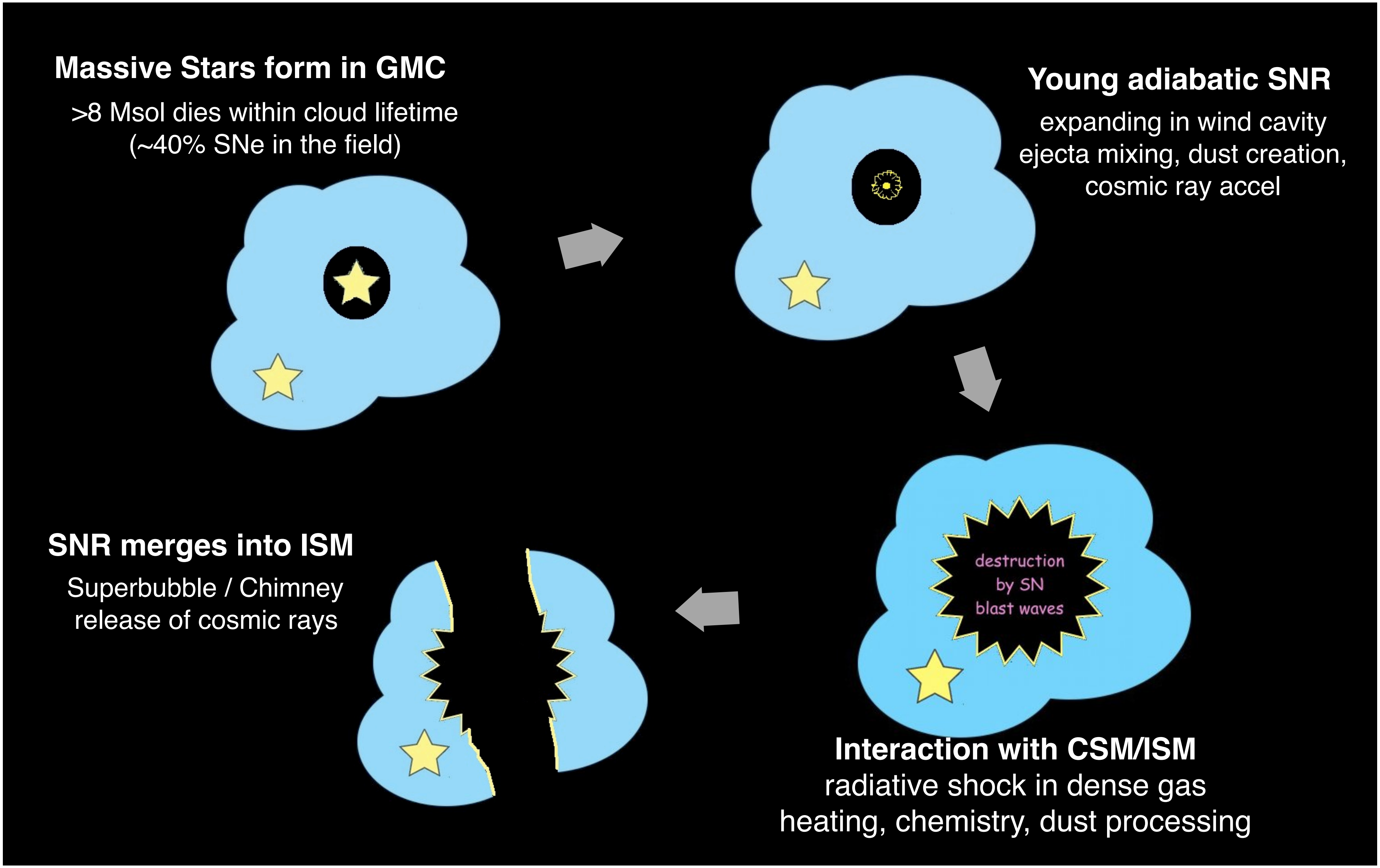
The Violent Evolution of Supernovae in Molecular Clouds



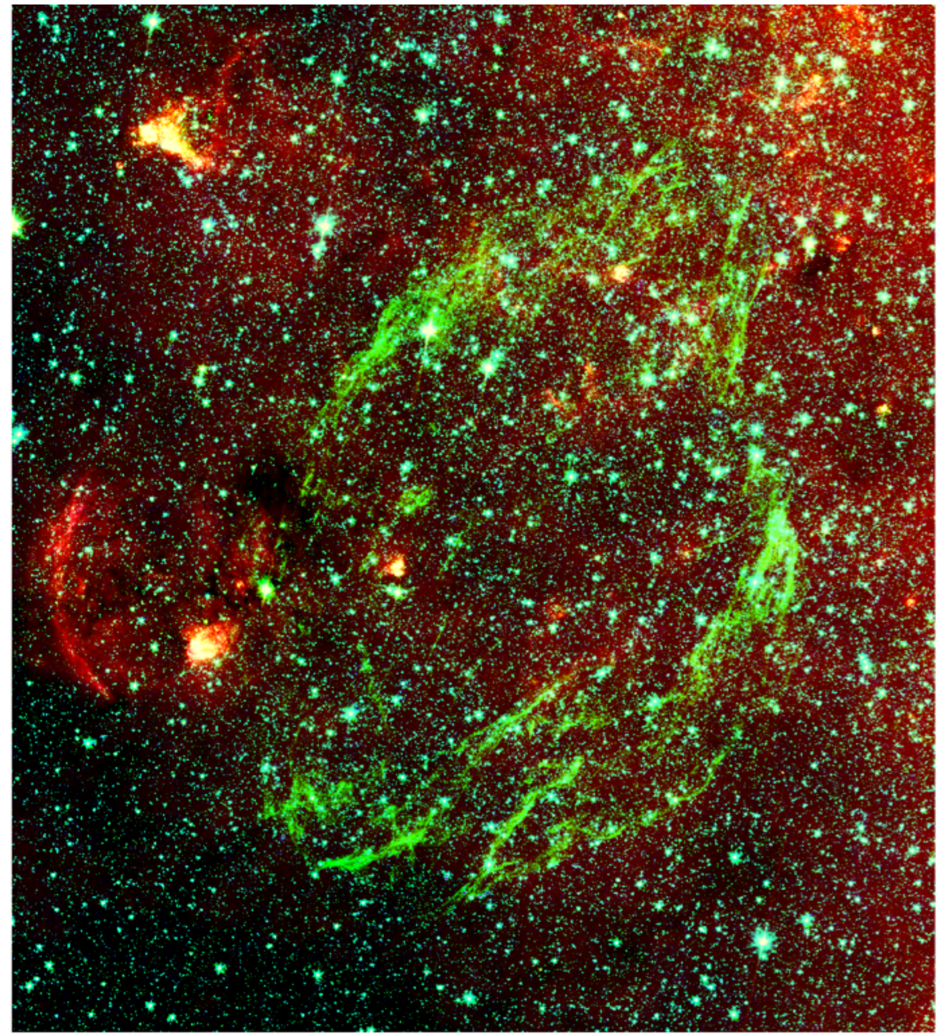
John W. Hewitt (NASA/Goddard)

R. Petre, J. Rho, W.T. Reach, M.A. Andersen, J.P. Bernard

Supernova Remnants Interacting with Clouds

W44, enveloped by a molecular cloud
Radiative signatures:

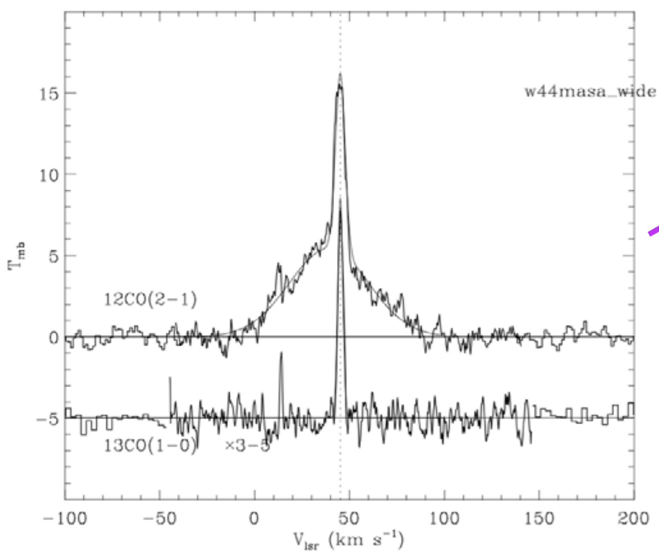
- IR-bright => shock cooling in relatively dense gas (>10^3 cm^{-3})

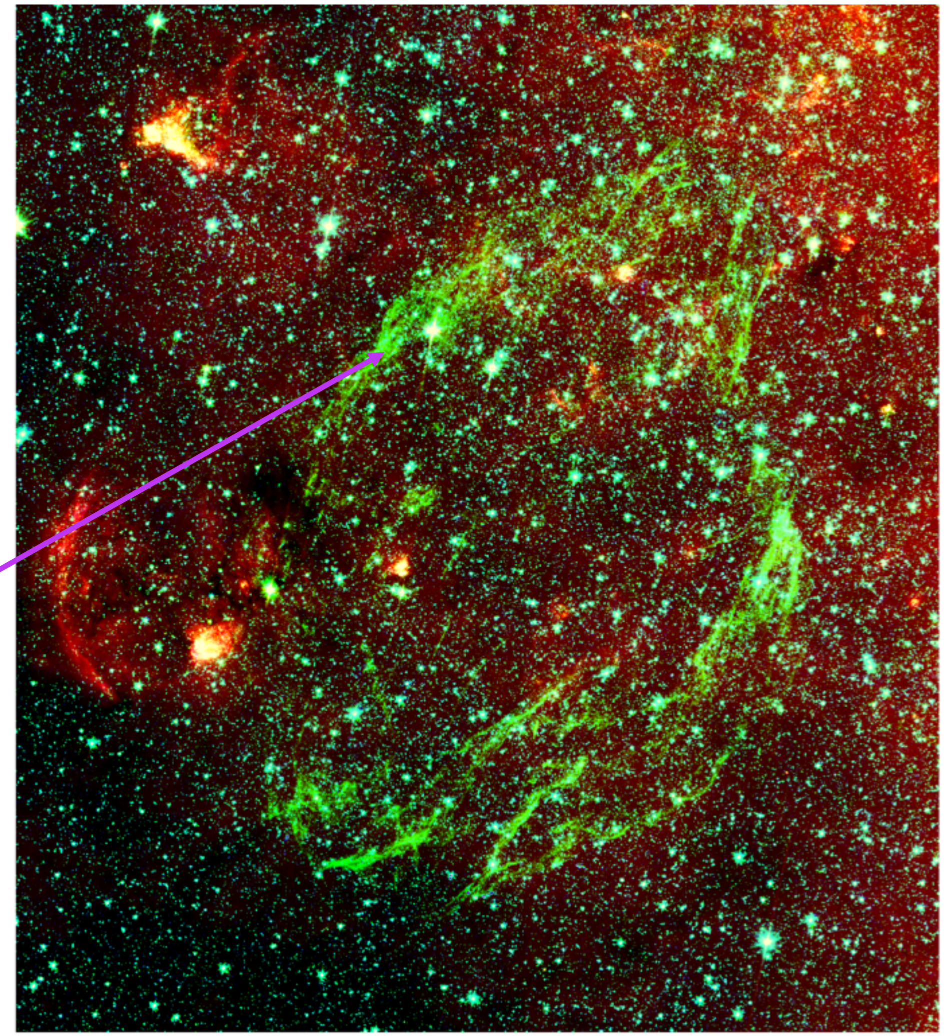


Supernova Remnants Interacting with Clouds

W44, enveloped by a molecular cloud
Radiative signatures:

- IR-bright => shock cooling in relatively dense gas ($>10^3$ cm^{-3})
- Broad molecular lines (eg. CO 2-1)





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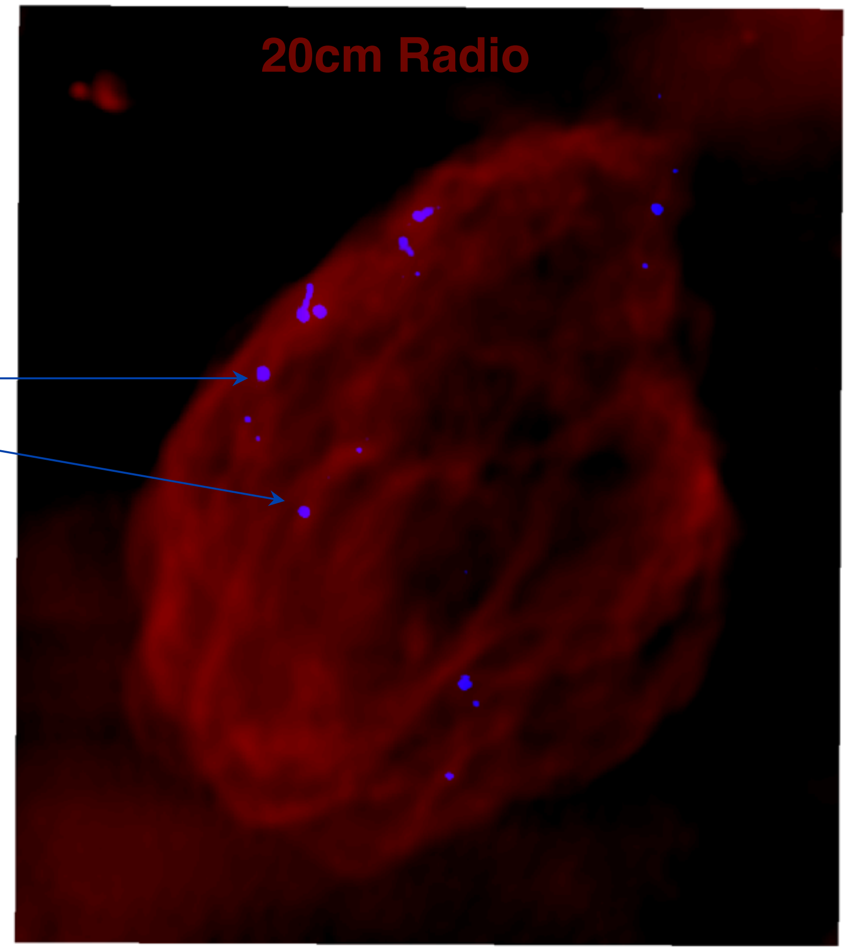

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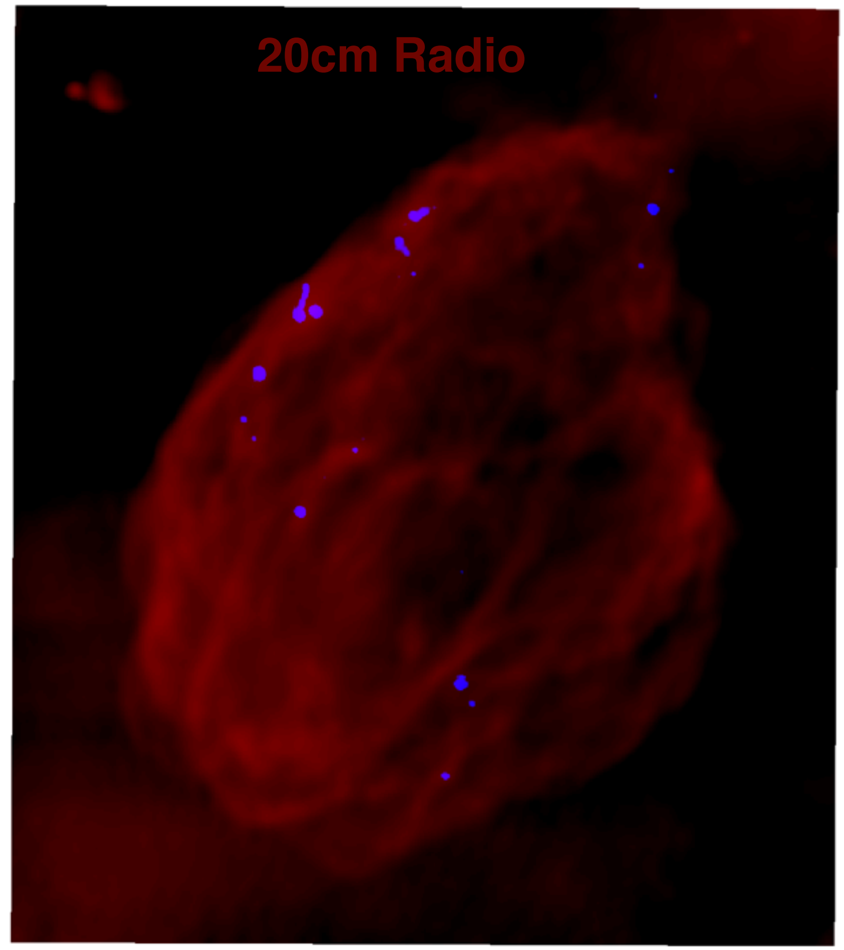
Catalog of SNR/MCs (Jiang et al. 2009)

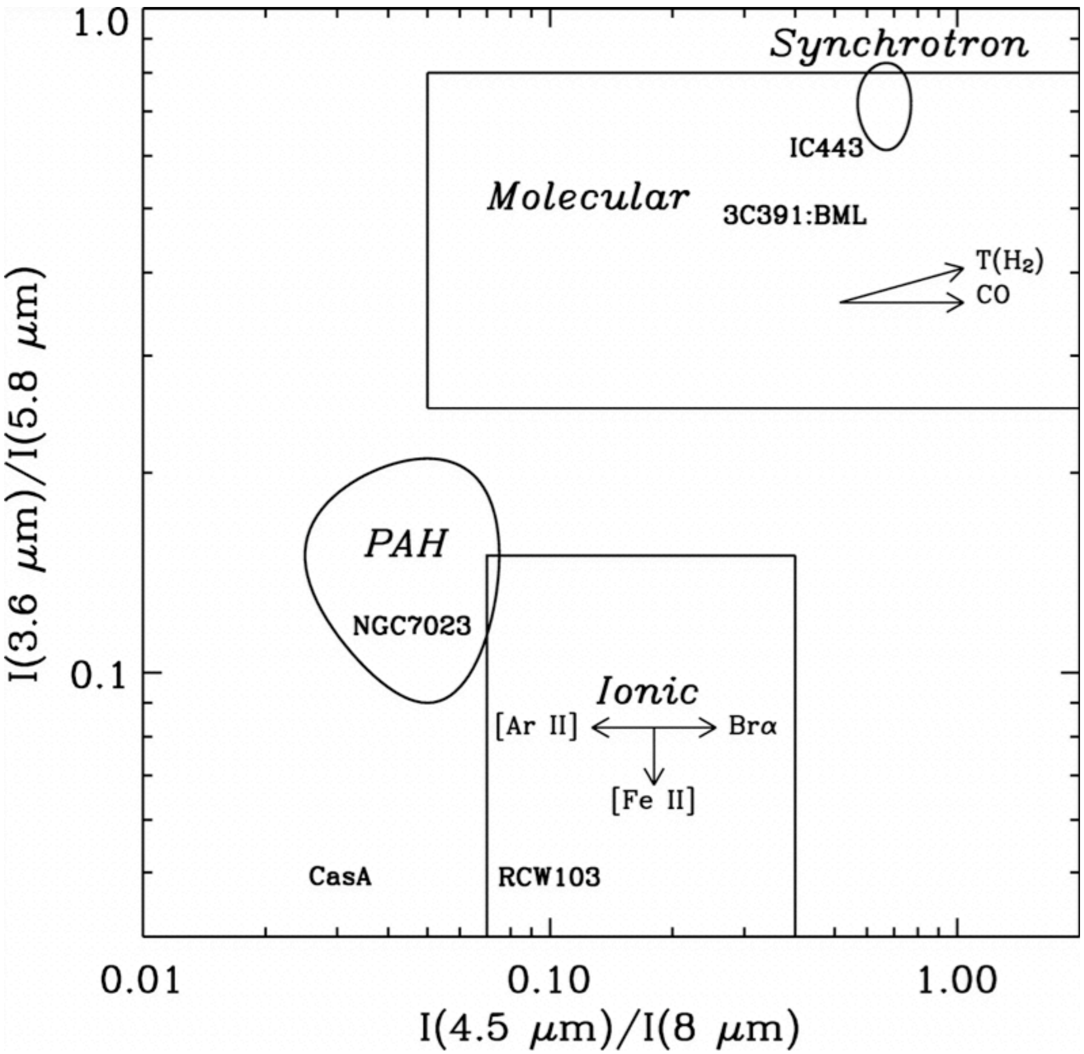
- 34 confirmed (24 w/Masers)
- 11 probable
- 19 possible

64 of 274 Galactic SNRs (~23%)
expect ~40% of SNe in field



Recent IR surveys have made the largest contribution

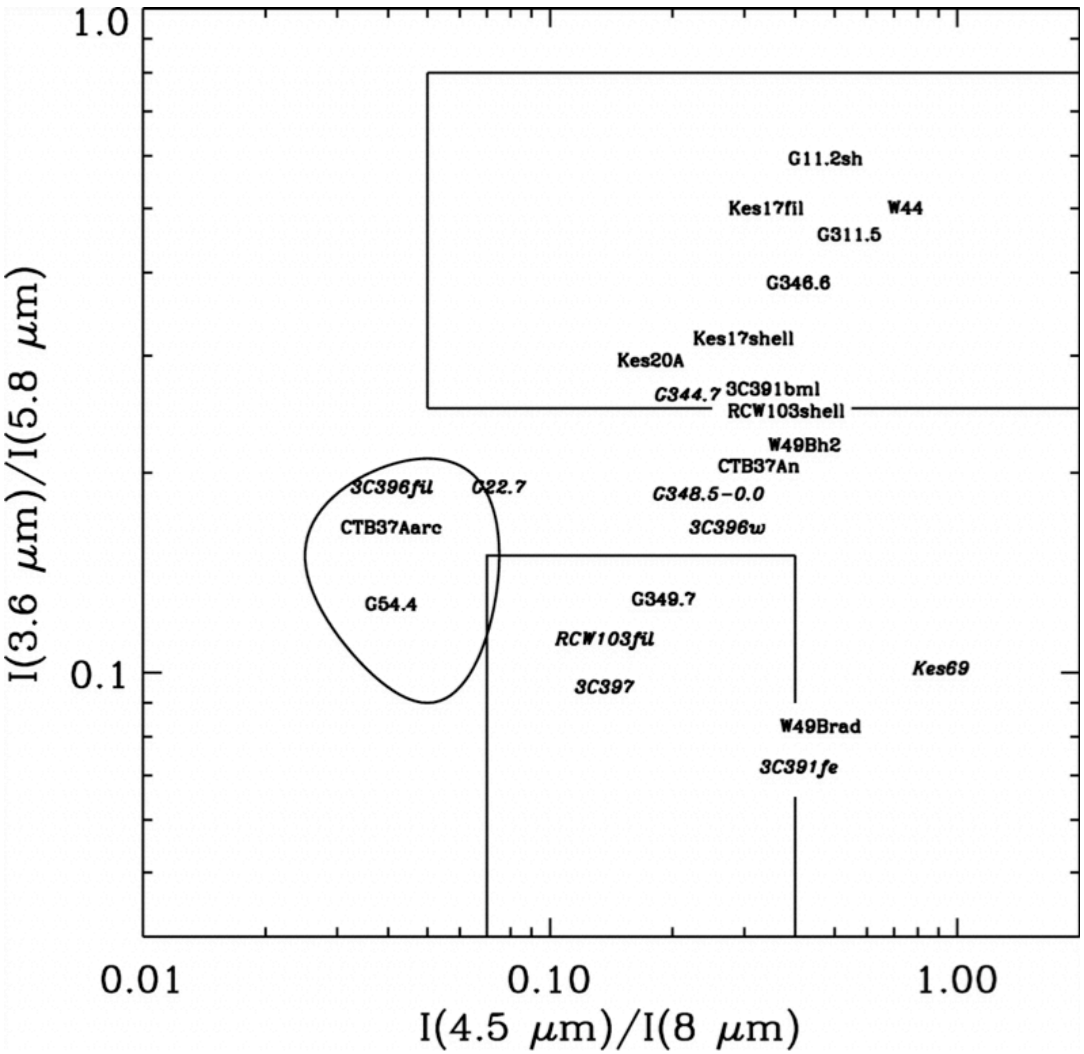
Supernova Remnants Interacting with Clouds



from Reach et al. 2006

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

Supernova Remnants Interacting with Clouds



from Reach et al. 2006

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- Colors hint at dominant cooling lines and shock type.

However...

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

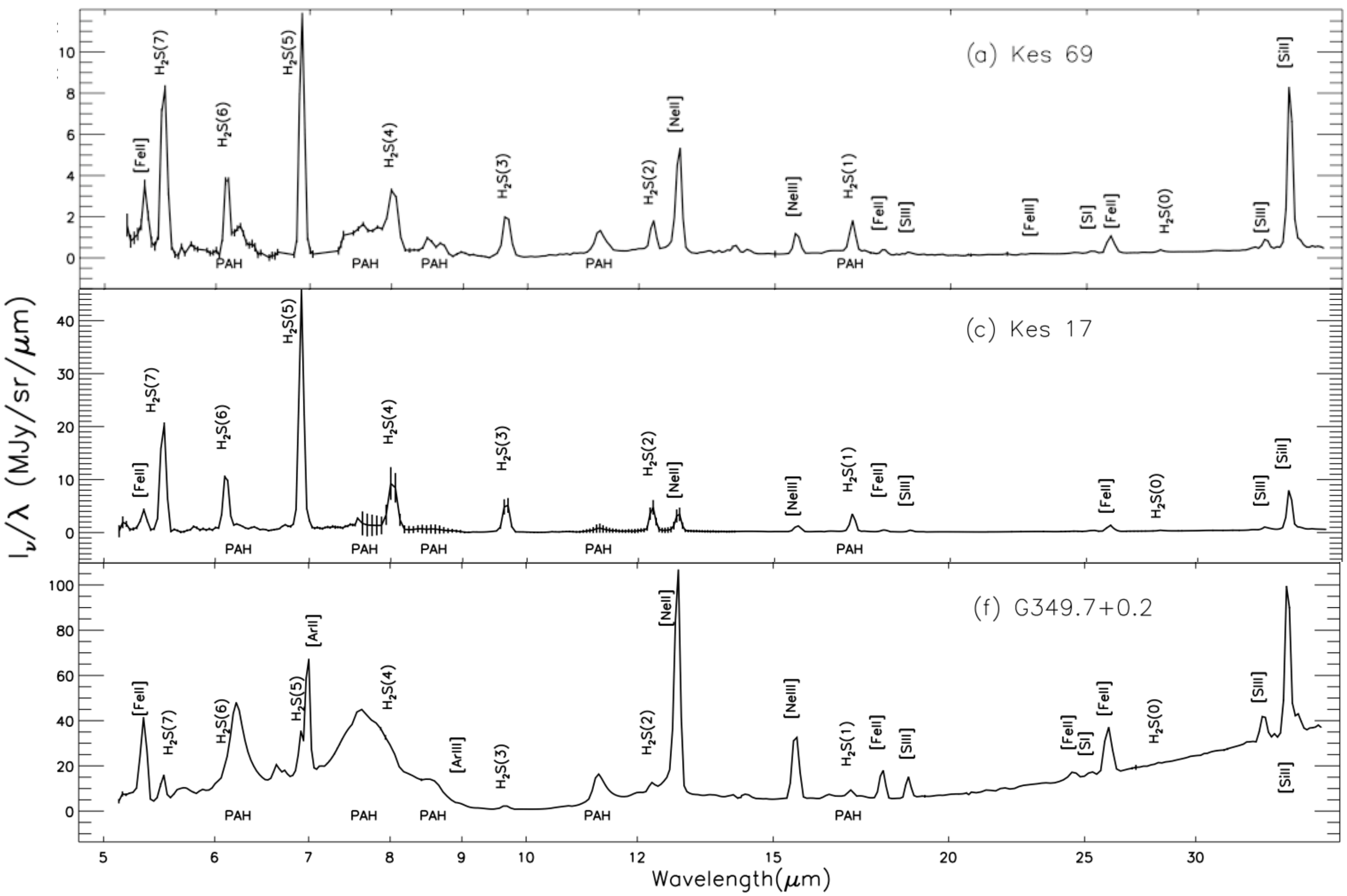
<u>IR spectroscopy is clearly needed</u>

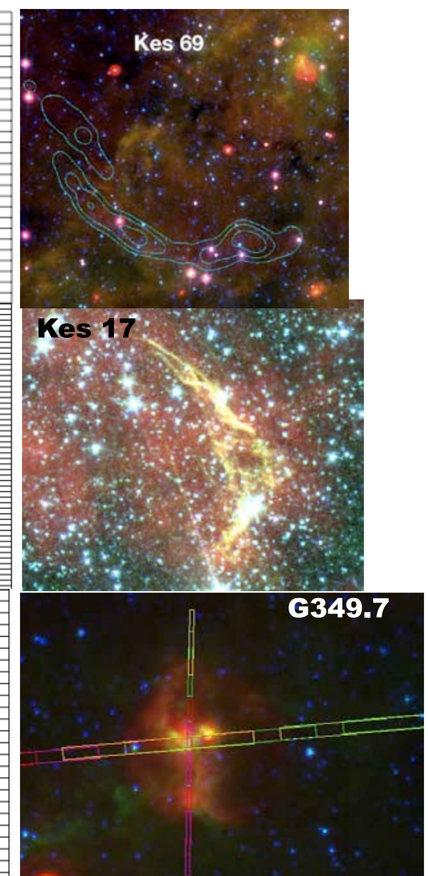
Spitzer 5 to 95 µm Spectroscopy

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

Hewitt et al. 2009, Andersen et al. (submitted)
Complements IRS mapping 4 SNRs (Neufeld et al.)

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

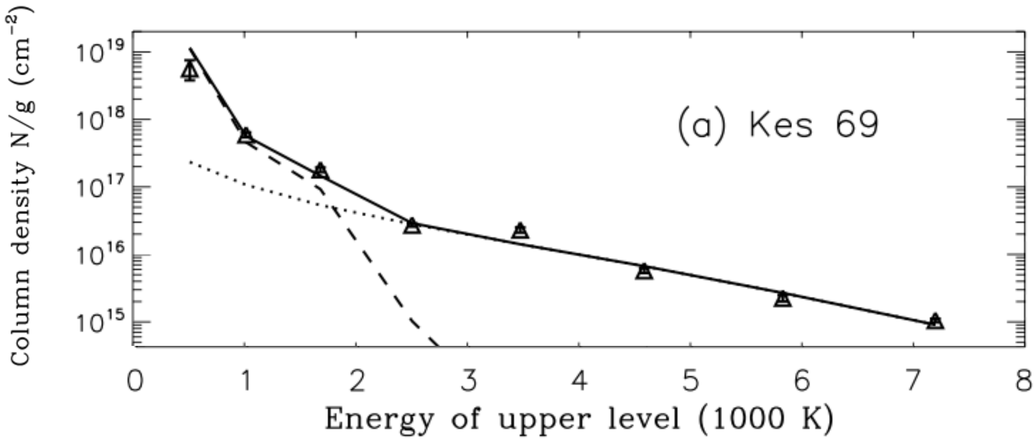




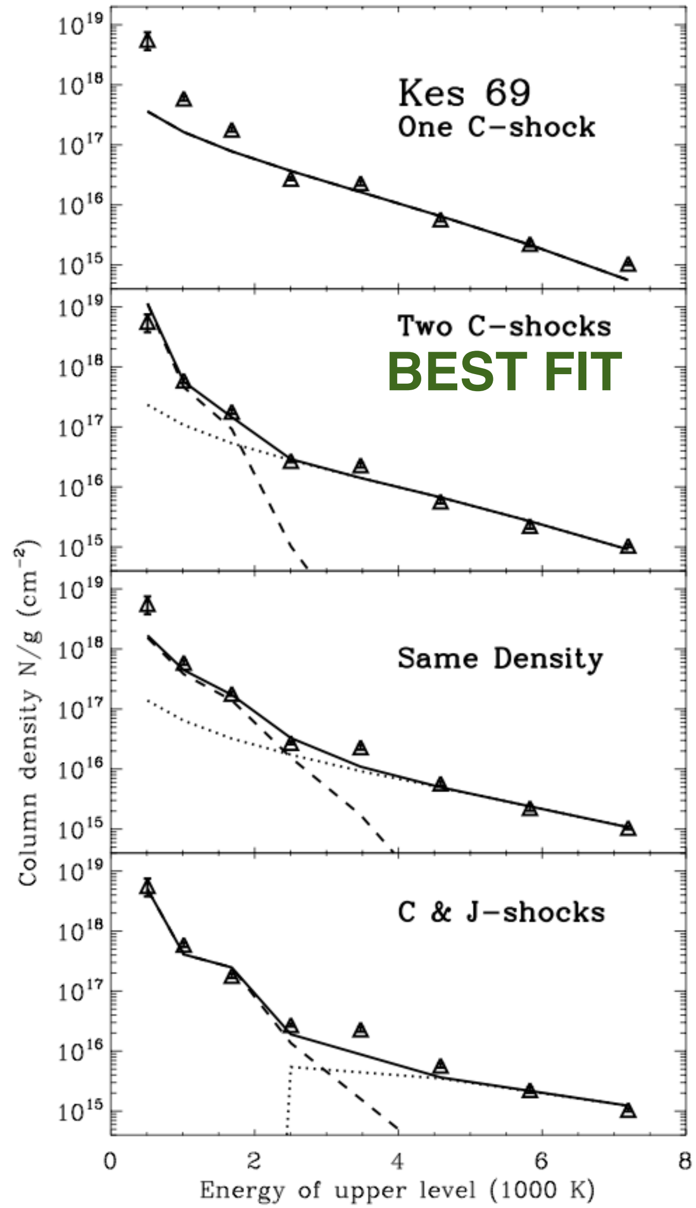
IRAC 3-color images

Spitzer IRS SL/LL 5-35µm *R*~100

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
- **H_2** fitting with shock models (Le Bourlot 2002)
  - $V_S =$ 10, 40 km/s
  - $n_H =$ 10^5, 10^4 cm^{-3}
  - $P_S =$ 1×10^{-6}, 3×10^{-7} dyne cm^{-2}

over-pressure in warm, dense clumps

H_2 Excitation: Ortho-to-Para

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

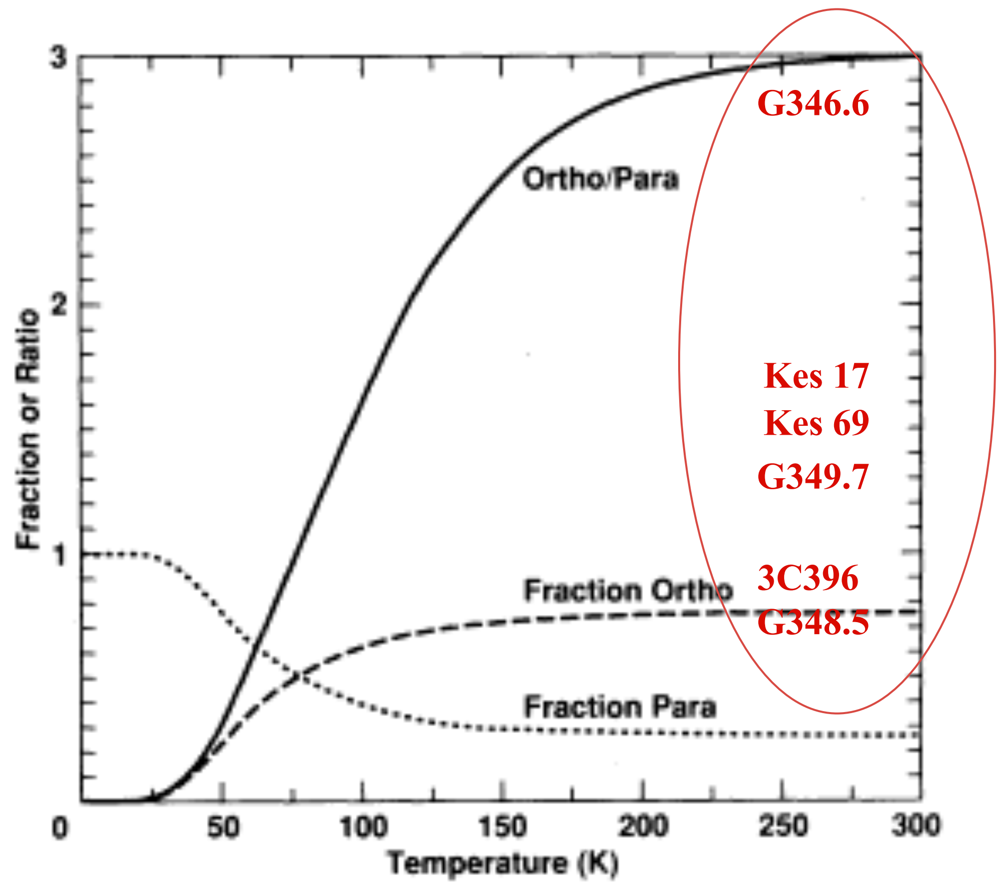
Para-to-ortho H_2 conversion via reactions with atomic-H:

$\tau_{conv} \approx 3000$ 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

Ortho-to-Para Ratio in Equilibrium



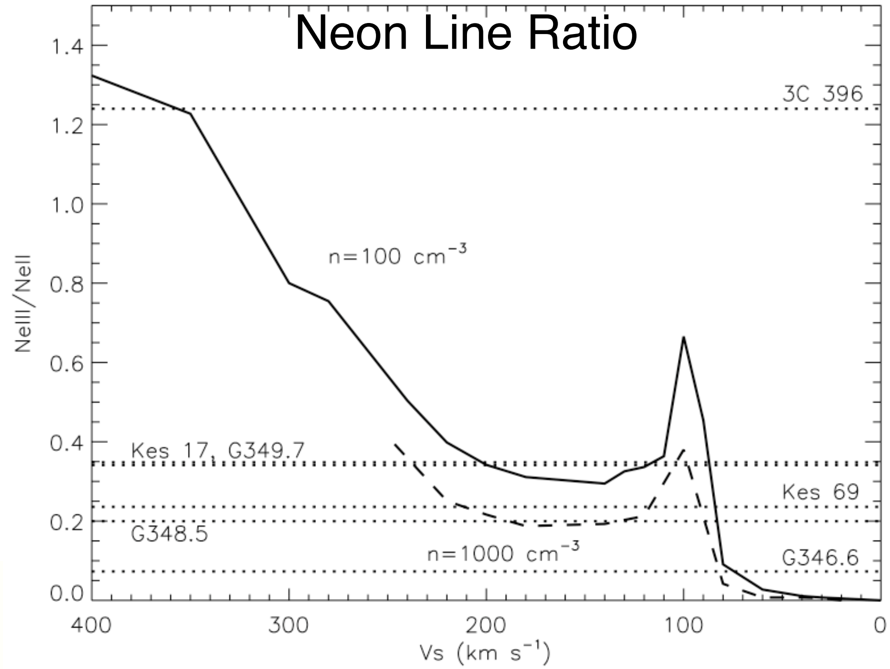
see also Yuan Yuan's poster #15

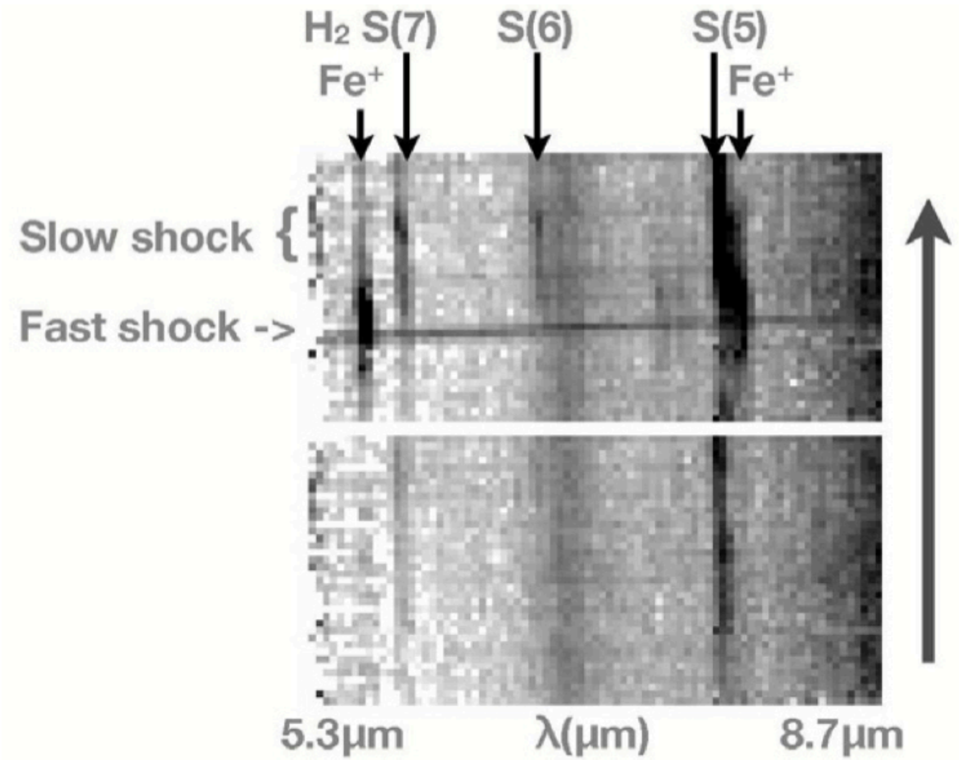
Fast, Dissociative Shocks

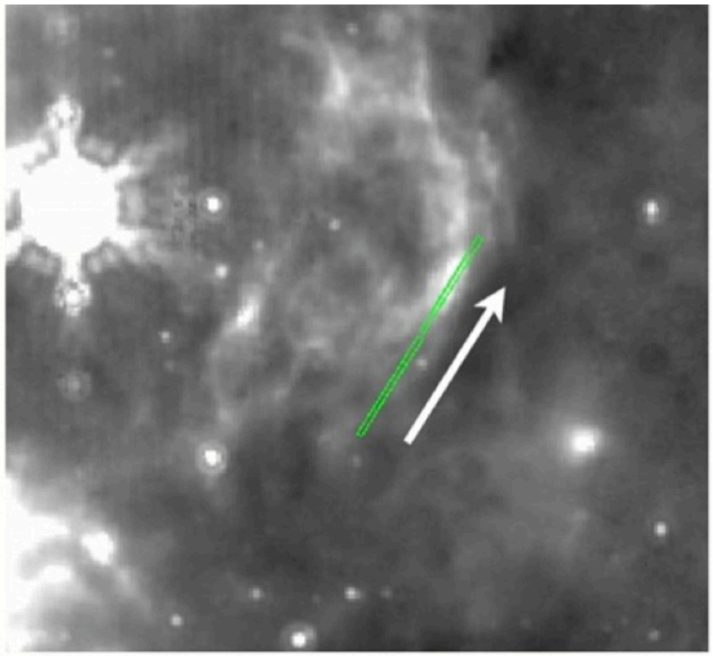
Excitation of ionic species:
Fe+, Ne+, Ne++, Si+, S++

requires V_S >100 km/s, n_e ~10^{2-3} cm^{-3}

Ionic emission spatially segregated from H_2 along the IRS slit.
=> multiple shocks







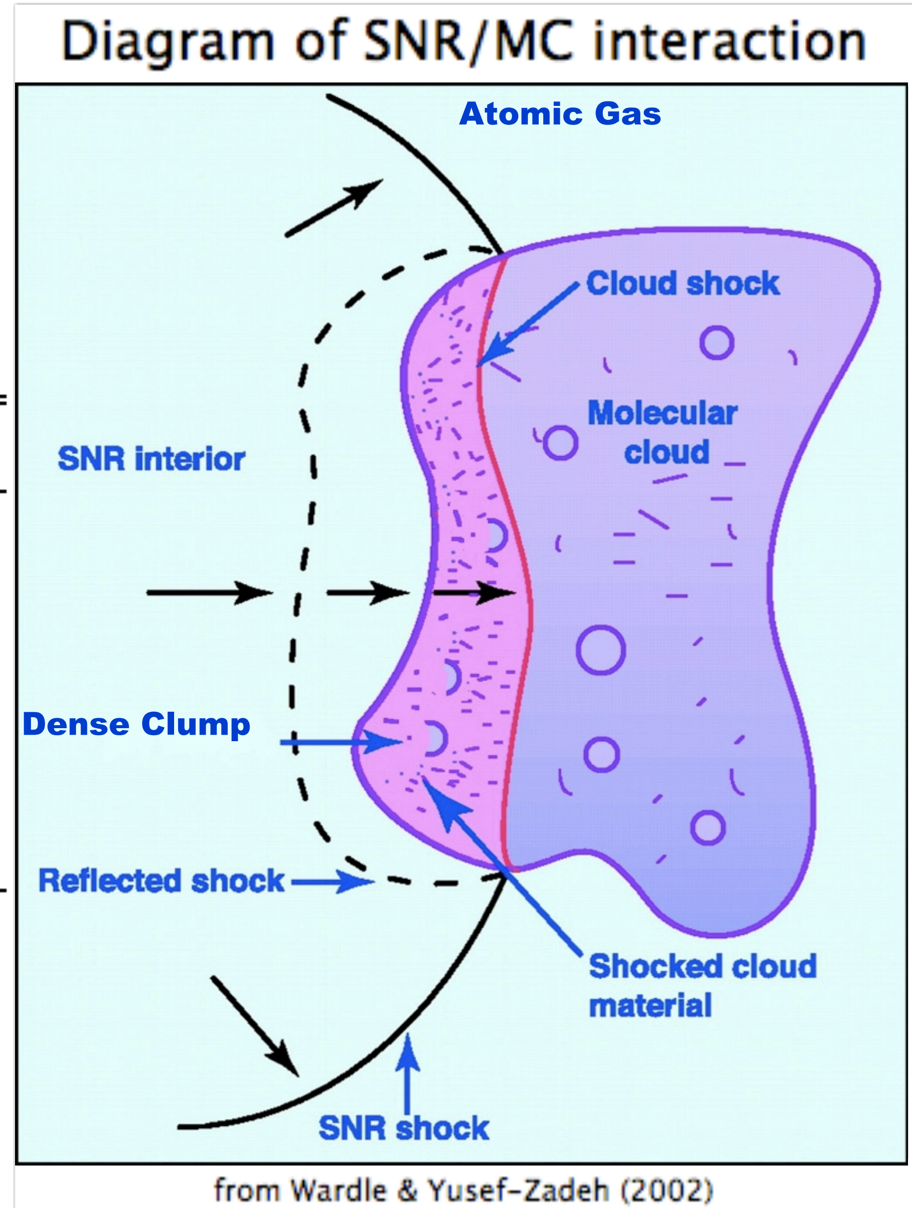
Shocks into multi-phase Molecular Clouds

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

(Chevalier 1999, Cox et al. 1999, Reach et al. 2005)



Dust Emission from SNRs

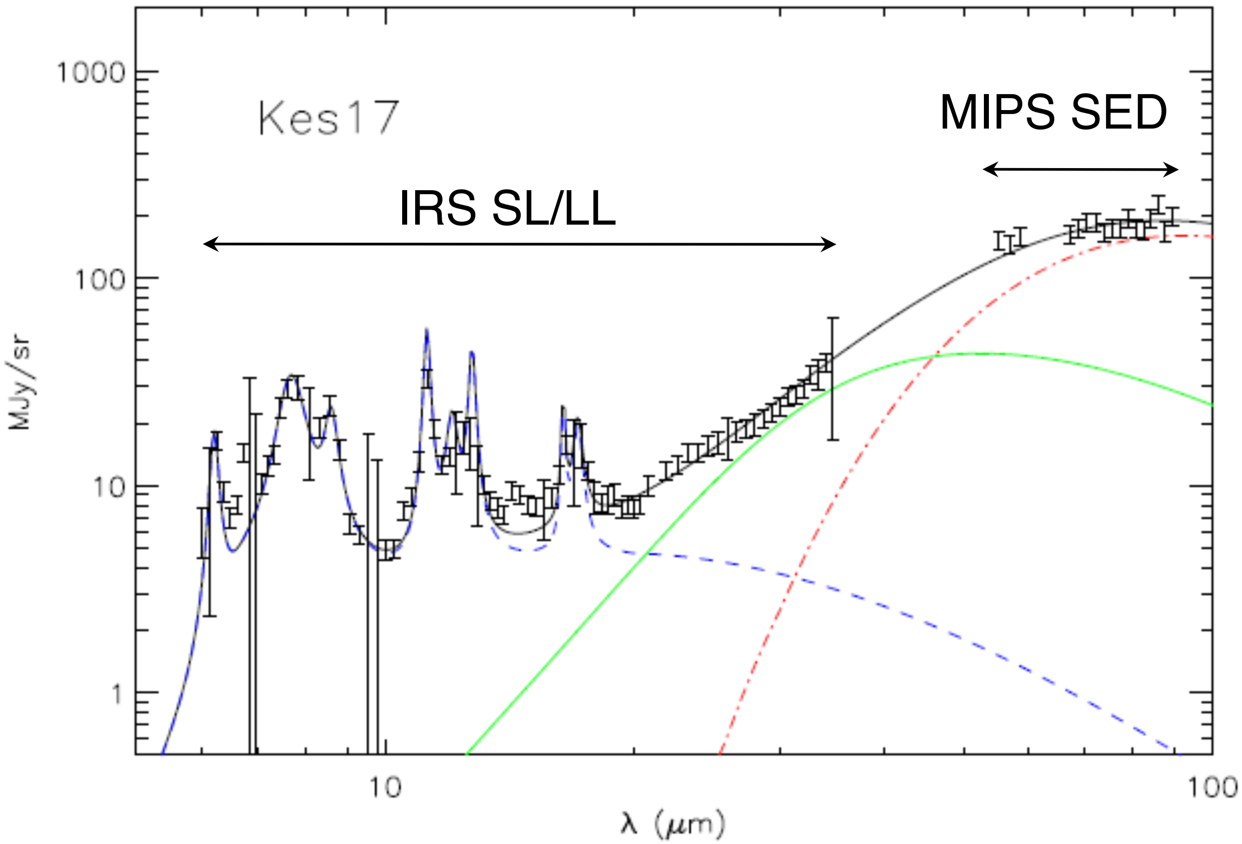
Dust continuum modeling (DUSTEM, Campiegne et al. 2008, Poster #35)
Parameters: Big Grains, Very Small Grains, PAHs, and Radiation Field
0.01-0.2 µm 0.001-0.01µm

Good fits obtained for Dust.
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

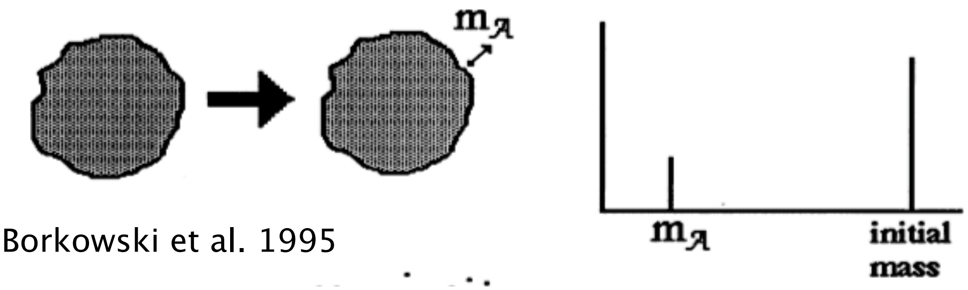


line-subtracted spectrum

Dust Processing by SNR shocks

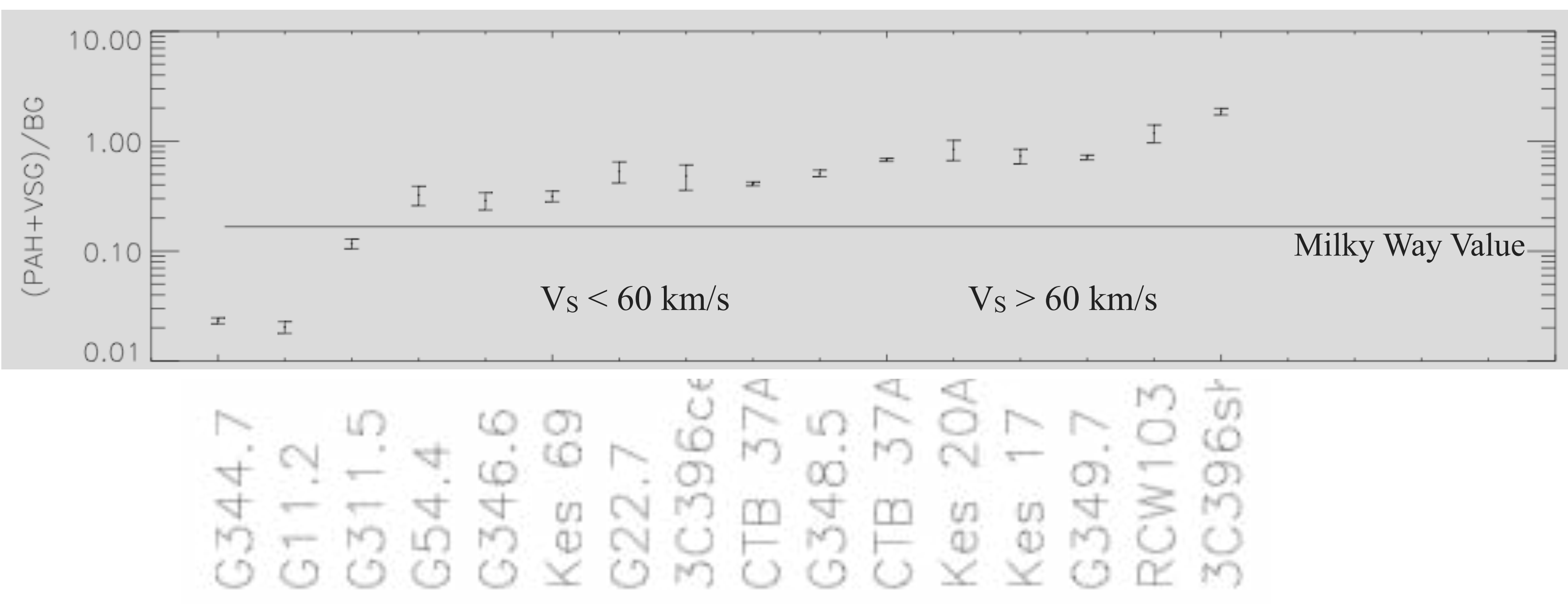
Shattering in dense/slow shocks, destroys BGs, but not VSG/PAHs

Sputtering efficient for fast shocks, affecting all grain sizes

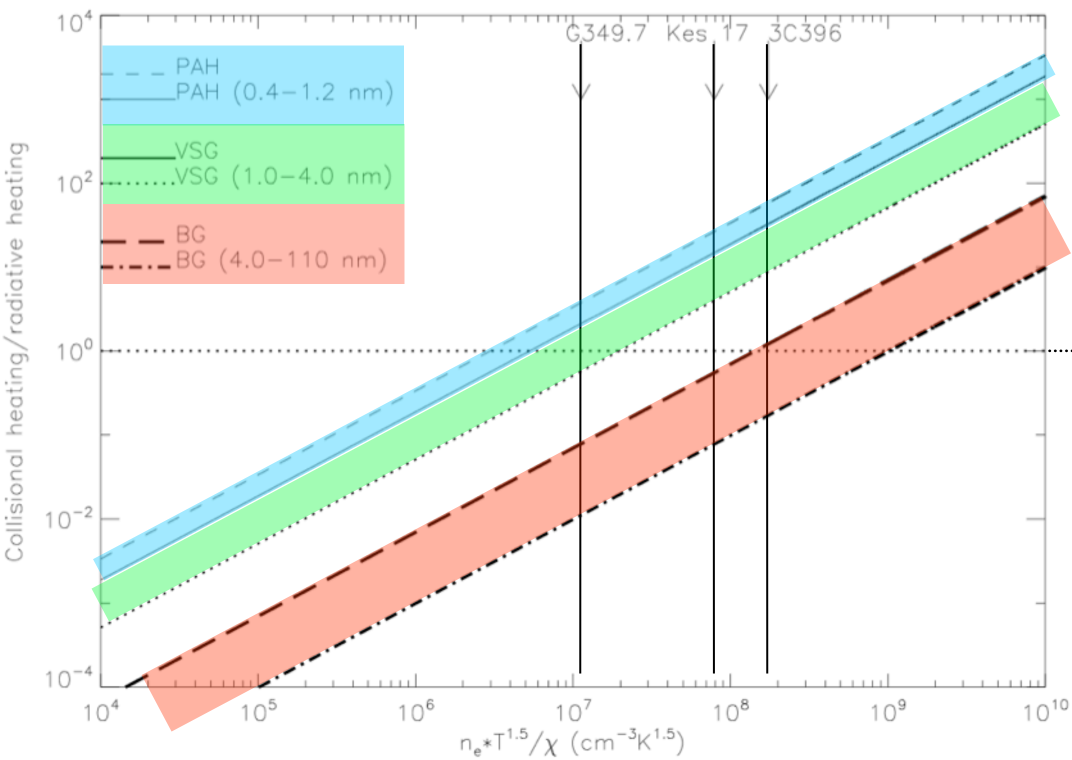


from Borkowski et al. 1995

Observe VSG/BG consistent with **shattering**, increasing with V_S



Dust Heating by SNR shocks



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

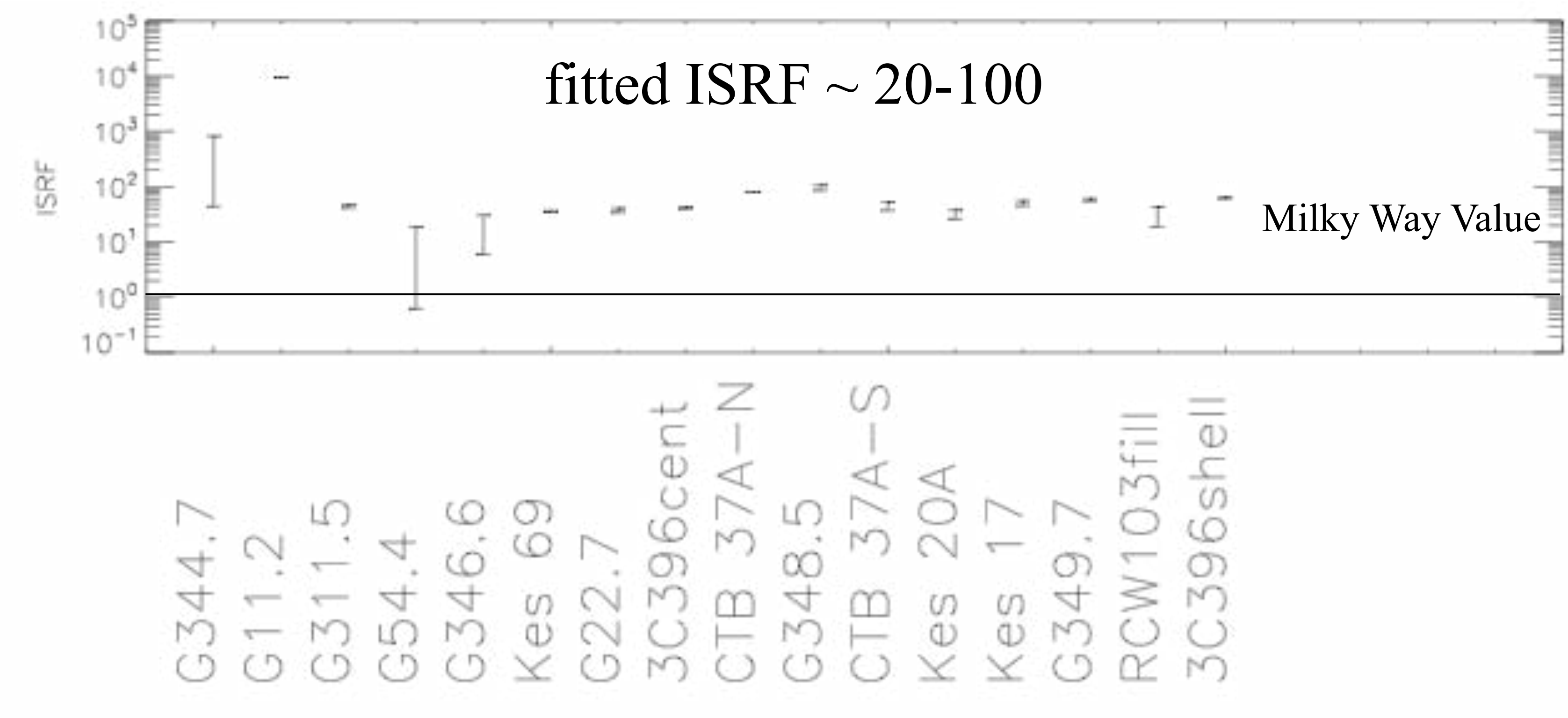
[Fe II] emitting gas:
n_e~100-1000 cm^{-3}, T=5-10x10^3 K

Above assumes radiative field is = ISRF

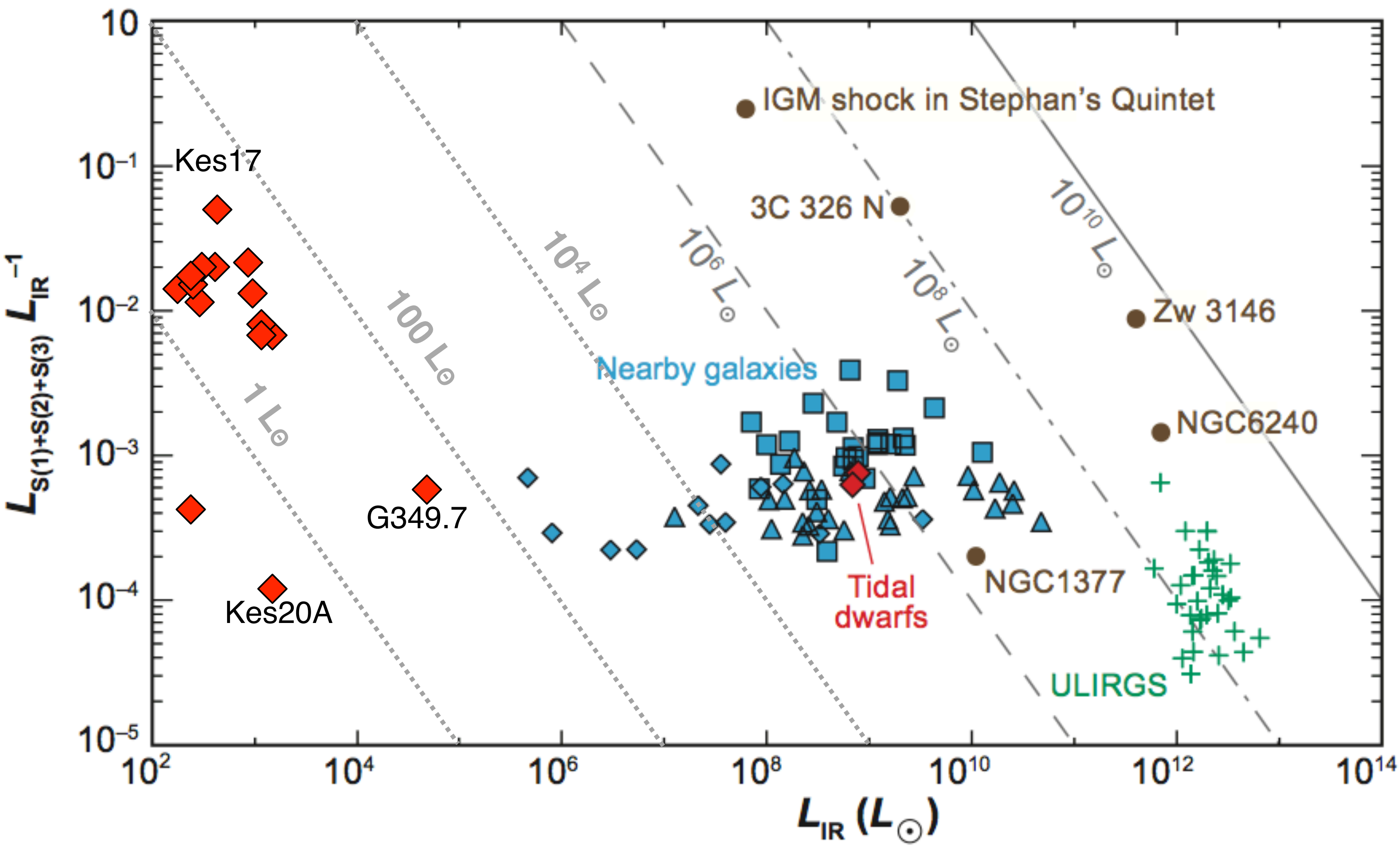
SNRs have ***even higher*** UV radiation from H-recomb (fast shocks, [Fe II])

Dust Heating by SNR shocks

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



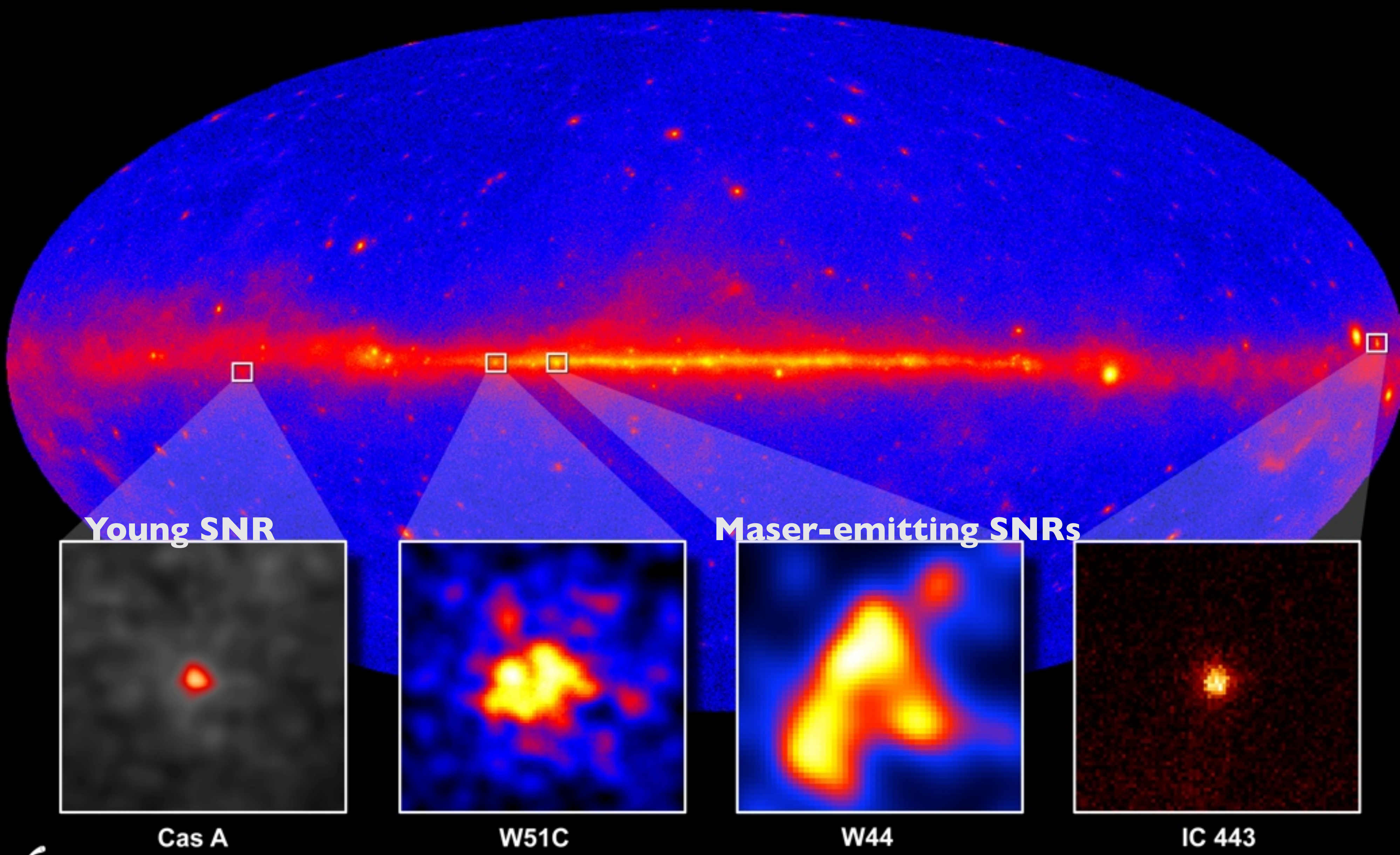
Radiative Cooling: SNR/MCs



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

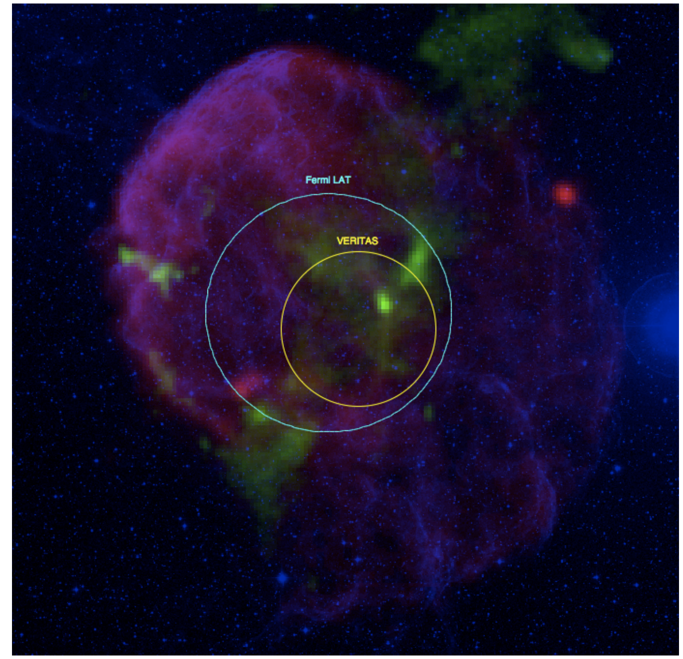
[O I] 63μm line detected in 10/14 SNRs, $L_{[OI]}/L_{Dust}$ ~ 1-7%

NASA's Fermi telescope resolves supernova remnants at GeV energies



γ-ray emission from SNR/MC IC 443

Extended TeV/GeV source detected, coincident with CO peak



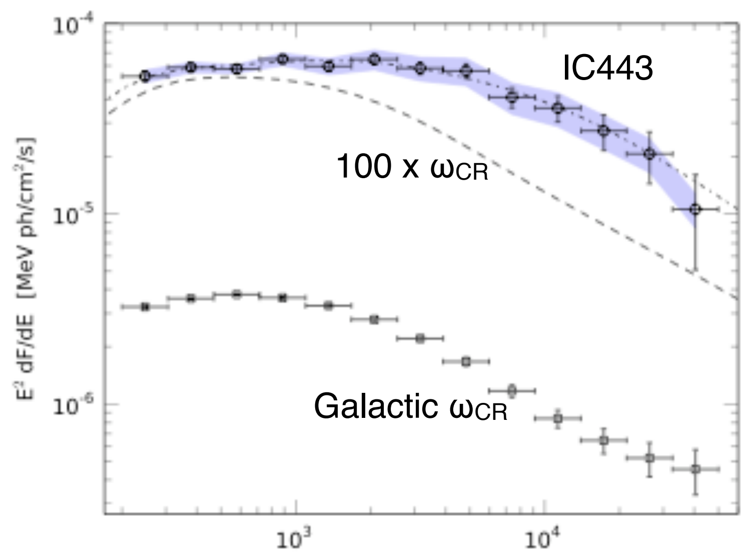
Spectral fitting using leptonic (inverse Compton + Bremsstrahlung) and hadronic (pion decay)

$W_p = 0.5\text{-}2.2 \times 10^{49}$ erg (~1% E_{SN})

$n_\gamma = 60\text{-}240$ cm^{-3}

Consistent with enhanced CR density ~100 in the adjacent molecular cloud.

Parameter	Atomic	Molecular	Clump
Density, n_0 (cm^{-3})	5–25	200	2×10^4
Fill factor, f	0.9	0.1	10^{-4}
Mass ($M_\odot$)	800	5000	300



Fermi LAT spectrum of IC443 (Abdo et al.)

Caveat: bulk of ionizing by MeV CRs, not GeV CRs measured by *Fermi*

Fermi γ-ray detections of SNR/MCs

Maser SNR subset: interaction, distance, cloud mass, n=10^5 cm^{-3}

- For π^0-decay origin (Drury et al. 1994)

$$F_\gamma \sim M_{cloud}\, d_{kpc}^{-2}\, \omega_{CR}$$

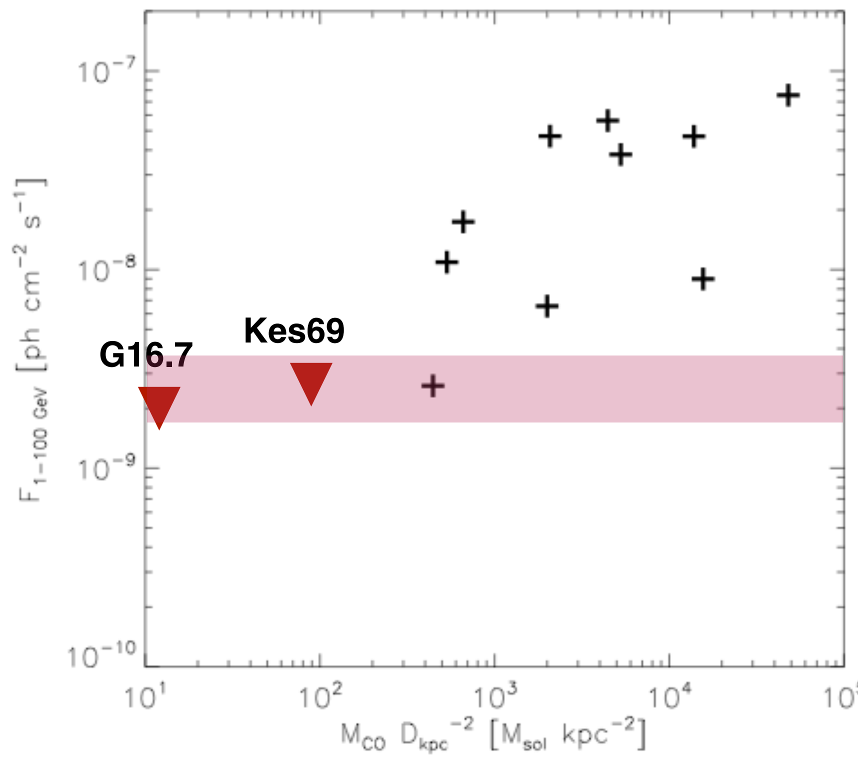
- Given M_{cloud}, d_{kpc} : determines CR ionization rate

$$\zeta_{CR} \approx \omega_{CR}\ \zeta_{local}$$

SNR	Distance (kpc)	M_{cloud} ($10^5\ M_\odot$)	F_γ(>100 MeV) (10^{-8} cm^{-2} s^{-1})	ζ_{CR} (10^{-16} s^{-1})
W28	2.0	0.5	74.2	3.4
W44	2.5	3.0	88.9	1.1
W51 C	6.0	1.9	40.9	4.4
IC 443	1.5	0.1	51.4	5.5

- Maser SNRs have ω_{CR} ~ 10-50 enhanced over local density
- **Significant ionization, >10^{-16} s^{-1}** enhances n(H,e)/n(H_2) in C-shocks

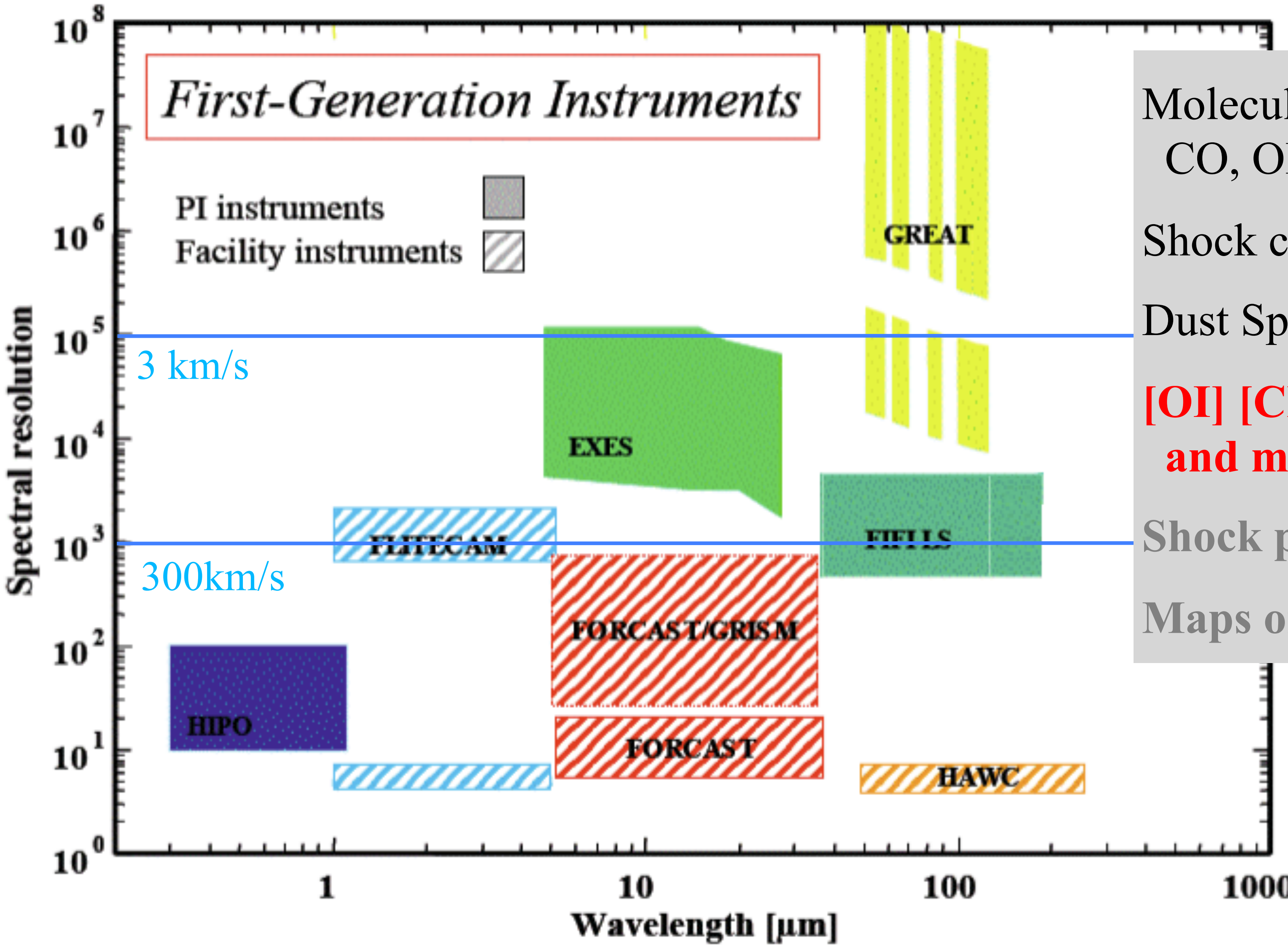
12/24 SNRs detected by Fermi



non-detections (eg, Kes69, G16.7) explained by low [$M_{CO}\, d^{-2}$]

Chemical tracers of CR ionization in SNRs: fertile ground for Herschel/SOFIA observations

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

SOFIA Future Proposal Calls

New SOFIA Instrument Proposal Call

- Asilomar Conference (Jun 7-9, 2010): New science instrument Opportunity (formal AO call expected next Spring)

http://www.sofia.usra.edu/Science/workshops/asilomar.html

- International partnership and opportunity to propose new instruments (after Herschel) for follow-up science: a new instrument can be built and available within 2-4 years.

Next Science Proposal Call

- Autumn of 2011: open to all astronomers in the world
- Data Analysis funding is available for US Investigators
- FORCAST (mid-IR camera) and GREAT (similar to Hi-Fi): fully commissioned
- One or more new instruments will be likely available (HIPO/FLITCAM/HAWK)

Prepared by J. Rho (SOFIA Science Center)

The violent lives of Supernova Remnants

<u>SNR shocks are a spectacular probe of molecular clouds</u>

- **Multiple shocks, through a multi-phase cloud**
  trace thermal history of the cloud (OPR)
- **Radiative cooling**: dust continuum, IR lines
- **Enhanced radiation field** ~20-100 x ISRF evidenced
  by Dust heating, H_2 UV excitation
- **Grain processing**: shattering decreases large grain size
- **Accelerate cosmic rays** yielding up to few % E_{SN}

<u>Future directions</u>

Processing of PAHs, small grains.
Non-equilibrium chemistry, driven by enhanced ionization?
Cosmic Ray escape/diffusion in ISM