Spontaneous emission noise is an important limit to the performance of active plasmonic devices. Here, we investigate the spontaneous emission noise in the long-range surface plasmon-polariton waveguide based optical gyroscope. A theoretical model of the sensitivity is established to study the incoherent multi-beam interference of spontaneous emission in the gyroscope. Numerical results show that spontaneous emission produces a drift in the transmittance spectra and lowers the signal-to-noise-ratio of the gyroscope. It also strengthens the shot noise to be the main limit to the sensitivity of the gyroscope for high propagation loss. To reduce the negative effects of the spontaneous emission noise on the gyroscope, an external feedback loop is suggested to estimate the drift in the transmittance spectra and thereby enhance the sensitivity. Our work lays a foundation for the improvement of long-range surface plasmon-polariton gyroscope and paves the way to its practical application.

Results
The spontaneous emission plays an important role in light amplification based gain[4], especially in Stimulated emission in SPP. In a plasmonic amplifier, the spontaneous emission exhibits a complex behavior due to a variety of energy decay channels engendered by the metal[12]. We proposed an active gyroscope based on LRSPP resonator...
with gain, as shown in Fig. 1. In our model, apart from non-radiation channels, the spontaneous emission’s energy into shot-range surface plasmon polariton would decay fast with the increase of propagation length. For the energy into LRSPP, we used a vertical pumping mechanism to realize the optical gain and the gain is anisotropic depending on the structure and gain material (for example, dye molecule). As a result the coupling of spontaneous emission with the signal LRSPP is weak. So the major part of the SE’s energy propagating in the LRSPP resonator is in the radiation channel which is a bit far away from the metal (~100 nm).

We assume that the loss of the LRSPP resonator is nearly compensated by gain with carefully control on the pumping power. The intensity of the propagating wave in the LRSPP waveguide with gain follows the function that: \( \frac{dI}{dz} = A P_{g} + g I \) (where \( I \) is the propagating wave’s intensity, \( A \) is a constant, \( P_{g} \) is the pumping power and \( g \) is the gain). In our model, \( g \) is negative and the spontaneous emission noise would attenuates propagating along the waveguide.

One of the most significant differences between spontaneous emission and stimulated emission is that, the phases of spontaneous emitted photons are random, but the stimulated emitted photons are the same as the stimulating photons, i.e. the spontaneous emitted light is incoherent but the stimulated emitted is coherent. As the light in the ring resonator is essentially under multiple beam interference, in the LRSPP gyroscope the spontaneous emitted light and stimulated emitted light are substantially oscillating in two different forms, i.e. coherent interference and incoherent interference and superposing with each other.

The LRSPP resonator is shown in Fig. 1. \( E_{1}, E_{2}, E_{b}, E_{4} \) are the amplitudes of signal LRSPP’s electric field in the four ports of the directional coupler and \( P_{n3}, P_{n4} \) are the powers of the spontaneous emission noise at port 2–4. Here, we consider only the clockwise case. We assume that the resonator is single-mode and the input signal is single-frequency.

For the coherent interference of the signal LRSPP, the relationships of \( E_{1}, E_{2}, E_{b}, E_{4} \) are given by:

\[
E_{2} = \sqrt{1 - \Delta}(-jE_{1}\sqrt{1 - k} + E_{3}\sqrt{1 - k})
\]

\[
E_{4} = \sqrt{1 - \Delta}E_{1}\sqrt{1 - k},
\]

\[
E_{3} = \sqrt{1 - \Delta}E_{2}\exp\left(-\frac{\rho\Delta}{2}(1 - j\beta L)\right)
\]

where \( \Delta \) is the insertion loss of the coupler, \( k \) is the coupling ratio of optical power coupled form the top straight waveguide into the ring, \( L \) is the ring’s perimeter, \( \rho \) is coefficient of net loss which represents the propagation loss of the LRSPP waveguide with gain, and \( \beta \) is the propagation constant. Combing Eq. (1) – (3) yields the power transmittance:

\[
T(\phi) = \frac{E_{4}^{2}}{E_{1}^{2}} = (1 - \Delta)(1 - \Delta)(1 - \Delta)\exp\left(-\frac{\rho\Delta}{2}(1 - j\beta L)\right),
\]

with \( x = \exp(-\rho_L/2) \) and \( y = \sqrt{1 - k} \).

Table 1 | The process of the power change of spontaneous emission noise in the resonator

| \( P_{n3} \) | \( P_{n4} \) |
|----|----|
| \( n=1 \) | \( \eta \) |
| \( n=2 \) | \( \eta[1 - \Delta](1 - k) \times \exp(-\rho_{rad}L) \) |
| \( \eta[1 - \Delta]^2(1 - k)^2 \times \exp(-\rho_{rad}L) \) |
| \( \eta[1 - \Delta]k(1 - \Delta) \times \exp(-\rho_{rad}L) \) |
| \( \eta[1 - \Delta]^n(1 - k)^n - 1 \times \exp(-n-1\rho_{rad}L) \) |
| \( \eta[1 - \Delta]^n(1 - k)^n \times \exp(-n-1\rho_{rad}L) \) |
| \( \eta[1 - \Delta]^n(1 - k)^n - 1 \times \exp(-n-1\rho_{rad}L) \) |

where \( \eta \) is the coupling ratio of optical power coupled form the top straight waveguide into the ring, \( L \) is the ring’s perimeter, \( \rho \) is coefficient of net loss which represents the propagation loss of the LRSPP waveguide with gain, and \( \Delta \) is the propagation constant. Combing Eq. (1) – (3) yields the power transmittance.

Table 1 | The process of the power change of spontaneous emission noise in the resonator

| \( P_{n3} \) | \( P_{n4} \) |
|----|----|
| \( n=1 \) | \( \eta \) |
| \( n=2 \) | \( \eta[1 - \Delta](1 - k) \times \exp(-\rho_{rad}L) \) |
| \( \eta[1 - \Delta]^2(1 - k)^2 \times \exp(-\rho_{rad}L) \) |
| \( \eta[1 - \Delta]k(1 - \Delta) \times \exp(-\rho_{rad}L) \) |
| \( \eta[1 - \Delta]^n(1 - k)^n - 1 \times \exp(-n-1\rho_{rad}L) \) |
| \( \eta[1 - \Delta]^n(1 - k)^n \times \exp(-n-1\rho_{rad}L) \) |
| \( \eta[1 - \Delta]^n(1 - k)^n - 1 \times \exp(-n-1\rho_{rad}L) \) |
basic working principle is to store the drift under zero input signal and when with none-zero input, feed it back to the output. Thereby, the gyroscope produces a stable output and an improved sensitivity.

**SNLS.** The sensitivity of resonator gyroscope limited by signal-to-noise-ratio (SNR) is expressed as

\[
\Delta \Omega \approx \frac{\lambda L}{4A} \frac{\sqrt{2} \Delta f_{\text{FWHM}}}{\text{SNR}},
\]

where \(A\) is the area enclosed by the ring, \(\Delta f_{\text{FWHM}}\) is the FWHM of the resonant peak. The signal current from the photodetector is given by

\[
i_s = \eta_{D} \frac{e}{h} (T_{\text{max}} - T_{\min}) P_{\text{in}},
\]

where \(\eta_{D}\) is the quantum efficiency of the photodetector, \(e\) is the electronic charge, \(h\) is Planck’s constant, \(\nu\) is the frequency of input signal, and \(T_{\text{max}}\) and \(T_{\min}\) are the maximum and minimum values of the transmittance in Eq. (8), respectively. If the limiting noise is shot noise, the rms noise current from the photodetector is given by

\[
i_n = e \sqrt{\frac{\eta_{D} P_{\text{in}}}{\tau D h \nu}} \left[ T_{\text{max}} + \frac{\eta}{P_{\text{in}}} M \right]
\]

combing Eq. (9) – (11) with \(\text{SNR} = i_s/i_n\), the Shot Noise limited sensitivity is given as

\[
\Delta \Omega_{\text{SNLS}} \approx \frac{\lambda L}{4A} \sqrt{\frac{\sqrt{2} \Delta f_{\text{FWHM}}}{\eta_{D} P_{\text{in}}}} \frac{1}{h \nu} \sqrt{\frac{T_{\text{max}} - T_{\min}}{T_{\text{max}} + \frac{\eta}{P_{\text{in}}} M}}
\]

In comparison with the SNLS in Ref. 13, the SNLS affected by spontaneous emission noise increases by the factor of \(\sqrt{1 + \eta M/(P_{\text{in}} T_{\text{max}})}\). It can be understood that after introducing the power of the spontaneous emission noise, the SNR of the ring resonator is reduced, thereby worsening the SNLS.

**Transmittance.** For a real gyroscope system, the photoelectric effect based photo-detector is non-selective to light with different wavelengths to some extent which means power of noises with various wavelengths could be detected and affect the output results. Therefore, the spontaneous emission with a relatively wide spectrum could make an unnegligible difference on the gyroscope’s performance (the optical resonant gyroscope requires highly narrowed input light, typically the input laser’s linewidth has to be less than 10 MHz). Based on the discussion before, the power transmittance at port 4 is driven as,

\[
T' = \frac{T \times P_{\text{in}} + P_{N4}}{P_{\text{in}}} = T + \frac{P_{N4}}{P_{\text{in}}} = T + \frac{\eta}{P_{\text{in}}} \times M,
\]

where \(M = \frac{(1 - \delta)(1 - k)}{(1 - \delta)(1 - k) \exp (- \rho_{\text{net}} L)}\) and \(P_{\text{in}}\) is the power of the input signal LRSPP at port 1. It can be seen from Eq. (8) that the spontaneous emission noise introduces a frequency-independent upward drift to the transmittance curve. For a given gyroscope system, this transmittance drift is related to the ratio of spontaneous emission’s noise, \(\eta\) and input signal. Fig. 2 shows the transmittance spectra without, (a) (c) and with, (b) (d) the power of spontaneous emission for different net losses. It’s obvious that the power of spontaneous emission expose a big drift in the transmittance curve which would certainly make a difference on the sensitivity. For practical application, an external circuit should be designed to eliminate the drift. We propose a feedback loop. Its basic working principle is to store the drift under zero input signal and when with none-zero input, feed it back to the output. Thereby, the gyroscope produces a stable output and an improved sensitivity.
SELS. The power of spontaneous emission mainly impacts the mean photon number of the resonant ring which is given by:

\[ \langle n \rangle = \frac{N_{\text{eff}} P_c L}{2 \hbar \nu_c} \]  

where \( P_c \) is the power of light in the ring. The power of light in the ring includes signal LRSPP, \( P_{\text{in}} \), and the spontaneous emission noise at port 2, \( P_{\text{N2}} \), as follows:

\[ P_c = \frac{1}{\pi} F P_{\text{in}} + P_{\text{N2}} \]  

combining Eq. (6) and Eq. (14), following the derivation in the supporting information of Ref. 13, we get the SELS as:

\[ \Delta \Omega_{\text{SELS}} \approx \frac{\lambda c}{4 \sqrt{2} \pi \tau_{\text{eff}} N_{\text{eff}}} \times \left[ \frac{x_{\text{intr}} \hbar \nu}{\tau_{\text{eff}} (FP_{\text{in}} + \frac{1}{k} \pi M \eta)} \right]^{1/2}, \]  

where \( x_{\text{intr}} \) is the propagation loss of LRSPP the waveguide without gain (intrinsic loss, IL). \( F \) is the finesse of the gyroscope. In comparison with the SELS in Ref. 13, the SELS reduces by the factor of \( \sqrt{1/[1 + (1-k)\pi M \eta/(k F \eta)])} \). It can be understood that after introducing the power of the spontaneous emission noise, the total number of photons in the ring resonator increases and thus the disturbance of a single spontaneous emitted photon on the phase of the signal LRSPP is weakened relatively.

Figure 3 | Relation between Sensitivity and net loss with different intrinsic losses. (a) is for situation without the power of spontaneous emission and (b) with. (c) shows the gyroscope’s ultimate sensitivity with a feed-back loop.

\[ \text{Sensitivity (deg/h)} \]

\[ \text{net loss (dB/m)} \]

\[ \text{Sensitivity (deg/h)} \]

\[ \text{net loss (dB/m)} \]
obvious that the sensitivity of the gyro could be improved by the for an IL of 1 dB/cm, SNLS becomes bigger than SELS. As a result, spontaneous emission on SELS is small and the SNLS is significantly

Fig. 3(b), it can be found can be clearly seen that the impact of power on the sensitivity can not be ignored.

The model is numerically calculated to show the impact of spontaneous emission. Our theoretical study shows that the propagating energy of spontaneous emission noise are mainly in the radiation channel and undergoes an incoherent multi-beam interface in the resonator, forming a steady noise power in the output. This output noise produces a drift in the transmittance spectra and lowers the SNR of gyroscope which results in increased SNLS. However it makes small modification on SELS. For high net loss, e.g. above 0.2 dB/cm for an IL of 1 dB/cm, the spontaneous emission strengthens the SNLS to be the main limit to the gyroscopes sensitivity. In a practical gyroscope system, an external feedback loop is suggested to estimate the drift in the transmittance spectra and reduce the SNR of gyroscopic noise could be more than 1 mW. Although our LRSPP waveguide is of negative gain, the experiment of LRSPP waveguide give us some support in determining the power of spontaneous emission, experimental work of LRSPP gyroscope is needed and ongoing to demonstrate the practical performance of LRSPP gyroscope.

**Methods**

The LRSPP waveguide resonator with gain medium is pumped under a vertical pumping light with wavelength of 982 nm, and the signal LRSPPs wavelength is 1550 nm. The LRSPP waveguide consists of Si substrate, silver strip, and Erbium-doped phosphate glass. The Erbium-doped glass could be fabricated with 4.2% Er2O3 and 1% Yb2O3.

The radius r of the ring resonator is 2 cm, the width and thickness of silver film are 6 mm and 11 nm respectively, the respective width of input signal is 1 mW, the loss of the directional coupler is 5%, and the quantum efficiency and integration time of the detector are 0.9 and 1 h, respectively. The propagation loss of LRSPP is 1 mW and the power of spontaneous emission is set to be 10 dB/cm. Comparing Fig. 2(a) and Fig. 2(b), the signal LRSPP waveguide without gain is in the order of magnitude of 1 dB/cm14,15. For a 2.7 mm long waveguide with an input power of 2.1 mW and net gain of 10%, the output signal LRSPP waveguide could be more than 1 mW. Although our LRSPP resonator is of negative gain, the scale of our pumping area is far bigger which could result in bigger SE noise. In this letter, the range of magnitude of r is set to 0 mW − 15 mW. The original driving process of SNLS and SELS could be seen in Ref. 13 in detail.

**Discussion**

The model is numerically calculated to show the impact of spontaneous emission on the gyroscopes sensitivity (see methods in detail). For a given gyroscopes, the drift in the transmittance spectra concerns with M, i.e. the coupling ratio and net loss of the LRSPP waveguide. The transmittance spectra under fixed coupling ratio and optimum coupling depth (with $k = k_r = 1 - \langle 1 - \delta \rangle \exp(-\rho_{net}L)^{20}$) are compared with each other. In Fig. 2, (a)(b) are for fixed coupling ratio of 0.1 and (c)(d) are for optimum coupling depth. Here, the power of input signal LRSPP is 1 mW and the power of spontaneous emission is set to be 0.7 mW. Comparing Fig. 2 (a) and Fig. 2 (b), with fixed coupling ratio, the drift decreases with the net loss increases. This could be easily understood that with increased loss, the power of spontaneous emission would decay faster, thereby resulting in lower output noise and lower upward drift in transmittance curve. On the other hand, comparing Fig. 2 (c) and Fig. 2 (d), the drift increases with the net loss which results from different net losses and $k_r$. Calculated $k_r$ for net losses of 0.01 dB/cm, 0.1 dB/cm and 1 dB/cm are 0.0527, 0.0771 and 0.2888 respectively. The two opposite trends indicate that the effects of coupling ratio on the upward drift is bigger than that of net loss. The upward drift in the transmittance spectra adversely affects the angular velocity detection of the gyroscopes.

Fig. 3 shows the sensitivity is (a), (b) worsen by the drift in transmittance and (c) improved by the feedback loop mentioned before. Here, the same optimizing strategy of coupling ratio $k$ as that in Ref. 13 is used and $r$ is 0.7 mW. In comparison with Fig. 3(a) and Fig. 3(b), it can be found can be clearly seen that the impact of spontaneous emission on SELS is small and the SNLS is significantly strengthened by it. When the net loss is big, for example 0.2 dB/cm for an IL of 1 dB/cm, SNLS becomes bigger than SELS. As a result, the cross point of SNLS and SELS goes down to lower net loss. It’s obvious that the sensitivity of the gyro could be improved by the feed-back loop as mentioned before. When the loss is higher than the cross point of SNLS and SELS, the feed-back loop could enhance the SNR and therefore suppress the SNLS. Fig. 3(c) shows the ultimate limited sensitivity (LS) in a real gyroscopes system with a feed-back loop. The improvement from the feed-back loop relates to the net loss and IL. For example when the net loss is 1 dB/cm and IL is 10 dB/cm the LS is reduced from 10 deg/h to 3 deg/h and when the net loss is 0.5 dB/cm and IL is 5 dB/cm the LS is reduced from 2.76 deg/h to 1.98 deg/h.

Fig. 4 shows the impact of the power of spontaneous emission on the sensitivity. Fig. 4 (a) is for net loss ranging from 10^-3 dB/cm to 1 dB/cm and Fig. 4 (b) from 0.01 dB/cm to 1 dB/cm. Here, the intrinsic loss is 1 dB/cm and the serrated section in Fig. 4 (a) results from a minimum step value of $k_{14}$. It can be clearly seen in Fig. 4 (a) that with increased power of spontaneous emission, the SELS changes very little (all curves for different powers of spontaneous emission overlap in the black dashed line). SELS is still greater than SNLS with low net loss, e.g. smaller than 0.01 dB/cm. It could be understood that loss net loss corresponds to low optimized coupling ratio making the spontaneous emission noise mainly decay in the ring resonator. On the other hand, Fig. 4 (b) shows that SNLS increases faster with bigger powers of spontaneous emission. It’s easy to understand that bigger spontaneous noise leads to lower SNR and worse SNLS. Above all, the power of spontaneous emission worsens the SNLS and a feed-back loop is required to reduce this negative effects.

In conclusion, we investigated the performances of the LRSPP gyroscope taking into account the noise power of spontaneous emission. 1. Bergman, D. J. & Stockman, M. I. Surface plasmon amplification by stimulated emission of radiation: quantum generation of coherent surface plasmons in nanosystems. *Phys. Rev. Lett.* **90**, 027402 (2003).

2. Noginov, M. A., Zhu, G., Bahoura, M., Adegoke, J., Small, C. E., Ritzo, B. A., Drachev, V. P. & Shalaev, V. M. Enhancement of surface plasmons in an Ag aggregate by optical gain in a dielectric medium. *Opt. Lett.* **31**, 3022–3024 (2006).
3. Noginov, M. A., Podolskiy, V. A., Zhu, G., Masy, M., Bahoura, M., Adegoke, J. A., Ritchie, B. A. & Reynolds, K. Compensation of loss in propagating surface plasmon polariton by gain in adjacent dielectric medium. Opt. Express 16, 1385–1392 (2008).

4. De Leon, I. & Berini, P. Theory of surface plasmon-polariton amplification in planar structures incorporating dipolar gain media. Phys. Lett. B 78, 161401 (2008).

5. De Leon, I. & Berini, P. Spontaneous emission in long-range surface plasmon-polariton amplifiers. Phys. Lett. B 83, 081414 (2011).

6. De Leon, I. & Berini, P. Theory of noise in high-gain surface plasmon-polariton amplifiers incorporating dipolar gain media. Opt. Express 19, 20506–20517 (2011).

7. Gather, M. C., Meerholz, K., Danz, N. & Leosson, K. Net optical gain in a plasmonic waveguide embedded in a fluorescent polymer. Nat Photonics 4, 457–461 (2010).

8. Ambati, M., Nam, S. H., Ulin-Avila, E., Genov, D. A., Bartal, G. & Zhang, X. Observation of stimulated emission of surface plasmon polaritons. Nano Lett. 8, 3998 (2008).

9. Krasavin, A. V., Vo, T. P., Dickson, W., Bolger, P. M. & Zayats, A. V. All-plasmonic modulation via stimulated emission of copropagating surface plasmon polaritons on a substrate with gain. Nano Lett. 11, 2231–2235 (2011).

10. Granddidier, J., Des Francs, G. C., Massenot, S., Bouchelier, A., Markey, L., Weeber, J. C., Finot, C. & Dereux, A. Gain-assisted propagation in a plasmonic waveguide at telecom wavelength. Nano Lett. 9, 2935–2939 (2009).

11. Colas des Francs, G., Bramant, P., Granddidier, J., Bouchelier, A., Weeber, J. C. & Dereux, A. Optical gain, spontaneous and stimulated emission of surface plasmon polaritons in confined plasmonic waveguide. Opt. Express 18, 16327–16334 (2010).

12. De Leon, I. & Berini, P. Amplification of long-range surface plasmons by a dipolar gain medium. Nat Photonics 4, 382–387 (2010).

13. Zhang, T., Qian, G., Wang, Y. Y., Xue, X. J., Han, F., Li, R. Z., Wu, J. Y. & Zhang, X. Y. Integrated optical gyroscope using active Long-range surface plasmon-polariton waveguide resonator. Sci. Rep. 4, 3855 (2014).

14. Falkenstein, W., Penzkofer, A. & Kaiser, W. Amplified spontaneous emission in rhodamine dyes: generation of picosecond light pulses and determination of excited state absorption and relaxation. Opt. Commun. 27, 151–156 (1978).

15. Sorek, Y., Reissfeld, R., Finkelstein, I. & Ruschin, S. Light amplification in a dye-doped glass planar waveguide. Appl. Phys. Lett. 66, 1169–1171 (1995).

16. Seidel, J., Grafström, S. & Eng, L. Stimulated emission of surface plasmons at the interface between a silver film and an optically pumped dye solution. Phys. Rev. Lett. 94, 177401 (2005).

17. Stokes, L. F., Chodorow, M. & Shaw, H. J. All-fiber stimulated Brillouin ring laser with submilliwatt pump threshold. Opt. Lett. 7, 509–511 (1982).

18. Boltasseva, A. & Bozhevolnyi, S. I. Directional couplers using long-range surface plasmon polariton waveguides. J. IEEE 12, 1233–1241 (2006).

19. Han, Z., Elezzabi, A. Y. & Van, V. Wideband V-spliter and aperture- assisted coupler based on sub-diffraction confined plasmonic slot waveguides. Appl. Phys. Lett. 96, 131106 (2010).

20. Einstein, A. The Photoelectric Effect. Ann. Phys. 17, 132 (1905).

21. Suzuki, K., Takiguchi, K. & Hotate, K. Monolithically integrated resonator microoptic gyro on silica planar lightwave circuit. Lightwave Technol. 18, 66–72 (2000).

22. Ciminelli, C., Peluso, F. & Armenise, M. N. A new integrated optical angular velocity sensor. Proc. SPIE 5728, 93–100 (2005).

23. Ciminelli, C., Dell’Olio, F. & Passaro, V. M. Advances in Gyroscope Technologies. Springer, p. 63 (2011).

24. Shupe, D. M. Fiber resonator gyroscopes: sensitivity and thermal nonreciprocity. Appl. Opt. 20, 286–289 (1981).

25. Hisao, H. K. & Winick, K. A. Planar glass waveguide ring resonators with gain. Opt. Express 15, 17783–17797 (2007).

26. Schwelb, O. Transmission, group delay, and dispersion in single-ring optical resonators and add/drop filters-a tutorial overview. J. Lightwave Technol. 22, 1380 (2004).

27. Ju, J.-I., Park, S., Kim, M.-S., Kim, J.-T., Park, S.-K., Park, Y.-J. & Lee, M.-H. 40 Gbit/s light signal transmission in long-range surface plasmon waveguides. Appl. Phys. Lett. 91, 171117–171117 (2007).

Acknowledgments
This work is supported by NSFC under grant number 61307066, Doctoral Fund of Ministry of Education of China under grant number 20110092110016 and 20130092120024, Natural Science Foundation of Jiangsu Province under grant number BK20130630, the National Basic Research Program of China (973 Program) under grant number 2011CB302004 and the Foundation of Key Laboratory of Micro-Inertial Instrument and Advanced Navigation Technology, Ministry of Education, China under grant number 201204.

Author contributions
Y.-Y.W. performed the calculations and wrote the manuscript. T.Z. provided advices and helpful theoretical discussion. All authors reviewed the manuscript and discussed the results.

Additional information
Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Wang, Y.-Y. & Zhang, T. Spontaneous emission noise in long range surface plasmon polariton waveguide based optical gyroscope. Sci. Rep. 4, 6369; DOI:10.1038/srep06369 (2014).

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivs 4.0 International License. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in the credit line; if the material is not included under the Creative Commons license, users will need to obtain permission from the license holder in order to reproduce the material. To view a copy of this license, visit http://creativecommons.org/licenses/by-nc-nd/4.0/