EXECUTIVE SUMMARY

Fedriani, Anglada, et al. report on IRAS 18162-2048, identifying IRS 7 as a B2/B3 ZAMS star powering an extended PDR. Radiative transfer modeling with Cloudy reproduces H_2 line populations with $T_{\rm gas} = 600$ K, $n_{\rm H} = 7.9 \times 10^3$ cm^{-3}, and an incident FUV field of $G_0 \approx 1.6 \times 10^4$. This provides an observational test case for 3D-PDR validation and informs future JWST H_2 studies. **Devine, Kathryn, et al.** introduce the MIRION catalog, comprising 6,176 compact PDRs identified from Spitzer mid-infrared data, with low $\log_{10}(F_{12}/F_8) \approx -0.48$. This is useful for benchmarking 3D-PDR and validating synthetic observations against observed IR color-property correlations.

I. E. López, E. Bertola, et al. used JWST observations of M58's low-luminosity AGN to investigate warm H_2 excitation. Pure rotational emission is consistent with low-velocity (10–40 km/s) C-type shocks, while a non-thermal component (10–30%) in rovibrational lines is attributed to AGN X-ray heating. Cosmic rays are ruled out as a dominant source, requiring an unphysically high ionization rate of $\zeta \sim 10^{-10} - 10^{-9}$ s^{-1}. This defines conditions where X-rays and shocks prevail over cosmic ray heating, contrasting with quiescent cloud environments. In dwarf galaxies, **Martin-Alvarez, Sijacki, et al.** report that CR feedback is crucial for driving fast (~ 70 km/s), mass-loaded ($\eta_{\rm WIM} \sim 1$–10) outflows in high-resolution RAMSES simulations. CR pressure dominates over thermal pressure in outflow regions, allowing the galaxy to retain metals consistent with observed mass-metallicity relations, unlike simpler models that ejected metals excessively ($Z_* < 10^{-2} Z_\odot$). These studies inform CR propagation and ionization rates across astrophysical settings, particularly in low-metallicity environments.

Jayashree Narayan, Aris Tritsis, and Christoph Federrath find that turbulence measurements from CO(1-0) and CO(2-1) lines systematically overestimate the true 3D turbulent velocity dispersion, reporting correction factors $\mathcal{R}_{\text{CO,1-0}} = 0.88^{+0.09}_{-0.08}$ and $\mathcal{R}_{\text{CO,2-1}} = 0.88^{+0.10}_{-0.08}$. This has implications for interpreting CO-derived turbulent properties and refining synthetic observations of molecular clouds, informing the application of carbon cycle tracers in PDR and low-metallicity environments.

ISM Simulations & Star Formation

A multi-scale evolutionary study of molecular gas in STARFORGE: I. Synthetic observations of SEDIGISM-like molecular clouds

Neralwar, Colombo, **Offner**, Karska, Figueira, **Wyrowski**, Neupane, Urquhart, **Duarte-Cabral**

Directly informs your statistical galaxy emulation goal by linking simulated cloud evolution to observed scaling relation scatter. Ideal for 3D-PDR post-processing to incorporate C-cycle tracers. →

The Pandora project. II: how non-thermal physics drives bursty star formation and temperate mass-loaded outflows in dwarf galaxies

Martin-Alvarez, **Sijacki**, **Haehnelt**, Concas, Yuan, **Maiolino**, Wechsler et al.

Highlights cosmic ray (CR) feedback as crucial for bursty star formation and realistic multi-phase outflows in dwarf galaxies, informing CR studies and low-Z galaxy emulation. →

Deuterium fractionation and CO depletion in Barnard 5

Petrashkevich, Punanova, **Caselli**, Pineda, Sipila, Vasyunin

Provides observational constraints on CO freeze-out for 3D-PDR. Useful for benchmarking freeze-out chemistry and informing turbulent cloud database in galaxy emulator. →

A pan-galaxy study of synthetic giant molecular filaments: a turbulence-dominated life cycle

Hu, Wang, **Krumholz**, Su

Provides statistical GMF data for the Galaxy Emulator. Supports sub-virial cloud findings. Relevant for synthetic CO observations and [CII] collision diagnostics. →

How is cold, star-forming gas in galaxies affected by magnetic fields?

Bogue, Smith, Treß, Mac Low, **Whitworth**, **Klessen**, Brucy, Girichidis, **Glover**, Göller, Soler, Traficante

Provides a galaxy-scale model for magnetic field impact on star formation. Supports sub-virial cloud findings. Useful for galaxy emulator physics and 3D-PDR post-processing. →

Rhea-RT: Dynamical impact of Central Molecular Zone conditions on ISM properties and stellar feedback coupling

Tress, Brucy, Girichidis, **Glover**, Goeller, Hirschmann, **Klessen**, Peter, Petersson, Sormani et al.

Offers relevant insights for radiative feedback modeling, indicating that galactic shear can decouple feedback in starburst-like regions. →

Magnetic Support Suppresses Star Formation in Galaxy Discs

Bogue, Smith, Treß, Mac Low, **Whitworth**, **Klessen**, Girichidis, **Glover**, Soler

Directly supports your sub-virial cloud findings. Essential for Galaxy Emulator's turbulent cloud database and 3D-PDR post-processing. →

PDRs, Astrochemistry & Radiative Transfer

Unbound Tails and Compressed Heads: A JCMT Study of the SFO 38 Cloud

Porel, Soam, Karoly, Chung, Won, Kim, Gupta, Sharma

Observational case study of RDI's dual role. Provides quantitative parameters for 3D-PDR simulations, ideal for synthetic CO isotopologue observations. →

Diverse stages of star formation in IRAS 18162-2048: Emergence of UV Feedback

Fedriani, Anglada, Caratti o Garatti, Gómez, Masqué, Osorio, Stecklum, Rodríguez-Kamenetzki et al.

Provides a well-constrained observational benchmark for 3D-PDR validation. Useful for synthetic observations and a direct scientific case for JWST H_2 studies. →

The influence of steady temperature on the noise-induced structures in the Orion Bar PDR

Pomelnikov, Riashchikov, Zavershinskii, Molevich

Provides a hydrodynamical mechanism for PDR input structures. Useful for 3D-PDR initial conditions and synthetic observation interpretation for JWST. →

Turbulence inference from CO spectral observations

Narayan, Tritsis, **Federrath**

Provides a quantifiable correction factor for CO-derived turbulence, relevant for synthetic observations and Carbon Cycle tracers. →

The Milky Way Project: Bridging Intermediate- and High-Mass Star Formation with the MIRION Catalog of Yellowballs

Devine et al.

Provides a large sample of compact PDRs for 3D-PDR code validation and benchmarking. The IR color-property correlations offer direct tests for your synthetic observations. →

Extragalactic & AGN Feedback

Shocked, heated, and now resolved: H_2 excitation in the low-luminosity AGN at M58 core with JWST

López, **Bertola**, Reynaldi, Ogle, Baldi, Brusa, García-Burillo, Sebastian et al.

Provides a direct contrast to CR-excited H_2 in quiescent clouds, defining conditions where X-rays and shocks dominate. Useful for your Cosmic Ray White Paper and 3D-PDR X-ray/shock module development. →

Signatures of star formation inside galactic outflows

Ong, D'Eugenio, **Maiolino**, Arribas, Belfiore, **Bellocchi**, **Carniani**, **Cazzoli**, **Cresci** et al.

Presents a novel environment to test gas tracer physics (Carbon Cycle, X_{CO}, X_{CI}) in kinematically disturbed, high-pressure gas. →

Turbulence & Numerical Methods

Statistical properties of compressible isothermal turbulence from sub- to supersonic conditions

Thiesset, **Federrath**

Provides foundational physics for your turbulent cloud database, quantifying how shock strength and gas structure depend on Ma and Re. Directly applicable for calibrating 3D-PDR inputs. →

MOGLI: model for multiphase gas using multifluid hydrodynamics

Das, **Gronke**, **Weinberger**

Offers a computationally efficient method for generating turbulent, multiphase cloud data for your galaxy emulator. →

Mitigating numerical dissipation in simulations of subsonic turbulent flows

Watt, **Federrath**, Birke, Klingenberg

Provides a less dissipative MHD scheme for your turbulent cloud database, enhancing fidelity for subsonic conditions relevant to 3D-PDR inputs. →

Lagrangian versus Eulerian Methods for Toroidally-Magnetized Isothermal Disks

Tomar, **Hopkins**

Informs 3D-PDR validation for magnetic field evolution. Supports magnetic field importance in low-metallicity clouds by differentiating numerical scheme behavior. →

General Implicit Runge-Kutta Integrators for Multifluid Gas-Dust Aerodynamic Drag

Tedeschi-Prades, **Birnstiel**, Dolag, **Ercolano**, Hutchison

Relevant for accelerating dust dynamics in your 3D-PDR and turbulent cloud database, particularly for freeze-out chemistry and multiple grain sizes. →

Machine Learning & Statistics

CosmoGLINT: Cosmological Generative Model for Line Intensity Mapping with Transformer

Moriwaki, Jun, Osato, **Yoshida**

Directly addresses your statistical galaxy emulation goal. Provides a Transformer architecture for populating dark matter simulations, useful for generating synthetic [CI]/CO maps. →

Galaxy Phase-Space and Field-Level Cosmology: The Strength of Semi-Analytic Models

de Santi, **Villaescusa-Navarro**, Araya-Araya, De Lucia, Fontanot, Perez, Arnés-Curto, Gonzalez-Perez et al.

Provides direct validation for your statistical galaxy emulation strategy. Demonstrates training on inexpensive models can generalize to complex hydrodynamical simulations. →

PolySwyft: sequential simulation-based nested sampling

Scheutwinkel, **Handley**, Weniger, de Lera Acedo

Offers an efficient inference engine for your Galaxy Emulator project. May reduce 3D-PDR simulation calls for parameter inference. →

Data-driven dust inference at mid-to-high Galactic latitudes using probabilistic machine learning

O'Callaghan, **Mandel**, **Gilmore**

Offers a direct blueprint for your Galaxy Emulator's statistical components. Provides robust 3D ISM context for 3D-PDR simulations. →

Lazy Diffusion: Mitigating spectral collapse in generative diffusion-based stable autoregressive emulation of turbulent flows

Sambamurthy, Chattopadhyay

Directly applicable to your “Statistical Galaxy Emulation” for turbulent ISM. Provides architectural solutions to spectral collapse. →

gp2Scale: A Class of Compactly-Supported Non-Stationary Kernels and Distributed Computing for Exact Gaussian Processes on 10 Million Data Points

Noack, Risser, Luo, Tekriwal, **Pandolfi**

Offers a scalable solution for your “Statistical Galaxy Emulation” project, handling large turbulent cloud databases while preserving GP flexibility. →

Bayesian Symbolic Regression via Posterior Sampling

Bomarito, Leser

Offers an interpretable alternative to black-box emulators. Applicable for deriving physical laws from 3D-PDR outputs or for automated discovery of $X_{\mathrm{CO}}/X_{\mathrm{CI}}$ relations. →

Generalized Spherical Neural Operators: Green's Function Formulation

Tang, Chen, Li

Useful for developing a more accurate NeuralPDR by handling anisotropic radiation fields on HEALPix grids for your Statistical Galaxy Emulation. →

ISM Simulations & Star Formation

This section covers advances in ISM simulations, including synthetic observations from STARFORGE, cosmic ray feedback in dwarf galaxies, CO depletion chemistry, giant molecular filament statistics, and the role of magnetic fields in star formation regulation.

1.1 Evolutionary Origin of Molecular Cloud Scatter

Paper: A multi-scale evolutionary study of molecular gas in STARFORGE: I. Synthetic observations of SEDIGISM-like molecular clouds ↑

Authors: Neralwar, K. R., Colombo, D., **Offner, S.**, Karska, A., Figueira, M., **Wyrowski, F.**, Neupane, S., Urquhart, J. S., **Duarte-Cabral, A.**

This study utilized STARFORGE MHD simulations, coupled with RADMC-3D radiative transfer, to generate synthetic ^{13}CO(2-1) observations designed to mimic the SEDIGISM survey. The synthetic observations successfully reproduce the flux distributions and integrated properties of observed molecular clouds, including their scaling relations. The work reports that the scatter in these observed scaling relations is related to the evolutionary stages of molecular clouds, with average properties evolving from super-virial ($\alpha_{\rm vir} \sim 10$) to near-virial ($\alpha_{\rm vir} \sim 2$) states, then increasing again as stellar feedback disperses gas. This framework provides a method to interpret observed cloud populations as evolutionary sequences, bridging detailed simulations and large-scale observational surveys.

- **Key Result:** The study demonstrates a distinct morphological life-cycle: clouds evolve from diffuse to filamentary, then to 3D bubble-like structures as they are dispersed by stellar feedback.
- **Method Note:** The STARFORGE simulations lack a real-time chemical network, relying on a constant CO abundance and ad-hoc freeze-out. This presents an opportunity for 3D-PDR to provide more accurate C-cycle abundances, especially in feedback-dominated regions.

1.2 Cosmic Rays Drive Dwarf Galaxy Outflows

Paper: The Pandora project. II: how non-thermal physics drives bursty star formation and temperate mass-loaded outflows in dwarf galaxies ↑

Authors: **Martin-Alvarez, Sergio**, **Sijacki, Debora**, **Haehnelt, Martin G.**, Concas, Alice, Yuxuan Yuan, **Maiolino, Roberto**, Risa H. Wechsler, Rodríguez Montero, Francisco et al.

This study utilizes high-resolution RAMSES cosmological zoom-in simulations of a dwarf galaxy, comparing models with progressively complex physics including hydrodynamics, radiative transfer, magnetohydrodynamics, and cosmic ray (CR) feedback. The full-physics model (RTCRiMHD), incorporating CRs, produced bursty star formation histories in agreement with recent JWST findings and drove fast (~ 70 km/s), mass-loaded ($\eta_{\rm WIM} \sim 1$–10), multi-phase outflows. CR pressure was found to dominate over thermal pressure in outflow regions, allowing for more efficient entrainment of dense, temperate gas and enabling the galaxy to retain metals consistent with observed mass-metallicity relations, in contrast to simpler models that ejected metals excessively ($Z_* < 10^{-2} Z_\odot$). This work suggests CR feedback is essential for accurately modeling dwarf galaxy evolution.

- **Key Finding:** Cosmic ray pressure, not thermal pressure, dominates in outflow regions, driving denser, more temperate, and highly mass-loaded outflows ($\eta_{\rm WIM} \sim 1$–10).
- **Implication:** The inclusion of cosmic ray feedback is necessary to reproduce observed bursty star formation histories in dwarf galaxies, consistent with recent JWST data.
- **Method Note:** Simulations were performed using the RAMSES code, incorporating modules for radiative transfer, MHD, and cosmic ray transport, comparing four distinct physics models.

1.3 CO Depletion & Deuteration in B5 Cores

Paper: Deuterium fractionation and CO depletion in Barnard 5 ↑

Authors: Igor Petrashkevich, Anna Punanova, **Paola Caselli**, Jaime E. Pineda, Olli Sipila, Anton I. Vasyunin

This study presents spatially resolved IRAM 30m observations of N_2H^+, N_2D^+, $H^{13}CO^+$, DCO^+, and $C^{18}O$ in the Barnard 5 region. It maps deuterium fractionation (R_D) and CO depletion (f_d) across adjacent starless and protostellar cores. The starless core exhibits higher deuteration ($R_D^{N_2H^+} = 0.43 \pm 0.10$) and CO depletion ($f_d = 5.0 \pm 0.1$) compared to the protostellar core ($R_D^{N_2H^+} = 0.15 \pm 0.03$, $f_d = 4.1 \pm 0.1$). This confirms that CO freeze-out and stellar heating jointly regulate deuterium chemistry.

- **Key Result:** Deuterium fractionation (e.g., $R_D^{N_2H^+} = 0.43 \pm 0.10$) and CO depletion factor ($f_d = 5.0 \pm 0.1$) are highest in the starless core, decreasing towards the protostar.
- **Implication:** Confirms a strong positive correlation between $R_D^{HCO^+}$ and CO depletion, demonstrating that gas-phase CO removal drives enhanced deuterium chemistry.
- **Method Note:** The spatially resolved maps of adjacent evolutionary stages (starless vs. protostellar) offer a robust differential test case for PDR codes modeling freeze-out.

1.4 Galactic Filaments: Turbulence and Fragmentation

Paper: A pan-galaxy study of synthetic giant molecular filaments: a turbulence-dominated life cycle ↑

Authors: Hu, Zipeng, Wang, Ke, **Krumholz, Mark R.**, Su, Keyun

This study analyzes over 700 giant molecular filaments (GMFs) from a high-resolution, pan-galactic magnetohydrodynamic simulation, post-processed with DESPOTIC to generate synthetic CO emission maps. It reports that GMFs are primarily formed by turbulent shocks from galactic shear and stellar feedback. Energetically, they are dominated by magnetized turbulence, with $(2E_k + E_B)/|E_g| \gg 1$, rendering them gravitationally subcritical. Fragmentation into star-forming clumps proceeds via a turbulence-driven sausage instability, not Jeans instability. GMFs exhibit a typical lifetime of ~ 14 Myr, with ~ 7 Myr molecular gas half-life.

- **Key Result:** Magnetized turbulence provides global support against GMF collapse while inducing local fragmentation. Over 70% of GMFs experience cloud-cloud collisions.
- **Method Note:** The use of DESPOTIC for synthetic CO emission maps aligns directly with your synthetic observation methodology.

1.5 Magnetic Support in Galaxy-Scale Star Formation

Paper: How is cold, star-forming gas in galaxies affected by magnetic fields? ↑

Authors: Kamran R. J. Bogue, Rowan J. Smith, Robin G. Treß, Mordecai-Mark Mac Low, **David J. Whitworth**, **Ralf S. Klessen**, Noé Brucy, Philipp Girichidis, **Simon C. O. Glover**, Junia Göller, Juan D. Soler, Alessio Traficante

This study presents AREPO simulations of an isolated star-forming galaxy, comparing magnetohydrodynamic (MHD) and hydrodynamic (HD) runs to investigate the role of magnetic fields without imposing a Kennicutt-Schmidt (KS) law. The MHD model reports a reduced star formation rate of $\sim 4.8\,\mathrm{M_\odot\,yr^{-1}}$ compared to $\sim 8.4\,\mathrm{M_\odot\,yr^{-1}}$ in the HD case, and shifts the KS relation to higher gas surface densities, peaking at $\Sigma_{\mathrm{gas}} \approx 28.8\,\mathrm{M_\odot\,pc^{-2}}$ for MHD versus $\approx 11.0\,\mathrm{M_\odot\,pc^{-2}}$ for HD. Magnetic fields, amplified to $\sim 2.5\,\mu$G, appear to provide support against gravitational collapse, altering galactic disk structure and star formation efficiency.

- **Key Result:** Magnetic fields reduce the galaxy-wide star formation rate by a factor of ~ 1.75 and shift the Kennicutt-Schmidt relation to higher gas surface densities.

1.6 Shear-Driven Decoupling of Stellar Feedback in the CMZ

Paper: Rhea-RT: Dynamical impact of Central Molecular Zone conditions on ISM properties and stellar feedback coupling ↑

Authors: Tress, R. G., Brucy, N., Girichidis, P., **Glover, S. C. O.**, Goeller, J., Hirschmann, M., **Klessen, R.**, Peter, T., Petersson, J., Sormani, M. C. et al.

Radiation magnetohydrodynamics (MHD) simulations using AREPO with $M_{\mathrm{cell}} = 20\,\mathrm{M_\odot}$ resolution compare the Central Molecular Zone (CMZ) and Solar neighborhood environments within a Milky Way galaxy. The primary finding suggests that the strong orbital shear and short dynamical timescales within the CMZ lead to a rapid decoupling of young stars from their natal gas, preventing the formation of disruptive superbubbles. Instead, stellar feedback acts as a diffuse source of background turbulence, fundamentally altering star formation regulation in such extreme environments.

- **Key Result:** Strong orbital shear in the CMZ rapidly decouples young stellar associations from their natal clouds, preventing localized disruptive superbubble formation.

- **Implication for 3D-PDR:** The inefficient feedback coupling due to shear provides a physical mechanism for driving background turbulence, relevant for modeling PDRs in starburst environments.
- **Galaxy Emulator Note:** Orbital shear and dynamical decoupling of feedback represent critical parameters for inclusion in the turbulent cloud database for galaxy emulation.

1.7 Magnetic Fields Suppress Galactic Star Formation

Paper: Magnetic Support Suppresses Star Formation in Galaxy Discs ↑
Authors: Kamran R. J. Bogue, Rowan J. Smith, Robin G. Treß, Mordecai-Mark Mac Low, **David J. Whitworth**, **Ralf S. Klessen**, Philipp Girichidis, **Simon C. O. Glover**, Juan D. Soler

This study used the AREPO moving-mesh code to compare magnetohydrodynamic (MHD) and hydrodynamic (HD) simulations of an isolated star-forming galaxy, incorporating non-equilibrium chemistry and supernova feedback. The MHD model yielded a lower average Star Formation Rate ($\sim 4.8\,M_{\odot}\,\mathrm{yr}^{-1}$ vs. $\sim 8.4\,M_{\odot}\,\mathrm{yr}^{-1}$ in HD) and a more compact galactic disc (radius of ~ 5.1 kpc vs. ~ 7.4 kpc). Magnetic fields, which reached strengths of approximately $1\,\mu$G, provided non-thermal pressure support that elevated the gas surface density threshold for star formation. This suggests magnetic fields are instrumental in regulating galactic star formation rates and morphology, aligning with observational constraints.

- **Key Result:** Magnetic fields reduce the galaxy-wide SFR by nearly a factor of two and shift the Kennicutt-Schmidt relation to higher gas surface densities.
- **Method Note:** Star formation was modeled with sink particles forming only in gravitationally-bound gas, avoiding an imposed Kennicutt-Schmidt law.
- **Implication:** The altered gas density and temperature distributions in MHD simulations will impact carbon cycle tracer abundances and excitation.

PDRs, Astrochemistry & Radiative Transfer

This section presents observational benchmarks and theoretical advances for PDR modeling, including RDI dynamics, well-constrained H_2 observations, thermal instability mechanisms, CO turbulence corrections, and a large catalog of compact PDRs.

2.1 RDI Dual Role: Head Compression, Tail Dispersion

Paper: Unbound Tails and Compressed Heads: A JCMT Study of the SFO 38 Cloud ↑

Authors: Puja Porel, Archana Soam, Janik Karoly, Eun Jung Chung, Lee Chang Won, Shinyoung Kim, Shivani Gupta, Neha Sharma

This study utilized JCMT-HARP observations of CO isotopologues (J=3-2) in the SFO 38 bright-rimmed cloud to investigate the dual effects of Radiatively Driven Implosion (RDI). The dense southern head ($n(\mathrm{H}_2) \approx 6.8 \times 10^3\ \mathrm{cm}^{-3}$) is gravitationally bound ($\alpha_{\mathrm{vir}} = 0.79$), showing evidence of ongoing star formation. Conversely, the northern tails, with lower densities ($n(\mathrm{H}_2) \approx 2.7$–$5.3 \times 10^3\ \mathrm{cm}^{-3}$), are gravitationally unbound with line masses well below critical values, exhibiting kinematic signatures of expansion. This work illustrates how RDI simultaneously compresses material to trigger star formation in cloud heads and disperses gas in tails, preventing their collapse.

- **Key Result:** Gravitational analysis shows the cloud head is gravitationally bound ($\alpha_{\mathrm{vir}} \approx 0.79$), while the tails are unbound, with line masses well below critical values.
- **Data Availability:** JCMT-HARP observational data (Project ID: M08BU15) is publicly available, serving as a direct test case for 3D-PDR.

2.2 PDR and HII Region Powered by B-Type Star

Paper: Diverse stages of star formation in the IRAS 18162-2048 region. Emergence of UV Feedback ↑

Authors: Fedriani, R., Anglada, G., Caratti o Garatti, A., Gómez, J. F., Masqué, J., Osorio, M., Stecklum, B., Rodríguez-Kamenetzki, A. R. et al.

This study employs multi-wavelength observations using VLT/SINFONI, VLA, and ALMA to characterize the high-mass star-forming region IRAS 18162-2048. It identifies IRS 7 as a B2/B3 ZAMS star, which powers an extended photodissociation region (PDR) with UV-fluorescent H_2 emission and a compact H II region, as confirmed by optically thin free-free radio emission. Radiative transfer modeling with Cloudy reproduces the H_2 line populations with $T_{\text{gas}} = 600$ K, $n_{\text{H}} = 7.9 \times 10^3$ cm^{-3}, and an incident FUV field of $G_0 \approx 1.6 \times 10^4$. The coexistence of this feedback-driven environment alongside deeply embedded protostars suggests a multi-generational star formation scenario.

- **Key Result:** The PDR parameters derived from Cloudy modeling are $T_{\text{gas}} = 600$ K, $n_{\text{H}} = 7.9 \times 10^3$ cm^{-3}, and an FUV field of $G_0 \approx 1.6 \times 10^4$ Habing units.
- **Implication:** The authors highlight the need for future JWST observations of pure rotational H_2 lines to better constrain the PDR density and further characterize the region.
- **Method Note:** PDR modeling was performed using the Cloudy code, which offers a direct comparison point for 3D-PDR simulations.

2.3 PDR Structures from Thermal Instability

Paper: The influence of steady temperature on the noise-induced structures in the Orion Bar PDR ↑

Authors: I. A. Pomelnikov, D. S. Riashchikov, D. I. Zavershinskii, N. E. Molevich

This paper employs 1D hydrodynamic simulations with Athena++ to investigate the formation of structures in the atomic zone of the Orion Bar PDR. By introducing small ($\sim 1\%$) random noise perturbations into an isentropically unstable medium, the simulations demonstrate the growth and saturation of these fluctuations into stable shock waves. Fourier analysis indicates a dominant characteristic structure size of approximately 5.0×10^{-3} pc, which remains consistent for initial temperatures $T_0 \geq 600$ K. This result aligns with observed widths of dense structures in the Orion Bar, suggesting thermal instability as a formation mechanism for fine-scale PDR morphology.

- **Key Result:** The simulations report a characteristic size of approximately 5.0×10^{-3} pc for the noise-induced density structures, consistent with observed filament widths in the Orion Bar.

- **Implication:** This mechanism offers a physical origin for complex density structures in PDRs, providing hydrodynamically generated initial conditions for advanced chemical modeling with tools like 3D-PDR.

2.4 CO Line Turbulence Overestimation

Paper: Turbulence inference from CO spectral observations ↑

Authors: Jayashree Narayan, Aris Tritsis, **Christoph Federrath**

This study utilized a chemo-dynamical magnetohydrodynamic simulation, post-processed with a non-local thermodynamic equilibrium radiative transfer code (PYRATE), to generate synthetic CO(1-0) and CO(2-1) spectral cubes. It reports that turbulence measurements from these CO lines systematically overestimate the true 3D turbulent velocity dispersion (σ_v) compared to an ideal optically thin tracer. A correction factor, $\mathcal{R}_{\mathrm{CO}}$, was determined, with $\mathcal{R}_{\mathrm{CO,1\text{-}0}} = 0.88^{+0.09}_{-0.08}$ and $\mathcal{R}_{\mathrm{CO,2\text{-}1}} = 0.88^{+0.10}_{-0.08}$. This suggests that prior CO-derived σ_v values may be overestimated by an average of 10–15%, which could influence calculations of turbulent Mach numbers and virial parameters in molecular clouds.

- **Key Result:** Turbulent velocity dispersion derived from CO(1-0) and CO(2-1) is systematically overestimated by ~ 10–15%, requiring a correction factor $\mathcal{R}_{\mathrm{CO}} \approx 0.88$.
- **Implication:** The derived correction factors apply to solar neighborhood conditions. Extending this analysis to low-metallicity or high-cosmic-ray environments, using tools like 3D-PDR, may be of interest to explore environmental dependencies.

2.5 MIRION Catalog: Thousands of Compact PDRs

Paper: The Milky Way Project: Bridging Intermediate- and High-Mass Star Formation with the MIRION Catalog of Yellowballs ↑

Authors: Devine, Kathryn et al.

This paper presents the Mid-InfraRed Interstellar Objects and Nebulae (MIRION) catalog, comprising 6,176 compact photodissociation regions (PDRs) identified via citizen science from Spitzer mid-infrared data. Analysis of multi-wavelength photometry and cross-matched molecular cloud properties reveals correlations between IR colors and the physical states of star-forming regions. Notably, these PDRs exhibit low

$\log_{10}(F_{12}/F_8) \approx -0.48$, indicative of compact regions, and distinct $\log_{10}(F_{24}/F_8)$ values differentiate intermediate- from high-mass star formation environments. This extensive observational dataset provides a valuable resource for studying the transition between different star formation regimes and validating PDR models.

- **Key Result:** The MIRION catalog contains 6,176 compact PDRs, with over 50% being candidate intermediate-mass star-forming regions ($10 < M_{\text{clump}} < 10^4\, M_\odot$, $10 < L_{\text{bol}} < 10^5\, L_\odot$).
- **Method Note:** Sources were identified by citizen scientists; photometry is subject to ongoing refinement through a student-led project.
- **Implication:** Specific mid-infrared color ratios serve as diagnostics for the compactness and hardness of the illuminating UV radiation field in PDRs.

Extragalactic & AGN Feedback

This section covers H_2 excitation diagnostics in AGN environments and evidence for star formation within galactic outflows.

3.1 H_2 Excitation by Shocks and X-rays in a Low-Luminosity AGN Core

Paper: Shocked, heated, and now resolved: H_2 excitation in the low-luminosity AGN at M58 core with JWST ↑

Authors: **I. E. López**, **E. Bertola**, V. Reynaldi, P. Ogle, R. D. Baldi, M. Brusa, S. García-Burillo, S. Sebastian, M. V. Zanchettin et al.

This study utilizes JWST NIRSpec and MIRI MRS observations of the central kiloparsec of M58 to investigate warm H_2 excitation in a low-luminosity AGN (LLAGN) environment. Analysis of 44 H_2 lines indicates that pure rotational emission is consistent with heating by low-velocity (10–40 km/s) C-type shocks, while rovibrational lines show a 10–30% non-thermal component attributed to AGN X-ray heating. Crucially, cosmic rays are ruled out as a dominant excitation source, requiring an unphysically high ionization rate of $\zeta \sim 10^{-10} - 10^{-9}\ \mathrm{s}^{-1}$. These findings demonstrate that even weak AGN feedback can subtly perturb and regulate nuclear molecular gas reservoirs through thermal heating and turbulence.

- **Key Result:** Pure rotational H_2 is excited by low-velocity C-type shocks; rovibrational H_2 shows a 10–30% non-thermal contribution from AGN X-rays. Cosmic rays are ruled out as a primary H_2 excitation mechanism, requiring an ionization rate orders of magnitude higher than typical Galactic values.
- **Implication:** This highlights a “gentle” mode of LLAGN feedback that heats gas and induces turbulence in the inner ~ 200 pc, subtly regulating nuclear gas reservoirs without driving massive outflows.
- **Method Note:** The JWST NIRSpec/MIRI MRS data (Program 3671) offers a robust dataset for benchmarking future 3D-PDR developments incorporating shock and X-ray physics.

3.2 Star Formation in Galactic Outflows

Paper: Signatures of star formation inside galactic outflows ↑

Authors: Ong, Dily Duan Yi, D'Eugenio, Francesco, **Maiolino, Roberto**, Arribas, Santiago, Belfiore, Francesco, **Bellocchi, Enrica**, **Carniani, Stefano**, **Cazzoli, Sara**, **Cresci, Giovanni** et al.

This study utilized VLT/X-shooter spectroscopic data to investigate the ionization mechanisms and physical properties of galactic outflows in 12 local (U)LIRGs. Through kinematic decomposition and spatially resolved BPT diagrams, combined with MAPPINGS V shock models and ionization parameter analysis, robust evidence for *in situ* star formation was identified within the outflow of IRAS 20551-4250. This outflow exhibits a star formation rate of approximately $5.2\,M_{\odot}\,yr^{-1}$, contributing around 3% to the host galaxy's total starburst SFR, with electron densities comparable to disk HII regions. These findings suggest that star formation within outflows may represent a distinct mode contributing to galaxy spheroid evolution.

- **Key Result:** Robust *in situ* star formation was found in the outflow of IRAS 20551-4250, with an estimated $SFR_{out} \approx 5.2\,M_{\odot}\,yr^{-1}$, contributing approximately 3% to the galaxy's total SFR.
- **Method Note:** The study rigorously rules out shocks and external photoionization for the observed optical line ratios, suggesting the need to consider alternative volumetric heating mechanisms in these environments.

SECTION 4

Turbulence & Numerical Methods

This section covers advances in turbulence physics, subgrid models for multiphase gas, numerical methods for subsonic MHD, magnetized disk evolution, and efficient integrators for dust dynamics.

4.1 Turbulence Statistics: Ma and Re Dependence

Paper: Statistical properties of compressible isothermal turbulence from sub- to supersonic conditions ↑

Authors: F. Thiesset, **C. Federrath**

This study presents high-resolution hydrodynamical simulations of driven, isothermal turbulence to systematically quantify the influence of Mach number (Ma) and Reynolds number (Re) on gas properties. It reports that while density PDFs are approximately log-normal with variance $\sigma_\rho^2 \propto Ma^2$, the PDFs of velocity divergence (θ) exhibit increasing intermittency with Ma and Re. A notable finding is that for $Ma \geq 2$, the variance of velocity divergence σ_θ^2 saturates, becoming dependent solely on Re rather than Ma. This suggests a physical limit to shock intensity in highly supersonic flows, shifting the kinetic energy cascade from a Kolmogorov-like ($\zeta \approx 2/3$) to a Burgers-like ($\zeta \approx 1$) scaling for $Ma > 1$.

- **Key Result:** The saturation of velocity divergence statistics at high Mach numbers ($Ma \geq 2$), where σ_θ^2 depends only on Re, offers a new physical constraint on shock intensity and energy dissipation in highly supersonic flows.
- **Data Availability:** The full 55 TB simulation dataset is available from the authors, offering a valuable resource for testing and calibrating the "Turbulent Cloud Database" within your Statistical Galaxy Emulation project.

4.2 Multifluid Subgrid for Multiphase Gas

Paper: MOGLI: model for multiphase gas using multifluid hydrodynamics ↑

Authors: Das, Hitesh Kishore, **Gronke, Max**, **Weinberger, Rainer**

This study presents MOGLI, a subgrid framework within multifluid AREPO, designed to simulate astrophysical multiphase gas (hot $\sim 10^6$ K, cold $\sim 10^4$ K) without resolving small scales. It incorporates drag, turbulent mixing, and cold gas growth. The model demonstrates good qualitative and quantitative agreement with high-resolution single-fluid simulations, reproducing cold gas survival criteria as an emergent property. This approach makes computationally prohibitive multiphase simulations feasible on larger scales.

- **Key Result:** The MOGLI framework achieves performance comparable to brute-force 3000^3 resolved simulations using a 64^3 grid, demonstrating significant computational savings for multiphase gas dynamics.
- **Method Note:** The model utilizes a velocity gradient-based estimator for local subgrid turbulent velocities, which is robust for inhomogeneous astrophysical turbulence.
- **Implication:** The current model lacks magnetic fields, but its multifluid approach could be extended to include additional gas phases (e.g., molecular gas), which may be relevant for future work.

4.3 Low-Dissipation MHD for Subsonic Turbulence

Paper: Mitigating numerical dissipation in simulations of subsonic turbulent flows ↑

Authors: James Watt, **Christoph Federrath**, Claudius Birke, Christian Klingenberg

This study evaluates numerical schemes in the FLASH MHD code, including a new USM-BK solver, for simulating subsonic ($\mathcal{M} < 1$) turbulent flows. It reports that conventional schemes exhibit excessive dissipation, whereas the USM-BK method demonstrably preserves kinetic and magnetic energy more effectively. For a turbulent dynamo at $\mathcal{M} = 0.01$, USM-BK yields a numerical hydrodynamic Reynolds number of approximately 800, notably higher than other schemes (e.g., ≈ 240 for USM-HLLD), and its effective Reynolds number shows independence from Mach number ($Re \propto \mathcal{M}^0$). This approach resolves finer turbulent structures, providing more accurate representations of low-Mach astrophysical environments.

- **Key Result:** The USM-BK scheme retains 88% of kinetic energy in a $\mathcal{M} = 0.01$ vortex, significantly outperforming other Riemann solvers which can dissipate more than 60% of energy.
- **Method Note:** The USM-BK scheme's effective Reynolds number is found to be independent of Mach number ($Re \propto \mathcal{M}^0$), contrasting with conventional schemes where Re degrades with decreasing $\mathcal{M}$ (e.g., $Re \propto \mathcal{M}^{0.4}$ for USM-HLLD).
- **Implication:** While superior in accuracy for low-Mach flows, the USM-BK scheme imposes stricter time-step constraints ($\Delta t \propto \mathcal{M}$), making it computationally more expensive; implicit implementations are suggested for future work.

4.4 Lagrangian vs. Eulerian for Magnetized Disks

Paper: Lagrangian versus Eulerian Methods for Toroidally-Magnetized Isothermal Disks ↑
Authors: Yashvardhan Tomar, **Philip F. Hopkins**

This study re-examines the idealized problem of toroidally-magnetized isothermal disks using the Lagrangian meshless finite-mass (MFM) and meshless finite-volume (MFV) methods within GIZMO. It finds that Lagrangian methods reproduce the vertical collapse and toroidal magnetic flux loss seen in high-resolution Eulerian simulations, with flux loss continuing until plasma $\beta \approx 1$. At low resolution ($\Delta x \gg H_{\text{thermal}}$), Eulerian methods exhibit no evolution, whereas Lagrangian methods still initiate collapse and flux loss to a one-cell thickness. This suggests that sustained strong toroidal fields in complex Lagrangian multi-physics simulations are physically robust, attributed to additional physics rather than numerical resolution effects.

- **Key Result:** Lagrangian codes show robust collapse and magnetic flux loss, even at low resolution, unlike Eulerian methods which can artificially preserve fields when the thermal scale height is unresolved.
- **Implication:** The persistence of strong magnetic fields in complex Lagrangian simulations is likely physical, arising from additional physics (e.g., turbulence, self-gravity) absent in idealized test problems.
- **Method Note:** The paper leverages GIZMO's MFM and MFV methods to compare against a previous Eulerian (Guo et al. 2025) study, offering a direct comparison of

numerical scheme convergence.

4.5 Efficient Implicit Runge-Kutta for Gas-Dust Drag

Paper: General Implicit Runge-Kutta Integrators for Multifluid Gas-Dust Aerodynamic Drag ↑

Authors: Giovanni Tedeschi-Prades, **Til Birnstiel**, Klaus Dolag, **Barbara Ercolano**, Mark Hutchison

This paper presents a novel General Implicit Runge-Kutta (GIRK) integrator for multifluid gas-dust aerodynamic drag. By leveraging an analytical solution, the method achieves linear scaling, $O(N_d)$, with the number of dust species, contrasting with the $O(N_d^3)$ scaling of matrix inversion methods. The GIRK integrator is compatible with Strang splitting, maintains second-order convergence in the stiff limit, and demonstrates A-stability, offering a robust solution for dust dynamics in hydrodynamical simulations.

- **Key Result:** Reduces computational cost from cubic to linear scaling with dust species, enabling more complex dust physics in simulations.
- **Method Note:** Maintains second-order convergence even in stiff regimes ($\Delta t > t_{\text{stop}}$) and with external forces, a notable improvement over standard implicit methods.
- **Code/Data Availability:** Implementation is publicly available, including a Mathematica notebook for parameter derivation and a 1D test code with a Jupyter notebook.

Machine Learning & Statistics

This section covers advances in ML architectures for galaxy emulation, including Transformer models for line intensity mapping, GNN-based cosmology inference, efficient nested sampling, probabilistic dust mapping, physics-aware diffusion models for turbulence, scalable Gaussian processes, Bayesian symbolic regression, and spherical neural operators.

5.1 Transformer for Galaxy Line Intensity Mapping

Paper: CosmoGLINT: Cosmological Generative Model for Line Intensity Mapping with Transformer ↑

Authors: Moriwaki, Kana, Jun, Rui Lan, Osato, Ken, **Yoshida, Naoki**

This study introduces CosmoGLINT, a Transformer-based generative model designed to efficiently create realistic galaxy populations from dark matter-only simulations. Trained on the IllustrisTNG hydrodynamic simulation, the model auto-regressively generates galaxy properties, including star formation rates and kinematics. It successfully reproduces key statistical properties of the parent simulation, such as the voxel intensity distribution and the 3D power spectrum of the SFR field in both real and redshift space. This framework offers a computationally efficient alternative for generating mock galaxy catalogs for upcoming Line Intensity Mapping and galaxy redshift surveys.

- **Key Result:** The Transformer architecture effectively captures intra-halo correlations and accurately reproduces the SFR power spectrum across cosmological scales, outperforming simpler models.
- **Code Availability:** The CosmoGLINT code is publicly available on GitHub, facilitating potential adoption and testing of the methodology.
- **Implication:** Future versions could generate metallicity directly, offering a more direct interface for metallicity-dependent X_{CO} and X_{CI} conversion factors.

5.2 GNN Cosmology Emulation from Semi-Analytic Models

Paper: Galaxy Phase-Space and Field-Level Cosmology: The Strength of Semi-Analytic Models ↑

Authors: de Santi, Natalí S. M., **Francisco Villaescusa-Navarro**, Araya-Araya, Pablo, De Lucia, Gabriella, Fontanot, Fabio, Perez, Lucia A. et al.

This study presents a Graph Neural Network (GNN) coupled with a Moment Neural Network, trained exclusively on galaxy phase-space data (3D positions and radial velocities) from the computationally efficient L-Galaxies semi-analytic model. The network accurately inferred the matter density parameter, Ω_m, with an approximate 10% precision. Notably, it successfully extrapolated these predictions to other semi-analytic models and, critically, to full hydrodynamical simulations (e.g., IllustrisTNG, SIMBA), maintaining an accuracy below 12% relative error. This work suggests that semi-analytic models effectively capture large-scale cosmological information, offering a robust and computationally efficient approach for training machine learning emulators to bridge disparate simulation paradigms for cosmological parameter inference.

- **Key Result:** The GNN's performance was robust against variations in subgrid physics, astrophysical parameters, and halo-finding methods across diverse simulation suites.
- **Method Note:** The model's success heavily relied on the comprehensive diversity of the L-Galaxies training data, which encompassed the properties of all test simulations.

5.3 Hybrid Nested Sampling for Simulation-Based Inference

Paper: PolySwyft: sequential simulation-based nested sampling ↑

Authors: Kilian H. Scheutwinkel, **Will Handley**, Christoph Weniger, Eloy de Lera Acedo

This paper introduces PolySwyft, a framework for simulation-based inference that integrates Neural Ratio Estimation (NRE) with Nested Sampling (NS). The NRE serves as a dynamic surrogate likelihood within the NS algorithm, which iteratively generates informative samples to refine the NRE. This approach reported a $\sim 75\%$ increase in sample efficiency on a cosmological inference problem, achieving convergence with approximately 6.5×10^5 simulator calls. The method provides a robust mechanism for exploring complex, multimodal posterior distributions.

- **Key Result:** Demonstrated $\sim 75\%$ greater sample efficiency for cosmological parameter inference, requiring 6.5×10^5 simulator calls versus 2.4×10^6 for standard nested sampling. Effectively recovers multimodal posterior distributions.
- **Method Note:** The approach uses Nested Sampling to intelligently guide where expensive simulations are performed, acting as an active learning strategy to focus computational effort on informative regions of parameter space.
- **Code Availability:** PolySwyft is released as open-source software for broader application.

5.4 Probabilistic Dust Mapping with Normalising Flows

Paper: Data-driven dust inference at mid-to-high Galactic latitudes using probabilistic machine learning ↑

Authors: O'Callaghan, Matthew, **Mandel, Kaisey S.**, **Gilmore, Gerry**

This paper presents FLOWER, a probabilistic machine learning method using normalising flows to infer dust reddening towards stars at mid-to-high Galactic latitudes. By learning the conditional probability distribution of intrinsic stellar colour-magnitude relations from Gaia, Pan-STARRS, and 2MASS data, the method accurately recovers unbiased posterior distributions. It achieves an average posterior standard deviation of $\sigma_{E(B-V)} \approx 0.038$ mag, successfully tracing known 3D dust structures at distances of approximately 370 pc and 1.7 kpc. This approach offers robust 3D ISM mapping by mitigating modeling errors and prior assumptions in low-extinction environments.

- **Key Result:** The method achieves an average posterior standard deviation of $\sigma_{E(B-V)} \approx 0.038$ mag using Gaia+PS1+2MASS data, demonstrating precision for low-extinction regions.
- **Method Note:** The normalising flow implicitly handles unresolved binaries by learning the full, complex colour-magnitude distribution, reducing biases from simplified stellar models.

5.5 Physics-Aware Diffusion for Turbulent Emulation

Paper: Lazy Diffusion: Mitigating spectral collapse in generative diffusion-based stable autoregressive emulation of turbulent flows ↑

Authors: **Anish Sambamurthy**, **Ashesh Chattopadhyay**

This study addresses spectral collapse in diffusion-based generative models when emulating turbulent flows with power-law spectra. By analyzing the forward diffusion process, the authors demonstrate that standard models inherently degrade high-wavenumber modes, causing an intrinsic spectral bias. They propose physics-aware solutions: a power-law noise schedule ($\beta(\tau) \propto \tau^{\gamma}$ with $\gamma \approx 5.0$) to preserve fine-scale structure, and "Lazy Diffusion," a one-step distillation method. These techniques restore physically realistic inertial-range scaling and enable stable, long-horizon autoregressive predictions, while Lazy Diffusion reduces inference cost by three orders of magnitude.

- **Key Result:** The study shows that standard diffusion models are incompatible with power-law physics, leading to spectral collapse. A physics-aware power-law noise schedule mitigates this, stabilizing predictions and reproducing correct inertial-range scaling.
- **Method Note:** Lazy Diffusion offers a one-step distillation approach that significantly reduces inference cost (three orders of magnitude) while maintaining spectral accuracy for multiscale turbulent systems.
- **Code Availability:** The authors provide their code on GitHub, which may be useful for initial implementation in your emulation efforts.

5.6 Scalable Exact GPs via Sparse Non-Stationary Kernels

Paper: gp2Scale: A Class of Compactly-Supported Non-Stationary Kernels and Distributed Computing for Exact Gaussian Processes on 10 Million Data Points ↑

Authors: **Marcus M. Noack**, Mark D. Risser, Hengrui Luo, Vardaan Tekriwal, **Ronald J. Pandolfi**

This paper introduces gp2Scale, a method enabling exact Gaussian Process (GP) regression on datasets exceeding 10 million points. The approach utilizes a novel class of compactly-supported, non-stationary kernels to identify intrinsic sparsity in the covariance matrix, circumventing the cubic computational scaling ($O(N^3)$) of traditional GPs. This allows for high-fidelity predictions and robust uncertainty quantification on massive, complex datasets, without the accuracy limitations of approximation techniques. For instance, it achieved an RMSE of 2.8509 on a 10 million point 3D temperature dataset.

- **Key Result:** The method scales exact Gaussian Process regression to over 10 million data points, addressing a fundamental limitation in GP applications.
- **Method Note:** The core innovation lies in engineering non-stationary, compactly-supported kernels to induce natural sparsity, which is then exploited with distributed computing (e.g., 1024 A100 GPUs).
- **Code Availability:** The gp2Scale methodology is implemented in the open-source Python package gpCAM, making it directly accessible for testing and integration.

5.7 Robust Symbolic Regression from Noisy Data

Paper: Bayesian Symbolic Regression via Posterior Sampling ↑
Authors: Bomarito, Geoffrey F. and Leser, Patrick E.

This paper reports a Bayesian symbolic regression (SR) approach utilizing a Sequential Monte Carlo (SMC) framework to infer governing equations from noisy data. This method approximates the posterior distribution over symbolic expressions, demonstrating superior performance on challenging noisy benchmark problems compared to traditional genetic programming baselines. It notably reduces overfitting, yielding more robust and generalizable solutions for automated scientific discovery.

- **Key Result:** The SMC-SR algorithm demonstrates improved performance over Genetic Programming baselines on noisy benchmark datasets, achieving lower test-set errors and reducing overfitting.
- **Method Note:** The framework approximates the Bayesian posterior distribution over symbolic expressions, which naturally provides uncertainty quantification for the discovered equations.
- **Implication:** This method enables more robust and interpretable discovery of phys-

ical laws from complex, noisy datasets, relevant for automated scientific discovery.

5.8 Generalized Spherical Neural Operators

Paper: Generalized Spherical Neural Operators: Green's Function Formulation ↑

Authors: Hao Tang, Hao Chen, Chao Li

This study introduces the Green's-function Spherical Neural Operator (GSNO), a novel machine learning architecture for solving parametric partial differential equations on spherical domains. By formulating the operator based on a designable spherical Green's function with harmonic expansion, GSNO achieves a flexible balance between rotational equivariance and invariance, enabling it to model complex, anisotropic physical constraints. When integrated into a hierarchical network (GSHNet), the method reports up to a 7.5% improvement in Mean Relative Error on spherical shallow water equations and a 3.3% improvement in Anomaly Correlation Coefficient for weather forecasting compared to prior state-of-the-art models. This approach presents a principled, physics-informed framework for spherical operator learning.

- **Key Result:** GSNO's kernel decomposition allows flexible modeling of anisotropic, position-dependent physical constraints, a notable advance over strictly equivariant methods.
- **Method Note:** The hierarchical GSHNet architecture combines multi-scale spectral modeling with spherical up-down sampling, enhancing feature representation for complex systems.
- **Implication:** Grounding the operator in Green's function theory provides a physics-informed approach, which may offer increased interpretability and robustness for emulating physical systems.