In [1]:
```
%matplotlib inline
import matplotlib.pyplot as plt
import numpy as np
from astropy.io import fits
```

Lab 6 -- Transiting exoplanet from TESS

Plase write your group members' names at the top of this assignment!

In this lab we will explore the transit method for detecting and characterizing extrasolar planets, using real data from the TESS mission

In [2]:
```
# load the data and print out variable names
f = fits.open('hlsp_qlp_tess_ffi_s0026-0000000157586003_tess_v01_llc.fi
ts')
print(f.info())
print(f[1].data.names)
```

```
Filename: hlsp_qlp_tess_ffi_s0026-0000000157586003_tess_v01_llc.fits
No.    Name      Ver    Type      Cards   Dimensions   Format
  0  PRIMARY       1 PrimaryHDU      29   ()
  1  LIGHTCURVE    1 BinTableHDU     65   1148R x 13C   [D, J, E, E,
E, J, J, E, E, E, E, E, E]
None
['TIME', 'CADENCENO', 'SAP_FLUX', 'KSPSAP_FLUX', 'KSPSAP_FLUX_ERR', '
QUALITY', 'ORBITID', 'SAP_X', 'SAP_Y', 'SAP_BKG', 'SAP_BKG_ERR', 'KSP
SAP_FLUX_SML', 'KSPSAP_FLUX_LAG']
```

1. Sample TESS transit light curve

The data are stored in the "LIGHTCURVE" portion of the FITS file, with variable names listed above. Looking at those, choose one that you think could represent the flux of the star vs time and write its name as flux_variable_name below. If there is more than one thing you think might be right try them out and see which one makes the most sensible plot!

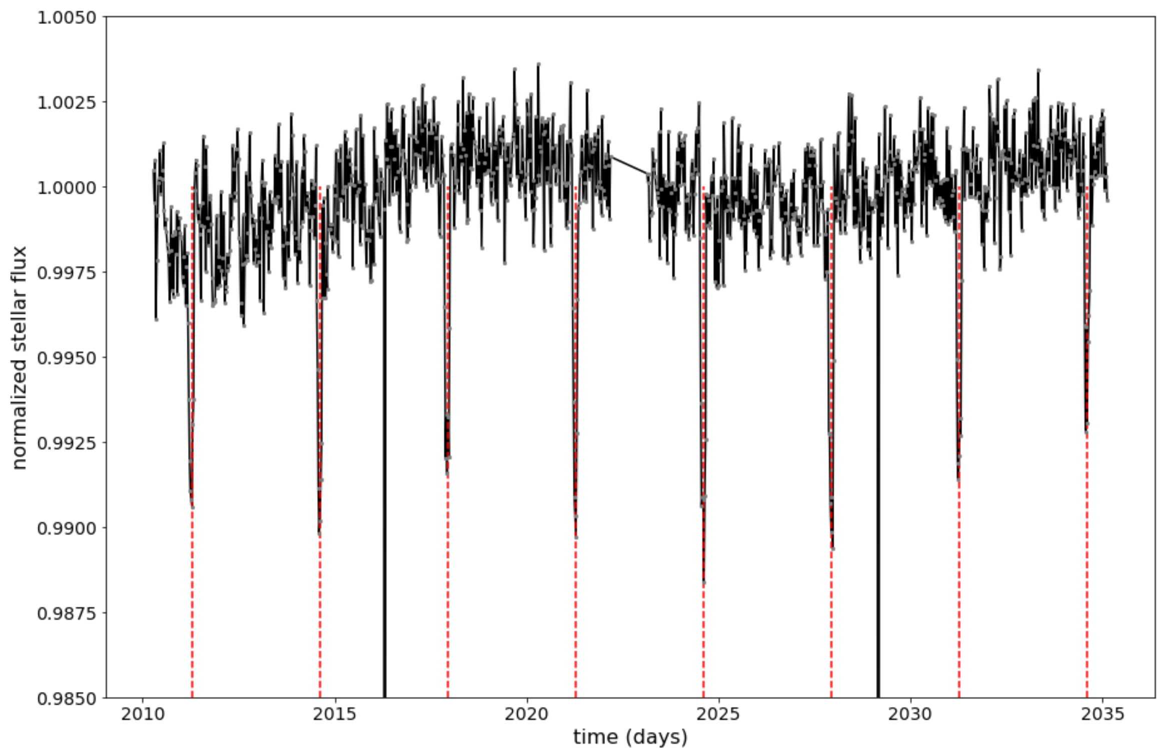
In [3]:
```
# write the variable name below
flux_variable_name='SAP_FLUX'
```

2. Identify and mark transit signatures

The plot below should make a light curve (flux of the star vs time).

Mark any promising transit signals (periodic drops in brightness) on the light curve plot. Fill in the time in days of the first transit, the period, and the depth of the signal in the variables below and then run the code to mark the transits on the plot.

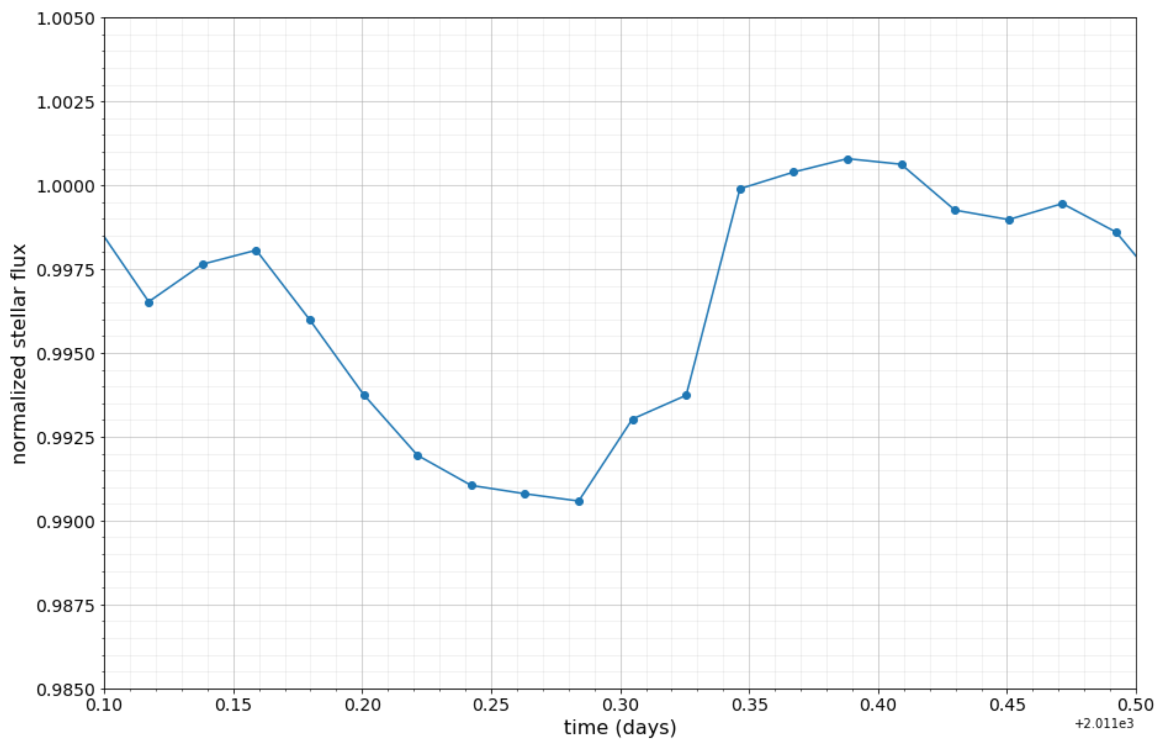
In [4]:
```
time_variable=f[1].data.field('TIME')
flux_variable=f[1].data.field(flux_variable_name)

fig = plt.figure(figsize=(15,10))
plt.plot(time_variable,flux_variable,color='k')
plt.scatter(time_variable,flux_variable,color='grey',s=5,zorder=3,marke
r='o')
plt.ylim(0.985,1.005)

plt.xlabel('time (days)',fontsize=16); plt.ylabel('normalized stellar f
lux',fontsize=16)

ax = plt.gca()
ax.xaxis.set_tick_params(labelsize=14)
ax.yaxis.set_tick_params(labelsize=14)

# replace these numbers with your own measurements!
first_transit_time=2011.3
period=3.33
depth=0.991

for i in range(8):
    plt.plot(first_transit_time+i*period+np.zeros(50),depth*np.arange(5
0)/49.+(1.-depth),linestyle='--',color='red')
```



3. Transit duration and depth

Use the plot below to zoom in on one of the transits and measure its duration + depth.

In [7]:
```
fig = plt.figure(figsize=(15,10))

plt.plot(time_variable,flux_variable,marker="o")
plt.ylim(0.985,1.005)

plt.xlabel('time (days)',fontsize=16); plt.ylabel('normalized stellar f
lux',fontsize=16)

ax = plt.gca()
ax.yaxis.set_tick_params(labelsize=14);ax.xaxis.set_tick_params(labelsi
ze=14)
plt.grid(b=True,which='minor',alpha=0.2);plt.grid(b=True,which='major',
alpha=0.7)
plt.minorticks_on()
plt.xlim(first_transit_time-0.2,first_transit_time+0.2)
ax.xaxis.grid(True,which='minor')
```



your estimated duration: 0.2 [days]

your estimated depth: 0.991 or 99.1%

4. The radius of the exoplanet

Write an equation for the radius of the exoplanet. What quantity does it depend on that we haven't measured from the transit light curve? [*Hint*: what ratio should the amount of light blocked depend on?]

Find the needed information in the FITS file header below, and solve for the radius of the planet in units of Earth radii.

In [6]:
```
print(f[0].header)
```

```
SIMPLE  =                    T / conforms to FITS standard
BITPIX  =                    8 / array data type
NAXIS   =                    0 / number of array dimensions
EXTEND  =                    T
NEXTEND =                    1 / number of standard extensions
EXTNAME = 'PRIMARY '           / name of extension
ORIGIN  = 'MIT/QLP '           / institution responsible for creating
this file TELESCOP= 'TESS    '           / telescope
INSTRUME= 'TESS Photometer'    / detector type
FILTER  = 'TESS    '           / the filter used for the observations
OBJECT  = 'TIC 157586003'      / string version of TICID
TICID   =            157586003 / unique TESS target identifier
SECTOR  =                   26 / last observed sector
CAMERA  =                    2 / camera
CCD     =                    4 / ccd
RADESYS = 'ICRS    '           / reference frame of celestial coordin
ates       RA_OBJ  =        279.262423557 / [deg] right ascension, J2
000                DEC_OBJ =         40.018689452 / [deg] declinat
ion, J2000                    TESSMAG =              12.0545 / [ma
g] TESS magnitude, TIC v8                RADIUS  =              1.
69483 / [solar radii] stellar radius                 LOGG    =
4.00101 / [cm/s2] log10 surface gravity                MASS    =
1.05 / [solar mass] log10 stellar mass               TEFF    =
5835.0 / [K] effective temperature                   MH      =
-1.0 / metallicity                                   EQUINOX =
2000.0 / equinox of celestial coordinate system        PMRA    =
8.778969999999999 / [mas/yr] RA proper motion                    PM
DEC    =             0.249596 / [mas/yr] DEC proper motion
TICVER  =                    8 / TIC Version
CALIB   = 'TICA    '           / pipeline used for image calibration
END
```

In [11]:
```
# the difference in transit depth is equal to the ratio of the cross se
ctional area of the planet to the cross sectional area of the star, so:

rStar = f[0].header['RADIUS'] # radius of star in solar radii

rPlanet = np.sqrt((1-0.991)*rStar**2) # radius of planet in solar radii

earthRadii = 109.076 # earth radii per 1 solar radii

rPlanet_earthRadii = rPlanet * earthRadii # convert solar radii to eart
h radii

print(f'So this exoplanet has a radius of {rPlanet_earthRadii:.1f} Eart
h radii')
```

```
So this exoplanet has a radius of 17.5 Earth radii
```

5. Transit duration and orbital semi-major axis

Use your measured transit duration and period to solve for the semi-major axis of the binary orbit. Express your answer in terms of the Earth-Sun distance 1AU = 1.5x10^13 cm. You may assume that the inclination is exactly edge-on ($i = 90^\circ$), although note that we do not know that here! [*Hint*: how far does the exoplanet travel during the transit?]

Using the semi-major axis and Kepler's 3rd law, solve for the total mass of the system. [Note: if you see the mass reported in the header above and are confused by the large discrepancy...so am I. It's definitely wrong so don't be distracted by it].

In [22]:
```
# during 1 transit, the planet appears to move a distance theta * a whe
re theta is the angular size of the planets transit and a is the semi-m
ajor axis
# so we know that theta / 0.2 = 2*np.pi / 3.33, thus:
theta = 0.2 * 2 * np.pi / 3.33 # in radians

# and since we're looking at it edge-on, i = 0, so the impact paramete
r, b = 0, thus the distance the planet has to travel across the disk is
given by l = np.sqrt((rPlanet + rStar)**2)

l = np.sqrt((rPlanet + rStar)**2)

# finally, by doing some simple trig, we find that:

semiMajor = l / np.sin(theta/2) # semi-major axis in solar radii

AUperSolar = 0.00465047 # AU per solar radii

MperSolar = 7e8 # meters per solar radii

semiMajor_m = semiMajor * MperSolar

semiMajor_AU = semiMajor * AUperSolar

# assuming the inclination is exactly edge-on and with my estimated per
iod of 3.33 days, we can use Kepler's 3rd law with the semimajor axis t
o find the total mass of the system
# rearranging Kepler's 3rd law to solve for M:

G = 6.67e-11 # graviational constant in SI units

period_days = 3.33 # days

period_years = period_days / 365

mass = semiMajor_AU**3 / period_years**2 # in solar masses

solarMass_kg = 1.989e30 # mass of sun in kg

mass_kg = mass * solarMass_kg

print(f'So this system has a total mass of {mass:.2f} Solar masses')
```

```
So this system has a total mass of 1.17 Solar masses
```

6. Planet mass from the radial velocity

This system also has radial velocity measurements, which show a line of sight velocity amplitude of 0.04 km s^{-1}. Solve for the mass of the planet, assuming it is much smaller than that of its host star. [*Hint*: recall the binary mass function!]

In [27]:
```
vPlanet = np.sqrt(G * mass / semiMajor_AU) # velocity of planet in m/s

vStar = 0.04 # velocity of star in km/s

vStar_ms = 0.04 * 1000 # velocity of star in m/s

# finally,

mPlanet = mass_kg * vPlanet / vStar_ms # mass of planet in kg
mPlanet
```

Out[27]: 2.396076152171734e+24

7. Daytime temperature

Given the effective temperature of the star above, how would the daytime temperature of the planet compare to that of Earth? [*Hint*: if you assume the only thing heating the planet is the incident starlight, what should this ratio depend on?]

In [29]:
```
# since the Teff is almost the same as our Sun, this ratio would depend on the semi-major axis of Earth squared, over the semi-major axis of this exoplanet squared

tempRatio = 1**2 / semiMajor_AU**2
tempRatio
```

Out[29]: 472.4343776928216

So apparently the daytime temperature is about 472 times that of earth.

8. Characterize the star - exoplanet system

Using your results above, how do the properties of this extrasolar planet compare to those in the Solar system? Which planet is it most similar to in radius and mass? Is its orbital location similar to where that planet is found in the Solar system?

Properties of solar system planets are listed e.g. at this link [https://nssdc.gsfc.nasa.gov/planetary/factsheet/ (https://nssdc.gsfc.nasa.gov/planetary/factsheet/)](https://nssdc.gsfc.nasa.gov/planetary/factsheet/)

My calculated radius and mass for this exoplanet don't really match any of the planets in our Solar system. With a radius of about 17 earth radii and a mass of only 2.4e24 kg, these properties seem very odd, which makes me think I did my calcuations wrong. If I had to answer, I would say Saturn is the planet that most resembles this one, but Saturn orbits at a MUCH larger distance than this exoplanet.