SOLAR PARAPHOTONS

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- Hidden sectors common in BSM theories
  - dynamical SUSY breaking
  - string compactifications
  - etc.

- Usual non-renormalizable interactions: suppressed by the high messenger scale

- Portals: renormalizable interactions
    - Higgs portal
    - neutrino portal
    - **kinetic mixing**

- **Kinetic mixing** term happens whenever there is a
  U(1) gauge field in the hidden sector
    - string Grand Unification
    - gauge-mediated SUSY breaking
    - etc.

Parameters:

•U(1)hidden gauge coupling

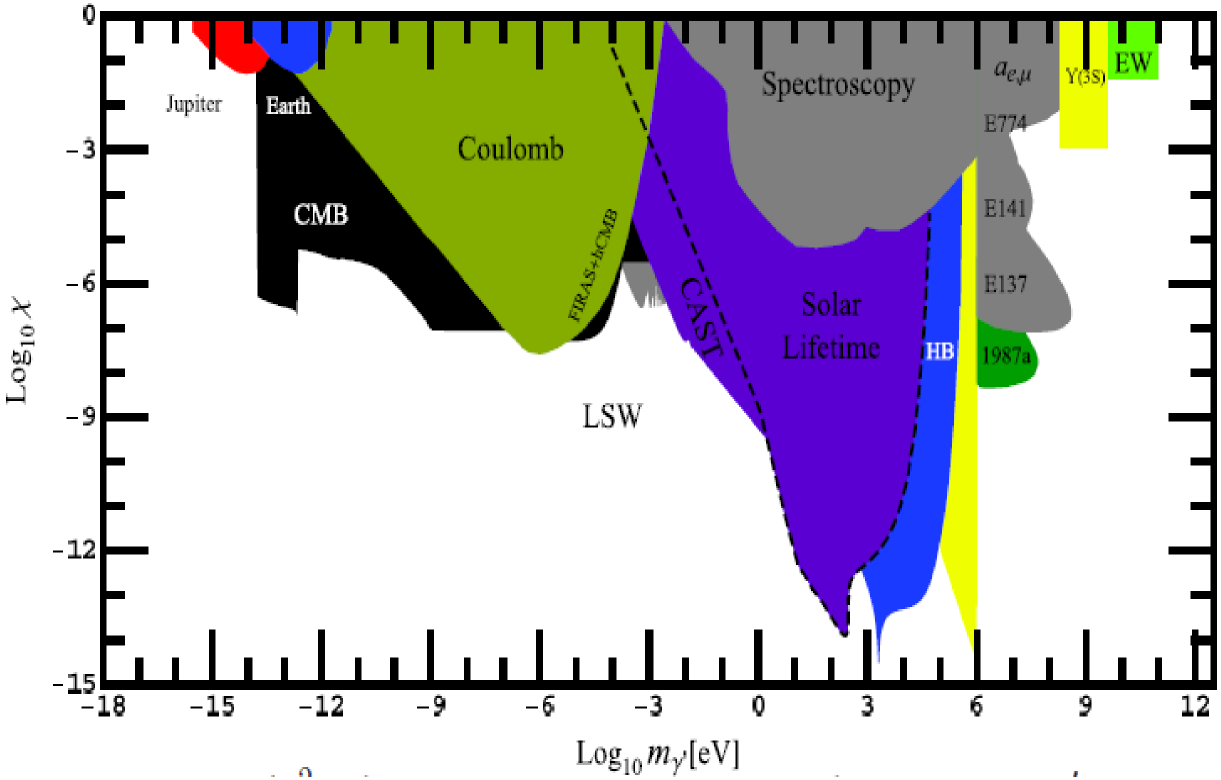
•mixing coupling

•paraphoton mass

$$\mathcal{L} = -\frac{1}{4}F'^2_{\mu\nu} - \frac{1}{4}B'^2_{\mu\nu} - \frac{\sin\chi}{2}F'_{\mu\nu}B'_{\mu\nu} + \frac{m^2}{2}B'^2_{\mu} - eA'_{\mu}j_{\mu} - gB'_{\mu}\eta_{\mu}.$$

m, *χ* relevant for oscillations

constraints on the parameters:



Hidden sector poorly constrained:
almost every allowed point in (m, χ) is motivated

However, three regions of special interest:

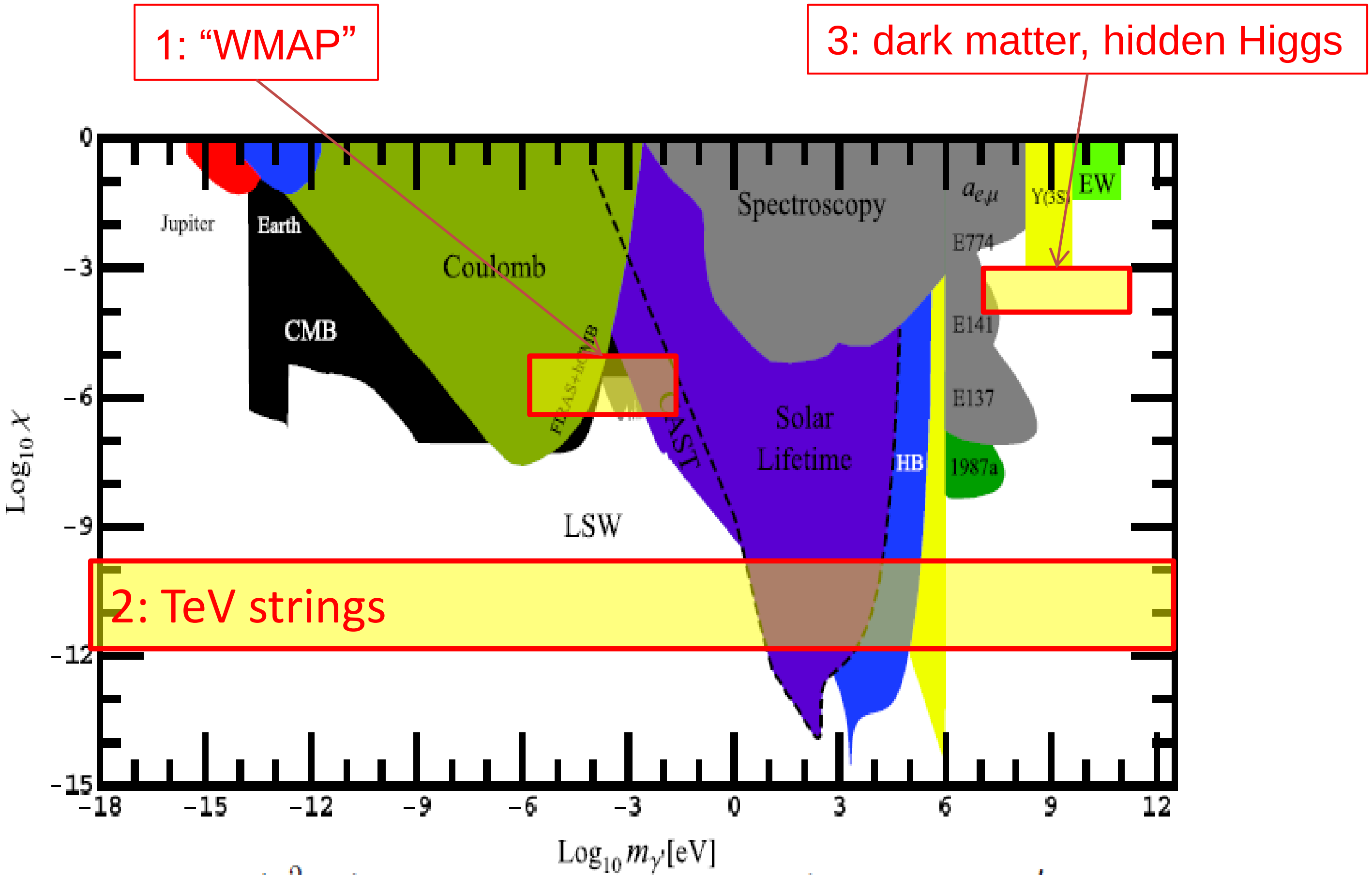
1. Mimicking extra neutrino flavour in CMB:
   (WMAP7: N_{eff} =4.34+0.86-0.88)
   $\chi = (1.1 - 2.4) \times 10^{-6}$
   $m=(10^{-5} - 10^{-2})$ eV

2. TeV scale gravity + strings (some models):
   M_{Planck} related to χ
   $\chi \sim (10^{-12} - 10^{-10})$

   (lower limit from early LHC searches)
3. "Unified" DM, "secluded" DM, "hidden" Higgs:
   - explain DAMA, PAMELA, ATIC, FERMI, INTEGRAL…
   - unusual decays of ~100 GeV Higgs (hide it)

   $\chi \sim (10^{-4} - 10^{-3})$
   m ~ GeV

constraints on the parameters:



1: LSW, solar eV
2: solar keV only
3: accelerators

oscillation probability:

$$P(B) = \left| \sin(\chi-\alpha_f)\cos(\chi-\alpha_i)\exp_{\bar{A}} - \cos(\chi-\alpha_f)\sin(\chi-\alpha_i)\exp_{\bar{B}} \right|^2$$

where:

$$\bar{A}(z) = \bar{A}(0)\exp\left[-i\omega z + \frac{1}{2\omega}\int_0^z m_{\bar{A}}^2(z')\,dz'\right] \equiv \bar{A}(0)\exp_{\bar{A}}(z),$$

$$\bar{B}(z) = \bar{B}(0)\exp\left[-i\omega z + \frac{1}{2\omega}\int_0^z m_{\bar{B}}^2(z')\,dz'\right] \equiv \bar{B}(0)\exp_{\bar{B}}(z),$$

$$m_{\bar{A}}^2 = \frac{\Pi\cos^2\alpha - G\sin^2\alpha}{\cos 2\alpha} = \Pi(1-\tan\chi\tan\alpha),$$

$$m_{\bar{B}}^2 = \frac{G\cos^2\alpha - \Pi\sin^2\alpha}{\cos 2\alpha} = \Pi(1+\tan\chi\cot\alpha),$$

$$\tan 2\alpha = \frac{\Pi\sin 2\chi}{\Pi\cos 2\chi - m^2}$$

$$\Pi = \Pi(z) = \omega_p^2(z) + i\omega\Gamma(z)$$

observation of astro paraphotons
from an optically thick emission region:

$$\alpha_f = 0$$

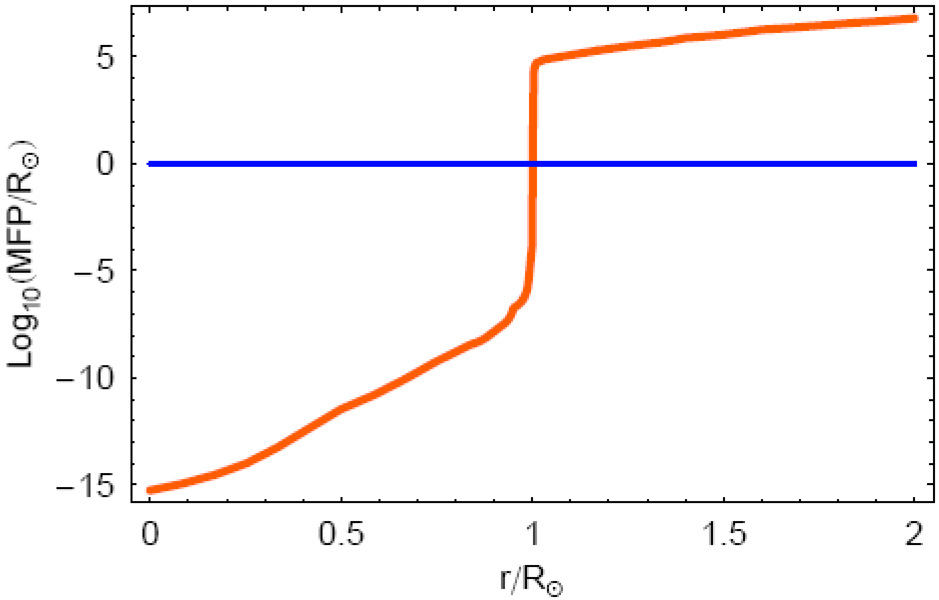
$$\tau \equiv \int \Gamma(z')\,dz' \gg 1$$

$$P(B) \simeq \cos^2\chi\,|\sin(\chi - \alpha_i)|^2 \simeq \chi^2 \frac{m_1^4}{\left(\omega_{p,i}^2 - m_1^2\right)^2 + \omega^2\Gamma_i^2}$$

SOLAR PARAPHOTONS:
converted from thermal photons inside the Sun due to kinetic mixing

Approximation: Sun = optically thick plus optically thin parts

Plot: mean free path of 1 keV photon vs. distance from the solar center



Optically thick: 0 ≤ r/Rsun ≤ 0.993

Transparent: 0.993 < r/Rsun <215 (mostly corona)

Transition region too thin to contribute significantly even at resonance

SOLAR PARAPHOTONS:
converted from thermal photons inside the Sun due to kinetic mixing

- opaque source: conversion probability determined by the emission point

$$\simeq \chi^2 \frac{m_1^4}{\left(\omega_{p,i}^2 - m_1^2\right)^2 + \omega^2 \Gamma_i^2}$$

mixing
plasma frequency
paraphoton mass
energy
photon absorption

- convolve with the photon emission rate and integrate over the Sun

- contribution of the transparent part subleading for the parameters of interest

SOLAR PARAPHOTONS:
converted from thermal photons inside the Sun due to kinetic mixing

- convolve with the photon emission rate and integrate over the Sun:

$$\frac{d\Phi}{d\omega} = \frac{3 \times 10^{24}}{\mathrm{cm}^2 \cdot \mathrm{s} \cdot \mathrm{eV}} \left(\frac{\chi}{10^{-5}}\right)^2 \left(\frac{m_1}{\mathrm{eV}}\right)^4 f_1(\omega, m_1)$$

$$f_1(\omega, m_1) = 1\ \mathrm{eV} \times \omega^2 \int_0^1 d\xi\, \xi^2 \frac{\Gamma(\xi R_\odot)}{e^{\omega/T(\xi R_\odot)} - 1} \frac{1}{\left(\omega_p^2(\xi R_\odot) - m_1^2\right)^2 + \omega^2 \Gamma(\xi R_\odot)^2}$$

plasma frequency in the Sun 0.1-300 eV:
if mass in this range, resonance dominates

if no resonance, central keV temperature dominates

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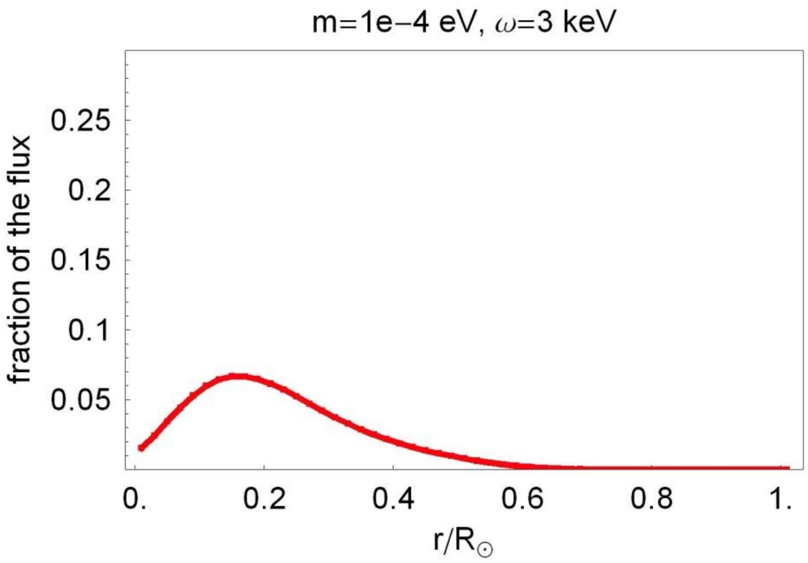
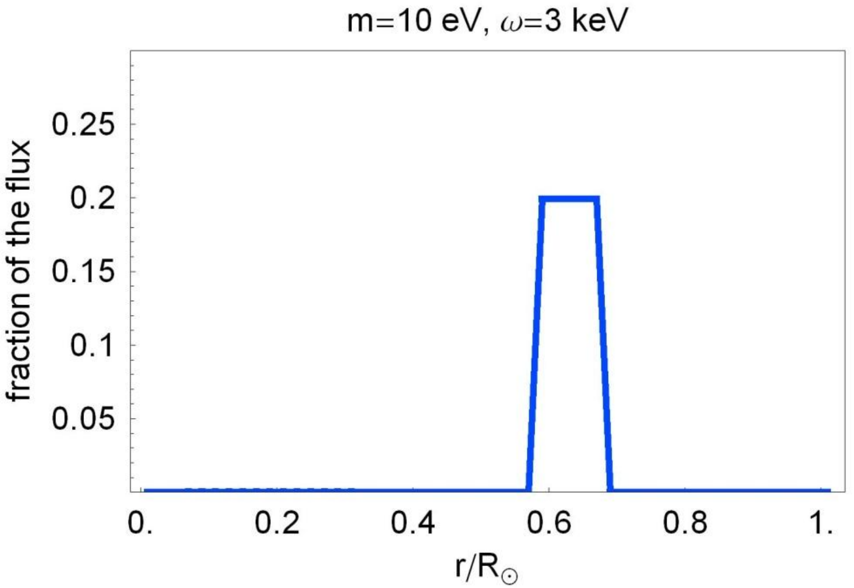
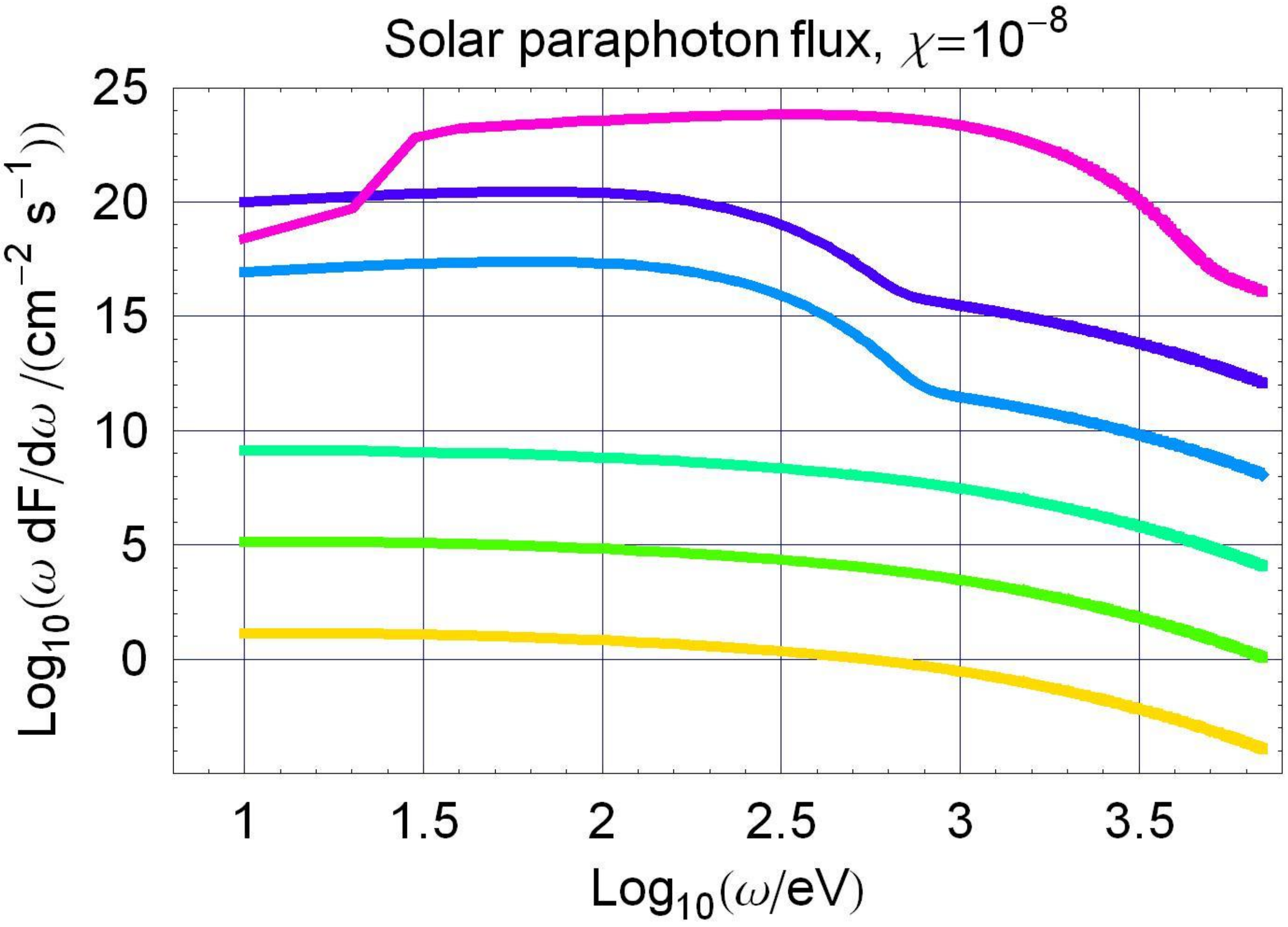




no resonance:
central part brighter

resonance:
thin slice brighter

SOLAR PARAPHOTONS:
converted from thermal photons inside the Sun due to kinetic mixing



m=10 eV

m=1 eV

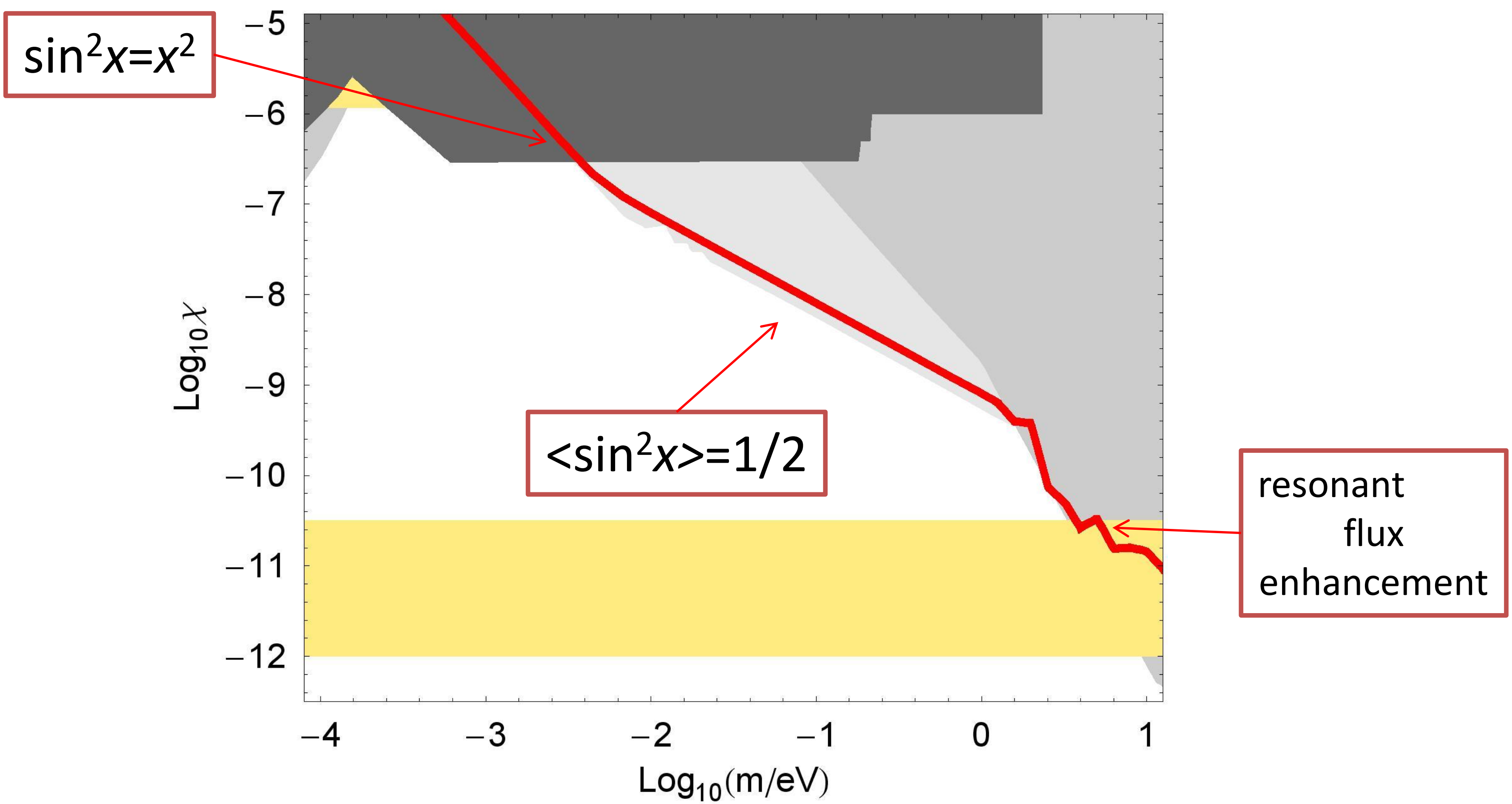
$m=10^{-1}$ eV

$m=10^{-2}$ eV

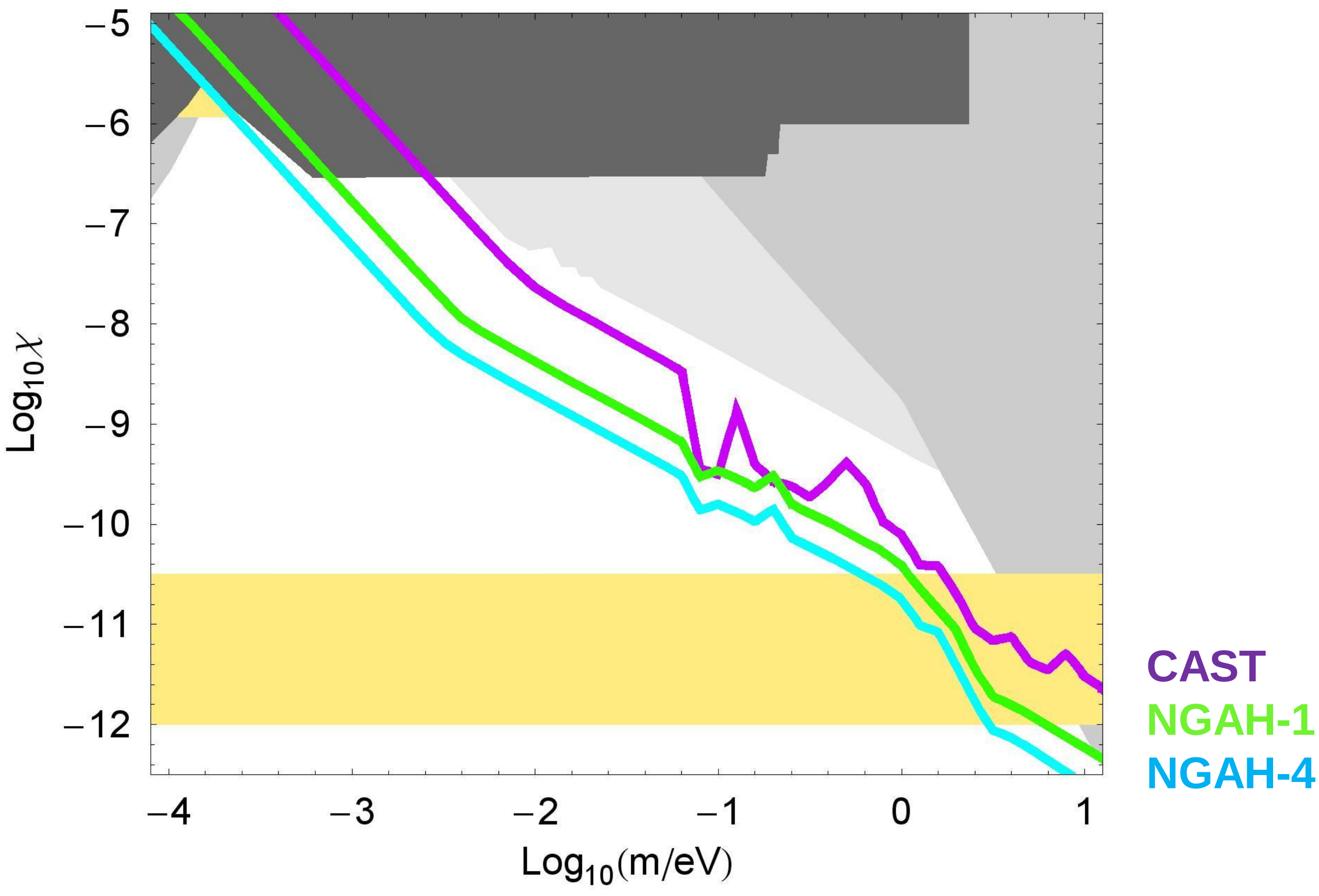
$m=10^{-3}$ eV

$m=10^{-4}$ eV

DETECTION (vacuum): $$P_{\text{vac}} = 4\chi^2 \sin^2\left(\frac{Lm^2}{2\omega}\right)$$



DETECTION PROSPECTS:



Transparent part:

an approximate relation between photon and paraphoton fluxes

$$\frac{d\Phi}{d\omega} = \frac{d\Phi_{\rm obs}}{d\omega} \frac{\int_{R_\odot}^{D} r^2 dr \, \frac{n_e^2(r)}{\exp(\omega/T(r))-1} P(B,r)}{\int_{R_\odot}^{D} r^2 dr \, \frac{n_e^2(r)}{\exp(\omega/T(r))-1} (1 - P(B,r))}$$

where

$$P(B) = \frac{1}{2} - \frac{1}{2}\cos 2\chi \frac{\cos 2\chi \left|\omega_{p,i}^2 - m_1^2\right| - \sin^2 2\chi \, \omega_{p,i}^2}{\sqrt{\left(\omega_{p,i}^2 - m_1^2\right)^2 + \omega_{p,i}^4 \tan^2 2\chi}}.$$

for keV energies and interesting m, χ
the corona contribution is negligible

FLARES:

[assume a homogeneous blob of plasma with thermal emission]

$$\frac{d\Phi}{d\omega} = \frac{d\Phi_{\rm obs}}{d\omega} \frac{\int_{R_\odot}^{D} r^2 dr \, \frac{n_e^2(r)}{\exp(\omega/T(r))-1} P(B,r)}{\int_{R_\odot}^{D} r^2 dr \, \frac{n_e^2(r)}{\exp(\omega/T(r))-1} (1 - P(B,r))}$$

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$$\frac{d\Phi}{d\omega} = \frac{d\Phi_{\mathrm{obs}}}{d\omega} \qquad \frac{P(B \quad)}{(1 - P(B \quad))}$$

FLARES:

[assume a homogeneous blob of plasma with thermal emission]

[no resonance: χ^4]

$$\chi \gtrsim 6 \times 10^{-4} \left(\frac{F_{\mathsf{obs}}}{10^5\ \mathsf{cm}^{-2}\,\mathsf{s}^{-1}\,\mathsf{eV}^{-1}}\right)^{-1/4} \left(\frac{t}{10^3\ \mathsf{s}}\right)^{-1/8} \left(\frac{n}{10^{-3}\ \mathsf{Hz}}\right)^{1/8} \left(\frac{S}{10\ \mathsf{cm}^2}\right)^{-1/4} \left(\frac{\omega}{\mathsf{keV}}\right)^{-1/4}$$

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[resonance: χ^2]

$$\chi \gtrsim 8 \times 10^{-7} \left(\frac{F_{\rm obs}}{10^5\ {\rm cm^{-2}\,s^{-1}\,eV^{-1}}}\right)^{-1/2} \left(\frac{t}{1\ {\rm s}}\right)^{-1/4} \left(\frac{n}{10^{-3}\ {\rm Hz}}\right)^{1/4} \left(\frac{S}{10\ {\rm cm^2}}\right)^{-1/2} \left(\frac{\omega}{\rm keV}\right)^{-1/2}$$

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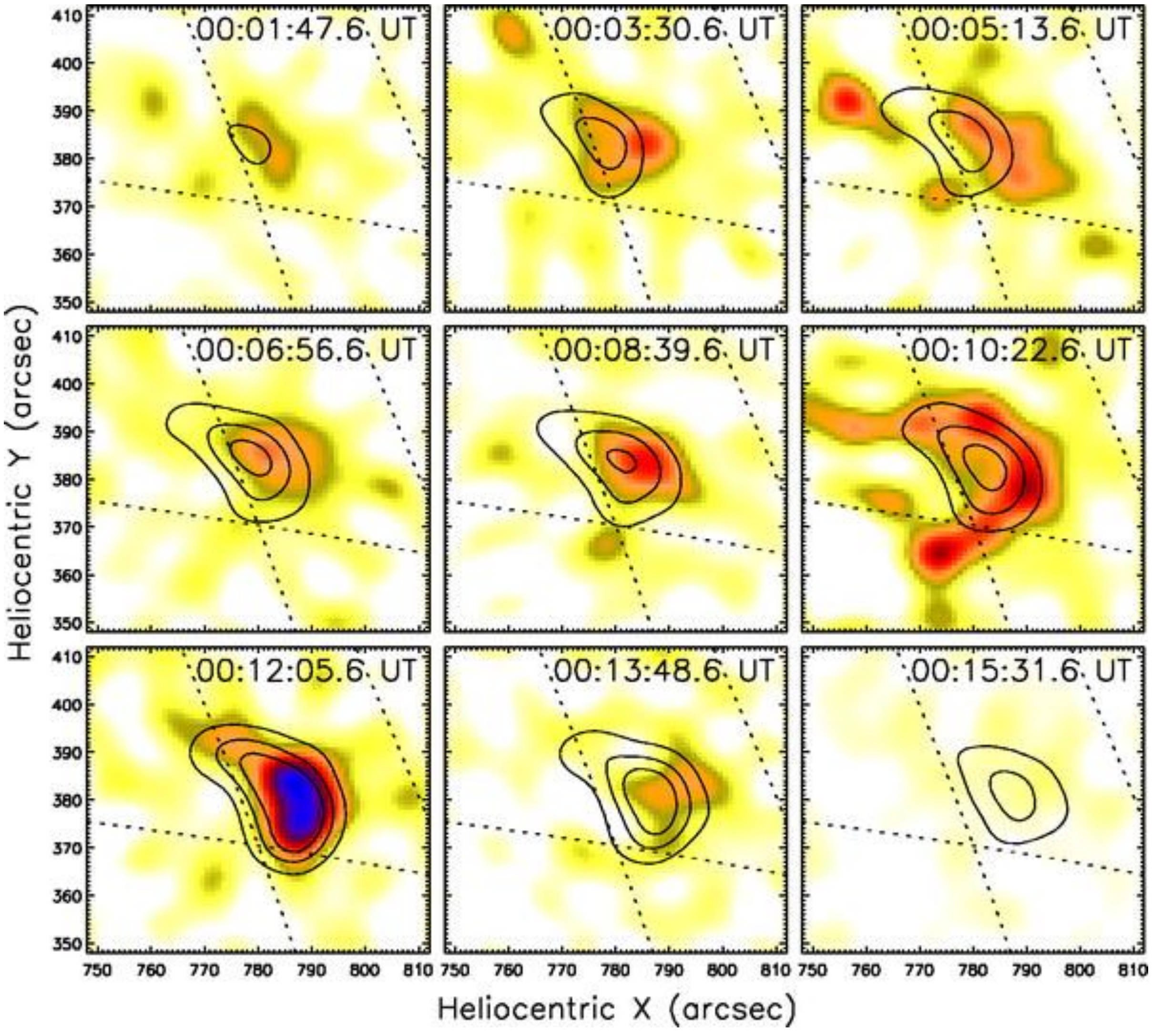
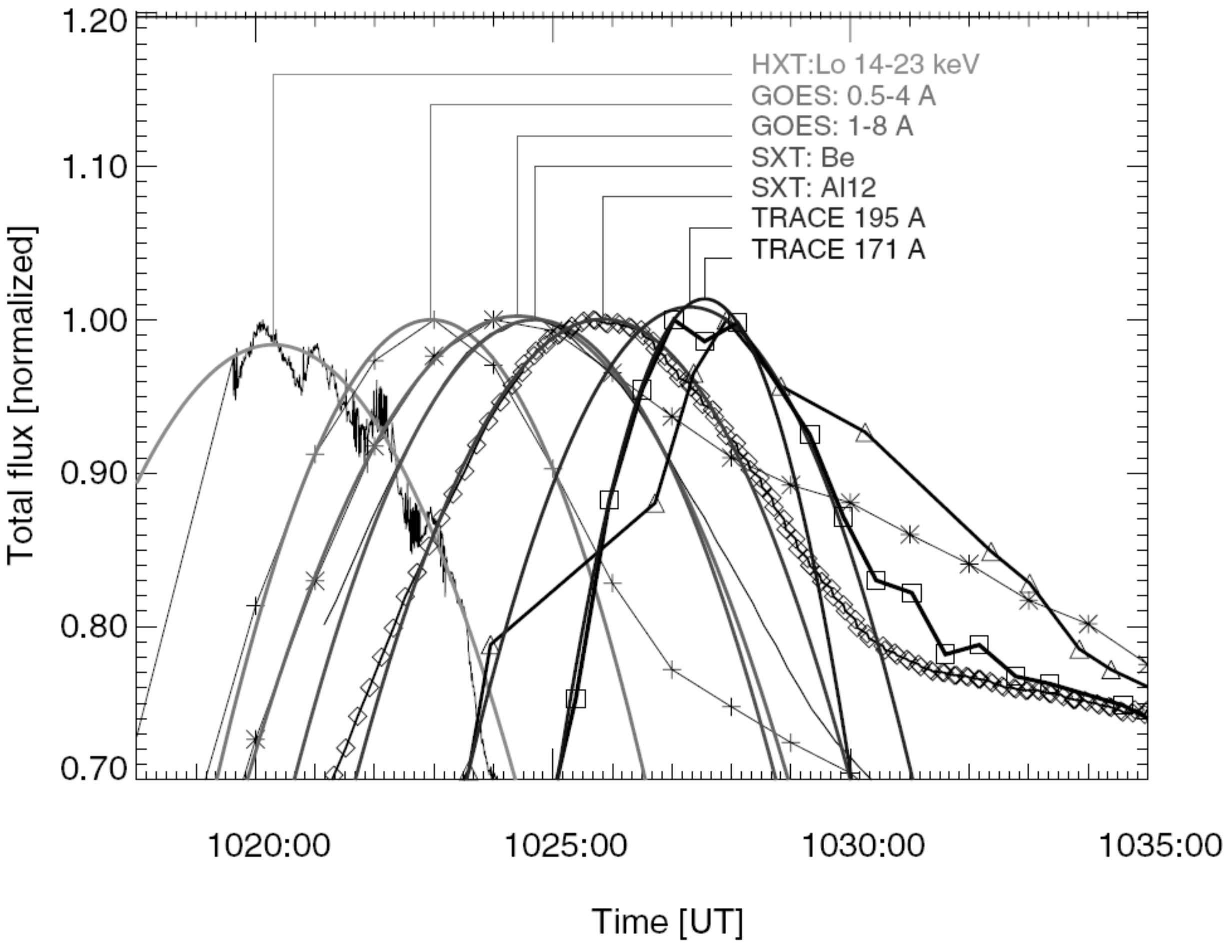
FLARES: look rapidly evolving

April 14, 2002 event



FLARES: n_e is NOT rapidly evolving

[reason of variability: temperature change, not movement]



July 14, 2000 event
[Aschwanden]

FLARES: n_e is NOT rapidly evolving

April 14, 2002 event

Time	$n = \sqrt{EM/V}$ (10^{10}cm^{-3})
23:57:48-00:04:00	9.3
00:05:00-00:10:00	11.8
00:16:00-00:24:00	8.8

[ApJ 730 (2011) L22]

FLARES:

[assume a homogeneous blob of plasma with thermal emission]

[resonance: χ^2]

$$\chi \gtrsim 8 \times 10^{-7} \left(\frac{F_{\rm obs}}{10^5\ \mathrm{cm^{-2}\,s^{-1}\,eV^{-1}}} \right)^{-1/2} \left(\frac{t}{1\ \mathrm{s}} \right)^{-1/4} \left(\frac{n}{10^{-3}\ \mathrm{Hz}} \right)^{1/4} \left(\frac{S}{10\ \mathrm{cm^2}} \right)^{-1/2} \left(\frac{\omega}{\mathrm{keV}} \right)^{-1/2}$$

DISCOVERY, NOT EXCLUSION?

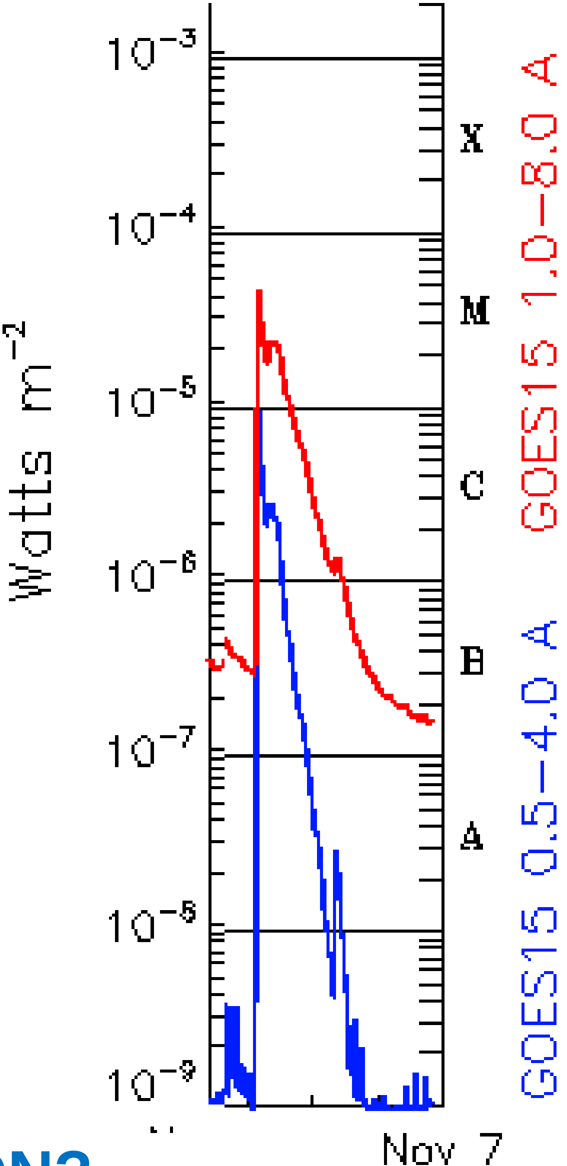
FLARES:

RESONANCE

DROP IN THE REGULAR
(NORMAL PHOTONS) LIGHT CURVE!

GOOD TIME-RESOLUTION
SOLAR INSTRUMENTS:

- SOXS (India)
- SPHINX (Russia-Poland)
- …



COINCIDENCE =
FIRM DISCOVERY, NOT EXCLUSION?

CONCLUSIONS:

1. PARAPHOTONS=WELL-MOTIVATED SM EXTENSION

2. PARASITICAL SEARCH WITH HELIOSCOPES

3. RESONANCES IN FLARES: A DISCOVERY CHANNEL
   (HELIOSCOPES + NORMAL TELESCOPES)