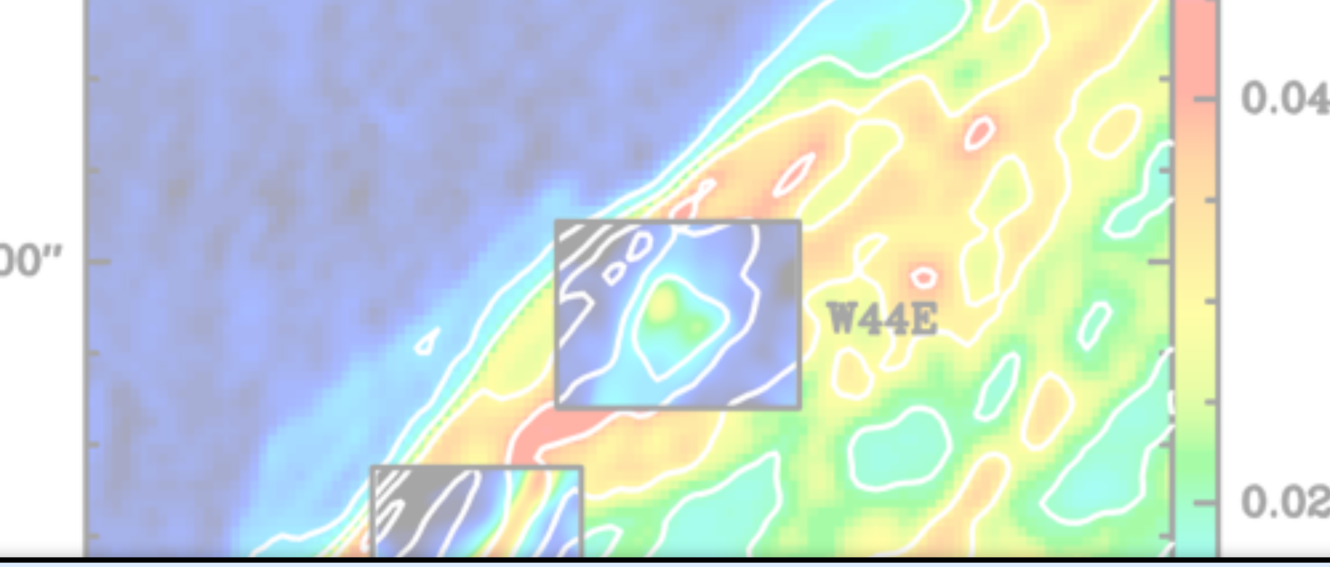
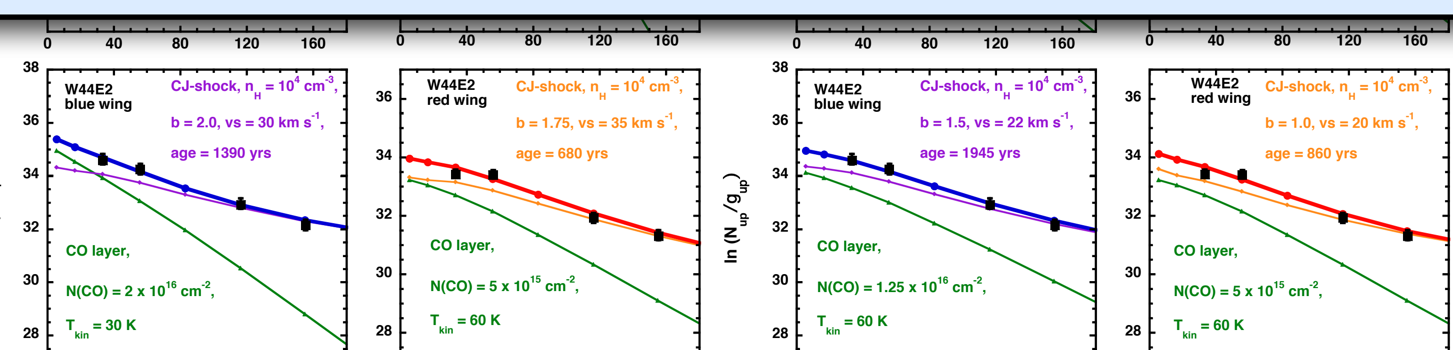


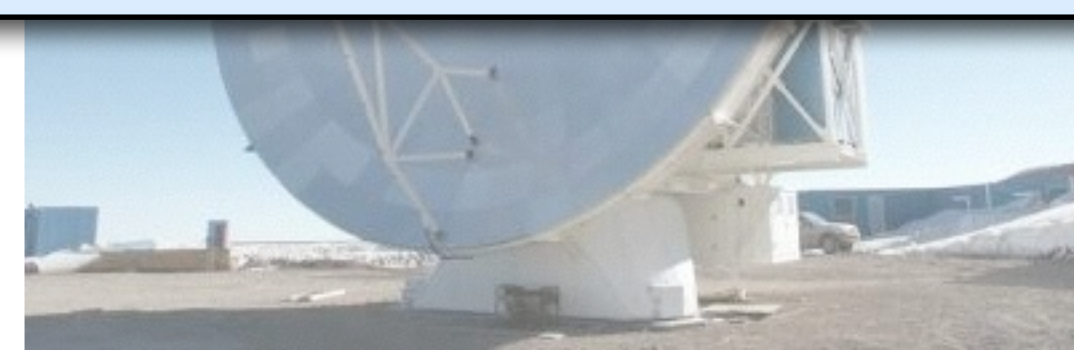
APEX observations of non-stationary magneto-hydrodynamical shocks in W44

Sibylle Anderl, IPAG Grenoble

CRISM 2014, Montpellier, June 27th

Collaborators:
Antoine Gusdorf (Paris), Rolf Güsten (Bonn)

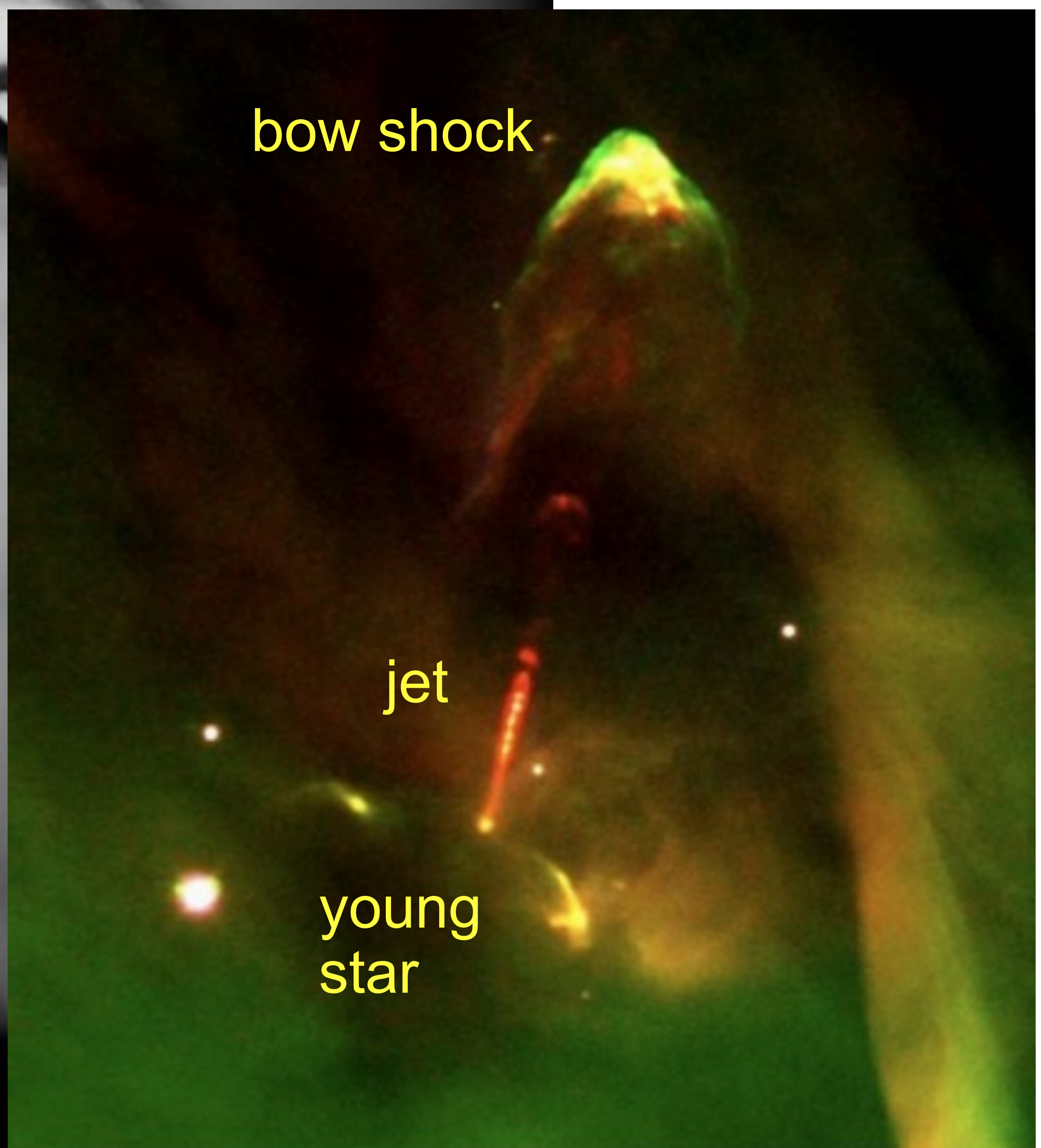


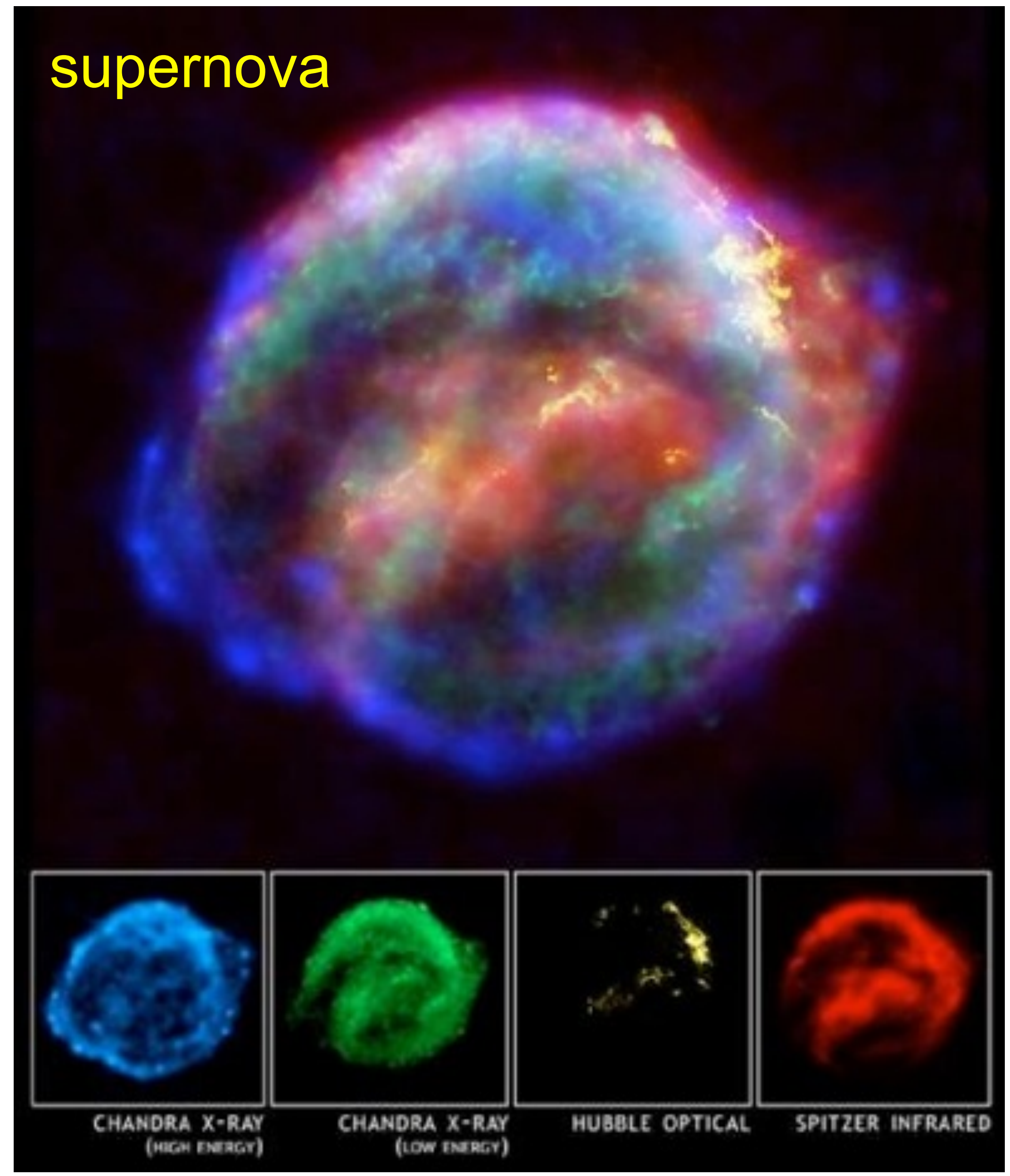


- MHD-shocks
- CO observations of W44
- Shock analysis
- Results
- Summary

What is a shock?

A shock is an irreversible, pressure-driven fluid-dynamical disturbance, moving faster than the local sound speed in the surrounding medium.





FORS/VLT/ESO

NASA/ESA/JHU/R.Sankrit & W.Blair

Importance of shocks

Shocks are all over and prominent in the ISM. They are important because:

- They propagate the energetic feedback of events such as supernovae, stellar winds, cloud-cloud collisions, or expanding HII regions.

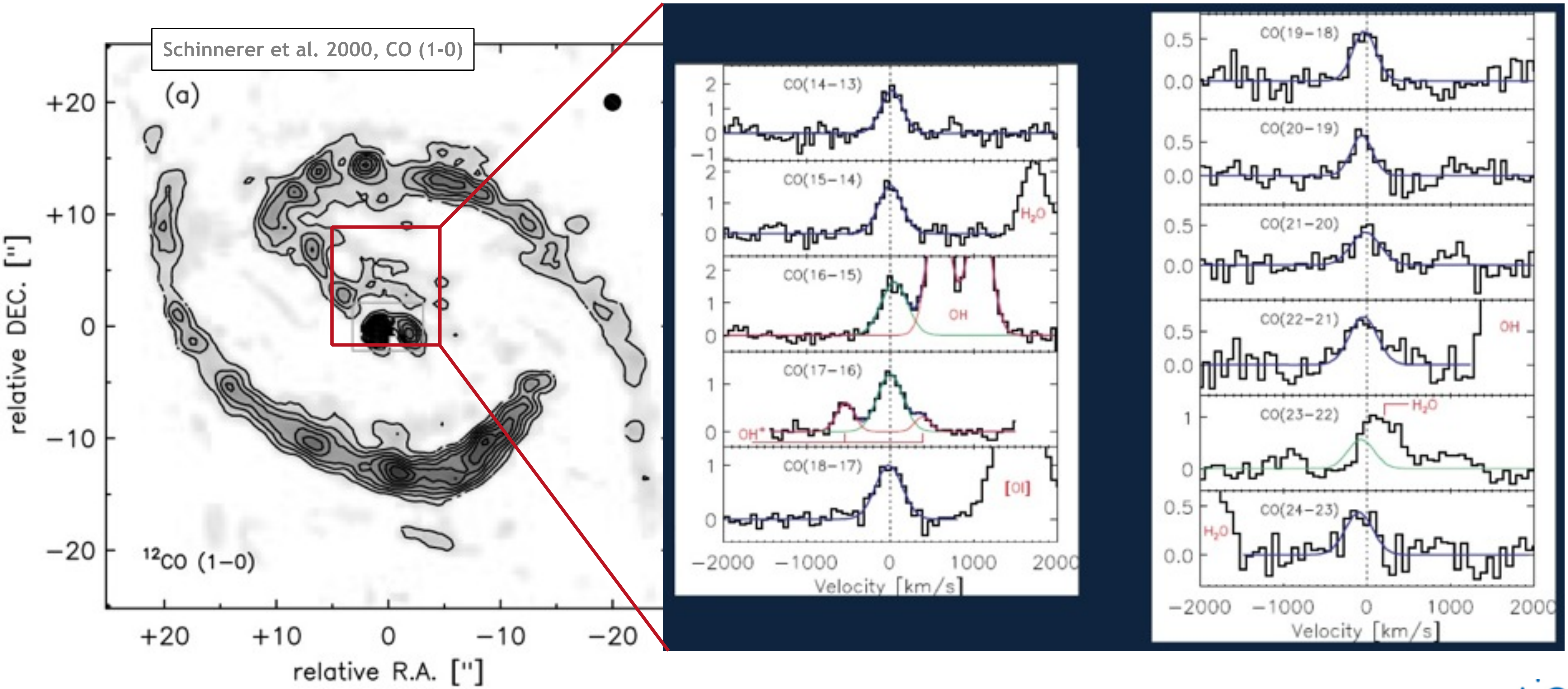
The energetic balance of galaxies

- CO ladder observations in external galaxies

Large scale effects from PDR, XDR, and shock contributions

NGC 253 Hailey-Dunsheath et al. 2008; M82 Panuzzo et al. 2010; NGC 891 Nikola et al. 2011, NGC 6240 Meijerink et al. 2013

- Herschel/PACS observations of NGC 1068 Hailey-Dunsheath et al. 2012

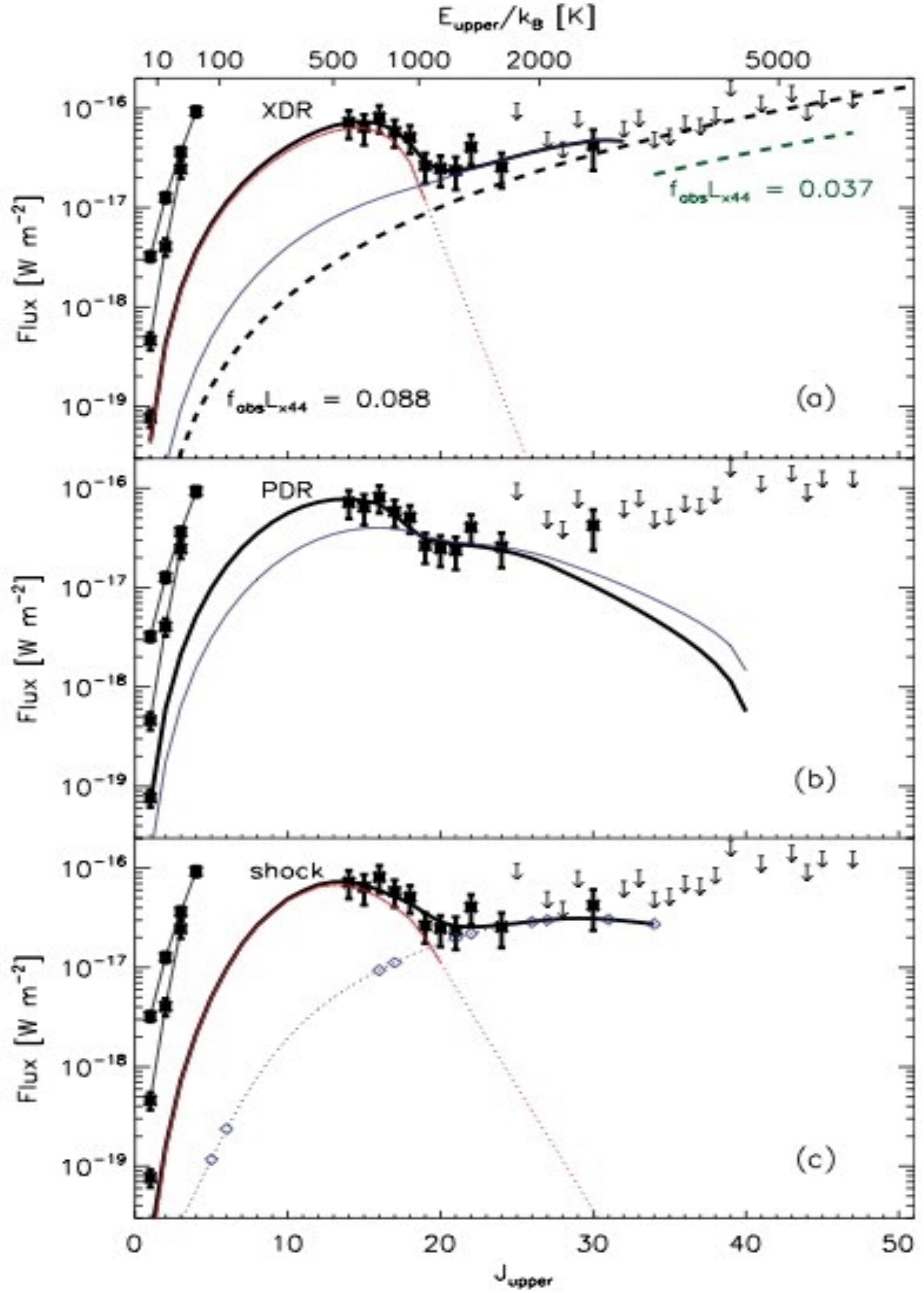


The energetic balance of galaxies

Table 4
Heating Mechanisms

	ME	HE	Full
XDR	$n_H = 10^{5.75}$ cm^{-3}	$n_H = 10^{5.25}$ cm^{-3}	...
	$F_X = 9$ erg cm^{-2} s^{-1}	$F_X = 160$ erg cm^{-2} s^{-1}	...
	$A \sim (130$ pc$)^2$	$A \sim (21$ pc$)^2$	...
PDR	...	$n_H = 10^{6.5}$ cm^{-3}	$n_H = 10^6$ cm^{-3}
	...	$G_0 = 10^{4.75}$	$G_0 = 10^5$
	...	$L_{FUV} \sim 2 \times 10^9 L_\odot$	$L_{FUV} \sim 10^{10} L_\odot$
Shock	C-shock	C-shock	...
	$n_0 = 2 \times 10^5$ cm^{-3}	$n_0 = 10^6$ cm^{-3}	...
	$v = 20$ km s^{-1}	$v = 40$ km s^{-1}	...
	$A \sim (150$ pc$)^2$	$A \sim (16$ pc$)^2$	...

Notes. Details for the models used in Figure 9. XDR and PDR models are from Meijerink et al. (2007), ME C-shock model is from Flower & Pineau Des Forêts (2010), and HE C-shock model is from Kaufman & Neufeld (1996).

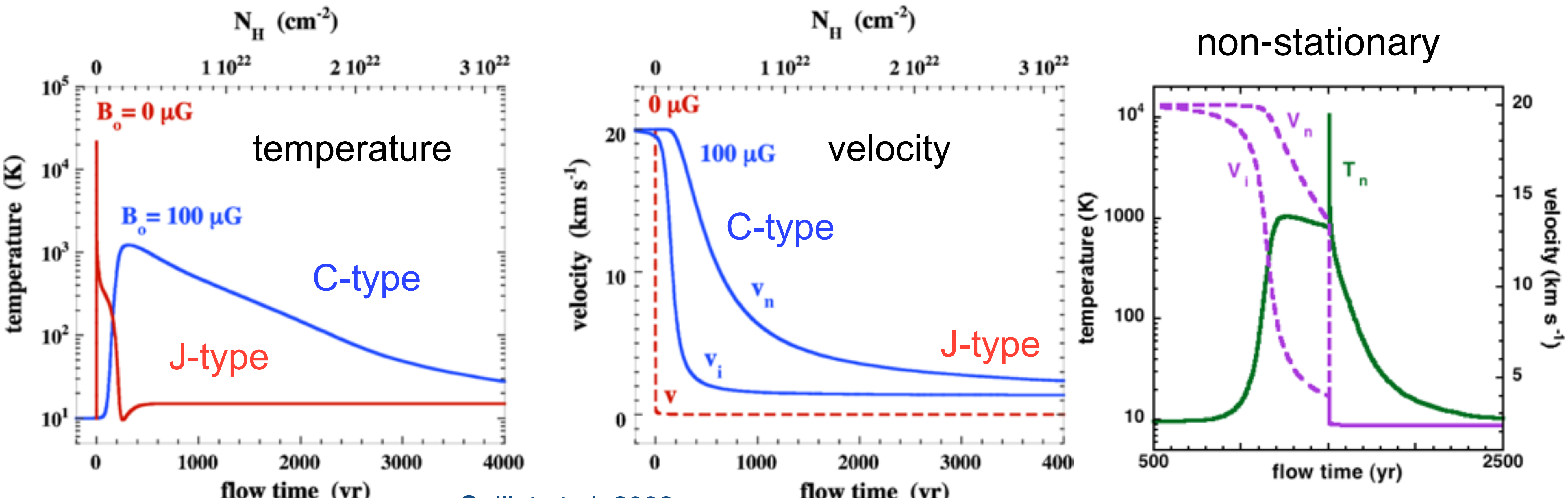


Importance of shocks

Shocks are all over and prominent in the ISM. They are important because:

- They propagate the energetic feedback of events such as supernovae, stellar winds, cloud-cloud collisions, or expanding HII regions.
- They strongly affect the chemistry of the interstellar medium.
- Bright shock emission provides excellent diagnostics for the study of the conditions in the shocked medium

C- and J-type shocks



Guillet et al. 2008

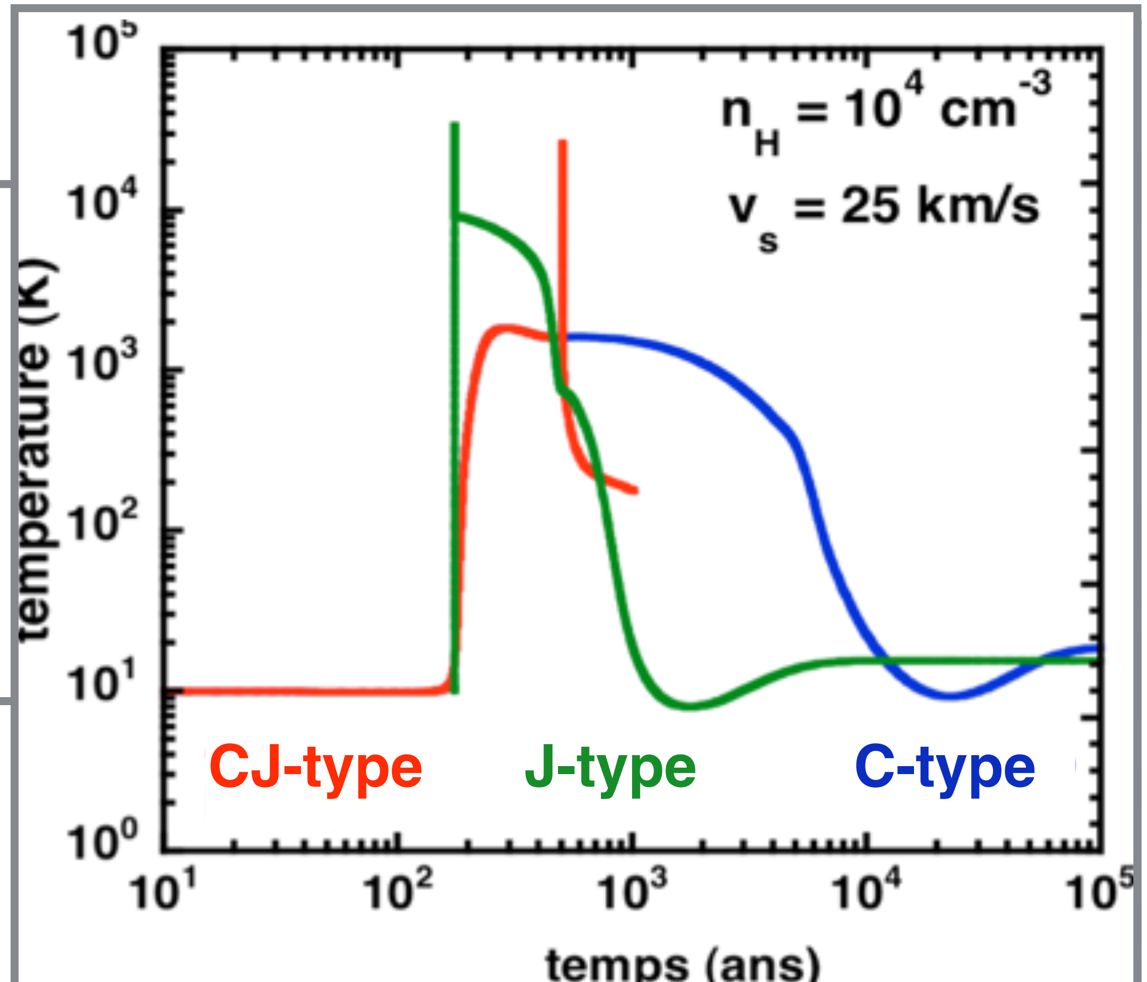
Depending on the value of the shock velocity, V_s, relative to the ions' magnetosonic speed, V_{ims}, and the sound speed, C_s, two basic types of shocks can be distinguished:
J-type ($V_{ims} < V_s$) and C-type ($C_s < V_s < V_{ims}$) shocks.

e.g. Draine 1980

The Paris-Durham shock code

MHD shock code
- 1D stationary (C, J)
- 1D non-stationary approximation (CJ)

Inputs:
- shock type,
- shock velocity
- magnetic field
- preshock density
- preshock chemistry



Macro physics
- conservation equations

Micro physics
- Molecular physics, chemistry, dust

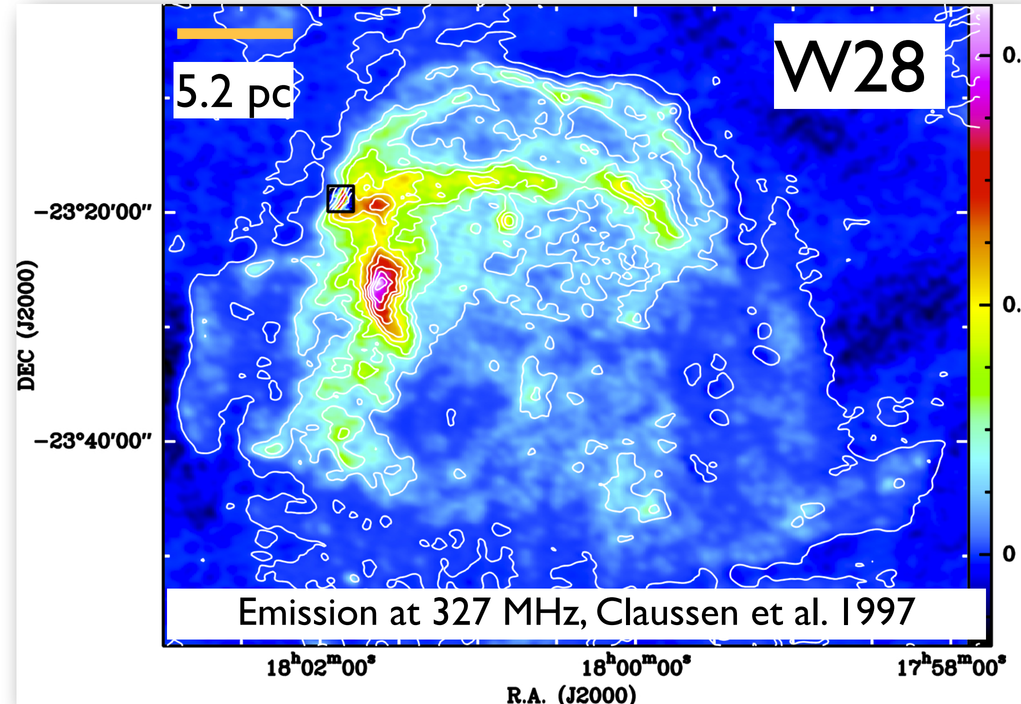
Output:
- Physical and chemical structure
- Level populations and emissivities of various species at each point of the shock

Radiative transfer
- LVG module, various molecules

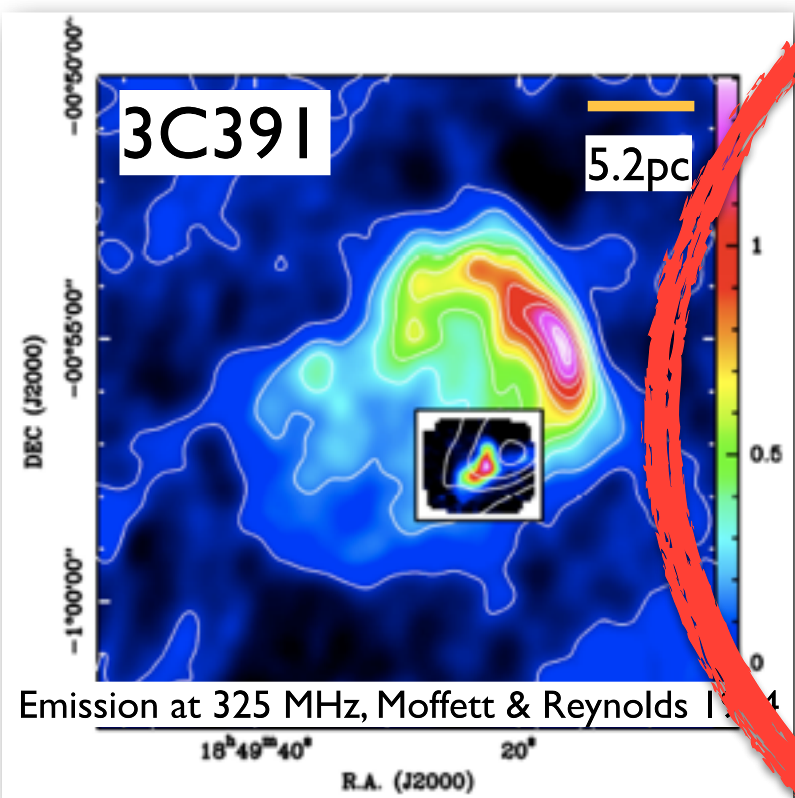
e.g. Flower & Pineau des Forêts 2003, Flower et al. 2003, Lesaffre et al. 2004a,b

Supernova remnants interacting with molecular clouds

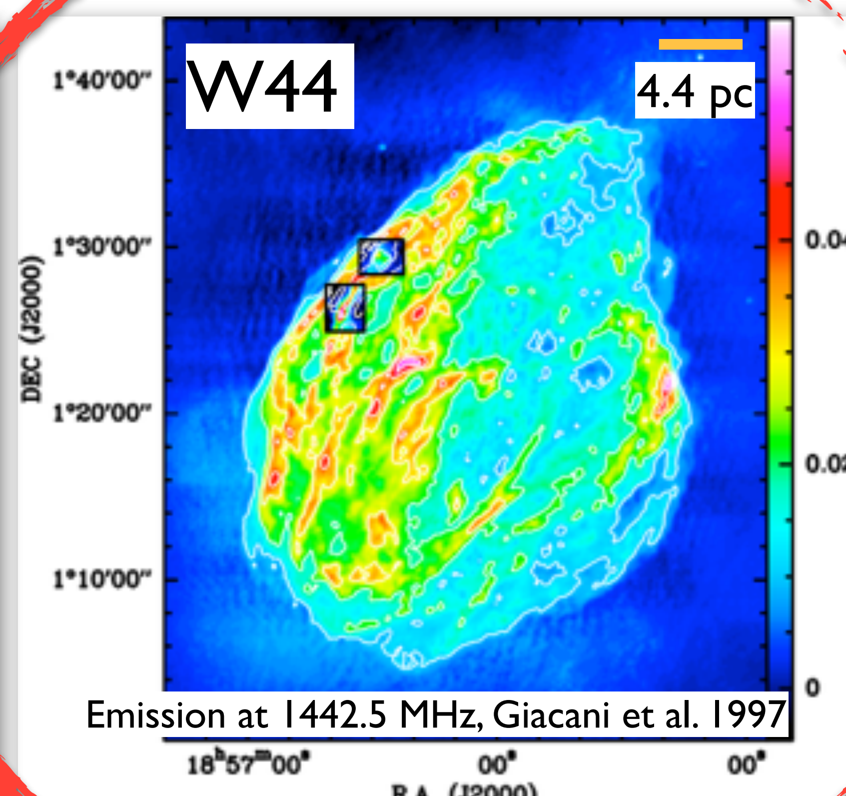
The modelling of shock observations can quantify the physical and chemical conditions of shocked regions and help to understand the environmental impacts of shocks.



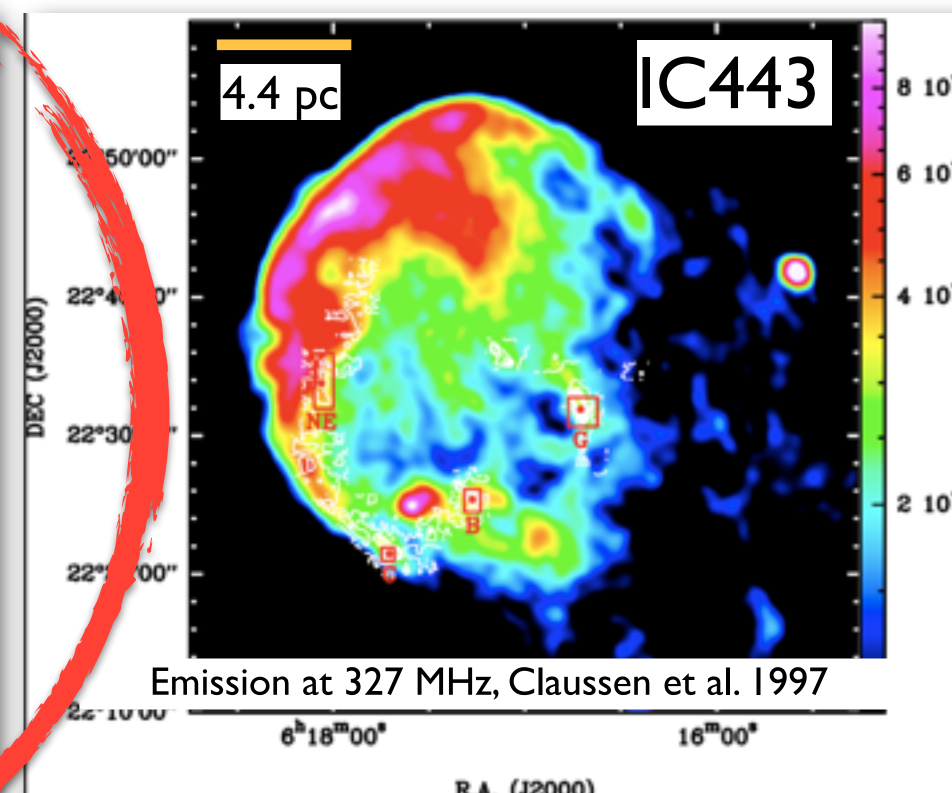
Gusdorf, Anderl et al. 2012



Gusdorf, Anderl et al. in prep.



Anderl et al. 2014, accepted

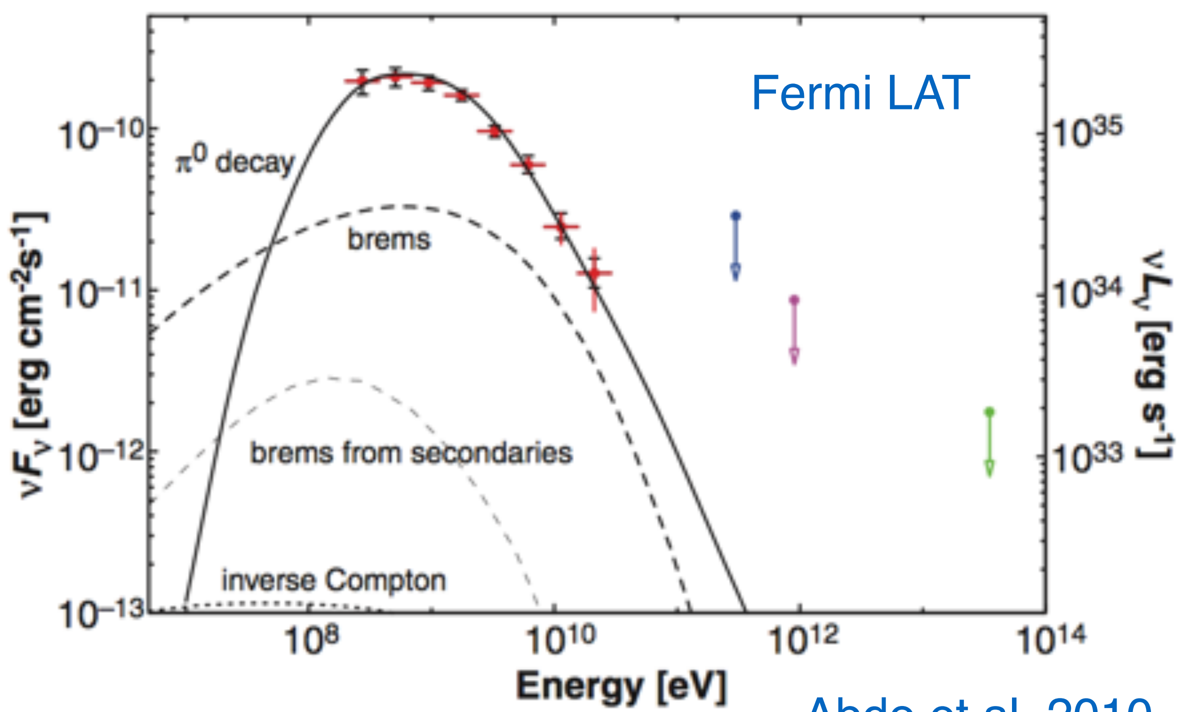


Gusdorf, Anderl et al. in prep.

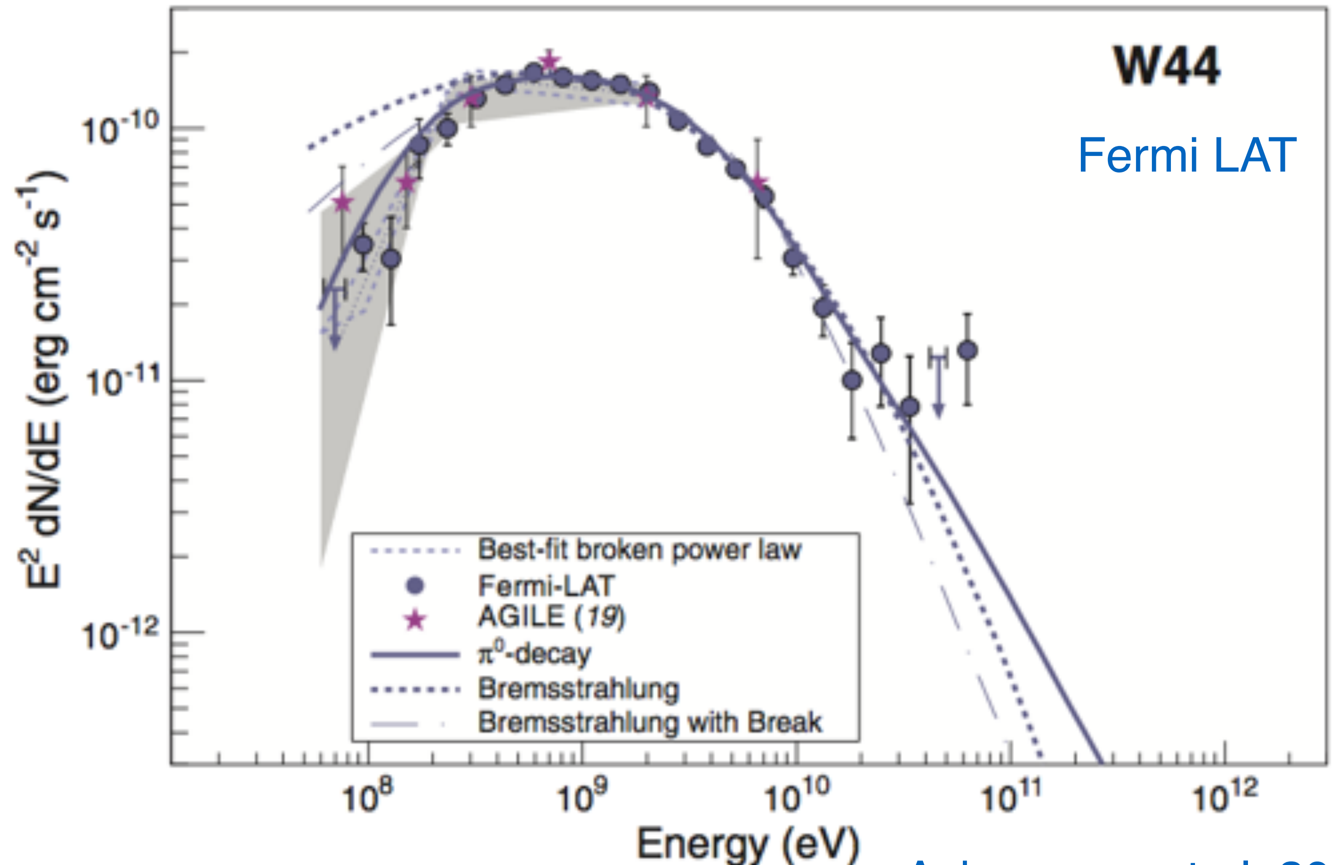
W44 (a.k.a. G34.7-0.4, or 3C 392)

- Prototype of the so-called mixed-morphology supernova remnant (centrally concentrated X-ray emission and shell-like radio morphology) Rho & Petre 1998
- Distance: ~ 3kpc e.g. Radhakrishnan et al. 1972, Abdo et al. 2010
- Age: 2 x 10^4 years, in the radiative phase over most of its surface Cox et al. 1999, Chevalier 1999
- Harbours a 267 millisecond radio pulsar Wolszczan et al. 1991
- Known to interact with a molecular cloud along its eastern limb e.g. Wootten 1977, Reach & Rho 1996
- Observed in cosmic rays, evidence for the acceleration of cosmic-ray protons Esposito et al. 1996, Abdo et al. 2010, Giuliani et al. 2011, Ackermann et al. 2013

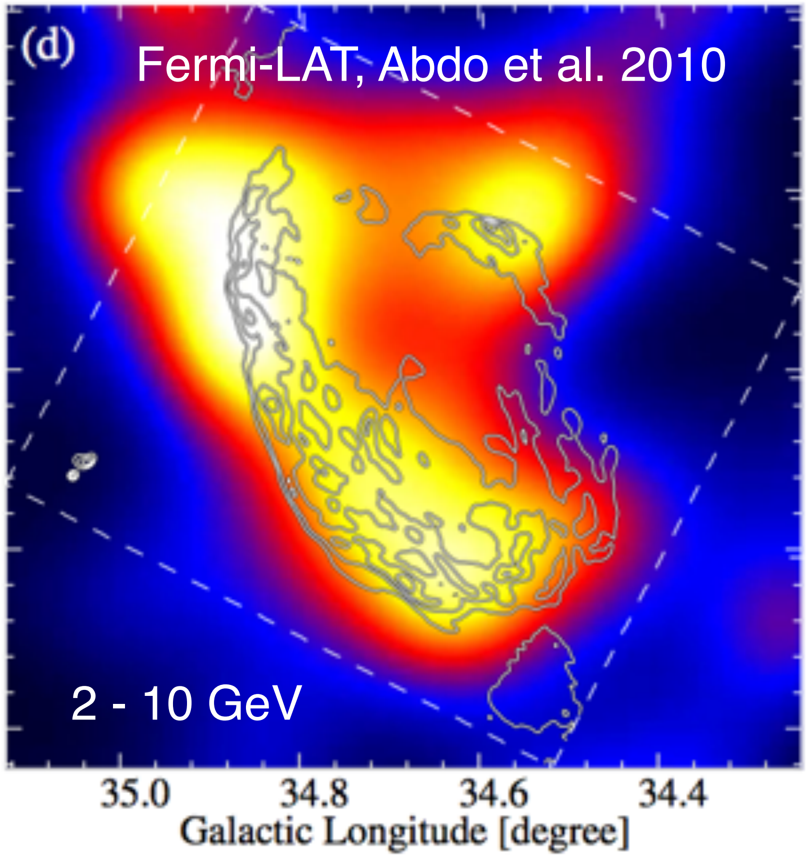
CRs in W44



Abdo et al. 2010



Ackermann et al. 2013



- Close and bright gamma-ray source
- First SNR clearly showing the "pion bump" from π^0-decay photons
- Hadronic models need information on density and magnetic field

Yoshiike et al. 2013

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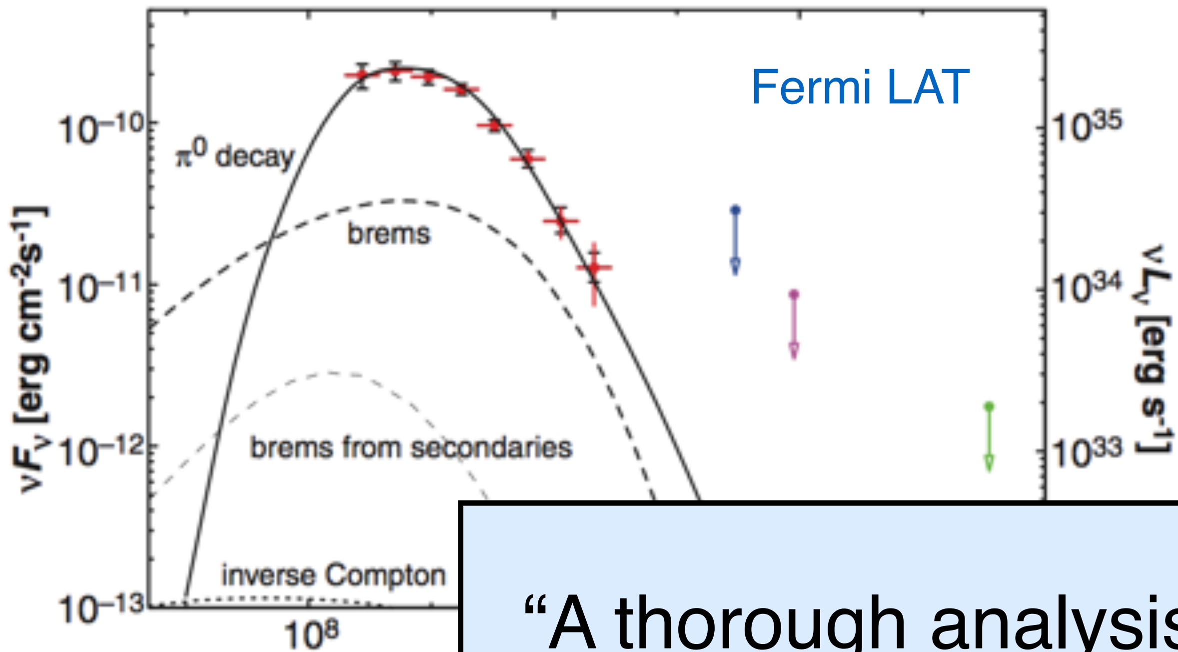
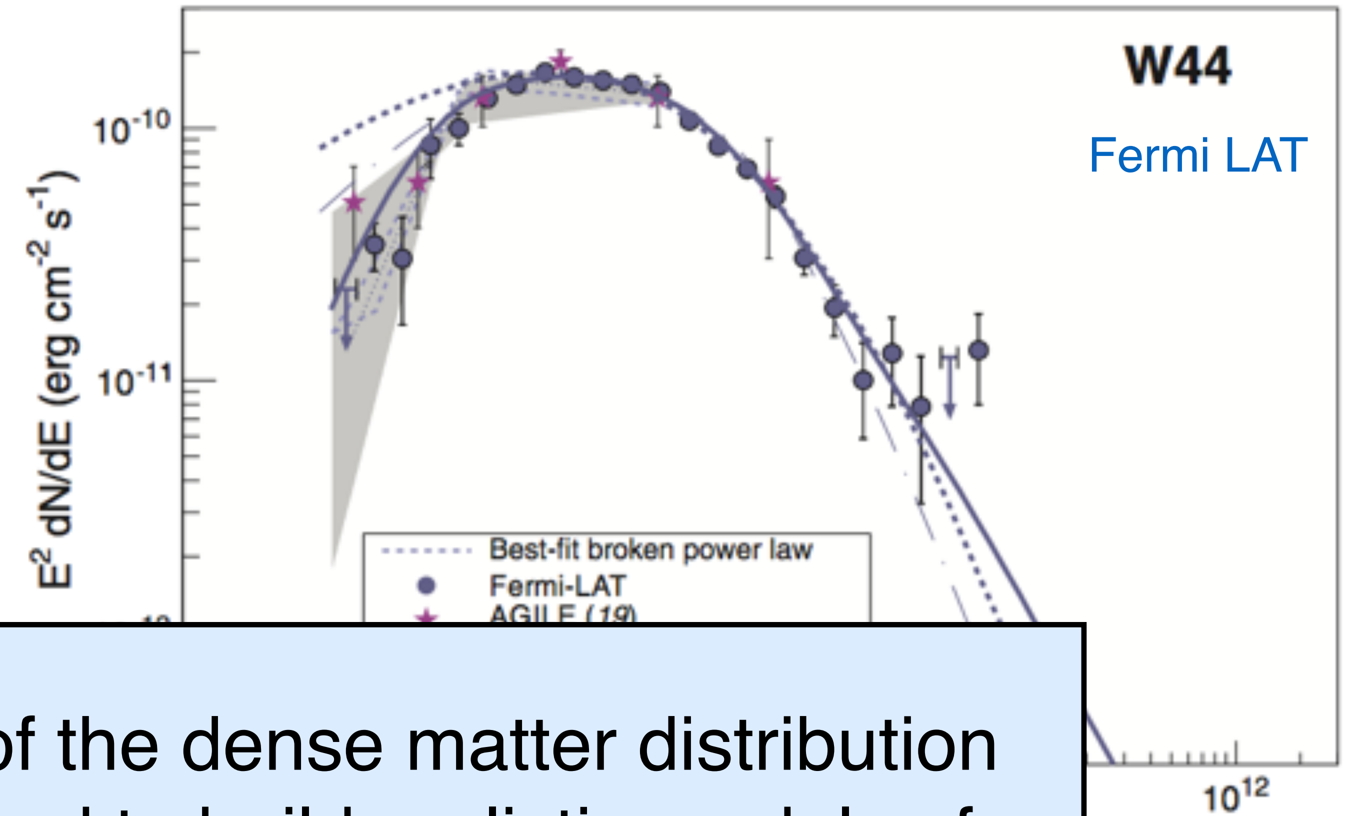
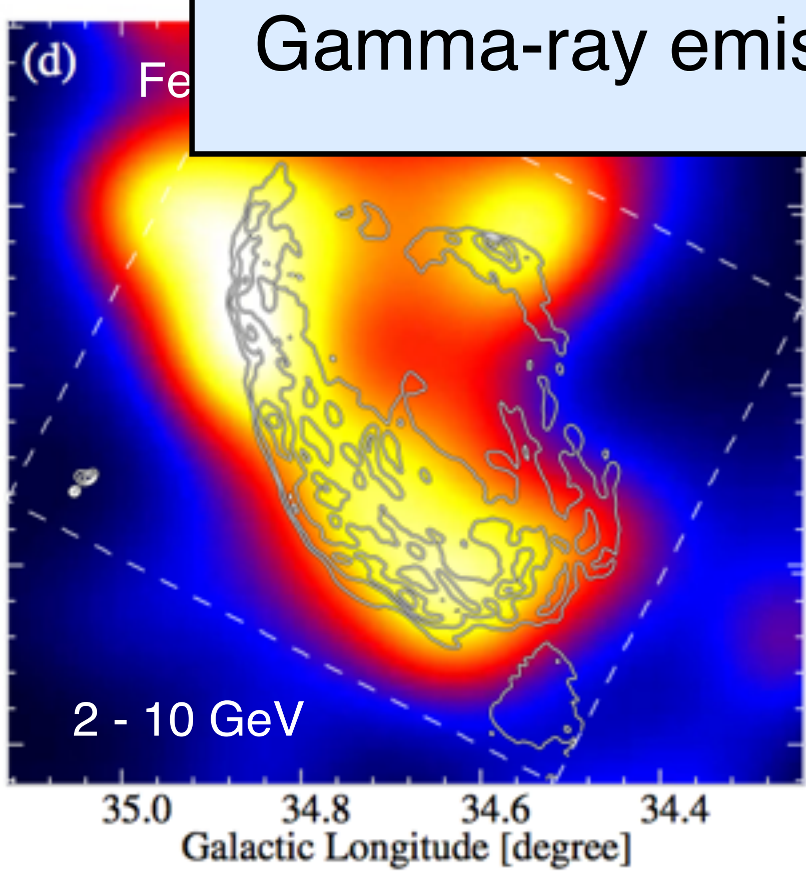
CRs in W44





ann et al. 2013

"A thorough analysis of the dense matter distribution around SNRs is required to build realistic models of Gamma-ray emission."



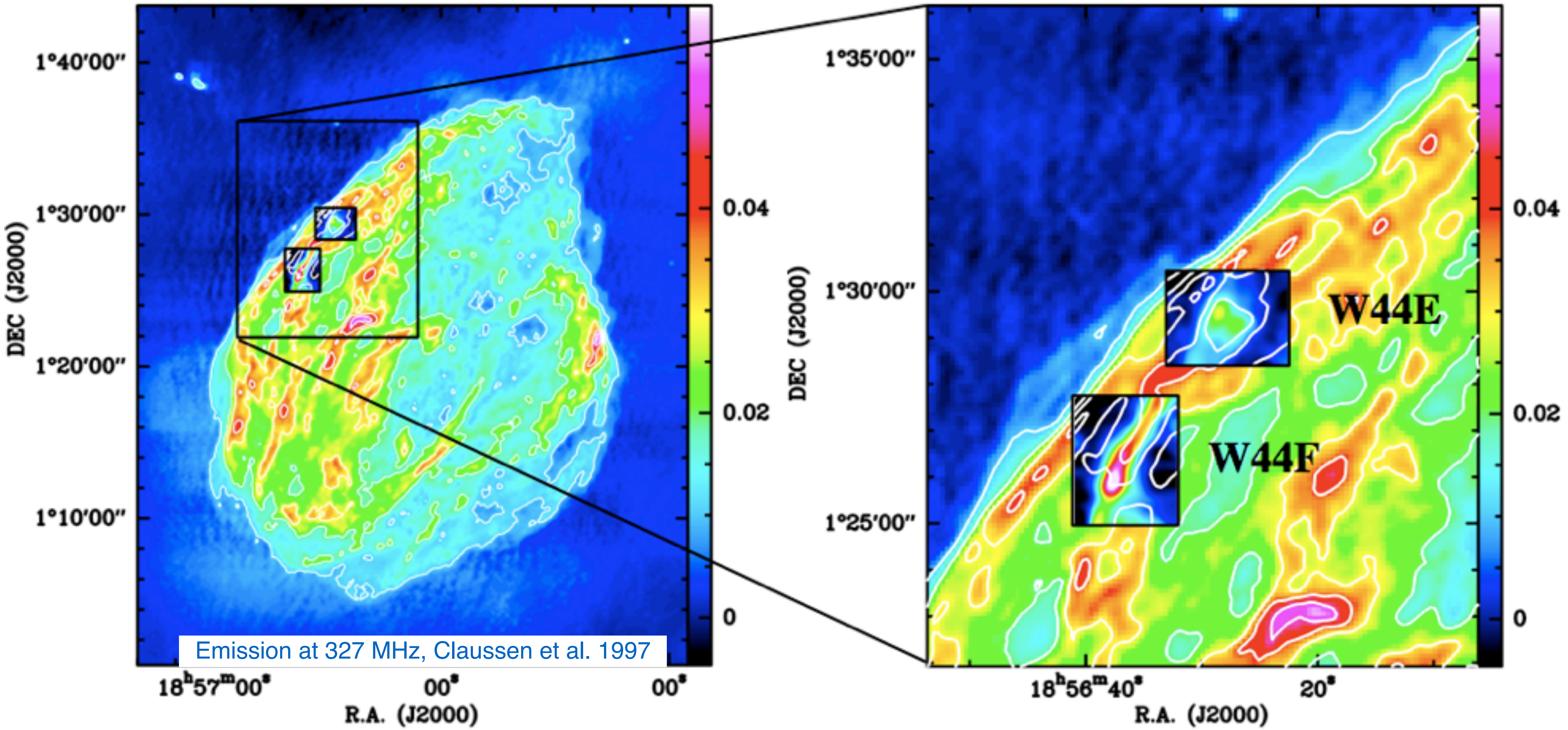
- Close and bright gamma-ray source
- First SNR clearly showing the "pion bump" from π^0-decay photons
- Hadronic models need information on density and magnetic field

Yoshiike et al. 2013

Observations

Observation of shocked molecular regions in

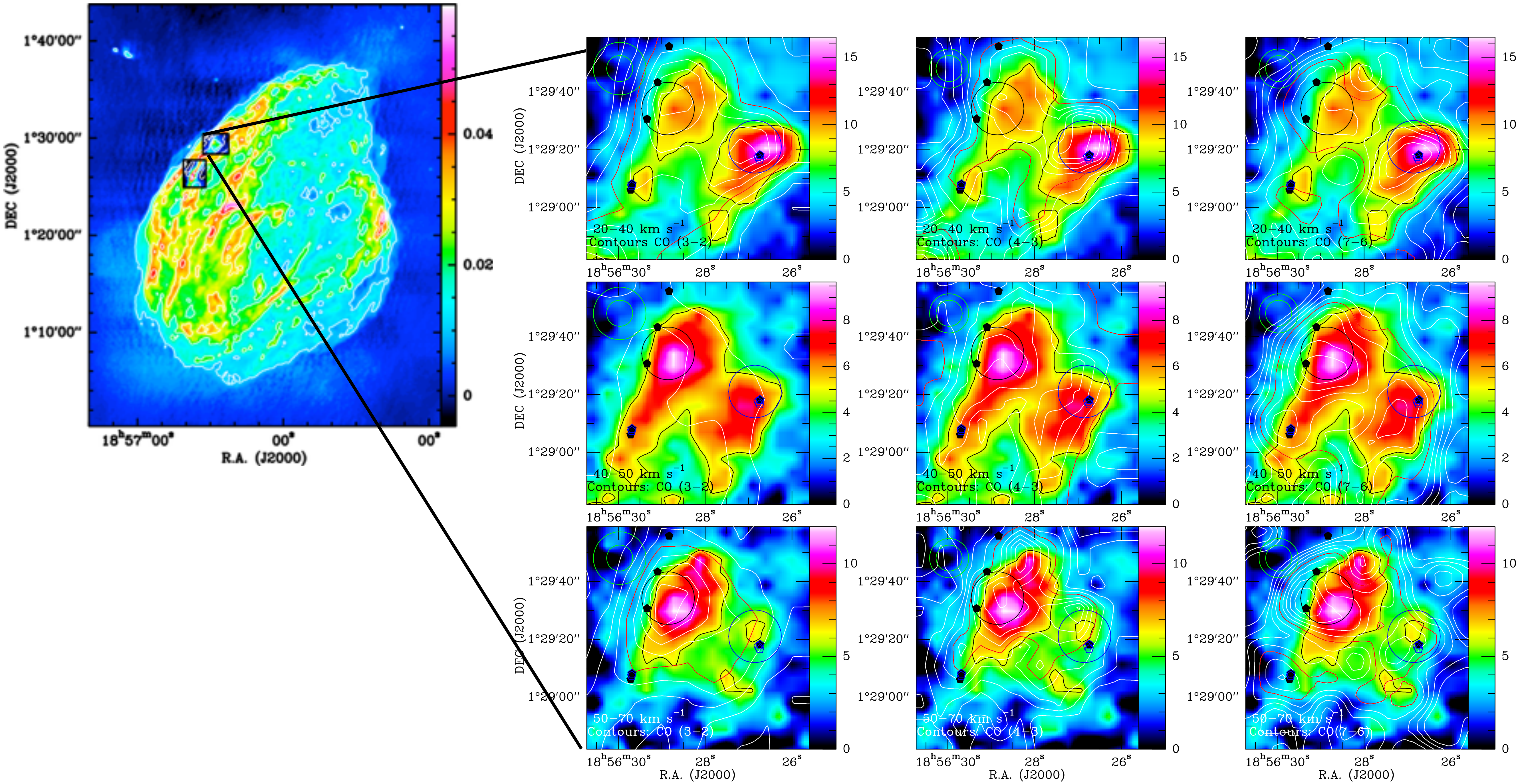
- multiple ^{12}CO rotational transitions (7-6, 6-5, 4-3, 3-2)
- ^{13}CO



Emission at 327 MHz, Claussen et al. 1997

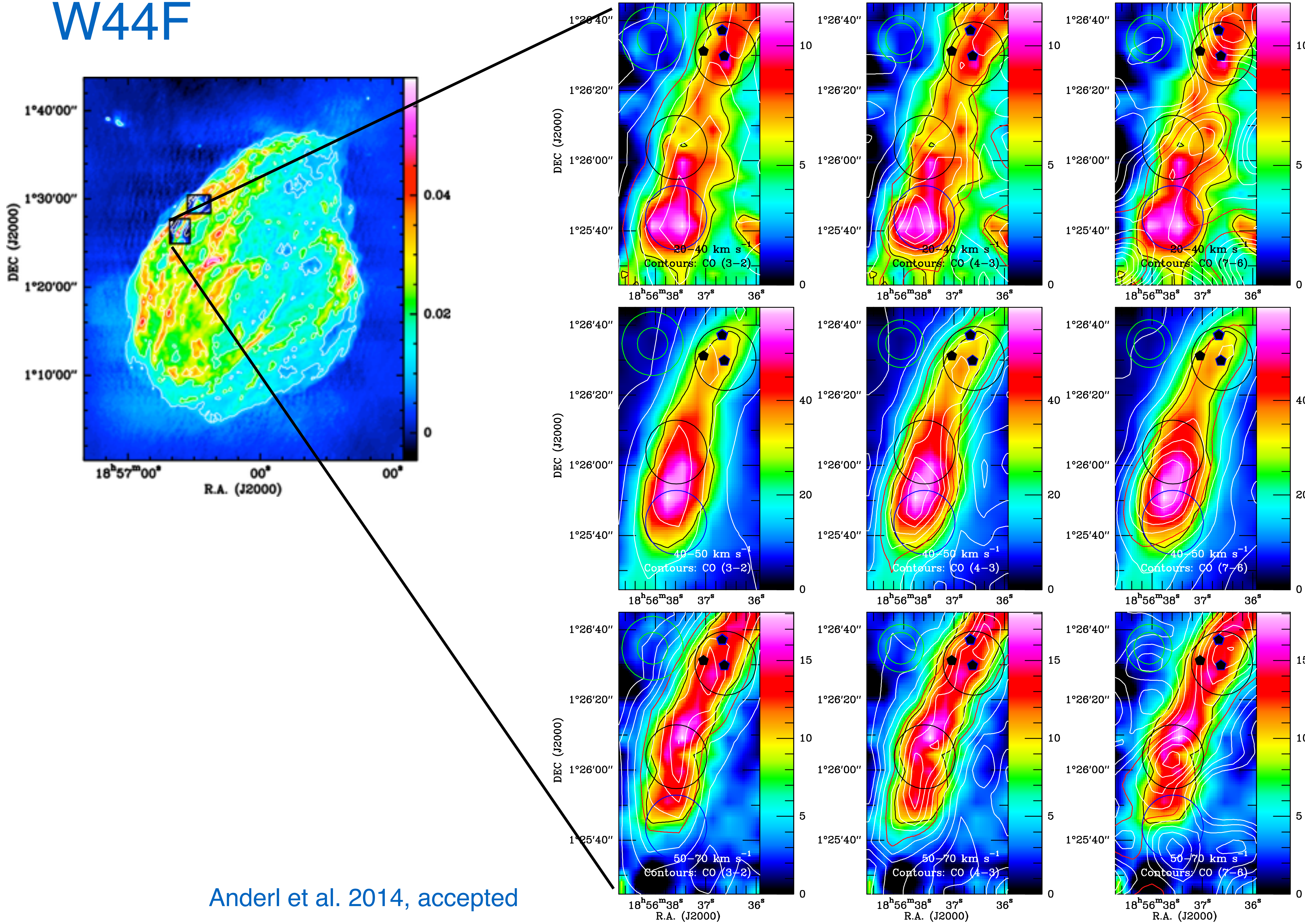
Anderl et al. 2014, accepted

W44E



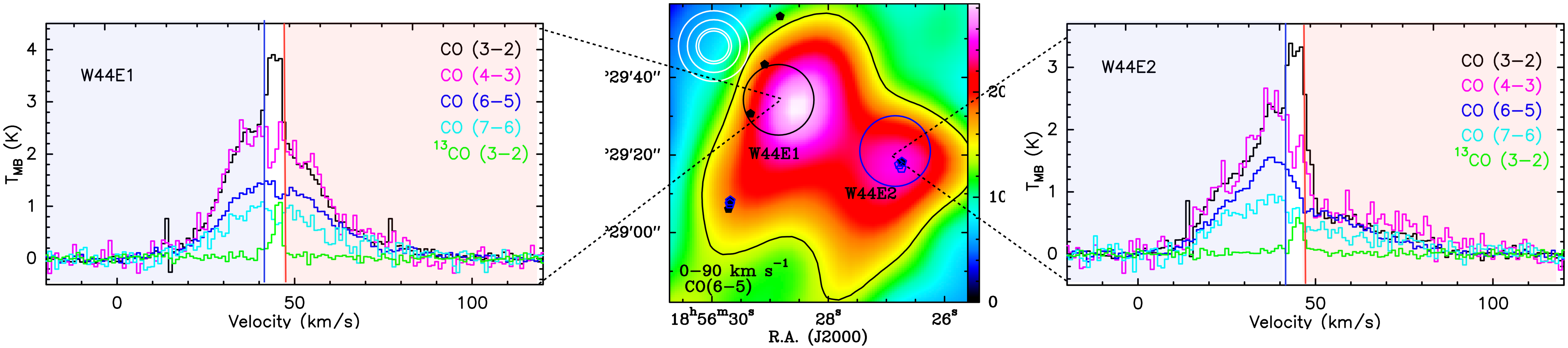
Anderl et al. 2014, accepted

W44F

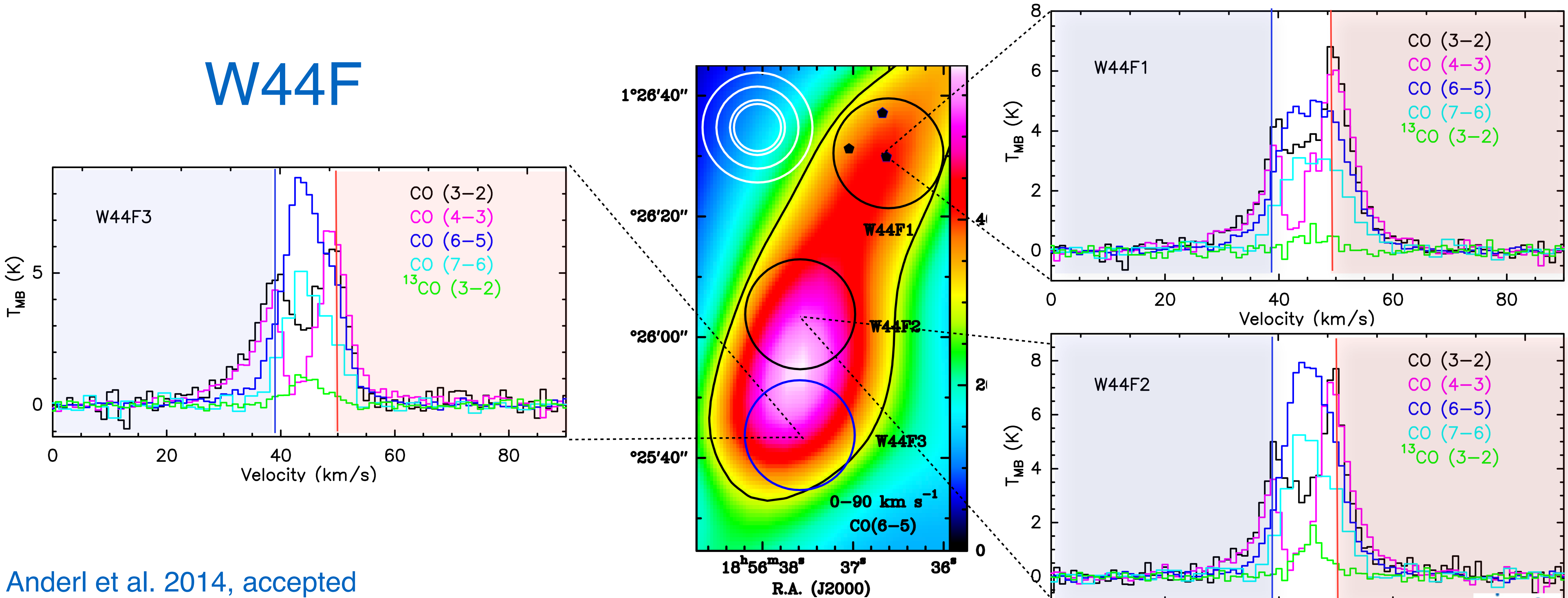


Anderl et al. 2014, accepted

W44E

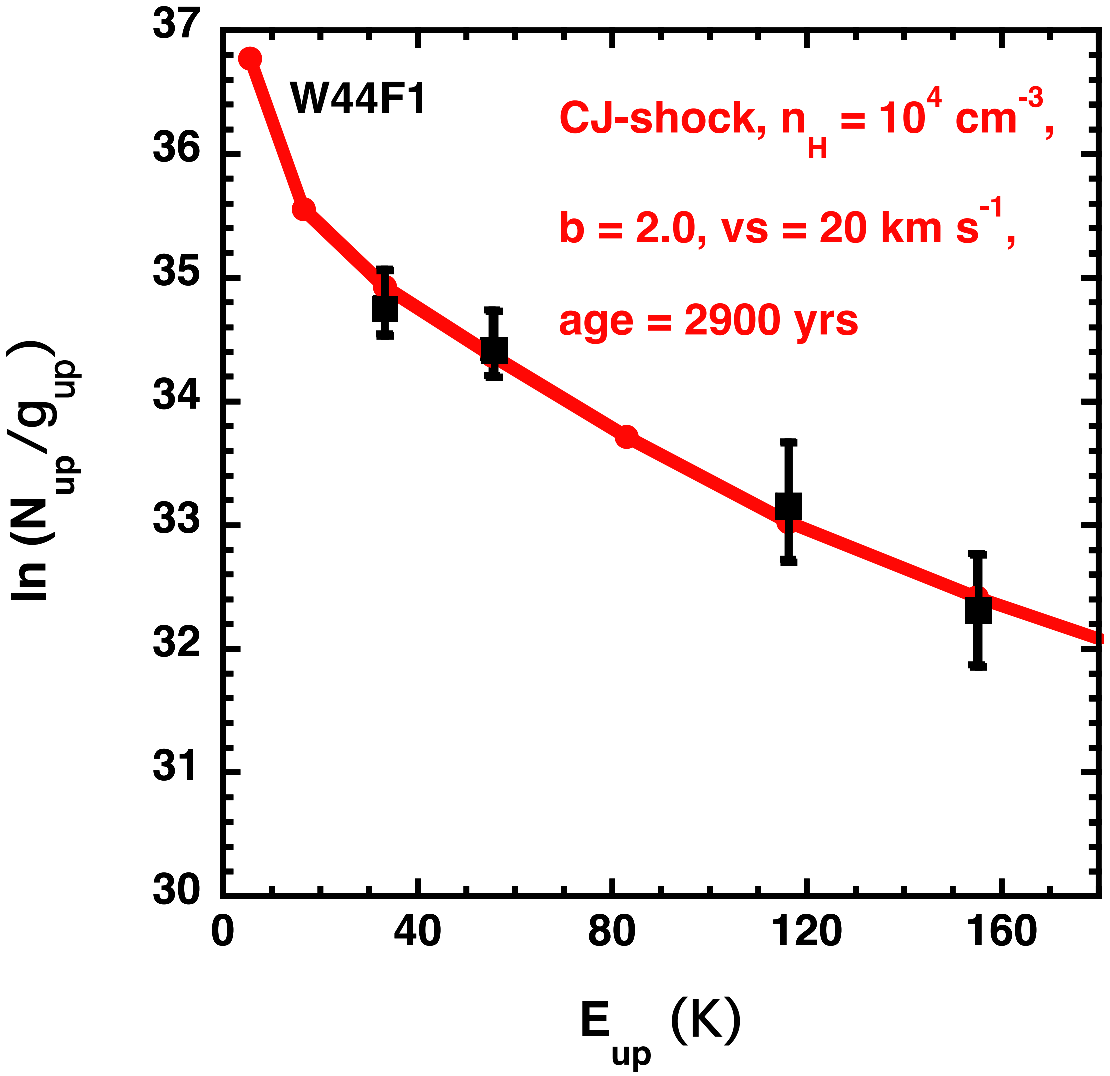


W44F

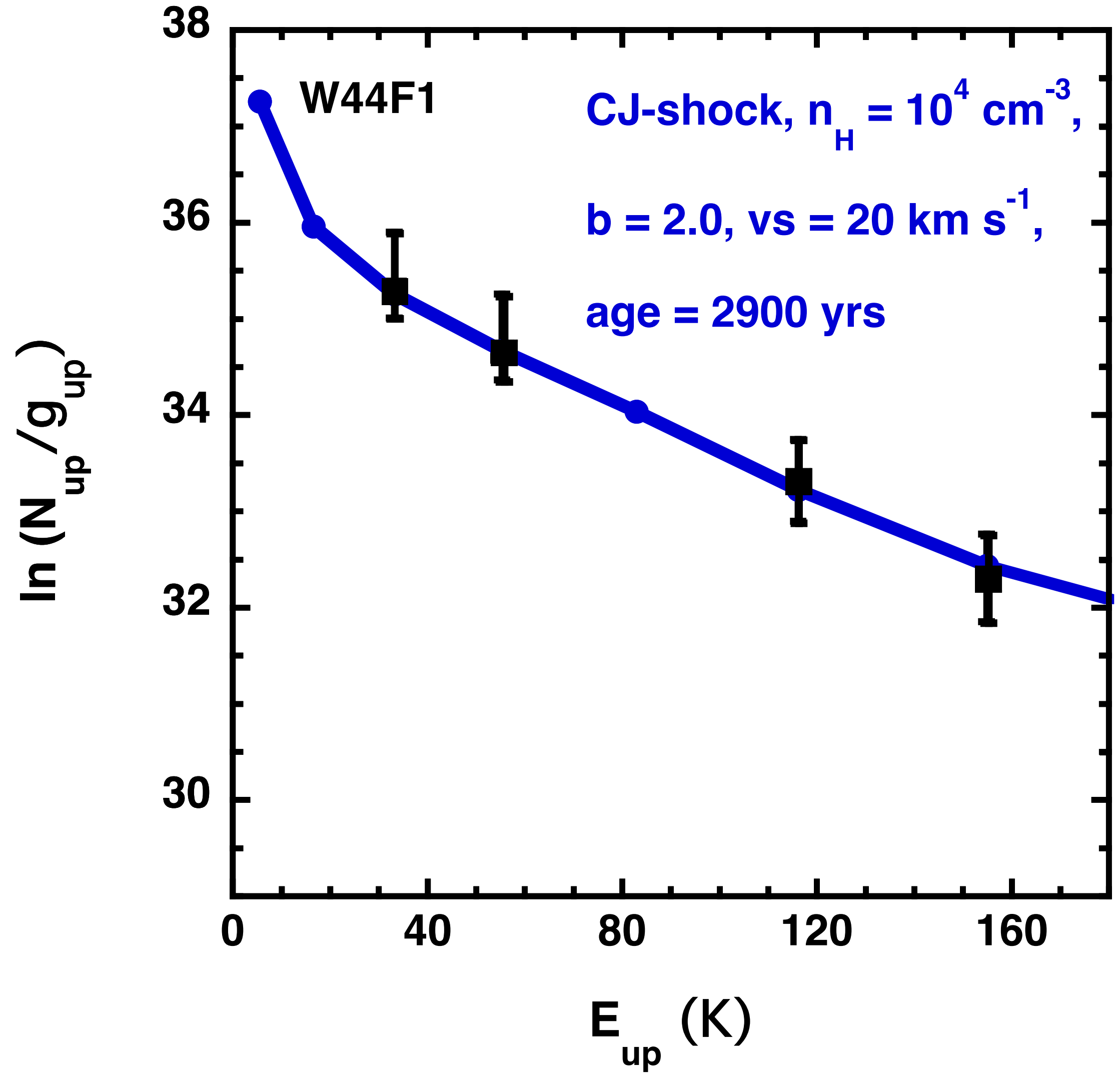


Anderl et al. 2014, accepted

Data fitting



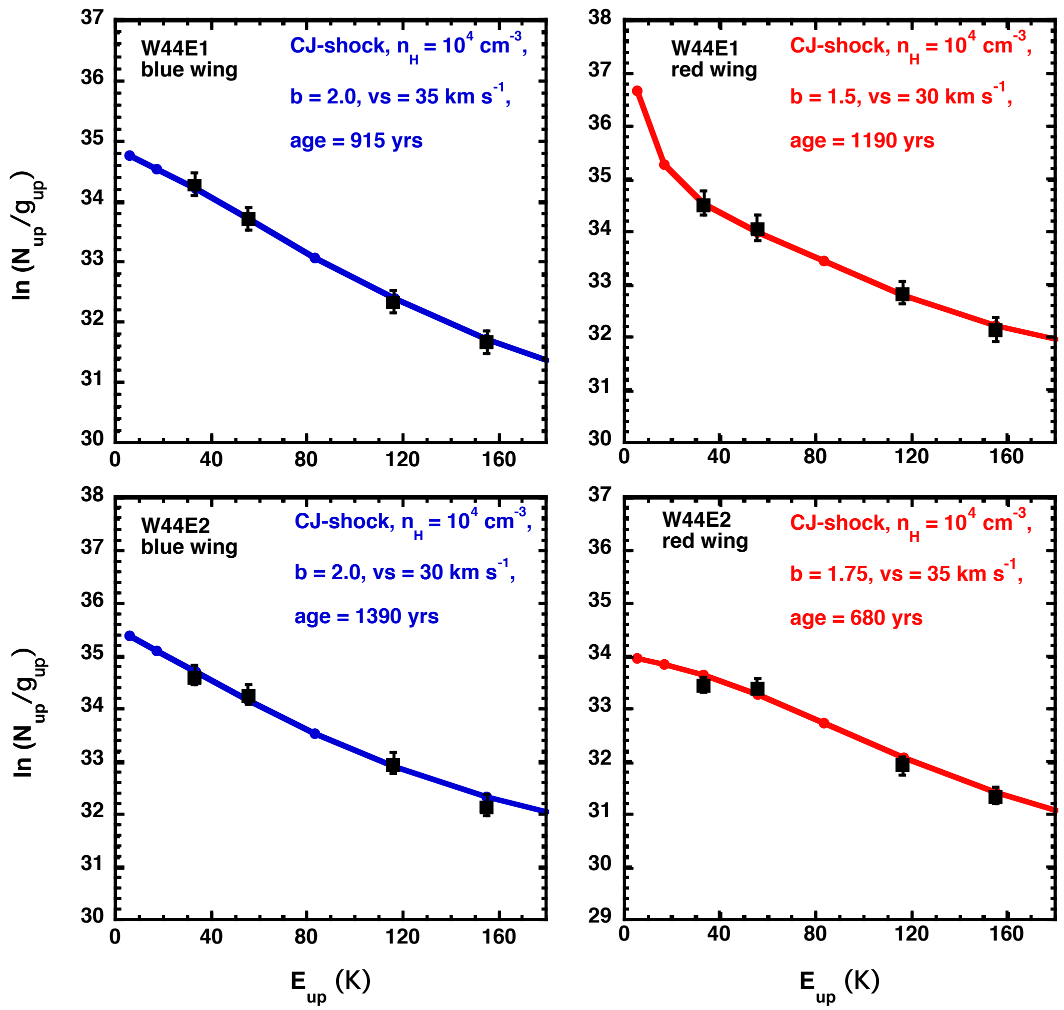
W44F1 - red wing



W44F1 - blue wing

Anderl et al. 2014, accepted

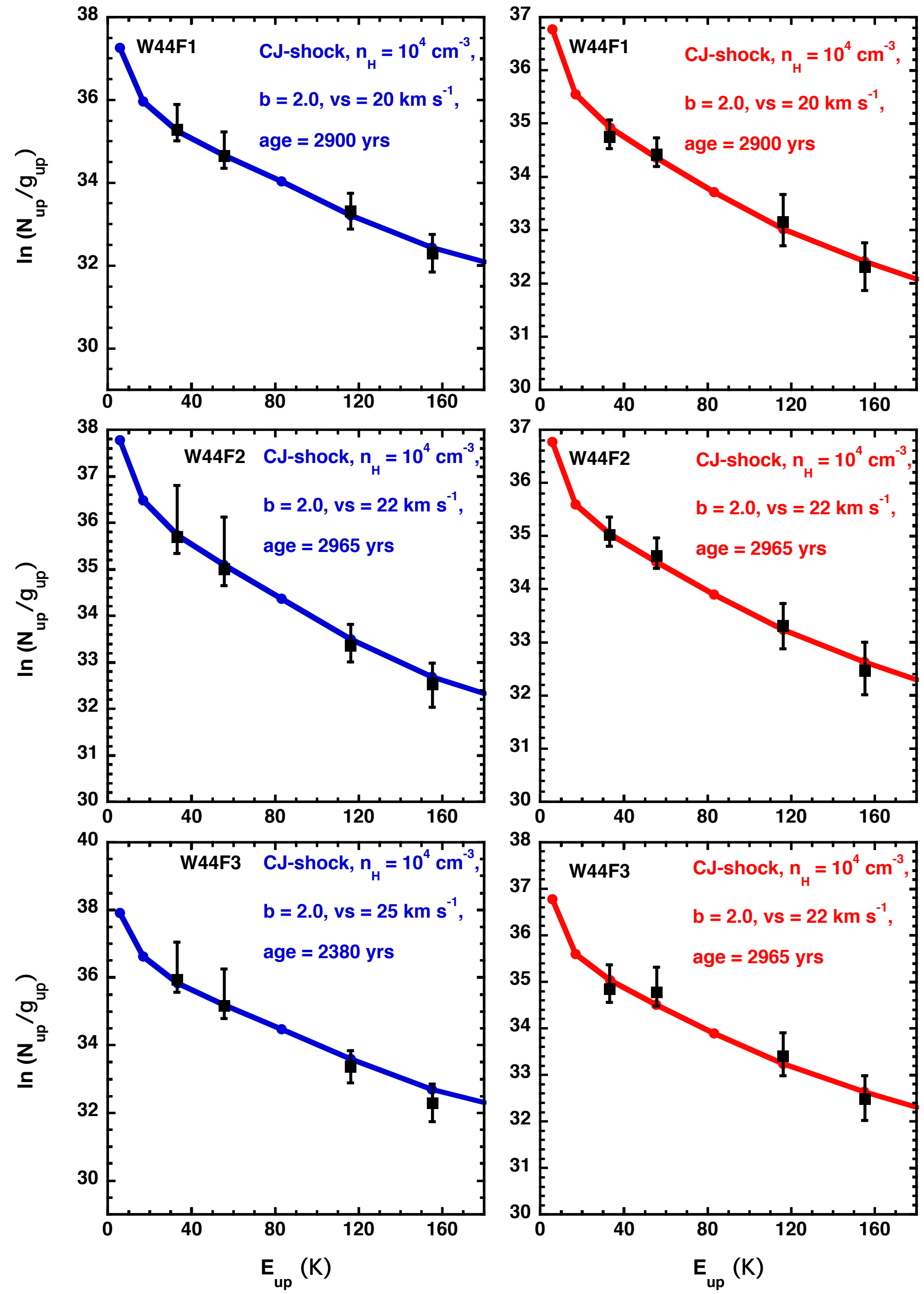
W44E - Fits



Position	integration interval	filling factor	shock type	b	velocity [km s^{-1}]	n_H [cm^{-3}]	age [yr]
W44E1	(-20 to 44.5 km s^{-1})	0.75	CJ	2	35	10^4	915
	low velocity fit:		*CJ*	*1.75*	*20*	*10^4*	*1745*
	(44.5 to 120 km s^{-1})	0.5	CJ	1.5	30	10^4	1190
	low velocity fit:		*CJ*	*1.75*	*20*	*10^4*	*2240*
W44E2	(-20 to 44.8 km s^{-1})	0.5	CJ	2	30	10^4	1390
	low velocity fit:		*CJ*	*1.5*	*22*	*10^4*	*1945*
	(44.8 to 120 km s^{-1})	0.75	CJ	1.75	35	10^4	680
	low velocity fit:		*CJ*	*1.0*	*20*	*10^4*	*860*

Anderl et al. 2014, accepted

W44F - Fits



Anderl et al. 2014, accepted

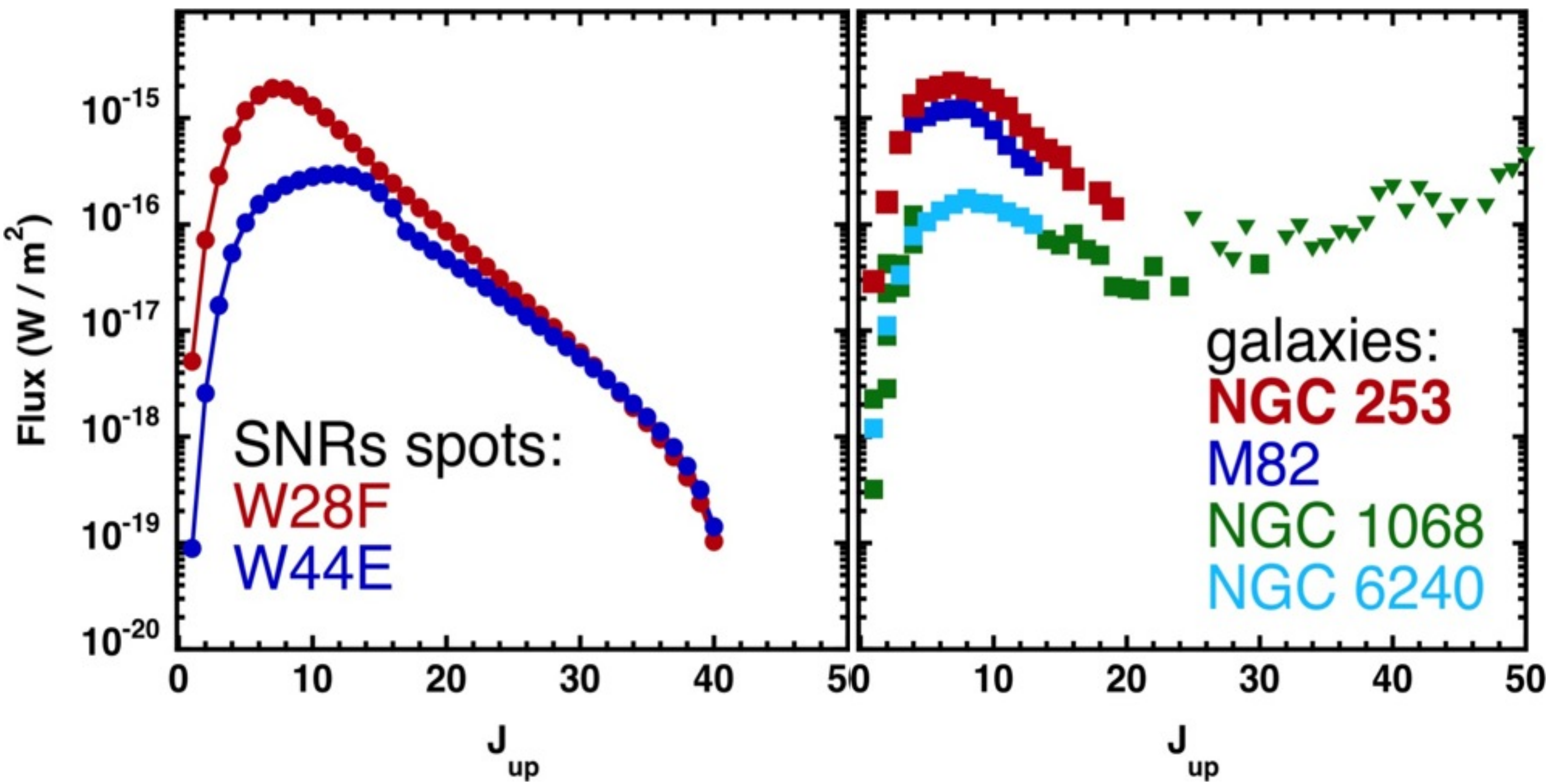
Position	integration interval	filling factor	shock type	b	velocity [km s^{-1}]	n_H [cm^{-3}]	age [yr]
W44F1	(0 to 46.2 km s^{-1})	0.5	CJ	2	20	10^4	2900
	(46.2 to 90 km s^{-1})	0.5	CJ	2	20	10^4	2900
W44F2	(0 to 45.7 km s^{-1})	0.5	CJ	2	22	10^4	2965
	(45.7 to 90 km s^{-1})	0.5	CJ	2	22	10^4	2965
W44F3	(0 to 44.4 km s^{-1})	0.5	CJ	2	25	10^4	2380
	(44.4 to 90 km s^{-1})	0.5	CJ	2	22	10^4	2965

W44 - Derived information and further constraints

- Fits require young, **non-stationary shocks**
- The preshock density is confined to **10^4 cm^{-3}**
- The preshock magnetic field strength is **100-200 μG**
- Shock velocities are between **20 and 35 km s^{-1}**
- Shock ages are **less than 3000 yrs.**

- Shocked gas mass: 1-2 M_{Sun} per beam
- Momentum injection:1-5 x 10^6 M_{Sun} cm s^{-1} per beam
- Energy injection: 1-8 x 10^{45} erg per beam

The energy balance of galaxies



Summary

- Based on the modeling of new CO observations towards SNRs interacting with molecular clouds, the shock characteristics and pre-shock conditions in W44E and F were constrained and the impact of SNRs on their environment in terms of mass, momentum and energy dissipation was quantified.

- For the first time, young non-stationary shock models were shown to be consistent with the shock emission in W44E and W44F.

- The pre-shock density was constrained to 10^4 cm^{-3}, the magnetic field strength is 100-200 μG, and the shock velocities are between 20 and 35 km s^{-1}

▸ Upcoming publication in A&A: (accepted) "APEX observations of supernova remnants - I. Non-stationary MHD-shocks in W44", **Anderl, S.**, Gusdorf, A. , Güsten, R.

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