

Galaxies: Shapes, Motion, and Evolution

- Galaxies are gravitationally bound systems of stars, gas, dust, and dark matter
- Building blocks that trace the universe's structure and history
- Shapes classify them; spectra reveal their internal motion
- Looking back in time shows their evolution over billions of years
- JWST and modern surveys are transforming this picture

GALAXY MORPHOLOGICAL SEQUENCE

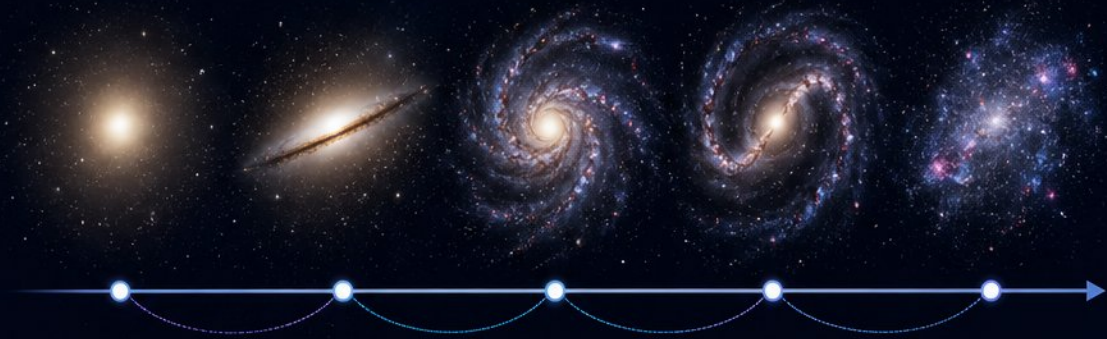
ELLIPTICALS

LENTICULARS

SPIRALS

BARRED SPIRALS

IRREGULARS



MULTI-WAVELENGTH VIEW OF A GALAXY

X-RAY

ULTRAVIOLET

OPTICAL

INFRARED

RADIO

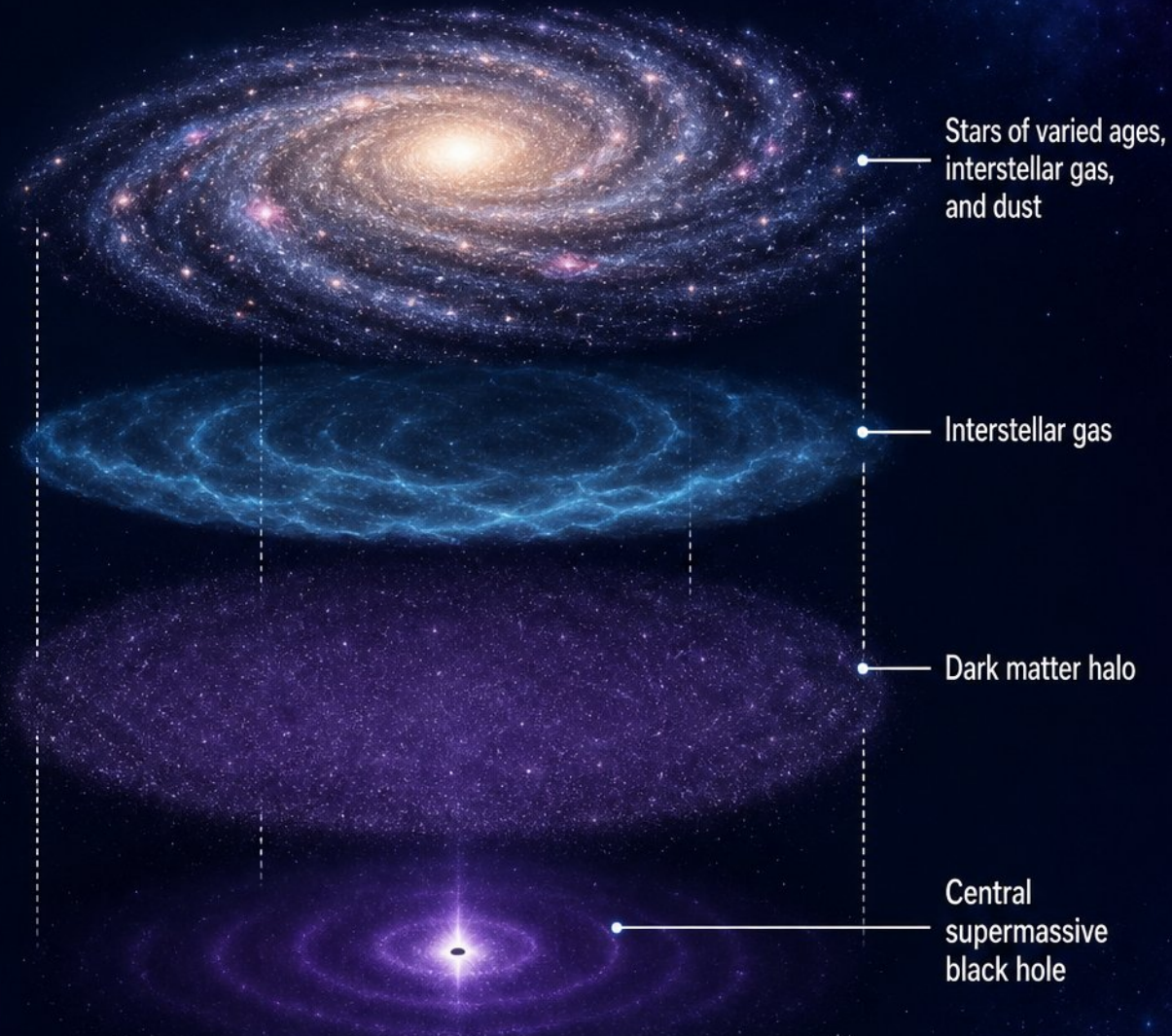


COSMIC EVOLUTION OVER BILLIONS OF YEARS



What Galaxies Are Made Of

- Stars of varied ages, interstellar gas, and dust
- Dark matter halos and central supermassive black holes
- Sizes and masses span orders of magnitude across the galaxy family
- Unseen mass shapes rotation, gravity, and observed light



Galaxy Shapes and the Hubble Tuning Fork



- Main types: elliptical, spiral, barred spiral, lenticular, irregular



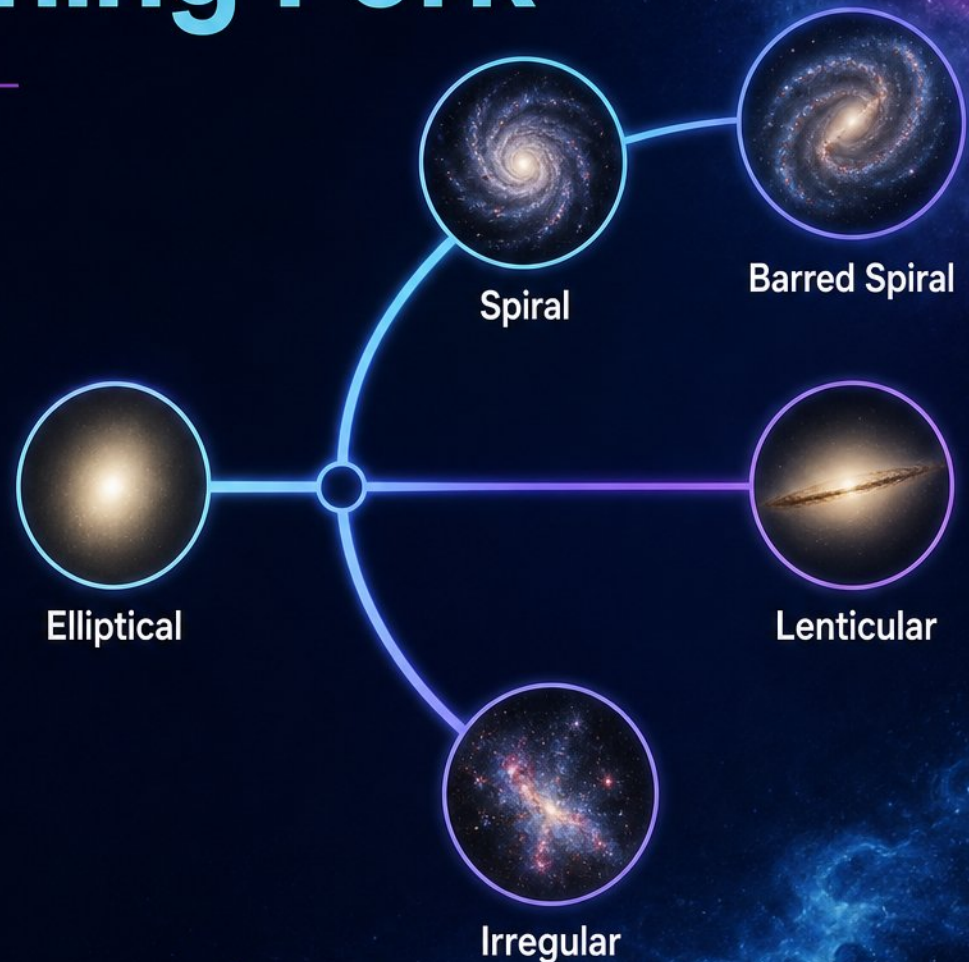
- Hubble tuning fork organizes types by visual structure



- Shape hints at stellar orbits, star formation, and mergers

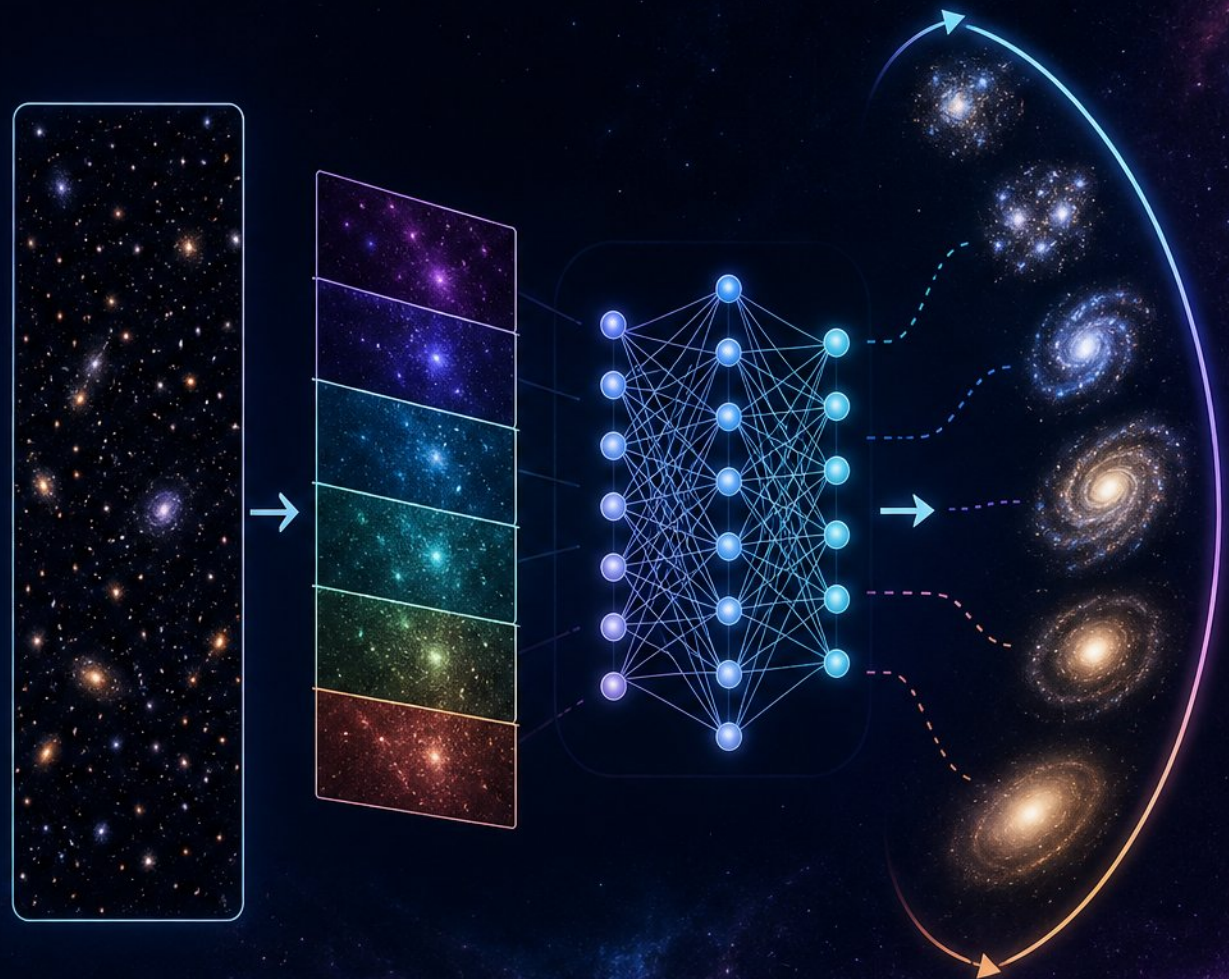


- Classification is a starting guide, not the final word



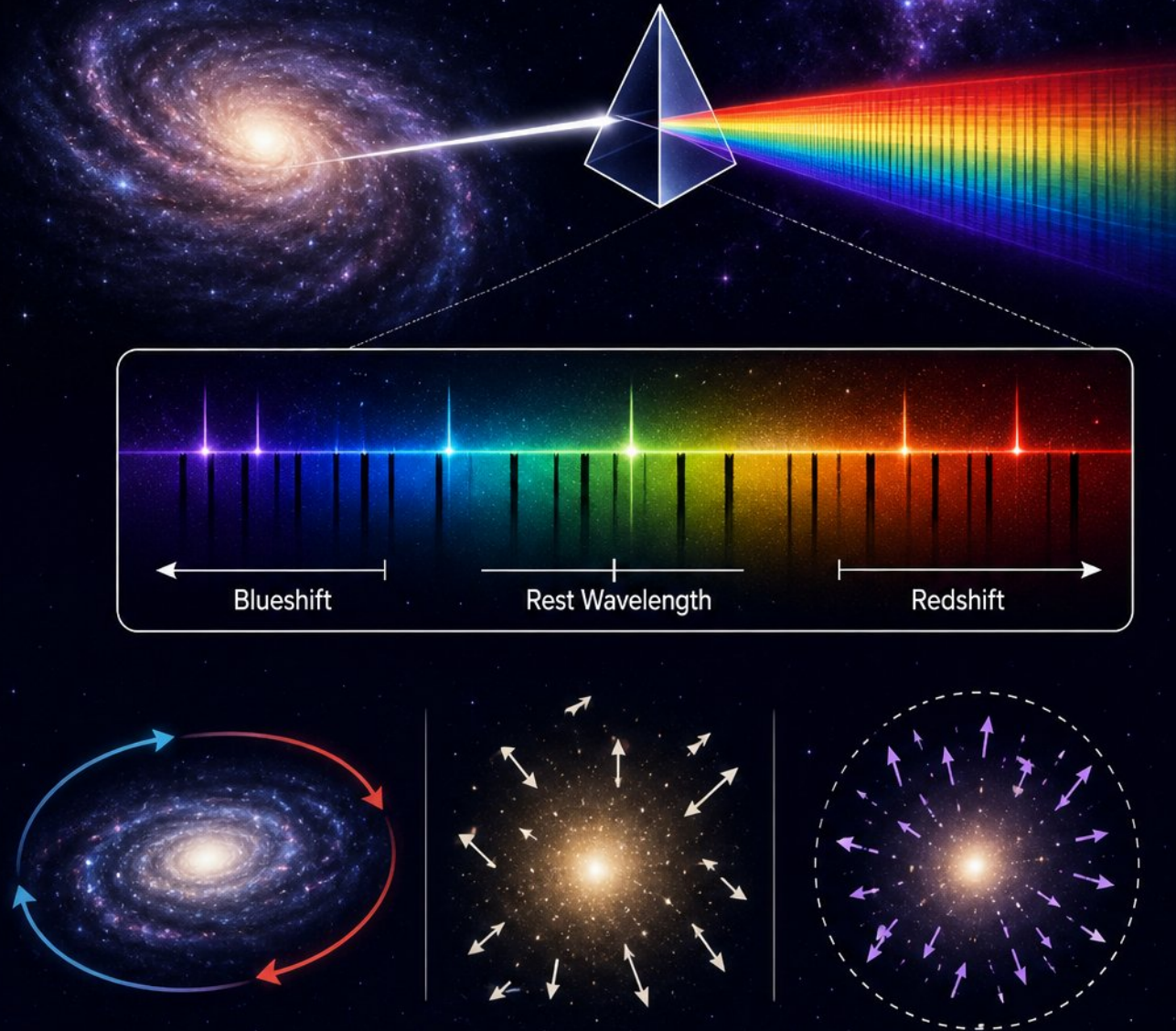
Beyond the Classical Sequence

- - Distant, faint, or clumpy galaxies defy visual Hubble types
- - Machine learning classifies using photometric colors and neural networks
- - COSMOS2025: only 6% of galaxies get intermediate type probabilities
- - Hubble-like sequence emerges surprisingly early, around $z \sim 3-4$
- - High-redshift disks and bulges blur the early-late dichotomy

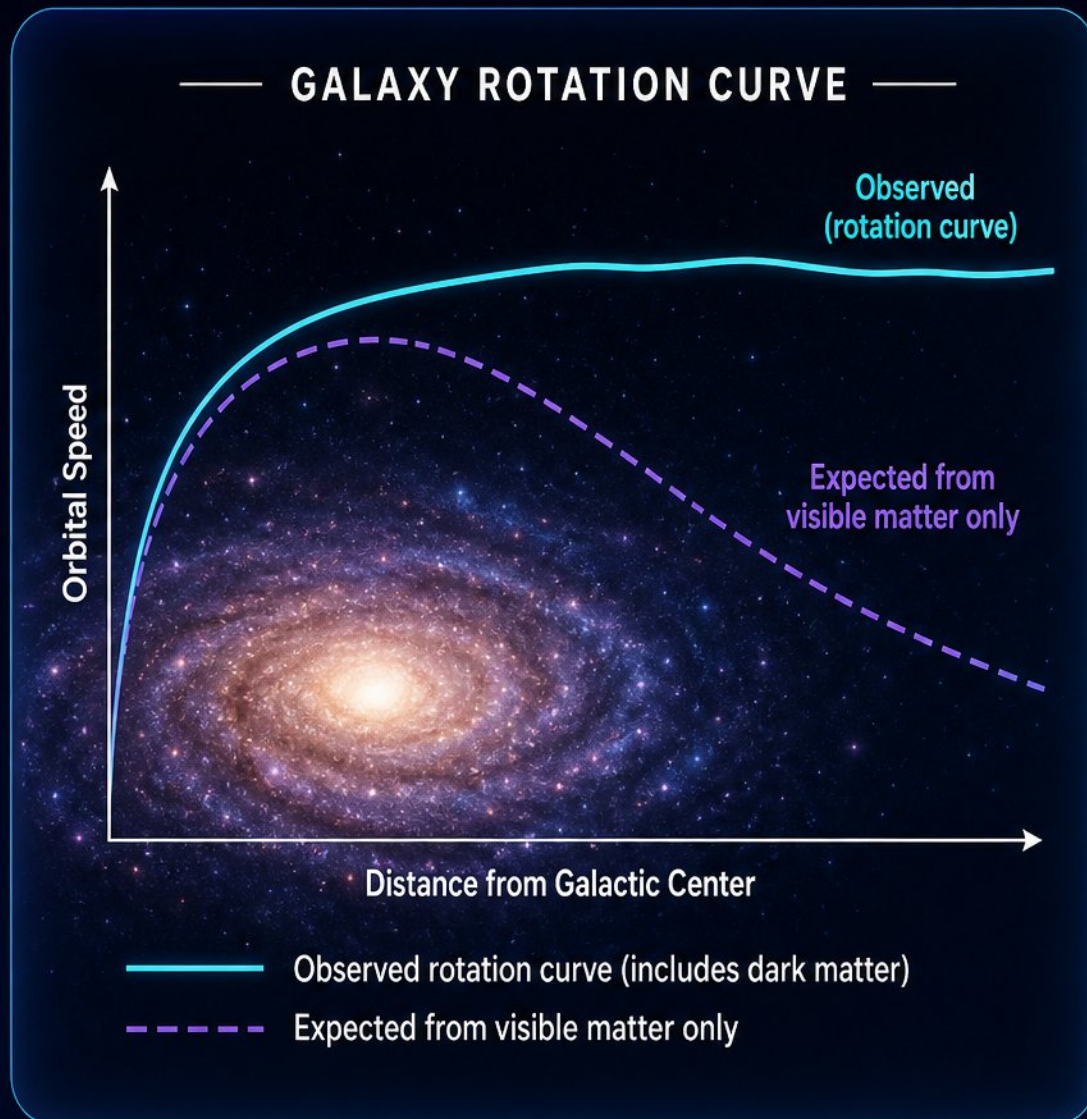


Reading Motion Through Spectra

- - Doppler shifts reveal rotation, orbital motion, and internal velocities
- - Galaxy rotation curves trace dark matter halos beyond visible matter
- - Ordered rotation in disks contrasts with random motion in spheroids
- - Velocity dispersion links galaxy type to central supermassive black hole mass



Dark Matter: Evidence and Open Questions



- Flat rotation curves imply mass beyond visible stars and gas



- Dark matter halos act as scaffolding for galaxy formation



- Simulations test dark matter distributions and galactic dynamics



- Tensions: missing satellites, cusp-core, dwarf galaxy diversity

Galaxy Collisions and Mergers

- Gravity-driven interactions reshape galactic structure
- Stages: approach, distortion, tidal tails, starburst, coalescence
- Major mergers convert ordered disks into spheroidal ellipticals
- Equal-mass mergers reduce, but not always erase, rotation
- Orbital configuration strongly influences final remnant structure



Mergers and Morphology Across Cosmic Time

- Minor mergers preserve rotation but thicken disks and build halos
- Major mergers convert ordered rotation into random motion
- Gas-rich mergers often regrow disks after gravitational disruption
- Orbital configuration shapes remnant bulge and disk fractions
- Even near-equal-mass mergers do not always fully destroy disks



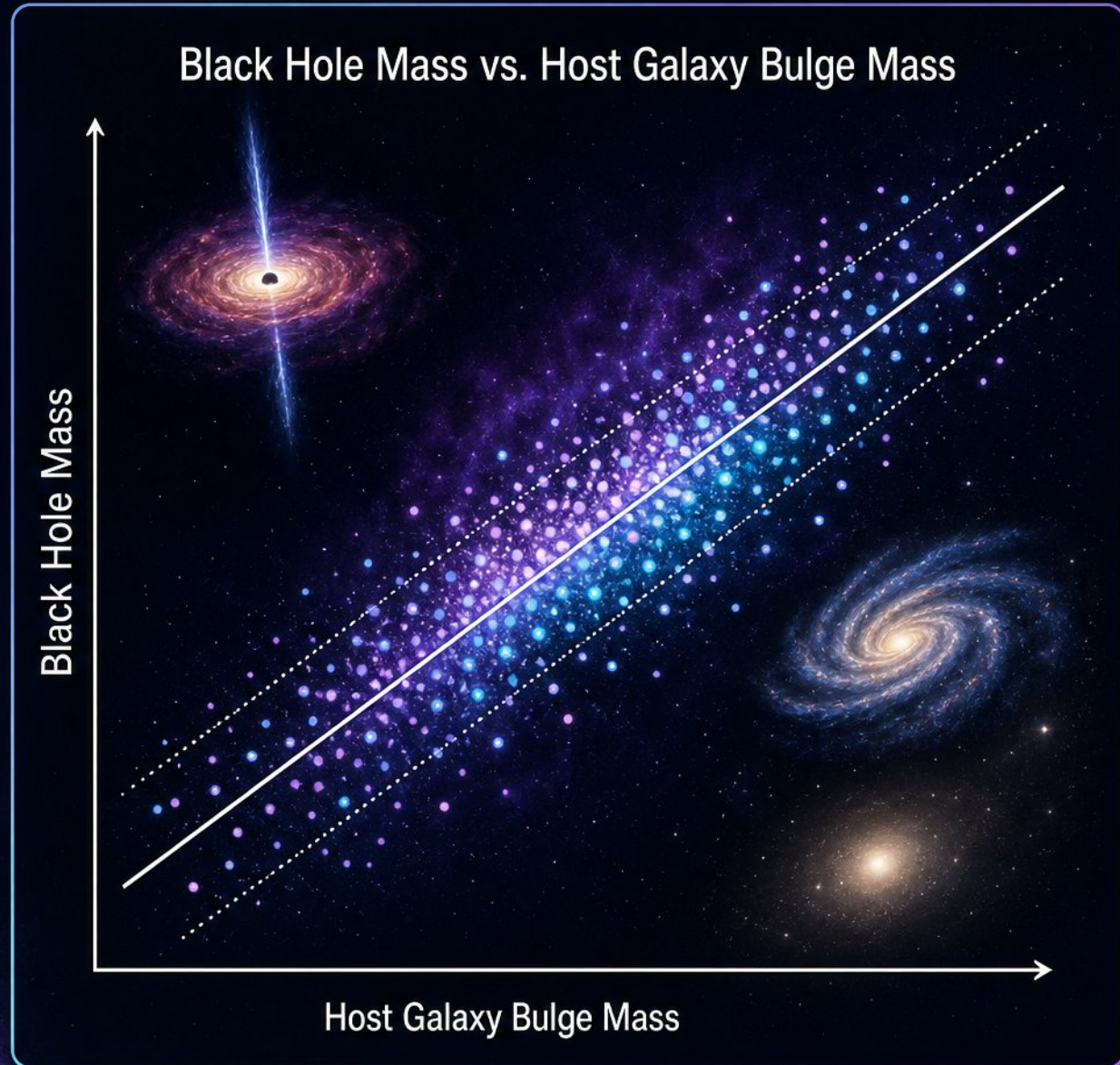
Star Formation and Galactic Environments

- Cluster ram pressure strips gas from the outer disk
- Gas removal reduces molecular gas density and star formation efficiency
- Starvation slowly depletes gas supply across the inner disk
- Moderate stripping can compress gas and briefly enhance star formation
- Massive galaxies quench rapidly; low-mass galaxies quench more gradually



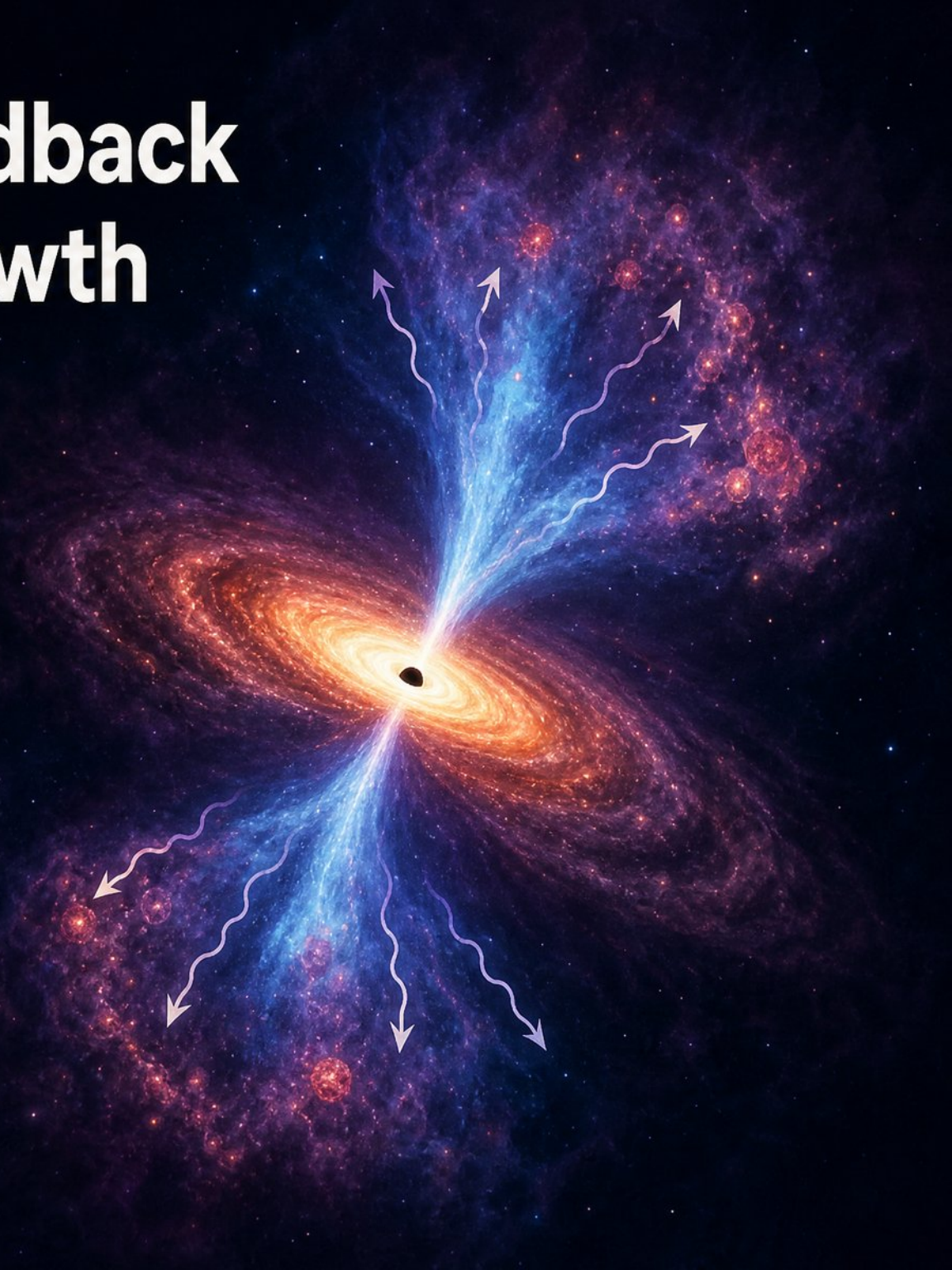
Supermassive Black Holes and Active Galaxies

- Most large galaxies host a central supermassive black hole
- Active galactic nuclei and quasars mark luminous accretion phases
- Black hole mass scales with host stellar mass and velocity dispersion
- Scaling relations show substantial scatter and evolve with redshift
- Coevolution pathways differ between spirals and ellipticals



Black Hole Feedback and Galaxy Growth

- - Black hole outflows heat gas and suppress star formation
- - Feedback is a key regulator of massive galaxy quenching
- - Coevolution is diverse: overmassive and undermassive black holes
- - Simulations disagree on growth timing and pathways



Galaxy Evolution Across Cosmic Time

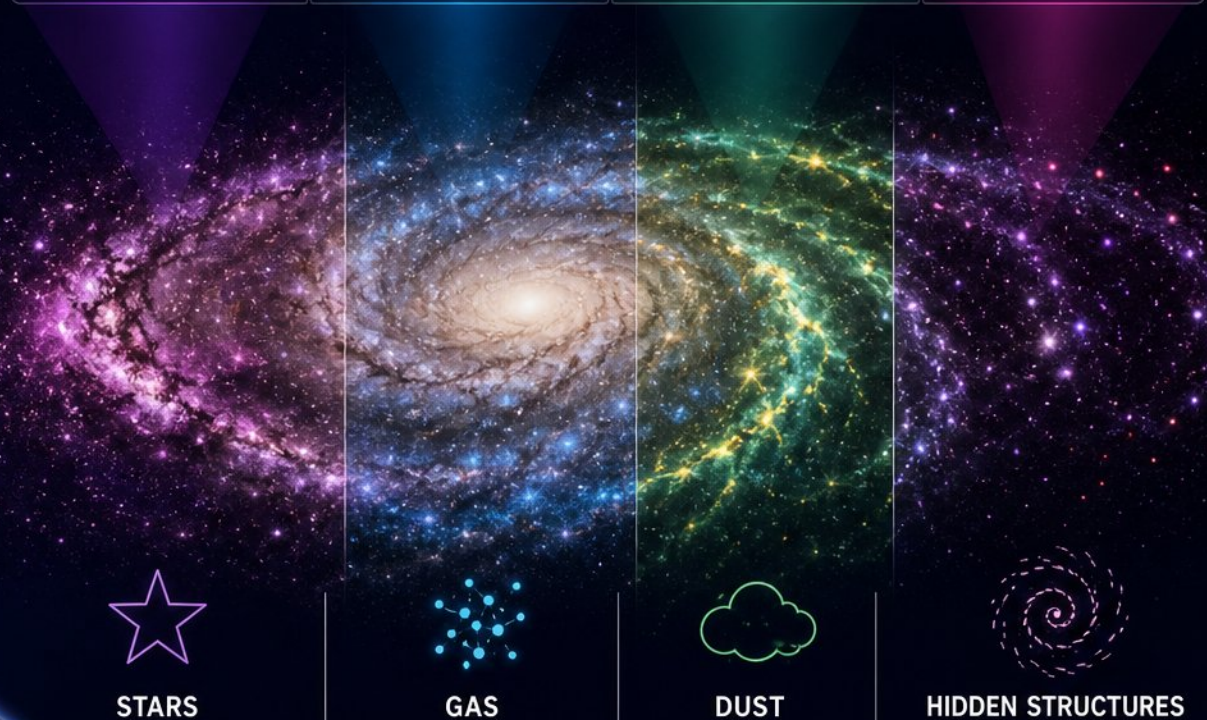


- Deep surveys act as time machines for distant galaxies
- Cosmic star formation peaked near $z \sim 2-3$
- Hubble-like disks emerged by $z \sim 4$
- First galaxies trace back to cosmic dawn
- Present-day mix reflects billions of years of assembly

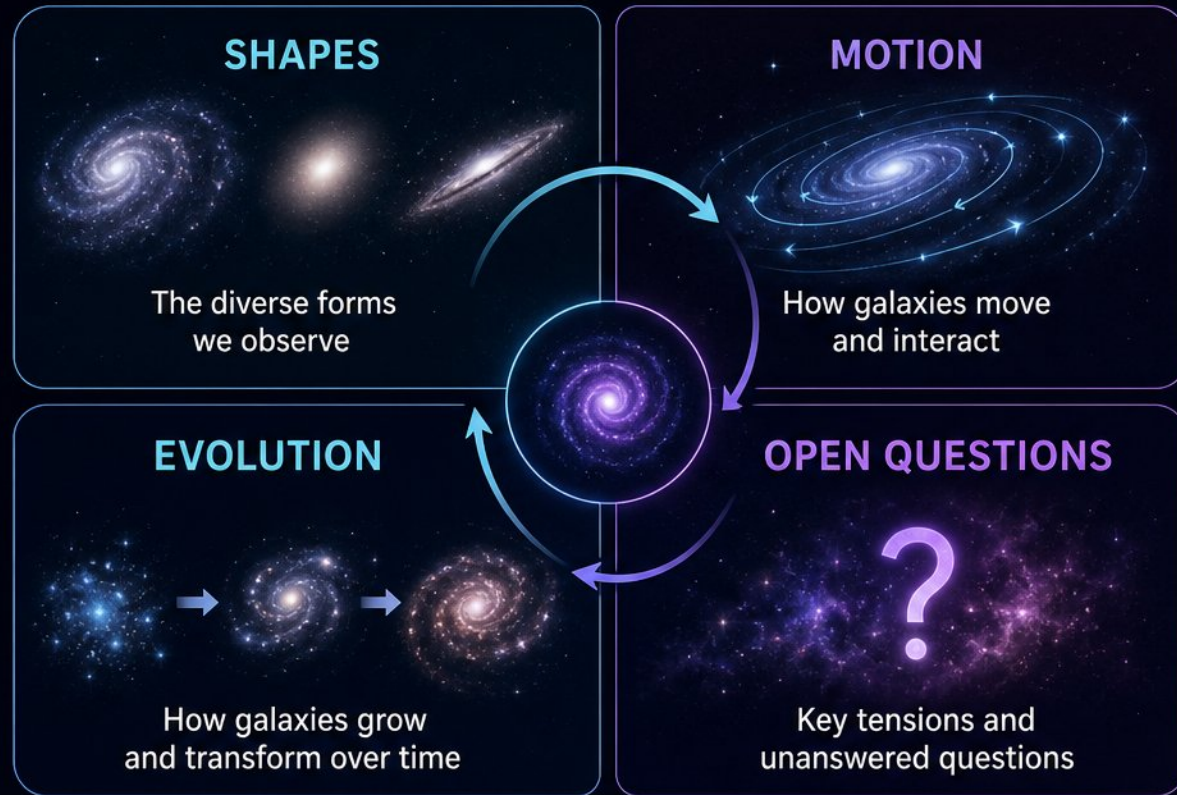
Observing Galaxies Today

- JWST, Euclid, ALMA, and wide-field surveys reveal different galactic components
- Multiwavelength data separates stars, gas, dust, and hidden structures
- Galaxy Zoo and Space Warps let volunteers classify real survey images
- Public archives and Zooniverse projects make real galaxy data explorable

MAJOR OBSERVATORIES AND THEIR WAVELENGTH COVERAGE



Synthesis and Open Questions



- Shapes, motion, and evolution form one integrated galaxy story



- Open problems: quenching, dark matter tensions, feedback, early assembly



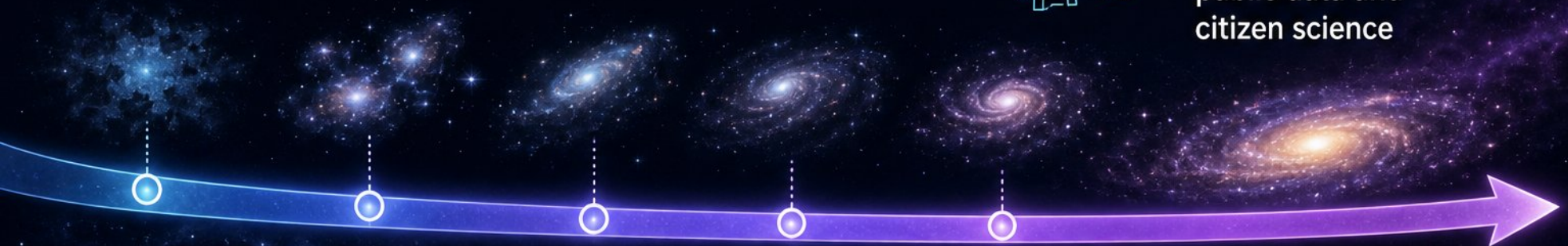
- JWST reveals 'too much too soon' massive early galaxies



- Future work: theory-observation comparison and new surveys



- Learners can explore public data and citizen science



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