External Galaxies and the Galactic Center

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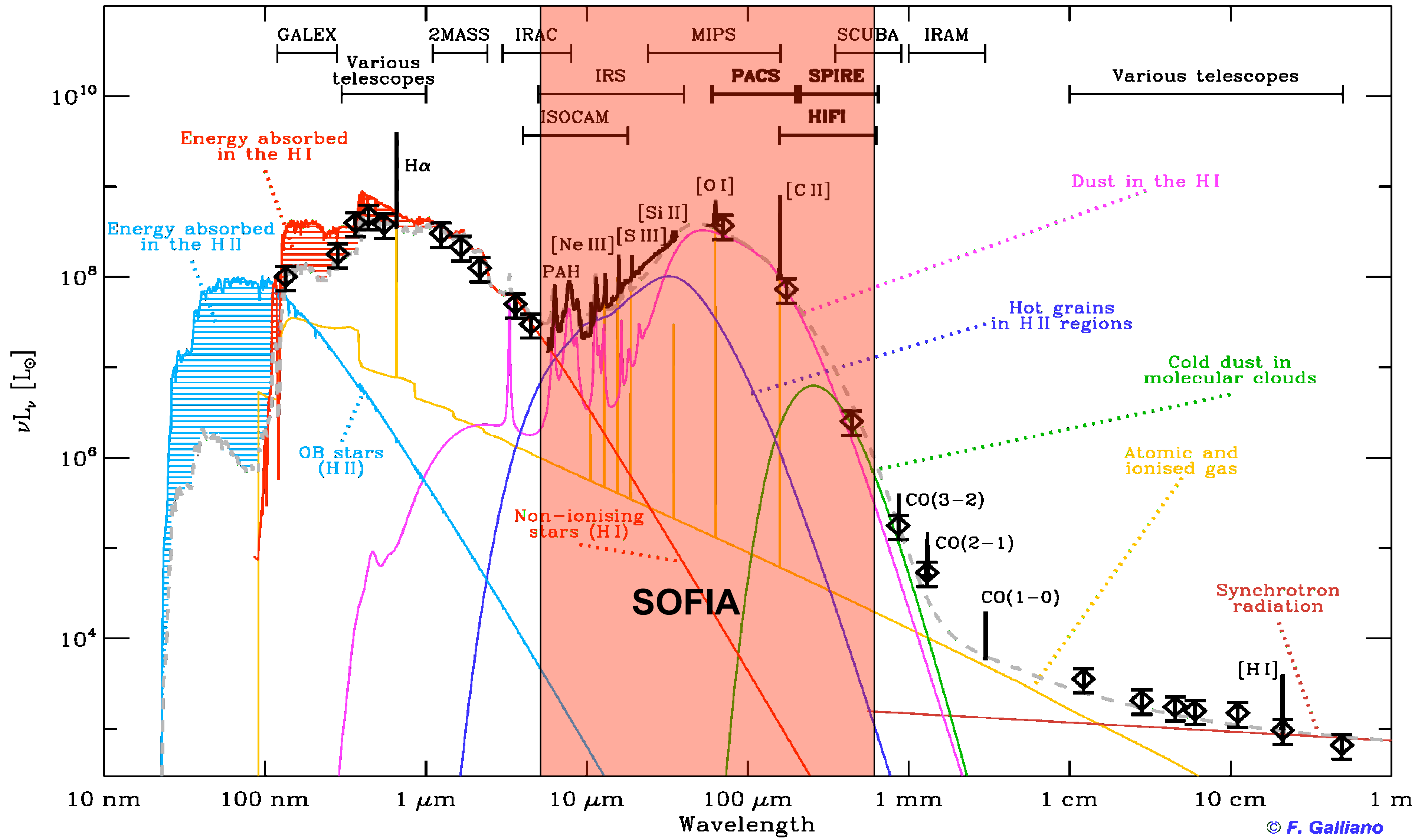
Galaxy Spectral Energy Distribution (SED)



Science Topics within Extragalactic and Galactic Center Theme

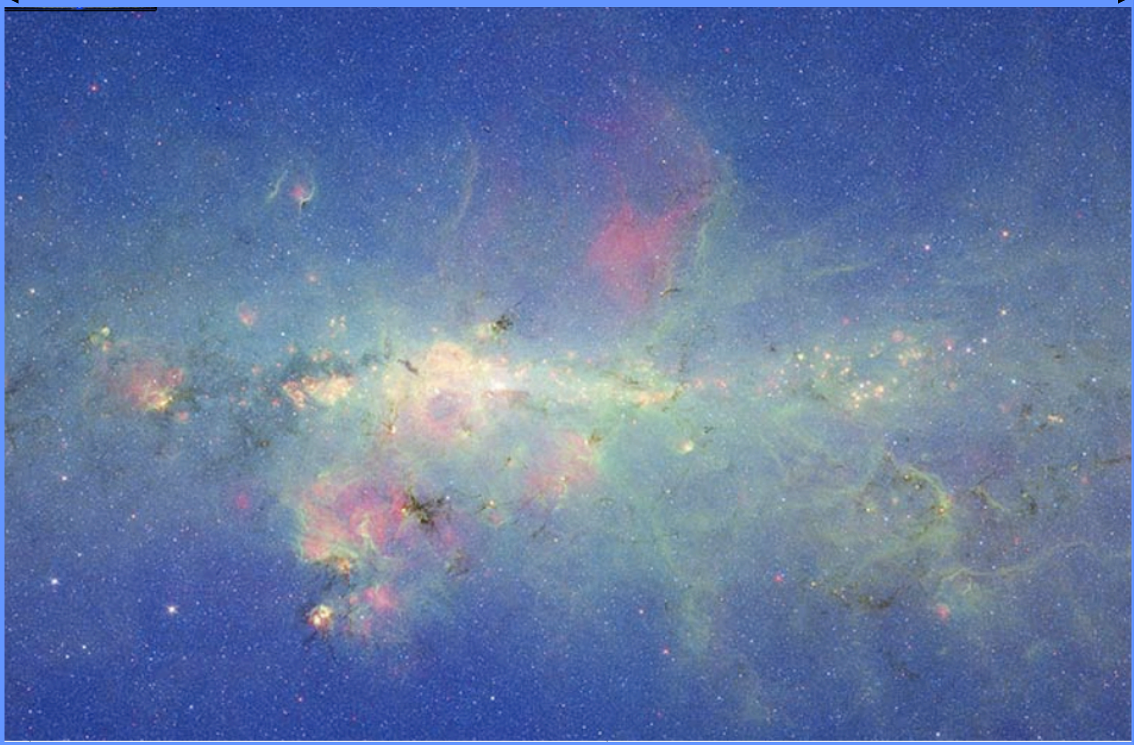
- The Galactic Center: Warm Clouds and Strong Magnetic Fields
  - The GC as a local template for AGN
  - The heating of the CMZ, influence of magnetic fields
- ‘Buried’ Stellar Clusters
  - Study the earliest phases (‘hidden’) of star formation in Nearby Galaxies
- Active Galactic Nuclei
  - Determine the parameters of the “confining torus”
- Evolution of Galaxies: Redshifted Fine-Structure Lines
  - Trace the ‘extinction-free’ history of star formation from the local Universe (z ~ 0) to z ~ 1.25 (‘Low Redshift Cosmology’)

- Will not discuss ISM in external galaxies (ISM theme)
  - Large scale mapping much faster with SOFIA than Herschel

The Galactic Center: Warm Clouds and Strong Magnetic Fields

- **Local Template:** Study distant AGN phenomena at hundreds of times better spatial resolution
- **Unique Phenomena:**
  - Super massive BH and accretion
  - Massive stars in deep potential well
  - High stellar densities ⇔ SN rates/volume
  - Massive, warm molecular clouds
  - Strong B fields
  - Intense X-ray background

500 pc ⇔ 3.3º



Spitzer Legacy Program (3.6/8.0 μm IRAC + 24 μm MIPS)

Because the GC is totally obscured in the optical, it is best studied with observations at the longer wavelengths available with SOFIA instrumentation

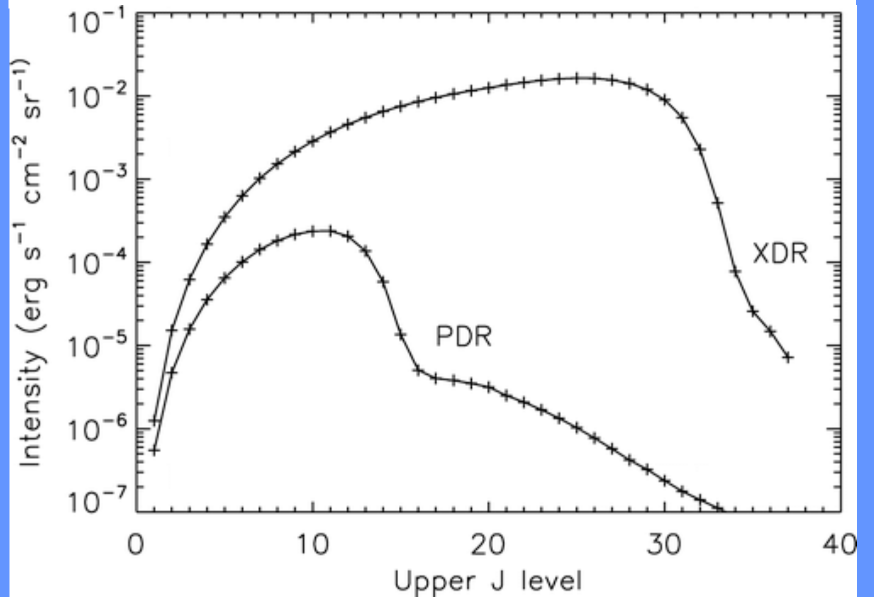
What heats the CMZ Clouds? Stars, Shocks, or X-rays?

- **Central molecular zone (CMZ) is a morphologically distinct region in the inner Galaxy (r < 150 pc) containing 4×10^{7} $M_{\odot}$ of warm (~200 K), dense molecular gas**

  What heats the CMZ gas?

  - **Diagnostics for stars vs X-rays:**
    - **High J CO lines**
    - **[SiII] 35 μm/[CII] 158 μm**
    - **[FeII] 26 μm/[CII] 158 μm**
  - **Diagnostics for shocks vs stars:**
    - **[OI] 63 μm/ [CII] 158 μm**
    - **[OI] 146 μm/[CII] 158 μm**
- **High Res and Large λ coverage essential for these studies**

CO line intensities (n = 10^{5} cm^{-3})

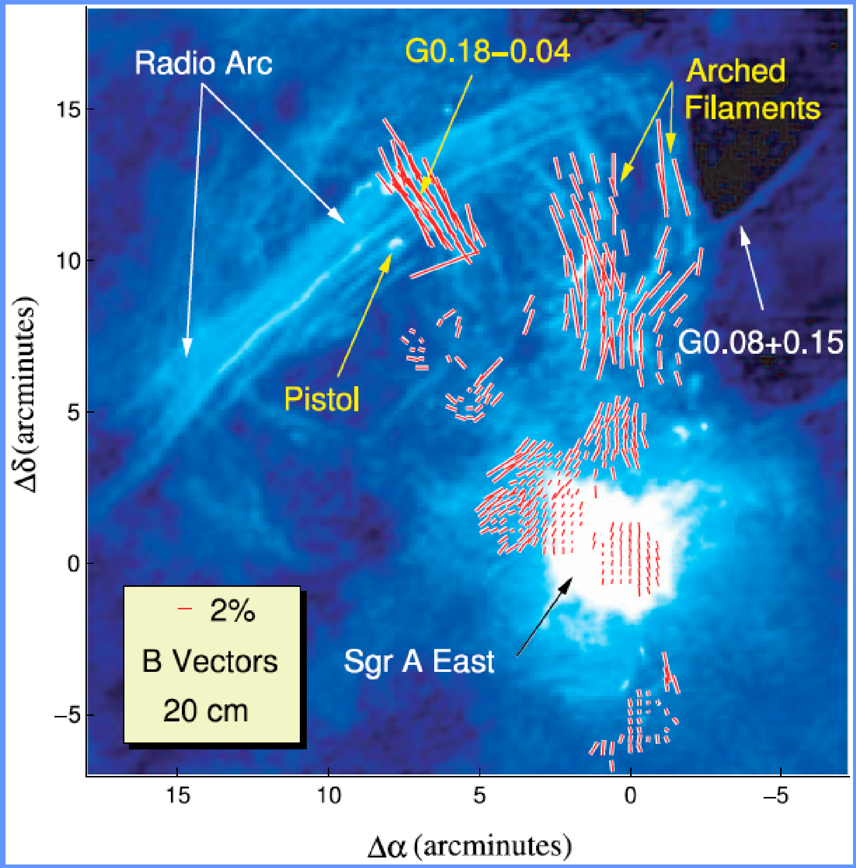


(Spaans & Meijerink 2008)

- **GREAT and CASIMIR will resolve multiple velocity components and identify individual clouds**
- **EXES, FORCAST, FIFI-LS provide unique information on shocks**
- **Sensitivity not a problem**
- **Large scale mapping possible**

What are dynamical and energetic consequences of strong B field in CMZ?

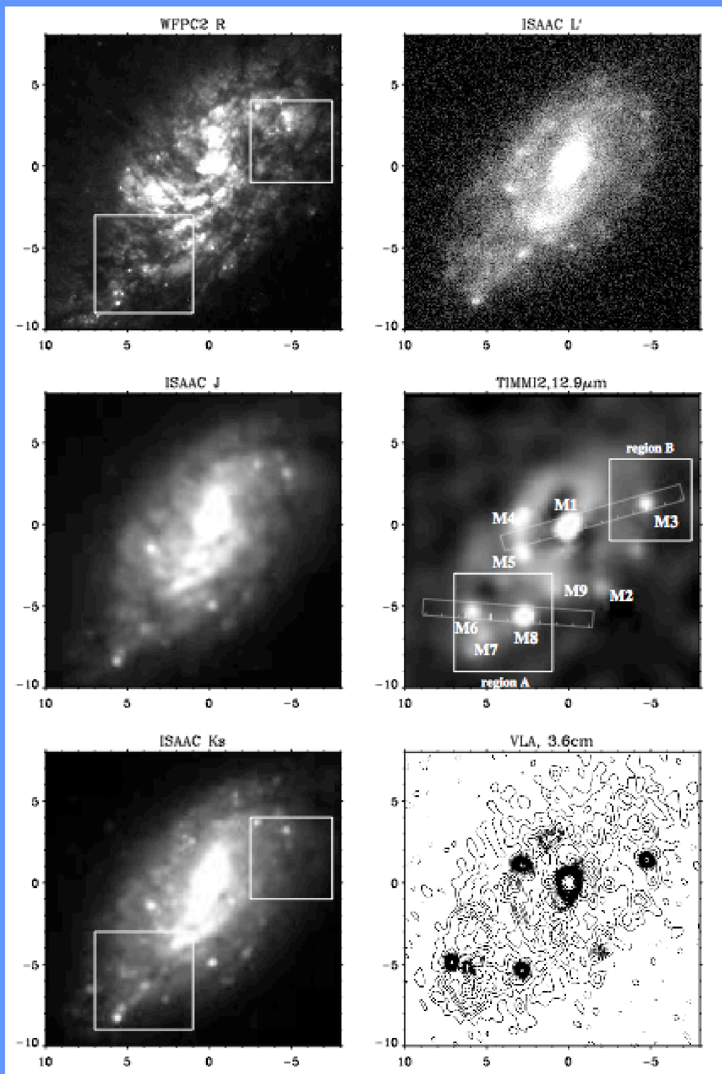
- **Measuring B field strength is critical to understanding cloud dynamics and heating, star formation in CMZ, dynamical evolution of circumnuclear disk, and accretion from disk onto BH**
- **KAO studies showed far-IR polarization determined by B-field geometry**
  - **Surprisingly, the field is largely parallel to Galactic plane due to shear of the CMZ molecular clouds dragging the field**
- **B-field strength inferred from fluctuations in polarization (Chandrasekhar-Fermi method)**



(Chuss et al. 2003)

HAWC + polarimeter (at 55 μm) could measure B field geometry, strength (via spatial fluctuations) in CMZ with 5x better spatial resolution than before

‘Buried’ Stellar Clusters in Nearby Galaxies

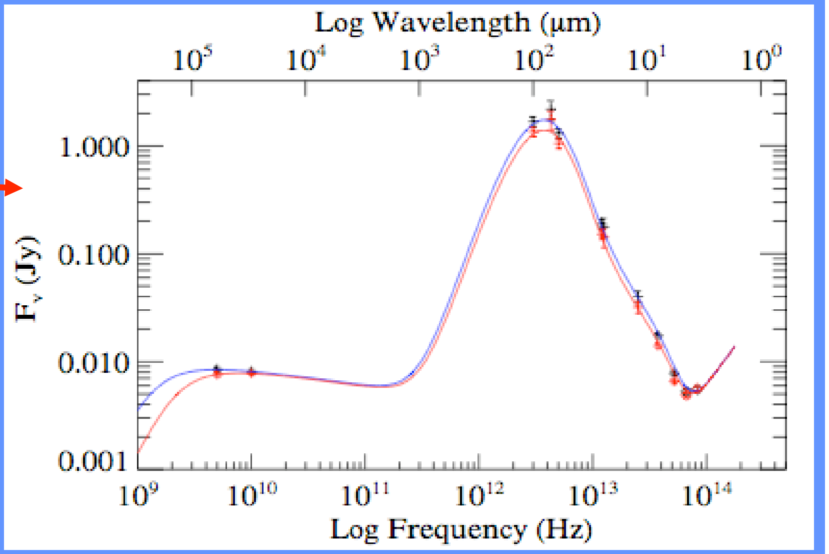


NGC 1808 (Galliano & Alloin 2008)

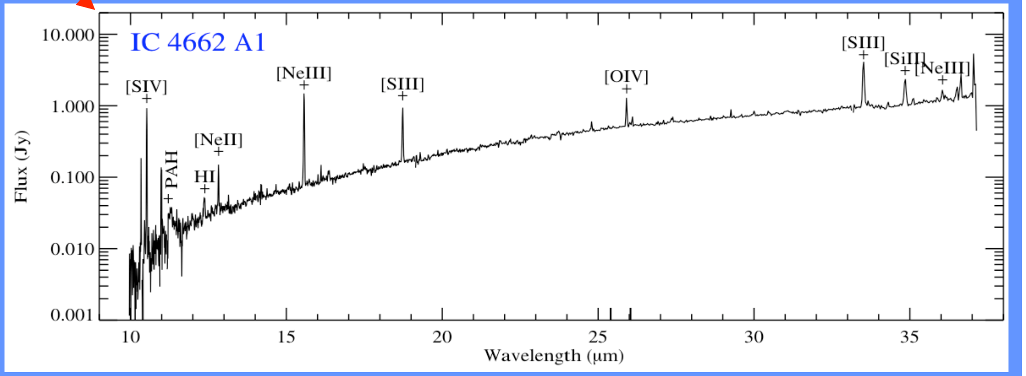
- How do Stars and Stellar Clusters form in Starburst Galaxies?
  - The formation of ‘Super Star Clusters’ (SSCs) is major mode of Star Formation in starburst galaxies
  - Large fraction of stars in a galaxy may form in SSCs
  - ‘Buried’ SSCs are young massive clusters still enshrouded in natal material, invisible in optical/NIR
  - ‘Buried’ SSCs responsible for large fraction of total galaxy IR luminosity
- SOFIA provides best (only) means of studying buried SSCs until JWST
  - SOFIA provides 3x better spatial resolution than *Spitzer* at same λ
  - *Spitzer*/IRAC resolution at 8 μm ≈ SOFIA/ FORCAST at 24 μm

Properties of 'Buried' Stellar Clusters in Nearby Galaxies

- Dust SEDS (FORCAST, HAWC):
  - Cluster luminosity, dust mass and properties
- Emission lines (FORCAST, FIFI-LS):
  - H, [S IV], [Ne II], [Ne III], [S III], [O IV], [Si II], [O III], [N III]
  - T_e, N_e, A_V, Nebular abundances
  - Radiation fields -- stellar pops/IMF, ages, masses
- Resolved lines (EXES):
  - High velocity cluster winds feedback, may trigger or suppress star formation
- Sensitivity not an issue for nearby (~ 10-20 Mpc) galaxies

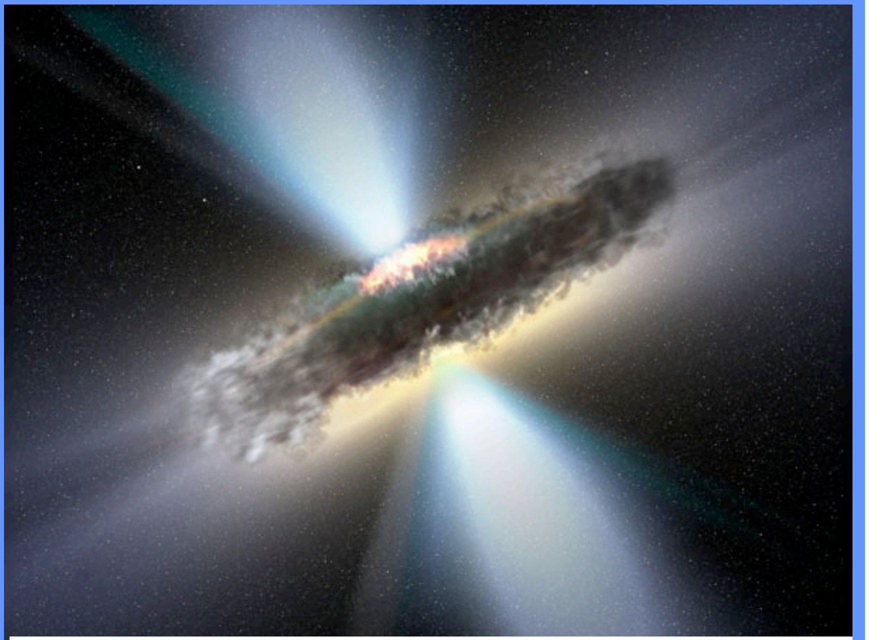


IC 4662 (*Spitzer*; Gilbert & Vacca 2008)



Active Galactic Nuclei

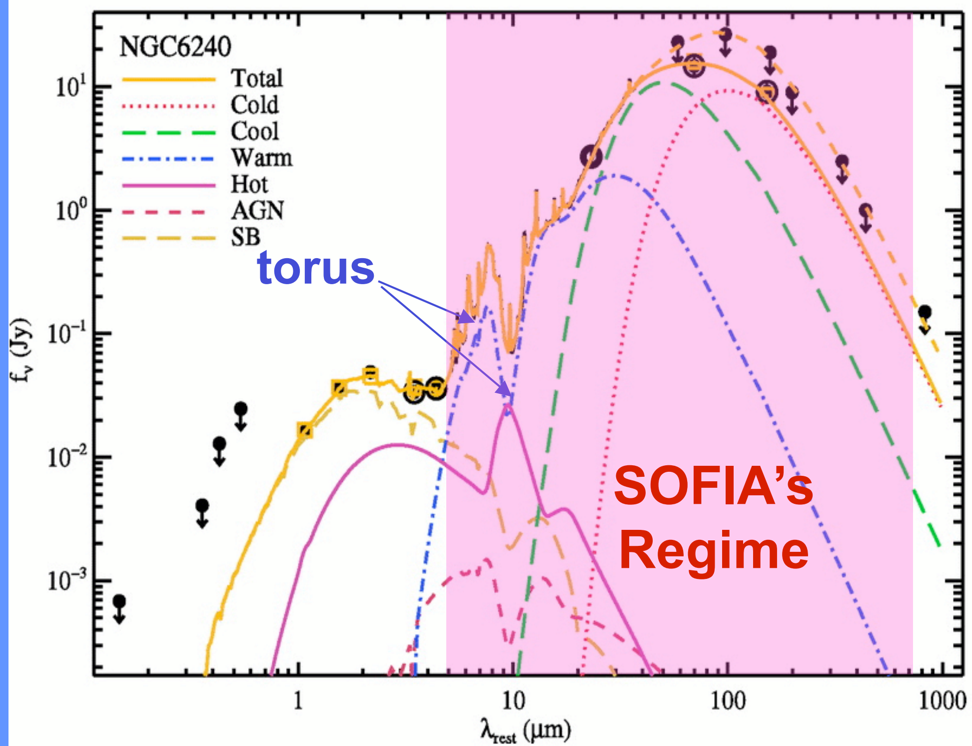
- Unified Theory of AGN posits a thick dust torus around a SMBH
  - Parsec scale torus, heated by strong X-rays from AGN, expected to be warm (1000 K) and dense (~ 10^7 cm^{-3})
  - Emits strongly in dust continuum and spectral lines
  - Covering factor for the torus is central feature but torus is very difficult to image in optical/IR so essential features remain unknown
- SOFIA will probe the torus through spectral line and continuum observations, allowing measurements of size, density, temperature, and the filling factor of clumps



Artist's conception of a confining torus (ESA / V. Beckmann (NASA-GSFC))

Characterizing the Torus: Decomposing the Continuum Emission

- Galaxy SED can be modeled with multiple components:
  - Host galaxy disk (cold/cool dust heated by ISRF and evolved stars)
  - Starburst (warm dust surrounding hot/young stars)
  - AGN/accretion disk
  - Torus (hot and warm dust)
- Shape of the torus SED and 9.7 μm silicate feature (emission or absorption) reveal the torus geometry
- Torus emission peaks in FORCAST range (30-40 μm)



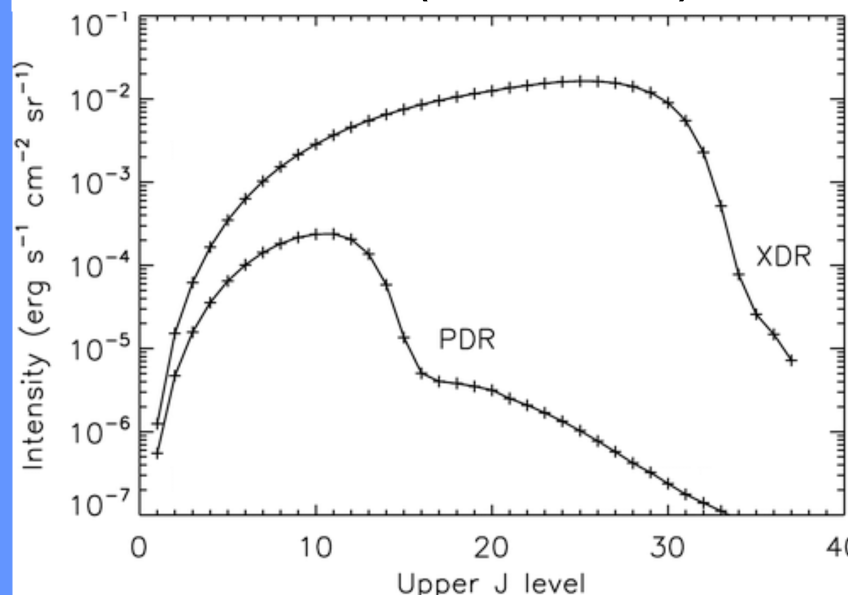
NGC 6240 (Marshall et al. 2007)

- SOFIA provides wide λ coverage required to disentangle components
- SOFIA's spatial resolution helps to isolate torus emission from other components

Characterizing the Torus: Spectral Lines

- **Warm, dense, X-ray heated torus should emit strongly in lines:**
  - **strong CO, [OI], H_2O emission**
- **CO SED is crucial**
  - **primary coolants of torus – *very sensitive* to the physical conditions (n, T, porosity)**
  - **Clear signature of torus as XDR (torus) emission will peak at higher J than PDR**
  - **Turn-over J is vital to constraining physical conditions and origins**
- **Typical sources easily detectable with FIFI-LS out to 100 Mpc**
  - **J~13 (200 μm) to J~58 (46 μm)**

CO line intensities (n = 10^5 cm^{-3})

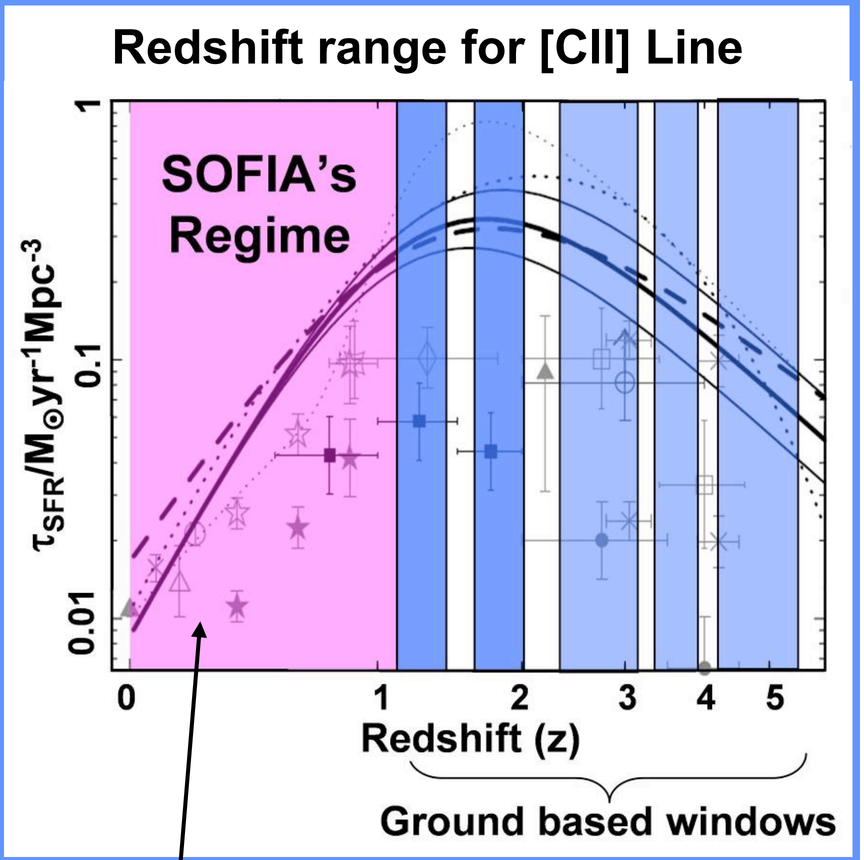


(Spaans & Meijerink 2008)

- **SOFIA will observe CO SED from J ~ 7-6 to J > 58 (46 μm)**
- **The highest J lines are observable *only* with SOFIA**

Evolution of Galaxies: Redshifted FIR Fine Structure Lines at 0 < z < 1

- SOFIA can observe redshifted FIR F-S lines to study SF history, from the peak (z~1) to today (z~0)
  - [NIII] 57μm, [OI] 63 μm, [OIII] 88 μm, [NII] 122, 205 μm, [CII] 158 μm
- F-S Lines are major gas coolants and *extinction free* probes of physical conditions in PDRs and HII regions:
  - Gas: T_e, n_e, mass
  - UV fields: hardness, intensity
    - LyC, G_0, IMF, presence of AGN
    - Age, size, strength of starburst
- SOFIA/SAFIRE quite competitive with, complementary to Herschel
  - SOFIA has better sensitivity between 210-330 μm (z ~0.3-1.1 for [CII] 158 μm)

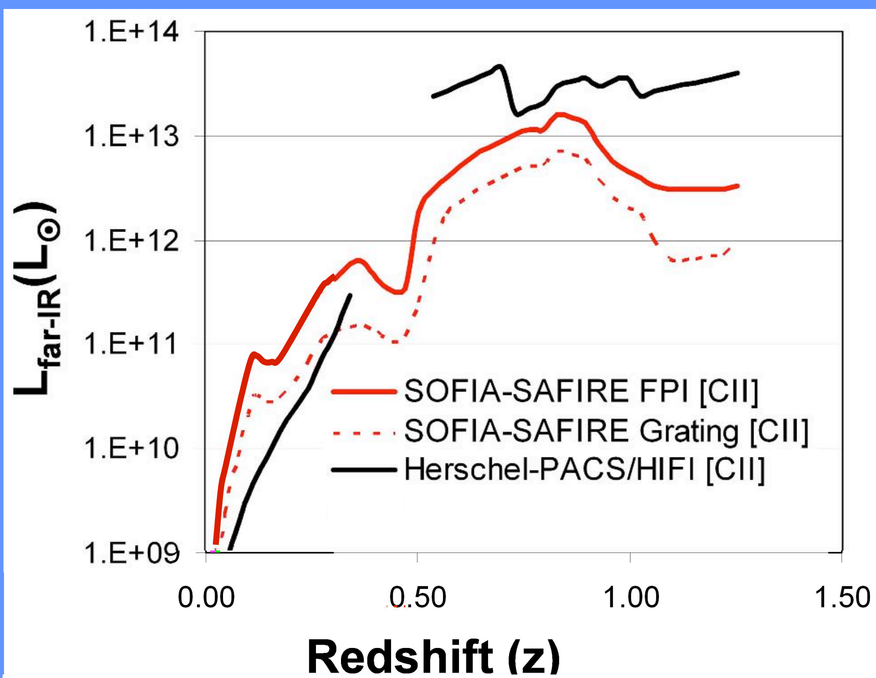


(Blain et al. 2002)

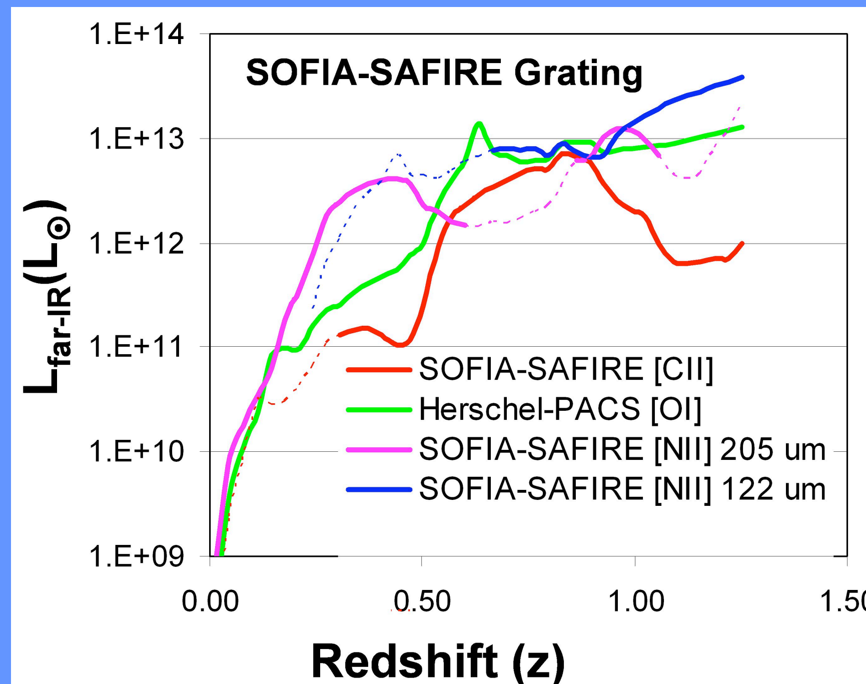
'Extinction-corrected' estimates of SFR/vol. from UV/optical/NIR

FIR F-S Lines with SAFIRE

- **Relatively common galaxies detectable in [CII] with SOFIA**
  - **< 5 × MW up to z ~ 0.5**
  - **(Dusty!) ULIRGs and HLIRGs between 0.5 < z < 1.25**
- **For 0.5 < z < 1, [NII] 122/205 μm, [CII], [OI] (Herschel) equally detectable**
  - **Any galaxy seen in [O I] with Herschel/PACS easily detectable in [CII] with SOFIA/SAFIRE to z > 1**



[CII] detectability: S/N = 5 in 2 hours



Far-IR Lines: S/N = 5 in 1 hour

Many Sources for SOFIA/SAFIRE

- **NED: > 50 sources with suitable redshifts and far-IR luminosities**
- **Spitzer/SWIRE (33° catalogue):**
  - **~ 40 HLIRGs**
  - **> 150 with $L_{far\text{-}IR} > 3\times10^{12}\ L_\odot$**
  - **many 100's ULIRGs.**
  - ***⇒ 50,000 on sky! Nearly all of these are within the SOFIA [CII] redshift niche.***
- **BLAST (19º) survey >1000 galaxies**
- **~ 10% of CCAT galaxies will have z ~ 0 to 1 ⇒ > 10,000 sources**
- **2/3 of CIB at 150 μm arises from LIRGs at z~0.7 (1/6 from L> $2\times10^{12}L_\odot$)**

SOFIA is critical for exploring the star formation history of the Universe, during the epoch when most of the CIB was formed

Summary

- SOFIA's unique wavelength coverage, spectral and spatial resolution and (potential) polarization capabilities enable many fascinating studies of the Galactic Center and external Galaxies. SOFIA will:
  - Explore the Galactic Center. What heats the warm CMZ clouds and what are the effects of the strong B fields that thread the region?
  - Characterize optically obscured super star clusters: stellar populations and their influence on the natal ISM, constraining theories of formation and feedback
  - Reveal and characterize the confining torus in AGN using dust SEDs and high-J CO rotational lines.
  - Explore the star formation history of the Universe from its peak at z > 1 to the current day using redshifted far-IR fine structure lines.