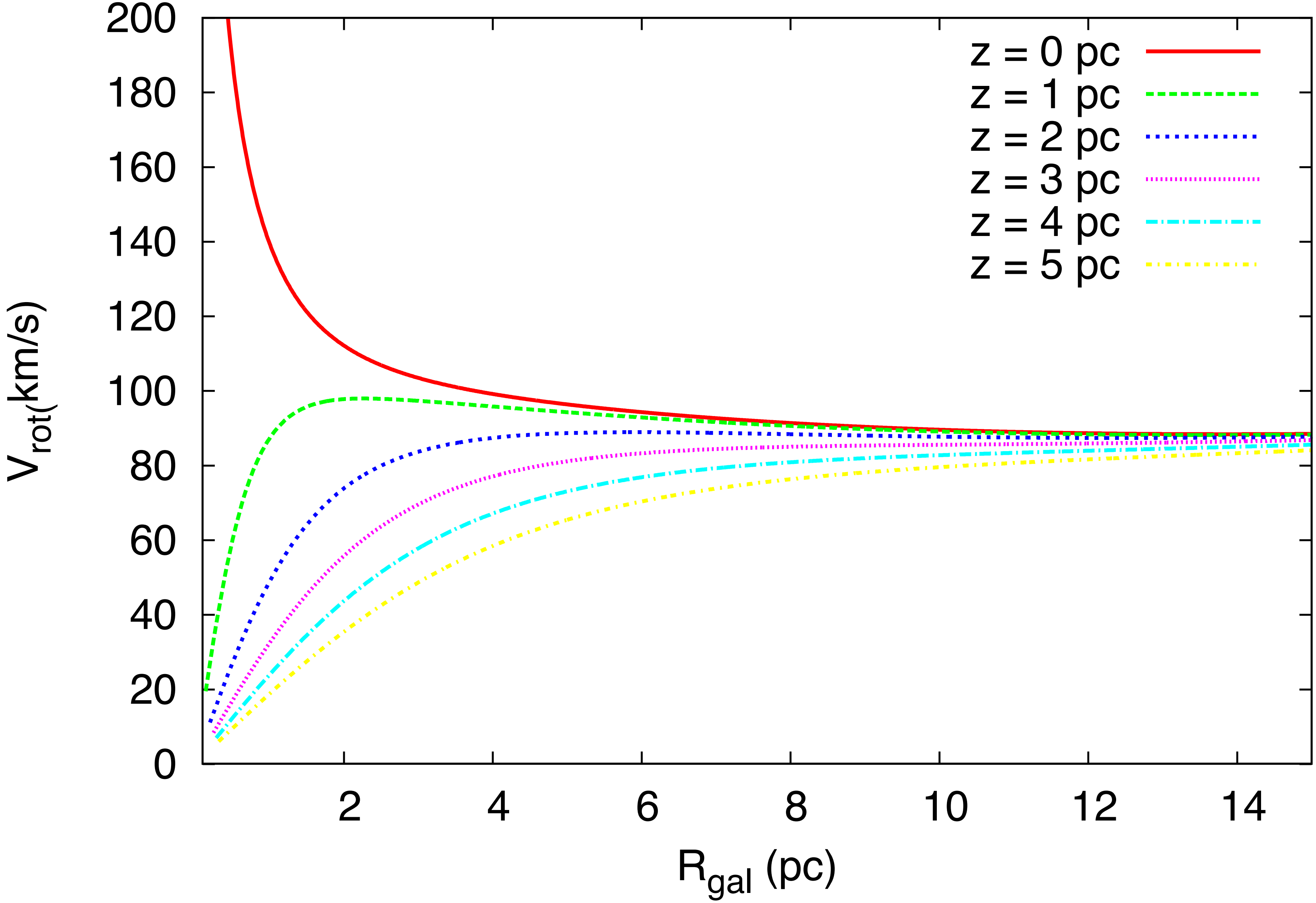
sources providing mass for loading

RING simplified hydro code – parameter studies

- Simplified hydrodynamic code
- Thin shell approximation
- Shell divided into elements
- Evolution of the shell wall: momentum and mass conservation
- Collecting ambient medium (only while shell is supersonic!)

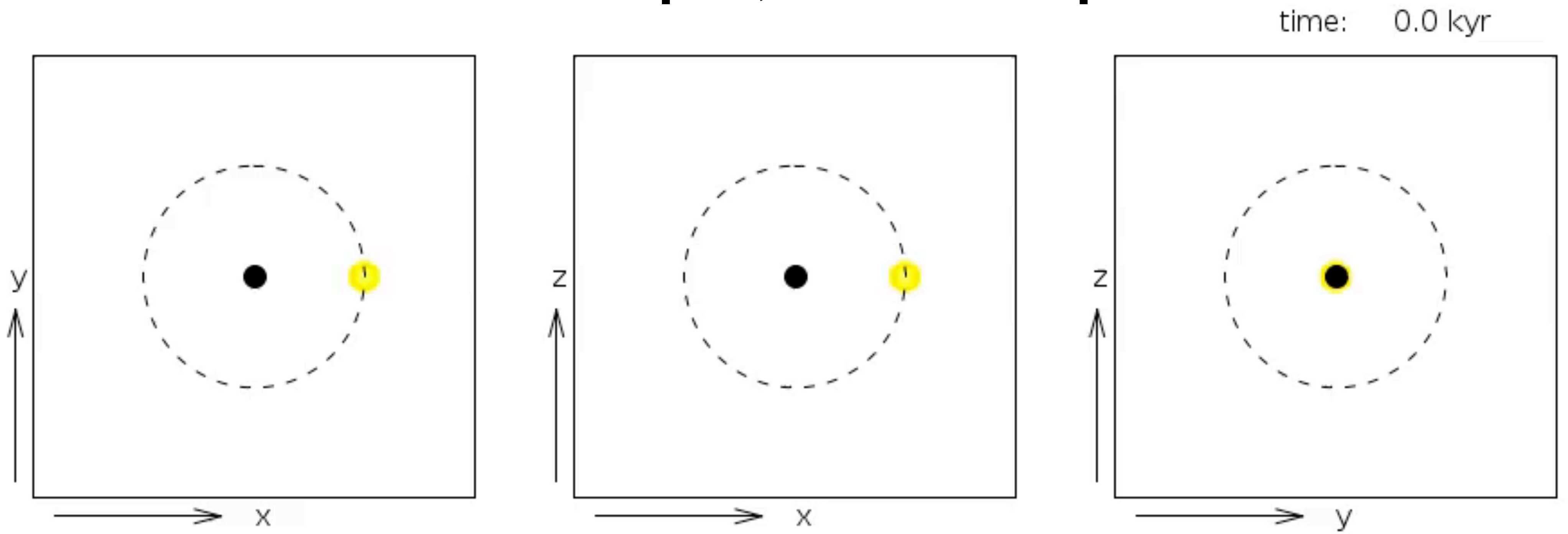


Rotation



z = 0 pc
z = 1 pc
z = 2 pc
z = 3 pc
z = 4 pc
z = 5 pc
200
180
160
140
120
100
80
60
40
20
0
2
4
6
8
10
12
14
V_{rot}(km/s)
R_{gal} (pc)

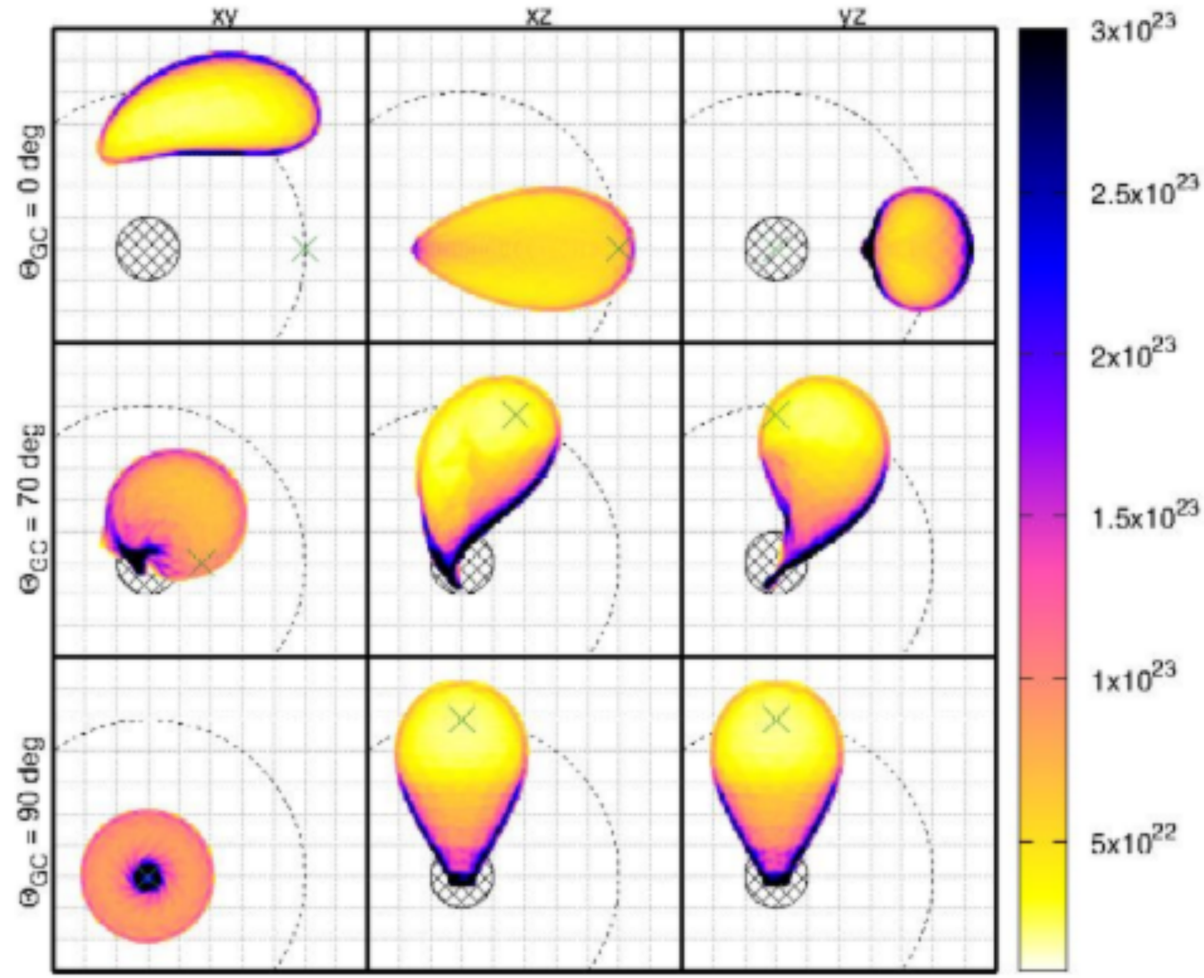
Rotation & Gravity in homogeneous medium R0 = 5 pc, z0 = 0 pc



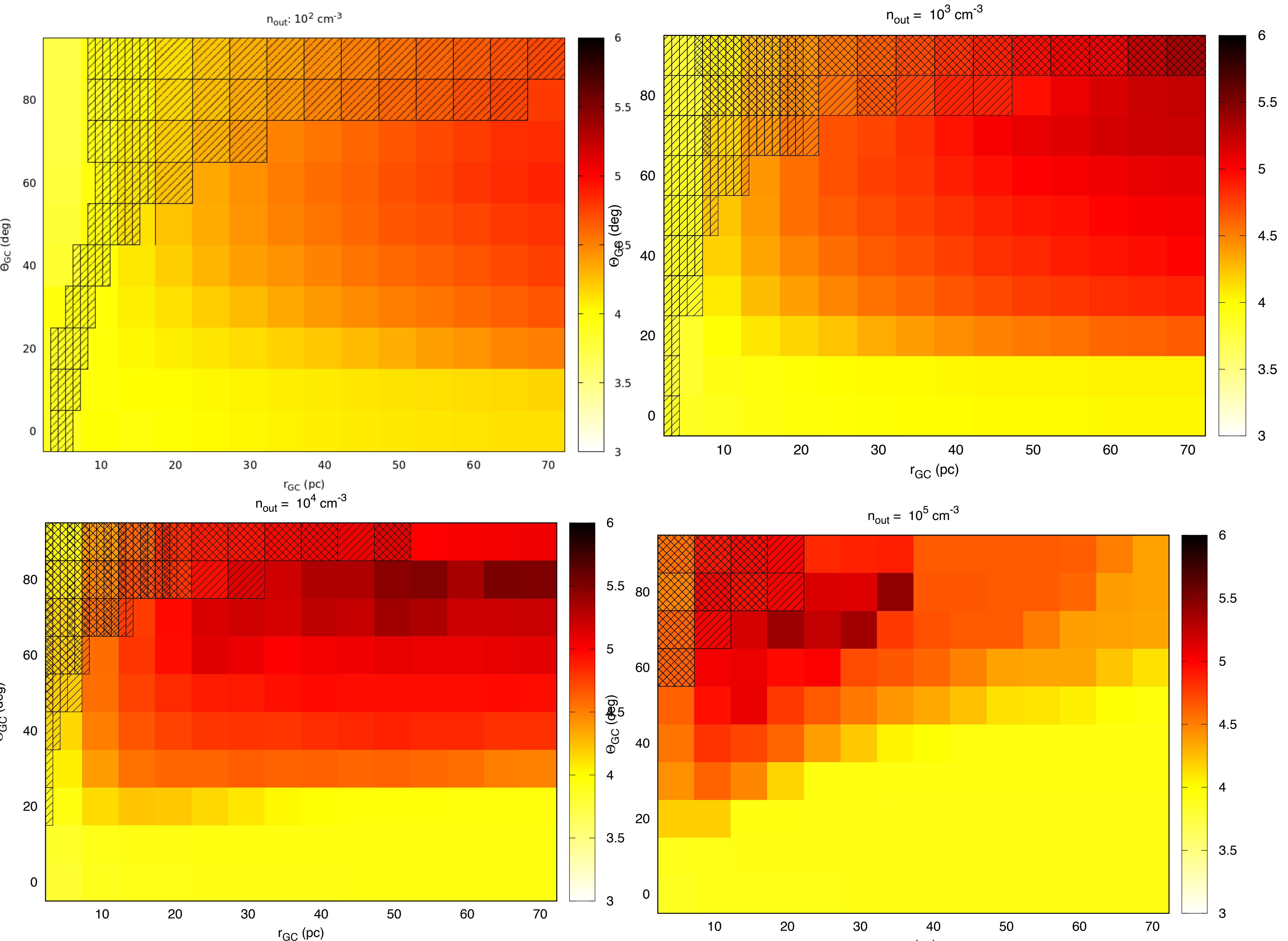
RING simulations around Sgr A*

- external gravitational potential:
  supermassive black hole, young and old nuclear star cluster
  rotation in the galactic (xy) plane

- ISM distribution
  homogeneous (10^2 - 10^5 cm



Palouš et al, 2020



n_{out}: 10^2 cm^{-3}
n_{out} = 10^3 cm^{-3}
n_{out} = 10^4 cm^{-3}
n_{out} = 10^5 cm^{-3}
Θ_{GC} (deg)
r_{GC} (pc)
0
20
40
60
80
10
20
30
40
50
60
70
3
3.5
4
4.5
5
5.5
6

Conclusions:
SN in the homogeneous medium
Palouš, Ehlerová, Wunsch & Morris
A&A 644, 72, 2020

- Expanding Shells can deliver mass to central pc from a restricted volume of space along the rotational axis;
- The time of the delivery is position dependent;
- The total mass depends on the average density.

FLASH-light on the RING: hydrodynamic simulations of expanding supernova shells near supermassive black holes

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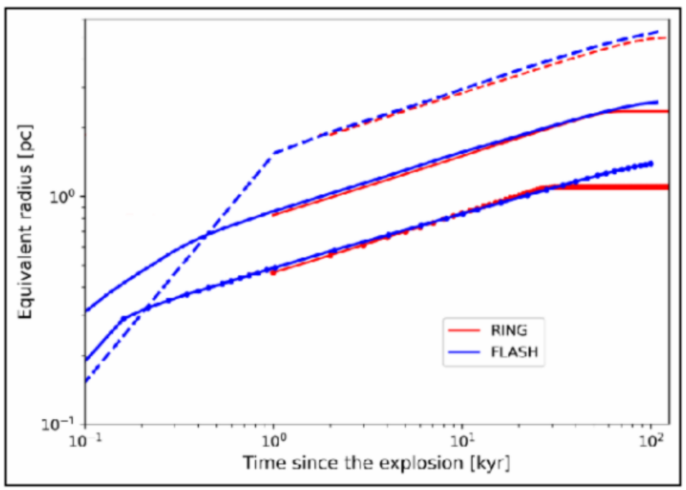
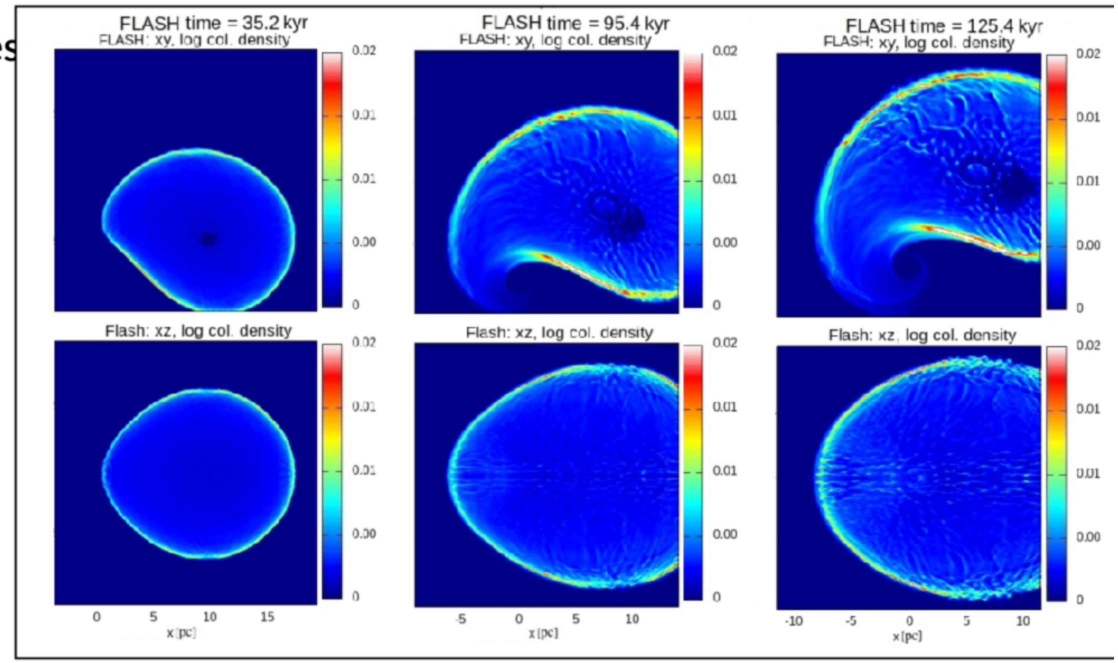
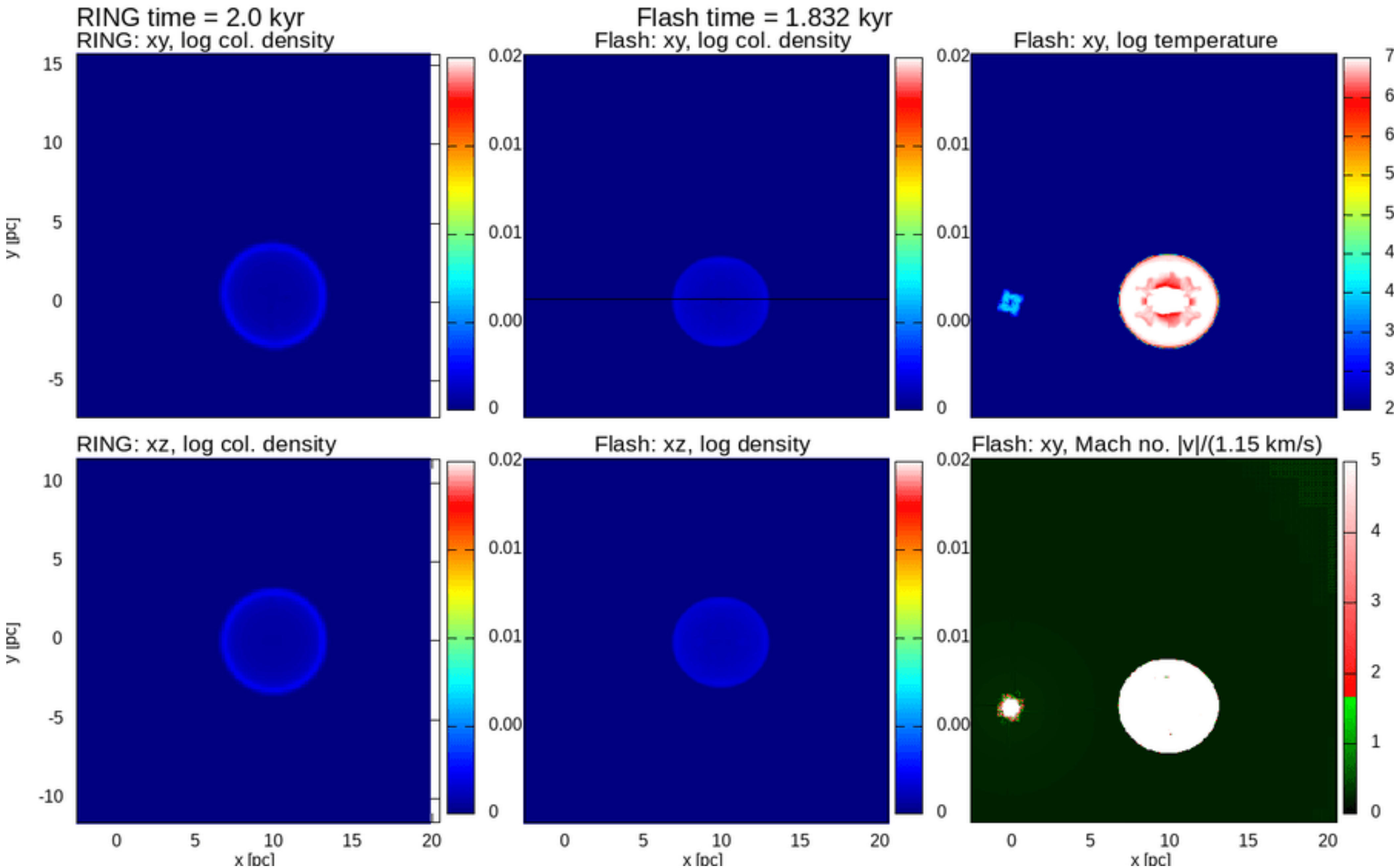
Verification of RING by
assuming multiple ambient medium densities
+ testing turbulent ISM







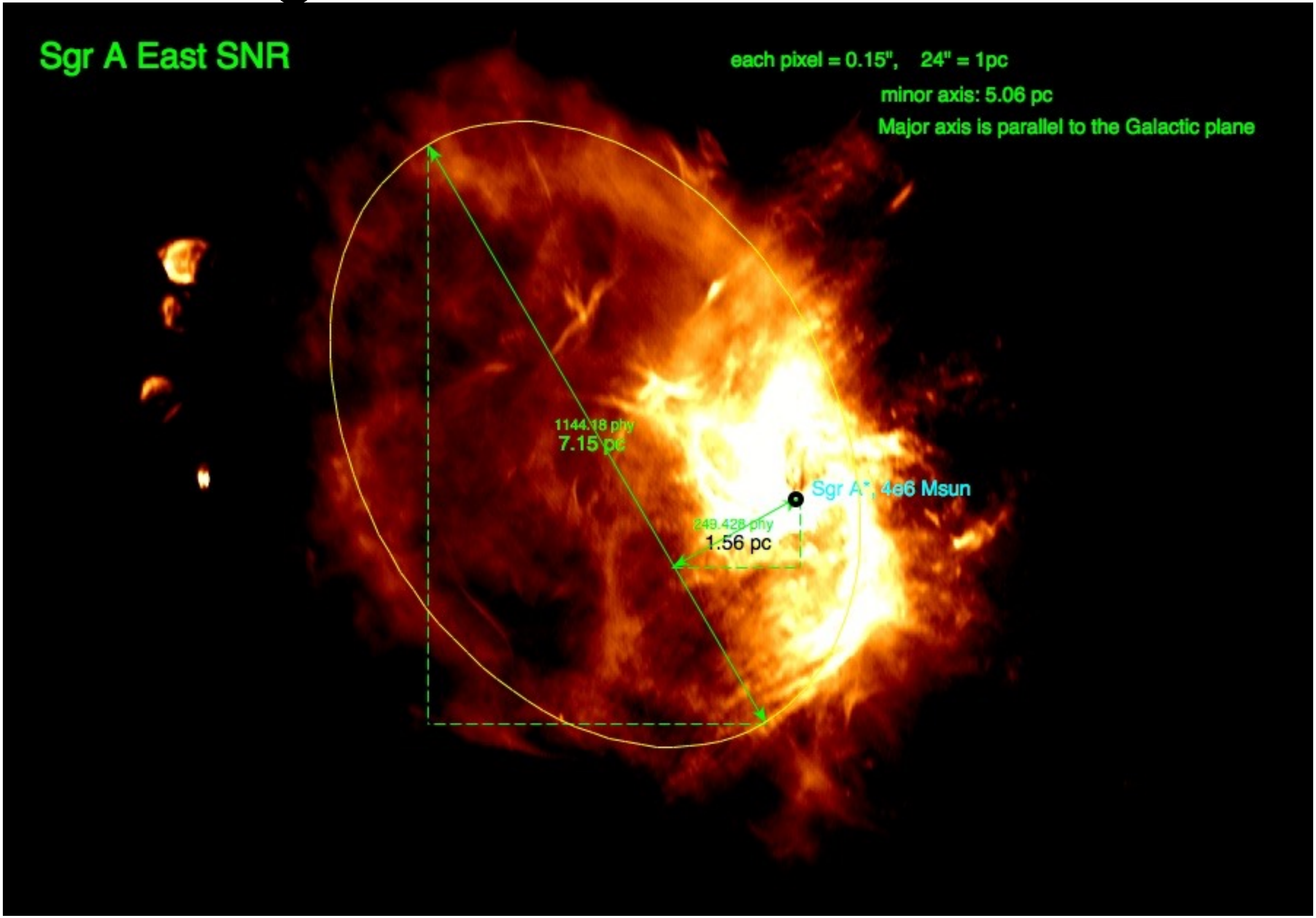
RING time = 2.0 kyr
Flash time = 1.832 kyr
RING: xy, log col. density
Flash: xy, log col. density
Flash: xy, log temperature
RING: xz, log col. density
Flash: xz, log density
Flash: xy, Mach no. |v|/(1.15 km/s)
y [pc]
x [pc]

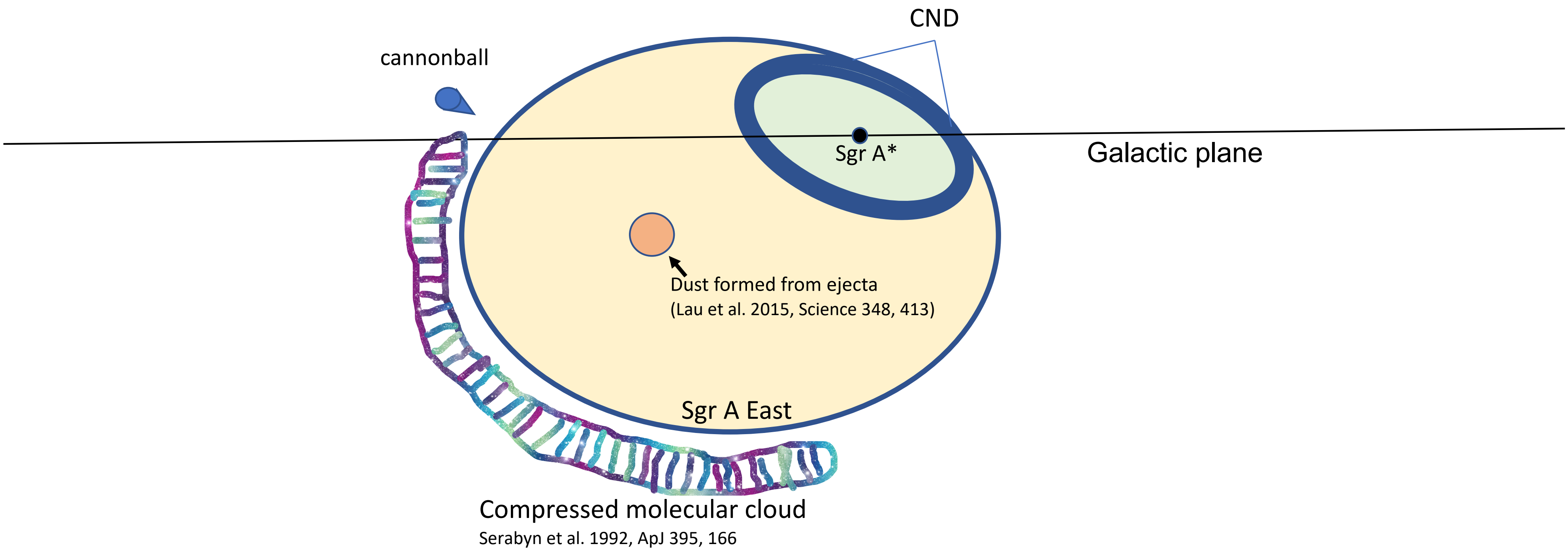
The Wind and The Cloud

How to create Sgr A East

Where did the supernova explode

Sgr A East: 6 cm VLA




CND
cannonball
Galactic plane
Sgr A*
Dust formed from ejecta
(Lau et al. 2015, Science 348, 413)
Sgr A East
Compressed molecular cloud
Serabyn et al. 1992, ApJ 395, 166

How to create Sgr A East
Where did the supernova explode
S. Ehlerová, J. Palouš, M. R. Morris, R. Wünsch, B. Barna & P. Vermont
A&A 668, 124, (2022)

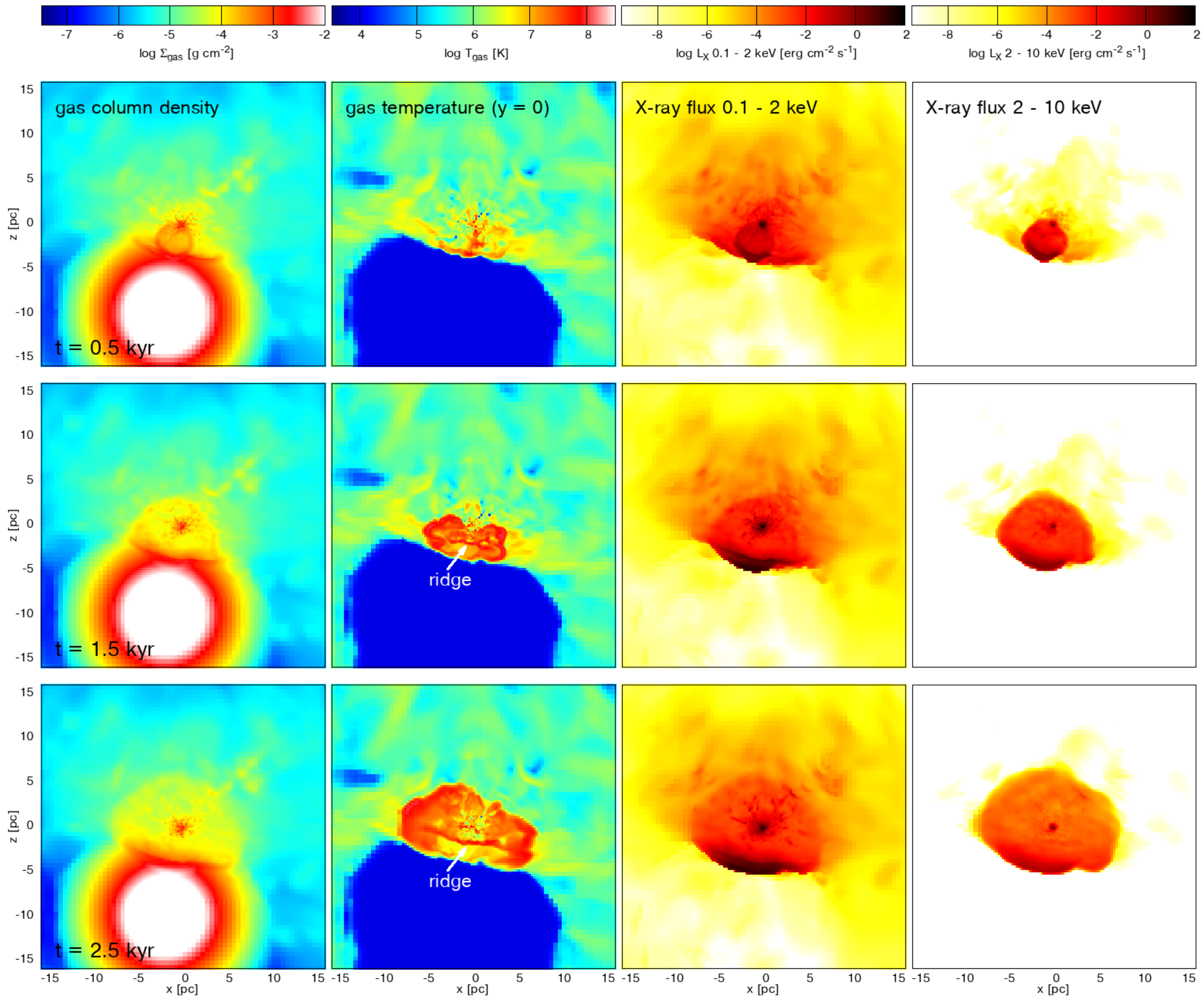
Best solution:

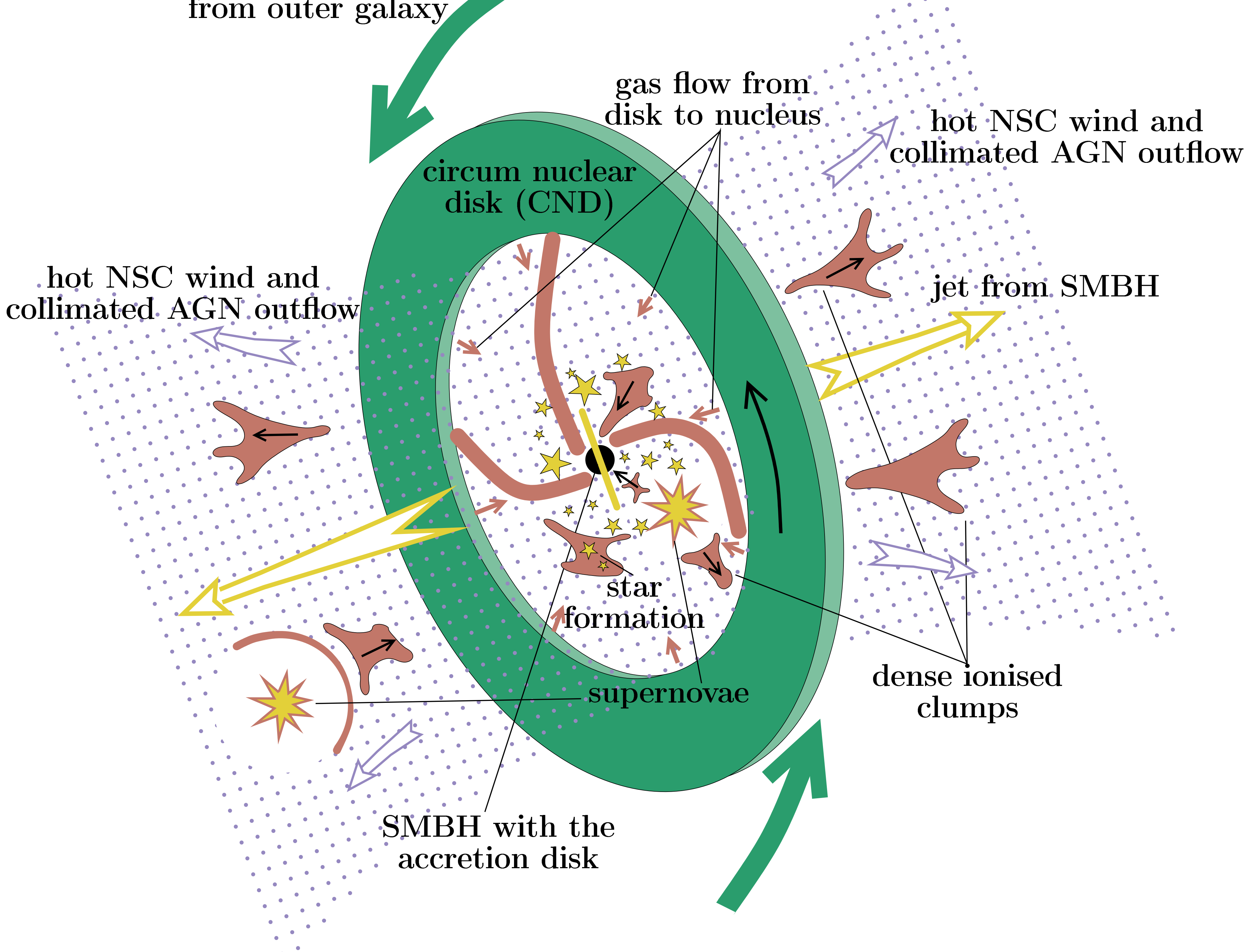
age = 10 kyr

explosion: 3.5 pc from SMBH

3 pc behind and below the Galactic plane

Hydro-simulations of Sgr A East (see the poster by Wunsch et al.)

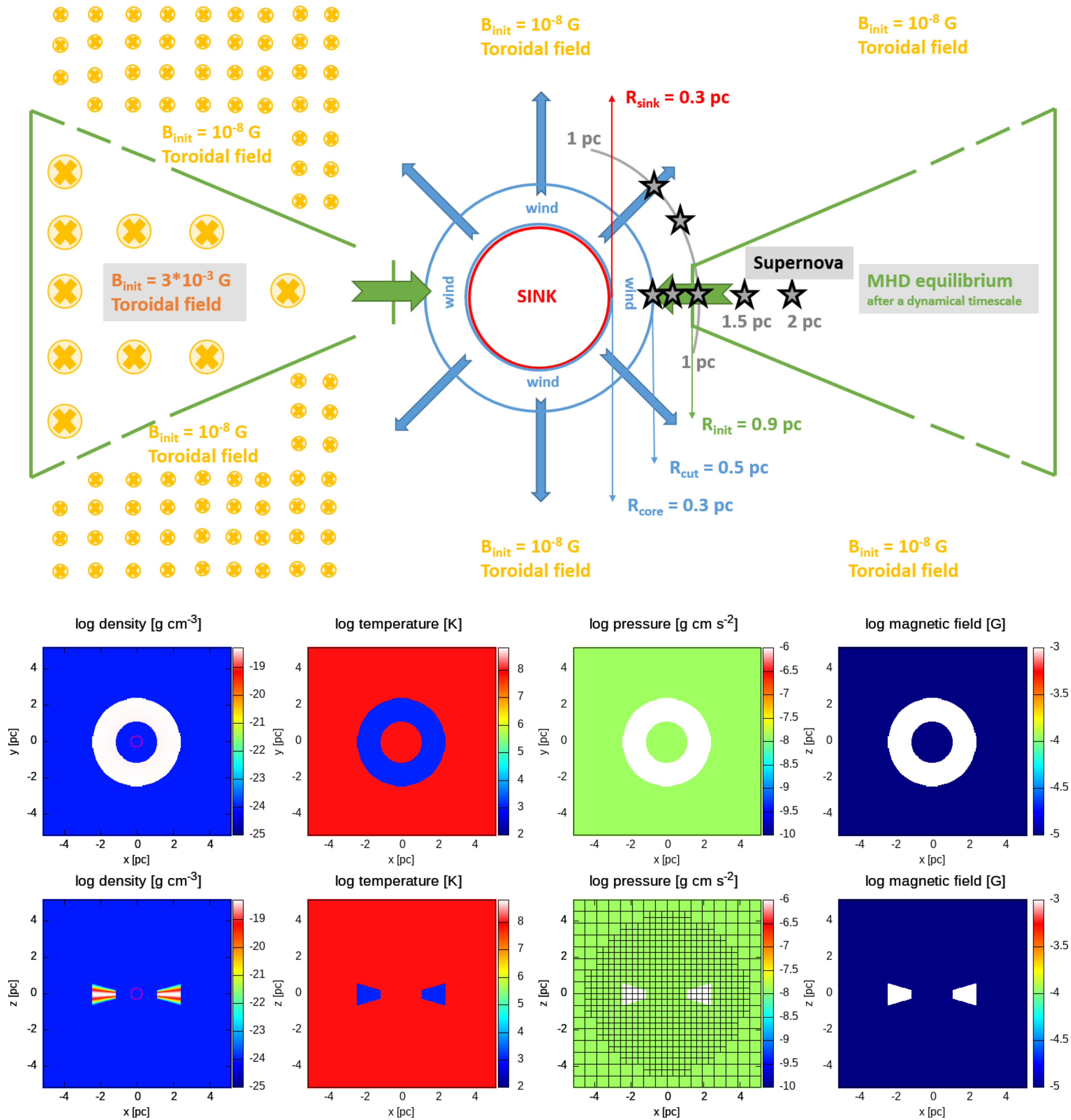




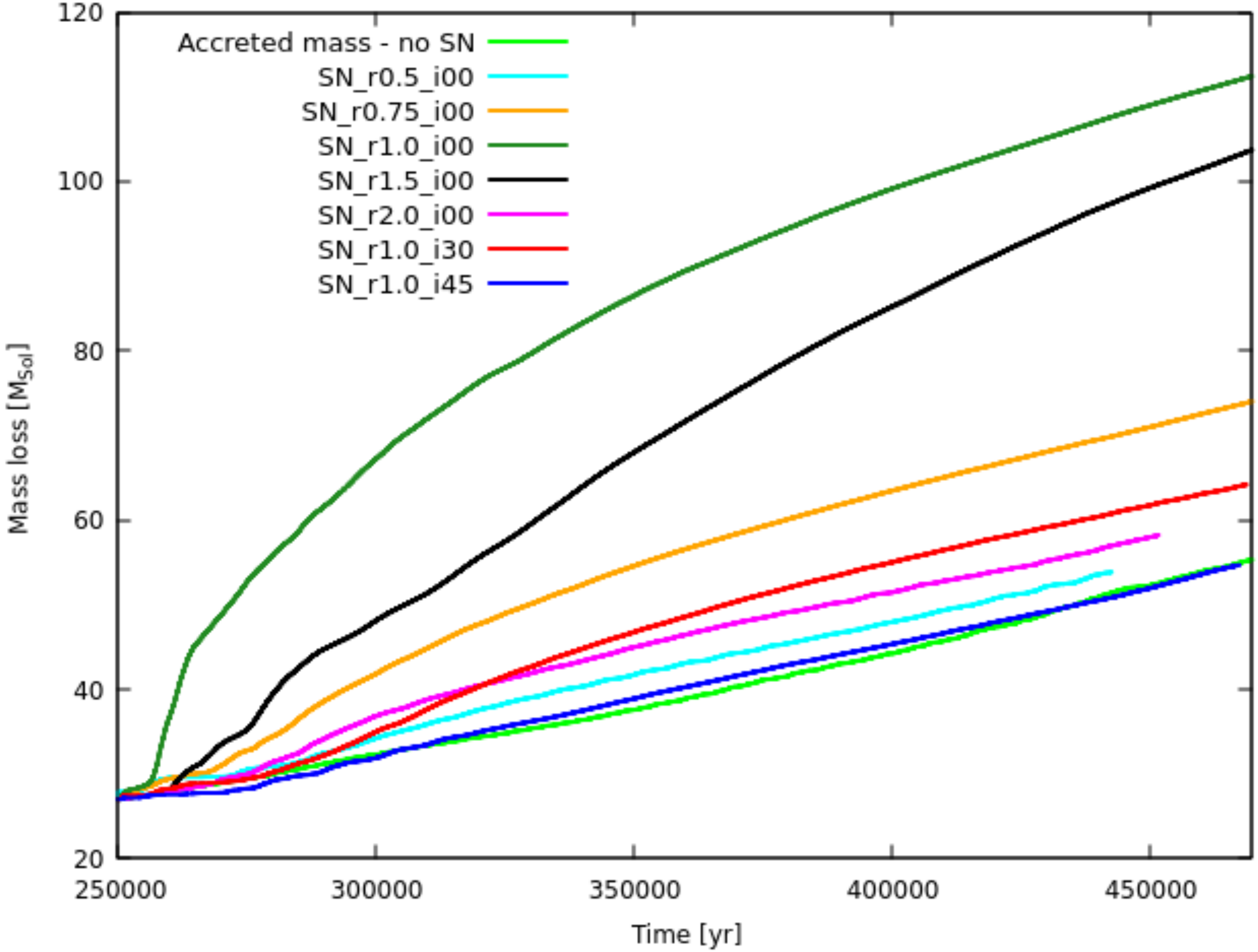
from outer galaxy
gas flow from disk to nucleus
hot NSC wind and collimated AGN outflow
circum nuclear disk (CND)
hot NSC wind and collimated AGN outflow
jet from SMBH
star formation
dense ionised clumps
supernovae
SMBH with the accretion disk

Supernovae in the CND

Barna, B., Wunsch, R., Palous, J.
Morris M. R., Ehlerova, S., and
Vermont, P.
A&A, 692, A92, 2025



B_init = 10^-8 G
Toroidal field
B_init = 10^-8 G
Toroidal field
B_init = 10^-8 G
Toroidal field
R_sink = 0.3 pc
1 pc
wind
wind
wind
wind
SINK
B_init = 3*10^-3 G
Toroidal field
Supernova
MHD equilibrium
after a dynamical timescale
1.5 pc
2 pc
1 pc
R_init = 0.9 pc
R_cut = 0.5 pc
R_core = 0.3 pc
B_init = 10^-8 G
Toroidal field
B_init = 10^-8 G
Toroidal field
B_init = 10^-8 G
Toroidal field
log density [g cm^-3]
log temperature [K]
log pressure [g cm s^-2]
log magnetic field [G]
x [pc]
y [pc]
z [pc]



Accreted mass - no SN
SN_r0.5_i00
SN_r0.75_i00
SN_r1.0_i00
SN_r1.5_i00
SN_r2.0_i00
SN_r1.0_i30
SN_r1.0_i45
Mass loss [M$_{Sol}$]
Time [yr]
120
100
80
60
40
20
250000
300000
350000
400000
450000

Supernova in the CND

- 50 - 100 Msun ejected outside the CND;
- additional mass inflow to the Galactic center of 2 - 70 Msun;
- less mass inflow compared the homogeneous ISM distribution.

Other AGNs

- Ionized region in the central arc second of NGC 1068: Vermont, P., Barna, B., Ehlerová, S., Morris M.R., Palouš, J., Wunsch, R.: A&A 678, A206 (2023);
- A 3D model for the stellar population in the nuclei of NGC 1433, NGC 1566, and NGC 1808: Vermot, P., Palouš, J., Barna, B., Ehlerová, S., Morris, M., and Wunsch, R.: A&A 674, A135 (2023);
- Ultraviolet to Mid-infrared Single Stellar Population high spectral resolution libraries: Vermot, P., Palouš, J., Barna, B., Ehlerová, S., Morris, M.R., and Wunsch: A&A, submitted.

Next steps

- more massive SMBH (NGC 1068, NGC 1433, NGC 1566, NGC 1808 …);
- more massive CND with or without a central cavity;
- mass loading of NSC wind (mini-spiral or other sources);
- tuning SFR & SNR;
- nature of the thermal halo.

The End

Thank you for your attention