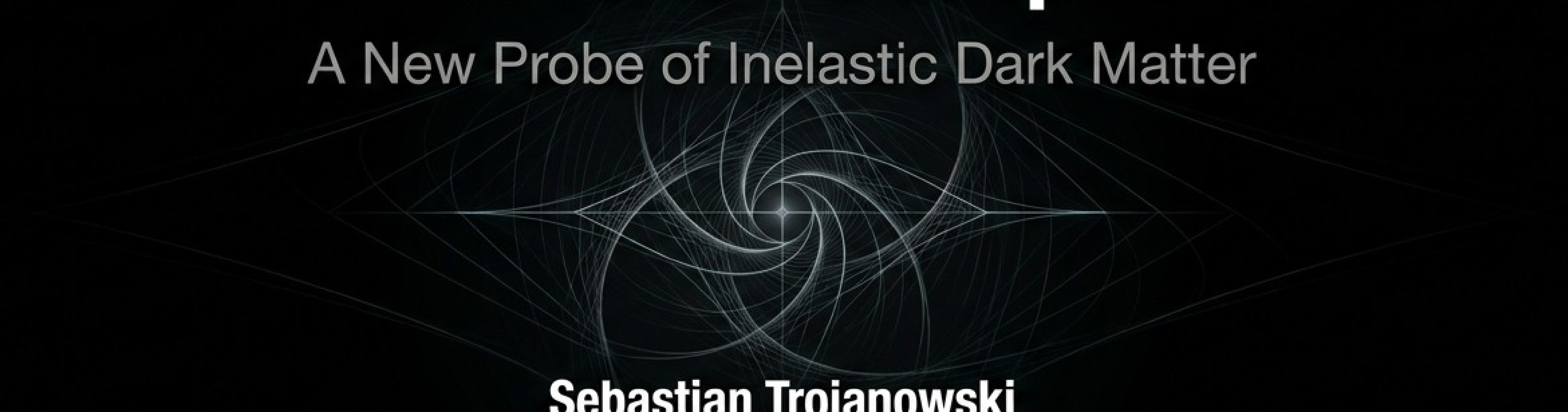
X-ray Smoking Guns from Galactic Center Compact Stars

A New Probe of Inelastic Dark Matter



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DARK MATTER DAY
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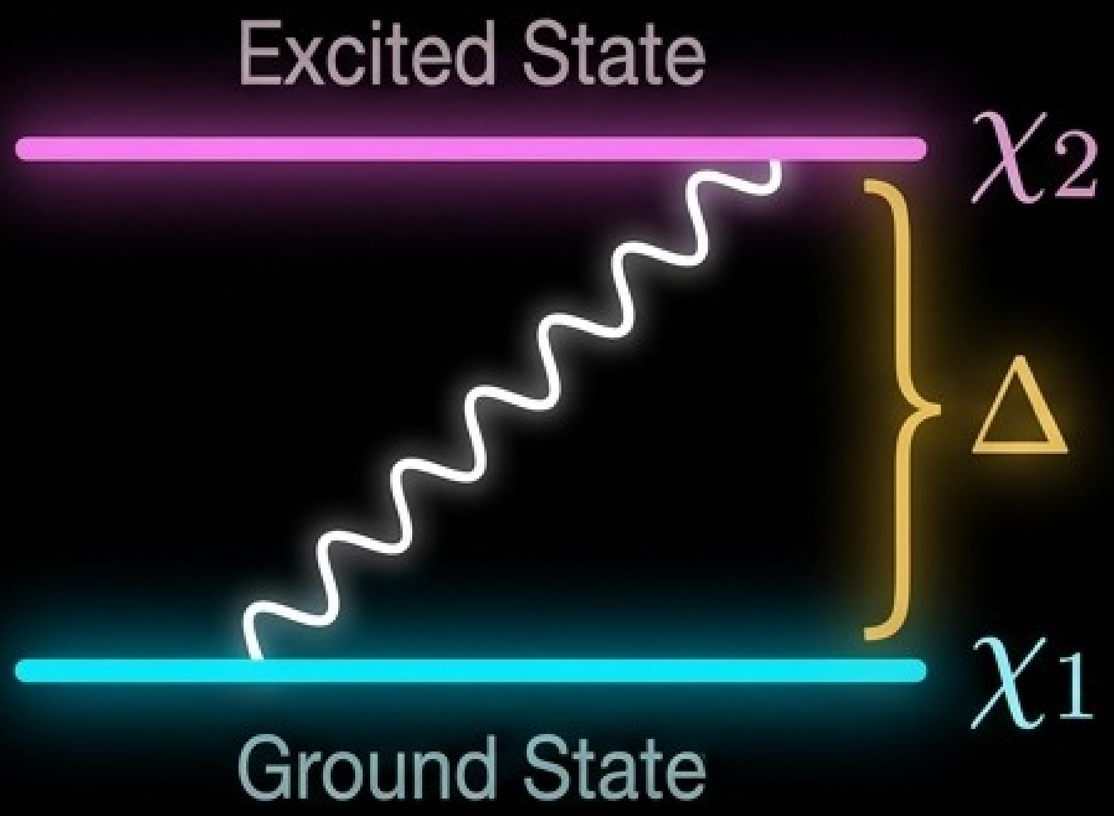
The Inelastic Paradigm:
A Formidable Experimental Target



Two dark states (χ_1, χ_2) separated by a small mass splitting (Δ). The primary gauge coupling is strictly **non-diagonal**.

Kinematically Blocked

Upscattering ($\chi_1 \to \chi_2$) requires kinetic energy. Earth's slow local halo DM ($v \sim 10^{-3}c$) cannot overcome splittings $\Delta \gtrsim 100$ keV.

Relic Depleted

In the early universe, χ_2 set the relic density but has long since decayed. Today, no χ_2 remains, suppressing present-day annihilations.

Compressed Spectra

Accelerators struggle with small mass splittings. Visible decay products are too soft, and long-lived χ_2 escapes the detector.

Inelasticity is a Generic Consequence of Symmetry Breaking

The Standard Model Precedent: Neutral Kaons

- Strong force preserves Strangeness → gives the bulk mass (K^0, $\bar{K}^0$ are degenerate).
- Weak force breaks Strangeness → induces oscillations and a tiny mass splitting (K_S^0, K_L^0).

This mass splitting is 14 orders of magnitude smaller than the Kaon mass!

Example 1: Pseudo-Dirac DM (Dark Photon)

Unbroken Dark $\mathrm{U(1)}_D$ gives Weyl fermions (η, ξ) a bulk Dirac mass M_D. A Dark Higgs breaks the symmetry, adding small Majorana masses m_L, m_R.

$$\mathcal{L}_{\text{mass}} \supset -M_D(\eta\xi) - \frac{m_L}{2}(\eta\eta) - \frac{m_R}{2}(\xi\xi) + \text{h.c.}$$

Splitting: Diagonalizes into two Majorana states χ_1, χ_2 with $\Delta \approx m_L + m_R$.

Coupling: Because χ_i are Majorana, diagonal vector currents must vanish ($\bar{\chi}_1\gamma^\mu\chi_1 \equiv 0$).

Decay: $\chi_2 \to \chi_1 + e^+e^-$

$$\mathcal{L}_{\text{int}} \supset i g_D A'_\mu(\bar{\chi}_1\gamma^\mu\chi_2)$$

Example 2: Higgsino Dark Matter

Unbroken SUSY: μ-term gives degenerate Dirac Higgsino mass. EWSB mixes them with Binos/Winos via the Higgs VEV (v).

$$\mathcal{L}_{\text{mass}} \supset -\mu(\tilde{H}_u\tilde{H}_d) + \frac{gv}{\sqrt{2}}(\tilde{W}\tilde{H}_u) + \ldots + \text{h.c.}$$

Splitting: Splits into two Majorana neutralinos ($\tilde{\chi}_1^0, \tilde{\chi}_2^0$) with $\Delta \sim m_Z^2/M_{1,2}$.

Coupling: The Z-boson inherits the off-diagonal structure.

Decay: $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + f\bar{f}$ or $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + \gamma$

$$\mathcal{L}_{\text{int}} \supset \frac{g}{2\cos\theta_W} Z_\mu \left(\overline{\tilde{\chi}}_1^0\gamma^\mu\gamma^5\tilde{\chi}_2^0\right)$$

Our Benchmark:
The Inelastic Dipole Portal

Effective Interaction: Dimension-5 transition dipole moment.

$$\mathcal{L} \supset \frac{1}{\Lambda_E} \bar{\chi}_2 \sigma^{\mu\nu} \gamma^5 \chi_1 F_{\mu\nu}$$

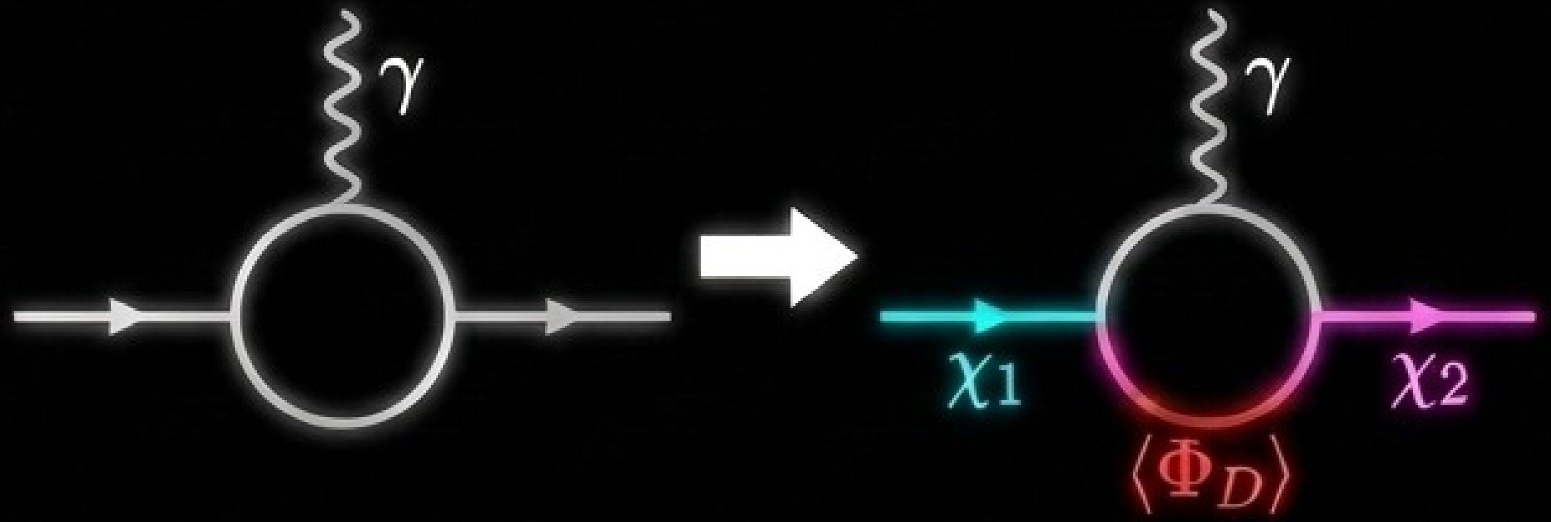
Radiative Decay: This operator naturally dictates a two-body decay: $\chi_2 \rightarrow \chi_1 + \gamma$.

The Terrestrial Kinematic Wall (e.g., XENONnT)

- Sub-GeV Benchmark: $m_{\chi_1} = 50$ MeV, splitting $\Delta = 10$ keV.
- In the local halo ($v \sim 10^{-3}c$), the available center-of-mass kinetic energy is $E_{\text{kin}} \sim 25$ eV.

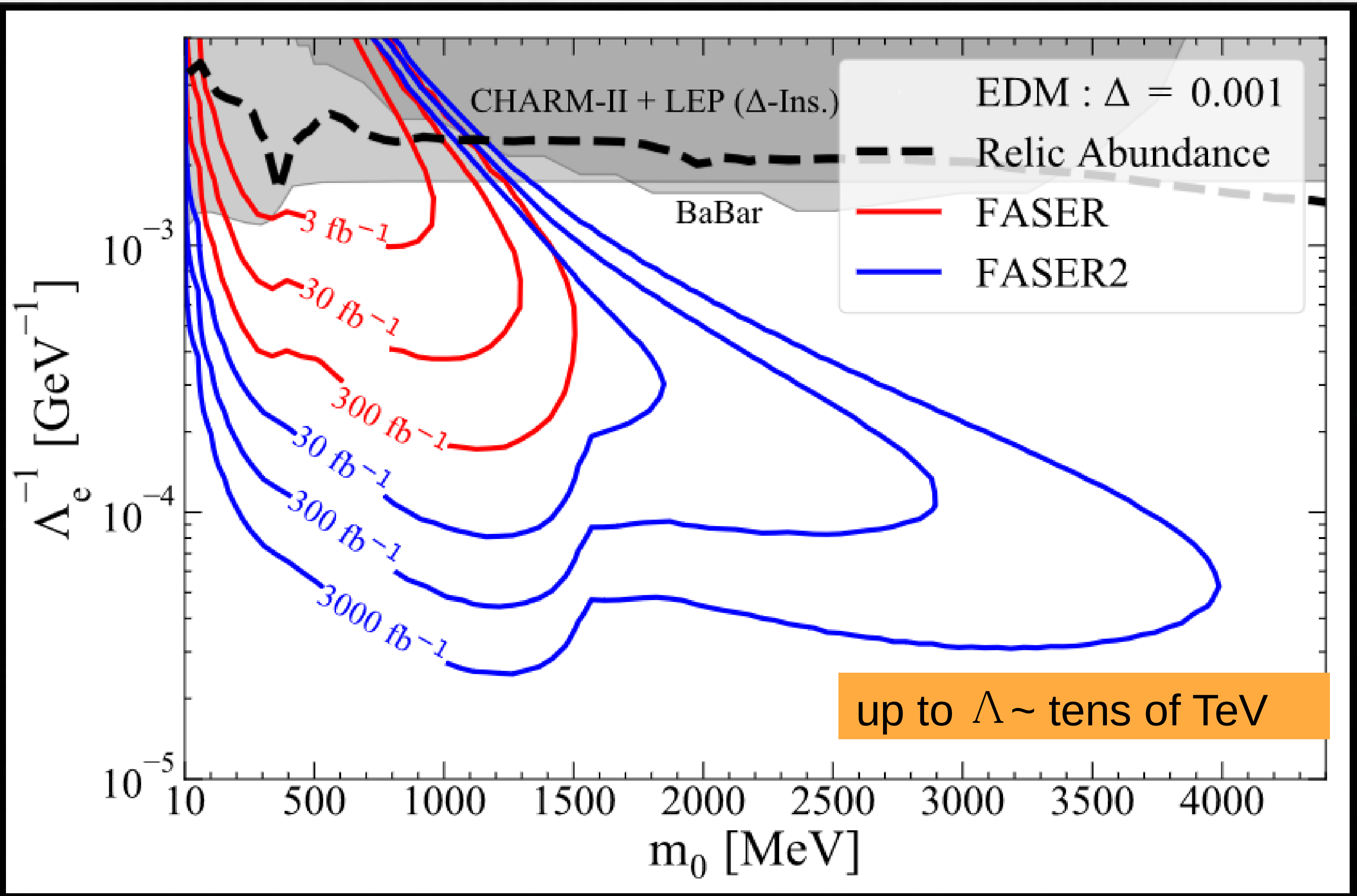
25 eV ≪ 10,000 eV → Upscattering on Earth is kinematically forbidden!

The UV Origin



1. Integrate out O(TeV) charged messengers → Elastic Dipole.

2. Majorana mass splitting projects elastic dipole into inelastic transition dipole.



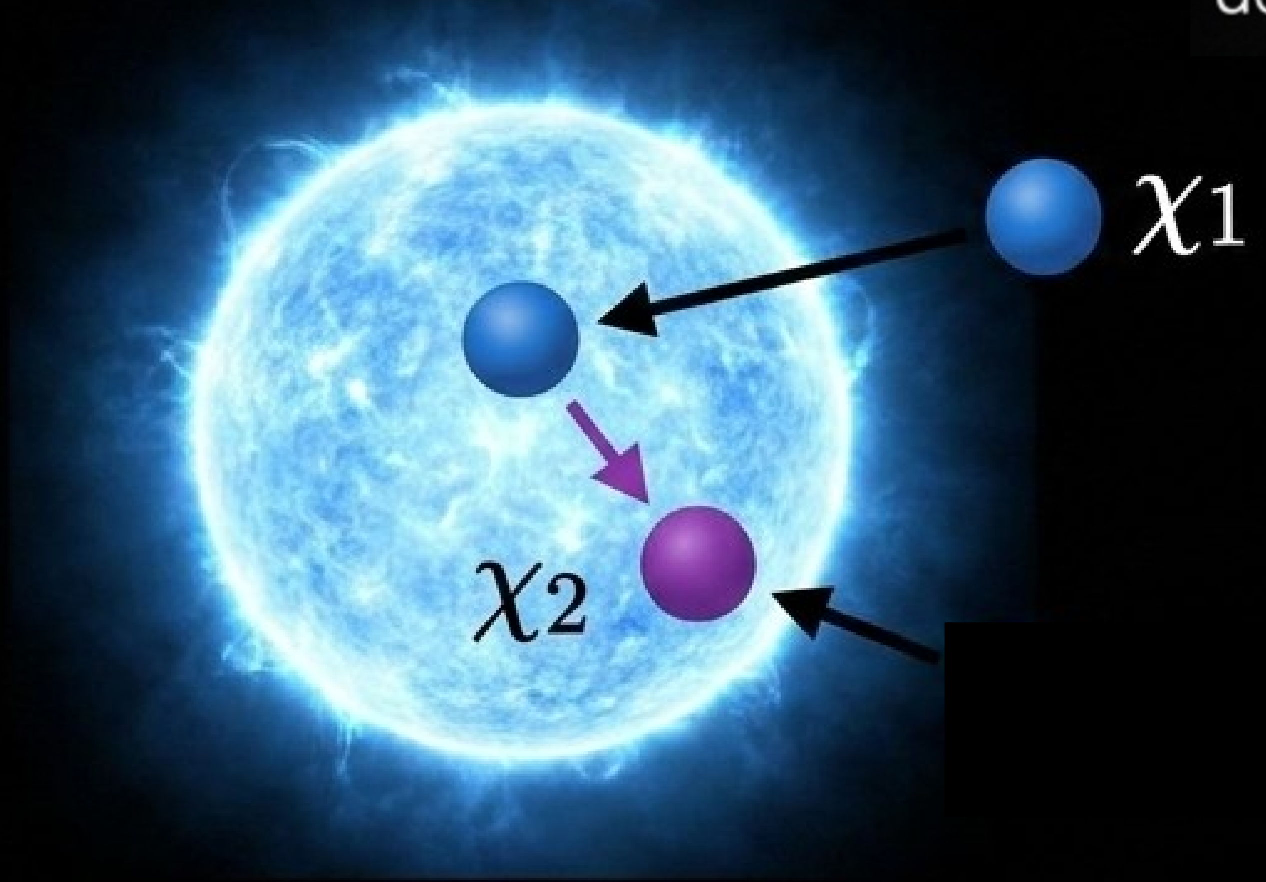
up to $\Lambda \sim$ tens of TeV

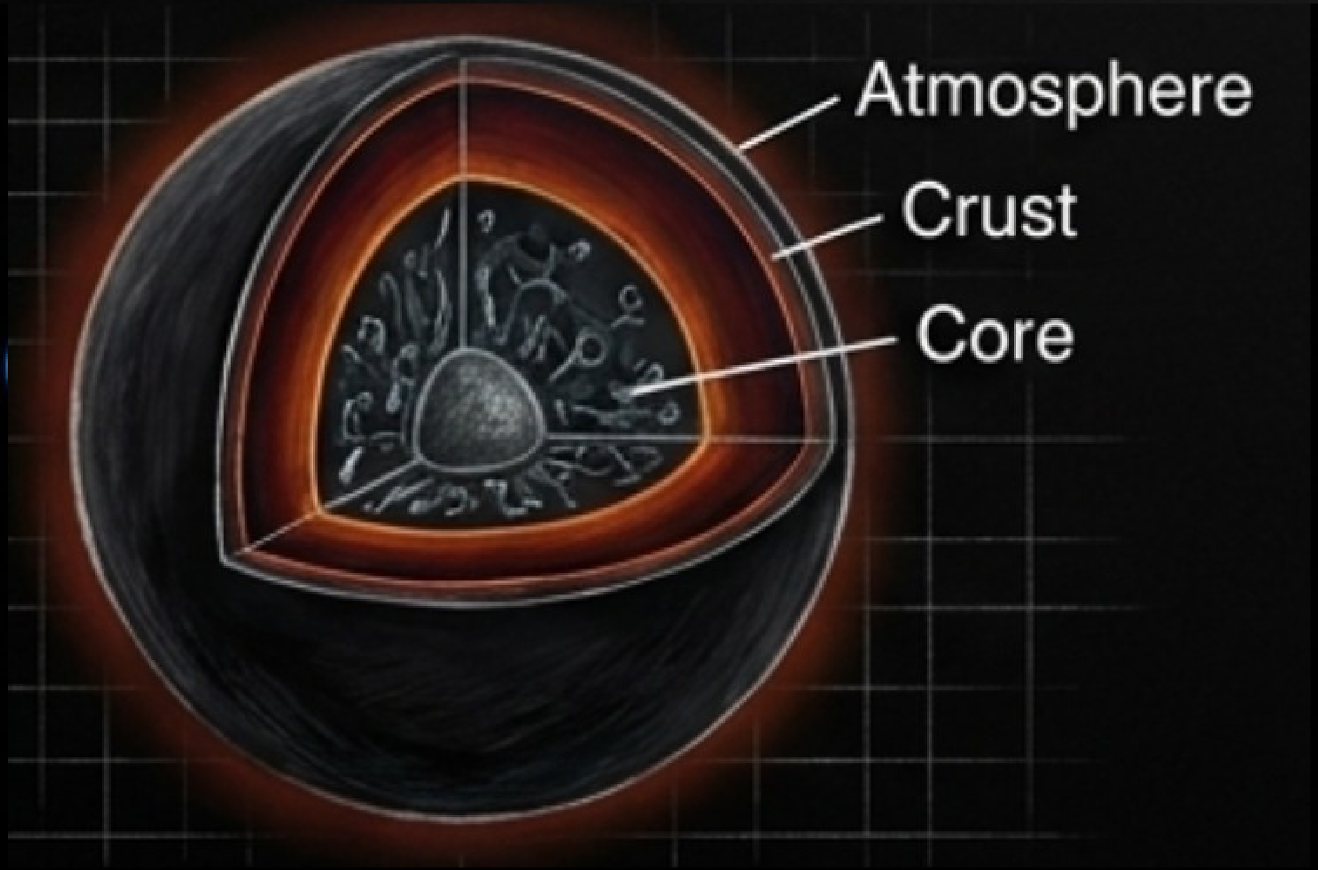
Neutron stars as dark matter labs

DM Kinetic Energy: For a 50 MeV benchmark, the local kinetic energy the surface is:

$$E_{\rm kin} = (\gamma_{\rm surf} - 1)m_{\chi_1} \approx 15.3\,{\rm MeV}$$

Extreme Compact Objects: Remnants of massive stars, packing $M \approx 1.4\,M_\odot$ into a sphere of $R \approx 10\,{\rm km}$. Incredible densities: an outer crust enveloping a core of degenerate nucleons and leptons.





$15.3\,{\rm MeV} \gg 10\,{\rm keV} \rightarrow$ Upscattering ($\chi_1 \rightarrow \chi_2$) is allowed!

Dark Matter Capture and Heating: The Standard Picture

1. Scattering & Capture

Accelerated dark matter enters the star and scatters off highly degenerate nucleons or leptons. Losing even a fraction of kinetic energy in one scatter is enough to become gravitationally bound.

2. Thermalization & Sinking

Through subsequent orbits and repeated scatterings, the captured particles continuously lose energy. They eventually thermalize with the stellar plasma, settling at the exact center of the star.

3. Stellar Heating

The transfer of falling kinetic energy heats the neutron star. A rich literature explores this thermal heating as a primary dark matter probe.

Current Record Holder: ~40,000 K

DM-Induced Heating: ~2,000 K

with DM annihilation in the NS center

$$L = 4\pi R^2 \sigma T^4$$

40000 K → 2000 K = several orders of magnitude difference in lumi L

Observational Challenge: Extremely faint targets. Standard thermal heating produces infrared signatures that are incredibly difficult to observe directly.

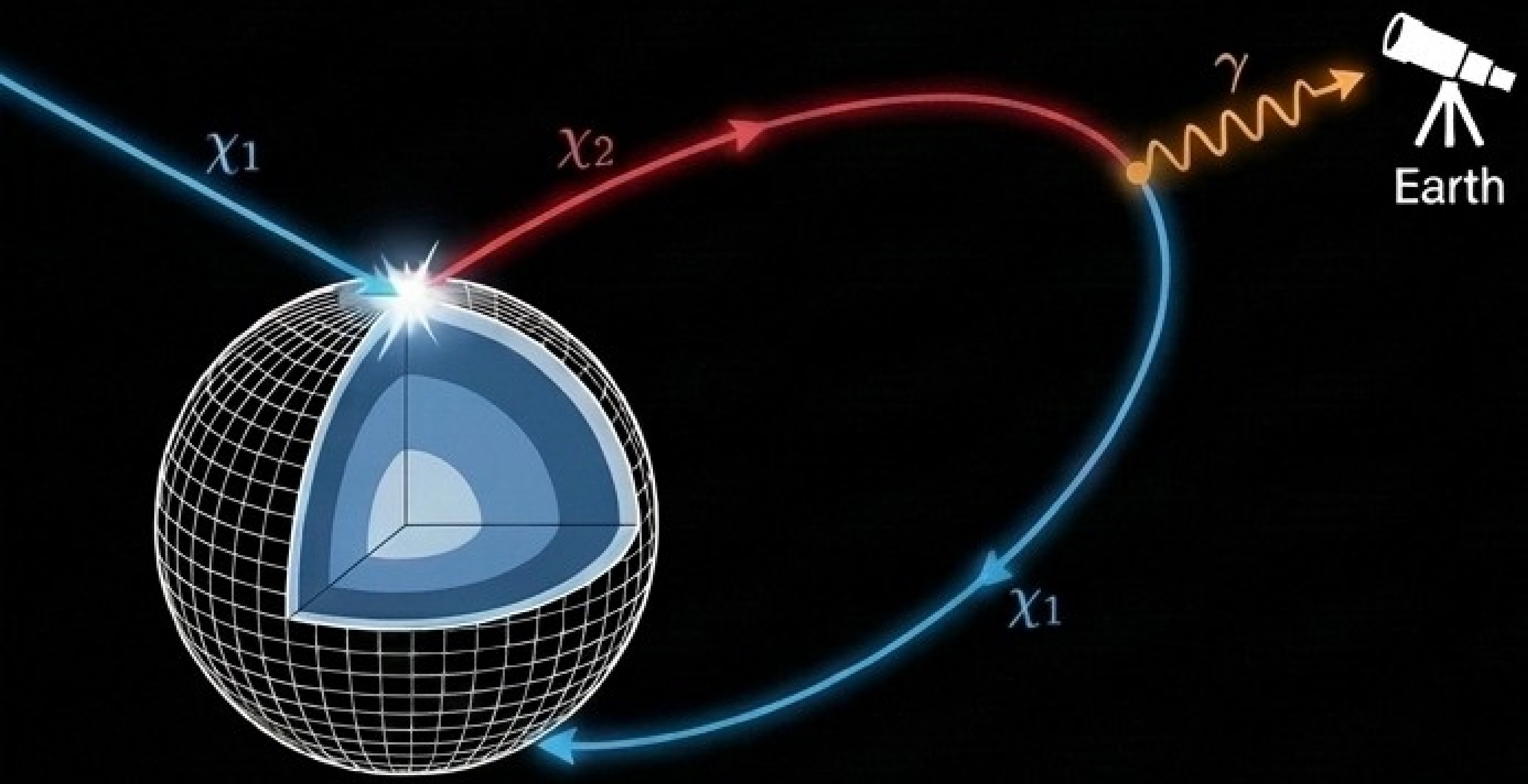
The Inelastic DM: Escaping the Core

Upscatter & Escape:

- The first scatter produces the excited χ_2 state.
- Because the decay width is suppressed by the small mass splitting ($\Delta \sim 10$ keV), χ_2 has a macroscopic lifetime.
- Instead of rapidly thermalizing, χ_2 follows a bound relativistic geodesic that can carry it outside the compact stellar volume.

Vacuum Orbits and Radiative Decay:

- The excited χ_2 travels on elliptical loops outside the star, before plunging back in.
- If it decays in the transparent vacuum ($\chi_2 \to \chi_1 + \gamma$), it produces a freely escaping X-ray!



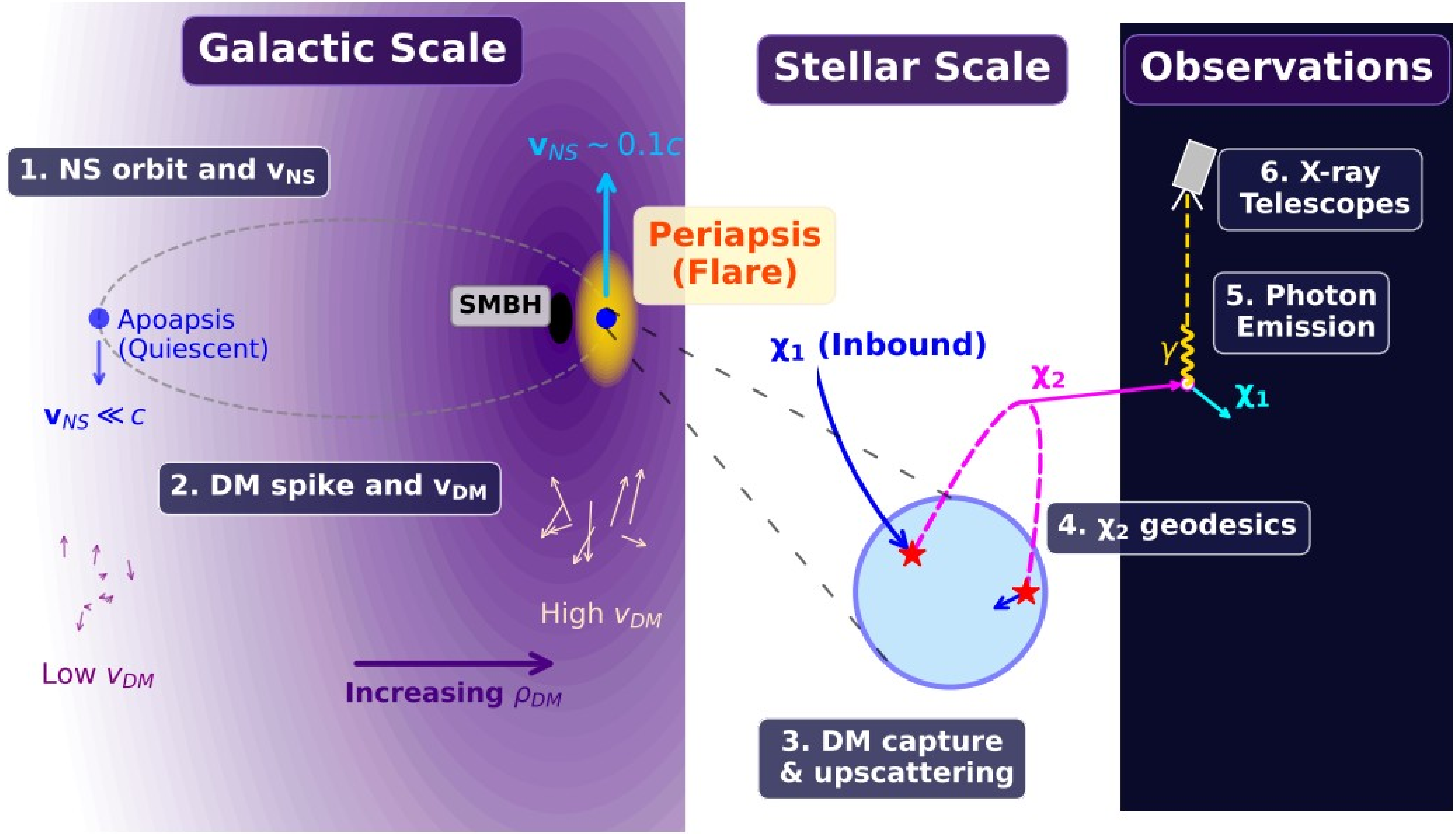
The Local Flux Bottleneck:

- Consider a nearby, isolated NS: RX J1856.5-3754 ($D \approx 120$ pc).
- Even at the maximum geometric capture limit, the local DM density yields $C \approx 10^{26}\,\mathrm{s}^{-1}$.
- Assuming 1 decay → 1 photon, the expected flux at Earth is:

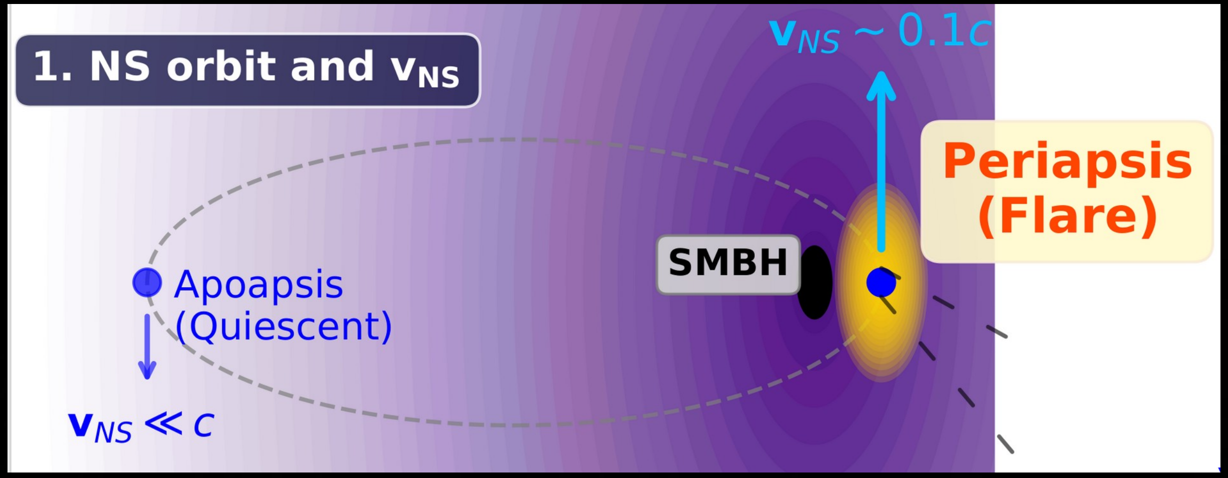
$$F = \frac{C}{4\pi D^2} \approx 5.8 \times 10^{-17}\,\mathrm{photons\,cm^{-2}\,s^{-1}}$$

- **The Problem:** Next-generation telescopes (ATHENA, Lynx) reach sensitivities of $\sim 10^{-11}\,\mathrm{cm^{-2}\,s^{-1}}$. A local NS is a million times too faint!

Signal is 10^6 times too weak. We need an amplifier!


Galactic Scale
Stellar Scale
Observations
1. NS orbit and v_{NS}
$v_{NS} \sim 0.1c$
Periapsis (Flare)
SMBH
Apoapsis (Quiescent)
$v_{NS} \ll c$
2. DM spike and v_{DM}
High v_{DM}
Low v_{DM}
Increasing ρ_{DM}
χ_1 (Inbound)
χ_2
3. DM capture & upscattering
4. χ_2 geodesics
6. X-ray Telescopes
5. Photon Emission
γ
χ_1

Neutron Star Orbits Close to Sgr A*



Extreme Observable Orbits:

The S-star cluster proves stable, highly eccentric orbits are standard near SgrA*.

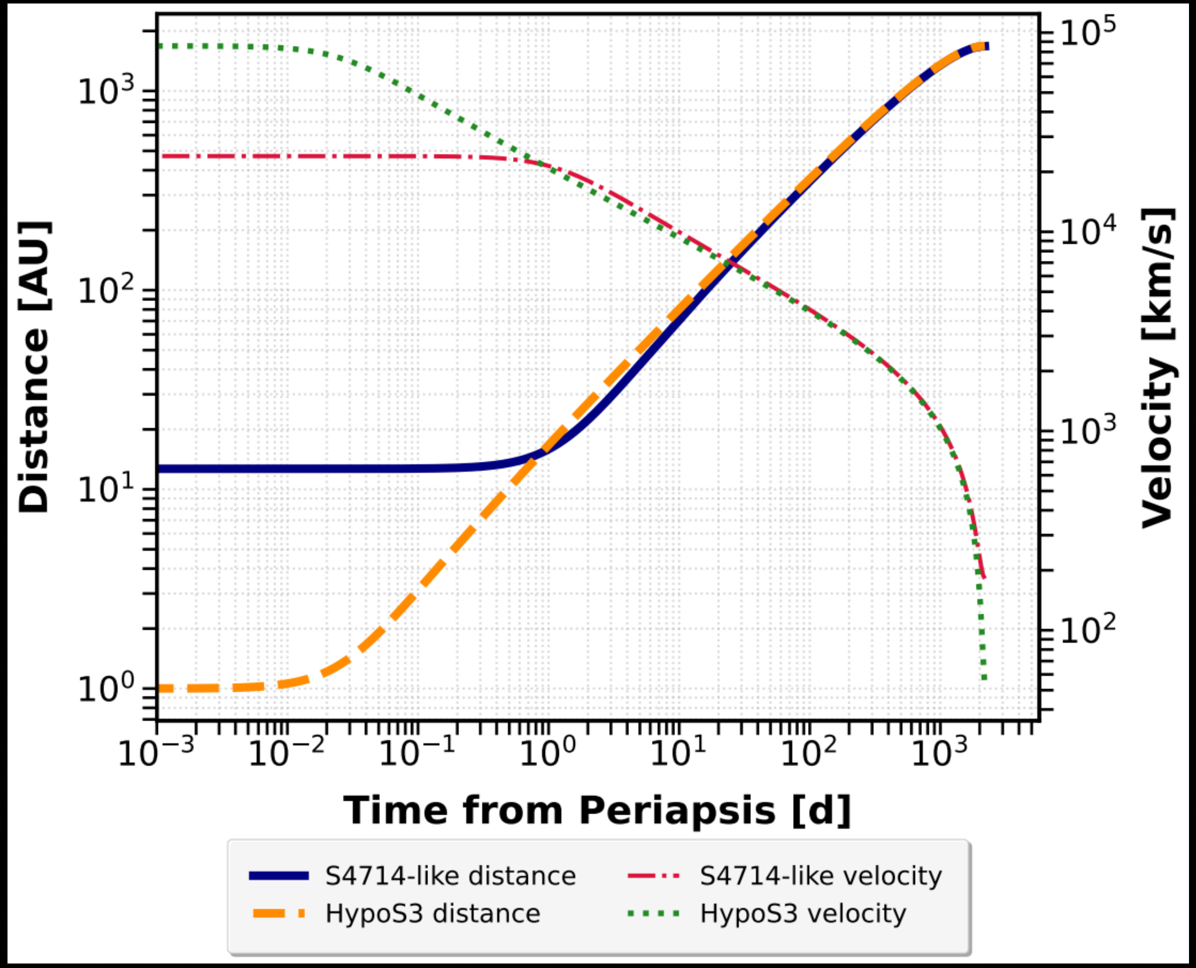
Record Holder S4714: Dives to Periapsis ($\sim 12.6\ \mathrm{AU}$, $v \sim 0.08c$), but spends most of its 12-yr orbit near Apoapsis ($\sim 1{,}670\ \mathrm{AU}$).

The Hidden "Dark Cusp":

Mass Segregation: Heavy remnants ($\sim 1.4\, M_\odot$) sink via dynamical friction, forming a steep density cusp ($n \propto r^{-1.5\ \mathrm{to}\ -1.7}$).

Population: Yields $\sim 60{,}000$ NSs in the inner parsec, translating to tens within $1000\ \mathrm{AU}$ and a few entirely within the inner $100\ \mathrm{AU}$.

Missing Pulsars: Extreme radio scatter-broadening by GC plasma completely hides them from standard surveys.



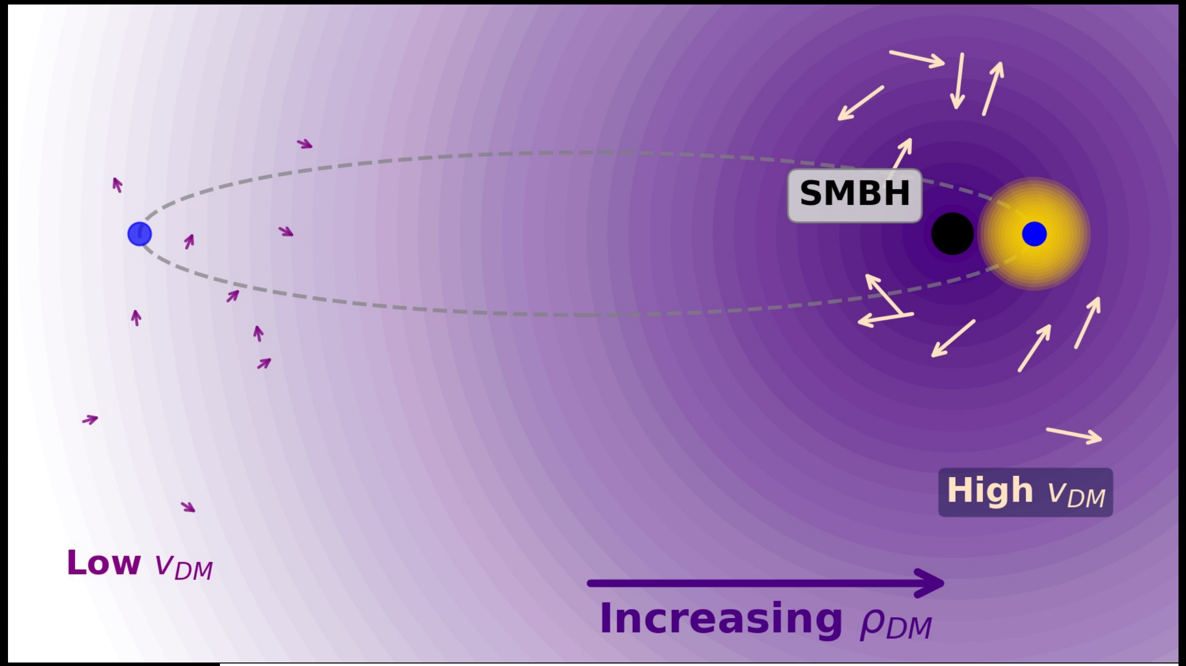
Why so Eccentric?

Resonant Relaxation, Hills mechanism, Supernovae Natal Kicks naturally pump NSs into plunging ($e \to 1$) trajectories.

No Tidal Disruption:

$1\ \mathrm{AU} \approx 12 R_s$ (Schwarzschild radii). NS tidal disruption radius $r_t \approx 1{,}400\ \mathrm{km} \ll R_s$. NSs cross the density spike structurally intact.

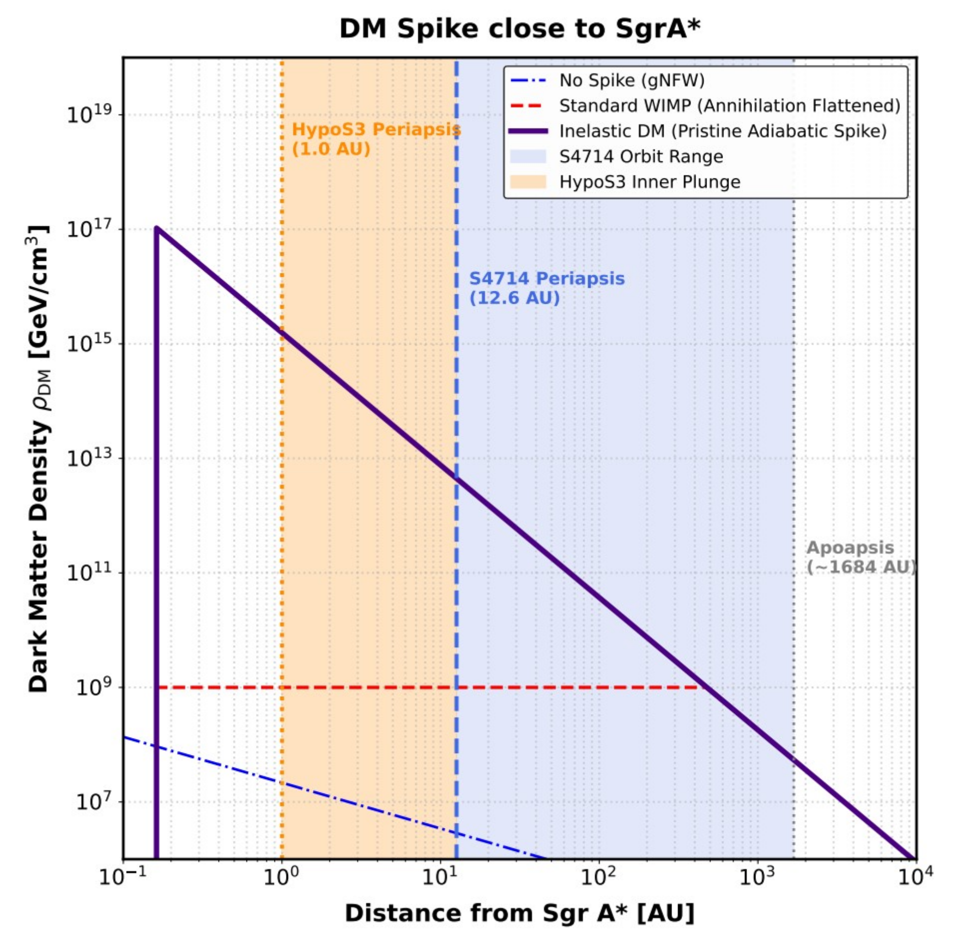
DM Density and Velocity close to SgrA*



- The Adiabatic Spike: Supermassive black hole growth concentrates DM into a steep density spike. Inelastic DM naturally preserves this spike (avoids annihilation-flattening).

- Relativistic Phase Space: Deep in the gravitational well, DM velocity dispersion v_d becomes a fraction of c.
- The Jüttner Distribution: Standard Maxwell-Boltzmann replaced with a relativistic phase-space distribution:

$$f(\gamma) = \frac{m\,\gamma\,\sqrt{\gamma^2-1}\,e^{-\frac{m\,\gamma}{T}}}{T\,K_2\left(\frac{m}{T}\right)} = \frac{2}{3v_d^2 K_2\left(\frac{2}{3v_d^2}\right)}\,\gamma\sqrt{\gamma^2-1}\,e^{-\frac{2\gamma}{3v_d^2}},$$



Dark Matter Capture and Upscattering

The Capture Interplay:

$$C = \frac{4\,\pi}{v_{\mathrm{NS}}}\frac{\rho_\chi}{m_\chi}\,\mathrm{Erf}\left(\sqrt{\frac{3}{2}}\,\frac{v_{\mathrm{NS}}}{v_d}\right) \times \int_0^{R_{\mathrm{NS}}} \sqrt{g_{rr}}\,r^2\,\frac{\sqrt{1-g_{tt}(r)}}{g_{tt}(r)}\,\Omega^-(r)\,\eta(r)\,dr$$

Standard Heating Fails (The Observational Gap):

- Thermalization is slow. The NS responds to the orbit-averaged capture rate $\langle C\rangle$.
- Heats the NS to 10^3–10^4 K, peaking in the Near-Infrared.
- Extreme dust extinction (A_V ~30) and stellar crowding make observing a faint IR point source impossible.

The Inelastic Advantage:

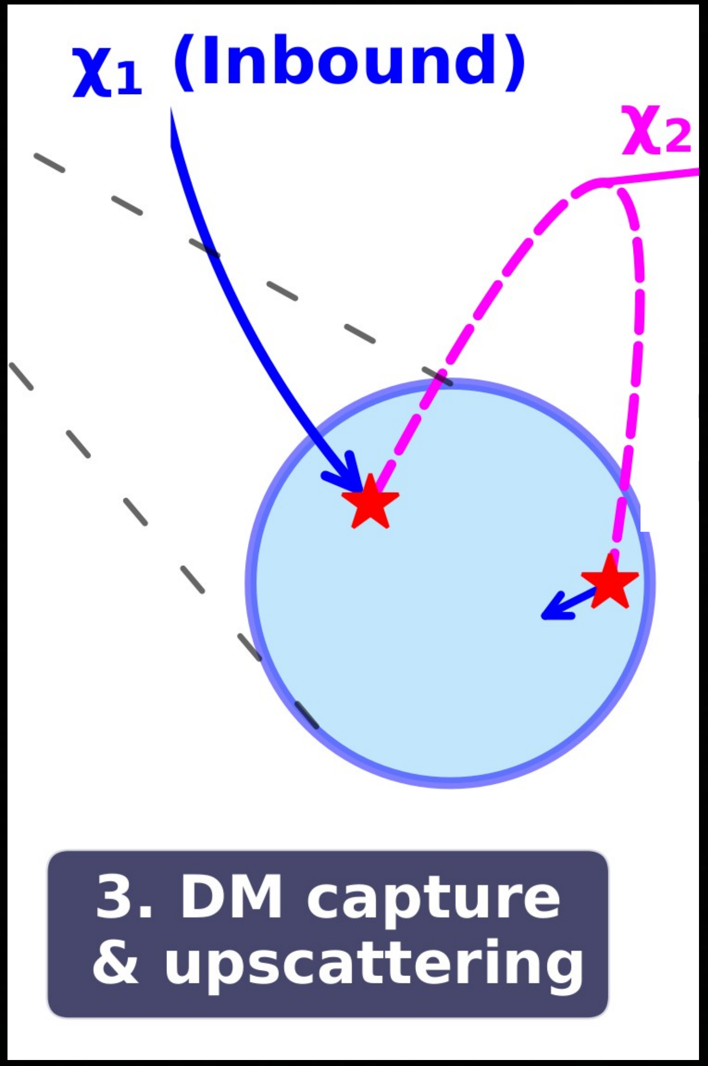
- Upscattering produces prompt, hard X rays at periapsis, penetrating the GC dust

Metric g_{rr}, g_{tt}:
- Outside neutron star: Schwarzshild
- Inside neutron star:
  Solve TOV eqs + Eq. of State (BSk25)

Interaction rate Ω^-:
- DM-target scattering amplitude
- Target nucleon/lepton distribution
- Pauli blocking

Opacity η:
- Attenutation of DM flux in the star

Post-doc: Jaime Hoefken Zink



Escaping the Star: χ_2 Geodesics & Decay

χ_2 Geodesics:

The escaping χ_2 is gravitationally bound with a radial trajectory $r'(\tau)$:

$$\frac{dr'}{d\tau} = \pm \frac{1}{\sqrt{g_{rr}(r')}} \sqrt{\frac{g_{tt}(r) E_{\chi_2}^2}{g_{tt}(r') m_2^2} - 1 - \frac{J^2}{m_2^2 r''^2}}$$

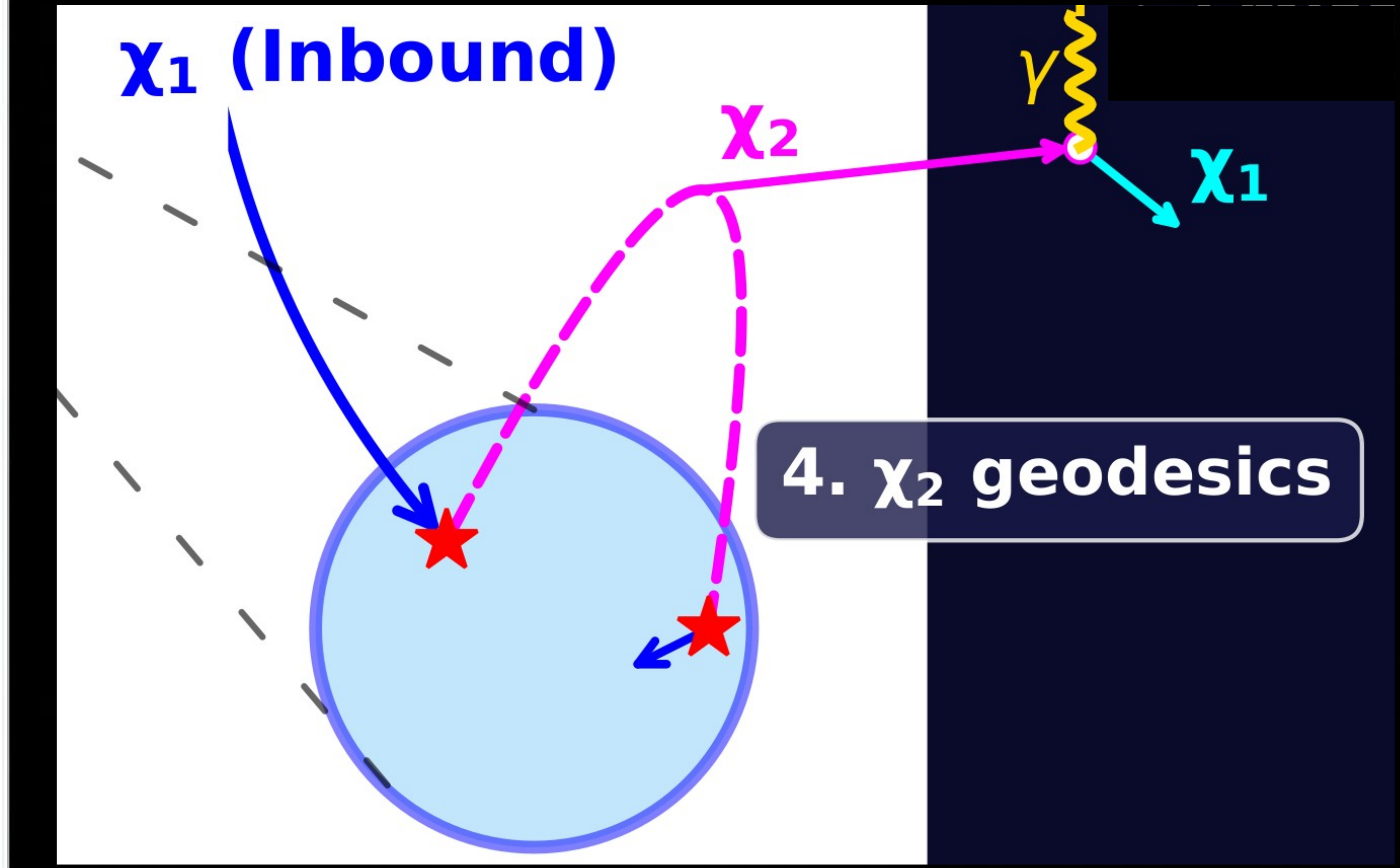
Decay Probability Outside the Star:

Accounts for the survival fraction η_2^{in} inside the star:

$$\mathcal{P}^{\text{out}}(r', r' + dr') = \Gamma \eta_2^{\text{esc}} \frac{e^{-\Gamma \tau(r')}}{1 - \eta_2^{\text{in}} e^{-\Gamma \tau_{\text{loop}}}} d\tau$$

Operating in the Geometric Limit (Bounce-Back):

- Sufficiently large cross sections cause $\chi_1 \to \chi_2$ upscattering to occur primarily at the stellar surface.
- **Inward** χ_2: Instantly absorbed by dense plasma ($\eta_2^{(+)\text{esc}} \to 0$).
- **Outward** χ_2: Bounce back directly into the vacuum with zero internal attenuation ($\eta_2^{(-)\text{esc}} \to 1$).
- **Result:** The χ_2 can successfully escape and decay outside!



For inelastic (electric) dipole portal:

$$\Gamma = \frac{1}{\pi \Lambda_E^2} \left(\frac{m_2^2 - m_1^2}{2m_2} \right)^3$$

Too large Λ_E → large lifetime,
rescattering in the NS
instead of decaying outside

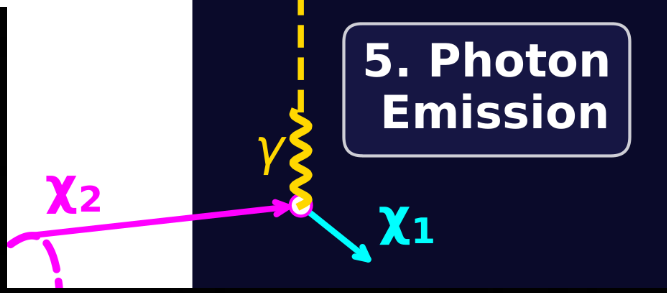
Limited by the χ_2 lifetime rather than scat. cross section

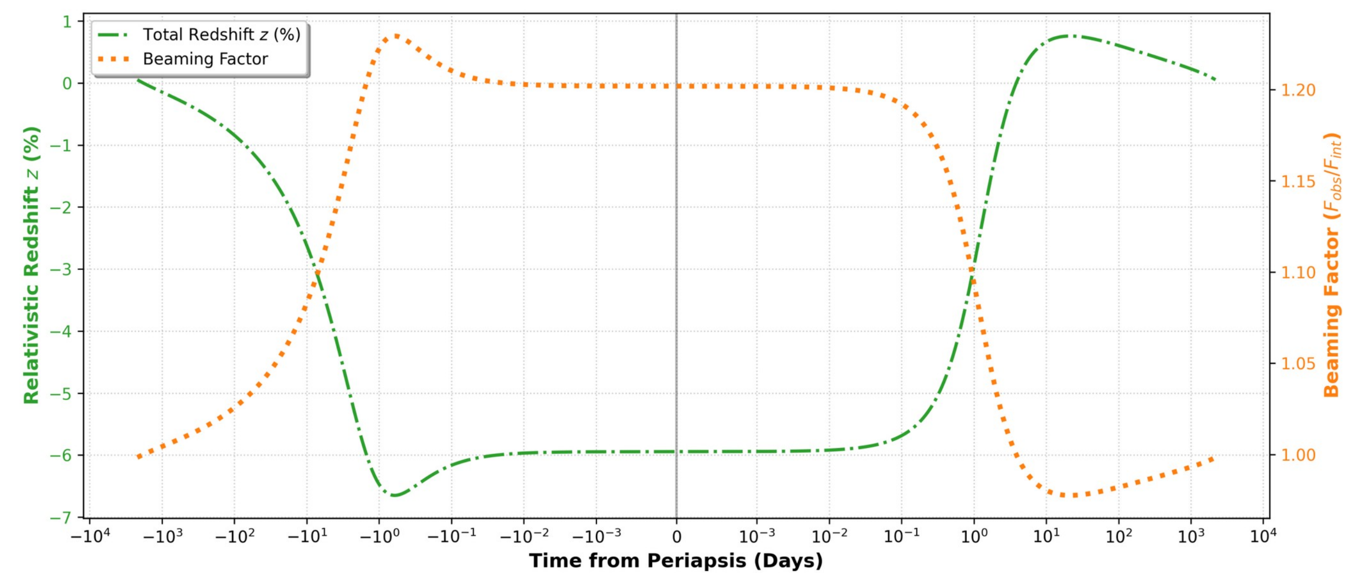
Shaping the Observable X-Ray Flare

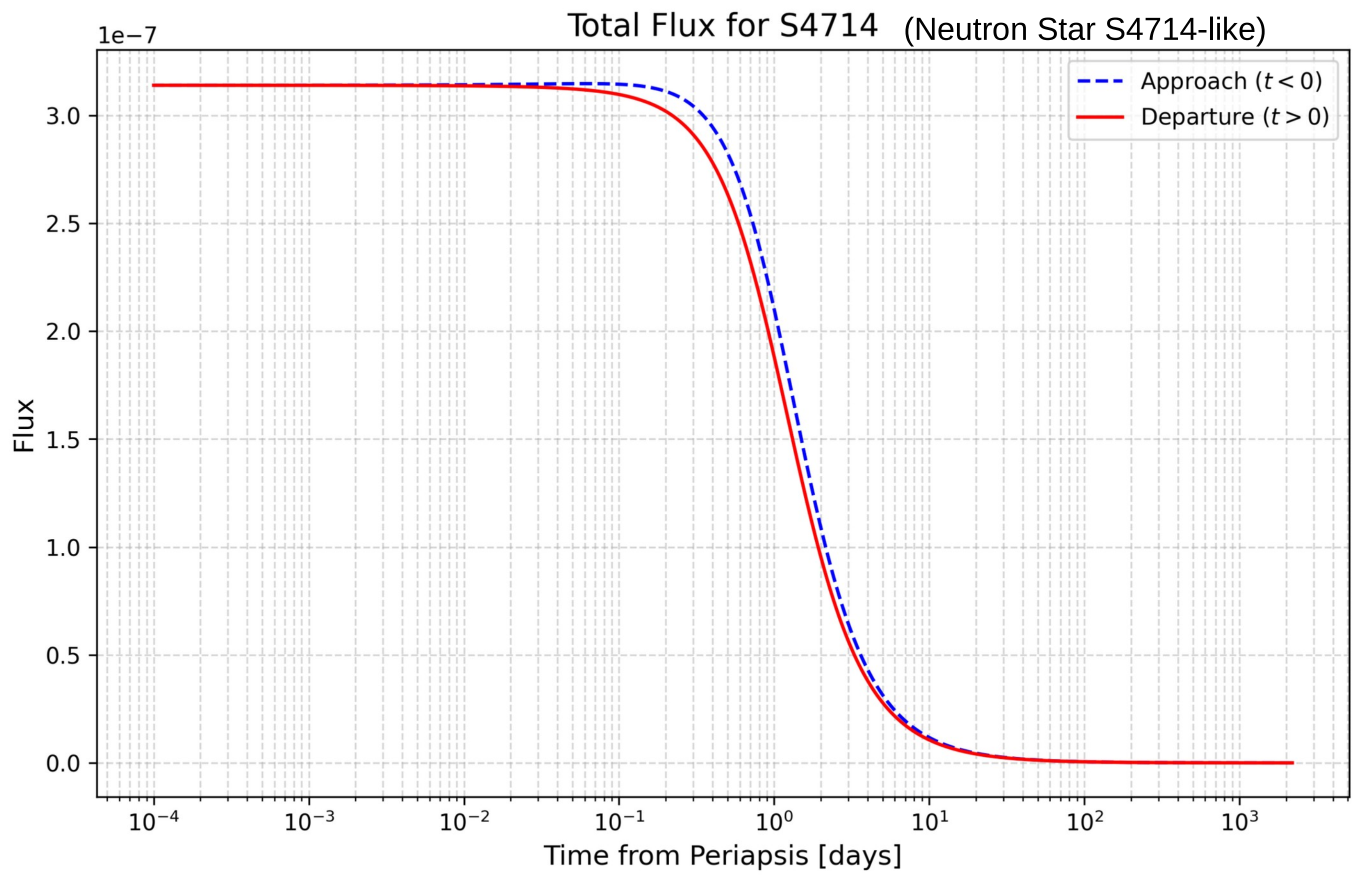
$$\Phi_\gamma^{\text{obs}} \propto \int \left[\begin{matrix}\text{[Capture} \\ \text{Rate]}\end{matrix} \right] \times \left[\begin{matrix}\text{[Kinematic} \\ \text{Broadening]}\end{matrix} \right] \times \left[\begin{matrix}\text{[Escape} \\ \text{Probability]}\end{matrix} \right]$$

1. The **Rest-Frame Emission**: The two-body decay ($\chi_2 \to \chi_1 + \gamma$) produces a strictly **monochromatic photon line** at $E_\gamma \approx \Delta$.
2. **Kinematic Distortions (Doppler & Beaming)**:
   - **Doppler Broadening**: Escaping semi-relativistic χ_2 ($v \sim 0.6c$) smears the line into a broad spectrum.
   - **Relativistic Beaming**: Photon emission is forward-boosted along the trajectory.
   - **Doppler Shift**: The extreme orbital velocity of the NS shifts the entire flare structure.
3. **General Relativistic Effects**:
   - **Gravitational Redshift**: Shifting the spectrum to lower energies.
   - **Light Bending**: The metric lenses outgoing photons, warping escape trajectories.
4. **Geometric Survival (Re-absorption)**: Any photon emitted inward, or lensed back toward the star, crashes into the surface and is lost.

The Result → A broadened hard X-ray flare that pulses strictly at the orbital periapsis.







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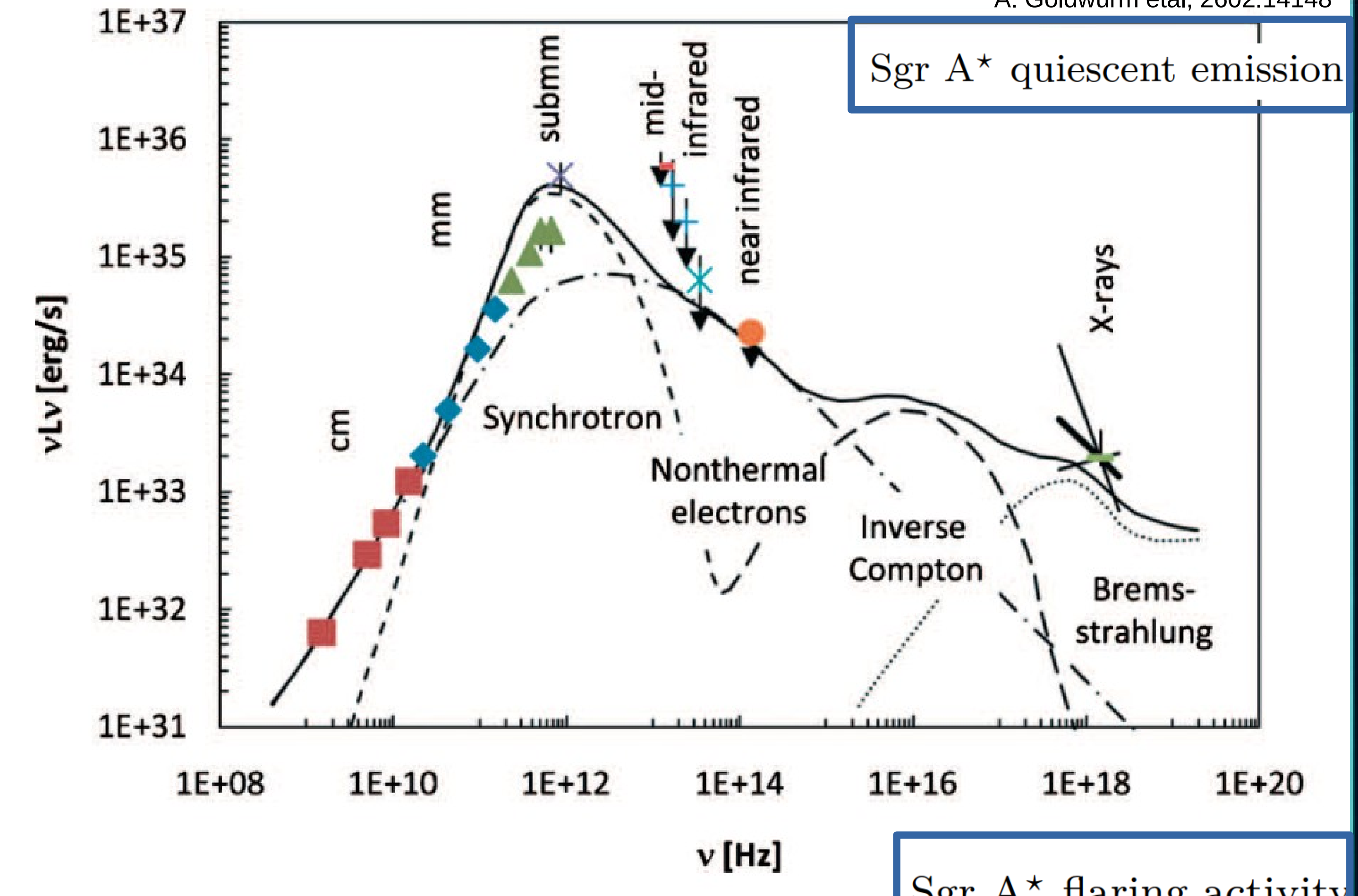
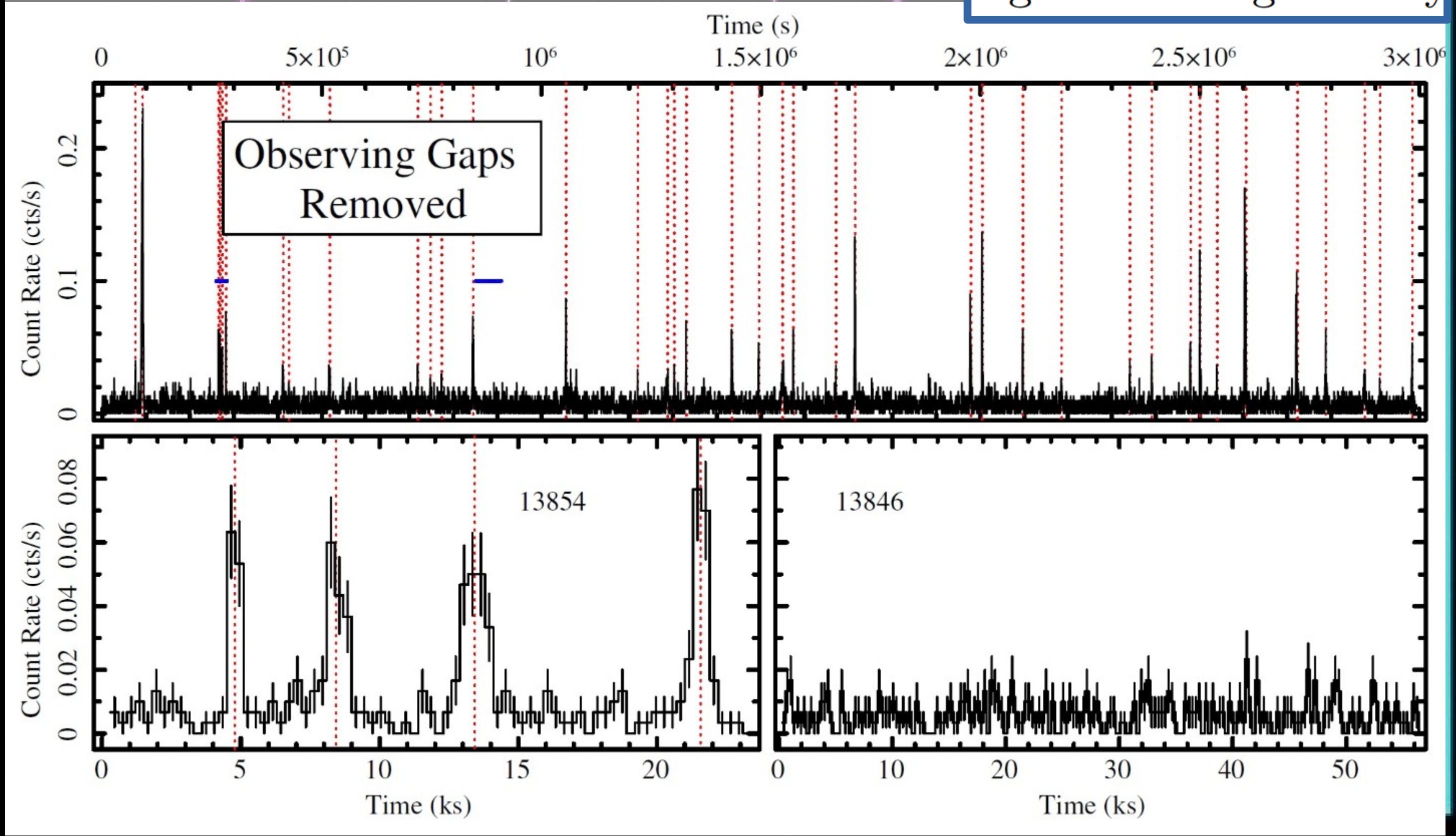
Sgr A* quiescent emission



Sgr A* flaring activity



Sgr A* Flares: The Astrophysical Context

- **A 'Starving' Black Hole**: Sgr A* is notoriously under-luminous in quiescence ($L_X \sim 10^{33}$ erg s^{-1}).
- **Violent Outbursts**: This quiescent state is randomly interrupted by brief, extreme flares.

- **Infrared (NIR) Flares:**
  Rate: Frequent (~3–4 per day).
  Mechanism: Synchrotron emission (highly polarized).

- **Hard X-ray Flares:**
  Rate: $\sim$ 1.1 per day (stochastic/Poissonian).
  Duration: Tens of minutes to $\sim$ 3 hours.
  Luminosity: Increases by 1–2 orders of magnitude (peaks up to $L_X \sim 5 \times 10^{35}$ erg s^{-1}).
  Spectrum: Featureless, absorbed hard power-law ($\Gamma \approx 2.3$).

- **The Correlation**: All X-ray flares have simultaneous NIR counterparts, but many NIR flares occur without X-rays.

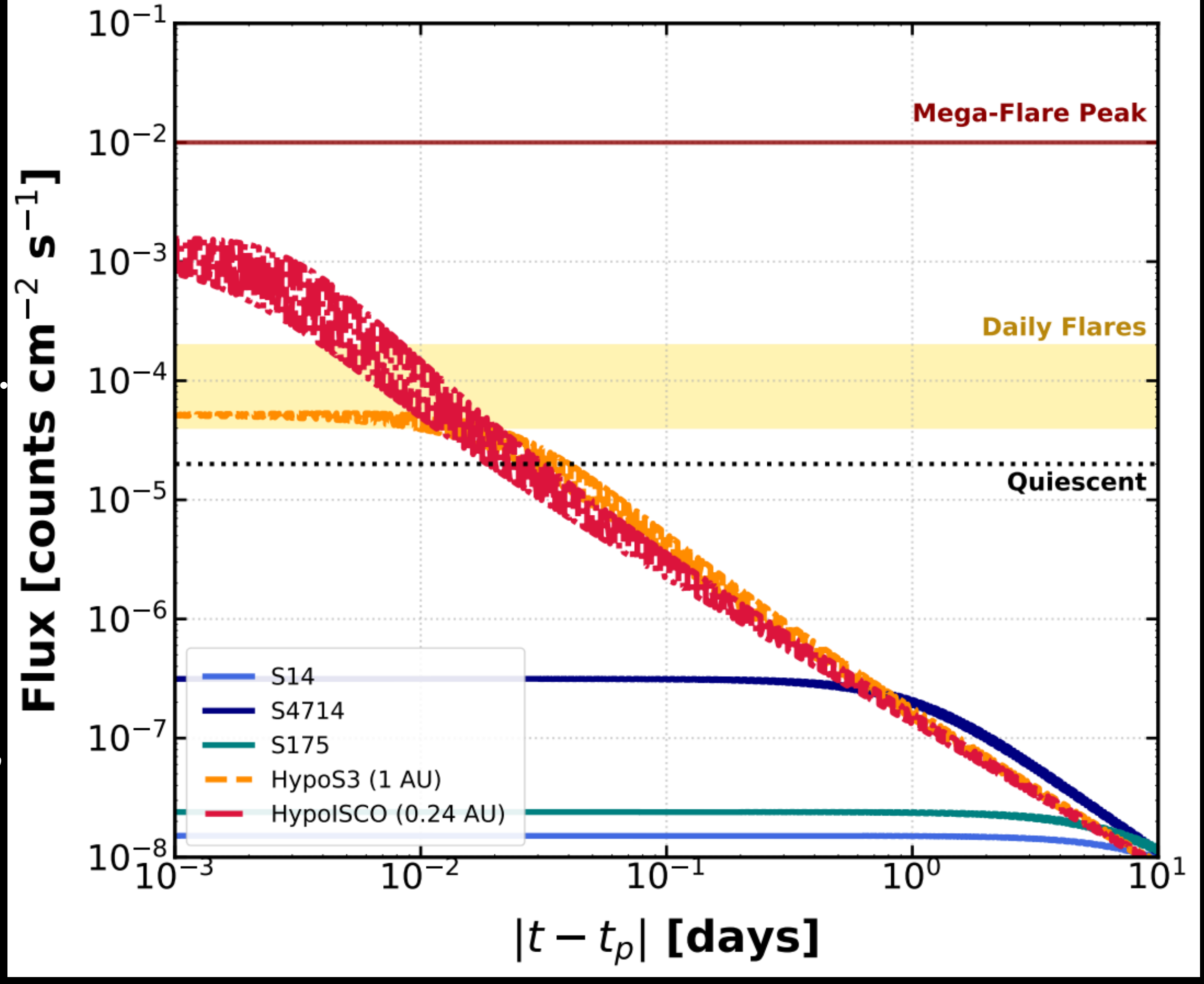
X-ray SgrA* vs DM-induced flares

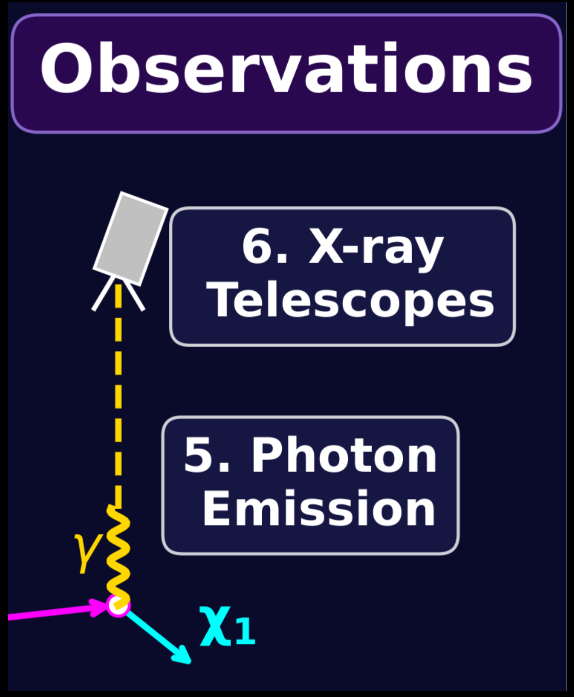
1. **Near Encounters Needed:** To outshine Sgr A*'s quiescent background (at 2-10 keV energy), the NS requires a periapsis of $r_p \sim 1$ AU.

2. **Harder X rays:** More room for signal extraction

3. **The "Hiding" Neutron Star:** On a highly eccentric orbit (e.g., 12-year period), the NS spends >99% of its life moving slowly in low DM density, completely hidden beneath the SMBH background.

4. **The Flare Window:** The competitive signal only emerges for a brief window (a few hours) during periapsis.

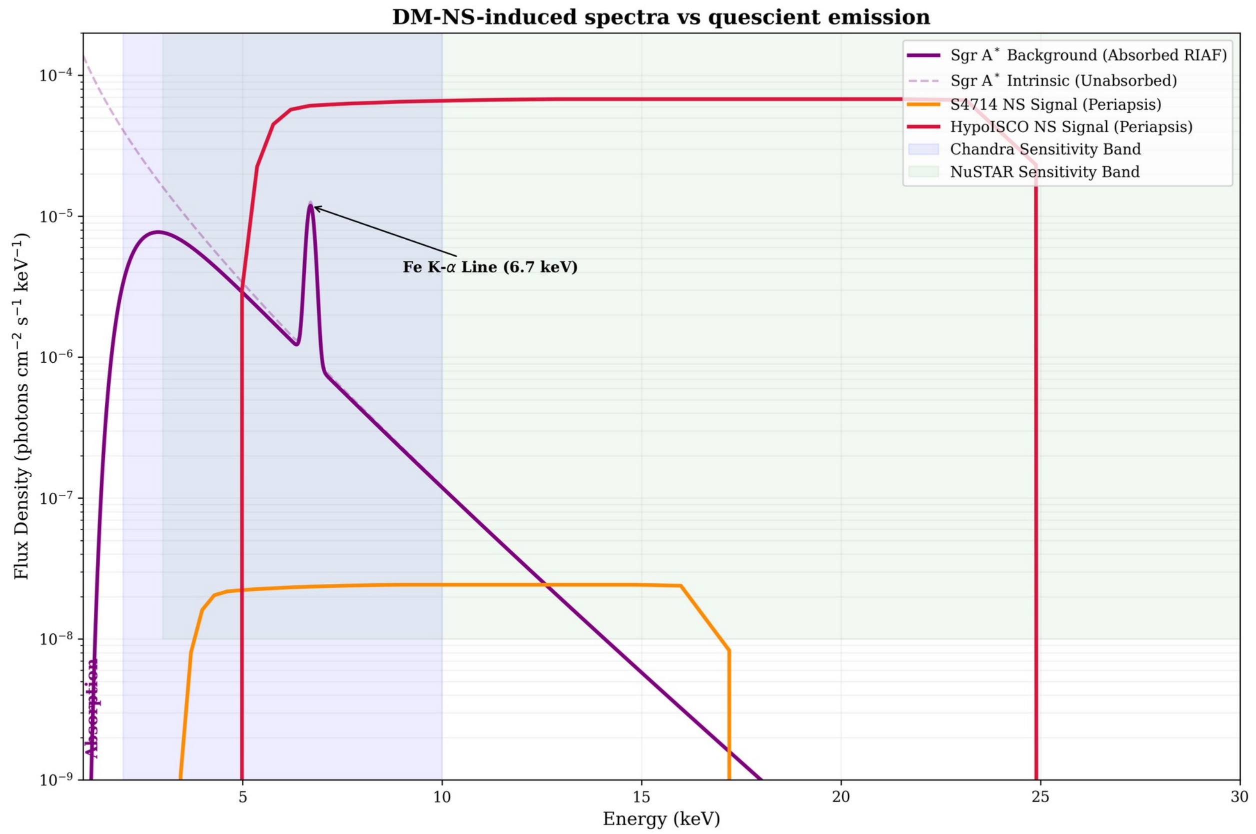




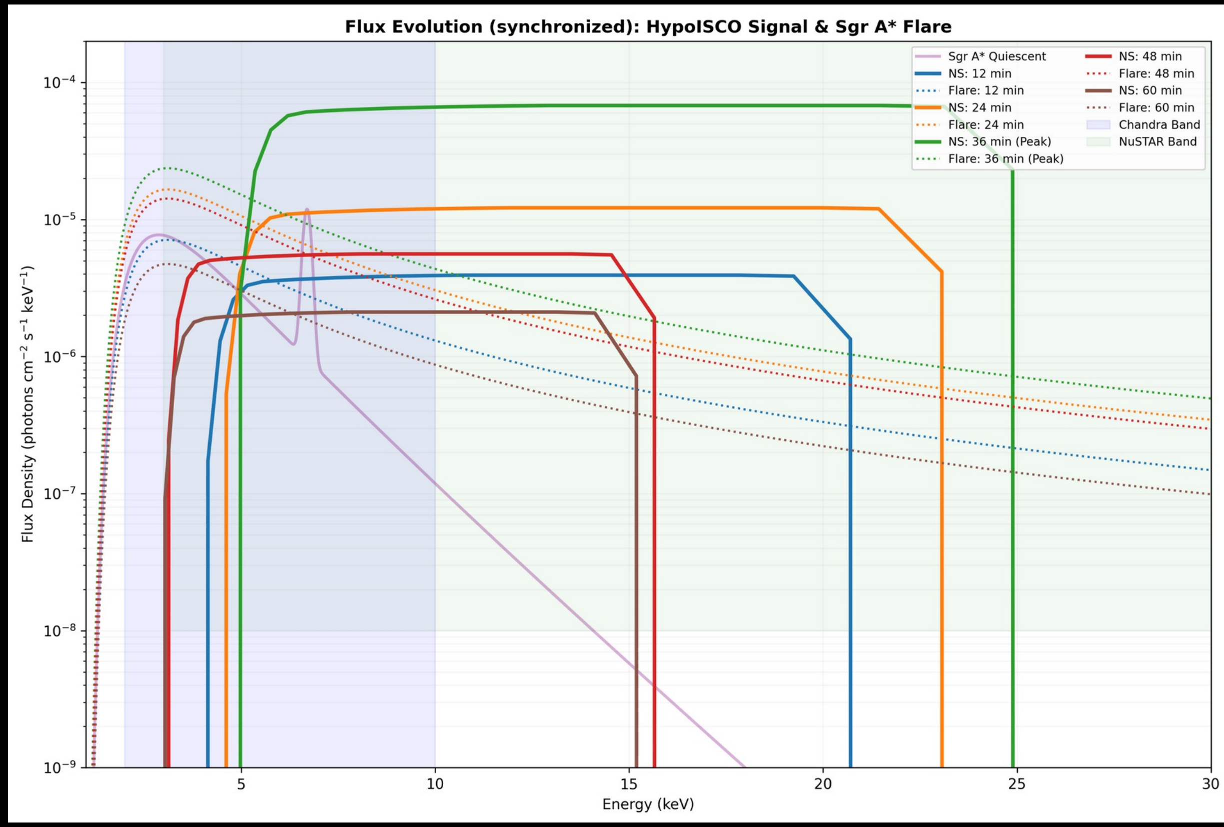
Observations

6. X-ray Telescopes

5. Photon Emission



DM-NS-induced spectra vs quescient emission



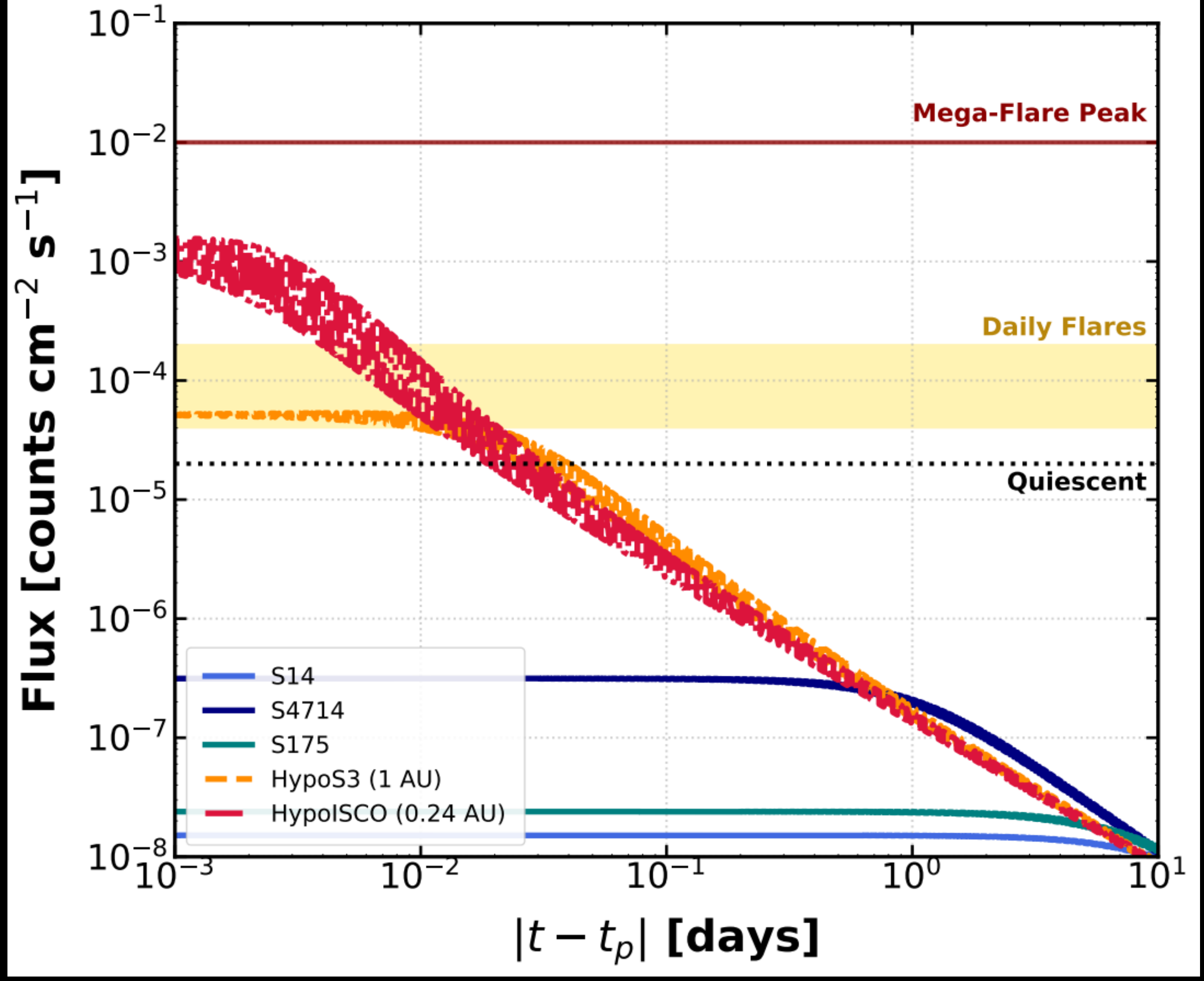
Flux Evolution (synchronized): HypoISCO Signal & Sgr A* Flare

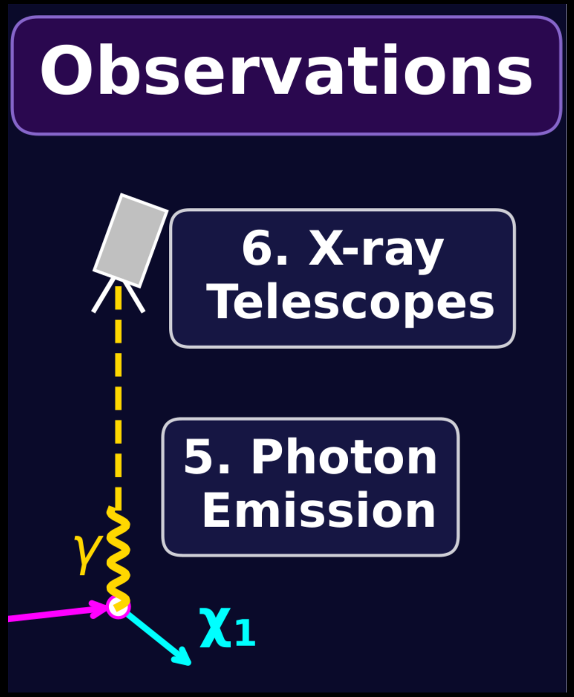
X-ray SgrA* vs DM-induced flares

1. Spectral Features:

- **Flat "Box" Spectrum:** Unlike the thermal accretion flow or natural X-ray flares (power-law $\Gamma \sim 2.2$), the iDM signal is kinematically flat.
- **Non-Trivial Time Evolution:** Natural Sgr A* flares maintain a remarkably constant spectral slope. Our signal hardens (blue-shifts) on approach and softens (red-shifts) on recession.
- **Orbital Periodicity:** Periods can be large (years).
  Can we predict them based on a DM-induced flare?

2. Smoking Gun: naked X-ray flare (no infrared counterpart)





Observations

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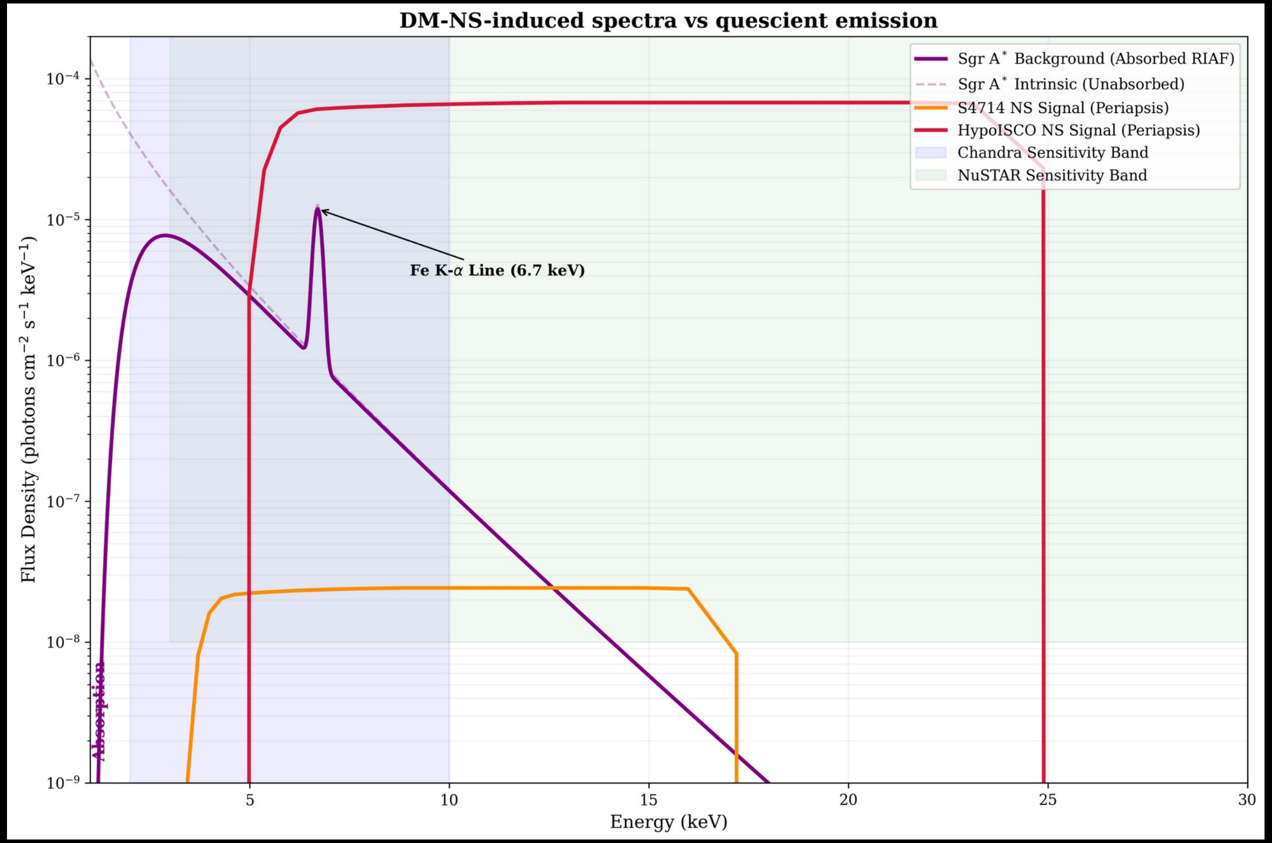
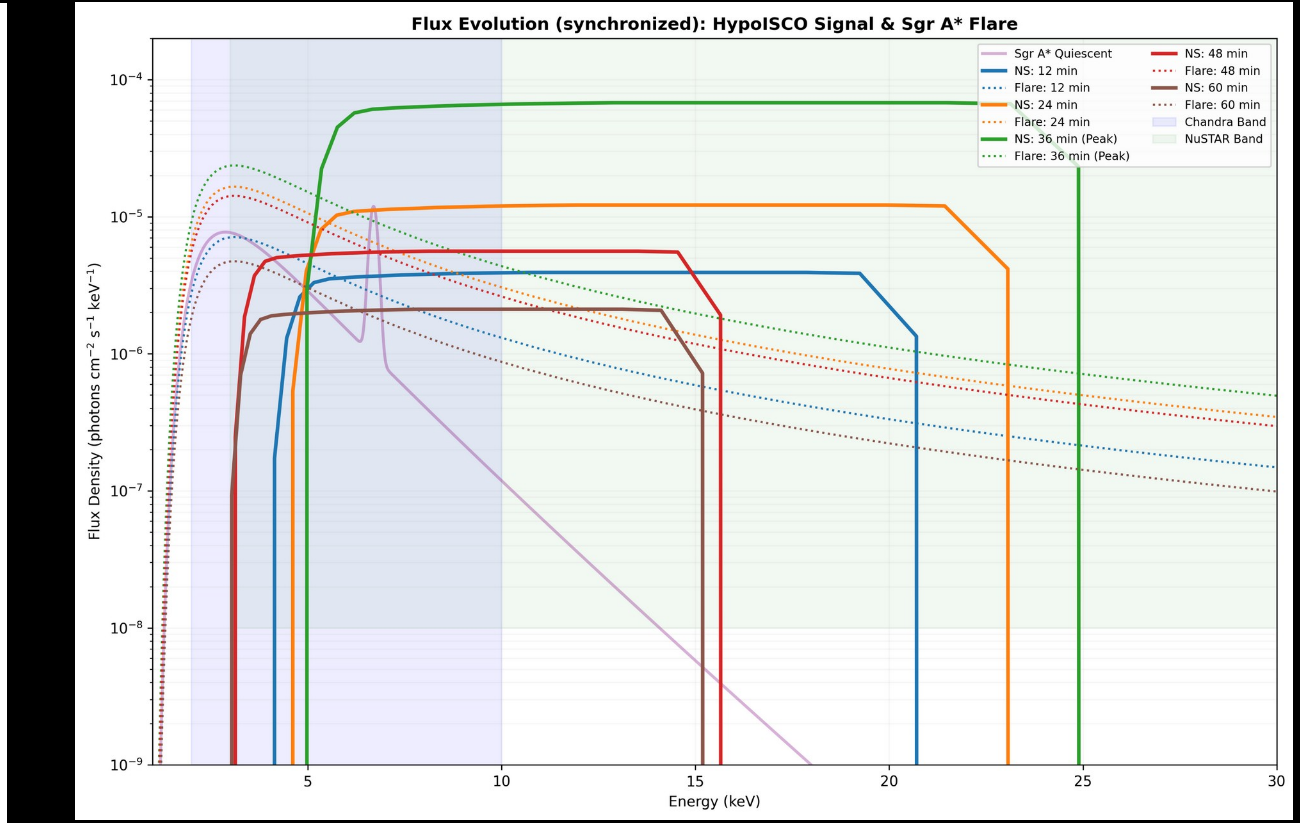
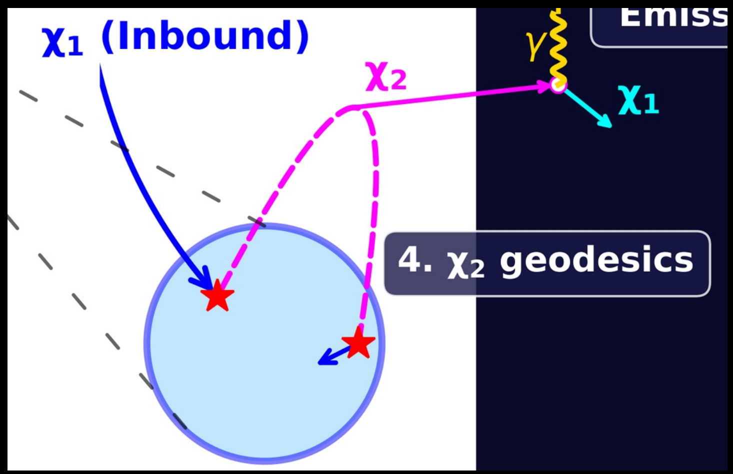




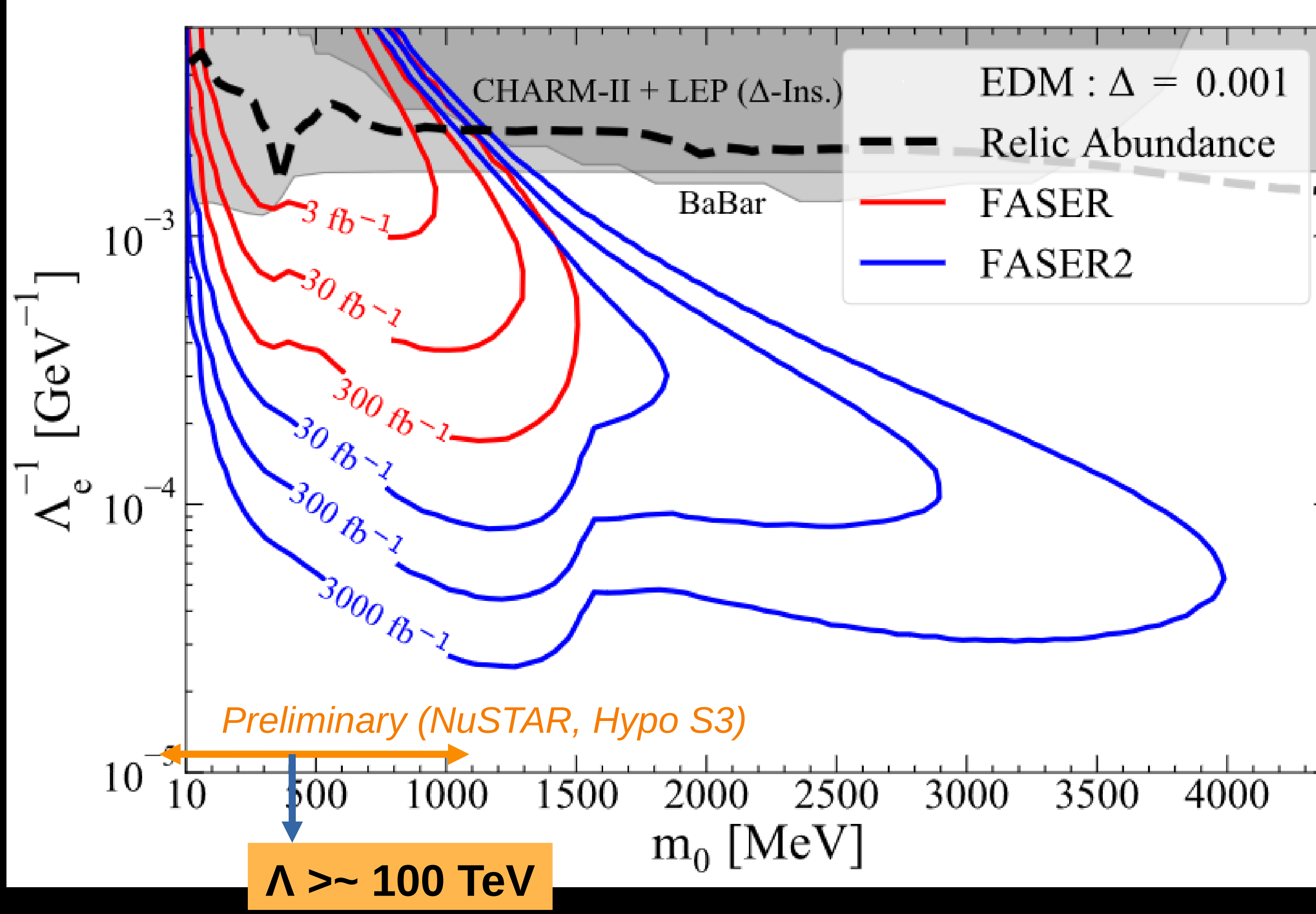
BSM sensitivity



$$\frac{d\sigma}{dE_R} \simeq \frac{4\alpha_{\rm EM}}{\Lambda^2 E_{\chi_1}^2}\left[\frac{E_{\chi_1}^2}{E_R} - \frac{m_{\chi_1}^2}{2m_p} - \Delta\frac{E_{\chi_1} m_{\chi_1}^2}{E_R m_p}\right] F_p^2(t)$$

Λ ~ 1 TeV (LHC probes): $\sigma_{\rm tot} \approx 9.40 \times 10^{-35}\ {\rm cm}^2$

Λ ~ 100 TeV (NS X rays): $\sigma_{\rm tot} \approx 9.40 \times 10^{-45}\ {\rm cm}^2$



Preliminary (NuSTAR, Hypo S3)

Λ >~ 100 TeV

2. Lifetime of χ_2 & re-scattering in NS

– limiting factor depending on the mass splitting

3. Sensitivity:

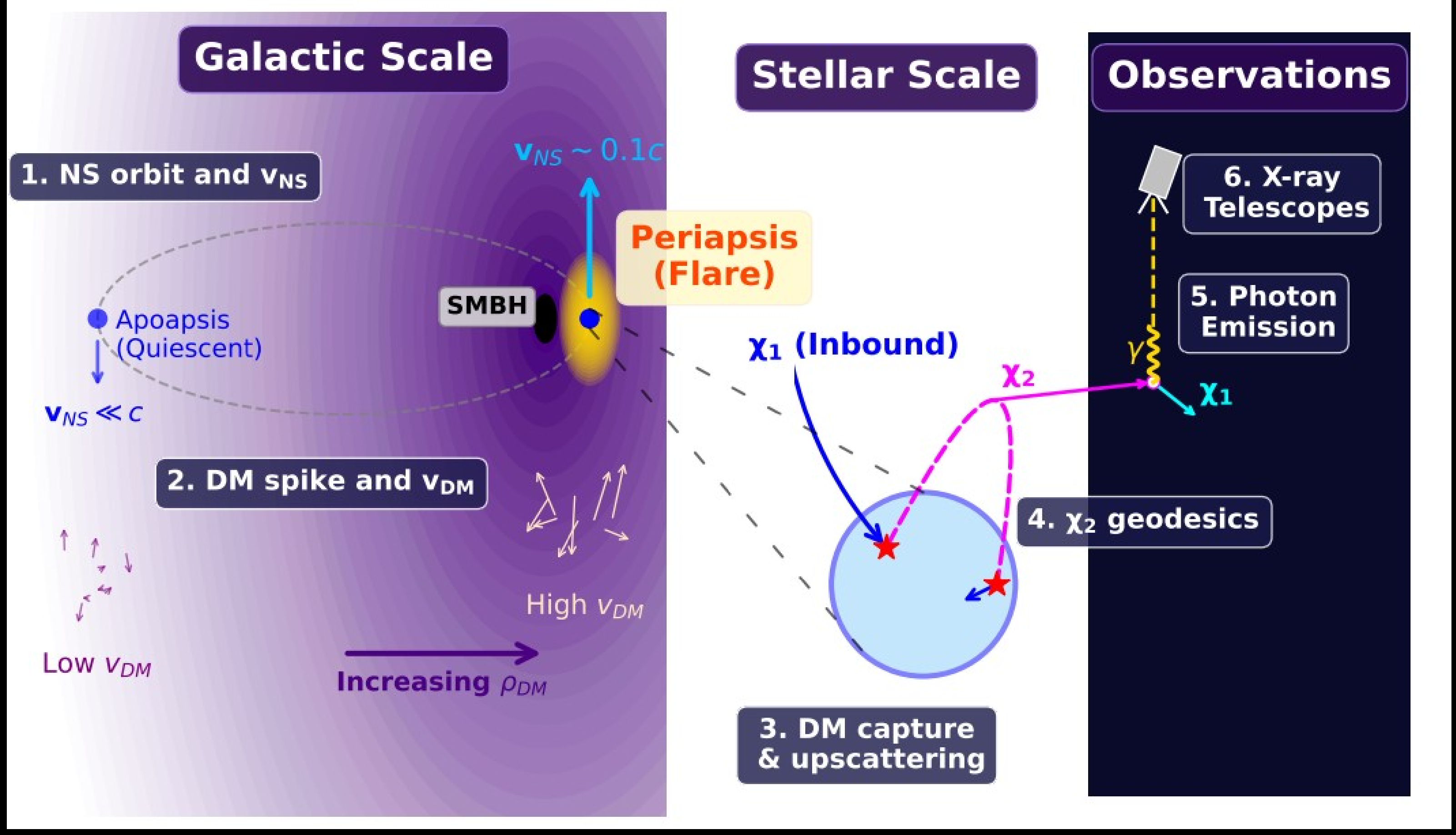
can be as large as Λ ~ 100 TeV for a few hundred MeV DM mass

4. Anomalous flare: if observed, strong hint of (inelastic) DM

DARK MATTER DISCOVERY TOOL

RATHER THAN EXCLUSION TOOL

To Take Home



1. Inelastic Dark Matter

- Can “naturally” appear due to symmetry breaking in the dark sector
- Heavier dark state: unique pheno, discovery opportunities

2. Neutron stars as dark matter laboratories

- Heating due to DM scattering & annihilation
- Difficult to observe
- Other: black hole formation, …

3. Novel X-ray signature

- DM-induced X-ray flares from neutron stars orbiting SMBH in the Galactic Center
- Distinct from “ordinary” X-ray flares of SgrA* (no NIR, flat spectrum, time evolution, periodicity)

4. Further steps

- Beyond neutron stars (white dwarfs, …)
- Beyond $\chi_2 \to \chi_1 \gamma$ (e.g., e^+e^- + magnetic field)
- Beyond X rays and ~ 10 keV mass splittings (secondary radiation,…)
- Future & proposed missions: ATHENA, AXIS, Lynx, HEX-P, eXTP, XRISM, …