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DETECTING ISOLATED NEUTRON STARS AND BLACK HOLES WITH MICROLENSING

Milano, 22/09/2011

ISOLATED NEUTRON STARS: A garden variety of observational properties: radio/gamma-ray pulsars, XDINS, RRAT, magnetars, CCO

$M \sim 1.4\ M_{sun}$

$P \sim 0.02 - 10$ s;

$B \sim 10^{11} - 10^{15}$ G

$v \sim 10^{2} - 10^{3}$ km/s

$t < 10^{7}$ years $<< t_{MW}$;

~ 10^{3} detected, ~ 10^{5} detecable (e.g. SKA);

CC SN rate + t_{MW} ⇓ *Rotational losses, Thermal cooling*

~ 10^{8} - 10^{9} old, dead objects

ISOLATED BLACK HOLES: *nomen omen*

No constraints on isolated objects;

A handful of candidates from microlensing observations (Bennett et al. 2002);

Hints on mass distribution from X-ray binaries

($M_{BH} \sim 4 - 15\ M_{sun}$, Agol & Kamionkowski, 2002);

From IMF (Salpeter (1955), Kroupa, (2001)): $\mathbf{N_{BH} \sim 1/10\ N_{NS}}$

- Ostriker et al. (1970): spherical accretion of ISM as recycling mechanism of dead pulsars;

Bondi-Hoyle-Littleton theory

$$\dot{M} = \frac{2\pi (GM)^2 m_p n}{(v^2 + c_s^2)^{3/2}} \sim 10^{11} n v_{10}^{-3}\ \mathrm{g\,s^{-1}}$$

$$L = \frac{G M \dot{M}}{R} \sim 2 \times 10^{31} \left(\frac{\dot{M}}{10^{11}\ \mathrm{g\,s^{-1}}} \right) \mathrm{erg\,s^{-1}}$$

n_{ISM} – 1 cm^{-3}; v ~ 10 km/s

L ~ 10^{31} erg/s
kT ~ 100 eV

- More refined models in the 1990s predicted ~ 10^2 - 10^3 accreting neutron stars detectable by the ROSAT satellite (Treves & Colpi 1991, Blaes & Madau 1993, Zane et al. 1995);

- Similar models proposed for recycling of isolated balck holes (Campana & Pardi 1993, Agol & Kamionkowski 2002, Beskin & Karpov 2005, Mapelli et al. 2006);

L ~ 10^{28} – 10^{33} erg/s larger uncertainties on parameters!

The harsh truth: no succesful candidate accretors found to date. The few sources discovered by ROSAT are "young" (t ~ 10^5 - 10^6 yr) isolated cooling neutron stars (e.g. Turolla 2009)

Possible reasons for the absence of accreting neutron stars/black holes

(Treves et al. 2000)

- Large spatial velocities, v ~ $10^2 - 10^3$ km/s
  (Hobbs et al. 2005; Gualandris et al. 2005)

- Interaction between magnetic field (NS) and accretion flow
  (Toropina et al. 2003, Perna et al. 2003);

$$r_A = \left(\frac{B^2\, R^6}{\sqrt{2GM}\,\dot{M}}\right)^{2/7} > r_{accr} = \frac{2GM}{v^2}$$

(georotator)

$$U_G = \frac{GMm_p n}{r} > U_B = \left(\frac{B^2}{8\pi}\right)\left(\frac{R^6}{r_c^6}\right)\left(\frac{r_c^2}{r^2}\right)$$

(ejector)

$$\left(\frac{GM}{r_A^2}\right) \gtrsim \left(\frac{2\pi}{P}\right)^2 r_A$$

(propeller)

- Low emission efficiency (BH)

A step back: dynamics of isolated neutron stars
in order to constrain their phase-space distribution

PSYCO
(Population SYnthesis of Compact Objects)

(Sartore et al. 2010, A&A 510, A23)

I - Spatial distribution of progenitors

II - Distribution of birth velocities

Initial conditions assigned with Monte Carlo procedures

III - Model for Galactic potential

Orbit integration for 150 000 simulated INS

$$\ddot{\mathbf{r}} = -\nabla\Phi$$

$$\frac{dR}{dt} = v_R\,,$$
$$\frac{dz}{dt} = v_z\,,$$
$$\frac{dv_R}{dt} = \frac{\partial\Phi}{\partial R} + \frac{j_z^2}{R^3}\,,$$
$$\frac{dv_z}{dt} = \frac{\partial\Phi}{\partial z}\,,$$

4th order Runge-Kutta algorithm with adaptive stepsize

Accuracy of integrations based on energy conservation: δE/E < 10^{-6}

Escape fraction (unbound objects): $f_{esc} \sim 0.2 - 0.3$

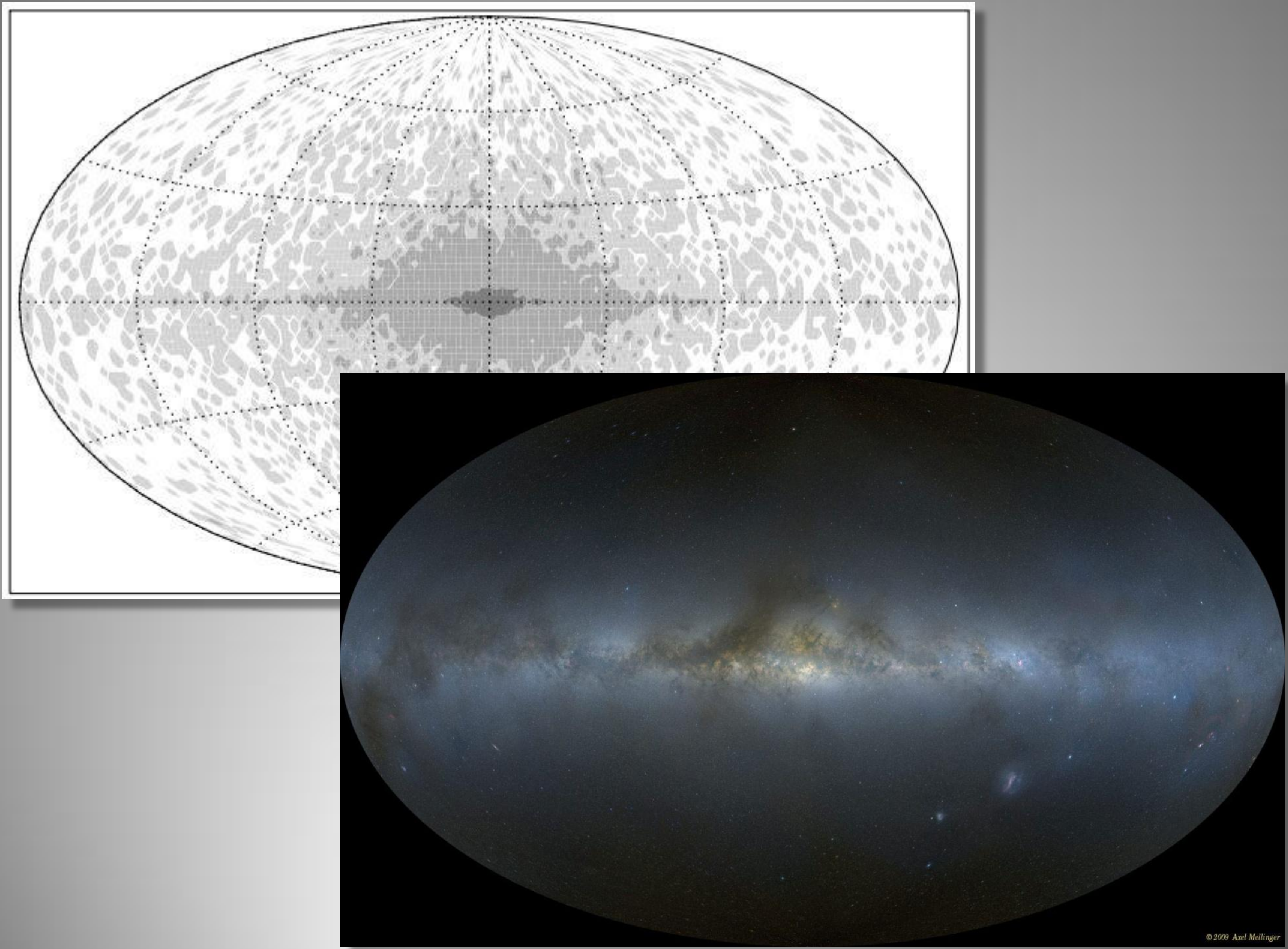
Only ~ 5 - 10% of INS reside in the disk. Still 100+ old INSs for each detectable young INS;

Local density of INS: $n_{INS} \sim 10^{-4}$ pc^{-3} (nearest INS @ ~ 10 pc)

Mean velocity (LSR): $v_{mean,} \sim 150 - 200$ km/s

- Accretion luminosity: $L_{accr} < \sim 10^{28}$ erg /s
  - Soft X-ray flux: $f_X < \sim 10^{-13}$ erg /s/cm^2 (below ROSAT limit)

INS accumulate towards the Galactic bulge



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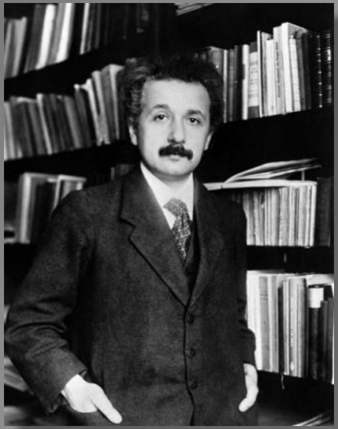
The microlensing way



Massive objects can deflect and amplify
the light of background sources
(Einstein, 1936)

Microlensing as a method to probe the distribution
of (dark) matter along the line-of-sight
(Packzynski, 1986)

Surveys: MACHO (Alcock et al. 1993), OGLE (Udalski et al. 1994),
EROS (Auburg et al. 1993), MOA (Abe et al. 1997)

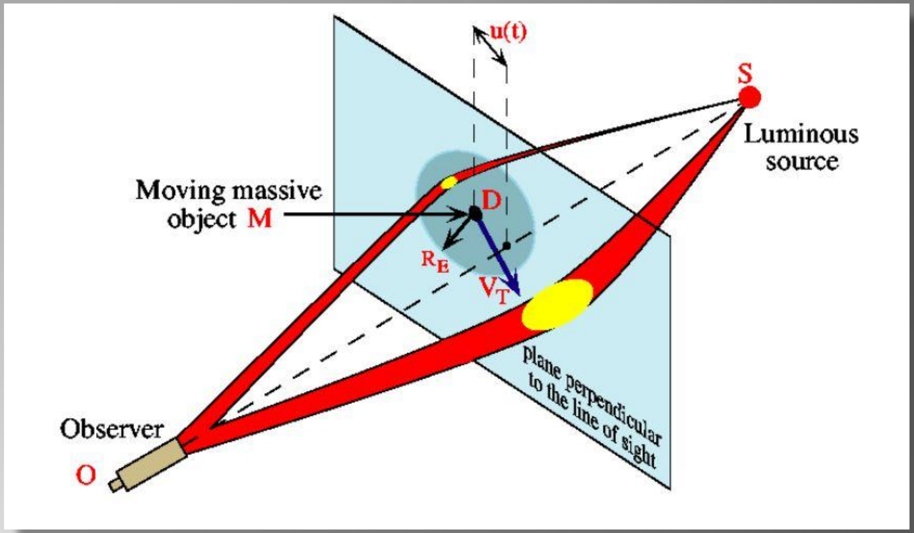
Microlensing theory in pills

Einstein radius

$$R_E = 2\left[\frac{G\,M}{c^2}\,\frac{D_l\,(D_s - D_l)}{D_s}\right]^{1/2}$$

Einstein time-scale

$$t_E = \frac{R_E}{v_\perp} = \frac{2}{v_\perp}\left[\frac{G\,M}{c^2}\,\frac{D_l\,(D_s - D_l)}{D_s}\right]^{1/2}$$



Source: Moniez (2010)

Amplification

$$A(t) = \frac{u(t) + 2}{u(t)\sqrt{u(t)^2 + 4}}$$

Optical depth

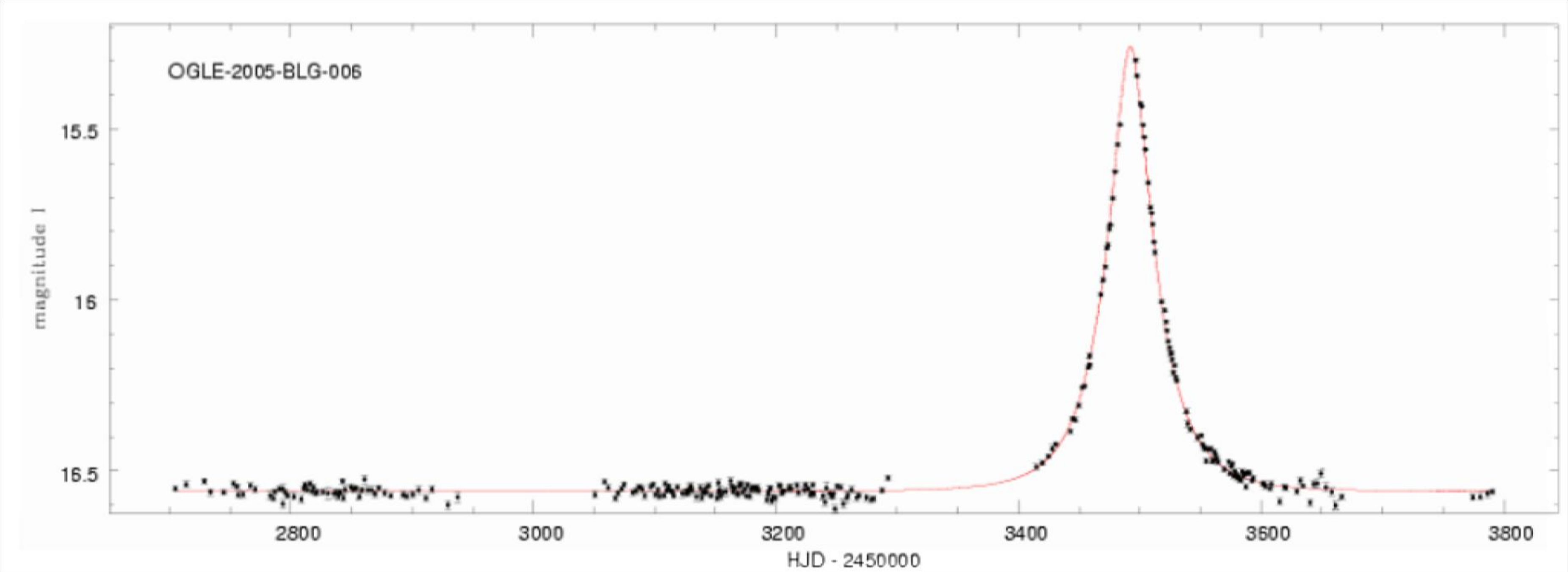
$$\tau(D_s) = \frac{4\pi G}{c^2}\int_0^{D_s} \rho_l(D_l)\,\frac{D_l(D_s - D_l)}{D_s}\,\mathrm{d}D_l$$

$$\tau = \frac{4\pi G}{c^2\,I}\int_0^{D_{max}} \tau(D_s)\,\rho_s(D_s)\,D_s^2\,\mathrm{d}D_s$$

Rate of events

$$\mathrm{d}\Gamma = \frac{n_l(D_l)\,\mathrm{d}^3 D_l}{\mathrm{d}t}\,\frac{n_s(D_s)\,D_s^2\,\mathrm{d}D_s}{I}\,f(\mathbf{v}_\perp)\,\mathrm{d}^2 v_\perp$$

$$\mathrm{d}N_{ev} = N_{obs}T_{obs}\mathrm{d}\Gamma$$



Courtesy of P. Jetzer

What surveys tell us

Optical depth towards the Galactic bulge:

Theory: $\tau \sim 10^{-6}$ (Paczynski 1991, Griest 1991)

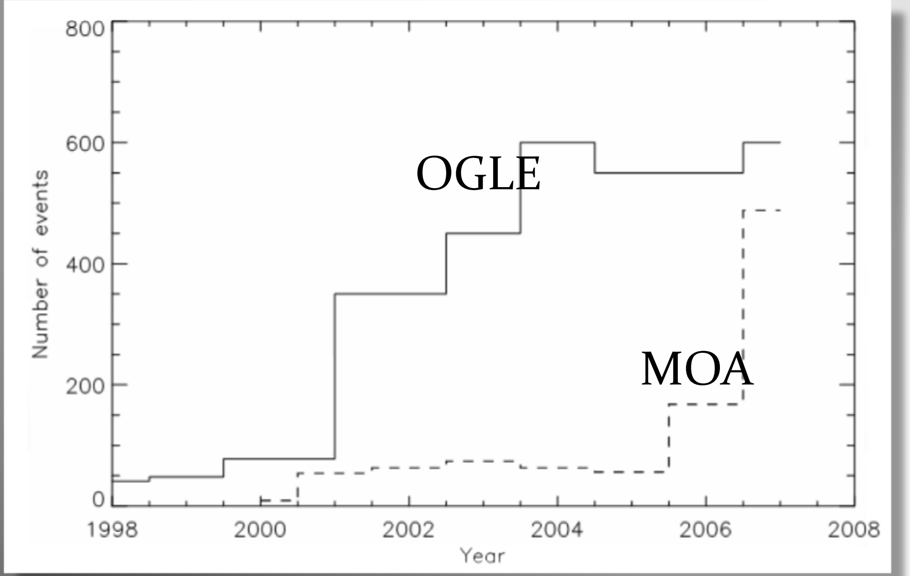
Surveys: $\tau \sim 2 \times 10^{-6}$ (Popowski et al. 2005, Hamadache et al. 2005, Sumi et al. 2006)

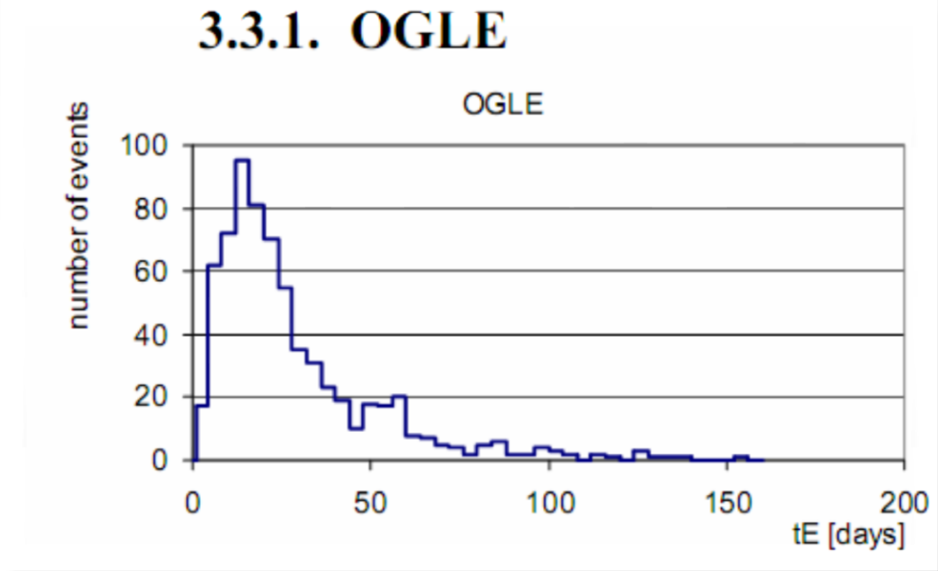
Self-lesing of bulge stars dominates, $t_E \sim 10 - 20$ days;

Number of events detected: $N_{ev} \sim 5 \times 10^3$, ~ 500/600 events/year

Excess of long duration events (Bennett et al. 2002/Popowski et al. 2005)**;**

Courtesy of P. Jetzer





Updated model

(Sartore & Treves 2010, A&A 523, A33)

Distribution of lens and source stars (and NS/BH progenitors)

Galactic (triaxial) bulge:
(Stanek et al. 1997)

$$\rho_B(x,y,z) = \rho_B \exp(-r), \qquad r = \sqrt{\left(\frac{x}{x_0}\right)^2 + \left(\frac{y}{y_0}\right)^2 + \left(\frac{z}{z_0}\right)^2}$$

Velocity dispersion, σ_v= 100 km/s

Age = 10 Gyr (burst of SF)

Exponential disk:
(Robin et al. 2003)

$$\rho_{D_i}(R,z) = \frac{M_{D_i}}{4\pi(L_i^2 - L_h^2)z_h}\left[\exp\left(-\frac{R}{L_i}\right) - \exp\left(-\frac{R}{L_h}\right)\right]\exp\left(-\frac{|z|}{H_i}\right)$$

Velocity dispersion, σ_v= 25 km/s

0 < Age < 10 Gyr (constant SFR)

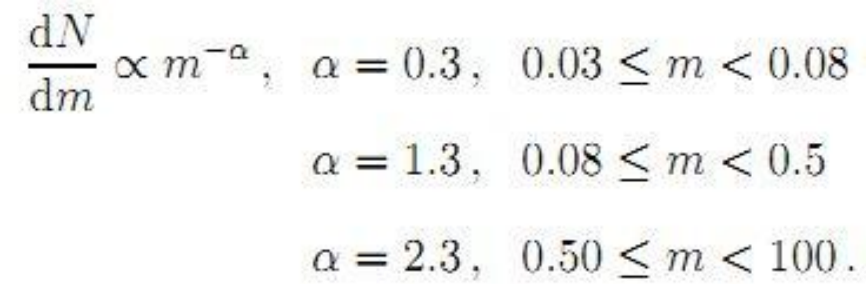
Gravitational potential from approximation of density profiles of MN disks

caveat: bulge potential axisymmetric!

Velocity distribution: same for NS and BH σ_v= 265 km/s (Hobbs et al. 2005)

Stellar populations: brown dwarfs (BD), main sequence (MS), white dwarfs (WD), neutron stars (NS), black holes (BH)

Mass function:
(Kroupa 2001)

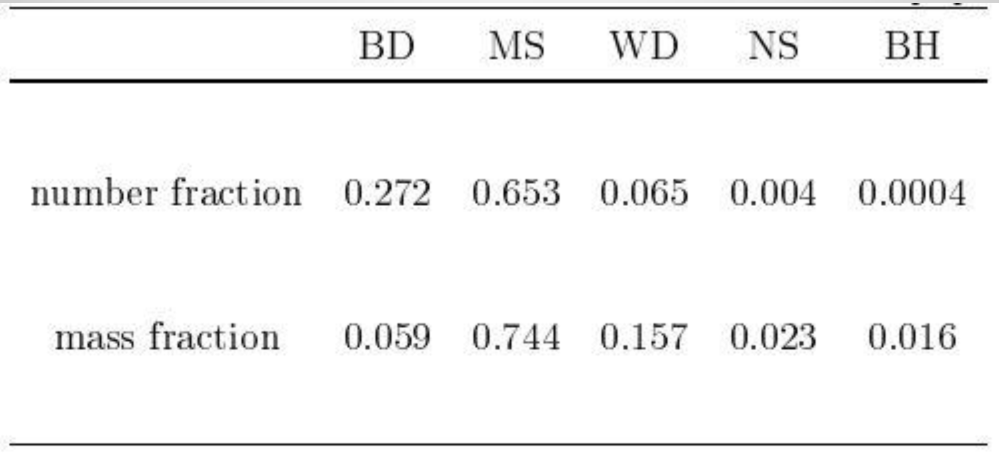


$$\frac{dN}{dm} \propto m^{-\alpha}, \quad \begin{aligned} &\alpha = 0.3\,, & 0.03 \le m < 0.08 \\ &\alpha = 1.3\,, & 0.08 \le m < 0.5 \\ &\alpha = 2.3\,, & 0.50 \le m < 100\,. \end{aligned}$$

$m = M/M_{sun}$

Average mass:

1. MS(+BD), $m < 1$, $m_{MS+BD} = 0.3$
2. WD, $1 < m < 8$, $m_{WD} = 0.6$
3. NS, $8 < m < 40$, $m_{NS} = 1.4$
4. BH, $m > 40$, $m_{BH} = 10$

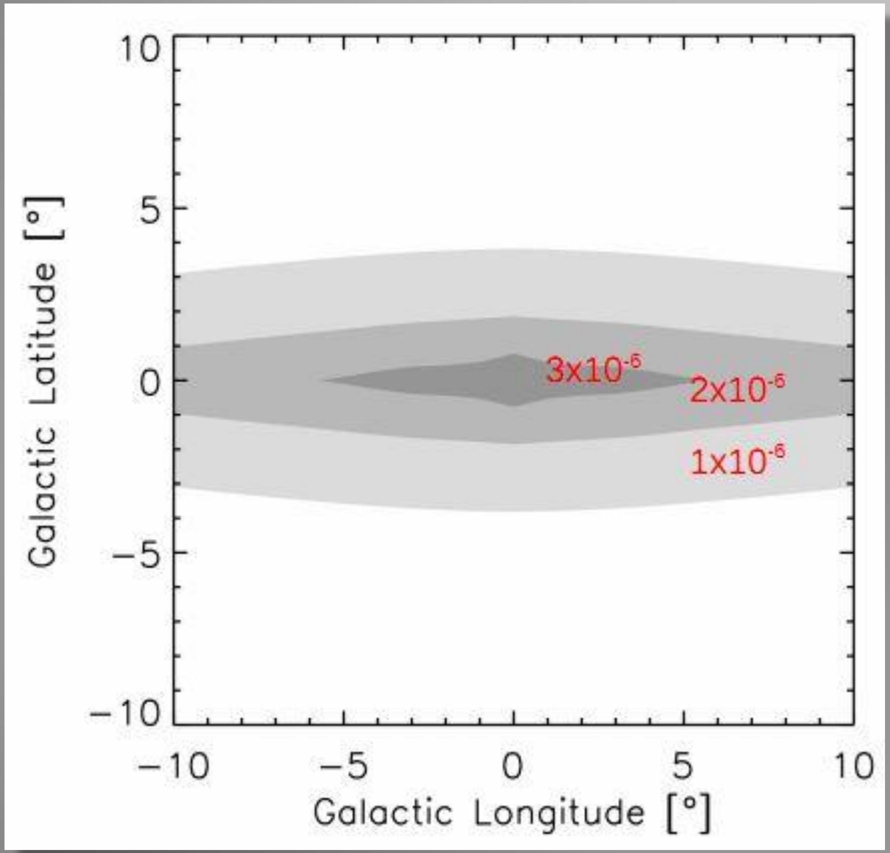


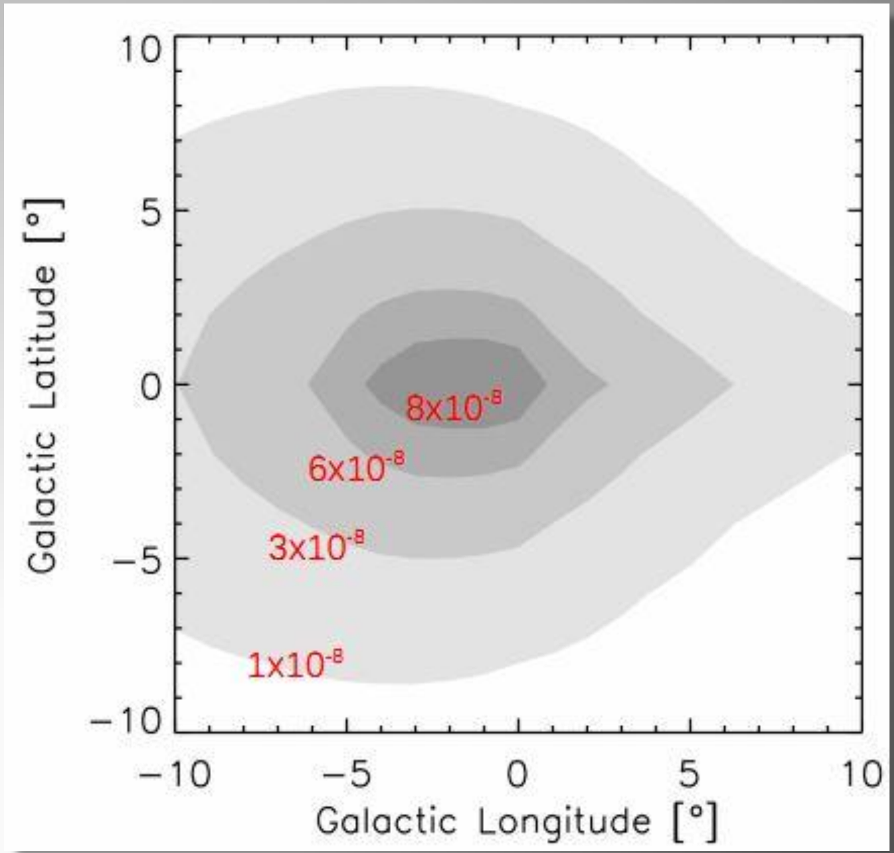
	BD	MS	WD	NS	BH
number fraction	0.272	0.653	0.065	0.004	0.0004
mass fraction	0.059	0.744	0.157	0.023	0.016

Example: the Baade's Window (l=1°, b=-3°.9)

$\tau_{tot} = 0.97 \times 10^{-6}$
$\tau_{NS} = 0.019 \times \tau_{tot}$
$\tau_{BH} = 0.013 \times \tau_{tot}$

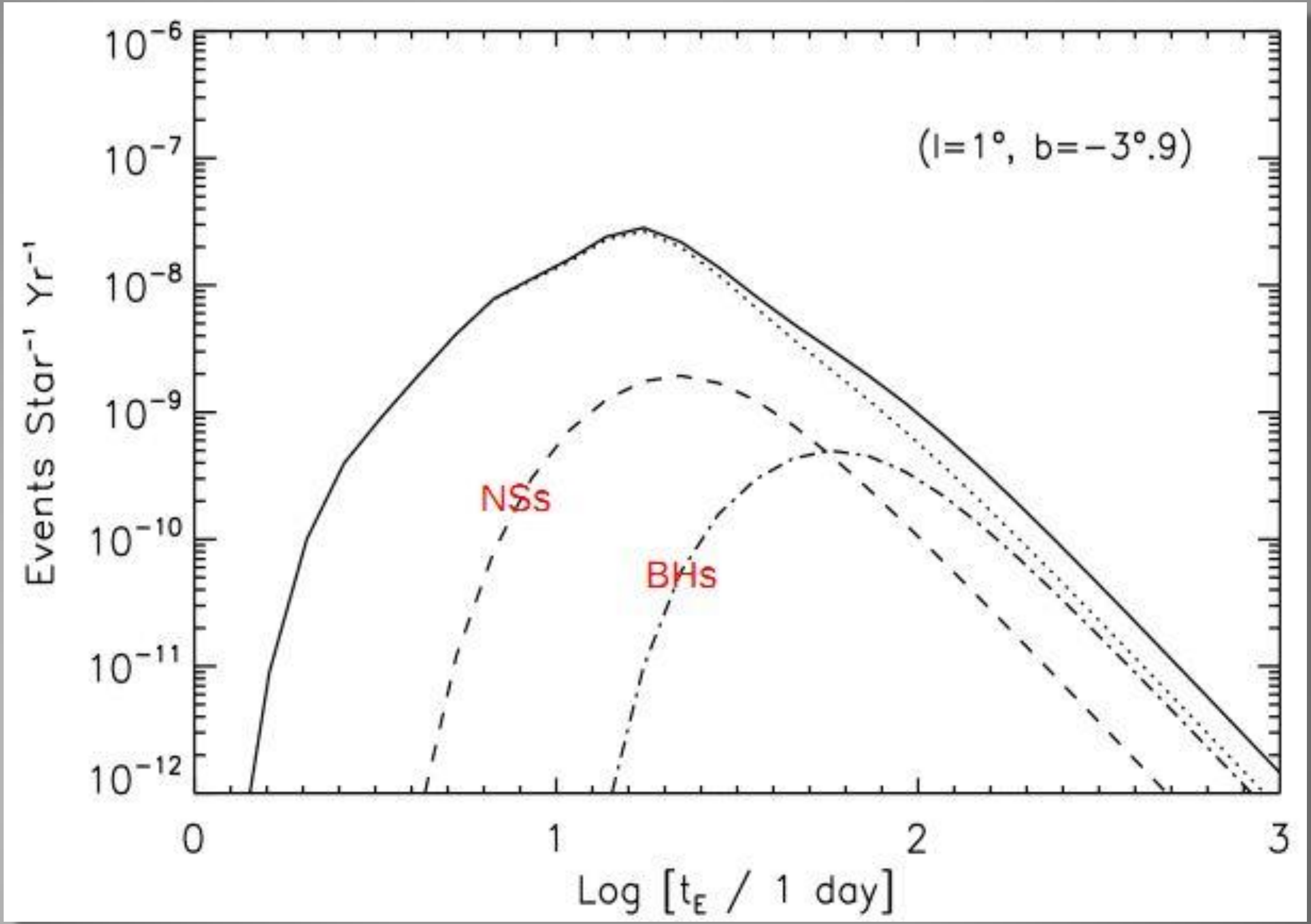
Lower than predictions of standard models (no kicks)

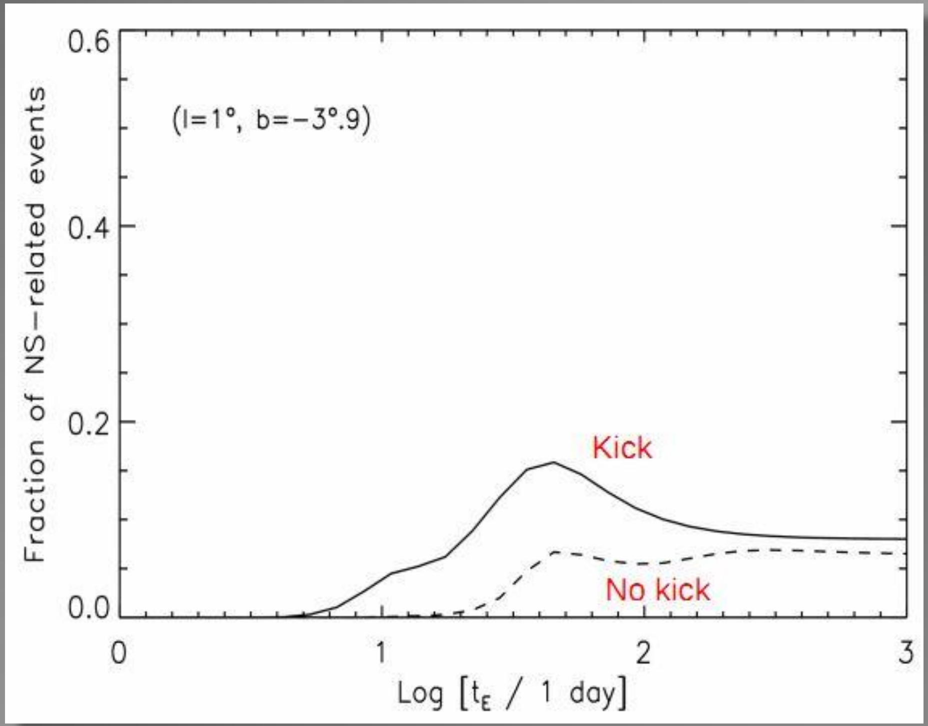


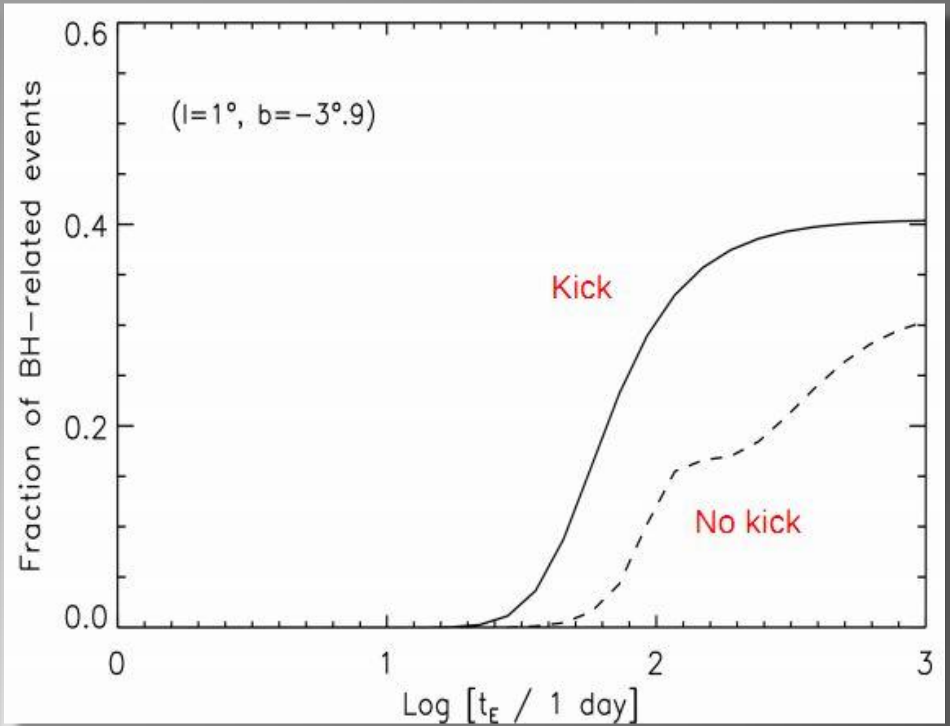


Difference in phase-space distribution

Distribution of event time-scales







Overall ~ 5x increase of the number of events from NS/BH

Fraction on NS-related events from ~ 1% to ~ 5%
Fraction on BH-related events from ~ 0.2% to ~ 1%

NS/BH contribute for ~ 40% of long duration (> 100 days) events!

Correlation of ML events with X-ray catalogs

(Sartore & Treves 2011, A&A, submitted)

ML event catalogs:

1. OGLE: 4117 events, 177 with t_E > 100 days
2. MACHO: 654 events, 38 with t_E > 100 days
3. MOA: 2622 events, 268 with t_E > 100 days

X-ray source catalogs:

1. 2XMM Data Release 3: 191870 sources
2. Chandra Source Catalog v1.1: 106586 sources

No constraints on spectrum and variability

Correlation based on positional coincidence (within errors) alone;

A candidate X-ray counterpart: 2XMM J180540.5-273427

Counts: ~ 312 photons

f_X [0.2 – 10 keV]: ~ 3.34 x 10^{-14} erg/s/cm^{-2}

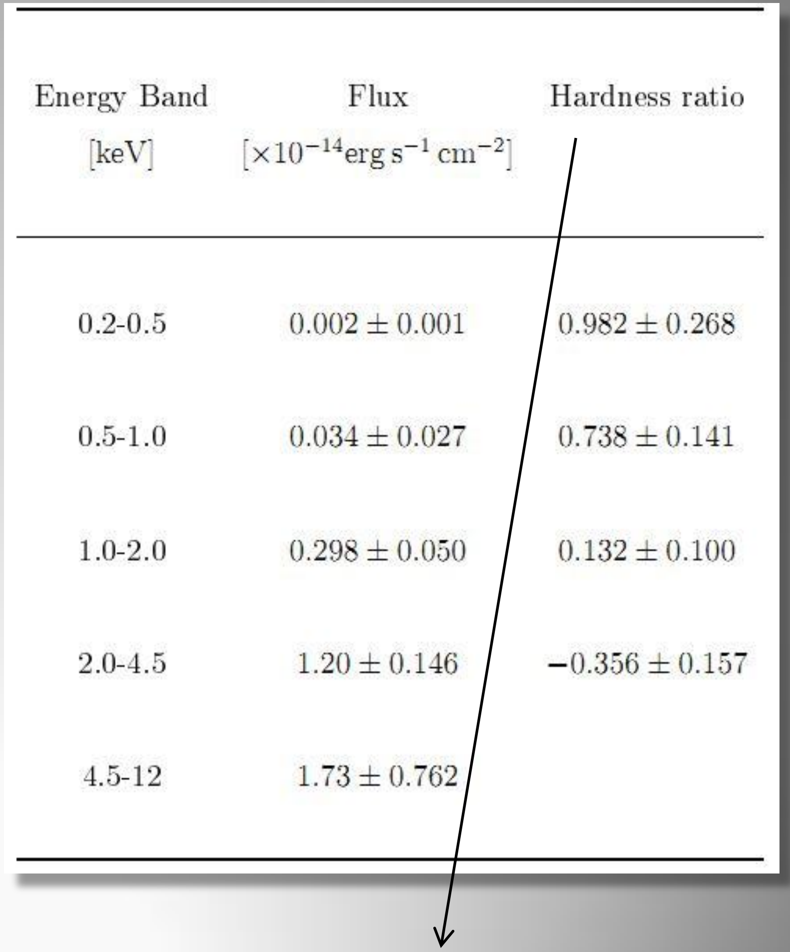
Pos. error: ~ 1.3” (1σ)

ML event @ 0.5”

$L_x \sim 4 \times 10^{30}$ (d / 1 kpc)^2 erg/s

Hardness ratios suggest hard (kT > 1 keV) or heavily absorbed spectrum;

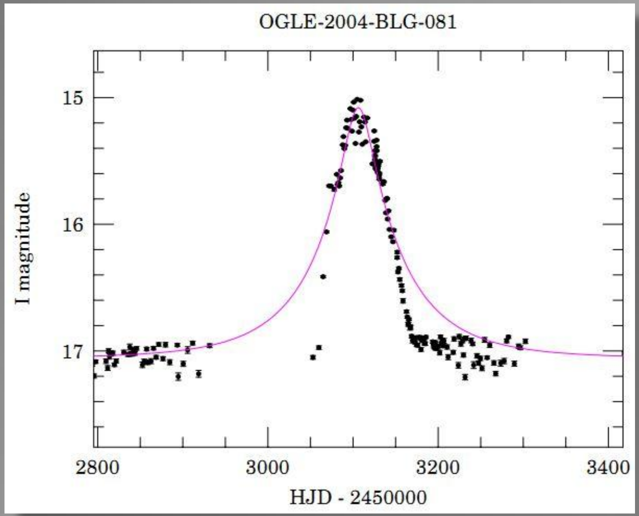
A black hole as accreting object



Energy Band [keV]	Flux [$\times 10^{-14}$erg s^{-1} cm^{-2}]	Hardness ratio
0.2-0.5	0.002 ± 0.001	0.982 ± 0.268
0.5-1.0	0.034 ± 0.027	0.738 ± 0.141
1.0-2.0	0.298 ± 0.050	0.132 ± 0.100
2.0-4.5	1.20 ± 0.146	-0.356 ± 0.157
4.5-12	1.73 ± 0.762	

$HR_i = (CR_{i+1} - CR_i) / (CR_{i+1} + CR_i)$

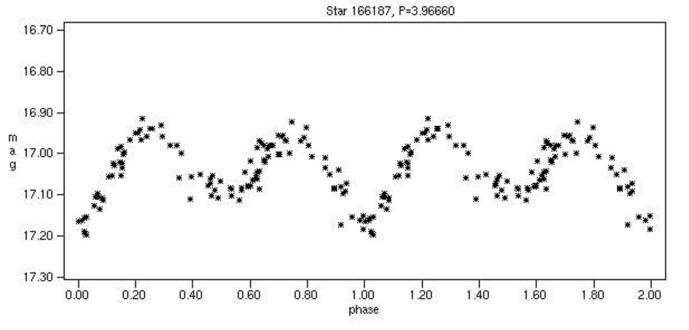
The lensing event: OGLE 2004-BLG-81



FIT PARAMETERS:
Io = 17.058 ± 0.001
tau = 103.630 ± 0.157 days
Amax = 6.193 ± 0.008

Fit inadequate
Symmetric light-curve

The lensed star: OGLE BUL_SC36_636869



Variable star
P = 3.96 days

Light curve suggests
contact binary

Proposed models

1. RS Canum Venaticorum star (Bernhard 2009);
2. Cataclysmic variable (Wyrzykosky et al.,2006);

Flaring activity!
Also X-ray sources!!

What scenario for OGLE 2004-BLG-81/2XMM J180540.5-273427?

- RS CVn star explains X-ray emission (log Lx = 30.36 ± 0.85) and ML event (flaring activity) but not symmetric light curve. Optical spectrum would show strong Ca II H and K lines (Padmakar et al. 2000);

- Cataclysmic variable explains X-ray emission and ML event (nova-like outburst) but not symmetric light curve and outburst timescale, nor orbital period (period gap, Kuulkers et al. 2003);

- Microlensing event explains symmetry , but not the shape, of light curve (Wyrzykowski et al. 2006). A different baseline?

- 2XMM J180540.5-273427 as accreting black hole would require low spatial velocity and/or high density of ISM and high emission efficiency;

Further observations needed in order to constrain the properties of the lensed star and the X-ray source

Conclusions

Large spatial velocities as key factor in determining the observability of isolated neutron stars and black holes…

- Evaporation from the Galaxy and Galactic disk;
- Very low accretion rates;

…favours their detectability through microlensing surveys

- Net increase in the number of ML events related to NS/BH;
- 40% of long duration events possibly related to NS/BH;
- Independent from emission properties;
- Precise localization of the object (vs blind searches);
- Large statistics already available;

A possible BH candidate from ML/X-ray cross-correlation

- First detection of isolated BH (with ML);
- Nature of ML event, lensed star and X-ray source still unclear;
- Further observations needed;

Future prospects

Enlargement of ML event catalogs;

- OGLE IV (in operation), ~ 1000 events detected each year;

Deeper X-ray surveys;

- eROSITA soft X-ray survey: $f_x^{lim} \sim 10^{-15}$ erg/s/cm^2
  - tighter constraints on X-ray emission from isolated neutron stars/black holes

Search for counterparts at other wavelengths (e.g. radio);

Follow-up observations of interesting ML events, based on duration and other secondary effects;

- X-rays: spectrum of the NS/BH candidate (XMM, Chandra);
  Optical: image shift;

THANKS!

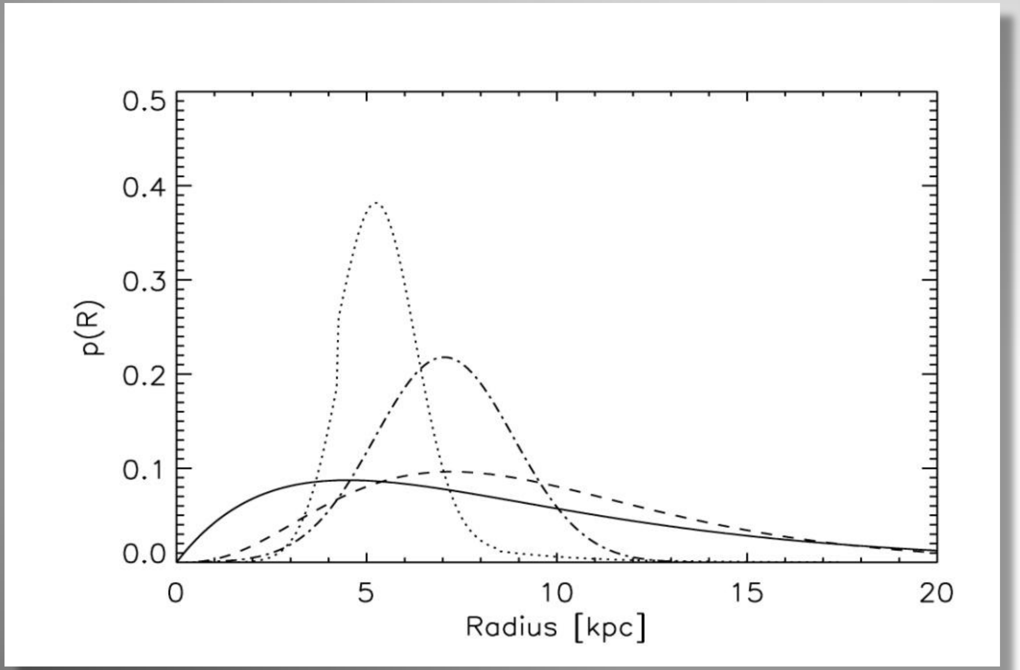
Code description - I

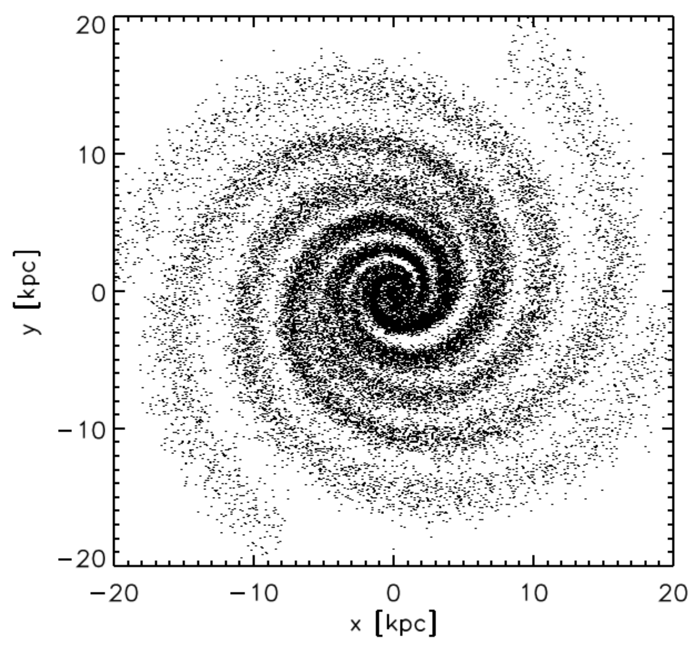
Distribution of progenitors:

- Radial distribution: (Paczynski 1990):

$$p(R)\,dR = a_R \frac{R}{R_{exp}^2} \exp\left(- \frac{R}{R_{exp}} \right) dR$$

- All INS born on the Galactic plane ($z_i = 0$);
- Spiral arms structure (Faucher-Giguère & Kaspi 2006):
- Constant birth rate (0 < age < 10 Gyr);





Code description - II

Distributions of birth velocities:

$$p(v) = \sqrt{\frac{2}{\pi}}\, v^2 \left[\frac{w}{\sigma_1^3} \exp\left(- \frac{v^2}{2\,\sigma_1^2} \right) + \frac{1-w}{\sigma_2^3} \exp\left(- \frac{v^2}{2\,\sigma_2^2} \right) \right]$$

$$p(v_i) = \frac{1}{2\, v_{exp}} \exp\left(- \frac{|v_i|}{v_{exp}} \right)$$

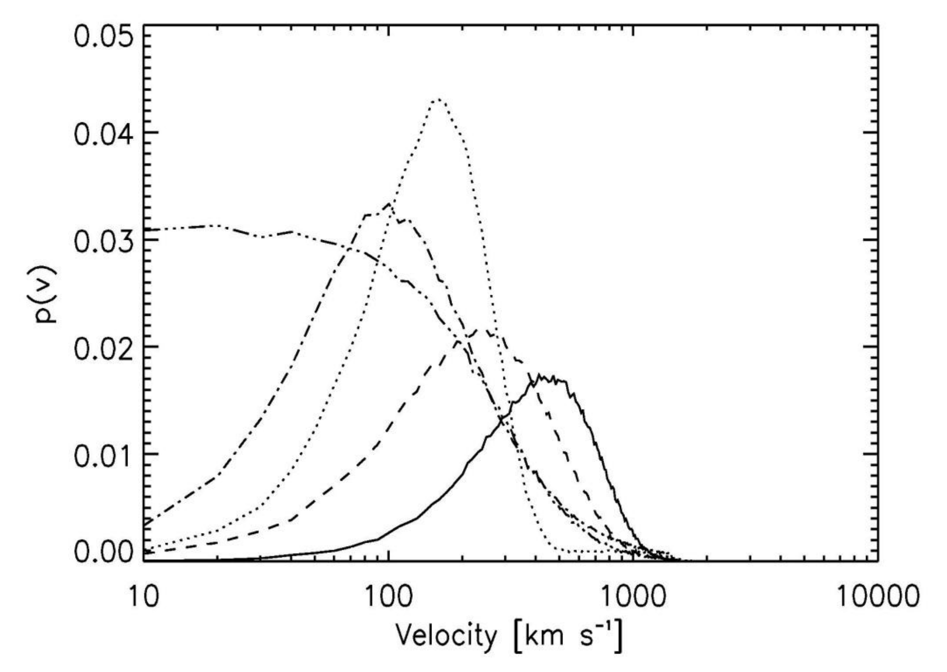
$$p(v_i) = \frac{1}{\pi\, \gamma \left(1 + \left(v_i^2 / \gamma^2 \right) \right)}$$

$$p(v) = \frac{4}{\pi\, v_* \left(1 + \left(v / v_* \right)^2 \right)^2}$$

Faucher-Giguère & Kaspi (2006)

$$p(v) = \sqrt{\frac{2}{\pi}} \frac{v^2}{\sigma^3} \exp\left(- \frac{v^2}{2\,\sigma^2} \right)$$

Hobbs et al. (2005)



Birth velocities are in the Local Standar of Rest (LSR)

$$\mathbf{v}_\mathrm{i} = \mathbf{v}_\mathrm{birth} + \mathbf{v}_\mathrm{circ}(\mathbf{r}_\mathrm{i})$$

Code description - III

Galactic potential:

Two models

1) R_o = 8.5 kpc, $v_{circ}(R_o)$ = 220 km s^{-1}, (IAU standard)
2) R_o = 8.4 kpc, $v_{circ}(R_o)$ = 254 km s^{-1} (Reid et al .2009)

$$\Phi_B = -\frac{GM_B}{r + r_B}$$

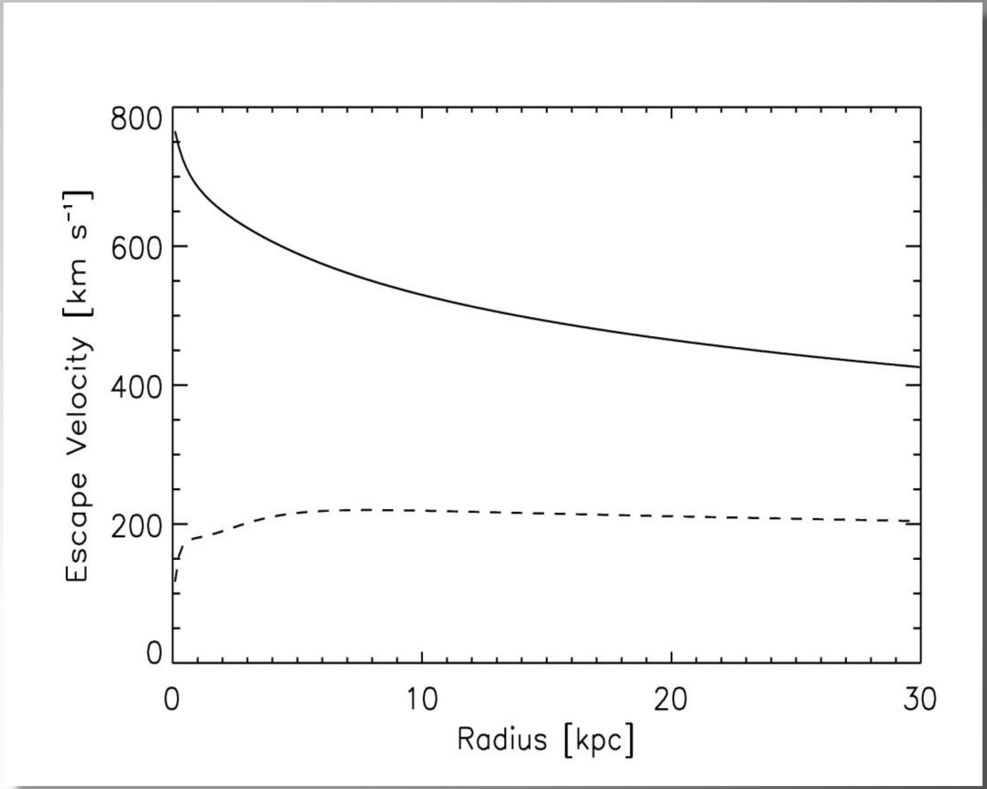
Bulge (Hernquist 1990)

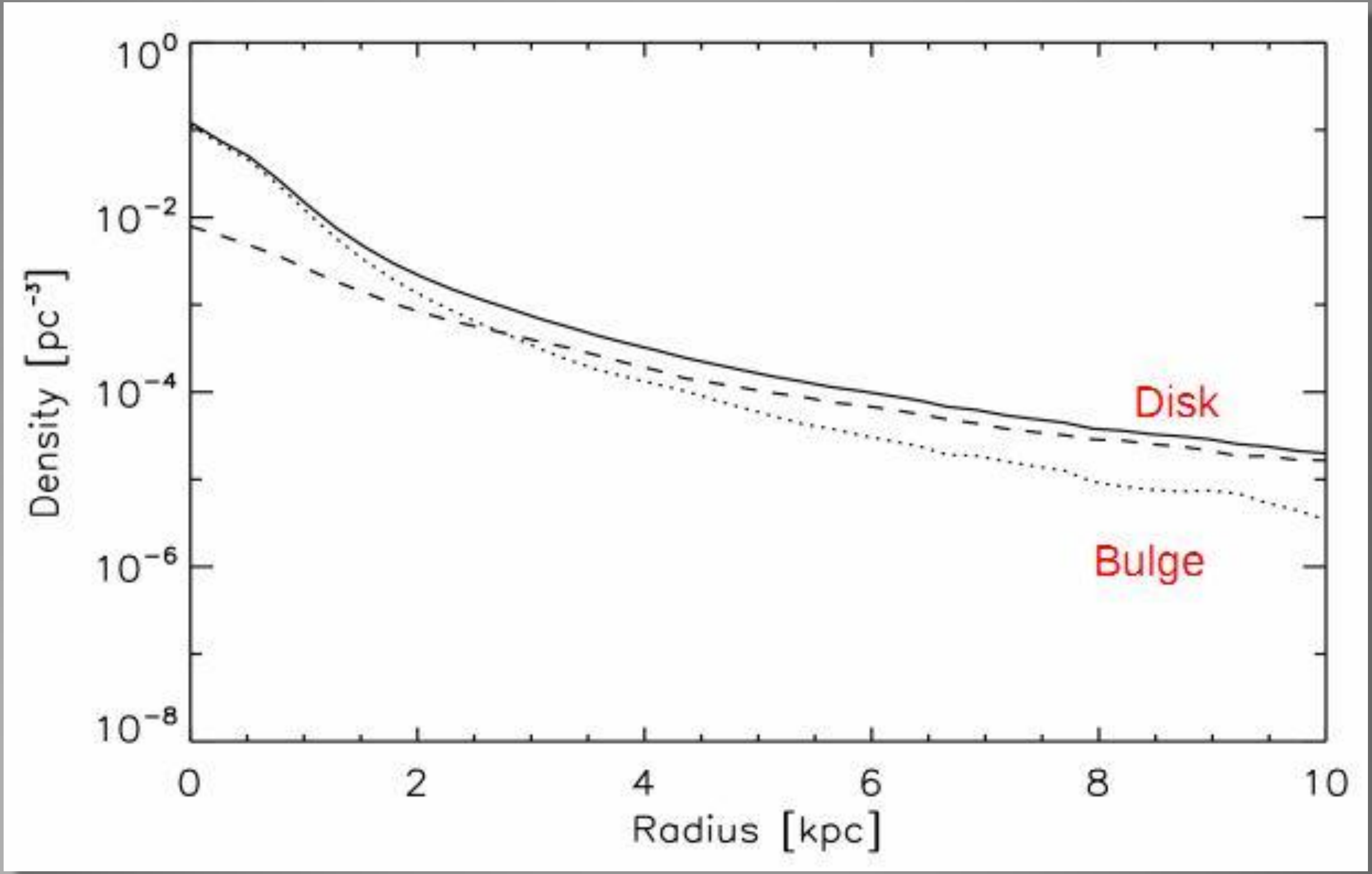
$$\Phi_D = -\frac{GM_D}{\sqrt{\left\{R^2 + \left[R_D + \sqrt{z_D^2 + z^2}\right]^2\right\}}}$$

Disk (Myiamoto & Nagai 1975)

$$\Phi_H = -\frac{4\pi G \rho_s r_{vir}^3}{c^3 r} \log\left(1 + \frac{c\,r}{r_{vir}}\right)$$

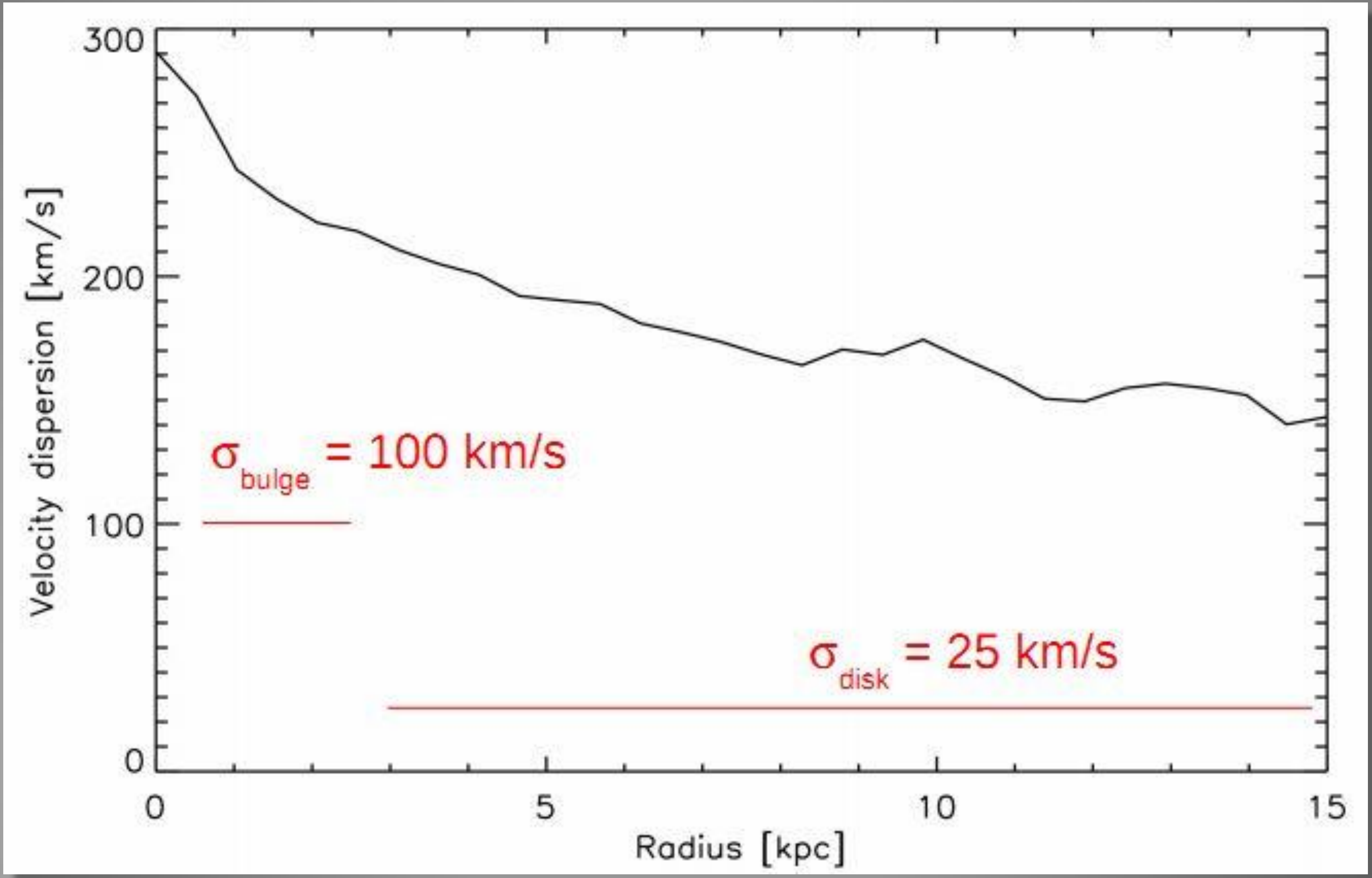
Halo (Navarro, Frenk & White 1996)

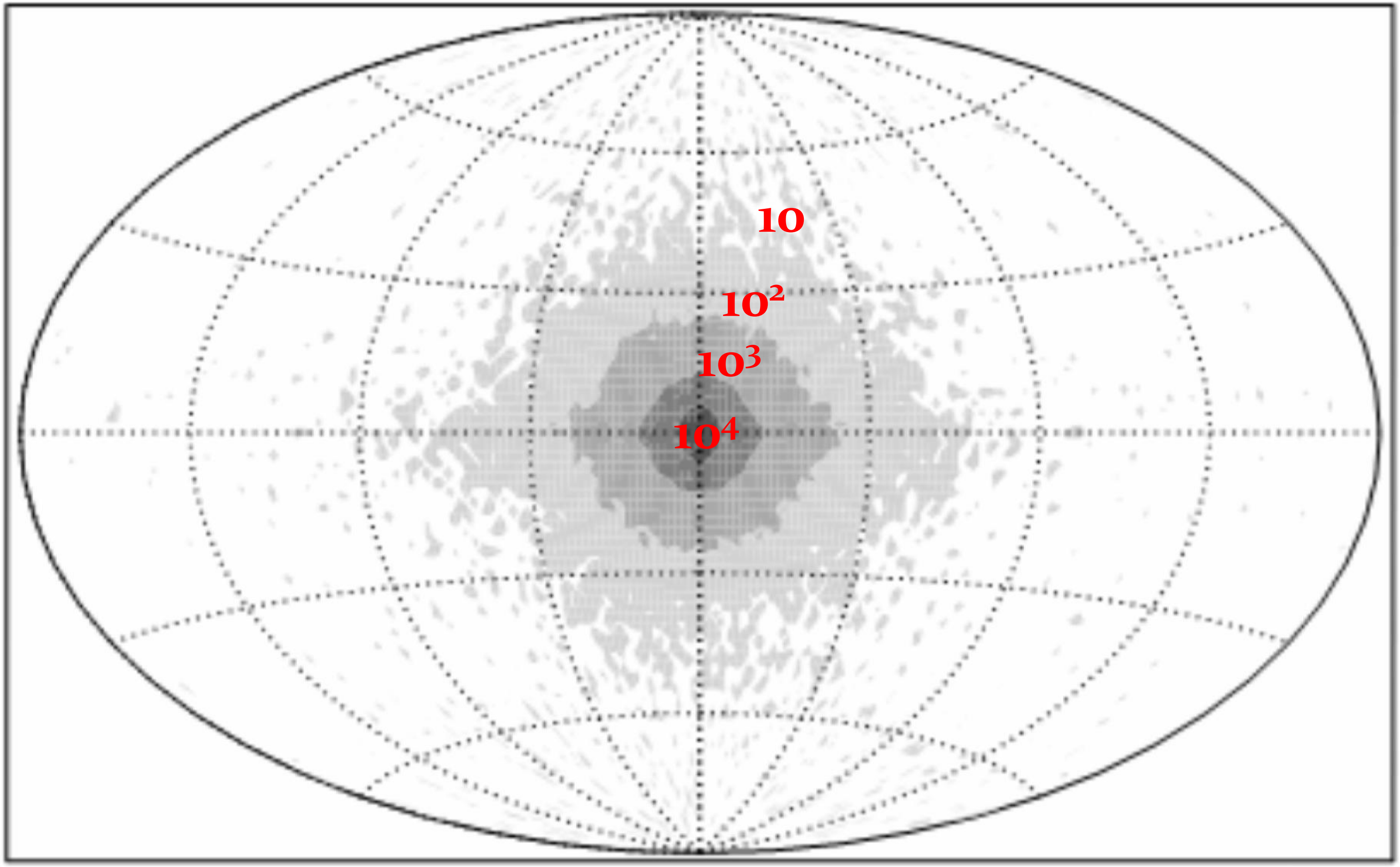


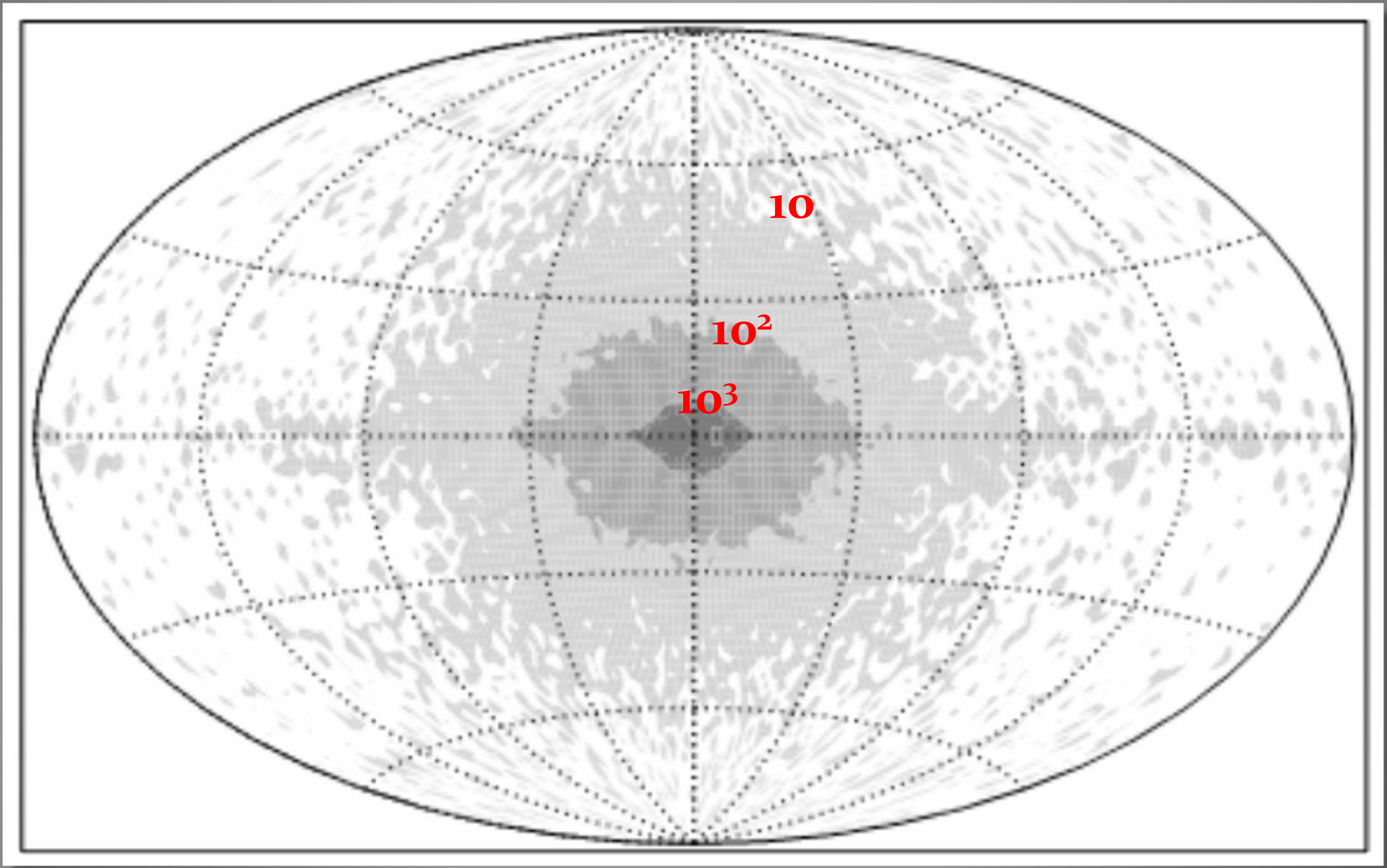


Local density, $n_0 \sim 3.3 \times 10^{-5}$ pc^{-3} (~ 20% from bulge)

Density @ Galactic Center ~ 0.12 pc^{-3} (~ 93% from bulge)


Velocity dispersion [km/s]
300
200
100
0
Radius [kpc]
0
5
10
15
σbulge = 100 km/s
σdisk = 25 km/s


10
10^2
10^3
10^4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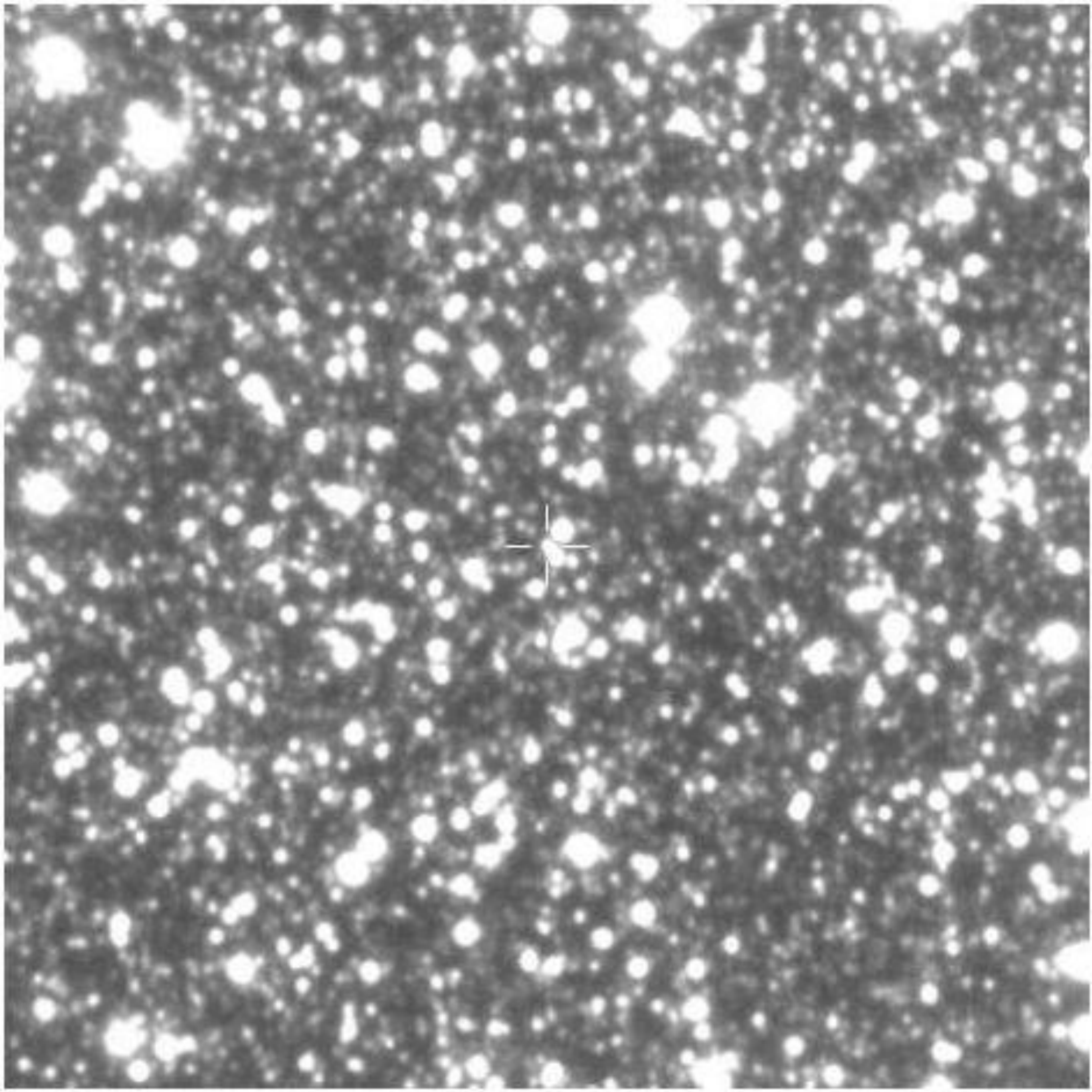

Light curve of SS Cygni in ourburst
(Kuulkers et al. 2003)