Supernovae, ISM & galactic outflows

Prateek Sharma, IISc
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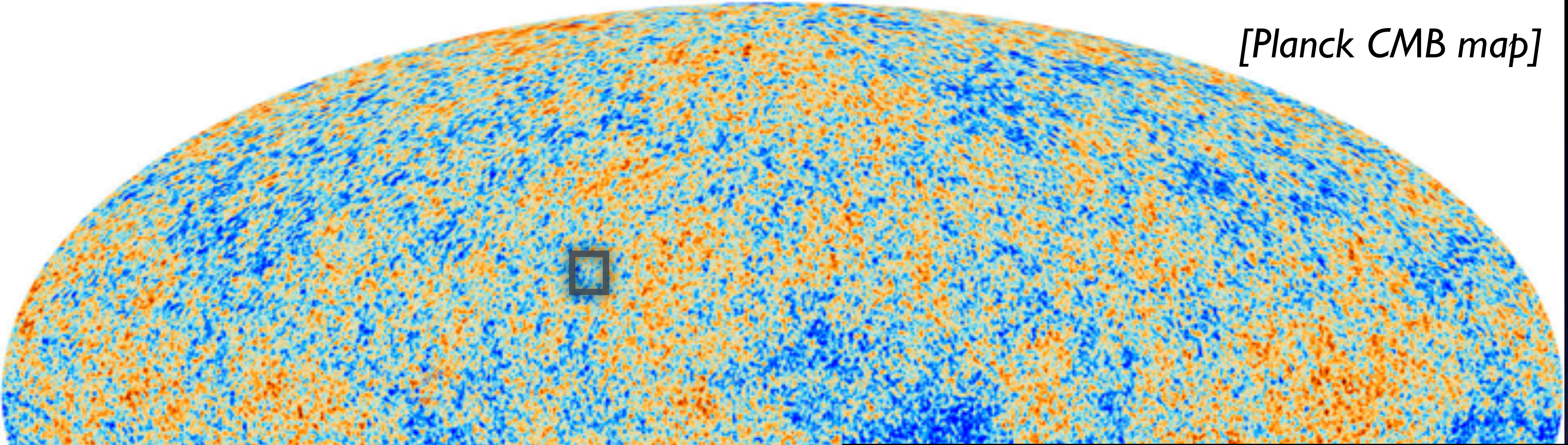
collaborators: Biman Nath, Arpita Roy, Kartick Sarkar, Naveen Yadav

Outline

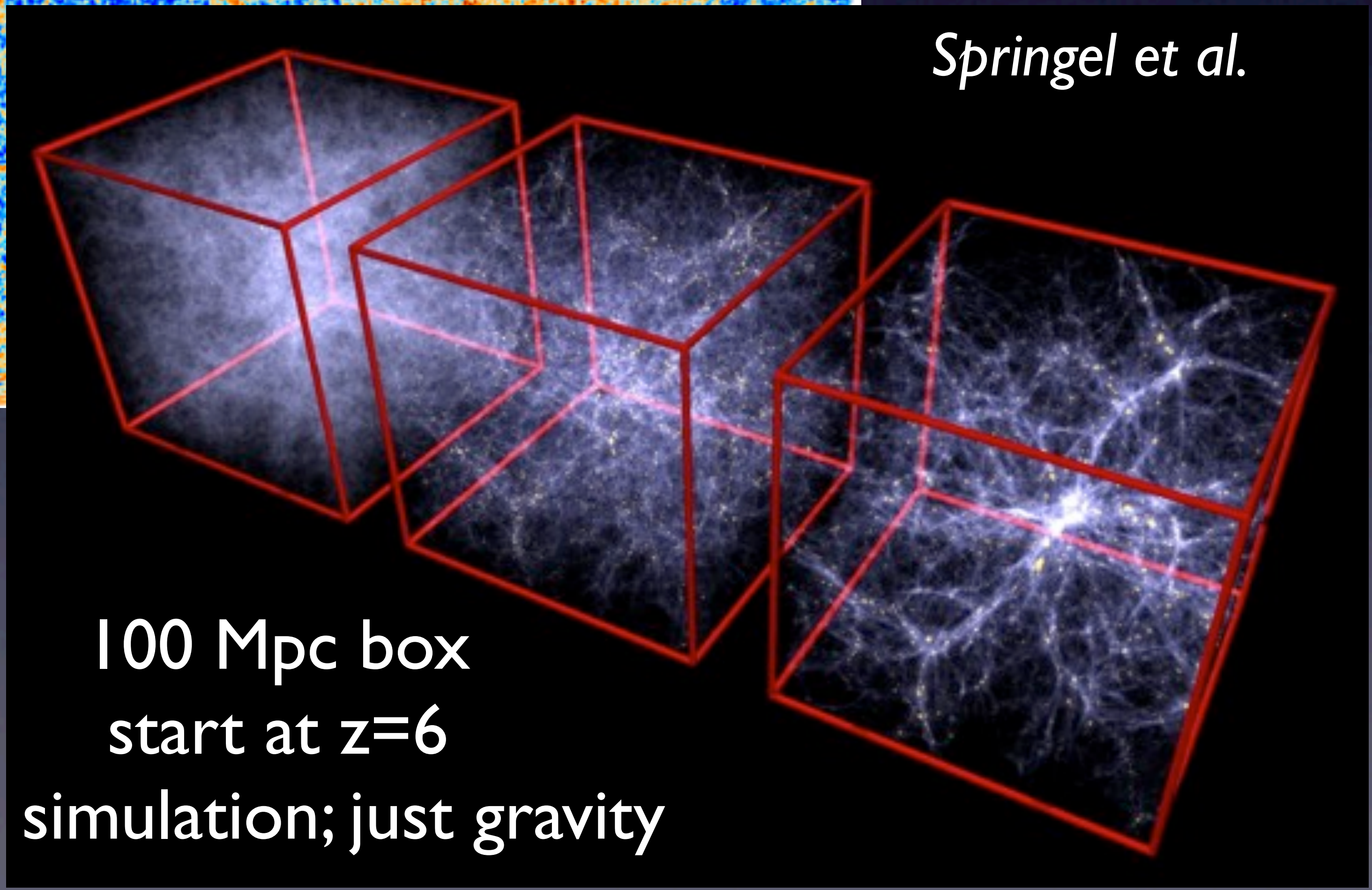
- Galaxy formation in cosmological context
- importance of cooling & feedback
- feedback regulation of star formation
- supernovae to superbubbles & galactic winds
- Fermi bubbles in MW
- escape of LyC photons from dense disks

Cosmological context



[Planck CMB map]

galaxy formation
due to gravitational
instability seeded by
CMB perturbations

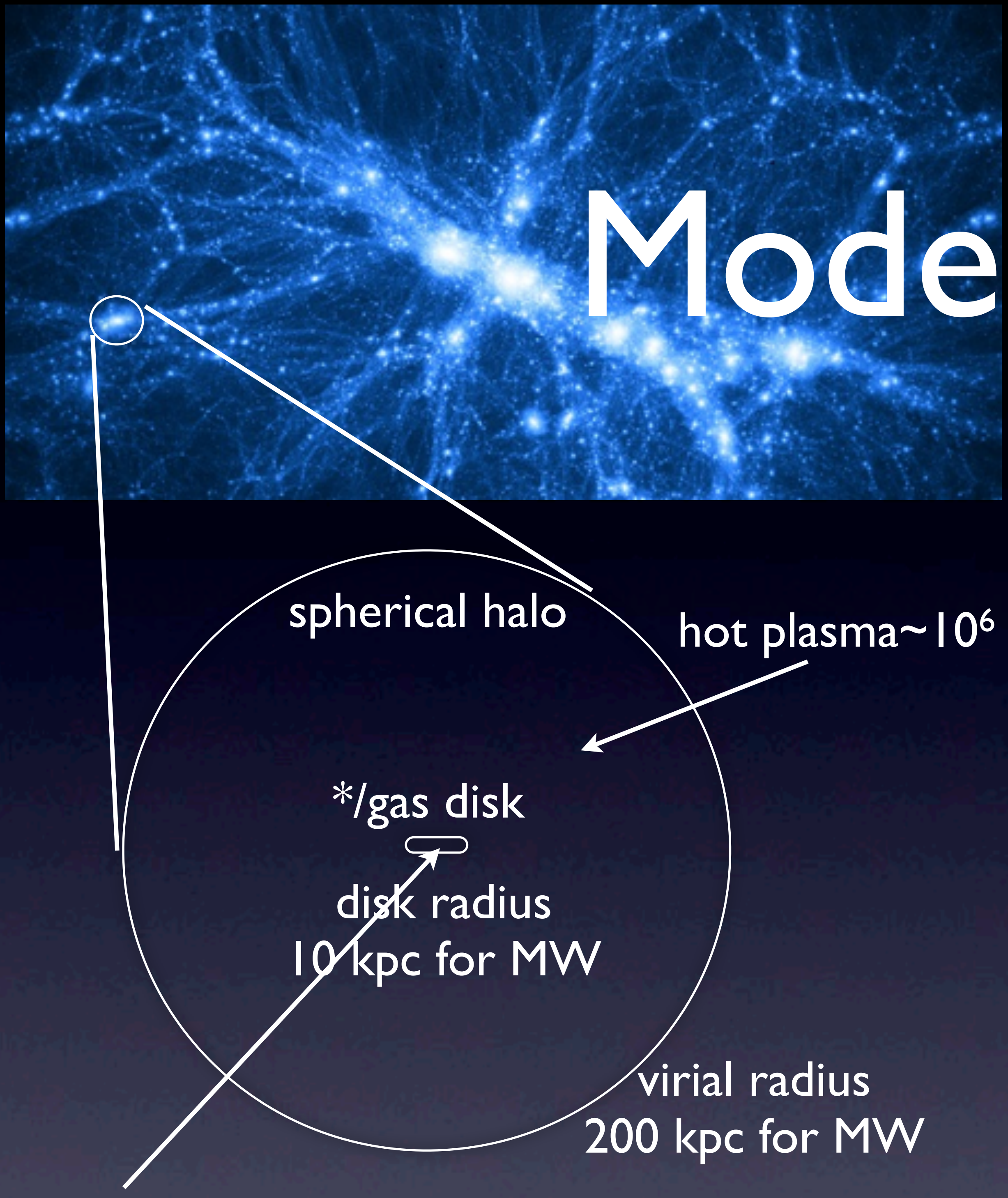


Springel et al.

galaxies form in overdense
sheets, filaments & halos

100 Mpc box
start at z=6
DM simulation; just gravity

Model for GF



spherical halo

hot plasma~10^6 K

*/gas disk

disk radius
10 kpc for MW

virial radius
200 kpc for MW

BH at center

gas cools and condenses into central galaxy
leaving behind hot gas with long cooling time

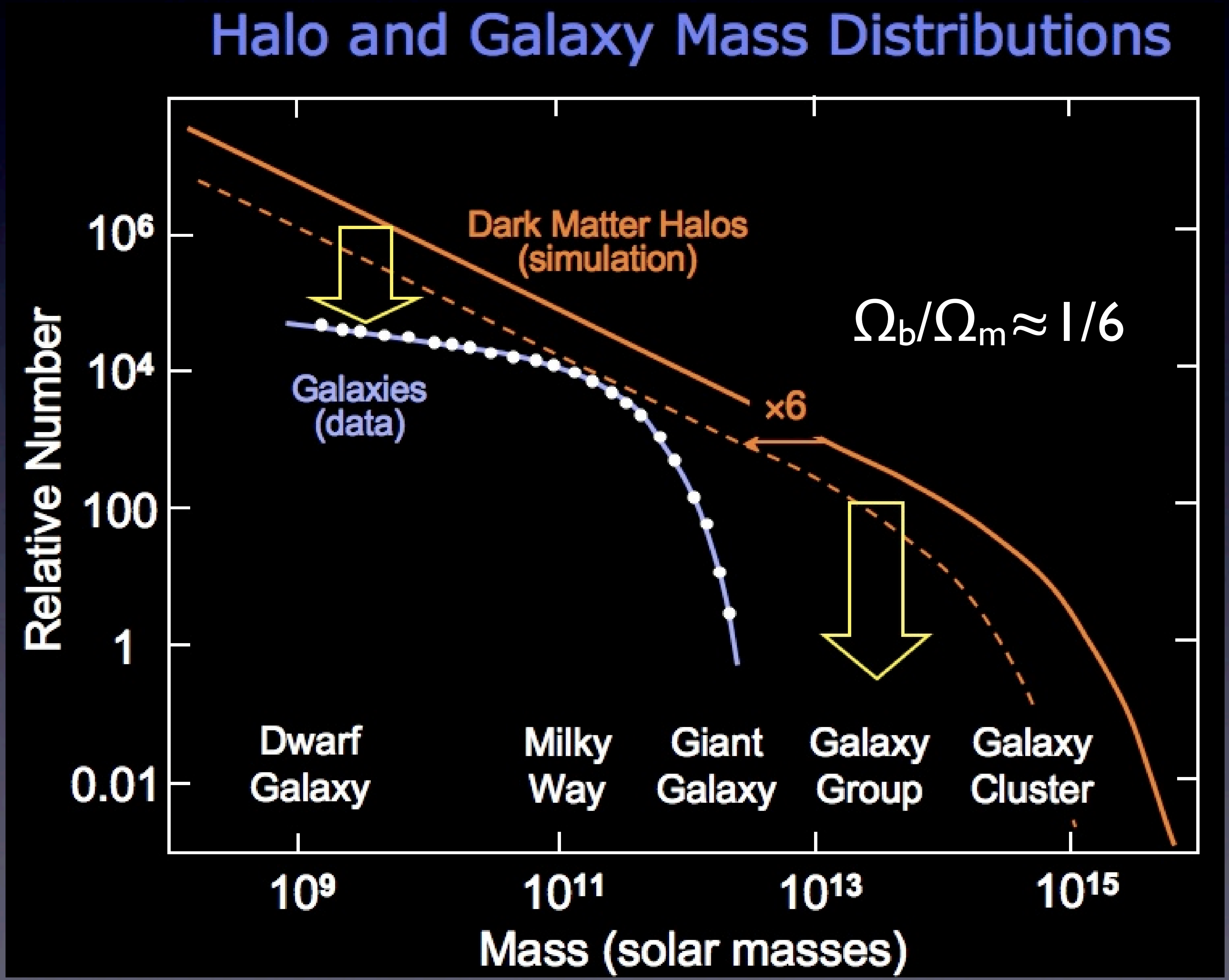
DM halo & hot gas extends much farther out
compared to the visible disk

How does the distribution of baryons
depend on the halo mass?
fraction of mass in stars, hot gas, cold gas, ...

1 kpc~$3\text{x}10^{21}$ cm

structure of hot gas, disk as a function of halo mass

DM halos vs. galaxies



https://www.astro.virginia.edu/class/whittle/astr553/Topic04/t4_LF_origin_2.jpg

need to understand galaxy distribution (i.e., stars) vs. DM halo distribution

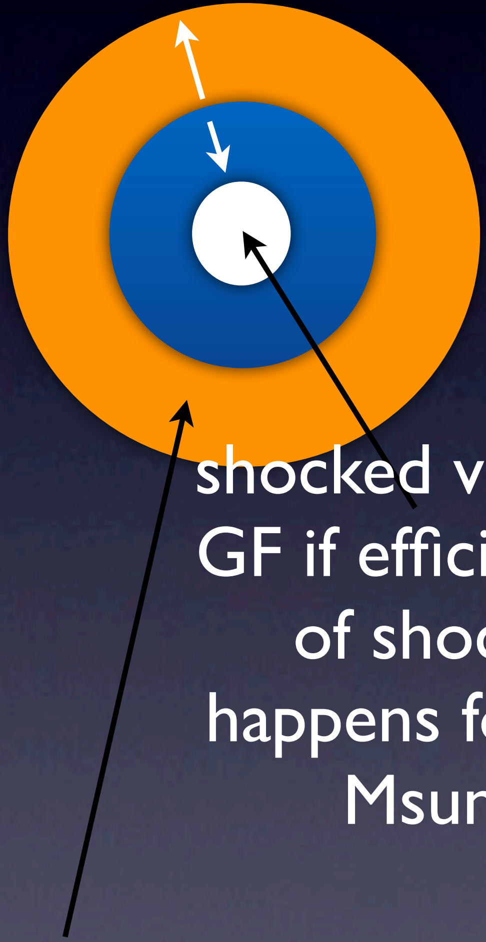
cooling picks out a sweet spot for galaxy formation

feedback is needed to suppress SF in both small and large halos

small: stellar/SN feedback
large: AGN/BH feedback

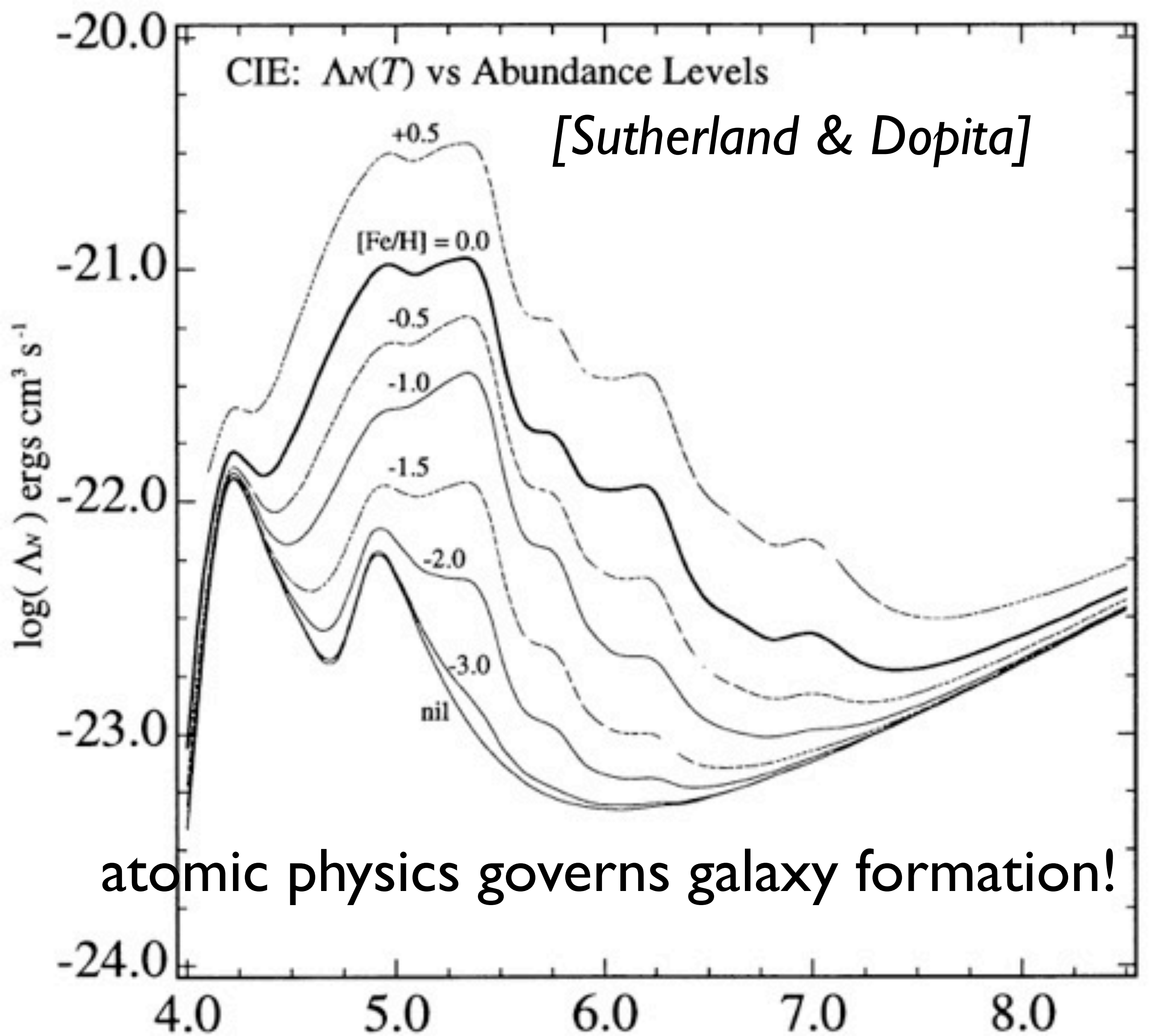
Physical model

no mass-scale picked out by gravitational physics
self-similarity is broken by cooling



shocked virial plasma;
GF if efficient cooling
of shocked gas
happens for 10^9-10^{12}
Msun halos

Hubble expansion
at large scales

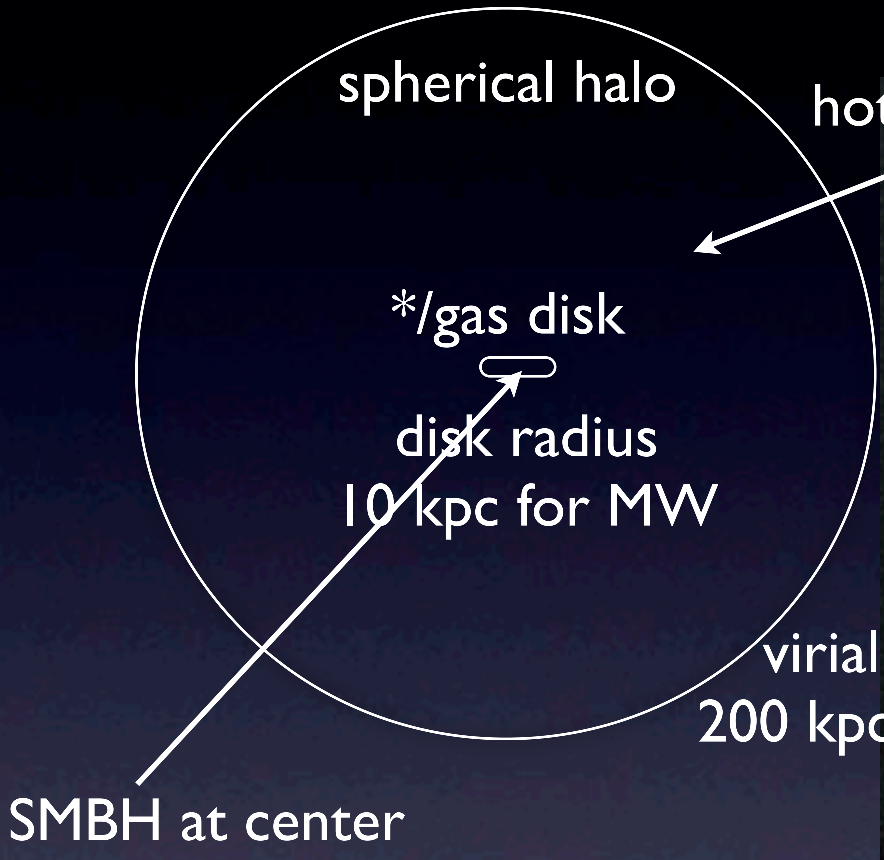


[Sutherland & Dopita]

atomic physics governs galaxy formation!

$\log_{10}T$

Scales in the problem



spherical halo

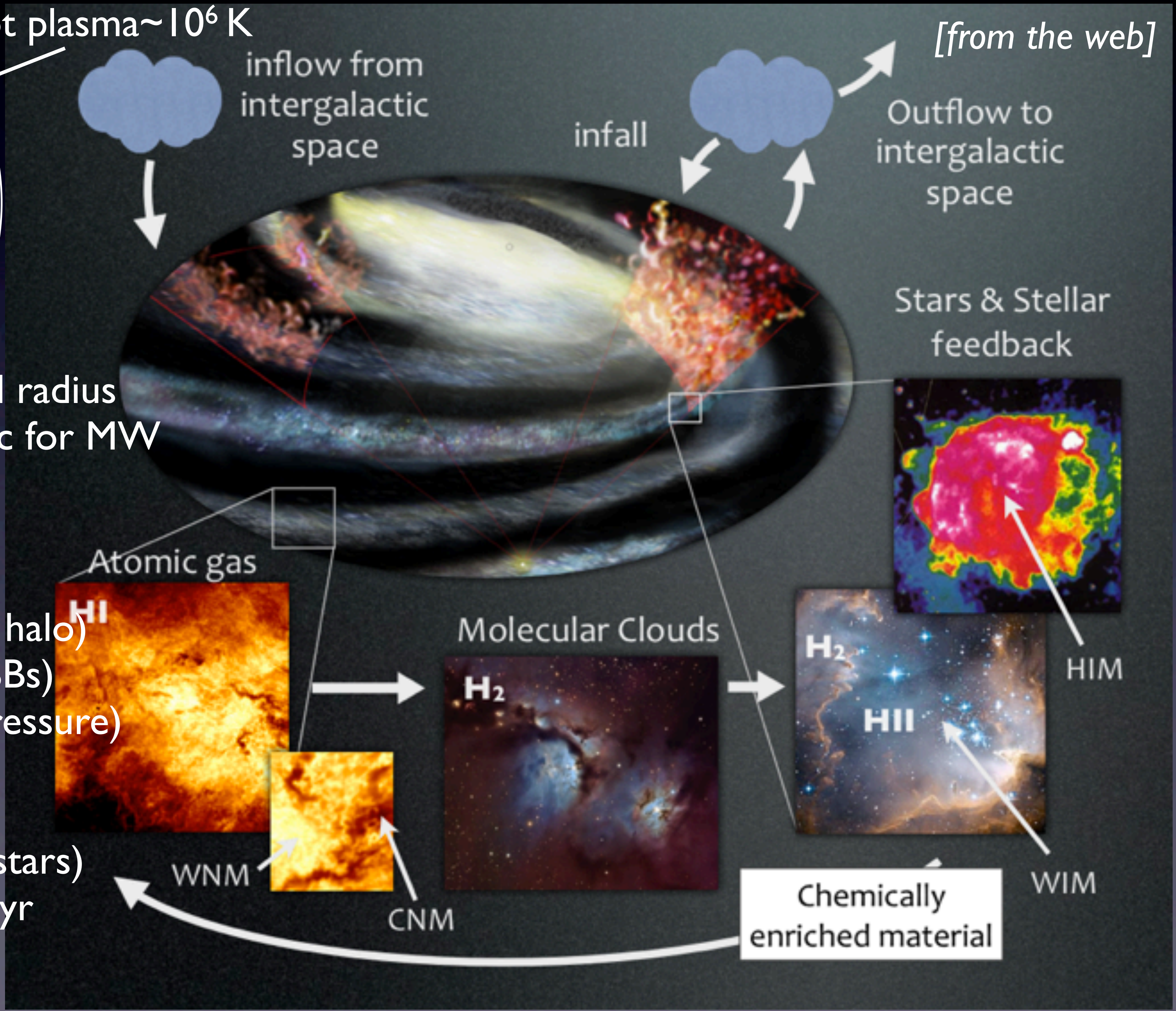
hot plasma~10^6 K

*/gas disk

disk radius
10 kpc for MW

virial radius
200 kpc for MW

SMBH at center



[from the web]

halo scale - 200 kpc - 1 Gyr (hot halo)
galaxy size - 10 kpc - 50 Myr (SBs)
GMCs - 100 pc - 1 Myr (UV, rad. pressure)

SN start in 5 Myr (lifetime of O stars)
isolated SN fizzle out in <1 Myr
need superbubbles!

What's needed?

to unbind gas from the disk & control SF

spherical halo

*/gas disk

disk radius
10 kpc for MW

energy: energy input rate > BE/(dynamical time)

$$\dot{E}_{\rm SN} > f_g \frac{GM^2}{r(r/\sigma)}$$

$$\sigma^2 \approx GM/2r => \dot{E}_{\rm SN} > \frac{4f_g}{G}\sigma^5$$

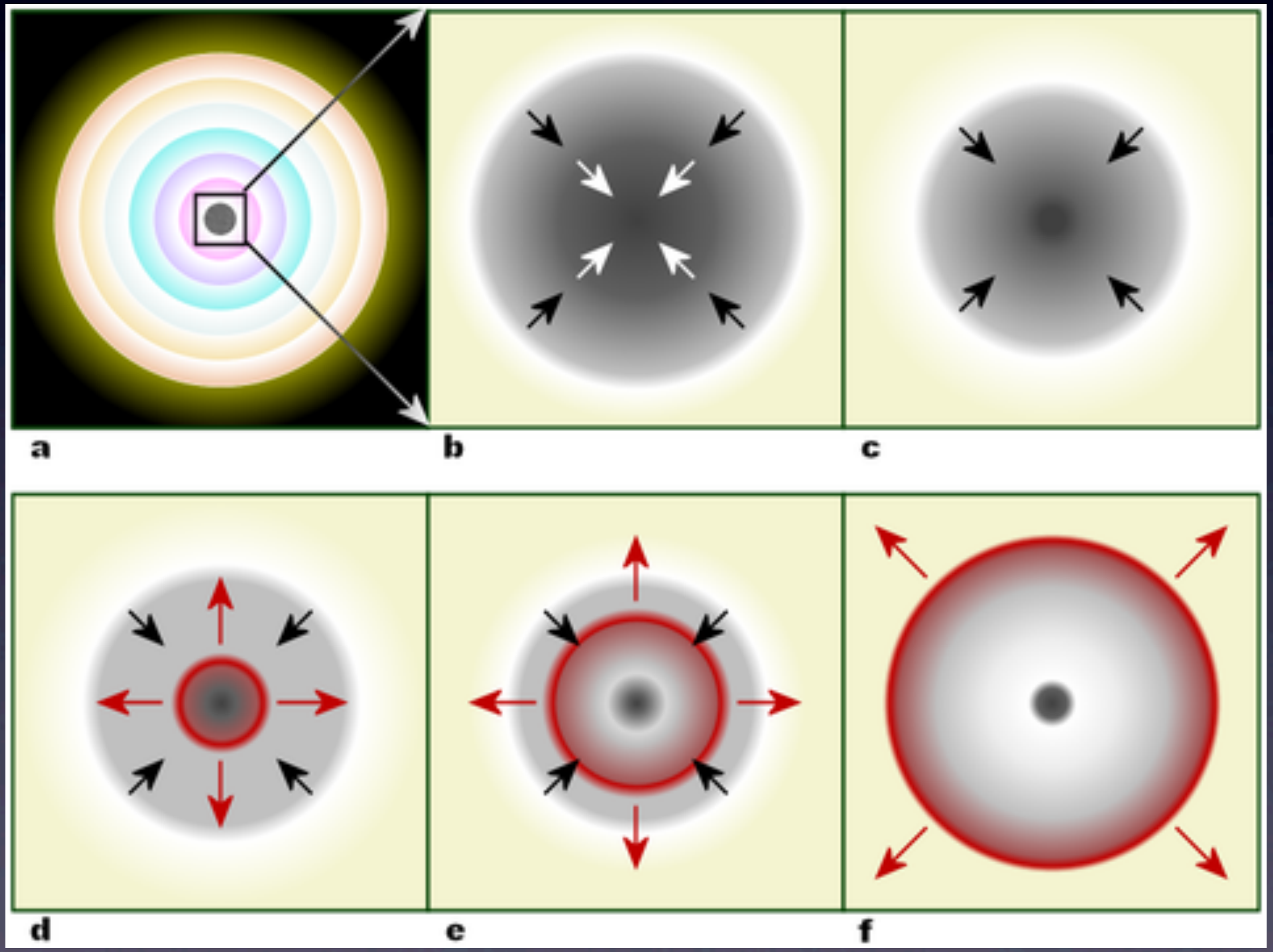
momentum: radiation force > gravity

$$\frac{L}{c} > f_g \frac{GM^2}{r^2} => L > \frac{4f_g}{G}\sigma^4 c$$

easy to push gas out of the shallow potential wells with small σ
SN thermal/energy feedback important if cooling losses are overcome
SBs can retain substantial energy!

CC Supernova

[Wikipedia]



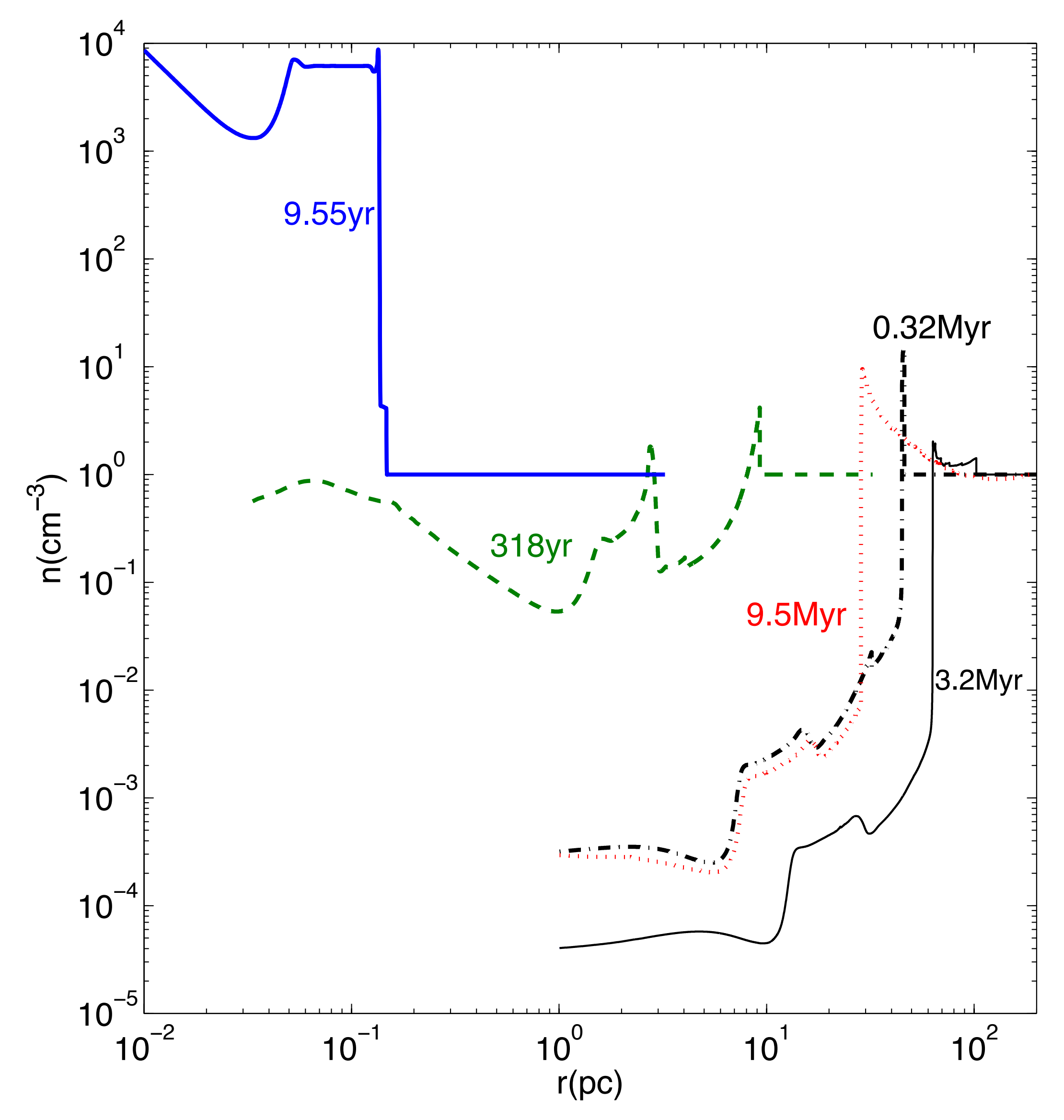
SN happens at the end stage of massive stars
1 SN for every ~150 M_{sun} of star formation

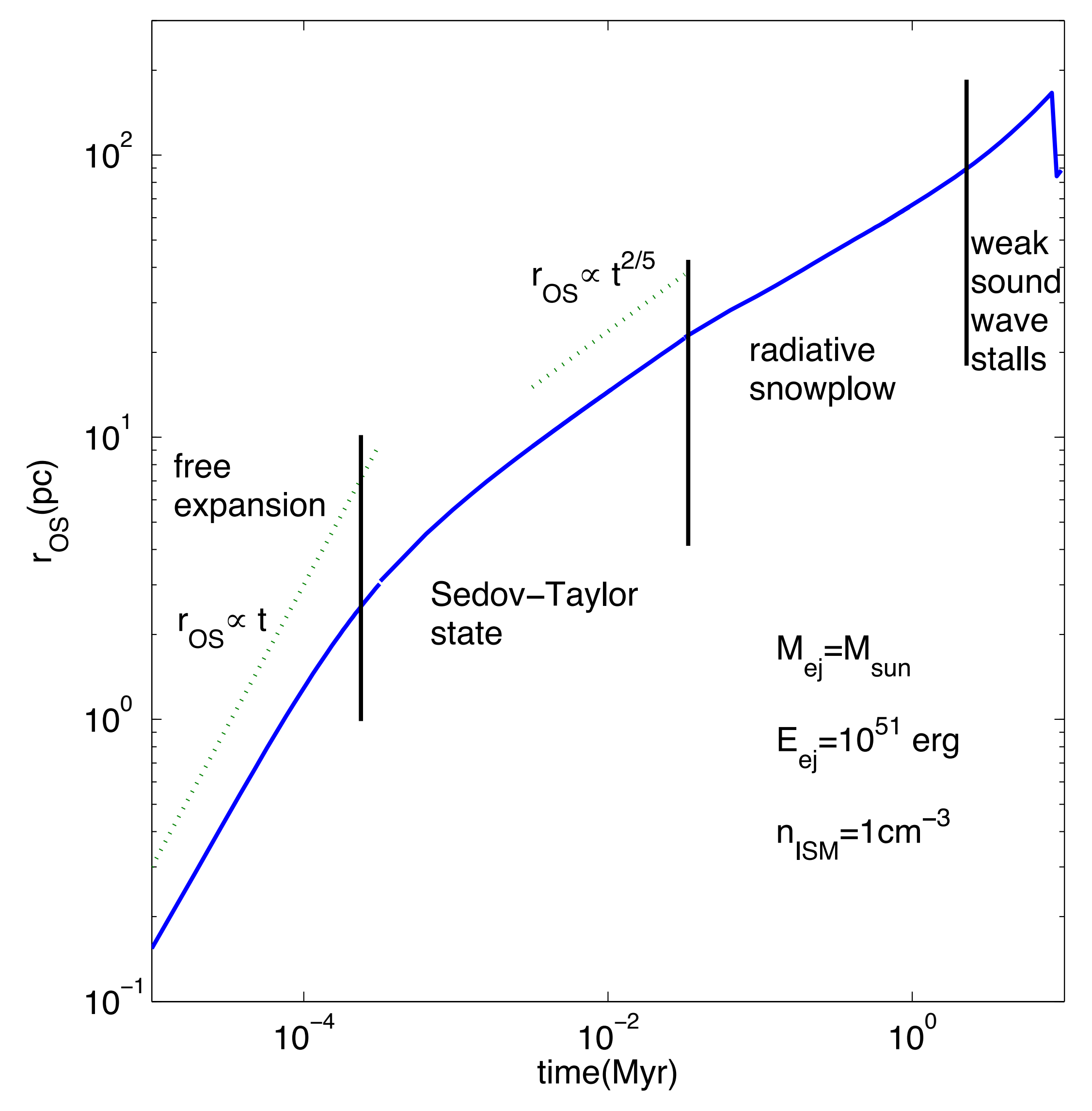
each SN produces ~10^{51} erg

mechanical energy produced per gram of SF: ~10^{15} erg/g ~10^{-6} c^2

SN evolution

interested in global (≳kpc) scale feedback, not inside molecular clouds





isolated SNe dissipate after a few Myr, 100 pc;
dynamical timescale is ~ 100 Myr, therefore isolated SNe insufficient

Stars form in clusters

stars form in clusters of size ~ 10s pc
supernovae go off in dilute bubbles created by previous SN can retain energy over 50 Myr, enough to unbind disk gas

30 pc, R136 in LMC

young stars buried in dust clouds

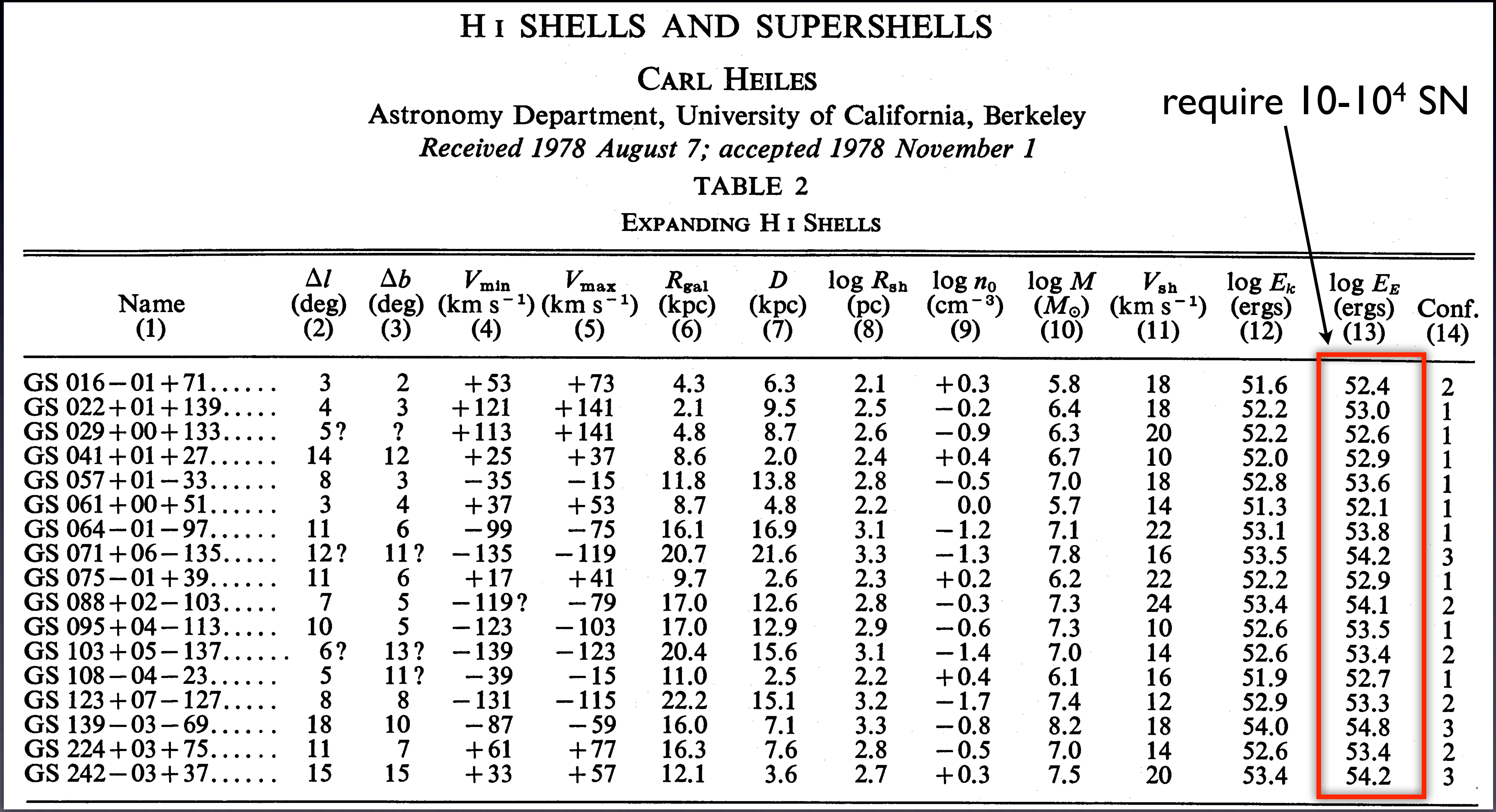
SCs put in almost constant mechanical luminosity

$$\frac{dE}{dt} \propto \frac{dn(M)}{dM}\frac{dM}{dt} \propto M^{-2.35}\frac{M}{t_{\rm MS}}$$

$$t_{\rm MS} \approx 30 \ {\rm Myr} \left(\frac{M}{10 M_\odot}\right)^{-1.6}$$

$$\frac{dE}{dt} \propto t^{2.35/1.6} t^{-1/1.16-1} \propto t^{-0.16}$$

HI shells & supershells



H I SHELLS AND SUPERSHELLS

CARL HEILES
Astronomy Department, University of California, Berkeley

Received 1978 August 7; accepted 1978 November 1

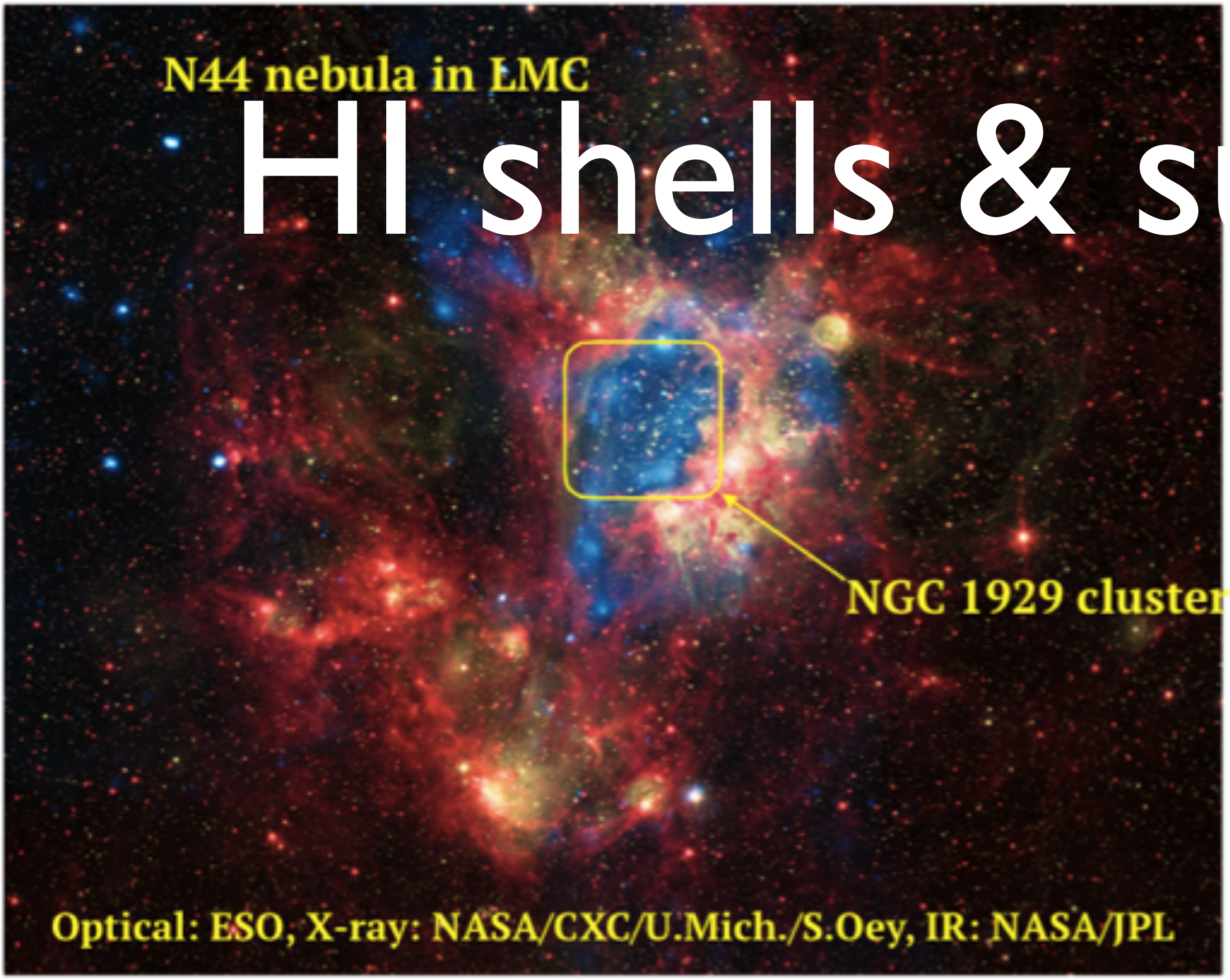
TABLE 2

EXPANDING H I SHELLS

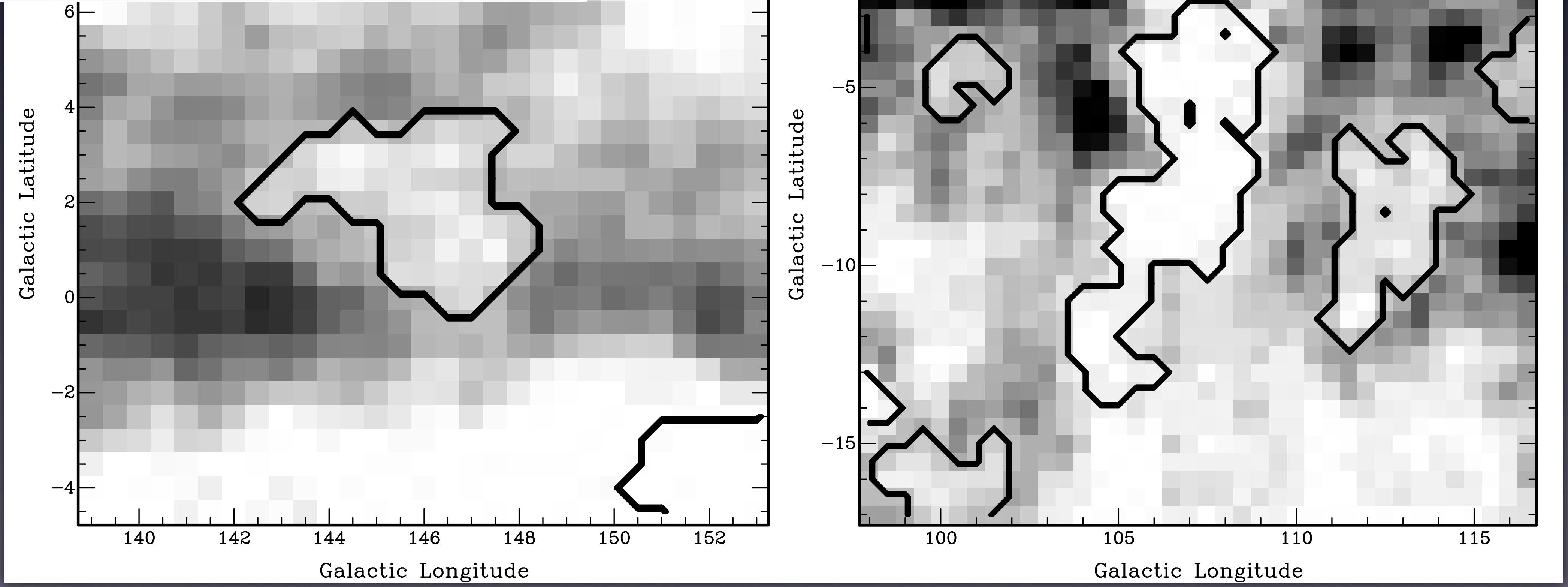
Name (1)	Δl (deg) (2)	Δb (deg) (3)	$V_{\rm min}$ (km s^{-1}) (4)	$V_{\rm max}$ (km s^{-1}) (5)	$R_{\rm gal}$ (kpc) (6)	D (kpc) (7)	log $R_{\rm sh}$ (pc) (8)	log n_0 (cm^{-3}) (9)	log M ($M_\odot$) (10)	$V_{\rm sh}$ (km s^{-1}) (11)	log E_k (ergs) (12)	log E_E (ergs) (13)	Conf. (14)
GS 016−01+71......	3	2	+53	+73	4.3	6.3	2.1	+0.3	5.8	18	51.6	52.4	2
GS 022+01+139.....	4	3	+121	+141	2.1	9.5	2.5	−0.2	6.4	18	52.2	53.0	1
GS 029+00+133.....	5?	?	+113	+141	4.8	8.7	2.6	−0.9	6.3	20	52.2	52.6	1
GS 041+01+27......	14	12	+25	+37	8.6	2.0	2.4	+0.4	6.7	10	52.0	52.9	1
GS 057+01−33......	8	3	−35	−15	11.8	13.8	2.8	−0.5	7.0	18	52.8	53.6	1
GS 061+00+51......	3	4	+37	+53	8.7	4.8	2.2	0.0	5.7	14	51.3	52.1	1
GS 064−01−97......	11	6	−99	−75	16.1	16.9	3.1	−1.2	7.1	22	53.1	53.8	1
GS 071+06−135.....	12?	11?	−135	−119	20.7	21.6	3.3	−1.3	7.8	16	53.5	54.2	3
GS 075−01+39......	11	6	+17	+41	9.7	2.6	2.3	+0.2	6.2	22	52.2	52.9	1
GS 088+02−103.....	7	5	−119?	−79	17.0	12.6	2.8	−0.3	7.3	24	53.4	54.1	2
GS 095+04−113.....	10	5	−123	−103	17.0	12.9	2.9	−0.6	7.3	10	52.6	53.5	1
GS 103+05−137......	6?	13?	−139	−123	20.4	15.6	3.1	−1.4	7.0	14	52.6	53.4	2
GS 108−04−23......	5	11?	−39	−15	11.0	2.5	2.2	+0.4	6.1	16	51.9	52.7	1
GS 123+07−127.....	8	8	−131	−115	22.2	15.1	3.2	−1.7	7.4	12	52.9	53.3	2
GS 139−03−69......	18	10	−87	−59	16.0	7.1	3.3	−0.8	8.2	18	54.0	54.8	3
GS 224+03+75......	11	7	+61	+77	16.3	7.6	2.8	−0.5	7.0	14	52.6	53.4	2
GS 242−03+37......	15	15	+33	+57	12.1	3.6	2.7	+0.3	7.5	20	53.4	54.2	3

require 10-10^4 SN

HI shells & superbubbles

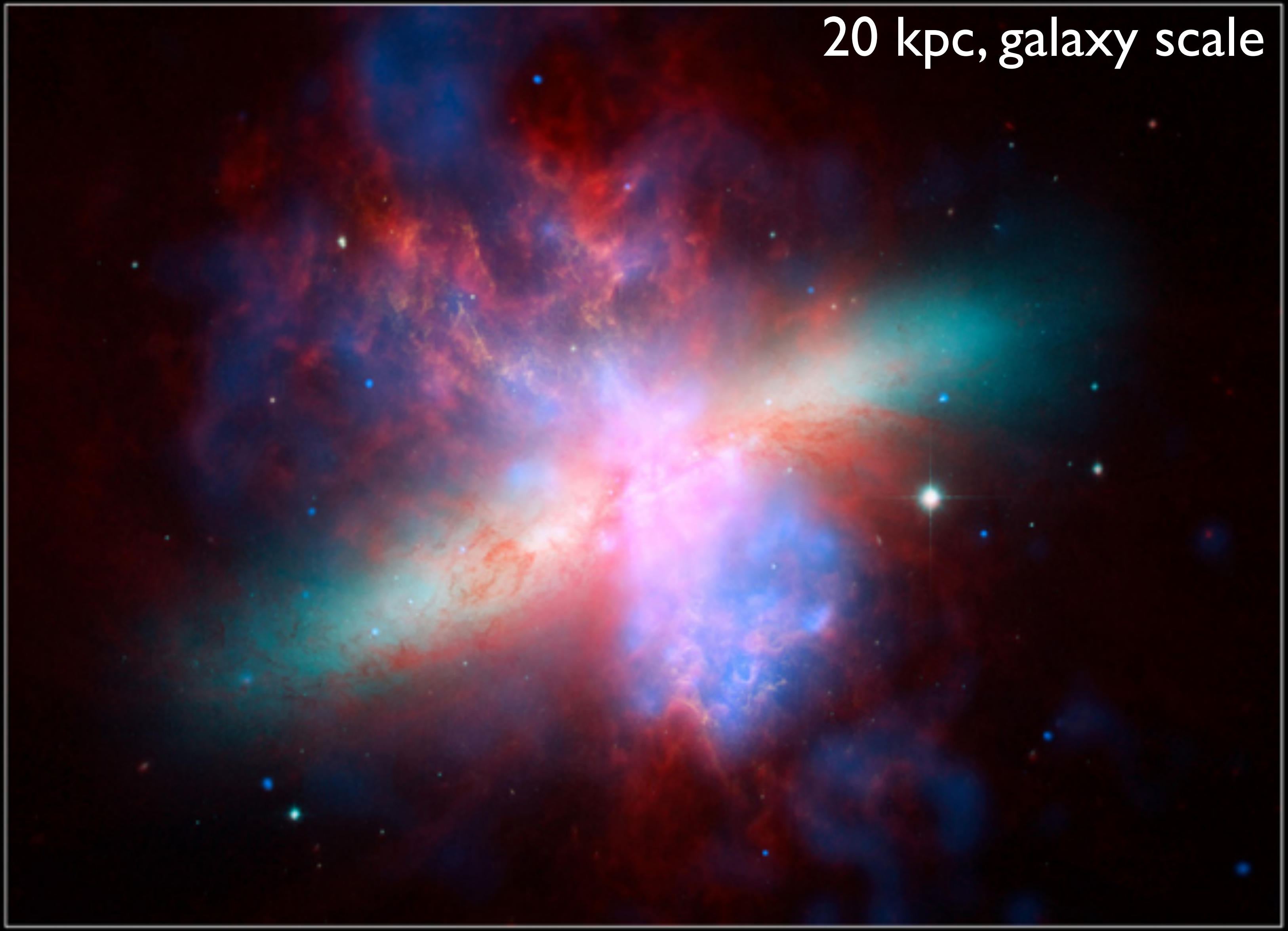


Optical: ESO, X-ray: NASA/CXC/U.Mich./S.Oey, IR: NASA/JPL



[Ehlerova & Palous 2005]

Overlapping SNe feedback



20 kpc, galaxy scale

Active Galaxy M82

Hubble Space Telescope • Chandra X-Ray Observatory • Spitzer Space Telescope

NASA, ESA, CXC, and JPL-Caltech

STScI-PRC06-14c

200 super star clusters within 200 pc of core

overlapping SN input mechanical energy & lead to galactic winds

SB evolution

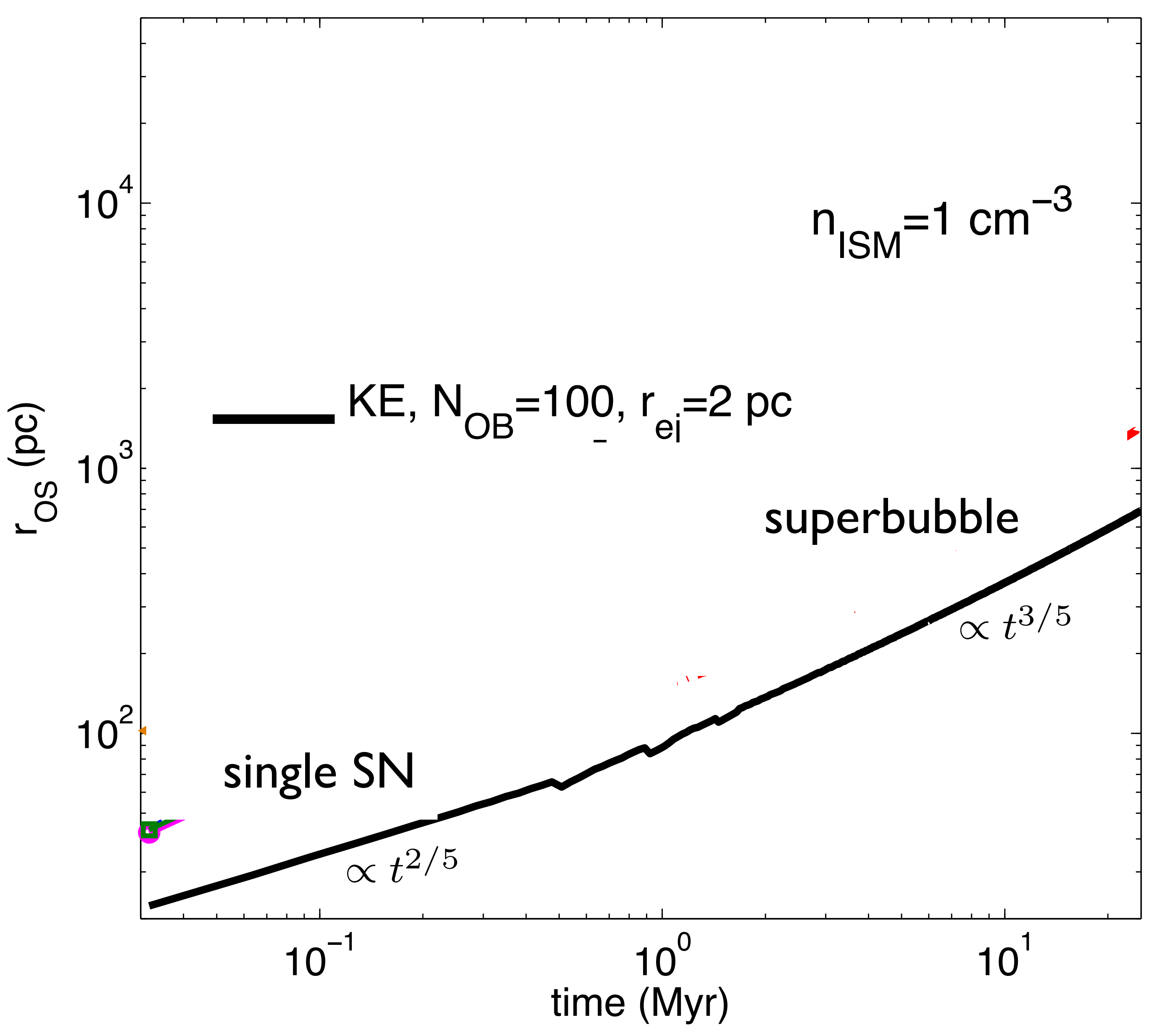
10^{51} erg in form of ejecta KE is put in at r=0 after every $t_{\rm SN}$ in uniform ISM

classic dimensional argument:

$$R_{\rm SN} = \left(\frac{Et^2}{\rho}\right)^{1/5}$$

$$R_{\rm SB} = \left(\frac{Lt^3}{\rho}\right)^{1/5}$$

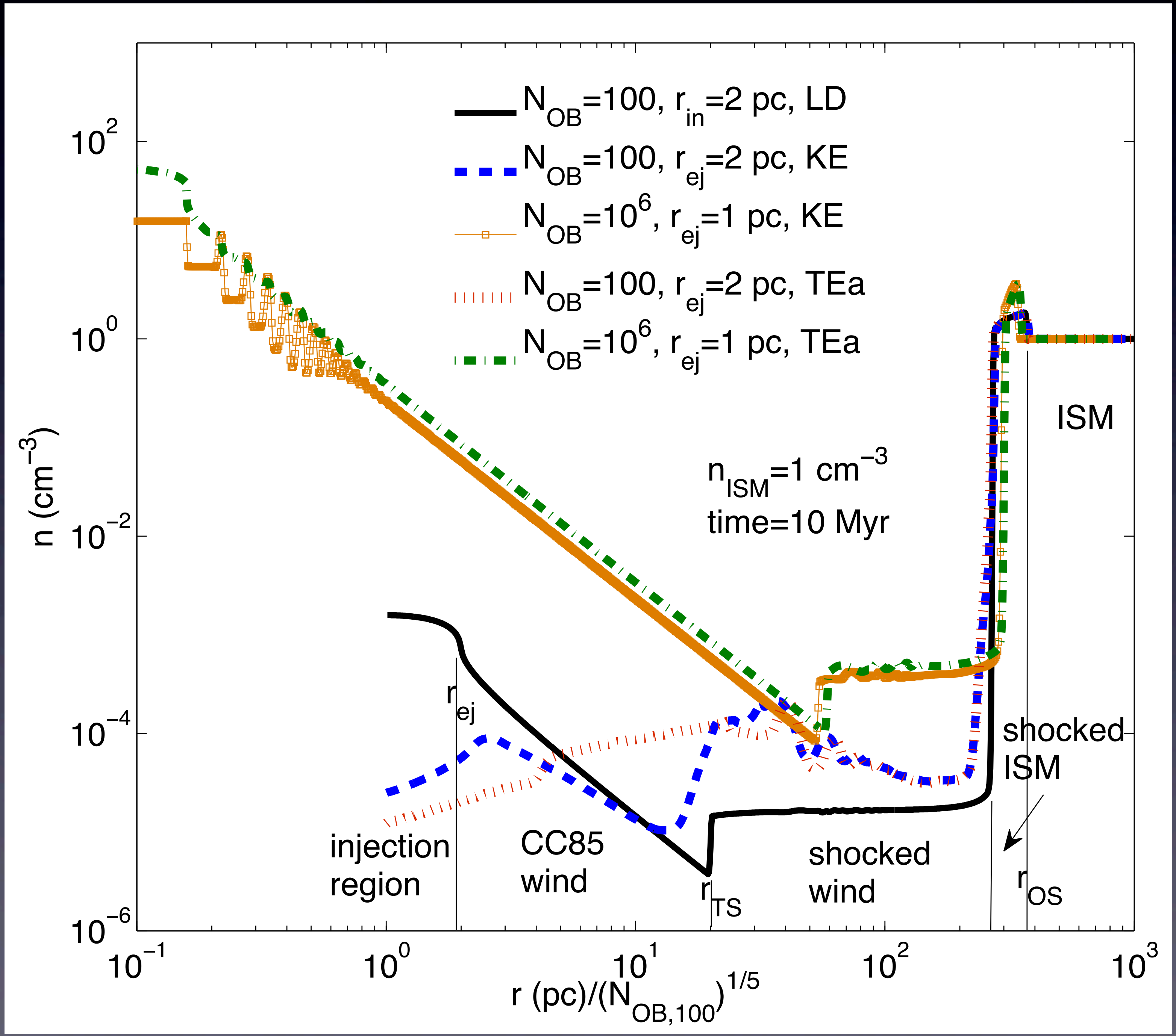
[Sharma et al. 2014]



NOB: number of OB stars/SNe over 30 Myr; $N_{\rm OB}$=100 corresponds to 10^{38} erg s^{-1}

Wind-bubble structure

[Sharma et al. 2014]



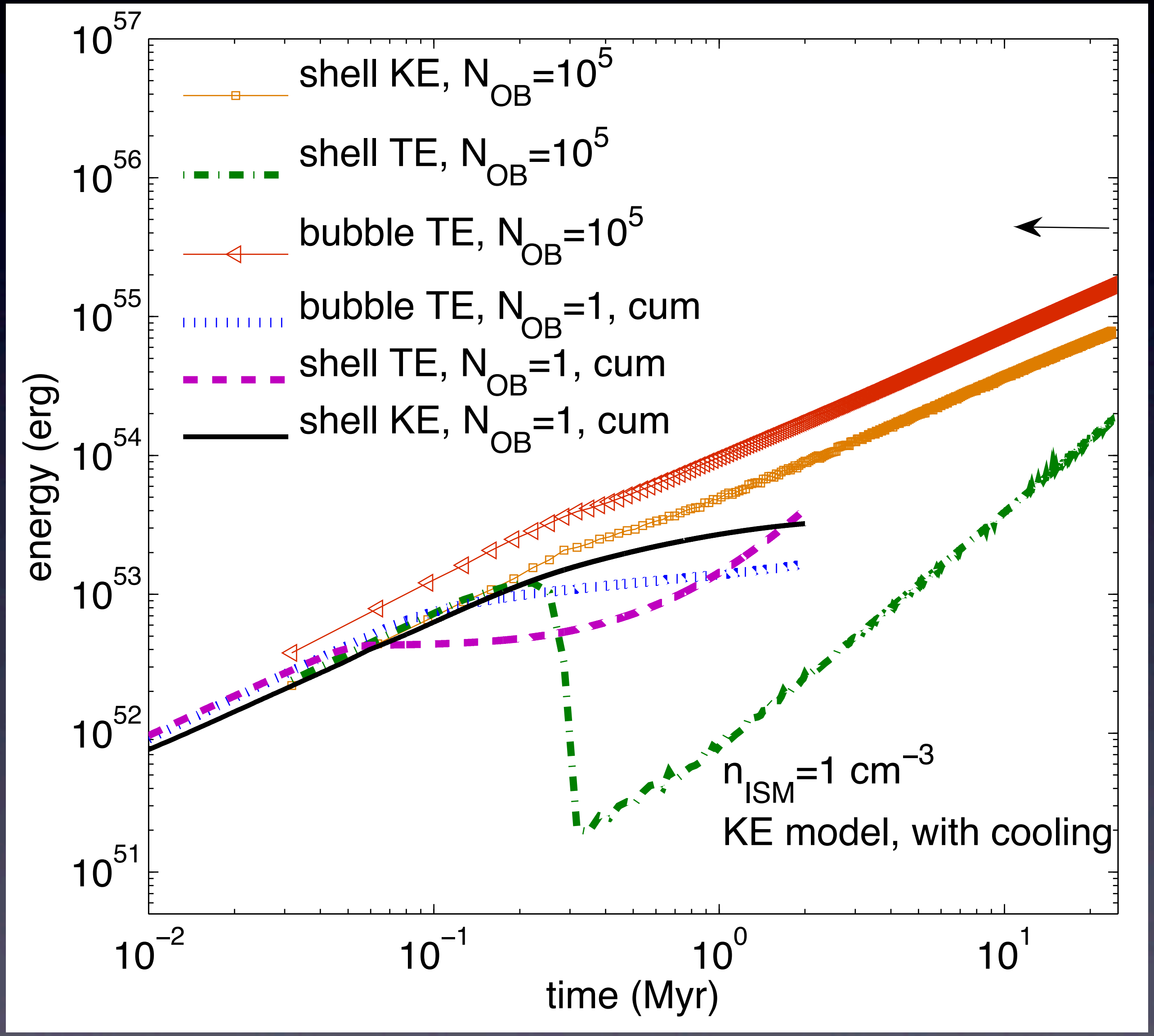
adiabatic scaling holds in absence of cooling

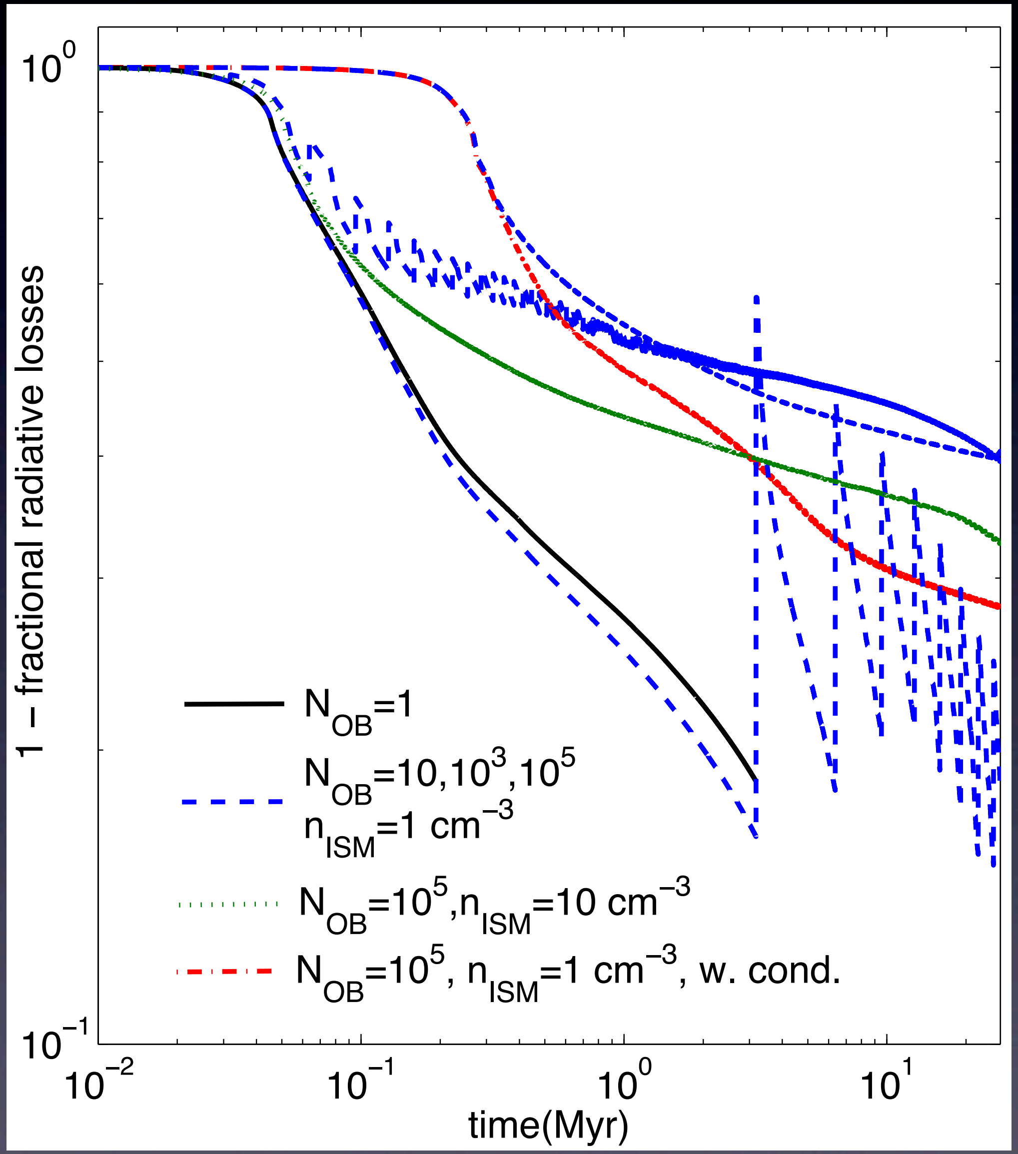
wind-bubble structure:
outer-shock, contact discontinuity, termination shock,
CC85 wind

CC85 wind results only for a large SSC/N_{OB} s. t. SN thermalizes before hitting TS also verified in 3-D sims.

Energetics w. cooling

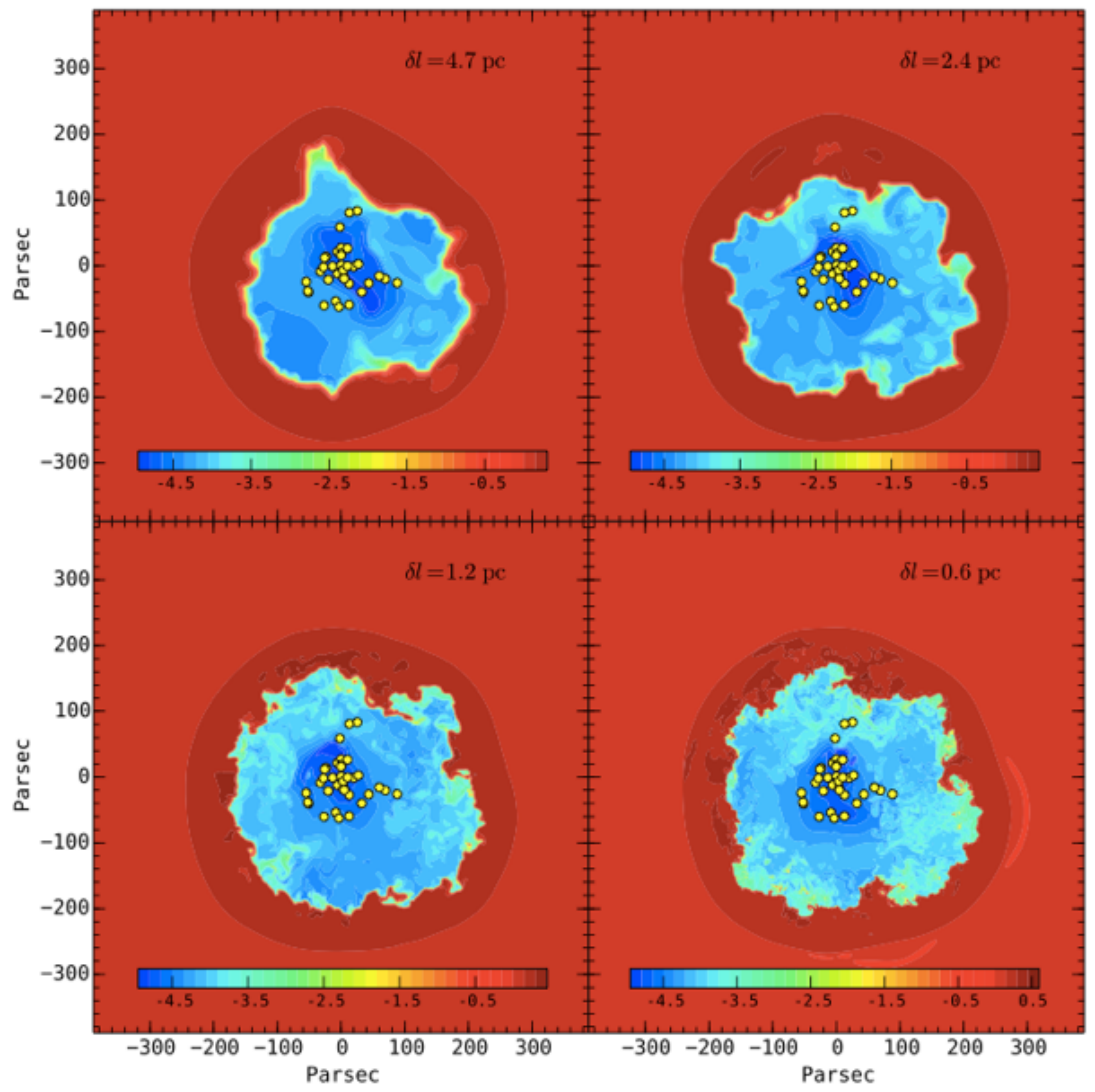
[Sharma et al. 2014]





while isolated SN totally fizzle out by few Myr, SBs retain >20% of the energy put in as long as SNe go off in the center

realistic 3-D sims.



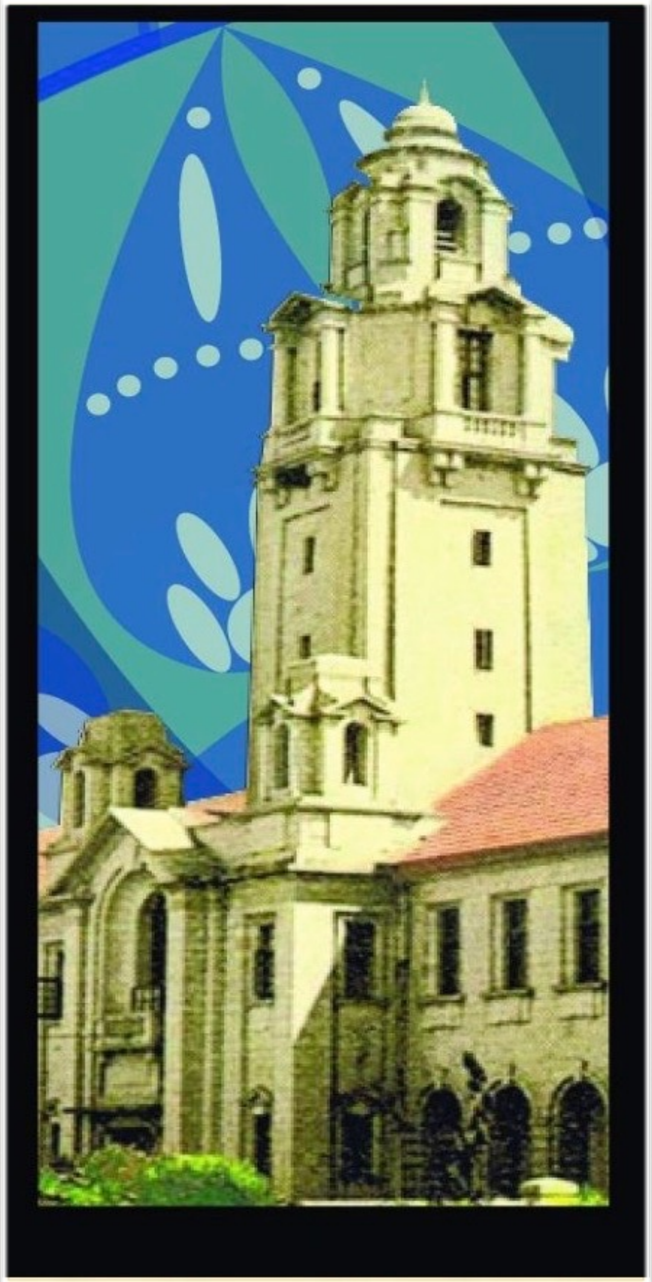
10^{51} erg thermal energy deposited/SN
100 SN in r=100 pc
cooling off below 10^4 K

mimicking a cluster

previously SN at same point

using PLUTO code, conserving total energy

Special thanks to SERC:



SahasraT

Cray XC40 Supercomputer

using up to
22000 cores

scales well

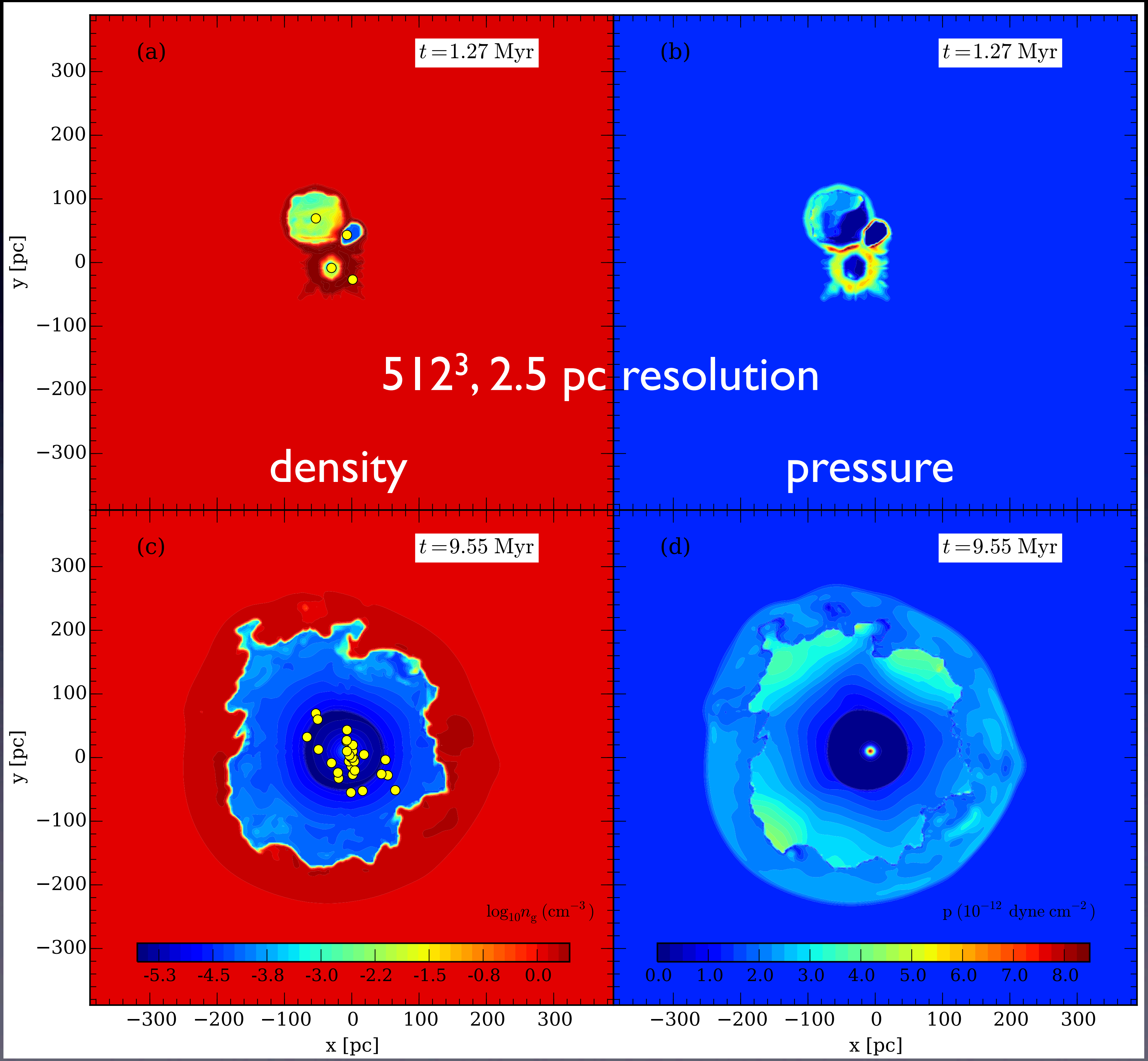
thermal energy
posited/SN
N in r=100 pc

cking a cluster

iously SN at
ame point

PLUTO code,
ing total energy

SNe to superbubble



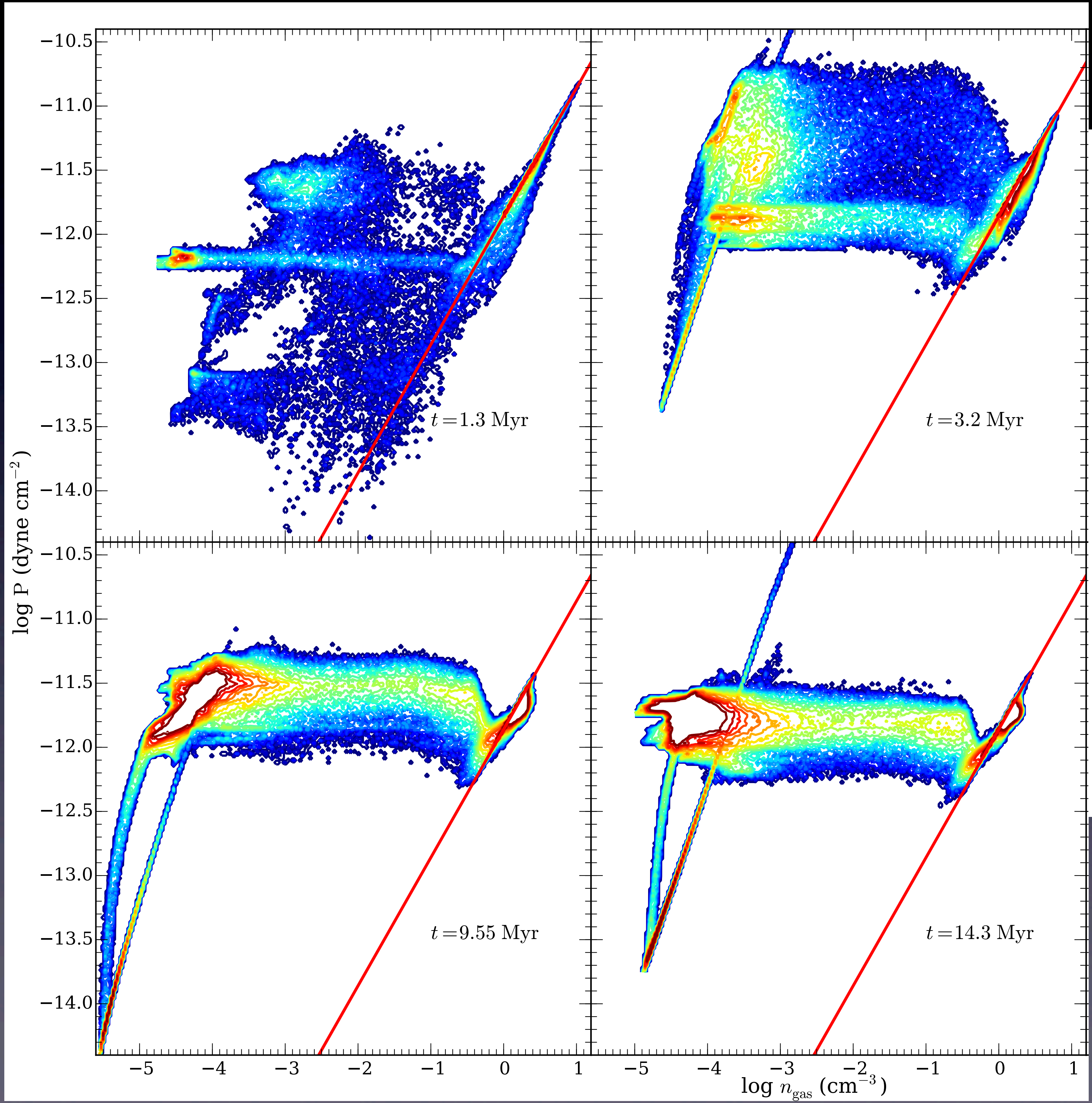
512^3, 2.5 pc resolution

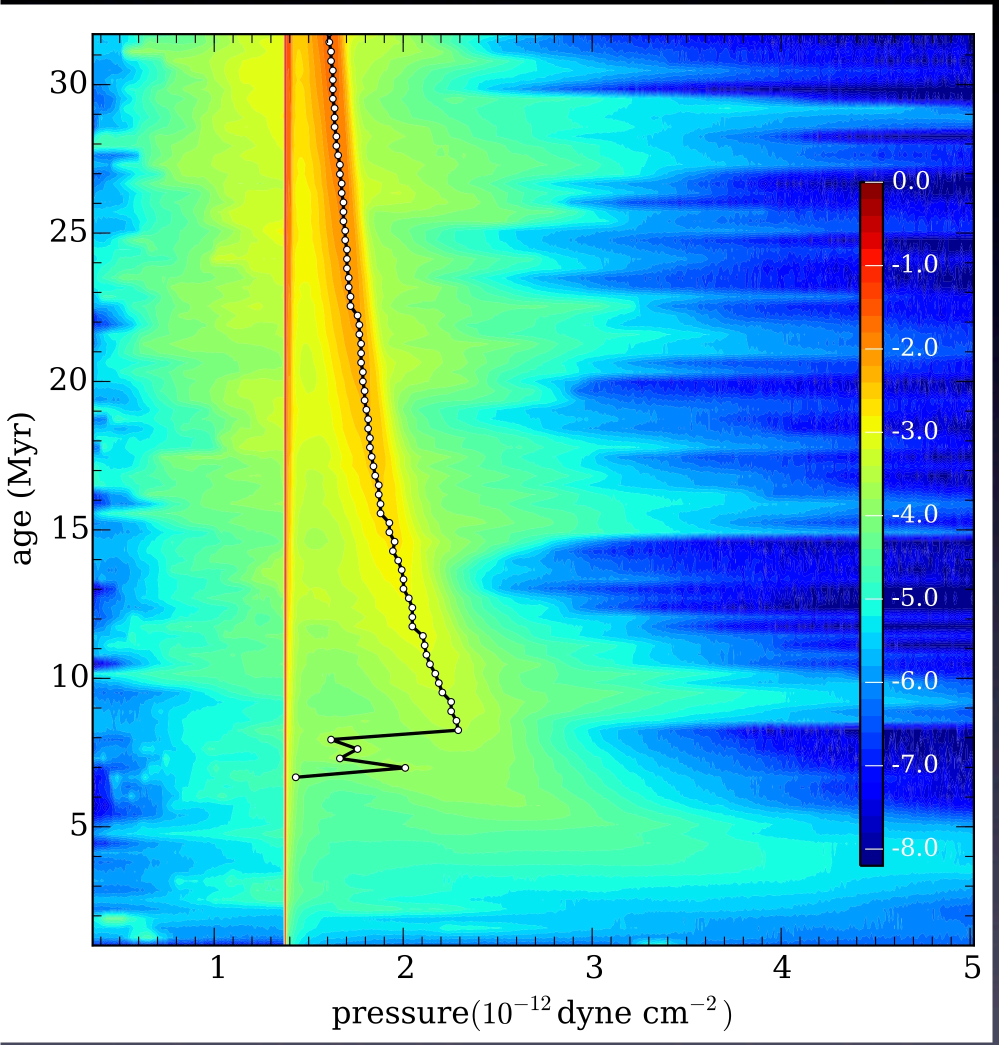
density

pressure

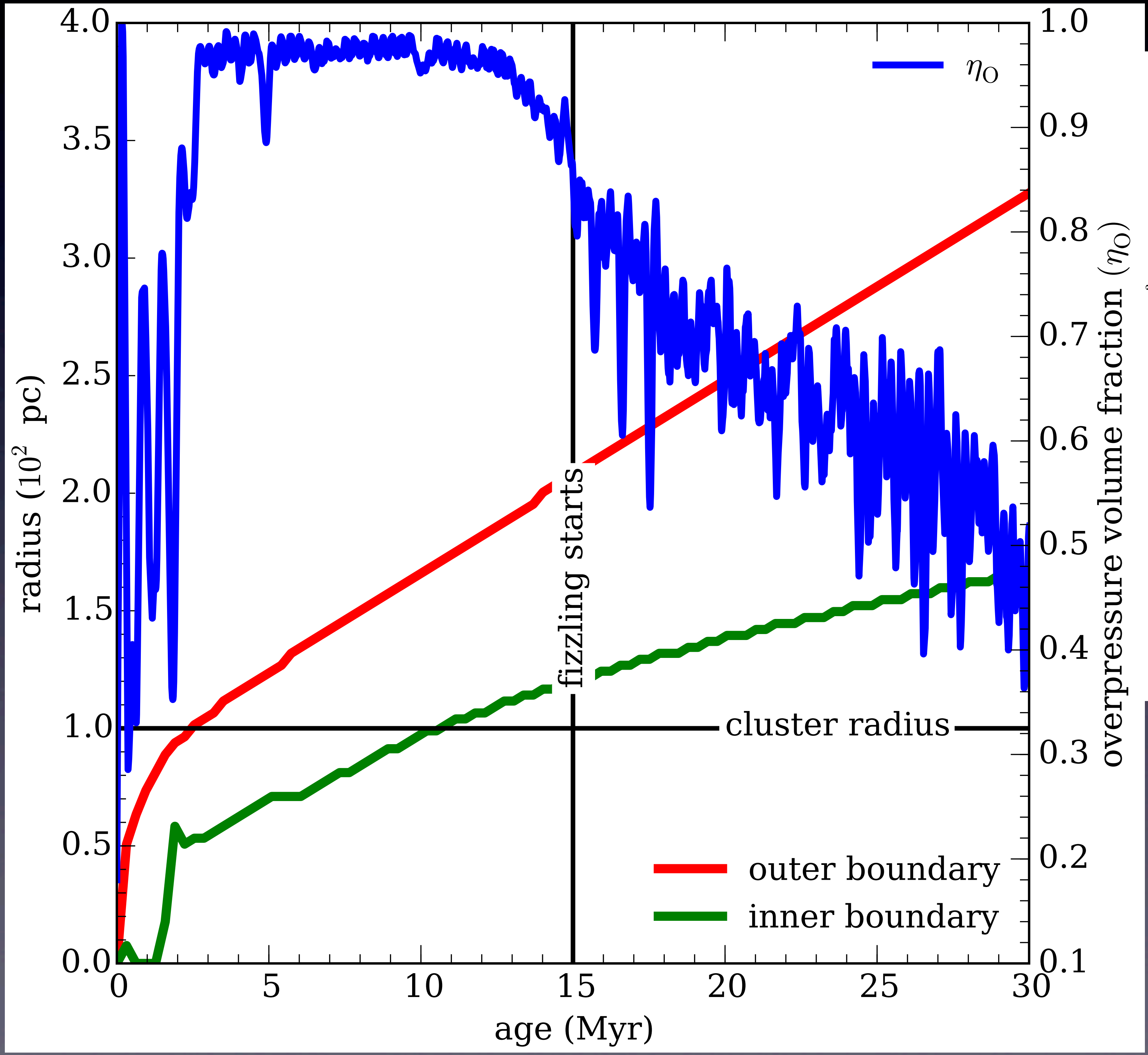
key parameters:
cluster size, r_{cl}
ISM density, n_g
number of SNe, N_{OB}

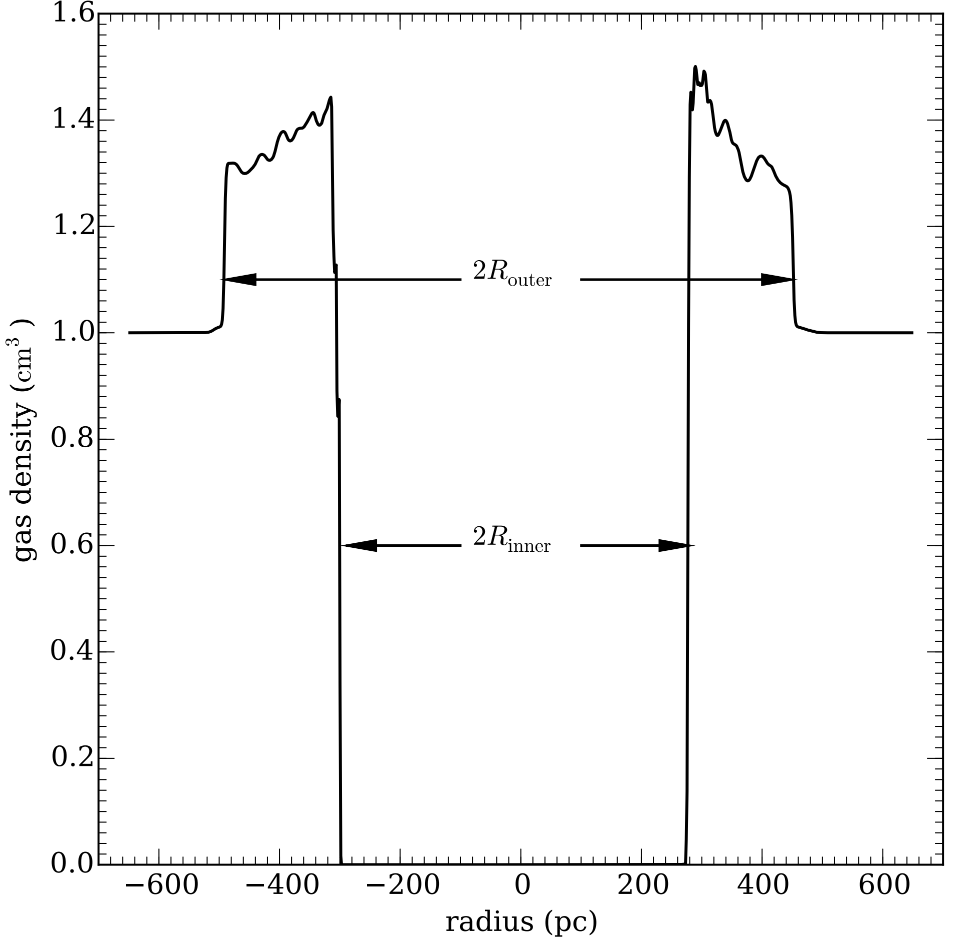
P-n_g evolution





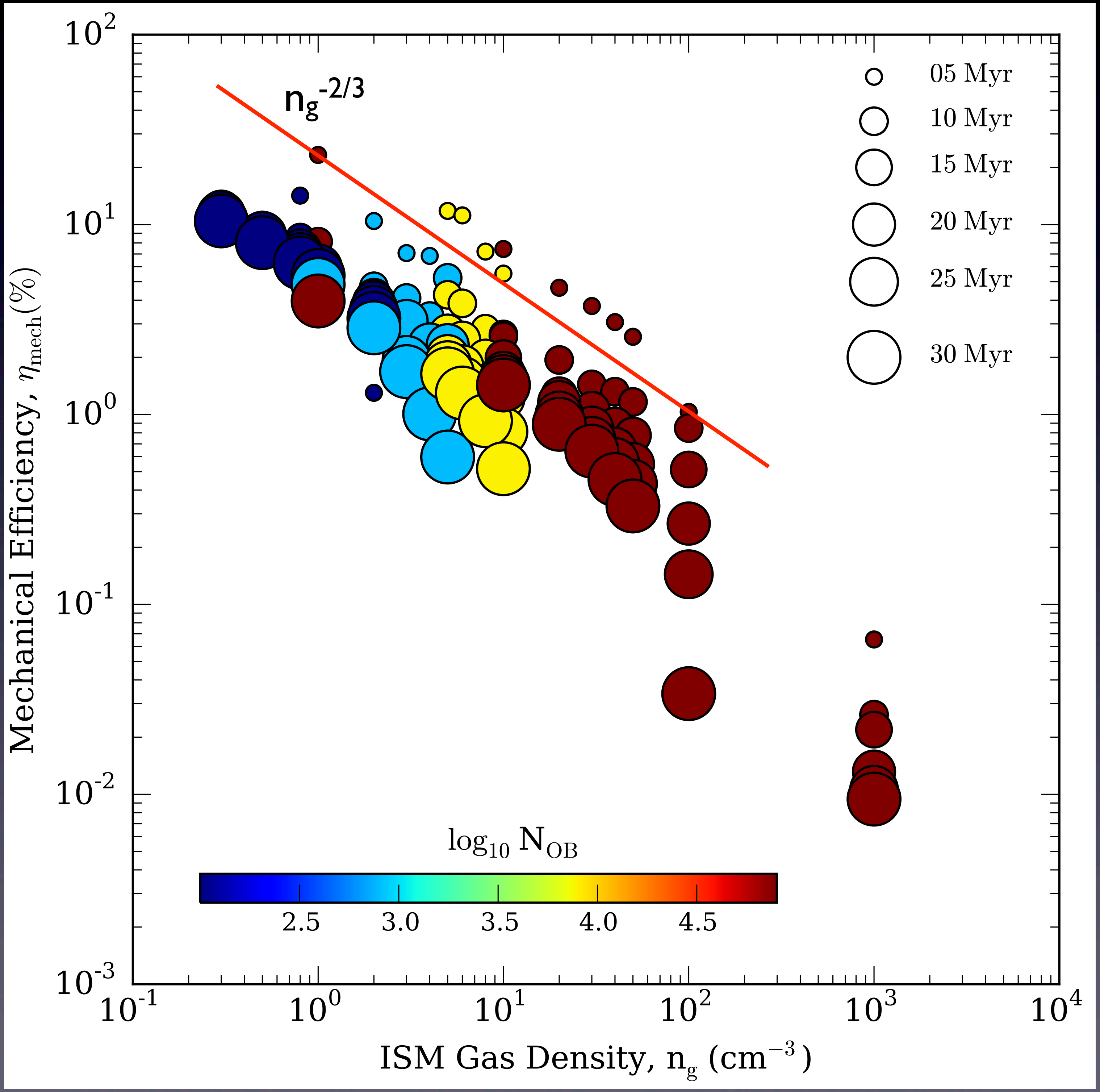
SB evolution





OP fraction: def. ind. of box size
fizzled out when
bubble pressure falls below
1.5 times the ISM value

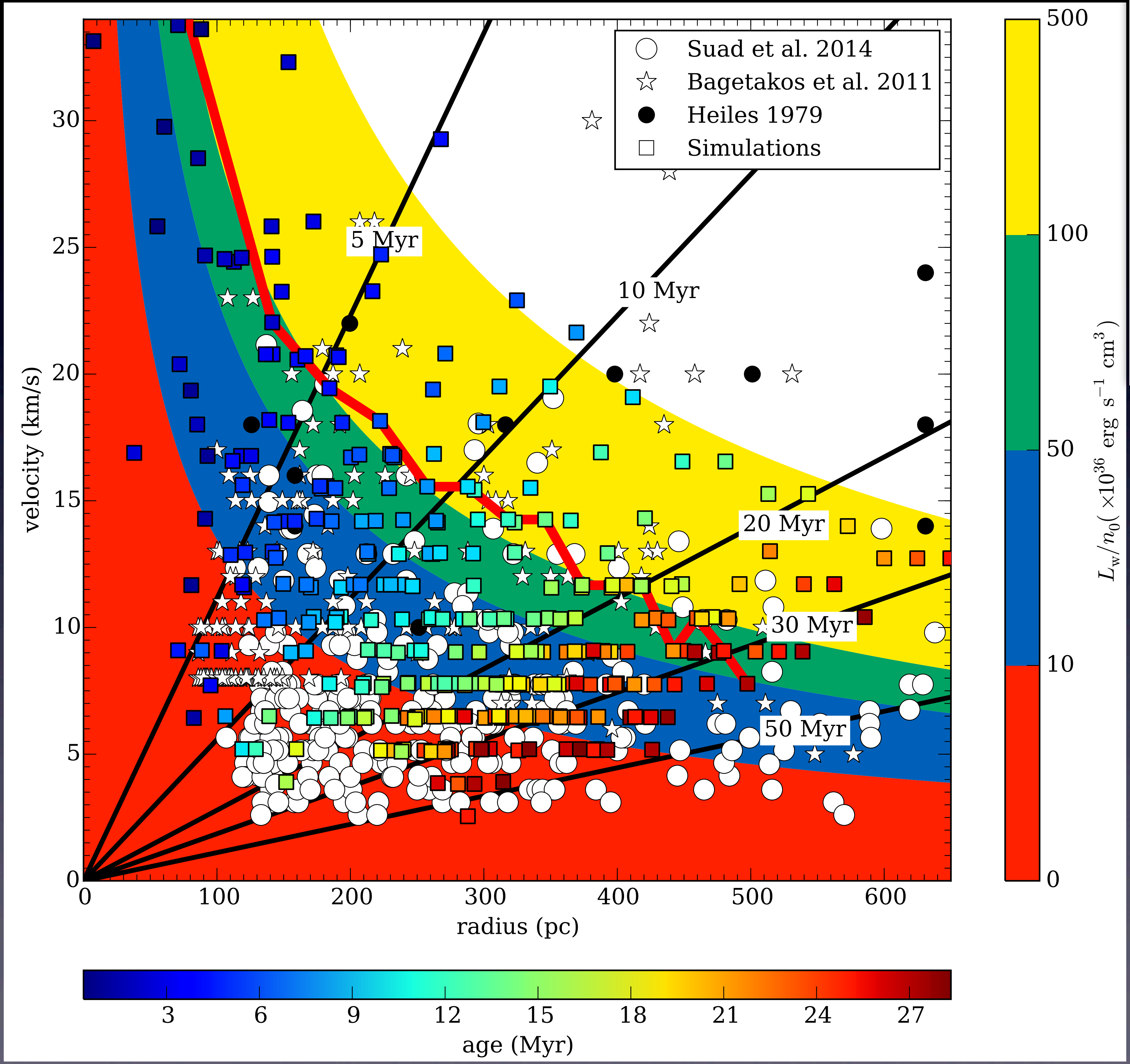
Mechanical Efficiency



we conserve energy exactly

efficiency to retain mechanical energy falls with time and ISM density

r-v plot



$$R \sim \left(\frac{Lt^3}{\rho}\right)^{1/5}$$

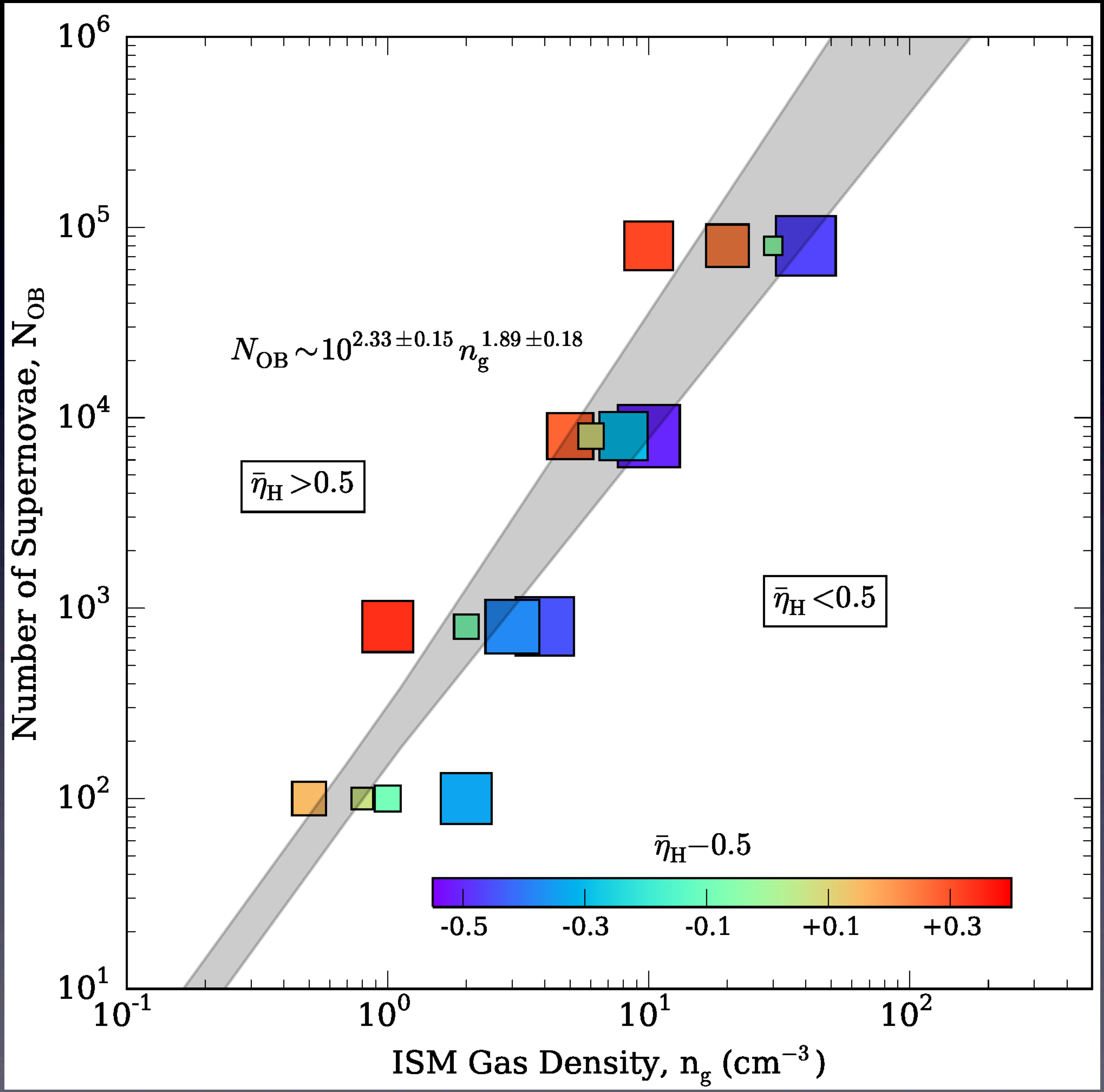
$$v \sim \frac{3}{5}\left(\frac{L}{\rho t^2}\right)^{1/5}$$

$$v \sim \frac{3R}{5t} \sim \frac{3}{5}\left(\frac{L}{\rho R^2}\right)^{1/3}$$

r-v plot from sims matches observations quite different from simple theory

red line: NOB=1000, n_g=1 cm^{-3} matches 10 times lower luminosity!

Critical N_{OB} vs n_g



require a critical N_{OB} to maintain large pressure at late times, even if cluster size is small

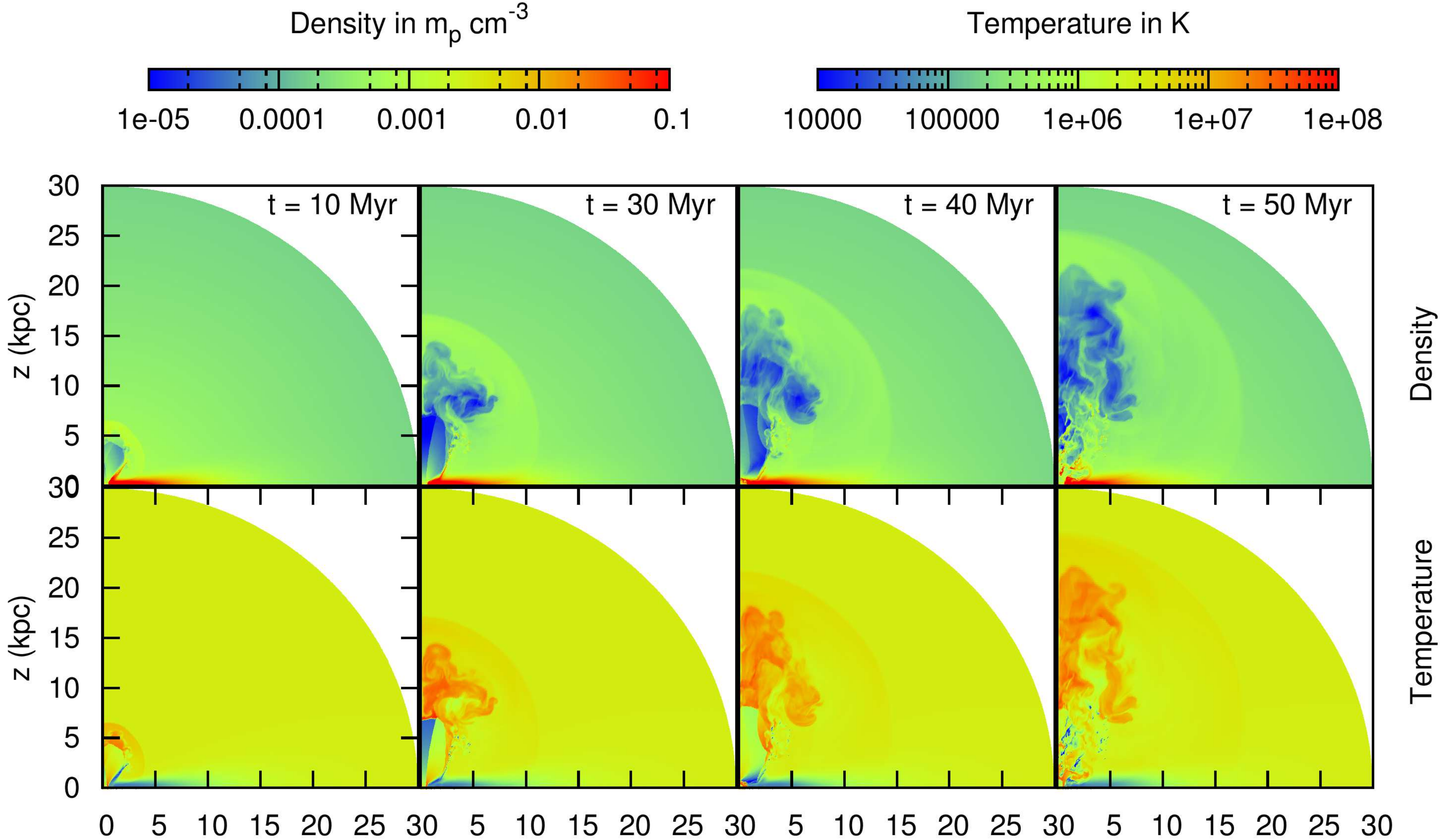
can be understood if mechanical efficiency decreases with density

study is in progress trying to understand results

Galactic outflows

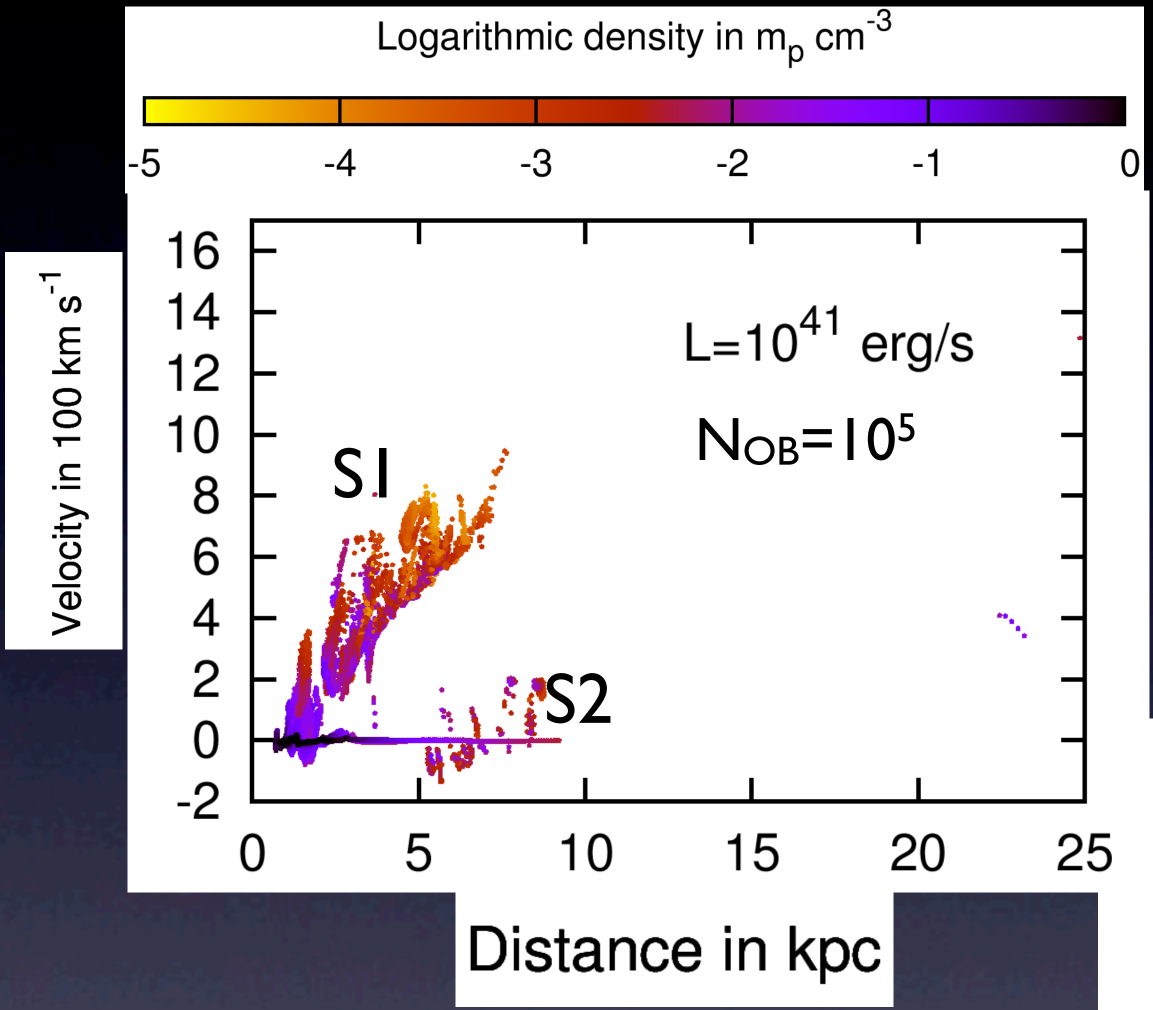
10^5 SN over 50 Myr; SFR~0.7 Msun/yr

[Sarkar et al. 2014]



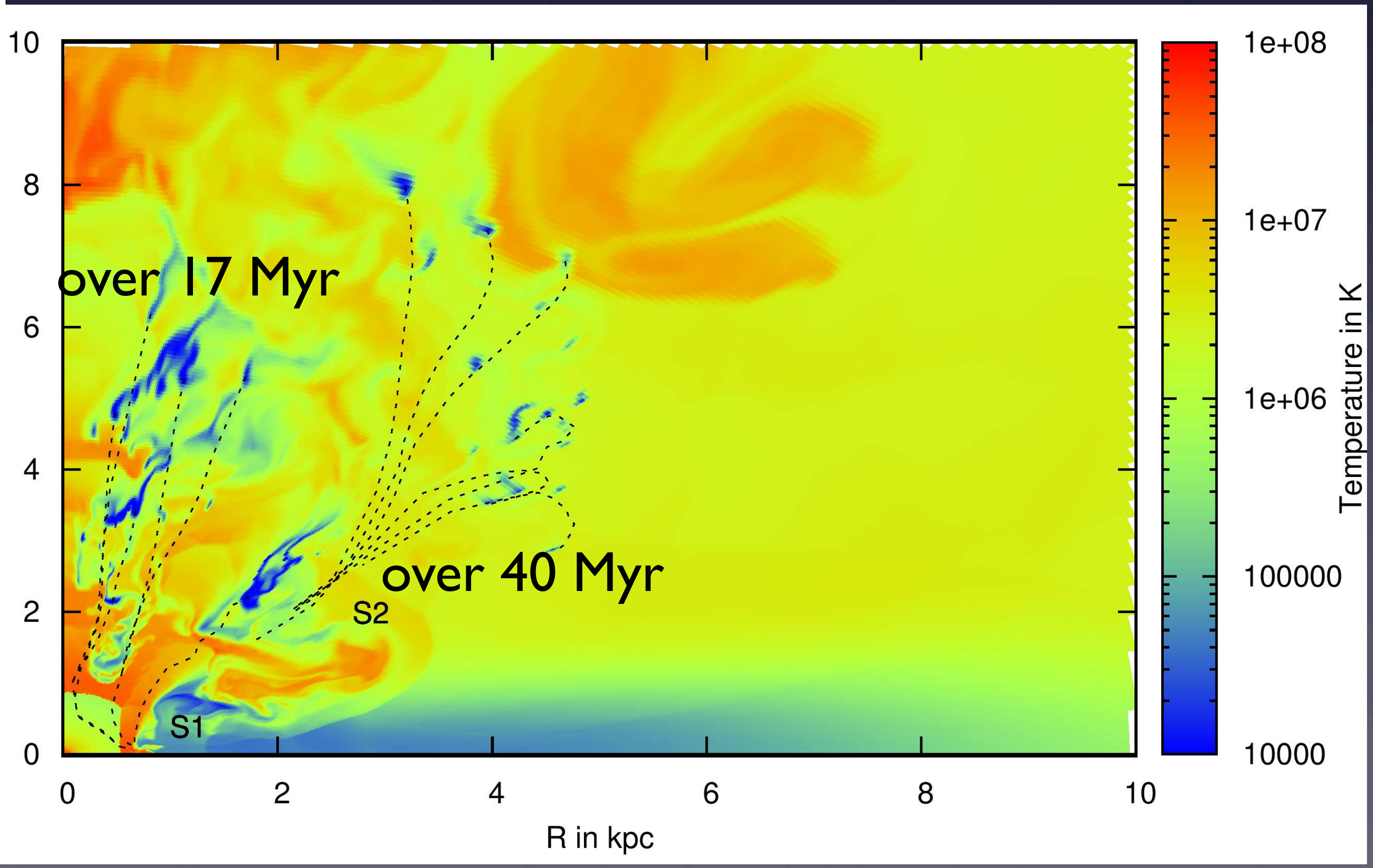
an equilibrium hot halo+rotating disk initialized
internal energy injected at small radius at a constant rate
SNe break out of the disk and pollute the halo with metals

Cold clouds



cold wind confined within 10 kpc
mixed in with the hot gas beyond that

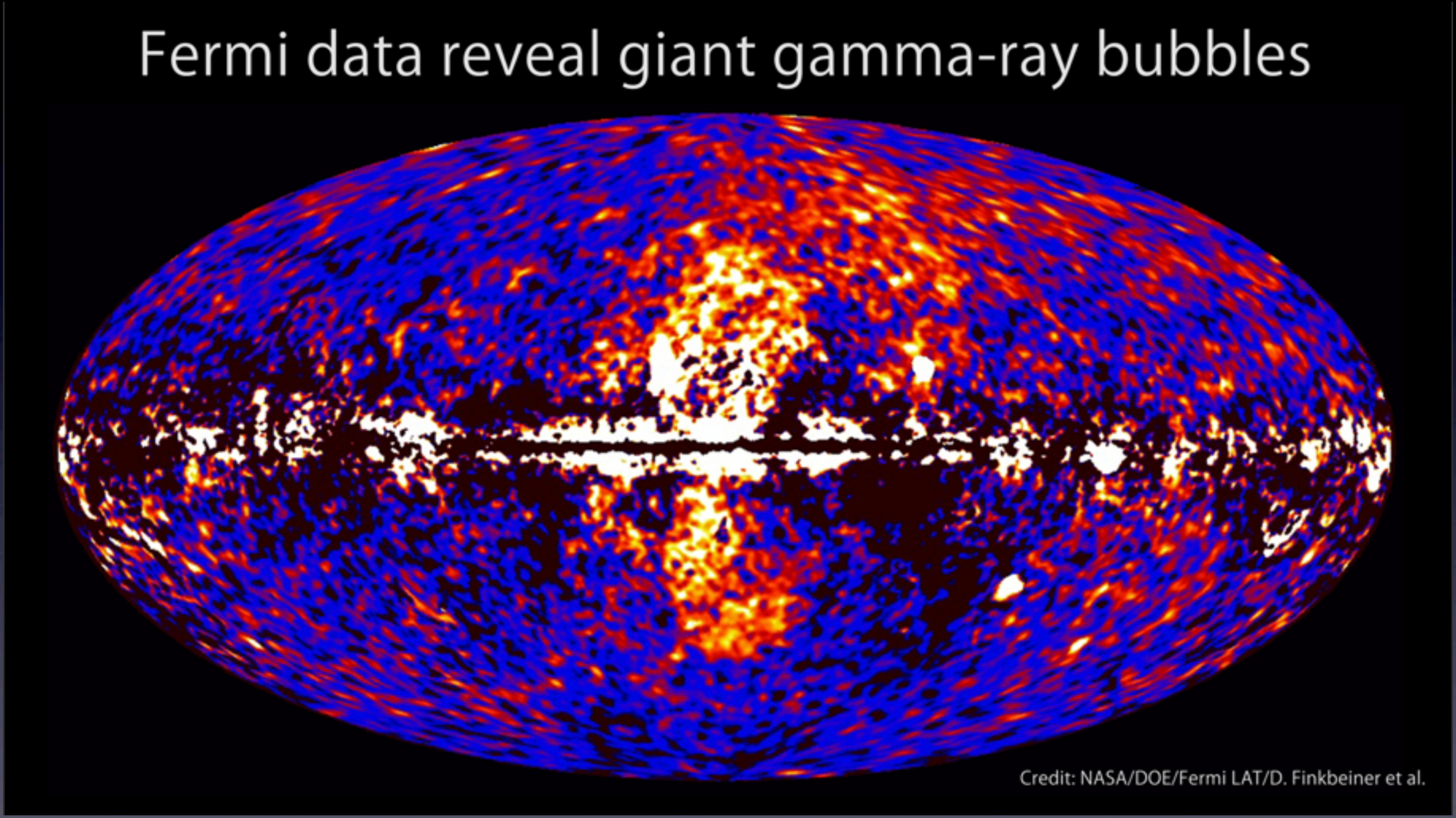
slow (~100 km/s) and fast (>500 km/s)
components of the wind



densest clumps closest to disk

S2: slow wind swept up in a funnel
S1: accelerated by shocked fast wind

Fermi bubbles



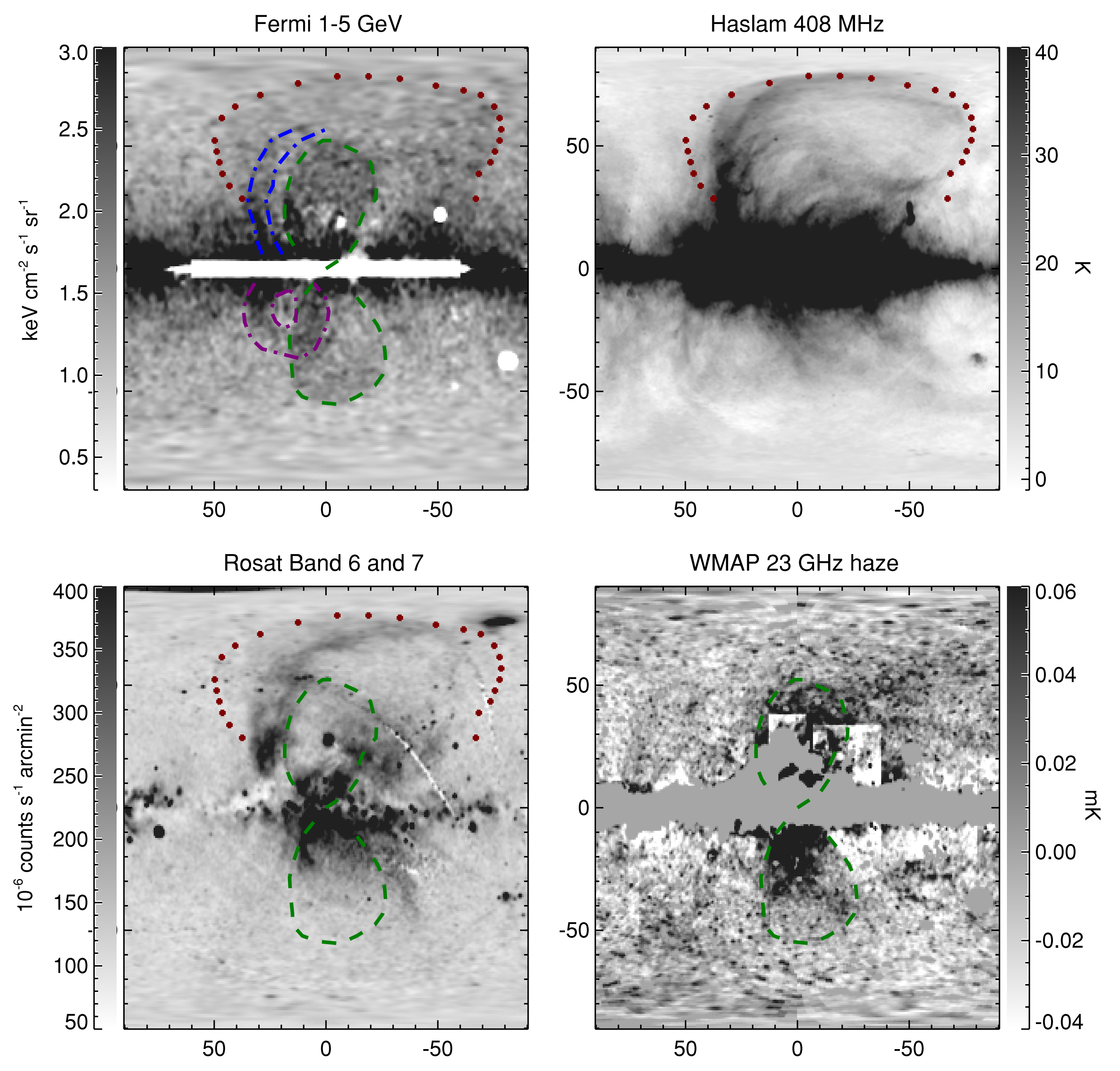
Fermi data reveal giant gamma-ray bubbles

Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

gamma ray sky after we remove the foregrounds and known gamma ray sources
large 55^0 diffuse gamma ray emitting bubbles from both sides of MW disk

other wavebands

[Su et al. 2010]

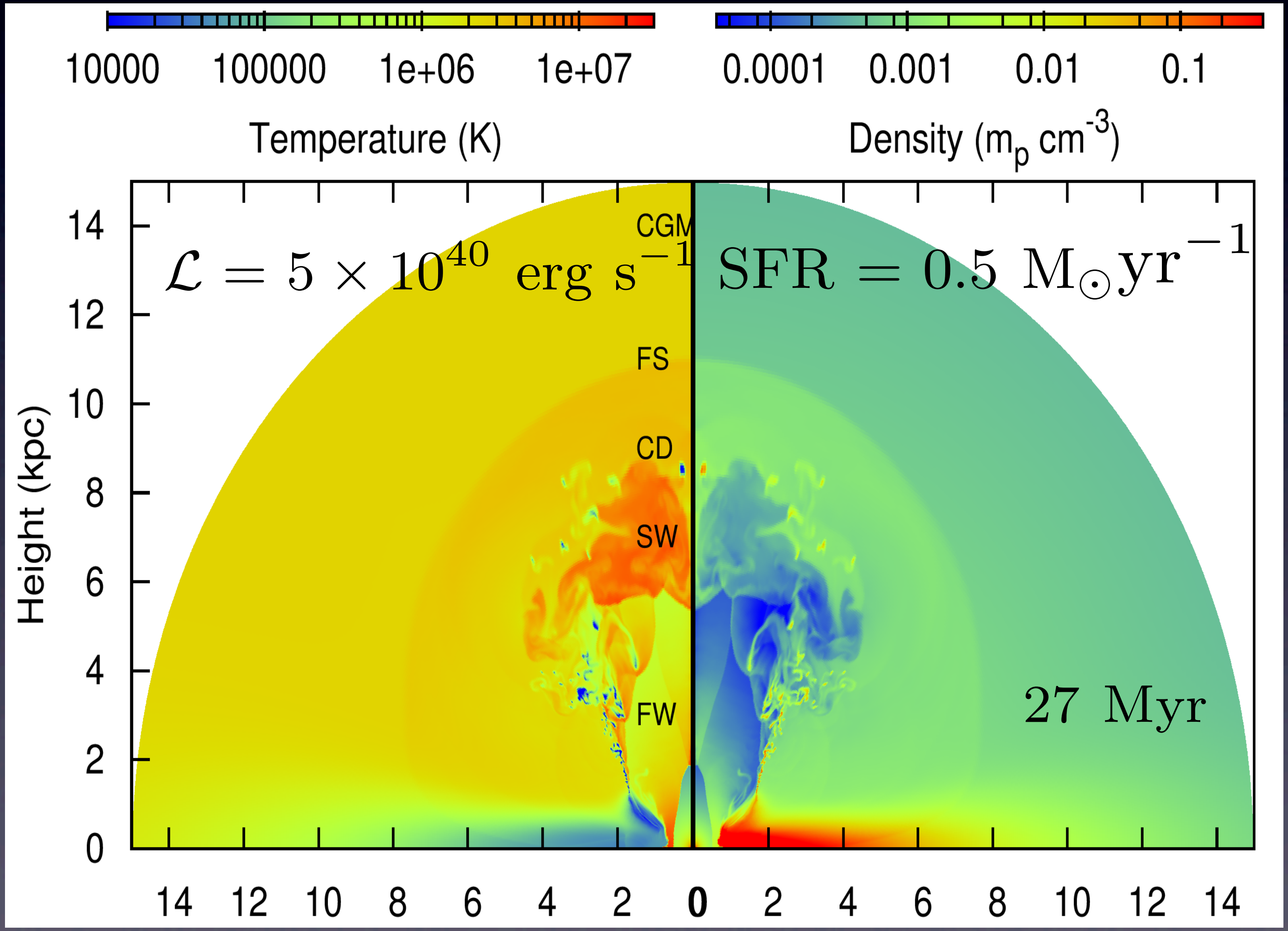


similar features seen in radio, mm, X-rays

same source for all these fireworks!

Starburst model for FBs

[Sarkar et al. 2014]



X-ray modeling least uncertain

γ-ray, radio non-thermal: Qs such as leptonic/hadronic, B-field, etc.

AGN jet models require younger FBs as v_{jet}~c (~1-10 Myr)

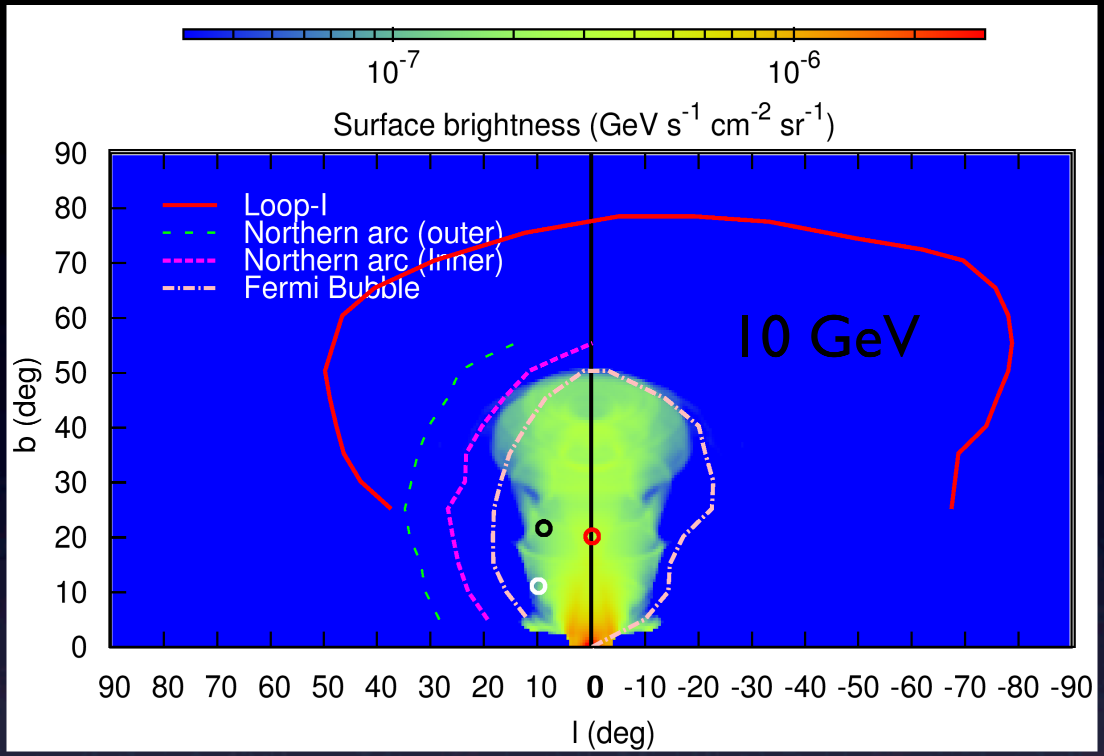
SB model fixes t~20-30 Myr, less sensitive to SFR and halo density

slower outer shock consistent w. X-ray obs.

$$\mathcal{R} \approx (\mathcal{L}t^3/\rho)^{1/5} \approx 10 \text{ kpc} \left(\frac{\mathcal{L}}{5 \times 10^{40} \text{erg s}^{-1}} \frac{0.001 m_p}{\rho} \left[\frac{t}{27 \text{Myr}} \right]^3 \right)^{1/5}$$

$$\mathcal{V} \approx 3\mathcal{R}/5t \approx 200 \text{ km s}^{-1} \left(\frac{\mathcal{L}}{5 \times 10^{40} \text{erg s}^{-1}} \frac{0.001 m_p}{\rho} \left[\frac{10 \text{kpc}}{\mathcal{R}} \right]^2 \right)^{1/3}$$

Simulated FB observations



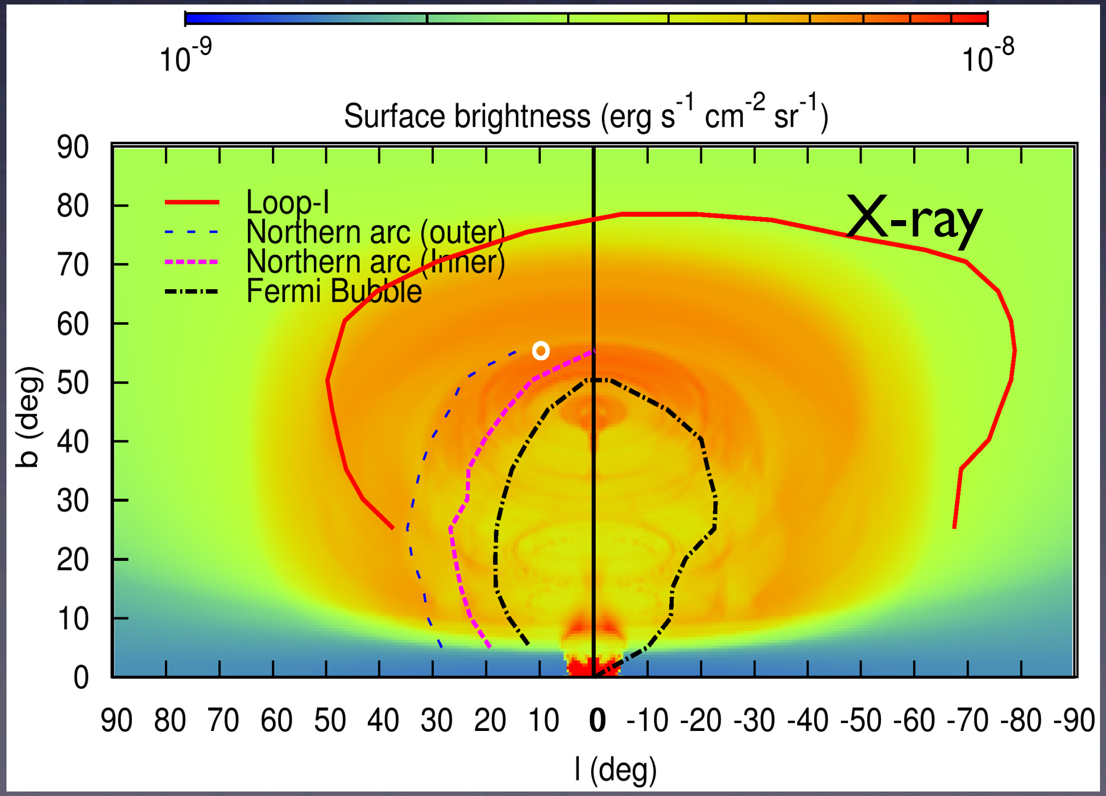
leptonic (IC) model gives a good fit to γ-rays

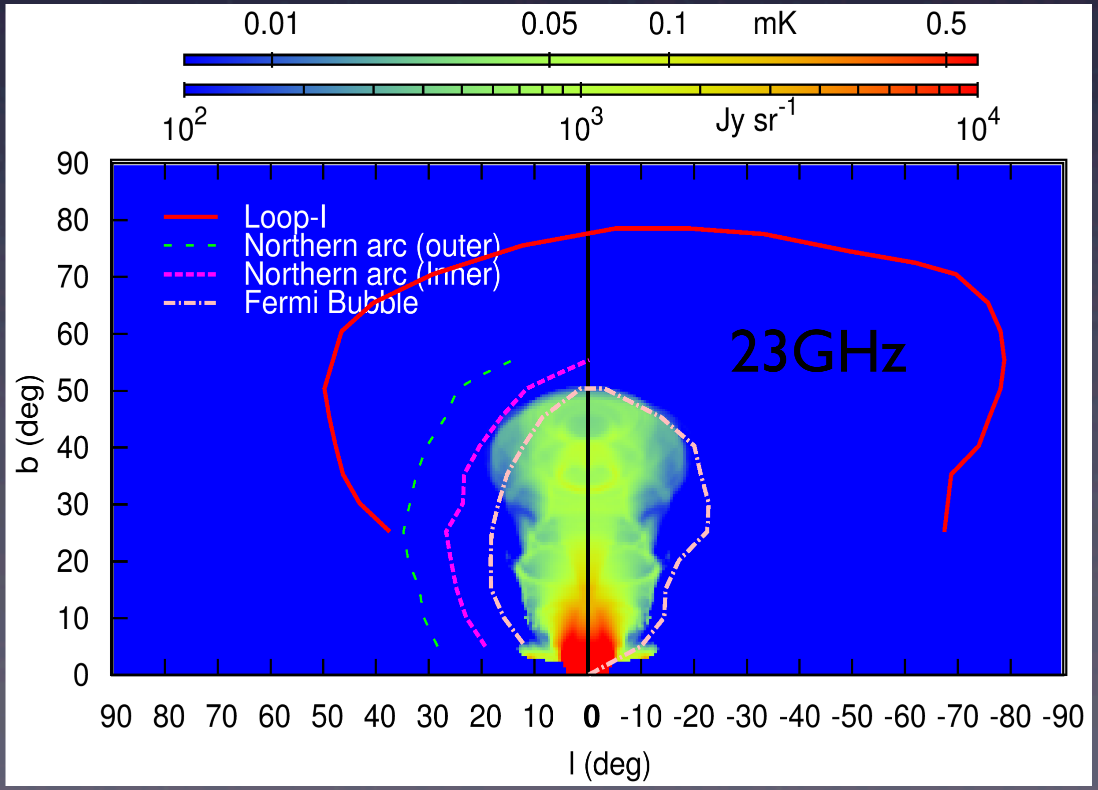
hadronic model ruled out as bubble is low density

synchrotron with B~5 μG (p~2.2) fits radio/mm

a good fit to morphology/spectra/fluxes

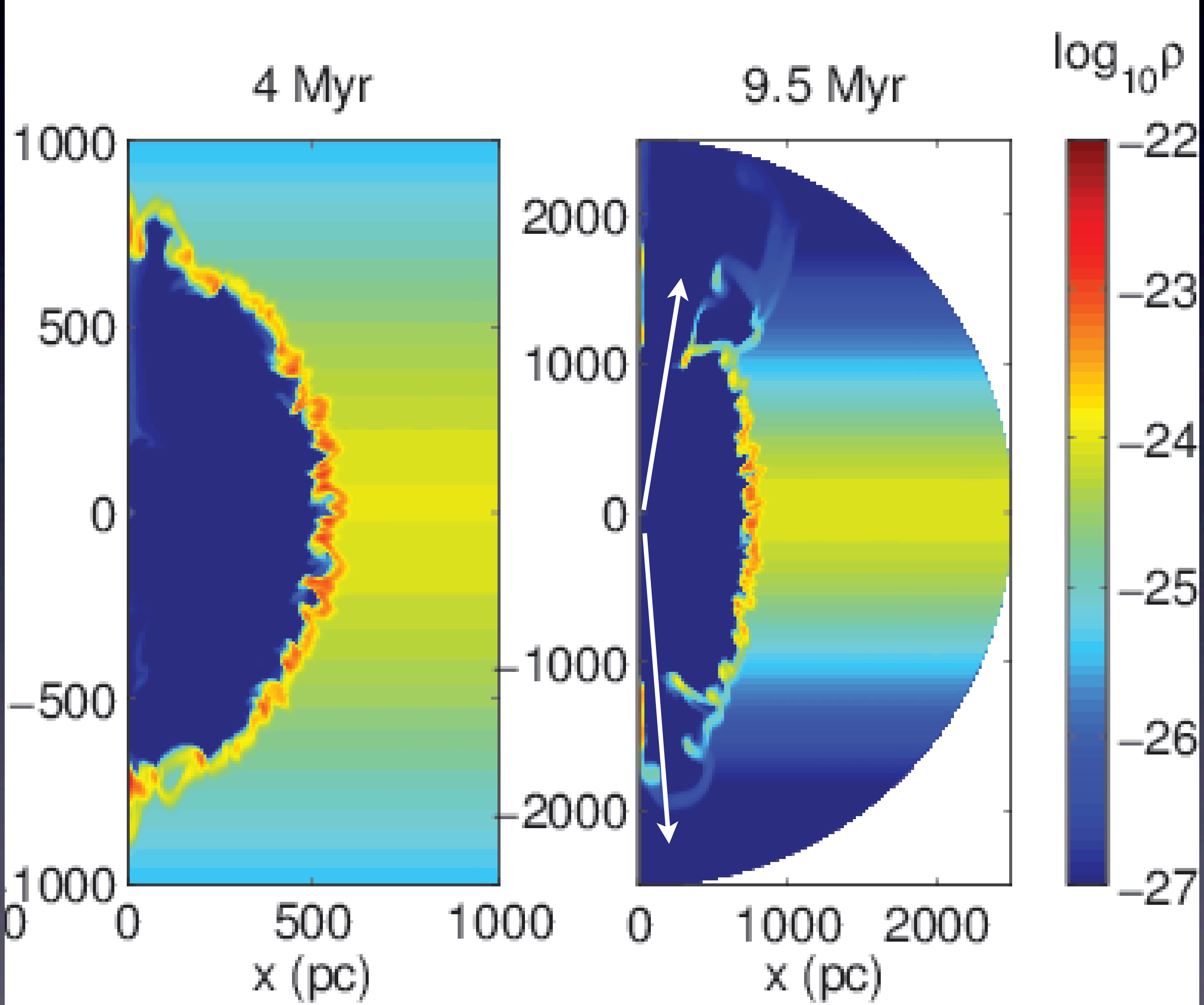
projection effects important





Escape of UV photons

[Roy et al. 2015]



even a small column (10^{17} cm^{-2}) of neutral gas can absorb UV radiation

How do then UV photons escape their dense molecular clouds?

escape required for reionizing universe

by blowing holes through the ISM!

escape through a patchy ISM perpendicular to the neutral disk

a picket-fence model

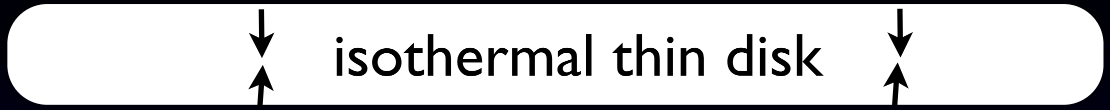
Modeling UV escape

$$\frac{dp(z)}{dz} = -\rho(z)g(z)$$

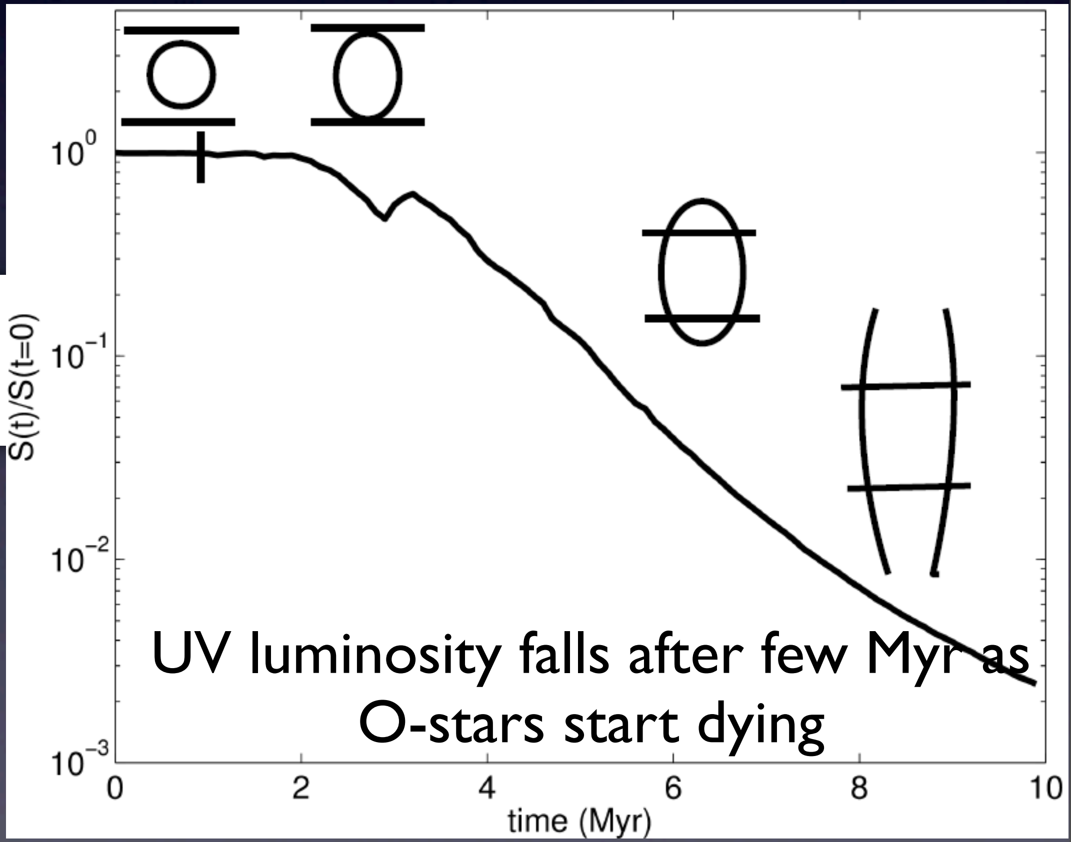
$$\frac{d^2\Phi}{dz^2} = 4\pi G\rho$$

$$n(z) = n_0 \,\mathrm{sech}^2\left(\frac{z}{\sqrt{2}z_0}\right), \quad z_0 = \frac{c_s}{\sqrt{4\pi G\mu m_p n_0}}$$

a self-gravitating
isothermal disk



[Roy et al. 2015]



UV luminosity falls after few Myr as
O-stars start dying

$$f_{esc}(\theta, t, N_O; n_0, z_0) \quad = \quad \frac{S d\Omega/4\pi - \int_0^\infty \alpha_H^{(2)} n_H^2(r) r^2 dr\, d\Omega}{S d\Omega/4\pi}$$

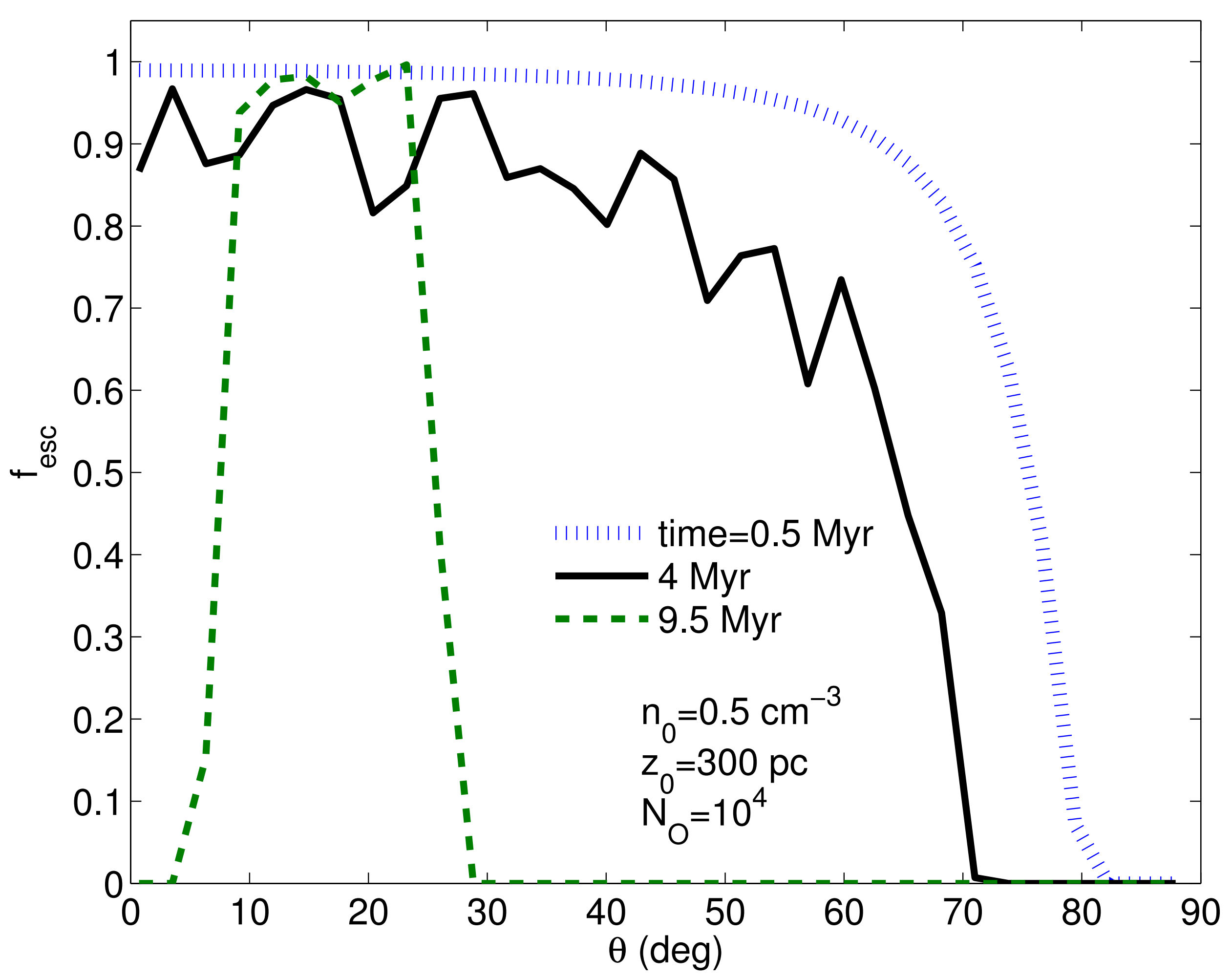
assumed ionization equilibrium
(ionization = recombination)
valid only when dynamical time >> recombination time

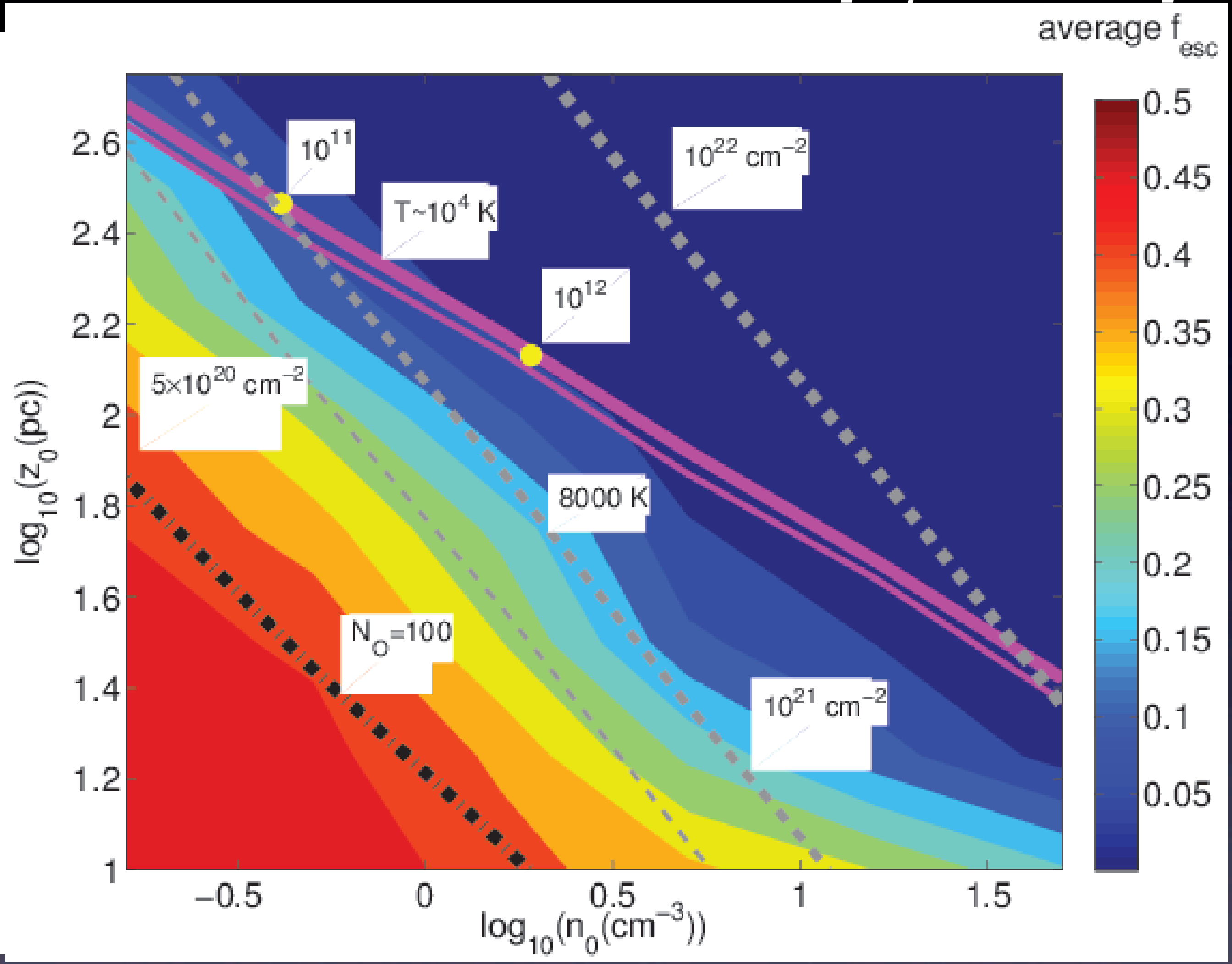
easier to escape molecular disk as it is thinner!
thus, ok to consider WNM disk

must punch holes before all
O-stars are gone!

Escape results

[Roy et al. 2015]





angle, time, stellar population averaged escape fraction as a function of WNM disk parameters

UV photons escape close to poles essentially through low density pathways

our results match MW value 5-10%
slightly higher for lower mass galaxies
weak galaxy mass dependence

Conclusions

- galactic outflows common
- isolated SN can’t power them
- need overlapping SNe => superbubbles
- SBs can retain substantial fraction of energy
- SB breakout & halo metal pollution
- Fermi bubble as a starburst-driven outflow
- crucial role in escape of ionizing photons

Thank you!