Observing and modeling the extragalactic ISM

Vianney Lebouteiller (CNRS/AIM, CEA Saclay)

Outline

- **External galaxies**
  - Parameter space
  - The ISM within the galaxy evolution and star formation contexts
- **Some highlights**
- **Modeling strategies**
  - Accounting for the ISM complexity & structure

(Wide topic, focus on spectroscopy and gas tracers)

Physical scales & components

Physical processes generally act on / originate from a wide range of spatial scales (e.g., SF)

Fig.: HI-H2 conversion and SF process as a function of spatial scales (Saintonge+ 2022).

Main challenges for extragalactic observations

- Reach small enough scales to disentangle ISM components or recover them through indirect, integrated, signatures
- Understand/generalize physical mechanisms in conditions $\neq$ from MW

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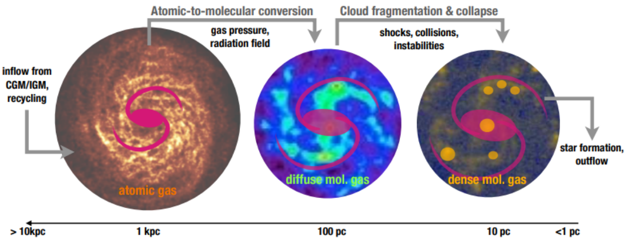

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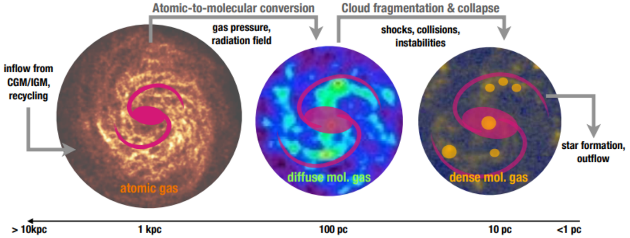

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Physical scales & components

Digest & process wealth of spatial information

Combine detailed ISM models with state-of-the-art radiative transfer and chemistry + complex enough geometries

Fig.: *NGC 4254, MUSE (blue/yellow) + ALMA (orange), PHANGS*

Fig.: *NGC 7496, HST+JWST, PHANGS*

Expanding the parameter space and generalizing mechanisms

Detailed studies of nearby galaxies...

- $\neq$ environments at large
  - Z & ISM phases, young stellar clusters, X-ray binaries, AGNs, interactions...
- $\neq$ predominance of physical processes
  - Photoelectric effect, X-ray photoionization, CR ionization, shocks...
- Main obstacles
  - Knowledge of dust & energetic sources
- Mixing biases when dealing with poor/no spatial/spectral resolution

... to be adapted to the Early Universe

- Multiphase ISM also revealed at very high-z (e.g., (CII) 158 μm, (OIII) 88 μm *(e.g., Harikane+ 2020)*
- Spatial information increasingly available *(e.g., Wong+ 2022, Dye+ 2022)*

Fig.: CO(7-6), H_2, and (CI) lines in a $z = 4.24$ lensed galaxy with ALMA (Dye+ 2022)

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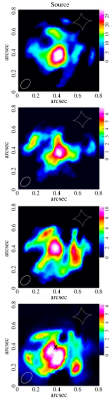

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Cosmic noon zoom

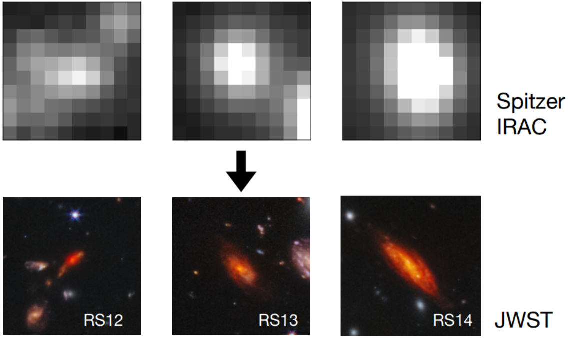

***Fig.**: IRAC1 blobs in SMACS0723 field are likely z=1-3 red spiral galaxies (NIRcam; Fudamoto+ 2022)*

... but spectra of $z \gtrsim 3$ galaxies will remain spatially-unresolved with JWST for the most part

Exploring the metal-poor ISM

- Mass-metallicity relation (MZR): metal-enriched outflow rate, variable integrated IMF, infall (radial for low M* vs. cosmological for high M*) rate *(e.g., Spitoni+ 2010)*

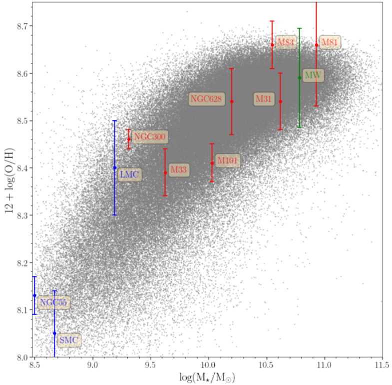

Fig.: *MZR in Local Group dIrr and dSph (Kirby+ 2013)*

Fig.: *MZR vs. z in cosmological simulations (IllustrisTNG; Torrey+ 2019). Absolute calibration somewhat uncertain due to Z calibration with observations.*

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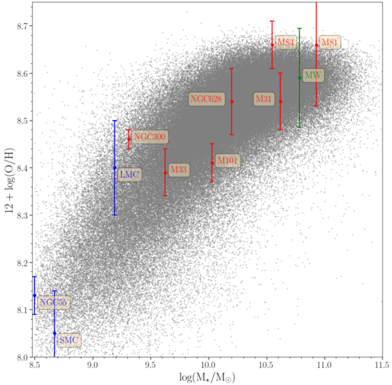

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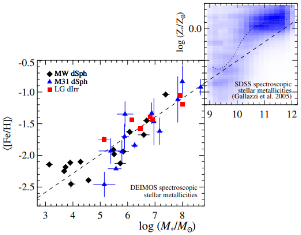

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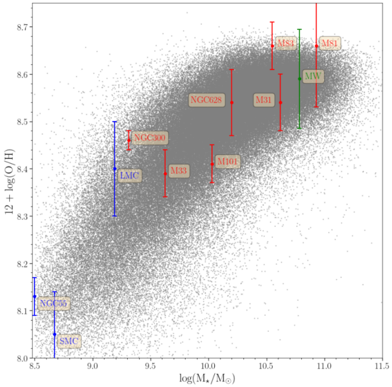

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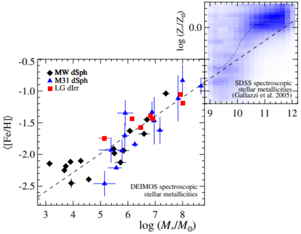

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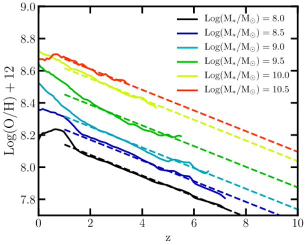

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Observed diversity in the ISM composition/physical conditions

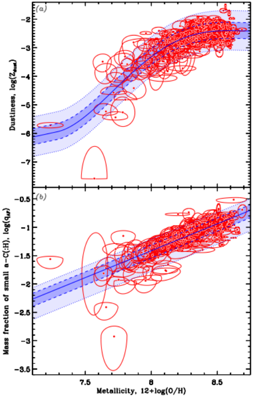

Fig.: D/G and mass fraction of small amorphous carbons (Galliano+ 2021)

Fig.: CO SLED (Cañameras+ 2018)

Fig.: Molecular line ratios in M51 (CLAWS; den Brok+ 2022)

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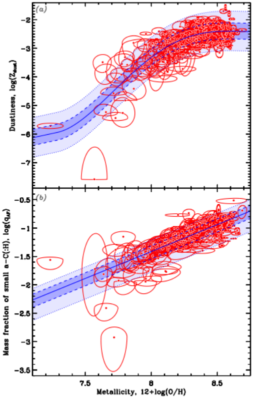

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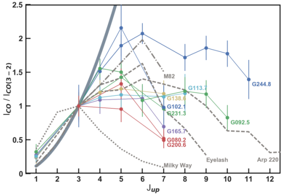

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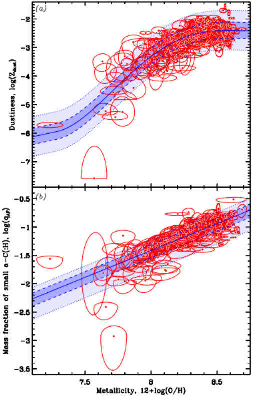

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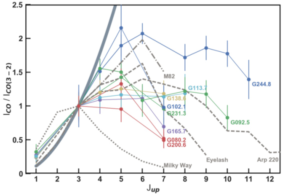

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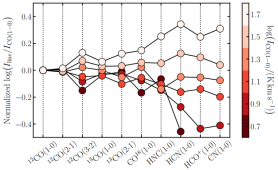

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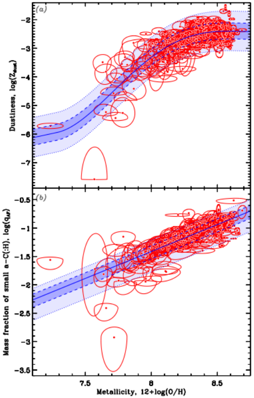

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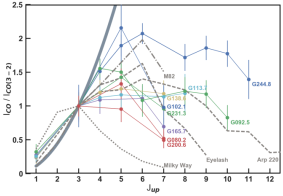

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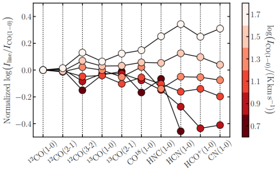

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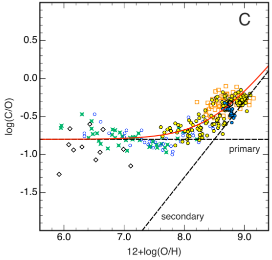

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Observed diversity in the radiation sources

Young massive clusters

- Upper cut-off mass value debated *(Mok+ 2019)* but maximum L & M reach $\gtrsim$ 2 dex above MW *(Portegies Zwart 2010)*

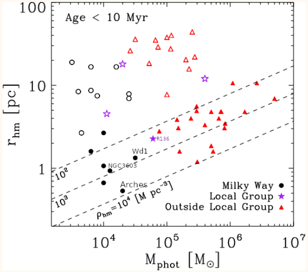

***Fig.**: Mass-size relationship in young star clusters and associations (Portegies Zwart 2010, Santoro+ 2022)*

High-mass X-ray binaries

- Often dominate the high-E output from nearby actively SF galaxies *(e.g. Grimm+ 2003, Mineo+ 2012)*
- Typically provide $\sim 10^{39-41}$ erg/s (i.e., ~1-10% of total L!). Feedback may keep the (dust-poor) ISM warm without removing a significant gas fraction *(Artale+ 2015)*
- Higher abundance & luminosity at low Z / high z *(Gilbertson+ 2022, Lehmer+ 2021)*
- Mass of stellar accreting partner & SFR correlation hints at production site / presence in young massive clusters

***Fig.**: Number of ULXs per unit SFR as a function of metallicity (Lehmer+ 2021).*

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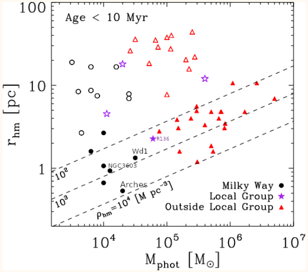

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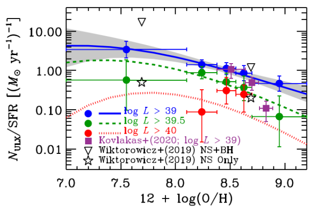

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Cold ISM within the galaxy evolution context

Star-formation main sequence (MS; SFR vs. M_*) set by gas content and efficiency gas → stars

- MS normalization with z set by available gas supply from accretion
- At low z, position along MS, including flattening above M_{knee}, follows M_{H2} vs. M_* while scatter around MS follows molecular gas fraction
- Time-independent shape of MS ⇒ long SF duty cycles (∼ Gyr) as opposed to quick ↑↓ due to SFH) *(e.g., Saintonge+ 2022)*
- Strong function of M_*: low mass galaxies in particular have extended HI reservoirs largely decoupled from the star formation process.

- Equilibrium of gas accretion, star formation, and gas outflows : the "gas regulator models" *(e.g., Bouché+10; Davé+12; Rathaus+16; Tacchella+20)*

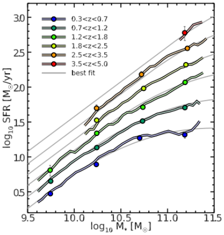
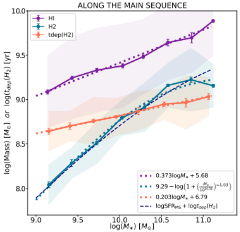


Fig.: *MS vs. z with Herschel stacking (Schreiber+ 2014)*



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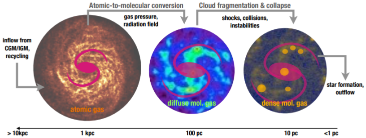
Cold ISM within the SF context



Dense gas fraction

- SF set by processes acting on different spatial scales
  - CO does not trace well the dense molecular gas *(e.g., Roman-Duval+ 2016)*
- Accounting for dense gas fraction within galaxies still results in non-constant SFE *(EMPIRE: Jimeñez-Donaire+ 2019, Beslic+ 2021)*
  - Dense gas threshold SF models (universal τ_{dep} above n_t) may remain valid even at small scales (<100pc) ⇒ use tracers with even higher critical densities?
  - Turbulence-regulated SF models with feedback *(e.g., Krumholz & Mc Kee 2005, Federrath & Klessen 2012)*?

Fig.: Top: SFE(dense) vs. P in EMPIRE (Jimeñez-Donaire+ 2019), bottom: vs. f(dense) in NGC3627 (Beslic+ 2021)

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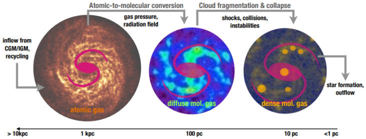

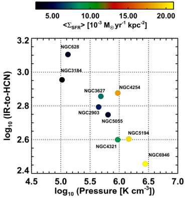

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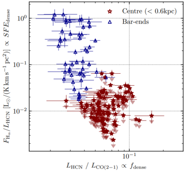

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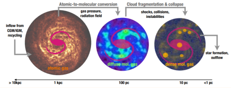
Physical processes to explore in a comprehensive way

Gas & SF

- How do molecular clouds form, how long do they live? What sets the SFE?
  - Conversion diffuse $\rightarrow$ dense, molecular gas vs. SF (CO-dark H_2, SK law)



- SF process itself ~ pc-scales: studies of protostars, SF filaments, and cloud-cloud collisions in Magellanic Clouds
  - Hot cores and complex organic molecules in the LMC (CH_3OCH_3, CH_3OCHO... with ALMA), chemical differences may suggest local mixing of gas with $\neq$ metallicity *(Sewiło+ 2018, 2022)*
  - Protostellar CO outflows in the SMC with ALMA *(Tokuda+ 2022)*
  - More to come with JWST, ELT...

***Fig.**: Bona fide hot core in the LMC (Sewiło+ 2022)*

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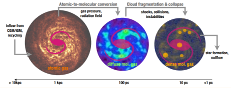

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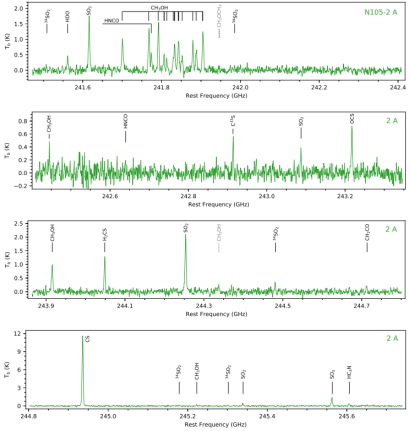

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Physical processes to explore in a comprehensive way (cont'd)

Turbulence

- CH^+ out-of-equilibrium H_2 / dissipation of mechanical energy in turbulence *(Godard+ 2022)*
- At high-z: shock waves powered by hot galactic winds & turbulent cool gas reservoirs *(e.g., Vidal-Garcia+ 2021, Falgarone+ 2017, Muller+ 2017)* ⇒ **A. Vidal-Garcia's talk**

Magnetic field

- SALSA Legacy Program: SOFIA HAWK+ observations of 14 nearby galaxies *(Lopez-Rodriguez+ 2022)*

Starburst ring of NGC 1097: B-field orientation and direction within 1 Kpc

***Fig.**: SALSA NGC 1097 (Lopez-Rodriguez+ 2022)*

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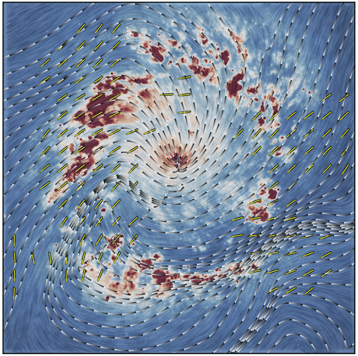

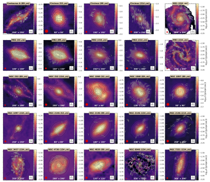

Fig.: *SALSA NGC 1097 (Lopez-Rodriguez+ 2022)*

Some highlights

CO-dark molecular gas and [CII]

⇒ **S. Madden's talk**

MW

- Dark gas mass fraction not traced by CO or HI is 20 — 40% in MW, most likely (CO-dark) molecular gas (DMG) as opposed to optically-thick HI *(Grenier+ 2005, Wolfire+ 2010, Hayashi+ 2019, Murray+ 2018)*

Local Group

- $f_{DMG} \approx$ 80-90% in SMC/LMC SF regions *(e.g., Piñeda+ 2017, Lebouteiller+ 2019)*
- α_{CO} > MW
- . . . but fully accountable for by the CO filling factor (i.e., confirming that Z effect is to reduce the filling factor of molecular gas traced by CO due to low D/G) *(Piñeda+ 2017)* *(see also Mookerjea+ 2016 in M33)*

Fig.: (Madden+ 2020)

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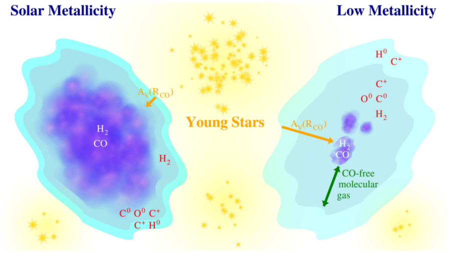

Fig.: (Madden+ 2020)

CO-dark molecular gas and [CII] (cont'd)

Extragalactic observations

- [CII] and other emission-lines readily available at high-z
- From models, [CII] and [CI] become increasingly good tracers of the H_2 column density profile at low Z and for cosmic ray ionization rate $\zeta_H \gtrsim 10^{-14}$ s^{-1} *(Bisbas+ 2021)*
- **Dwarf Galaxy Survey** (metal-poor SF galaxies) *(Madden+ 2013)*
  - Integrated [CII] emission
  - f_{DMG} ≈70-100%, M_{H2} follows closely L_{CII} in a single 1D model approach where A_V traced by [CII]/CO is the main parameter *(Madden+ 2020)*
  - CO-to-H_2 conversion factor (α_{CO}) not a simple function of Z but depends on the CO filling factor which can be partly recovered from the models *(Ramambason+ in prep.)*

Fig.: *CO-to-H_2 value between MW value and extreme case of CO uniformly distributed (Ramambason+ in prep.)* (⇒ **L. Ramambason's poster**)

CO-dark molecular gas and (CII) (cont'd)

Extragalactic observations

- (CII) and other emission-lines readily available at high-z
- From models, (CII) and (CI) become increasingly good tracers of the H_2 column density <u>profile</u> at low Z and for cosmic ray ionization rate $\zeta_H \gtrsim 10^{-14}$ s^{-1} *(Bisbas+ 2021)*
- **Dwarf Galaxy Survey** (metal-poor SF galaxies) *(Madden+ 2013)*
  - Integrated (CII) emission
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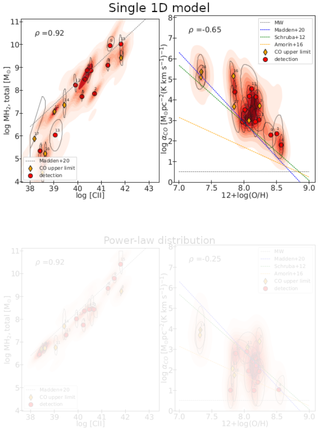

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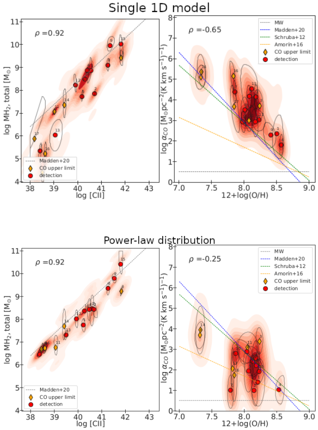

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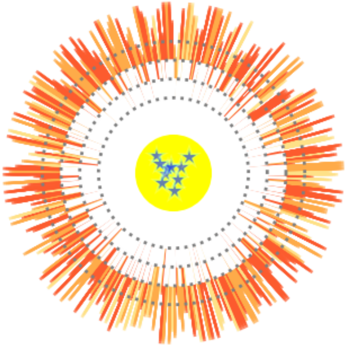

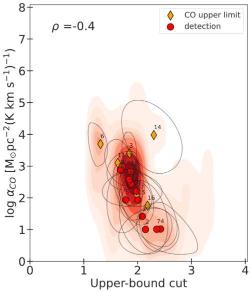

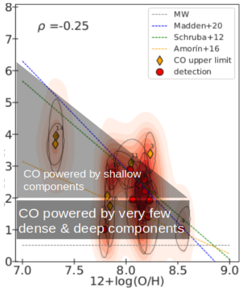

Possible to receover distributions of dense clouds even for integrated galaxies

PDR heating

Limits of the PE heating

- Evidence for PAH emission tracing (and PAH carriers likely dominating) neutral atomic gas heating through PE *(Helou+ 2001, Croxall+ 2012, Lebouteiller+ 2012, 2019, Lambert-Huyghe+ 2022, Berné+ 2022)*
- Low D/G and PAH abundance *(e.g., Galliano+ 2021)* ⇒ low Z? Compensation by very small grains? By other heating mechanisms related to SF?

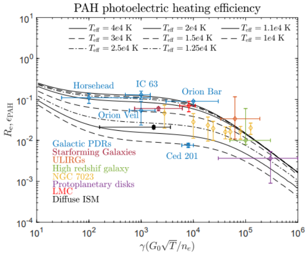

***Fig.**: PE heating efficiency and observational proxy (CII)+(OI) / PAH (Berné+ 2022)*

***Fig.**: (CII)+(OI) / PAH in Magellanic Clouds (Lambert-Huyghe+ 2022)*

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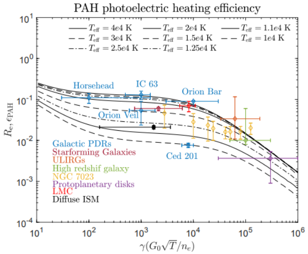

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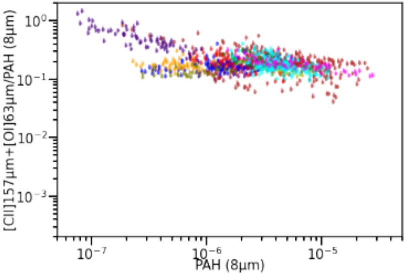

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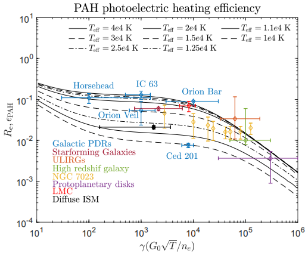

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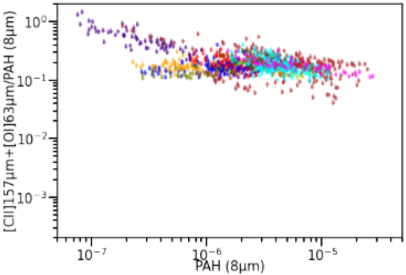

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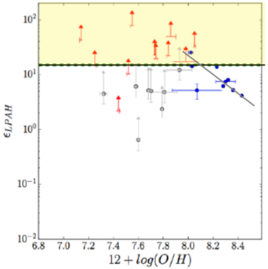

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Pushing (CII) and PE to the limit

Model

- IZw18, 18Mpc, 1/35 $Z_\odot$, D/G $\sim$ 1000 lower than MW

Fig.: IZw18 modeling strategy (Lebouteiller+ 2017)

Beyond the MW PE paradigm

- Single ULX dominates neutral gas heating with negligible contribution from PE
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Fig.: Cooling/heating contributions in the radiation-bounded (PDR) sector (Lebouteiller+ 2017)

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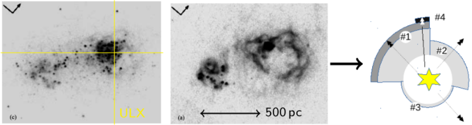

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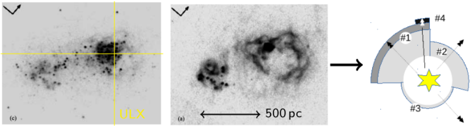

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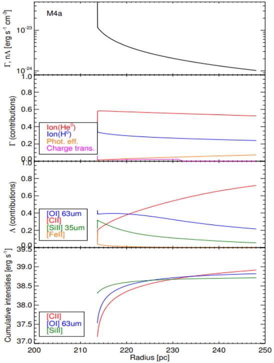

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Cosmic rays

CRIR

- H_3^+ measurements: $\zeta_H \approx 3 \times 10^{-16}$ s^{-1} MW disk *(e.g., Indriolo+ 2009, 2012)*, $\sim$ 10 – 1000 larger in GC *(Oka+ 2019)*
- Nearby SB galaxy disks *(e.g., Van der Tak+ 2016)*, nuclei *(e.g., ALCHEMI, Holdship+ 2022)*, and ULIRG nuclei *(e.g., González-Alfonso+ 2018)* with ionized molecules in dense gas (e.g., H_2O^+), even lensed galaxies beyond $z > 2$ *(Indriolo+ 2018)*, all suggesting MW-like range of values $10^{-16,-13}$ s^{-1}.
- ζ_H is larger in regions of more copious star formation: depends on proximity to cosmic-ray accelerators, particle propagation effects, and losses via interactions with the ISM *(Indriolo+ 2018)*

CR impact on ISM

- Ionization of molecules in dense gas $\Rightarrow$ chemical network
- Along with gas density, CRIR impact ISM fractionation in external galaxies (isotopic ratios) *(e.g. Viti+ 2019, 2020)*
- Impacts the use of (CII) and (OI) through increased C, C^+ column densities wrt CO, impacts somewhat X_{CO} factor as well *(Bisbas+ 2021)*
- Difficult distinction between CR and hard X-rays...

Prospectives for the diffuse/large-scale ISM

- Cosmic-ray-induced near-IR H_2 line emission with JWST *(Bialy+ 2021, Gaches+ 2022)*
- Also $H_3{}^+$ with JWST *(Indriolo+ 2007)*

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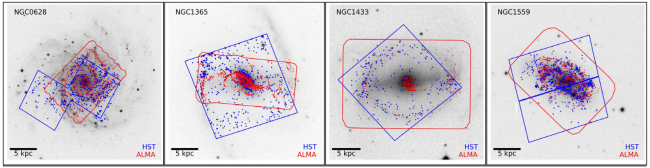
Formation/destruction timescales of molecular clouds

- PHANGS-* (ALMA, Hα, MUSE, VLA...): timescales for GMC formation, cluster formation, HII region formation and front expansion, decorrelation cloud/cluster



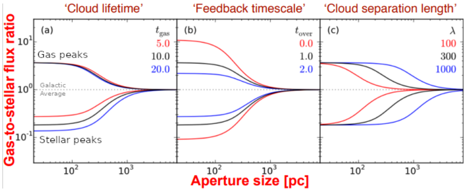


Fig.: Gas-to-SFR ratio, see, e.g., (Kruijssen+ 2019, Chevance+ 2022a)

Formation/destruction timescales of molecular clouds (cont'd)

Short-lived molecular clouds and rapid feedback $\Rightarrow$ inefficient SF

LMC

- LMC: GMC lifetime $\approx$11Myr likely set by internal processes rather than galactic dynamics, contrary to HI clouds *(Ward+ 2022)*

MS galaxies

- Molecular cloud lifetime ("inert" phase) $\sim$16 Myr *(Kim+ 2022)*
- Efficiently dispersed by stellar feedback within 1-5 Myr once the star-forming region becomes partially exposed. Early feedback mechanisms (photoionisation and stellar winds) efficiently disperse molecular clouds, prior to SNe explosions (see also *Chevance+ 2022b*) $\Rightarrow$ **A. Zakardjian's talk**
- (integrated cloud-scale star formation efficiency $\approx$1-8%)
- 1/2 CO and Hα is diffuse
- CO-visible cloud lifetimes become shorter with decreasing galaxy mass, attributed to CO-dark H_2 mass at low Z

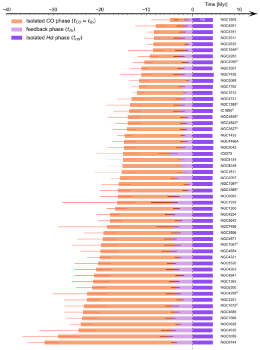


***Fig.**: Timescales for the various phases (Kim+ 2022).*

Last word on observations

Period is ripe for synergistic dataset analyses

- Resolved, IFUs: (Blue)MUSE, JWST, ALMA/NOEMA then SKA
- Sweet spot @$z \lesssim 2$ (UV $\rightarrow$ opt., opt. $\rightarrow$ NIRspec, near-IR $\rightarrow$ MIRI, CO ladder with ALMA)
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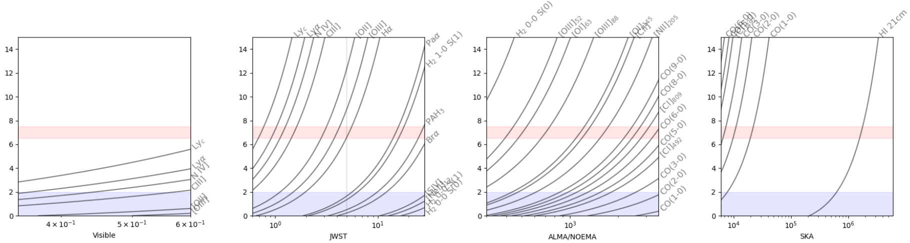

Few considerations

- UV emission lines N IV), C IV, He II, O III), Si III), C III)... (~1400-1900Å): accurate diagnostics for E(B-V), n_e, T_e, O/H, U... *(Mingozzi+ 2022)*
- Mid-IR diagnostics will remain unavailable at $z \sim 2 - 10$ until PRIMA (`http://agora.lam.fr`)

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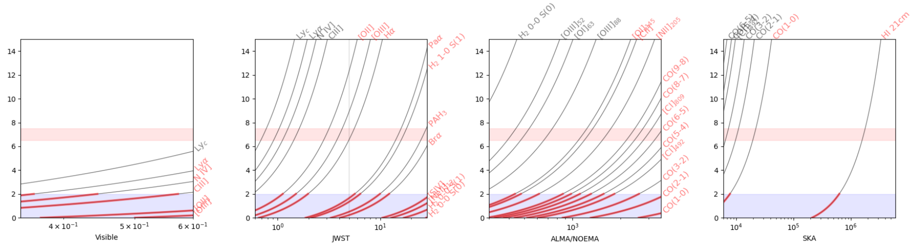

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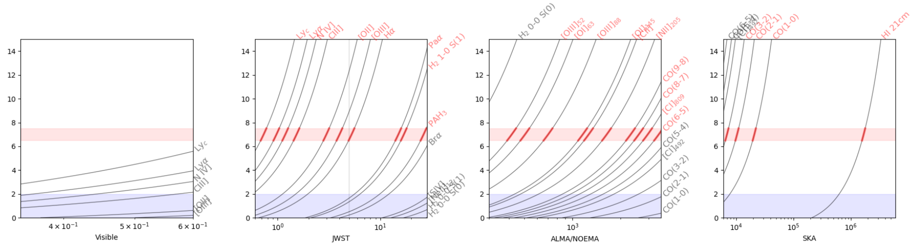

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Modeling strategies

Scale & adapt

Challenges

- Integrate adapted prescriptions in models (e.g., low metallicity chemistry, dust properties etc. . .) and in the input energetic sources
- Distinguish physical processes for galaxies (e.g., photoionization, shocks, turbulence, B, CRs. . .) from spatially/spectrally unresolved tracers
- Account for ISM complexity (e.g., phases, distribution of matter. . .)
- Account for geometry gas+sources (distribution, optical depth, projection effects. . .), only partly alleviated by spatial/spectral decomposition and/or IFUs
- High level of degeneracy $\Rightarrow$ manage multiple solutions in large grids

Many potential approaches

Method	Advantages	Difficulties
Simulations	Dynamical effects, large volume 3D RT post-processing tools exist, e.g., with MOCASSIN	Comparison with specific observations (statistics), light chemistry network
1D	State-of-the-art RT & chemistry	Scale to complex geometries
Pure 3D	3D RT, diffuse light…	Geometry (gas+sources) not free parameter
MC 3D	Good 3D approximation	Geometry not free parameter
Pseudo-3D from 1D	State-of-the-art RT & chemistry Central ionizing source (AGN, PN, HII region)	Not 3D! Geometry not free parameter
Topological 3D from 1D	Inferred geometry	Not 3D!

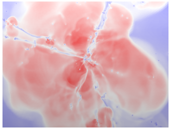

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Fig.: *MULTIGRIS+Cloudy (Lebouteiller Ramambason 2022)*

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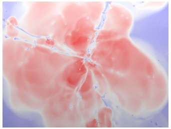

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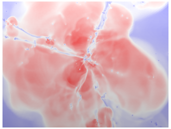

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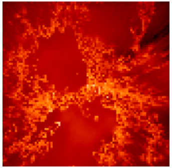

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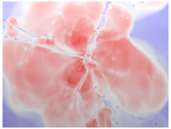

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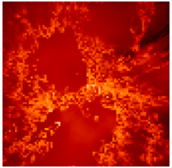

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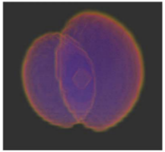

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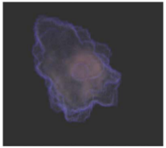

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Fig.: *MULTIGRIS+Cloudy (Lebouteiller Ramambason 2022)*

Many potential approaches

Method	Advantages	Difficulties
Simulations	Dynamical effects, large volume 3D RT post-processing tools exist, e.g., with MOCASSIN	Comparison with specific observations (statistics), light chemistry network
1D	State-of-the-art RT & chemistry	Scale to complex geometries
Pure 3D	3D RT, diffuse light. . .	Geometry (gas+sources) not free parameter
MC 3D	Good 3D approximation	Geometry not free parameter
Pseudo-3D from 1D	State-of-the-art RT & chemistry Central ionizing source (AGN, PN, HII region)	Not 3D! Geometry not free parameter
Topological 3D from 1D	Inferred geometry	Not 3D!

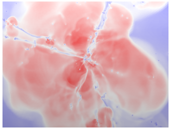


Fig.: *SPHINX (Rosdhal+ 2018)*

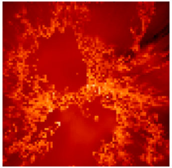
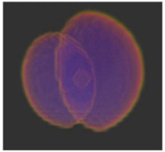


Fig.: *MOCASSIN (Hubber+ 2016)*



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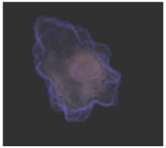

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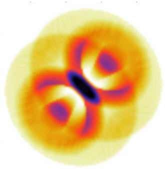

Fig.: *PyCloudy, PyCROSS (Fitzgerald+ 2020; Morisset+ 2013)*

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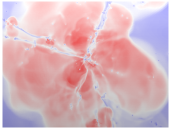

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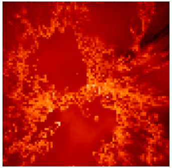

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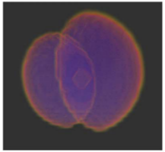

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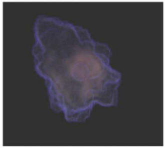

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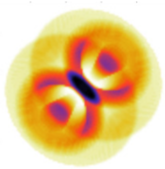

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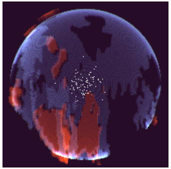
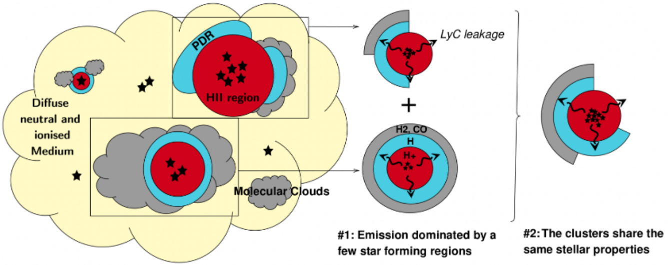


***Fig.**: MULTIGRIS+Cloudy (Lebouteiller Ramambason 2022)*

Topological models: multi-sector

- Observed emission is the sum of N components distributed in several stellar clusters surrounded with several sectors described by 1D models
  (Péquignot 2008, Cormier+ 2012, Cormier+ 2019, Lebouteiller+ 2017, Polles+ 2019, Lebouteiller Ramambason 2022, Ramambason+ 2022)

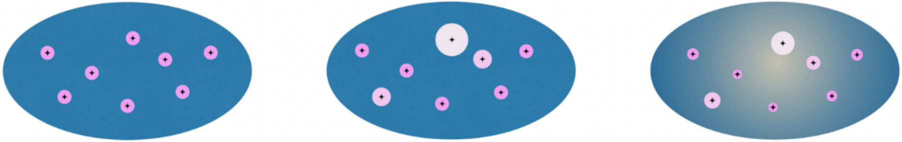


Explanations

- Combine 1D models that propagate radiation through HII region+PDR(+molecular cloud) ⇒ 1D (depth) structure constrained, need to constrain the spherical geometry (diffuse/reflected light and geometry simplification but still better than 1D though. . . !)

Topological models: locally optimally emitting clouds (LOC)

- Observed emission is the result of strong selection effects due to the fact that some lines emit preferentially under some physical conditions *(Ferguson+ 1997, Richardson+ 2014, 2016)*.



$$L_{line} = \underbrace{\int \ldots \int}_{\mathrm{n}} L(p_1, \ldots, p_n)\psi(p_1, \ldots, p_n)dp_i \ldots dp_n \qquad \psi = U^{\alpha} u n^{\alpha_n} \ldots$$

Applications

- Machine Learning application *(Morisset+ in prep.)*
- Depth/A_V: Application to statistical distribution of clouds with log-normal A_V in PDRs *(Bisbas+ 2019)*
  - + power-law tail due to self-gravity (possibly leading to star formation) reminiscent of result obtained in *Ramambason+ (2022)* for which only power-law distributions of depth can reproduce CO emission.

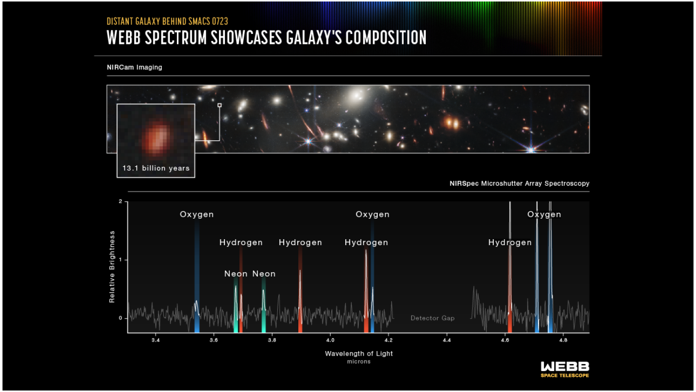
Global SED approach adapted to galaxy evolution parameters (z, SFH, IMF. . .)

Galaxy-wide parameters & gas properties

- CIGALE & x-CIGALE: global energy balance *(Boquien+ 2019)*
  - Full SED models from far-UV to far-IR
  - Using geometry templates for dust attenuation
- BEAGLE *(Chevallard Charlot 2016)*
  - Dust attenuation prescription related to inclination, global geometry (e.g., disk, bulge)
  - RT through ISM & IGM
- General
  - Nebular emission is accounted for (PDRs and CO in progress)
  - So far simple grids with tabulated U and Z, constant n$\sim$100 cm^{-3}

Complex models for single spectra

Still a relevant problem for single-dish/long-wavelength observations or for distant Universe



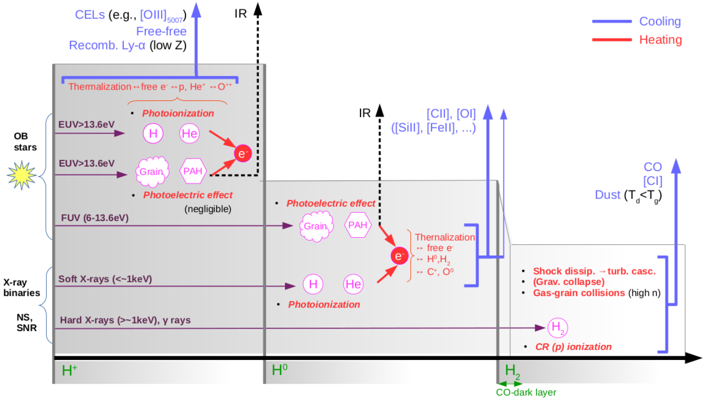
Objective: use the tracers to recover model parameters, including potentially geometry

End

Physical processes to explore in a comprehensive way (cont'd)

Energy input and gas heating mechanisms

- Neutral atomic gas: PE heating, soft X-rays, CRs. . .
- Molecular gas: hard X-rays, shocks, cosmic ray ionization. . .
  - Main challenge: knowledge on dust content, X-ray sources, CR propagation and SFR dependency
- All phases/scales: shocks expected from various sources acting on various scales (from mergers, AGNs, starbursts. . . to protostellar outflows and stellar winds)
  - Main challenge: lack of spatial decomposition/resolution – mixing biases



Dense gas fractions and SFE

Dense gas fraction in extragalactic ISM

- HCN, HCO^+ more and more observations but still few studies apart from very nearby galaxies (e.g., Magellanic Clouds; *Galametz+ 2020*) and starbursts/AGNs
- Consistent results in that SFE ↘ when dense gas fraction (or stellar surface density, interstellar P. . .) ↗, at kpc-scales *(EMPIRE; Jiménez-Donaire+ 2019)* down to <100pc-scales *(Beslic+ 2021, PAWS Schinnerer in prep.)*
  - SFE traced by IR/HCN or Hα/HCN

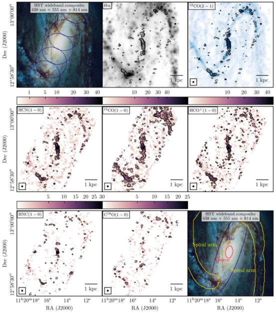


Fig.: NGC3627 with NOEMA and PHANGS-MUSE (Beslic+ 2021)

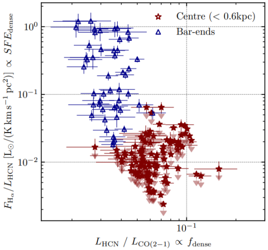


Fig.: SFE(dense) vs. f(dense) in NGC3627 (Beslic+ 2021)

All in all favoring turbulence-regulated SF models *(e.g., Burkhart & Mocz 2018)*

& much more. . .

Shocks

- Near/mid-IR H_2 as well as optical lines for tracing relatively diffuse shocks *(e.g., Hong+ 2013, Medling+ 2015)* but difficult interpretation without spatial resolution JWST important for nearby galaxies

Dust and mineralogy with JWST

- PAHs, fullerenes, CO_2 ice. . .
- Spitzer: crystalline silicates are a common component of the ISM *(Spoon+ 2022)*
  - Strength of crystalline silicate bands toward nuclei correlate with strength of amorphous silicate strength
  - Transition from emission to absorption at high obscuration consistent with an origin for the amorphous/crystalline silicate features in a centrally heated dust geometry (edge-on disk or cocoon).
  - Crystalline silicate bands able to classify the obscuration level of AGNs, even in the presence of strong circumnuclear star formation

Fig.: Simulated MIR spectra of centrally heated dust shells with increasing dust mass (Spoon+ 2022) – amorphous silicates.

Fig.: Observed spectra showing the transition emission/absorption for crystalline silicates (Spoon+ 2022).

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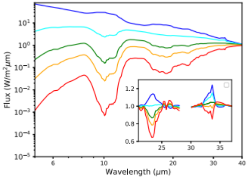

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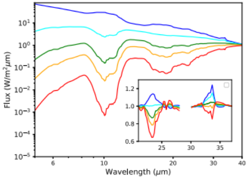

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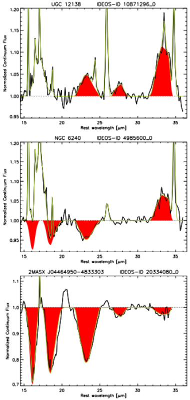

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