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Infrared Supernova Remnants and Their Infrared to X-ray Flux Ratios

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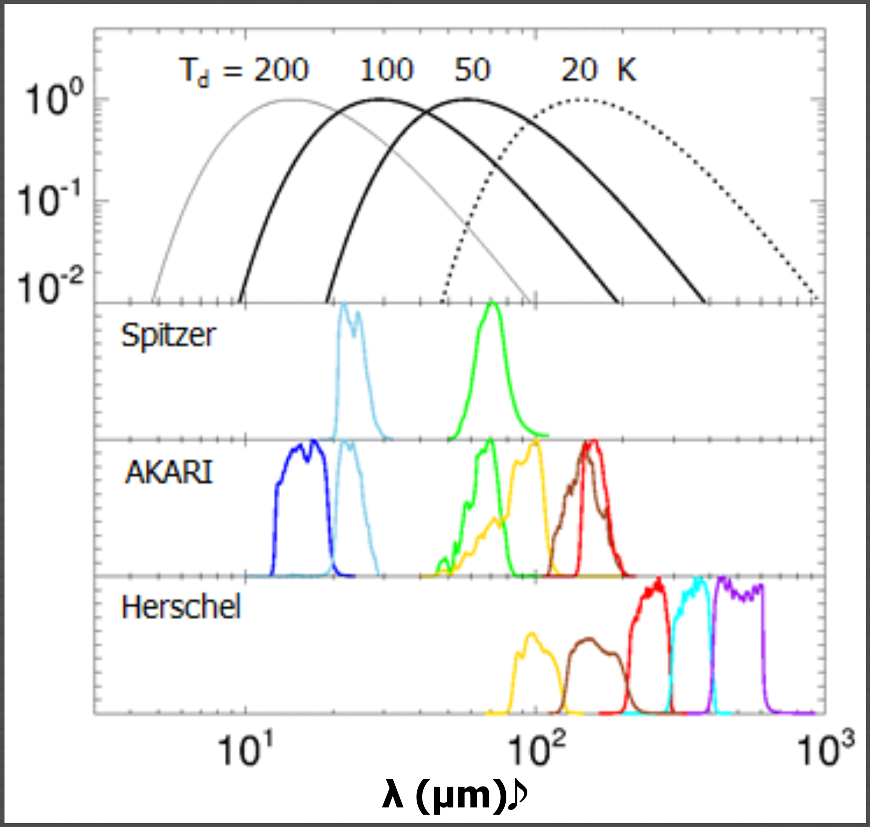
SNRs in FIR (≥25 μm)

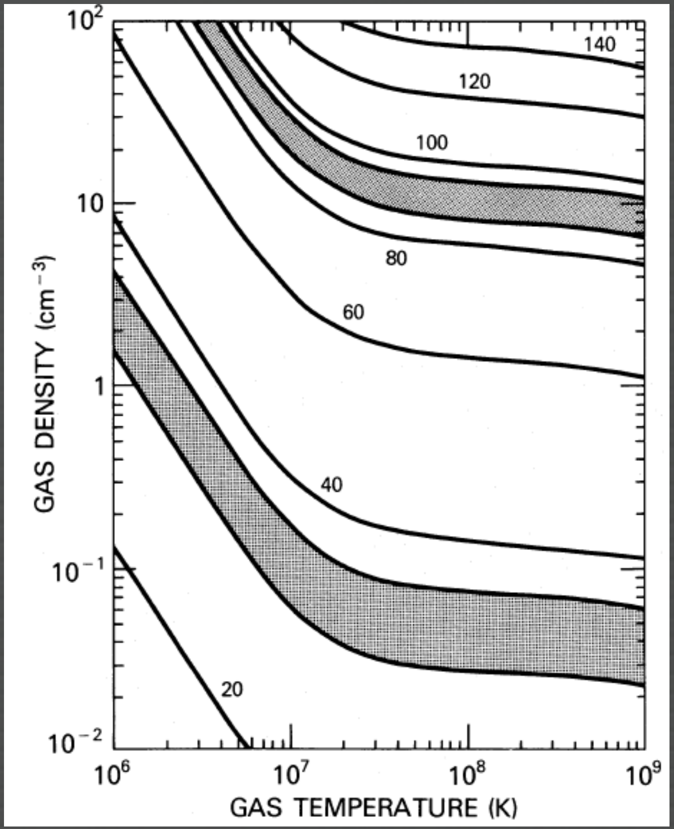
gl=10.6 to 13.8 deg

Spitzer 24 um + Herschel 70 and 160 um

FIR Emission from SNRs

- **Thermal emission from dust collisionally heated by X-ray emitting hot plasma**
  - T_d~40-80 K (cf) ISM dust T_d~20 K





Equilibrium dust T (Dwek 1987)

DUST COOLING OF HOT GAS

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ABSTRACT

The cooling rate of a hot gas by ion-grain collisions is evaluated and shown to be significant at temperatures above 10^6 ° K.

Subject headings: galactic nuclei — intergalactic medium

to point out in this *Letter* that, at the very high temperatures implied for this gas, any dust grains which survive in the gas will be heated by collisions with thermal particles, radiating the absorbed energy in the far-infrared, thus efficiently cooling the gas. The process has been noted by several authors (cf. Spitzer 1968; Dalgarno and McCray 1972); we note here that it may be an important (and possibly dominant) cooling mechanism in certain phases of supernova explosions, Seyfert nuclei, and intergalactic matter in galaxy clusters (Burke and Silk 1973; Yahil and Ostriker 1973). We shall also discuss high-temperature modifications of the simple cooling mechanism which have so far escaped attention in the literature.

The grain cooling rate per unit volume is proportional to the number of grains per unit volume, the number of thermal particles per unit volume, the collision cross-section, the relative velocity between grains and thermal particles, and the particle thermal energy. The cooling rate per unit volume for pure hydrogen can thus be expressed

$$H = 2^{5/2}(\pi M_p)^{-1/2} N_g N_p \sigma_g (kT)^{3/2} Q(T) f(T), \qquad (1)$$

where, in addition to the standard symbols, N_g is the number of grains per unit volume, σ_g is the geometrical grain cross-section (assumed spherical), and $Q(T)$ is a correction factor to account for charging of the grains. Here $f(T)$ is a factor (see Burke and Silk 1973 for details) which corrects for the inefficient deposition of energy at high temperatures, and allows for energy transfer via ionization losses and excitation of lattice vibrations.

At low temperatures, sputtering and secondary electron emission can be ignored, and the velocity of the electrons is larger than that of the protons; hence they will tend to collide more frequently with grains. Then, in order to maintain a constant charge on the grain, the cross-section for electron collisions must be decreased and the cross-section for ion collisions increased, and the grain becomes negatively charged. Following the procedure outlined by Spitzer (1968, p. 145) we find the proton collision cross-section increased by $(1 + \phi)$, where $\phi = -eV/KT = 2.51$ and V is the surface potential on the grain; V corresponds to 2.2 volts at 10^4 ° K. In addition to thermal energy, each proton releases on impact the energy gained by falling through the electrostatic potential. Combining the two effects and integrating over Maxwellian velocity distributions, we find that $Q(T)$ is $2(1 + \phi/2)^2 = 10.18$ and $f(T)$ is 1 under these circumstances. Then, for any assumed dust to gas ratio,

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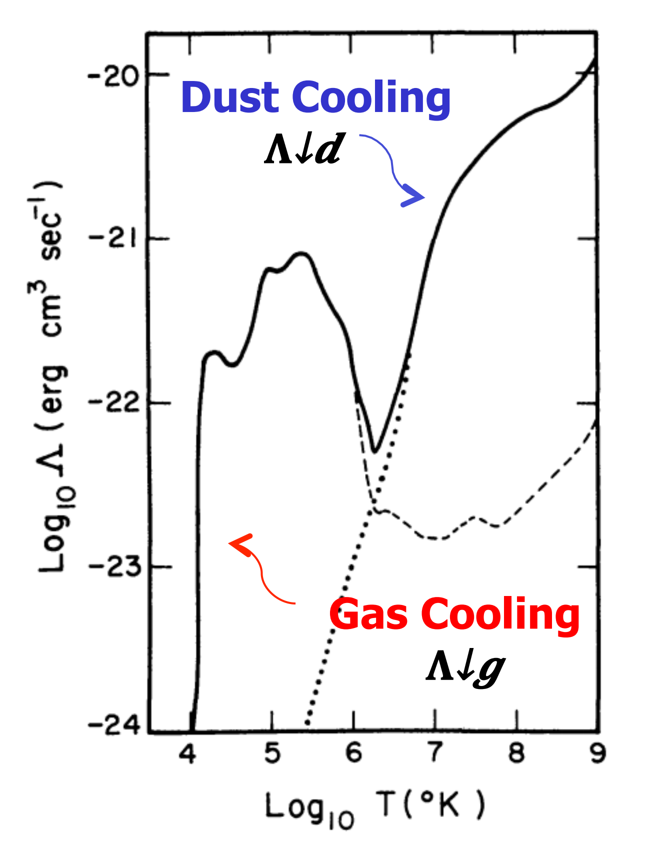
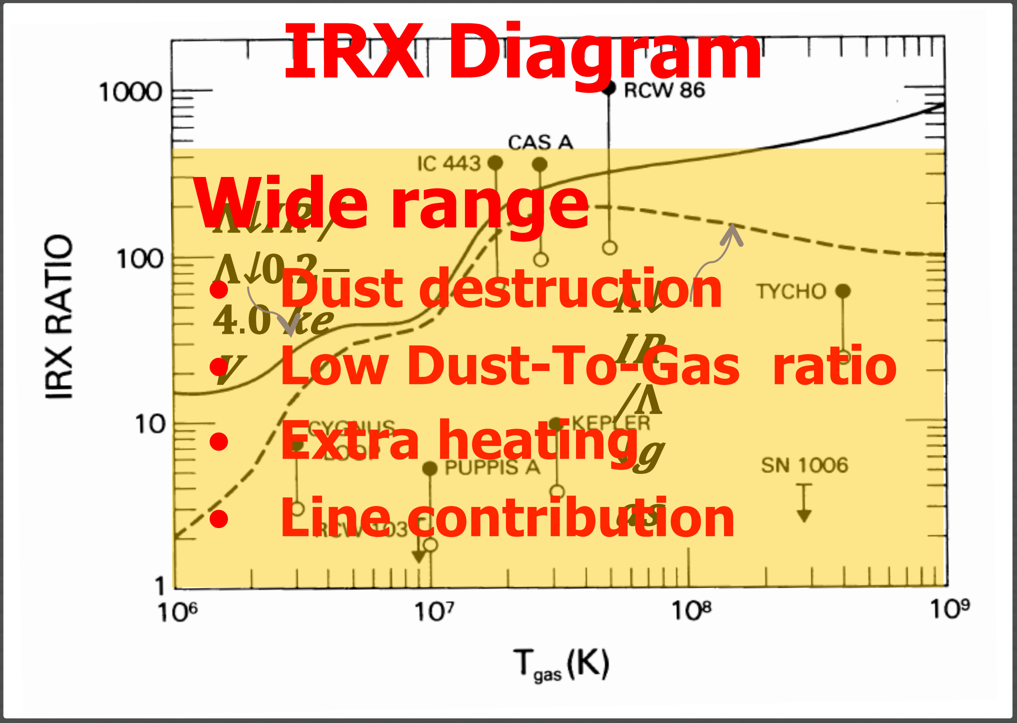


IR Cooling of SNRs ♪

- **IRAS era**
  - Dwek 1981; Draine 1981; Dwek+ 1987; Graham+ 1987; Arendt+ 1990, 1992
  - **Infrared to X-ray (IRX) flux ratio** > 1
    → IR dust cooling is more efficient than the gas cooling

$IRX\ ratio = \Lambda_{IR}(T)/\Lambda_{X}(T)$ ♪

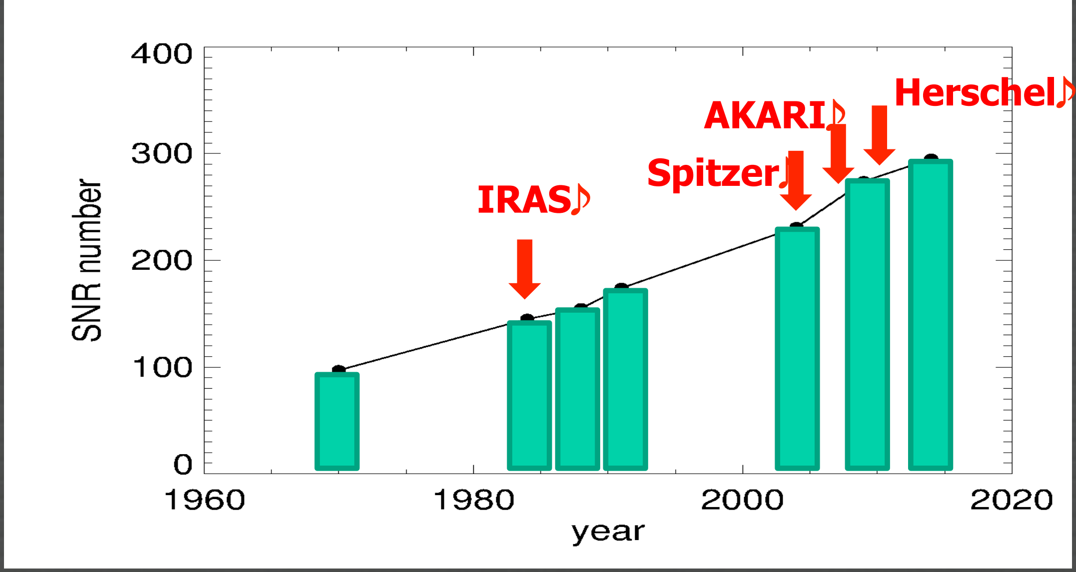
where $\Lambda_{IR}(T)$ and $\Lambda_{X}(T)$ are dust IR and gas X-ray (0.2-4.0 keV) cooling functions ($cm^3\ s^{-1}$)♪



- **Post IRAS era**
  - Spitzer MIPSGAL, AKARI FIS All Sky, Herschel Hi-GAL
    - 18/95 (Reach+06), 39/121 (Goncalves+11), 59/294 (Jeong+ 15 PhD thesis)

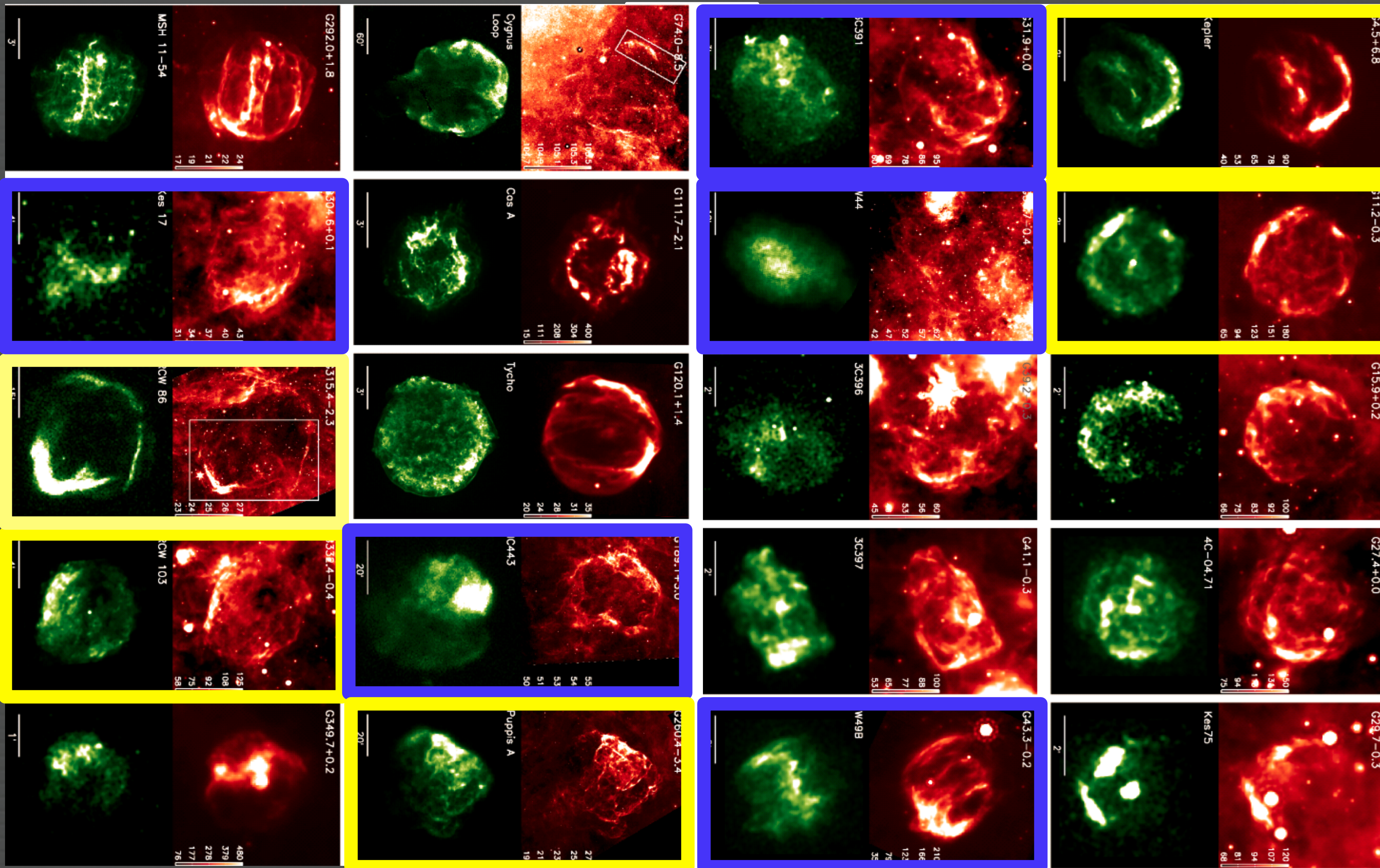
    → IRX flux ratios: 1987A (Dwek+ 2008), Puppis A (Arendt+ 2010; Dubner+ 2013), RCW 86 (Williams+ 2011), 13 SNRs (Pinheiro Goncalves+ 2011) , …

In this work, we present an IRX diagram for a sample of 20 Galactic SNRs and explore how the natural and/or environmental properties of SNRs affect the IRX flux ratios.



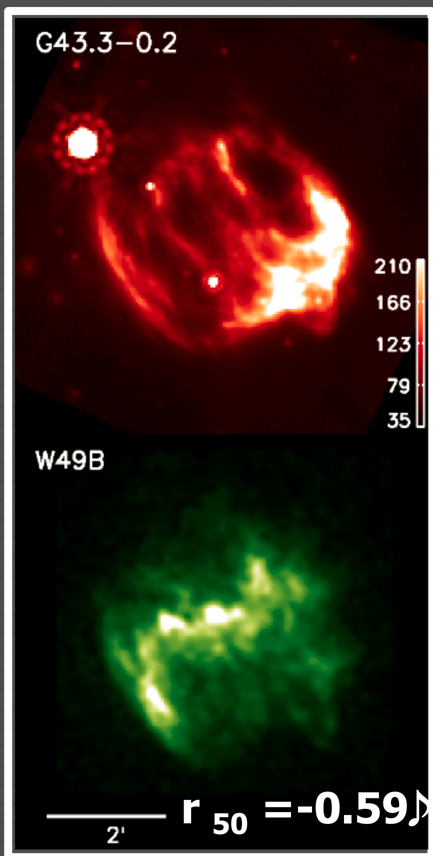
20 Target SNRs♪

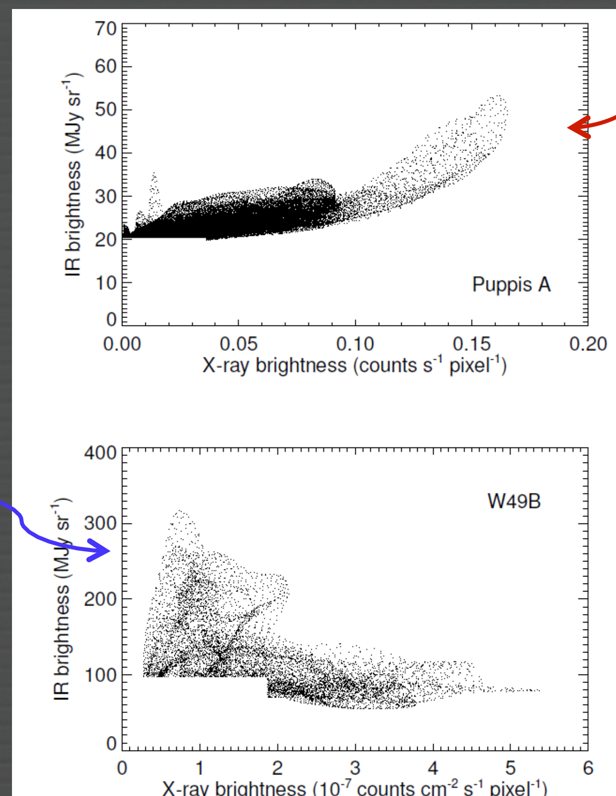
Red= Spitzer 24 um; WISE 22 um
Green=Chandra 0.3-2.1 keV; ROSAT; XMM

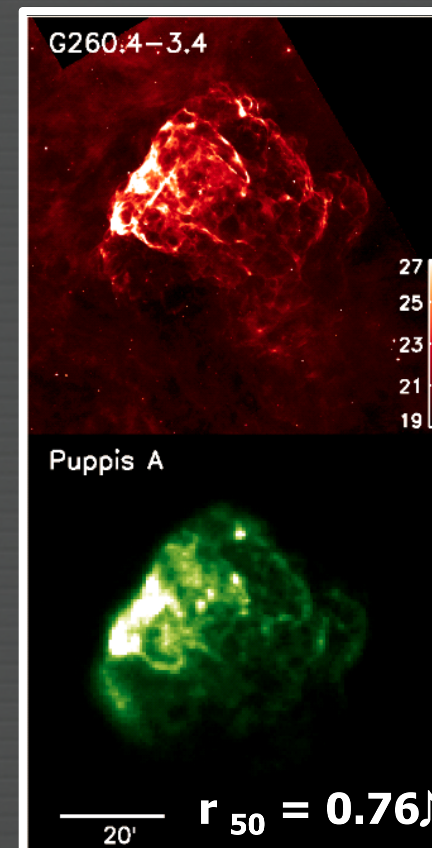


IR to X-ray correlation♪

- **Correlation coefficient r_{50}**
  - –Bright pixels contributing 50% of either IR or X-ray fluxes
  - –r_{50}=-0.59 to 0.76







IR/X-ray parameters of SNRs♪

- **Infrared: F_{IR}, T_d**
  - Spitzer MIPS 24 um flux, Herschel S 70 um flux + others
  - 7 SNRs from previous studies
    - Kepler, Cygnus Loop, Cas A, Tycho, MSH 11-54, Kes 17, RCW 86
  - Caveat: MIR line emission

$$\frac{F_{24}}{F_{70}} = \left(\frac{\lambda_{24}}{\lambda_{70}}\right)^{\beta} \frac{B_{24}(T_d)}{B_{70}(T_d)},$$

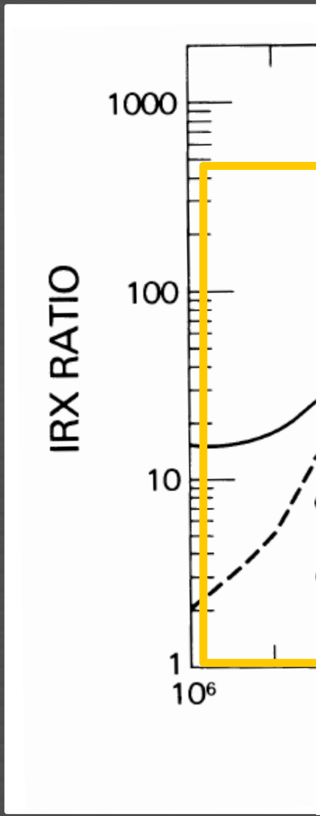
β=2

$$F_{\mathrm{IR}} = F_{70}\frac{\int \kappa_\nu B_\nu(T_d) d\nu}{\kappa_\nu B_\nu(T_d)}$$

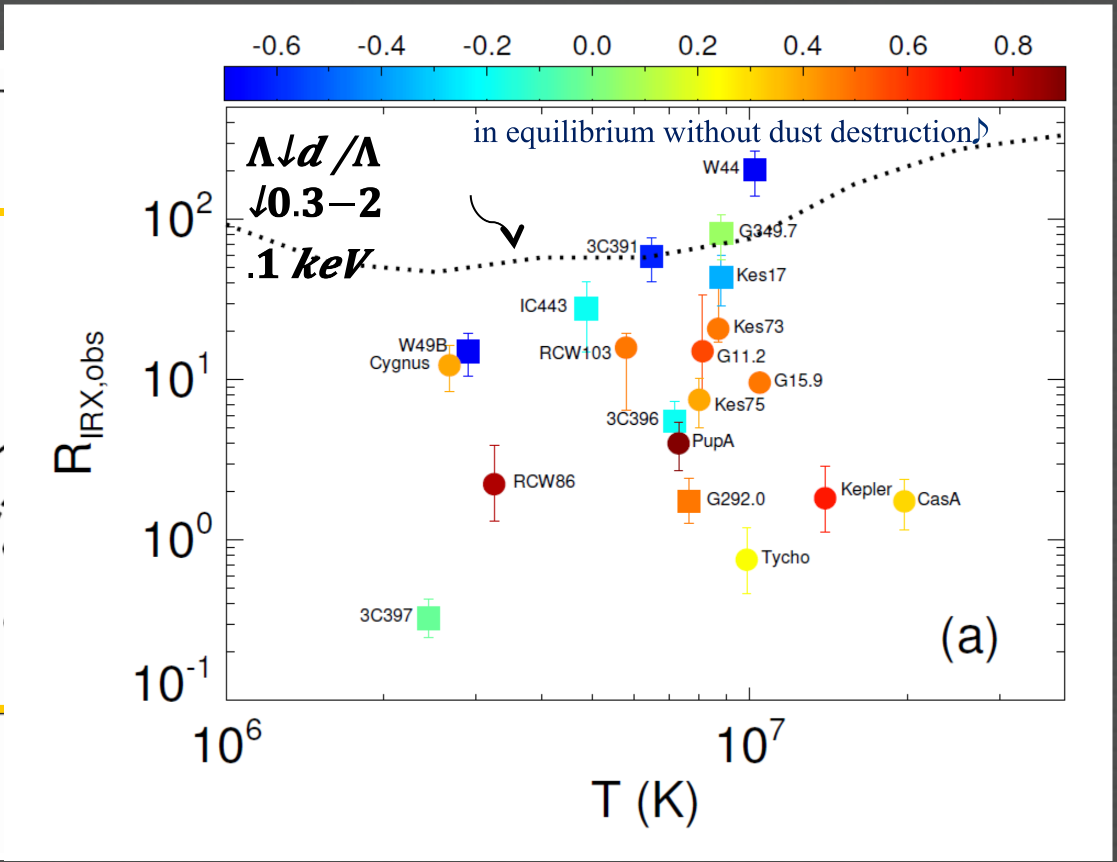
- **X-ray: F_X, T_e, *τ↓ion***
  - Chandra 0.3-2.1 keV + others
  - Either all parameters are from previous works or onl y F_X is derived in this work, except 3 SNRs for which we derived improved fit parameters
    - G11.2-0.3, Kes 73, RCW 103

IRX Diagram

- **IRX flux ratio** $R_{IRX} = F_{IR}/F_X$ (=0.32-204)
  - SNRs with R_{IRX}>30 are the ones with large negative r_{50}

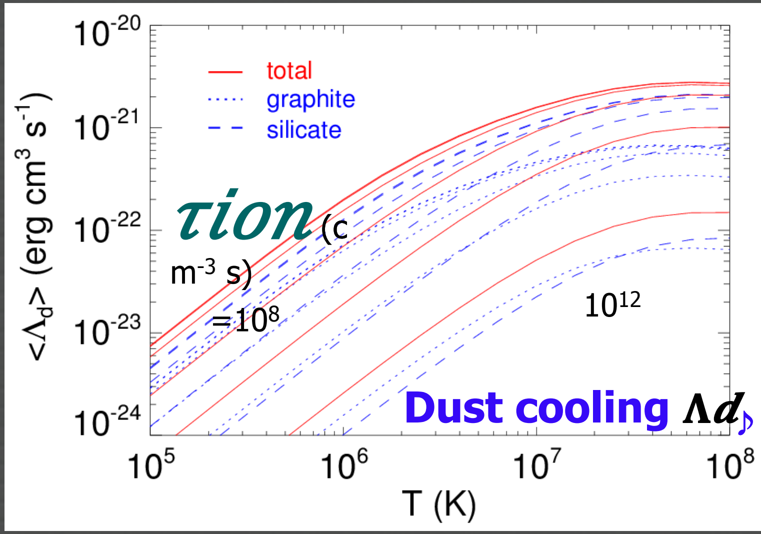


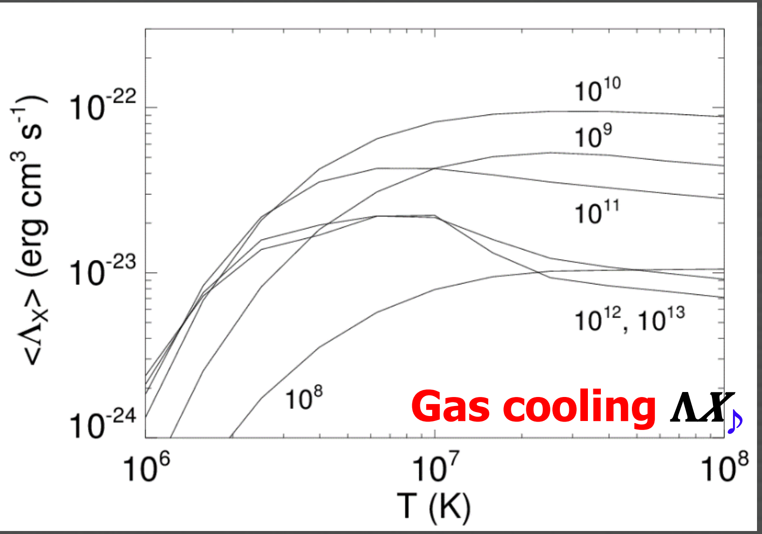
Dwek+ 1987



Time-dependent Collisional Heating♪

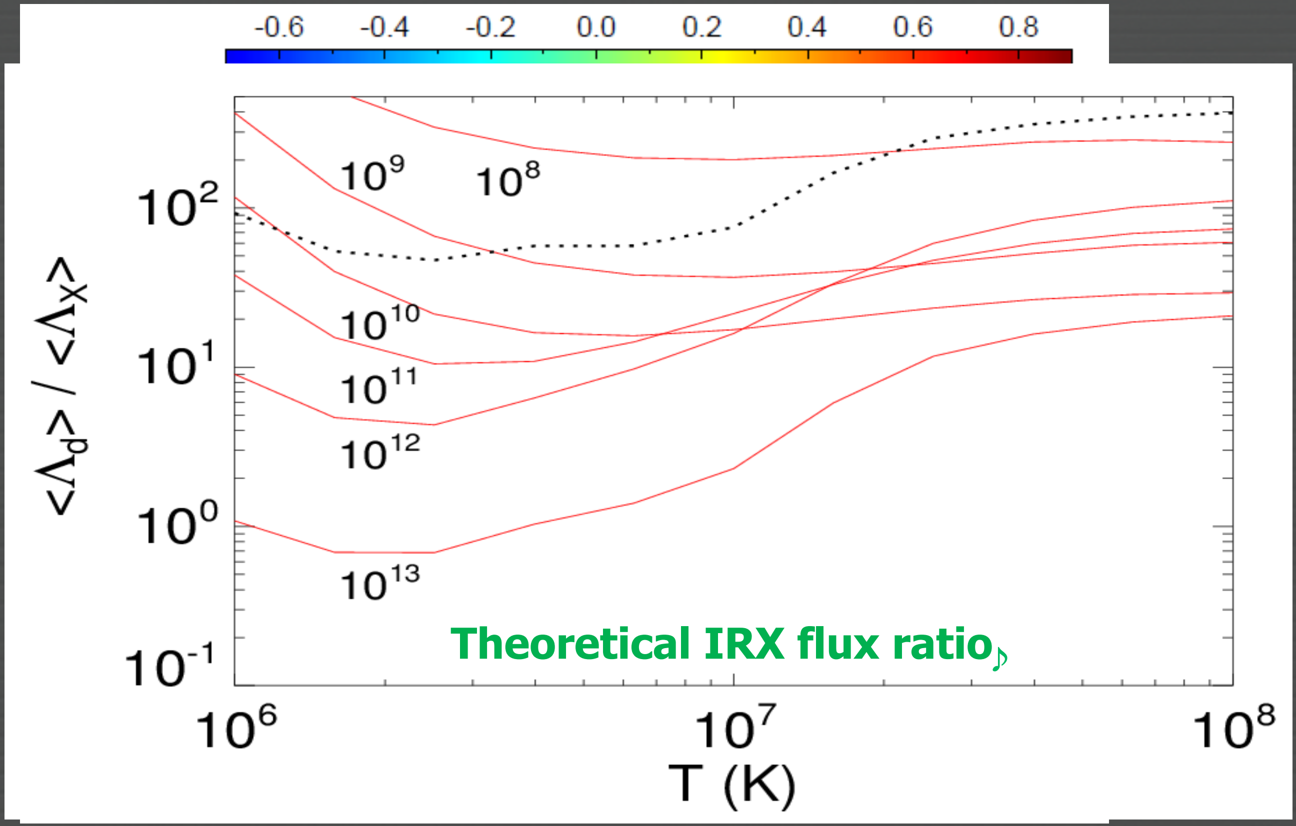
- **Plane shock model**
  - **Dust cooling**
    - Dust destruction by sputtering
    - ISM dust model (Weingartner & Draine 2001)
    - MRN size distribution (Mathis et al. 1977)
  - **NEI X-ray cooling** with abundance variation



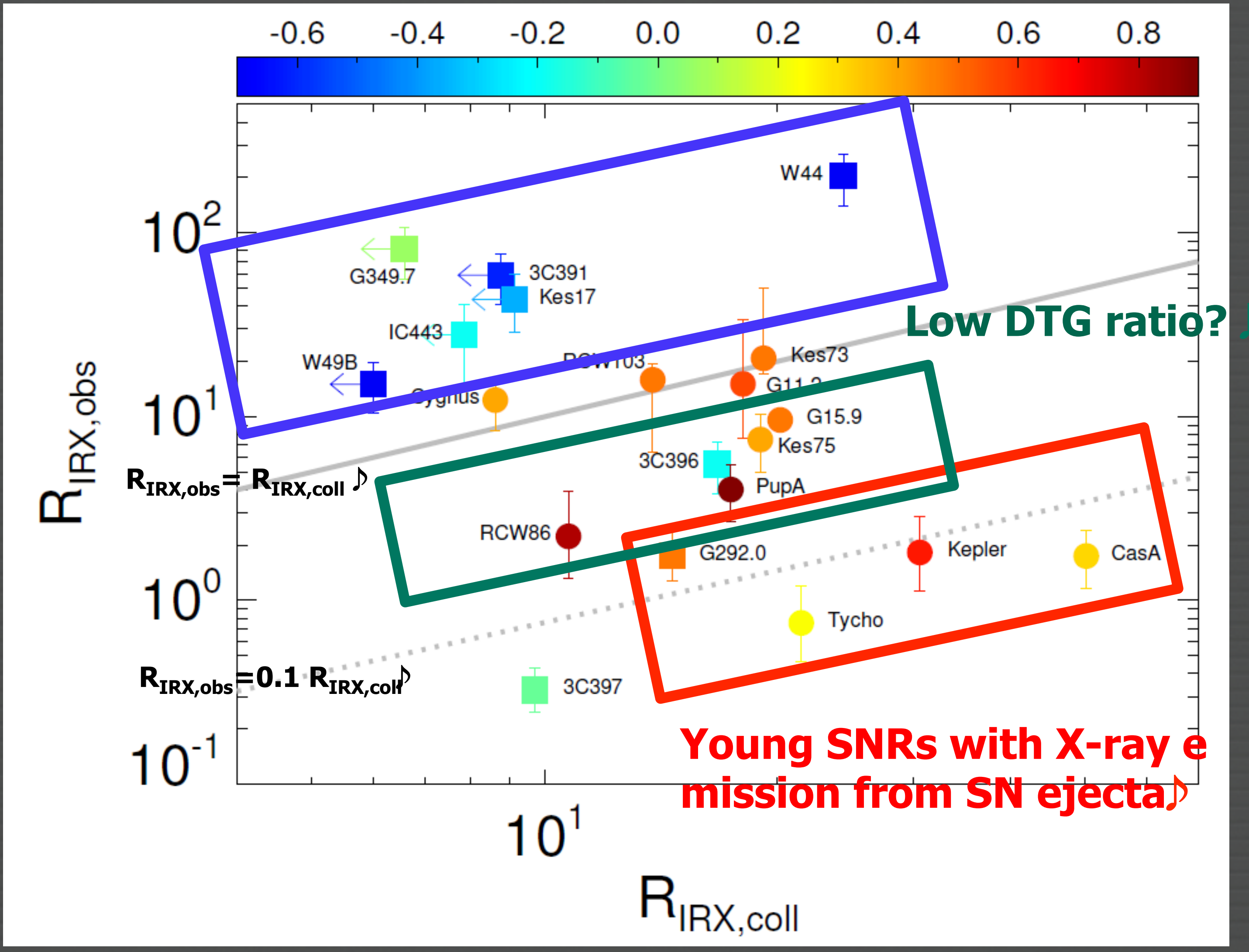


IRX flux ratio due to collisional cooling

- **Even if we consider the dust destruction and NEI cooling, most SNRs are below the theoretical curve.** (τ_{ion} from X-ray~10^{11} cm^{-3} s)

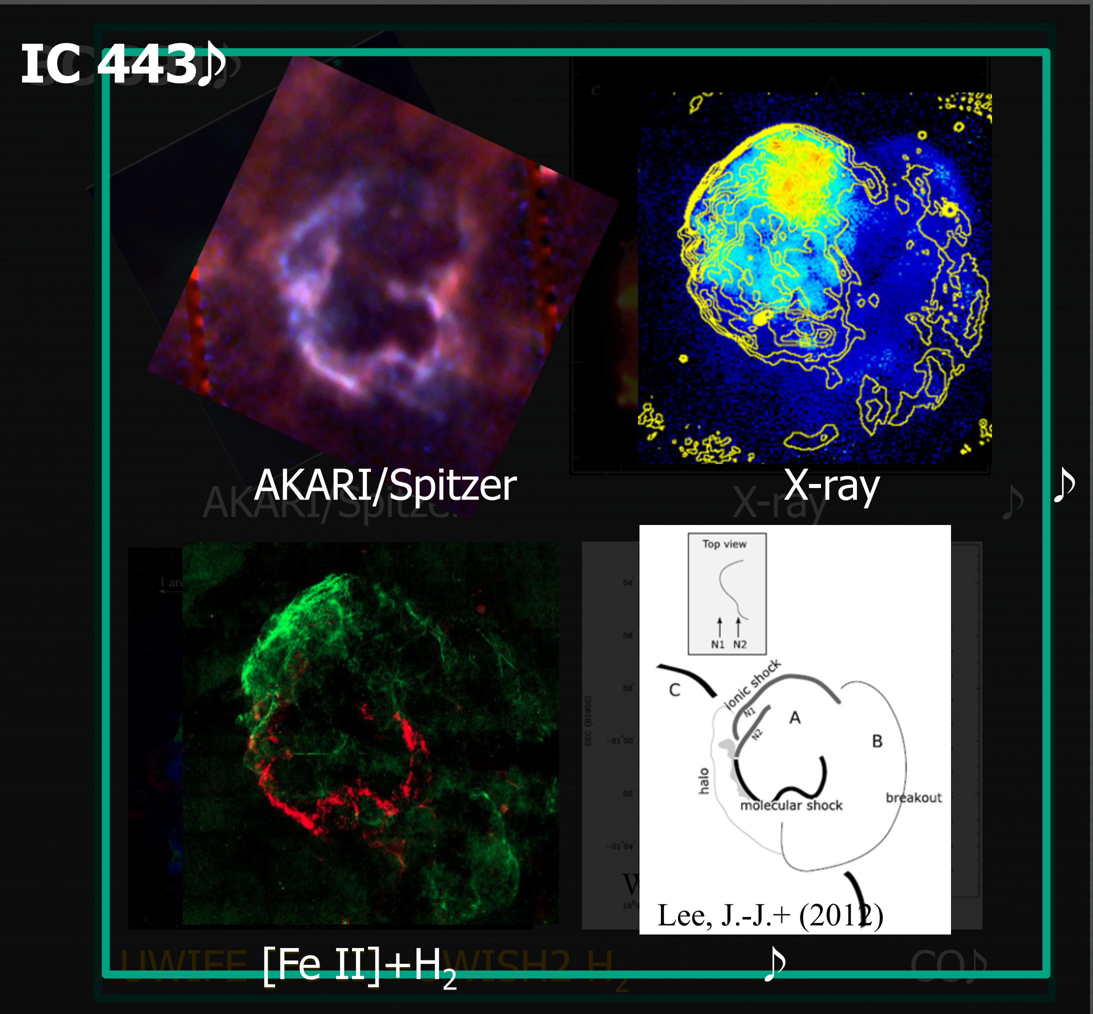


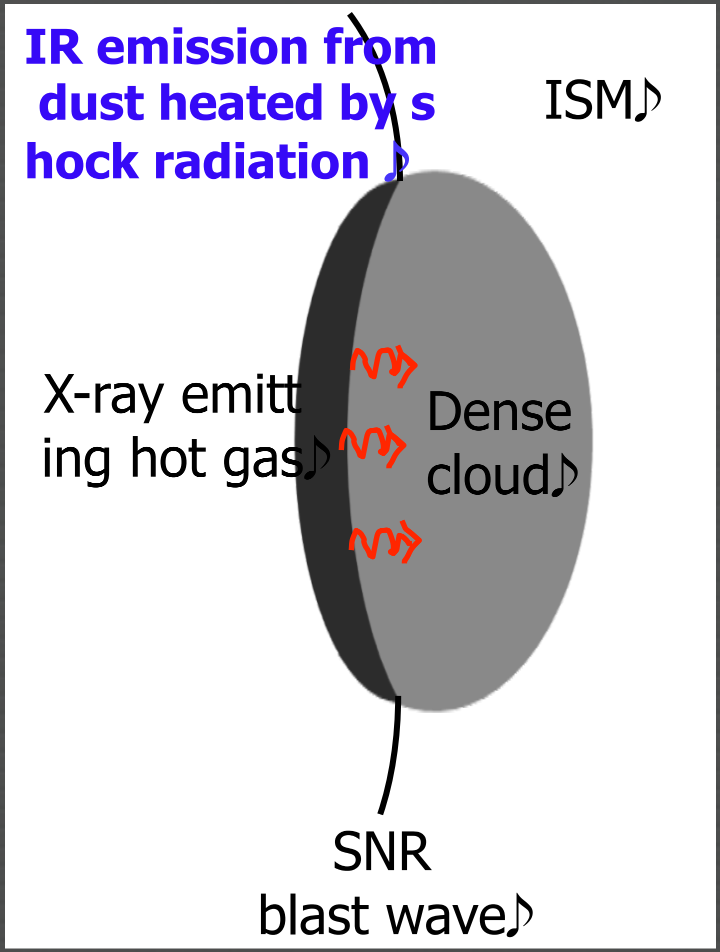
Obs. vs Theoretical IRX Flux Ratios



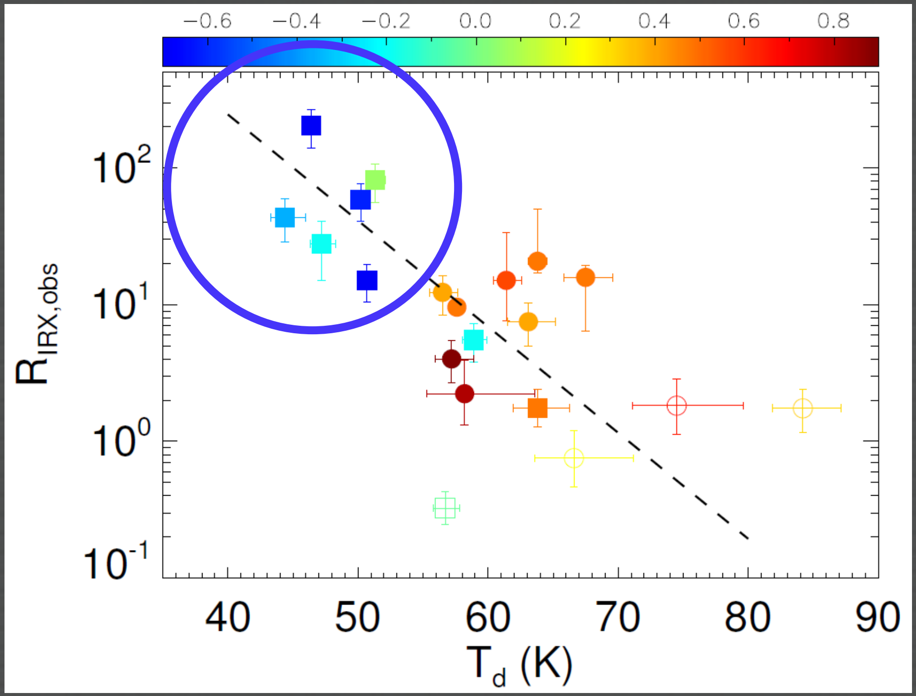
SNRs with High $R_{IRX,obs}/R_{IRX,coll}$♪

- SNRs interacting with dense ambient mediu m & shock is radiative.





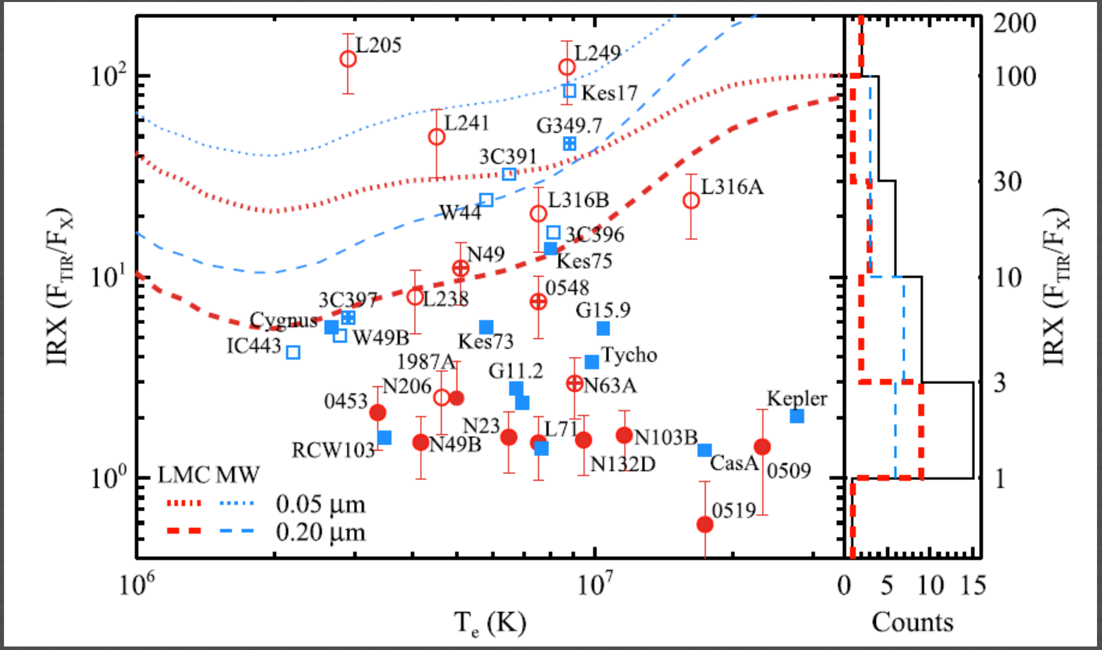
- **SNRs with high $R_{IRX,obs}/R_{IRX,coll}$ have low (40-50 K) dust temperature♪**



→ The SNRs with high IRX flux ratios are the ones interacting with dense environment and their IR emission is probably from radiatively heated dust.

IRX Diagram of LMC SNRs

- **Similar trend in IRX flux ratios**
- **IRX ratios of LMC SNRs are systematically lower than those of the Galactic SNRs**
  - DTG ratio of LMC = 0.0017 (cf) Milky Way = 0.0062



definite

partial

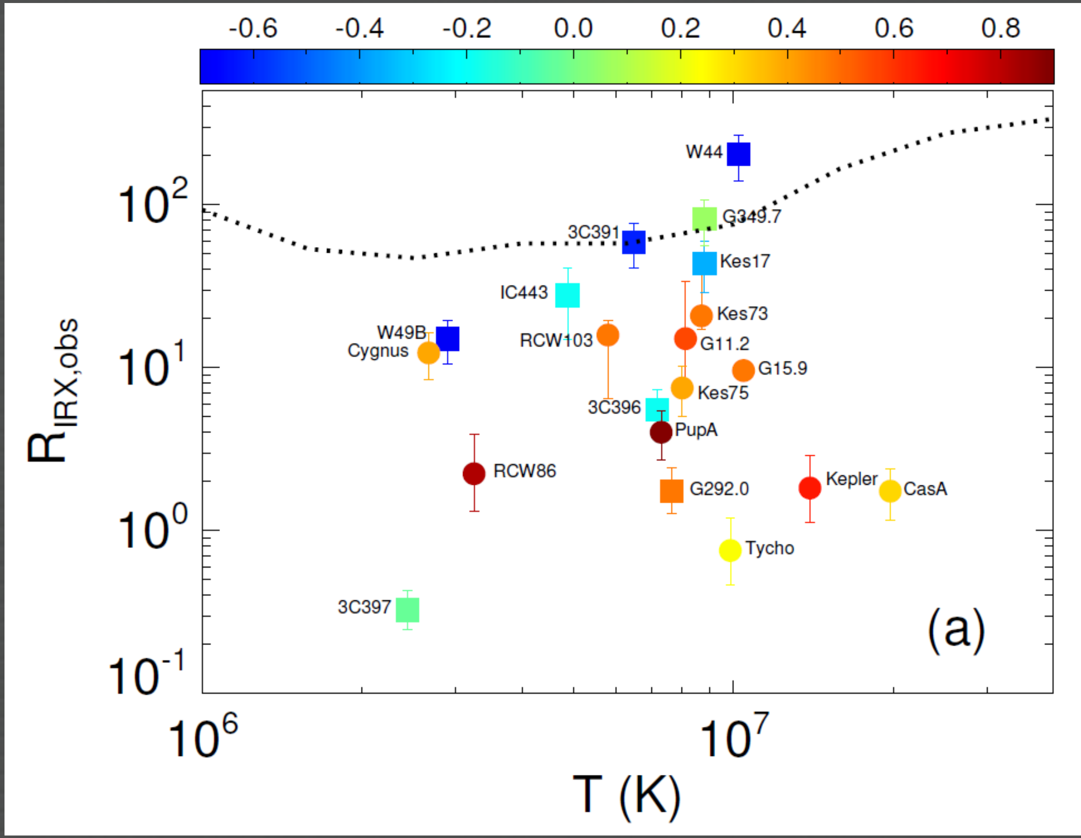
lack of

resemblance between IR and X-ray morphologies

Seok+ 2015

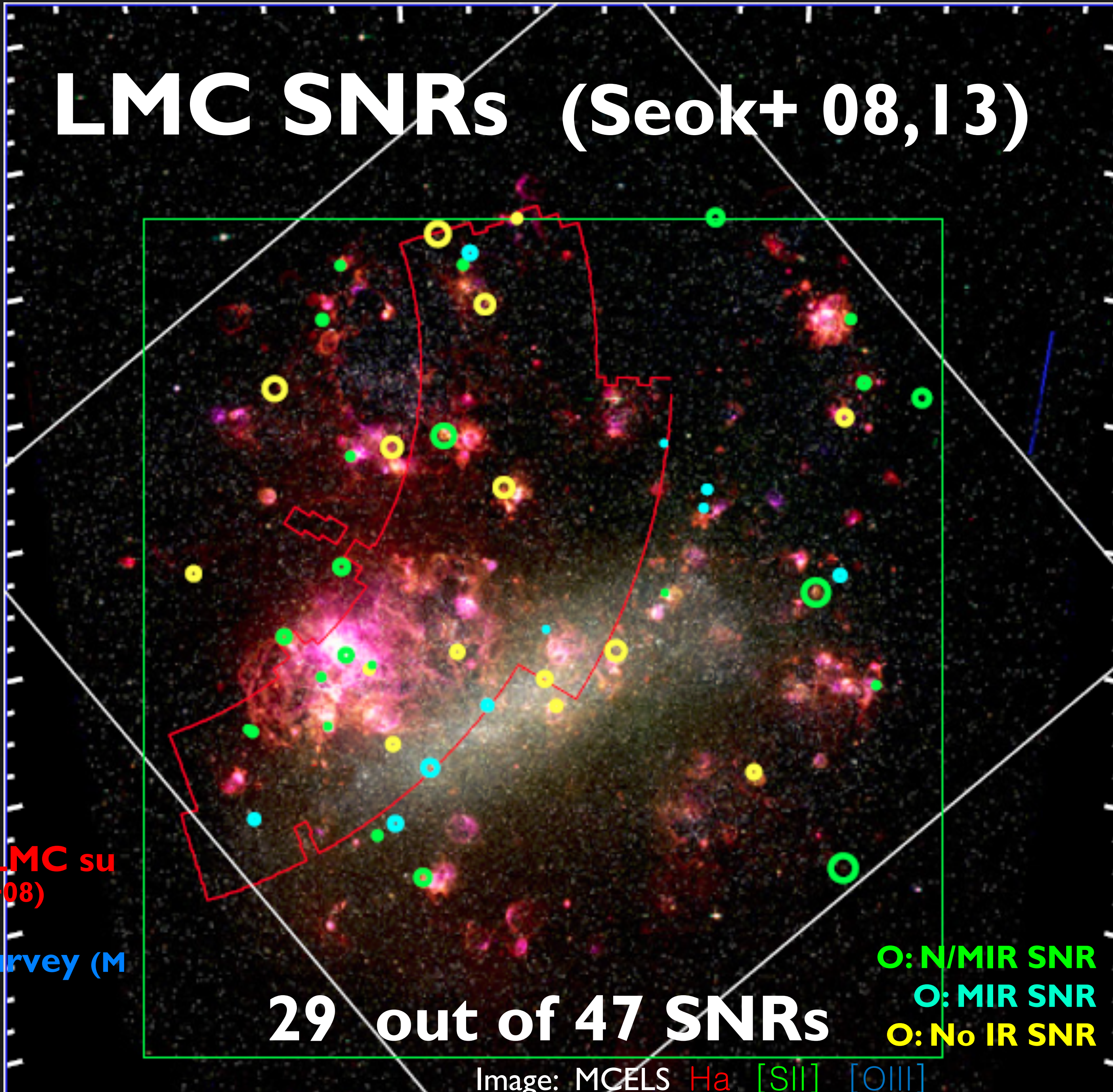
Summary♪

- **IRX diagram can be helpful in understanding the natural and/or environmental properties of SNRs.**



Koo et al. 2016 ♪

LMC SNRs (Seok+ 08,13)



AKARI LMC survey (Ita+08)

SAGE survey (Meixner+06)