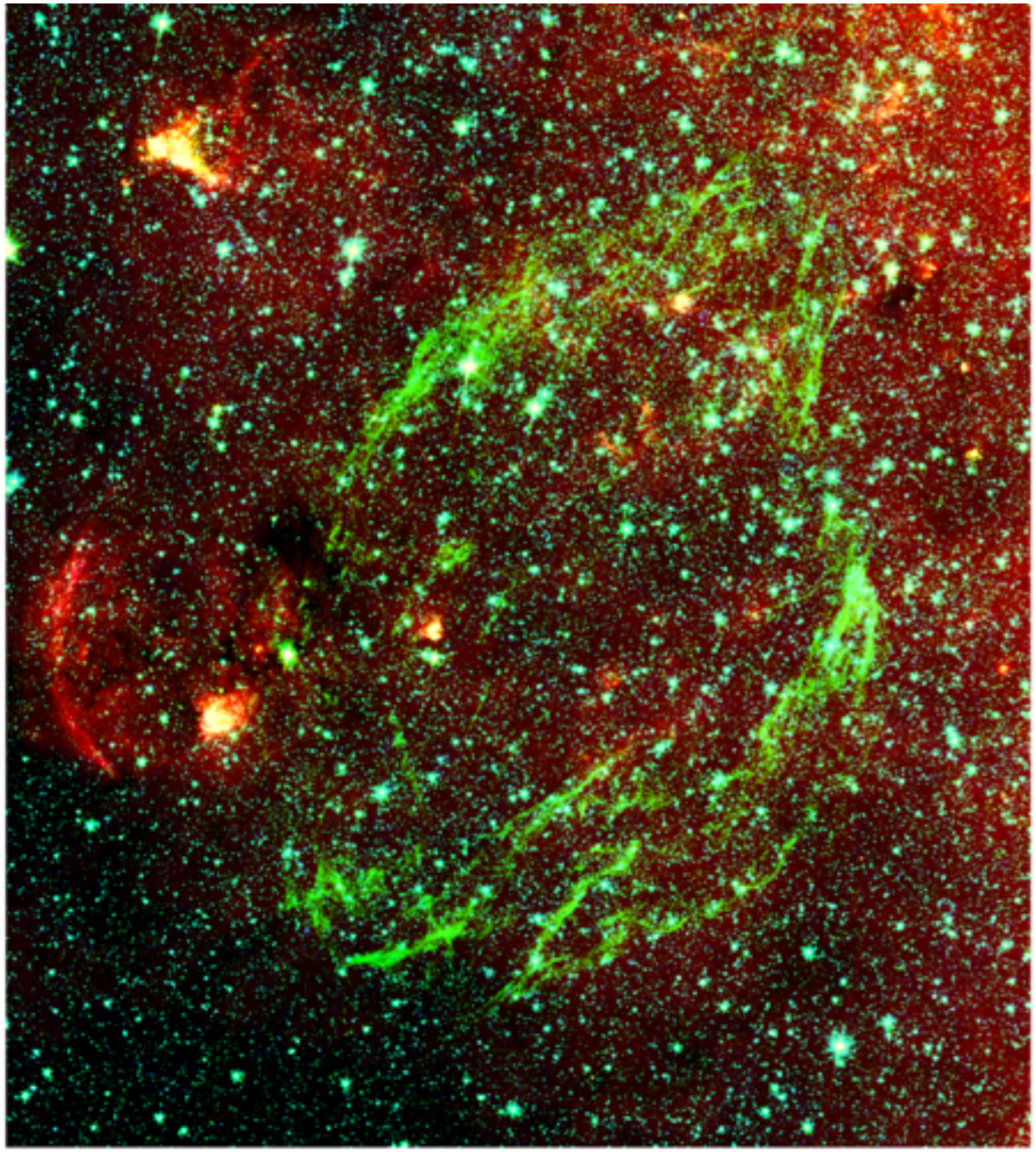
Supernovae in Molecular Clouds:

Extreme Laboratories for the Dense ISM

IC 443 - 24μm warm dust



W44 - 3.6μm, 4.5μm (H_2), 8μm

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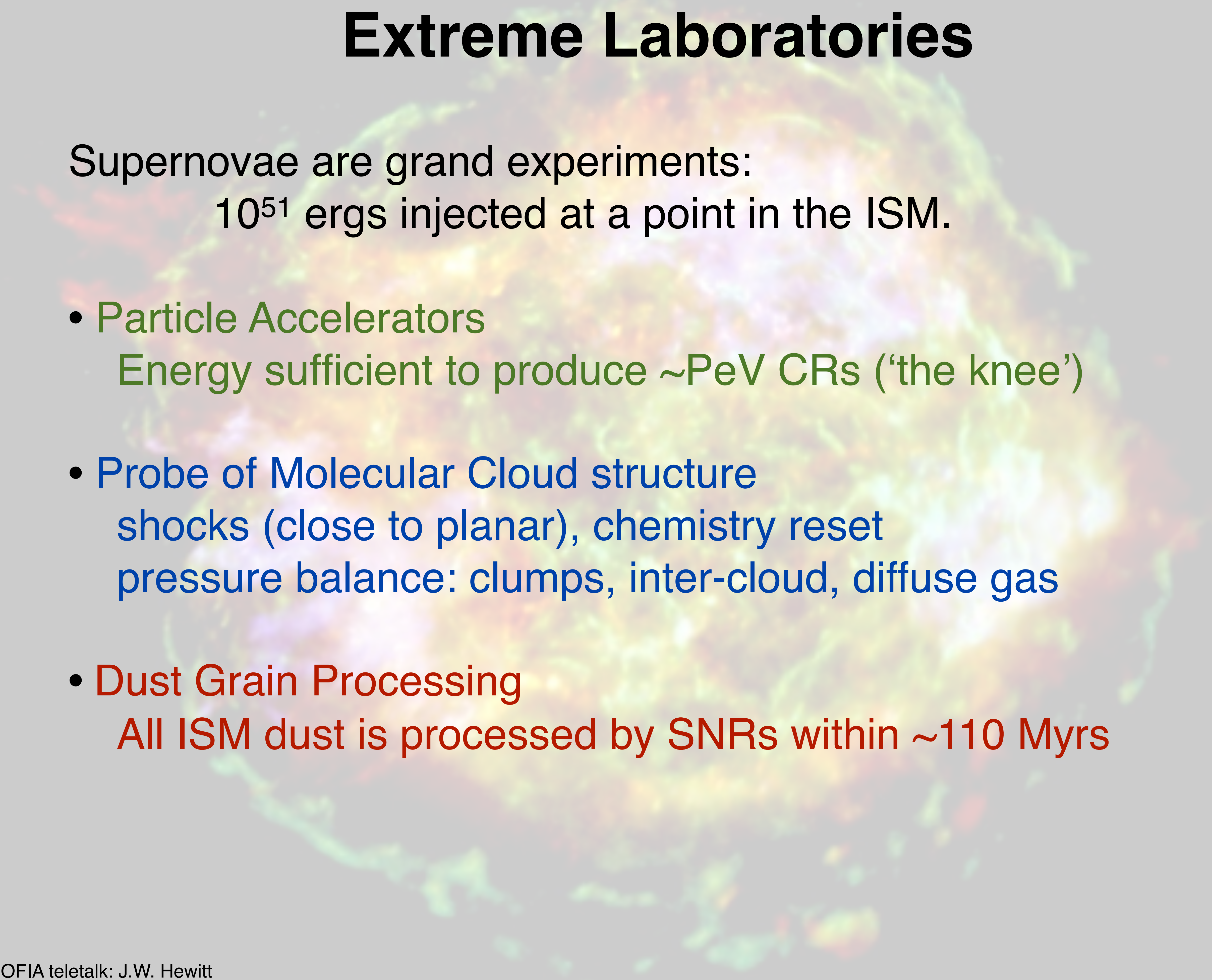
Extreme Laboratories



Supernovae are grand experiments:

10^{51} ergs injected at a point in the ISM.

- Particle Accelerators
  Energy sufficient to produce ~PeV CRs (‘the knee’)

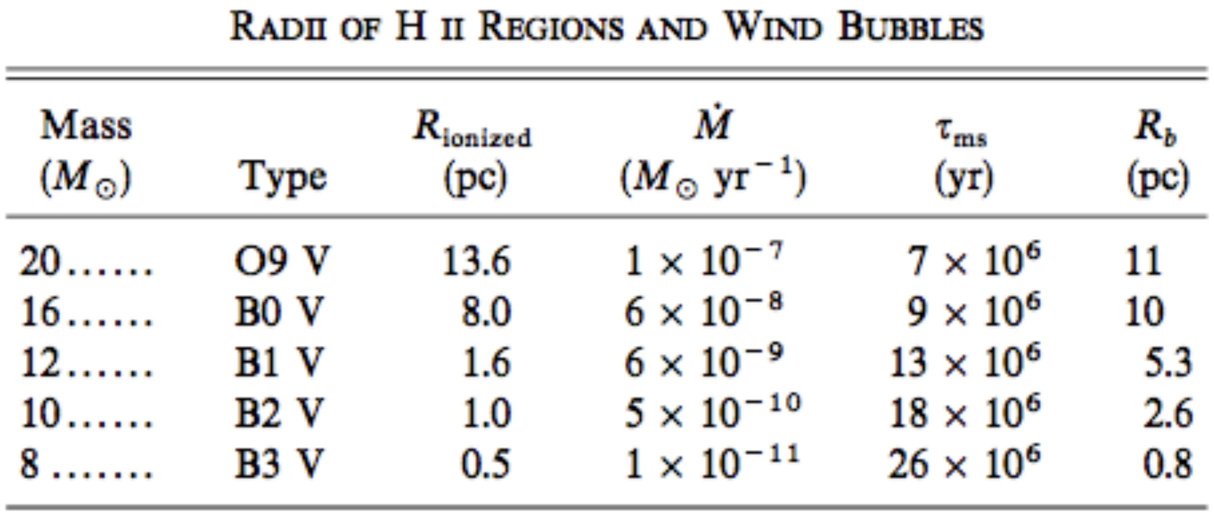
- Probe of Molecular Cloud structure
  shocks (close to planar), chemistry reset
  pressure balance: clumps, inter-cloud, diffuse gas

- Dust Grain Processing
  All ISM dust is processed by SNRs within ~110 Myrs

SNR/MC Interaction

Typical Molecular Cloud

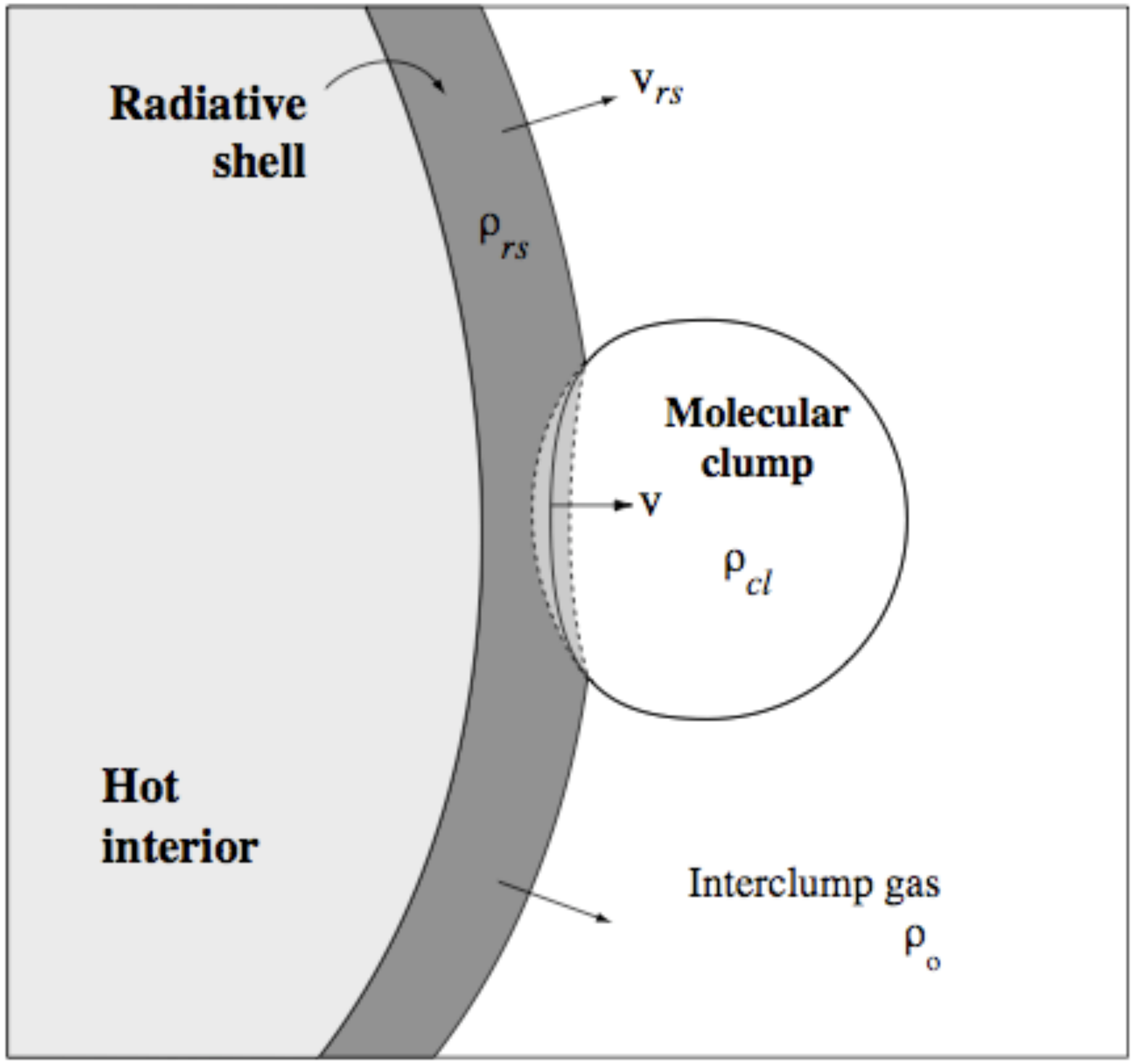
- dense clumps, in diffuse molecular gas
- gas pressure ~10^5 K cm^{-3} confines clumps, supports against collapse



RADII OF H II REGIONS AND WIND BUBBLES

Mass ($M_\odot$)	Type	$R_{\rm ionized}$ (pc)	$\dot{M}$ ($M_\odot$ yr^{-1})	$\tau_{\rm ms}$ (yr)	R_b (pc)
20……	O9 V	13.6	1×10^{-7}	7×10^6	11
16……	B0 V	8.0	6×10^{-8}	9×10^6	10
12……	B1 V	1.6	6×10^{-9}	13×10^6	5.3
10……	B2 V	1.0	5×10^{-10}	18×10^6	2.6
8 …….	B3 V	0.5	1×10^{-11}	26×10^6	0.8

~10^4 M_{sol} cloud yields ~1 O-star



(Chevalier 1999)

Prototypical SNR/MC Interaction

2MASS NIR imaging, Rho et al. (2001)

SNR IC 443

interacting w/10^4 Msol cloud

Parameters

age ~10-30 kyr

distance = 1.5 kpc

radius = 7.4 pc

v_S ~ 100 km/s

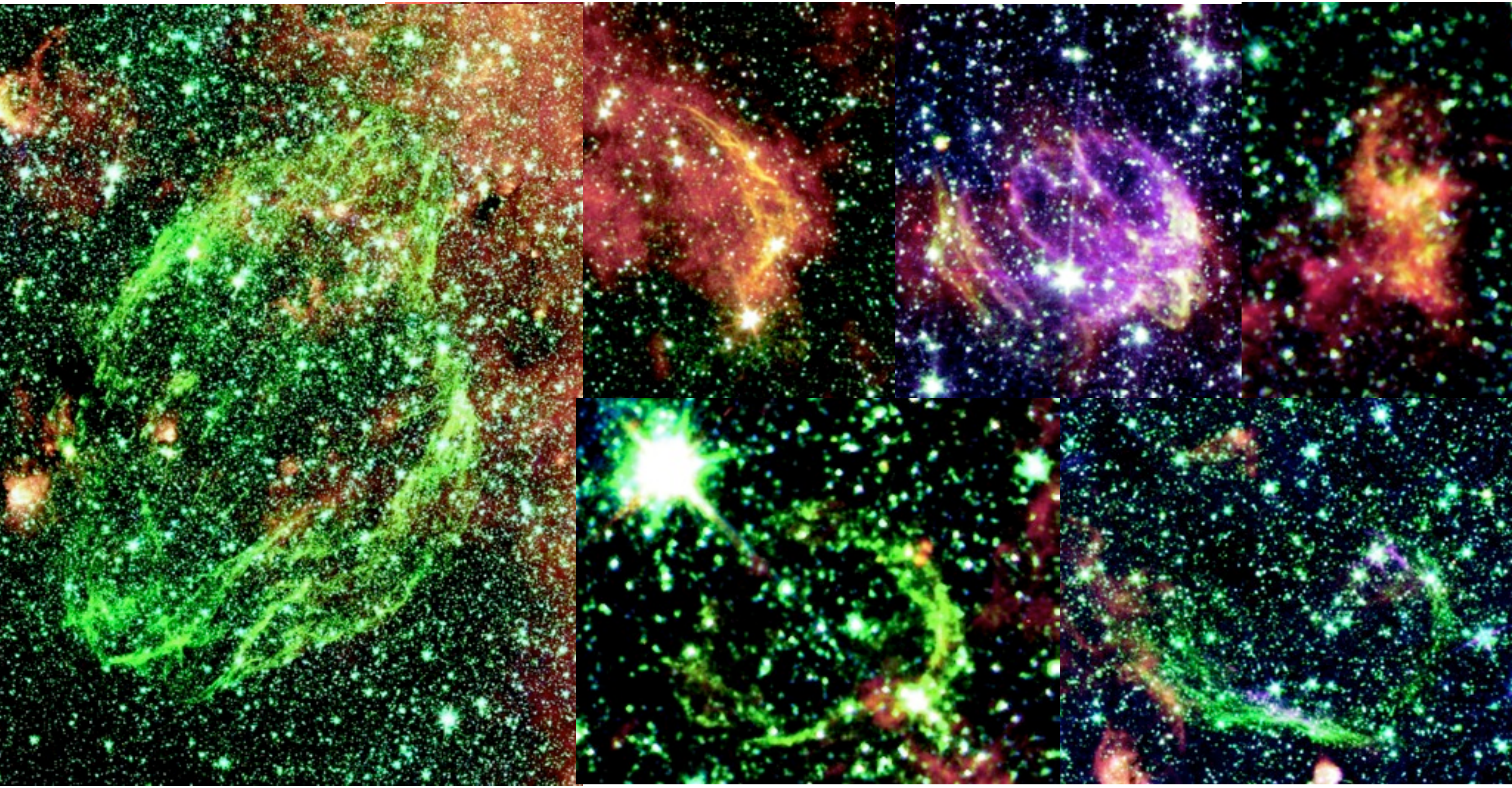
H2 shell in south

NE fast shock, low density
(radiative shell)

NW shock breakout (radio)
lowers pressure in shell

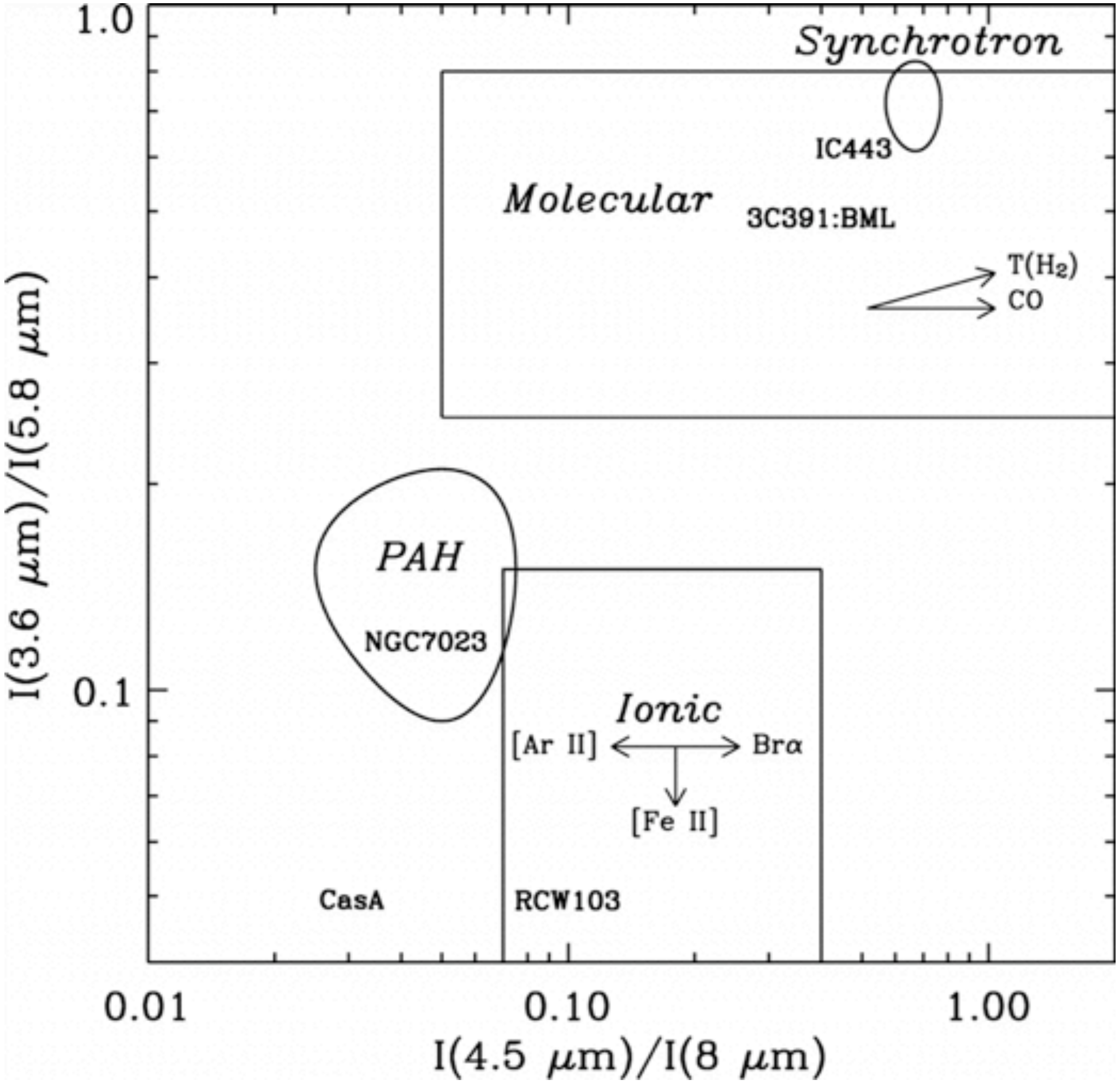
Spitzer GLIMPSE Survey of SNRs

red = 8 μm, yellow = 5.8 μm, green = 4.5 μm, blue = 3.6 μm



(from Reach et al. 2006)

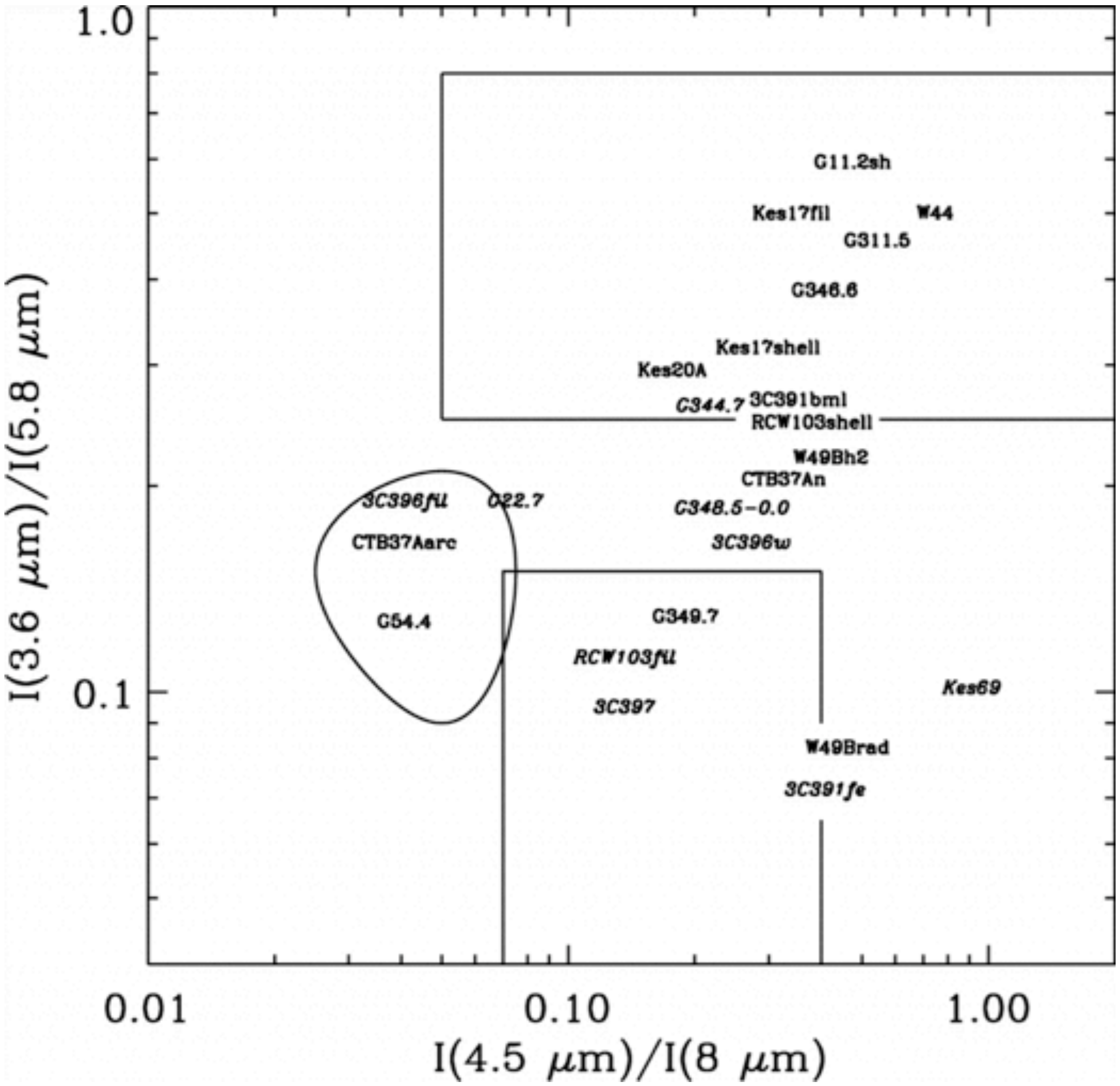
Supernova Remnants Interacting with Clouds



from Reach et al. 2006

- *Spitzer* GLIMPSE survey detected 18 IR-bright SNRs
- Colors indicate dominant cooling lines and shock type.

Supernova Remnants Interacting with Clouds



from Reach et al. 2006

- *Spitzer* GLIMPSE survey detected 18 IR-bright SNRs

- Colors indicate dominant cooling lines and shock type.

However...

Color-typing shows large scatter, even within the same SNR

IR spectroscopy is clearly needed

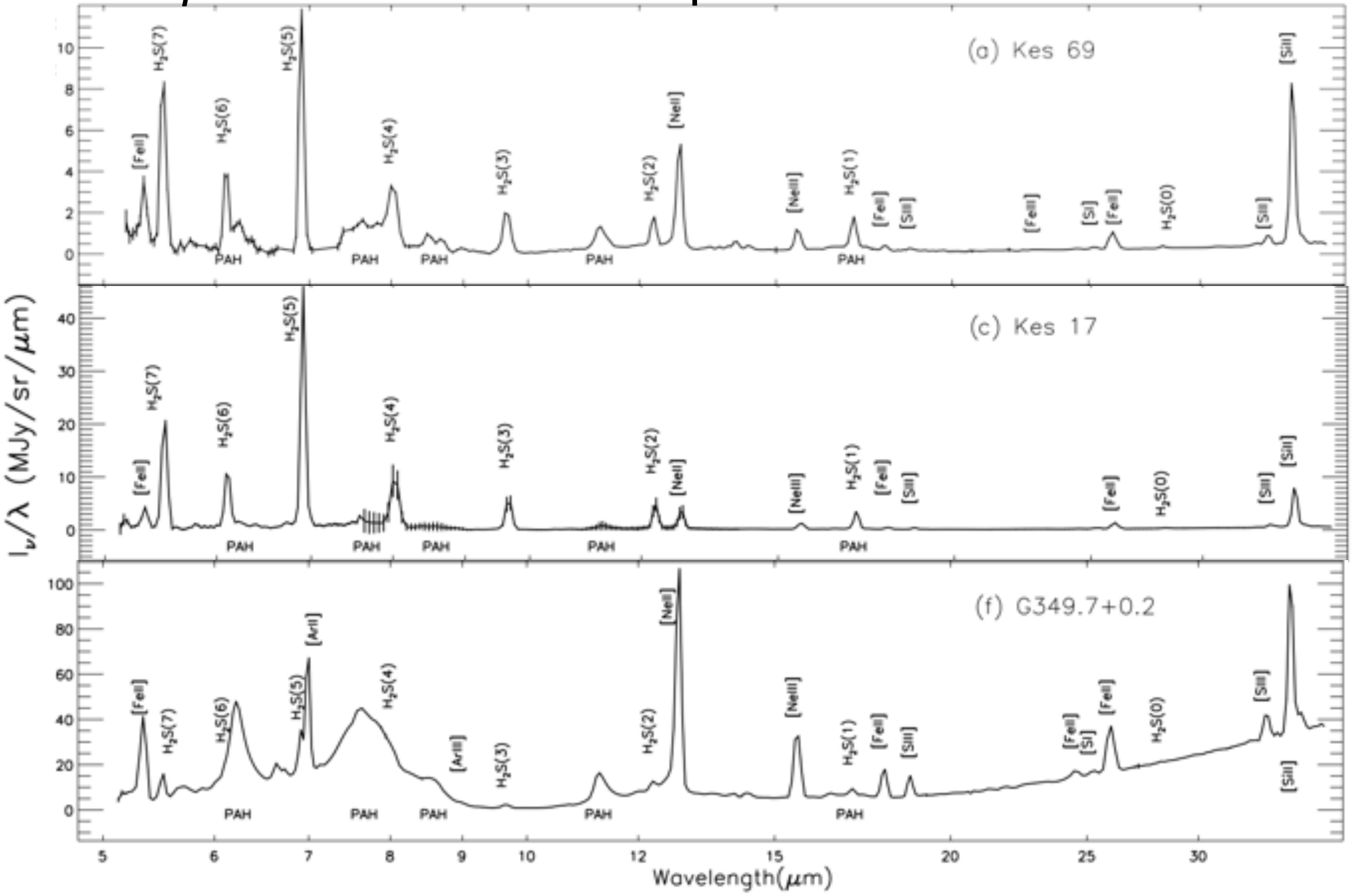
Spitzer Spectroscopy of IR-bright SNRs

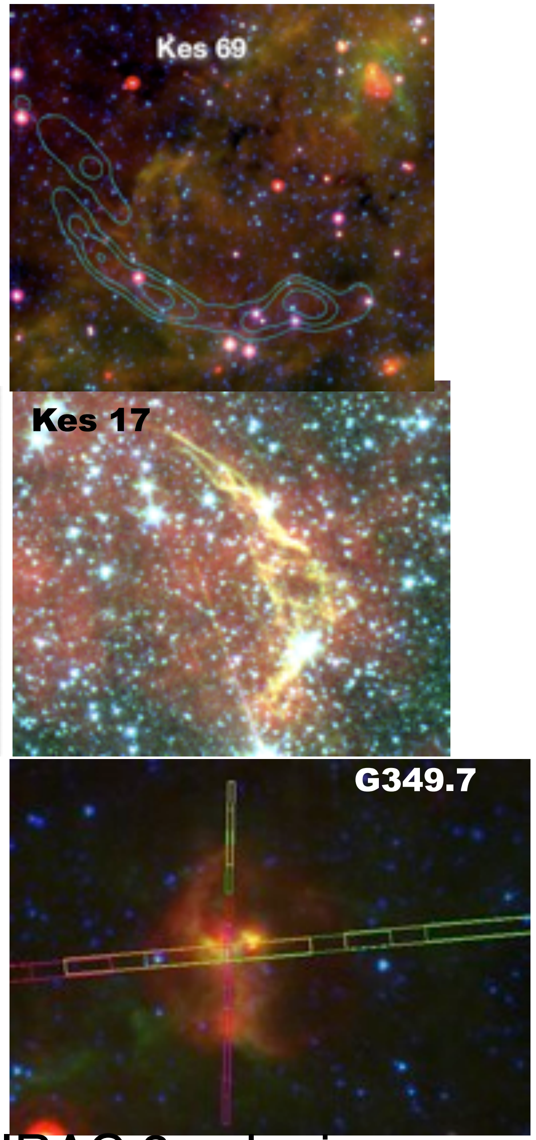
- brightest IR clumps in 14 SNRs
- long-slit: remove Galactic emission

(Hewitt et al. 2009, Andersen et al. 2011)

Must explain mix of IR lines:
H_2 S(0)-S(7)
[Fe II], [Ne II], [Si II], [S III]
PAHs, Dust continuum

Spitzer IRS SL/LL 5-35µm *R*~100

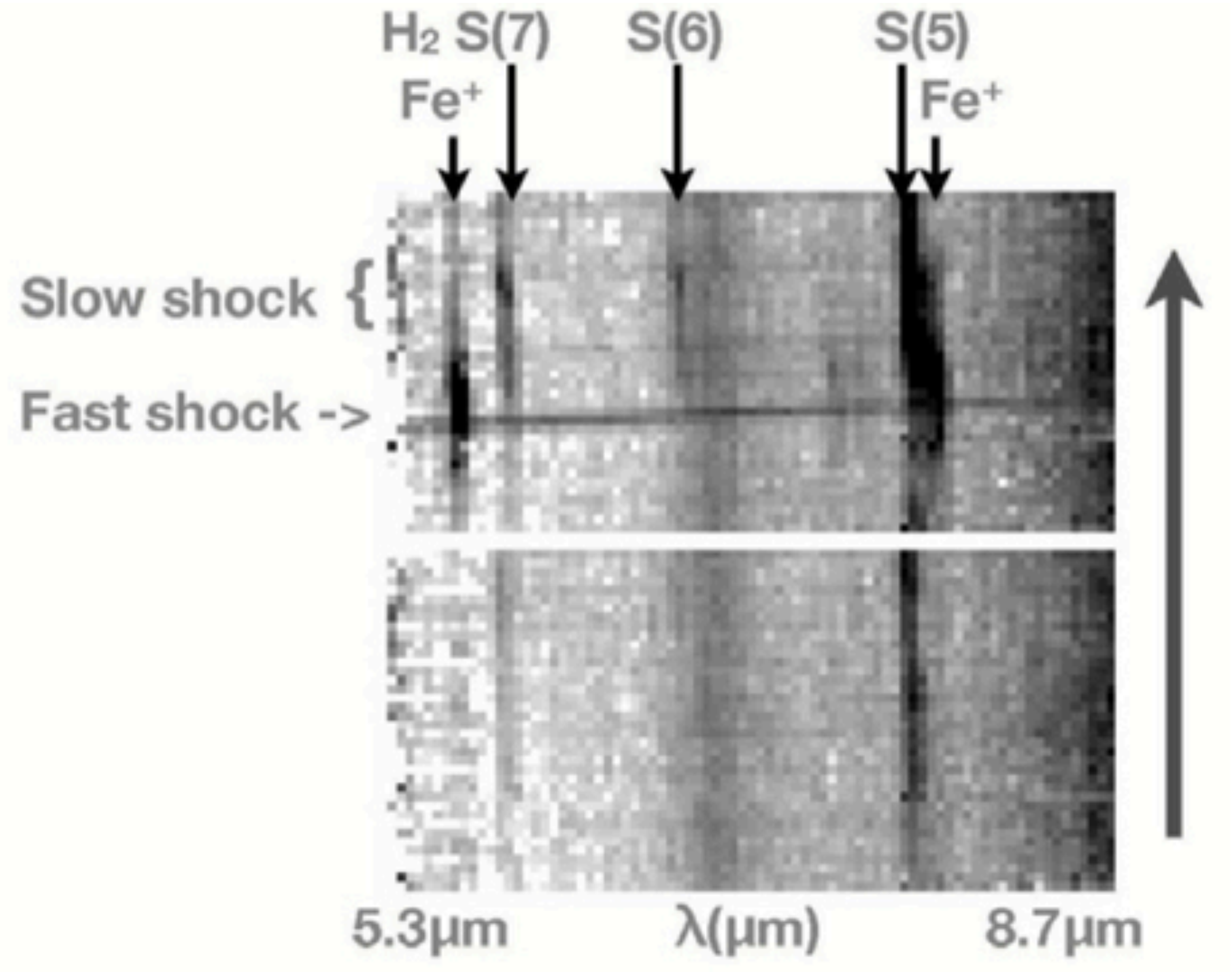


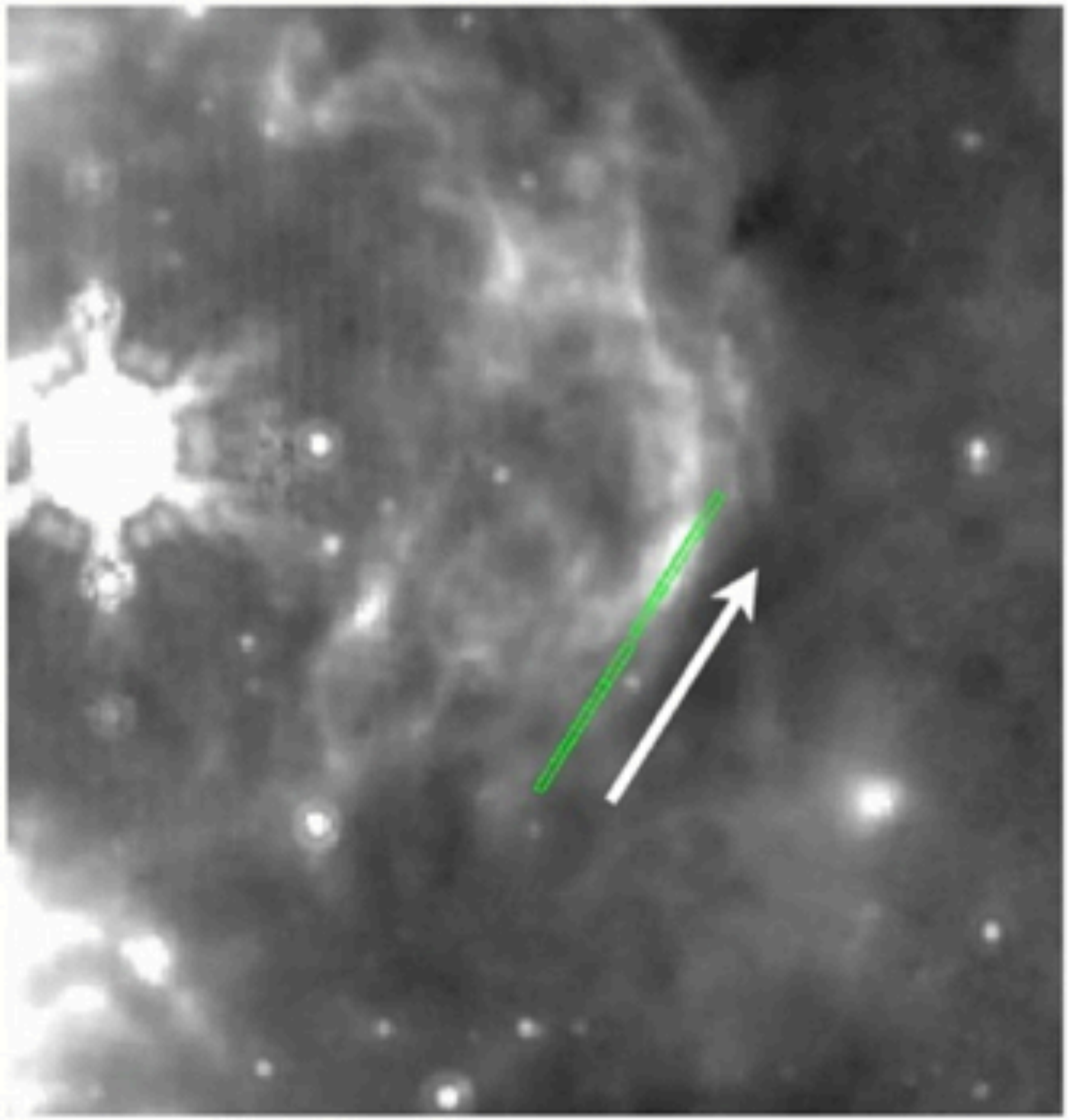


IRAC 3-color images
(Hewitt et al. 2009)

Spectra: both H_2 *and* Ionic lines

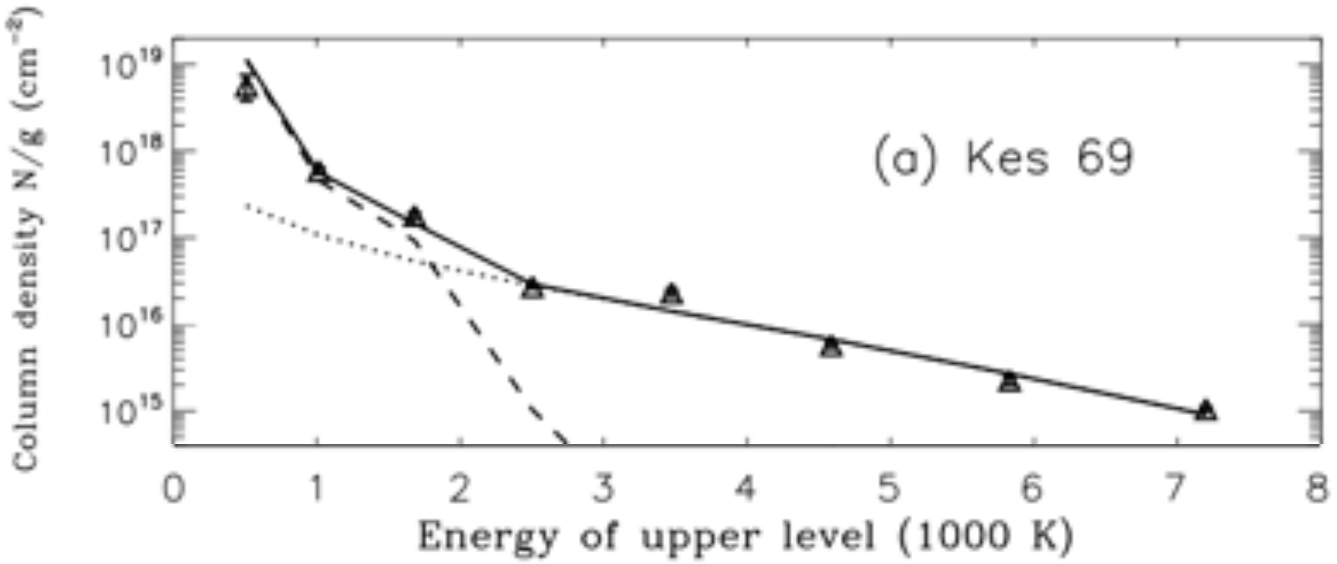
Ionic, H_2 lines spatially separated along IRS slit => multiple shocks



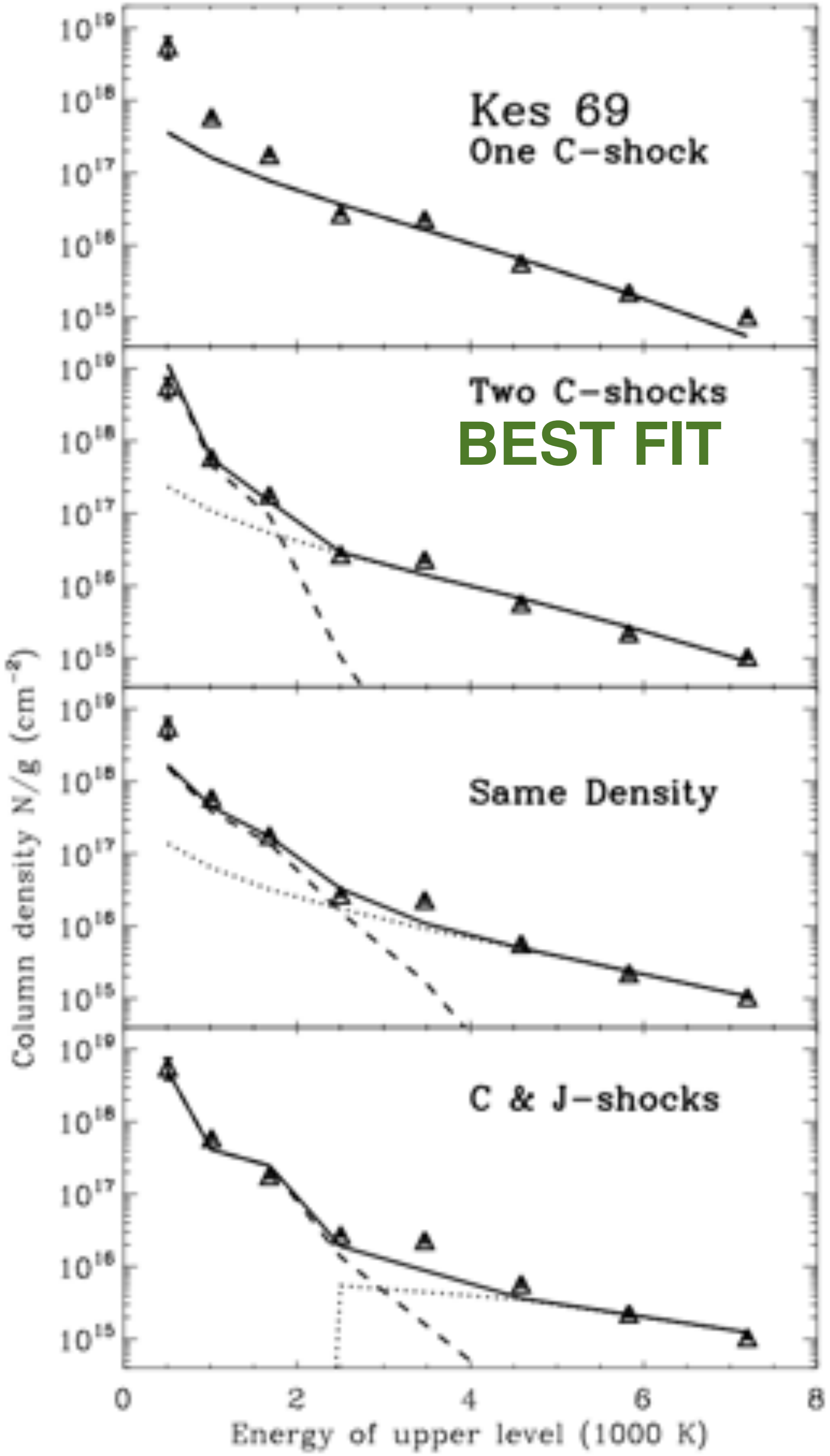


(Hewitt et al. 2009)

H_2 Excitation in Kes 69



Multi-shock fitting:



- Two H_2 components (warm, hot)

  T($\mathbf{H_2}$)= 320 1150 K

  OPR = 1.0 3.0

- $\mathbf{H_2}$ fitting with shock models (Le Bourlot 2002)

  V_S = 10 40 km/s

  n_H = 10^5 10^4 cm^{-3}

  P_S = 1x10^{-6} 3x10^{-7} dyne cm^{-2}

over-pressure in warm, dense clumps

(Hewitt et al. 2009)

H_2 Excitation: Ortho-to-Para

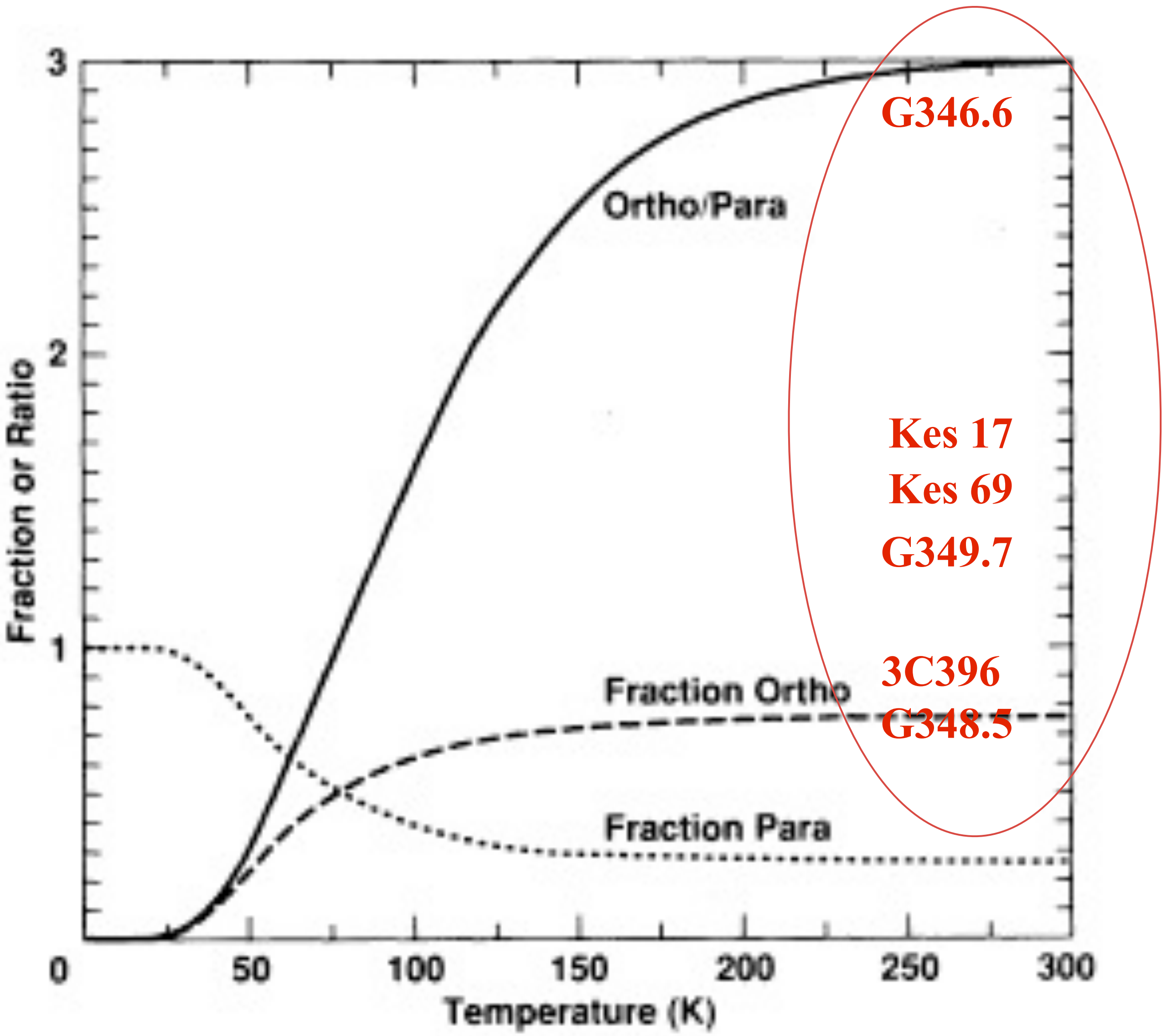
warm H_2: OPR ~ 0.4-3
equilibrium: OPR_{LTE} ~ 3

Para-to-ortho H_2 conversion via reactions with atomic-H:

$\tau_{conv} \approx 3000$ yrs $[100\ cm^{-3}/n(H)]$
$E_A/k \sim 4000$ K

OPR < 3 in T_{H2} = 250-600 K
requires $\tau_{shock} < \tau_{conv}$

=> slow C-shocks into cold, quiescent clouds;
no significant pre-heating of MC



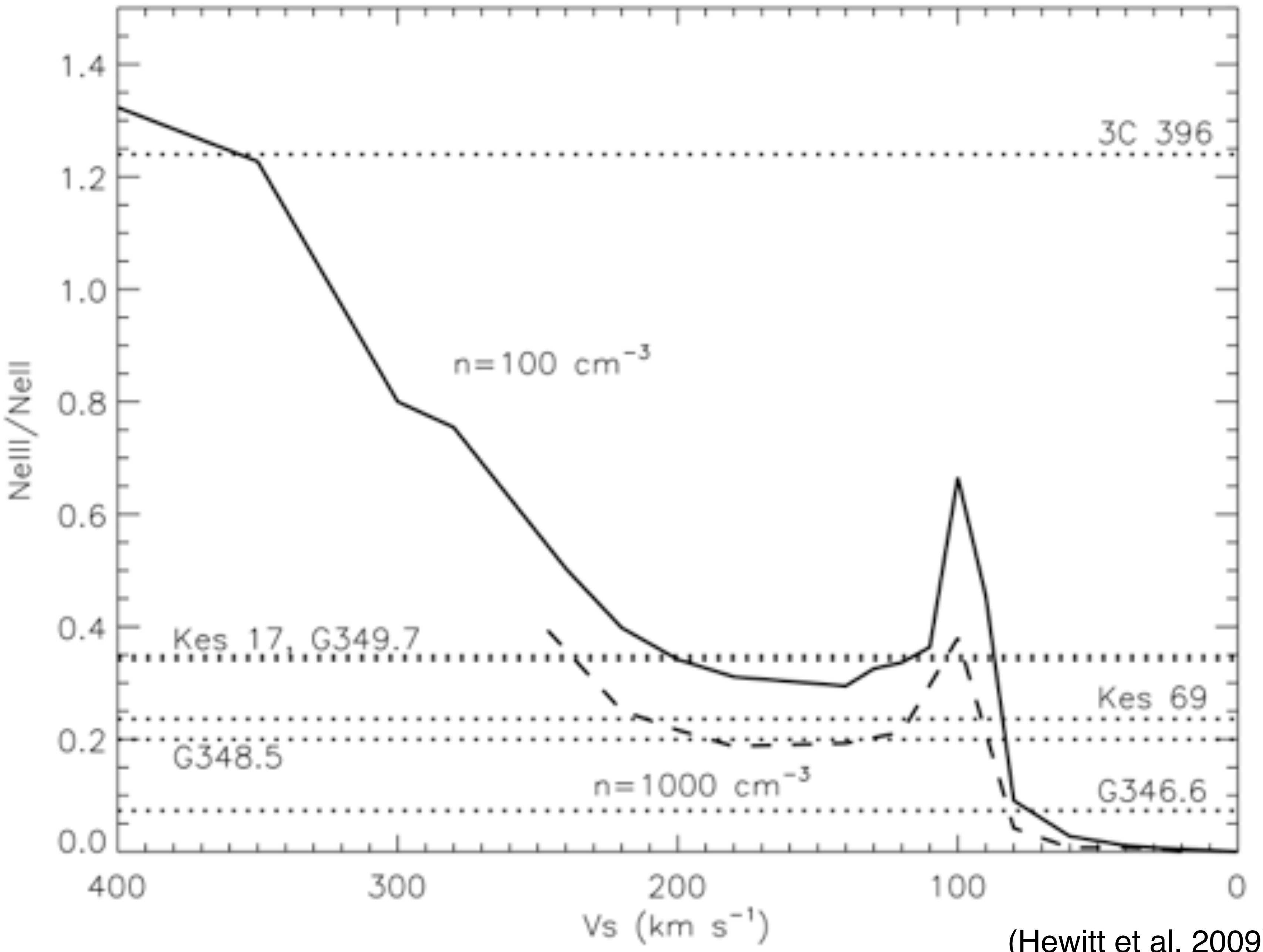
(Wilgenbus et al. 2000)

Fast, Dissociative Shocks

Excitation of ionic species: Fe+, Ne+, Ne++, Si+, S++

requires V_S >100 km/s, $n_e \sim 10^{2\text{-}3}$ cm^{-3}

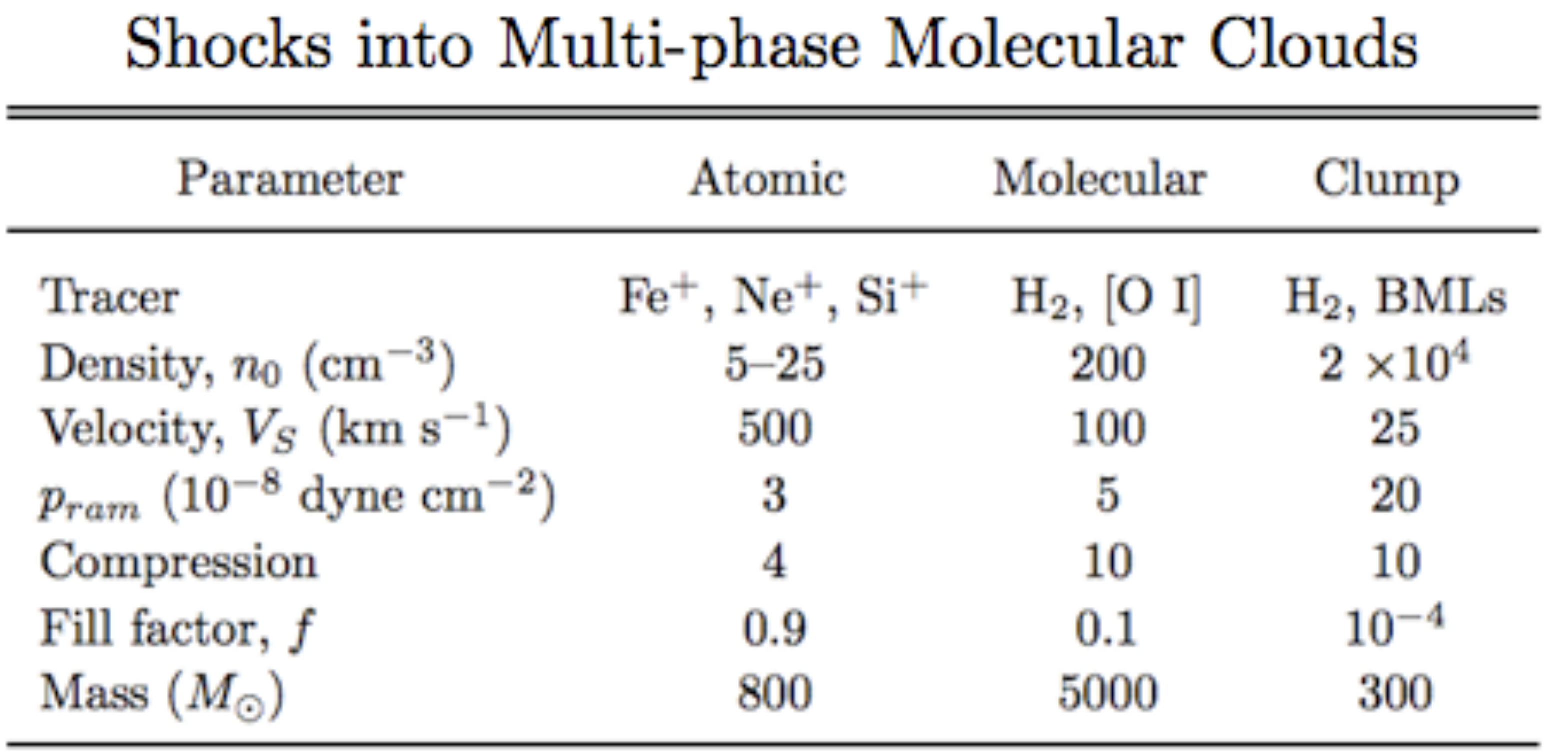
Neon Line Ratio



(Hewitt et al. 2009)

Shocks into multi-phase Molecular Clouds

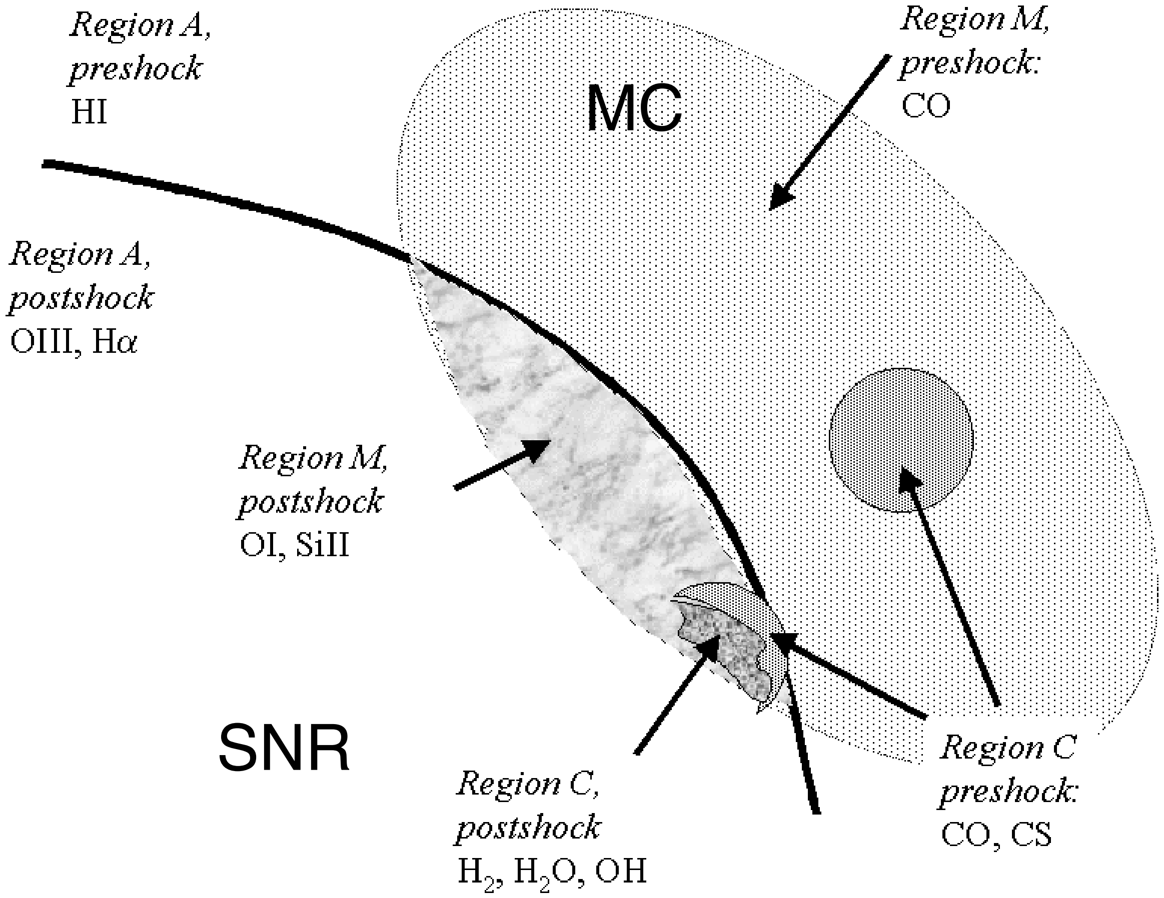
How to reconcile different IR lines?
multiple shocks in a multi-phase medium



Shocks into Multi-phase Molecular Clouds

Parameter	Atomic	Molecular	Clump
Tracer	Fe^+, Ne^+, Si^+	H_2, [O I]	H_2, BMLs
Density, n_0 (cm^{-3})	5–25	200	2×10^4
Velocity, V_S ($km\ s^{-1}$)	500	100	25
p_{ram} (10^{-8} dyne cm^{-2})	3	5	20
Compression	4	10	10
Fill factor, f	0.9	0.1	10^{-4}
Mass ($M_\odot$)	800	5000	300

(Reach et al. 2005)



Dust Emission from SNRs

Dust continuum modeling (Andersen, Rho et al. 2011)

Parameters: Big Grains, Very Small Grains, PAHs, and Radiation Field

0.01-0.2 µm 0.001-0.01µm

Good fits obtained

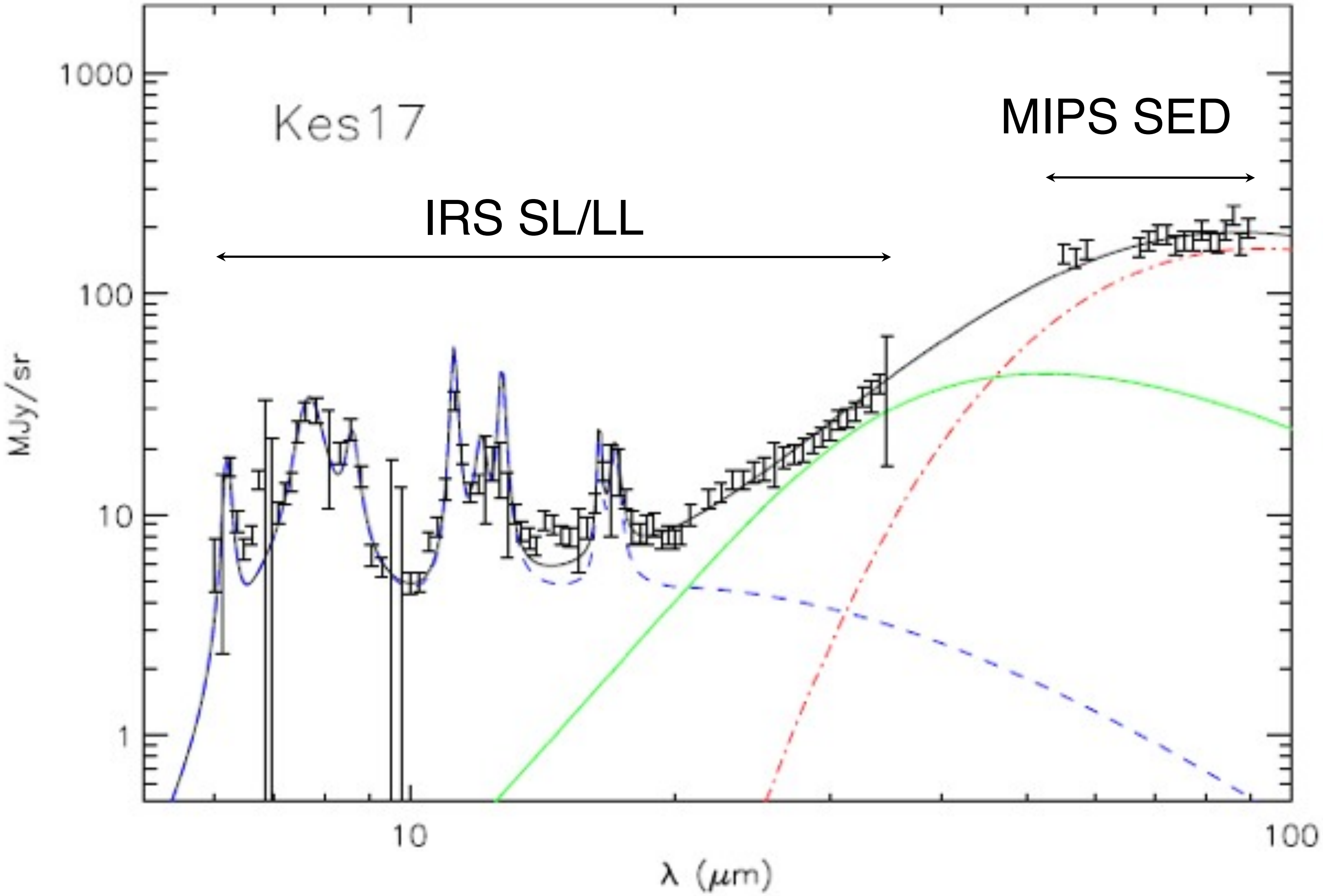
T_{BB} = 35-50 K

Relative grain abundances:

	SNRs	MW
$Y_{VSG/BG}$	0.23-1.0	0.13
$Y_{PAH/BG}$	0.01-0.2	0.004

=> Processing of grain size distribution by SNR shock

(Andersen et al. 2011)

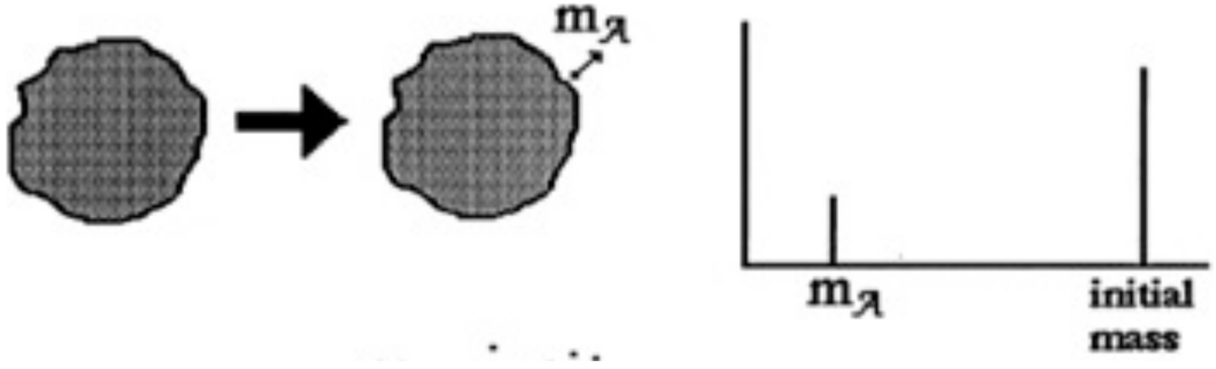


line-subtracted spectrum

Dust Processing by SNR shocks

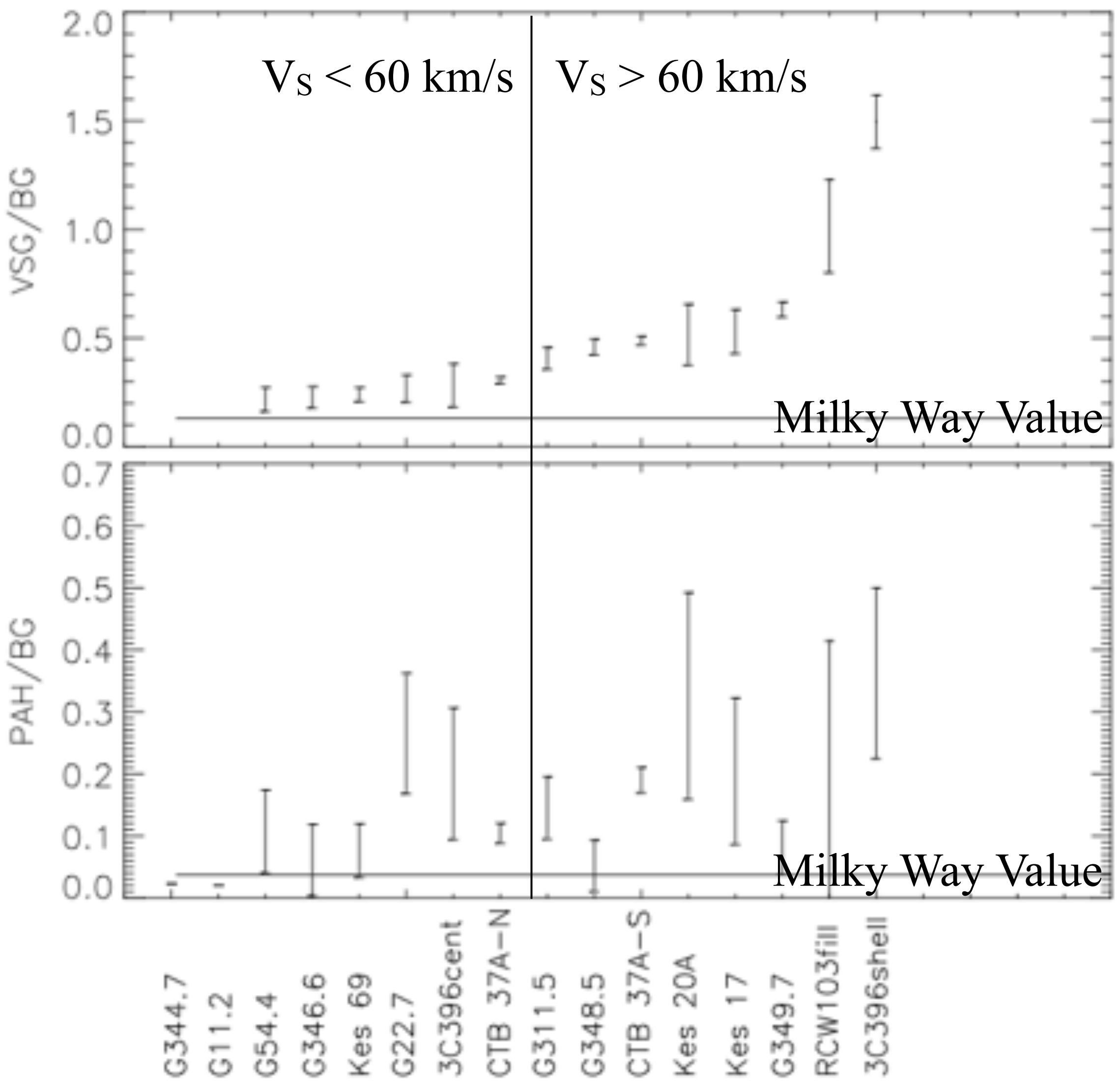
Shattering in dense/slow shocks, destroys BGs, but not VSG/PAHs

Sputtering efficient for fast shocks, affecting all grain sizes

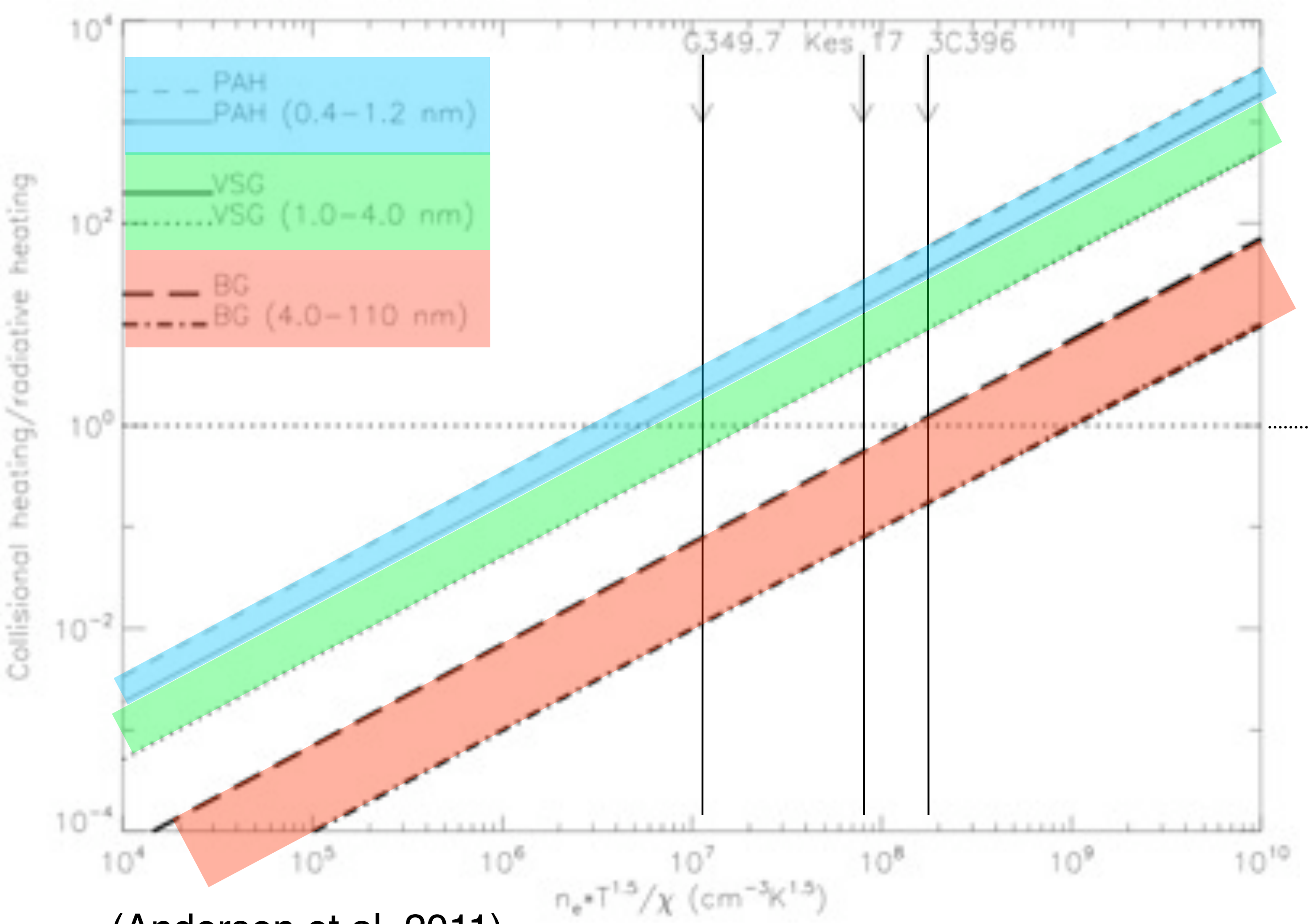


from Borkowski et al. 1995

VSG/BG increases with V_S indicative of shattering



Dust Heating by SNR shocks



(Andersen et al. 2011)

Collisional Heating dominates
through collisions with electrons
$H_{coll} \approx 5.4\text{E-}18\ a^2\, n_e\, T^{3/2}$ [erg/s]

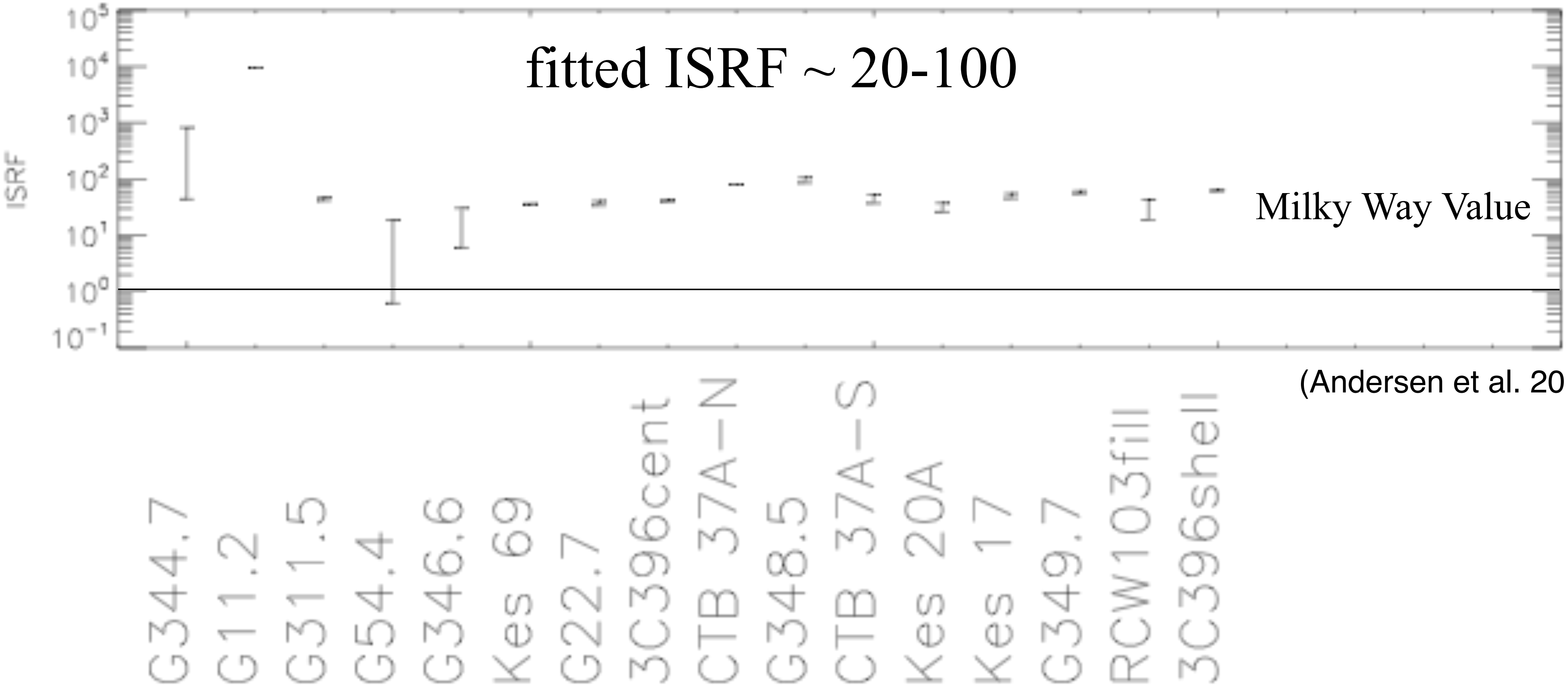
Radiative Heating dominates
through H recomb. emission

[Fe II] emitting gas:
$n_e \sim 100\text{-}1000\ \text{cm}^{-3}$, $T = 5\text{-}10 \times 10^3$ K

SNRs have ***enhanced*** radiation field (due to fast shocks, [Fe II])

Dust Heating by SNR shocks

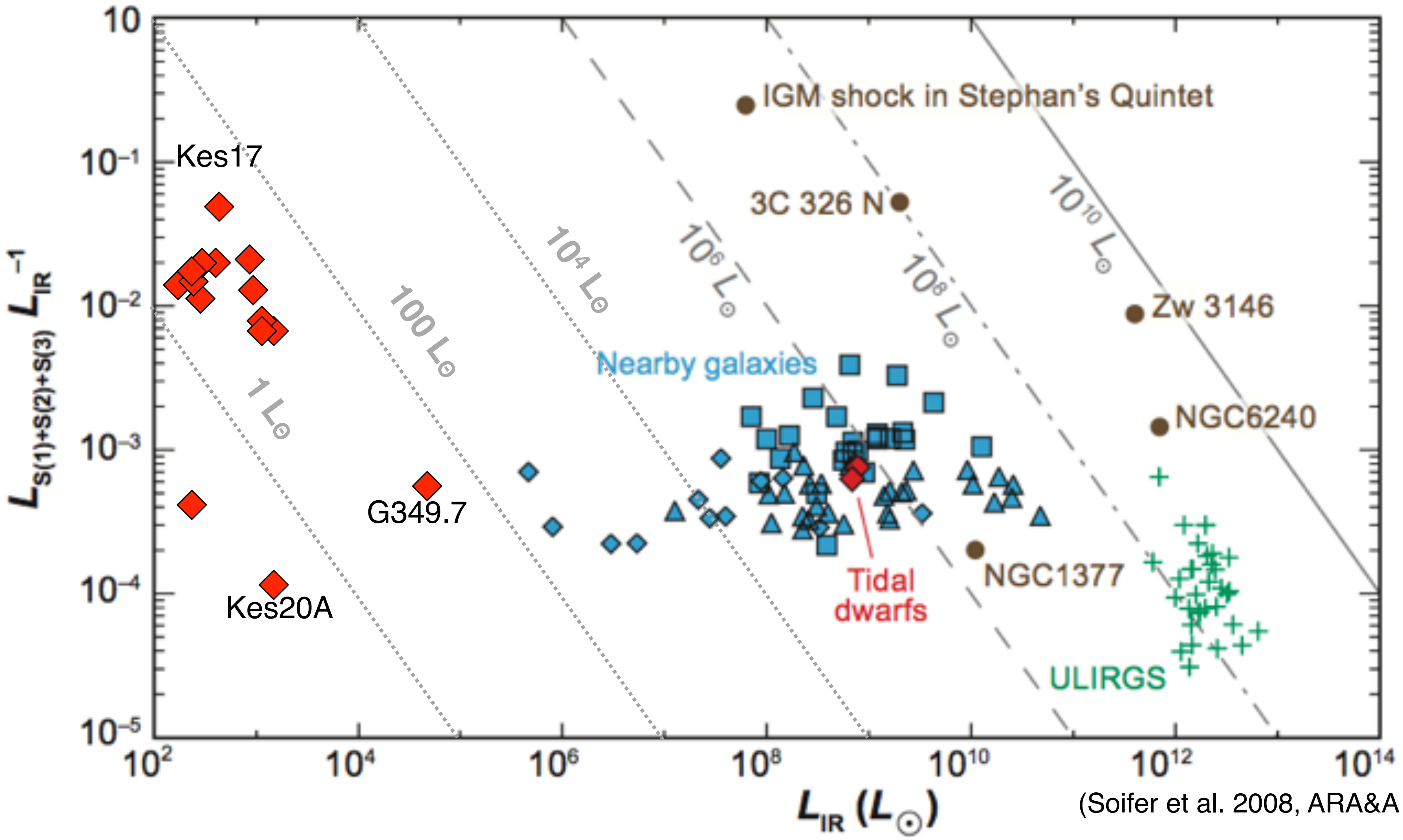
Fit Radiation Field, case B H-recomb. (normalized to ISRF)



(Andersen et al. 2011)

Dust continuum is a significant coolant!

Radiative Cooling: SNR/MCs



(Soifer et al. 2008, ARA&A 46, 201)

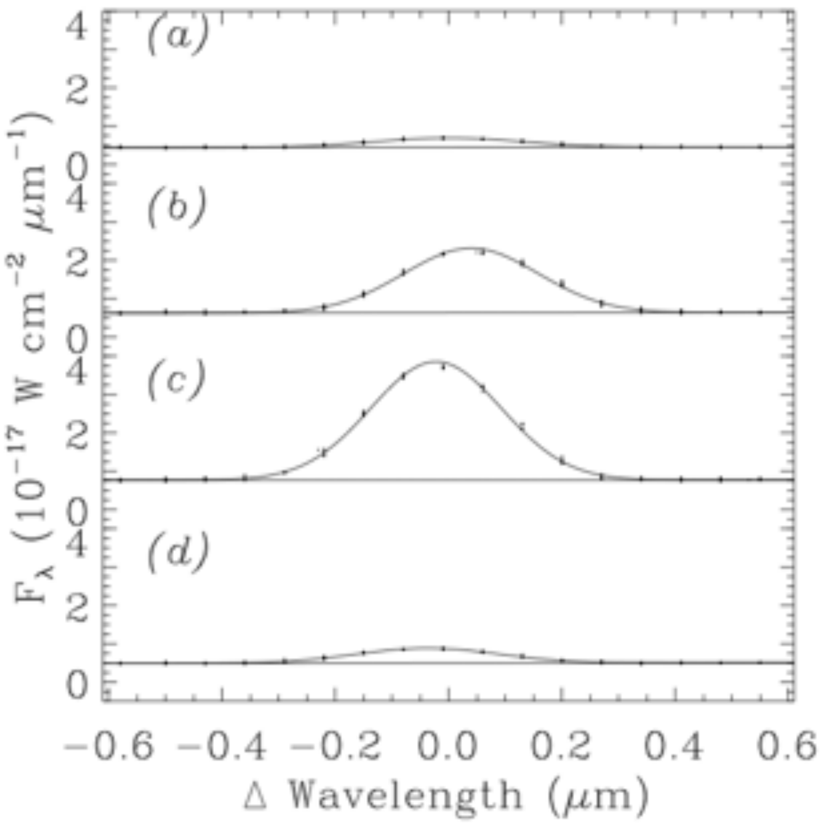
L_{H2} is only ~0.6-6% of L_{Dust} in SNR/MCs

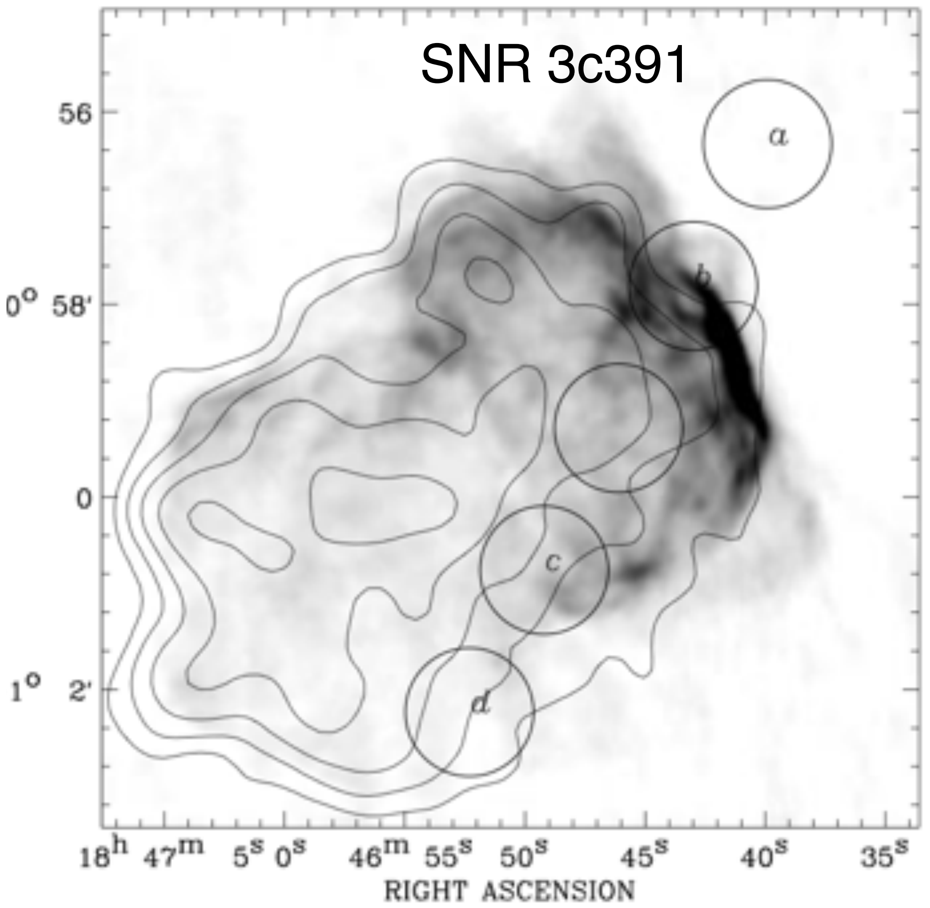
[O I] 63µm line detected in 10/14 SNRs, $L_{[OI]}/L_{Dust}$ ~ 1-7%

Radiative Cooling: [O I] 63 µm

ISO mapping of [O I] brightest at SNR shell (Reach & Rho 1996)

Spatially correlated with $H_2$1-0 S(1) line (Burton et al. 1990)





(from Reach & Rho 1996 A&A 315, L277)

Possible origins:

Fast C-shock (hot H_2) produces significant [O I] emission, *only if oxygen chemistry suppressed (eg, high n_e)*

Slow C-shock (warm H_2)... 10 km/s, 10^5 cm^{-3}

Oxygen Shock Chemistry

"If it moves, it emits water" - Lars Kristensen (WISH)

for T > 400 K

$$O + H_2 \rightarrow OH + H\ ,$$
$$OH + H_2 \rightarrow H_2O + H$$

C-shocks produce copious H_2O

Chemical models predict all available O into H_2O, with little OH
(Kaufman & Neufeld 1996)

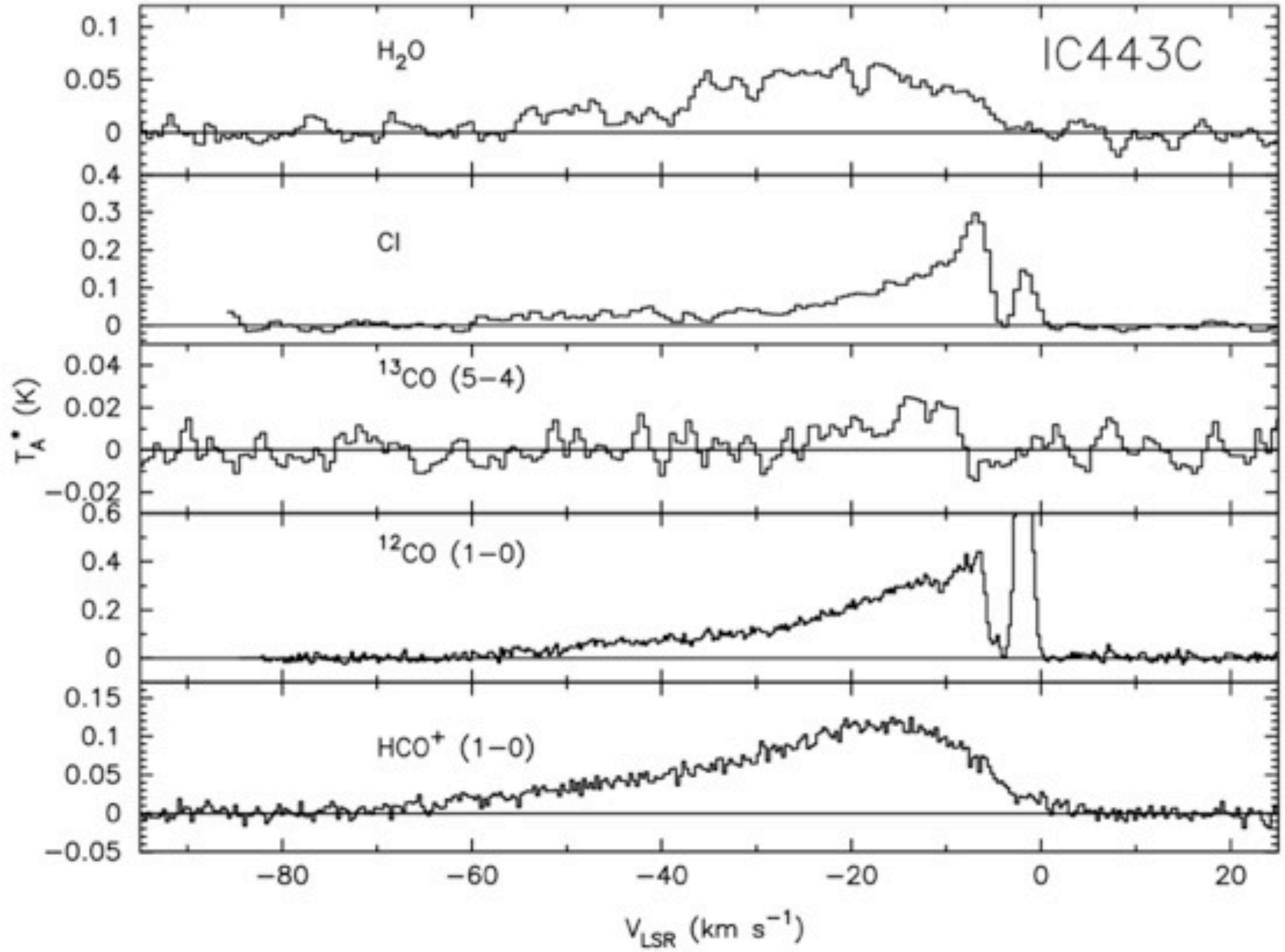
Conflicting observational evidence

Unexpectedly high OH/H_2O ratio ~ 15 (3C391; Reach+ 1998)

IC443 is surprisingly lacking in water... (SWAS, Snell+ 2005)

SWAS ground-state H_2O

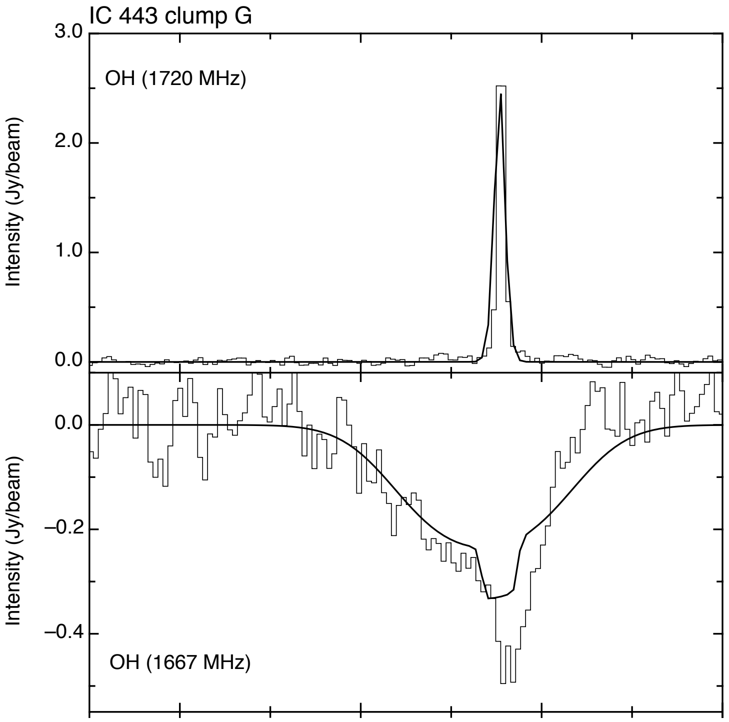
(from Snell et al 2005 ApJ 620, 758)



OH Masers: Signposts of C-shocks

- Uniquely trace slow shocks into dense molecular clump in SNRs

discovery paper: Frail et al. (1994)
pump models: Lockett et al. (1999), Wardle (1999)



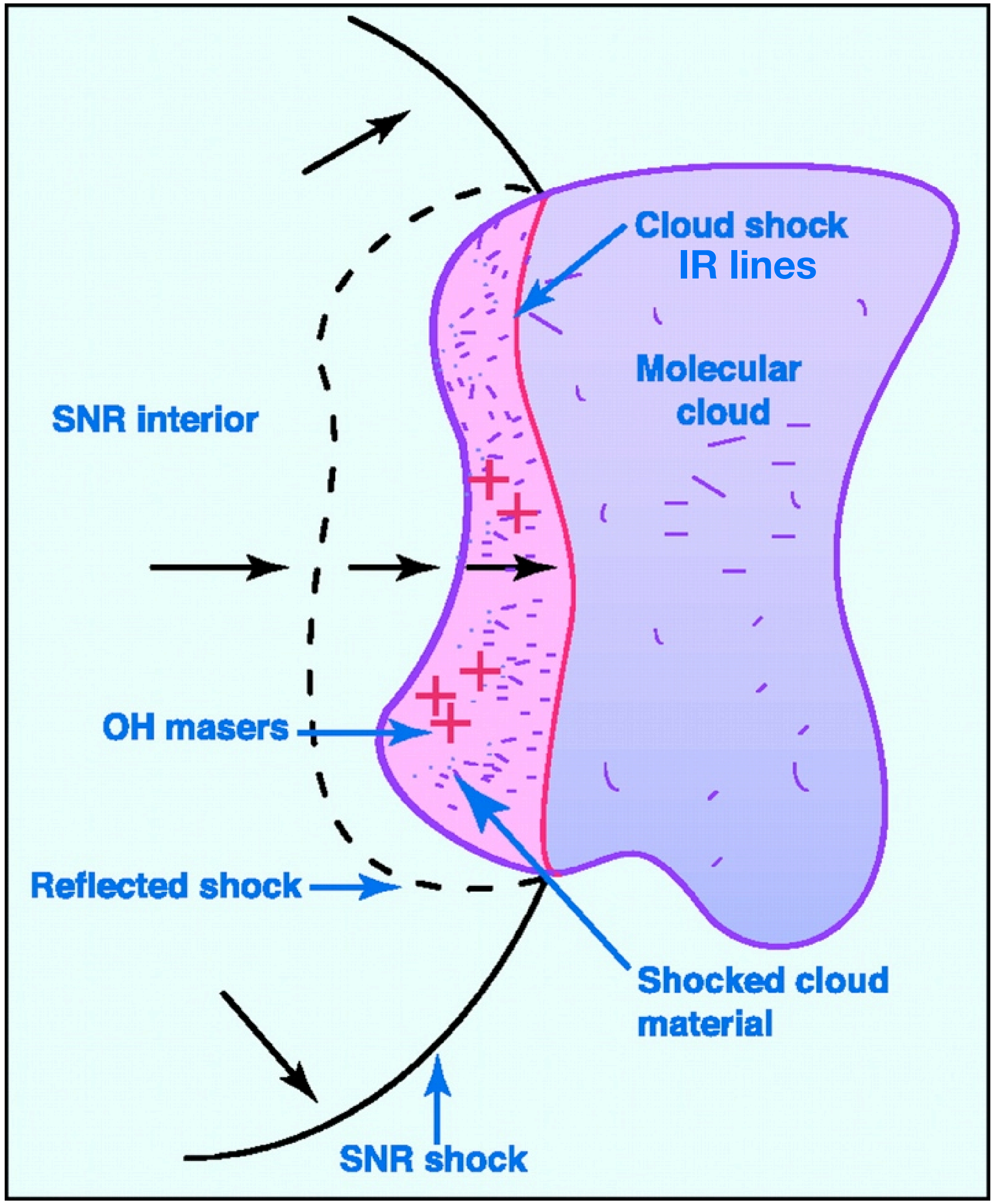
1720 MHz
Maser

1667 MHz
Absorption

- *Need* line-of-sight geometry to maximize velocity-coherence

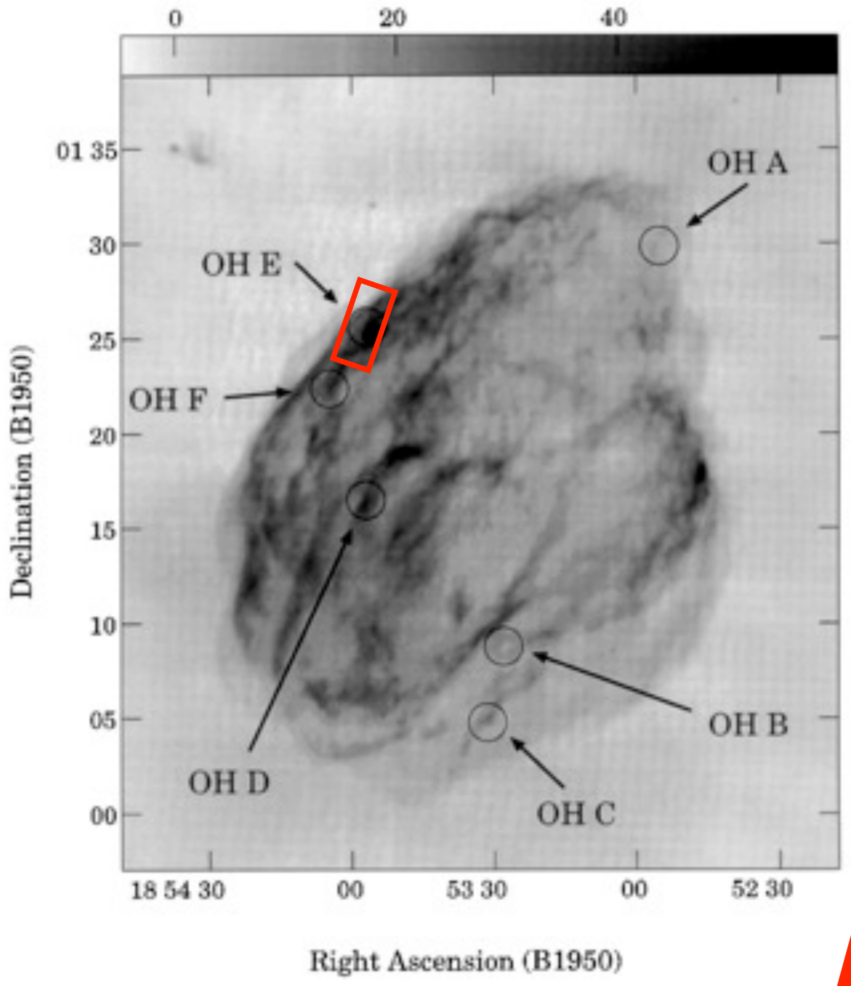
  V_{LSR} => kinematic distance

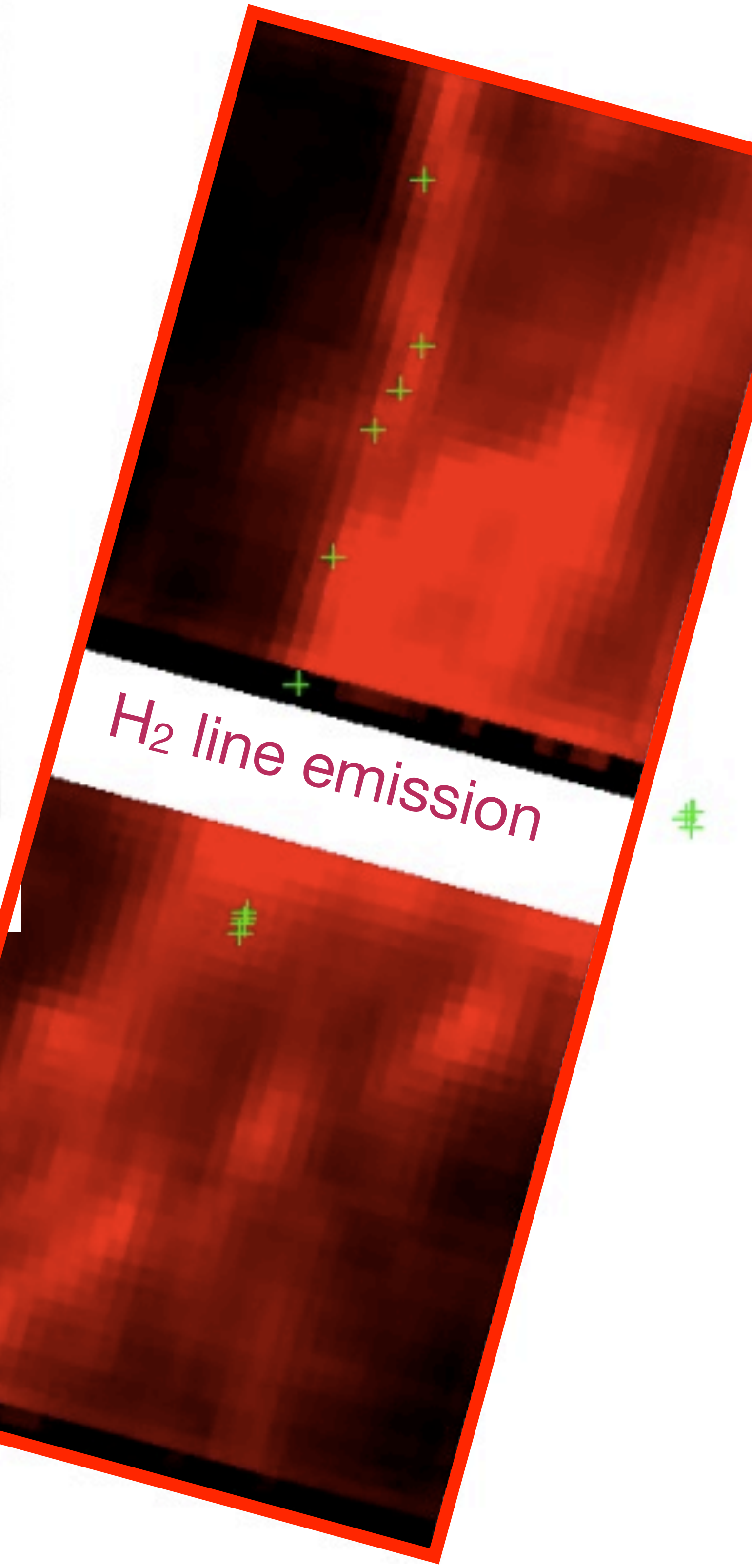
Diagram of SNR/MC interaction



from Wardle & Yusef-Zadeh (2002)

OH Masers: Signposts of C-shocks





- Only 24/265 SNRs have detected OH masers
- Require narrow conditions:
  - dense gas, $n=10^5$ cm^{-3} ⇒ MC ~10^{4-5} M_{sol}
  - T_k=50-125 K
  - T_{dust}<75 K: intense FIR kills 1720 MHz pumping
  - Require a broad cooling region only present for C-shocks (not J-shocks)
- Projected sizes ~10^{16} cm ≈ shock width
- Zeeman splitting => line-of-sight B ~0.1-5 mG
- **N(OH) = 10^{16}-10^{17} cm^{-2}, X(OH/H_2) ~ 10^{-5}**

Anomalous Oxygen Chemistry

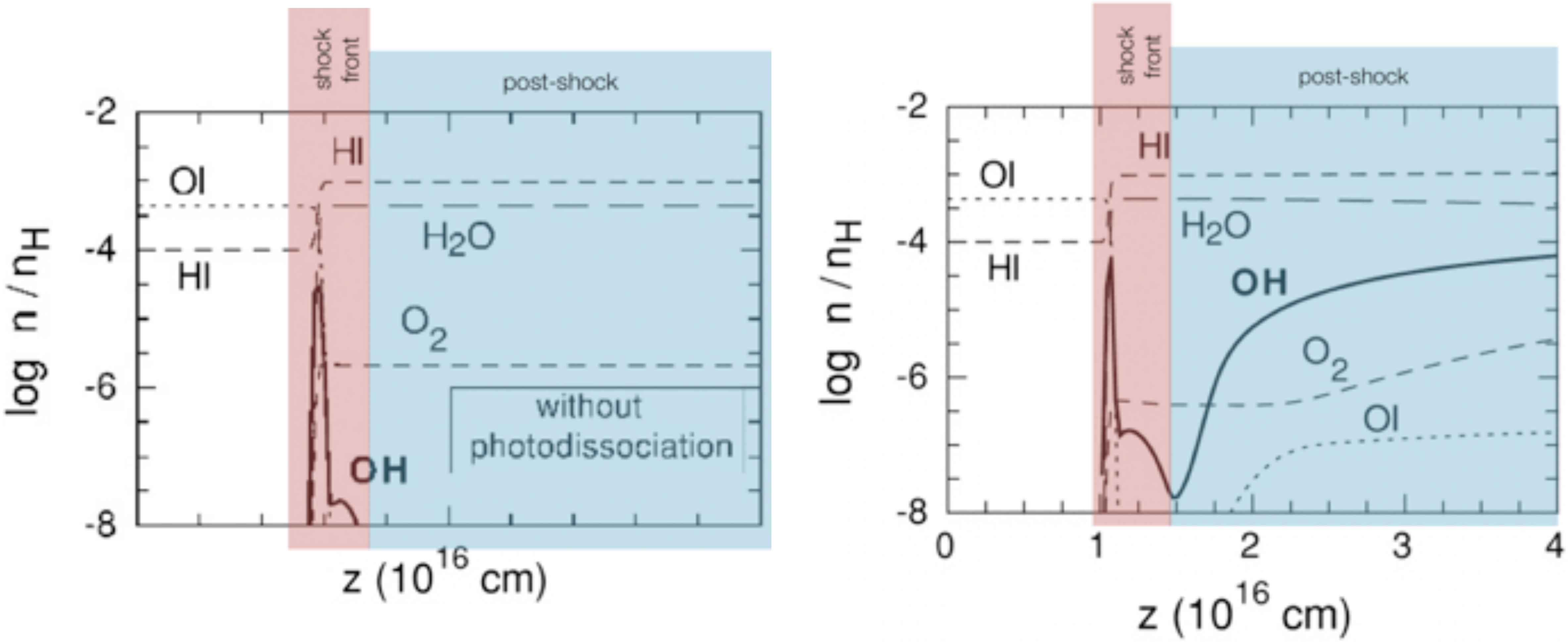
C-shocks predict copious post-shock water

Observations show high post-shock OH column
OH Masers, OH Absorption, far-IR lines

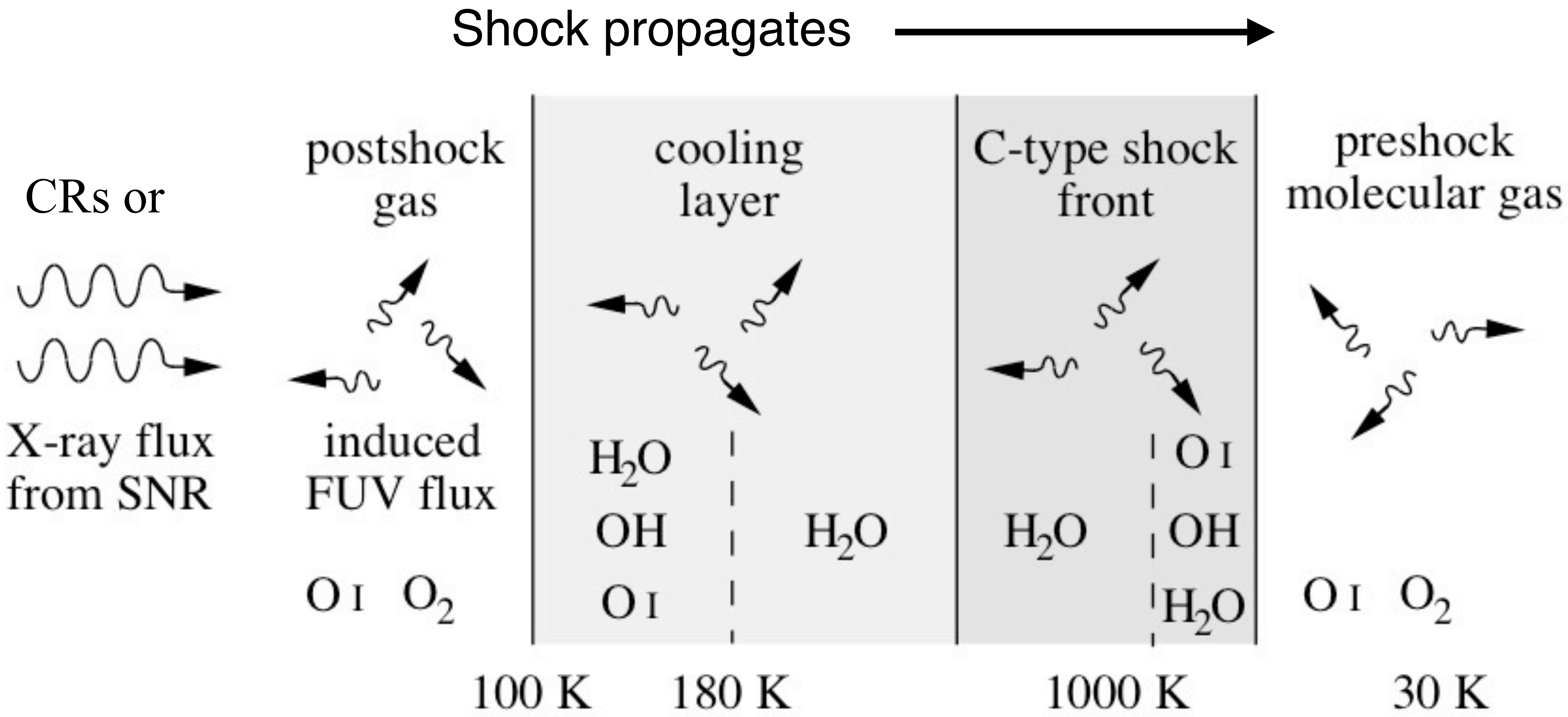
for T > 400 K

$$O + H_2 \rightarrow OH + H\,,$$
$$OH + H_2 \rightarrow H_2O + H$$

- Solution: dissociate ~few% of post-shock H_2O into OH (Wardle 1999; Lockett et al. 1999)
  Ionization sources: CRs, interior X-rays, UV from fast shocks?



Post-shock OH production

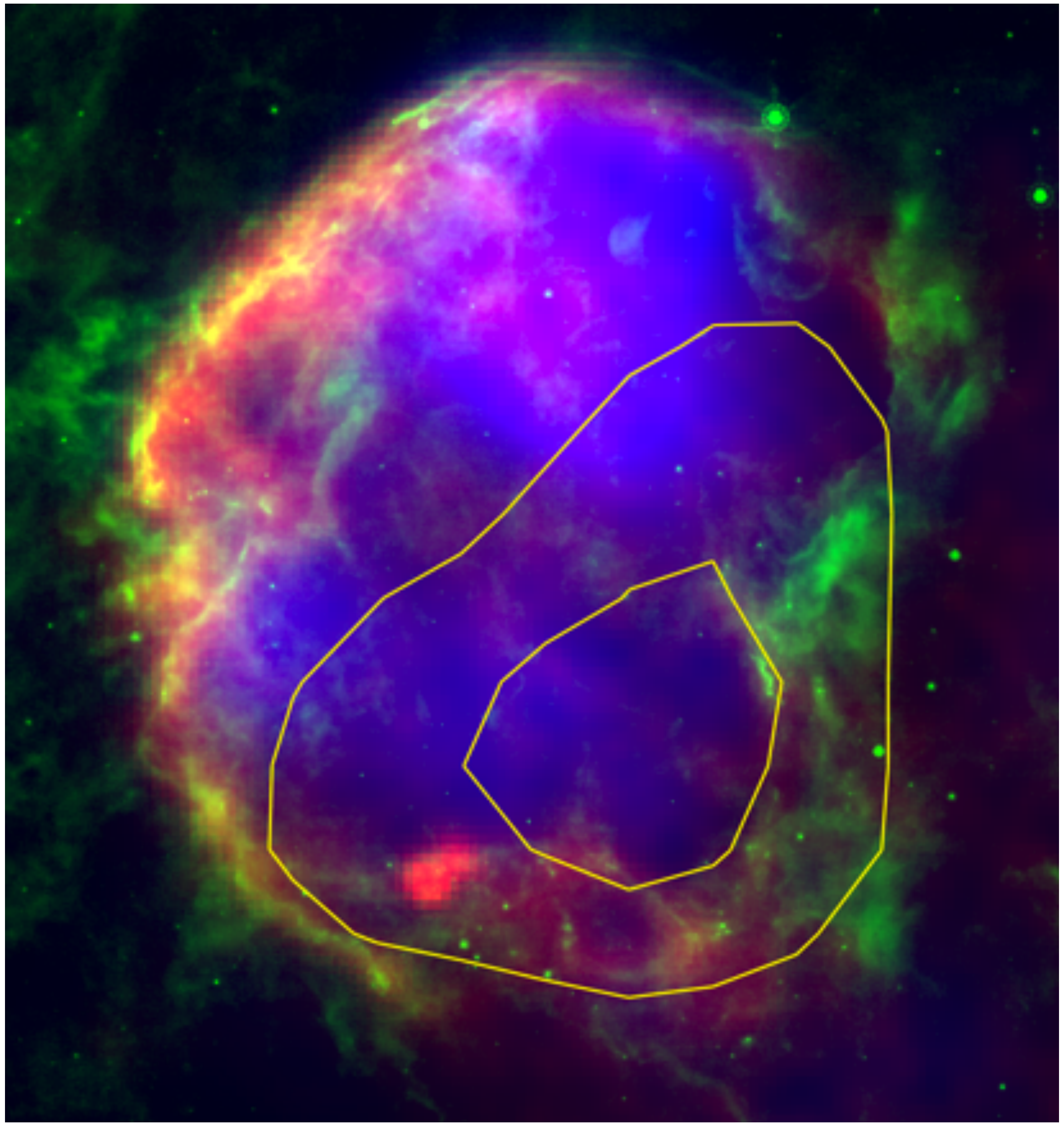


(from Wardle 1999 ApJ 525L, 101)

A Prototypical Cosmic Ray Accelerator

Evidence for an enhanced CR density in IC443:

- GeV/TeV γ-ray detection supports ~1-10% E_{SN} converted to CRs
  (Abdo et al. 2010, ApJ 712, 459)
- "Flat" radio spectral index, α ~ 0.36 suggests CR interactions with dense gas
  (Castelletti et al. 2011, arXiv:1104.0205)
- H_3^+ absorption shows $\varsigma_{CR} > 10^{15}$ s^{-1} enhanced ~100x ISM rate $\varsigma_{CR} \sim 10^{17}$ s^{-1}
  (Indriolo et al. 2010, ApJ 724, 1357)
- Lower ^{7}Li/^{6}Li isotopic ratio due to Li production from CR spallation
  (Ritchey, et al. 2011)



20cm Radio 24µm Dust Th. X-rays

>5 GeV γ-ray contours (from Fermi LAT)

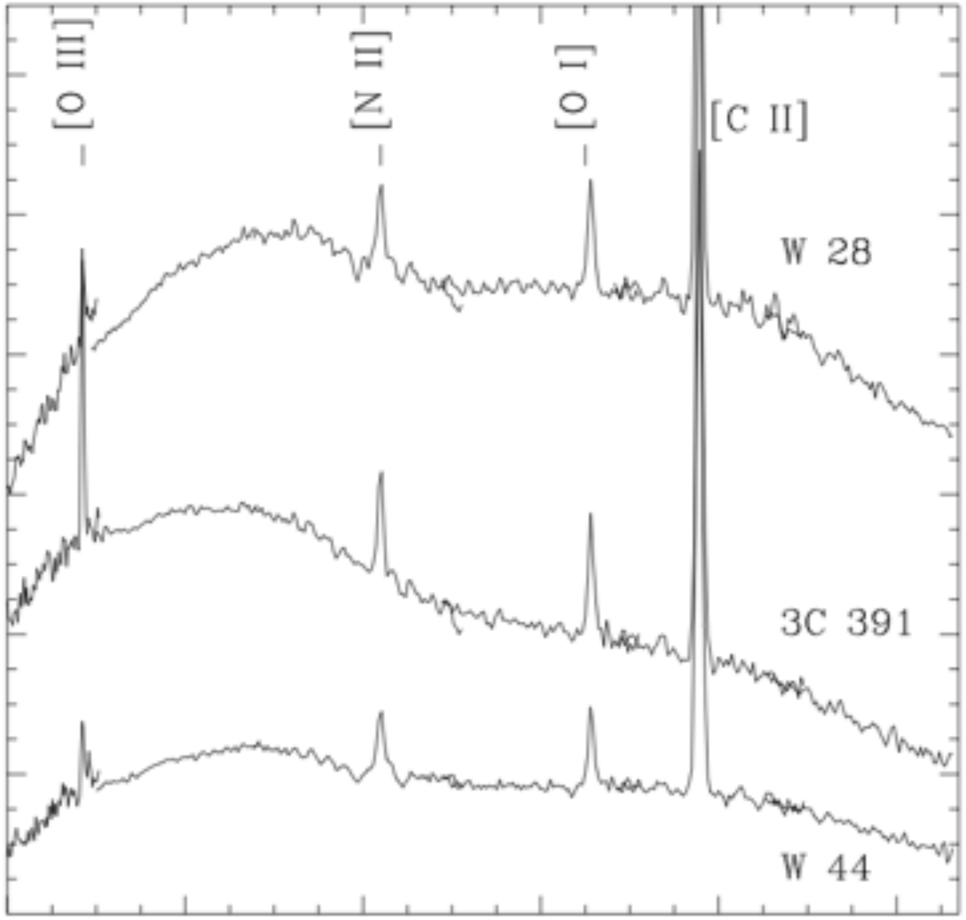
GREAT Diagnostics of SNR shocks

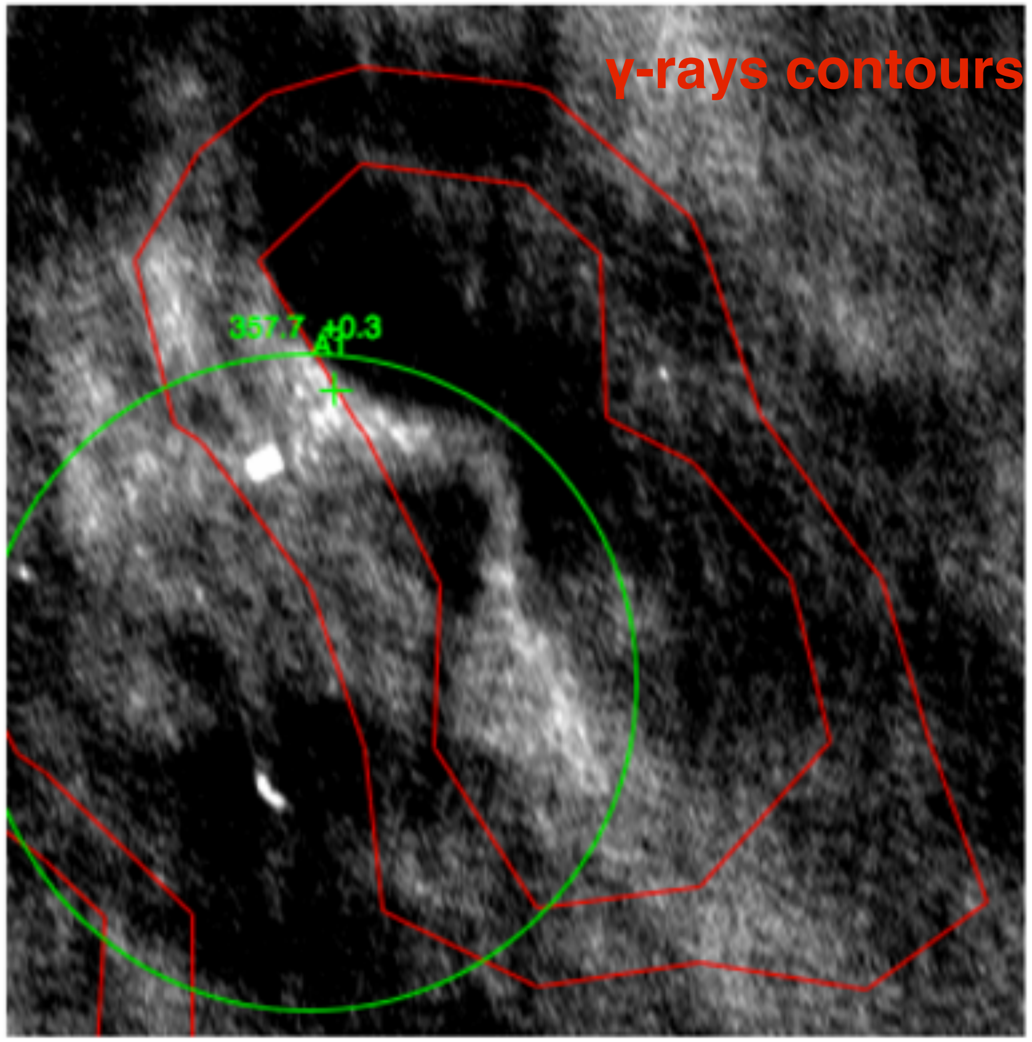
Basic Science observations

1 hour to observe SNR G357.7

Velocity resolved spectra of:
[C II], [N II], OH 163µm, CO 11-10

ISO detection for bright SNRs
(Reach & Rho 2000)




20cm Radio Continuum

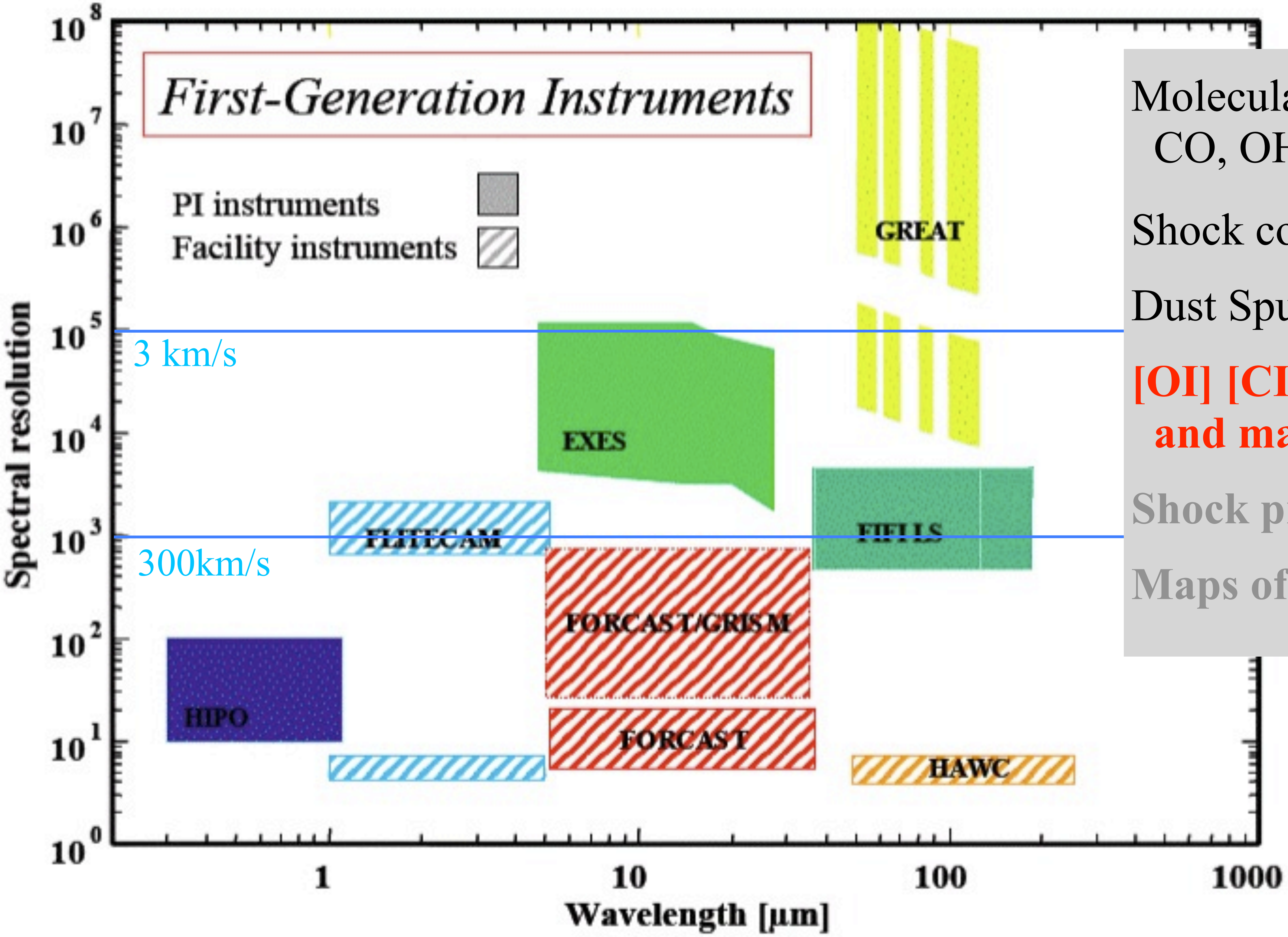
SOFIA+Herschel Science Goals

1. What is the origin of OH?
2. C/J-Shocks (Molecular + Ionic lines)
3. Feasibility of future observations

SNe as probes of Molecular Clouds

- Pristine molecular clouds, destructively probed by SNR revealing a complex multi-phase environment
- SNR/MC shock cooling dominated by H-recomb. emission, re-radiated as IR dust emission
- Grain processing: shattering decreases large grain sizes
- Dense cloud acts as target for CR protons to be measured, SNe yield few % E_{SN}
- Far-IR window with *SOFIA*, *Herschel* can provide resolution to complicated shock modeling of IR lines.

SOFIA Observations of Shocks/PDRs



Molecular lines:
CO, OH, H_2O

Shock cooling, Ionic lines

Dust Sputtering: Fe, Si

[OI] [CII] velocity and mapping

Shock processed PAHs

Maps of dust processing